Heavy Quark Production at the Tevatron

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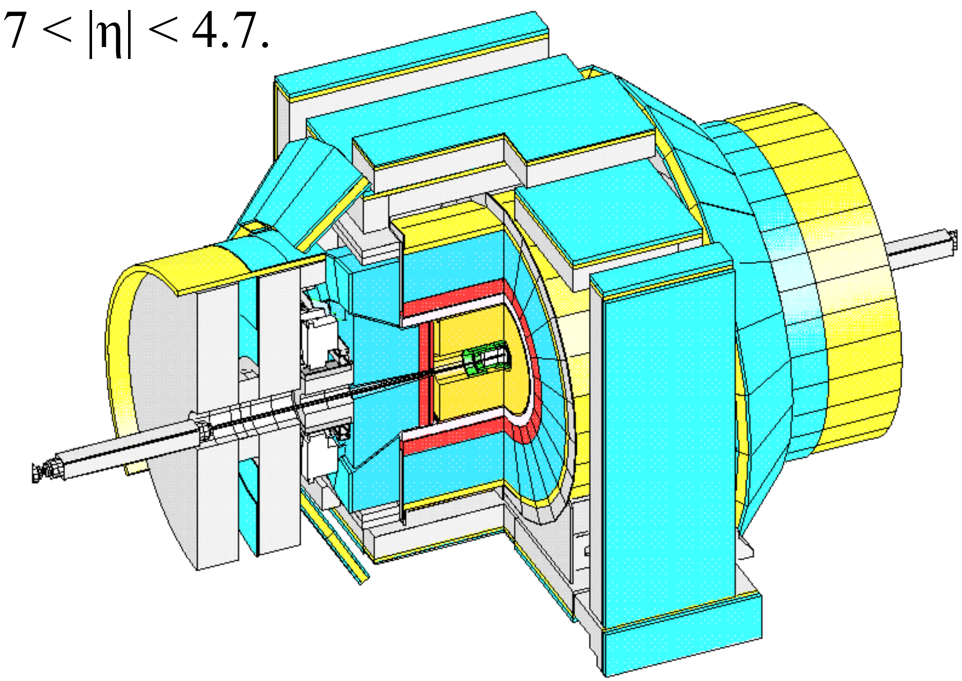
ICHEP 08, Philadelphia
31 July 2008

4 Studies by CDF

- Measurement of b-quark jet shapes
- Production cross section of $\psi(2S)$
- Inclusive b-jet production
- Production of $b\bar{b}$ dijets

The CDF Detector

- *silicon vertex detector* (L00+SVXII+ISL): 8 layers at radii from 1.5cm to 28cm. Resolution on d_0: 40 μm. Resolution on z_0: 70 μm.
- *central outer tracker* (COT): Ar-C_2H_6 multiwire drift chamber with 8 superlayers (96 measurement layers) at radii from 40 to 140 cm, alternately stereo (±2°) and axial. Radii from 40 to 137 cm, length 3.1 m. $|\eta| \leq 1$. Position resolution: 140 μm. $\sigma(p_T)/p_T^2=0.0015\ (\mathrm{GeV}/c)^{-1}$.
- scintillator + PMT *TOF*: 100 ps resolution. K/π separation ≥ 2σ for p < 1.6 GeV/c.
- 1.4 T *superconducting solenoid* (1.5m radius x 4.8m long)
- EM (Pb/scint) and HAD (Fe/scint) *calorimeters* cover $|\eta| < 3.64$: 5.5 interaction lengths. Resolutions $13.5\%/\sqrt{E_T} \oplus 2\%$ (CEM) and $75\%/\sqrt{E_T} \oplus 3\%$ (CHA).
- *muon detection*: 8 layers, scintillators and proportional chambers to $|\eta| < 1.5$, detect muons with $p_T > 1.4$ GeV/c (CMU) or > 2.0 GeV/c (CMP).
- gas Cherenkov *luminosity counters* at $3.7 < |\eta| < 4.7$.



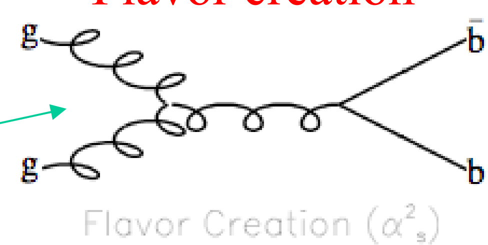
Measurement of b-jet Shapes in Inclusive Jet Production[*]

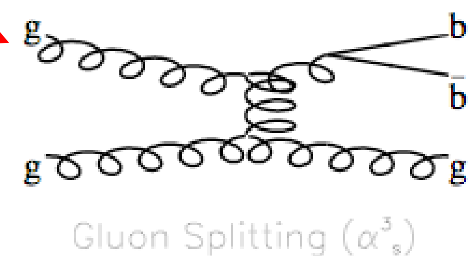
Jet shape: p_T of particles as a function of distance from the jet axis

Motivation: The structure of jets derives from the gluon emissions from the primary parton. In heavy quark jets, the quark decay must also be modeled. The underlying event (initial and final state radiation, multiple interactions, and beam-beam remnants) must be included. Multi-gluon emission is difficult to calculate and often approximated by parton shower models.

Jet shape is known to depend upon whether the primary parton is a quark or gluon. It is expected to depend upon flavor. It is expected to depend upon production mechanism: The b and $\bar{b}$ from gluon splitting are expected to be often in the same jet,[†] producing a broader jet than does flavor creation. Measurement of jet shapes casts light on all these aspects of jet evolution and heavy flavor production.

Flavor creation





Gluon splitting

[*]arXiv:0806.1699 [hep-ex], June 2008

[†]S. Frixione et al, hep-ph/9702287

Question: is the fraction of b-jets originating from gluon splitting, and its evolution, well described by contemporary models?

To answer this, we define the jet shape:

- a measure of the fraction of total jet p_T inside a given radius in (y,φ)-space from the jet, so that
- Integrated jet shape

$$\Psi(r/R) = \left\langle \frac{p_T(0 \to r)}{p_T(0 \to R)} \right\rangle$$

is the fraction of total p_T in cone R carried by particles in subcone r, averaged over an ensemble of jets, normalized to 1.

- $\Psi(0) = 0$, and particles outside the cone are excluded.

b-jet Event Selection

Online, examine datasets resulting from 4 trigger paths, all based solely on calorimeter E_T threshold per jet:

- Level 1: requires 1 calorimetric trigger tower, $E_T > E_T^{min}$ (5-10 GeV)
- Level 2: Clusters about the L1 tower are formed from adjacent towers above 1 GeV. At least one cluster must exceed threshold (15-90 GeV)
- Level 3: Jets are reconstructed with the Run 1 cone algorithm, one jet must exceed E_T^{min} (20-100 GeV)
- jet minimum p_T requirement is set to ensure that only events for which the trigger is $\geq$ 99% efficient are used.

