QCD Tevatron Results

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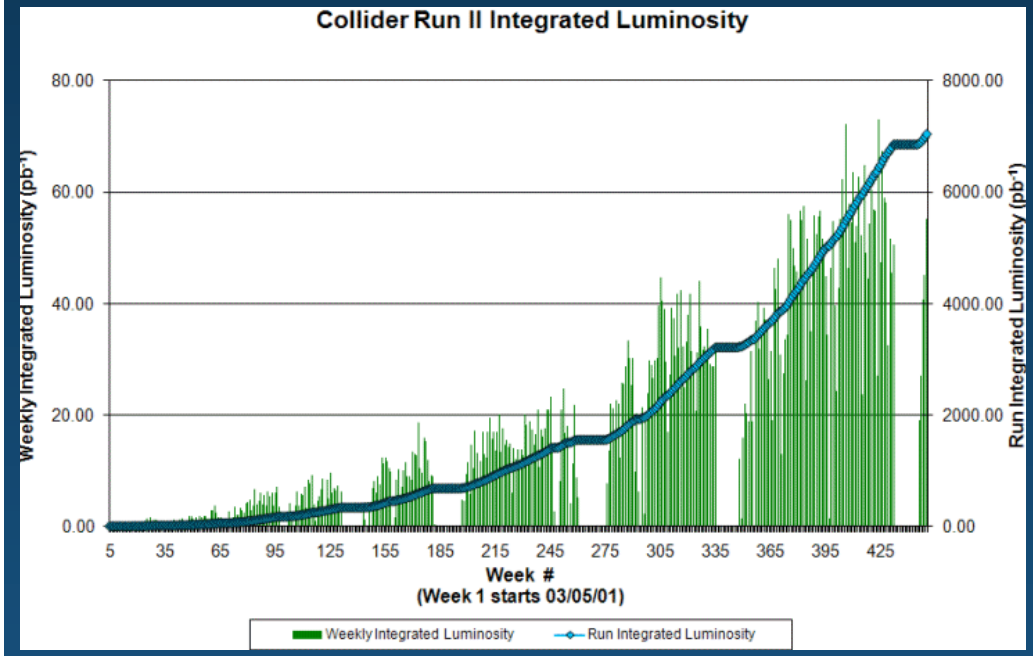
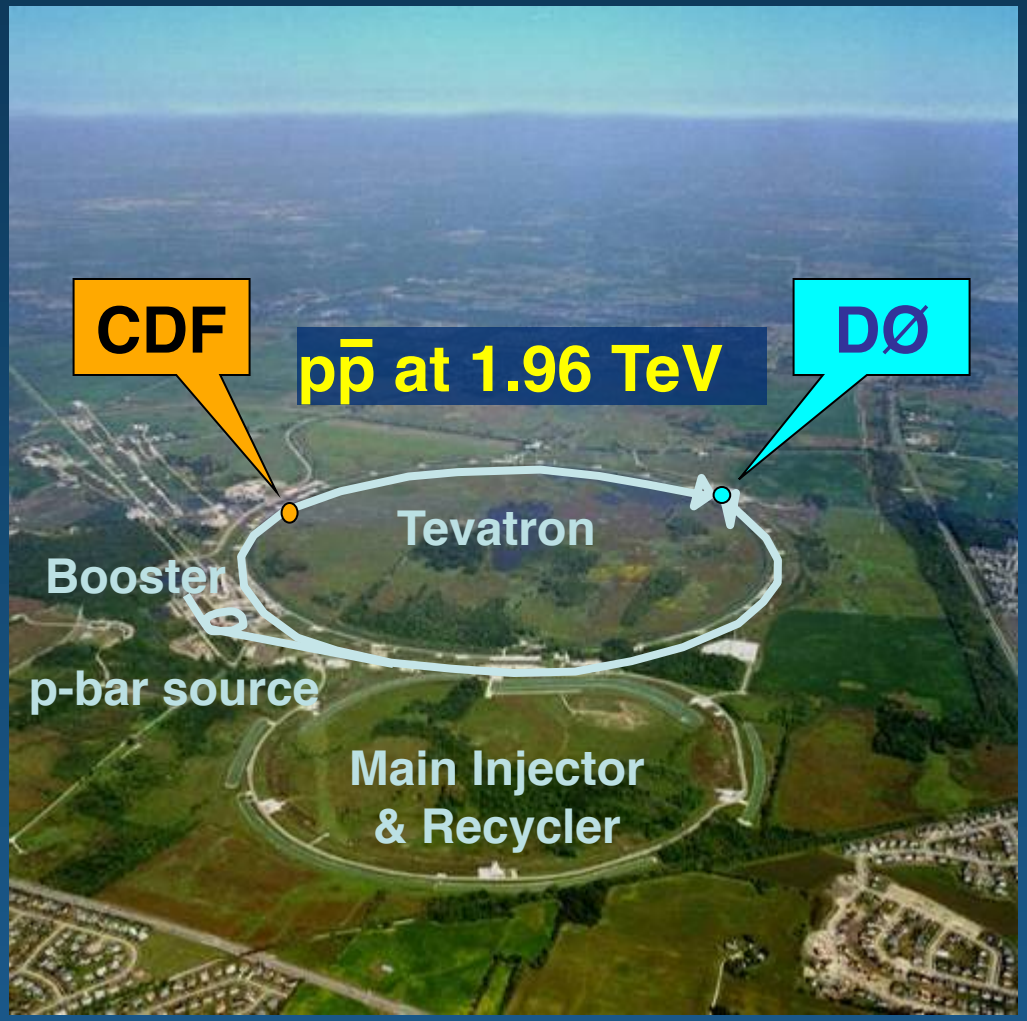
Representing the CDF and DØ Collaborations

XXth Hadron Collider Physics Symposium
HCP 2009
Evian, France
2009.11.16

Fermilab Tevatron – Run II





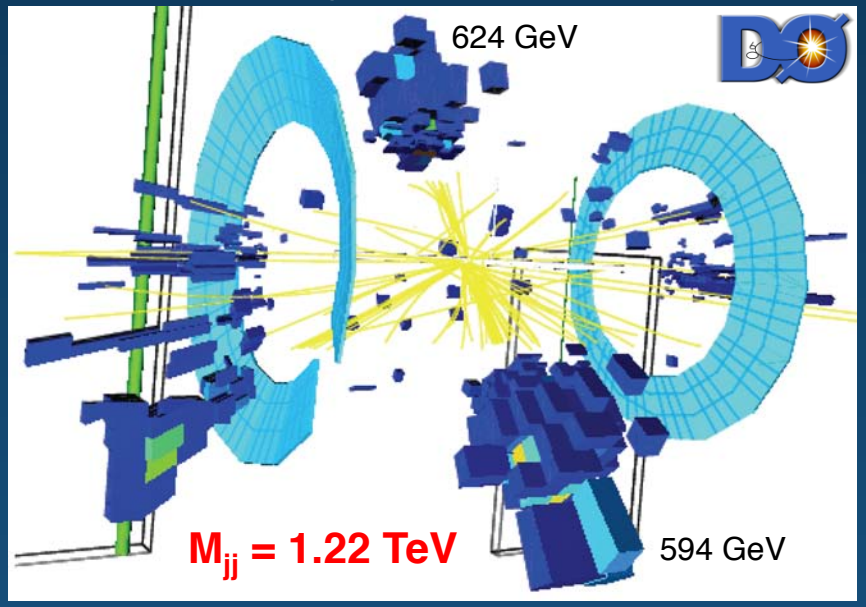
36 × 36 bunches; 396 ns spacing
Run II began March 2001
Delivered luminosity: ~7 fb^{-1}
Acquired luminosity: ~6 fb^{-1}/ experiment

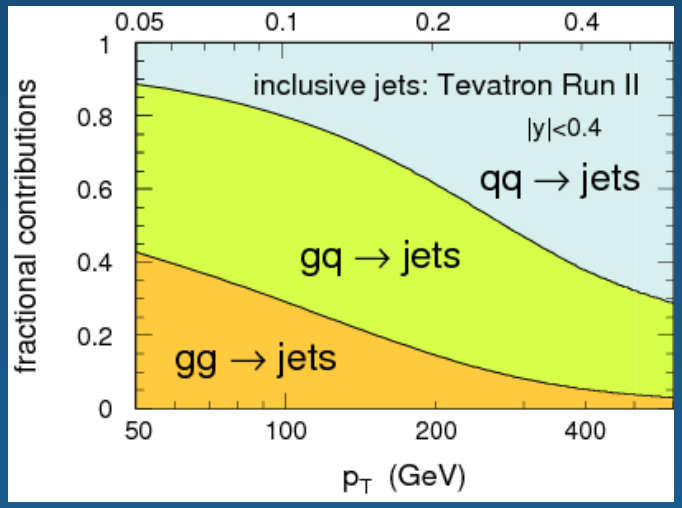
This talk: analyses covering up to 2.7 fb^{-1}

Run II goal: 12 fb^{-1} before end 2011

Quantum Chromodynamics in Hadron Collisions

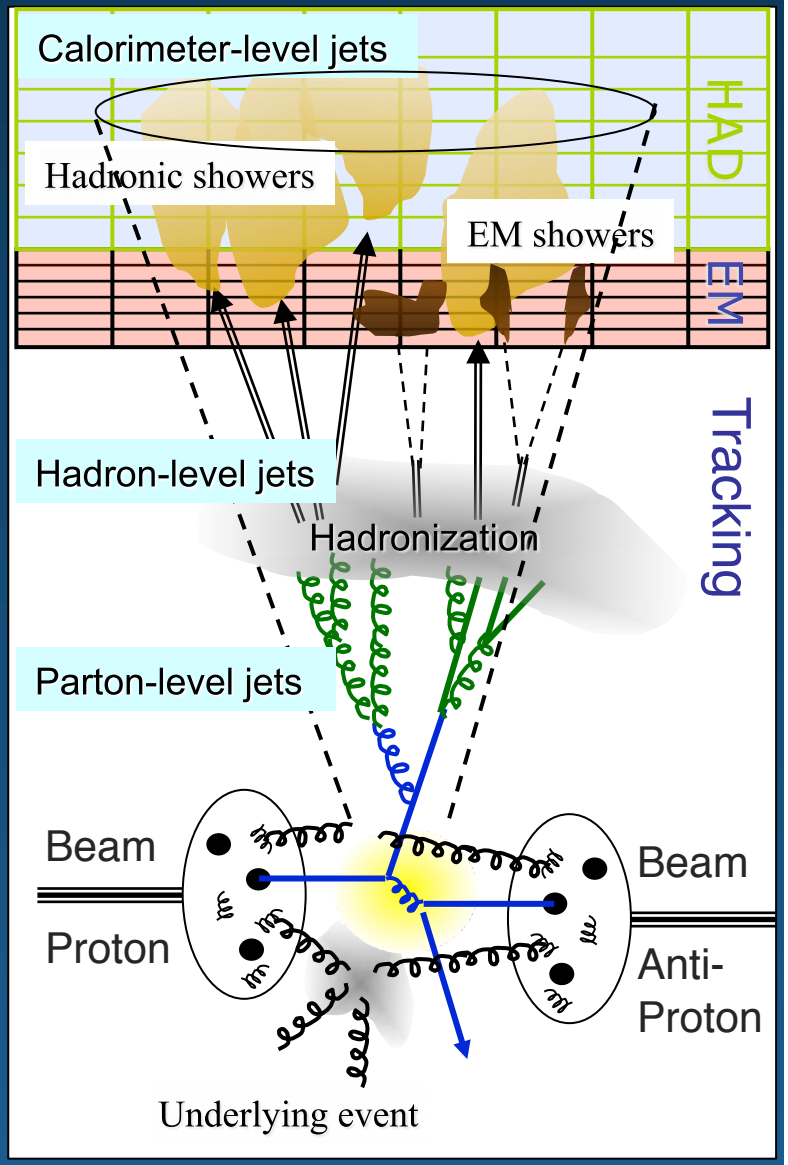
3-jet Event





Unfold measurements to hadron level

Correct parton-level theory for non-perturbative effects (*e.g.*, hadronization, underlying event)



