QCD Results from the Tevatron

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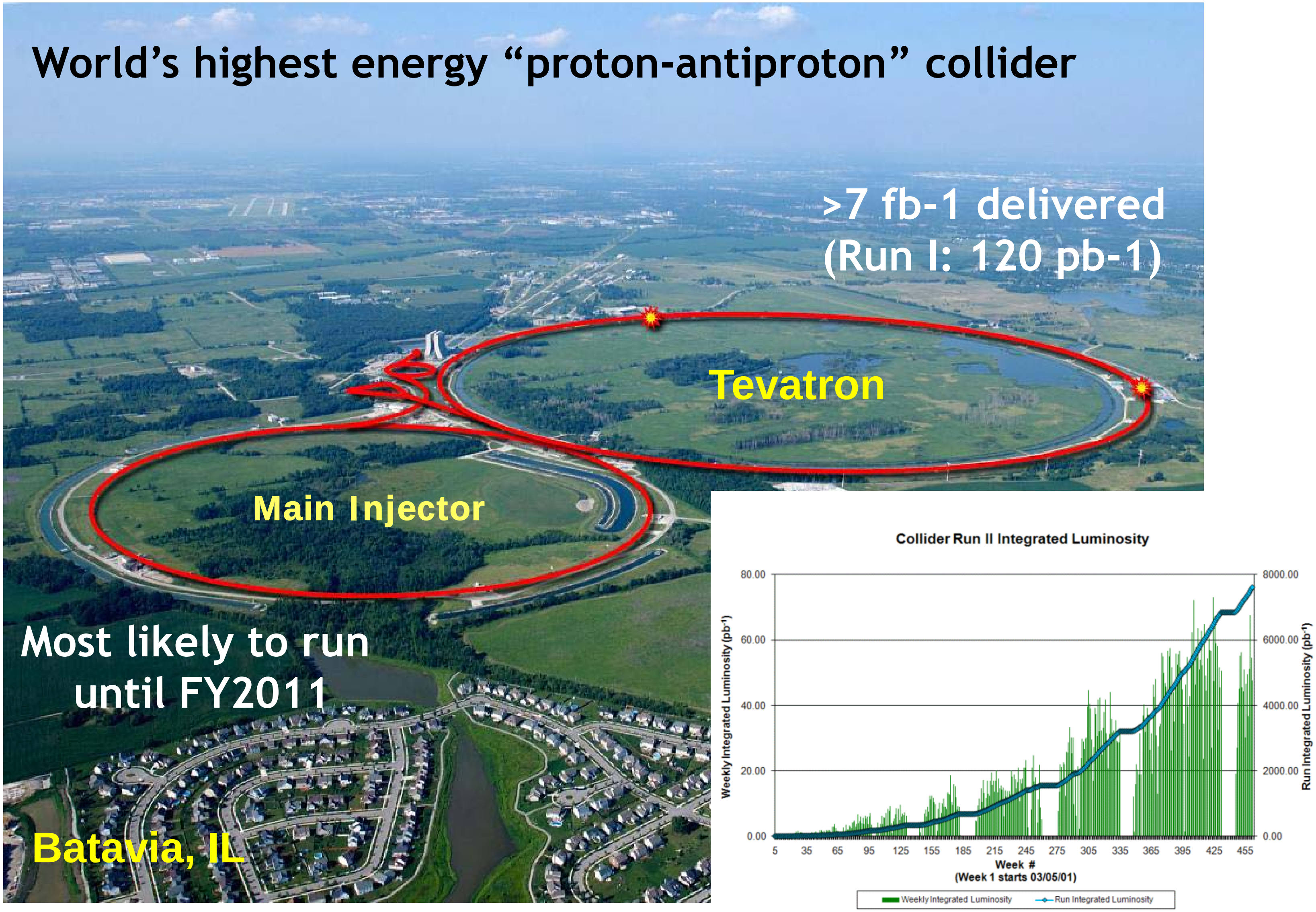
Outline

- Fermilab Tevatron, CDF and D0 Detectors
- Inclusive jets and dijets
- Photons
- W/Z+jets
- Soft QCD and Exclusive Production
- Summary & Remarks

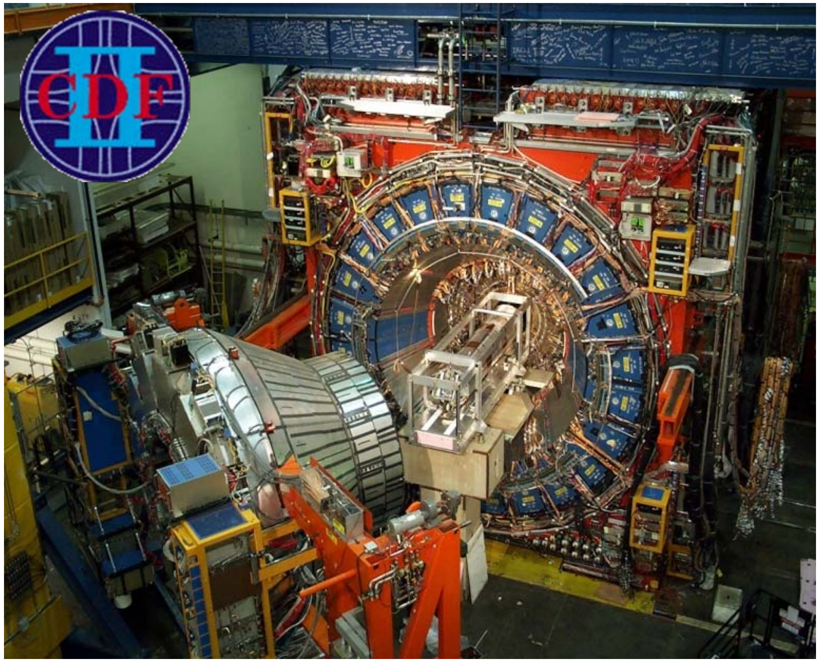
Only a small fraction of extensive QCD results from the Tevatron can be covered in 20 minutes. More results can be found on:

- http://www-cdf.fnal.gov/physics/new/qcd/QCD.html
- http://www-d0.fnal.gov/Run2Physics/WWW/results/qcd.htm

Fermilab Tevatron



CDF and DØ



CDF & DØ running well and recording physics quality data with high efficiency (85-90 %)

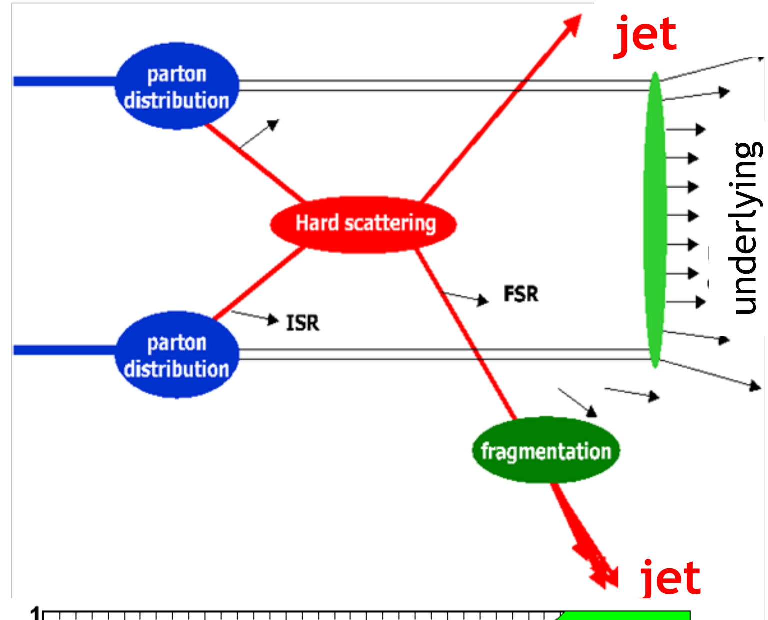
Both experiments have already collected > 6 fb-1 on tape

Inclusive Jets & Dijets

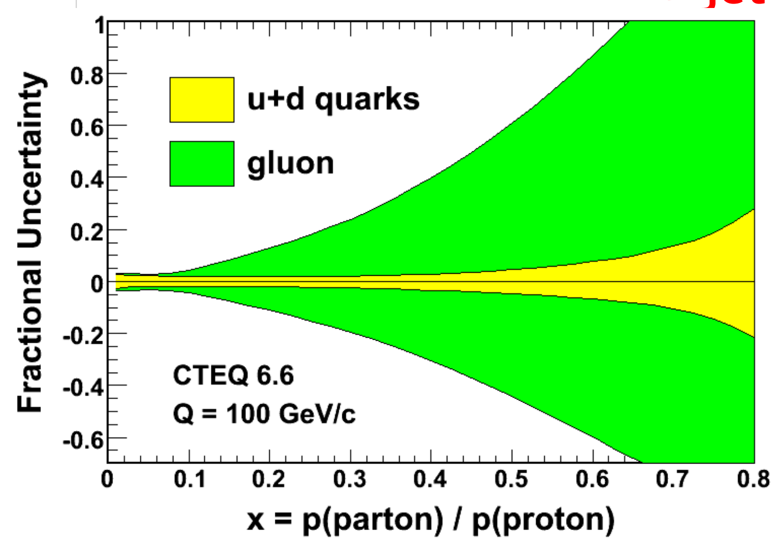
α_s, PDFs,
Physics beyond the Standard Model

Jet Production at the Tevatron

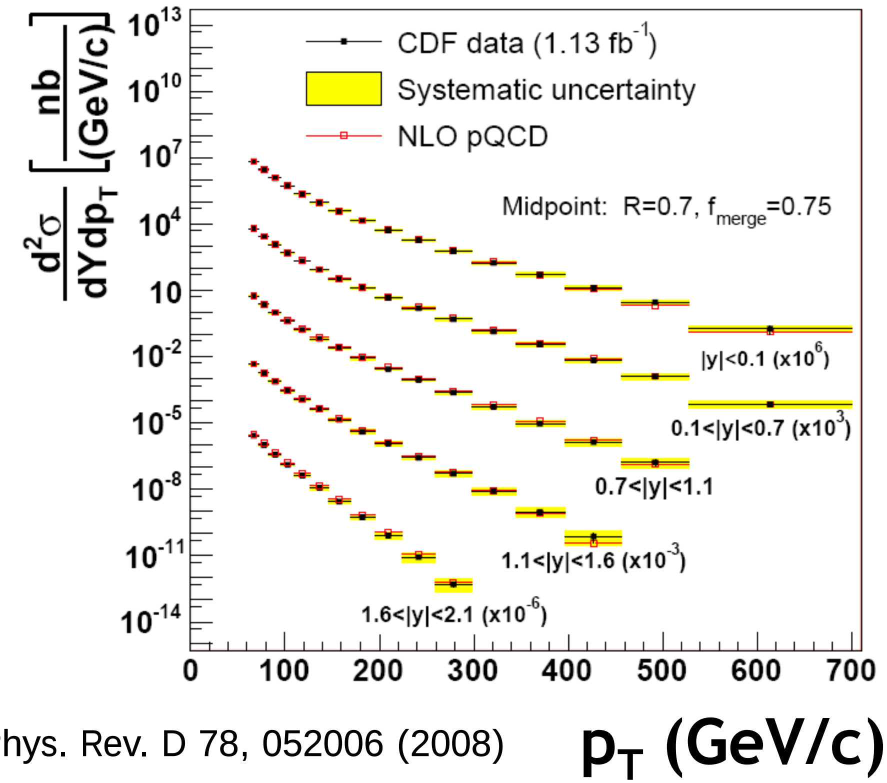
$$d\sigma_{jet} = \underbrace{\sum_a \sum_b \overbrace{f_{a/p}(x_1,\mu_F^2)\, f_{b/\bar{p}}(x_2,\mu_F^2)}^{\text{PDFs}} \otimes \hat{\sigma}_{a,b}(p_1,p_2,\alpha_s,Q^2/\mu_R^2,Q^2/\mu_F^2)}_{\text{Hard Scatter}}$$



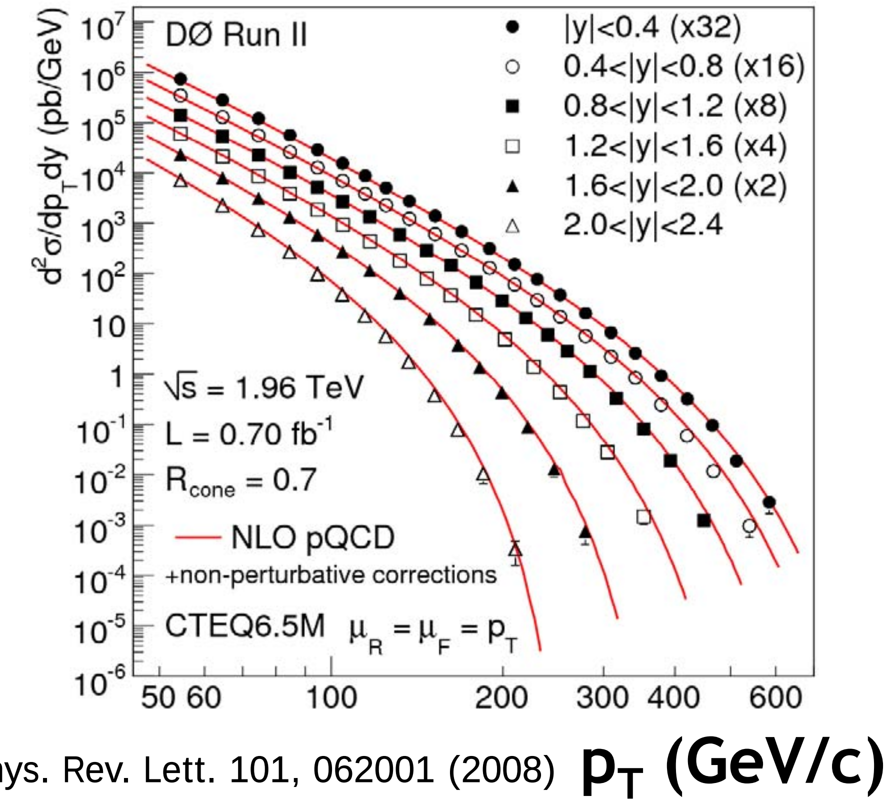
- Test pQCD at highest Q^2.
- Unique sensitivity to new physics
  - Compositeness, new massive particles, extra dimensions, …
- Constrain PDFs (especially gluons at high-x)
- Measure α_s



