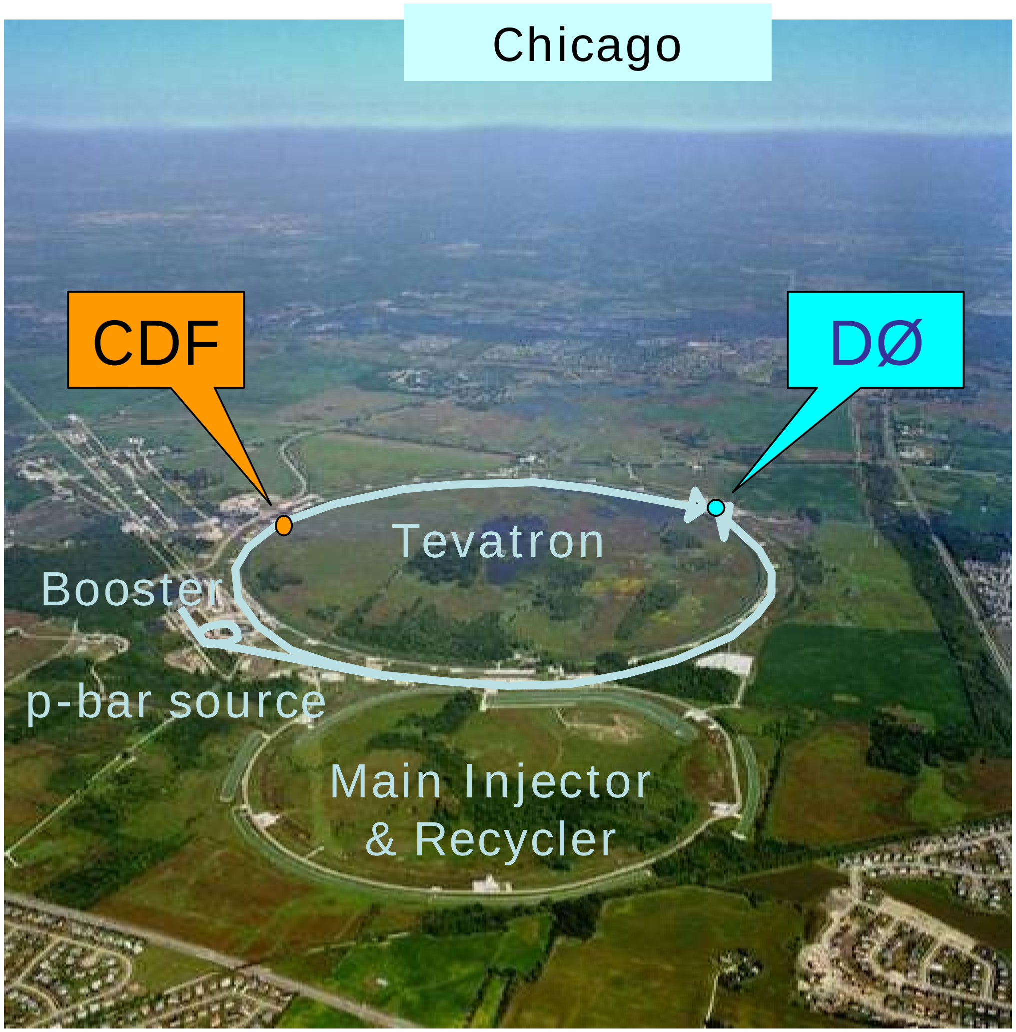
Precision QCD at the Tevatron

Markus Wobisch, Fermilab

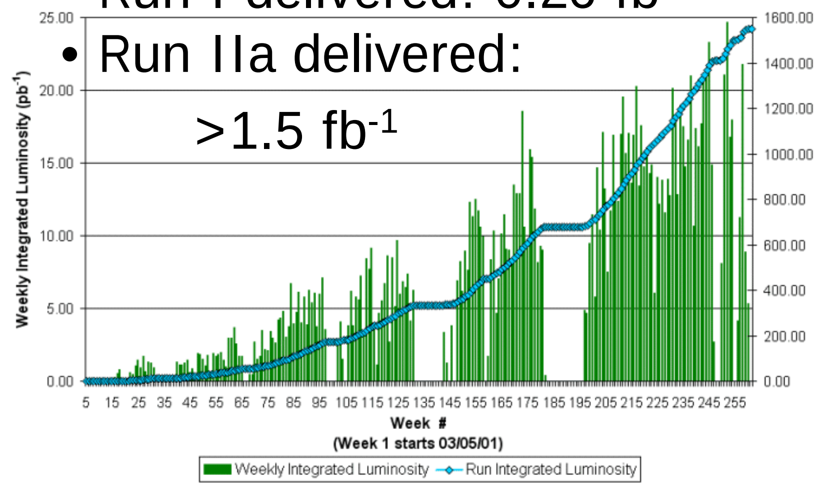
for the CDF and DØ Collaborations

Fermilab Tevatron - Run II



- Ecm: 1.8 → 1.96 TeV
- more Bunches 6 → 36
- Bunch Crossing 3500 → 396ns

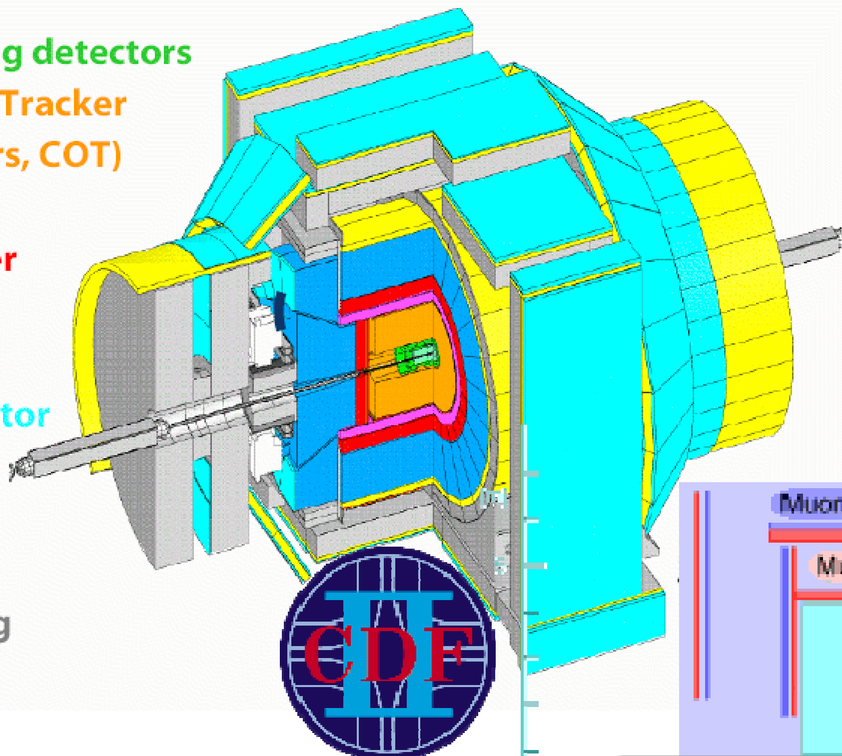
- Run II started in March 2001
- Peak Luminosity:
  1.7E32 cm^{-2} sec^{-1}
- Run I delivered: 0.26 fb^{-1}
- Run IIa delivered:
  >1.5 fb^{-1}



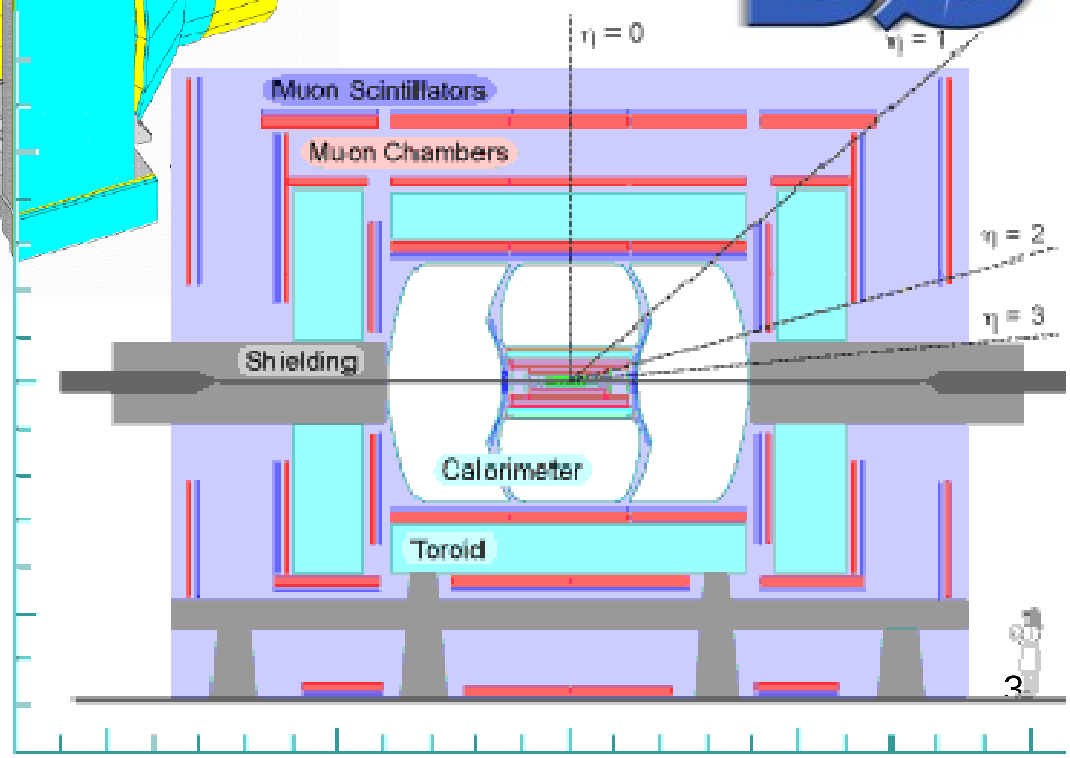
- Run IIb Goal: 8 fb^{-1} before 2009

Run II Detectors

- Silicon tracking detectors
- Central Outer Tracker (drift chambers, COT)
- Solenoid Coil
- EM calorimeter
- Hadronic calorimeter
- Muon scintillator counters
- Muon drift chambers
- Steel shielding