Offline, reconstruct jets using the Midpoint cone algorithm:*

- Combine hadronic and EM towers to form physics towers
- Compute the p_T of each tower, assume particle masses = 0, save towers with $p_T >$ 0.1 GeV
- Every tower with $p_T > 1$ GeV/c is a jet seed. Draw a search cone (radius "R/2") around every seed, beginning with the highest p_T. Each cone defines a cluster in y, φ, and four-momentum.
- Compute the energy-weighted centroid of each cluster; use it to redefine the cluster center.
- Repeat until the cluster center is stable: the geometrical center and energy-weighted centroid align.
- For every pair of stable cluster centroids separated by less than 2x the cone radius, add the midpoint to the list of cluster centroids.
- Iterate to reach a new set of stable clusters.
- Increase cluster radius from R/2 to R.
- If 2 jets overlap, share their momentum; for overlap > 75%, merge.

*G.C. Blazey et al., hep-ex/0005012; D. Acosta et al., PRD 74, 071103(R) (2006)

Then enhance selection of b jets by requiring secondary vertex:

- Because *b*'s tend to be found near axis, search inside "tagging" cone of R = 0.4
- Rank tracks by reconstruction quality including distance d_0 of closest approach to the primary vertex.
  - Begin with highest quality track, attempt to reconstruct secondary vertex.
    - If successful, add to it all other tracks with $d_0/\sigma(d_0)$ < threshold
    - If fail, add to it second-highest quality track and iterate
  - If fail, begin with second highest quality track.
- Require $L_{xy}/\sigma(L_{xy})$ > threshold: two-dimensional projection along the jet axis of the distance between primary and secondary vertices
- General event quality cuts:
  - reject multiple interactions: 1 and only 1 primary vertex with $|z| < 50$ cm
  - reject cosmics: $\dfrac{\not{E}_T}{\sqrt{E_T}}$ < threshold (3.5-7 $\mathrm{GeV}^{1/2}$)
  - jet rapidity $|y_{jet}| \leq 0.7$
- Correct jets to hadron level by matching hadron and calorimeter level jets in MC (typical correction increases p_T by 20% to 10% with no change to jet shape)

Next step: *compare data to predictions from Monte Carlo*

- Two leading order Monte Carlo models, both with *CTEQ5L* pdf's
  - PYTHIA Tune A (based on v6.203): tuned to the CDF Run 1 underlying event, uses ordering in virtuality (increasing Q^2) during the evolution, decreasing Q^2 of the final state radiation, Lund string model fragmentation and hadronization; heavy quark decay via QQ.
  - HERWIG v6.506: uses angular ordering of successive gluon emissions to simulate color flow, decreasing angular ordering of final state radiation, the cluster model for fragmentation into hadrons; no multiple interactions.

Corrections, and unfolding the b-jet shape

❖Correct for the effects of tagging: The requirement of the secondary vertex tag biases the measured jet shapes by requiring clean well-defined tracks. Define r-dependent bias corrections by comparing MC jet shapes before and after detector simulation.

❖Correct for the presence of non-b jets misidentified as b-jets. These are:

- ❖ c-jets whose L_{xy} passes the b-jet cuts and
- ❖ mis-reconstructed light jets.

Use MC jets to create template distributions, then compare data to templates as a function of p_T to infer fraction of true b-jets.

❖Correct for detector effects (e.g., number of calorimeter towers scales with p_T).

❖Correct for the presence of a second b quark in the jet: Compare PYTHIA with NLO, determine that $[N_{2b's}/N_{incl\text{-}b}]^{(NLO)} - [N_{2b's}/N_{incl\text{-}b}]^{(LO)} \approx 0.2$ (almost p_T-independent). Reweight the MC to decrease the fraction of jets with 1b by 20%. Then fit data to 2b and 1b templates separately.

The final function to be fitted:

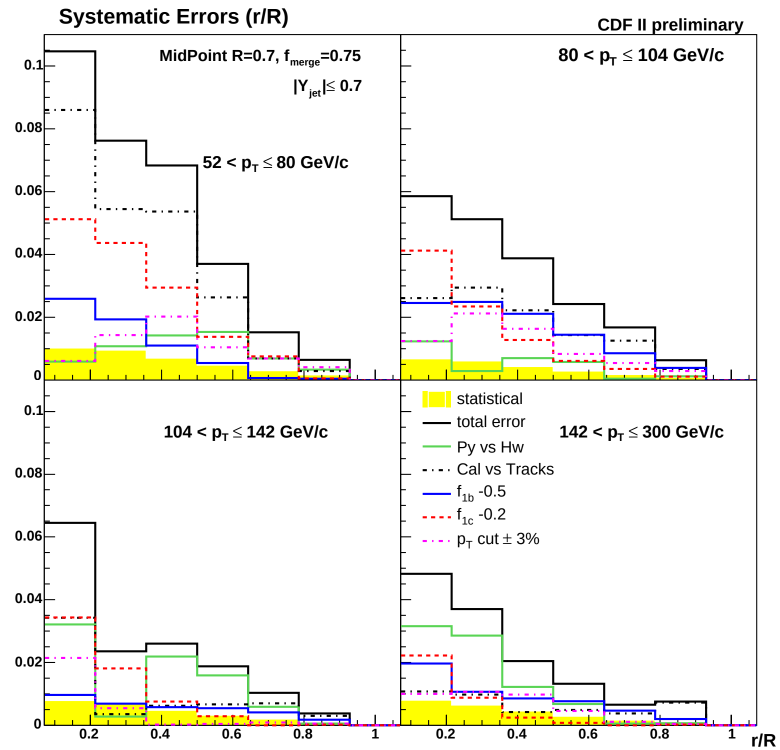
$$\Psi^{b}_{had}(r/R) = C^{had}(r/R)\frac{\Psi^{tag}_{\det}(r/R) - (1-p_b)b_{non-b}(r/R)\Psi^{non-b}_{\det}(r/R)}{p_b b_b(r/R)}$$