Inclusive Jet Cross Section



Phys. Rev. D 78, 052006 (2008)

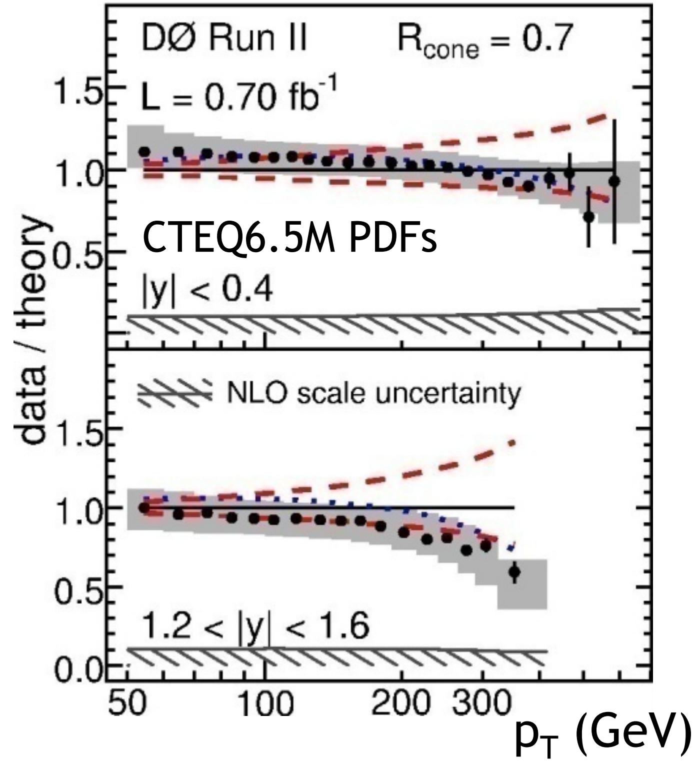


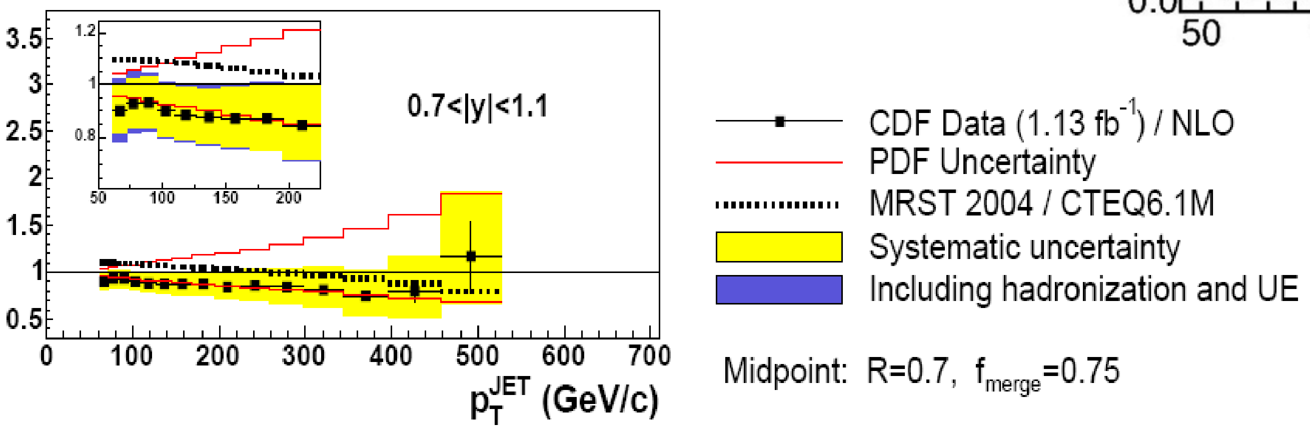
Phys. Rev. Lett. 101, 062001 (2008)

- Measurements span over 8 order of magnitude in $d\sigma^2/dp_Tdy$
- Highest p_T^{jet} > 600 GeV/c

Inclusive Jet Cross Section

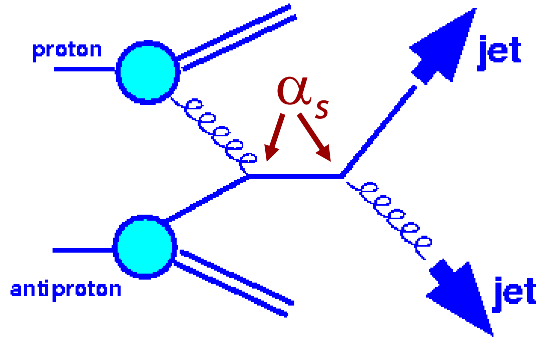
- Both CDF and D0 measurements are in agreement with NLO predictions
  - Both in favor of somewhat softer gluons at high-x
- Experimental uncertainties: smaller than PDF uncertainties
- Discussions on the impact to PDF in a different talk





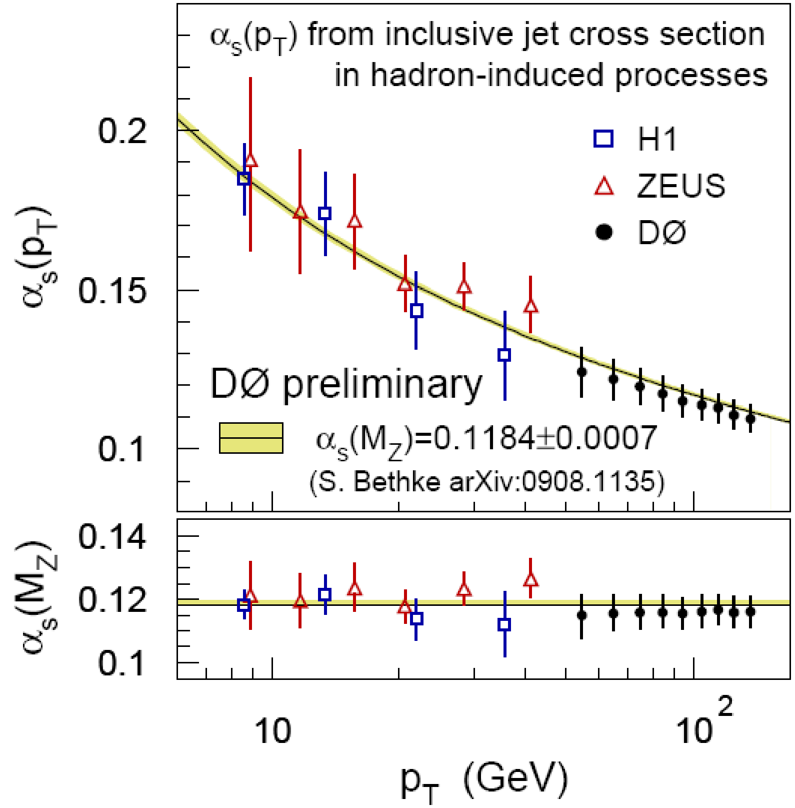
see also, Inclusive jets with Kt, CDF, Phys. Rev. D 75, 092006.

Strong Coupling Constant



$$\sigma_{jet} = \left(\sum_n \alpha_s^n c_n\right) \otimes f_1(\alpha_s) \otimes f_2(\alpha_s)$$

From 22 (out of 110) inclusive jet cross section data points at $50 < p_T < 145$ GeV/c



- NLO + 2-loop threshold corrections
- MSTW2008NNLO PDFs
- Extend HERA results to high p_T

$$\alpha_s(M_Z) = 0.1173^{+0.0041}_{-0.0049}$$

3.5-4.2% precision

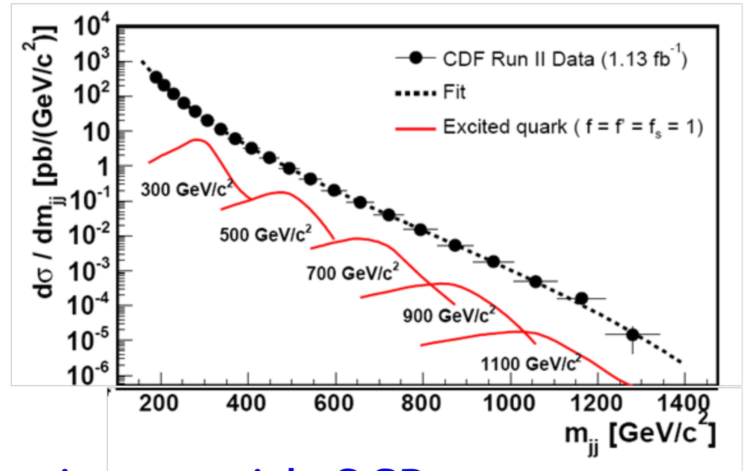
Phys. Rev. D 80, 111107

CDF results in Phys. Rev. Lett. 88, 042001

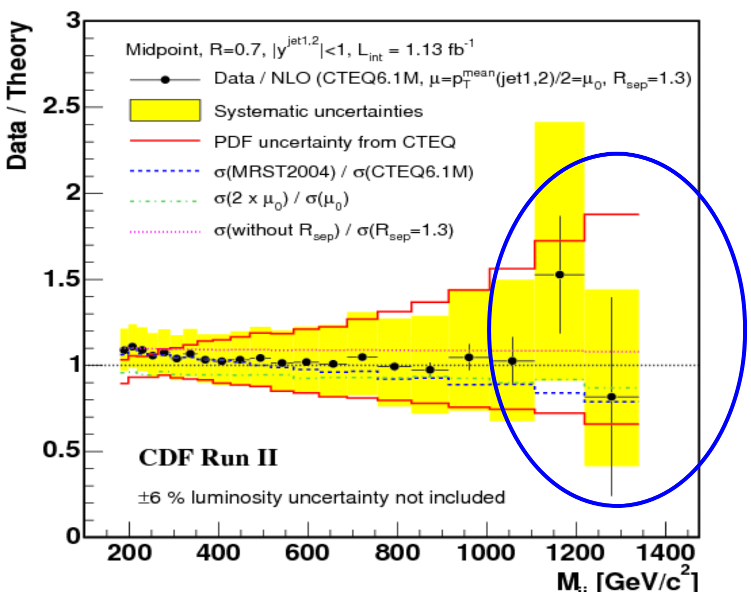
Dijet Mass Spectrum

Phys. Rev. D 79, 112002

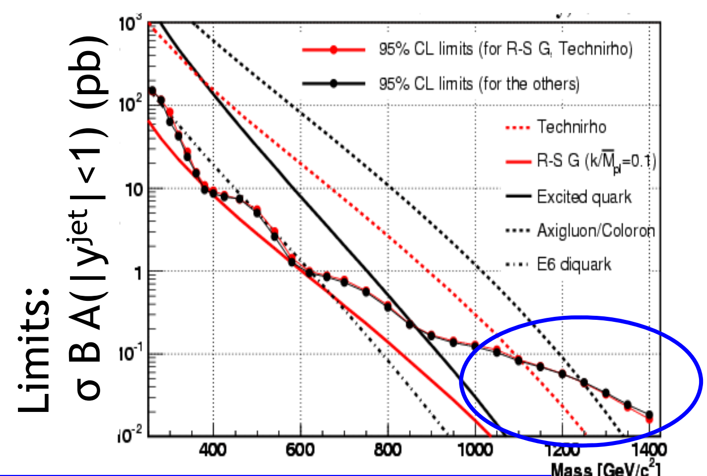
- Test pQCD predictions
- Sensitive to new particles decaying into dijets: excited quarks, heavy gluons, techni-ρ, etc



Dijets with jets $|y^{jet}|<1$



- Consistent with QCD - no resonance
- Most stringent limits on many new heavy particles



