QCD at the Tevatron

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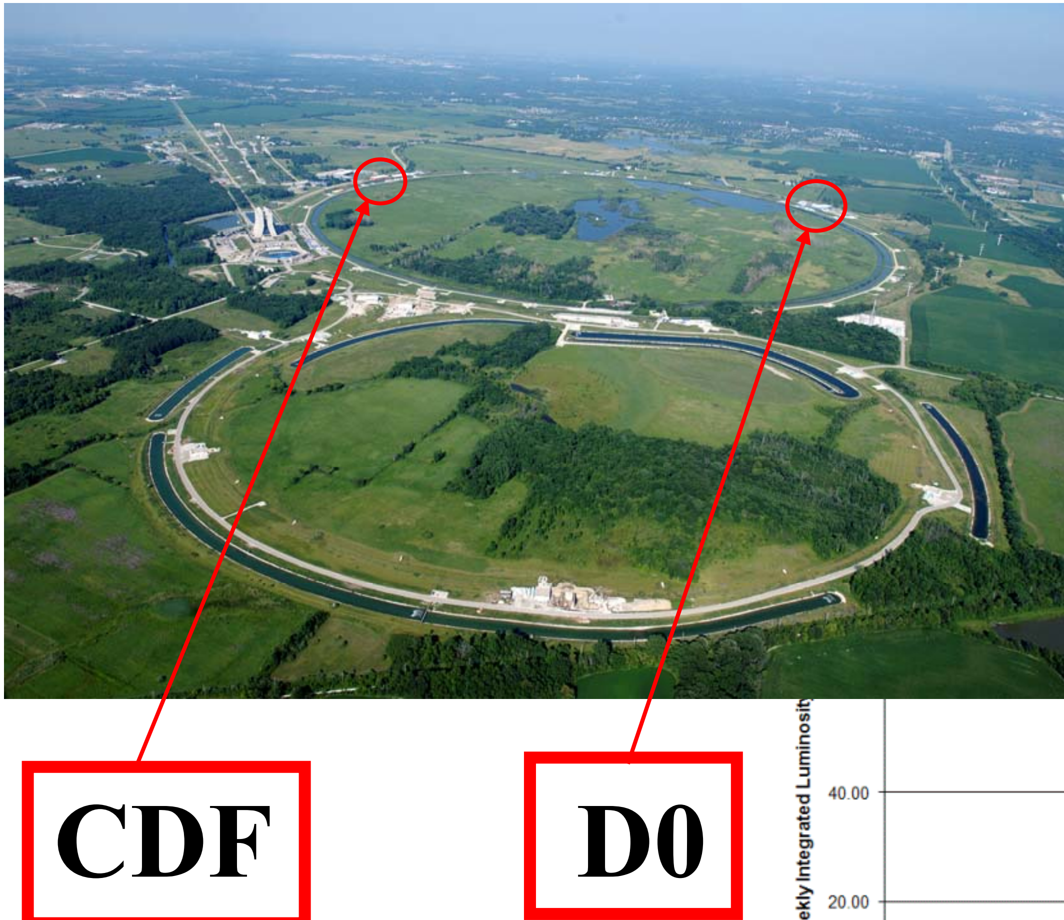
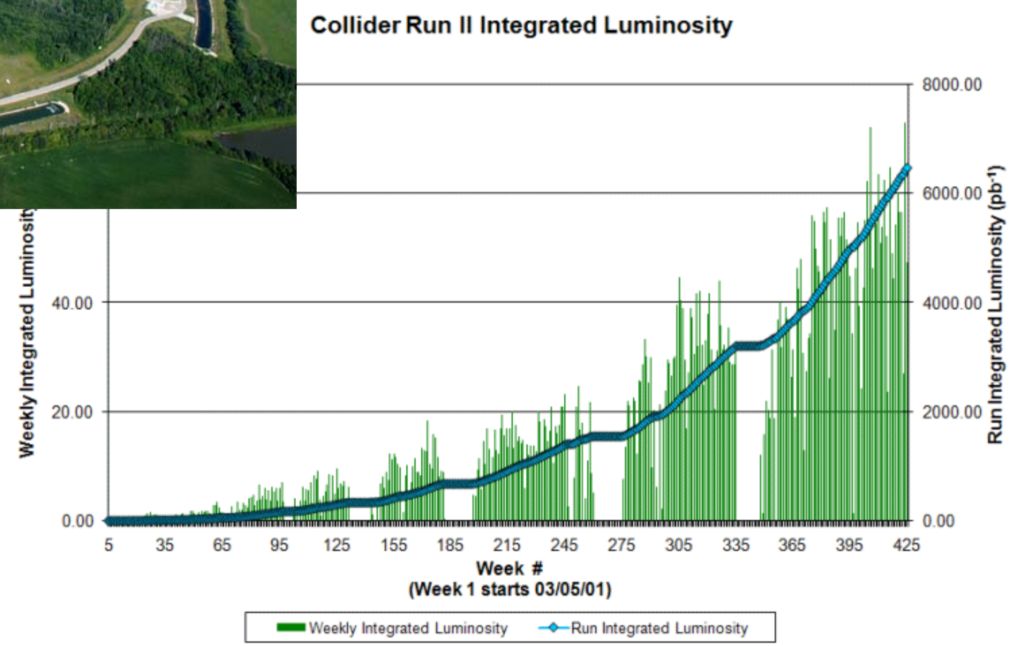
XXIèmes Rencontres de Blois
23 June 2009

The Tevatron proton-antiproton collider at Fermilab, with the Main Injector



- Center of mass energy 1.96 TeV.
- Over 6 fb^{-1} data collected. Results here use 1-3 fb^{-1}.



15 Studies by CDF and D0…in the past 12 months

- Inclusive jet cross section update (CDF, D0)
- Search for quark substructure in dijet angular distributions (CDF,D0)
- Search for new particles decaying to dijets (CDF, D0)
- Cross section for photon + jet (D0, CDF)
- Inclusive cross section for Z + jets (D0)
- Inclusive cross section for Z + jet (D0)
- Cross section for b-jet production in events with a Z boson (CDF)
- Cross section for b-jet production in events with a W boson (CDF)
- σ(W+c-jet)/σ(W+jets) (D0)
- Production cross sections for γ+b+X and γ+c+X (D0)
- The k_T distribution of particles in jets (CDF)

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. $\sigma(p_T)/p_T^2=0.0015\ (\mathrm{GeV}/c)^{-1}$.

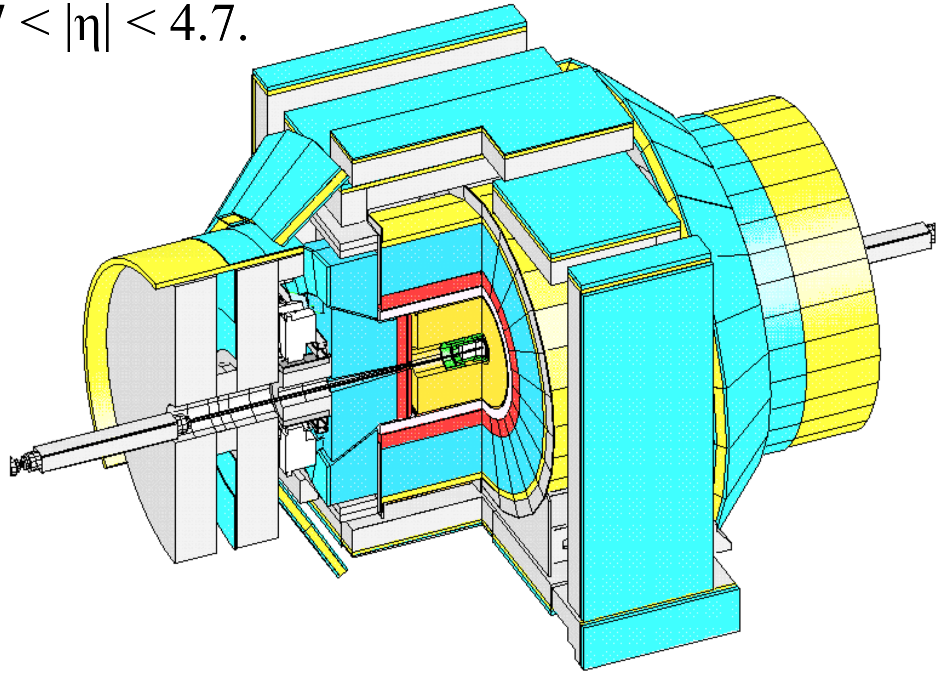
- scintillator + PMT *TOF*: 100 ps resolution. K/π separation ≥ 2σ for $p < 1.6$ GeV/c.

- 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 $3.7 < |\eta| < 4.7$.



The D0 Detector

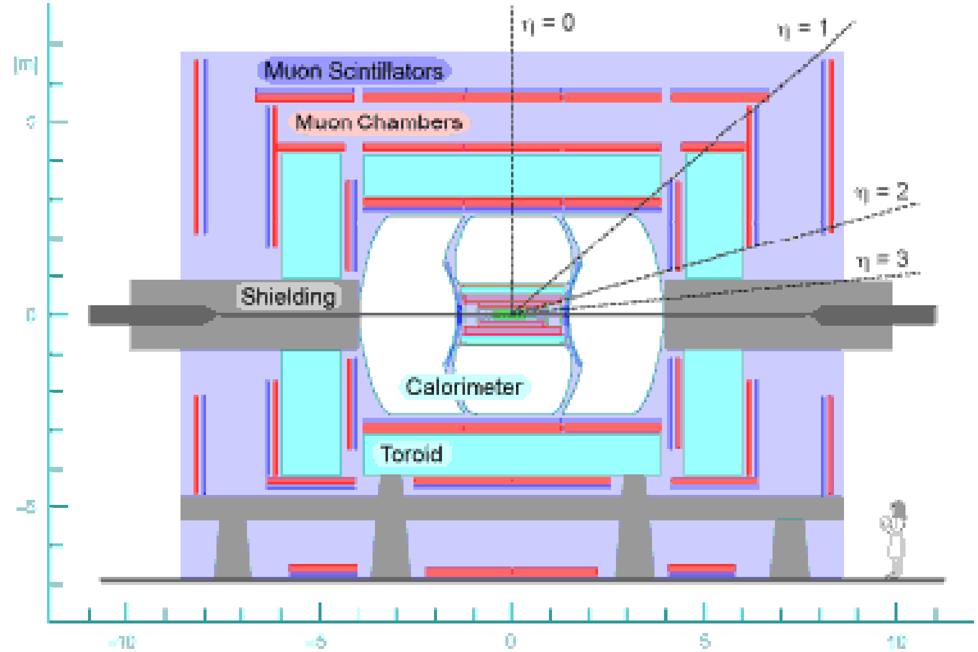
- *Central tracking:*

silicon microstrip tracker Barrels interspersed with disks from r = 2.7 to 10.5 cm.
central fiber tracker Doped polystyrene scintillating fibers on 8 concentric cylinders from r = 20 to 52 cm.

The combined tracking system resolves the primary vertex to within 35 microns in z. Impact parameter resolution 15 microns in r-φ.

- *solenoidal magnet* 1.42 m diameter x 2.73 m length for 2T.

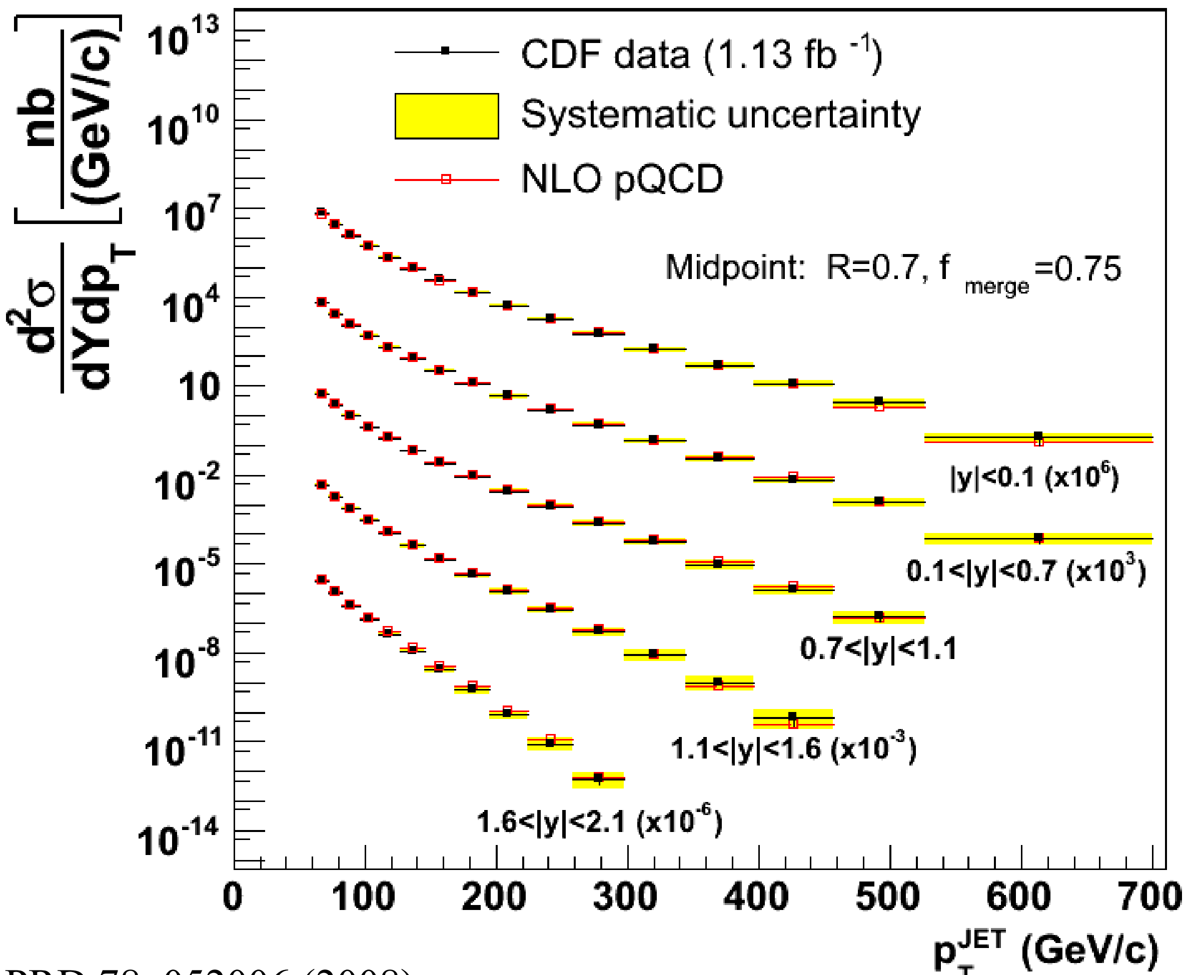
- *preshower detectors* Scintillator with wavelength shifting fiber upon $2X_0$ absorber over $1.1 < |\eta| < 1.4$.