where

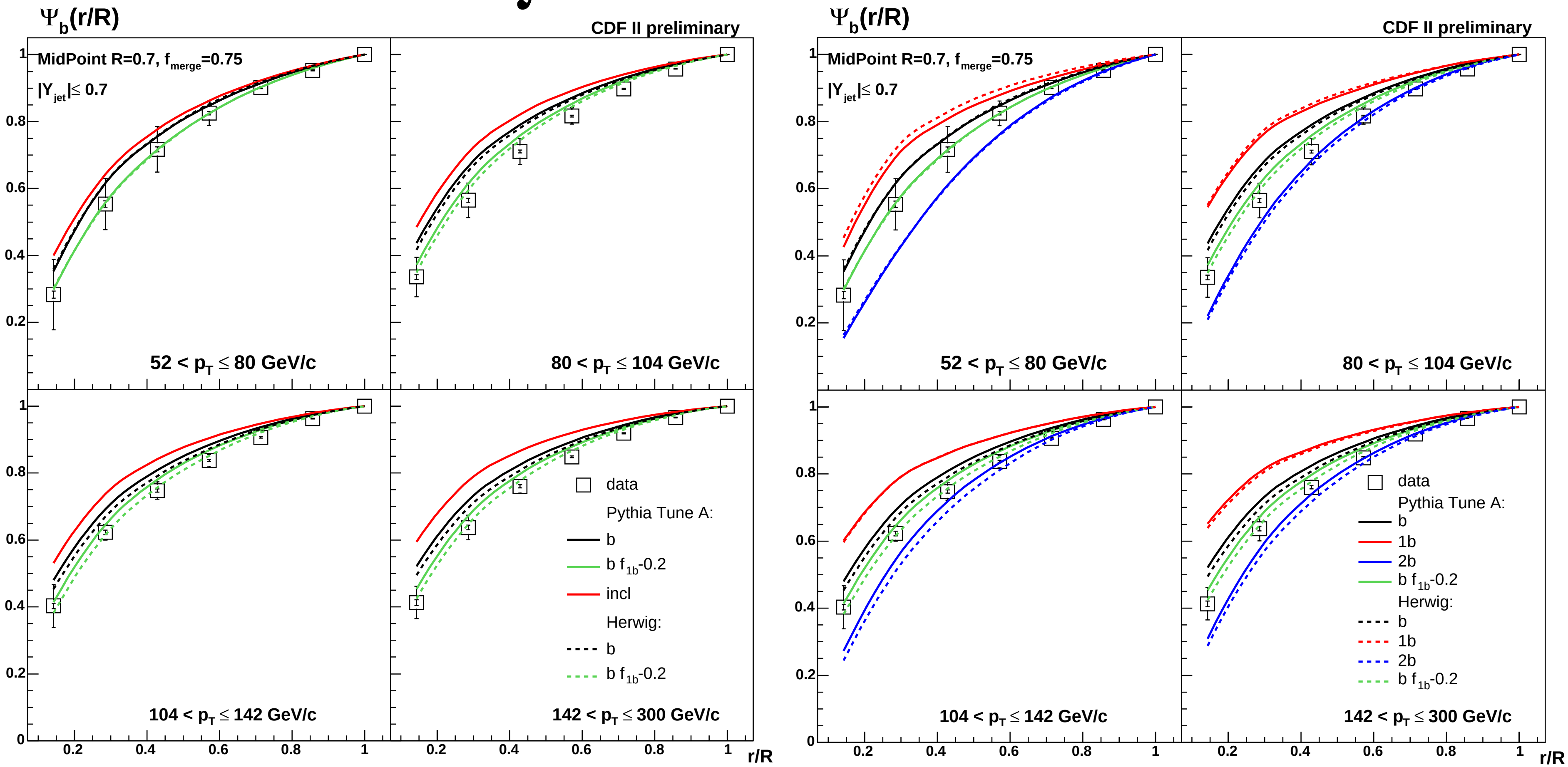
- C^{had} is the unfolding factor, $\dfrac{\Psi^{b}_{had}(r/R)}{\Psi^{b}_{\det}(r/R)}$
- $\Psi^{tag}_{\det}$ is the measured jet shape for the tagged sample
- $\Psi^{non-b}_{\det}$ is the measured inclusive jet shape
- p_b is the purity of b's in the tagged jet sample, determined by comparing the mass of the secondary vertex to a Monte Carlo distribution
- b_b($b_{non\text{-}b}$) corrects for biases to the jet shape arising from the secondary vertex requirement.

Systematics:

- choice of Monte Carlo model: estimated by comparing PYTHIA with HERWIG
- effect of calorimeter model estimated by replacing calorimeter tower info with charged track info
- Monte Carlo model of secondary vertex parameters: negligible
- choice of p_T cut---varied from 0.1 to 0.5 GeV: negligible
- jet energy: 3% measured from inclusive jets
- b-jet fragmentation: 0.6%
- $\not{E}_T$ significance: negligible
- cut on primary vertex location: negligible
- c-jet content of non-b-jets: 5%
- fraction of jets containing 2 c quarks instead of 1



Results, for $\int Ldt = 300\, pb^{-1}$, and conclusions :



•data are incompatible with inclusive predictions: jet shapes are influenced by heavy quarks. *b-jets are broader.*

•data jets are broader than both PYTHIA and HERWIG defaults ---LO underestimates the fraction of *b*'s from gluon splitting, and the fraction of jets with 2*b*'s.

Production of ψ(2S) Mesons

Motivation: The mechanism for producing heavy vector mesons in hadron collisions is not well understood. CDF Run 1 data on production cross sections for prompt J/ψ and ψ(2S) were 1-2 orders of magnitude above predictions by color singlet models. Subsequent theoretical efforts (NRQCD)[*] with adjusted production matrix elements match the cross section but predict increasing transverse polarization with production p_T that is not confirmed by the data.[†] New approaches (k_T-factorization,[§] gluon tower model[‡]) have been proposed.

ψ(2S) is a good testing ground for studying charmonium hadroproduction as there are no significant charmonium states above it to produce feeddown.

Goal: a measurement of $\sigma(p\bar{p} \to \psi(2S) \cdot BR(\psi(2S) \to \mu^+\mu^-)$ for $2\ \mathrm{GeV/c} \le p_T \le 30\ \mathrm{GeV/c}$.

[*] G.T. Bodwin, E. Braaten, and G.P. Lepage, PRD 51, 1125 (1995); E. Braaten and S. Fleming, PRL 74, 3327 (1995).

[†] A. Abulencia et al., PRL 99, 132001 (2007).

[§] S.P. Baranov, PRD 66, 114003 (2002).

[‡] V.A. Khoze et al., Eur. Phys. J. C 39, 163 (2005).

Data selection

- Muon reconstruction: Level 1 charged tracks reconstructed in 4 COT layers, projected and matched to 3-4 hit tracks in muon detector.
- Dimuon trigger: 2 opposite sign tracks, each with $p_T > 1.5$ GeV/c.
- Begin with events passing dimuon trigger, then require 3 hits in the SVX II and $p_T > 2$ GeV/c (if tracked in CMU) or 3 GeV/c (if tracked in CMP, behind more steel).
- $\psi(2S)$ mass and lifetime are then fit with a likelihood function (see below).
- Finally require 3.5 GeV/c^2 < $m(\mu\mu)$ < 3.8 GeV/c^2 and $|y(\mu\mu)| < 0.6$.

Reconstruction goals:

- Separate signal from background, and prompt from *b*-decay ψ's, with an *unbinned maximum likelihood fit in candidate mass and proper decay length ct*.

- *Mass separates signal from background.* Model signal with the Crystal Ball Function*, a Gaussian core with a low side tail:

$$A \cdot e^{-\frac{(Et-Em)^2}{2\sigma^2}} \qquad \text{for } \frac{\text{Em - Et}}{\sigma} > -\alpha$$

$$A \cdot \left(\frac{n}{\alpha}\right)^n \frac{e^{-\frac{\alpha^2}{2}}}{\left(\frac{Et-Em}{\sigma} + \frac{n}{\alpha} - \alpha\right)^n} \qquad \text{for } \frac{\text{Em - Et}}{\sigma} \leq -\alpha$$

where Em is the fit mass centroid, Et is the invariant mass of each event, A is normalization, and α and *n* model the tail.

- Model mass background with a first order polynomial.

* J. Gaiser, SLAC-0255 (1982).