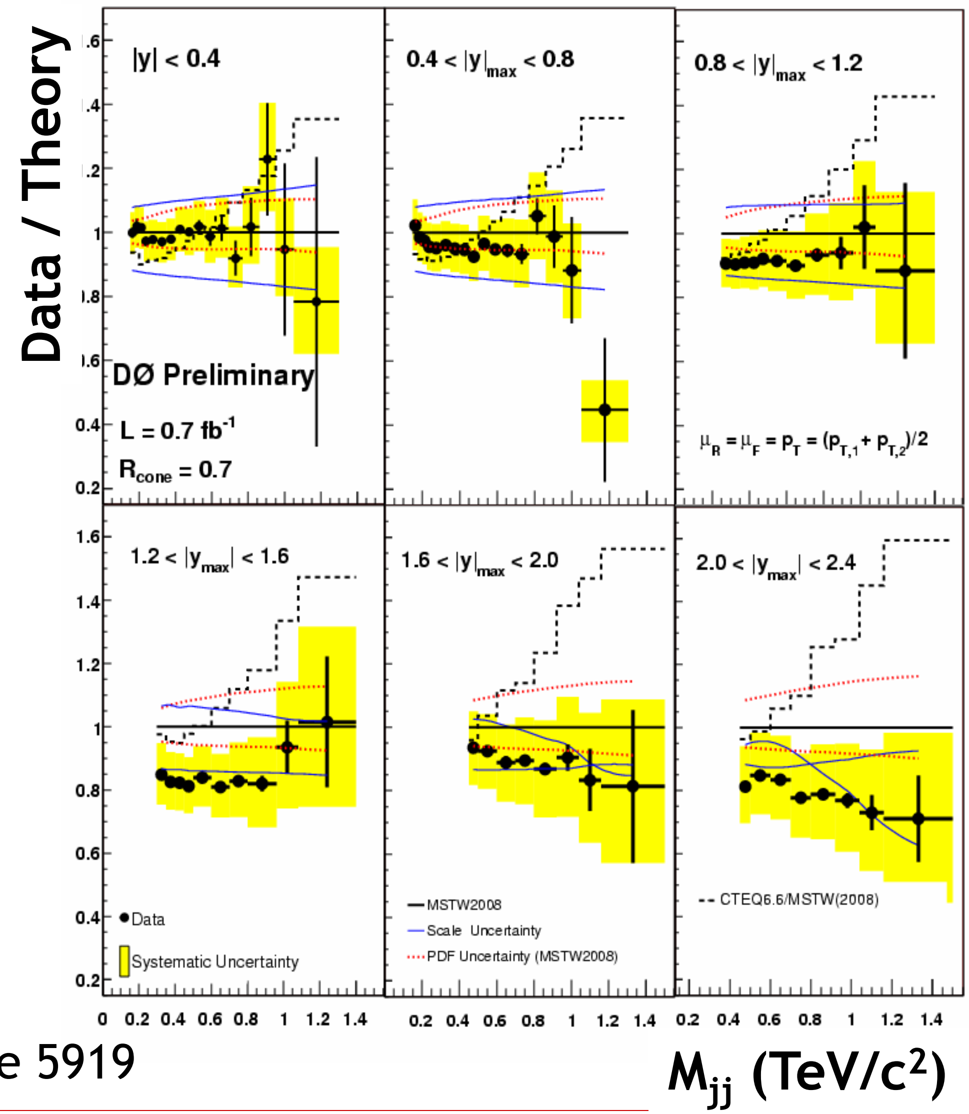
Mass reach up to ~ 1.2 TeV/c^2

Dijet Mass Spectrum

D0 measurement goes to forward rapidity regions

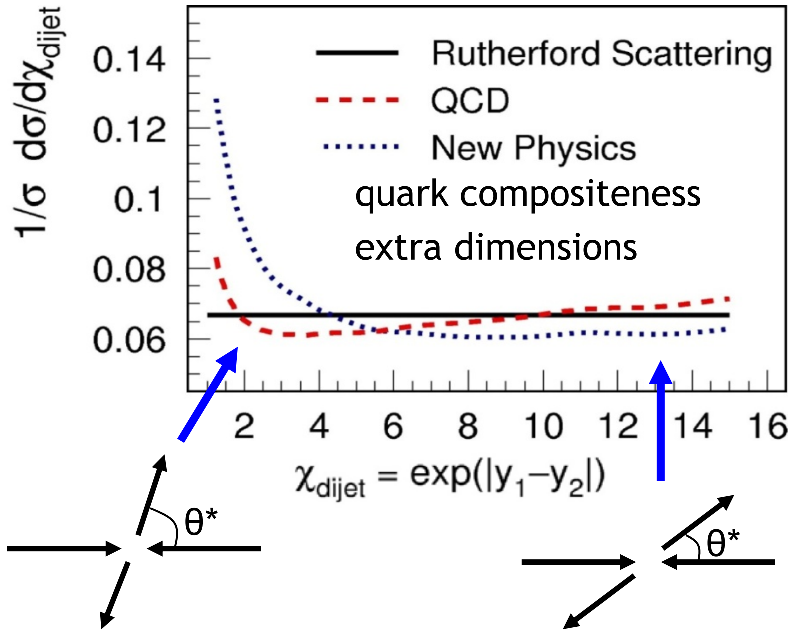
- six $|y_{max}|$ regions ($0<|y_{max}|<2.4$)

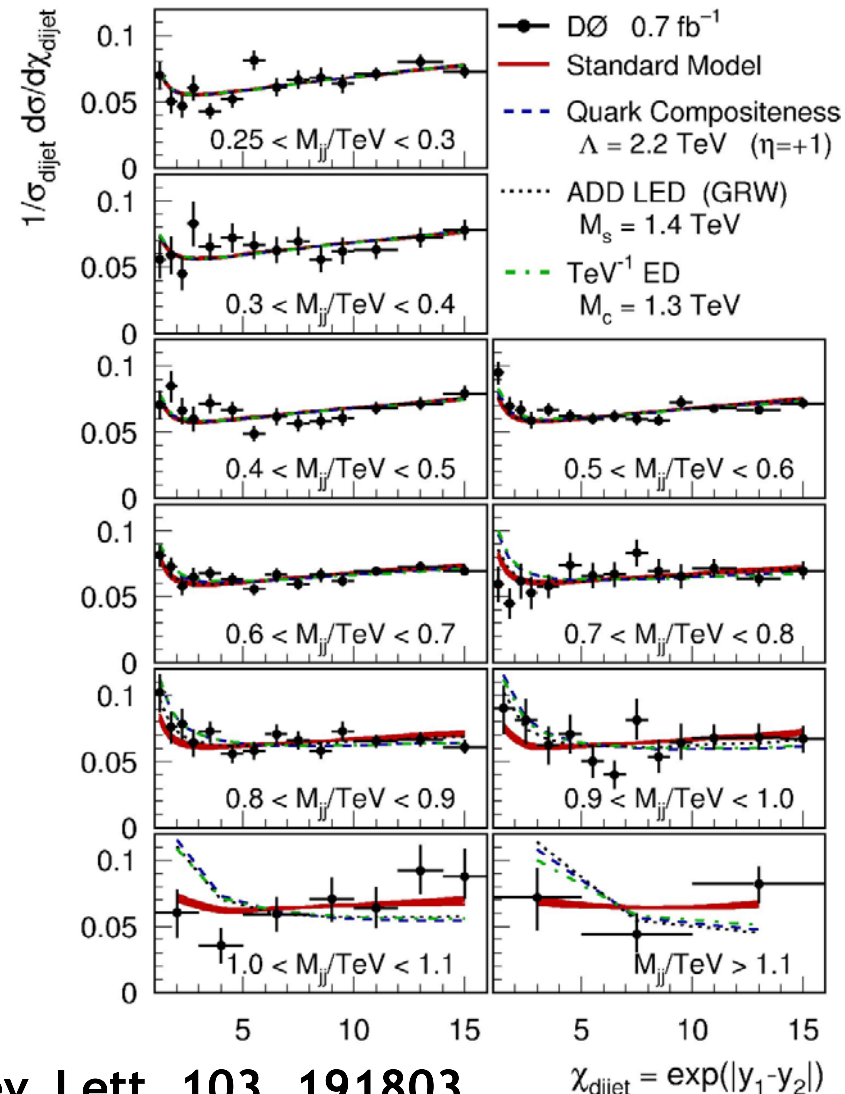
- PDF sensitivity at large $|y_{max}|$
- Favor softer high-x gluons
- No indications for resonances



D0 Conf Note 5919

Dijet Angular Distribution





- Consistent with NLO pQCD
- Limits on Compositeness & LED
  - Quark Compositeness Λ > 2.9TeV
  - ADD LED (GRW) Ms > 1.6 TeV
  - TeV-1 ED Mc > 1.6 TeV

Phys. Rev. Lett. 103, 191803.

Also CDF results in CDF public note 9609

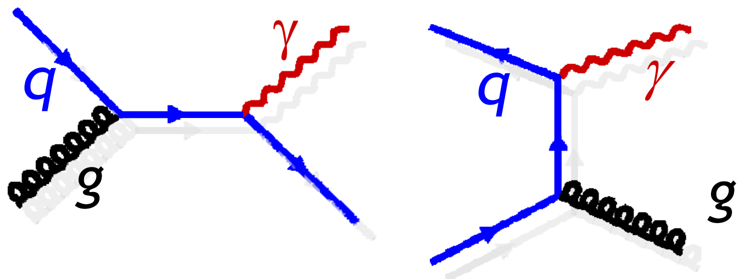
Photons

Photons: “direct” probes of hard scattering

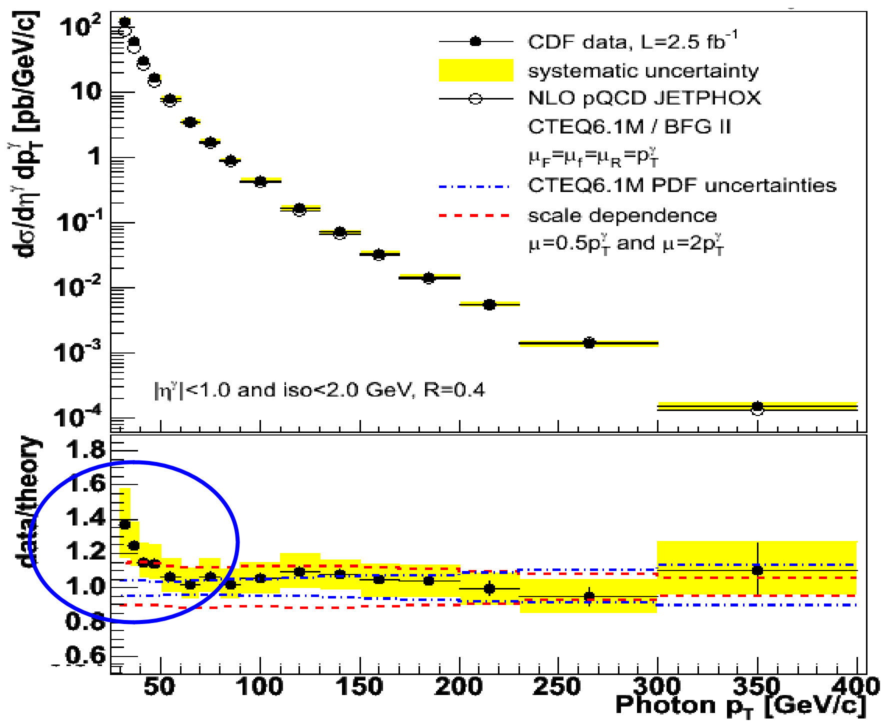
Test perturbative QCD, PDFs

Inclusive Photon Cross Sections

Phys. Rev. D80, 11106 (2009)

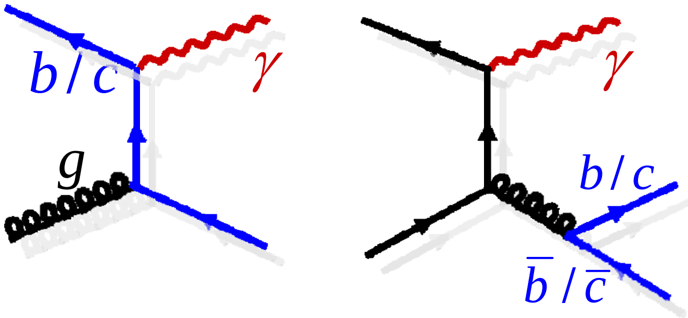


Directly sensitive to hard scatter

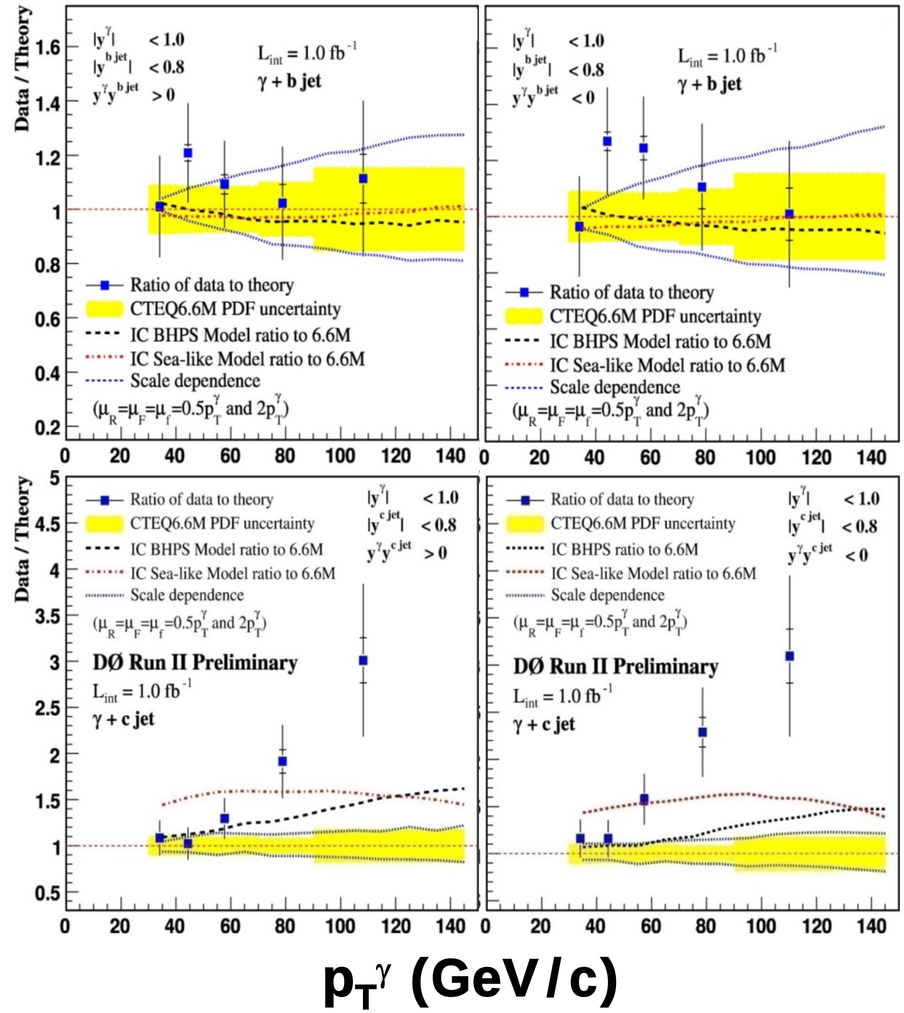


- Data/NLO pQCD: In agreement at high p_T, but enhancement at low p_T
- D0 measurement shows similar trends (Phys. Lett. B 639, 151)
  - Similar shape also in Run 1 analyses – need to be understood

Photon + HF Jet Production



Phys. Rev. Lett. 102, 192002



- Sensitive to HF-content of proton
- Bkgd for many BSMs

Photon p_T: 30 – 150 GeV/c
Rapidities: $|y^{\gamma}|<1.0$, $|y^{jet}|<0.8$

<u>Photon+*b*:</u>

- Agreement over full p_T^{γ} range

<u>Photon+*c*:</u>

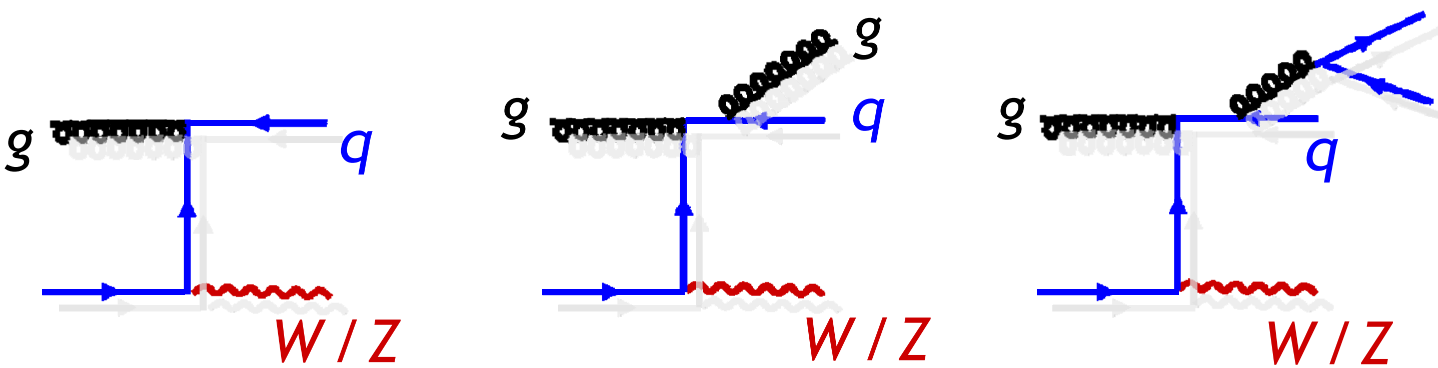
- Agree only at $p_T^{\gamma}<50$ GeV/c.
- Disagreement increases with p_T^{γ}.
- Using PDF including the intrinsic charm (IC) improves, but data and theory still not compatible

