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Chapter 2

Physics Goals

2.1 Overview

In this chapter we will describe the physics goals of the CDF II experiment, and the connection between the physics and the detector design. Our physics plan includes six complementary lines of attack on the open questions of the Standard Model:

- search for a light Higgs boson
- characterization of the properties of the top quark
- a global precision electroweak program
- direct search for new phenomena
- tests of QCD at large $Q^2$
- constraint of the CKM matrix with B hadrons

This physics program is comprehensive in its methods and its scope. It has classic precision measurements, such as $m_W$ and $\alpha_s$, taken to a new level of accuracy; it has a survey of newly discovered territory, in the first complete study of the top quark; and it extends our reach for new phenomena into a regime where current theoretical speculation suggests new structure. We believe that the power of the CDF II detector combined with the sensitivity of the Run II data sets will result in a significant advance in our understanding of the behavior of elementary particles, if not outright discovery of physics beyond the Standard Model.

In this chapter we will justify this claim. We begin with a summary of our conclusions and then turn to each of the six topics in detail. Since the CDF II experiment re-uses or extends many of the same detector technologies and strategies as its predecessor, the physics analyses of Run II will employ many of the techniques refined during Run I. The physics projections and detector specifications will therefore frequently appeal to a brief review of the current status. We note that our conclusions have the power of direct extrapolations from a well tuned device in a well measured environment.

Table 2.1 shows the expected yields for some benchmark processes with 15 fb$^{-1}$ of Tevatron collisions recorded by the CDF II detector. These are the numbers of identified events available for offline analysis. The statistical precision of Run II, combined with capability of the CDF II detector, will provide rich programs of measurement in each of the six sub-fields, summarized below.

2.1.1 Higgs Boson Physics

The origin of electroweak symmetry breaking is one of the most fundamental questions in elementary particle physics. One explanation is the existence of Higgs bosons. Fits to precision electroweak data suggest that one of the Higgs bosons should be light (below 200 GeV/$c^2$), and the minimal supersymmetric model requires a Higgs boson with mass less than about 130 GeV/$c^2$. These facts make the search for light Higgs bosons one of the most important goals of experimental elementary particle physics. The CDF and D0 experiments have the opportunity to make this discovery in Tevatron Run II. This search directly drives our plan to upgrade the CDF detector to a configuration that will operate with B tagging capabilities at instantaneous luminosities of $5 \times 10^{32}$ cm$^{-2}$s$^{-1}$ and integrated luminosities approaching 30 fb$^{-1}$. The details of the Tevatron search strategy for a light Higgs boson have been explored in a Fermilab Higgs Workshop [2]. A brief summary of this workshop and the CDF plans for Higgs boson searches are presented in Section 2.2.
<table>
<thead>
<tr>
<th>Mode</th>
<th>Yield ($15 \text{ fb}^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOP</td>
<td></td>
</tr>
<tr>
<td>dilepton</td>
<td>1125</td>
</tr>
<tr>
<td>$W + 3j \cdot b$</td>
<td>6750</td>
</tr>
<tr>
<td>$W + 4j \cdot b$</td>
<td>5440</td>
</tr>
<tr>
<td>$W + 4j \cdot bb$</td>
<td>1350</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>VECTOR BOSONS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$W \rightarrow \ell \nu (e, \mu)$</td>
<td>32M</td>
</tr>
<tr>
<td>$Z \rightarrow l^+l^- (e, \mu)$</td>
<td>4.5M</td>
</tr>
<tr>
<td>$W\gamma, W \rightarrow e\nu$</td>
<td>30K</td>
</tr>
<tr>
<td>$Z\gamma, Z \rightarrow e^+e^-$</td>
<td>13.5K</td>
</tr>
<tr>
<td>$W^+W^- \rightarrow \ell\nu\nu$</td>
<td>1500</td>
</tr>
<tr>
<td>$W^+Z^- \rightarrow \ell\nu\ell$</td>
<td>375</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>QCD</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$j + X,</td>
<td>\eta</td>
</tr>
<tr>
<td>$jj + X, M_{jj} \geq 600$ GeV</td>
<td>225K</td>
</tr>
<tr>
<td>$\gamma + X, p_T(\gamma) \geq 25$ GeV</td>
<td>45M</td>
</tr>
<tr>
<td>$\gamma\gamma + X, p_T(\gamma_1, \gamma_2) \geq 12$ GeV</td>
<td>105K</td>
</tr>
<tr>
<td>$W^+ \geq 1j, E_T(W) \geq 100$ GeV</td>
<td>75K</td>
</tr>
<tr>
<td>$Z^+ \geq 1j, E_T(Z) \geq 100$ GeV</td>
<td>7.5K</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$B$</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow J/\psi K_S$</td>
<td>150K</td>
</tr>
<tr>
<td>$B^0 \rightarrow \pi^+\pi^-$</td>
<td>38K</td>
</tr>
<tr>
<td>$B_s \rightarrow J/\psi\phi$</td>
<td>60K</td>
</tr>
</tbody>
</table>

Table 2.1: Representative yields for known processes, after selection. We use the CDF Run I selections modified for increased coverage of the CDF II detector (see text) and we assume 2.0 TeV collisions. $j \equiv$ jet, and $j \ast b \equiv$ b-tagged jet.

### 2.1.2 Properties of the Top Quark

A sample of almost 7,000 b-tagged, identified events will allow a detailed survey of the properties of the top quark. A review of this program is given in Section 2.3.

The top mass will be measured with a precision conservatively estimated to be 2.0 GeV/c^2. The total cross section will be measured to 6%, and non-standard production mechanisms will be resolvable down to total cross sections of ~90 fb. The branching fraction to b quarks will be measured to 1%, decays to non-W states may be explored at the level of 3%, and branching ratios to the various W helicity states will be measured with uncertainties of order 1%. The magnitude of any FCNC decay will be probed down to branching fractions of 0.5% or less. We will isolate the electroweak production of single top, allowing a cross section measurement with an uncertainty of 12%, and inference of $|V_{tb}|$ with a precision of 6%.

The final top physics program will undoubtedly be richer than this list, which should be interpreted as a catalog of probable sensitivities for the baseline top survey and whatever surprises the top may have in store.

### 2.1.3 A Precision Electroweak Program

The study of the weak vector bosons at the Tevatron is anchored in the leptonic decay modes. The new plug, intermediate muon system and integrated tracking will give triggerable electron coverage out to $|\eta| = 2.0$, triggerable muon coverage out to $|\eta|$ of at least 1.2 and taggable muon coverage out to $|\eta| = 2.0$. This will double the number of $W \rightarrow e\nu$ events and triple the acceptance for $Z$’s and dibosons in the electron and muon channels. A data set of 15 fb$^{-1}$ in combination with the acceptance and precision of the CDF II detector results in the comprehensive program in electroweak physics discussed in detail in Section 2.4.

One of our main goals is the measurement of $m_W$ with a precision of $\pm 20$ MeV/c$^2$. The combined precision on $m_W$ and $m_{t_{	ext{top}}}$ will allow inference of the Standard Model Higgs mass $m_H$ with precision of 30%.

The W decay width, $\Gamma_W$, will be measured to 15 MeV, a factor of twelve improvement on the LEP-II expectation. The precision on $A_{FB}$ at the $Z^0$ pole will be sufficient to improve on the measurement of $\sin^2 \theta_W^{\text{eff}}$ over LEP and SLD results, and measurement off the pole will be sensitive to new phenomena at high mass scales. Limits on anomalous WWV and ZZ$\gamma$ couplings, bolstered by the forward tracking and lepton identification, will surpass those of LEP-II. The W charge asymmetry measurement, also augmented by unambiguous lepton ID in the plug region, will provide much improved constraints on parton distribution functions.

### 2.1.4 Search for New Phenomena

The CDF II experiment will search for new objects at and above the electroweak scale. There is at present a great deal of theoretical activity focused on new phenomena in this regime, with predictions from models invoking supersymmetry, technicolor, and new U(1) symmetries. The magnitude of the top quark mass
and speculation about an excess in the top cross-section have led to other theoretical predictions about phenomena well within our reach in Run II, such as topcolor. Search strategies for these and other models are discussed in Section 2.5.

We will be sensitive to charginos up to 130 GeV/c², to gluinos up to 270 GeV/c², and to stop squarks up to 150 GeV/c². Second generation lepto-quarks can be observed up to masses of 300 GeV/c², new vector bosons can be probed up to masses of 900 GeV/c², and excited quarks up to 800 GeV/c². Quark compositeness can be observed up to a scale of approximately 5 TeV. These are all model dependent limits, and, as in the case of the top survey above, we believe that our catalog of prospects here is best interpreted as a list of probable sensitivities for the real surprises waiting at the electroweak scale.

2.1.5 Precision QCD at Large $Q^2$

The QCD sector of the Standard Model will be stringently tested using the production and fragmentation properties of jets, and the production properties of W/Z bosons, Drell-Yan lepton pairs, and direct photons. We will evaluate the precision of QCD calculations beyond leading order (higher order perturbative calculations and soft gluon resummation corrections), and determine the fundamental input ingredients, namely parton distribution functions and the running coupling constant $\alpha_s$.

The precision of QCD measurements at CDF II with 15 fb⁻¹ will provide sensitivity to many sources of new physics. For example, the strong coupling constant $\alpha_s$ will be measured over the entire range $10^3 \text{GeV}^2 < Q^2 < (500 \text{ GeV})^2$, and deviations from the Standard Model running could signal loop contributions from new particles. A direct search for the substructure of quarks at the level of $10^{-19}$ m will be possible with high $E_T$ jets and the production angular distribution of di-jets. Finally a broad range of searches will be carried out for the decays of massive particles to various combinations of jets, W/Z bosons, photons and neutrinos via missing $E_T$.

2.1.6 Constraining the CKM Matrix

CDF II plans to take advantage of the copious production of the various species of $b$ hadrons at the Tevatron to make measurements which will test the consistency of the Standard (CKM) Model of weak quark mixing and $CP$ violation. By extending the capabilities developed in Run I into Run II, CDF II expects to be able to measure $CP$ asymmetries in $B^0 \to J/\psi K_S$ and $B^0 \to \pi^+ \pi^-$ decays with a precision comparable to the $e^+ e^-$ colliders. Complementary information will come from a sensitive search for $CP$ violation in $B_s \to J/\psi K_S$ decays. The effects of mixing in the $B_s - \bar{B}_s$ system will be measured, allowing a determination of the ratio of CKM elements $|V_{td}/V_{ts}|$ over the full range allowed by the Standard Model.

In addition CDF II will continue to improve the precision on measurements of $b$ hadron decay properties (e.g. $B^0$ vs. $B^+$ lifetimes) and pursue the observation and study of rare decays (e.g. $B^0 \to K^{*0}\mu^+\mu^-$). The physics of heavier $b$ hadrons, for instance $B_c$, will be the exclusive domain of the Tevatron collider for at least the next decade. An overview of CDF II expectations for $B$ physics in Run II is given in Section 2.7.

2.1.7 Detailed Discussion

The scientific prospects for CDF II are discussed in the following sections of this chapter.

The physics opportunities provide much of the rationale for the CDF II design choices, and the discovery prospects detailed here underscore our excitement about completing this upgrade and returning to high luminosity data taking at the Tevatron Collider as quickly as possible.
2.2 Higgs physics in Run 2b

The search of the origin of electroweak symmetry breaking is the central question in high energy physics today. The most recent fits to the world’s combined electroweak data[1] favor the existence of a Standard-Model-like Higgs with mass in the range 100-200 GeV. The lower limit on the Higgs mass from the LEP2 experiments is 113.4 GeV; the data from all four experiments show a 2-sigma excess at a Higgs mass of about 115 GeV.

The Tevatron experiments have the opportunity, in the years before the LHC turns on, to search for the Higgs both in the Standard Model (SM) and in supersymmetry, using a variety of search channels discussed here. The Run 2b upgrades, and in particular the replacement for the Run 2a silicon vertex detector, are crucial to carrying out this physics program.

2.2.1 Standard Model Higgs

Events with a SM scalar Higgs can be produced at the Tevatron in several ways. The most copious production mode is gluon-gluon fusion via a heavy quark loop, giving a single Higgs produced. The Higgs can also be produced in association with a W or Z boson via its couplings to the vector bosons. Figure 2.1 shows the production cross section for various modes as a function of Higgs mass.

Figure 2.2 shows the branching ratios of the Standard Model Higgs as a function of Higgs mass. In the range below about 135 GeV Higgs mass, the decay to \( bb \) dominates, and for larger masses the decay to \( W \) pairs dominates.

In the gluon fusion case, for low mass Higgs, there is an overwhelming background from QCD production of \( bb \) pairs. The \( WH \) and \( ZH \) modes, however, have been extensively studied[2] and lead to several distinct signatures in which a Higgs signal can be observed with sufficient integrated luminosity.

2.2.2 Low-mass Higgs

For low mass (< 135 GeV) Higgs, the most sensitive signatures arise from the leptonic decays of the W and Z, and are denoted \( ℓνbb \), \( ννbb \), and \( ℓ+ℓ−bb \). Hadronic decays of the W and Z lead to the \( q̅qb̅b \) final state which suffers from large backgrounds from QCD multijet production.

In Run 1 in CDF, all four of these channels were studied, and led to limits on the Higgs cross section times branching ratio to \( bb \) as depicted in Figure 2.3. As the plot shows, the Run 1 limits are more than an order of magnitude above the expected Standard Model cross section, naturally provoking the question of whether and how this search can be carried out in Run 2.

Improvements to the detector, coupled with much higher instantaneous luminosity in Run 2 lead to greatly enhanced sensitivity in the Standard Model Higgs search. Unlike the Run 1 detector, the CDF Run 2 detector has a silicon vertex detector covering the entire luminous region, and has measurements of the z coordinates of tracks. Overall, the tracking coverage out to nearly \( |η| = 2 \) and the new muon chambers lead to greatly improved acceptance for Higgs. For the missing \( E_T \) channel (\( ννbb \)) channel, the trigger efficiency can be improved by using the silicon vertex trigger (SVT) to tag the jets. Coupled with the fact that the accelerator is expected to deliver a data sample over a hundred times larger than that in Run 1, the overall sensitivity of the Higgs search is dramatically improved in Run 2.

Beyond the improvements to the detector itself, maximizing the sensitivity of the search for the Higgs depends most critically on attaining the best possible \( bb \) mass resolution, and attaining the best possible \( b \) jet tagging efficiency and purity, and understanding and controlling the main irreducible backgrounds from vector boson plus heavy flavor production.

In Run 1 the top quark discovery and subsequent determination of its mass demonstrated that one could use jet information, even jets from \( b \) quarks, which have a significant semileptonic branching ratio, to determine the top mass. The case of the Higgs is simpler than that of the top, which suffers from large combinatorics. For the Higgs, the mass resolution is limited by basic physics (missing energy from neutrinos and gluon radiation) and detector resolution.

The benefit of making corrections for missing neutrinos is illustrated by CDF’s search in Run 1 for \( Z \to bb \). Figure 2.4 shows the successive effects of correcting for overall missing energy, and muon \( p_T \), and more general jet energy corrections. The mass resolution attained in this analysis was 13.5%; for a 120 GeV Higgs (in the background-dominated process \( Z \to bb \)) the resolution predicted is 12%.

One can improve upon the jet energy corrections employed in most Run 1 analyses by making the best possible use of all detector information, including tracking, shower max, calorimeter, and muon cham-
bers. Figure 2.5 shows the improvement to jet energy resolution possible by determining jet energy from an optimum linear combination of all jet information. Using all information results in a 30% improvement in jet energy resolution.

A great deal of simulation and calibration work remains and is presently underway. Optimistically, by putting together all the best kinematic corrections with optimal jet energy corrections, we hope to eventually achieve 10-12% mass resolution for the Higgs in the main low-mass search channels. (This is not as good as the $Z \to b\bar{b}$ case because there is additional missing energy in the Higgs channels due to neutrinos from $W$ and $Z$ decay.)

Figure 2.6 shows the raw mass distribution and Figure 2.7 shows the background-subtracted signal in the $t\bar{t}b\bar{b}$ case, for a 120 GeV SM Higgs, combining data from both CDF and D representing 15 fb$^{-1}$ integrated luminosity, assuming a 10% $b\bar{b}$ mass resolution, which is what was assumed (optimistically) in the Tevatron Run 2 Higgs report. The figure clearly illustrates that even with the best resolution attainable, discovering the Higgs remains a major challenge.

### 2.2.3 High-mass Higgs

For larger Higgs masses (> 135 GeV), the Higgs decays predominantly to $WW^(*)$. Two modes have been shown[2] to be sensitive in this mass range: $t\bar{t}V$ (from gluon fusion production of single Higgs) and $t\bar{t}jj$ (from tri-vector-boson final states).

The critical issues in these search modes are accurate estimation of the very large (~10 pb) $WW$ background in the $t\bar{t}V$ case and channel and estimation of the $t\bar{t}$ and $W/Z+\text{jets}$ backgrounds in the like-sign dilepton channel.

### 2.2.4 SM Higgs Reach in Run 2

The integrated luminosity required to discover or exclude the Standard Model Higgs, combining all search channels and combining the data from CDF and D, is shown in figure 2.8. The lower edge of the bands is the nominal estimate of the Run 2 study, and the bands extend upward with a width of about 30%, indicating the systematic uncertainty in attainable mass resolution, $b$ tagging efficiency, and other parameters.

The figure clearly shows that discovering a SM (or SM-like) Higgs at the 5-sigma level requires a very large data sample: even with 15 fb$^{-1}$, the mass reach is about 120 GeV at best. A 95% CL exclusion can, however, be attained over the entire mass range 115-190 GeV with the integrated luminosity foreseen in Run 2b.

The $b\bar{b}$ mass resolution assumed in making these estimates is 10% in the central part of the distribution. This represents a significant improvement over the 14-15% resolution achieved in this analysis in Run 1, which did not benefit from the more detailed corrections described above and developed after the analysis was completed. A great deal of effort, presently underway, is needed to understand the jet energy corrections to the level required to attain 10% resolution. The required integrated luminosity for Higgs discovery scales linearly with this resolution.

The estimates of required integrated luminosity assume that the $b$ tagging efficiency and purity are essentially the same as in Run 1 in CDF, per taggable jet. The better geometric coverage of the Run 2a and 2b silicon systems, however, is taken into account and leads to a much larger taggable jet efficiency. Since the required integrated luminosity scales inversely with the square of the tagging efficiency (assuming constant mistagging rates), however, there is a potentially great payoff for developing high-efficiency algorithms for $b$-tagging. Any such algorithms depend crucially on the quality of the information coming from the silicon vertex tracking system; the Run 2b silicon system has indeed been designed to optimize the performance in high-$E_T$ $b$ jet tagging.
Figure 2.2: Branching ratios for Standard Model Higgs.

Figure 2.3: Limits on SM Higgs cross section times branching ratio to $b\bar{b}$ from CDF in Run 1.

Figure 2.4: Mass resolution improvement for $Z \rightarrow b\bar{b}$ events as successive corrections are applied. After all corrections the resolution is 12%.

Figure 2.5: Jet energy resolution as a function of jet $E_T$, comparing standard corrections based on calorimeter only with energy determination combining information from tracking detectors, calorimetry, and shower max.
Figure 2.6: Distribution of $b\bar{b}$ mass in the $t\bar{t}b\bar{b}$ Higgs search channel, showing expected background sources and expected signal from 120 GeV SM Higgs, combining 15 fb$^{-1}$ of data from CDF and D.

Figure 2.7: Background subtracted $b\bar{b}$ mass distribution in the $t\bar{t}b\bar{b}$ channel, showing expected signal from 120 GeV SM Higgs, combining 15 fb$^{-1}$ of data from CDF and D.

Figure 2.8: The integrated luminosity required per experiment to either exclude a SM Higgs boson at 95% CL or discover it at the $3\sigma$ or $5\sigma$ level, as a function of the Higgs mass. These results are based on the combined statistical power of both CDF and D and combining all search channels.

2.2.5 SUSY Higgs

In the context of the minimal supersymmetric standard model (MSSM) the Higgs sector has two doublets, one coupling to up-type quarks and the other to down-type quarks and leptons. There are five physical Higgs boson states, denoted $h$, $A$, $H$, and $H^\pm$. The masses and couplings of the Higgses are determined by two parameters, usually taken to be $m_A$ and $\tan\beta$ (the ratio of the vacuum expectation value of the two Higgs doublets), with corrections from the scalar top mixing parameters.

The light scalar $h$ can appear very Standard-Model-like or nearly so over a larger range of MSSM parameter space. In this scenario the results of the search for the SM Higgs produced in the $WH$ and $ZH$ modes are directly interpretable. Figure 2.9 shows the range in the space of $m_A$ versus $\tan\beta$ in which a 5-sigma discovery can be made, as a function of integrated luminosity, for one choice of stop mixing.

More interesting is the case of large $\tan\beta$. Since the coupling of the neutral Higgses ($h/A/H$) to down-type quarks is proportional to $\tan\beta$, there is an enhancement factor of $\tan^2\beta$ for the production of $b\bar{b}\phi, \phi = h, A, H$ relative to the SM rate appearing in figure 2.1. This leads to distinct final states with four $b$ jets; if we demand that at least three of the jets be tagged, the background from QCD multijet processes is relatively small. In Run 1, CDF searched for this process, and from the null result excluded a
large swath of MSSM parameter space inaccessible to LEP, as shown in figure 2.10.

Based on the Run 1 analysis, and taking into account the improved $b$-tagging efficiency, Figure 2.11 shows the regions of $m_A$ versus $\tan\beta$ that CDF can cover for different integrated luminosities. It is interesting to note that the sensitive region in this analysis includes the region which is difficult to cover using the results of the SM Higgs search (shown in Figure 2.8). For this analysis the Run 2 $b$ silicon vertex system plays an absolutely crucial role: the accepted signal rate is proportional to the cube of the $b$ tagging efficiency!

### 2.2.6 Summary

With an upgraded detector and more than an order of magnitude larger instantaneous luminosity the CDF experiment, combined with D, has a significant chance of discovering a SM (or SM-like) Higgs boson in Run 2. If the Higgs mass is larger than about 130 GeV, the experiment is sensitive to the WW decay modes in two main channels. The experiment also has the chance to discover the Higgs in the MSSM, if $\tan\beta$ is large, via the striking four-$b$-quark final state.

The key experimental issues are maintaining the excellent secondary vertex tagging efficiency throughout the run, and working hard to understand and improve the dijet mass resolution. Clearly the physics motivation for the Run 2b upgrade to the silicon vertex system is strong, and without it this physics cannot be addressed at all.
Figure 2.11: Anticipated limits in the plane of $\tan \beta$ versus $m(A)$ using $b\bar{b}$ final state.
Bibliography


2.3 Properties of the Top Quark

The top quark, with mass $\sim 175$ GeV/c$^2$, is strongly coupled to the electroweak symmetry breaking mechanism, and decays to a real $W$ and a $b$-quark before hadronizing. A program to characterize the properties of this unconventional fermion is an obvious scientific priority. The accessibility of the top quark at the Fermilab Tevatron, in conjunction with the planned luminosity and detector upgrades for Run II, creates a new arena for experimental particle physics at an existing facility, and we should fully exploit this unique opportunity over the next decade.

Tevatron Run I brought the discovery of the top quark, the first direct measurements of its mass and cross section [2, 3, 4], and valuable first experience in top quark physics. We established techniques to identify $b$-quark jets using secondary vertices and soft leptons from the decays $B \rightarrow \ell \nu X$ as well as establish the essential utility of $b$-tagging in the isolation of the top signal. We established techniques for the accurate measurement of the mass and decay kinematics of a heavy object in final states with jets, and the essential utility of in situ jet calibration techniques. We have explored a variety of other measurements, all of them presently limited by statistics. [44, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 45]

Armed with this experience, we have just embarked on Run IIa, a new physics program with an expected delivered luminosity of 2 fb$^{-1}$ here at the Tevatron [1]. With this data in hand, we expect to make significant contributions to our current understanding of the top quark as discussed in the Run II Technical Design Report (TDR) [35].

This document takes as a basis the Run II TDR but takes it one step further by examining the top quark physics potential with 15 fb$^{-1}$ worth of data. We will show that the CDF IIb detector will be capable of a complete characterization of the main properties of the top quark, and we will establish the probable precisions that can be achieved using 15 fb$^{-1}$ of Tevatron collider data.

Since Run IIa is still in its infancy, we are not currently able to report any new physics results. Instead, we begin by reviewing the top analysis results of Run I. Next, we discuss the impact of the detector upgrade components on the top physics of Run IIb. Finally, we describe the Run IIb top physics program, including yields, the mass measurement, production properties, branching ratios, and decays.

Figure 2.12: $\Delta \phi$ vs. $E_T$ in the dilepton sample. The small grey dots are the result of a $t\bar{t}$ Monte Carlo simulation with $m_{top} = 175$ GeV/c$^2$.

2.3.1 Review of Run I Analysis

Using 19.3 pb$^{-1}$ from Run Ia, CDF presented initial evidence for the top quark in the spring of 1994 [2]. A year later, with an additional 48 pb$^{-1}$ from Run Ib, CDF confirmed its original evidence for the top quark [3]. Upon completion of Run I in 1996, CDF wrote a series of papers describing the current state of understanding of the top quark utilizing the 105 pb$^{-1}$ Run I dataset. We summarize here the results of those first measurements in this new area of physics.

2.3.1.1 Dilepton Mode

In the standard model, the $t$ and $\ell$-quarks both decay almost exclusively to a $W$-boson and a $b$-quark. In the “dilepton” channel, both $W$’s decay leptonically ($W \rightarrow \ell \nu$), and we search for leptonic W decays to an electron or a muon. The nominal signature in this channel is two high-$P_T$ leptons, missing transverse energy (from the two $\nu$'s), and two jets from the $b$-quarks. Acceptance for this channel is small, mostly due to the product branching ratio of both $W$'s decaying leptonically (only about 5%). In the 105 pb$^{-1}$ from Run I, CDF observed 7 $e\mu$ events, 2 $\mu\mu$ events, and 1 $ee$ event. Figure 2.12 shows the 10 candidate events in the parameter space $\Delta \phi$ (the angle between the $E_T$ and the nearest lepton or jet) vs
$E_T$ (the missing transverse energy) as well as where one would expect top to lie. The background estimate for the dilepton channel is $2.4 \pm 0.4$ events$^3$. Although not an a priori part of the search, we examine the jets in dilepton events for indications that they originated from $b$-quarks. In the 10 dilepton events, we find 6 jets in 4 events (1 $\mu \mu$ and 3 $e\mu$) which are identified ("tagged") as $b$-jets. This provides evidence for $b$-quarks produced in association with two W's, as expected from the decay of a $t\bar{t}$ pair.