Reconstruction goals, continued

- *Separate prompt from feeddown with a proper time (ct) fit*.
  - Prompt signal: a double-Gaussian centered at zero.
  - Long-lived signal $E \otimes G$:

$$\frac{1}{c\tau}\exp\left[\frac{\sigma^2}{2c\tau^2}-\frac{x}{c\tau}\right]\cdot\left[1-Freq\left(\frac{\sigma}{c\tau}-\frac{x}{\sigma}\right)\right]$$

where

$$Freq(y)=\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{y}e^{-t^2/2}dt$$

  - Model lifetime background by a (prompt) double gaussian + symmetric long-lived + positive ct long-lived + negative ct long-lived components.

Reconstruction, continued

- Likelihood function:

$$L = f_s P_s^{mass}(f_p P_p^{ct} + (1-f_p)P_{E\otimes G}^{ct}) + (1-f_s)P_{bkg}^{mass}(f_{sym}P_{sym}^{ct} + f_+ P_+^{ct} + f_- P_-^{ct} + (1-f_{sym}-f_+-f_-)P_p^{ct})$$

where the *f*'s are fractions of signal (*s*, from the total number of candidates in the fit), prompt (*p*), symmetric long-lived bkg (*sym*), positive-ct long-lived bkg (+), and negative-ct long-lived bkg (-)

and the *P*'s are probability density functions for signal mass (P_s^{mass}), linear mass background (P_{bkg}^{mass}), prompt signal double Gaussian proper time (P_p^{ct}), *b*-decay signal ($P^{ct}_{E\otimes G}$), and lifetime backgrounds (P^{ct}_{sym}, P^{ct}_{+}, and P^{ct}_{-}).

Efficiency calculation

- $\varepsilon_{reco} = \varepsilon^2_{COT} \cdot \varepsilon_{SVX} \cdot \varepsilon^2_{CMU} \cdot \varepsilon^2_{\mu-\chi^2} \cdot \varepsilon_{z_0} \cdot \varepsilon_{\Delta z_0}$ where these efficiencies range from 95.3% (SVX offline) to 99.9% ($\Delta z_0 \leq 5$cm).

Acceptance calculation

- *Acceptance depends upon polarization* per p_T bin. CDF polarization data on $\psi(2S)$ are too weak for direct application. Theory predicts that J/ψ polarization (for which strong CDF data exist) is a good predictor of prompt $\psi(2S)$ polarization. We confirm that CDF polarization data for J/ψ and $\psi(2S)$ are consistent, then use the J/ψ polarization values for the $\psi(2S)$ p_T bins.

- Generate Monte Carlo $\psi(2S)$ samples with fixed extreme polarizations (0 or -1) and flat distributions in p_T, η, and φ. Simulate them in the CDF detector, then reconstruct.

- Compute geometrical acceptance x trigger efficiency:

$$A = \frac{N^{rec}(p_T) \times (N^{eff}(p_T) / N^{rec}(p_T))}{N^{gen}(p_T)}$$

where for N^{gen} generated events, N^{rec} survive geometric and reconstruction requirements and N^{eff} survive the trigger.

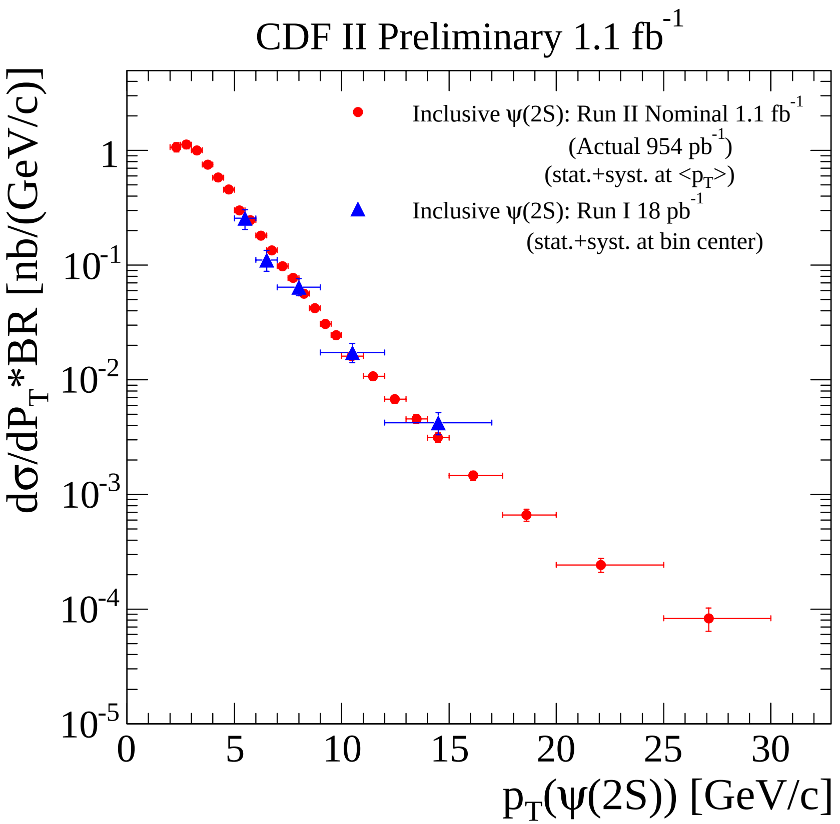
- Graph the results, and interpolate for intermediate polarization values predicted from J/ψ data. A ranges from 0.0053 ($2.0 < p_T < 2.5$ GeV/c) to 0.2548 ($25 < p_T < 30$ GeV/c).

Systematics:

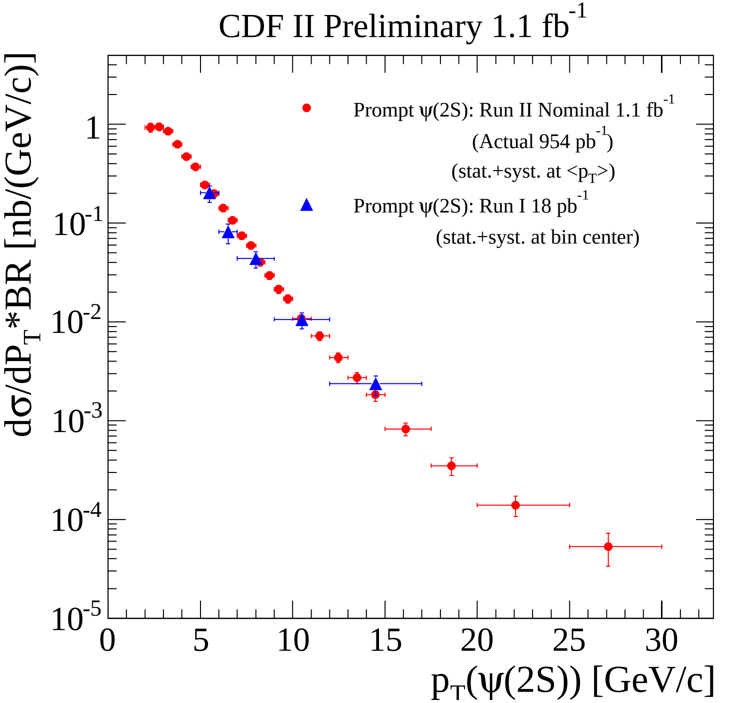
- Luminosity: 6%
- Reconstruction efficiency: 2.5%
- Dimuon trigger efficiency: 1.2% - 3.1%
- Mass probability density function: 0.7%
- Prompt fraction, from decay length fit function: 0.3%
- $\psi(2S)$ polarization: 0.7% - 3.8%
- Mass and lifetime model parameters: 0.2% - 0.5%