- *calorimeters* LAr + U, Cu, or stainless cover 6 λ_A with $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$ over $|\eta| < 1.1$ and $1.5 < |\eta| < 4.2$.
- *muon system* Proportional drift tubes + toroidal magnets, and scintillation counters. Coverage to $|\eta| = 2.0$ with resolution ≈ 1mm.
- *luminosity monitor* Plastic scintillation counters with PMT readout over $2.7 < |\eta| < 4.4$.

Inclusive jet cross section using a midpoint cone algorithm

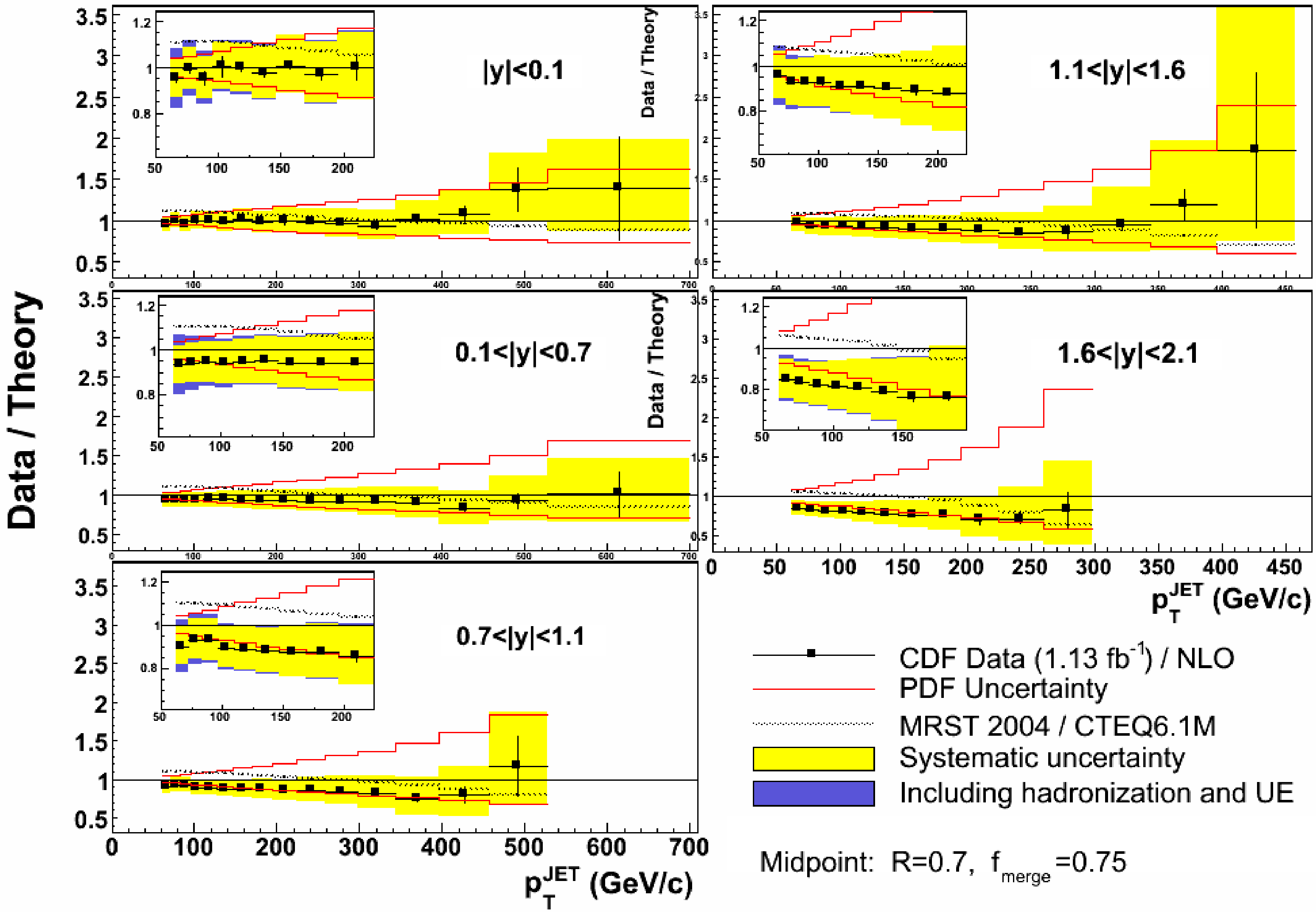
Probes the highest momentum transfers currently available; is sensitive to new physics including quark substructure; constrains the PDF of the antiproton.



PRD 78, 052006 (2008).

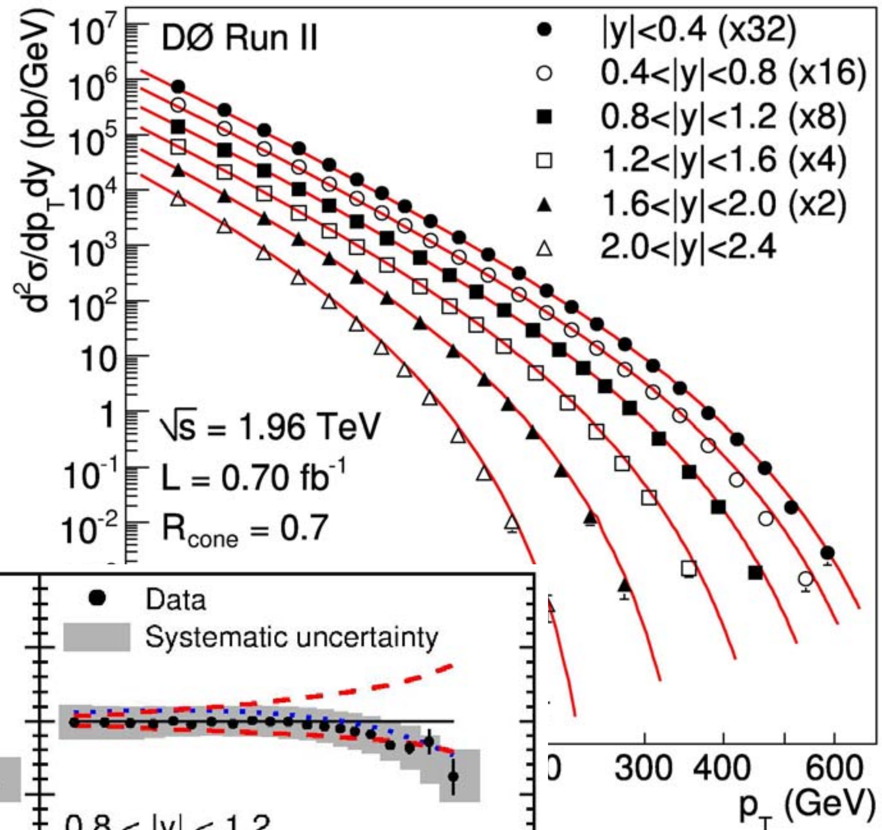
- Data slightly lower than theory but still consistent within systematics.
- Systematics on data in forward region < PDF uncertainties: high-x gluon constraint.
- Improved agreement with k_T clustered data.

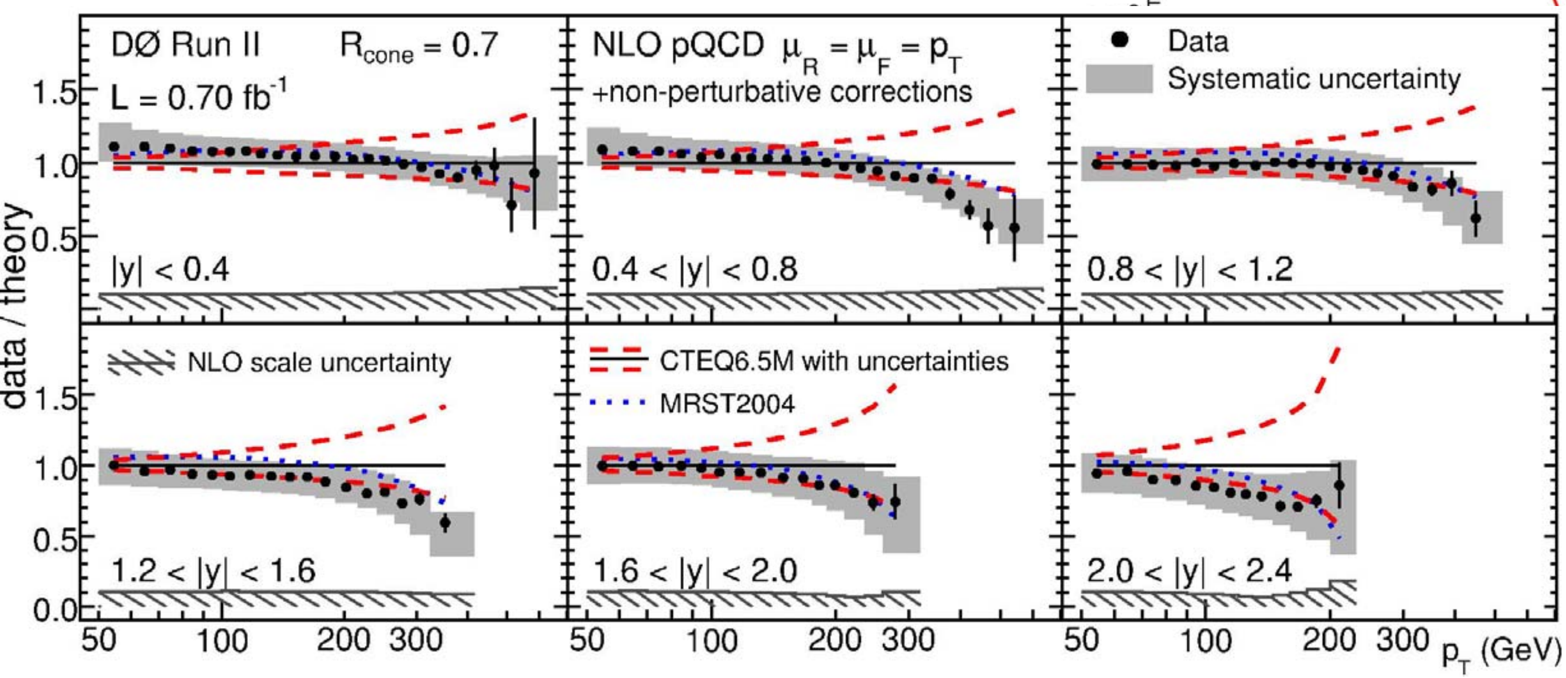
Inclusive jet cross section using a midpoint cone algorithm, continued



D0 inclusive jet cross section measurement

- NLO pQCD with MRST2004 or CTEQ6.5M agrees with data, favoring low edge of the CTEQ PDF uncertainty band and the shape of the MRST

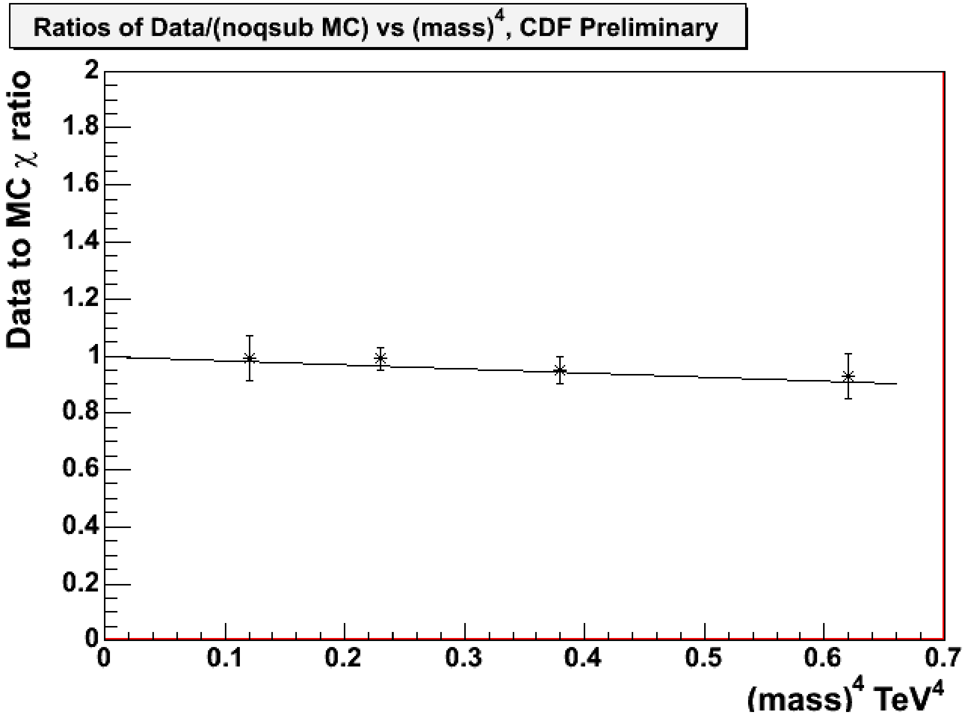




PRL 101: 062001 (2008)