CDF has also investigated top decays involving the $\tau$-lepton. We have searched for dilepton events with one high-$p_T$ electron or muon and one hadronically decaying $\tau$-lepton which is identified using tracking and calorimeter quantities$^7$. As in the $e\mu$, $ee$, or $\mu\mu$ channel two jets from $b$-quarks and significant missing transverse energy are required. Due to the additional undetectable $\tau$-neutrino, the $\tau$ hadronic branching ratio and the lower efficiency for $\tau$ identification, the acceptance in this channel is considerably smaller than in the case of $e\mu$, $ee$, or $\mu\mu$. In 105 pb$^{-1}$ we expect about 1 event from $t\bar{t}$ and 2 events from background. We observe 4 candidate events ($2 e\tau$ and $2 \mu\tau$). There are 4 jets in 3 candidate events that are identified as $b$-jets ("tagged"). More data with excellent tracking will enable us to conclusively establish this "all 3rd generation" decay mode of the top quark, which is important for charged Higgs searches and tests of weak universality.

### 2.3.1.2 Lepton + Jets Mode

In this channel, one of the W's decays leptonically to either an electron or muon (plus neutrino) and the other W decays hadronically to a pair of quarks. The nominal signature is a lepton, missing transverse energy (the neutrino from the leptonic W decay), and four jets; two from the $b$-quarks and two from the decay of the W. Approximately 30% of the $t\bar{t}$ events have this decay signature. Our lepton+jets selection requires that a leptonic W decay be accompanied by at least three central ($|\eta| < 2.0$) jets for an event to be considered part of the sample.

The background from W+multijet production is large. However, $t\bar{t}$ events contain two $b$-quark jets, and these can be distinguished from gluon and light quark jets in the background using two $b$-quark tagging techniques. The first technique locates a displaced vertex using the silicon-vertex detector (SVX Tag). The second locates a low-$P_T$ electron or muon primarily from the semileptonic decay of a $b$-quark or sequential c-quark (SLT Tag). The efficiency for tagging a $t\bar{t}$ event is (43 ± 4)% and (20 ± 3)% for the SVX and SLT algorithms, respectively. In 105 pb$^{-1}$, 37 SVX tags are observed in 29 events. The background, in the 29 SVX tagged events, is estimated from a combination of data and Monte Carlo simulation to be 8.0 ± 1.1 events. Using the SLT tagging algorithm, 44 tags are found in 40 events. The background here is estimated to be 25.2 ± 3.8 events. The two samples have 10 events in common$^3$. Figure 2.14 (upper left) shows the jet multiplicity spectrum for the SVX $b$-tags and the background.

In the 1 and 2-jet bins, we expect little contribution from $t\bar{t}$ events. The predicted background and the observed number of events agree well in the 1-jet bin, and agree at the 1.5 sigma level in the 2-jet bin as well. In the 3 and 2+4-jet bins, a clear excess of tagged events is observed. Fig. 2.13 shows the proper time distribution expected for $b$-tagged jets in the signal region (≥ 3 jets), compared with that for the SVX $b$-tagged jets in the data: the tagged jets are consistent with $b$ decays.
Figure 2.14: **Top Left:** The jet multiplicity distribution in SVX tagged W+jet events. Closed circles are the number of b-tagged events in each bin and shaded areas are the background prediction for the number of tagged events and its uncertainty. **Top Right:** Mass spectrum using the optimized mass sample in lepton+jet events using 105 pb$^{-1}$ of data. The yellow (light) shaded area is the expectation from background. The red shaded area (dark) is the expectation for background plus top production. The points are the data. The likelihood fit is shown as an inset. **Bottom Left:** The jet multiplicity distribution for the all-hadronic mode. The dark circles represent the observed number of b-tags in each jet multiplicity bin and the hatched areas represent the background prediction as well as its estimated uncertainty. **Bottom Right:** Mass spectrum for all-hadronic b-tagged events in 105 pb$^{-1}$ of data. The shaded area is the expectation from background. The histogram is from background plus top production. The likelihood fit is shown as an inset.
2.3.1.3 All Hadronic Mode

We have found a clear signal in the all-hadronic decay channel for \( \bar{t}t \) events. In this decay mode there are six final state jets, four of which come from the hadronic decays of the two W’s and two from the \( b \)-quarks. Approximately 44% of \( \bar{t}t \) events have this decay signature. Achieving a reasonable signal-to-background ratio is the challenge in this data set which is dominated by QCD multijet production. In order to isolate a signal and maintain efficiency, we require at least five well-separated jets, one of which must be SVX \( b \)-tagged. After additional topological cuts, we find 222 tags in 187 events with an estimated background of 151 ± 10 events. Figure 2.14 (lower left) shows the jet multiplicity spectrum for the all-hadronic channel. In the 4-jet bin where we expect little contribution from \( \bar{t}t \) events, the background and observed tags are in good agreement (12 observed vs 11.7 expected). Where we expect to see a signal for \( \bar{t}t \), in the 5, 6, and \( \geq 7 \)-jet bins, an excess of tags is observed over the background predictions. [8]

2.3.1.4 Kinematic Discrimination

In addition to the search techniques based on the dileptons and \( b \)-quark tagging, CDF has isolated \( \bar{t}t \) events based on the kinematical properties predicted from Monte Carlo simulations. These methods use the lepton+jets event sample but do not rely on \( b \)-tagging to reduce the background. One technique examines the jet \( E_T \) spectra of the second and third highest \( E_T \) jets [5]. The second technique uses the total transverse energy of the event [6]. In both cases, there is a clear \( \bar{t}t \) component in our data.

2.3.1.5 \( \bar{t}t \) Production Cross Section

The counting experiments which lead to a confirmed signal can be turned directly into measurements of the \( \bar{t}t \) production rate. Figure 2.15 shows the \( \bar{t}t \) production cross section measured in several channels in comparison to recent theoretical predictions. Our best measurement is obtained from the weighted average of the counting experiments performed in the dilepton channel, the two lepton+jets channels, SVX \( b \)-tagging and SLT \( b \)-tagging, and the all-hadronic channel. With 105 pb\(^{-1}\) of data, we measure a production cross section by combining the measurements in each of the separate channels to be 6.5\(^{+1.7}_{-1.4}\) pb[36, 37]. The production cross section in the individual decay channels are found to be 5.7\(^{+1.9}_{-1.5}\) pb for the Lepton+jets mode [36], 8.4\(^{+1.3}_{-1.5}\) pb for the dilepton mode [38], and 7.6\(^{+3.5}_{-2.7}\) for the hadronic mode [39]. A theoretical cross section calculation by Mangano et al. predicts 5.2 pb[18] at 175 GeV/c\(^2\), and other recent theoretical cross sections are within approximately 10% of this value.[18, 19]

2.3.1.6 Top Quark Mass

The top quark mass has been measured in three different channels. The primary method is based on fully reconstructing the \( \bar{t}t \) system with lepton+jets events. These events must contain a lepton and at least four jets such that each final state parton can be assigned to an observed jet or lepton. The reconstruction is performed using a constrained fitting technique which selects the best assignment of observed jets to final state partons based on the lowest \( \chi^2 \). Without any \( b \)-tagging information there are 24 combinations which must be considered (12 parton assignments \( \times \) 2 possible longitudinal momentum components for the neutrino). When one or two jets are tagged as \( b \)-quarks, the number of combinations is reduced to 12 and 4, respectively. In order to make the best use
of the data sets for measuring the top quark mass, the lepton+jets sample is divided into four orthogonal subsamples based on b-tagging: the SVX single-tagged set, the SVX double-tagged set, the SLT-only tagged set, and the not-tagged set [13]. The backgrounds are determined separately for each subset. The mass is determined by combining the likelihood functions defined in each subsample to extract a single optimized measurement of the top quark mass. This method currently yields the world’s best top mass measurement of 176.1 ± 5.1 (stat.) ± 5.3 (syst.) GeV/c² [3] (see Figure 2.16). The systematic uncertainty is dominated by the uncertainty in final state gluon radiation and the detector energy scale.

The same constrained fitting technique was also used to reconstruct the top mass in the all-hadronic channel where at least one b-tag was required; the result is seen in Figure 2.14 (lower right). Applying a maximum likelihood technique to the data in this channel results in a top mass of 186 ± 10 (stat.) ± 5.7 (syst.) GeV/c².

Reconstructing a top mass in the dilepton channel is difficult because this system is underconstrained due to the two undetected neutrinos. To solve this problem, we scan the two neutrinos and top mass to determine a probability function. Given the top mass, W mass, ην1, ην2, the two b jets, and two leptons, one can solve for the top mass independently and compare the predicted missing energy with the measured as a weight estimator. This technique gives a top mass from dileptons of 167.4 ± 10.3 (stat.) ± 4.8 (syst.) GeV/c².

In the subsample of lepton+ ≥ 4-jet events where two b-tags are required, we have looked for evidence of the decay of the hadronic W-boson. Fig. 2.17 shows the reconstructed mass of the unconstrained jet-jet system. A fit yields a jet-jet mass of 79.8 ± 6.2 GeV/c² [15]. This will be an important in situ technique for jet energy scale calibration in Run II. The top mass from this double b-tagged subsample has been determined to be 174.8 ± 8 (stat.) ± 6 (syst.) GeV/c² [14].

### 2.3.2 Lessons from Run I

- The detector should have the greatest possible acceptance for high-PT electrons and muons from the chain \( t \to W \to lν \).
- The detector should have the greatest possible acceptance and efficiency for tagging b-jets. This is a question of geometrical coverage, efficiency, and signal-to-noise ratio, most importantly for secondary vertex finding but also for soft lepton identification.
- Precision measurement of the top mass requires that the detector have \textit{in situ} capability for understanding the systematics of jet energy calibration, including the ability to accumulate large samples triggered on low-PT charged tracks, inclusive photons, and inclusive \( W \to lν \) and \( Z \to ll \).
- Understanding of b-tagging systematics has relied on the ability to accumulate a large, reasonably pure control sample of inclusive b-jets using low-PT inclusive lepton triggers. We anticipate doing this again, with some demand on DAQ bandwidth. However, we have learned that jets containing \( b \to cνX \) are a biased control sample, and we believe that a large sample of b-
jets collected with a secondary vertex trigger will be extremely useful.

2.3.3 Impact of Upgrades on Top Physics

The impact of the CDF IIb upgrades is to maintain the significant increases in overall top acceptance that will be achieved in Run IIa and to maintain that increased acceptance and precision at high luminosity and maintain the precision for large integrated luminosity.

- **Silicon Vertex Detector (SVX IIb)**: SVXII was not built to survive the radiation levels that it would be exposed to for Run IIb. Layer 00 as well as the three innermost layers of SVXII need to be replaced in order to complete Run IIb with reasonable detector performance and thus meet our physics goals. Time constraints on the length of the Run IIa to IIb shutdown require that all of SVXII be replaced. The goal of the replacement device is to have comparable performance to SVXII - the one now in place for Run IIa. Since SVXII is still being commissioned, comparisons will be made between the Run I silicon and the proposed SVXII replacement.

In top physics, the name of the game is accept ance and purity. The tagging of $b$-quarks from top quark decays will be greatly improved in the long, 7-layer device from what was used in run I. Increasing the length of the silicon from 52 cm to 96 cm will extend the region of "contained $b$-jets" to cover the entire interaction region. With seven measurements in two views for any given track, it will be possible to make stringent track quality requirements, reducing the level of mistags, while still improving the overall track finding efficiency.

Taking all of these factors into account, we anticipate that the SVX II replacement will increase the efficiency for tagging at least one $b$-jet in a $t\bar{t}$ event to better than 65% (a 60% increase over the Run 1 efficiency), and will raise the double $b$-tag efficiency to 20% (a 200% increase from Run I performance) [23].

Finally we point out that the 3D capability of the new silicon detector will allow a precision measurement of the primary vertex in the event, improving a variety of measurements including the $E_t/P_t$ of the primary leptons, the $E_t$ of the jets, and the missing transverse energy.

- **Central Outer Tracker (COT) Upgrade**: The top analysis of Run I depended crucially on the large central tracking chamber. Similarly, the success of Run IIa top analysis will depend upon the performance of the Central Outer Tracker (COT). As luminosities increase for Run IIb, the inner superlayers of the COT will become less effective due to an increase in occupancy. Although track finding utilizing the outer superlayers will still be possible, the ability to point back to the silicon will be degraded due to low hit usage on the inner superlayers. On complicated events such as those found in $t\bar{t}$, this effect would be extremely detrimental to our ability to reconstruct the event properly. Thus deadening the sense wires at large $|\eta|$ would give back most of the fine performance expected in the Run IIA COT.

- **Muon Detection System**: In the Run I top analysis, only "central" muons were used as the primary lepton - that is those muons which were detected in the region covered by the CMU and CMP detectors. Muons that passed through the
CMX detector (at higher $|y|$) were used to identify secondary leptons only — the very high rates and dynamic pre-scales used in the trigger proved too difficult to untangle. Much of this problem has been addressed for Run IIA by substantially increasing the steel shielding between the interaction region and these counters. This shielding should reduce the number of fake hits such that the trigger rates in the CMX region will be manageable.

Since the drift times in the muon chambers are now appreciably longer than the bunch crossing, scintillation counters, which shadow all of the muon chambers, were added so that muon stubs can be assigned to a particular bunch crossing. Some of this scintillator, like those mounted on the CMX muon arch chambers were installed in Run I and are now showing signs of aging. Current aging projections show that the performance of these counters will be substantially degraded in the next 2-3 years. If it is not replaced, this region of rapidity unusable for top physics in Run IIb. This loss would decrease the muon acceptance by approximately 10% from Run IIA.

- **Central Calorimeter:** With the increased luminosity and smaller bunch spacing of Run IIb, the central preshower and central crack chambers will need replacement. Their relatively poor segmentation and slow readout times will render these detectors useless in this new environment.

The loss of these detectors will cripple both electron and photon identification - both critical to top quark physics. The central prescillator in Run I offered a factor of 2 to 3 more rejection of charged pions that pass all other cuts using tracking, calorimetry, and shower maximum information. This extra rejection is crucial in minimizing background in soft electron ID for b-jet tagging (SLT).

### 2.3.4 Event Yield

To estimate the yield of top events, we extrapolate from our current measured acceptance in Run I using the theoretical cross section ($6.8 \, pb$) at $m_{top} = 175$ GeV/c$^2$ and $\sqrt{s} = 2$ TeV [22, 11].

At $\sqrt{s} = 2$ TeV, the $t\bar{t}$ cross section is approximately 40% higher than at $\sqrt{s} = 1.8$ TeV. We assume that the additional lepton and $b$-tagging acceptance outlined in Sec. 2.3.3 above can be incorporated while maintaining a signal-to-background ratio comparable to the Run I analysis.

Table 2.2 summarizes the acceptance and yields for various decay channels in the Run II configuration. The Run Ib acceptances are shown for comparison. A data sample of 15 fb$^{-1}$ at the Tevatron will provide over 7500 identified $b$-tagged $t\bar{t}$ events.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Acc. $A_{IB}$ (Run I)</th>
<th>Acc., $A_{II}$ (Run II)</th>
<th>Run I Results</th>
<th>Run IIb Yield (w/ $A_{II}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Produced $t\bar{t}$</td>
<td>-</td>
<td>-</td>
<td>525</td>
<td>100k</td>
</tr>
<tr>
<td>Dileptons ($ee, \mu\mu, e\mu$)</td>
<td>0.78%</td>
<td>1.1%</td>
<td>10</td>
<td>1200</td>
</tr>
<tr>
<td>Tau dileptons ($\tau\tau, \mu\tau$)</td>
<td>0.12%</td>
<td>0.14%</td>
<td>4</td>
<td>142</td>
</tr>
<tr>
<td>lepton+$\geq 3j$</td>
<td>9.2%</td>
<td>11.2%</td>
<td>324</td>
<td>10000</td>
</tr>
<tr>
<td>lepton+$\geq 3j$ w/ $\geq 1$ b tag</td>
<td>3.7%</td>
<td>7.3%</td>
<td>34</td>
<td>7425</td>
</tr>
<tr>
<td>mass sample w/ $\geq 1$ b SVX tag</td>
<td>3.0%</td>
<td>5.8%</td>
<td>20</td>
<td>6000</td>
</tr>
<tr>
<td>mass sample w/ $\geq 2$ SVX tags</td>
<td>0.52%</td>
<td>1.8%</td>
<td>5</td>
<td>1800</td>
</tr>
</tbody>
</table>

Table 2.2:
Acceptance and yield of $t\bar{t}$ events for a Run IIb upgraded detector. The yield is determined using the theoretical cross section ($6.8 \, pb$) at $m_{top} = 175$ GeV/c$^2$, $\sqrt{s} = 2$ TeV, and 15 fb$^{-1}$ data sample. For comparison, the acceptances for Run Ib are shown as well as the number of events seen in Run I prior to background subtraction. The acceptances include branching ratios and leptonic and kinematic selection (e.g. jet counting).

2-17
2.3.5 Measurement of the Top Quark Mass

The top quark mass will be one of the most important electroweak measurements made at the Tevatron. In combination with the W mass, \( m_t \) gives information about the mass of the standard model Higgs boson. The precision electroweak program and the W mass measurement are discussed in the electroweak section of Chapter 2. Figure 2.14 shows how the predicted top and W mass measurements constrain the Higgs mass. In that figure, the uncertainty on the top mass is taken as 4 GeV/\( c^2 \).

Currently, the statistical and systematic uncertainties on CDF’s top mass measurement are both about 5 GeV. The statistical uncertainty should scale as \( 1/\sqrt{N} \). Using the yields in Table 2.2, we anticipate that the statistical uncertainty on the top mass in the optimized lepton+\( \geq 4 \)-jet sample will be much less than 1 GeV/\( c^2 \). Thus in Run IIb, the overall uncertainty will be dominated by systematics. In fact, we expect approximately 1800 double-tagged lepton+\( \geq 4 \)-jet events on tape with a 15 fb\(^{-1}\) data sample. That one sample alone is sufficiently large that the statistical uncertainty will be less than 1 GeV. Since both b-jets are identified in the double-tagged subsample, it may turn out that the systematics for these events are better understood. If this is the case, there would be no need to include the other 3 subsamples (no-tag, single SVX tag, SLT tag) as was done in Run I.

Almost all of the systematic uncertainties in the top mass measurement are coupled to the reliability of the Monte Carlo models for the spectrum of fit masses in signal and background. Assuming the theory model is accurate, most of the uncertainty is related to resolution effects. Instrumental contributions include calorimeter nonlinearity, losses in cracks, dead zones, and absolute energy scale. A larger and more difficult part of the energy resolution concerns the reliability of the extrapolation to parton energies. Ultimately, it may be our understanding of QCD and not the detector which limits the mass resolution.

Many of these issues can be addressed by \textit{in situ} calibration procedures. For example, Z+jet events are used to understand the systematic uncertainty due to energy scale and gluon radiation, two of the dominant uncertainties. In 15 fb\(^{-1} \), we expect to have 200K (525) Z’s with 1 (4) or more jets. The effect of gluon radiation will also be studied in large statistics samples of W+jets, \( \gamma \) +jets, and \( b\bar{b} \) events. In addition, the mass peak from \( W \to q\bar{q} \) (see Figure 2.17) in the lepton \( + \) jets top sample allows an energy scale calibration \textit{in exactly the same events and environment} as the mass measurement. [1].

In any case, if all systematic effects can be measured or otherwise connected with mean quantities in large statistics control samples, the systematic uncertainties should also scale as \( 1/\sqrt{N} \). We can conservatively assume in this case that we can reduce our systematic error to \( \approx 2 \) GeV/\( c^2 \).

2.3.6 Production Cross Section, \( \sigma_{tt} \)

An accurate measurement of the \( tt \) production cross section is a precision test of QCD. A cross section which is significantly higher than the theoretical expectation would be a sign of non-standard model production mechanisms, for example the decay of a heavy resonant state into \( tt \) pairs or anomalous couplings in QCD. As in the case of the top mass, large statistics in the lepton+jets mode imply that systematic uncertainties will be the limiting factor in the cross section measurement.

For the acceptance, the reliability of jet counting and \( b \)-tagging are at issue. Initial state radiation can be examined using a sample of Z+jets, while the jet energy threshold uncertainty can be addressed as in the top mass discussion. With 15 fb\(^{-1} \) of data it will be possible to measure the \( b \)-tagging efficiency \textit{in top events}, using dilepton events selected without a \( b \)-tag and the ratio of single to double tags in lepton+jets events. We assume that these studies will give uncertainties that scale as \( \sqrt{N} \). Hence we expect of order a 3 fold improvement in these systematic uncertainties from what was estimated for Run IIa.

With large samples, one can measure the bottom and charm content as a function of jet multiplicity in W + jet events using the \( c\bar{c} \) distribution of the tagged jets and use this to tune the Monte Carlo models for W+\( \geq 3 \)-jet backgrounds. Finally, in Run II and beyond, the luminosity will be measured either through the \( W \to \ell \nu \) rate, or the mean number of interactions per crossing, and we will assume 5% for the future precision of the luminosity normalization.

Accounting for all effects we find that the total \( tt \) cross section can be measured with a precision of \( \approx 5\% \) for 15 fb\(^{-1} \). This will challenge QCD, and provide a sensitive test for non-standard production and decay mechanisms.
2.3.7 Measurement of a \( t \to W \) Branching Fraction

The ratio of the \( t \bar{t} \) cross section measured using dilepton events to that measured using lepton+jets events is a test for non-standard model decay modes of the top quark. Since the cross section in each case assumes that each top decays into W-bosons, a ratio different from 1.0 would signal decays without a W-boson, such as charged Higgs \( (t \to H^+ b) \) or light supersymmetric top (stop). The reach for a particular non-standard decay is model dependent, but we can say that with 15 fb\(^{-1} \) of data, we will be able to measure the basic dilepton to lepton+jets ratio to 8\%, and the top branching fraction to W in association with \( b \) with a precision of 5\%.

2.3.8 Measurement of a \( t \to b \) Branching Fraction

In the standard model with 3 generations, existing experimental constraints and the unitarity of the CKM matrix require \( V_{tb} \simeq 1 \), predicting that the weak decay of the top will proceed almost exclusively through W + b. In events containing a W, the top branching fraction to b’s is related to the CKM element according to:

\[
B_b = \frac{B(t \to W(b))}{\sigma(t \to Wb)} = \frac{\sigma(t \to Wb)}{\sigma(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}
\]

The notation above is meant to indicate that a W has been required in the final state, and this is not the decay fraction to W+b, but the fraction of decays with W’s which also contain b’s. Since the standard analysis identifies \( t \bar{t} \) events by requiring at least 1 W and 1 b, \( B(t \to W(b)) \) is measured from the number and distribution of tagged b-jets in top events. Four different techniques can be used to measure this distribution: \[20, 21\]

- The ratio of single \( b \)-tagged to no \( b \)-tagged events in a lepton+jets sample in which kinematic criteria have been applied: since there is no a-priori tag requirement, we can extract the branching ratio from the ratio of single tagged events to not-tagged events. An ideal sample for this is the W+4 jet mass sample prior to applying the \( \chi^2 \) cut. \[21\]

- The number of \( b \)-tagged jets in the dilepton sample: Since \( b \)-tagging is not required to identify tops decaying to dileptons, the whole \( b \)-tag multiplicity distribution in these events contains information on \( B(t \to W(b)) \). Despite the smaller branching fraction to dileptons, the statistical powers of the dilepton and lepton+jets samples are comparable.

- The distribution of double tags: If there are two tagging algorithms (soft leptons and secondary vertex), one can compare the number of times that events tagged by both algorithms have both tags in the same jet vs. the number of times the tags are in different jets. Small values of \( B(t \to Wb)/B(t \to Wq) \) result in large values of the same to different jet ratio.

These techniques are not exclusive, and can be combined. We have used a maximum likelihood estimator to do this combination in Run I data. With 105 pb\(^{-1} \), CDF has a ±25\% statistical uncertainty on the branching fraction, but only an ±11\% systematic uncertainty. The systematic uncertainty is dominated by the uncertainty on the tagging efficiency, which is measured in the data using \( b \)-rich inclusive lepton samples. This uncertainty should fall as \( 1/\sqrt{N} \). The small non-\( t \bar{t} \) backgrounds will be measured to high accuracy by Run II. For Run II, we expect to measure \( B(t \to W(b)) \) to 3.0\%.

2.3.9 Anomalous Couplings and Weak Universality

Since the top quark is so heavy, it is possible that the physics of the underlying theory may manifest itself via new non-universal top interactions. The top quark is unique in that it decays prior to hadronization and therefore the decay products carry helicity information related to the fundamental couplings. In the standard model, the top quark decays only to longitudinal or left-handed W’s, where the ratio is given by
Lepton $P_T$ as a Function of W Helicity
(CDF Preliminary)

Figure 2.18: The lepton Pt as a function of W helicity for 175 GeV $t\bar{t}$ events

$$W_{\text{long}} = \frac{1}{2} \left( \frac{m_{\text{top}}}{m_W} \right)^2$$

For $m_{\text{top}} = 175.9$ GeV/c$^2$, the branching fraction to longitudinal W's is $70.6 \pm 1.6\%$. In many cases non-universal top couplings will appear as as a departure of $B(t \to bW_{\text{long}})$ from the standard value and we use this quantity as our precision benchmark for probes of anomalous weak couplings.

Experimentally, we have two ways to access the polarization state of the decay W. The first way and perhaps the most obvious way is through the charged lepton helicity angle, $\cos \theta^e_\gamma$ which can be measured in the lab frame as

$$\cos \theta^e_\gamma \approx \frac{2M_{cb}^2}{m_{cb}^2 - M_W^2} - 1 \quad (2.1)$$

The resulting distribution can then be fit to a superposition of W helicity amplitudes in order to measure any possible contribution of non-universal weak couplings in the top decay.

The second way uses the shape of the lepton Pt spectra. The idea here is that the charged lepton from the left handed W tends to move opposite to the W direction while that from the longitudinal W tends to be perpendicular to the W direction. In the lab frame, this implies that leptons from longitudinal W's have a somewhat harder Pt distribution than those from the left-handed W's. See Figure 2.18 for an illustration using Herwig MC.

For Run 1 data, it turned out that both techniques have roughly equal statistical sensitivity, but $P_T$ offers many advantages over the angular distribution. It eliminates systematic uncertainties related to parton combinatorics and neutrino reconstruction in the mass fitter and as a variable is more accurately measured.

The following cuts were used in the Run 1 analysis [40, 41]. We start with the cuts used in the $t\bar{t}$ cross-section analysis for event selection and then pick 4 subsets out of this $W+3$ jet heavy flavor data set.

- A displaced vertex tag identified by our algorithm SECVTX.
- A 4th lower energy jet ($E_T > 8$ GeV) and a soft lepton tag (SLT) within a cone of 0.4 of one of the 3 leading jets and NOT have a SECVTX tag
- A 4th high energy jet ($E_T > 15$ GeV) and a mass fitter value $\chi^2 < 10$.
- Standard dilepton search criteria

A likelihood procedure is performed using the lepton Pt as a variable to determine the fraction of top quarks which decay to longitudinal W bosons. For 105 pb$^{-1}$, the fraction of top quarks which decay longitudinally is $0.91 \pm 0.37$ (stat) $\pm 0.13$ (syst). The fraction of top quarks which decay to right handed W bosons (helicity of +1) is measured to be $0.11 \pm 0.15$ (stat) $\pm 0.06$ (syst). The dominant systematic contributions are due to the uncertainty in top mass and the relative fractions of background contributions.