Results, for $\int Ldt = 1.1\, fb^{-1}$:

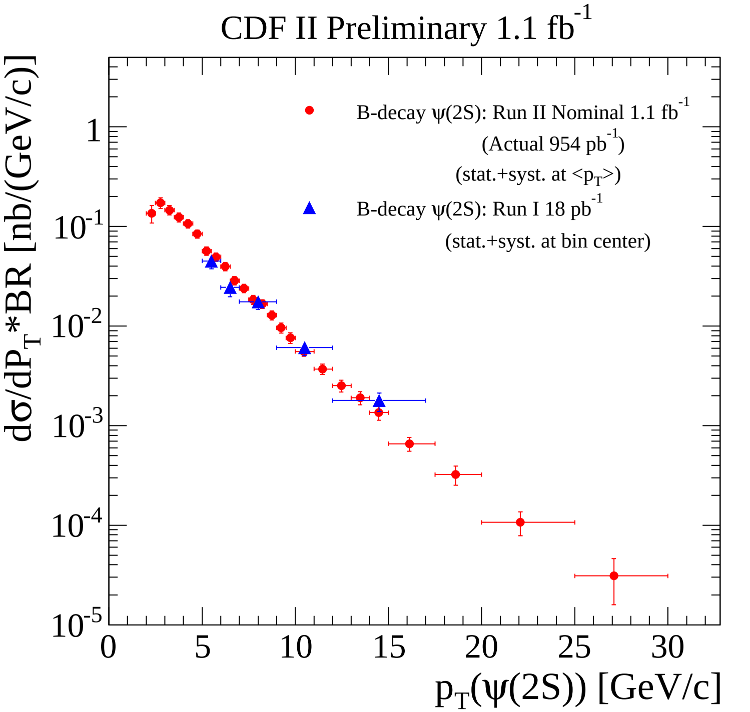
- The trigger prescale varied during the course of the run, leading to an effective luminosity $\int Ldt = 954\, pb^{-1}$.
- *The inclusive differential cross section*, $\dfrac{d\sigma(\psi 2S))}{dp_T} = \dfrac{N(\psi(2S))}{A \cdot \varepsilon_{reco} \cdot \int Ldt \cdot \Delta p_T}$, is:



- the prompt ψ(2S) cross section is given by:



- the ψ(2S) from B-decay cross section is:



Conclusions:

❖ Integrated results, for Run II:

$$\sigma(p\bar{p} \to \psi(2S)X) \cdot BR(\psi(2S) \to \mu^+\mu^-) =$$
$$0.68 \pm 0.01(stat) \pm 0.06(syst)\ \text{nb}$$

❖ Comparison to Run I, over identical p_T ranges ($p_T > 5$ GeV/c):

$0.68 \pm 0.01 \pm 0.06$ nb [Run II]

$0.57 \pm 0.04^{+0.8}_{-0.9}$ nb [Run I]

Ratio : $18 \pm 19\%$

Theoretical prediction,* based on energy dependence of parton distribution functions :

$14 \pm 8\%$

❖ *Run I trends are confirmed with an order of magnitude increased statistics.*

*K. Anikeev et al., hep-ph/0201071 (2001).

Inclusive b-jet Production

Motivation: Measurements of b-quark production in hadronic collisions test pQCD. The CDF Run I inclusive B meson cross section measurement[†] motivated theoretical developments beyond NLO.[*] Continued comparisons, at higher p_T and with increased statistics, drive improvements.

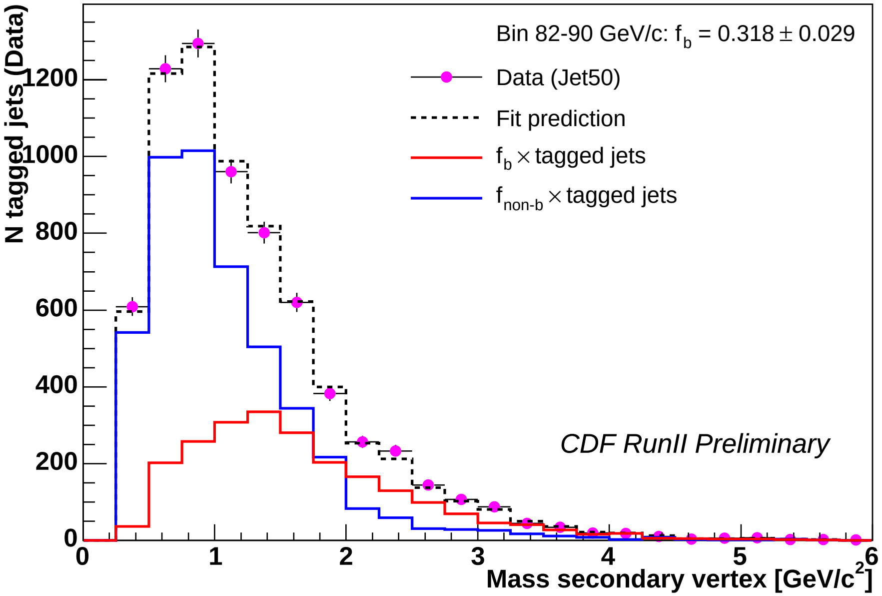
Event selection:

- 5 trigger paths based on energy deposition in the calorimeter
- Primary vertex $|z| < 50$ cm
- $\frac{\not{E}_T}{\sqrt{E_T}} <$ threshold (2 to 7 $GeV^{1/2}$ depending on trigger path)
- jets reconstructed with midpoint cone algorithm ($R = 0.7$), heavy flavor jets tagged via secondary vertex.
- $38 < p_T^{jet} < 400$ GeV/c; $|y^{jet}| < 0.7$.

[†] F. Abe et al., PRL 75, 1451 (1995).

[*] M. Cacciari, P. Nason, PRL 89, 122003-1 (2002).

- *Jet energy corrections:*
  - Use minimum bias events to measure p_T deposited in the calorimeter, as a function of number of primary vertices: 0.93 ± 0.14 GeV/c per extra vertex
  - Measured energy underestimates hadron level energy due to deposition in partially instrumented regions and calorimeter nonlinearities. Use Monte Carlo to implement a p_T-dependent correction.
  - Monte Carlo: PYTHIA 6.203, with CTEQ5L and Tune A
  - Detector to hadron-level unfolding factors range from 1.6 to 2.1.
- *b-quark content of the jet ("b-tagging") relies on the shape of the invariant mass of all charged tracks attached to the secondary vertex:*



Theoretical prediction:[*]

- $m_b = 4.75$ GeV/c^2
- CTEQ6M
- $\mu_R = \mu_F = \frac{1}{2}\sqrt{\left(p_T^{b-jet}\right)^2 + m_b^2}$
- cone-based algorithm with effective cone size R' = 0.7 x R_{sep}, for R_{sep} = 1.3
- Additional theoretical correction factor for non-perturbative effects associated with hadronization and the underlying event: 1.2 (low p_T) – 1.0 (above 140 GeV/c)
- Theoretical uncertainties are associated with choice of PDF (±7% - ±20%), choice of scale (±40% - ±20%), and differences between the data and theory jet algorithms (±10%).