Search for quark substructure in dijet angular distributions

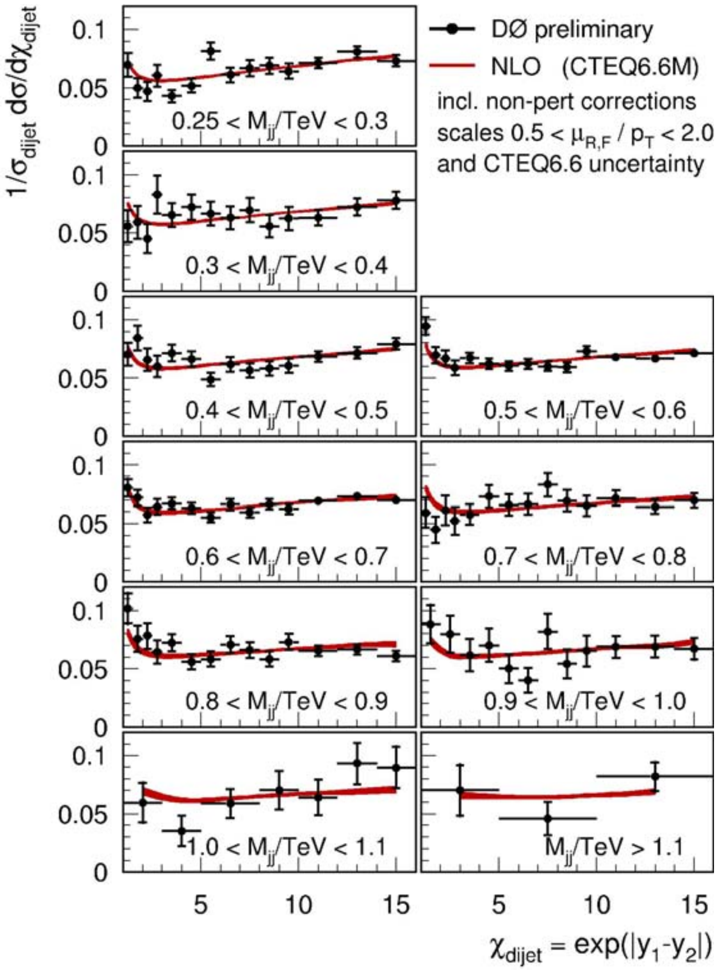
Substructure can enhance QCD cross section near 90^o in the diquark (dijet) center of mass---amplitude ~$\hat{s}/\Lambda^2$. Calculate ratio of # events in different angular ($\chi = \exp^{|\eta 1 - \eta 2|}$) regions and compare to PYTHIA as a function of dijet mass.



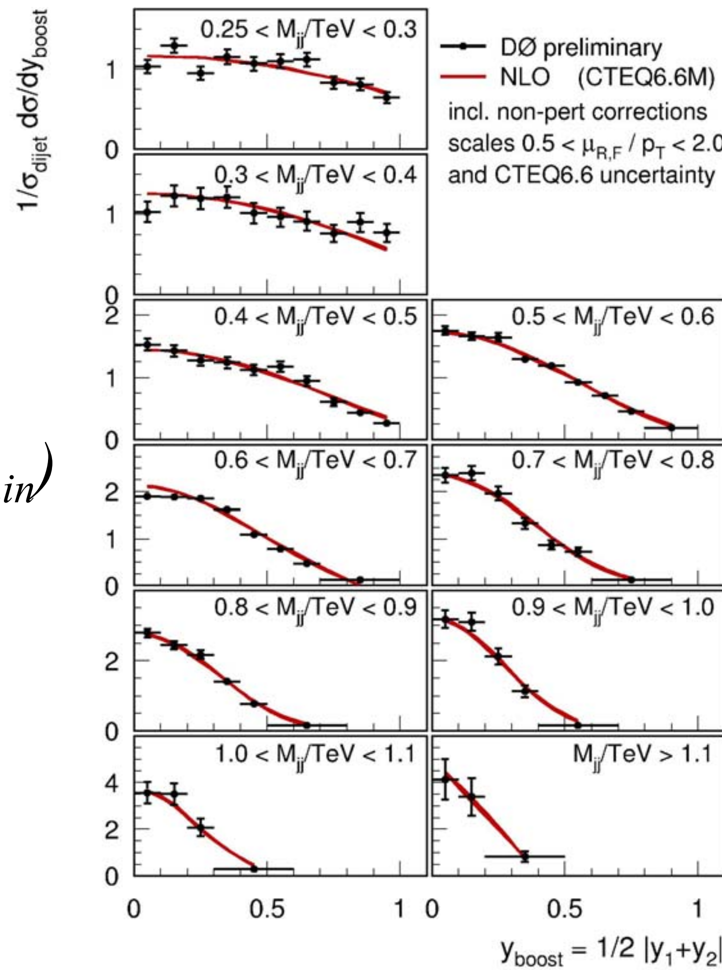
95% CL limit on contact interactions: $\Lambda > 2.4$ TeV

Principal systematics: scale Q^2 and jet energy corrections.

And comparable results from D0…their Search for quark substructure in dijet angular distributions:



For massless $2\rightarrow2$, y_{boost}= $1/2 \ln (x_{max}/x_{min})$ where x are parton momentum fractions.

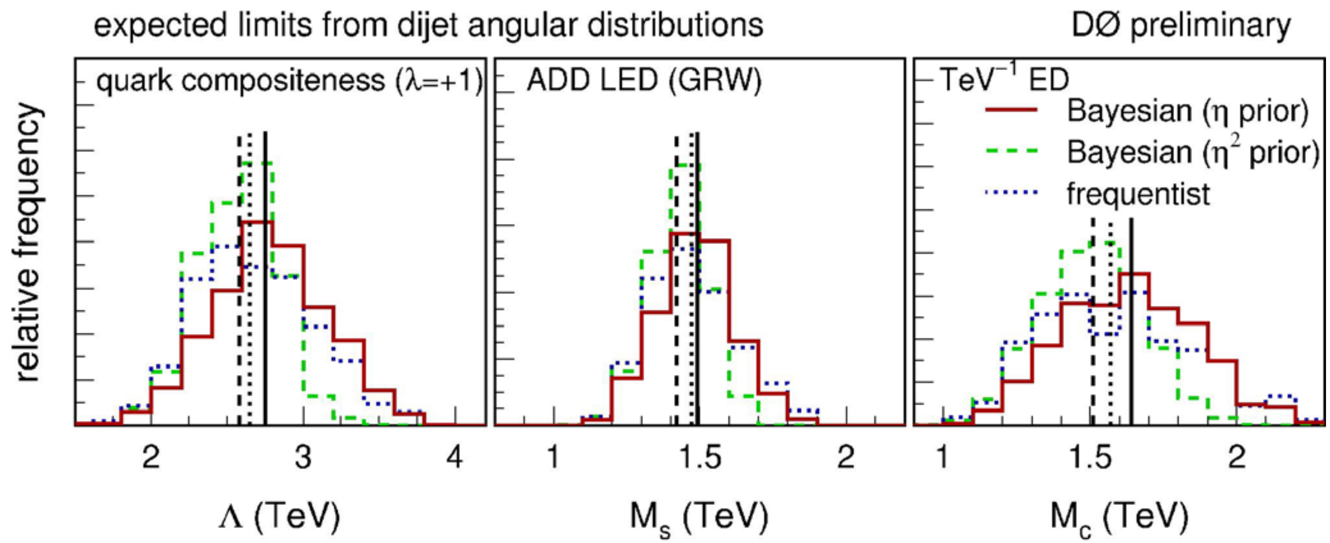


For massless $2\rightarrow2$, $\chi_{dijet} = (1+\cos\theta^*)/(1-\cos\theta^*)$ where θ^* = polar scattering angle in partonic c-o-m frame, flat for Rutherford scattering.

D0 Note 5733-CONF.

D0 Search for quark substructure in dijet angular distributions, continued

Limits, *independent of Higgs mass*, set using 3 consistent statistical approaches:



Example Bayesian limits:

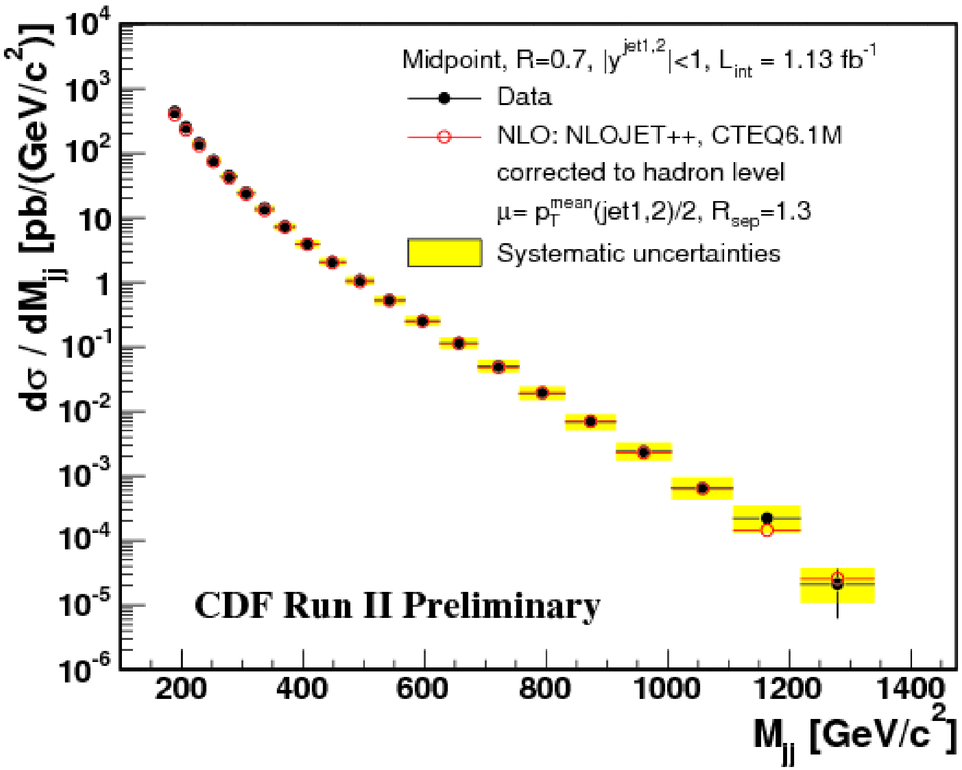
- $\Lambda > 2.58$ TeV (quark compositeness)
- $M_C > 1.42$ TeV (TeV^{-1} extra dimensions)**
- $M_S > 1.56$ TeV (Large Extra Dimensions)***

**N. Arkani-Hamed et al., Phys. Lett. B 429, 263 (1998); D. Atwood et al., PRD 62, 056008 (2000).

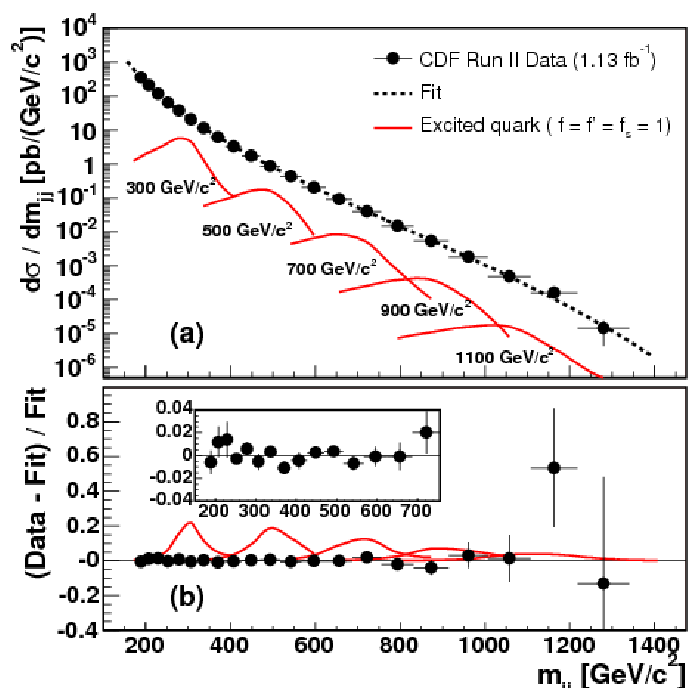
***K.R. Dienes et al., Nucl. Phys. B 537, 47 (1999); A. Pomarol et al., Phys. Lett. B 438, 255 (1998); K. Cheung et al., PRD 65, 076003 (2002).

Search for new particles decaying to dijets

Many extensions of the Standard Model (motivated by the generational structure and mass hierarchy) predict resonances in the dijet mass spectrum.