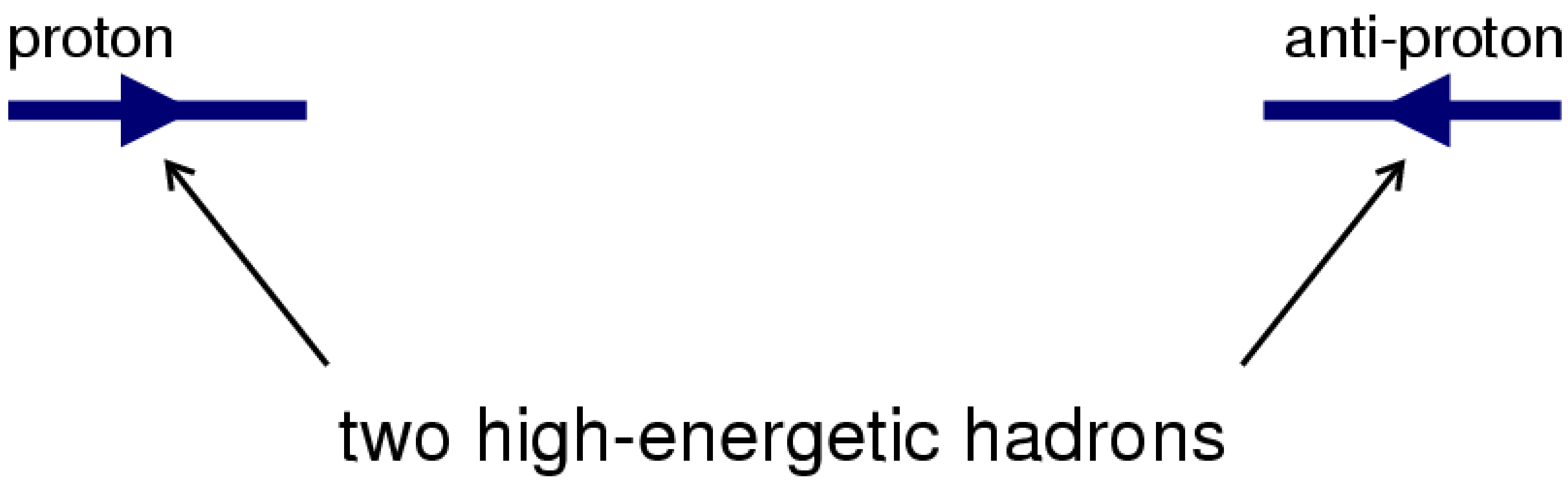


Multi-Purpose Detectors:
- Tracking
- Calorimeter
- Muon System

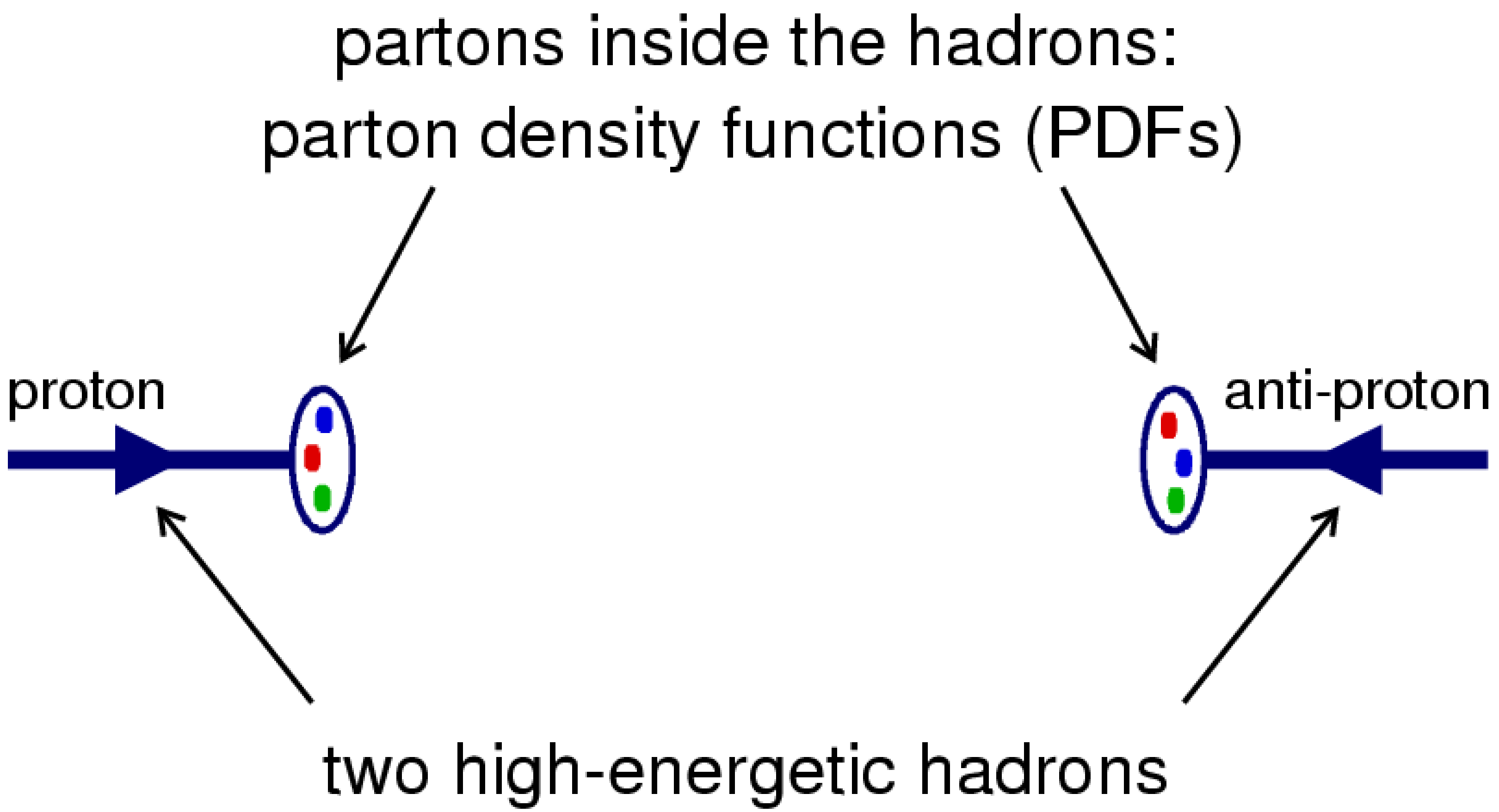


New in D0 for Run IIb:
Innermost "Layer 0" Silicon

Hadron-Hadron Collisions



Hadron-Hadron Collisions



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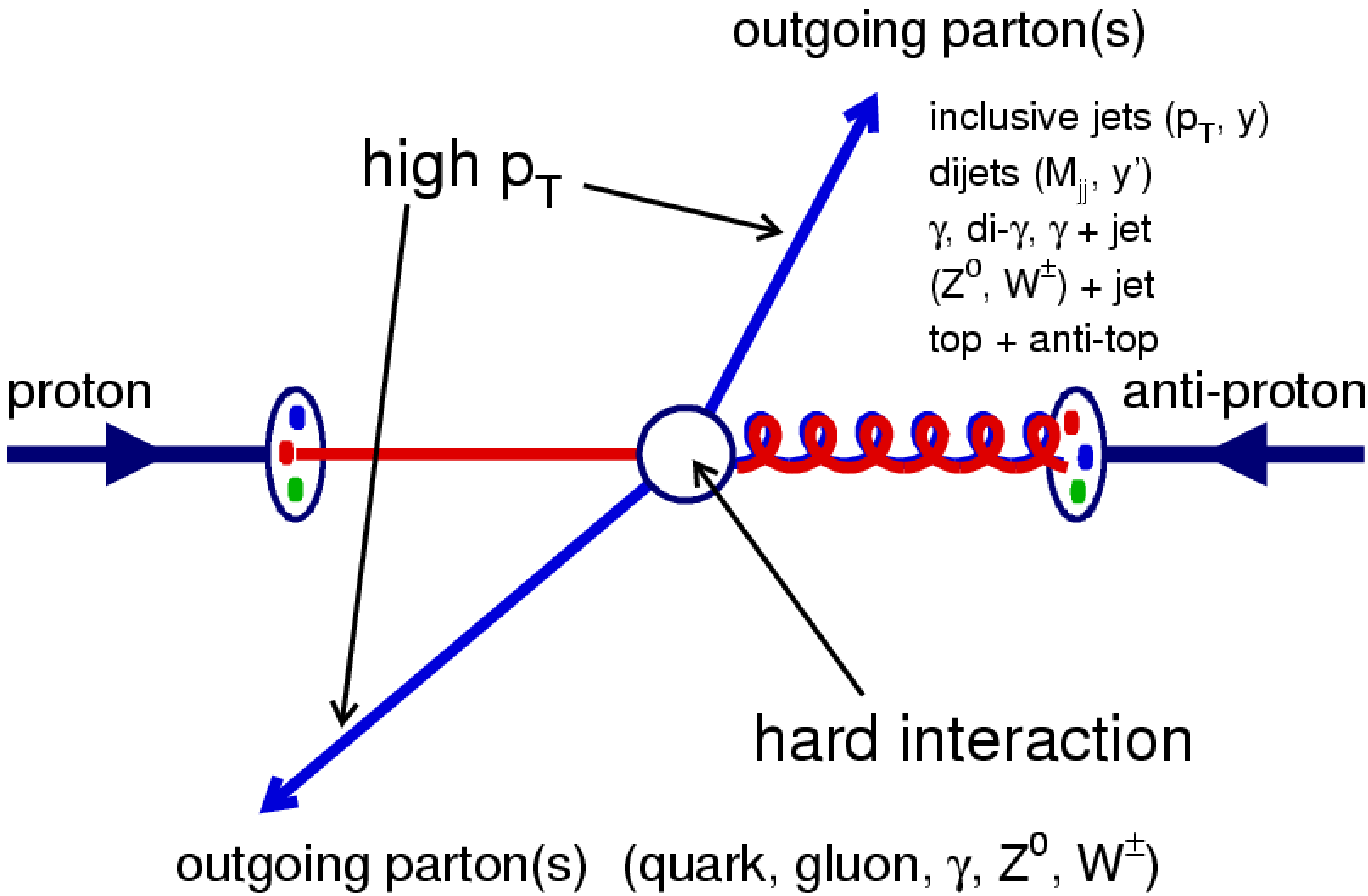
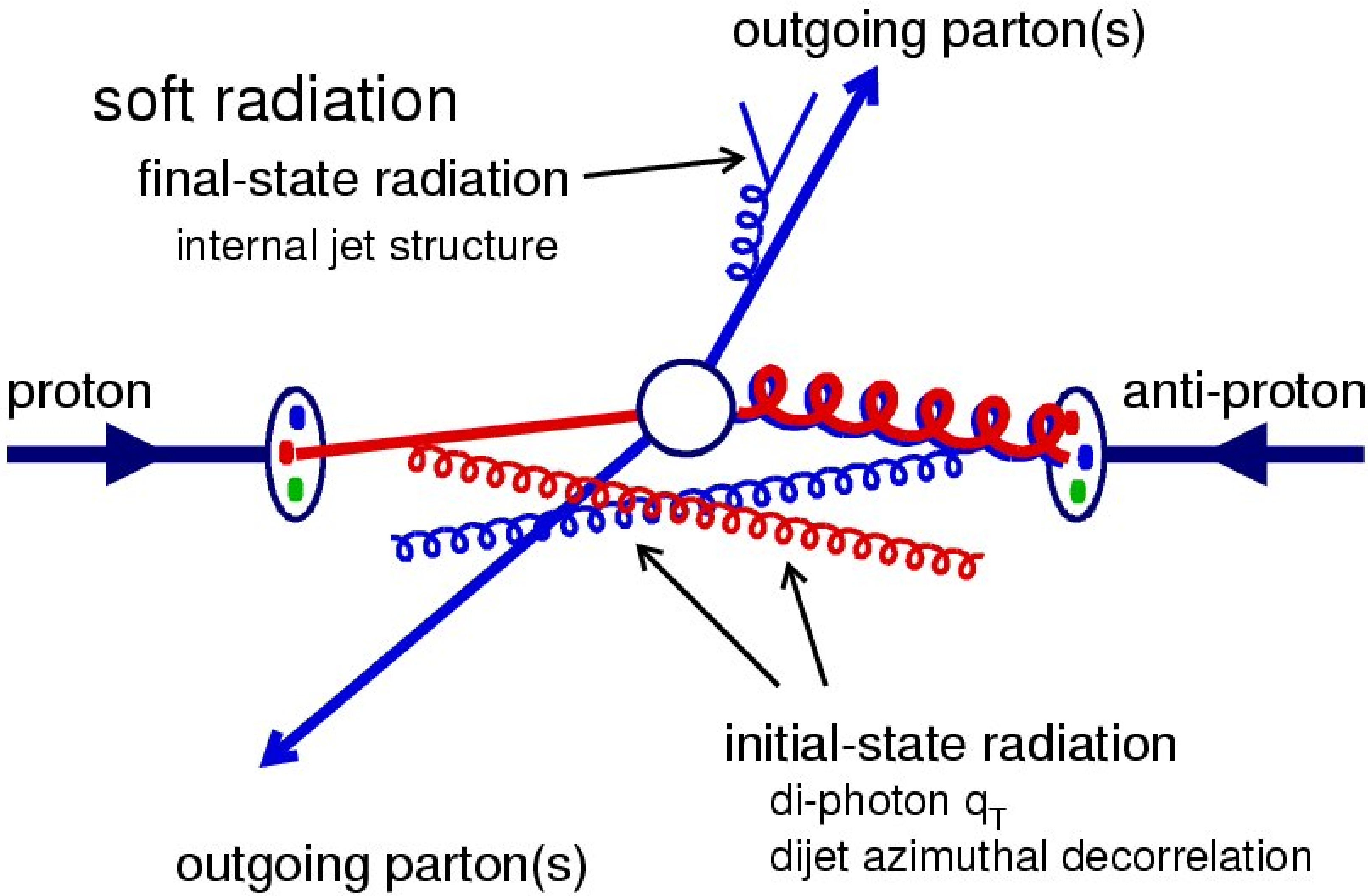
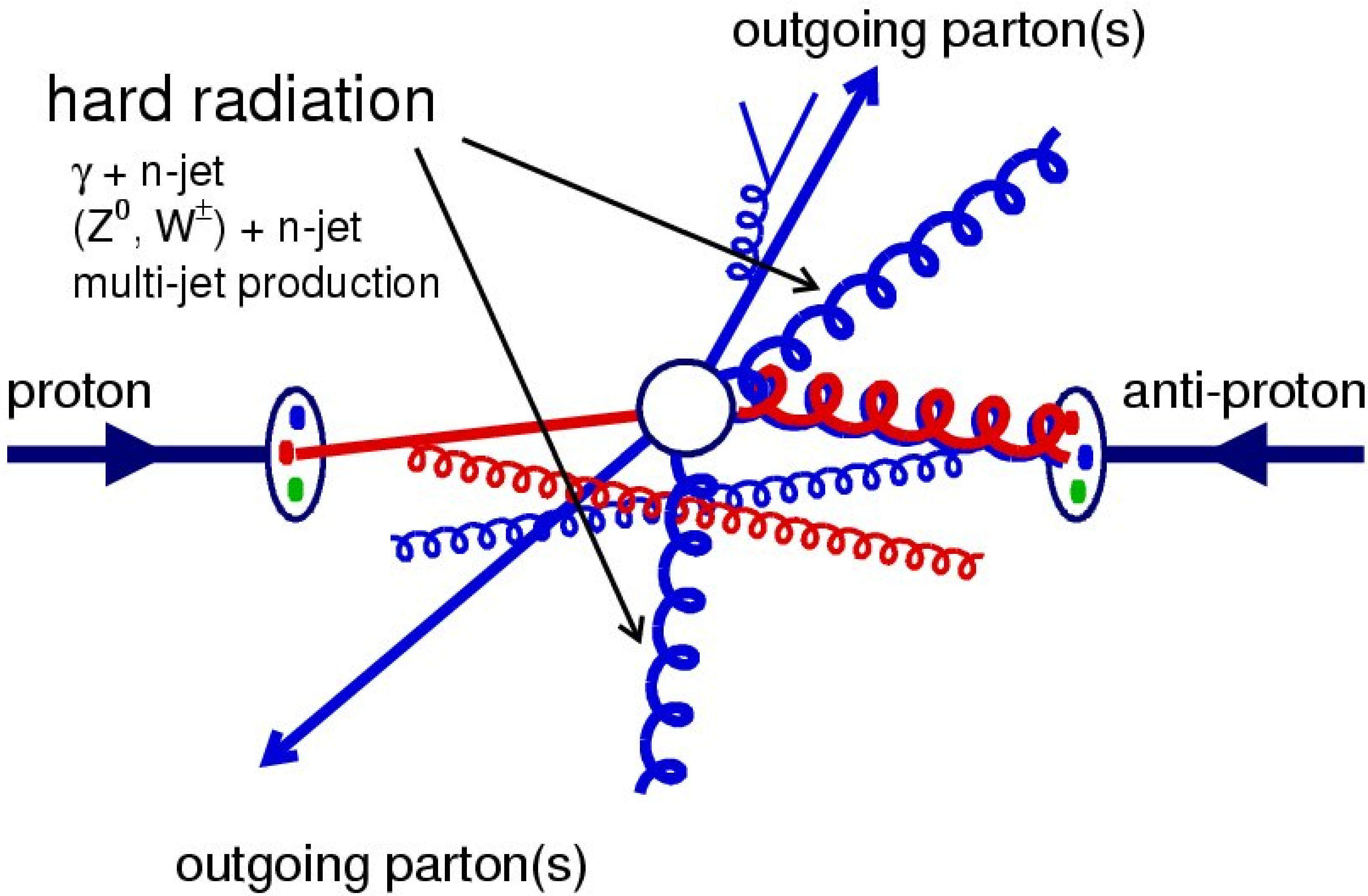