[*] S. Frixione, M. Mangano, Nucl. Phys. B 483, 321 (1997)

Result, for $\int Ldt = 300\,pb^{-1}$:

Differential b-jet cross section is

$$\frac{d^2\sigma_{b-jet}}{dp_{T,cor}\,dy} = \frac{N_{tagged}\,f_b}{\varepsilon_{b-tag}\,\Delta y^{jet}\,\Delta p^{jet}_{T,cor}\int Ldt}$$

where

N_{tagged} = #tagged jets in p_T bin

$\Delta p_{T,cor}$ is bin size

f_b = fraction of b-jets in tagged sample:

0.35 (@ p_T = 38 GeV/c) to

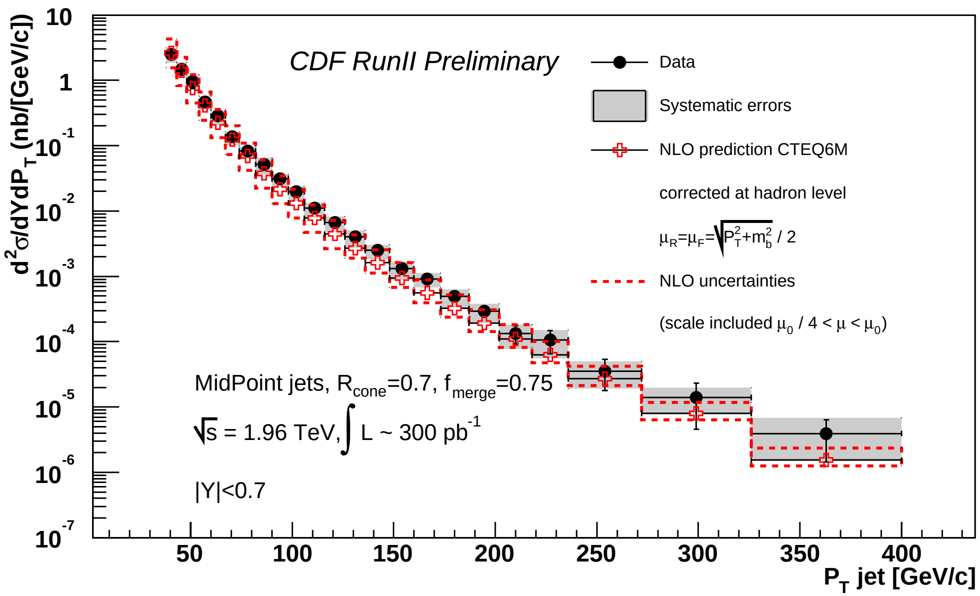
0.14 (@ p_T > 250 GeV/c)

$\varepsilon_{b\text{-}tag}$ = b-tagging efficiency: (fraction of tagged b-jets to all b-jets) · ε_{MC}

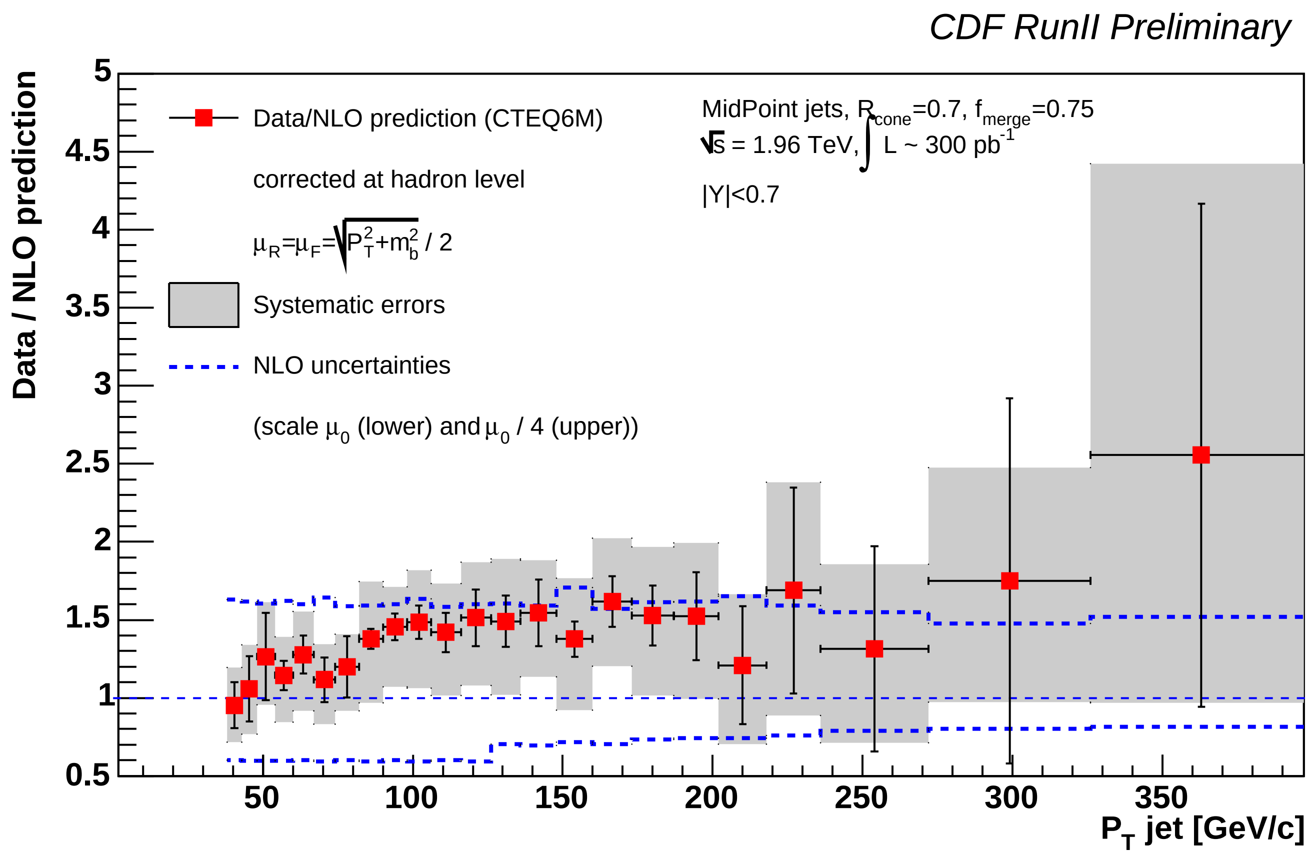
ε_{MC} = 0.91, MC sim/recon imperfections

Δy^{jet} = jet rapidity range

L = luminosity



Data/Theory:



The measured cross section is consistent with theory throughout the full (6 orders of magnitude) p_T^{jet} range. The strong dependence on scale μ suggests that higher orders may make large contributions.