Compare data to predicted signal shapes, e.g. excited quark:



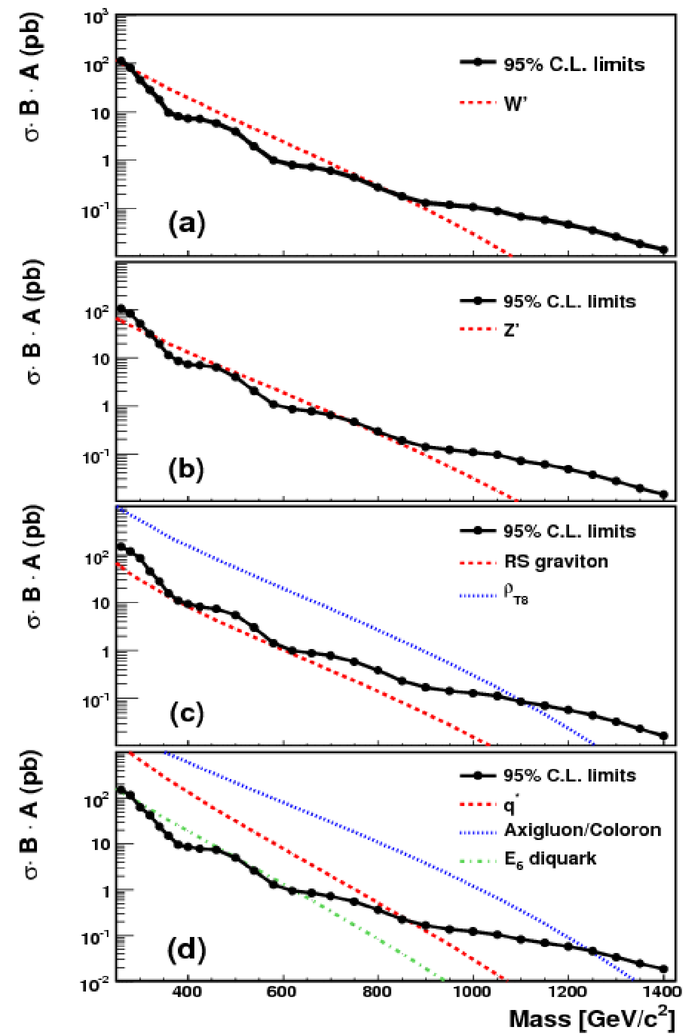
arXiv:0812.4036 [hep-ex], Dec 2008.

Search for new particles decaying to dijets, continued

Results: the most stringent lower mass limits available on excited quark[1], axigluon[2], flavor-universal coloron[3], E_6 diquark[4], and color-octet techni-ρ[5].

Excluded mass limits (GeV):

q*	260-870
axigluon, coloron	260-1250
E_6 diquark	290-630
ρ_{T8}	260-1100
W'[6]	280-840
Z'[6]	320-740

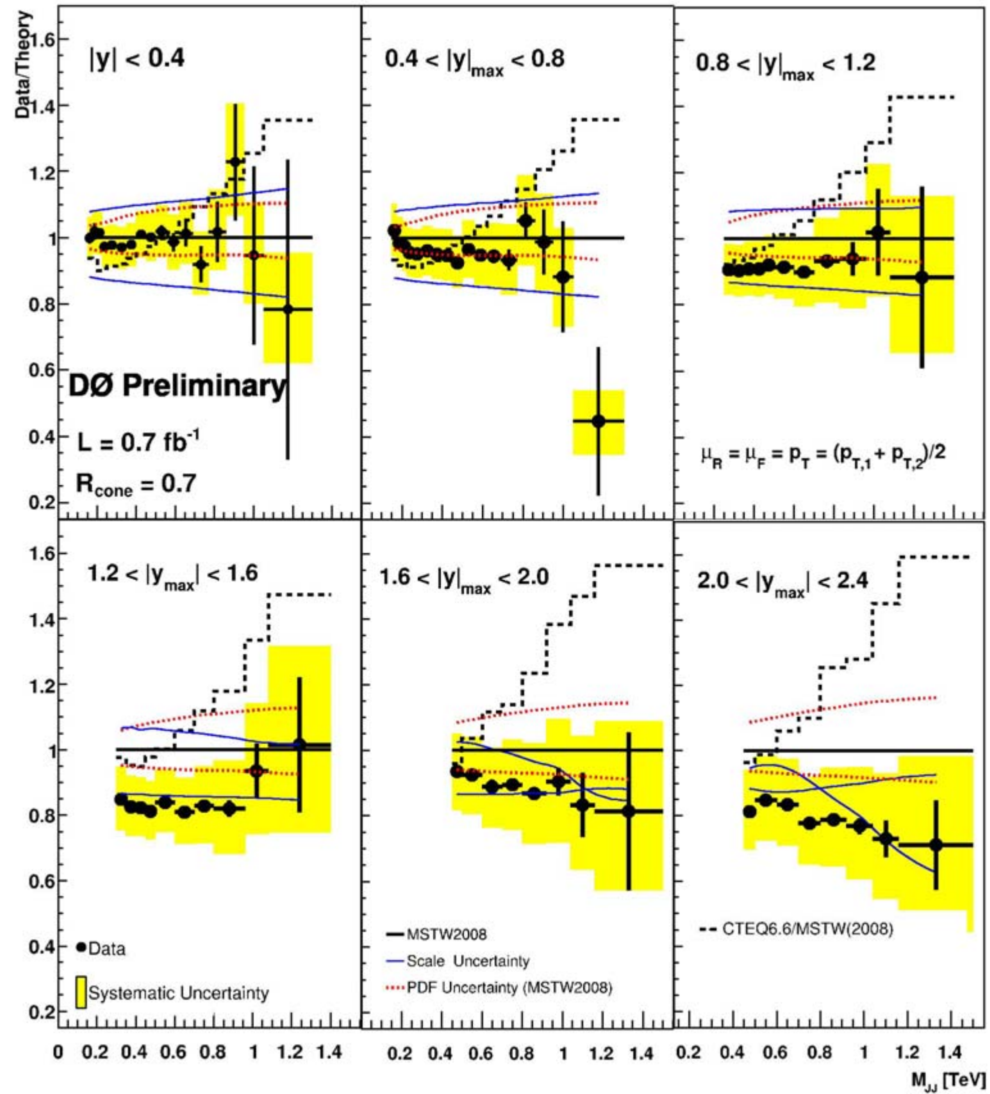


[1] PRD 42, 815 (1990).
[2] Phys. Lett. B 190, 157 (1987); PRD 37, 1188 (1988).
[3] Phys. Lett. B 380, 92 (1996); PRD 55, 1678 (1997).
[4] Phys. Rept. 183, 193 (1989).
[5] PRD 44, 2678 (1991); PRD 67, 115011 (2003).
[6] Rev. Mod. Phys. 56, 579 (1984); Rev. Mod. Phys. 58, 1065 (1986).

The Dijet Mass Cross Section

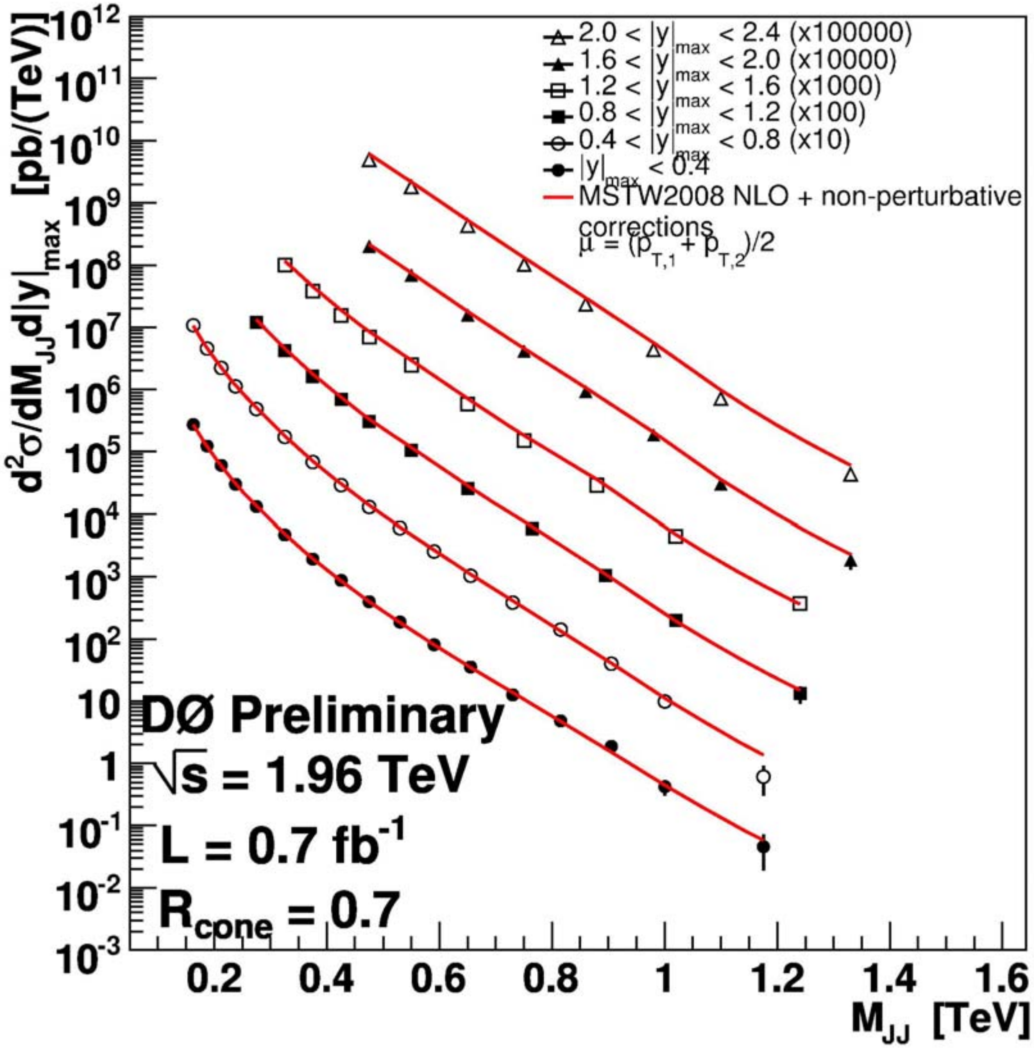
Like the inclusive jet cross section, the dijet mass cross section is sensitive to new physics and can constrain the PDF's.

- |y| up to 2.4 (previously 1.1)
- comparative study of MSTW vs. CTEQ6.6 PDF's: up to 40-60% variation in the cross section at highest M_{jj}.
- MSTW favored.
- measurement systematic ~PDF uncertainty: constraints on future predictions.



D0 Note-5919-CONF

The Dijet Mass Cross Section, continued



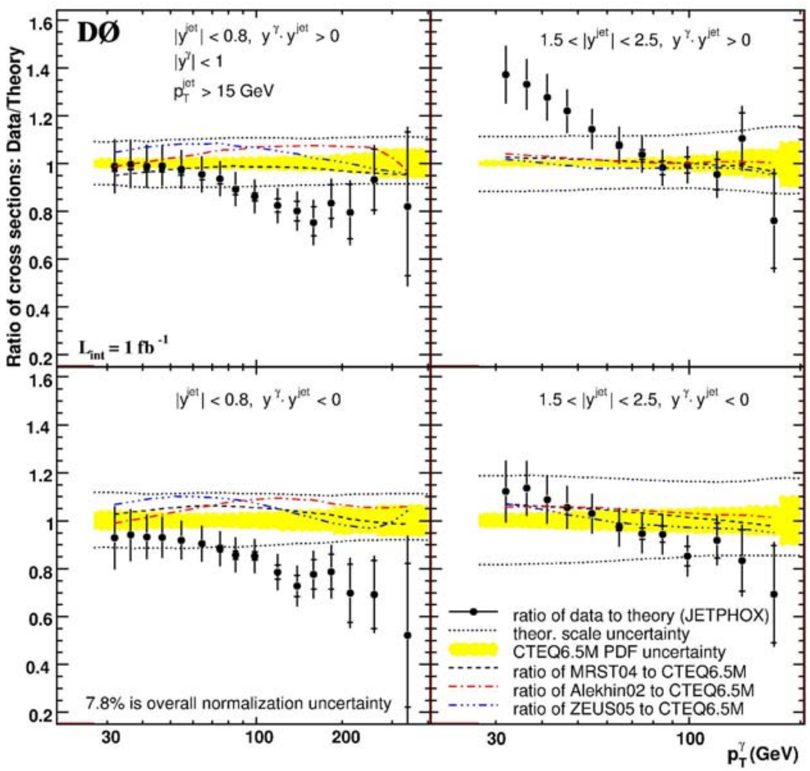
Differential cross section for production of an isolated photon with associated jet

This probes the gluon distribution, and generally the dynamics of hard QCD interactions, over a range of x and Q^2 through $qg \rightarrow q\gamma$ and $q\bar{q} \rightarrow g\gamma$.

leading jet central **leading jet forward**

$y^{\gamma} \cdot y^{jet} > 0$

$y^{\gamma} \cdot y^{jet} < 0$

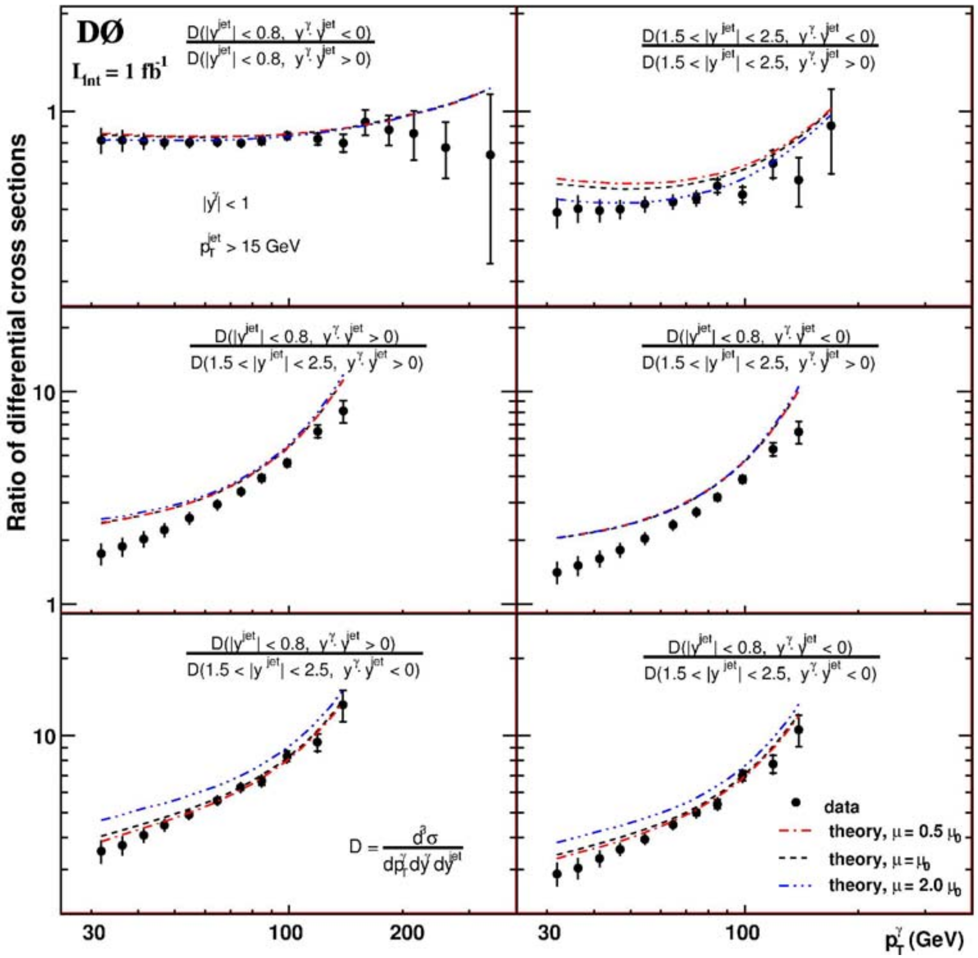


- Explores $0.007 \leq x \leq 0.8$ and $900 \leq Q^2$, i.e. $(p_T^{\gamma})^2 \leq 1.6 \times 10^5\ GeV^2$.
- NLO QCD predictions do not describe shape over full range in p_T^{γ}.
- Scale variations cannot describe normalization simultaneously for 4 rapidity ranges.