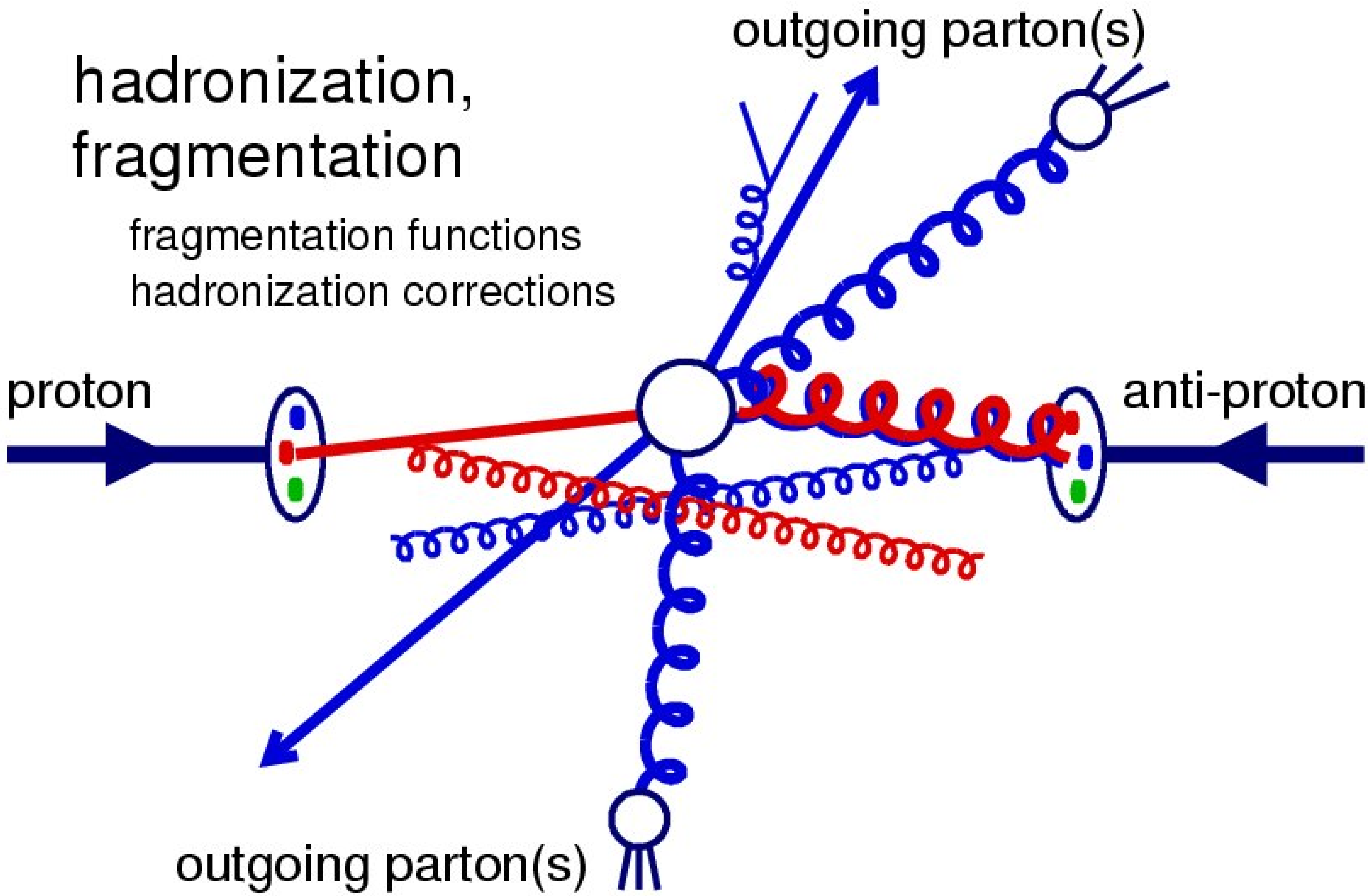
Hadron-Hadron Collisions



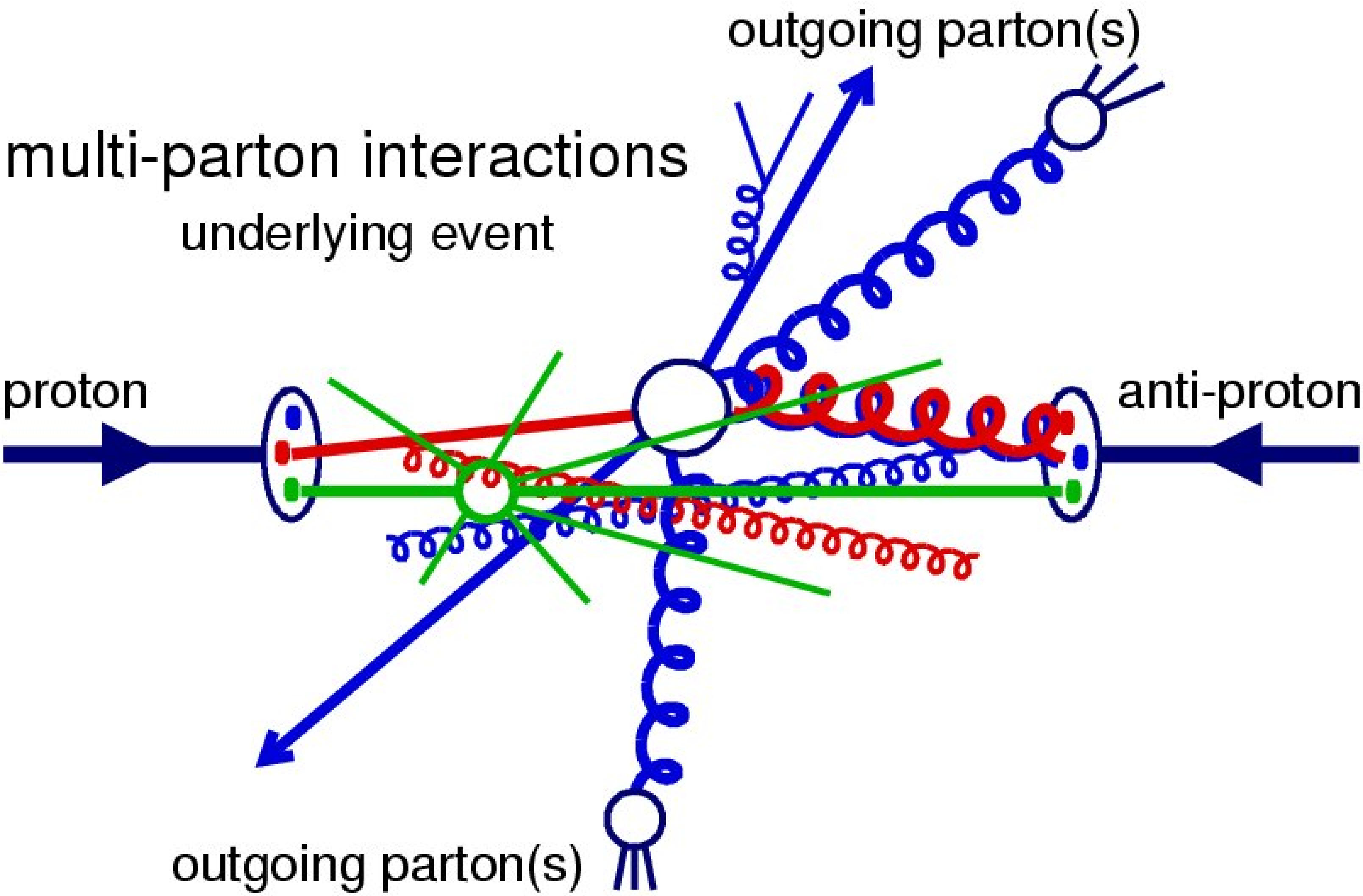
Hadron-Hadron Collisions



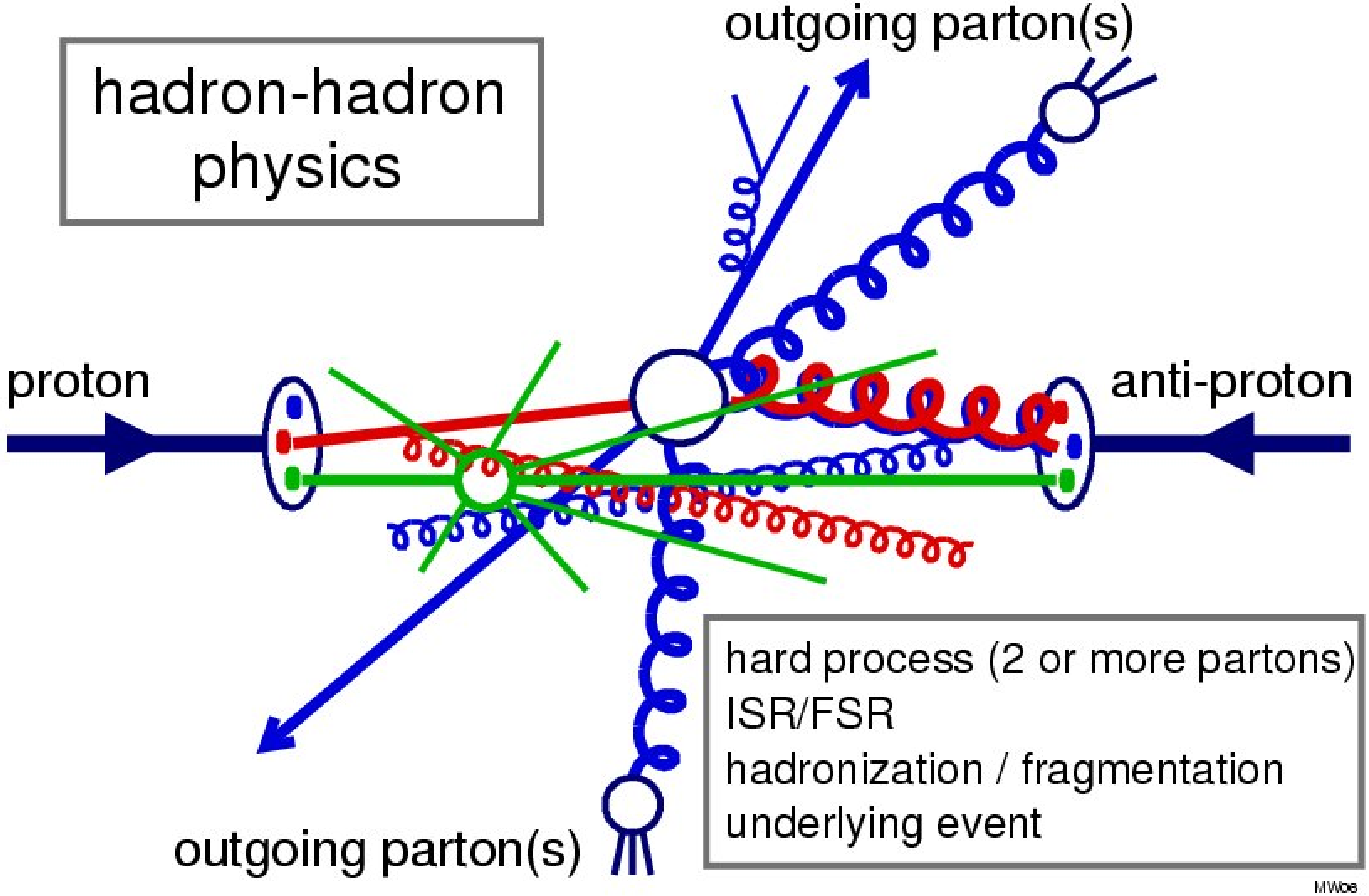
Hadron-Hadron Collisions



Hadron-Hadron Collisions



Hadron-Hadron Collisions



Outline

- W-Asymmetry
- Photon Production
- Jet Production
- Jets beyond 2→2
- Vectorboson + Jets
- Heavy Flavor Jets

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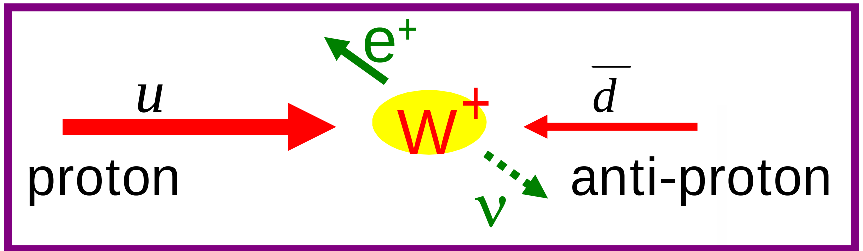
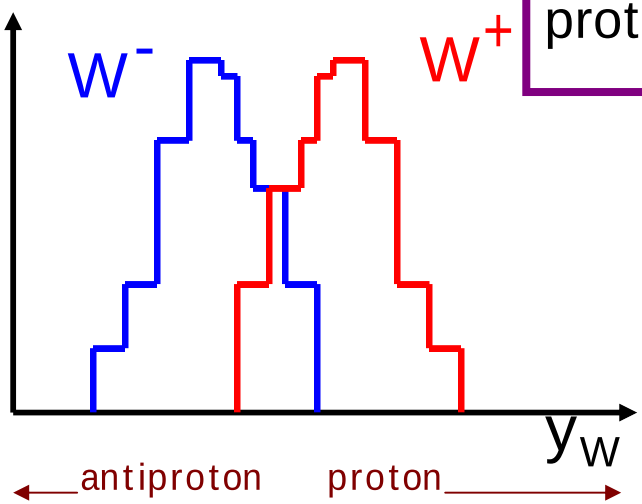
W-Asymmetry

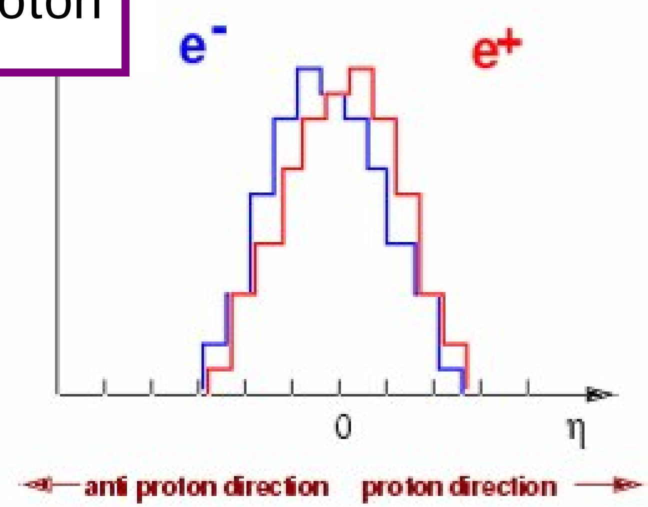
PDFs

W-Asymmetry



Valence-Quarks Dominate



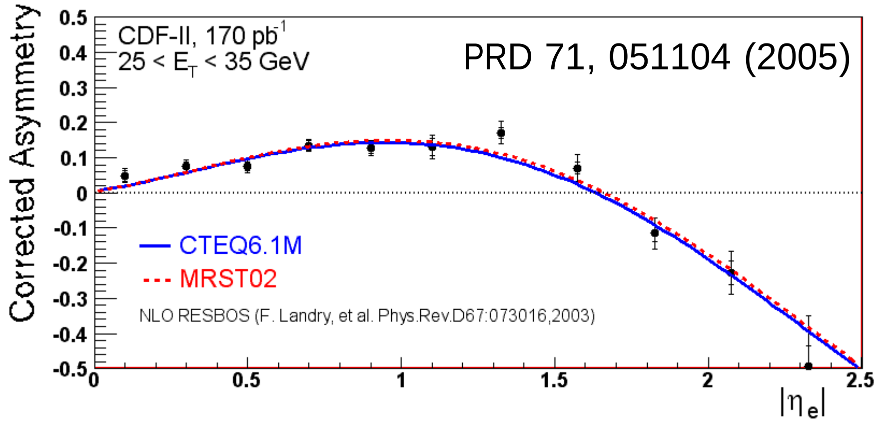


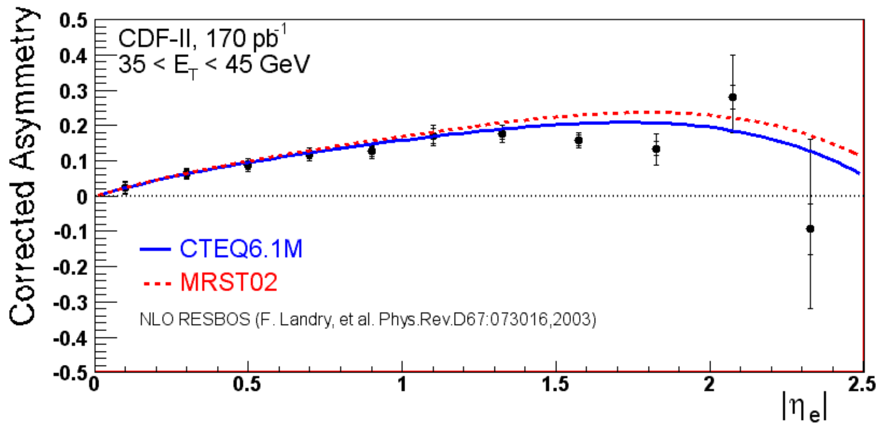
$$A = \frac{d\sigma(W^+)/dy_W - d\sigma(W^-)/dy_W}{d\sigma(W^+)/dy_W + d\sigma(W^-)/dy_W} \approx \frac{d}{u}$$

$$A_l(\eta) = \frac{d\sigma(e^+)/d\eta - d\sigma(e^-)/d\eta}{d\sigma(e^+)/d\eta + d\sigma(e^-)/d\eta} \simeq \frac{\mathrm{d(x)}}{\mathrm{u(x)}}$$

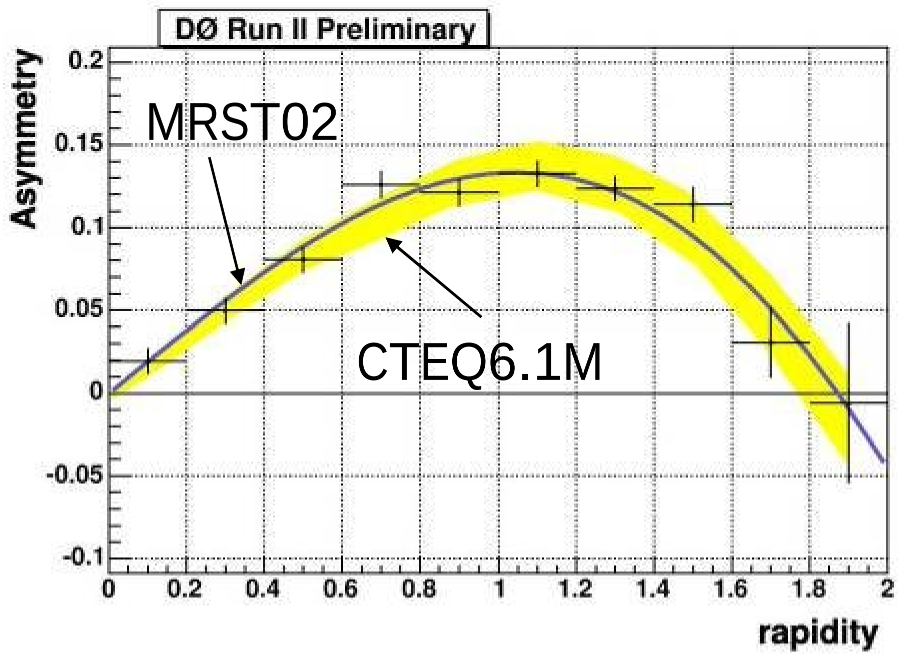
W-Asymmetry → Lepton-Asymmetry

W Charge Asymmetry





CDF (170pb-1): Electron Channel
In two Electron-ET Bins
(Different Sensitivity)



D0 prel. (230pb-1): Muon Channel
Limited by Statistics
Potential for 1fb-1! (→Run IIb)

Important Input in Future PDF Fits!

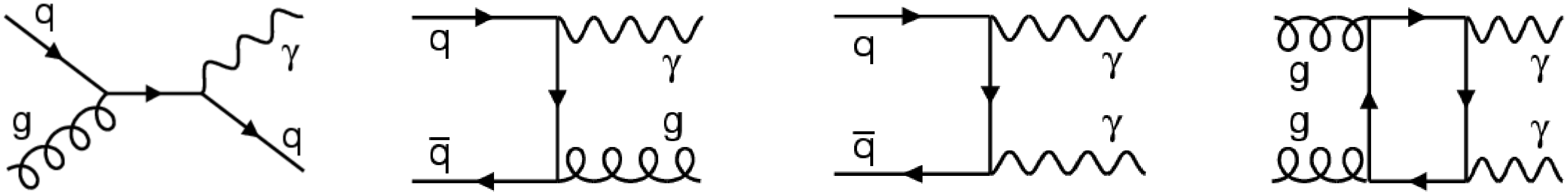
Photons

Fixed-Order: NLO

Resummation

PDFs

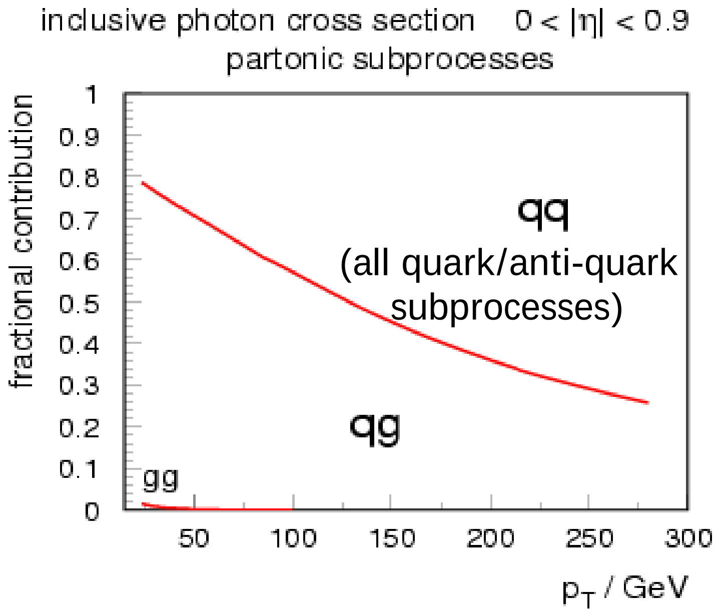
Direct Photon Production



Direct Photons come unaltered from the Hard Subprocess

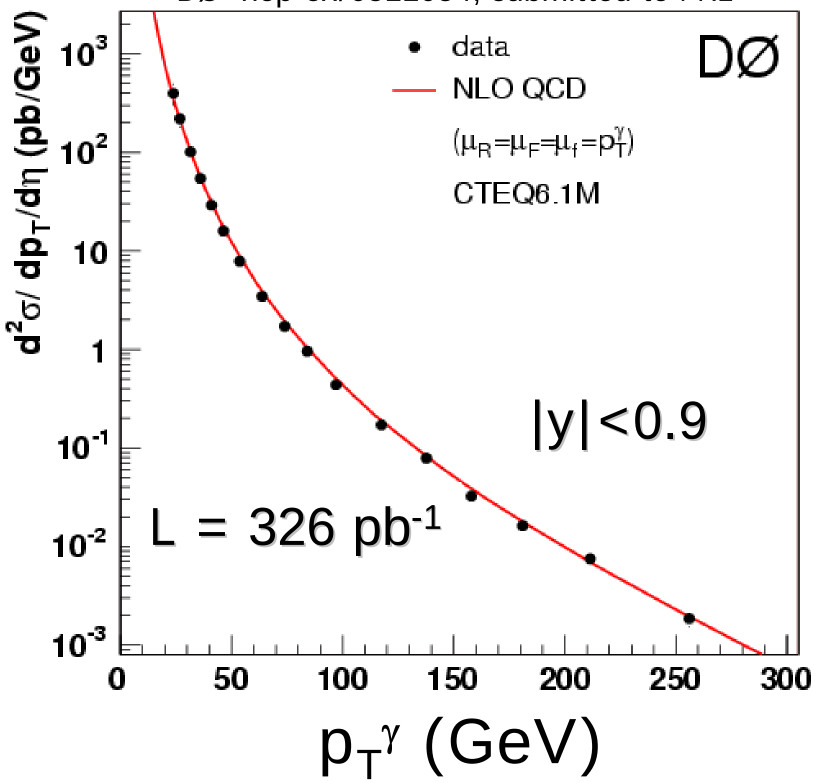
→ Direct Probe of the Hard Scattering Dynamics

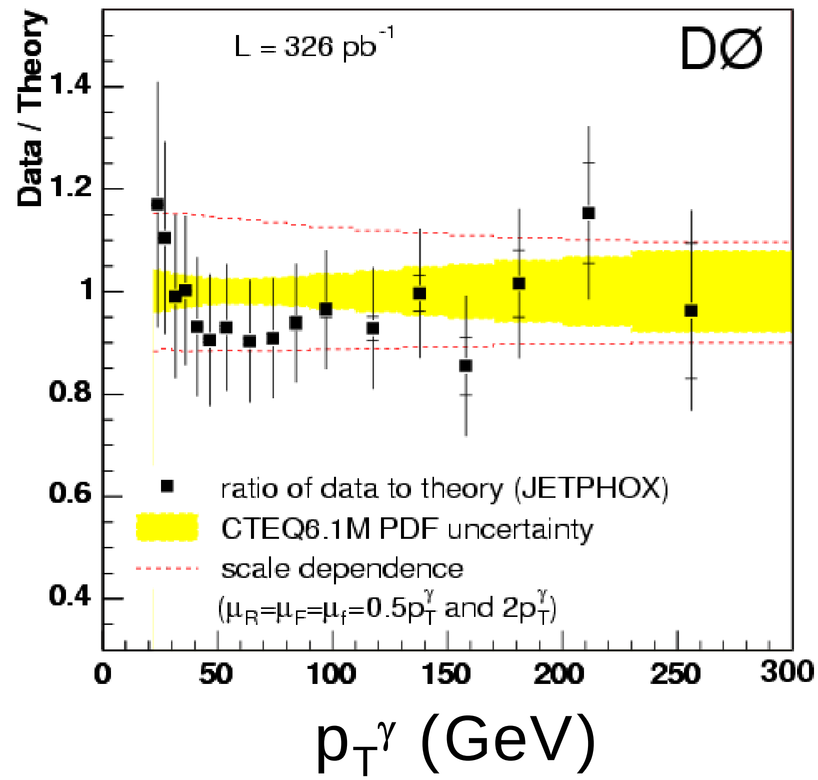
→ Sensitivity to PDFs



Isolated Photon Cross Sect.