Systematic uncertainties:

- total luminosity: 5.8%
- jet energy scale: ±3% leads to cross section uncertainty from ±10% (low p_T) to ±30% (high p_T)
- jet energy resolution: ±10% leads to cross section uncertainty ±6%
- unfolding process: ±5% - ±15%
- f_b, fraction of b-jets leads to cross section uncertainty from ±15% (low p_T) to ±50% (high p_T)
- b-tagging efficiency: ±7%
- other selection criteria: <1%

These combine to a total systematic uncertainty ranging from ±25% (low p_T) to ±70% (high p_T)

Measurement of the $b\bar{b}$ cross section using a dedicated trigger

Motivation: Momentum conservation requires that the azimuthal angle φ between a b and $\bar{b}$ produced at lowest order must be 180°. Higher order QCD processes produce additional partons in the final state, modifying the range of allowed azimuthal angle difference, $\Delta\varphi$. Order α_s^3 diagrams are thought to contribute the same magnitude to the cross section as order α_s^2 diagrams. Measuring the cross section as a function of $\Delta\varphi$ provides information on the contributions of the leading order and NLO terms.

Event selection:

- Level 1: Require 2 central calorimeter towers with $E_T > 5$ GeV and 2 tracks in the COT with $p_T > 2$ GeV/c.
- Level 2: Calorimeter towers are clustered. Events with 2 clusters, $E_T > 15$ GeV each, are retained. Tracks are reconstructed with the Silicon Vertex Trigger.* Events with 2 tracks having impact parameters > 100 μm relative to the primary vertex are retained.

* A. Bardi et al., Nucl. Instr. and Meth. A 485, 178-182 (2002).

- Level 3: Jets are reconstructed with the Run 1 cone algorithm. Events with 2 jets with $E_T > 20$ GeV, each associated with a large impact parameter SVT track, are retained.

- Offline:

  - *require one or more primary vertices* with $|z| < 60$ cm from nominal crossing point.

  - *Jets are confirmed* with cone opening angle $R = 0.4$.

  - *Jet energy scale corrections* applied.

  - Individual jets' *energies corrected for features of b-jets* including harder fragmentation

  - *Select events* with 2 jets with corrected $E_T > 35$ GeV and 32 GeV, $|\eta| < 1.2$, both b-tagged, both associated with one track with $p_T > 2$ GeV/c and $|d_0| > 120$ μm.

The Monte Carlo comparisons

The data are compared to predictions from

❖PYTHIA, with Tune A and CTEQ5L

❖HERWIG

❖MC@NLO with HERWIG Parton Shower, the underlying event from Jimmy4.3 (multiple interactions from remnants not multiple hard scatters), CTEQ6M, and $\mu_R = \mu_F = \sqrt{p_T^2 + m^2}$.

Systematics

- Jet energy scale: 15-20%
- Luminosity: 6%
- b-tagging efficiency: 3%
- fraction of b-jets containing more than one b-quark: 1-3%
- unfolding factors: 2-6%
- $b\bar{b}$ purity, influenced by different tracking environments inside jets for data and MC: 7-8%

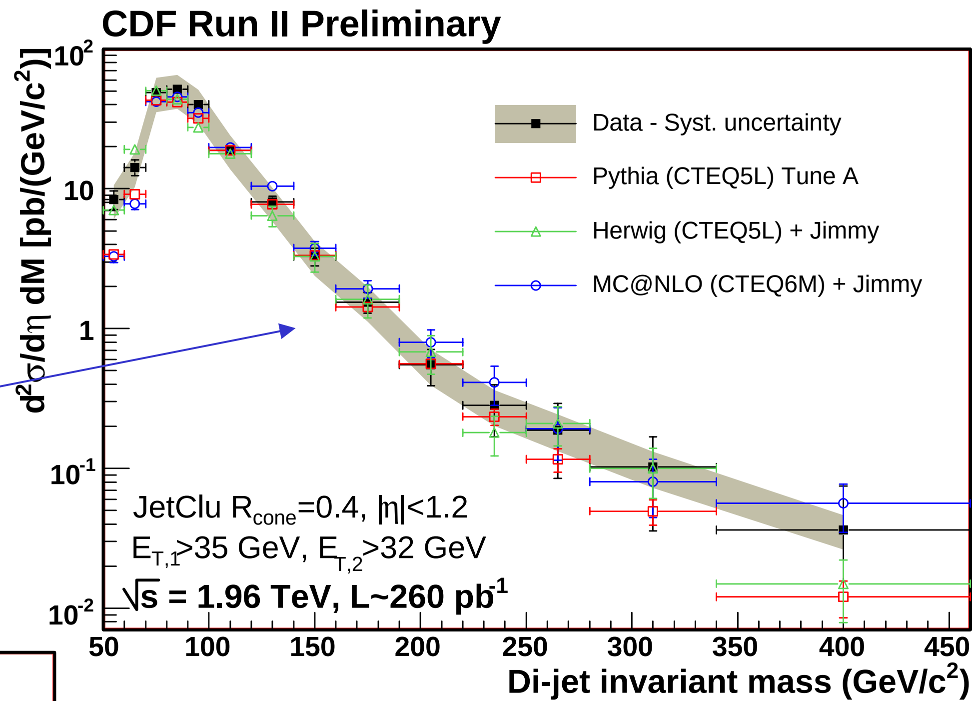
Total systematic uncertainty: 20-30%

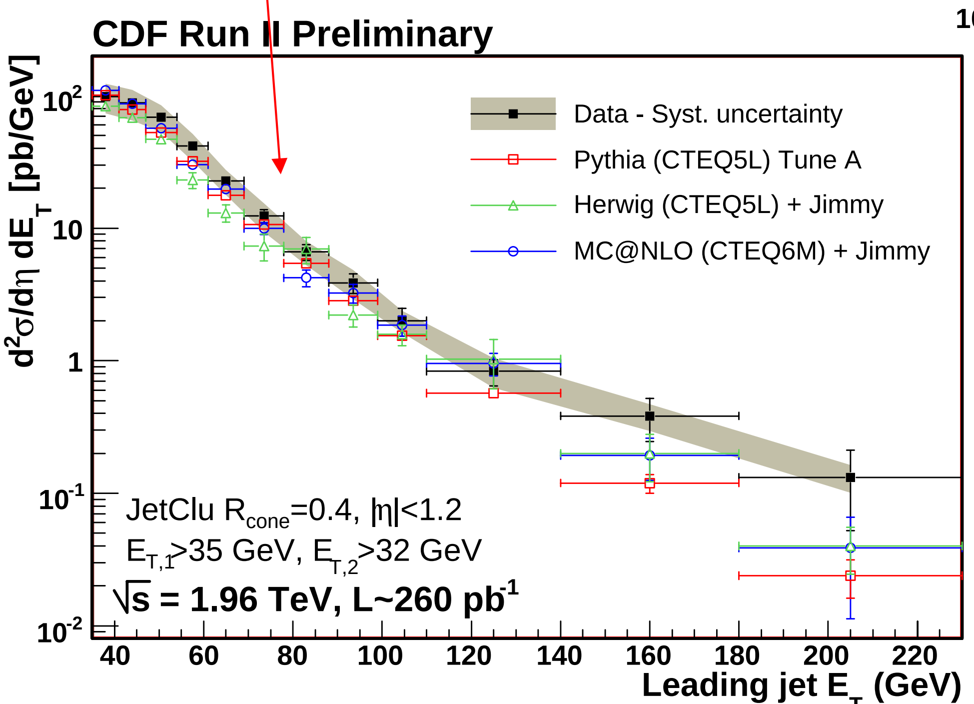
Results, for $\int Ldt = 260\, pb^{-1}$:

$$\sigma_{b\bar{b}} = \frac{N_{2SVT} f_{b\bar{b}}}{\varepsilon \Delta\eta \int Ldt} C$$

where C = unfolding factors

All the Monte Carlos show similar agreement with data distributions in leading jet E_T and dijet mass