To date, no study has been performed to see how one would measure this quantity in Run IIb. The data samples will be significantly larger which would help measure the polarization angle. However even with double tagged events, there is still a bias due to mass fitter. It is important to note that even with relatively small data samples in run 1, the systematic uncertainty on this measurement is already quite small. With 15 fb$^{-1}$ of data, we should be able to measure the top quark decay branching fraction to longitudinal W-bosons with a total precision approaching of order 1%. The V+A term in top decay should have similar sensitivity.
2.3.10 Single Top Quark Production

In addition to $t\bar{t}$ pair production via the strong interactions, top quarks can also be produced singly via the electroweak interaction. This process depends on the $t$-$W$-$b$ vertex, and the production rate is a measure of the top decay width to $W$+$b$ and the CKM matrix element $|V_{tb}|^2$. Single top is of theoretical interest because it provides a direct window on the charged-current interaction of the top quark. Unlike the case of top pair production where the electroweak vertex $tWb$ plays a role only in the top quark's decay, in single top, the production cross section contains information on the coupling of top to $W$ and $b$. Thus the production cross-section for single top contains information on the top partial width.

So far, we have assumed the validity of the Standard Model. Nonstandard couplings could invalidate the above simple extrapolation between $V_{tb}$ and the top width or even render the entire concept of $V_{tb}$ ill defined. Examples of proposed anomalous couplings that could impact single-top production rates include a $q^2$-dependent form factor at the $tWb$ vertex or new flavor-changing neutral current couplings like $tZc$ or $tgc$. New particles such as heavy $W'$ boson would also lead to unexpected rates of single top production. Thus measuring single-top production is a win-win proposition. Either we get information on the top width and $V_{tb}$ or we find evidence of new physics.

The two dominant single top processes at the Tevatron are the $s$-channel mechanism $qq \rightarrow t\bar{b}$, referred to here as $W^*$ production, and the $t$-channel interaction $q\bar{b} \rightarrow qt$, referred to as $W$-gluon fusion. Other processes become important at higher energies, but are negligible here because they have such heavy final states. Based on theoretical calculations, the $W$-gluon fusion process is thought to dominate the production with an estimated cross section of 1.7 pb at a 900 GeV Tevatron; the uncertainties on this calculation are on the order of 15%. The $W^*$ production mode is roughly half as large and has an estimated cross section of 0.73 pb with a theoretical uncertainty of 9%. The combined rate for single top production by these two processes is $\approx 2.4$ pb, only a little more than a factor of 2 down from the $t\bar{t}$ rate at this energy.

As is the case for $t\bar{t}$, single top events present themselves in the CDF detector as the leptonic or hadronic $W$ decay products accompanied by one or more additional jets. Single top events are interspersed among a vast background of QCD processes which appear as energetic jets in the detector. Since hadronic $W$ decay products are not easily distinguished from ordinary QCD jets, a first step in isolating the single top signal is to demand evidence of a leptonic $W$-decay as is done with $t\bar{t}$ - namely applying leptonic $W$ selection criteria of a high Pt electron or muon plus large missing energy. As in $t\bar{t}$, dilepton and $Z$ removal cuts are used to reduce unwanted backgrounds further. B-tagging is also used. What remains are backgrounds of $W$+heavy flavor and $t\bar{t}$ production. Thus, additional cuts are required to separate single top events from these backgrounds.

There are differences between the final states in $Wg$ fusion and $W^*$ production. The final state for $W^*$ production features a second high-$P_T$ central $b$-jet in addition to the $b$ coming from the top decay $t \rightarrow Wb$. The second $b$ in a $W$-gluon event is expected to be soft and forward and thus not detectable as such in the CDF detector. Furthermore, the $Wg$ event is expected to contain an additional hard forward light-quark jet. Cuts must be developed with these differences in mind to isolate the individual processes.

The data selection criteria that were used to isolate the signal over background in the Run I analysis include:

- High $P_T$ lepton events with 1, 2, or 3 jets with $E_T > 20$ GeV, $|\eta|_{jets} < 2.4$
- $E_T > 20$ GeV
- $E_T$(electron) > 20 GeV
- $|\eta|_{electron} < 1.0$
- $Z$ and Dilepton removal
- At least one jet tagged as a $b$-jet.
- Reconstruct mass of lepton, neutrino and $b$-tagged jet to be inside the window $140 < M_{\nu b} < 210 GeV$
- Fit the $H_T$ distribution where $H_T$ is the energy of the jets, leptons and MET in the event

After selection cuts we expect a $4.3$ signal events ($W^*$ and $Wg$uon combined) and $62$ background events. Thus we expect a $S/\sqrt{B} = 0.5$. See Table 2.3 for a breakdown by bin and by data sample type. A likelihood fit is then performed based on the variable $H_T$ and a 95
<table>
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<th>$W + 2J$</th>
<th>$W + 3J$</th>
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<td>$Wg$ Signal</td>
<td>0.80</td>
<td>1.50</td>
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<tr>
<td>$W^*$ Signal</td>
<td>0.25</td>
<td>0.80</td>
<td>0.23</td>
</tr>
<tr>
<td>$t\bar{t}$ Bkg</td>
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<td>2.28</td>
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<tr>
<td>QCD Bkg</td>
<td>37.4</td>
<td>13.9</td>
<td>2.7</td>
</tr>
<tr>
<td>Total</td>
<td>38.7</td>
<td>18.5</td>
<td>9.6</td>
</tr>
</tbody>
</table>

Table 2.3:

Bin by Bin predictions for the single top processes and backgrounds for a data size of 105 pb.

The above analysis was optimized for a small statistical data set. With the large samples expected in Run IIb, one could remove the 1 jet bin, cut harder on some of the kinematic variables and separate out the two separate single top processes. By just removing the 1 jet bin for large data samples, the $S/\sqrt{B} = 2.9!$ Based on the theoretical cross section and acceptances from this analysis, one could expect to see roughly 100 $W^*$ events in the $W+2$ jet bin per fb$^{-1}$ and 150 $Wg$ events per fb$^{-1}$. Hence in Run IIb, we expect a total sample of single top events to be of order 4000 events on tape. Assuming that the background normalization is understood (through the large statistics top cross section measurement), the statistical precision on the single top cross section using 15 fb$^{-1}$ will be about 10%.

Many of the sources of systematic uncertainty in the single top cross section are common to the $t\bar{t}$ cross section discussed earlier. We assume that systematic uncertainties related to selection efficiencies and backgrounds will shrink as $\sqrt{N}$. For the case of 15 fb$^{-1}$ we find that the measurement of the single top cross section will have a total uncertainty of approximately 12%.

The single top cross section is directly proportional to the partial width $\Gamma(t \to Wb)$ and assuming there are no anomalous couplings, this is a direct measure of $|V_{tb}|^2$. There are theoretical uncertainties in converting the cross section to the width, notably for the gluon fusion process. Taking these into account, we anticipate that a measurement of the total single top rate with 15 fb$^{-1}$ will translate in a precision of 6% on $|V_{tb}|$.

The theoretical determination of $W^*$ is more reliable than that of $W$-gluon fusion since initial state effects can be measured in the similar Drell-Yan process, and if the data set is large enough this may afford the best precision on the width. The two processes can be separated by requiring two b-tags since the double tag rate for $W^*$ production is close to a factor of 5 more than that of $W$-gluon fusion.

2.3.11 Search for Anomalously Large Rare Decays

- $t \to Zc, \gamma c$
- $t \to WZb$
- $t \to W^+W^-c$
- $t \to Hc$

The standard model predicts that the branching fractions of FCNC top decays are around $10^{-10}$ [29],
out of reach for even the LHC. Any observation of such decays will signal new physics. As illustration, we consider the signal for a flavor changing neutral current decay \( t \to c \gamma \) in a \( t\bar{t} \) event. If the other top in the event decays in the leptonic channel, the acceptance is almost the same as the standard model lepton+jets mode, and it then becomes a simple matter to scale from present results. The background from \( W^+ \gamma + \text{two jets} \) is about 1 fb. Although it is unlikely that this background will be kinematically consistent with \( \bar{t} \) (for example, that \( m(\gamma + j) = m(t) \)), we take the very conservative assumption that this background is irreducible. We find that 15 fb\(^{-1} \) will probe branching fractions for this decay down to \( 1.0 \times 10^{-3} \).

Sensitivity to other rare decays can be scaled from this estimate. For the case \( t \to Z + c \), where the \( Z \) decays to leptons, after adjusting for branching ratios and different backgrounds, we find sensitivity down to of order 0.5%.

### 2.3.11.1 Dynamical Symmetry Breaking

Because of its large mass, the top quark is an excellent probe for physics beyond the standard model. Theories which implicate top in the electroweak symmetry breaking mechanism, such as a color-octet vector meson associated with a top condensate[33] or multiscale technicolor[34], predict enhancements or changes in the shape of the \( t\bar{t} \) invariant mass spectrum \( (m_{t\bar{t}}) \) and the top quark transverse momentum distribution \( (P_T^{t\bar{t}}) \).

CDF performed a search for resonances, \( X \to t\bar{t} \), in the \( M_{t\bar{t}} \) spectrum by reconstructing \( M_{t\bar{t}} \) on an event-by-event basis using the same event sample and constrained fitting techniques used in the top mass measurement, with an additional constraint that the top mass. Effectively once the fit for \( M_{t\bar{t}} \) is done, one then looks at the 3 body masses and asks whether they “wanted” to be fit to top. 63 events satisfied the selection criteria. The \( M_{t\bar{t}} \) distribution of 63 data events yields a \( \chi^2 \) of 80% when compared to the hypothesis that the spectrum is comprised of Standard Model \( t\bar{t} \) production and the predicted rate of non-\( t\bar{t} \) background events. A 95% confidence level cross-section limits for generic objects in the mass range of 400 GeV/c\(^2 \) to 1 TeV/c\(^2 \) which decay to \( t\bar{t} \). These results exclude the existence of a lepto-phobic top-color \( Z' \) with masses less than 480 GeV/c\(^2 \) for \( \Gamma = 0.012 \)M and 780 GeV/c\(^2 \) for \( \Gamma = 0.04 \)M.

In the absence of a signal, limits in Run II will be as high as 1000 GeV/c\(^2 \). New resonances with masses below the limit could be observed. For example, Figure 2.19 shows the \( M_{t\bar{t}} \) spectrum for 2 fb\(^{-1} \) with standard model \( t\bar{t} \) production plus the addition of a top-color \( Z' \) at 800 GeV/c\(^2 \) [31], where the \( Z' \) decays to a \( t\bar{t} \) pair. In this theory, the branching fraction of \( Z' \) to \( t\bar{t} \) pairs is potentially large (50-80\%) but depends on the \( Z' \) width. In the case shown in Figure 2.19, we would expect 17 events from standard model \( t\bar{t} \) production in the range \( 700 < M_{t\bar{t}} < 900 \) GeV/c\(^2 \) and 70 events from \( Z' \to t\bar{t} \) in this range. The \( M_{t\bar{t}} \) spectrum along with other \( t\bar{t} \) production distributions provide an excellent means for searching for new phenomena.

#### 2.3.12 Summary of Top Physics

For the next 5 years, the Tevatron will be the only accelerator capable of producing the top quark. Maintaining the capability of the CDF Run IIa detector is critical for setting limits on rare top searches, understanding the production rates for single top, and first significant measurements of both the top width and \( V_{tb} \) as well as on advancing the precision of Run IIa measurements.

The top physics program possible with this sample is summarized in Table 2.4. Measurements of branching ratios, angular distributions, and top production mechanisms with the sensitivities listed in Table 2.4 will provide the first complete characterization of this new fermion and provide another stringent test of the Standard Model. Our catalog of possible measurements is hardly complete. But in the event that the top quark yields surprises, these sensitivities benchmark the capability to explore new physics at the Fermilab Tevatron.
<table>
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<td>total precision GeV/c$^2$</td>
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<tr>
<td>Production</td>
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<tr>
<td>$\delta\sigma_f$</td>
<td>6%</td>
<td>test top QCD couplings</td>
</tr>
<tr>
<td>$\delta\sigma_{ll}/\sigma_{l+j}$</td>
<td>9%</td>
<td>test non W decay</td>
</tr>
<tr>
<td>$\delta\sigma_{bX+bX}$</td>
<td>12%</td>
<td>isolate “single top”</td>
</tr>
<tr>
<td>Decay</td>
<td></td>
<td></td>
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<td>$\delta B(t \to W(b))$</td>
<td>1%</td>
<td>from N(bb)/N(bX)</td>
</tr>
<tr>
<td>$\delta B(t \to b(W))$</td>
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<td>from N(ll)/N(lX)</td>
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<td>$W \to l \nu$ helicity</td>
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<tr>
<td>$\delta V_{tb}$</td>
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<td>from above</td>
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<tr>
<td>Rare Decays</td>
<td></td>
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<tr>
<td>$B(c \gamma)$</td>
<td>$\leq 1 \times 10^{-3}$</td>
<td>(95% CL)</td>
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<tr>
<td>$B(cZ)$</td>
<td>$\leq 5 \times 10^{-3}$</td>
<td>(95% CL)</td>
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<tr>
<td>$B(Hb)$</td>
<td>$\leq 9%$</td>
<td>from $\sigma_{ll}/\sigma_{l+j}$</td>
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Table 2.4: Summary of expected measurement accuracies for an integrated luminosity of 15 fb$^{-1}$
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2.4 Precision Electroweak Program

2.4.1 Introduction

The comparison of diverse precision experimental measurements to expectations from the Standard Model [1] allows precise tests sensitive to new physics at scales above the electroweak scale, as well as a determination of the Higgs mass within the framework of the model [2]. Global electroweak fits receive contributions from LEP, LEP II and SLC, W mass measurements in $\bar{p}p$ interactions, neutrino neutral current data, and the measurement of the top mass at the Tevatron.

Precision measurement of the top mass and the W mass are primary goals of CDF II. In addition, in the electroweak sector, the W width and leptonic branching ratio, the tri-linear couplings of the $W$, $Z$ and $\gamma$, and the forward-backward charge asymmetry of dileptons at the $Z$ pole and above are important Standard Model parameters. These measurements together will take the global electroweak fit to a new level of precision, and do so completely in the context of a single experiment.

In this section we discuss measurements directly involving the gauge bosons. We begin with a comparison of the the expected event yields of $W$, $Z$, and diboson production for Run IIa with 2 fb$^{-1}$ and Run IIb with 15 fb$^{-1}$, which illustrates the electroweak physics potential (see Table 2.5). We then discuss the CDF Electroweak measurement prospects for Run IIb.

Studies of the Run II sensitivities for Electroweak physics at CDF II, and their competitiveness with LEP-II, LHC and NLC experiments are detailed in the Summary Report of the Workshop on QCD and Weak Boson Physics in Run II [3]. A review of the Run I results on W boson physics can be found in [4].

2.4.2 Impact of Proposed Run IIb Upgrades

Most of the proposed Run IIb upgrades are aimed at maintaining the enhanced detector capabilities that were achieved over Run I by the Run IIa upgrades. Apart from the obvious need to maintain triggering and data acquisition capability in order to record the large data samples, we mention the relevant detector upgrades for electroweak physics.

The momentum measurement from the COT is clearly very important for leptons. At very high instantaneous luminosities, the occupancy in the inner superlayers will hurt pattern recognition and track resolution. The proposed upgrades to the COT inner layers and the silicon detector are both relevant for maintaining track efficiency and quality.

2.4.2.1 Electrons

The detection capabilities for forward electrons and photons were significantly enhanced over Run I by the plug calorimeter and the SVX II+ISL+COT integrated tracking. The charged tracking and momentum information will be better, more efficient, and available over a wider range in $\eta$. Plug electrons will significantly improve the yields for $W$ and $Z$ bosons, and allow us to examine some previously inaccessible electroweak physics topics at high $\eta$. When considering the purely leptonic decay modes, the acceptance for $W$ bosons is almost doubled, for $Z$ bosons tripled, and for the rarer diboson modes quadrupled by increasing the electron coverage from $|\eta| < 1$ to $|\eta| < 2$. More importantly, the high $\eta$ leptons and photons provide opportunities for previously inaccessible physics. The high $\eta$ leptons are very sensitive to physics in the small $x$ region, and the high $\eta$ leptons and photons are essential to observe the radiation zero in the $W\gamma$ production (see Section 2.4.5).

It is therefore important to preserve the tracking capability to high $\eta$. The COT tracking efficiency falls off rapidly beyond $|\eta| \sim 1$. The replacement of the radiation-damaged SVXII with a new silicon detector will maintain tracking capability at high $\eta$.

2.4.2.2 Muons

Concerns about the aging and inefficiency of the CSX central muon scintillators have prompted their study and the proposal to eventually replace these counters. These counters are important for triggering and timing of muons and are therefore very important for the electroweak physics goals of Run IIb.

2.4.2.3 Photons

Cosmic rays are a significant background for analyses involving photons and/or $E_T$, such as studies of diboson production. Most electromagnetic showers produced by cosmic rays are out-of-time with the beam crossing. The proposed Run IIb upgrade to add timing information to the electromagnetic calorimeter would significantly reduce the cosmic ray back-
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<td>$W \rightarrow e\nu$</td>
<td>(e$p$)</td>
<td>448,000</td>
</tr>
<tr>
<td>$W \rightarrow \mu\nu$</td>
<td>($\mu^c$)</td>
<td>672,000</td>
</tr>
<tr>
<td>$W \rightarrow \mu\nu$</td>
<td>($\mu^f$)</td>
<td>49,000</td>
</tr>
<tr>
<td>$Z \rightarrow ee$</td>
<td>($e^c$, $e^c$p,f)</td>
<td>146,000</td>
</tr>
<tr>
<td>$Z \rightarrow \mu\mu$</td>
<td>($\mu^c$, $\mu^c$)</td>
<td>56,000</td>
</tr>
<tr>
<td>$W\gamma$, $E_T$ &gt; 10 GeV</td>
<td>($\gamma^c$,p)</td>
<td>1,700</td>
</tr>
<tr>
<td>$Z\gamma$, $E_T$ &gt; 10 GeV</td>
<td>($\gamma^c$,p)</td>
<td>509</td>
</tr>
<tr>
<td>$WW \rightarrow \ell\ell\ell\ell$</td>
<td>90</td>
<td>675</td>
</tr>
<tr>
<td>$WZ \rightarrow \ell\nu\ell\ell$</td>
<td>12</td>
<td>90</td>
</tr>
<tr>
<td>$ZZ \rightarrow \ell\ell\ell\ell$</td>
<td>1.4</td>
<td>10</td>
</tr>
<tr>
<td>$WZ \rightarrow \ell\nu b\bar{b}$</td>
<td>4</td>
<td>30</td>
</tr>
<tr>
<td>$ZZ \rightarrow \ell\ell b\bar{b}$</td>
<td>0.5</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 2.5: Expected $W$, $Z$, and diboson event yields with 2 fb$^{-1}$ and 15 fb$^{-1}$ when the Run Ib configuration is assumed. $c$, $p$, and $f$ for electrons represent Run I CEM, PEM, and FEM, and $c$ and $f$ for muons represent Run I CMU/P and FMU.

ground and have a big impact on the sensitivity in diboson analyses. This is exemplified by the $Z\gamma$ coupling measurements in the powerful $Z\gamma \rightarrow \nu\nu\gamma$ channel, where photon identification is of paramount importance. With improved photon identification, this channel will become available to CDF in Run IIb.

### 2.4.3 W Mass

The mass of the $W$ boson is a fundamental parameter of the Standard Model. A direct measurement of $M_W$ can be compared with the prediction from other LEP and SLC results as a test of the SM. In the context of other precise electroweak measurements, direct and precise measurements of $M_W$ and $M_{top}$ provide an indirect constraint on the Higgs boson mass, $M_H$, via electroweak radiative corrections. The ultimate test of the SM may lie in the comparison of this indirect determination of $M_H$ with its direct observation.

At the Tevatron, the $W$ mass is extracted from a fit to the $W$ transverse mass, $M_T^W$, and the lepton $p_T$ distributions. The 4 pb$^{-1}$ of the 1988-89 Tevatron Collider run enabled CDF to measure the $W$ mass to be

$$M_W = 79.91 \pm 0.39 \text{ GeV/c}^2 [6],$$

and with 19 pb$^{-1}$ from Run Ia CDF measured

$$M_W = 80.41 \pm 0.18 \text{ GeV/c}^2 [7].$$

With 85 pb$^{-1}$ from Run Ib CDF measured

$$M_W = 80.470 \pm 0.089 \text{ GeV/c}^2 [8].$$

The uncertainties in the current Run Ib measurement scale rather well with statistics from the previous measurements; while the difficulty of the measurement has increased, no systematic limitation is yet evident. The fits to the data from Run Ib are shown in Figure 2.21. The uncertainties for the Run Ib measurement are shown in Table 2.6.

Figure 2.20 (a) shows the sensitivity in the $M_W$-$M_{top}$ plane of the combined CDF $W$ mass measurement of $M_W = 80.433 \pm 0.079 \text{ GeV/c}^2 [8]$ and the top mass measurement $M_{top} = 176.1 \pm 6.6 \text{ GeV/c}^2 [5]$, compared to theoretical predictions based on electroweak radiative corrections [2].

In the Run IIa TDR we made a case that a data set of 2 fb$^{-1}$ will allow CDF II to measure the $W$ mass to $\pm 40 \text{ MeV/c}^2$, which is comparable to the overall LEP2 expectation ($\sim 40 \text{ MeV}$). Figure 2.20 shows the sensitivity in the $M_W$-$M_{top}$ plane of this estimate when combined with the expected precision $\delta M_{top} = 4 \text{ MeV/c}^2$ for the same dataset. With a dataset of 15 fb$^{-1}$, we make the case below that $\delta M_W = 20 \text{ MeV/c}^2$ (and $\delta M_{top} = 2 \text{ GeV/c}^2$) is within reach. The precision measurement of the $W$ boson and top quark mass with CDF IIb will allow inference of the Standard Model Higgs boson mass
Figure 2.20: The data point labeled “Run I” represents the CDF measurements of $M_W$ and $M_{top}$, and the points labeled “Run IIa” and Run IIb” represent the CDF II estimates for 2 fb$^{-1}$ and 15 fb$^{-1}$. The curves are from a calculation [2] of the dependence of $M_W$ on $M_{top}$ in the minimal standard model using several Higgs masses. The bands are the uncertainties obtained by folding in quadrature uncertainties on $\alpha(M_Z^2)$, $M_Z$, and $\alpha_s(M_Z^2)$. Also indicated is the calculation based on a minimal supersymmetric extension of the standard model (MSSM) [9], with an uncertainty of $\delta M_H/M_H \sim 30\%$, assuming we will not be limited by the uncertainty in $\alpha(M_Z)$.

For Run II, the statistical uncertainty and most of systematic uncertainties are expected to be reduced significantly compared to Run I. A salient feature of the $W$ mass analyses has been that most of the inputs required for the measurement have been constrained from the collider data. Thus we believe that, with a factor of 7.5 more data, a reduction of the total uncertainty by a factor of 2 is feasible and includes some conservatism. The individual uncertainties are briefly discussed.

2.4.3.1 Statistical Uncertainty

For Run Ib the typical instantaneous luminosity at the beginning of runs was about $2 \times 10^{31}$ cm$^{-2}$ sec$^{-1}$ and we had about 2.5 extra minimum bias events overlying $W$ and $Z$ events on average. This results in about a 10% loss in statistical precision due to the degraded resolution in the recoil measurement in Run Ib as opposed to Run Ia. For 132 ns operation in Run II the increased number of bunches will more than compensate for the higher luminosity and the number of extra minimum bias events will be to the Run Ia level. This will give us a situation which is better than Run Ib in terms of the statistical power of the data.

2.4.3.2 Track momentum scale and resolution

Scale: Knowledge of material in the tracking volume is of importance in determining the momentum and energy scale. The associated systematics are the uncertainties in the muon energy loss ($dE/dx$) for the momentum scale and in the radiative shift of the electron $E/p$ peak for the energy scale. Although the amount of material in the tracking volume will be changed we have shown that photon conversions allow us to measure the amount of material in radiation length quite accurately, as illustrated in Figure 2.22 and can reduce the uncertainties on the $W$ mass mea-
Figure 2.21: Transverse mass distributions and fits for $W \rightarrow e\nu$ (left) and $W \rightarrow \mu\nu$ (right) from Run Ib.

<table>
<thead>
<tr>
<th>Source</th>
<th>$W \rightarrow e\nu$</th>
<th>$W \rightarrow \mu\nu$</th>
<th>common</th>
</tr>
</thead>
<tbody>
<tr>
<td>statistical</td>
<td>65</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>lepton scale</td>
<td>75</td>
<td>85</td>
<td></td>
</tr>
<tr>
<td>lepton resolution</td>
<td>25</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>pdfs</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>$p_T^W$</td>
<td>15</td>
<td>20</td>
<td>3</td>
</tr>
<tr>
<td>recoil</td>
<td>37</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>higher order QED</td>
<td>20</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>trigger, lepton identification bias</td>
<td>-</td>
<td>15 @ 10</td>
<td></td>
</tr>
<tr>
<td>backgrounds</td>
<td>5</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>total</td>
<td>92</td>
<td>103</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 2.6: Systematic uncertainties in the $W$ mass (in MeV) in the CDF measurements from the Run 1B data.
<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>Uncertainty (MeV/c²)</th>
<th>W → eν</th>
<th>W → μν</th>
<th>Common</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical</td>
<td></td>
<td>5</td>
<td>8</td>
<td>–</td>
</tr>
<tr>
<td>Lepton Energy/Momentum Scale</td>
<td></td>
<td>10</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Lepton Energy/Momentum Resolution</td>
<td></td>
<td>4</td>
<td>3</td>
<td>–</td>
</tr>
<tr>
<td>Recoil modeling</td>
<td></td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Trigger, Event Selection</td>
<td></td>
<td>5</td>
<td>5</td>
<td>–</td>
</tr>
<tr>
<td>Backgrounds</td>
<td></td>
<td>5</td>
<td>5</td>
<td>–</td>
</tr>
<tr>
<td>$p_T^W$</td>
<td></td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>PDF</td>
<td></td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>QED radiative corrections</td>
<td></td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td><strong>Total Uncertainty</strong></td>
<td></td>
<td>17</td>
<td>17</td>
<td>12</td>
</tr>
</tbody>
</table>

$e$ and $μ$ Combined Uncertainty: 15

Table 2.7: Estimates of uncertainties in the $W$ mass measurement for 15 fb⁻¹.

Measurement. During the commissioning run for Run IIa, a precisely-known aluminum radiator was placed inside the COT inner wall to provide a calibration reference using conversions.