Primary Aims

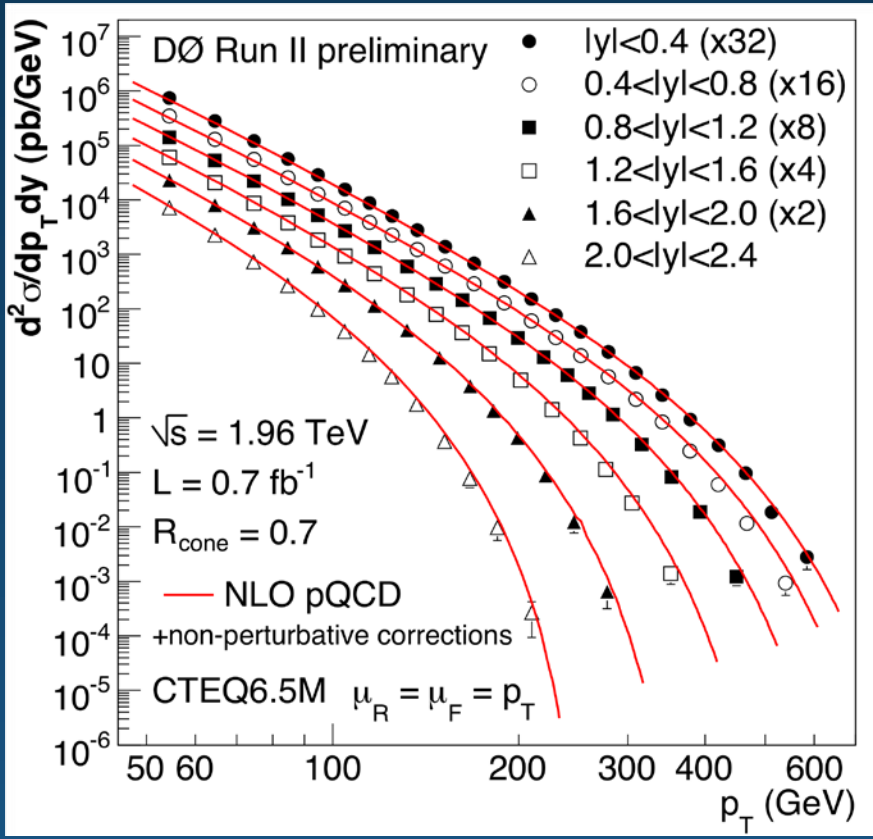
- Search for New Phenomena
- Test perturbative QCD (pQCD)
- Inform MC/background models

Selected Topics [dates released / updated]

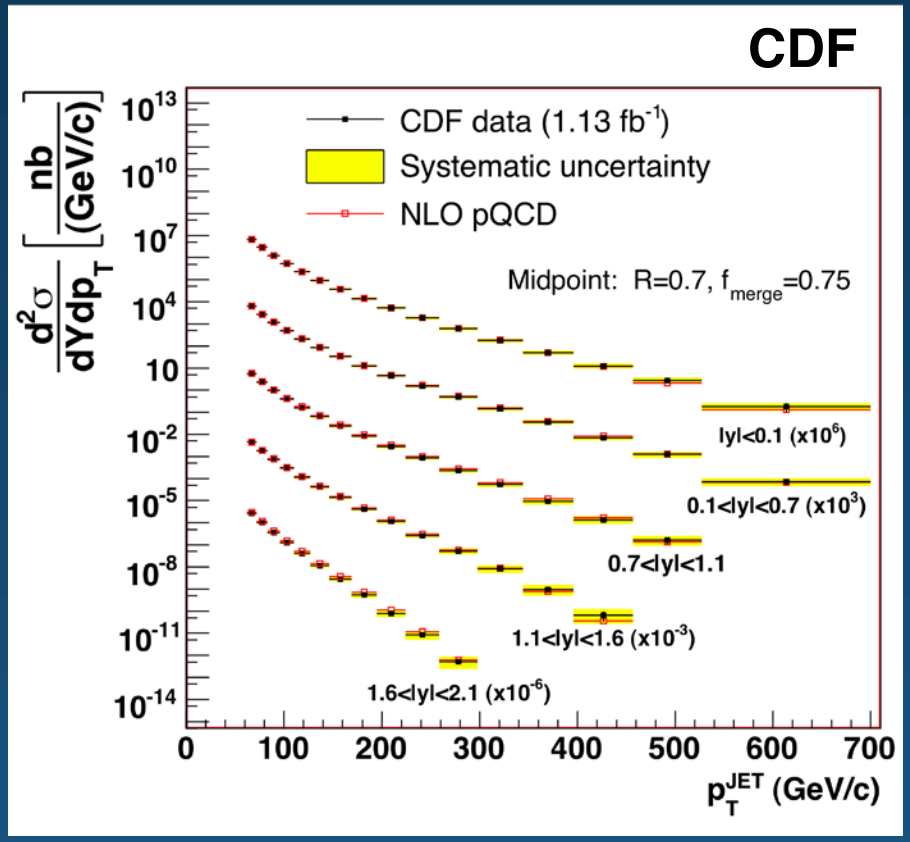
1. Jet Production (Inclusive) [2008.08]
2. Strong Coupling Constant α_s [2009.08]
3. Dijet Production (Inclusive) [2009.04]
4. Dijet Angular Distributions [2009.06]
5. Prompt Isolated Photon Production (Inclusive) [2009.01]
6. Double-Parton Scattering [2009.04]
7. Central Exclusive Particle Production [2008.11]
8. k_T Distributions of Intra-Jet Particles [2008.11]
9. The Underlying Event [2008.07]
10. Minimum-Bias Particle Production [2009.10]

All topics are new or have updated aspects since HCP 2008

1. Inclusive Jet Production



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



Phys. Rev. D **78**, 052006 (2008)

Effect of ±1% in jet energy calibration
- ➔ ±(5 – 10)% central x-section
- ➔ ±(10 – 25)% forward x-section

Test of pQCD over 10^8 in $d^2\sigma/dp_T dy$

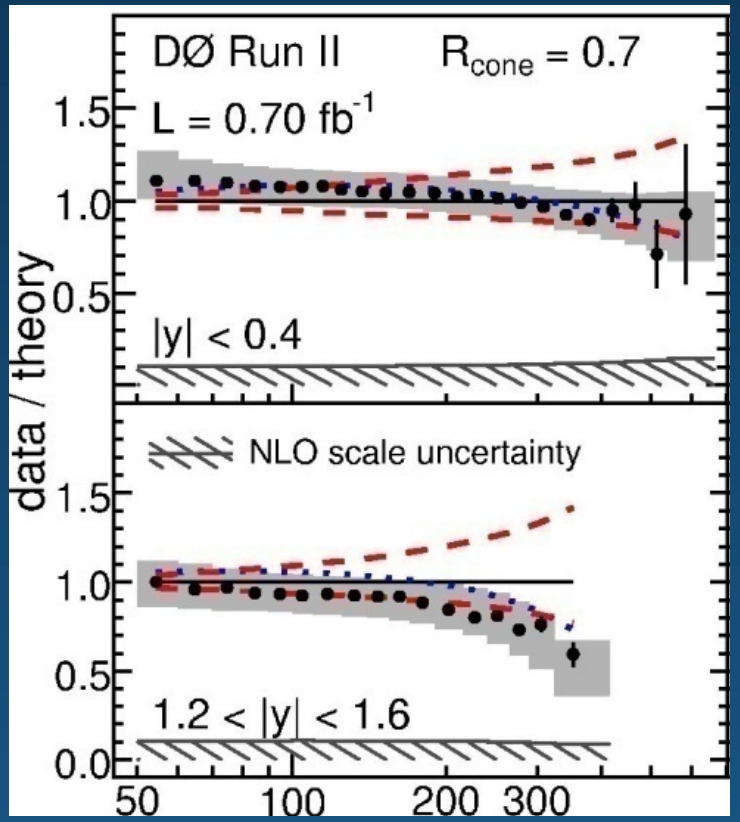
<u>Run II vs. Run I</u>

~10× data

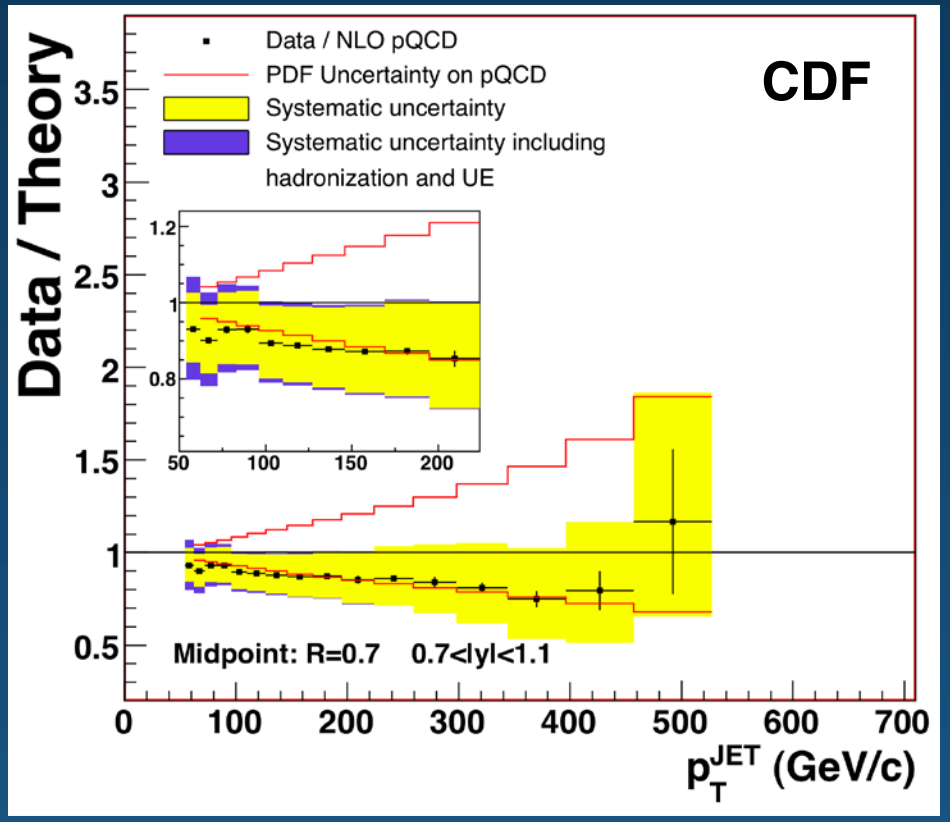
√s: 1.8 ➔ 1.96 TeV

Highest p_T(jet) > 600 GeV

1. Inclusive Jet Production



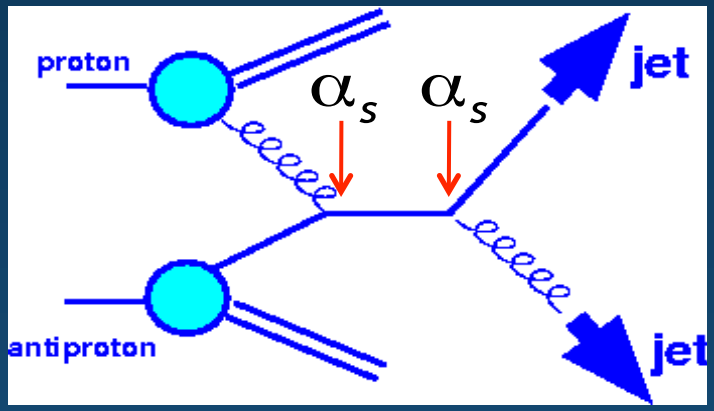
Phys. Rev. Lett. **101**, 062001 (2008)



Phys. Rev. D **78**, 052006 (2008)

CDF and D0 results agree mutually and with NLO pQCD
Precision now exceeds that of the PDF uncertainties
Data can inform the PDF fits: Suggestive of softer gluons at high-x

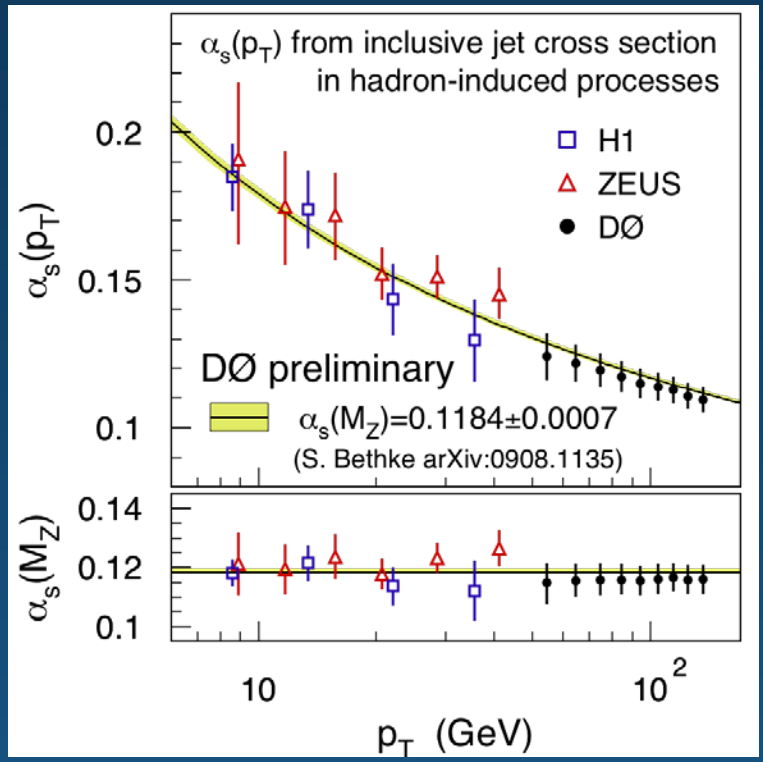
2. Strong Coupling Constant α_s



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

Derived from 22 / 110 inclusive jet cross section points in $50 < p_T < 145$ GeV
(high-x points excluded to minimize PDF correlations)

NLO + 2-loop threshold corrections, MSTW2008NNLO PDFs



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

3.5 – 4.2% precision

[Consistent with CDF Run I result using $40 < p_T < 250$ GeV Phys. Rev. Lett. **88**, 042001 (2002)]