Phys. Lett. B 666, 435 (Aug. 2008).

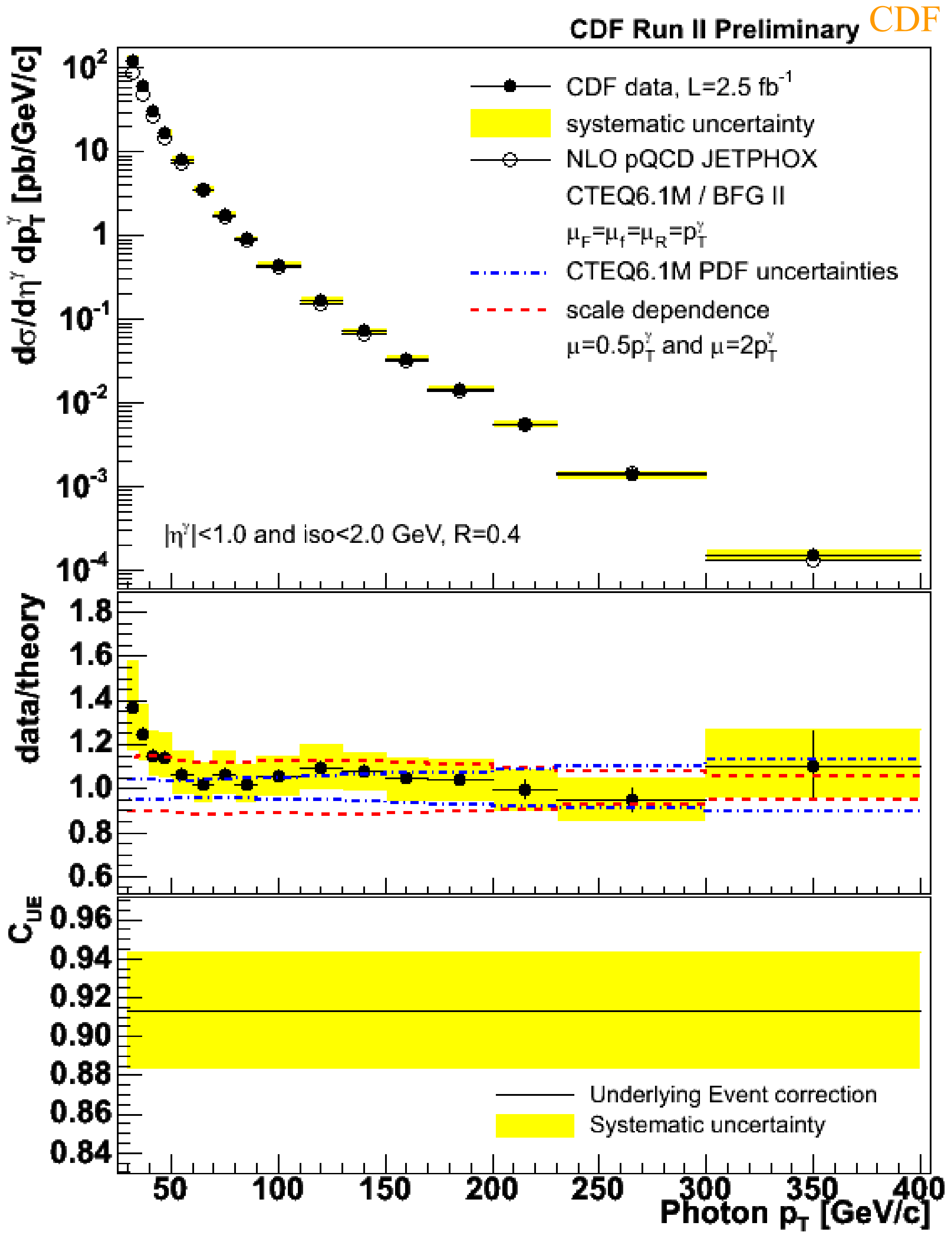
Differential cross section for production of an isolated photon with associated jet, continued

- Measurement of differential cross section reduces uncertainties by cancellations, but disagreement persists.
- Theoretical uncertainties:
  - threshold resummation ~3%
  - scales: 3%



Compare the CDF result on the inclusive isolated prompt photon production cross section…

Correcting the signal to the hadron level, and comparing to NLO pQCD (JETPHOX) with CTEQ6 and non-perturbative corrections… agreement between data and theory.

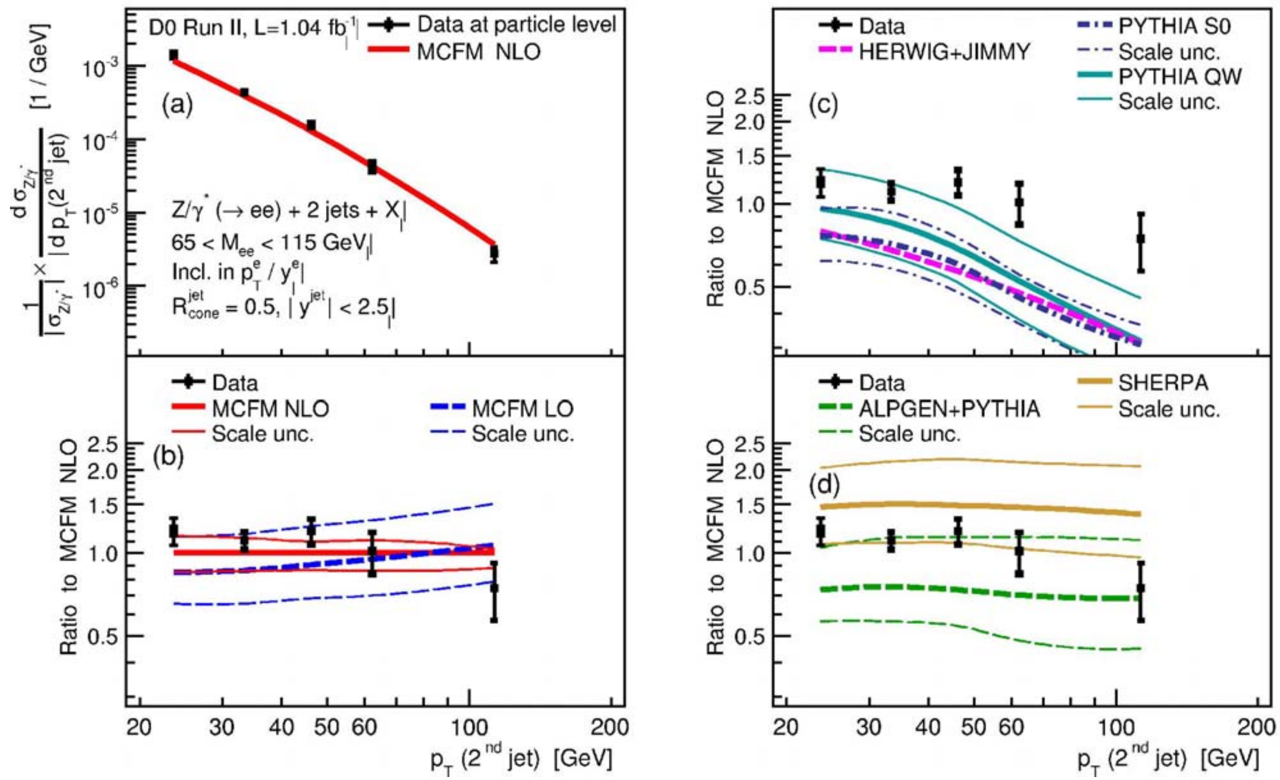


Inclusive cross section for $Z/\gamma^*(\rightarrow e^+e^-)$ + jets

Test NLO pQCD and control background for new physics.

- Events are binned in the p_T of the N^{th} jet. Data agree well with NLO-MCFM but diverge from PYTHIA, HERWIG increasingly with p_T^{jet} and #jets.

- p_T-ordered PYTHIA describes leading jet well.



- SHERPA, ALPGEN improve upon particle shower-based generators. Some discrepancies remaining in production rates, p_T^{jet} spectra.

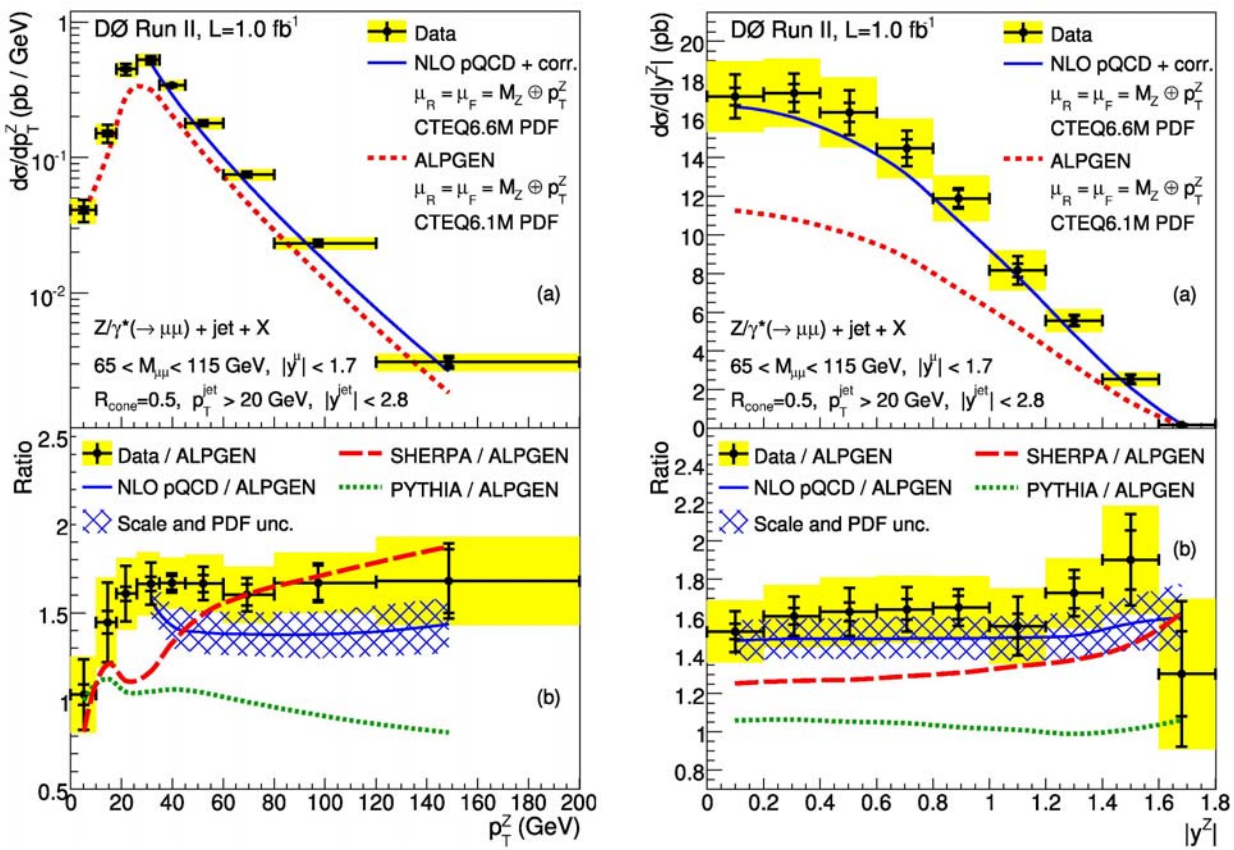
hep-ex/0903.1748 (Mar. 2009)

Inclusive cross section for Z + jet

Tests pQCD at the scale of M_Z and is the main background to many mechanisms with smaller cross sections for Higgs, top, and SUSY production.

- $\sigma(Z/\gamma^*(\rightarrow\mu\mu)+jet+X)=18.7\pm0.2(stat)\pm0.8(syst)\pm0.9(muon)\pm1.1(lumi)$ pb

- within 5% of prediction by pQCD MCFM; above PYTHIA, ALPGEN.
- These are the first measurements differential in Z p_T, η.
- Shapes best described by pQCD, ALPGEN.