Vector Boson + Jets

Prerequisites for top, Higgs, SUSY, BSM

Test perturbative QCD calculations
& Monte Carlo Models

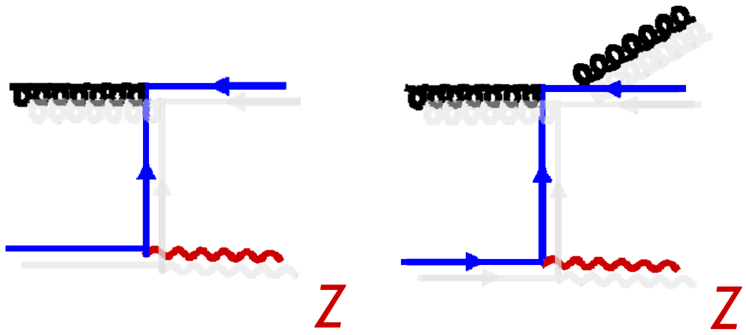
W/Z+Jets Production

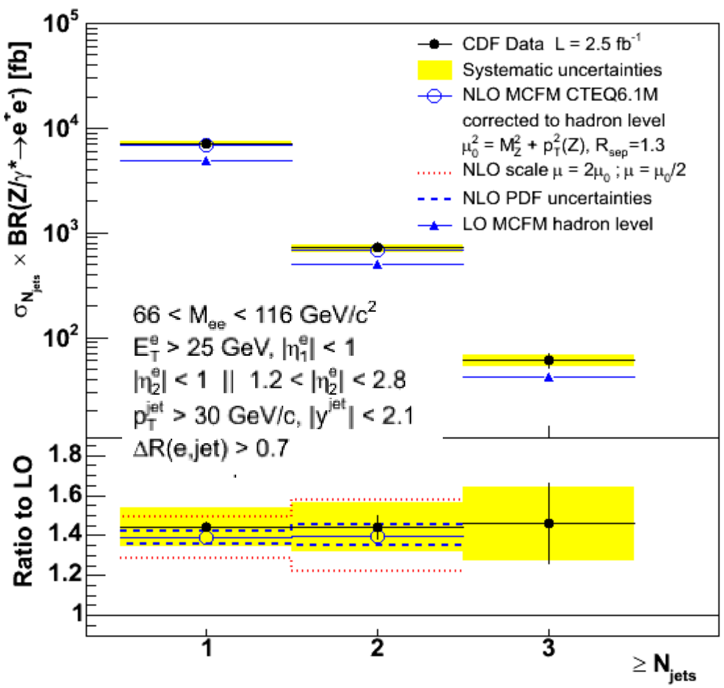


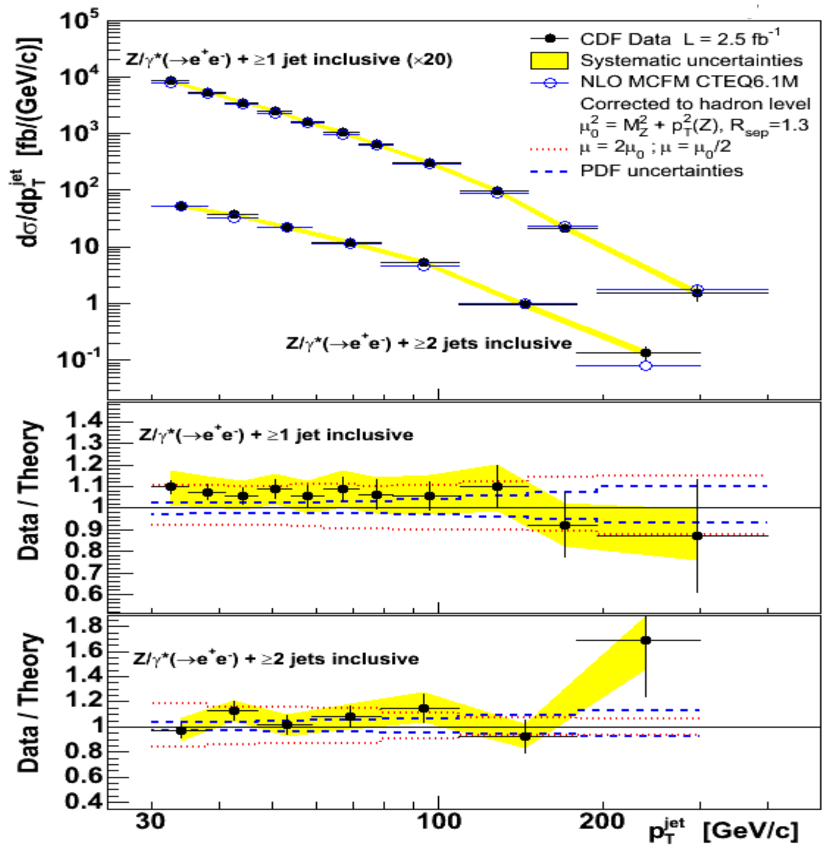
- W/Z+jets are critical for physics at the Tevatron and LHC: top, Higgs, SUSY, and other BSM
- NLO pQCD calculations are available up to 2(3) jets
- Many Monte Carlo tools are available
  - LO + Parton shower Monte Carlo (Pythia, Herwig,)
  - MC based on tree level matrix element + parton showers, matched to remove double counting: Alpgen, Sharpa, …
- These calculations and tools need “validation” by experimental measurements

Z+Jets Production

Phys. Rev. Lett 100, 102001 & update







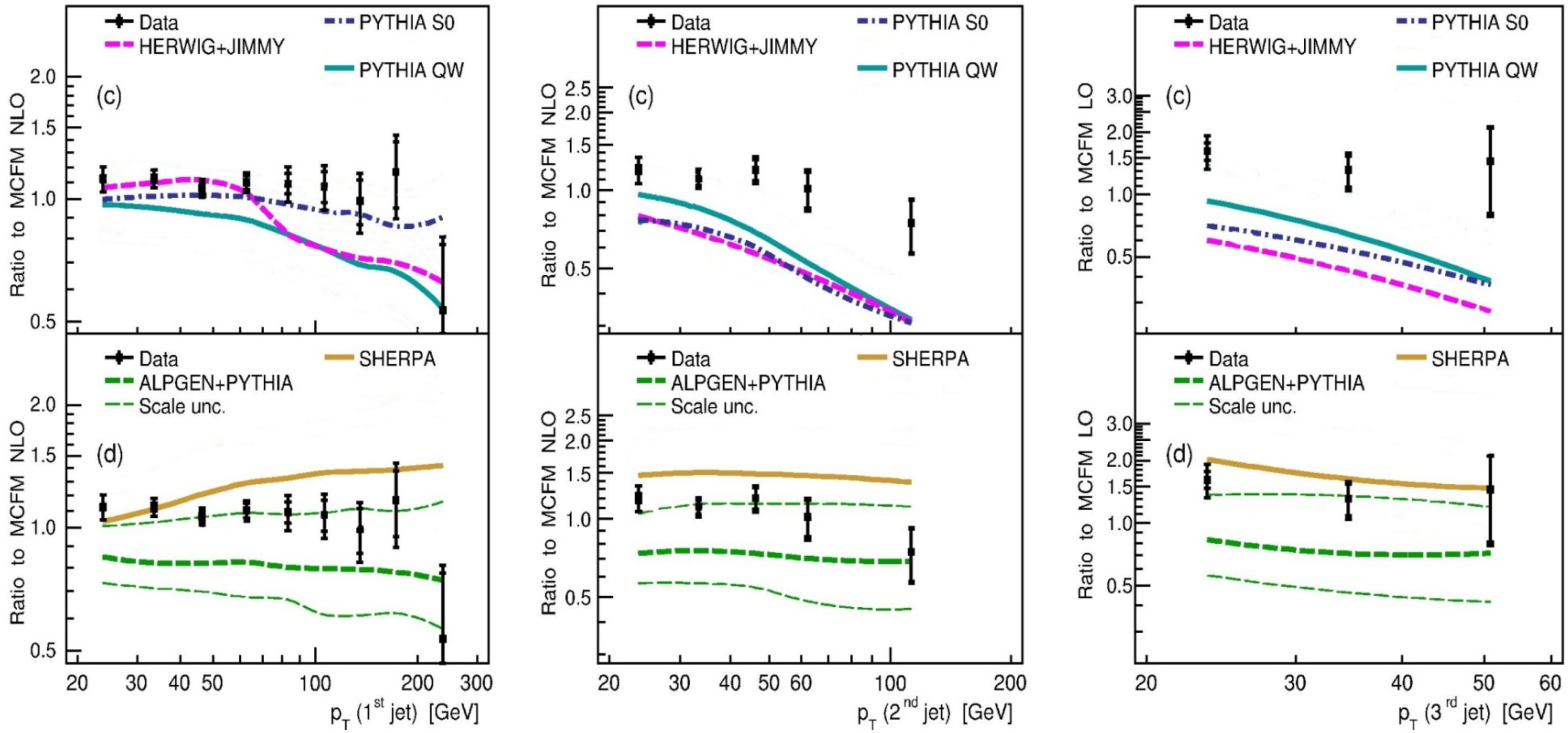
Data and NLO pQCD in agreement

Good control sample for SUSY search

Z + (1, 2, 3) Jets

Testing Monte Carlo Models: favor Alpgen with low scale

Leading jet in Z + jet + X   Second jet in Z + 2jet + X   Third jet in Z + 3jet + X



Phys. Lett. B 669, 278, Phys. Lett. B 678, 45, Phys. Lett. B 682, 370.

See also W+jets, CDF, Phys. Rev. D 77, 011108(R).

Soft QCD and Exclusive Production

Prerequisites for High Pt Physics

Monte Carlo Tuning

Exclusive Higgs Production at the LHC

Particle Production in Non-Diffractive Inelastic Events

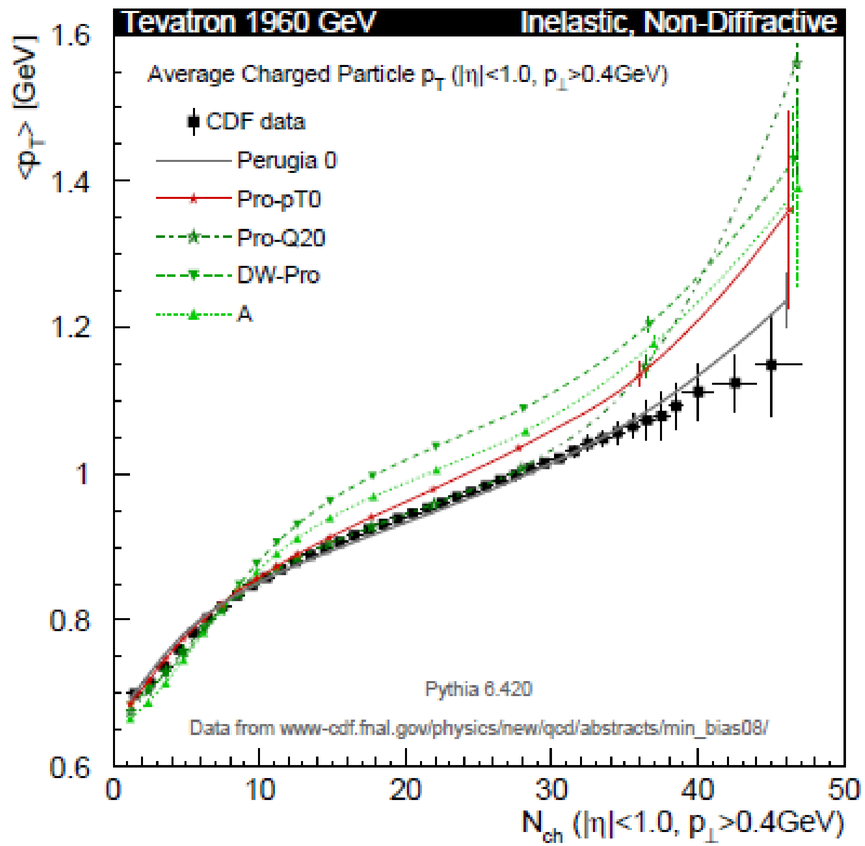
- Particle production in “soft” collisions

- Interesting soft QCD

- Important for MC tunings
  - Complement the underlying event study in hard-scattering events
  - Actively used for recent MC tunes