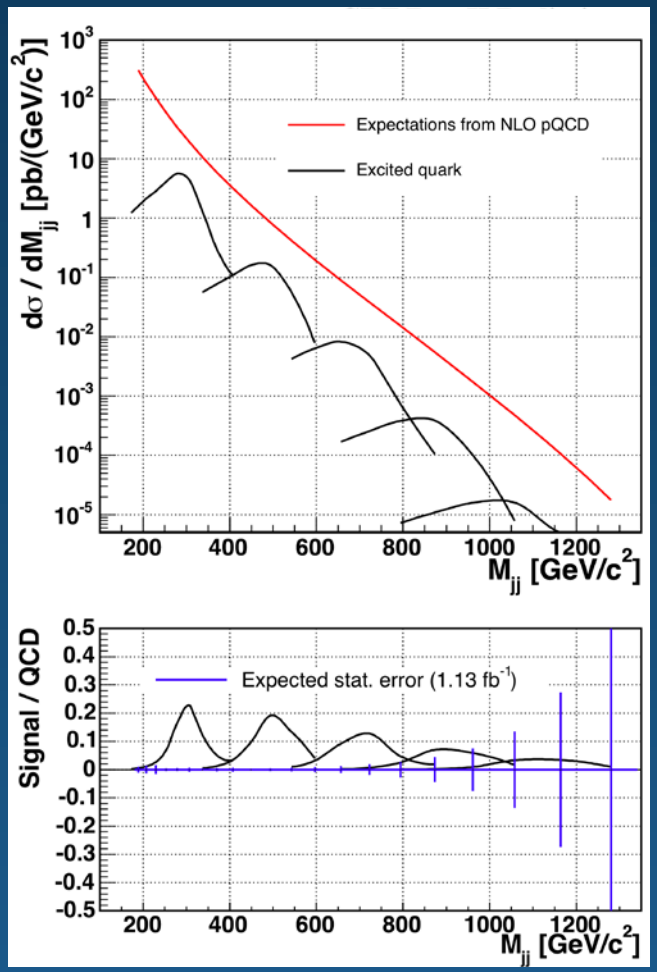
http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/QCD/Q15/

3. Dijet Production – Probe for Exotic Physics

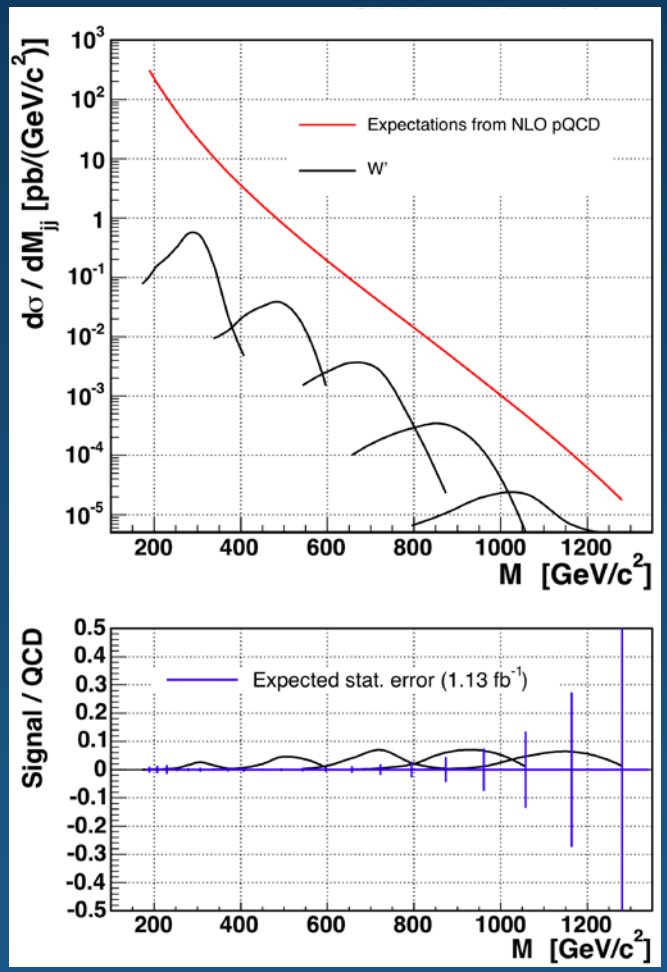
Dijet Invariant Mass Observable M_{jj}:

- SM Extensions predict BSM resonances in M_{jj}
- *e.g.*, q*, Z', W', RS Gravitons, techni-ρ, axigluons / colorons
- Sets stringent exclusion limits
- Tests pQCD predictions

Excited Quark

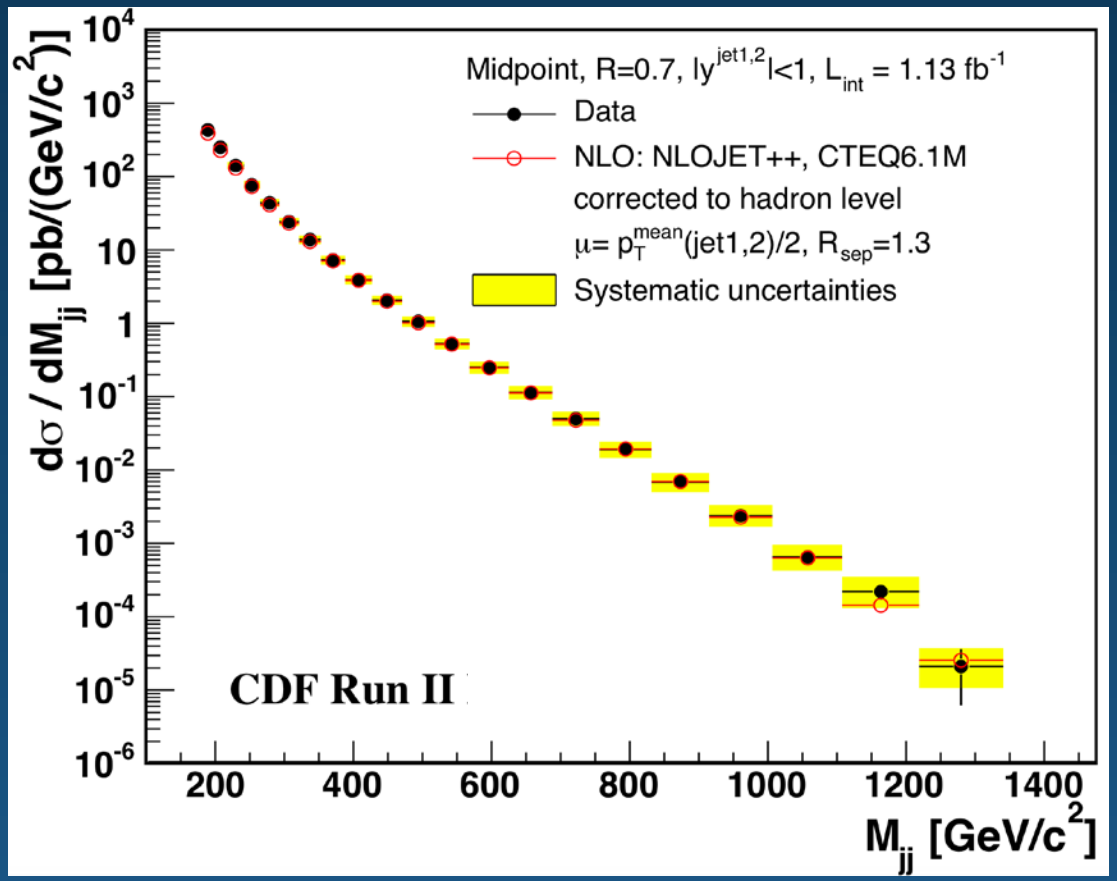


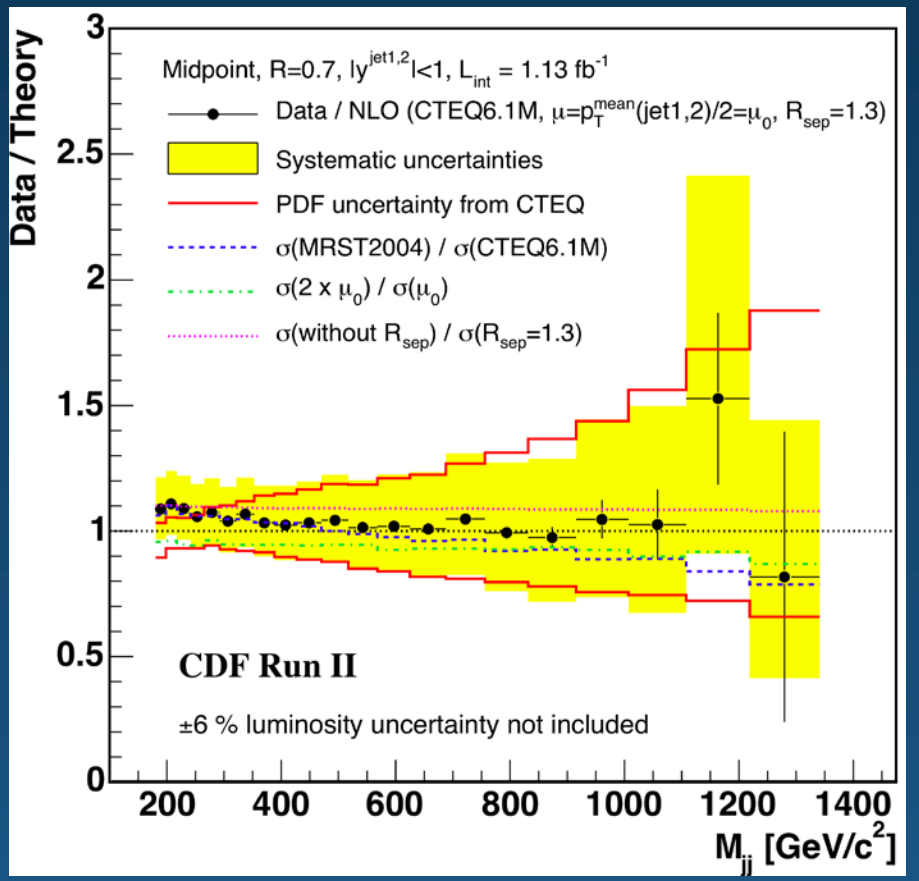
W' Boson



Phys. Rev. D **79**, 112002 (2009)