DØ hep-ex/0511054, submitted to PRL





data/theory (NLO: JETPHOX): good agreement over 23<pT<300GeV

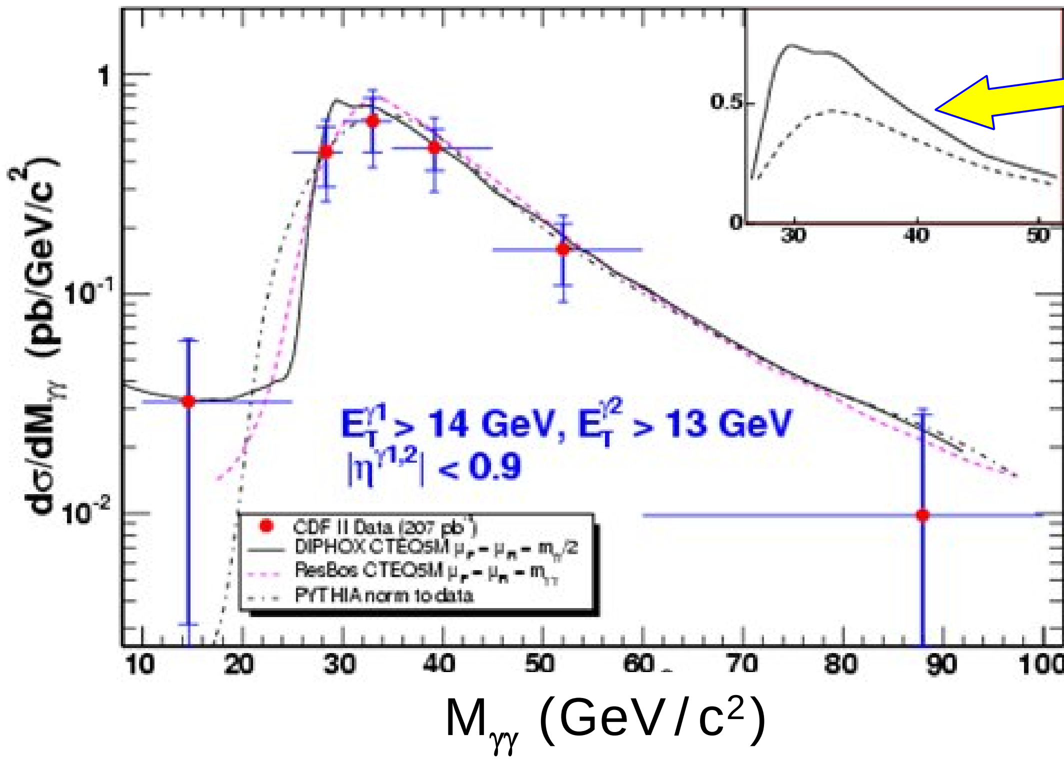
→ PDF sensitivity requires:

- Reduced exp. uncertainties – dominated by purity uncertainty
- Improved theory (resummation / NNLO)

Di-Photon Cross Section

CDF Collab., Phys. Rev. Lett. 95, 022003, 2005. (207pb-1)

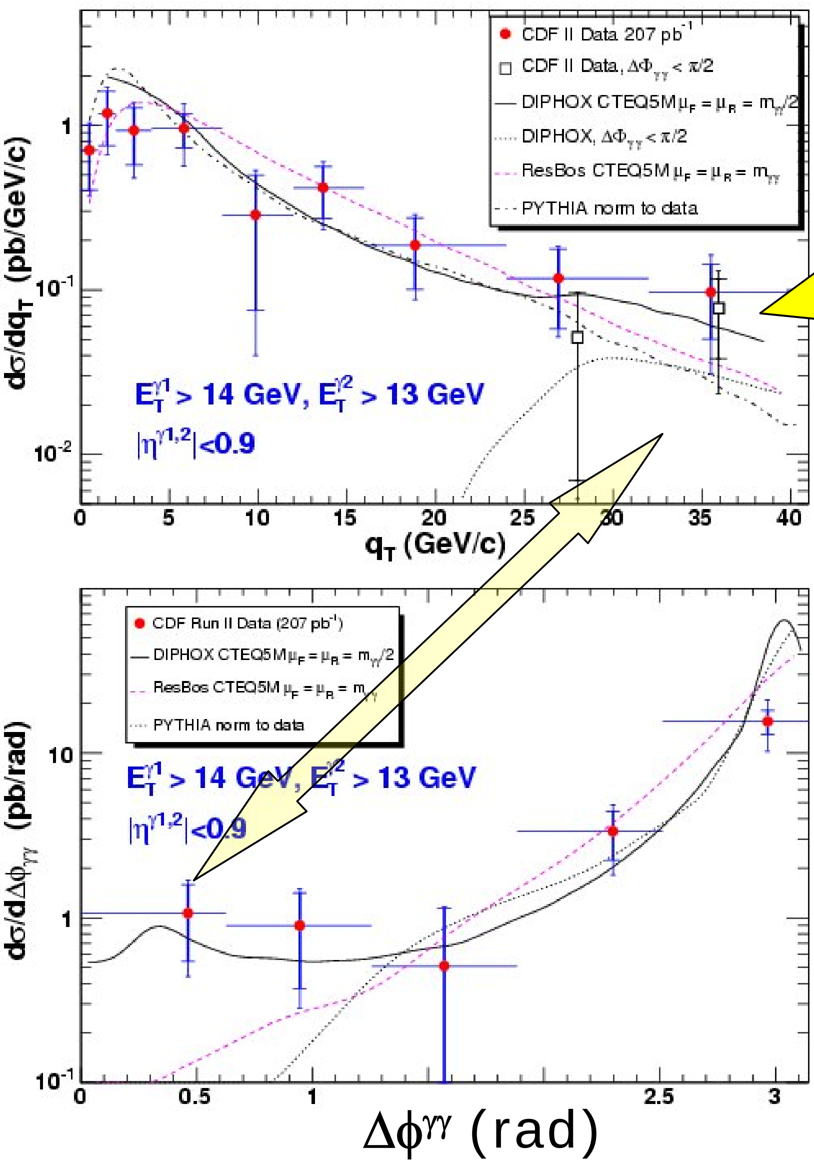
- Pseudorapidity < 0.9
- Photon pT> 13 & 14 GeV



DIPHOX: with and w/o NNLO gg-diagram

- DIPHOX:
  - NLO prompt di-photons
  - NLO fragmentation (1 or 2 γ)
  - NNLO gg→$\gamma\gamma$ diagram
- ResBos:
  - NLO prompt di-photons
  - LO fragmentation contribution
  - Resummed initial state gluon radiation (important for qT)
- PYTHIA (increased by factor 2)

Di-Photon Cross Section



Additional measurement for $\Delta\phi$ (gamma-gamma) < $\pi/2$ (open markers) compared to DIPHOX

- NLO fragmentation contribution
  - only in DIPHOX
  → at high qT, low $\Delta\phi$, low mass
- Resummed initial-state gluon radiation – only in ResBos → at low qT

<u>Important:</u>

Combined Calculation with

NLO Fragmentation

& Initial State Resummation

Jets

PDFs

New Physics?

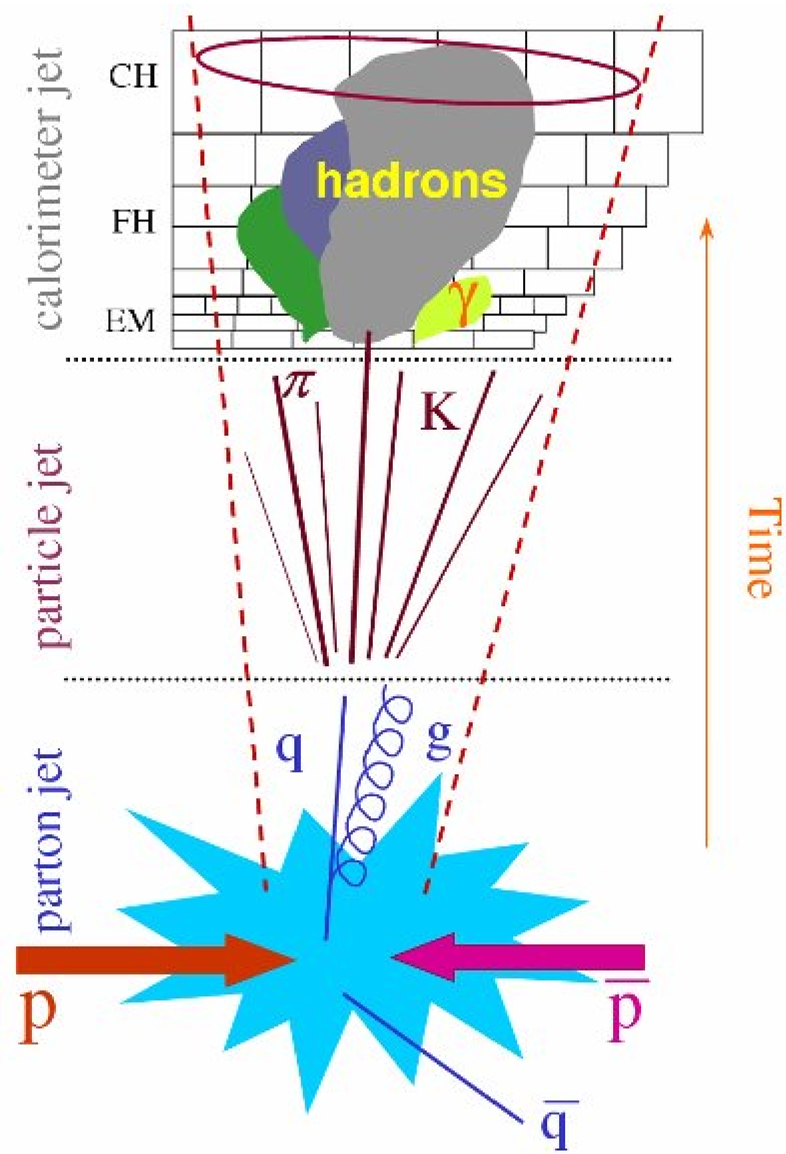
Biggest Misconception:

"A Jet Represents a Parton from the LO 2→ n Process."

"The Jet Algorithm should find this Parton with high Efficiency."

Nonsense!

Parton-, Hadron-, Detector- “Jets”



- Use Jet Definition to relate Observables defined on Partons, Particles, Detector

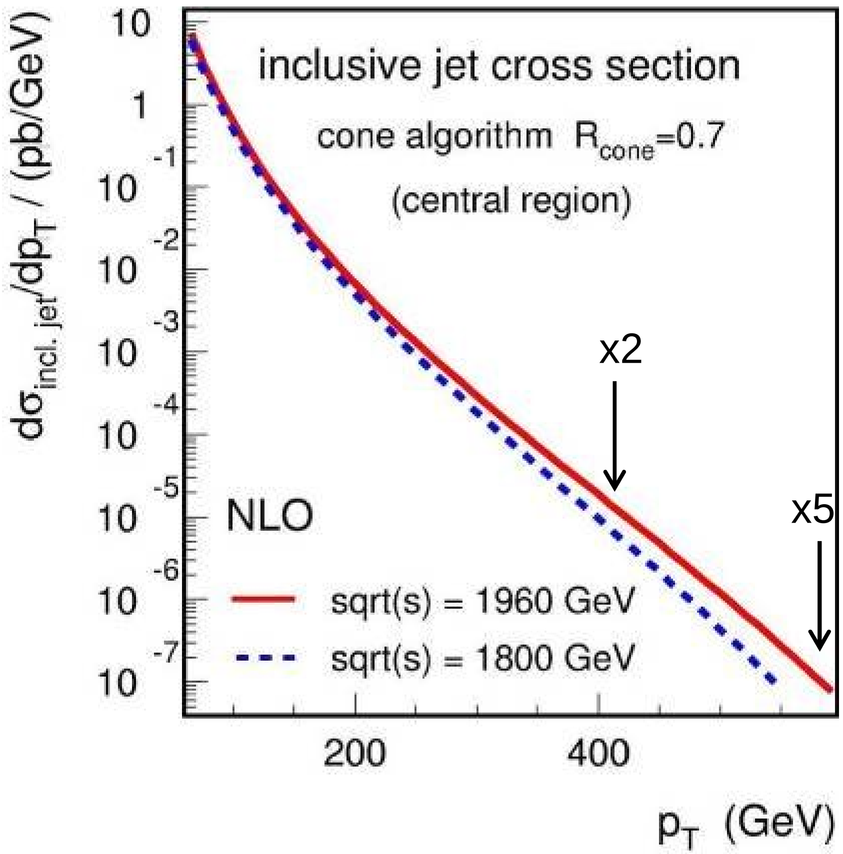
- Direct Observation:
  Energy Deposits / Tracks

- Stable Particles (=True Observable)

- Idealized: Parton-Jets
  no Observable (color confinement)
  But only Quantity that can
  be predicted in pQCD

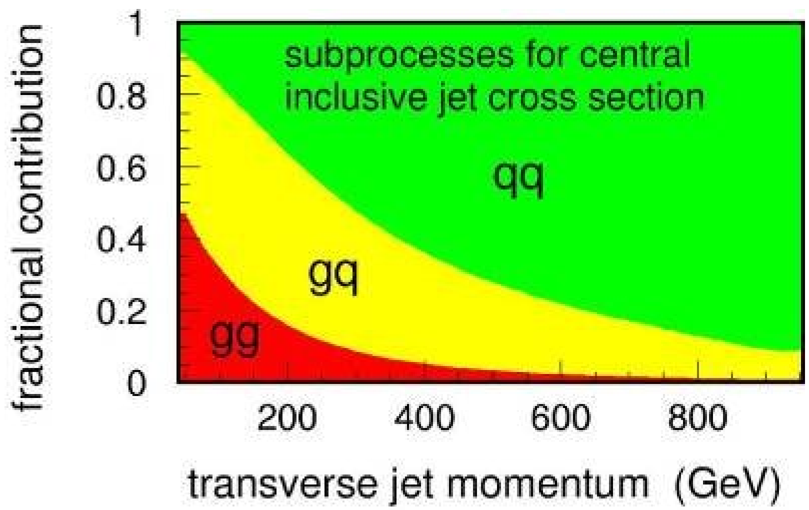
- Jet Algorithm:
  required to be IR- / Collinear Safe

Inclusive Jet Cross Section



- Theory @NLO is reliable (±10%)
  - → Sensitivity to PDFs
  - → Unique: High-x Gluon
- Run II: Increased x5 at pT=600GeV
  - → Sensitive to New Physics: Compositeness, LED, ...(?)...

DØ	- midpoint cone algorithm
CDF	- Run I cone algorithm
	- modified midpoint cone algorithm
	- kT algorithm



From Particle to Parton Level

- Measurement: pp-bar → Jet Cross Section (on "Particle-Level")

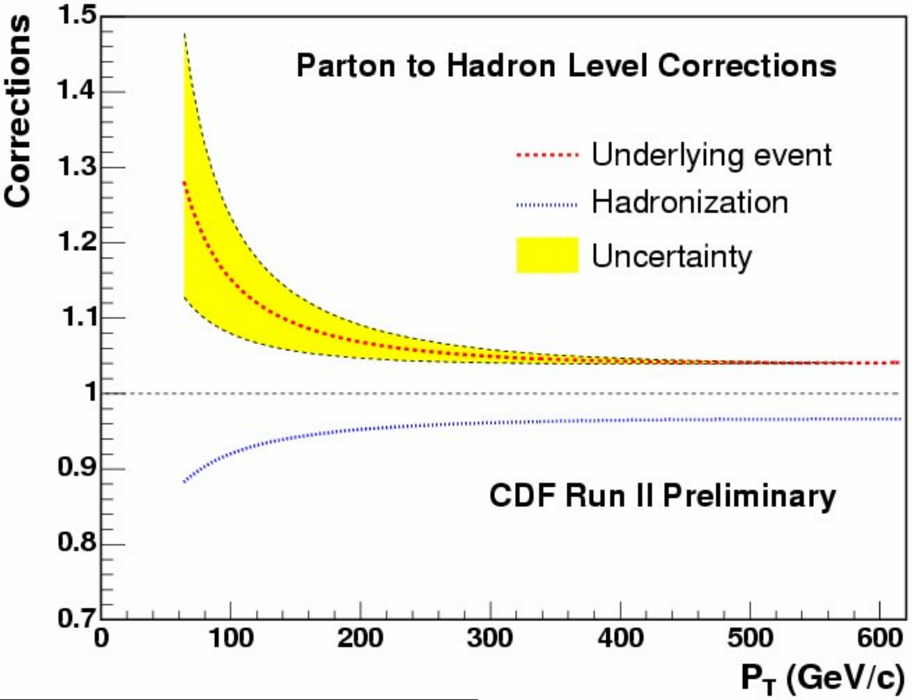
  Corrected for Experimental Effects (Efficiencies, Resolution, ...)

Use Models to Study Effects of Non-Perturbative Processes (PYTHIA, HERWIG)

Here (CDF Study):

- Hadronization Correction
- Underlying Event Correction

for central Jet Cross Section



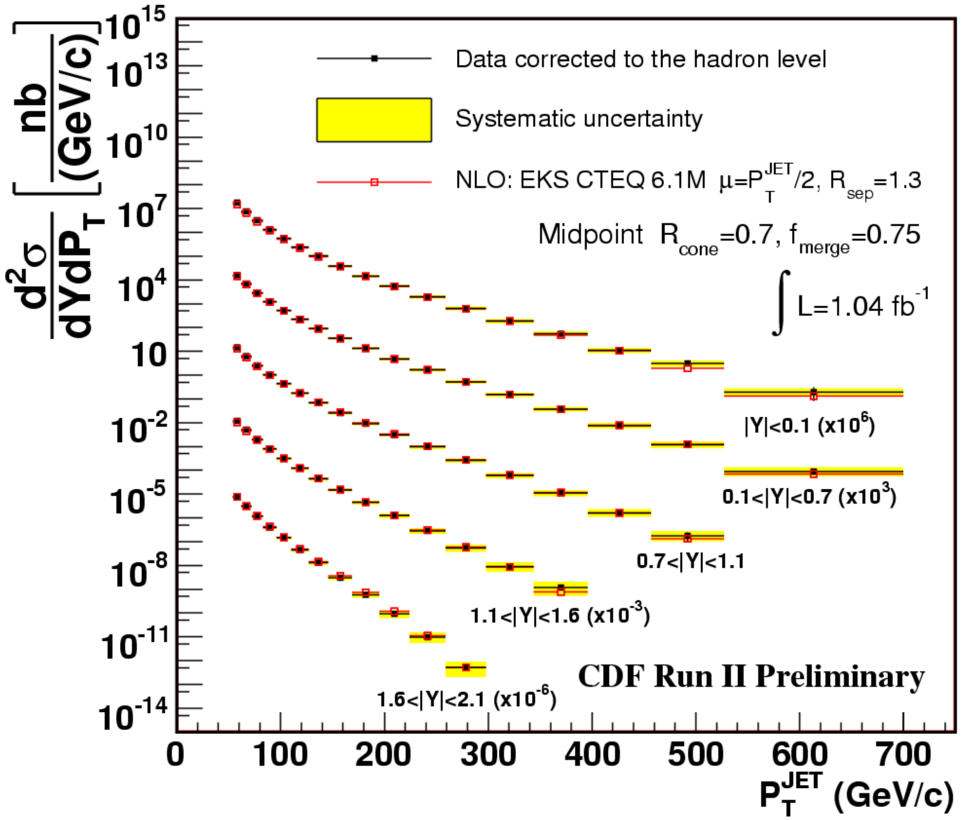
At pT>150GeV: Non-Perturbative Effects are below 10%
→ Apply this Correction to the pQCD Calculation

New in Run II !!!