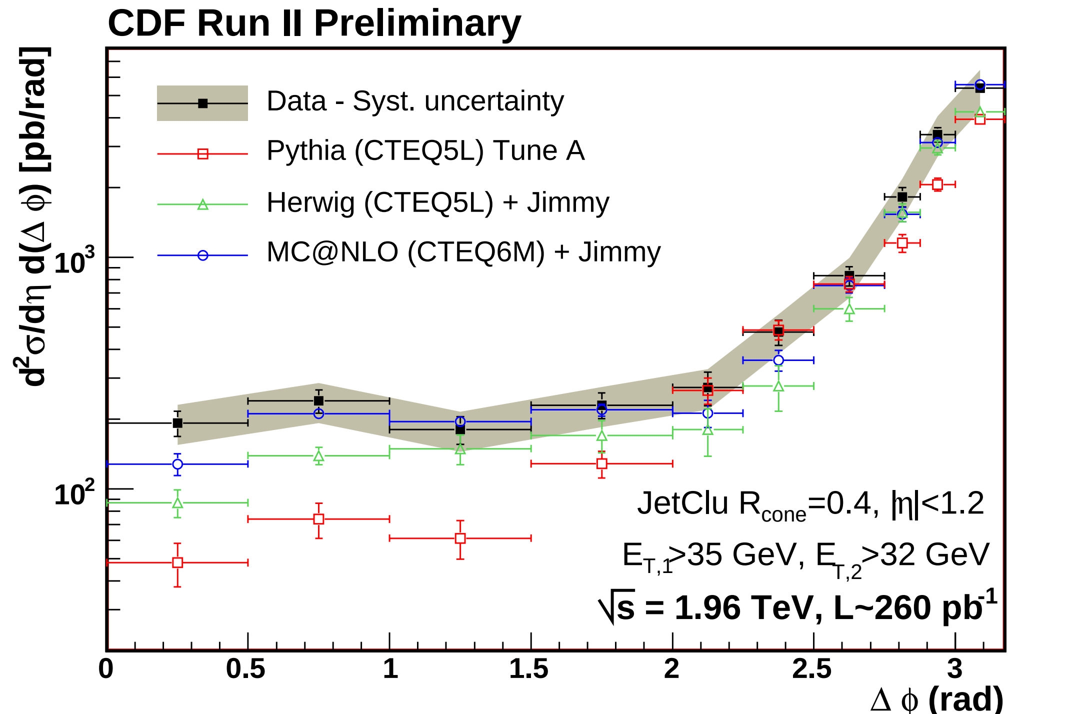


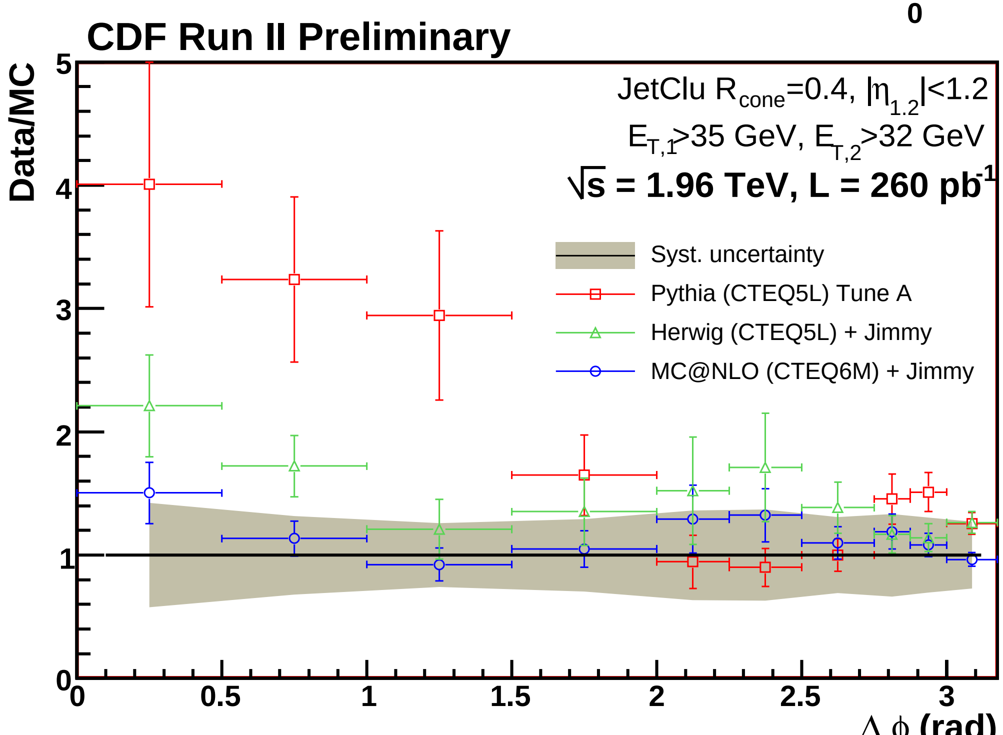
but…

Significantly better model of the Δφ data by MC@NLO.

Peak at large angles: LO flavor creation.

Excess at small angles: higher order diagrams and multiple interactions.





Measured total cross section for $|\eta_{12}| < 1.2$, $E_{T1} > 35$ GeV, $E_{T2} > 32$ GeV:

$\sigma = 5664 \pm 168 \pm 1270$ pb

Summary

Results are presented from 4 CDF analyses involving heavy quark production at the Tevatron.

- *b-jet shapes are broader than inclusive predictions, and broader than both PYTHIA and HERWIG defaults*---suggesting that LO underestimates the fraction of b's from gluon splitting and the fraction of jets with 2 b's.
- *A measurement of the production cross section for ψ(2S) is consistent with Run 1 with an order of magnitude more statistics and consistent with the theoretical prediction* for increase due to parton distribution function energy dependence.
- *Measured inclusive b-jet production is consistent with theory* over 6 orders of magnitude in jet p_T. The result is sensitive to scale choice μ suggesting that higher orders are non-negligible.
- *The $b\bar{b}$ differential production cross section as a function of azimuthal angle is much better described by MC@NLO + JIMMY* than by PYTHIA with Tune A or HERWIG.