3. CDF: Dijet Mass Distribution



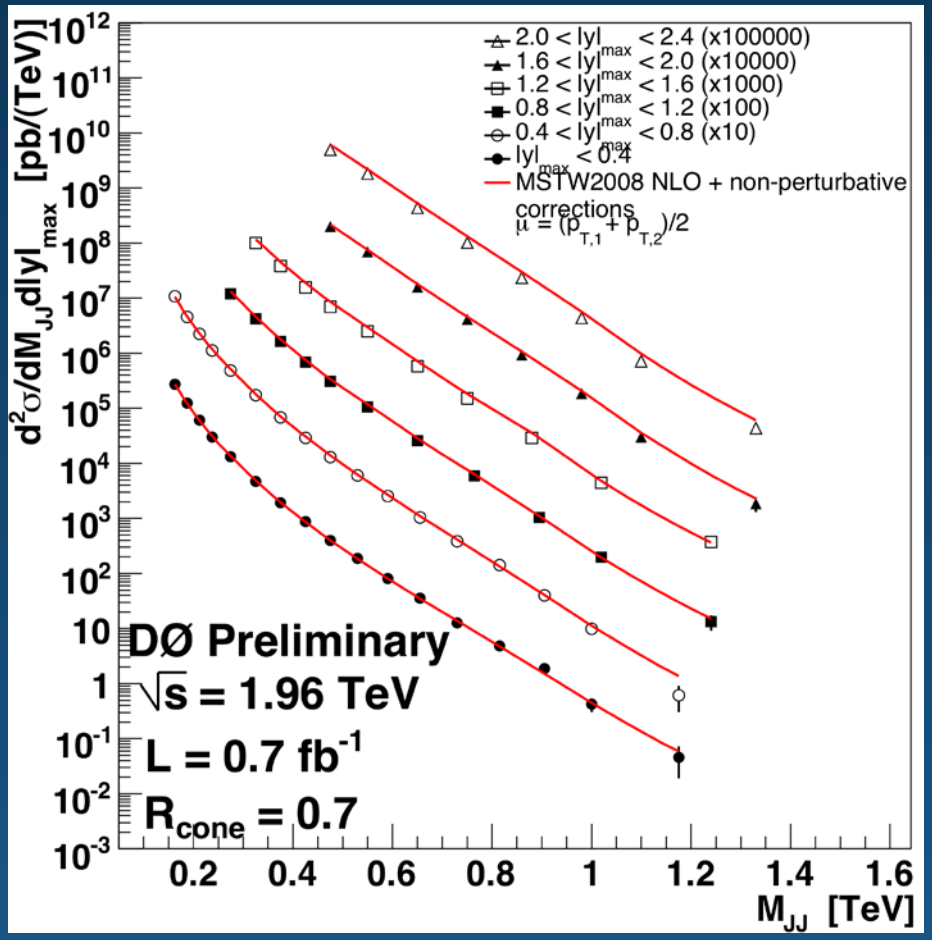


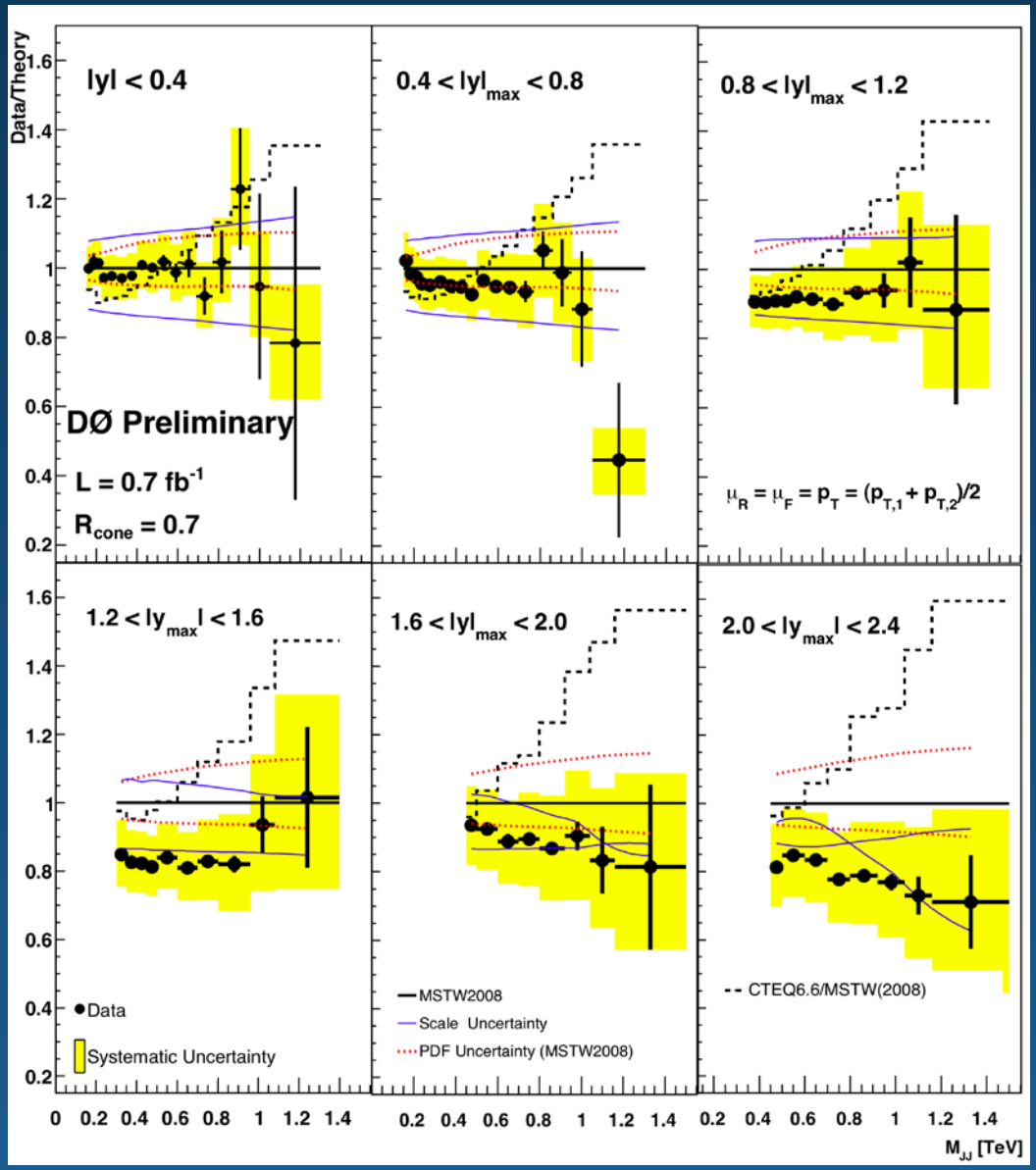
Phys. Rev. D **79**, 112002 (2009)

Central production: $|y^{jet}| < 1$

Mass reach now beyond ~ 1.2 TeV/c^2 !!

3. D0: Dijet Mass Distribution





http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/QCD/Q14/

Extend pQCD test to forward y regions
Mass reach now beyond ~ 1.2 TeV/c^2 !!
[NB: MSTW2008 PDFs include Run II data]

3. Implications: Dijet Mass Distribution

No indications of resonances

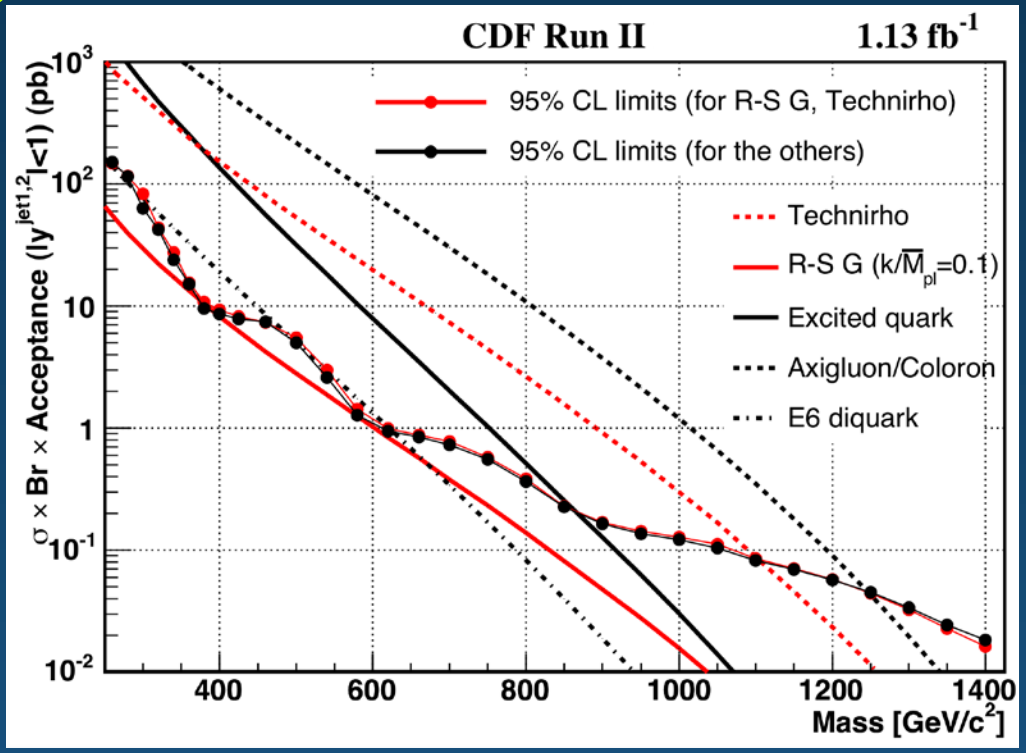
Consistency with NLO pQCD

D0:

- PDF sensitivity at large $|y_{max}|$
- Softer high-x gluons favoured

CDF:

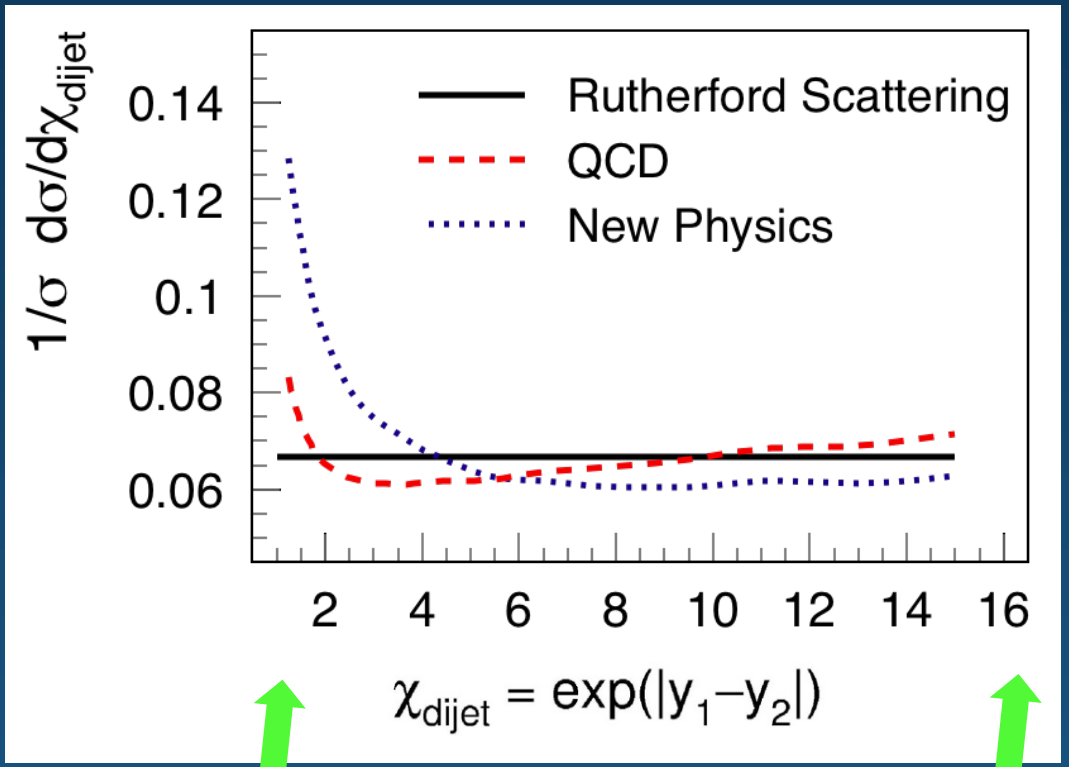
- Stringent limits on many new heavy hypothetical particles

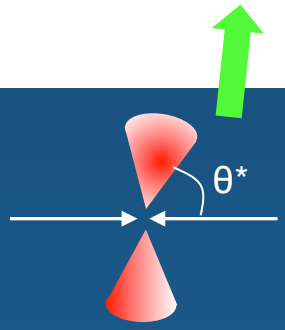


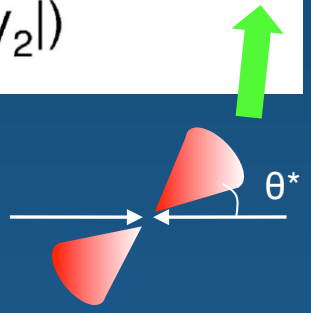
Phys. Rev. D **79**, 112002 (2009)

Model Parent Particle	CDF Mass Exclusion (95% CL)
Excited Quark f=f'=fs=1	260 – 870 GeV/c^2
Colour-Octet techni-ρ	260 – 1100 GeV/c^2
Axigluon / Coloron	260 – 1250 GeV/c^2
E_6 diquark	290 – 630 GeV/c^2
W' (SM couplings)	280 – 840 GeV/c^2
Z' (SM couplings)	320 – 740 GeV/c^2

4. Dijet Angular Distribution







Variable: $\chi_{\rm dijet} = \exp(|y_1 - y_2|)$

At LO, related to CM scattering angle:

$$\chi_{\rm dijet} = \frac{1+\cos\theta^*}{1-\cos\theta^*}$$

- Rutherford scattering: independent
- QCD: mild dependence
- New Physics (*e.g.*, composite quarks, extra spatial dimensions [LEDs]):

  ➔ peaking at central rapidities, low $\chi_{\rm dijet}$

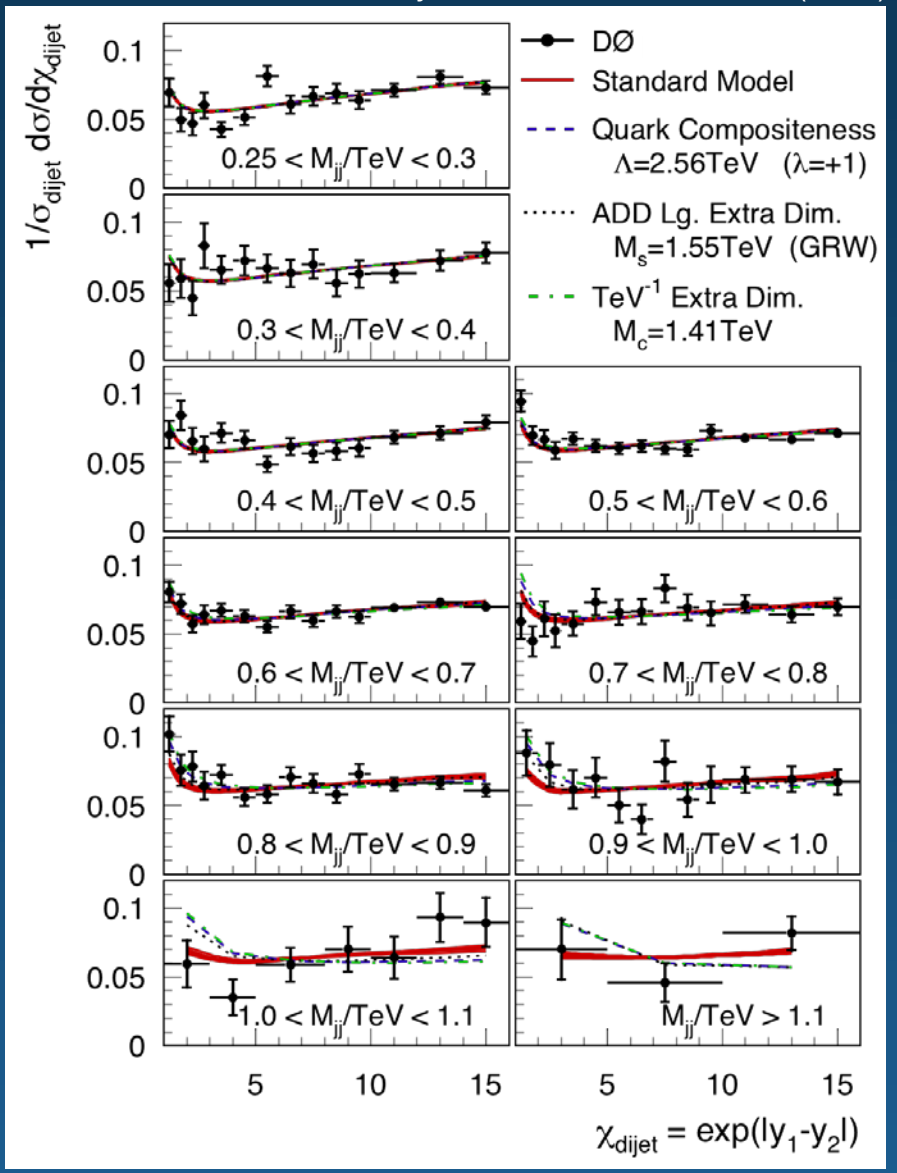
4. Dijet Angular Distribution

Phys. Rev. Lett. **103**, 191803 (2009)