The $dE/dx$ muon energy loss requires information of the material type in addition to the radiation length. For example, an unknown type of 1% X₀ material leads to about 10 MeV uncertainty in the $W$ mass measurement. We have fairly detailed information available on the construction of the Run IIa tracking detectors and do not expect this to be a limitation.

**Resolution:** It is important to assess the impact of high luminosity running on the track momentum resolution. In Run Ib, the CTC track resolution degraded with luminosity, but could be recovered when SVX hits or the SVX beam position were added to the tracking. For instance, if we compare early Run Ib ($L \sim 0.2 \times 10^{34}$) to later Run Ib ($L \sim 1 \times 10^{34}$), the CTC track resolution observed in the width of the $J/\psi$ peak worsens by 35%, but the SVX + CTC track resolution worsens by only 10%. The new tracking system incorporates this linking naturally across all detectors (for $|\eta| \leq 1.0$). It is clearly important here to maintain the tracking capability of the Run IIa SVXII-ISL-COT integrated system.

The $M_W$ uncertainty due to the momentum resolution uncertainty will scale with statistics since the resolution is determined using $Z \rightarrow e\mu$ events.

### 2.4.3.3 Calorimeter energy scale and resolution

The dominant uncertainty in the electron energy scale for Run I was from the uncertainty in amount of material in radiation length, and statistics. As described above, the amount of material is expected to be well measured by photon conversion events for Run IIb and the uncertainty should scale with statistics.

The $M_W$ uncertainty due to the energy resolution uncertainty will scale with statistics since the resolution is determined using $Z \rightarrow ee$ events.

### 2.4.3.4 Recoiling energy modeling

The detector response to the recoil energy against $W$ is directly calibrated using $Z \rightarrow ee$. Therefore the uncertainty will scale with statistics. For Run II with the muon coverage at high $\eta$, $Z \rightarrow \mu\mu$ can also be used.

### 2.4.3.5 $W$ Production model

$P_T^W$: For the $P_T^W$ spectrum, the $P_T^Z$ distribution from $ee, \mu\mu$ and a new theoretical calculation which includes soft gluon resummation effects and $W$, $Z$ decays are expected to provide appropriate checks and improved theoretical guidance, and will allow the reduction of the current uncertainty in $M_W$ substantially.

The Run I measurement of $d\sigma/dP_T^Z$ [10] is shown in
Figure 2.23: The $d\sigma/dp_T$ of $e^+e^-$ pairs in the mass range $66–116$ GeV/$c^2$. The inset shows the $p_T < 20$ GeV/$c$ region with a linear ordinate. The crosses are the data with all errors included, except the 3.9% luminosity error. The dashed (solid) curve is the EV ($Z$-only RESBOS) prediction with the cross section normalized to 248 pb.

Fig. 2.23. With $15$ fb$^{-1}$ of Run IIb data, the errors in the low $p_T^Z$ region are expected to be $1\%$, providing a very strong constraint on the theoretical model in the region relevant for the $W$ mass measurement.

**Parton Distribution Functions:** The Run I uncertainty in PDF's was constrained by the CDF $W$ asymmetry measurement (see Figure 2.24), which will become more precise with statistics. Forward coverage is very important for this measurement since the PDF sensitivity increases with the rapidity coverage. The data in the central region probes the $d$ and $u$ distributions in the $x$ region between 0.02 and 0.15. The forward data probes the region between 0.006 (a new region of $x$) and 0.35.

However, Monte Carlo studies have shown that the $W$ charge asymmetry does not have the same sensitivity to all aspects of the PDF's as the $W$ mass measurement. Therefore additional measurements are likely to be needed which will constrain PDF's in different ways. The $y$ distributions of $Z$ ($y_Z$) from dileptons have sensitivity to constrain PDFs, and this may help reducing the PDF uncertainty in $M_W$. A precise measurement of $Z$ efficiency as a function $y_Z$ in a wide rapidity region is required, which can be measured using the $Z$ sample itself with sufficient statistics. Figure 2.25 shows the Run I measurement [11] of $d\sigma/dy$ for Drell-Yan production. The measurement is completely limited by statistics in Run I, and is likely to remain so even beyond 2 fb$^{-1}$. For this measurement forward coverage is essential. Similar but additional information on PDF’s can be obtained by measuring the lepton rapidity distribution in $W$ decays.

Cross section measurements of Drell-Yan production [12] (especially the low mass region) can be used to get further constraints on PDFs. The Run I Drell-Yan cross section measurements using central electrons are shown in Figure 2.26. The low mass data is sensitive to the very low $x$ region. Run IIb upgrades to the DAQ bandwidth will be important for this program in order to preserve our ability to trigger on low $p_T$ lepton pairs.

The PDF uncertainty can also be reduced by raising the minimum $M_W^T$ for fitting. This will imply a larger statistical uncertainty, and is an example of using the huge Run IIb statistics to reduce systematics and the total uncertainty.

While the PDF uncertainty will warrant attention, it is likely that a program of measurements with collider data will prevent it from dominating the $W$ mass measurement. It should be noted that the combined D run I measurement, including the forward calorimeter data, already quotes a PDF uncertainty of 7 MeV [13].

**QCD higher order corrections:** The effects of higher-order QCD corrections on the $W$ polarization have been calculated at $O(a_s^3)$. The $W$ mass is measured using the low $p_T^W$ sample where the higher order QCD corrections are modest. The uncertainty is negligible in current analyses, and should not be a fundamental problem in the future. This effect has been measured in Run I [14] and the measurement is statistically limited. With Run IIb statistics, a precise measurement of the $W$ polarization as a function of $p_T^W$ will be possible.

**QED Radiative corrections:** Radiative corrections in $M_W$ are rather large: the shifts in $M_W$ due to the final state radiation are 65 MeV in the $W \to e\nu$ channel and 168 MeV in the $W \to \mu\nu$ channel. For Run IIb, the uncertainty in these shifts due to missing diagrams was estimated to be 20 MeV and 10 MeV for the electron and muon channels respectively. Recently, a more thorough calculation [15] of electroweak radiative $W$ and $Z$ boson production and decay, in-

2-33
including initial and final state radiation, finite lepton masses, and finite $W, Z$ width effects. A two-photon calculation is also available \[16\]. This will make it possible to reduce the error associated with radiative corrections substantially in the future.

### 2.4.3.6 Backgrounds

The $Z \to \mu \mu$ background (one muon in the central muon chambers and the other muon in high $\eta$ region) in the $W \to \mu \nu$ sample is the dominant background for this channel and its uncertainty derives from the choice of PDF's and the tracking efficiency at high $\eta$. For Run II, the tracking upgrade (well measured ISL+SVXII tracks in the region $1 < |\eta| < 2$) and the forward muon upgrade (muons in the region $1.5 < |\eta| < 3$) together with the muon signature in the plug upgrade calorimeter will remove most of this background and will reduce the uncertainty. This uncertainty does not scale easily with statistics, but forward tracking and muon coverage is clearly very important to control this source of background.

### 2.4.3.7 Trigger and Selection Bias

For Run Ia, there was a 15 MeV uncertainty due to a possible momentum dependence of the muon triggers in the $W \to \mu \nu$ channel. The measurement of the momentum dependence was statistically limited. The muon selection is also possibly affected by the presence of nearby jets.

For Run IIb, it is important to maintain unbiased triggers. That is, the momentum thresholds should be low enough not to introduce a $P_T$ or $E_T$ dependence above 25 GeV. Also, the lepton selection should not be biased by hadronic activity. This means we must maintain high tracking efficiency as the luminosity increases.

### 2.4.3.8 $W$ mass summary

We make a conservative estimate that 15 fb$^{-1}$ will allow CDF II to measure the $W$ mass to $\pm 20$ MeV/$c^2$, which will be a significant improvement over the Run Ia measurement and the world average, giving the Tevatron the leading role in the measurement of this important parameter. Coupled with a commensurate improvement in the top mass precision, this will give the Tevatron the dominant position in constraining the Higgs mass. The estimates of individual uncertainties is shown in Table 2.7.

### 2.4.4 $W$ Width

The leptonic branching ratio of the $W$ may be inferred from the ratio $R = \sigma \cdot Br(W \to l\nu)/\sigma \cdot Br(Z \to ll)$, using LEP measurements for the $Z$ couplings and a theoretical prediction of the production cross section ratio. It provides a standard model consistency check. For Run Ia [17] CDF measured $Br(W \to e\nu) = 0.109 \pm 0.0033$(stat) $\pm 0.0031$(syst). If one further assumes standard couplings for $W \to e\nu$, one can derive a value for the total width of the $W$ boson, $\Gamma_W = 2.064 \pm 0.0060$(stat) $\pm 0.0059$(syst) GeV. The theoretical uncertainty in the cross section ratio is expected to limit precision to about $\pm 1\%$. How-
ever, the upgraded momentum measurement in the region $1 < |\eta| < 2$ should give improved acceptance systematics, reducing the dependence on the parton distribution functions.

The $W$ width can be measured directly from the shape of the transverse mass distribution (see Figure 2.27). For $M_T^W > 100$ GeV/c$^2$ resolution effects are under control and using Run Ib in the modes $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$, CDF measured $\Gamma_W = 2.04 \pm 0.11$ (stat) $\pm 0.09$ (syst) GeV [19]. The direct measurement of the $W$ width closely follows the measurement of the $W$ mass. The uncertainties will likely scale with statistics allowing a $\pm 15$ MeV measurement for 15 fb$^{-1}$, much better than the LEP2 expectation of $\pm 200$ MeV, and providing a stringent test of the standard model.

### 2.4.5 Gauge Boson Couplings

The Standard Model makes specific predictions for the trilinear couplings of the gauge bosons, $W$, $Z$, and $\gamma$. The nature of these couplings can be investigated via studies of $W\gamma$ and $Z\gamma$ production [20] and $WW$, $WZ$ and $ZZ$ pair production [21]. The major goals of these studies will be testing the Standard Model prediction(s) and searching for new physics. The Run I results are summarized in Table 2.8 (see also [3] for details).

$W\gamma$ production in $p\bar{p}$ collisions is of special interest due to the SM prediction of a radiation amplitude zero in the charge-signed $Q_W \cdot \cos \theta_\gamma^*$ distribution at $\sim -0.3$. The radiation zero is also predicted to manifest itself as a “channel” in the charge-signed $Q_W \eta_\gamma$ vs. $Q_W \eta_\gamma$ 2-dimensional distribution [22], and as a strong “dip” in the charge-signed photon-$W$ decay lepton rapidity difference distribution, $Q_W \cdot (\eta_\gamma - \eta_\gamma)$ at $\sim -0.3$.

By using central and plug electrons and photons, it will be possible in Run IIa to conclusively establish the dip in the photon lepton rapidity difference distribution. On the other hand, for central electrons and photons only, the dip is not statistically significant with Run IIa statistics and will benefit from Run IIb statistics. Also, the increased statistics will help to measure the location of the dip more precisely and provide a better test of the standard model prediction.

Backgrounds from electromagnetic showers induced by cosmic rays are important for diboson analyses. For example, a $W \rightarrow e\nu$ event with a cosmic ray would look like a $W\gamma$ event with anomalous $E_T$. Similarly, a $Z \rightarrow ee$ event with an overlapping cosmic ray would give an $e\gamma E_T$ signature. The process $p\bar{p} \rightarrow Z(\rightarrow \nu\bar{\nu}) + \gamma + X$ has large cosmic ray backgrounds. Sensitivity to $Z\gamma$ anomalous couplings is statistics-limited and this channel has the advantage over the $\ell^+\ell^-\gamma$ channel by a factor of 3 in the branching ratio, and almost a factor of 2 in the acceptance. The D experiment has taken advantage of its pointing calorimeter to control cosmic ray backgrounds, and has produced the best $Z\gamma$ measurement by using the $\gamma E_T$ channel [23]. By using the EM calorimeter timing information provided by the proposed Run IIb upgrade, the cosmic ray background can be controlled much better and the sensitivity of these diboson analyses will increase significantly.

For Run II, we anticipate that the current results from CDF will undergo further significant improvements with 15 fb$^{-1}$ integrated luminosity, in conjunction with the Run II upgrades of the overall tracking, calorimeter, muon and DAQ systems. Since the acceptance for diboson events increases rapidly with rapidity coverage, it is important to maintain this capability through Run IIb to fully exploit the increased luminosity. The sensitivity for $WW$ and $ZZ\gamma$ anomalous coupling is limited by the statistics of backgrounds and potential signal and therefore benefits from larger data sizes, improving as $N^{1/4}$. The CDF IIb measurements with 15 fb$^{-1}$ (see Table 2.9) are anticipated to surpass those from LEP-II experiments. The Tevatron also has a significant advantage over LEP-II because the Tevatron can produce all the three ($W\gamma$, $WW$ and $WZ$) final states and therefore obtain independent sensitivity to the different couplings with fewer assumptions.

In addition to the increased sensitivity to anomalous couplings through potential excesses in the data, 15 fb$^{-1}$ of integrated luminosity makes it possible to measure all the diboson production cross sections with good precision. This is particularly true for the $WW$, $WZ$ and $ZZ$ cross sections which are statistically limited even with 15 fb$^{-1}$ (see Table 2.5). The precise measurements of these cross sections means that we will also be sensitive to deficits compared to the predicted cross sections. This will add a whole new dimension to diboson physics and new physics searches, which makes a strong case for going beyond 2 fb$^{-1}$ and acquiring 15 fb$^{-1}$ of data.

The statistics of Run IIb will also make possible for the first time a study of two new diboson channels, $WZ \rightarrow \ell\nu b\bar{b}$ and the $ZZ$ final state. The former chan-
Table 2.8: 95% C.L. Anomalous gauge boson coupling limits achieved in Run I analyses by the CDF Collaboration.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Luminosity (fb⁻¹)</th>
<th>Anomalous Coupling limit (95% C.L.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W\gamma \rightarrow \ell\nu\gamma$</td>
<td>20</td>
<td>$-0.7 \leq \lambda \leq 0.7, -2.2 \leq \Delta \kappa \leq 2.3$</td>
</tr>
<tr>
<td>$WW \rightarrow$ dilepton</td>
<td>108</td>
<td>$-0.9 \leq \lambda \leq 0.9, -1.0 \leq \Delta \kappa \leq 1.3$</td>
</tr>
<tr>
<td>$WW$ and $WZ \rightarrow$ leptons + jets</td>
<td>19.6</td>
<td>$-0.81 \leq \lambda \leq 0.84, -1.11 \leq \Delta \kappa \leq 1.27$</td>
</tr>
<tr>
<td>$Z \rightarrow \ell\ell\gamma$</td>
<td>20</td>
<td>$-3.0 \leq h_Z^{20} \leq 3.0, -0.7 \leq h_{40}^{20} \leq 0.7$</td>
</tr>
</tbody>
</table>

Table 2.9: 95% C.L. Anomalous gauge boson coupling limits that might be achieved in run IIb.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Luminosity (fb⁻¹)</th>
<th>Anomalous Coupling limit (95% C.L.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined $W\gamma, WW$ and $WZ$</td>
<td>2</td>
<td>$-0.086 \leq \lambda \leq 0.090, -0.12 \leq \Delta \kappa \leq 0.19$</td>
</tr>
<tr>
<td>Combined $W\gamma, WW$ and $WZ$</td>
<td>15</td>
<td>$-0.052 \leq \lambda \leq 0.054, -0.073 \leq \Delta \kappa \leq 0.115$</td>
</tr>
<tr>
<td>$Z\gamma \rightarrow ll\gamma$</td>
<td>15</td>
<td>$-0.045 \leq h_Z^{20} \leq 0.045, -0.0027 \leq h_{40}^{20} \leq 0.0027$</td>
</tr>
<tr>
<td>$Z\gamma \rightarrow \nu\nu\gamma$</td>
<td>15</td>
<td>$-0.019 \leq h_Z^{20} \leq 0.019, -0.0014 \leq h_{40}^{20} \leq 0.0014$</td>
</tr>
</tbody>
</table>

2.4.6 Forward-Backward Z Asymmetry

The presence of both vector and axial-vector couplings of electroweak bosons to fermions in the process $q\bar{q} \rightarrow Z^0/\gamma \rightarrow e^+e^-$ gives rise to an angular asymmetry, “Forward-Backward Asymmetry”, in the emission angle of the electron in the rest frame of the electron-positron pair. This asymmetry, $A_{FB}$, is a direct probe of the relative strengths of the vector and axial-vector couplings over the range of $Q^2$ being considered. In addition, $A_{FB}$ constrains the properties of any hypothetical heavy neutral gauge bosons not included in the Standard Model. For values of $Q^2$ significantly larger than $M_Z^2$, $A_{FB}$ is predicted to be large and positive (approximately 0.5), which makes it sensitive to deviations induced by new physics.

From $\sim$110 fb⁻¹ of the Run I dielectron data, CDF has measured [24] $A_{FB}$ to be $0.070 \pm 0.016$ using a sample of 5463 events in the $Z$ pole region defined by $75 < M_{ee} < 105$ GeV, and $0.43 \pm 0.10$ using a sample of 183 events in the high mass region defined by $M_{ee} > 105$ GeV. These measurements can be compared with the Standard Model predictions of $0.052 \pm 0.002$ and $0.528 \pm 0.009$. Table 2.10 summarizes our measured values for $A_{FB}$ and its uncertainties in both invariant mass regions. The statistical errors are dominant, and the sources of systematic uncertainty (from background level determination and electron pair mass resolution) are expected to scale with statistics as well. This means that these measurements will benefit from increased statistics even beyond 15 fb⁻¹.

In the vicinity of the $Z^0$ pole it will be possible to extract a precision measurement of $\sin^2 \theta_W^{eff}$ from $A_{FB}$. The uncertainty in $\sin^2 \theta_W^{eff}$ should also scale with statistics since $A_{FB}$ is proportional to $(\sin^2 \theta_W^{eff} - 0.25)$. Under the assumption that all uncertainties scale with statistics, we expect an uncertainty in $A_{FB}$ of 0.001 and an uncertainty in $\sin^2 \theta_W^{eff}$ of 0.0004 with 15 fb⁻¹. The theoretical uncertainty in $A_{FB}$ due to parton distribution uncertainty should be below 0.001, and with further improvements in PDF’s should not pose a limitation.

It should be noted that if $\sin^2 \theta_W^{eff}$ is measured to within 0.0004 as expected, then the CDF IIb result will improve upon the LEP I and SLD results which measure $\sin^2 \theta_W^{eff}$ from jet charge asymmetries in hadronic $Z^0$ decays with an uncertainty of $\sim 0.001$. Since the initial and final states are reversed in the two cases, the systematics are also different.

Well above the $Z^0$ pole, for electron pairs with invariant mass in excess of 105 GeV/c², $A_{FB}$ is dominated by $Z^0/\gamma$ interference, and a large positive value is predicted for $A_{FB}$ with a very flat dependence in
<table>
<thead>
<tr>
<th></th>
<th>75 GeV/c² &lt; M_{ee} &lt; 105 GeV/c²</th>
<th>M_{ee} &gt; 105 GeV/c²</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Raw event sample</strong></td>
<td>CC 2602 CP 2861</td>
<td>CC 98 CP 85</td>
</tr>
<tr>
<td><strong>Background</strong></td>
<td>0.052 ± 0.002</td>
<td>110 ± 36</td>
</tr>
<tr>
<td><strong>Predicted Asymmetry</strong></td>
<td>1.14 ± 0.21</td>
<td>1.07 ± 0.21</td>
</tr>
<tr>
<td><strong>Measured Asymmetry</strong></td>
<td>0.070 ± 0.016</td>
<td>0.528 ± 0.009</td>
</tr>
</tbody>
</table>

Table 2.10: Run I (110 pb⁻¹) measurements of $A_{FB}$.

electron pair invariant mass. There can be strong variations in $A_{FB}$ with invariant mass due to a variety of exotic physics at higher invariant mass scales, including most $Z'$ or composite $Z$ models [25], and also lepton compositeness models, exchange of left-handed or R-parity violating SUSY particles, and extra dimensions. Moreover, if new physics is discovered at CDF II, $A_{FB}$ measurements will provide discrimination between various models.

As with the measurements of $A_{FB}$ at the $Z^0$ pole, we expect the uncertainty in the measurements above the $Z^0$ pole to scale with statistics compared to the Run I measurement [24]. For electron pairs with invariant mass between 105 GeV/c² and 195 GeV/c², we expect to collect approximately 20,000 events with 15 fb⁻¹. Using this entire sample we expect to measure $A_{FB}$ to within 0.007. For electron pairs with invariant mass above 195 GeV/c² (above the LEP 200 maximum √S), we expect to collect approximately 2,000 events, which should allow a measurement of $A_{FB}$ to within 0.025. Parton distribution function uncertainty will not significantly affect this sensitivity.
Figure 2.25: \(d\sigma/dy\) distributions of \(e^+e^-\) pairs in (a) the \(Z\) boson mass region, and (b) the high mass region. The error bars on the data include statistical errors only. The theoretical predictions have been normalized to the data in the \(Z\) boson mass region. The top horizontal axes on the figures are the corresponding values of \(x_1\) and \(x_2\) as a function of \(y\). The \(M\) used to obtain \(x_1\) and \(x_2\) in (b) is the mean mass over the bin.

Figure 2.26: Drell-Yan dilepton \((e^+e^-,\mu^+\mu^-)\) production cross section from Run I as a function of the dilepton invariant mass. Also shown are expectations from compositeness models.

Figure 2.27: Run Ib transverse mass distributions (filled circles) for \(W \rightarrow e\nu\) (upper) and \(W \rightarrow \mu\nu\) (lower), with best fit Monte Carlo fits superimposed as a solid curve. The lower curve in each plot shows the sum of the estimated backgrounds. Each inset shows the 50-100 GeV region on a linear scale.
Figure 2.28: (a) $d\sigma/dM$ distribution of $e^+e^-$ and $\mu^+\mu^-$ pairs. All errors (except for the overall 3.9% luminosity error) have been combined in quadrature. The standard model theoretical predictions (solid lines) have been normalized to the data in the $Z$ boson mass region. Also shown are the $e^+e^-$ measurements from D. (b) $A_{FB}$ versus mass compared to the standard model expectation (solid line). Also, predicted theoretical curves for $d\sigma/dM$ and $A_{FB}$ with an extra $E_6$ $Z'$ boson (width of 10%) with $M_{Z'} = 350$ GeV (dotted line) and 500 GeV (dashed line). The inset in (a) shows the difference, "$\Delta$" in fb/GeV/c^2, between the CDF $e^+e^-$ $d\sigma/dM$ data and the standard model prediction (on a linear scale) compared to the expectation from these two $Z'$ models.
Bibliography


2.5 Search for New Phenomena

2.5.1 Introduction

The Standard Model is widely believed to be incomplete. Indeed, precision electroweak data, combined with the direct search limit from LEP for the Higgs ($H^0$), are moderately inconsistent.[1, 2] Strong theoretical arguments suggest that new physics should emerge at the scale of electroweak symmetry breaking, for example in scenarios invoking supersymmetry, new strong dynamics, or large extra-dimensions.

If we assume that no discoveries are made in the 2 fb$^{-1}$ Run IIa, nevertheless an order of magnitude increase in integrated luminosity will greatly extend the discovery potential of CDF II. This is despite the fact that, as illustrated in Figure 2.29, the reach in mass grows only logarithmically with integrated luminosity. However, numerous models have been suggested that predict new phenomena at a scale accessible at the Tevatron– for example in models of supersymmetry [3, 4, 5, 6, 7, 8], technicolor [9], gauged flavor symmetries[10], and large extra dimensions [11, 12, 13]. However, in many cases small branching ratios for experimentally viable signatures make detection difficult. In this situation one gains as the square-root of the integrated luminosity. Thus, a large discovery potential for CDF II exists in a high-luminosity Tevatron run.

The situation is well illustrated by the case of supersymmetry in a supergravity (SUGRA) scenario. As part of the Physics at Run II Workshop [14], the SUGRA working group studied five choices of SUGRA parameters (for details, see reference [15].) In SUGRA models, charginos and neutralinos tend to be light (100-200 GeV range) and therefore $\tilde{\chi}\tilde{\chi}$ pair production cross sections tend to dominate. This is illustrated in Table 2.11, where $\tilde{\chi}\tilde{\chi}$ production is dominant for all cases except the fourth where there is a large $t$-pair cross section. An effective search strategy in SUGRA models is therefore to look for tri-lepton final states.[19] However, tri-lepton final states, which might arise from three-body decays (e.g. $\tilde{\tau}_1^+ \rightarrow \ell\nu\chi^0$) or lepton decays of the $\tau$ (particularly in large tan $\beta$ models such as cases 2,3,5), result in rather small signal cross sections (see Table 2.12). The Standard Model backgrounds from this study are shown in Table 2.13. Whereas with 2 fb$^{-1}$ only case 1 is observable at the 3$\sigma$ level in the tri-lepton channel, with 15 fb$^{-1}$ all cases except case 4 are observable at this level in this channel.

Table 2.11: Parameter space choices, sparticle masses and total signal cross sections for the five chosen case studies of the mSUGRA group. The total cross section and fractional contribution to the signal from various subprocesses in the five parameter space cases of reference [15].

<table>
<thead>
<tr>
<th>case</th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{tot}(fb)$</td>
<td>404</td>
<td>653</td>
<td>2712</td>
<td>3692</td>
<td>1393</td>
</tr>
<tr>
<td>$g, q(%)$</td>
<td>4.3</td>
<td>6.6</td>
<td>50.4</td>
<td>66.2</td>
<td>0.01</td>
</tr>
<tr>
<td>$g\bar{\chi}, q\bar{\chi}(%)$</td>
<td>2.4</td>
<td>3.6</td>
<td>2.9</td>
<td>1.2</td>
<td>0.01</td>
</tr>
<tr>
<td>$\tilde{\chi}(%)$</td>
<td>85.0</td>
<td>85</td>
<td>45.7</td>
<td>32.6</td>
<td>99.5</td>
</tr>
<tr>
<td>$\bar{\ell}(%)$</td>
<td>8.3</td>
<td>4.7</td>
<td>1.0</td>
<td>0.04</td>
<td>0.4</td>
</tr>
<tr>
<td>$\bar{\ell}(%)$</td>
<td>1.8</td>
<td>1.5</td>
<td>41</td>
<td>65</td>
<td>0.01</td>
</tr>
<tr>
<td>$\tilde{\chi}_1^+ \tilde{\chi}_1^0 (%)$</td>
<td>43.8</td>
<td>45</td>
<td>26.5</td>
<td>13</td>
<td>16.7</td>
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<tr>
<td>$\tilde{\chi}_3^0 \tilde{\chi}_1^0 (%)$</td>
<td>33.5</td>
<td>33</td>
<td>17.6</td>
<td>13</td>
<td>24.6</td>
</tr>
</tbody>
</table>

Table 2.12: The $3\ell$ signal (fb) in 5 parameter points (adapted from [15]) The lepton $p_T$ thresholds are 11, 7, and 5 GeV.