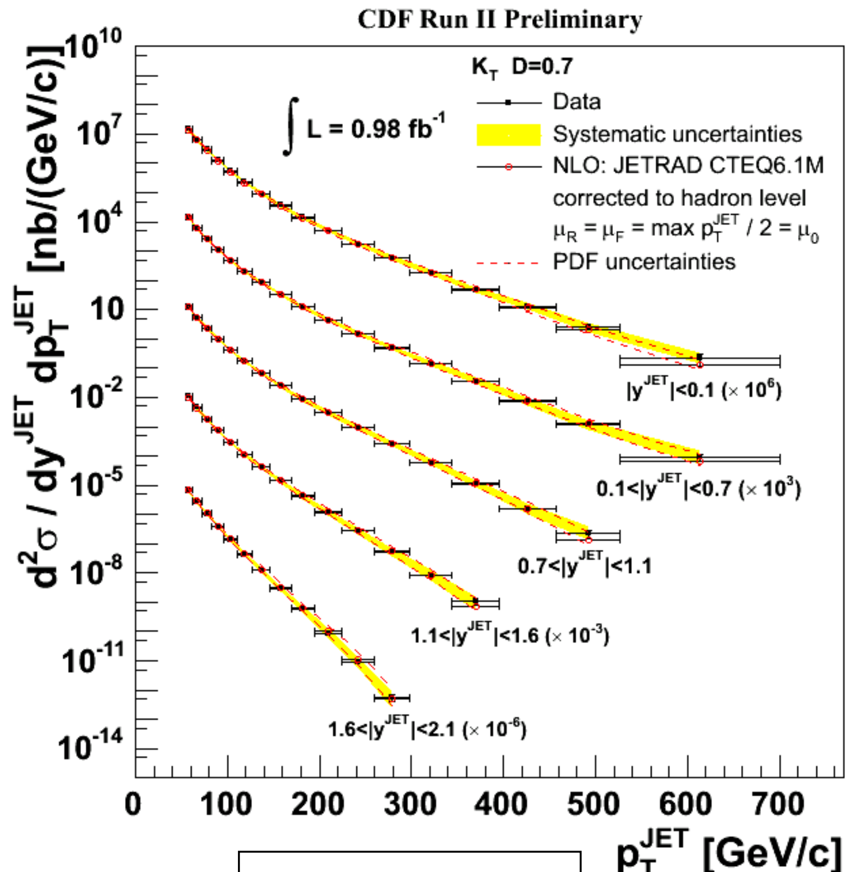
Inclusive Jets
Cone and kT Algorithms

In 2005: published both central cone and kT jets with 400pb-1

Here: new preliminary results with full rapidity coverage for 1fb-1

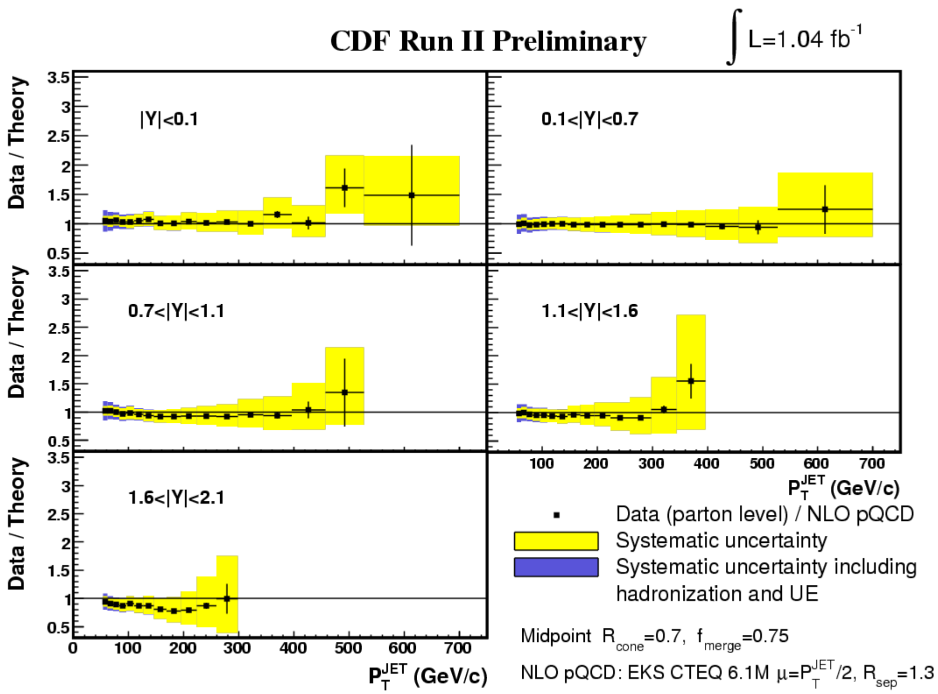


Midpoint Searchcone Algorithm

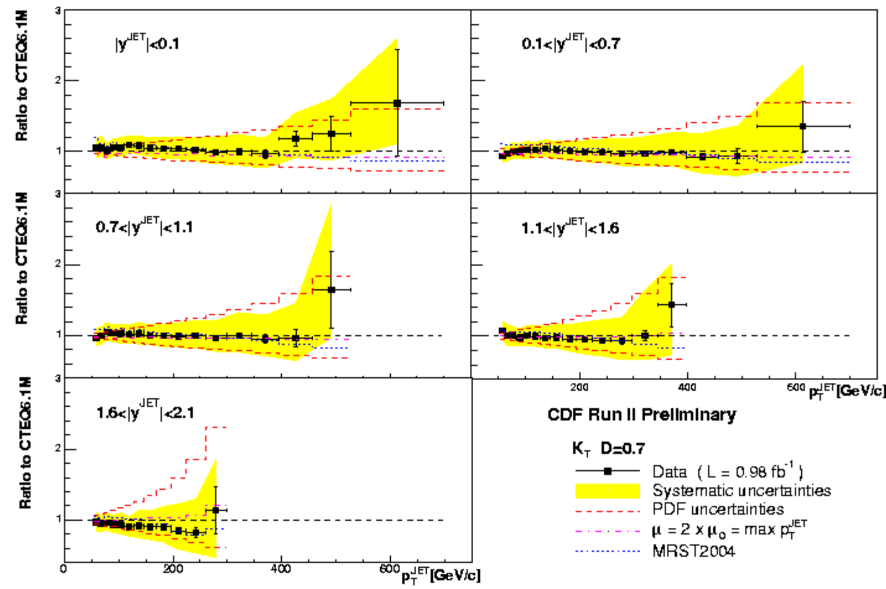


kT Algorithm

Inclusive Jets
Cone and kT Algorithms



Midpoint Searchcone Algorithm



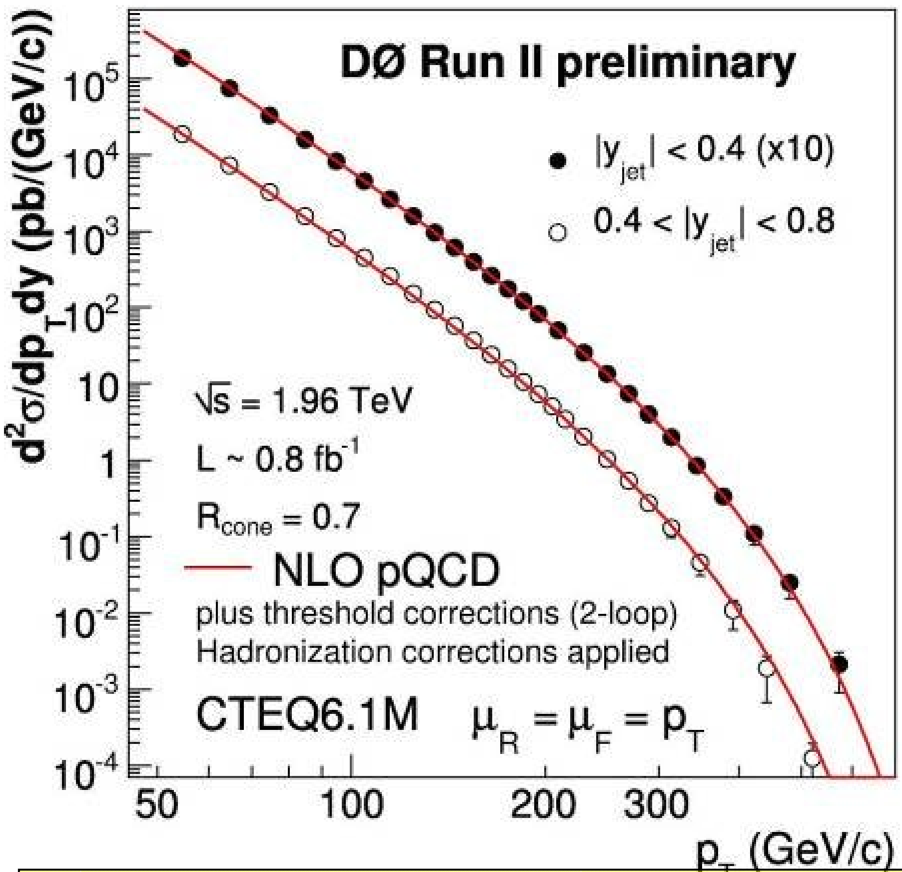
kT Algorithm

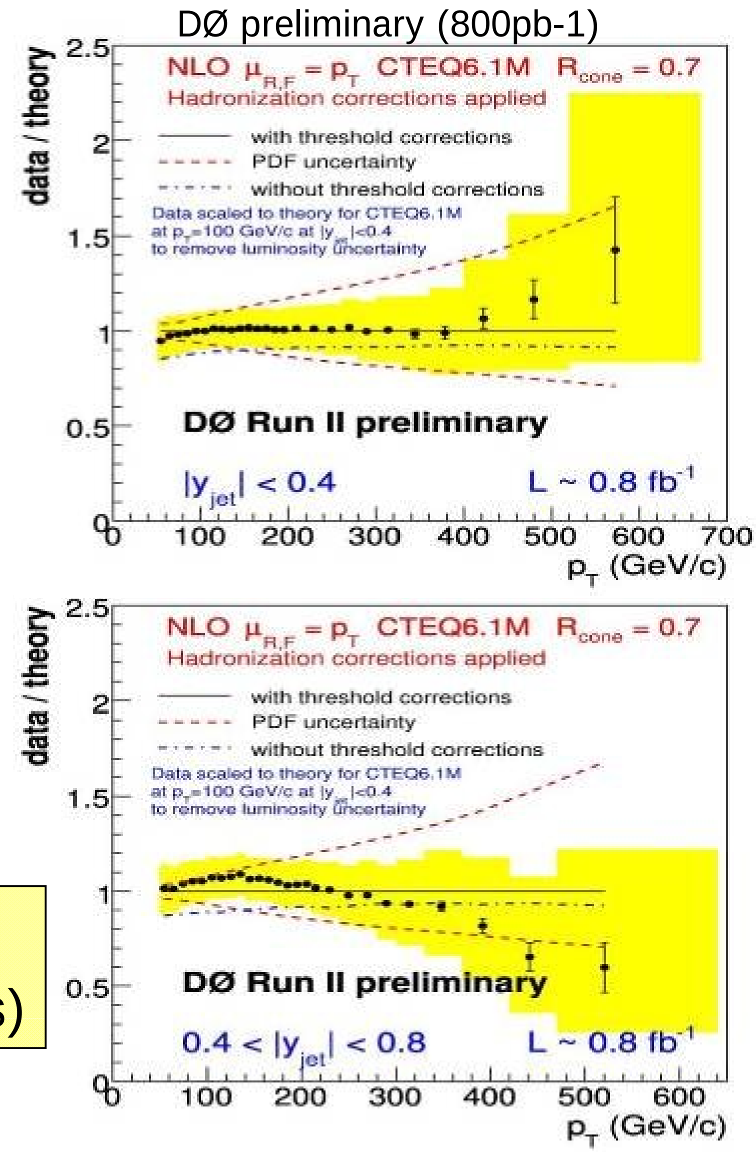
Data are well-described by NLO pQCD

Experimental Uncertainties: Smaller than PDF Uncertainties!!

(only shown for kT Algorithm)

Inclusive Jet Cross Section

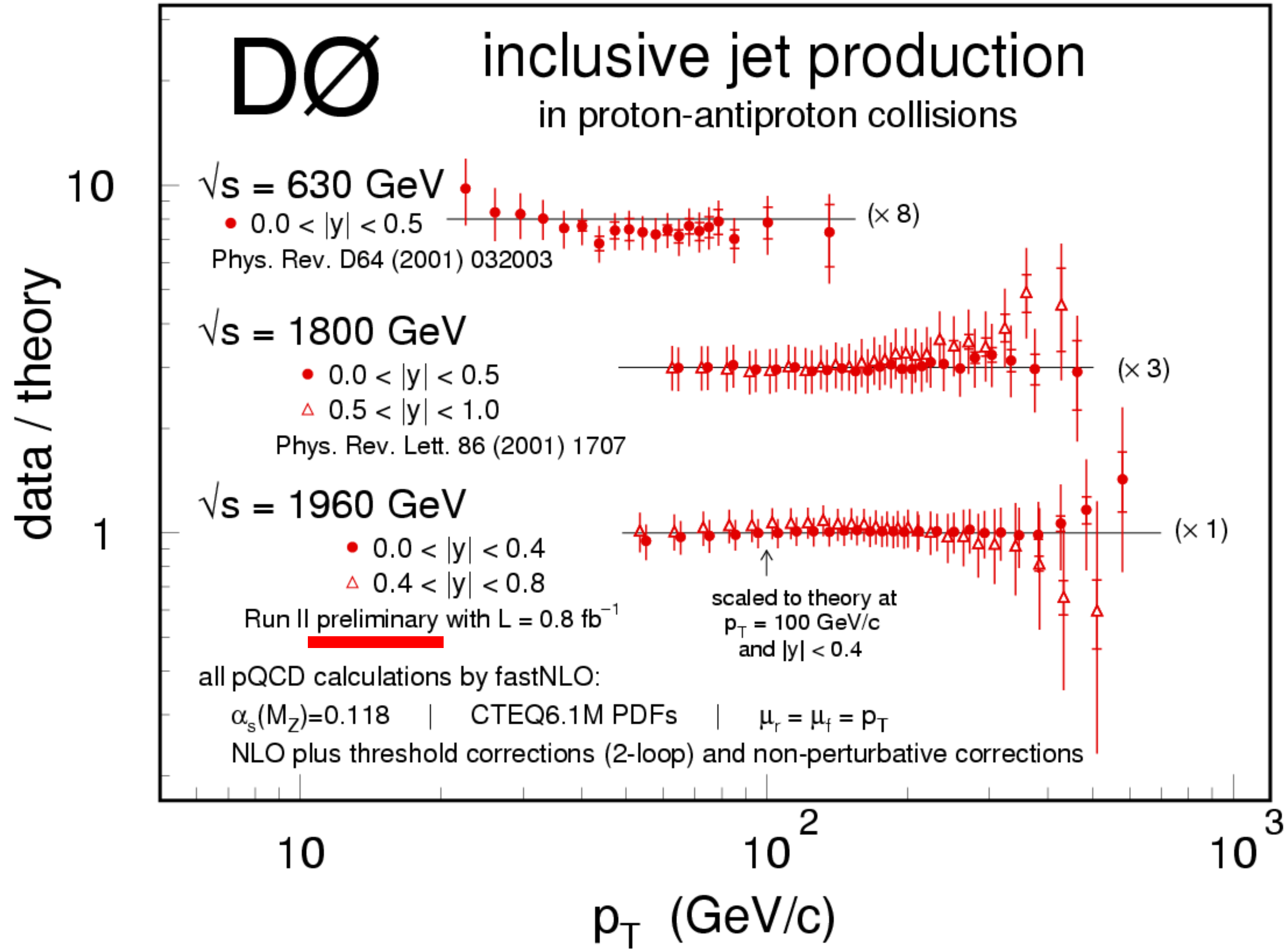




Compare to NLO pQCD + 2-loop Threshold Corrections (Kidonakis, Owens)

→ Sensitive to PDFs!!

Run I and Run II so far...