- Early physics from the LHC

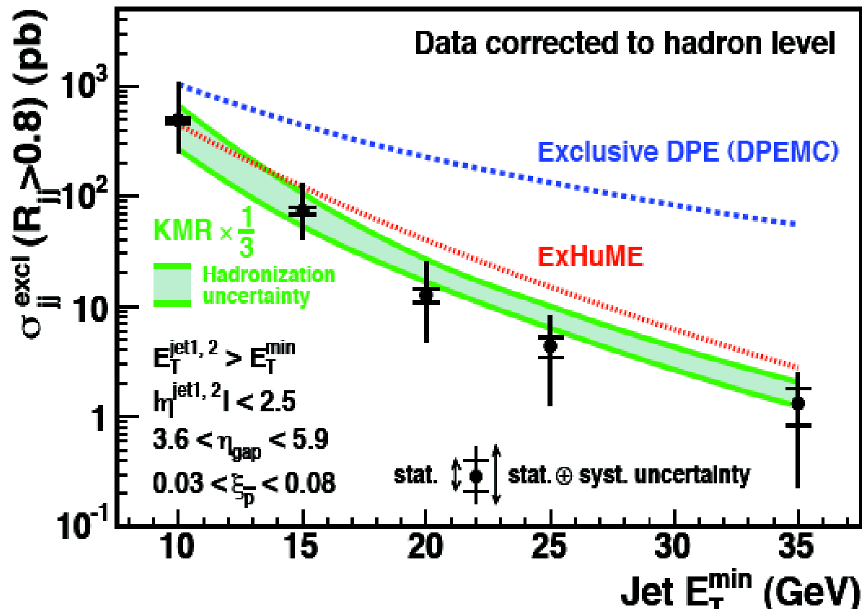
Phys. Rev. D 79, 112005

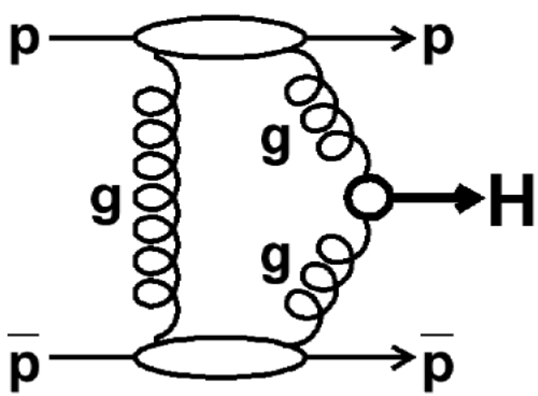


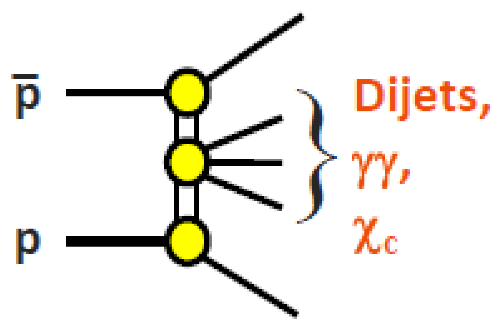
Exclusive Production

- Attractive channel for Higgs physics at the LHC
- At the Tevatron, the cross section too small
  - Study similar channels to "calibrate" theory prediction

Phys. Rev. D 77, 052004







Reliable calculations from Khoze, Martin, and Ryskin. *Eur. Phys. J C14,525(2000).*

Summary & Remarks

Tremendous progress has been made to advance understanding of QCD at the Tevatron

- Determination of α_s and PDFs from jet x-section measurements
- Photon + c-jet measurement challenge theorists
- Z/W+jet(s) measurements test pQCD, help MC modeling and Higgs/BSM searches
- Soft QCD interactions and Underlying event measurements important for MC tuning
- Tevatron exclusive production measurements provide basis to LHC exclusive Higgs studies
- Much more to come - Tevatron expects ~12 fb^{-1} by 2011

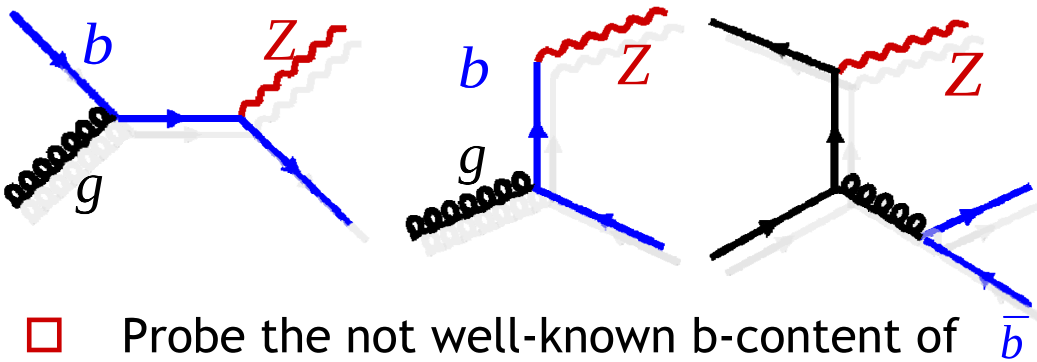
Acknowledgement

- Many thanks to:

  S. Pronko, C. Mesropian, D. Bandurin, S. Lammers, D. Lincoln, A. Bhatti, J. Dittmann, …

Backup

Z+*b*-jets Production



- Probe the not well-known b-content of the proton
- Backgrounds for SM Higgs Search (ZH→vvbb) and SUSY

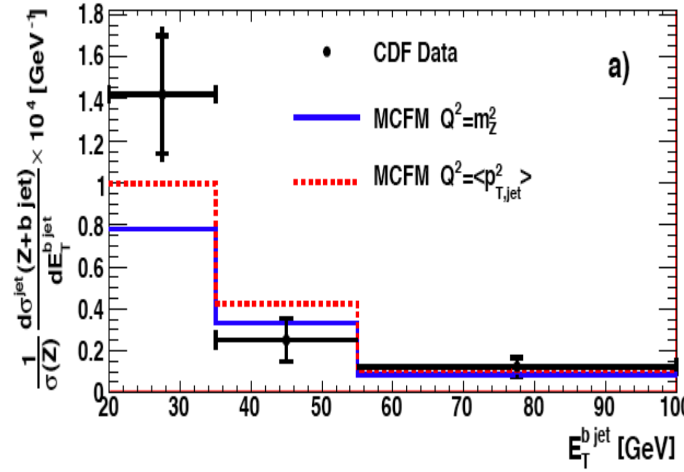
Both electron and muon channels
Jets with Et > 20 GeV and |η| < 1.5

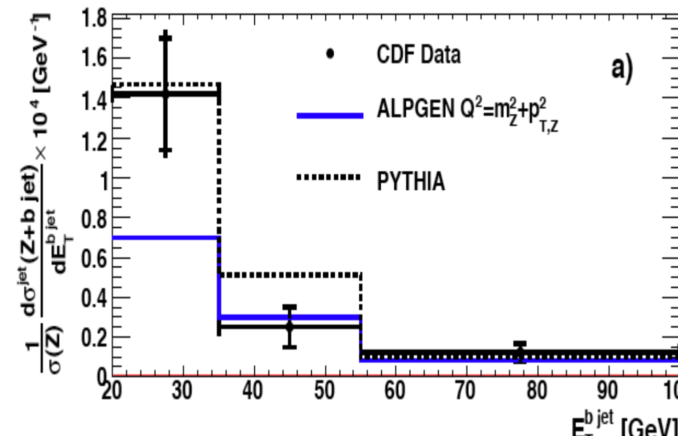
$$\frac{\sigma(Z+b)}{\sigma(Z+jets)} = 2.08 \pm 0.33 \pm 0.34(\%)$$

$$pQCD(MCFM): 1.8\%\ (Q^2 = M_Z^2 + P_{T,Z}^2)\ ;\ 2.2\%\ (Q^2 = < P_{T,Jet}^2 >)$$

Data and theory in agreement but both have sizable uncertainties (No complete NLO prediction for Z+bb)

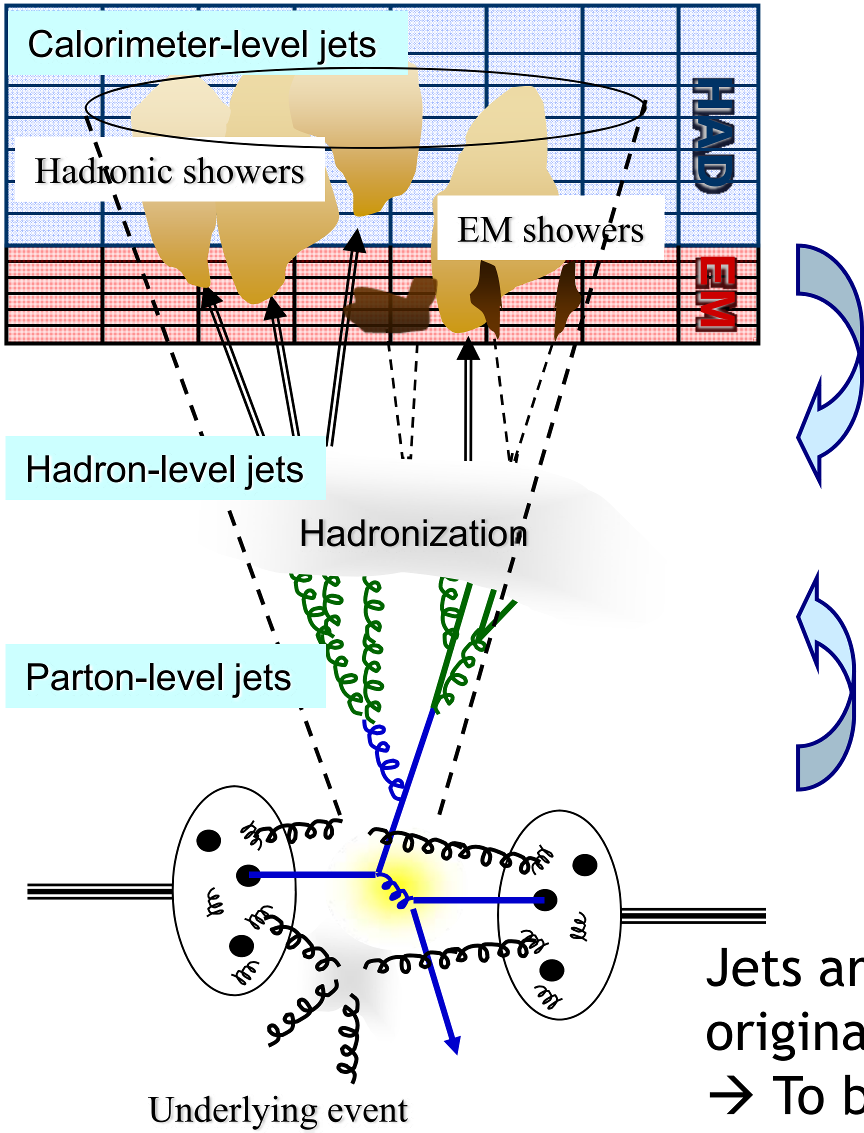
Phys. Rev. D79, 052008 (2009)





Large variations between MC models (important inputs for tuning)

Jet Production and Measuremnt

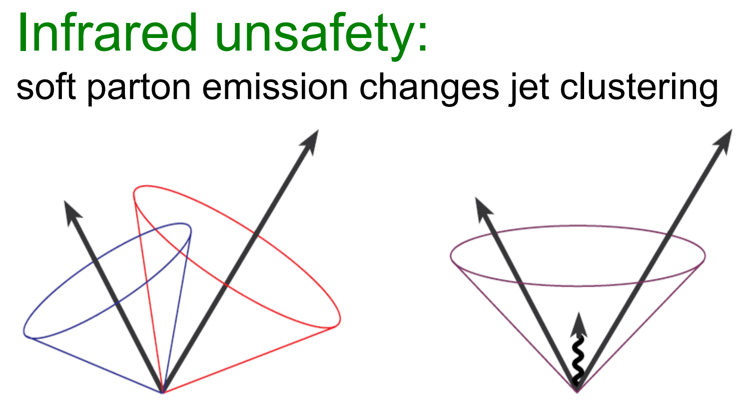


Unfold measurements to the hadron (particle) level

Correct parton-level theory for non-perturbative effects (hadronization & underlying event)

Jets are collimated spray of particles originating from parton fragmentation.
→ To be defined by an algorithm

Jet "Definitions" - Jet Algorithms



Midpoint cone-based algorithm

- Cluster objects based on their proximity in y-ϕ space
- Starting from seeds (calorimeter towers/particles above threshold), find stable cones (kinematic centroid = geometric center).
- Seeds necessary for speed, however source of infrared unsafety.
- In recent QCD studies, we use "Midpoint" algorithm, i.e. look for stable cones from middle points between two adjacent cones
- Stable cones sometime overlap
  → merge cones when p_T overlap > 75%

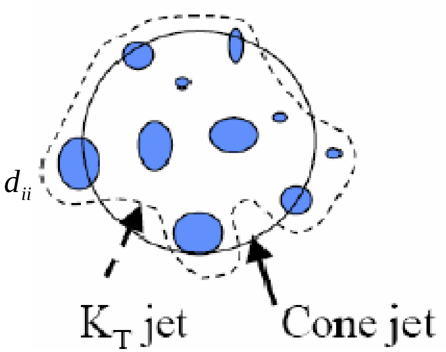
More advanced algorithm(s) available now, but negligible effects on this measurement.

Jet "Definitions" - Jet Algorithms

k_T algorithm

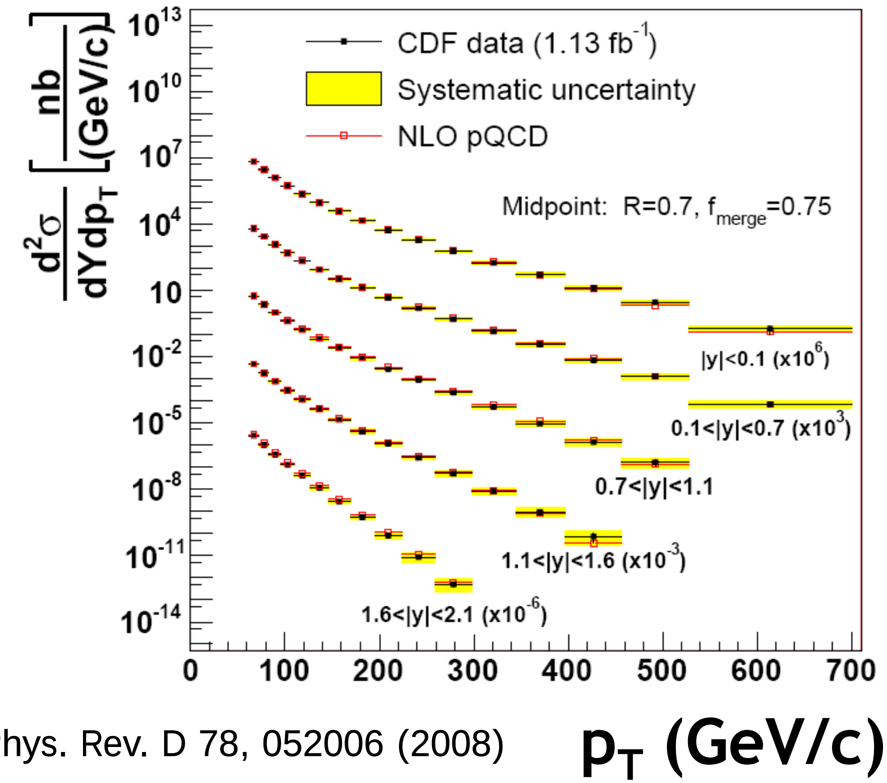
- Cluster objects in order of increasing their relative transverse momentum (k_T)
  - $d_{ii} = p^2_{T,i}, \quad d_{ij} = \min(p^2_{T,i}, p^2_{T,j}) \dfrac{\Delta R^2}{D^2}$

  until all objects become part of jets
- D parameter controls merging termination and characterizes size of resulting jets