<table>
<thead>
<tr>
<th>case</th>
<th>$\sigma$ fb</th>
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</thead>
<tbody>
<tr>
<td>(1)</td>
<td>7.39 ± 0.12</td>
</tr>
<tr>
<td>(2)</td>
<td>0.93 ± 0.06</td>
</tr>
<tr>
<td>(3)</td>
<td>1.08 ± 0.12</td>
</tr>
<tr>
<td>(4)</td>
<td>2.72 ± 0.23</td>
</tr>
<tr>
<td>(5)</td>
<td>0.63 ± 0.07</td>
</tr>
</tbody>
</table>

An additional analysis was performed for sensitivity in a more general minimal SUGRA model with essentially the same cuts.[15] As shown in Figure 2.30, the reach increases significantly for a high luminosity run (here taken as 30 fb$^{-1}$).

2.5.2 Generic exotic signatures and the CDF II upgrade

The search for new phenomena looks for any deviation from Standard Model expectations. However, guided by theory, historical precedent (e.g. high $p_T$ leptons), and sometimes serendipity (e.g. the CDF $ee\gamma\mathbb{E}_T$ candidate event), certain generic signatures emerge: missing transverse momentum($\mathbb{E}_T$), high-$p_T$ leptons ($e, \mu$), multi-leptons, high-$p_T$ jets, displaced vertices, high-$p_T$ photons, hadronic $\tau$-decays, and highly-ionizing particles. The CDF upgrade has been designed to detect these objects with precision and
Figure 2.29: The expected mass reach, defined as the 95% C.L. lower limit on the mass vs. integrated luminosity at the Tevatron for searches for new gauge bosons. The potential to discover increasingly heavy objects grows only logarithmically with luminosity.

Figure 2.30: The contours of 99% C.L. observation at Run II and 5σ discovery as well as 3σ observation at Run III (30 fb⁻¹) for $p\bar{p} \rightarrow$ SUSY particles $\rightarrow 3\ell + X$ with soft lepton cuts in the $(m_{1/2}, m_0)$ plane, for $\tan \beta = 2$, (a) $\mu > 0$ and (b) $\mu < 0$. (from reference [15])
Table 2.13: SM backgrounds (fb) for low-\(p_T\) triletons as defined in reference [15] (“soft B” cuts). (adapted from [15])

<table>
<thead>
<tr>
<th>BG</th>
<th>(\sigma) fb</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\ell\nu\ell)</td>
<td>0.45 (\pm) 0.003</td>
</tr>
<tr>
<td>(\ell\nu\ell)</td>
<td>0.20 (\pm) 0.004</td>
</tr>
<tr>
<td>(\ell\nu\tau)</td>
<td>0.36 (\pm) 0.008</td>
</tr>
<tr>
<td>(\tau\nu\ell)</td>
<td>0.13 (\pm) 0.008</td>
</tr>
<tr>
<td>(\ell\ell\tau)</td>
<td>0.06 (\pm) 0.001</td>
</tr>
<tr>
<td>(t\bar{t})</td>
<td>0.06 (\pm) 0.004</td>
</tr>
<tr>
<td>total</td>
<td>1.26</td>
</tr>
<tr>
<td>99% C.L. (2 fb(^{-1}))</td>
<td>2.5</td>
</tr>
<tr>
<td>3(\sigma) (2 fb(^{-1}))</td>
<td>2.38</td>
</tr>
<tr>
<td>3(\sigma) (15 fb(^{-1}))</td>
<td>0.87</td>
</tr>
</tbody>
</table>

efficiency.

Certain aspects of the Run IIb upgrade are needed to maintain CDF’s excellent performance in the high luminosity environment. Precision tracking is clearly critical, not only for lepton detection and photon discrimination, but for identification of primary and secondary vertices. Thus the silicon detector, which will discriminate between multiple primary vertices along the interaction region, and detect secondary vertices with high efficiency and precision, is essential for the exotics program. In addition, the ‘projective’ modification of the inner layers of the COT will allow for continued high-efficiency tracking in the central rapidity (\(|\eta| < 2\)) region. Of critical importance is the ability to trigger on muons. This capability depends on scintillator timing in addition to stub finding in the muon drift chambers. In the intermediate rapidity range, this timing is provided by the CSX scintillators. These counters will need to be replaced for the high-luminosity run.

Several of the proposed upgrades will significantly enhance the performance of the detector for Run IIb in ways highly relevant to exotic searches. The addition of stereo information to the Level 1 trigger will have a major impact on signatures with multiple, low-\(p_T\) leptons or displaced vertices. The additional \(Z\) information should significantly reduce fake rates. In addition, because Level 1 tracks are available for the Level 2 decision, this upgrade will allow for enhanced Level 2 track-based triggers, for example one based on a multi-track mass. This is illustrated in Figure 2.31 for the dimuon \(J/\psi\) trigger. In this case the additional stereo information allows the application of a mass cut which dramatically reduces the trigger rate. Stereo tracking at the trigger level will also impact the Level 1 track trigger (Track Trigger module) which is primarily aimed at selecting hadronic decays of \(B\) hadrons. Currently this module looks for pairs of tracks. We are proposing an upgrade to the Track Trigger module that will additionally trigger on three tracks. This upgrade is primarily designed to maintain the capability for triggering on displaced vertices in a high luminosity environment.

The proposal to add timing information to the readout of the central and plug Electromagnetic calorimeters will significantly enhance our capability to do physics with photons. This timing information will already be available for the hadron calorimeters in Run IIA (central hadronic timing was available in Run I); it is critical in removing noise hits as well as identifying cosmic rays. However, the hadron timing is obviously ill-suited for the timing of electromagnetic particles. In current searches for extremely rare events, cosmic ray backgrounds remain a problem. Additionally, the timing will ensure that all photons are from the primary interaction. This will be essential at high luminosity with multiple interactions (mean \(\sim 5\)) per crossing. This situation is illustrated by the \(ee\gamma\) candidate event, where the hadron calorimetry timing was available for one electron and one photon in the event (see Figure 2.32). [20] In this case, both electron and photon are both consistent with the (unoptimized) 4 ns resolution. The cosmic rays background, uniform in time, is also shown. However, no timing information is available for the plug electron candidate or the second photon. The instrumentation of the electromagnetic calorimetry with timing both for central and plug calorimeters will allow timing for all electromagnetic clusters. Additionally, a 1 ns resolution is achievable with calibration. This capability would allow for searches of long-lived particles predicted in some models of gauge-mediated supersymmetry decaying to photons.

### 2.5.3 Illustrative signatures in specific models

Beginning with the Tev-2000 Workshop in 1996 [21] and continuing through the more recent Physics at Run II set of workshops sponsored by Fermilab[14], a great deal of effort has gone into studying the physics
potential of a high-luminosity Tevatron run. For example, the Physics at Run II workshop identified 25 distinct channels with significant discovery potential for supersymmetry in Run II. We make no attempt to summarize this very large body of work here. Rather, our purpose in this section is to give a few examples in a number of important exotics channels of the discovery potential of the CDF upgraded detector with a large luminosity exposure. These examples illustrate the large potential for discovery, particularly in supersymmetric models, of physics beyond the Standard Model.

2.5.3.1 Signatures with missing transverse momentum

Missing transverse momentum ($E_T$), is the classic signal for R-parity conserving supersymmetry. It is important not only as a trigger and a generic signature, but as an essential component in a large number of signatures. The CDF Run I search for squarks and gluinos in the missing energy plus multijet channel excludes at 95% C.L. gluino masses below 300 GeV for $m_{\tilde{q}} \approx m_{\tilde{g}}$, and below 195 GeV independent of the squark mass. The exclusion contour at 95% C.L. in the $m_{\tilde{q}}$-$m_{\tilde{g}}$ mass plane is shown in Figure 2.33. This recent result, using a ‘blind’ search technique, is a significant improvement over previous searches and is starting to probe the interesting mass region for constrained supersymmetric models. In Run II we expect substantial improvement in our $E_T$ resolution as a result of the plug calorimeter upgrade. The addition of timing information to the electromagnetic calorimetry will also have a significant impact on analyses with $E_T$ as they remove an insidious type of cosmic ray backgrounds which could otherwise not be reduced.

A study of the five SUGRA points discussed above was done by the SUGRA working group for the jets plus $E_T$ channel.[15] The analysis assumed a detector resolution comparable to that expected for CDF II. The range of $\tilde{q}/\tilde{g}$ masses in these models are in the range $\sim (350-450)$ GeV for cases 2,3,4, with heavier masses for cases 1 and 5. With a hard cut of $E_T > 75$ GeV and the removal of events with $E_T$ correlated with jets, the background is dominated by Standard Model processes with neutrinos- top, and W/Z plus jets. The total background cross section is about 300 fb, giving signal cross sections for discovery (5$\sigma$) of 61 fb at 2 fb$^{-1}$, and 22 fb at 15 fb$^{-1}$. The signal cross sections are listed in Table 2.14. Here it can be seen that a high luminosity run is needed to be sensitive for squark and gluino masses in the range of 350-400 GeV.

Figure 2.31: Dimuon trigger cross section vs. muon trigger $p_T$ threshold in Run I. Solid points are for tightly matched, opposite-charge pairs. The open squares are the rates with a mass cut as would be available from the proposed Level 1 track upgrade. The fits are to a power-law form.
Figure 2.32: Left: The CDF event with 1 central electron, 2 central photons, a plug electron candidate, and $E_T$. Only the central electron and one of the photons ($\gamma_1$) has hadronic timing information. Right: The timing for the central electron and photon from the $ee\gamma\gamma E_T$ candidate event are consistent with having originated at the primary interaction. Shown for comparison are the timing of electrons from $Z$ decays and the flat background from photons from cosmic rays.

Figure 2.33: Exclusion contour at 95% C.L. in the $m_{\tilde{\nu}}$ - $m_{\tilde{\nu}}$ mass plane based on based on 84 $pb^{-1}$ of Run I data for the mSUGRA model with $\tan \beta = 3$. (From reference [16]).
Table 2.14: SUSY signal (fb) for $E_T$ jets events for the Tevatron for the 5 SUGRA cases (from reference [15]).

<table>
<thead>
<tr>
<th>case</th>
<th>$\sigma$ fb</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>5.7 ± 0.1</td>
</tr>
<tr>
<td>(2)</td>
<td>16.6 ± 0.2</td>
</tr>
<tr>
<td>(3)</td>
<td>61.9 ± 0.9</td>
</tr>
<tr>
<td>(4)</td>
<td>18.5 ± 0.6</td>
</tr>
<tr>
<td>(5)</td>
<td>1.3 ± 0.2</td>
</tr>
</tbody>
</table>

2.5.3.2 Signatures with high-$p_T$ leptons

High $p_T$ leptons are the classic signature for extra gauge bosons that are predicted in grand unified theories with gauge groups larger than SU(5). CDF has placed 95% C.L. limits of $M_{Z'} > 690$ GeV and $M_{W'} > 755$ GeV for standard model couplings. Such searches are also sensitive to quark-lepton compositeness in models where quarks and leptons share constituents. For example, the compositeness scale limit set by CDF from the dielectrons is $M_{Z'} > 2.5(3.7)$ TeV.[17] These limits will continue to improve (albeit logarithmically) with increasing luminosity (Figure 2.34).

The possibility of detecting extra dimensions in Drell-Yan production at the Tevatron has been suggested by Hewett.[22, 23] Such extra dimensions may be detectable at the Tevatron in theories where gravity becomes strong near the weak scale. The interaction of massive gravitons with quarks and leptons gives rise to an enhancement in the cross section at high pair-mass and a forward-backward charge asymmetry. Figure 2.34 (left) shows the invariant mass distribution for dielectron pairs from CDF in Run I.[18] The agreement with the Standard Model expectation is excellent, and in particular there is no excess of events at high mass. Hewett has calculated that a 0.1 fb$^{-1}$ data set consistent with the Standard Model constrains the effective Plank (string) scale to be greater than 990 (930) GeV depending on the sign ($\mp$) of the graviton amplitude. Shown in Figure 2.34 (right) is the projected limit as a function of luminosity.

2.5.3.3 Multi-lepton signatures

As has already been mentioned, tri-leptons are a good signature for chargino-neutralino production. Multi-lepton signatures are also predicted in models with R-parity violation and in models of gauge-mediated supersymmetry (GMSB). For example, multileptons are predicted in a model of GMSB with nearly degenerate sleptons that share the role of next-lightest particle (NLSP).[22] In theories with GMSB, the LSP is an essentially massless, spin-1/2 Goldstino ($\tilde{G}$), the particle resulting from the spontaneous breaking of supersymmetry. The decay rate of any superpartner $\tilde{X} \rightarrow X\tilde{G}$ is proportional to $m_X/F^2$, where $\sqrt{F}$ is the symmetry breaking scale.[24] Depending on the scale $\sqrt{F}$, the NLSP may be long-lived. The Run II Workshop considered many scenarios for NLSP, including the degenerate slepton NLSP case.[25] In this case, three-body decays of $\tilde{e}_R$ and $\tilde{\mu}_R$ to $\ell\tau\tilde{\nu}$ are forbidden. For low $\sqrt{F}$ decays of the sleptons to $\ell\tilde{G}$ are prompt giving a signature of multi-leptons and $E_T$. Based on the Run I trilepton search, the number of background events was estimated to be 0.5 per fb$^{-1}$.[26] (The $E_T$ cut was increased to 25 GeV for this study.) The resulting limit is shown in Figure 2.35.

2.5.3.4 Signatures with high-$p_T$ jets

Many extensions of the Standard Model predict exotic particles with decays to quarks and gluons which would appear as bumps or enhancements in the dijet mass spectrum. For example, the existence of a larger chiral color group, $SU(3)_L \times SU(3)_R$, would lead to massive color-octet axial vector gluons (axigluons) which would be produced and decay strongly giving a very large cross section times branching ratio to dijets.[27, 28] Technicolor models predict relatively light technihadrons, which might include color-octet technihbosons that decay to dijets or color-singlet technihinos with signatures of W or Z plus dijets. [30] Models of gauged flavor symmetries have additional gauge (flavoron) bosons giving rise to an enhancement at high-mass in the dijet cross section.[10] If quarks are composite particles, then excited states of composite quarks are expected and couple to $gg$. New gauge bosons, $W'$ and $Z'$, in addition to coupling to leptons, would produce dijet mass bumps. Superstring-inspired $E_6$ grand unified models predict the existence of many new particles [31] including a color-triplet scalar diquark $D(D')$ with charge $\pm 1/3$ which couples to $\tilde{u}\tilde{d}(\tilde{u}d)$.

The dijet mass spectrum is described within errors by next-to-leading order QCD using CTEQ4HJ parton distributions.[32] In Run I we have searched for resonances and set limits on the production of high-
Figure 2.34: Left: The dielectron invariant mass distributions compared to background predictions from the 0.1 fb⁻¹ Run I. The agreement with the standard model everywhere is excellent. Right: 95 % C.L. limit on the string scale as a function of integrated luminosity using the forward-backward asymmetry of high-mass lepton pairs. The parameter $\lambda$ is the relative sign between the graviton and Standard Model amplitudes. [23]

Figure 2.35: The projected Run II CDF limit on cross section times branching ratio in the degenerate slepton NLSP model. The solid line is the theoretical prediction.
mass resonances.[33] The data (see Figure 2.36, left) is well described by a fit to a smooth curve and resonances are excluded. The predictions for Run II are shown on the right of Figure 2.36.

Particularly important for exotic searches are b-
flavor jets and therefore secondary vertex tagging. For
example, in technicolor models the technipion couplings are expected to be proportional to mass.[30] Topcolor models predict a $Z'$ and topgluons which preferentially decay to $bar{b}$.[34, 35] In models of supersymmetry, the stop ($\tilde{t}$) could be significantly lighter than the squarks.[36] In gauge-mediated supersymmetry with a higgsino-like neutralino NLSP, the neutralino will have a large branching ratio to the Higgs.[37] In Run I we searched for resonances in secondarily tagged dijets (see Figure 2.36) and set limits on $Z_{\text{top}}'$ and topgluons. We have also searched for a fourth generation $\mathcal{V} \to bZ$, and a technihiggsino decaying to $Wb\bar{b}$, and a techniomega decaying to $\gamma b\bar{b}$.[38, 39, 40] We have done a study for Run II of the higgsino-like NLSP model with the signature of $b\bar{b}\mathcal{E}_T$. [25] In Figure 2.37 we have calculated the cross-section times branching ratio limit for 2, 10, and 30 fb$^{-1}$. It is seen that at least 10 fb$^{-1}$ is needed to have any sensitivity in this channel.

### 2.5.3.5 Signatures with high-$p_T$ photons

From Run I data we have published a detailed search for anomalous events with two isolated, central, high-$p_T$ photons.[41, 42] The diphoton mass distribution is shown in Figure 2.38. The results are consistent with standard model expectations, with the possible exception of one event (the $ee\gamma\mathcal{E}_T$ event). The $E_T$ distribution was used to set a limit in the light gravitino SUSY scenario. We have also looked for narrow diphoton resonances as might be the signature for a scalar-goldstino, new extra dimensions, new contact interaction, or ‘bosophilic’ Higgs.[43]

We have studied the prospects for Run II discovery of a bino-like neutralino in gauge-mediated supersymmetry. In this scenario, the NLSP decays to a photon plus the Goldstino. Depending on the supersymmetry breaking scale $\sqrt{F}$, this decay may or may not be prompt. In the case of prompt decays, we can project our sensitivity based on the Run I search. As a result of the plug calorimeter upgrade and tracking upgrades we expect a significantly enhanced acceptance to $|y| < 2$. This improves our efficiency by 60%. The primary background is from QCD and is estimated to be $\sim 0.5$ fb, based on the Run I data corrected for the increased center-of-mass energy. The projected limits as a function of neutralino mass are shown in Figure 2.39, for 2, 10 and 30 fb$^{-1}$. A significant increase in sensitivity is gained at the higher luminosities. In addition, the electromagnetic calorimeter timing upgrade will give a handle which can indicate that the photon is indeed from the collision; a significant improvement for searches with final state photons which suffer from cosmic ray backgrounds.

In the case of a long-lived, bino-like neutralino it is possible that a non-prompt photon would be produced. In this case, the only handle we have for this signature is the proposed electromagnetic calorimeter timing. With an expected resolution of about 1 nsec, Figure 2.39 shows the range of neutralino and Gravitino masses that would give rise to a detectable delayed signal.

### 2.5.3.6 Detecting hadronic $\tau$ decays

We have demonstrated that it is possible to detect hadronic decays of the $\tau$, having measured the cross section times branching ratio for $W \rightarrow \tau\nu$. [44] This technique which identifies narrow, hadronic jets is shown in Figure 2.40 from a search for third generation leptoquarks.[45] The charged particle multiplicity distribution shows that the characteristic one-plus-three prong signature is very clean. This technique can significantly increase the sensitivity to Run II exotic signatures. This is especially true in the case of supersymmetry. In SUGRA models with large $\tan \beta$, decays to taus are favored.[46] In gauge-mediated models, the stau can be the NLSP.

For example, a model studied in the SUGRA working group was a large $\tan \beta$ scenario where $\tilde{\chi}_1^+ \tilde{\chi}_2^0 \rightarrow \tau\tau X$. Figure 2.41 shows the improvement in sensitivity gained by including hadronic tau decays in addition to leptonic decays in a trilepton signature. A $3\tau$ exclusion is possible for luminosity greater than 10 fb$^{-1}$. [47]

### 2.5.4 Detecting long-lived, massive particles

Massive stable particles are possible features of several theories for physics beyond the standard model including supersymmetry, mirror fermions, technicolor, and compositeness. We have searched in the 88/89 data for heavy stable charged particles [48,
Figure 2.36: Left: The invariant mass distribution of dijets, and the invariant mass distribution with one at least one secondary vertex tag (b tag). Right: The 95% C.L. lower limit on the mass of new particles decaying to dijets versus integrated luminosity.

Figure 2.37: Projected Run II limits on the total SUSY cross section times branching ratio in the $b\bar{b}E_{T}$ channel along the higgsino-like neutralino as a function of chargino mass. The solid line is the theoretical expectation.
Figure 2.38: Left: The diphoton mass distribution from 100 pb\(^{-1}\) Run I data. Right: The \(E_T\) spectrum for events with two central photons compared to the expected distribution from \(E_T\) resolution.

Figure 2.39: Left: Projected limits on the SUSY cross section for the bino-like neutralino NLSP in the \(\gamma E_T\) channel. Right: Lifetime of the NLSP for various masses as a function of the Gravitino mass. \(\kappa\) is a parameter measuring the photino content of the neutralino.
Figure 2.40: Charged particle multiplicity distribution in hadronic jets for opposite-sign Run I data compared to \( Z \to \tau^+ \tau^- \) Monte Carlo plus fakes estimated from same-sign data (from ref [45]).

Figure 2.41: The total integrated luminosity \( L \) needed for a 3σ exclusion (solid lines) or observation of 5 signal events (dashed lines), as a function of the chargino mass \( m_{\tilde{\chi}^\pm} \), for (a) sample A; (b) sample B; (c) sample C and (d) sample D, as defined in Table ??; and for the following channels: trileptons (x), dileptons plus a tau jet (□) and like-sign dileptons plus a tau jet (◇).
49] based upon their expected high transverse momenta, relatively low velocities (via time-of-flight), and muon-like penetration of matter. We obtained upper limits on the cross-section for the production of heavy stable particles as a function of their mass. This can be translated into a mass limit from the cross-section for any particular theory and varies from about 140 GeV for color triplets to 255 GeV for color decuplets as shown in Figure 2.42b. This analysis is currently being extended using Run I data. Rather than using time-of-flight, the analysis takes advantage of the large ionization depositions, dE/dx, expected for massive particles, with measurements in both the SVX and in the outer tracker (CTC for Run I). For example, see Figure 2.42 (left). Using half of the Run Ib data, we have obtained a preliminary limit of 190 GeV/c^2 for color triplets. The extrapolations to Run II are shown in Figure 2.42b.

An interesting possibility for supersymmetry is that the \( \tilde{\chi}_1^\pm \) is long-lived. [50] This happens in models where the \( \tilde{\chi}_1^\pm \) is nearly degenerate with the LSP \( \tilde{\chi}_1^0 \), a scenario which arises naturally in anomaly-mediated models. [50, 51] In the paper by Feng et al., the possibility of detecting the \( \tilde{\chi}_1^\pm \) as a massive, stable charged particle was explored. They considered both a heavy-ionizing track trigger and an isolated stiff-track trigger. The cross section for this signal as a function of chargino mass is shown in Figure 2.44. The expected background from Run I as a function of particle mass is shown in Figure 2.45. Above 125 GeV we expect very little background. We should be able to discover \( \tilde{\chi}_1^\pm \) with masses above 250 GeV with 15 fb^{-1}.

2.5.5 Summary

CDF has produced most of the strongest limits to date in direct searches for physics beyond the Standard Model. This experience allows us to make realistic predictions of the physics potential of a high-luminosity run. The proposed upgrades are critical for maintaining our current tracking and muon detection capabilities in a high luminosity environment. In addition, we have proposed enhancements to the lepton triggers and to electromagnetic calorimeter timing.
Figure 2.43: The projected limits on the cross-section times branching ratio for a long-lived stau in a NLSP stau model. Projections are shown based on $dE/dx$ in the COT and silicon, and with an additional time-of-flight measurement assuming 100 ps timing resolution.

Figure 2.44: Cross section for $\tilde{\chi}_2^\pm$ production (solid) with a at least one $\tilde{\chi}_1^\pm$ traveling a radial distance $L$ with $|\eta| < 1.2$. The dependence on the decay length $\gamma$ is shown. Dashed contours further require the long-lived $\tilde{\chi}_2^\pm$ to have $\beta\gamma < 0.85$. (from reference [50])

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that will significantly extend our sensitivity in many important exotics channels.

Based on detailed studies in a broad range of theoretical models, there is a large potential for discovery in Run IIb. This is particularly true in the area of theories with supersymmetry. Barring these discoveries, we will be able to place many strong constraints on theories that predict new physics beyond the Standard Model.
Bibliography


[14] See http://fnth37.fnal.gov/run2.html for a list of these workshops.


2.6 QCD

2.6.1 Introduction

Quantum Chromodynamics, QCD, the theory of the strong interaction, is the least precisely known component of the Standard Model. In Run IIb, the QC sector will be tested with increased precision using single production and fragmentation of jets, and the production of W/Z bosons, Drell-Yan lepton pairs, single and double photons [1, 2]. The data sample, possible with an integrated luminosity of 15 fb^{-1}, is increased center of mass energy, and an improved rapidity coverage, coupled with the increasingly sophisticated theoretical techniques developed within perturbative QCD, will allow for stringent tests of the Standard Model down to distance scales of the order of 0.1 millimeters or less.

One of the goals for Run II will be to obtain a level of precision for QCD measurements similar to those obtained at LEP. Until the turn-on of the LHC the Tevatron will remain the “high \( Q^2 \) frontier” and it’s quite plausible that any new physics beyond the Standard Model may manifest itself as deviations from the predictions of QCD. The data taken will serve to determine the fundamental input ingredients of the theory, including the strong coupling constant \( \alpha_s \) and parton distribution functions (PDFs). Next-to-leading order (NLO) QCD predictions for the inclusive jet and dijet cross sections have been available for almost a decade [3, 4, 5]. More recently, the 3 jet cross section has also been calculated to NLO [6] and the techniques to extend this to other 3-body observables such as W/Z + 2 jet are available. The inclusive W and Z cross sections are available at NNLO and an extensive 5-year program to calculate the inclusive jet cross section to that order should be complete by the start of Run IIb [7]. At NNLO, the theoretical uncertainties due to still higher orders will be greatly reduced as shown in Figure 2.46.

In the same timescale (or less), PDFs will be widely available at NNLO, leading to a precision for QCD predictions never before achieved. In addition to extending calculations to higher order, a number of other theoretical tools have been developed and are, or will be, available for Run IIb. Among the most promising of the methods is resummation. For processes involving two disparate scales, e.g. the transverse momentum (\( Q_T \)) and mass of gauge bosons (W, Z, Higgs), or processes involving large parton x values, e.g. the high \( E_T \) jet cross section, double logarithmic contributions to the cross section arise due to the imbalance of the phase space available for the radiation of real and of virtual gluons. These contributions due to the effects of soft gluon radiation need to be resummed and can lead to important changes in the QCD observables. There have been many recent calculations involving resummation relevant to collider observables [1, 2] and more progress is expected in the next few years.