Good agreement of theory and data over large pT range 20-700 GeV

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Vector Boson + Jets

Fixed-order: NLO

NLO + Parton Shower

Matched Tree-Level + PS

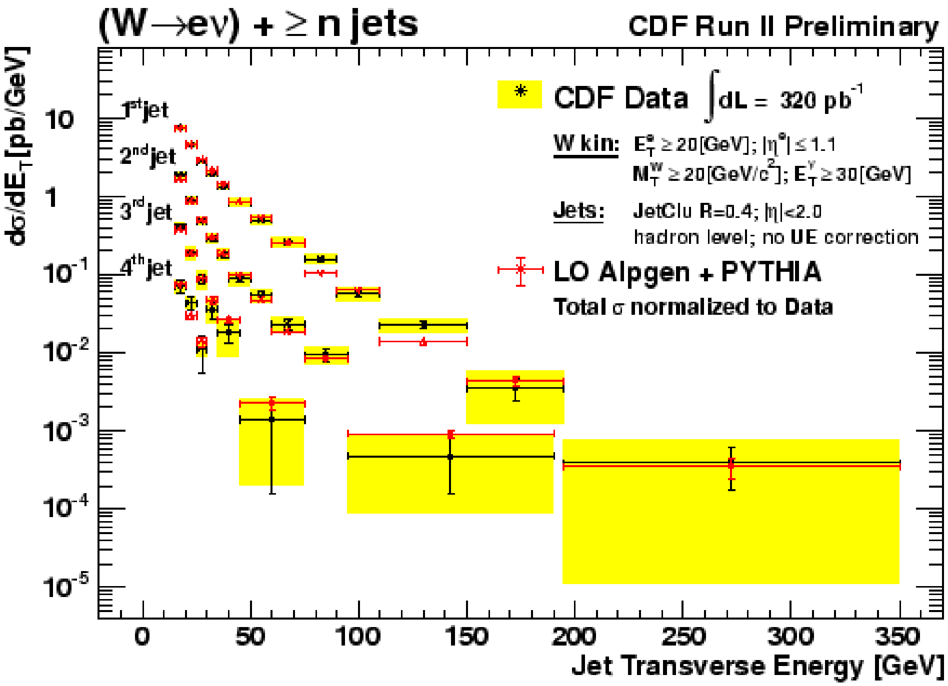
(CKKW / MLM)

W+n Jets

W+2 Jets

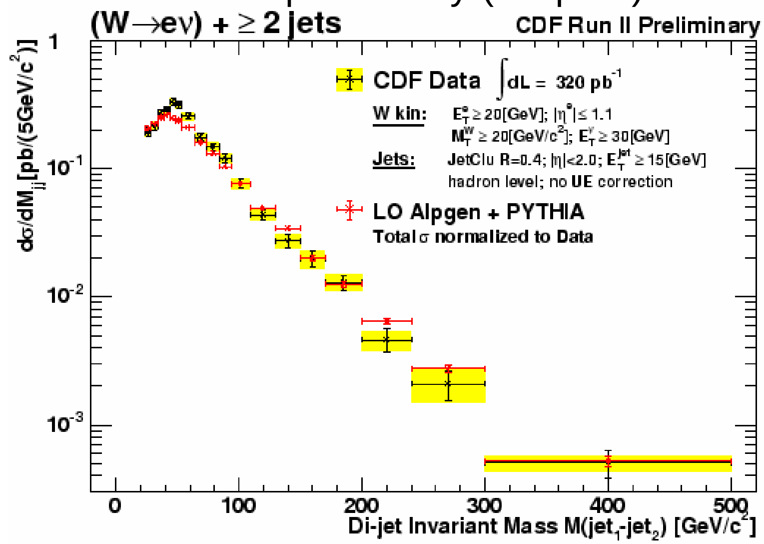
Cross Section for Restricted W Phase Space

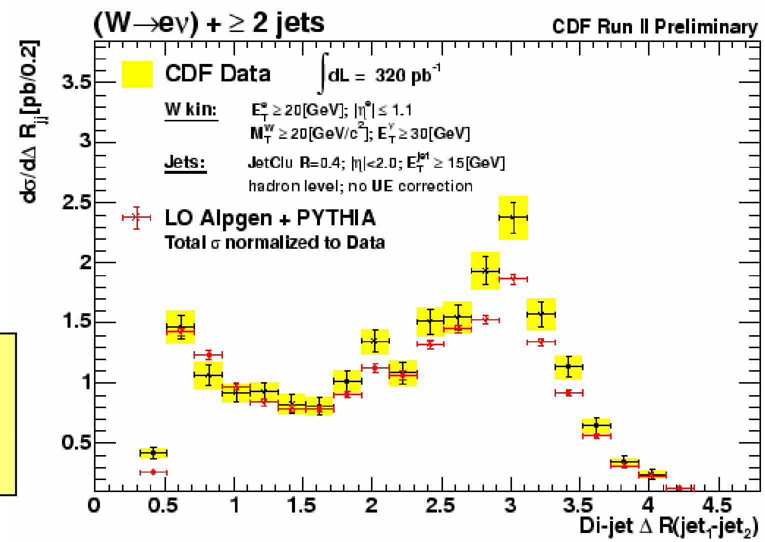
→ Avoid Model-Dependent Acceptance Corr.



Shape-Comparison with LO Alpgen+PYTHIA: Reasonable Agreement!

CDF preliminary (320pb-1)



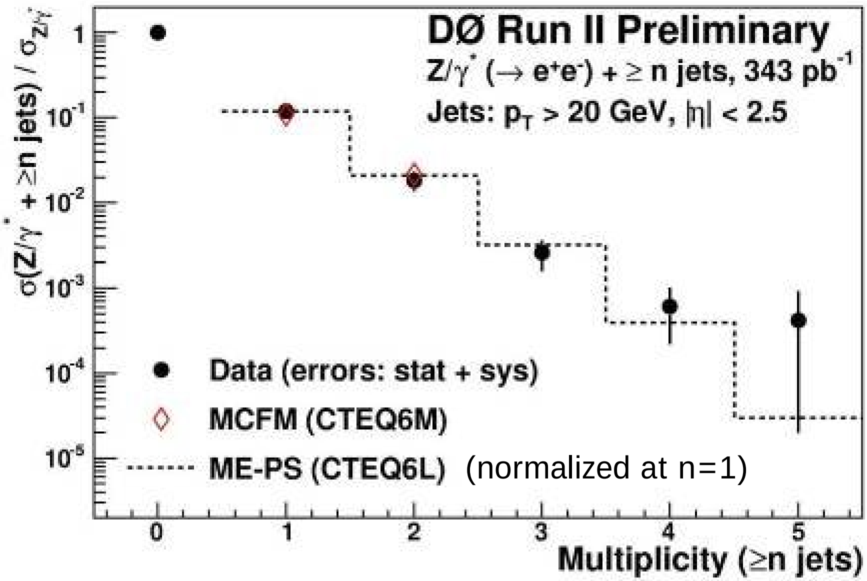


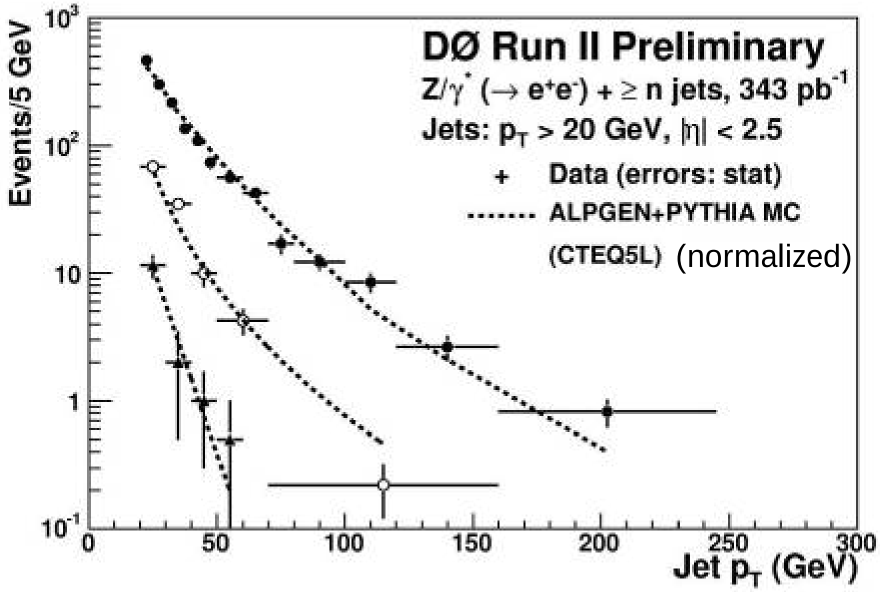
Z+n Jets

D0 preliminary (340pb-1)

- Smaller Cross Section than (W+Jets) but cleaner exp. Signature

Ratios to total inclusive Z→ee





Data are described by:

MCFM: NLO for Z+jet, Z+2-jet

Madgraph: ME+PS (Z+ <= 3 parton) tree-level + PYTHIA parton shower

ALPGEN (pT Dependence)

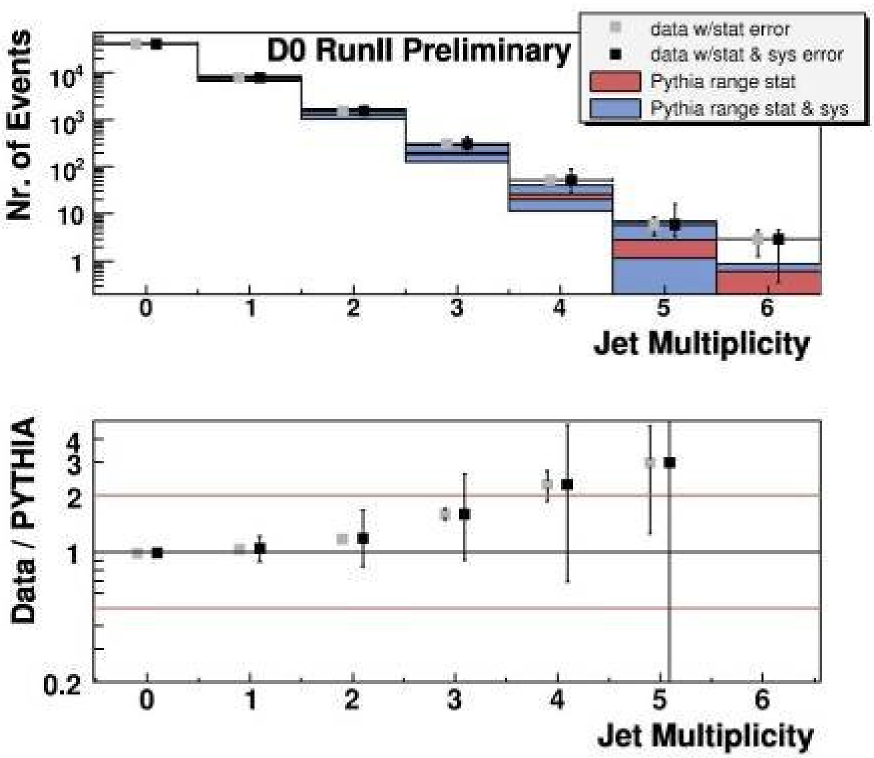
Z + Jets

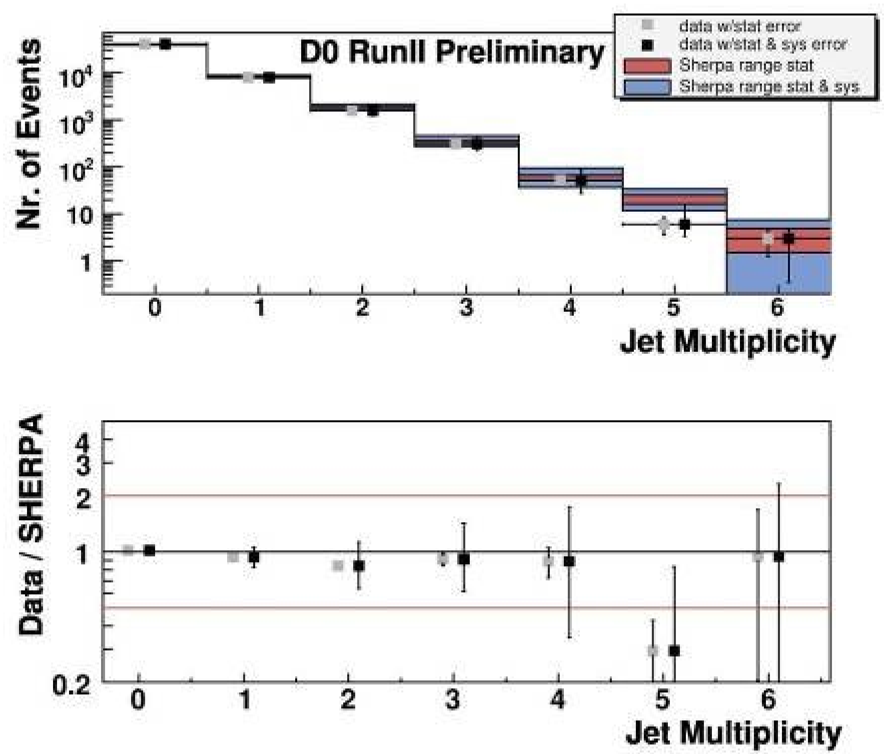
D0 preliminary (950pb-1)

- Comparison on Detector-Level: Data vs. PYTHIA and SHERPA

PYTHIA does not describe Higher Jet Multiplicities

SHERPA is pretty good!





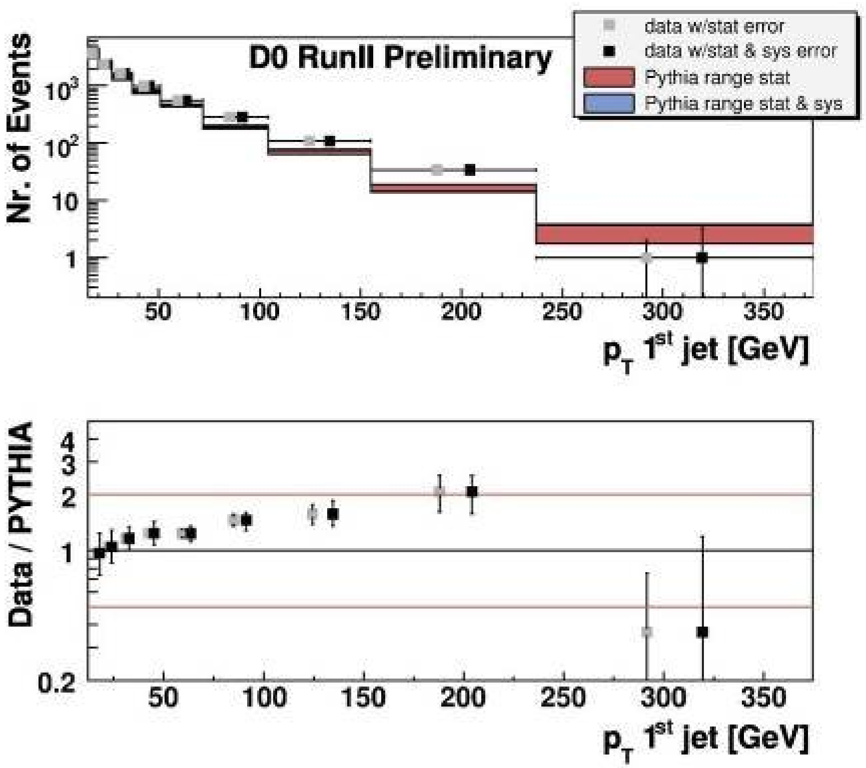
Z + Jets

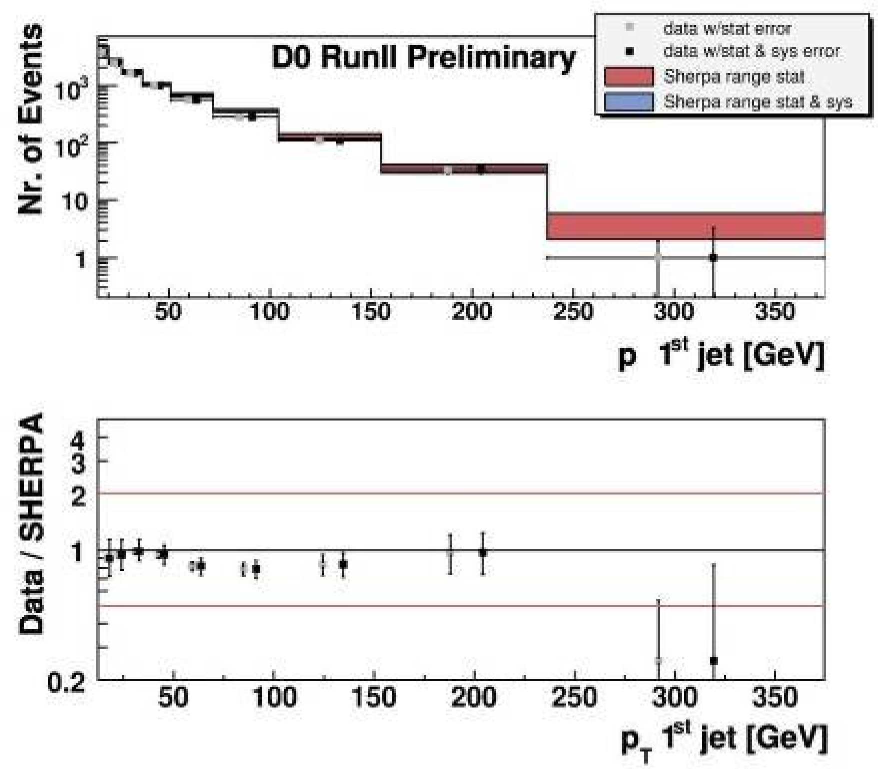
D0 preliminary (950pb-1)

- Comparison on Detector-Level: Data vs. PYTHIA and SHERPA

PYTHIA does not describe Leading Jet pT Spectrum

SHERPA is pretty good!