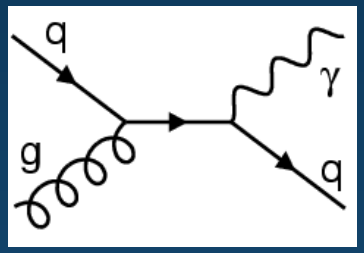
$$\frac{1}{\sigma}\frac{d\sigma}{d\chi_{dijet}}$$

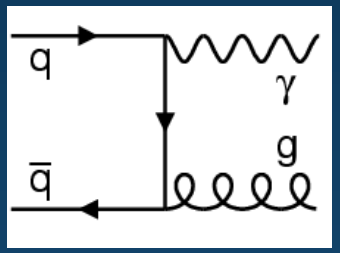
Normalized Distribution:
reduces effect of experimental and theoretical uncertainties

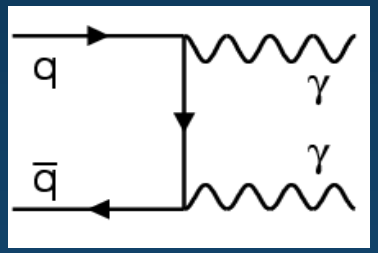
- Findings consistent with NLO pQCD
- Limits on New Physics (95% CL):
  - Quark Compositeness $\Lambda > 2.9$ TeV
  - ADD LED (GRW) $M_s > 1.6$ TeV
  - TeV^{-1} ED $M_c > 1.6$ TeV
- First Rutherford experiment above 1 TeV !!

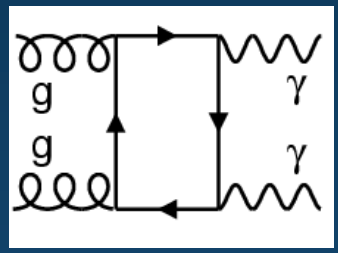


5. Direct Photon Production at the Tevatron

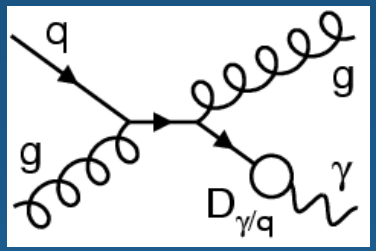


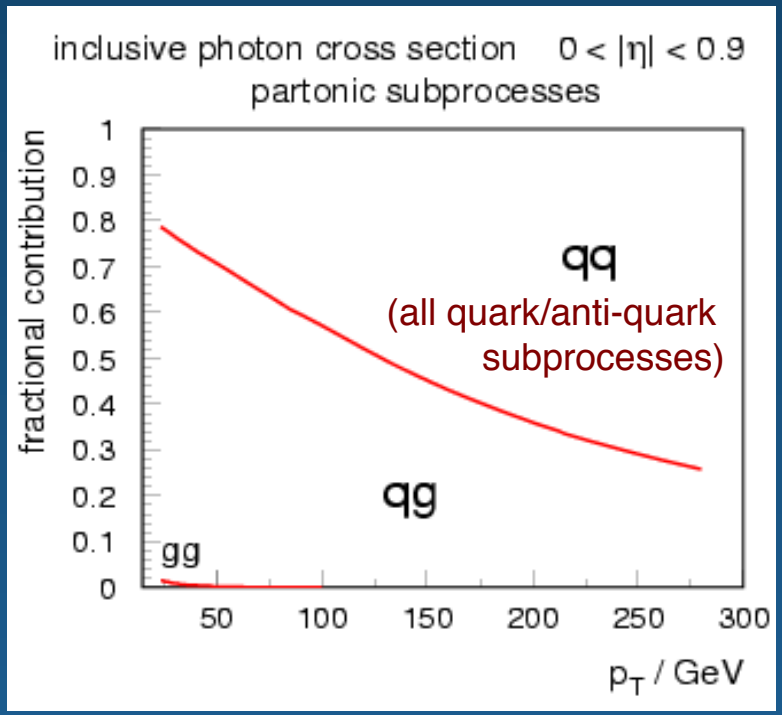




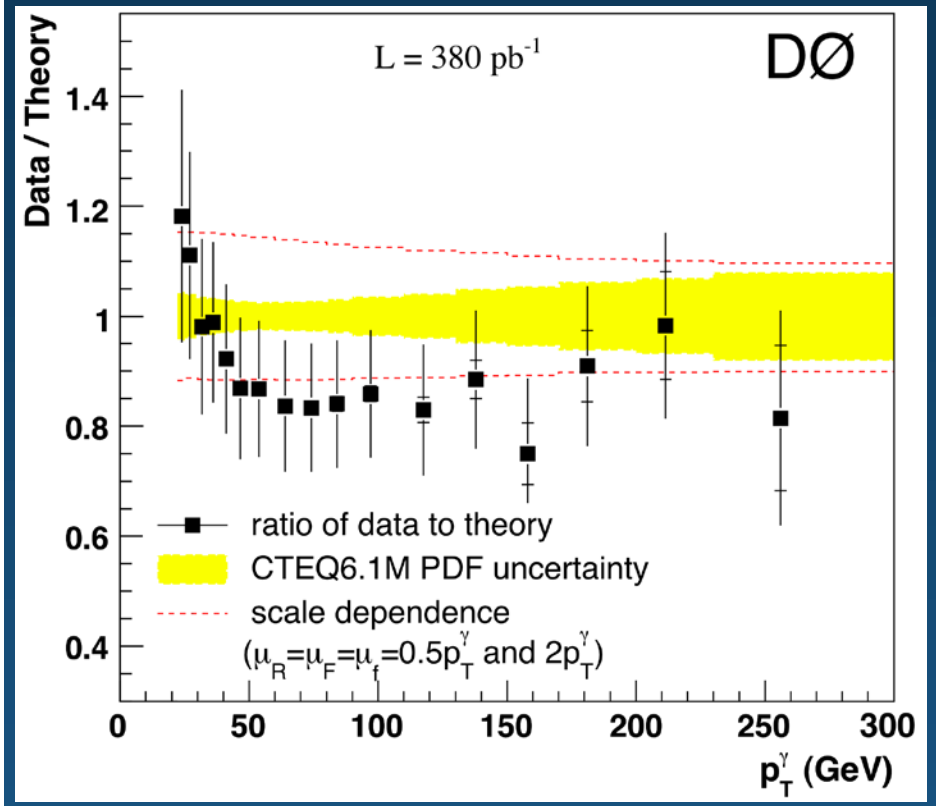


- Photons directly probe the hard scatter dynamics
- Potentially sensitive to gluon PDFs
- To suppress fragmentation photons (and fakes), define isolation criterion in experimental selection
  [*e.g.*, CDF: $E_T < 2$ GeV in $R < 0.4$]

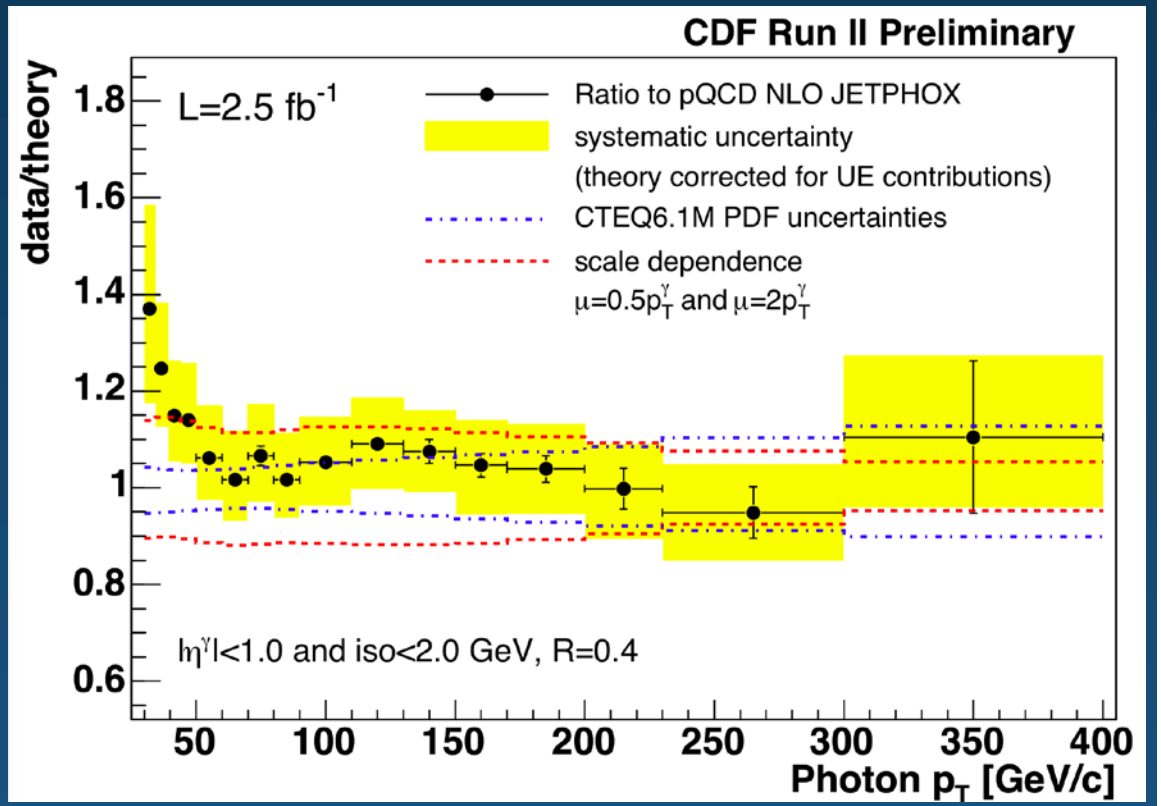




5. Inclusive Isolated Photon Production



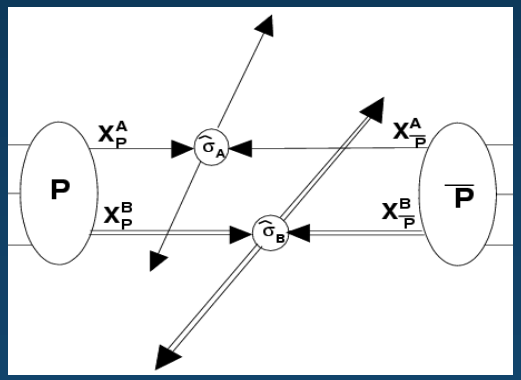
Phys. Lett. B **639**, 151 (2006); Erratum *ibid.* **658**, 285 (2008)



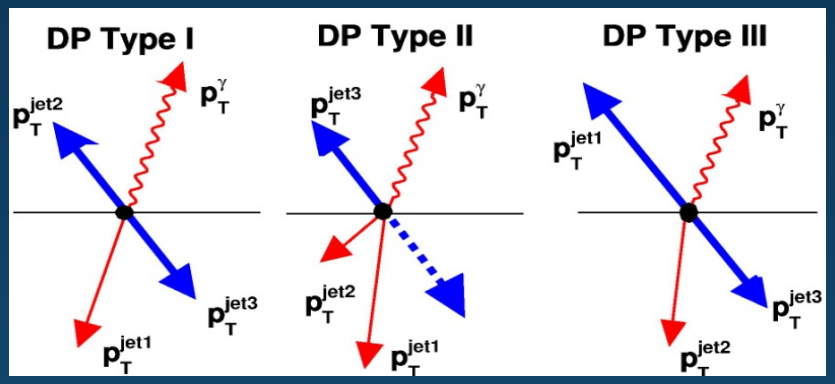
http://www-cdf.fnal.gov/physics/new/qcd/inclpho08/web.html

D0 and CDF measurements agree mutually over $20 < p_T(\gamma) < 400$ GeV
Not sensitive to PDFs: experimental and theoretical uncertainties dominate
Data / NLO pQCD: shape discrepancy in low p_T region (also seen in Run I)