QCD-based Monte Carlo programs such as Herwig [8], Pythia [9] and Isajet [10] are used extensively in essentially all high energy physics experiments [11]. The gluon radiation from the parton showering and the resultant hadronization incorporated into the programs allows for detailed comparisons to experimental data. But, the basis for all of the above programs are 2 → 2 matrix elements. Parton showering provides only an approximation for more complex signatures involving multiple jets, photons, W/Zs and heavy quarks in the final state. There has been progress in incorporating exact matrix elements into the QCD Monte Carlos [12, 13] and recently a universal interface has been developed between matrix element and Monte Carlo programs that allows for the advantages of the use of the exact matrix element and the ad-

![Renormalisation scale dependence](image)

Figure 2.46: The jet cross section at an \( E_T \) value of 100 GeV/c plotted as a function of the relative renormalization scale \( \mu/E_T \). For renormalization scales within a factor of 2 of the jet energy, the renormalization scale uncertainty of the cross section prediction is reduced from 20% at leading order to 9% at NLO to a few percent at NNLO. The 3 NNLO curves correspond to 3 assumptions regarding the currently uncalculated terms for the NNLO inclusive jet cross section.
ditional gluon radiation and hadronization from the parton shower [14]. The current implementation of all QCD Monte Carlo programs is at leading order, but progress has been made at extending the weighting to NLO [15], and such implementations should be available by the start of Run IIb.

2.6.2 Inclusive Jets

The inclusive jet cross section has been measured in CDF over the $E_T$ range from 15 GeV/c to 450 GeV/c, spanning 9 orders of magnitude [16, 17]. (See, for example, Figure 2.47.) Good agreement is observed with NLO QCD [3, 5] predictions using conventional PDFs except at the highest values of transverse energy, starting at 200 GeV/c, where an apparent excess is observed. As the high $Q^2$ region is one where new physics may cause a deviation from NLO QCD predictions, any excess is of great interest. Similar deviations have been observed in other CDF jet cross section measurements such as the dijet mass [18], differential dijet [19] and $\Sigma E_T$ [20] analyses. A detailed examination of the angular distribution for dijet production indicates that it is consistent with QCD-type production mechanisms [21].

![Figure 2.47: The inclusive jet cross section measurements for Run Ia and Ib.](image)

One possible explanation for the excess of high $E_T$ jets is that the gluon distribution at high $x$ is larger (by a factor of 2) than conventional PDF fits have indicated. A CTEQ analysis [22, 23] has shown that such a change in the gluon distribution is possible given the constraints from the data sets included in the global PDF fits. The resulting PDF (CTEQ 4HJ and then later CTEQ 5HJ [24]) provide the best agreement not only with the CDF jet cross sections but also with D0 as well [25]. The improved agreement provided by CTEQ5HJ for the CDF Run IB inclusive jet data can be observed in Figure 2.48.

![Figure 2.48: The CDF jet cross section measured in Run Ib compared to NLO predictions using the CTEQ5M and CTEQ5HJ pdf's.](image)

A data sample of 15 $fb^{-1}$ will enable the jet cross section to be probed for higher $E_T$ (and $x$) values than were possible in Run I. In Run IIa, the jet cross section can be measured up to $E_T$ values of approximately 550 GeV/c, extended to approximately 600 GeV/c in Run IIb. The yield of jet events in the central rapidity region in Run II can be seen in Figure 2.49 using NLO QCD predictions [26] with the CTEQ5M and CTEQ5HJ PDFs, along with a parameterization of the physics cross section observed in Run IB. In addition to the increased statistics of Run II, the increase in the center-of-mass energy from 1.8 to 1.96 TeV has a dramatic effect on the jet cross section at high $E_T$.

The goal of the Run II calorimeter upgrade was to provide calorimetry as precise in the forward region as in the central one. Unlike Run I, the inclusive jet cross section will be measured out to rapidity values of 3 in Run II. The number of events expected in the rapidity intervals 0.7-1.4, 1.4-2.1 and 2.1-3.0 can be seen in Figure 2.50, using predictions with both the CTEQ5M and CTEQ5HJ pdf’s.

In Run I, there were approximately 20 events with an $E_T$ value above 400 GeV/c. In Run II, the increase in energy and integrated luminosity will result in a
sample of such events about 500 times as large. With this high statistics data sample, it will be possible to study the detailed properties of the events in order to probe more precisely the production mechanisms. Any additional $s$–channel contributions, as for example from compositeness, to the dijet cross section will tend to flatten the angular distributions. Predictions for the dijet mass distribution are shown in Figure 2.51 for the central rapidity region and in Figure 2.52 for the full rapidity region [26]. A measurement of the dijet angular distribution should be possible out to dijet masses of the order of 1000 GeV/c$^2$.

In addition, one can examine the pattern of soft gluon emission in the jet events. These hadronic antenna patterns provide a tool to diagnose different patterns of color flow in high $E_T$ events. They reflect the underlying short-distance physics and are sensitive to color coherence and interference between initial and final-state partons. These patterns may be used to distinguish between conventional QCD and new physics production mechanisms such as a possible Z-prime or compositeness [27]. In addition, it may be possible to determine if there is an enhanced $gq$ scattering component of the high $E_T$ jet cross section (expected with a CTEQ5HJ-like gluon distribution) compared to the dominant $q\bar{q}$ production mechanism.

As discussed in the introduction, threshold logarithms ($ln(1-x)$), where $x$ is the parton momentum fraction), become important when the final state object is forced to carry a large fraction ($x \rightarrow 1$) of the available center of mass energy. In this case, the radiative tail of real gluon emission is strongly suppressed. Resummation of the soft gluon radiation for this circumstance typically results in an enhancement of the cross section in the relevant kinematic region. The resummation of the threshold logs for the inclusive jet cross section at the Tevatron has been performed and found to result in only a moderate increase in the cross section in the kinematic region measured in Run I [28]. Nonetheless, it will still be important to fully
consider such effects for the high $E_T$ and $x$ values accessible in Run IIb.

### 2.6.3 $\alpha_s$ and PDFs

An important goal of QCD analyses in CDF is the extraction of $\alpha_s$ and/or parton distributions from all processes for which there are both reliable data samples and reliable predictions. Examples include the inclusive jet, dijet mass, differential dijet, inclusive photon, photon + jet and W/Z/DY cross sections. The CDF inclusive jet cross section and inclusive W/Z cross sections, along with the W asymmetry have been utilized in global PDF fits. The jet cross section, in particular, has provided in the past critical constraints on the gluon distribution in the $x$ range from .05-20.

The inclusive jet cross section from Run IIb has been used by CDF to extract a measurement of the strong coupling constant $\alpha_s$ [29]. A value of $\alpha_s$ of $0.118\pm0.001(stat)\pm0.01(exp\ syst.)$ (obtained by fitting the jet cross section over the $E_T$ range from 40 to 250 GeV/c), consistent with the world average, is obtained. More importantly, as shown in Figure 2.53, the running of $\alpha_s$ is measured over an extremely wide $Q^2$ range. The slowing of the running of $\alpha_s$ is a manifestation of the jet excess when using conventional PDFs.

In Run IIb, a measurement of the running coupling constant will be possible from a $Q^2$ of $(10\text{GeV})^2$ to over $(600\text{GeV})^2$. Deviations in the SM running of $\alpha_s$ may be due to loop contributions of new particles.

### 2.6.4 Exploring High $x$

The high $x$ region can be probed more directly by measuring the differential dijet cross section, as a function of the $E_T$ and $\eta$ of the two leading jets. Assuming a $2 \rightarrow 2$ hard scattering, the event kinematic variables ($x$, $Q^2$) are related to the jet’s transverse energy, $E_T$, and pseudorapidity, $\eta$, by

$$x_{12} = \frac{\sum_i E_{T,i}}{\sqrt{s}} \pm \eta; \quad Q^2 = 2E_T^2 \cosh^2 \eta^* (1 - \tanh \eta^*)$$

(2.2)

where the sum is over all the jets in the event. The parton momentum fractions are represented by $x_1$ and $x_2$, and for a two body process the four momentum transfer in the interaction is given by $Q^2$. We define $x_1$ to be the maximum of the two momentum fractions in the event and $x_2$ as the minimum.

The differential dijet cross section was measured in CDF in Run IIb, requiring one jet (the trigger jet) to be in the central region ($0.1 < |\eta| < 0.7$) and the other jet to be in one of four rapidity regions. The measured cross sections and kinematic coverages can be seen in Figure 2.54. An excess similar to that observed for the inclusive jet cross section in the central region was observed.

The higher energy and larger statistics in Run IIb
will enable this measurement to be extended to larger values of $x$ and $Q^2$. The better calorimetry in the forward region will allow cross section measurements where both jets are non-central.

### 2.6.5 W and Z production

#### 2.6.5.1 Inclusive cross sections

The inclusive W and Z theoretical cross sections are currently known to NNLO. In addition, the cross sections are sensitive to quark distributions in an $x$ range already very well determined by high statistics deep-inelastic scattering (DIS) and Drell-Yan (DY) experiments. Experimentally, the measurement of the W and Z cross sections have relatively low systematic errors. Approximately, 12 million $W \rightarrow e\nu$ and 1.5 million $Z \rightarrow e^+e^-$ events are expected with $15fb^{-1}$. Given the above factors, the W and Z cross sections will be extremely useful for determining the luminosity of the Tevatron, especially given the current uncertainty in measuring the total inelastic cross section. It is interesting to note that the majority of the differences in the CDF and D0 Run Ib cross sections are due to different assumptions as to the size of the total inelastic cross section. If the CDF and D0 jet cross sections, for example, are normalized to their respective W and Z cross sections, then the normalization difference essentially disappears.

#### 2.6.5.2 W/Z $p_T$ distributions

Double logarithmic contributions due to soft gluons arise in all of the kinematic configurations where radiation of real and virtual gluons are highly unbalanced [30]. This occurs for the the case of hard scattering production near threshold, as for example was discussed for jet production at high $E_T$, and for the transverse momentum distributions of vector bosons at low transverse momenta.

The W and Z $p_T$ distributions have been extensively studied in CDF in Run IB. The distributions are well-described by resummation calculations over the entire range of measurement, as shown in Figure 2.55 for the case of Z production. In Run Ib, the W and Z $p_T$ distributions can be extended out to 350-400 GeV/c [31]. In addition, the increased statistics and coverage will allow the measurements to be extended to new kinematic regions.

The factorization of the hadron-hadron cross sections into a hard part and into PDFs (for example, in the Drell-Yan process) can be proven if the initial-state partons probed in the hard collision have $x_1$ and $x_2$ sufficiently close to 1. This factorization picture does not necessarily apply at small $x$, when the probed partons lose the dominant fraction of their energy in the process of the evolution. Ultimately, at very small $x$ the DGLAP logs become negligible in comparison to the BFKL logs. Semi-inclusive DIS
Figure 2.54: The differential dijet cross section for CDF from Run Ib.

(SI-DIS) data from HERA [32] (transverse energy flow, charged particle multiplicity) shows a consistent increase in the average $q_T$, when the $x$ value is below 0.005-0.01. In the framework of the generalized factorization formalism (CSS) [33], the HERA SI-DIS data is described consistently only if one assumes the rapid growth of the non-perturbative Sudakov factor (i.e., the rapid growth of intrinsic $k_T$) [31]. Hence the SI-DIS HERA data may be revealing the universal transition from the DGLAP dynamics to the BFKL dynamics at $x$ values of less than approximately 0.005-0.01, i.e., at much higher $x$ values than is commonly assumed. This then questions the accuracy of the predictions of the conventional factorization picture for the $p_T$ distributions at the LHC and VLHC.

At the Tevatron, a similar effect may show up in the dependence of the shape of the $p_T$ distributions of the W and Z boson production on the rapidity of the vector boson. In order to observe this effect, it is necessary to measure distributions in the forward rapidity region. At HERA, the broadening of the $q_T$ distributions is visible at $x=0.002$, which approximately coincides with the minimal $x$ that can be achieved with Z boson production in Run IIb. In any case, it will be interesting, from the point of view of predictions for the LHC, to test the resummation formalism in this kinematic region.

2.6.5.3 W/Z + jets

In Run I, the distributions for W/Z + n jets have been measured out to an n value of 4 (with an $E_T$ cut on the jets of 15 GeV/c). The cross section for $W(\rightarrow e\nu) + \geq n\text{jets}$ from Run I is shown in Figure 2.56.

Figure 2.55: The Z $p_T$ distribution measured by CDF in Run Ib. The data is compared to predictions from the resummation program ResBos [34] (curve) and Pythia 6.1 (histogram).

Figure 2.56: The cross section for $W(\rightarrow e\nu) + \geq n\text{jets}$ for CDF from Run I.

In Run IIb, the cross section will be measured for W/Z with up to 8 jets. Such measurements are interesting not only in their own right, but also as a check on the backgrounds for new physics involving W/Z (or leptons plus missing transverse energy) production with a large number of jets. Current calcula-
sections can cover this region, but only at leading order. Thus, it is important to have experimental measurements against which to normalize the theoretical predictions. Of particular interest are final states consisting of W/Z plus a heavy quark pair (+jets). The foremost example is Wb, the primary background for a low mass Higgs search at the Tevatron. With 15 fb⁻¹, CDF will have a sample of approximately 7500 W(→ēν) + b+jets events, 2100 of them with 1 or more additional jets (all jets required to have |η| < 2.5 and Et > 20 GeV/c), 500 of them with 2 or additional jets and 90 of them with 3 or more additional jets [35]. (No efficiency or tagging corrections have been applied and the calculation is at leading order.)

2.6.6 Single and Double Photon Production

Single and double photon production at high transverse momenta have long been viewed as ideal processes for testing the formalism of perturbative QCD, as both the experimental and theoretical systematic errors have traditionally been lower than for jet production in the same kinematic range. NLO calculations are available for both processes [36, 37, 38] and NNLO calculations should be available by the start of Run IIb. [39]. The inclusive photon cross section is approximately a factor of 3000 lower than the cross section for inclusive jet production at high Et. Given the factor of 1500 increase in statistics in Run IIb (compared to Run I), the reach for photons in Run II will be slightly less than achieved for the inclusive jet cross section in Run I, as shown in Figure 2.57 [40].

At low to moderate values of Et, the gluon-quark (Compton) scattering subprocess dominates the isolated photon cross section while quark-antiquark scattering is the dominant subprocess at high Et. There are backgrounds to photon production from the decay of π°s (resulting from jet fragmentation). These backgrounds are greatly suppressed by isolation cuts applied to the data, but even without explicit isolation cuts the background becomes less important as the transverse momentum of the photon is increased. The same isolation cuts also suppress Bremsstrahlung mechanisms for producing photons (the photon brems off of a quark line), which otherwise would tend to dominate the production at low Et. Above an Et value of 100 GeV/c, the signal fraction for the photon candidate sample approaches 100%. The current level of agreement of the CDF direct photon data with NLO QCD theory is shown in Figure 2.58. The data lies above the theory at low Et and below the theory at higher Et. The deviation at low Et is believed to be due to the effects of soft gluon emission (kt [41]), while the cause for any deviation at higher values of Et is currently unknown. It will be extremely interesting both to understand the lower Et region better and to probe the higher Et region in Run II.

In addition there will be measurements with tagged final states. Run I measurements of photon plus muon events allowed for measurements of the bottom and charm content of the photon events using the relative pt of charged tracks around the muon [42]. This sample will benefit both from the added luminosity and also from the improved detection of displaced vertices allowing for heavy flavor tagging in both the inclusive photon and muon plus photon samples.

![Figure 2.57: The expected reach in Et for inclusive photon production in Run II using a NLO QCD prediction and CTEQ5M pdfs.](image)

Diphoton production is a small cross section and will benefit greatly from the increased statistics of Run IIb. The diphoton cross section from Run Ib is plotted in Figure 2.59, as a function of the diphoton mass [43]. The backgrounds from jet fragmentation have been subtracted. The measurement is statistics-limited but good agreement is observed with the NLO QCD prediction [37]. The reach in diphoton mass in Run IIb can be observed in Figure 2.60 [44].

The dominant production mechanism for low diphoton mass is gg scattering while q̅q scattering dominates for higher diphoton mass values. (As for the case of single photon production, the imposition of an isolation cut reduces the contribution from Bremsstrahlung subprocesses, which otherwise would
dominate the cross section for low diphoton masses).

The understanding of the production mechanisms and yields for single and double photon production (and of the production and yield for the π⁰ backgrounds) is of importance for Higgs searches in the γγ decay mode at the LHC. In addition, Higgs production, both at the Tevatron and at the LHC, can be affected by soft gluon emission from initial state partons, and separation of signal and background can benefit from a reliable resummation formalism. Low mass diphoton production at the Tevatron offers an opportunity for the predictions of this formalism to be studied for gg initial states [45]. By measuring diphoton production at forward rapidities as well, the gg resummation formalism can be studied in a kinematic regime similar to that relevant for light Higgs production at the LHC.

The rapidity distribution for diphoton production (2 entries for each pair) for Run IIb is shown in Figure 2.61 [46]. A sizeable cross section is present in the forward rapidity region.

Anomalous high mass diphoton production can also serve as a signature for new physics, such as the presence of large extra dimensions [47]. Thus, an understanding of the QCD production mechanisms is crucial.

2.6.7 Diffractive Physics

Diffractive processes in high energy hadron-hadron collisions are still not well understood, although great progress has been made by CDF and D in recent years. QCD is the fundamental theory of strong interactions but is only directly applicable to hard (large Q²) processes for which the coupling α_s is small enough that the perturbative series converges rapidly. In every collision involving hadrons this condition is violated (after a hard scatter, hadronization takes place on all scales down to the pion mass). The process of confinement is sometimes considered to be the main issue in QCD. In the transition from partons to color singlet hadrons, sometimes color singlet clusters of hadrons are formed, well separated in rapidity from other color singlet clusters. These events have rapidity gaps, where there are no hadrons over a large (typically > 3 units) region of rapidity y. The largest gaps, 15 units at the Tevatron, are in elastic scattering p̅p → p̅p. It is to be hoped that one day we will be able to predict elastic scattering on the basis of QCD. Today it is partially described by Regge theory. Regge theory is based on some sound principles such as analyticity, crossing symmetry and unitarity but it is not a complete theory. Perhaps one will be able to derive Regge Theory (or a similar theory) from QCD. Then it will be important to have as complete data as possible on diffractive processes includ-
ing elastic scattering. Up to now this has only been measured at the Tevatron out to \( t = -0.6 \text{ GeV}^2 \), but at lower energies (ISR and SpS) there is structure at larger \( |t| \) (\( \frac{d \sigma}{dt} \) becomes flat). In Regge theory the 4-momentum transferred between the \( p \) and \( \bar{p} \) when they scatter elastically at these high energies is almost entirely carried by a *pomeron* at low \( |t| \) (and by a photon for *very* low \( |t| \) which is Coulomb scattering) with a possible transition to *odderon* exchange at large \( |t| \). The pomeron carries positive C-parity and the odderon negative C-parity, and it would change sign between \( p\bar{p} \) and \( pp \) scattering. To first order it is believed that the “soft” (low \( Q^2 \)) pomeron is 2-gluon exchange (together with multiple exchanges) and the odderon is 3-gluon exchange (two gluons cannot have \( C = -1 \)). Progress in understanding diffractive (large rapidity gap) processes has come mostly from studying hard (high \( Q^2 \)) interactions that have gaps and/or a leading (Feynman \( x_F > 0.9 \)) (anti-)proton. In CDF from Run 1 we have measured diffractive production of high-\( E_T \) jet pairs, \( J/\psi \), \( b \)-jets, and \( W \)-bosons. We have also measured double diffractive (double pomeron exchange) production of dijets. Because these processes have different dependencies on quarks and gluons in the initial state, it has been possible to test the notion that diffraction can be viewed as the emission of a pomeron, considered like a virtual spacelike hadron with a universal structure function, and its subsequent interaction with the other beam particle. From this notion is derived the term *factorization* which if true means that one can factorize the process into the emission, propagation and interaction of pomeron. Using such a picture we have derived a “gluonic fraction” of pomeron in hard processes (\( Q^2 \) typically 2000 GeV\(^2 \)) to be 0.54 \( \pm 0.15 \). Importantly we have also found that factorization in hard interactions is badly violated. This conclusion comes both from comparing our diffractive cross sections with those measured in \( ep \) collisions at HERA, and from comparing our single diffractive dijet cross section with our double pomeron dijet cross section. One of the basic quantities in QCD is the structure function of the proton \( F(x, Q^2) \). By comparing our diffractive data with non-diffractive data we have been able to derive, and have published, *diffractive structure functions* which can be compared with such *dsf* measured in \( ep \) collisions at HERA. We find non-universality.

A new paradigm for hard diffraction is needed. A new description should presumably also take into account another phenomenon we discovered at the Tevatron, that of large rapidity gaps between balancing high \( E_T \) jets (hard double diffractive dissociation *DDD*). The exchanged 4-momentum-squared across the gap is in this case of order 2000 GeV\(^2 \) where the
concept of a pomeron is probably meaningless. Perhaps a better description is that a hard parton-parton scatter occurs in the normal way by gluon exchange (on a very short time scale) and on a much longer time scale another gluon (or gluons) is exchanged to cancel the color. A similar description may be adequate also for hard single diffraction (and double diffraction). The rapidity gaps would be produced by one hard and one or more soft partons but on very different time scales, so at no *one time* is there a pomeron. There is not yet a good universal description of these processes, and it is clear that this is a data-driven field. A lot more data on all processes (higher statistics over a larger range of kinematic variables) is needed.

In Run 1B we made diffractive studies\(^{[50]}\) without observing the scattered \(p\) or \(\bar{p}\) using large rapidity gaps to tag diffraction. We studied diffractive production of \(b\)-jets, \(W\), \(b\)-jets, and \(J/\psi\). We also studied rapidity gap between pairs of balancing high \(E_T\) jets, and soft double diffractive dissociation.

In Run 1C (the last 3 months of Run 1) we added three Roman pots 55 m downstream of CDF with scintillating fiber trackers to measure high \(x_F\) (low \(\xi = 1 - x_F\)) antiprotons. More detailed studies of single diffraction were possible and we observed double pomeron production of \(b\)-jets (central \(di\)-jets with a low \(\xi\) antiproton and a rapidity gap on the proton side). This sample of 130 events corresponds to a cross section of \(\approx 44\) nb, thus could have been obtained in about 5 minutes of *live time* at \(L = 10^{31}\) cm\(^{-2}\) s\(^{-1}\) given a selective trigger.

In Run 2A we have re-installed\(^{[51]}\) the Roman pot spectrometer on the antiproton side with the same detectors but new electronics. We have installed a new set of *rapidity gap counters* along both beam pipes, called Beam Shower Counters (BSC). These will be used in some Level 1 triggers to select diffractive (and double pomeron) candidate events that occurred by themselves (no pile-up). We are installing in the October 2001 shut down a pair of MiniPlug calorimeters covering the regions \(3.5 < \eta < 5.5\) (\(0.5^\circ < \theta < 3.0^\circ\)) on the East and West sides. These will be used both for very forward jets (for the *Jet-Gap-Jet* studies) and as rapidity gap detectors (where the edge can be varied off-line over the \(\eta\) coverage). The forward detectors will be read out for all CDF events, and we will be able to study hard diffractive processes (di-jet, \(W\), \(Z\), high \(p_T\) \(b\)-jets, etc) with several hundred times the statistics of Run 1C. For the double pomeron di-jet production, which is a subject of great interest, the gain is more like a factor \(10^4\) if we have an effective trigger. This means that we should be able to measure jet pairs with \(E_T (jet) \geq 50\) GeV rather than the 7-10 GeV of the Run 1C data. We will also be able to tag the jets using the SVX tracker and measure double pomeron production of \(b\bar{b}\) di-jets. It has been proposed\(^{[52]}\) that di-jets produced in double pomeron exchange are essentially pure gluon jets, with a small admixture of \(b\bar{b}\) di-jets, the light quarks being suppressed by the \(J_z = 0\) selection rule. In this case we can produce samples of tens of thousands of \(> 99\%\) pure gluon jets (to be compared to a present world sample, from \(Z \rightarrow b\bar{b}g\) at LEP, of \(< 450\) pure \(g\)-jets).

We will also in Run 2A study soft double pomeron exchange processes, including exclusive processes where the \(p\) and \(\bar{p}\) go undetected down the beam pipes and a few central hadrons are produced \((\pi^+, \pi^-, K^+, K^-, \phi, \phi, J/\psi, \eta, \pi^+, \pi^-), \Lambda\bar{\Lambda}, \Omega, \chi_c, \chi_b\), etc). These processes probe QCD at very low \(Q^2\), providing information on gluball and hybrid spectroscopy, and on the spin of the pomeron (through the \(\Lambda\) and \(\Omega\) polarizations).

For Run IIb we want to continue single diffractive studies especially of the \(W\) and \(Z\), and to be able to do these studies in the presence of multiple interactions. This can be done with high precision timing on the forward \(p/\bar{p}\), matching the forward particle to the \(W/Z\) decay products using the central Time of Flight counters. However we envisage that the main thrust of our diffractive studies in Run IIb will be on double pomeron exchange, or events with both \(p\) and \(\bar{p}\) having \(\xi < 0.1\) and well measured, with a central massive system, especially \(di\)-jets and \(b\bar{b}\) di-jets, high \(p_T\) leptons and photons. This is the subject of a separate proposal, to be submitted\(^{1}\) to the April 2002 PAC, following the Letter of Intent\[^{[53]}\]. The proposal is to replace the existing Roman pots on the \(\bar{p}\) side with new pots with silicon microstrips replacing the scintillating fiber hodoscopes and quartz Cerenkov counters (for timing) replacing the scintillator trigger counters. It is also proposed to move some Tevatron magnets to make warm space on the \(p\) side and install identical detectors there, to study the reaction \(p\bar{p} \rightarrow pX\bar{p}\). Measuring both the \(p\) and \(\bar{p}\) with high precision, \(M_X\) is known to about 250 MeV. The system \(X\) is measured in CDF. It is especially interesting to plot \(M_X\) when \(X\) is a \(b\bar{b}\) dijet, a \(\tau^+\tau^-\) pair, or a \(WW^{(*)}\) candidate, as it has been proposed that the Higgs boson might

\(^{1}\)Subject to approval by CDF.
be observable in such interactions. If it is seen, its mass is measured very well (\(\approx 100 \text{ MeV}\)). High-\(|t|\) elastic scattering, which has not yet been measured at the Tevatron, will be measured in parallel (indeed it is used to calibrate the spectrometers). There is still disagreement among theorists on the observability of the Higgs boson with this method at the Tevatron. Nevertheless the field of high mass double pomeron exchange is unexplored territory and there have been many suggestions that it might give surprises. Timing resolution \(\approx 50 \text{ ps}\) in the Roman pots will minimize problems associated with pile-up at high luminosity. More details will be presented in the VFTD Proposal at the April 2002 PAC.
Bibliography

[1] See, for example, the website for the Les Houches Workshops on Physics at TeV Colliders, http://wwwlapp.in2p3.fr/conferences/LesHouchesHouphys/2001; the proceedings for the QCD/SM section of the 1999 workshop can be found at hep-ph/0005114.

[2] See, for example, the website for the website for the Run 2 Workshop on QCD and Weak Boson Physics, http://www-theory.fnal.gov/people/ellis/QCDWB/QCDWB.html, and references therein.


[26] We would like to thank Steve Ellis for generating these figures.


[30] See, for example, the discussion by S. Catani in Reference 1.


[40] We would like to thank J. Owens for generating this plot.


[44] We would like to thank C. Balazs for the generation of this figure.


[46] We would like to thank J.P. Guillet for the generation of this figure.