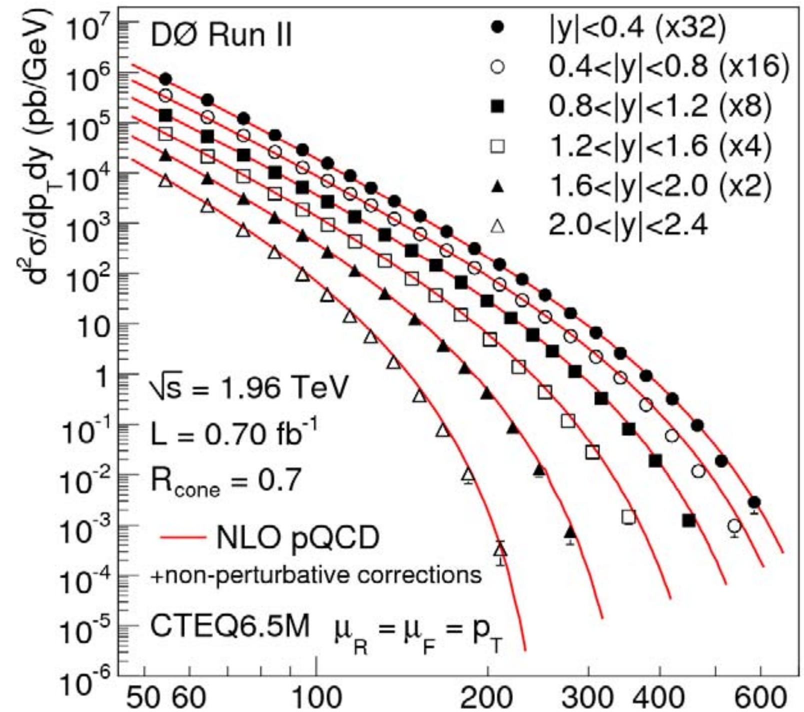


- No issue of splitting/merging. Infrared and collinear safe to all orders of QCD.
- Every object assigned to a jet: concerns about vacuuming up too many particles.
- Successful at LEP & HERA, but relatively new at the hadron colliders
  - More difficult environment (underlying event, multiple *pp* interactions…)

Inclusive Jet Cross Section



Phys. Rev. D 78, 052006 (2008)



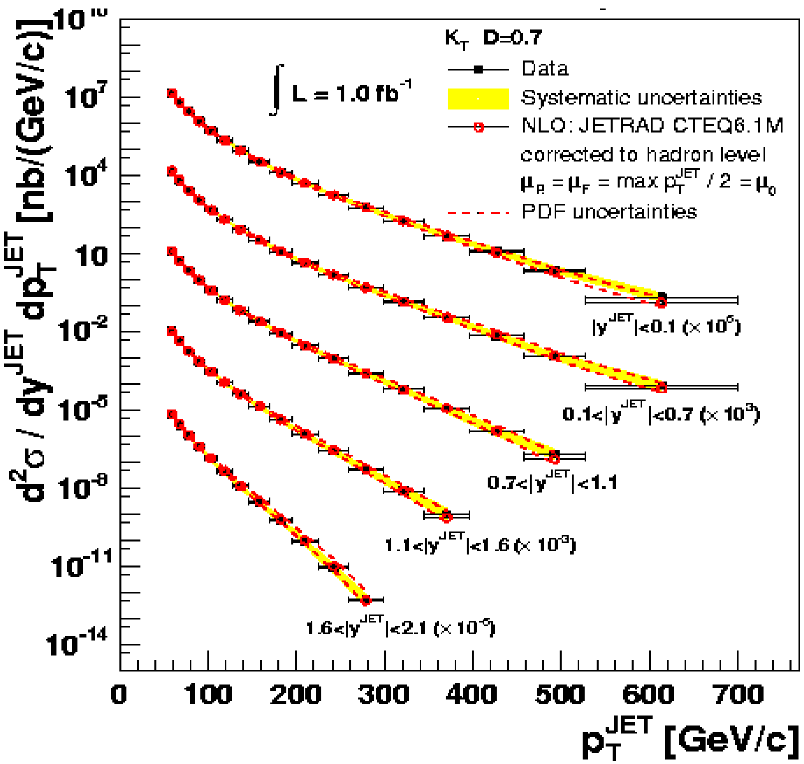
Phys. Rev. Lett. 101, 062001 (2008) p_T (GeV/c)

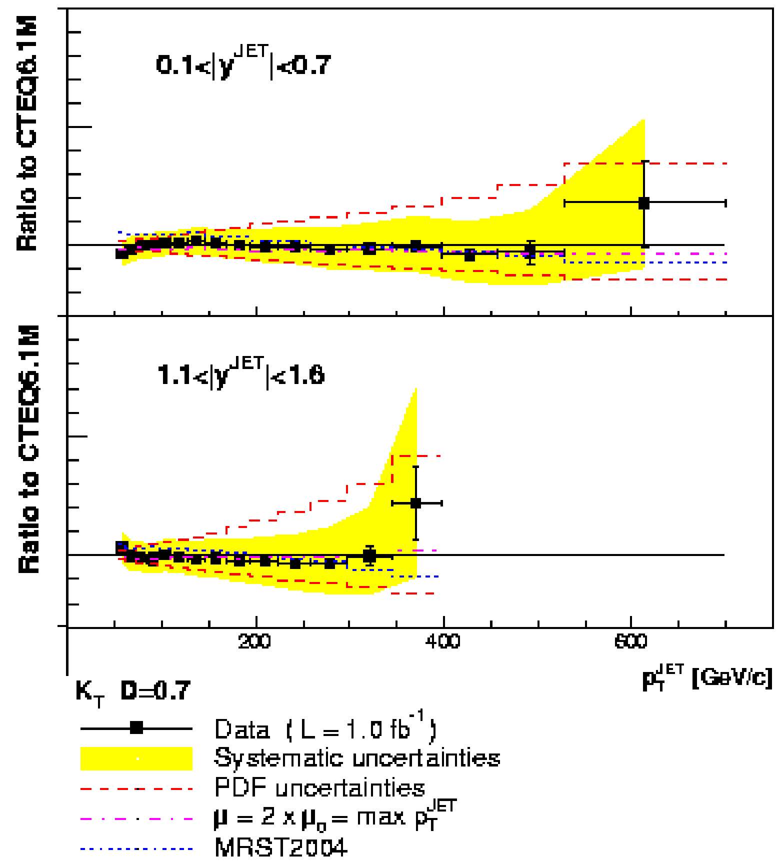
- Test pQCD over 8 order of magnitude in $d\sigma^2/dp_T dy$
- Highest p_T^{jet} > 600 GeV/c
- Jet energy scale (JES) is dominant uncertainty: CDF (2-3%), D0 (1-2%)
- Spectrum steeply falling: 1% JES error → 5—10% (10—25%) central (forward) x-section

Inclusive Jets with Kt Algorithm

- Data/theory comparison consistent between measurements with cone and Kt algorithms and with different D values (jet sizes)

Phys. Rev. D 75, 092006 (2007)



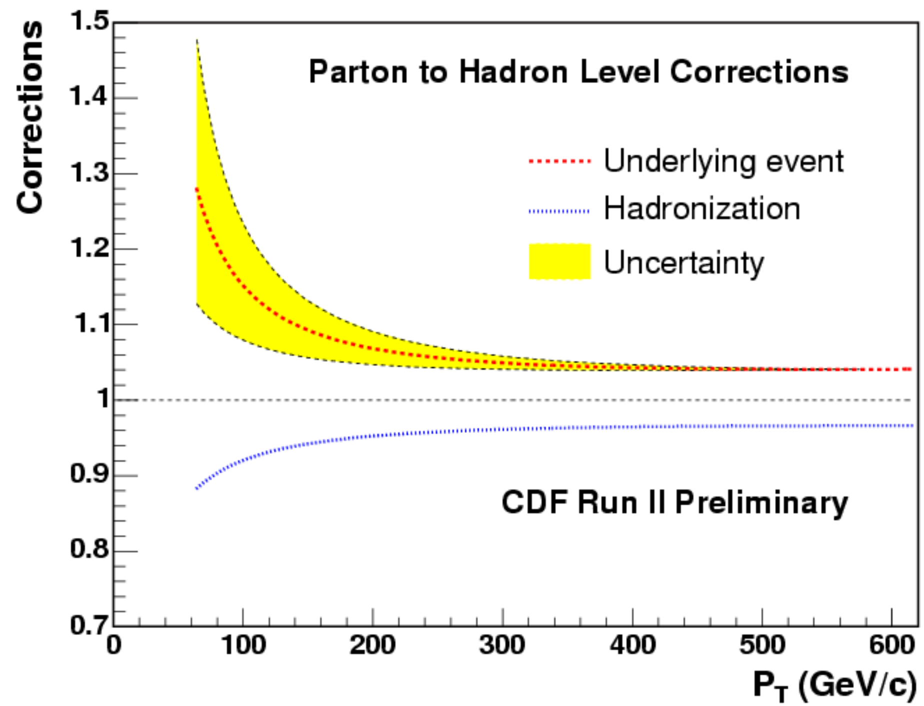


From Particle to Parton Level

use models to study effects of non-perturbative processes (PYTHIA, HERWIG)

- hadronization correction
- underlying event correction

CDF study for cone R=0.7 for central jet cross section



→ apply this correction to the pQCD calculation

→ to be used for future MSTW/CTEQ PDF results

→ first time consistent theoretical treatment of jet data in PDF fits

new in Run II !!!

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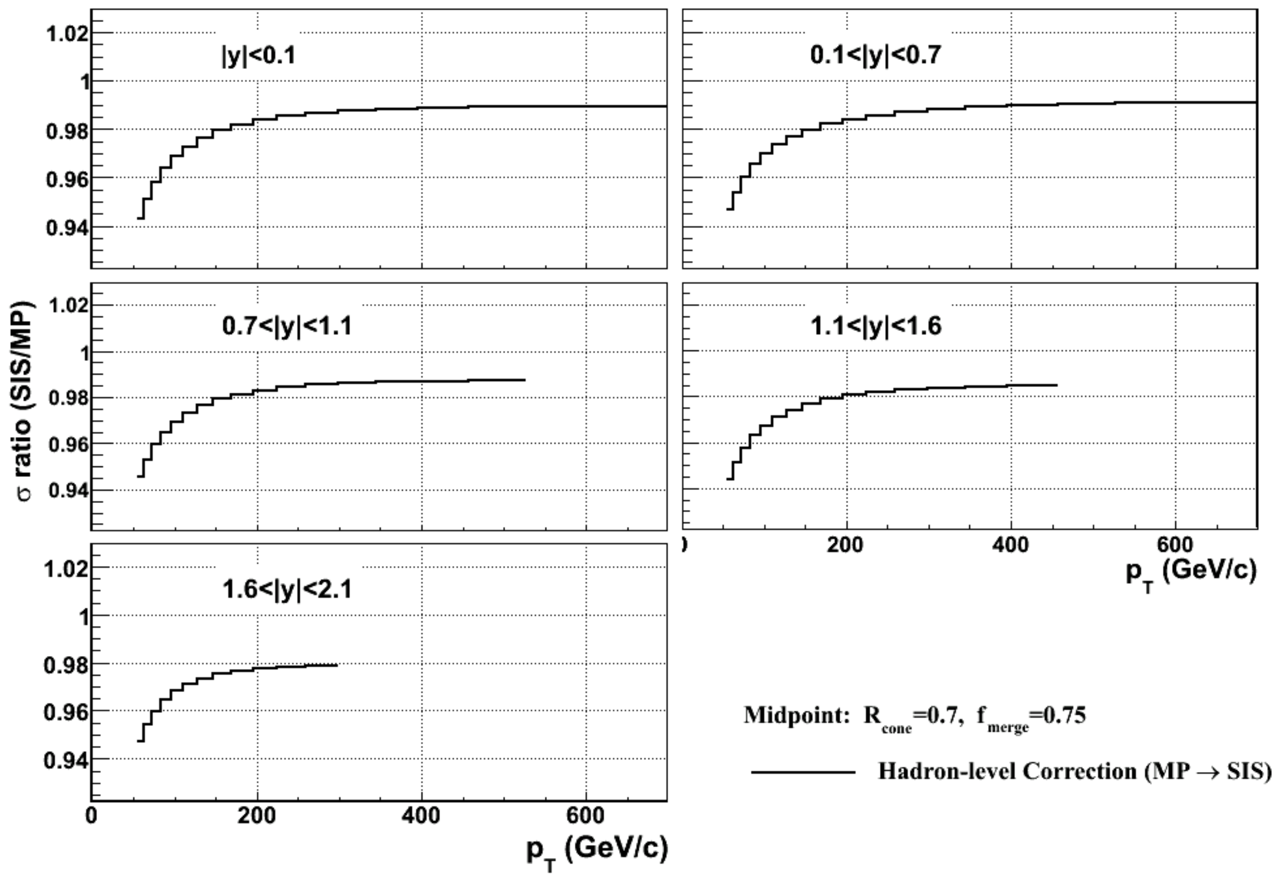
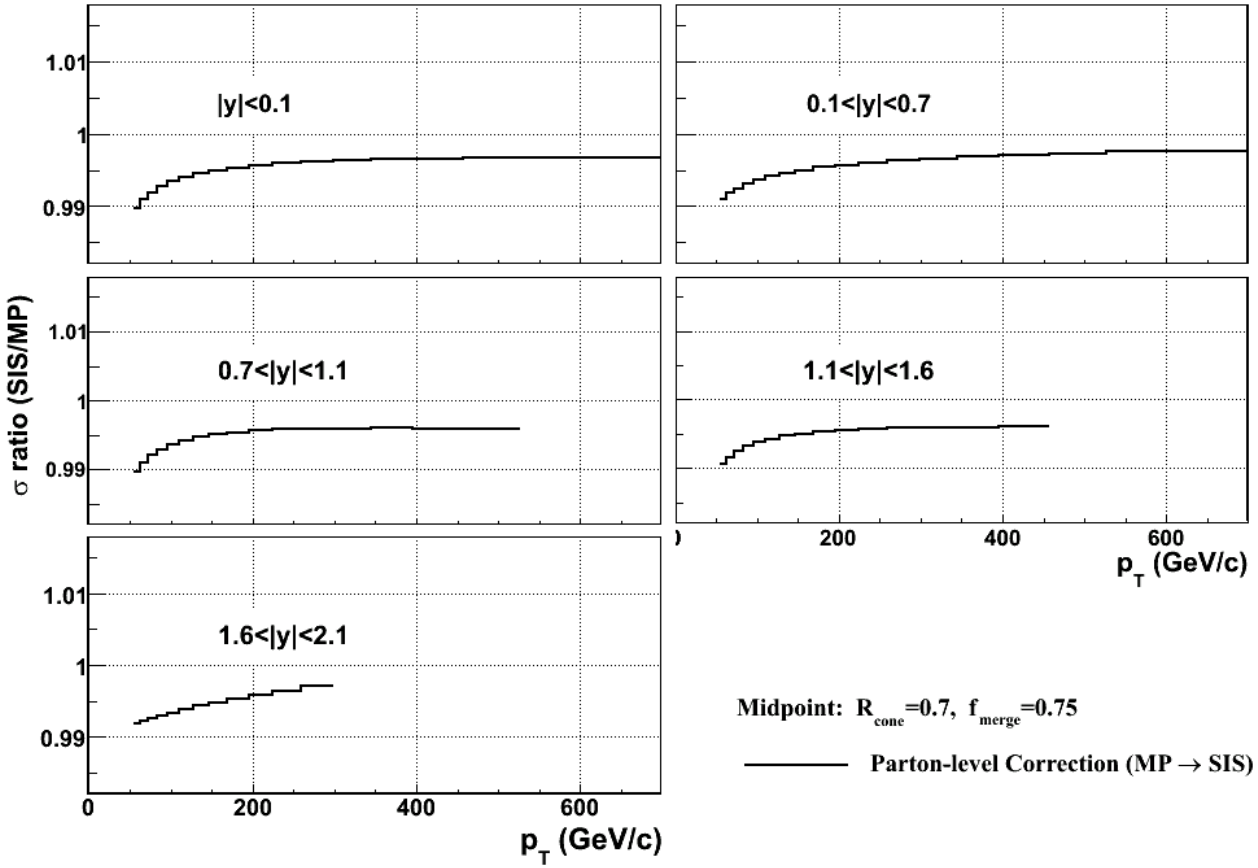
Midpoint vs SIScone: hadron level