Phys. Lett. B 669, 278 (2008)

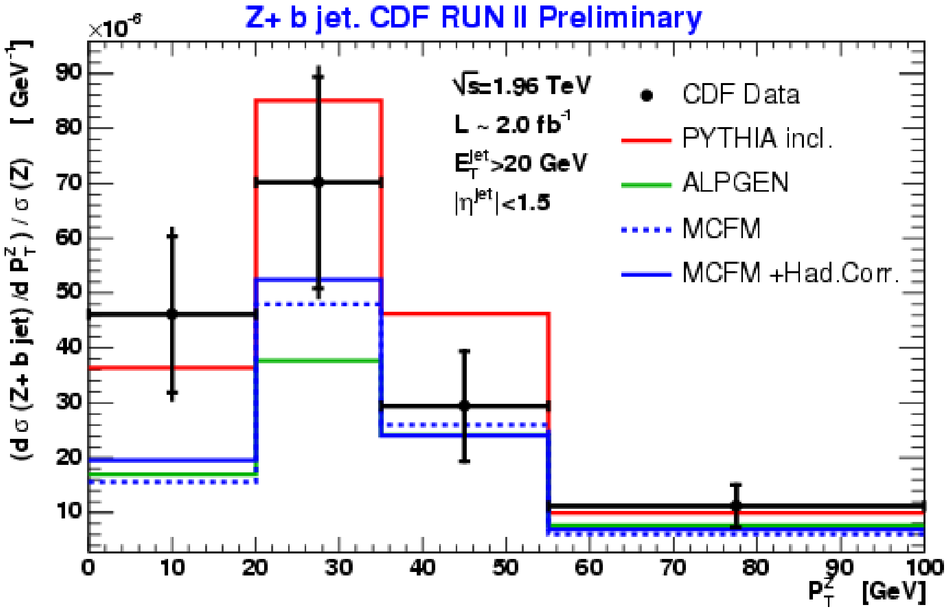
Cross section for b-jet production in events with a Z

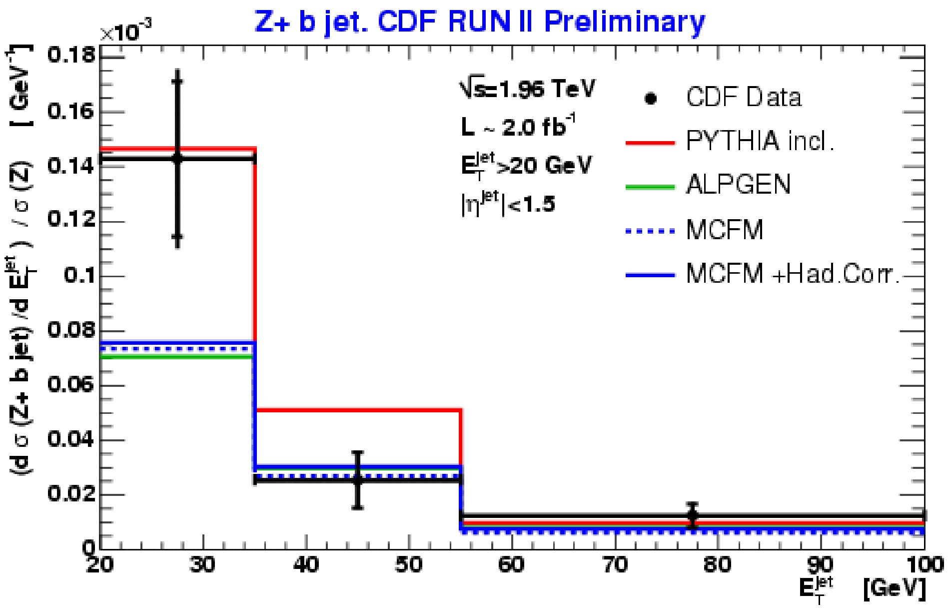
CDF

gb→Zb and qq→Zb$\bar{b}$ are the largest background to the search for SM Higgs through ZH→Zb$\bar{b}$ and to searches for sbottom. Also the cross section is sensitive to the b content of the proton. Measure σ^{jet}(Z+bjet)/σ(Z) and σ^{event}(Z+bjet)/σ(Z) and differentially versus jet and Z kinematical variables η, E_T, p_T, #jets, #b-jets.

- $\sigma_{jet}/\sigma = (3.32 \pm 0.53 \pm 0.42) \times 10^{-3}$

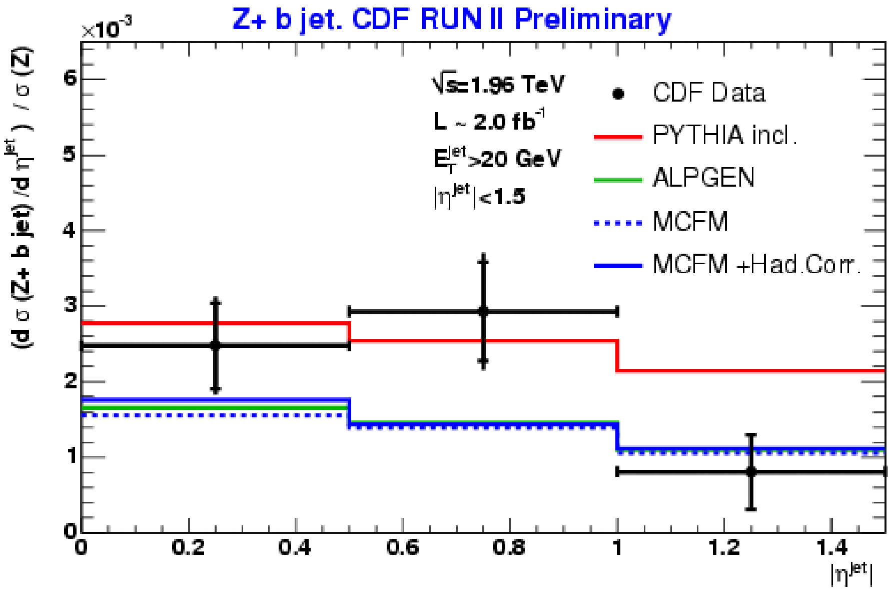
arXiv:0812.4458 [hep-ex], Dec 2008.

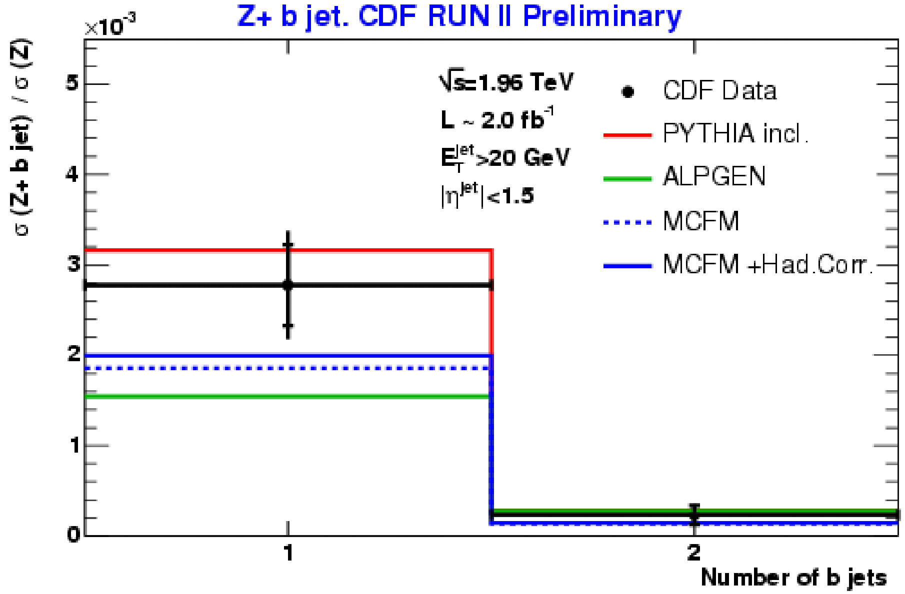


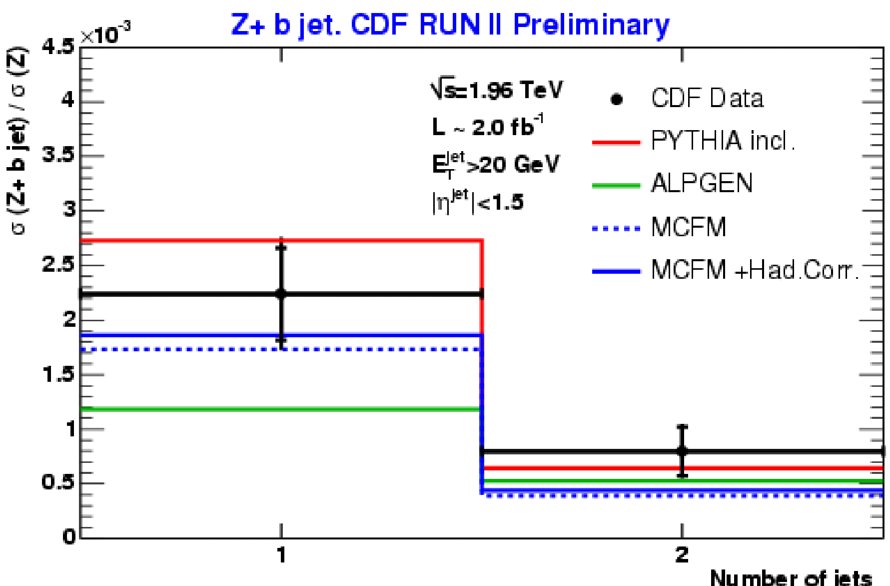


Cross section for b-jet production in events with a Z, continued

CDF







arXiv:0812.4458 [hep-ex], Dec 2008.

- Data and theory generally agree, but scale-dependent differences up to 2σ: higher orders important.
- 20% lower uncertainty than earlier.
- best agreement for low scale factors.

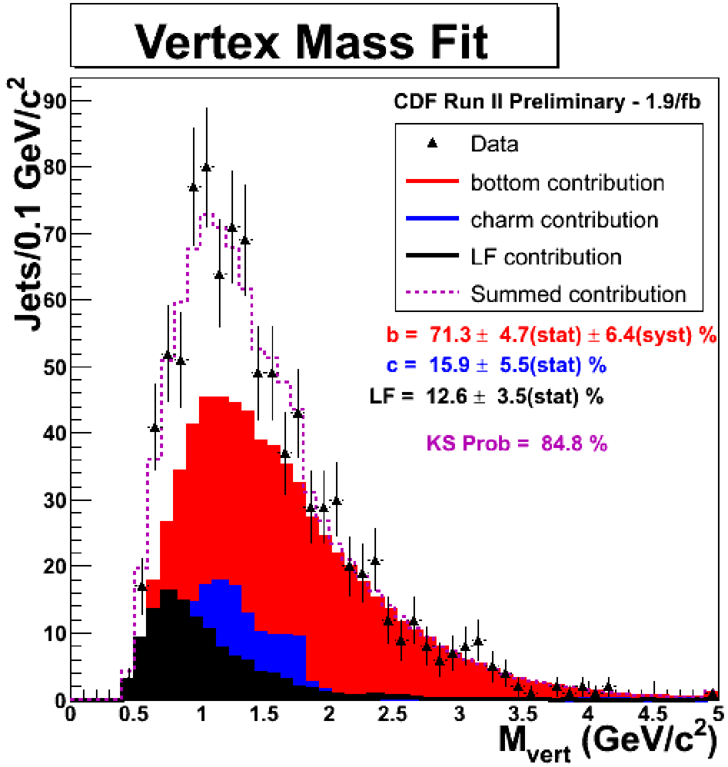
Cross section for b-jet production in events with a W

CDF

This is a search channel for Higgs through $p\bar{p} \rightarrow W(\rightarrow e\nu)H(\rightarrow b\bar{b})$, *and for new physics,* and a platform for measurements of top through* $t \rightarrow Wb$.

Tag the jet as originating from a *b* through displaced secondary vertex. Remove light quark contaminants by a max likelihood fit to the invariant mass of charged tracks associated with the vertex.

Result: σ(b-jets) x BR(W→eν) = 2.74 ± 0.27 ± 0.42 pb.
Available fixed-order predictions ALPGEN and PYTHIA are 2.5 – 3 times lower. A NLO calculation** is in preparation.

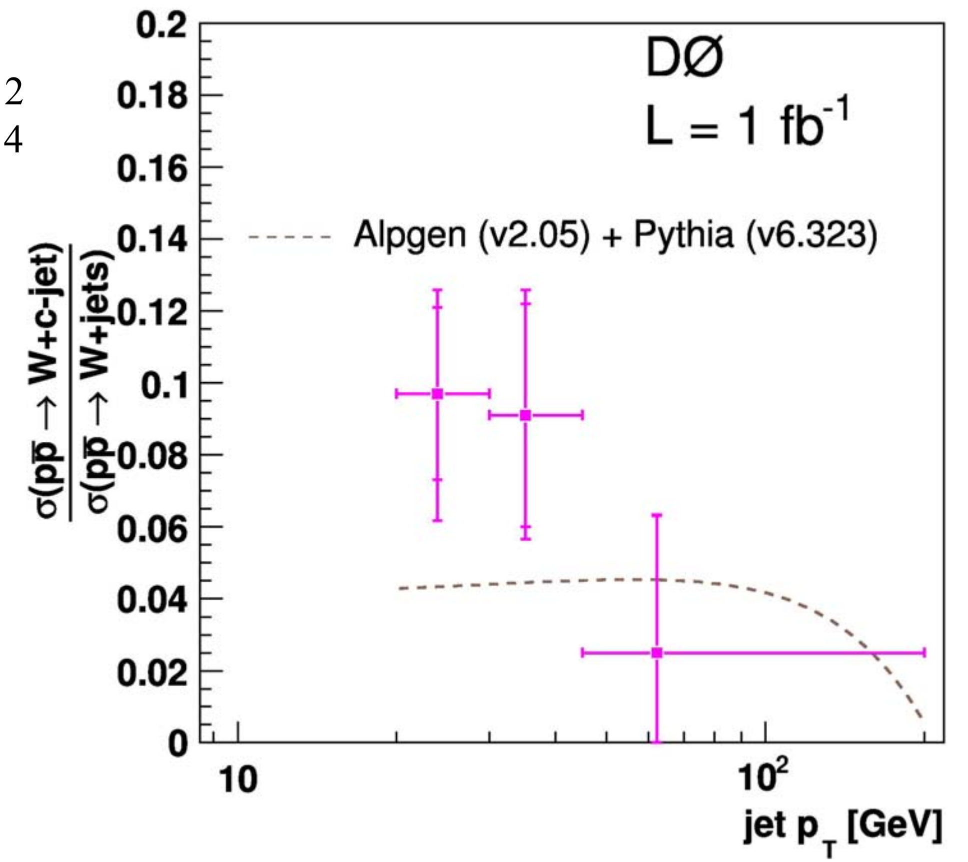


*H.S. Goh and S. Su, PRD 75: 075010 (2007).
**J. Campbell et al., arXiv:0809.3003 (2008).