2.7 B Physics in Run IIb

2.7.1 Introduction

The study of particles containing the bottom quark has provided valuable insights into the weak interactions and QCD: e.g. the long lifetime of b hadrons, the large mixing observed in the $B^0$—$\bar{B}^0$ system, the discovery of heavy quark symmetries and the utility of heavy quark effective theories, and the observation of “penguin” decays. This is not surprising given that the bottom quark is heavy and that its preferred charged current coupling to the top quark occurs only in virtual higher-order processes. The b hadrons provide a valuable laboratory in which to extract fundamental parameters of the Standard Model, test its consistency, and search for rare processes which are sensitive to physics beyond the Standard Model.

Measurements with b hadrons can in principle be used to extract information on 5 of the 9 elements of the CKM matrix that relates the weak-interaction and mass eigenstates of quarks. The CKM matrix can be written as:

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$  \hspace{1cm} (2.3)

or in the Wolfenstein [1] parameterization:

$$V \simeq \begin{pmatrix} 1 - \lambda^2/2 & \lambda & \lambda A \lambda^3 (\rho - i \eta) \\ -\lambda & 1 - \lambda^2/2 & \lambda A \lambda^2 \\ \lambda A \lambda^3 (1 - \rho - i \eta) & -\lambda A \lambda^2 & 1 \end{pmatrix}$$  \hspace{1cm} (2.4)

given here to $O(\lambda^4)$, where $\lambda = \sin(\theta_{\text{Cabibbo}})$ and the other three parameters $A$, $\rho$, and $\eta$ encode the remaining two weak mixing angles and the irreducible complex phase that introduces CP violation.

Unitarity of the CKM matrix requires the relationship

$$V_{tb}^* V_{td} + V_{tb}^* V_{ts} + V_{ud}^* V_{ub} = 0,$$  \hspace{1cm} (2.5)

which can be displayed as a triangle in the complex plane, as shown in Figure 2.62. The base of this triangle has been rescaled by $A \lambda^3$ to be of unit length. Also shown are the angles $\alpha$, $\beta$, and $\gamma$ which lead to CP violating effects that can, in principle, be measured with b hadrons.

The b physics goals for CDF II include:

- Observation of CP violation in $B^0 \rightarrow J/\psi K_S^0$ and a measurement of $\sin(2\beta)$ to $\pm0.02$.
- Measurement of the CP asymmetries in $B^0_s \rightarrow J/\psi \phi, J/\psi \eta(1S)$.
- Observation of CP violation in $B^0 \rightarrow \pi^+ \pi^-$ and $B^0_s \rightarrow K^+ K^-$ and a measurement of $\gamma$ to $\pm3^\circ$.
- Observation of $B_c^0$ mixing and measurement of $\Delta m_s$ and $\Delta \Gamma_s / \Gamma_s$.
- Observation of exclusive decays of the $B_c^+$ meson, allowing precise determination of its mass and lifetime.

The copious production of b hadrons of several species at the Tevatron offers the opportunity for measurements that will allow us to fully check the consistency of the CKM picture. To take advantage of the broad spectrum and high production rate of b hadrons at the Tevatron, the challenges of triggering and event reconstruction in high energy pp collisions must be successfully met.

2.7.2 The Run I CDF b program

CDF has demonstrated the ability to mount a b physics program exploiting the unique aspects of hadron production. More than fifty papers have been published (or are submitted and under review) in PRL and PRD by CDF on the subject. Many of the CDF results are highly competitive with measurements from LEP or CLEO and some of them are the
best measurements from a single experiment. These measurements include:

- Individual $b$ hadron masses ($B^+, B^0, B_s^0, \Lambda_b$) [2, 3]
- Individual $b$ hadron lifetimes ($B^+, B^0, B_s^0, \Lambda_b$) [4, 5, 6]
- The $CP$ violation parameter $\sin 2\beta$ [7]
- Polarization in $B^0 \rightarrow J/\psi K^{*0}$ and $B_s^0 \rightarrow J/\psi K^0$ [8]
- Observation of the $B_c^+$ meson [10]
- $B^0$ mixing and limits on $B^0$ mixing [11, 12]
- Searches for rare decays ($B^0, B_s^0 \rightarrow \mu^+\mu^-$; $B^\pm \rightarrow \mu\mu K^\pm$; $B^0 \rightarrow \mu\mu K^{*0}$; $B^0, B_s^0 \rightarrow \mu e$) [13]

CDF has also carried out several studies of $B$ and quarkonium production and of $b\bar{b}$ production correlations [14, 15]. The QCD aspects of these results have generated much interest. In addition, they provide the understanding of $B$ production necessary for studies of $B$ decay.

The analyses carried out by CDF have shown that the mass resolution obtained with the CTC coupled with the vertex resolution obtained with the SVX allows us to (a) isolate fully–reconstructed $B$ decays and (b) measure the lifetime of the decaying mesons.

One of the most interesting measurements by CDF in Run II was the first significant measurement of the $CP$-violation parameter $\sin 2\beta$ using a sample of approximately 400 $B_d^0 \rightarrow J/\psi K_s$ decays from 110 pb$^{-1}$ of data. Using several flavor tagging methods, it was determined that $\sin 2\beta = 0.79^{+0.41}_{-0.39}$. This measurement also demonstrates CDF’s ability to tag the flavor of $B$ mesons at production, which is crucial to many of the measurements we expect to do in Run II.

2.7.3 CDF strategy for $b$ physics in Run II

Recently, Babar and Belle presented measurements of $\sin 2\beta = 0.59 \pm 0.14(stat) \pm 0.05(syst)$ [16] and $0.99 \pm 0.14(stat) \pm 0.06(syst)$ [17], respectively, showing that $CP$ is definitely violated in decays of $B$ mesons, beginning a new era. The next step is to acquire sufficient statistics to make precision measurements that fully constrain the unitarity triangle and the CKM matrix. Then, by making further measurements, it will be possible to explore whether the Standard Model can fully explain $CP$ violation in the $B$ sector or whether there are indications of new sources of $CP$ violation.

CDF’s Run II $B$ Physics program enhances and complements those of the $B$ factories. The $e^+e^-$ experiments have the advantages of already collecting a significant amount of data and of having cleaner event topologies, allowing observation of more modes and higher tagging rates. The advantages of doing $B$ physics at the Tevatron include the higher $B$ production rates and the production of $B_s^0$ mesons and $B$ baryons. Although the $B$ factories have been running for a couple of years, if CDF acquires the expected 2 fb$^{-1}$ of data in the next two years, it will have a measurement of $\sin 2\beta$ that is at least as good as those of the $B$ factories. CDF’s extensive experience doing $B$ physics in Run I indicates its ability to isolate clean signals and do precision measurements. In addition, there are important measurements, such as determining $\Delta m_s$ from $B_s^0$ mixing and searching for $CP$ violation in $B_s^0 \rightarrow J/\psi K_s$, that cannot be done at the $B$ factories, but which CDF is well suited to do.

In Run II, CDF will take advantage of the broad spectrum of $b$ hadrons produced at the Tevatron to make measurements with $B_s^0$ mesons, $B_c^+$ mesons and $b$ baryons as well as with $B^0$ and $B^+$ mesons. Key elements of CDF that made the Run I high-$p_T$ physics program (for example, top and $W$) so successful include excellent tracking resolution, lepton identification (including $dE/dx$), secondary–vertex reconstruction, and a flexible and powerful trigger and data acquisition system. These same elements are also the foundation upon which a successful $b$ physics program was built.

The strategy for CDF II is to build on our experience in Run I, to optimize the quality of information in the central region while expanding coverage, and to exploit many additional $b$ hadron decay channels. The tracking upgrades (SVXII/ISL/COT) are expected to improve the present mass resolution while the 3D silicon tracker (SVXII) is expected to improve the vertex finding ability. The lepton and tracking coverage will be increased (SVXII, ISL and CMX/IMU). The $dE/dx$ information from the COT will be employed for particle identification. For Run II, CDF has installed a time-of-flight (TOF) system in the space at the outer diameter of the tracking volume (COT) to provide for $K/\pi/\rho$ separation at low to moderate transverse momenta. From these improvements, we also expect to increase our tagging efficiencies and dilutions to $\varepsilon D^2 = 9.1\%$ for $B^0$ mesons and to $11.3\%$
2.7.4 Plans for Run IIb

Since data is just beginning to be accumulated for Run II, the current performance of the detector cannot be fully assessed, although early evaluation of the detector performance looks very promising. However, the CDF collaboration is confident from its extensive experience doing $B$ physics in Run I that we can accurately extrapolate to Run IIb.

It is assumed that the detector performance anticipated for Run IIa will be maintained in Run IIb. This includes the excellent momentum resolution of the COT, the electron identification capabilities of the calorimeters, and muon identification.

Of particular importance for doing $B$ physics is the excellence secondary vertex resolution of the SVX II detector with Layer 00, expected to be less than 20 microns. It is assumed that the replacement silicon vertex detector for Run IIb will have comparable resolution and coverage as the one for Run IIa.

Since most of the measurements planned for Run IIb are not expected to be systematically limited, previous studies done for Run IIa apply or can be straight-forwardly extrapolated from the 2 fb$^{-1}$ of Run IIa to the 15 fb$^{-1}$ of Run IIb. This assumes that the increased instantaneously luminosity of Run IIb can be handled without needing to prescale the relevant triggers. The most important triggers for the physics discussed below are the $J/\psi$, inclusive lepton, two displaced track, and dimuon plus displaced track triggers. The current bandwidth needed for the $J/\psi$ and dimuon plus displaced track triggers are a sufficiently small fraction of the total available that it is anticipated with improvement in DAQ system that these triggers will not be a limiting factor in Run IIb. The inclusive lepton trigger will be bandwidth limited, but for $B$ physics can be augmented with a displaced track requirement, which will reduce the rate without significant loss of signal.

On the other hand, the two displaced track trigger is more problematic, since it is currently the largest single component of the available trigger bandwidth, particularly at Level 1. For Run II, CDF has investigated three displaced track trigger strategies for different Tevatron conditions ($A$, $B$, and $C$ in table 2.15). For Run IIb, the third scenario will work, but would result in a 50% loss of signal compared to the scenario $A$ to be used in Run IIa. To avoid this loss, the ability to select on invariant mass in the Level 1 trigger is desired. This will allow the displaced track trigger

for $B^0_s$ mesons.

In addition, the high-rate capability of the upgraded trigger/data acquisition system will enable us to handle the high luminosity of the Main Injector era while lowering thresholds and acquiring events in many more channels. Of particular importance will be the ability to form triggers based on track information alone at Level 1 (XFT) and detect the presence of tracks with displaced vertices at Level 2 (SVT). Figure 2.63 shows the impact parameter resolution obtained online with the SVT during the commissioning run in the Fall of 2000. The excellent resolution will give CDF a powerful tool for triggering on tracks that did not originate at the primary vertex, particularly the decays products of $B$ hadrons.

Thus, the CDF II detector will provide for a competitive $b$ physics program that has unique features and addresses a wide variety of topics of fundamental importance.
to remain efficient at an acceptable rate for two-body B hadron decays.

Several B physics measurements of importance in Run IIb are described below. The topics included here were selected because (1) the physics is interesting, (2) the measurement is competitive or better than the corresponding measurement expected from other experiments, (3) the measurement represents a unique measurement at the Tevatron, and/or (4) the measurement illustrates requirements on the detector performance. This list of physics measurements is not exhaustive but is illustrative of the exciting B physics that will be possible in Run IIb.

### 2.7.5 CP Violation in the B system

The most important goal of the CDF II B physics program is to study CP violation in the B system. This will continue into Run IIb with an emphasis on greater precision and expansion into lower rate, but interesting, modes.

The decay $B_s^0 \to J/\psi K_S$ is the golden mode, which all experiments, including CDF, will use to make precision measurements of $\sin 2\beta$. The decays $B^0 \to J/\psi \phi$ and $J/\psi \eta$ are interesting because the CP asymmetries in the Standard Model are expected to be very small, making them very sensitive to new CP violating physics. Once $\sin 2\beta$ and $\Delta m_s$ (see below) are precisely measured, the unitarity triangle will be fully constrained. It then becomes important to measure other properties to see if they are consistent. The other angles of the unitarity triangle are notoriously difficult to measure precisely, but CDF may have a unique opportunity to measure the angle $\gamma$ very well using the decays $B^0 \to \pi \pi, K \pi$ and $B^0 \to K K, K \pi$. Various $B \to DK$ decays are also sensitive to $\gamma$ but are statistically limited due to small branching ratios, making them ideal to pursue in Run IIb. Finally, CDF will be able to search for direct CP violations in various decay modes (the $B$ physics equivalent to $\epsilon'/\epsilon$ in the K system), such as $\Lambda_b \to p K, p \pi$.

#### 2.7.5.1 CP Asymmetry in $B^0 \to J/\psi K_S$

For measuring CP violation in the B system, the decay mode most frequently discussed in the literature [18] is $B^0 \to J/\psi K_S$. CP violation manifests itself as an asymmetry in the partial decay rates of $B^0$ and $\bar{B}^0$ to the same final state, $J/\psi K_S$ (a CP eigenstate). This results in an asymmetry:

$$A_{CP} = (N - \bar{N})/(N + \bar{N})$$

in the number of decays from $B^0$ ($N$) and $\bar{B}^0$ ($\bar{N}$) mesons. The asymmetry in the partial decay rates is directly related to the angle $\beta$ of the CKM unitary triangle:

$$\Gamma(B^0, \bar{B}^0 \to J/\psi K_S) \propto e^{-i\beta}[1 \pm \sin(2\beta) \sin(\Delta mt)]$$

where $\Delta m$ is the mass difference between the heavy and light $B$ meson states and $t$ is the proper decay time. The observed asymmetry $A_{CP}^{obs}$ will be smaller than $A_{CP}$ by a factor known as the “dilution” $D$; $A_{CP}^{obs} = D A_{CP}$. The dilution receives contributions from the proper time resolution, from the method used to tag the flavor of the $B$ meson at the time of production, and from backgrounds.

From the full data sample accumulated in Run I (110 $pb^{-1}$), CDF used 400 $B_d \to J/\psi K_S$ decays to measure $\sin 2\beta = 0.79^{+0.41}_{-0.44}$. We obtained this sample with a dimuon trigger that required both muons to have transverse momentum ($p_T$) greater than 2.0 GeV/$c$. For this analysis, we did not require that the events be in the SVX fiducial region, although we used SVX information if available.

For Run IIa, due to (1) the increased cross section at $\sqrt{s} = 2$ TeV, (2) increased coverage of SVX II, (3) increased muon coverage, (4) improved tagging using the TOF system, (5) lowering the $p_T$ threshold for the dimuon trigger, (6) addition of a $J/\psi \to e^+e^-$ trigger (see figure 2.64), and (7) the increased integrated luminosity from 110 $pb^{-1}$ for Run I to 2 $fb^{-1}$ for Run IIa, we conservatively expect a 50-fold increase in the yield, giving 20,000 $B_d \to J/\psi K_S$ events from the dimuon channel and 8,000 from the dielectron channel. The systematic uncertainty on $\sin 2\beta$ is dominated by the uncertainty on the dilution. Since the dilution is also determined from the data, its uncertainty also scales with the statistics. Using only the dimuon events, we conservatively expect to measure $\sin 2\beta$ with an uncertainty of 0.05 in Run IIa.

Since we do not see a limiting systematic uncertainty in Run IIb or a problem with triggering, the uncertainty on $\sin 2\beta$ will also scale with the integrated luminosity, giving an uncertainty of 0.02 for the 15 $fb^{-1}$ of Run IIb. A measurement of this precision will be very competitive with those from Babar and Belle at that time and will tightly constrain the unitarity triangle and CKM matrix.
<table>
<thead>
<tr>
<th>Luminosity ($10^{32}$cm$^{-1}$s$^{-1}$)</th>
<th>Scenario A</th>
<th>Scenario B</th>
<th>Scenario C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam crossing interval (ns)</td>
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<td>1 - 2</td>
<td>1 - 2</td>
</tr>
<tr>
<td>$p_T^{(1)}$, $p_T^{(2)}$ (GeV/c)</td>
<td>&gt; 2</td>
<td>&gt; 2.25</td>
<td>&gt; 2.5</td>
</tr>
<tr>
<td>$p_T^{(1)} + p_T^{(2)}$ (GeV/c)</td>
<td>&gt; 5.5</td>
<td>&gt; 6</td>
<td>&gt; 6.5</td>
</tr>
<tr>
<td>$\Delta \phi$</td>
<td>&lt; 135°</td>
<td>&lt; 135°</td>
<td>&lt; 135°</td>
</tr>
<tr>
<td>Cross section ($\mu$b)</td>
<td>252 ± 18</td>
<td>152 ± 14</td>
<td>163 ± 16</td>
</tr>
</tbody>
</table>

Table 2.15: Level-1 XFT trigger cuts and cross sections for the three Tevatron operating scenarios considered.

### 2.7.5.2 CP Asymmetry in $B_s^0 \rightarrow J/\psi \phi$

While the $CP$ asymmetry in $B^0 \rightarrow J/\psi K_S$ measures the weak phase of the CKM matrix element $V_{td}$ in the standard convention, the $CP$ asymmetry in $B_s^0 \rightarrow J/\psi \phi$ measures the weak phase of the CKM matrix element $V_{ts}$. The latter asymmetry is expected to be very small in the Standard Model, but in the context of testing the Standard Model has the same fundamental importance as measuring the more familiar $CP$ asymmetries. This measurement is most accessible, if not unique, to experiments at a hadron collider.

Our Run I $B_s^0$ mass analysis indicates that our yield of reconstructed $B_s^0 \rightarrow J/\psi \phi$ events is 40% that of $B^0 \rightarrow J/\psi K_S$ (see Figure 2.65). Since the improvements for $B^0 \rightarrow J/\psi K_S$ ($\approx$ 20,000 dimuon events) apply equally to $B_s^0 \rightarrow J/\psi \phi$, we can expect $\approx$ 8000 events for this decay mode in Run IIa.

The flavor tagging techniques for the $B_s^0$ are the same as those for the $B^0$, with one exception: The fragmentation track correlated with the $B_s^0$ meson is a kaon instead of a pion. A PYTHIA study indicates that the Time–of–Flight system, by identifying kaons, will allow us to increase the efficiency of the same-side kaon algorithm from 1.0% to 4.2% [19]. Thus, we assume a total flavor tagging efficiency ($e \beta D^2$) for $B_s^0$ mesons of 11.3%.

The magnitude of a $CP$ asymmetry in $B_s^0 \rightarrow J/\psi \phi$ decays will be modulated by the frequency of $B_s^0$ oscillations. Thus, for a meaningful limit, we must be able to resolve $B_s^0$ oscillations. If we neglect $(c\tau)$ resolution effects and scale from the $B^0 \rightarrow J/\psi K_S$ mode, we can expect a precision on the asymmetry of $\pm 0.07$ from a time dependent measurement in Run IIa. However, resolution effects smear the oscillations and produce
an additional dilution factor of

\[ D_{\text{res}} = e \left( \frac{x_s^2 \sigma_\tau^2}{\tau^2} \right), \quad (2.8) \]

where \( x_s = \Delta m / \Gamma_s \), \( \sigma_\tau \) is the resolution on the proper decay time, and \( \tau \) is the average \( B_s^0 \) lifetime. With the addition of Layer 00, we expect that the proper lifetime resolution for the SVX II will be \( \sigma_\tau \approx 0.03 \) [20]. For \( x_s = 25 \), this dilution degrades the resolution on the asymmetry by a factor of 1.3.

There is an additional complication in this mode if the \( J/\psi \phi \) final state is not a \( CP \) eigenstate. If this mode were a \( CP \) eigenstate, then the full resolution on the \( CP \) asymmetry would apply. If the mode is a mixture of \( CP \) states, then an angular fit including the \( CP \) violation is needed. Studies indicate that if this mode is an equal mixture of \( CP \)-even and \( CP \)-odd states, then the resolution on the \( CP \) asymmetry as determined from the angular fit is degraded by a factor of roughly 2. In Run I, CDF measured the \( CP \) even fraction to be 0.77 ± 0.19 [8].

With 15 fb\(^{-1}\) of data in Run 2b, \( x_s = 25 \), and vertex resolution comparable to Run IIa, we expect to measure the \( CP \) asymmetry in \( B_s^0 \rightarrow J/\psi \phi \) with a resolution between 0.03 and 0.06, depending on the \( CP \) content of the final state. This is close to the Standard Model expectation of roughly 0.02, making us quite sensitive to new \( CP \)-violating physics in this mode.

2.7.5.3 \( CP \) Asymmetry in \( B_s^0 \rightarrow J/\psi \eta^{(l)} \)

Measuring the \( CP \) asymmetry in \( B_s^0 \rightarrow J/\psi \eta^{(l)} \) decays is very similar to measuring it in \( B_s^0 \rightarrow J/\psi \phi \), with two notable exceptions. First, the \( J/\psi \eta \) and \( J/\psi \eta' \) final states are \( CP \) eigenstates, so no angular fit is required and hence there is no degradation.

Second, the presence of photons in the final state (we detect the \( \eta^{(l)} \) via its \( \gamma \gamma \) decay mode) make these modes much more difficult for CDF. The CDF calorimeter was not designed to detect and measure low energy photon with very good energy resolution. However, CDF is capable of detecting these signals. Figure 2.66 shows the invariant mass of diphotons selected from our inclusive electron trigger data, which represent a data sample enhanced in \( b \bar{b} \) events. Photon candidates were required to be in separate calorimeter towers, have \( E_T > 1 \) GeV/c\(^2\), and satisfy

2-75
requirements on $E_{\text{had}}/E_{\text{EM}}$, isolation, and pulse in the strip chambers. Clear $\pi^0$ and $\eta$ signals can be seen.

The resolution on the reconstructed $B_s^0$ mass can be improved by constraining the photons to the $\eta$ or $\eta'$ mass. Monte Carlo studies show that the $B_s^0$ mass resolution will be better than 40 MeV/c^2, which is more than a factor of two worse than our mass resolution in all charged track decays but still should be more than sufficient to observe this mode.

Scaling from the expected number of $B^+ \rightarrow J/\psi K^+$ events, the ratio of $B^0$ to $B_s^0$ production, and the expected relative branching ratios, we expect 8000 $B_s^0 \rightarrow J/\psi \eta$ events in Run IIb[9]. Studies of $J/\psi$ events in Run I indicate that with a 40 MeV/c^2 mass resolution, the background to signal ratio should be no more than 2. Using $x_s = 25$ and a proper time resolution of $\sigma_{\tau}/\tau = 0.03$, we expect to measure the $CP$ asymmetry in this mode with a resolution of 0.11.

### 2.7.5.4 CP Asymmetry in $B_s^0 \rightarrow \pi^+\pi^-$ and $B_s^0 \rightarrow K^+K^-$

The $CP$ asymmetry in the decay $B_s^0 \rightarrow \pi^+\pi^-$ is often touted as a way to measure $\sin 2\alpha$. In the absence of $penguin$ diagrams, this is certainly true. However, $penguin$ diagrams are expected to make a significant contribution to this decay mode, greatly complicating the extraction of CKM information from the observed $CP$ asymmetry.

Many studies have been done of how to obtain precision CKM information from the $CP$ asymmetry, including measurement of the decay mode $B^0 \rightarrow \pi^0 \pi^0$ and detailed analysis of the Dalitz plot in the similar $B^0 \rightarrow \rho\rho$ mode. These methods are complicated and difficult for any experiment and are not feasible for CDF due to the necessity of accurately and efficiently detecting $\pi^0$'s.

We have investigated a very promising method suggested by Fleischer [21] that measures the CKM angle $\gamma$ by relating the $CP$ violation observables in the decays $B^0 \rightarrow \pi^+\pi^-$ and $B_s^0 \rightarrow K^+K^-$. The necessity of the $B_s^0$ mode makes this strategy unique and well suited to the Tevatron.

The decays $B^0 \rightarrow \pi^+\pi^-$ and $B_s^0 \rightarrow K^+K^-$ are related to each other by interchanging all down and strange quarks, that is, through the so-called “$U$-spin” subgroup of the SU(3) flavor symmetry of strong interactions. For the decay $B^0 \rightarrow \pi^+\pi^-$, the tree diagram is expected to be dominant with the $penguin$ diagram being subdominant (but significant). For the decay $B_s^0 \rightarrow K^+K^-$, the opposite is expected, that is, the $penguin$ diagram is expected to dominate. The strategy in reference [21] uses the U-spin symmetry to relate the ratio of hadronic matrix elements for $penguins$ and trees, and thus uses $B_s^0 \rightarrow K^+K^-$ to correct for the $penguin$ pollution in $B^0 \rightarrow \pi^+\pi^-$. This strategy does not rely on “plausible” dynamical or model-dependent assumptions, nor on final-state interaction effects, as do many other methods of extracting $\gamma$. The theoretical accuracy is only limited by U-spin-breaking effects. We have evaluated the likely size of these effects and find them to be small compared to the expected experimental error on $\gamma$ in Run II.

The key to measuring the $CP$ asymmetries in $B^0 \rightarrow \pi^+\pi^-$ and $B_s^0 \rightarrow K^+K^-$ is to trigger on these decays in hadronic collisions. We will do this with the two displaced tracks trigger, which is a significant fraction of the Level 1 bandwidth in Run IIa. To maintain the viability of this trigger in Run IIb, we will add the ability to obtain three dimensional tracking information and make an invariant mass selection in Level 1.

Observation of these modes is further complicated by similar branching ratios for the modes $B^0, B_s^0 \rightarrow K\pi$ and the lack of good particle identification in CDF. The CLEO, Babar, and Belle experiments have measured $Br(B^0 \rightarrow K^+\pi^-) = (17.3 \pm 1.5) \times 10^{-6}$ and $Br(B^0 \rightarrow \pi^+\pi^-) = (4.4 \pm 0.9) \times 10^{-6}$ (these are weighted averages of the results in [22]). The corresponding $B_s^0$ decays have not been observed, but we can make an educated guess based on SU(3) symmetry, giving

$$Br(B_s^0 \rightarrow K^+K^-) = (F_K/F_\pi)^2 \times Br(B^0 \rightarrow K^+\pi^-)$$

$$Br(B_s^0 \rightarrow \pi^+\pi^-) = (F_K/F_\pi)^2 \times Br(B^0 \rightarrow \pi^+\pi^-)$$

where $(F_K/F_\pi)^2 = 1.3$ accounts for SU(3) breaking. Taking into account the production ratio of $f_s/f_d \sim 0.4$, we expect the following relative yields:

$$(B^0 \rightarrow K\pi) : (B^0 \rightarrow \pi\pi) : (B_s^0 \rightarrow KK) : (B_s^0 \rightarrow \pi K) \sim 4 : 1 : 2 : 1$$

(2.11)

Based on the measured branching ratios, our observed Run I $B$ cross sections, and Monte Carlo studies, we expect 20,000 $B^0 \rightarrow K^\pm\pi^\mp$; 5,000 $B^0 \rightarrow \pi^+\pi^-$; 10,000 $B_s^0 \rightarrow K^+K^-$; and 2,500 $B_s^0 \rightarrow K^\pm\pi^\pm$ events in Run IIa, with an expected increase of a factor of 7.5 in Run IIb. Special runs in Run I were used to estimate the signal to background to be roughly
0.4, although we expect the 3-dimensional vertexing capability in Run II to improve this. Figure 2.67 shows the expected invariant mass peak for the number of signal events above with 56,250 background events. The signals overlap, but detailed studies have shown it is possible to extract the $CP$ asymmetries by exploiting the excellent mass resolution of CDF, dE/dx information from the COT, and the greatly different oscillation frequencies of the $B^0$ and $B^0_s$ mesons.