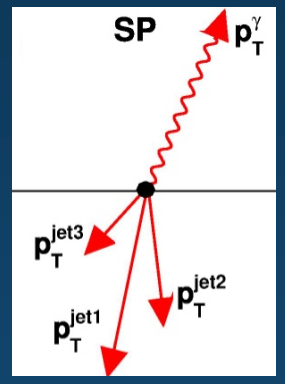
6. Double-Parton Scattering: γ + 3-jet



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



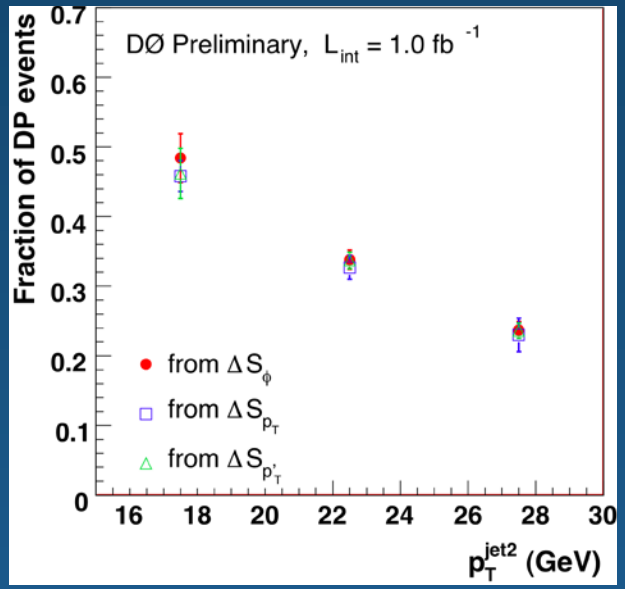
Signal Configurations

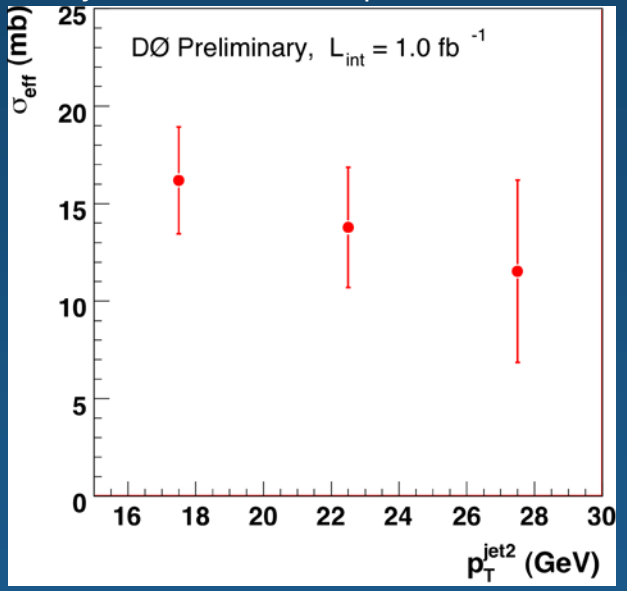


Main Background

http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/QCD/Q13/

- ≥2 partons interact / hadron collision
- Provides info on spatial distribution of partons in proton
- May impact PDFs
- Background to many rare processes
- DP fraction drops from 0.47 ± 0.04 in $15 < p_{T2} < 20$ GeV to 0.23 ± 0.03 in $25 < p_{T2} < 30$ GeV
- Effective cross section ~constant: averages to σ_{eff} = 15.1±1.9 mb
- In agreement with CDF Run I measurement [Phys. Rev. D **56**, 3811 (1997)]



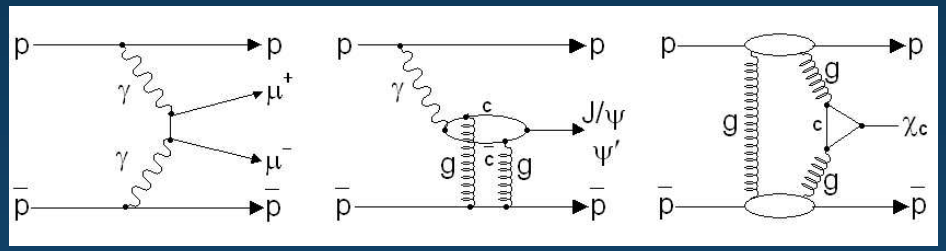


7. Central Exclusive Production

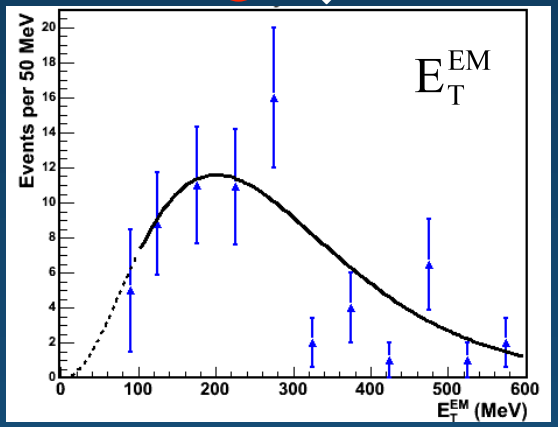
$$p + \bar{p} \rightarrow p + X + \bar{p}$$

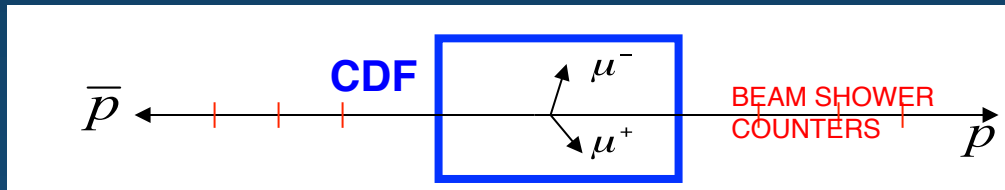
$$X = \gamma\gamma, \chi_c^0, JJ, H$$

CDF LHC

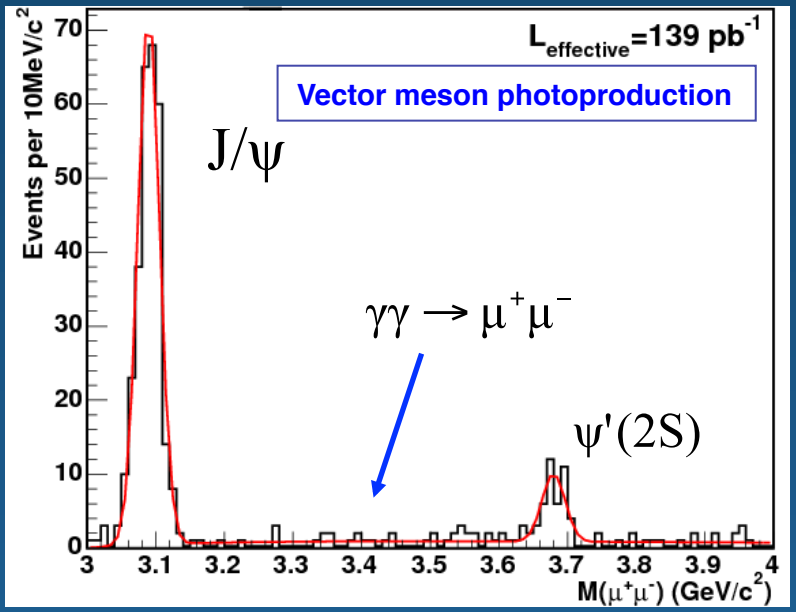


$\rightarrow J/\psi + \gamma$





No other particles (or 1 γ) detected out to |η| = 7.4



Signature:

Colliding hadrons emerge intact

Produced state has small rapidity and is fully measured

Surrounding rapidity regions are devoid of particles

CDF: First Observations

$$p + \bar{p} \rightarrow p + \gamma\gamma + \bar{p}$$

$$p + \bar{p} \rightarrow p + \chi_c + \bar{p}$$

$$p + \bar{p} \rightarrow p + JetJet + \bar{p}$$

Phys. Rev. Lett. **102**, 242001 (2009)
Phys. Rev. D **77**, 052004 (2008)

LHC: Implications

$$pp \rightarrow p(\gamma\gamma)p \rightarrow p(W^+W^-)p...$$

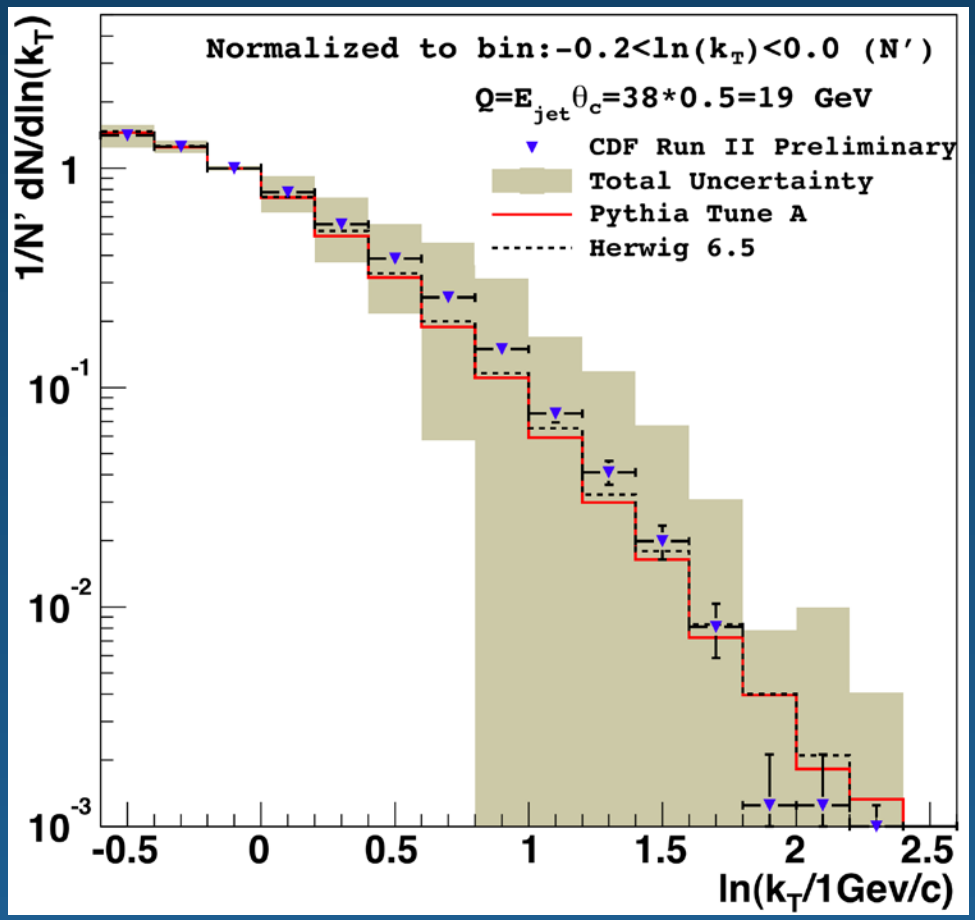
$$pp \rightarrow p(gg)p \rightarrow p(H)p$$

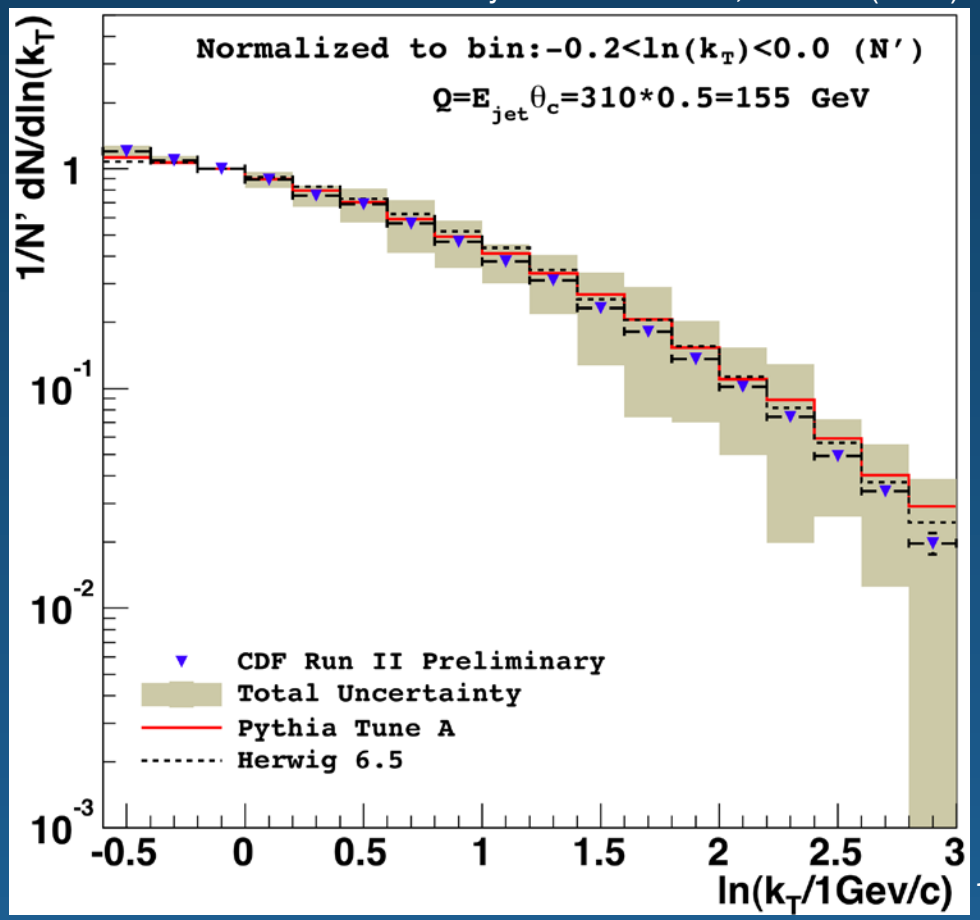
[1-10 fb]