- Differences between the currently-used Midpoint algorithm and the newly developed SIScone algorithm in MC at the hadron-level.



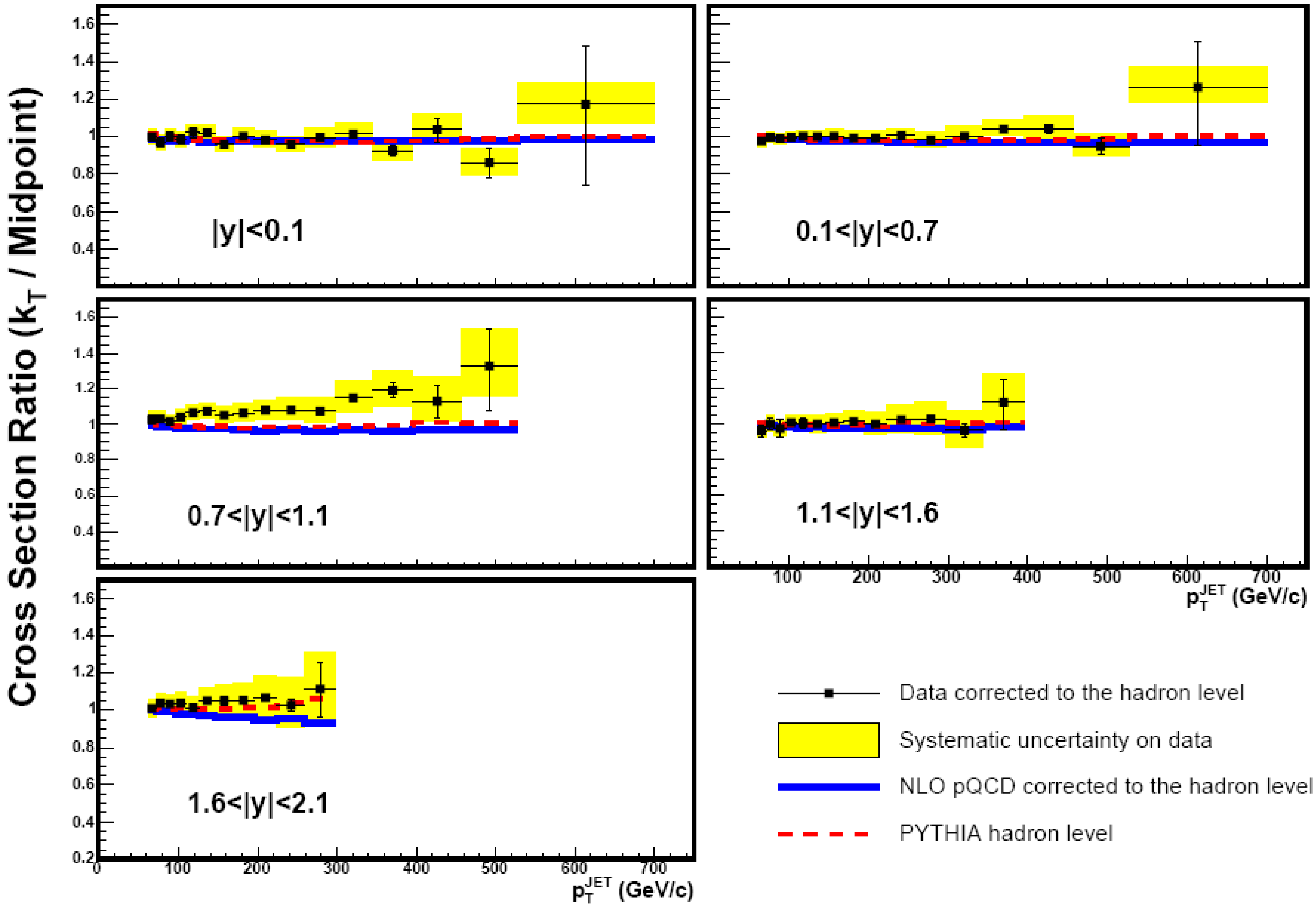
Midpoint vs SIScone: parton level

- Differences between the currently-used Midpoint algorithm and the newly developed SIScone algorithm at the parton-level.



Differences < 1% → negligible effects on data-NLO comparisons

Inclusive Jets: Cone vs Kt Algorithms



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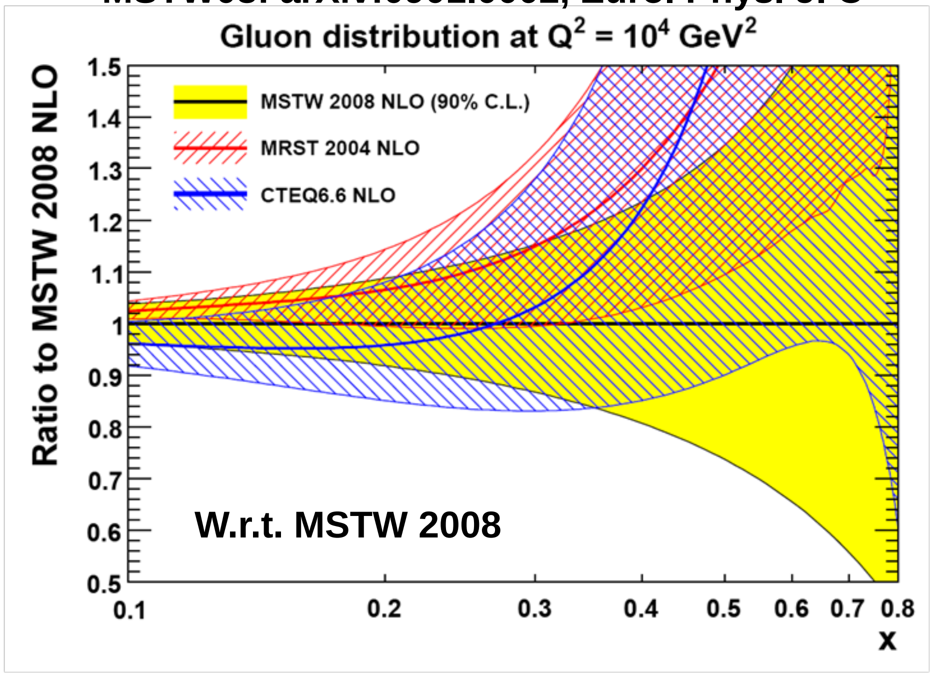
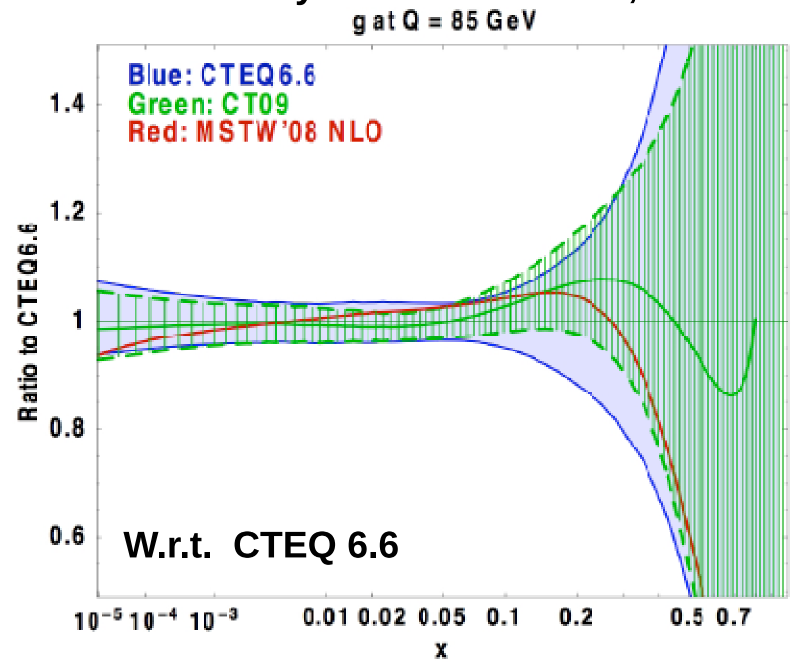
PDF with Recent Tevatron Jet Data

MSTW08: arXiv:0901.0002, Euro. Phys. J. C

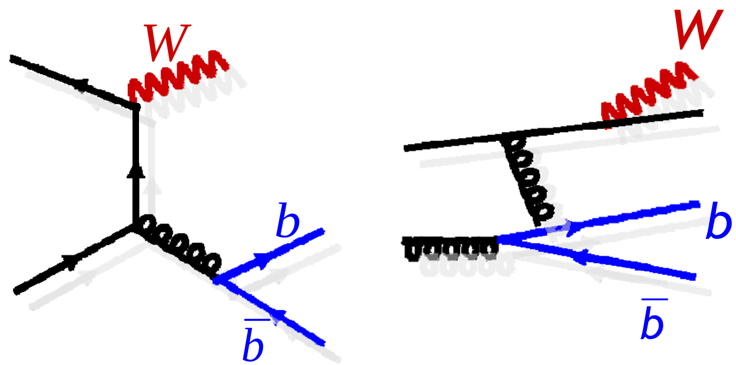


CT09: Phys.Rev.D80:014019,2009.



- Tevatron Run II data lead to softer high-x gluons (more consistent with DIS data) and help reducing uncertainties
- MSTW08 does not include Tevatron Run 1 data any longer while CT09 (CTEQ TEA group) still does, which makes MSTW08 high-x even softer (consistent within uncertainty)

W+*b*-jets production



Large bkgd for many analyses

- SM Higgs (WH) production
- Single top quark production
- $t\bar{t}$ production

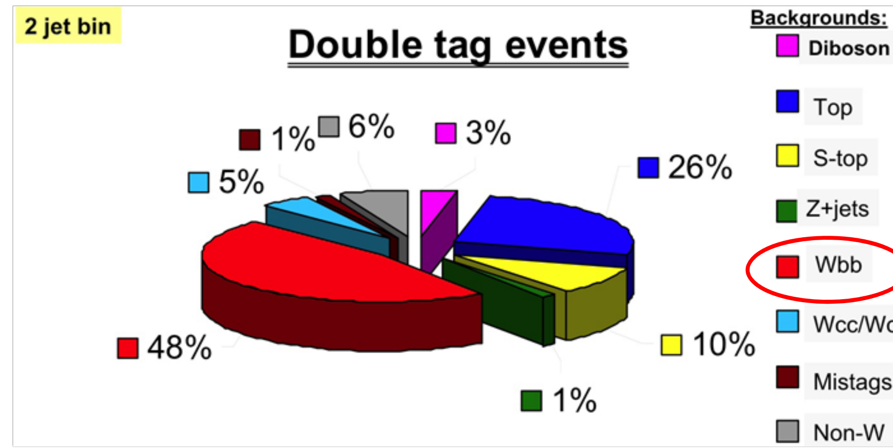
(See Bernd's and Krisztian's talks.)

Can we better understand this bkgd?