Ratio of cross sections: $p\bar{p} \to W + c\text{-jet}$ to $p\bar{p} \to W + \text{jet}$

Potential signal for new physics; probe of the s-quark PDF, background to Higgs, stop, and top studies.

$$\frac{\sigma[W + c\text{-jet}]}{\sigma[W + \text{jets}]} = 0.074 \pm 0.019^{+0.012}_{-0.014}$$



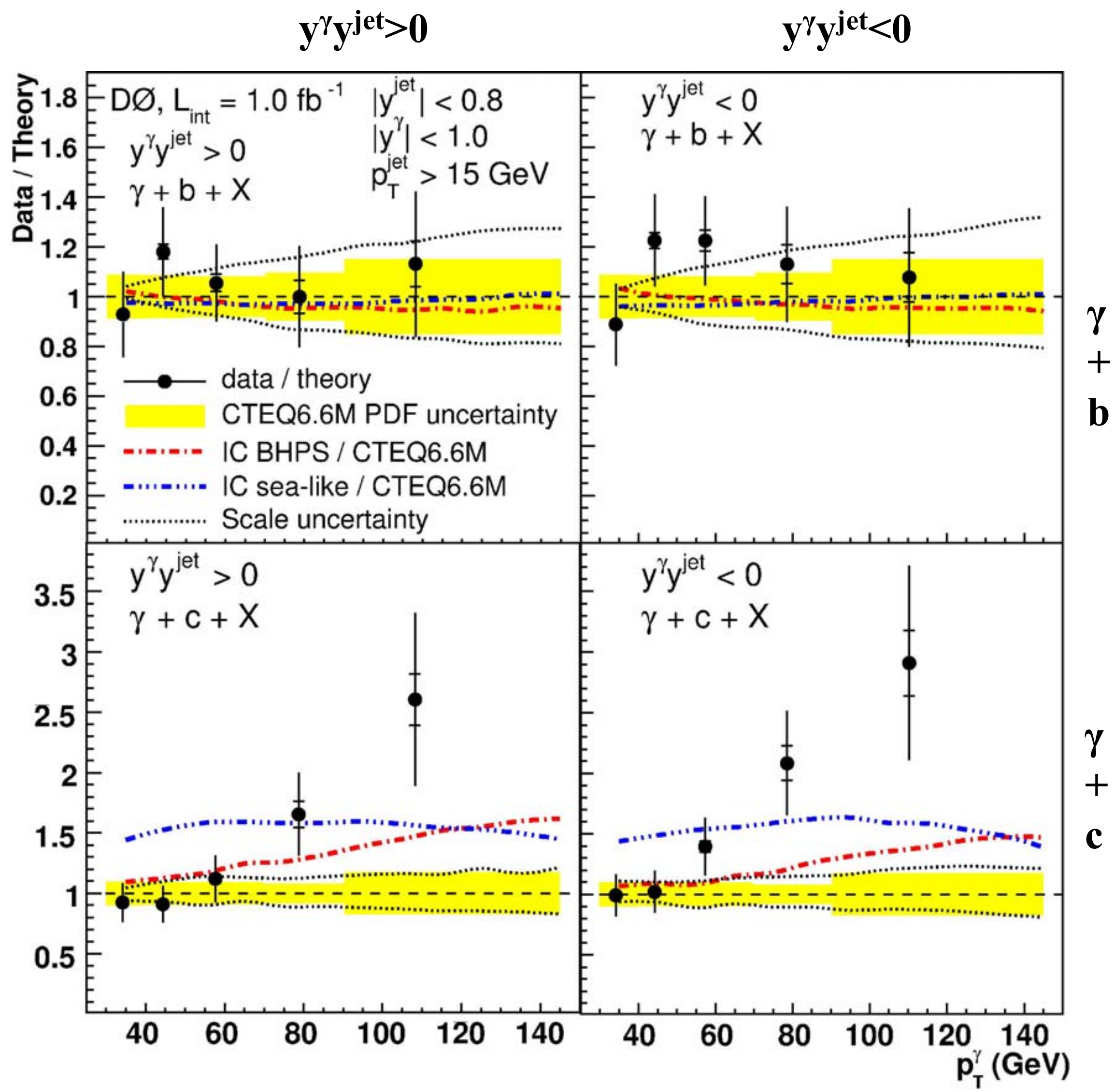
The measurement is consistent with LO pQCD and with an *s*-PDF evolved from Q^2 scales 2 orders lower. This is direct evidence of the process $qg \to Wq'$.

Phys. Lett. B 666, 23, July 2008.

Production cross sections for γ + b + X and γ + c + X

D0

- *This first measurement of $d^3\sigma/dp_T^\gamma dy^\gamma dy^{jet}$ probes b, c, and g PDFs through $gQ\to\gamma Q$.*
- *$0.01 \leq x \leq 0.3$, $900 \leq Q^2$, i.e., $(p_T^\gamma)^2 \leq 2 \times 10^4$ GeV^2.*



Good agreement over full range for b-quark. For the c-quark, disagreement with theory for $p_T^\gamma > 70$ GeV. Underestimation of $g\to q\bar{q}$?

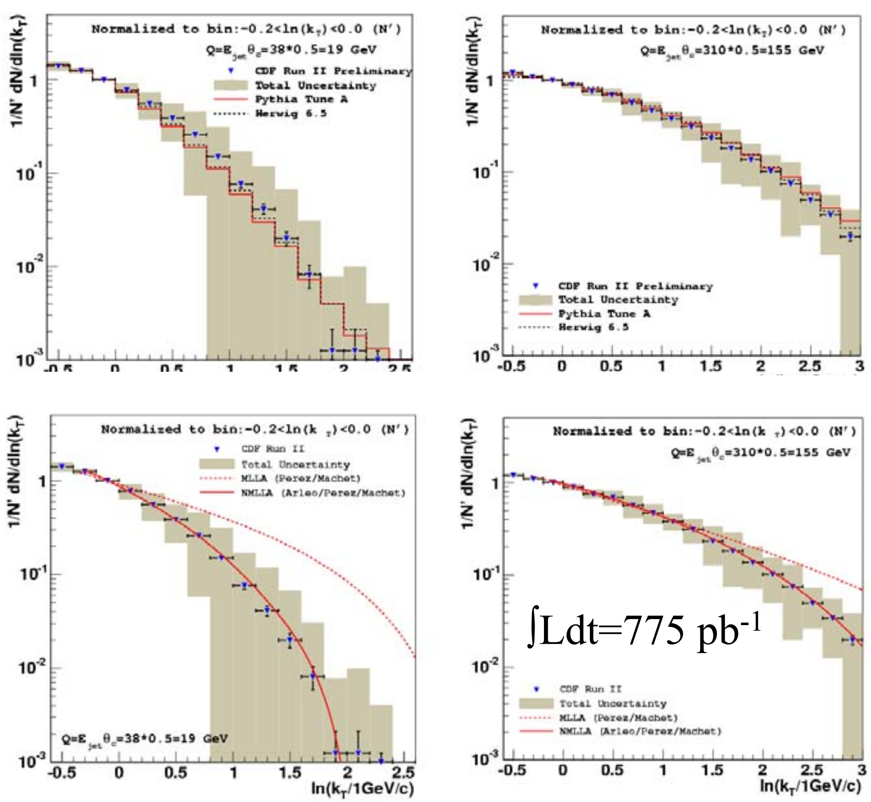
hep-ex/0901.0739 (Jan. 2009)

The k_T distribution of particles in jets

The goal: to discover which stage of jet formation is most significant in determining the characteristics of jets. Measuring the transverse momenta of particles within a jet, with respect to the jet axis, as a function of jet energy, tests the applicability of pQCD to jet fragmentation and probes the boundary with hadronization.

vs. Pythia and Herwig:

vs. MLLA and NMLLA:



Conclusion: parton shower dominates, hadronization effects are small, LPHD is supported; NMLLA describes data well over dijet mass range 66-737 GeV

arXiv:0811.2820 [hep-ex], Nov. 2008

Summary

Results are presented from 15 CDF + D0 analyses involving QCD processes at the Tevatron.

- *New inclusive jet cross sections constrain PDFs, change the Higgs cross section predictions for Tevatron and LHC.*

- *No evidence for quark substructure found in dijet angular distributions; new limits on Λ, M_C, M_S.*

- *CDF dijet mass spectrum provides new most stringent lower limits set on excited quark, axigluon, flavor-universal coloron, E6 diquark, and color-octet techni-ρ; D0 dijet mass cross section favors MSTW, constrains gluon PDF.*

- *D0 differential cross section for isolated γ + jet does not agree with NLO QCD through full range $30 < p_T^{\gamma} < 400$ GeV and rapidity y up to 2.5; CDF inclusive cross section agrees with theory.*

Summary, continued

- *Cross section for Z+b-jet agrees with theory, with improved precision, but sensitive to scale.*

- *Cross section for W+b-jet challenges LO calculations and opens a search channel for Higgs and other new physics.*

- *σ[W+c-jet]/σ[W+jets] is consistent with LO pQCD, provides a complementary measurement of the s-PDF, and offers direct evidence for qg→Wq'.*

- *New inclusive cross section for Z+jets agrees best with MCFM, challenges PYTHIA, HERWIG, SHERPA, ALPGEN; important control for background to new physics.*

- *First measurement available of inclusive cross section for Z + jet differential in Z* p_T *and* η*. This significant SM background for several Higgs and SUSY channels is within 5% of pQCD MCFM prediction.*

Summary, continued

- *First measurement of production cross sections for γ+b+X and γ+c+X probes c, g, and b PDF's: c-quark channel disagrees with theory increasingly above p_T^γ=70 GeV.*
- *The k_T distribution of particles in jets indicates that parton shower dominates jet formation, with hadronization effects small. Local Parton Hadron Duality is supported. Next-to-modified leading log approximation works for 66 < m_{jj} < 737 GeV.*

Backup slides
for technical
details

Dijet angular distribution

- Compare PYTHIA+CDFSim with substructure turned ON to same with substructure OFF.
- Substructure enhances QCD x-section near 90º in the diquark (dijet) COM. Amplitude goes as $\hat{s}/\Lambda^2$
- Trigger L1 (single tower E_T>10 GeV), L2 (cluster E_T> 90 GeV), L3 (jet E_T> 100 GeV) using nominal origin of detector
- Jet cone radius 0.7
- Energy corrections for η, mult int, fragmentation, UE, out of cone
- Require missing-E_T signif < 5, $|Z_{vtx}|$< 60 cm
- $\chi = e^{|\eta_1 - \eta_2|}$
- $M^2 = 2 \times E_{T1} \times E_{T2} (\cosh(\eta_1 - \eta_2) - \cos(\varphi_1 - \varphi_2))$
- $Q^2=\hat{s}$ and p_T^2 give different angular dist
- Calc R=#events(1<χ<5)/#events(15<χ<25) for each mass. Calc R(Λ)/R(∞), plot it vs mass^4, calc slope. Plot slope vs. $(1/\Lambda)^4$. Fit to quadratic. Quadratic parameter converts to measured Λ.
- Fitted slope = -0.16 ± 0.08, unphysical. Generate pseudo-experiments for Feldman and Cousins method. For slope < 0.25%, Λ > 2.4 TeV @ 95% CL.
- Systematics: (pdfs: neglible effect as valence quarks well known), Q^2, jet energy corrections (3%)

Search for new particles decaying to dijets

- Midpoint algorithm, cone radius = 0.7
- Jet p_T>0.1 GeV
- Requirement on missing E_T significance < min(3 + 0.0125 x p_T^{jet1}, 6)
- Correct for pileup (0.97 GeV per extra PV), calorimeter non-linearity
- Bin width = 10% of dijet mass resolution
- $|y|<1$
- Use trigger at energy for which it is > 99.8% eff
- MC based "unsmearing": bin by bin correction from jet to hadron
- Systematics: jet energy scale (absolute 10-74%, relative 3-10%), jet energy resolution (1-6%), unfolding correction (2-8%), lumi (6%). Total 12-76%
- Scale = avg p_T of 2 leading jets
- Theoretical uncertainties: PDF, scale (5-10%), hadronization (1.16-1.02%), UE
- Fit spectrum to $d\sigma/dm_{jj}=p_0(1-x)^{p1}/x^{(p2+p3\ln(x))}$ where $x=m_{jj}/\sqrt{s}$
- Theory parameters: q*: couplings to SM gauge groups = 1, and compositeness scale = q* mass; W' and Z': SM couplings

Z+b-jet cross section

•b quark density essential input to prediction of EW production of single top or H production in SUSY models

•Z→ee or μμ with $76 < m_{ll} < 106$ GeV

•e channel events trigger: EM cluster with E_T>18 GeV + track with p_T> 9 GeV or 2 EM clusters with E_T > 18 GeV. Refined by quality cuts depending on central or forward.