8. k_T Distributions of Particles in Jets

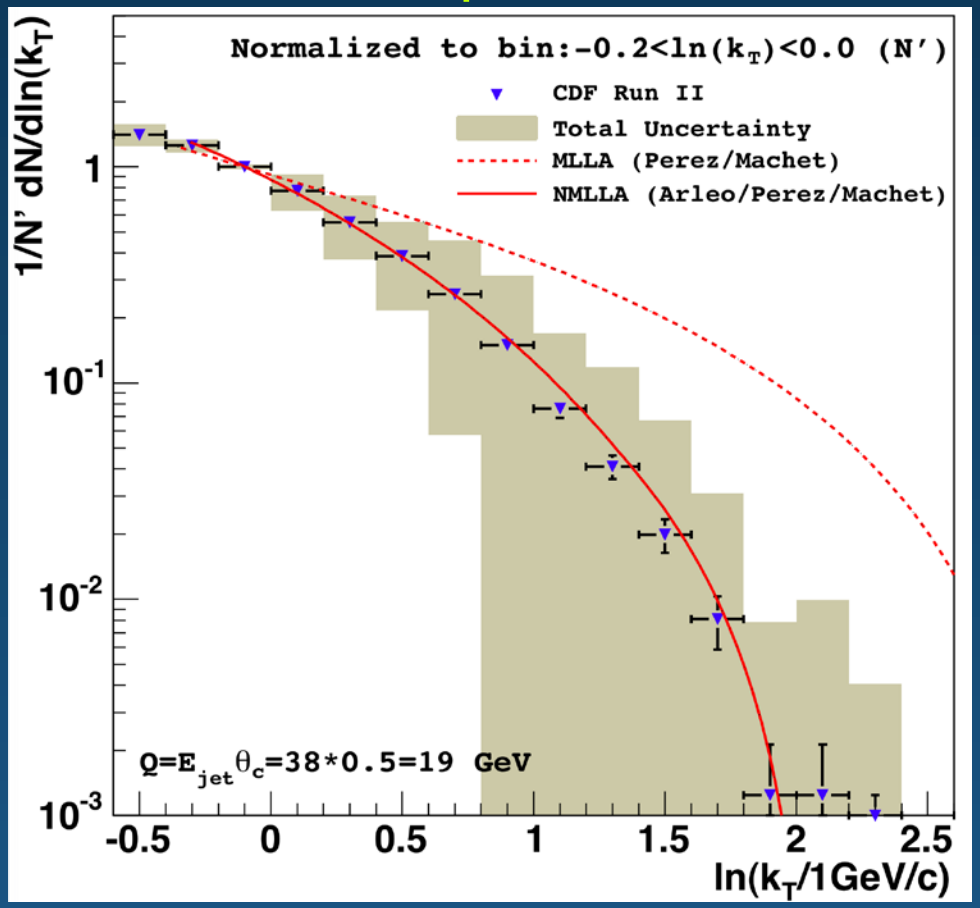
k_T: transverse momenta of intra-jet particles, with respect to their jet axis
Question: Which stage of jet formation principally determines jet characteristics?
Approach: Examine k_T shape distributions vs. jet energy; compare to calculations
Comparisons with Pythia and Herwig:

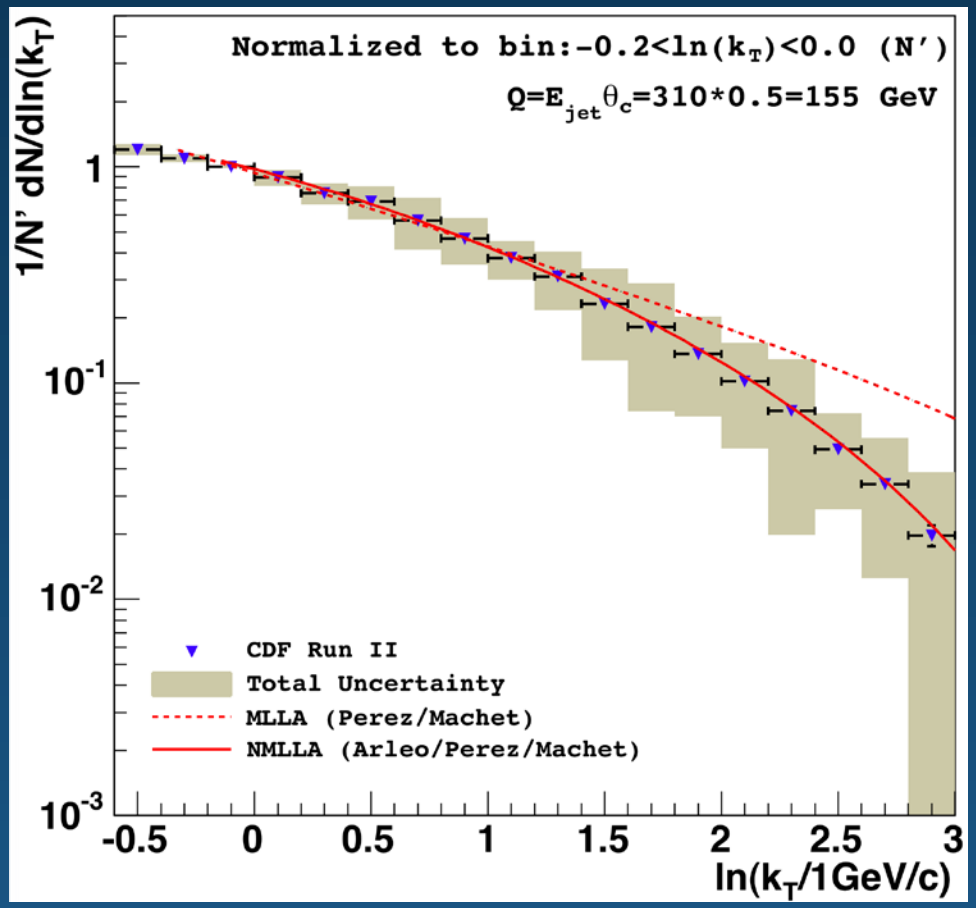
Phys. Rev. Lett. **102**, 232002 (2009)





8. k_T Distributions of Particles in Jets



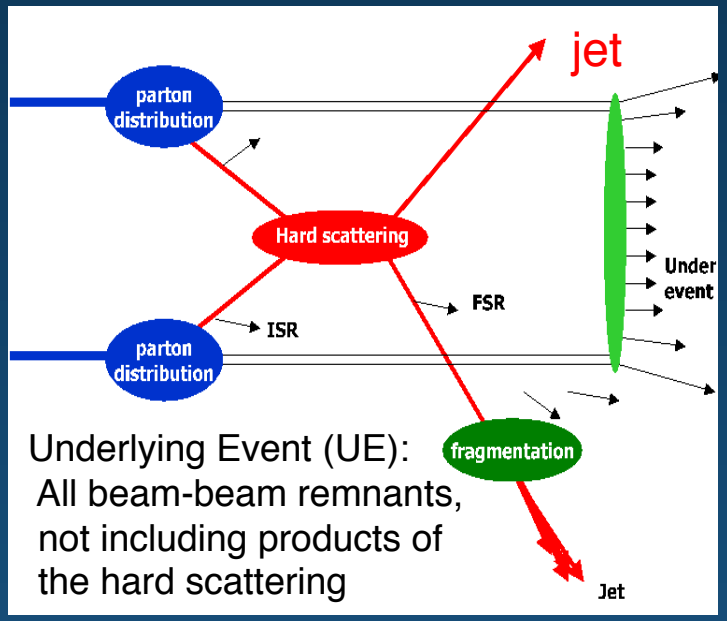


Phys. Rev. Lett. **102**, 232002 (2009)

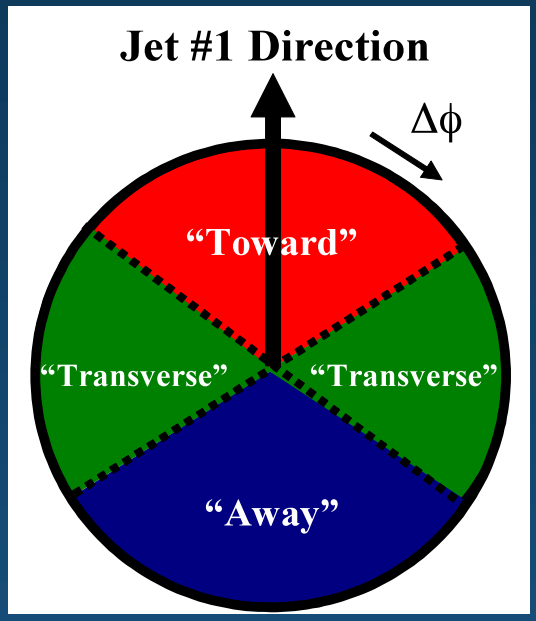
Comparisons to MLLA and NMLLA resummed pQCD predictions:

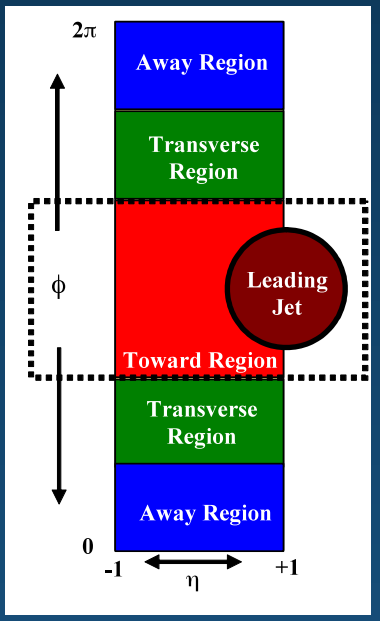
- Jet characteristics derive dominantly from pQCD parton-shower effects
- Non-perturbative hadronization effects are small; LPHD is supported
- NMLLA describes shapes well for dijet masses in the range 66 – 737 GeV/c^2

9. UE in Jet and Drell-Yan Production



Underlying Event (UE):
All beam-beam remnants, not including products of the hard scattering