Both electron and muon channels

Jets with Et > 20 GeV and |η| < 1.5

WH→lvbb search



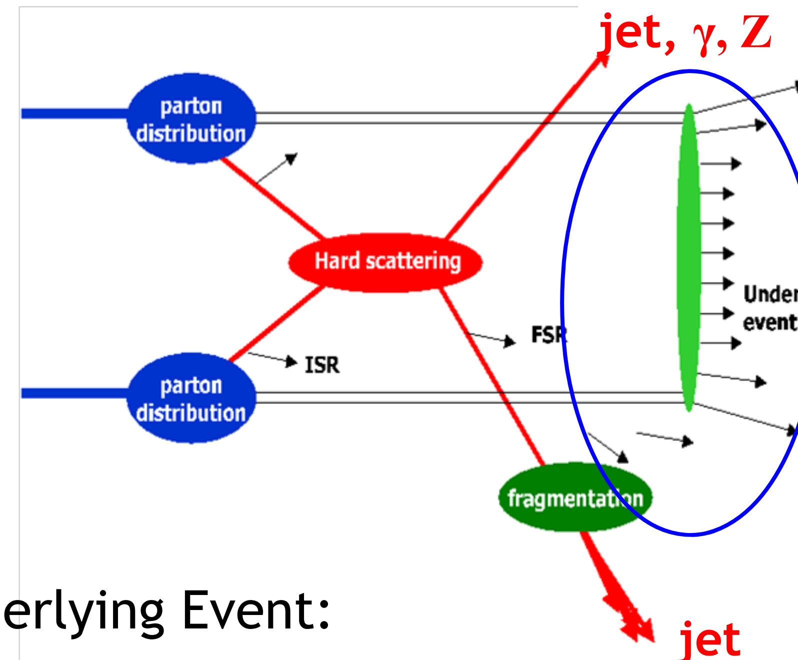
$\sigma \cdot B = 2.74 \pm 0.27(stat) \pm 0.42(syst)\ pb$

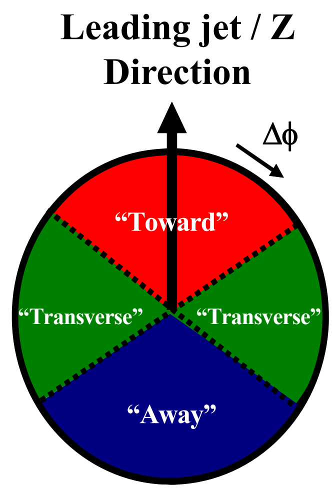
$NLO: 1.22 \pm 0.14\ pb$

$Alpgen: 0.78\ pb$ **arXiv: 0909.1505**

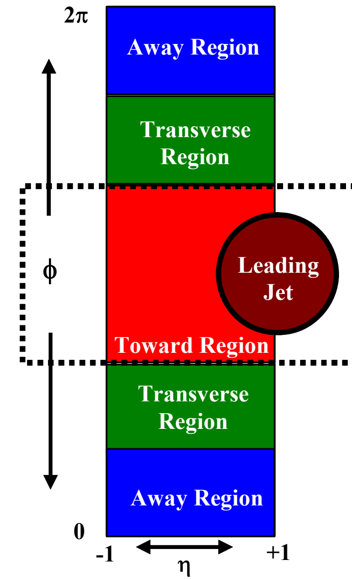
Success of NLO QCD. Awaiting for differential measurements.

UE in Jet and Drell-Yan Production





Transverse plane



η-ϕ Plane

Underlying Event:
everything except hard scatter

Jet production:

- Transverse region sensitive to UE
- High statistics jet sample
- Studies in various dijet topologies

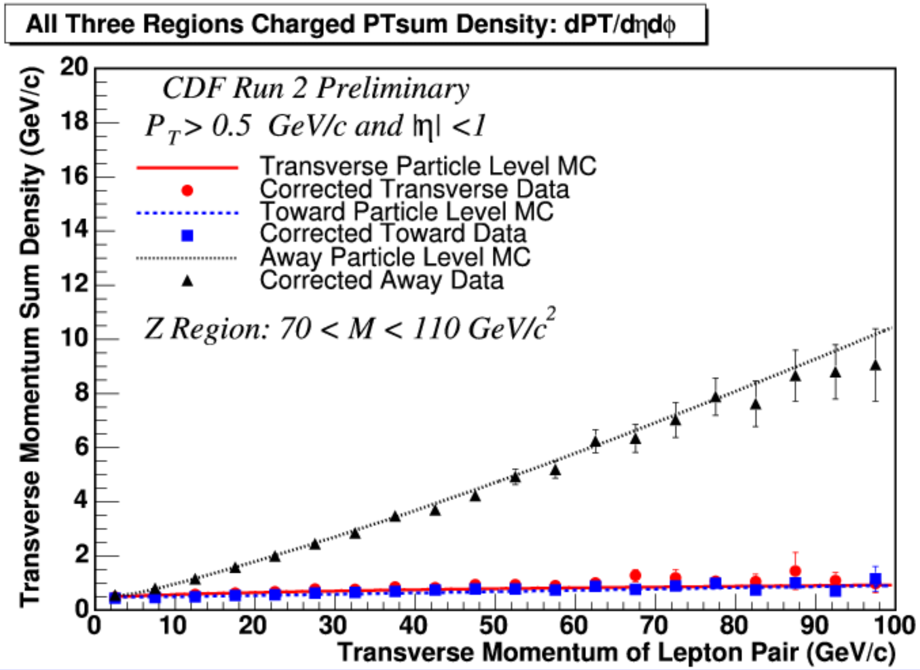
DY production:

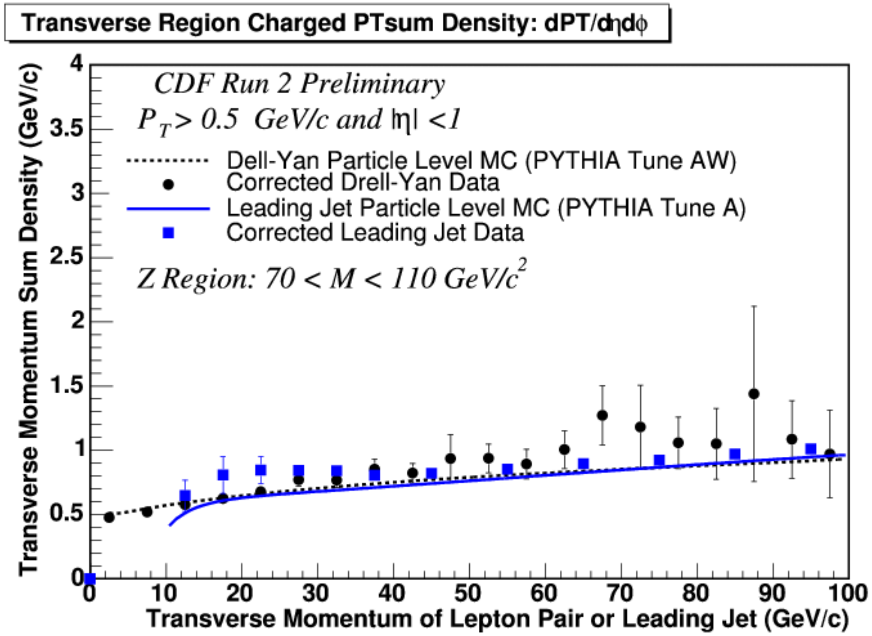
- Transverse and toward regions (excluding lepton-pairs) sensitive to UE
- Cleaner environment (Z/γ* carries no color)
- Limited statistics

UE in DY and Jet Production

Comparisons of three regions

- Away region p_T density goes up with lepton-pair p_T, while the transverse and toward region p_T densities are mostly flat with lepton-pair p_T



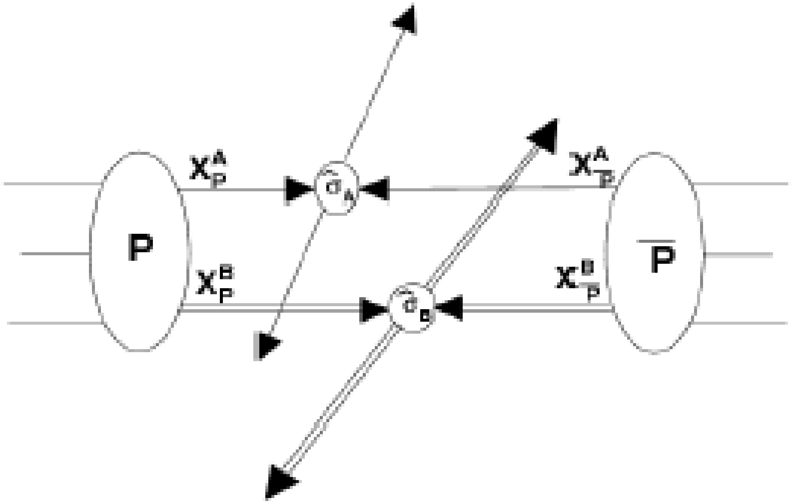


Comparisons between jet and DY

- Similar trend in jet and DY events: UE universality?
- Tuned Pythia describe data reasonably well.

There are many more plots for UE in jet and Drell-Yan production corrected to hadron level: Very important for MC generator tuning/development

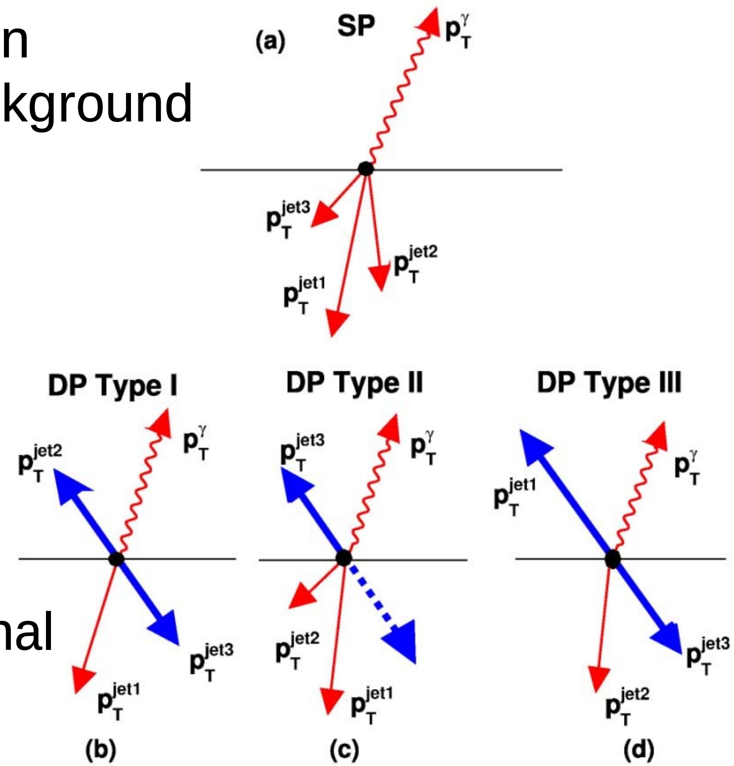
Double Parton using γ+3 Jets



$$\sigma_{DP} = \sigma_{\gamma j}\,\sigma_{jj}/\sigma_{eff}$$

σ_{eff} : effective interaction region
(Large σ_{eff}: partons more uniformly distributed)

Main background



signal

- Study interactions of two parton pairs in single proton:
  - Insight to parton spatial distributions in the proton
  - Background to other process especially at high luminosities

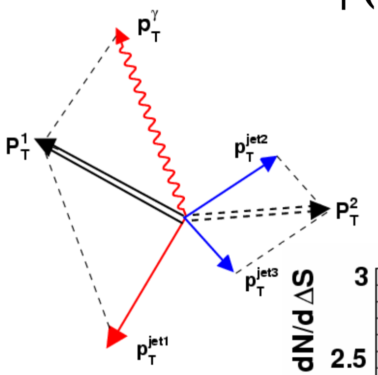
Double Parton Scattering

- Calculated for the pair that gives the minimum value of *S*:

$$S_\varphi = \frac{1}{\sqrt{2}}\sqrt{\left(\frac{\Delta\varphi(\gamma,i)}{\delta\varphi(\gamma,i)}\right)^2 + \left(\frac{\Delta\varphi(j,k)}{\delta\varphi(j,k)}\right)^2}$$

$$S_{p_T} = \frac{1}{\sqrt{2}}\sqrt{\left(\frac{|\vec{p}_T(\gamma,i)|}{\delta p_T(\gamma,i)}\right)^2 + \left(\frac{|\vec{p}_T(j,k)|}{\delta p_T(j,k)}\right)^2}$$

$$\Delta S = \Delta\phi(p_T^{\gamma,jet-i}, p_T^{jet-j,jet-k},)$$



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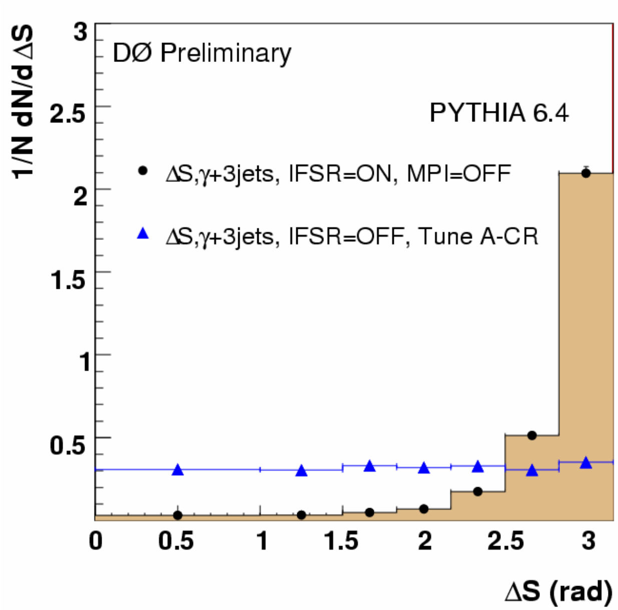

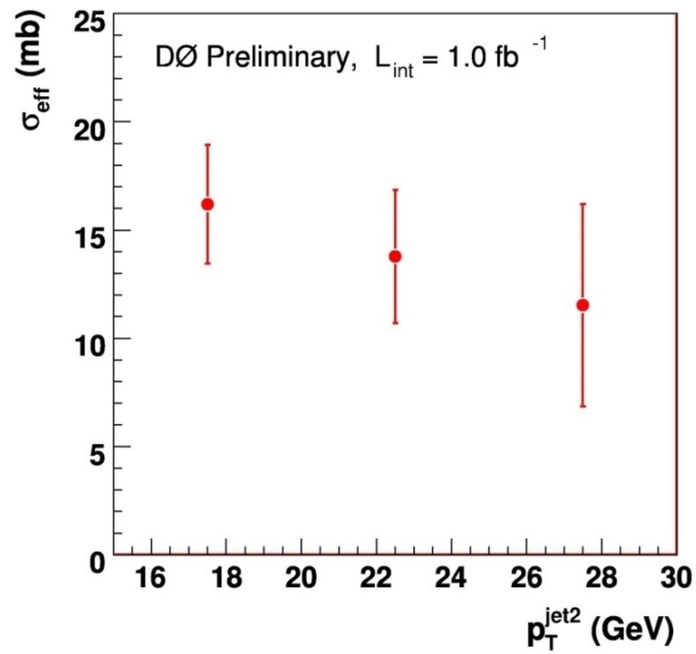

σ_{eff} = 15.1±1.9 mb

(consistent with previous CDF results.)