Detailed studies of the expected error on the $CP$ asymmetries show that $\gamma$ can be measured to $\sim 10^0$ with a four-fold ambiguity in Run IIa, assuming that $\sin 2\beta$ is precisely known from $B^0 \rightarrow J/\psi K_s$. By allowing 20% SU(3) symmetry breaking, we estimate the theoretical uncertainty to be $\sim 3^{0}$. With the increased luminosity of Run 2b, the statistical uncertainty should be $\sim 3^{0}$, making this a very promising method for measurement of $\gamma$.

### 2.7.5.5 Measuring $\gamma$ With $B^0_s \rightarrow D^\mp K^\pm$ Decays

$CP$ violation occurs in $B^0_s \rightarrow D^\mp K^\pm$ decays via interference between direct decays $B^0_s \rightarrow D^\mp K^\pm$ and cases where the $B^0_s$ first mixes to a $\overline{B}^0_s$ with the subsequent decay $\overline{B}^0_s \rightarrow D^\mp K^\pm$. Since $B^0_s$ mixing is expected to have very small $CP$ violating phase, the relative phase of these decays is $e^{i\gamma}$, and penguin contributions are expected to be small, these decays potentially give a theoretically clean measurement of $\gamma$. Since the final states are not $CP$ eigenstates, there is a strong phase $\delta$ which cannot be reliably calculated with present theoretical techniques.

The time dependent decay rate for these four processes are

\[
\Gamma(B^0_s \rightarrow D^-_s K^+) = \frac{|A|^2 e^{-\Gamma_s t}}{2} \left( (1 + |\lambda|^2) \cosh(\Delta \Gamma_s t/2) + (1 - |\lambda|^2) \sinh(\Delta \Gamma_s t/2) - 2 |\lambda| \sin(\delta - \gamma) \sinh(\Delta \Gamma_s t/2) + 2 |\lambda| \sin(\delta + \gamma) \sinh(\Delta \Gamma_s t/2) \right)
\]

where $|A|$ is the magnitude of the $B^0_s \rightarrow D^-_s K^+$ amplitude and $|\lambda|$ is the magnitude of the ratio of this amplitude to the one for $B^0_s \rightarrow D^+_s K^-$. By fitting the time dependent decay rates for these four modes, the parameters $|A|$, $|\lambda|$, and $\delta \pm \gamma$ can be extracted. Since the rates depend on $\sin(\delta \pm \gamma)$ and $\cos(\delta \pm \gamma)$, there is a two fold ambiguity, namely,
\[ (\delta, \gamma) \text{ and } (\delta + \pi, \gamma + \pi) \] are equivalent solutions. If \( \Delta \Gamma_s / \Gamma_s \) is sufficiently small that the sinh terms cannot be resolved, then there is an 8-fold ambiguity in the solutions.

The branching ratios for the decays \( B_s^0 \to D_s^- K^+ \) and \( B_s^0 \to D_s^+ K^- \) are expected to be comparable, namely, \( 2.4 \times 10^{-4} \) and \( 1.4 \times 10^{-4} \), respectively. In Run IIa, these events would satisfy the displaced track trigger. Monte Carlo studies indicate that CDF expects to reconstruct about 850 \( B_s \to D_s^- K^+ \) events in the Run IIa data. Studies of Run I data indicate that the signal to background ratio should be between 0.5 and 2, not including improvements that may be made with dE/dx information and 3-dimensional vertexing. With these conditions, we expect to measure \( \sin(\delta \pm \gamma) \) to around 0.4 to 0.7 in Run IIa.

In Run IIb, if we can maintain the trigger rates, we would expect a factor of three improvement, which begins to place significant limits on \( \gamma \), assuming that the sinh term is measurable or that \( \delta \) is reliably determined theoretically (otherwise, the multiple ambiguities still allow most values of \( \gamma \)). However, as discussed above, the rate for the displaced track trigger is problematic in Run IIb, and since these are multibody decays, they would not pass a two-body invariant mass cut in Level 1. Another option is trigger scenario C described above, which can operate at the high instantaneous luminosities of Run IIb, but which has half the yield for signal events.

### 2.7.5.6 Measuring \( \gamma \) With \( B^- \to D^0 K^- \) Decays

In a similar manner, the angle \( \gamma \) can be determined from the decays \( B^- \to D^0 K^- \) and \( B^- \to \bar{D}^0 K^- \) where the \( D^0 \) and \( \bar{D}^0 \) decay to both \( K^\pm \pi^\mp \). Note that these modes are self-tagging and no time dependent measurement is necessary. However, the significant difference in the branching ratios limit CP violating effects to \( O(10\%) \).

Table 2.16 shows the branching ratios for the relevant modes. The decay \( B^- \to K^- \bar{D}^0 \) is particularly problematic due to the small expected branching ratio. All these decays have significant physics and combinatoric backgrounds that must be reduced to acceptable to make this method feasible. Studies show that physics backgrounds from similar modes and particle misassignments can be reduced to about the same level as the signals by using invariant mass selections and dE/dx information. These modes also have the problem that they are multi-body and hence are problematic for the displaced track trigger in Run IIb.

If the combinatoric backgrounds can be controlled and the decay \( B^- \to \bar{D}^0 K^- \) measured to about 20\%, then \( \gamma \) could be determined to about 15°.

### 2.7.5.7 Direct CP Violation in \( \Lambda_b \to pK, p\pi \)

It should also be possible to observe direct CP violation in \( B \) decays, the analog in the \( B \) system to measuring \( \ell^- / e^- \) in the neutral kaon system. It is most straightforward to do this in decays where the de-
Table 2.16: Estimated branching ratios of decays involved in the analysis of $B^- \to D^0 K^- \to [K\pi]K^-$ at CDF.

<table>
<thead>
<tr>
<th>Decay</th>
<th>Branching Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$BR(B^+ \to K^+ D^0)$</td>
<td>$2.6 \pm 0.08 \times 10^{-4}$ (CLEO)</td>
</tr>
<tr>
<td>$BR(B^+ \to K^+ D^0)$</td>
<td>$\approx 2 \times 10^{-6}$ (Estim., [23])</td>
</tr>
<tr>
<td>$BR(D^0 \to K^- \pi^+)$</td>
<td>$1.3 \pm 0.3 \times 10^{-4}$ (CLEO)</td>
</tr>
<tr>
<td>$BR(D^0 \to K^+ \pi^-)$</td>
<td>$3.8 \pm 0.1 \times 10^{-2}$ (PDG)</td>
</tr>
</tbody>
</table>

2.7.6 Mixing and Lifetime Differences

One of the primary goals of CDF in Run IIa is to observe $B_s^0$ mixing. The ratio of oscillation frequency $\Delta m_s$ to the oscillation frequency $\Delta m_d$ determines the ratio $|V_{td}/V_{ts}|$ up to theoretical uncertainties on the order of 5-10%.

With the addition of Layer 00 for excellent vertex resolution and the displaced track trigger to give a large sample of exclusive decays (such as $B_s^0 \to D_s \pi$), CDF expects to have a reach in $\Delta m_s$ which is far beyond the Standard Model expectation. Furthermore, once a statistically significant signal is observed in $B_s^0$ oscillations, the value of $\Delta m_s$ has a very small statistical uncertainty. Thus, we expect that $B_s^0$ mixing will be observed in Run IIa, and its usefulness for determining $|V_{td}/V_{ts}|$ and constraining the unitarity triangle will be limited by theoretical uncertainties.

CDF will continue to pursue measurements of $B^0$ and $B_s^0$ mixing in Run IIIb since precise knowledge of $\Delta m_d$ and $\Delta m_s$ is necessary for extraction of other physics signals, such as, time dependent CP asymmetries in $B^0$ and $B_s^0$ decays. However, we do not expect further improvements in these measurements to directly impact our understanding of CKM physics.

2.7.6.1 $\Delta \Gamma_s/\Gamma_s$

The calculation of $\Delta m_s$ depends upon the evaluation of the real part of the mass matrix element. The imaginary part of the same matrix describes the decay widths of the two mass eigenstates $B_s^H$ and $B_s^L$. Within the Standard Model it is possible to calculate the ratio $\Delta \Gamma_s/\Delta m_s$ [24]:

$$
\Delta \Gamma_s/\Delta m_s = -\frac{3}{2} \frac{m_s}{m_t} \frac{\Lambda_{QCD}^{\Delta \Gamma_s}}{\Lambda_{QCD}^{\Delta m_s}} \tag{2.14}
$$

where the ratio of the QCD correction factors ($\eta$) in the numerator and denominator is expected to be of order unity [25]. This ratio does not depend on CKM parameters. Thus, a measurement of $\Delta \Gamma_s$ determines $\Delta m_s$ up to QCD uncertainties. Moreover, the larger
$\Delta m_s$ becomes the larger $\Delta \Gamma_s$ is. Thus, as it becomes more difficult to measure $\Delta m_s$, $\Delta \Gamma_s$ becomes more accessible. Using the above expression, Browder et al. [25] show that if $x_s = 15$, a 7% difference in lifetime is expected. They estimate that the uncertainties in calculating $\Delta \Gamma_s/\Delta m_s$ contribute an uncertainty of $\sim 30\%$ on $|V_{td}/V_{ts}|^2$ (that is, a 15% uncertainty on $|V_{td}/V_{ts}|$). This contribution to the theoretical uncertainty should be added in quadrature to the 10% uncertainty discussed in the previous section, for a total uncertainty of $\approx 20\%$.

We do not expect $\Delta \Gamma_s/\Gamma_s$ to be measured sufficiently well in Run IIa that its usefulness is dominated by theoretical uncertainties. Thus, we will continue to pursue this measurement with the higher statistics available from Run IIb.

Several techniques can be used to determine $\Delta \Gamma_s$ [26]. First, the proper time distribution of a flavor-specific $B^0_s$ mode (e.g. $B^0_s \to D_s \ell \nu$ or $B^0_s \to D_s^- \pi^+$) can be fit to the sum of two exponentials, although for the small lifetime differences expected, this method is not efficient and not competitive with the ones below. Second, the average lifetime of such a flavor specific mode can be compared to the lifetime of a mode that is dominated by a single $CP$ state (such as $B^0_s \to D_s \bar{D}_s$) [27]. Finally, a decay such as $B^0_s \to J/\psi \phi$ can be decomposed into its two $CP$ components (via a transversity analysis [28]) and fit for a separate lifetime for each component. It is noted that CDF has measured the helicity structure of the decays $B \to J/\psi K^*$ and $B^0_s \to J/\psi \phi$ using Run Ia data [8]. The results obtained for the parity-even fraction are $0.87^{+0.12}_{-0.09}$ for $B \to J/\psi K^*$ and $0.77 \pm 0.19$ for $B_s \to J/\psi \phi$.

The statistical uncertainty on the $B^0_s$ lifetime from semileptonic $B$ decays in Run II will be below 1%. The Run II expectation is for $\approx 60,000 B^0_s \to J/\psi \phi$ events in 15 fb$^{-1}$. The $B^0_s \to J/\psi \phi$ helicity structure should then be known to about 1%.

Using the current CDF number for the $B^0_s \to J/\psi \phi$ helicity structure, with 15 fb$^{-1}$, $\Delta \Gamma_s/\Gamma_s$ could be determined to 0.01. Including current theoretical uncertainties of 20%, this determination of $\Delta \Gamma_s$ would either measure $|V_{td}/V_{ts}|$ or set an upper bound on $x_s = \Delta m_s/\Gamma_s \leq 15$. Thus, using the direct $x_s$ measurement and $\Delta \Gamma_s/\Gamma_s$, CDF II should be able to measure $|V_{td}/V_{ts}|$ over the full range permitted by the Standard Model in Run II.

It is important to note that the discussion of $B^0_s$ mixing (and $CP$ violation) has been in the context of the three generation Standard Model. New physics associated with large mass scales can also reveal itself through a study of the mass and width differences for the neutral $B$ mesons [29].

2.7.6.2 $\Delta \Gamma_d/\Gamma_d$

The lifetime difference for the $B^0$ eigenstates is expected to be very small in the Standard Model, around 0.3%. This is smaller than probably can be measured, even in Run IIb. However, the lifetime difference is sensitive to new physics and may be as large as a few per cent in some extensions to the Standard Model, which should be measurable.

The lifetime difference $\Delta \Gamma_d/\Gamma_d$ can be measured by comparing the lifetime measured in a high statistics $CP$ eigenstate mode, such as $B^0 \to J/\psi K^0_s$, to the lifetime measured in a flavor specific mode, such as semileptonic decays or $B^0 \to J/\psi K^{*0}, K^{*0} \to K^+\pi^-$. Note that flavor tagging is not needed here and the full statistics of the samples are available.

For the $\sim 150,000 B^0 \to J/\psi K_s$ decays expected in Run IIb, the statistical error on the lifetime is $\sim 0.3\%$, comparable to the lifetime difference in the Standard Model. At this level, effects of backgrounds and other systematic effects are probably important, but significant deviations from the Standard Model prediction should be observable.

2.7.7 $B^{+}_s$ Decays

In Run I, CDF discovered the $B^+_s$ meson via its semileptonic decay $B^+_s \to J/\psi \ell \nu X$ [10]. In Run II, we expect to observe this meson in several exclusive decay modes, making precise determination of its mass and lifetime possible.

One of the cleanest exclusive modes is $B^+_s \to J/\psi \pi^+$. We estimate the number of expected events by scaling from the observed number of $B^+_c \to J/\psi \ell \nu X$ events and theoretical predictions of the relative branching ratios [30], which range from 0.06 to 0.32. This gives us an expectation of 9 events in Run I on an observed background of roughly 6 events.

Extrapolating to Run IIb, including the detector and trigger improvements for Run II, we expect to ob-
serve about 3000 $B_c^+ \to J/\psi \pi^+$ events. These events plus those from other exclusive decays will allow us to make very precise measurements of the $B_c^+$ mass and lifetime.

We also note that the decay $B_c^+ \to J/\psi \pi^+$ which may exhibit a direct CP violating effect at the few percent level [31]. The mode is self–tagging and no time dependence is required. Any non–vanishing effect would immediately exclude the superweak model of CP violation. In Run IIb, for 3000 events, we expect about a 2% error on the asymmetry.

The relatively short lifetime observed for the $B_c^+$ (albeit with large errors) indicates the it decays primarily by decay of the charm quark, that is, via the decay $B_c^+ \to B_s^0 \pi^+$. Based on the approximately 150,000 fully reconstructed $B_s^0$ decays we expect in Run IIb, we should observe a few hundred $B_c^+ \to B_s^0 \pi^+$ decays.

### 2.7.8 Rare $B$ decays

Rare $B$ decays provide a stringent test of the Standard Model for possible new physics effects, such as an anomalous magnetic moment of the $W$ or the presence of a charged Higgs. Experimentally, rare decays such as $B^0 \to K^{*0} \mu \mu$, $B^0 \to \mu \mu$, and $B_s^0 \to \mu \mu$ are accessible via the dimuon trigger.

The straight dimuon trigger for muons outside the narrow $J/\psi$ mass window will become problematical for the high luminosities of Run IIb. In Run IIa, we have implemented a dimuon trigger that requires an additional displaced track. It is expected that this trigger will be sufficient to search for rare $B$ decays with dimuons in Run IIb.

#### 2.7.8.1 $B^0 \to K^{*0} \mu \mu$

The decay $B^0 \to K^{*0} \mu \mu$ is expected in the Standard Model to have a branching ratio of approximately $1.5 \times 10^{-6}$. For this branching ratio, we expect to observe $36 \pm 7$ events in Run IIa and $270 \pm 50$ events in Run IIb with the dimuon plus displaced track trigger.

The forward-backward asymmetry $A_{FB}$ of the muons relative to the $B$ direction in the dimuon frame is expected to be extremely sensitive to new physics. In the Standard Model, $A_{FB}$ is expected to cross zero as a function of the dimuon mass $M_{\mu \mu}$ at a value around 2 GeV/c^2. New physics can change, or even eliminate, where this zero crossing occurs. Figure 2.68 shows the expected forward-backward asymmetry as a function of $M_{\mu \mu}$ for the Standard Model and several possible extensions to the standard model.

Figure 2.69 shows the expected $A_{FB}$ distribution with 50 and 400 $B^0 \to K^{*0} \mu \mu$ events after all trigger and offline requirements. The solid line in the figure corresponds to the Monte Carlo generated distribution. It is clear that the statistics in Run IIa will be marginal for extracting information on $A_{FB}$. The situation is still challenging in Run IIb but hopeful. We are exploring methods to best extract the zero crossing point of $A_{FB}$, including in the presence of backgrounds.

The statistics of Run IIb are definitely needed for this measurement. The events come from the dimuon plus displaced track trigger, which should not need to be prescaled in Run IIb.

#### 2.7.8.2 $B \to \mu \mu$

The dimuon plus displaced track trigger is also useful to search for the two-body decays $B^0, B_s^0 \to \mu \mu$, predicted to have branching ratios of $1.5 \times 10^{-9}$ and $3.5 \times 10^{-8}$, respectively. Since these branching ratios are at the limits of CDF’s reach, even in Run IIb, we...
quote “single-event sensitivities”, that is, the branching ratio for which we would expect one observed event in 15 fb⁻¹.

CDF searched for these decays in Run I [13] with single-event sensitivities of

\[
\begin{align*}
S(B^0 \to \mu\mu) & = (2.0 \pm 0.5) \times 10^{-7} \quad (2.15) \\
S(B^0_s \to \mu\mu) & = (6.0 \pm 1.6) \times 10^{-7}. \quad (2.16)
\end{align*}
\]

The Run IIb expectations extrapolated from these, including the difference in trigger, muon coverage, and cross section, are

\[
\begin{align*}
S(B^0 \to \mu\mu) & = 2.1 \times 10^{-9} \frac{15 \text{fb}^{-1}}{\mathcal{L}(\text{fb}^{-1})} \quad (2.17) \\
S(B^0_s \to \mu\mu) & = 3.5 \times 10^{-8} \frac{15 \text{fb}^{-1}}{\mathcal{L}(\text{fb}^{-1})}. \quad (2.18)
\end{align*}
\]

Thus, for the expected Standard Model branching fractions, we would expect to not see $B^0 \to \mu\mu$ and to see a few $B^0_s \to \mu\mu$ events.

Note that it is possible for new physics (such as a charged Higgs) to substantially increase these branching fractions, to which we would be sensitive. Also note, that we have not yet done an extensive study of the backgrounds expected at these levels, which, of course, is crucial for understanding whether we could actually see a signal above the background.

### 2.7.9 Radiative B Decays

In the absence of long distance effects, radiative $B$ decays provide an alternative approach for measuring $|V_{td}/V_{ts}|$. Radiative decays are also interesting because they proceed solely through penguin diagrams. It is likely that the $B$ factory experiments will measure $B^-$ and $B^0$ radiative decays better than is possible at CDF. Still, CDF will measure radiative decays, including $B^0_s$ and $B_s$ radiative decays, which are not accessible to the $B$ factories.

CDF will use two methods to search for radiative penguin decays. The first identifies photons as clusters in the Central EM calorimeter. For Run II, a trigger requiring a 5 GeV EM cluster (the photon) and two tracks above 1.5 GeV/c is being implemented. From this trigger, we expect to observe $\sim 2700 B^0 \to K^*\gamma$ events in 2 fb⁻¹ for a branching ratio of $4.5 \times 10^{-5}$. The mass resolution of the reconstructed $B$ is dominated by the resolution on the
photon energy and is \( \sim 140 \text{ MeV} \). We have studied our ability to reject combinatorial background using Run I photon data and have studied with Monte Carlo the discrimination against \( B \to K^*\pi^0 \) and \( \rho^0 \) and higher multiplicity penguin decays [34]. These backgrounds are manageable. However, the off-line cuts to remove background are expected to reduce the signal by about a factor of 2. The mass resolution is not adequate to separate \( \gamma \rho \) from \( \gamma K^* \) on an event-by-event basis; however, a statistical separation is possible. In addition, the COT \( dE/dx \) system should provide 1\( \sigma \) \( K^-\pi \) separation in the momentum range of interest.

The second method looks for photon conversions where the electron or positron satisfies the 4 GeV electron with displaced track trigger. The probability for a photon to convert in the material around the beam pipe in Run I was \( \sim 5\% \), which is expected to increase to \( \sim 10\% \) in Run II due to additional material in SVX II. The main advantage of the conversion method is that the \( B \) mass is calculated solely from charged tracks, giving a resolution comparable to \( B \) signals observed in Run I, that is, 20 to 30 MeV/\( c^2 \). The backgrounds are also less for the conversion sample. The improved resolution gives cleaner signals and allows separation of \( B^0 \to \rho \gamma \), \( B^0 \to K^*\gamma \), and \( B_s^0 \to K^*\gamma \) signals. These advantages will probably make the conversion method the optimal one for Run II.

The numbers of radiative penguin decays expected in the conversion sample in Run II are

\[
N(B^0 \to K^*\gamma) = 170 \times \frac{\int L(b^{-1})}{2b^{-1}} \times \frac{Br(B_d \to K^*\gamma)}{4.5 \times 10^{-5}}
\]

\[
N(B_s^0 \to \phi\gamma) = 63 \times \frac{\int L(b^{-1})}{2b^{-1}} \times \frac{Br(B_s \to K^*\gamma)}{4.5 \times 10^{-5}}
\]

\[
N(B_s^0 \to \gamma\gamma) = 2.2 \times \frac{\int L(b^{-1})}{2b^{-1}} \times \frac{Br(B_s \to K^*\gamma)}{4.5 \times 10^{-5}}
\]

\[
N(\Lambda_b \to \Lambda\gamma) = 5 \times \frac{\int L(b^{-1})}{2b^{-1}} \times \frac{Br(B_d \to K^*\gamma)}{4.5 \times 10^{-5}}
\]

Thus, the 15 fb\(^{-1}\) of Run IIb will be needed to observe the \( B^0 \to K^*\gamma \) and \( \Lambda_b \to \Lambda\gamma \) modes.

### 2.7.10 Semileptonic Decays

In Run II, CDF will observe large numbers of semileptonic decays of all species of \( B \) hadrons. Here, we concentrate on \( \Lambda_b \to \Lambda_c \ell\nu \) decays, which are not produced in \( e^+e^- \) \( B \) factories, as being illustrative. Semileptonic decays of \( B \) hadrons are acquired via the inclusive electron and muon triggers. For \( B \) physics, the rates for these triggers can be kept under control by also requiring a displaced track.

Measuring the differential decay rate \( (1/\Gamma) d\Gamma/dQ^2 \), where \( Q^2 \) is the momentum transfer, is a stringent test of Heavy Quark Effective Theory (HQET). These tests require large data samples and so are ideally suited to Run II. In the Run I \( \Lambda_b \) lifetime analysis, \( 197\pm25 \) \( \Lambda_b \to \Lambda_c \ell\nu \), \( \Lambda_c \to pK\pi \) events were partially reconstructed [6]. Extrapolating to Run IIb, including the improvements in the detector and trigger, gives an expected yield of 150,000 events in 15 fb\(^{-1}\).

Tests of HQET in \( \Lambda_b \) semileptonic decays could be compromised by contamination from decays of the \( \Lambda_b \) to higher order charmed baryons. Monte Carlo studies show that rejection of events with extra tracks having a small impact parameter with respect to the \( \Lambda_b \) vertex controls these backgrounds at acceptable levels.

#### 2.7.11 \( \psi(2S) \) Polarization

In Run I, CDF measured the direct production of both \( J/\psi \) and \( \psi(2S) \) mesons, giving cross-sections approximately 50 times greater than those predicted by QCD using the color-singlet model. This anomalous production can be explained in nonrelativistic QCD by the inclusion of color-octet \( \sigma \) states in the hadronization process. A consequence of this production mechanism is that the transverse polarization of the \( J/\psi \) and \( \psi(2S) \) mesons approaches 100% for transverse momenta \( p_T \gg m_c \), where \( m_c \) is the charm quark mass. Measurements in Run I by CDF of the \( J/\psi \) and \( \psi(2S) \) polarizations [35] did not support the color octet models, but statistics were limited at large transverse momenta, where the theory is most reliable.

In Run IIa, the uncertainties on the polarization of \( J/\psi \)’s will be \( \pm 0.2 \) at a transverse momentum of 30 GeV/c, providing a stringent test of the color octet models. However, direct \( J/\psi \)’s have the problem that some of them come from decays of prompt \( \psi(2S) \)’s and \( \chi \) states, adding some uncertainty to the interpretation of the measurement. Direct \( \psi(2S) \)’s do not have this problem, but to measure their polarization out to comparable transverse momenta will require the statistics of Run IIb.
2.7.12 Concluding remarks

From the previous discussion it should be clear that in Run IIb CDF plans to fully exploit the copious production of all species of $b$ hadrons at the Tevatron. We believe we will have a complete and competitive program, with unique strengths, for example, in rare decays and $B^0_s$ physics.

With the experience gained so far in the analyses of Run I data and the planned capabilities of the CDF II detector, we are able to confidently project our expectations for Run IIa and Run IIb which include:

- Observation of $CP$ violation in $B^0 \rightarrow J/\psi K^0_S$ and measurement of $\sin(2\beta)$ to better than $\pm 0.02$.

- Measurement of the $CP$ asymmetries in $B^0_s \rightarrow J/\psi \phi, J/\psi \eta (0)$, which measure the phase of $V_{ts}$ in the Standard Model and are sensitive to new $CP$ violating physics.

- Observation of $CP$ violation in $B^0 \rightarrow \pi^+ \pi^-$, $B^0_s \rightarrow K^+ K^-$ and measurement of the unitarity triangle angle $\gamma$ to better than $\pm 3^\circ$.

- Observation of $B^0_s$ mixing and precise determination of $\Delta m_s$.

- Measurement of $\Delta \Gamma_s/\Gamma_s$ to 0.01.

- Observation of exclusive decay modes of the $B^+_c$ meson, allowing precise determinations of its mass and lifetime.

- Observation of radiative penguin decays.

- Observation of the rare decays $B^0 \rightarrow \mu \mu K^{*0}$ and $B^\pm \rightarrow \mu \mu K^\pm$.

With these and other measurements that we will pursue with $b$ hadrons in Run IIa and Run IIb, we expect to greatly improve the understanding of weak-interaction quark mixing and $CP$ violation in the Standard Model and be very sensitive to new physics in these areas.
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