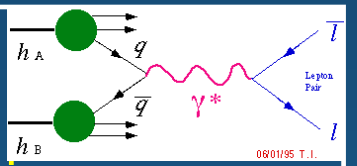




Jet Production

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

Drell-Yan (DY) Production

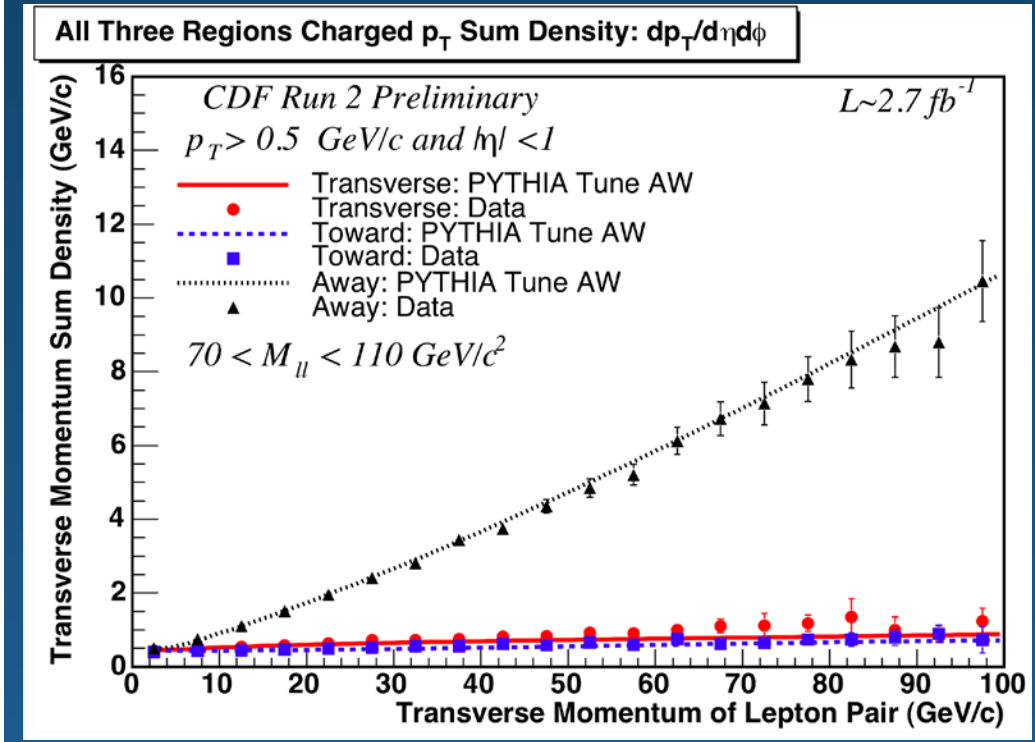


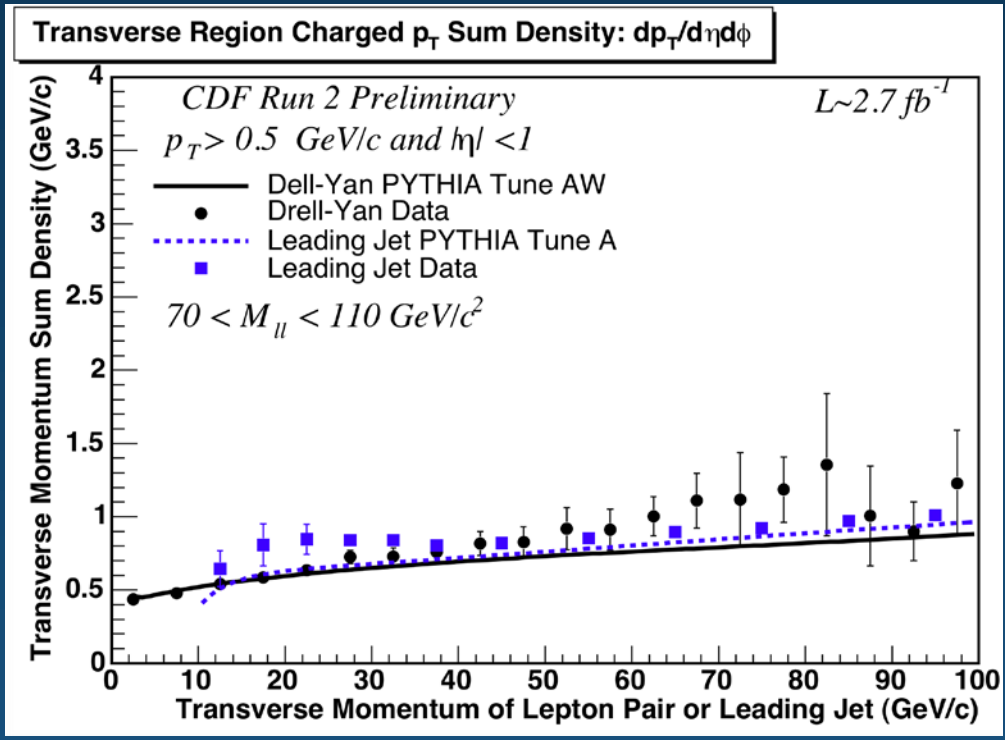
- Transverse and Toward regions (excluding lepton pairs) sensitive to UE
- Cleaner environment (Z/γ* – no colour)
- Reduced statistics

Observables: charged-particle density; p_T sum density; E_T sum density

9. UE in DY and Jet Production

Three Regions Compared:
Away region p_T density rises with lepton-pair p_T, while the Transverse and Toward region p_T densities remain largely insensitive





http://www-cdf.fnal.gov/physics/new/qcd/UEinDY_2008/analysis.html

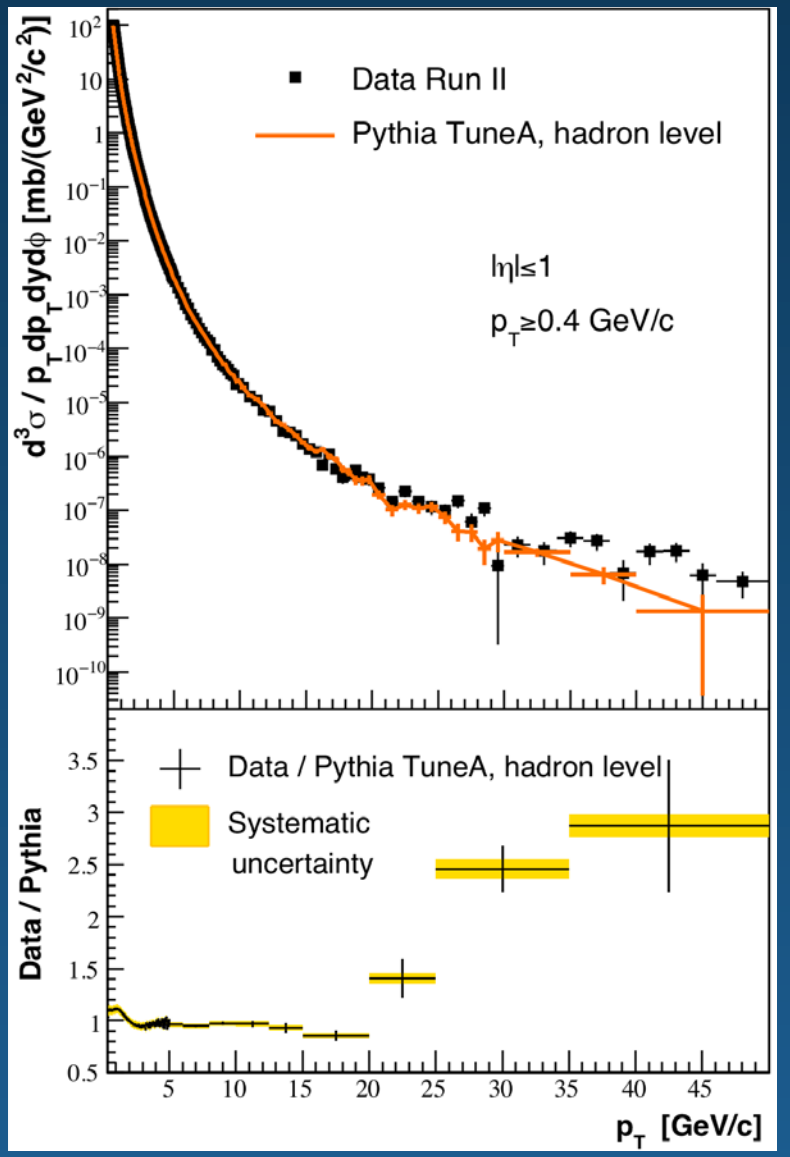
Jet and DY Compared:
Similar trends; UE universality?
Pythia tunes describe data ~well

NB: Many more distributions available; important for MC tuning & development!

10. Minimum Bias Inclusive Particle Production

Phys. Rev. D **79**, 112005 (2009)

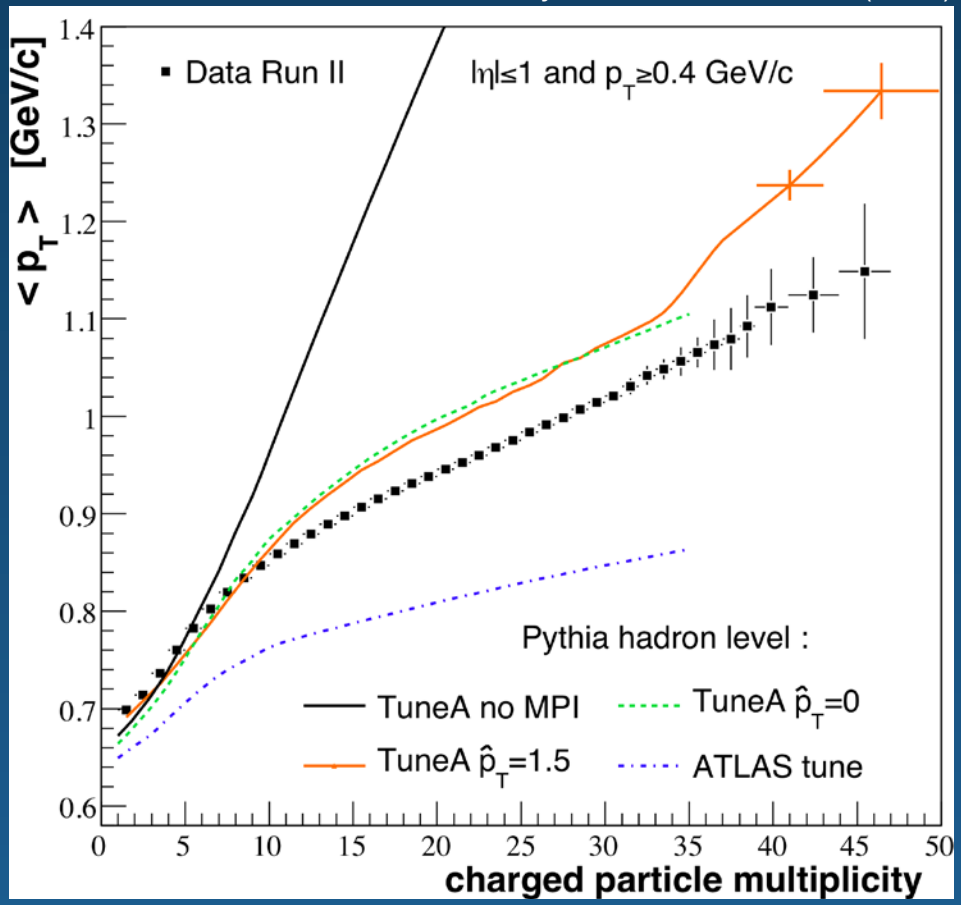
- Particles from inelastic $p\bar{p}$ collisions
- Minbias trigger under low luminosity conditions
- Measure inclusive charged particle p_T
- p_T range extended by 10× over previous work
- $d^3\sigma/p_T dp_T dy d\Phi$ measures 11 orders of magnitude
- Pythia agrees poorly at higher momenta

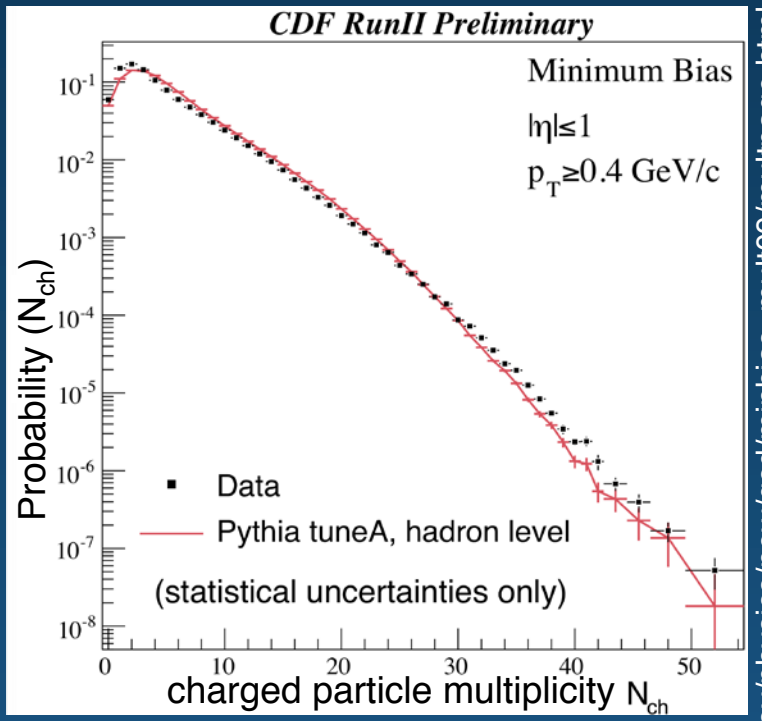


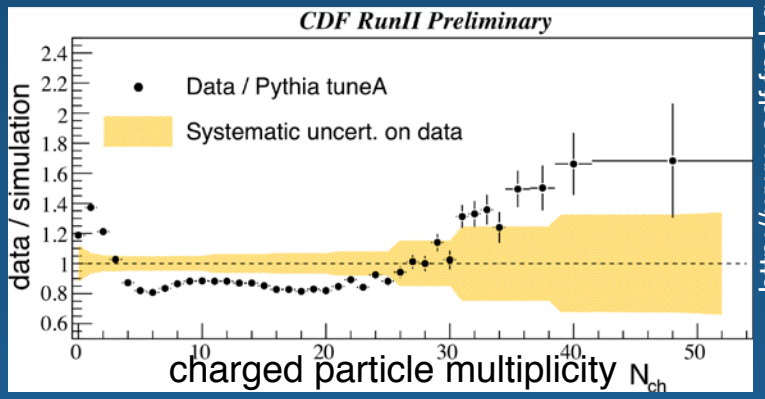
10. Charged-Particle Multiplicity:
Challenging the MC Generators

Observables probe hadronic sub-processes
Multiple Parton Interactions (MPI) suggested
Refined baseline for extrapolation to LHC √s

Phys. Rev. D **79**, 112005 (2009)







http://www-cdf.fnal.gov/physics/new/qcd/minbias_mult09/multpage.html

Concluding Remarks

- Tevatron is providing for precision QCD physics at 1.96 TeV
- Consistency between CDF and D0 results
- Jet Production (inclusive p_T, dijet mass, dijet angle)
  - Rutherford scattering ➔ TeV regime
  - Constraints on New Physics, high-x gluon; precise α_s measurement
- Charged particle studies ("soft physics" crucial to high-p_T HEP)
  - Insight into jet fragmentation characteristics:
    ➔ perturbative parton-showering dominance over hadronization
  - Detailed underlying event studies: several observables, MC tuning
  - Inclusive minbias particle production: call for MC refinements
- Community looks forward to QCD re-/discoveries at the LHC
- More to come from the Tevatron: expect 12 fb^{-1} by 2012

Special Thanks

- M. Albrow
- D. Bandurin
- D. V. Elvira
- R. Field
- K. Hatakeyama
- D. Lincoln
- M. Wobisch
- Fermilab Accelerator Division
- Other CDF / D0 Colleagues