•mu channel events trigger: mu chamber candidate with |η|<1 and p_T>18 GeV + second mu in COT, p_T > 10 GeV

•Leptons isolated by ΔR > 0.4

•Selection eff 41% for ee, 23% for μμ

•Jet E_T>20 GeV, |η|<1.5, use cone radius 0.7

•Displaced secondary vtx: b-tagging eff=30-40%. Mistag 8% c-jets and 0.5% light jets

•Jets corrected to hadron level, i.e., correct for calor response + multiple int but not UE nor out of cone losses nor in-cone (fragmentation) energy changes. Latter are applied to theoretical calculation

•Discriminate light+charm jets based on inv mass of charged particles from secondary vtx

Z+b-jet cross section continued

- γ^* contribution < 1% of Z
- Uncertainty on integrated lumi and lepton ID eff cancel
- Per evt cross section prop to #evts with b-jets; per jet cross section prop to #b-jets; indep of # b-jets so prop to eff for finding a b-jet, i.e. smaller systematic error.
- Main bkgs: ZZ or t-tbar producing true b-jet; W+jets or multi-jet events with jets misidentified as leptons; bkg subtracted
- Main uncertainties: MC E_T^{jet} dep (8%), MC η^{jet} dep, track finding eff, b-tag eff, mis-ident lepton bkg, b-bbar/b and c-cbar/c fractions…total 12.7%
- CTEQ5L, Tune A UE
- b hadron decays via EVTGEN
- Require positive b-tag: sec vtx in same direction as jet. Use negative b-tag to measure fraction of b-jets.
- To reject t-tbar: reject if missing E_T>25 GeV or sum of all E_T+missing E_T>150 GeV
- eff (Z+bjet) = 8.7%

W+b-jet cross section

•b-jets selected by displaced vertex (=long lifetime). Inv mass of charged particle tracks from vtx is sensitive to the decaying flavor

•Cross section prediction for single top is 10x smaller; for WH production with Higgs mass 100-140 GeV, 100x smaller.

•Present systematic on ratio σ(W+bjets)/σ(W+jets) is 40%

•Jet E_T>20 GeV, $|\eta|<2.0$, cone radius = 0.4. Lepton p_T>20 GeV, $|\eta|<1.1$ and isolated, neutrino p_T>25 GeV

•b-tagging requires imp param significance > 3.5, track p_T>0.5 GeV, tracks within 2cm of PV in z-direction to suppress multiple int, imp param < 0.15 cm, hits in silicon

•Decay length (L_{2d}) signif > 7.5, pseudo-cτ < 1.0cm

•Simulation of b-jets checked against double-tagged dijet events, one jet including a trigger muon from B decay

•Bkg: t-tbar, single top, WZ, WW, ZZ that produce final state b-jet

•Uncertainties: tagging eff (6%), production cross section predictions (8%), lumi (6%), jet energy scale, renorm + factorization scales, PDF

$$\sigma(p\overline{p} \rightarrow W + c - jet) / \sigma(p\overline{p} \rightarrow W + jets)$$

•Because V suppresses d-quark gluon fusion, W+c is directly sensitive to s-PDF (gs→Wc) previously measured only in fixed target neutrino-nucleon DIS at Q^2=100 GeV^2

•W→lepton, jet contains a muon charge-correlated to lepton. Other significant processes e.g. g+W or Z+jets do not produce charge correlation. Other correlated processes (t-tbar, W+b) have small cross section or CKM suppression.

•Lepton isolated, p_T>20 GeV; E_T>20 GeV, associated with track, pass likelihood criteria, within 60 cm of detector center and 3cm of IP in z

•Jet p_T>20 GeV, |η|<2.5, cone radius 0.5, corrected to the particle level

•Reject CR with scintillator timing. Cut on lepton transverse mass.

•Ratio cancels uncertainties in luminosity, jet energy scale, recon eff. Trigger efficiency cancels fully in e channel and partially in μ channel

•Use opposite sign pairs for signal, same sign pairs to estimate bkg

•Bkg: photons and jets misidentified as electrons; c-cbar and b-bbar multi-jets that produce a muon

•Acceptance x eff = 1.2%

•Systematics: cross section and jet fragmentation models, PDFs, MC statistics, jet p_T resolution, c-jet tagging eff

•The electron and muon channels are consistent with each other so they are combined.

•Probability that this is a bkg fluctuation: 2.5 x 10^{-4}, 3.5 σ significance

Differential cross sections for Z+jets in p_T of 3 leading jets

- Goal: Test particle-level event generators: parton shower Pythia, PS+matrix elt Sherpa, Alpgen+Pythia
- $Z \rightarrow ee$ in range $65<M_{ee}<115$ GeV
- e's identified by longitudinal and transverse shower profiles. Shower must point to track with consistent momentum. Bkg rejected by likelihood profiles.
- Jets: cone radius 0.5, shape cuts suppress electronics bkg. Correct for out-of-cone, pile-up, multiple interactions using photon + jet and dijet balancing. $p_T>20$ GeV, $|\eta|<2.5$
- Background with 2 real electrons is < 6% and subtracted. W+jets bkg<1%
- Exclude FSR with cone around electrons
- Electron id eff corrected for jet number and proximity
- Correct for resolution-derived migration to higher p_T bins in steeply falling jet spectrum
- Jet p_T corrected to particle level using MC-derived weights
- Principal systematics: correcting jet energy scale in sim to data (50-80%); conversion from jet to particle level; jet energy resolution correction, jet and electron id eff, PDF (5-15%)

Differential cross sections for Z+jets in p_T of 3 leading jets, continued

- Ratio result cancels uncertainties in luminosity and (partially) on electron trigger eff and electron id eff
- Model predictions normalized to predicted inclusive cross section
- CTEQ6.1M and evolution of α_s to 2 loops
- Jets 1 and 2 compared to NLO MCFM, Jet 3 to LO MCFM. MCFM corrected for multiple interactions + hadronization
- Data points are located where theoretical diff x-section = average within bin

Differential cross section for Z+jet

- p_T jet extends lower, and yjet extends more widely, than previously.
- $Z \rightarrow \mu\mu$ reconstructed after FSR
- Midpoint algorithm, cone radius = 0.5
- $|y^{jet}|<2.8$, $p_T^{jet}>20$ GeV
- $65<M_{\mu\mu}<115$ GeV, μ p_T > 15 GeV, μ $|\eta|$ < 1.7
- Corrections to the particle level
- Cross section binned in leading jet p_T, using bins wider than detector resolution (to suppress migration) and containing sufficient events to suppress fluctuations. Migration matrix inverted to correct.
- PV requires 3 or more tracks + quality cuts
- Muons must be consistent with PV in directions transverse + parallel to beam
- Jet cone 0.5, jet p_T > 20 GeV, jet $|y|<2.8$
- Bkg: semileptonic decays in jets or W+jet. Require muons isolated in calorimetry and tracking, not overlapping any jets.
- 5% cross section uncertainty due to muon trigger and id eff; 2% due to p_T migration, 3% due to MC weights in jet to particle correction; 10% due to jet energy scale, 2% due to muon resolution in MC vs. data
- Theoretical uncertainties: PDF 3%, scale 7%, FSR 2%
- Predictions $\sigma=17.3\pm1.2$(scale)±0.5(PDF) pb (MCFM NLO); 11.6 (ALPGEN); 15.0 (SHERPA); 12.1 (PYTHIA)

γ+b+X and γ+c+X cross sections

- Leading photon $|y^{\gamma}|<1.0$ and leading jet $|y^{jet}|<0.8$. $30<p_T^{\gamma}<150$ GeV and $p_T^{jet} > 15$ GeV
- Same photon selection as for photon +jet. jet cone 0.5
- Uncertainties: jet energy scale, jet energy resolution, difference in energy response of light versus heavy quarks: 8-2%
- Uncertainties: photon purity (10%), heavy flavor fraction fit (9%), jet selection eff (8-2%), photon selection eff (5%), luminosity (6%)
- Jet must have 2 tracks with p_T>0.5GeV, leading track must have p_T>1.0GeV
- Light jets suppressed with ANN that exploits long lifetimes of heavy hadrons. 1% of light jets are misidentified as heavy
- PV within 35cm of detector center, along beam axis
- Background: dijets in which one jet is misidentified as a photon
- NLO pQCD compared with scale set to p_T^{γ}
- CTEQ6.6M with correction for parton to hadron fragmentation
- Non-perturbative models including intrinsic charm (x-sect growing with p_T^{γ}) have been compared to the data.

Isolated photon + jet

- Large uncertainties on gluon PDF at large x, small x, and large Q^2
- Colliding parton x values x_{12} are given approximately by $x_{1,2}=(p_T^{\gamma}/\sqrt{s})(e^{\pm y(\gamma)} + e^{\pm y(jet)})$
- Leading photon central: $|y|<1.0$
- CTEQ6.5M
- EM calorimeter calibrated on the Z peak
- Require PV within 50 cm of detector center along beam axis
- Photon cone radius R = 0.2, jet cone radius 0.7
- Photon EM cluster must not spatially match a track
- Backgrounds: CR, W→isolated e suppressed by missing-E_T requirement
- S/B enhanced by ANN: ANN outputs for simulated photon signal and dijet background are fitted to the data for each p_T^{γ} using max likelihood to obtain fractions of S and B without unitarity constraint.
- Uncertainties: fragmentation model (1-5%), fit, p_T bin migration correction (1%), purity estimation (10-4%), photon and jet selections (8-5%), photon energy scale (4-6%), integrated luminosity (6%)
- Compare data to NLO QCD JETPHOX with BFG fragmentation and scales=$p_T^{\gamma}f(y^*)$ where $f(y^*)=\mathrm{sqrt}\{1+\exp(-2|y^*|)/2\}$ and $y^*=0.5(y_{\gamma}-y_{jet})$
- UEC and parton to hadron fragmentation are negligible

k_T distribution of particles in jets

- k_T = transverse momenta of particles with respect to jet axis
- Test applicability of pQCD to the soft process of fragmentation. Probe boundary between parton shower and hadronization, understand relative roles of pert and non-pert processes in forming jet.
- Measurements of inclusive dist's of particles in jets + 2-part momentum correlation in jets suggest pQCD is dominant. This study tests the LPHD by checking whether pQCD predictions for partons are reproduced in hadrons
- Jet incorporates particles up to angle 1.0; cone angle for particle relative to jet axis: 0.5
- $66 < m_{jj} < 737$ GeV
- $k_T > 0.5$ GeV for reconstruction quality; $k_T << E_T$ for soft approximation.
- Expect gluons produce more particles with large k_T than quarks
- Correct for calo non-lin and non-uniformity, leading parton energy out of cone, UE
- Uncertainties: jet energy scale 3%; cone angle 1%; non-excluded secondary tracks 3%; PDFs < 1%
- Single calo trigger tower, 2 leading jets balanced in E_T, up to 2 small E_T extra jets. Use pion ID for Lorentz boost, charged $p_T > 0.3$ GeV; select on imp param, radius of conversion, $|z_{track}-z_{vtx}|$ to exclude CR, multiple int, gamma conversions, K^0, Λ^0 decays
- NMLLA for Q_{eff}=230 MeV agrees well over full k_T and dijet mass range of expt
- PYTHIA Tune A, parton shower cutoff 500 MeV agrees qualitatively with NMLLA at hadron level, deviates at parton level. HERWIG shows results similar to PYTHIA's

CDF Inclusive Isolated Prompt Photon Cross Section

- Photon $p_T > 30$ GeV, $|\eta|<1.0$
- Calorimeter isolation distribution estimates contamination level from jets faking photons
- Correct signal to hadron level, compare to pQCD including 9% non-perturbative corrections (UE)
- pQCD from JETPHOX with CTEQ6.1M, Bouris frag. functions. Scales = photon p_T
- 2 triggers 100% efficient: (1) isolated photon with $p_T>25$ GeV → photon with $p_T<90$ GeV; (2) any photon with $p_T>70$ GeV→ photon with $p_T>90$ GeV.
- calorimeter corrected with $Z\rightarrow ee$
- QCD bkg ($\pi^0\rightarrow\gamma\gamma$) separated from signal using MC templates binned in p_T
- unfolding factors: 0.64-0.69 (p_T-dependent)
- uncertainties (6%+10-15%): photon signal fraction (13%-5%, dominates at low p_T), photon energy scale (1.5%, dominates at high p_T), photon isolation scale (10%), photon ID (3%+5% below 90 GeV/c), lumi (6%)
- Signal fraction error estimated using multiple extraction methods

Dijet angular distributions: D0

- Restriction to shape reduces uncertainties on jet energy calib, lumi, renorm. scale, PDFs
- M_{jj}> 0.25 TeV, χ_{dijet}< 16, y_{boost}< 1: $|y_{jet}|$< 2.4
- Midpoint alg. cone radius = 0.7
- Suppress CR: require missing p_T<$0.7p_T^{max}$ (if p_T^{max}<100 GeV) or <$0.5p_T^{max}$ (if p_T^{max}>100 GeV)
- Jets corrected for calorimeter response, pile-up, multiple interactions, showering in or out of cone, non-reconstructed muons and neutrinos in jet
- Pythia 6.412 tune QW, CTEQ6.5M reweighted with fastNLO cross sections
- systematics: jet energy calib, jet p_T (these 2 dominate), θ, φ, resol, systematic shifts in y, jet recon eff, vertex position modeling, vertex mis-id, M_{jj} weighting in simulation
- 3 statistical approaches to limits: frequentist + 2 Bayesian (results all agree within 8%)