Heavy Flavor Jets

Heavy Flavor PDFs

Fixed-Order: NLO

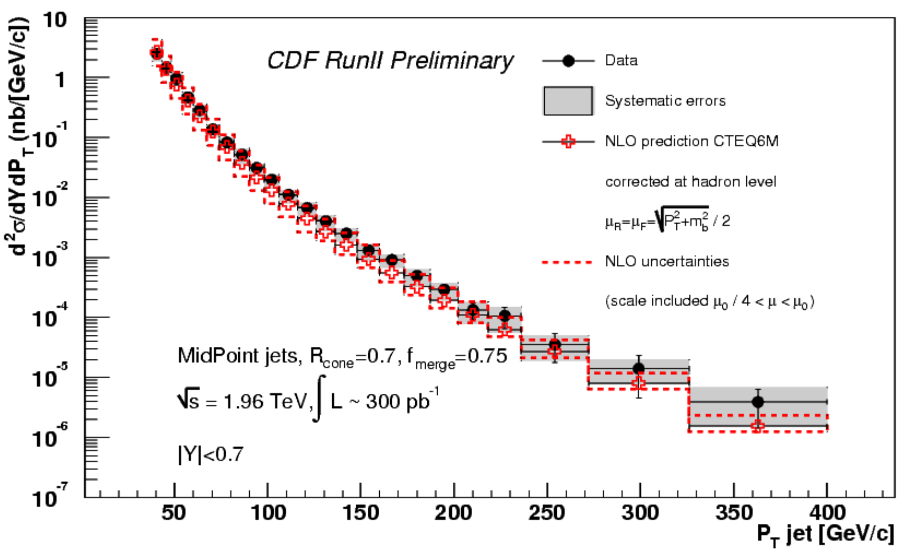
LO + Parton Shower

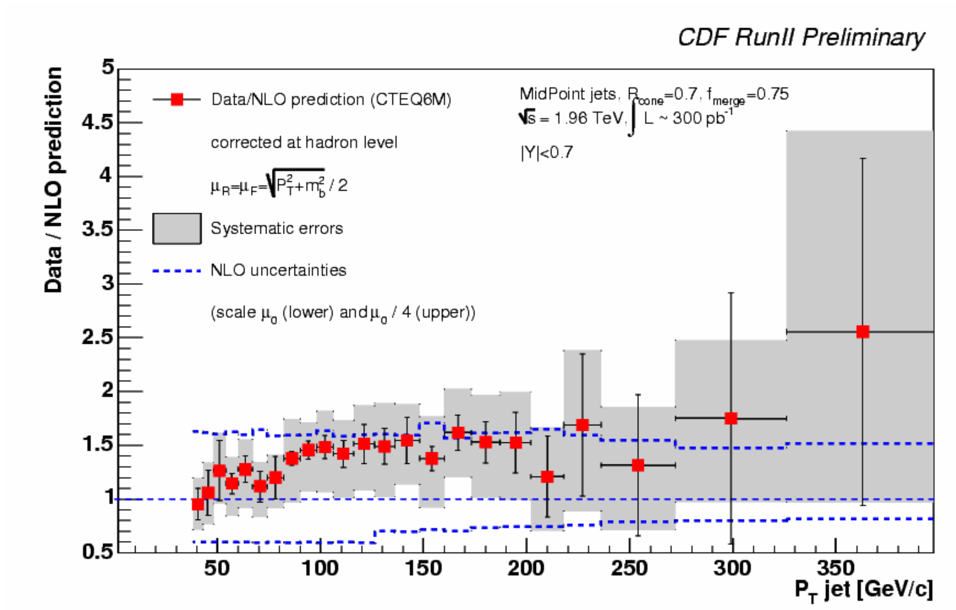
Inclusive b-Jet Cross Section

CDF preliminary (300pb-1)

- Reconstruct Secondary Vertex from B Hadron
- Dominant Syst. Uncertainties
  - Jet Energy Calibration
  - Purity of Tagged B-Jet

- Agreement of Data / NLO Theory Within Uncertainties
- Huge Scale Dependence @NLO

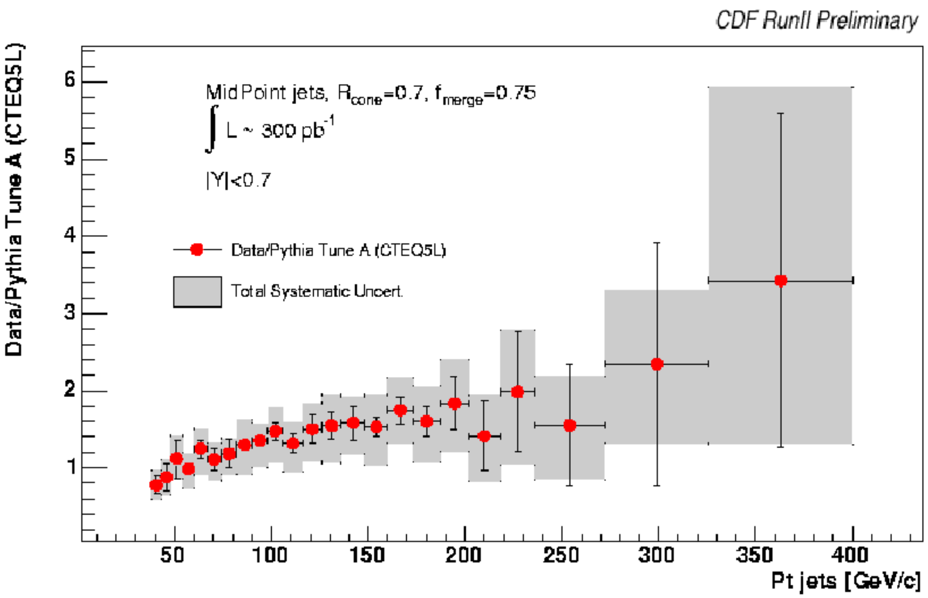


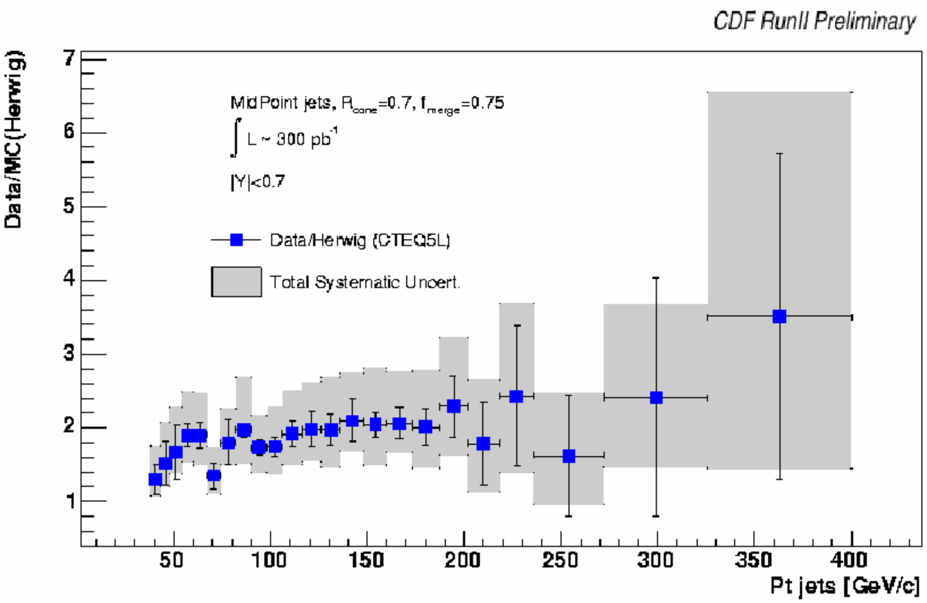


Inclusive b-Jet Cross Section

CDF preliminary (300pb-1)

Comparison with PYTHIA and HERWIG
- Both low (Factor 1.5-2)
- PYTHIA: pT dependent
- HERWIG: more flat

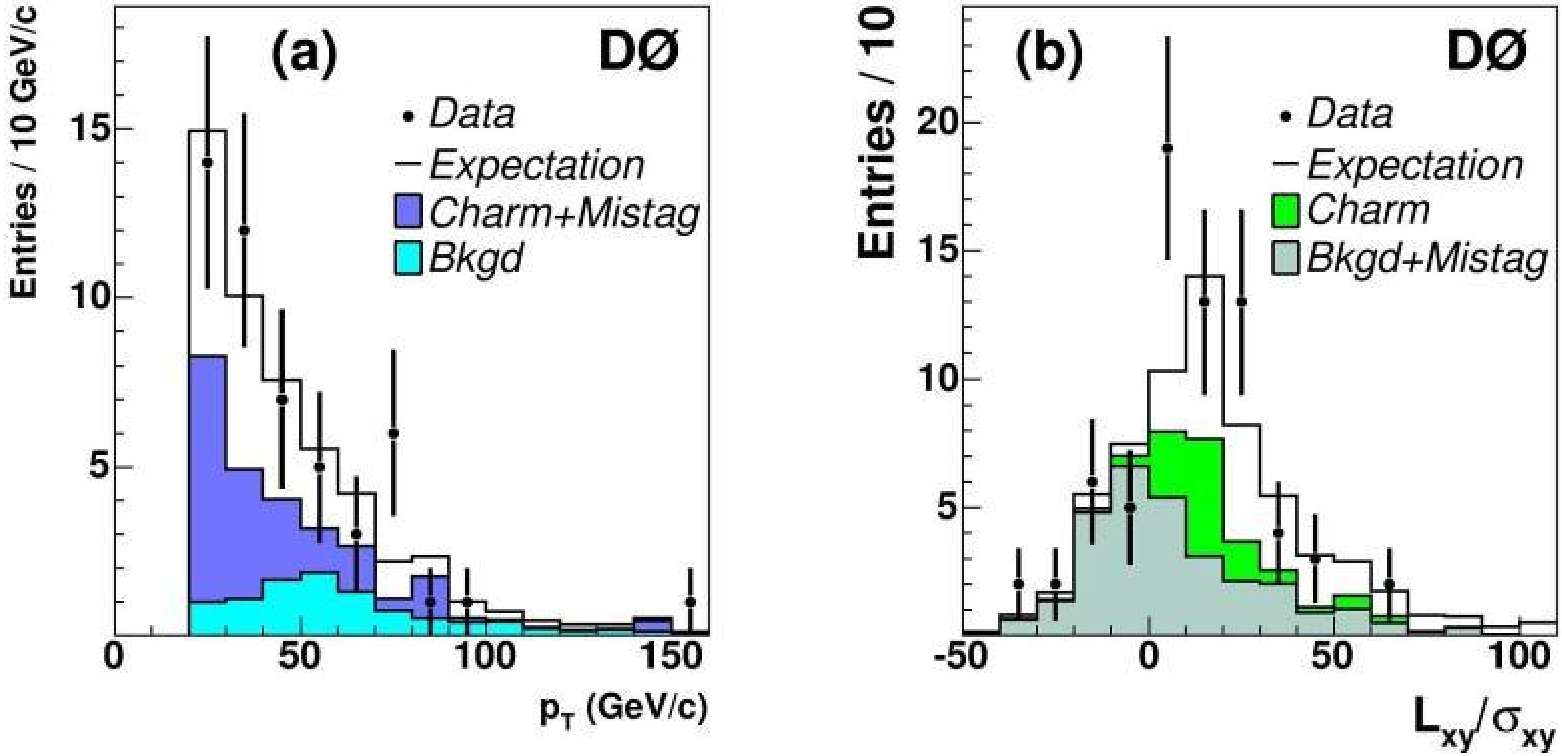




Z + b-jet

D0 (180pb-1), Phys. Rev Lett. 94, 161801 (2005)

Cross Section Ratio (Z+b-jet)/(Z+jet) pT-jet>20GeV, |eta-jet|<2.5



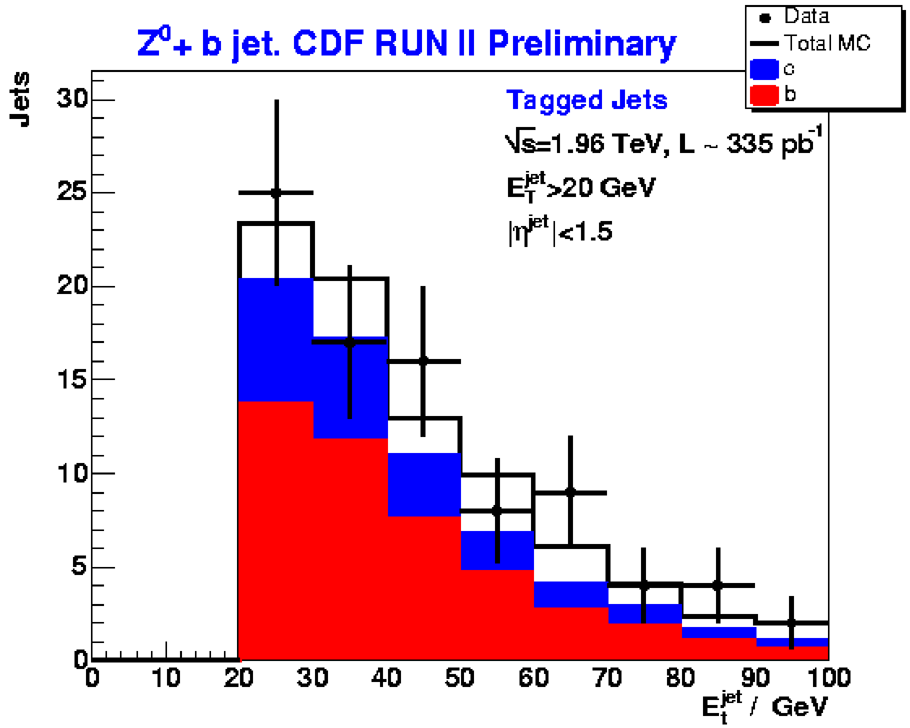
Ratio = 0.023±0.004(stat) +0.002/-0.003(syst)

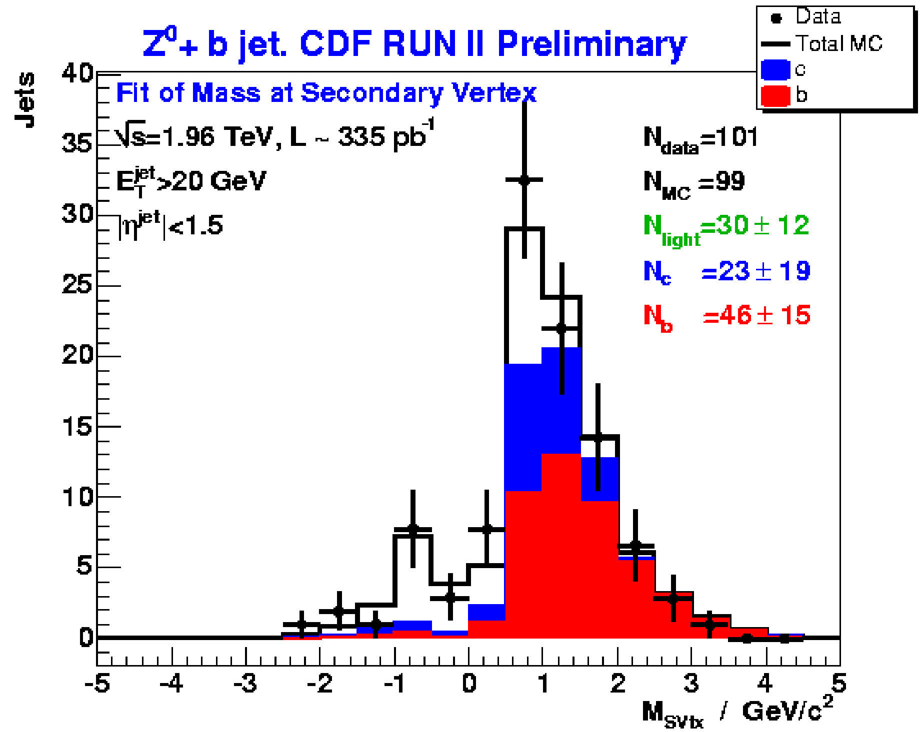
NLO (MCFM) = 0.018±0.004 (CTEQ6.1M)

Z + b-jet

CDF (335pb-1), submitted to PRD, hep-ex/0605099

Z+b-jet production: pT-jet>20GeV, |eta-jet|<1.5





sigma = 0.96±0.32(stat)±0.14(syst) pb NLO: 0.48pb

ratio over (Z+jet) = 0.0237±0.0078(stat) ±0.0033(syst) NLO: 0.018±0.004

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Jets beyond 2→2

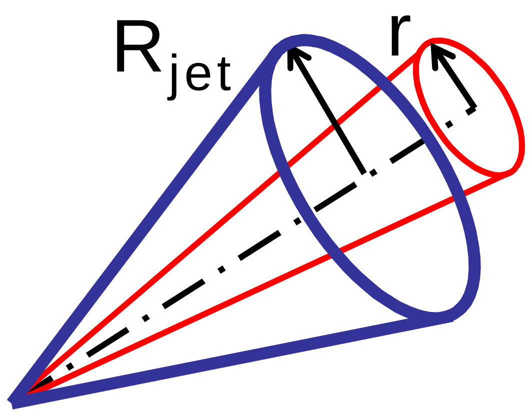
Internal Jet Structure

Dijet Azimuthal Decorrelation

Underlying Event
Parton Shower
Matched Predictions
3-Jet NLO

Internal Jet Structure

CDF, PRD, hep-ex/0505013 (170pb-1)

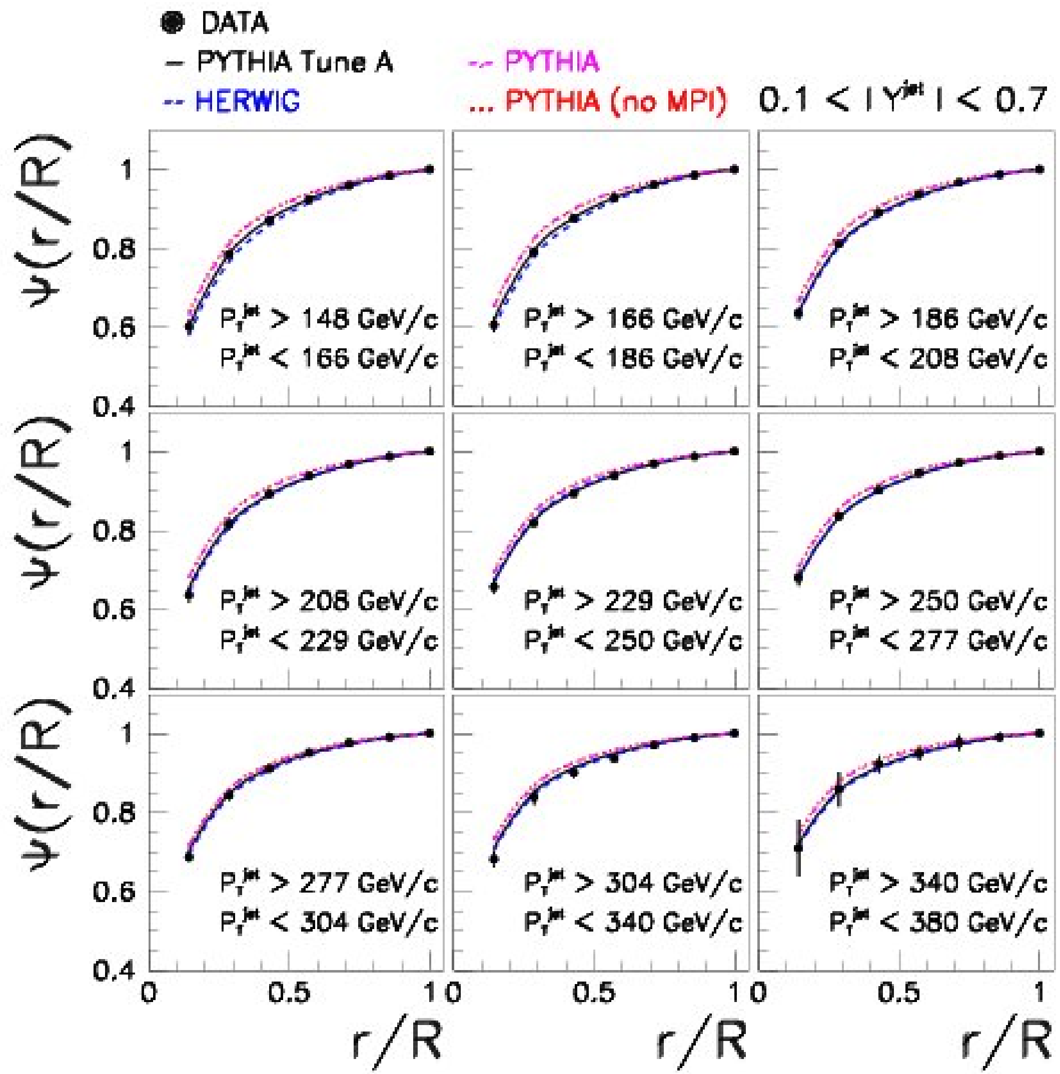


Integrated Jet Shape:

Fractional pT in Subcone vs.(r/R)

Sensitive to Soft and Hard Radiation – and UE

Well-Described by (tuned) MCs

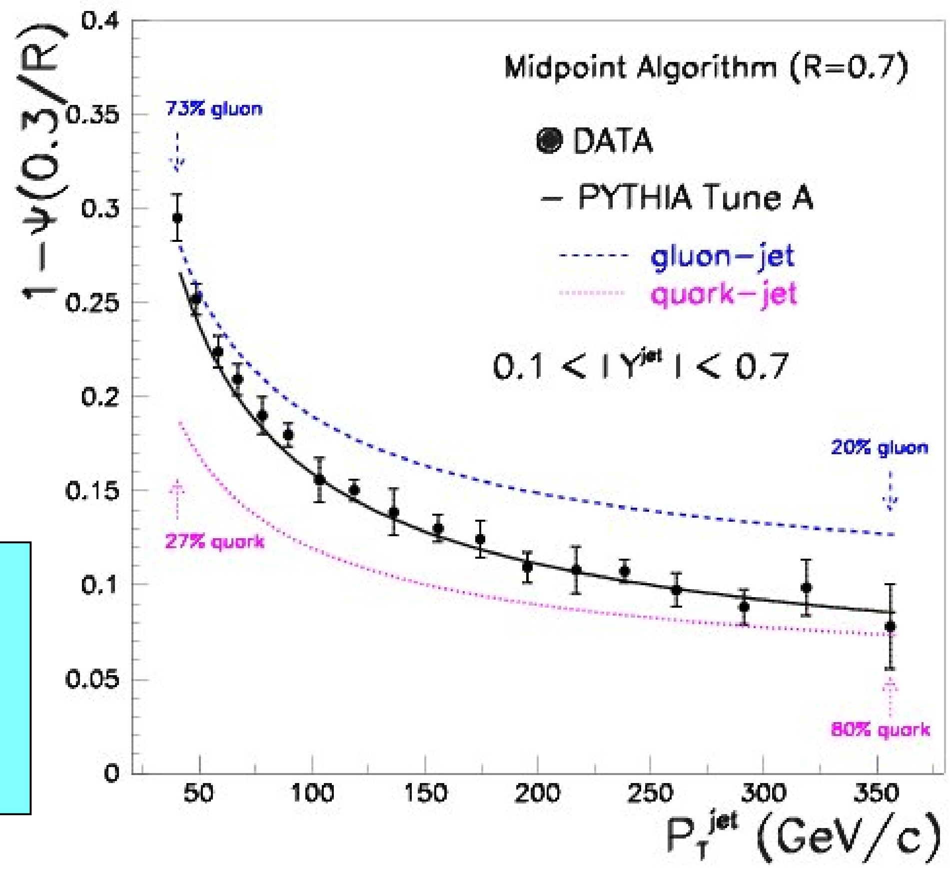


Internal Jet Structure

At fixed r=0.3 (38<pT<400GeV)

Study pT Dependence of predicted Psi(r/R) for Quark- & Gluon-Jets
→ Significant Difference

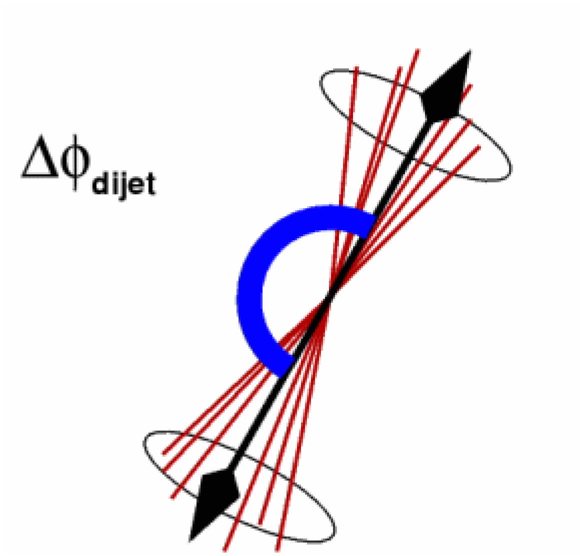
Quark- & Gluon-Jet Mixture in PYTHIA gives Perfect Description of Data

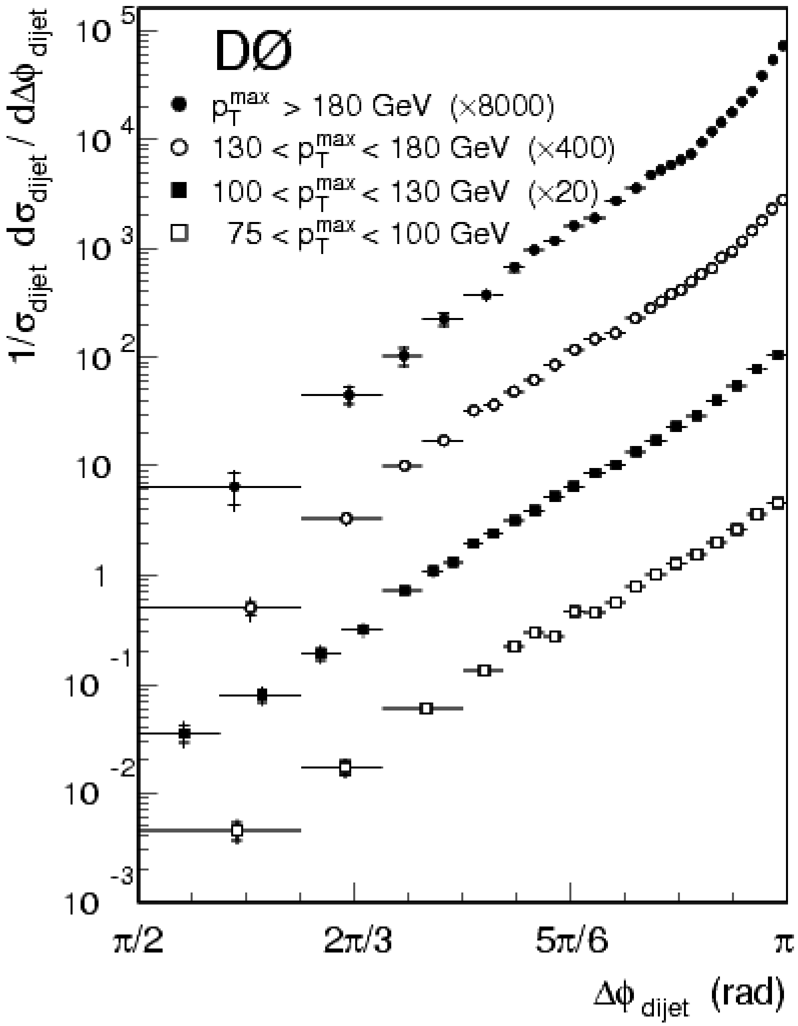


Dijet Azimuthal Decorrelation

Idea: Dijet Azimuthal Angle is Sensitive to Soft & Hard Emissions:

- Test Parton-Shower
- Test 3-Jet NLO



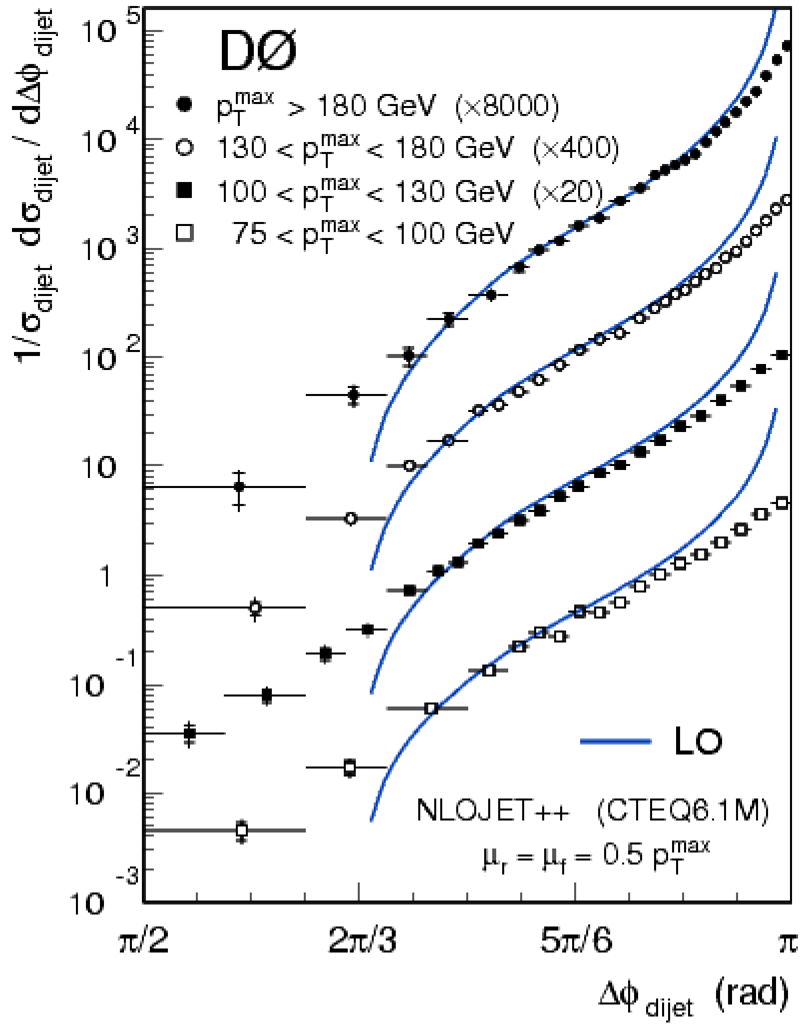


Dijet Azimuthal Decorrelation

Compare with theory:

- LO has Limitation >2pi/3

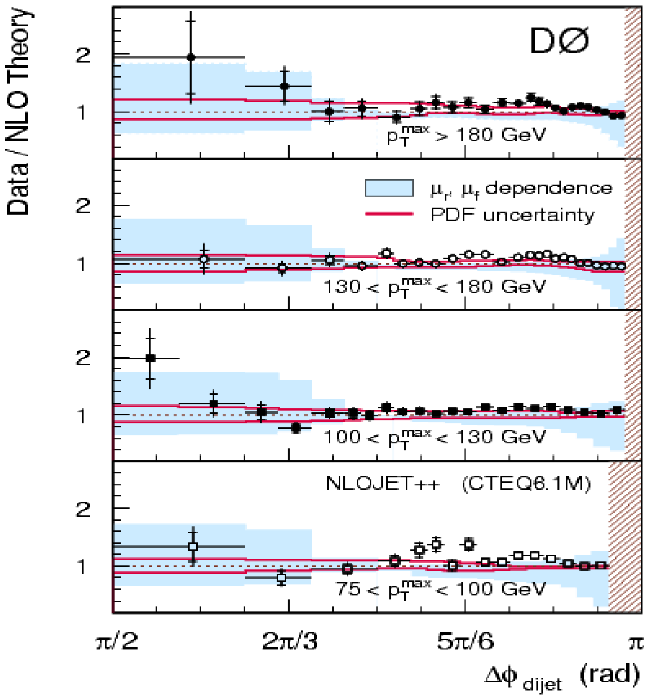
  & Divergence towards pi

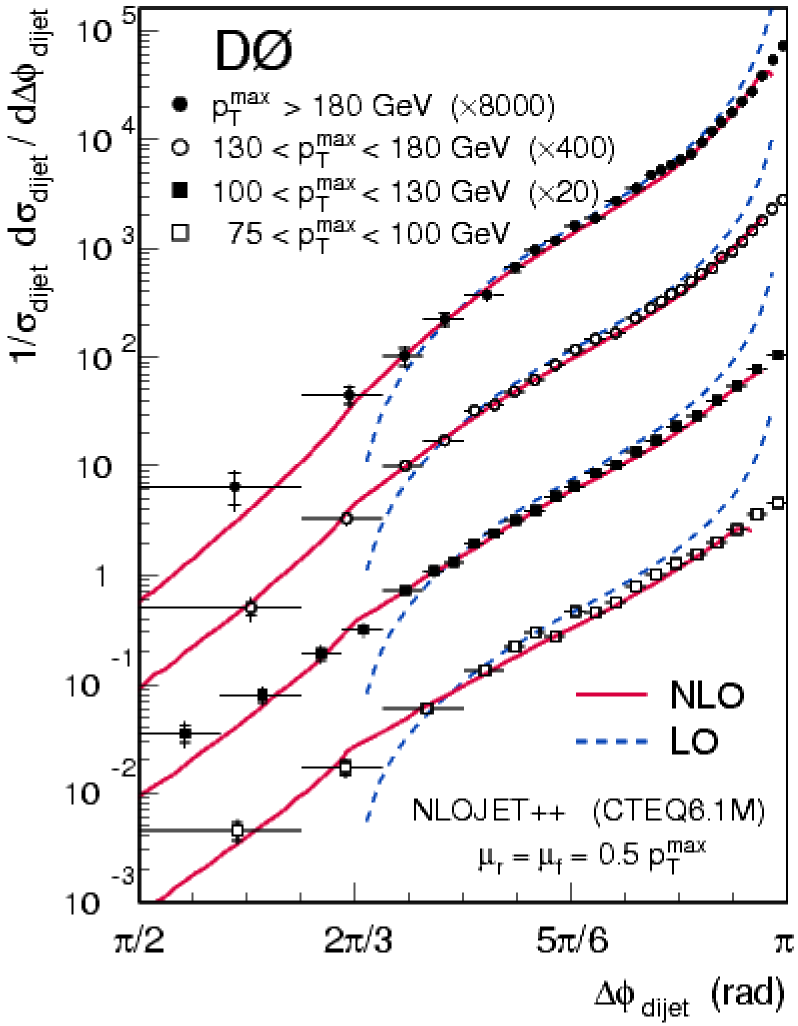


Dijet Azimuthal Decorrelation

Compare with theory:

- LO has Limitation >2pi/3
  & Divergence towards pi
- NLO is very good – down to pi/2
  & better towards pi
  ... still: resummation needed





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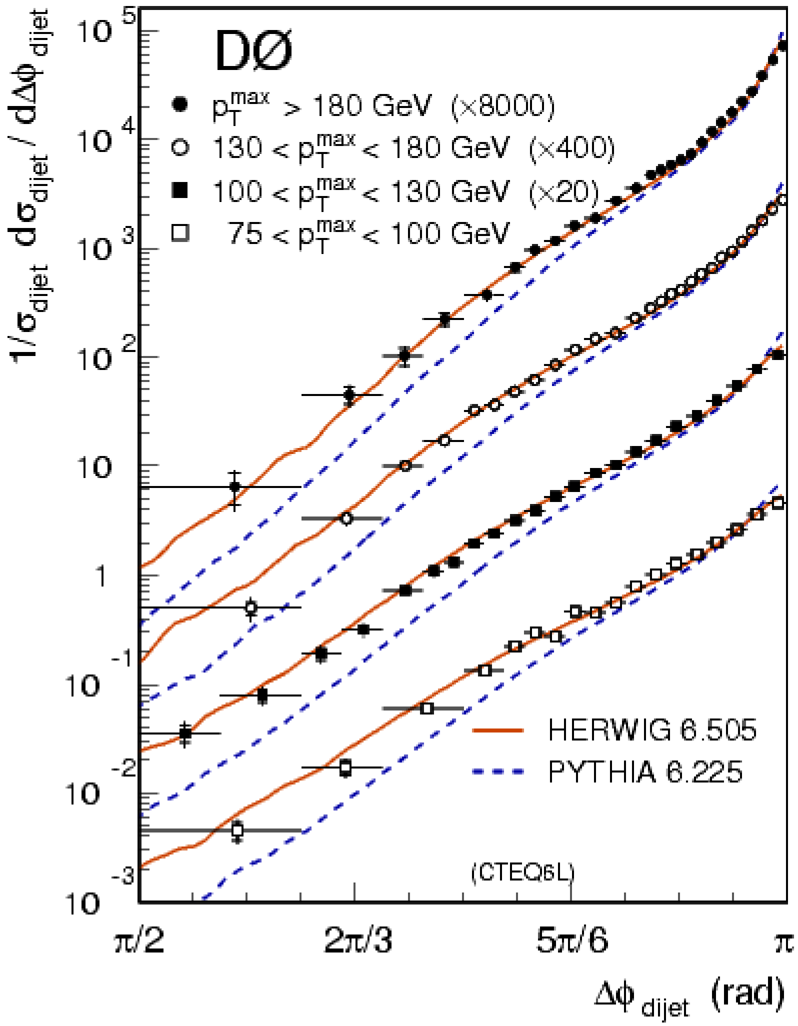
- PYTHIA is too low in tail ...



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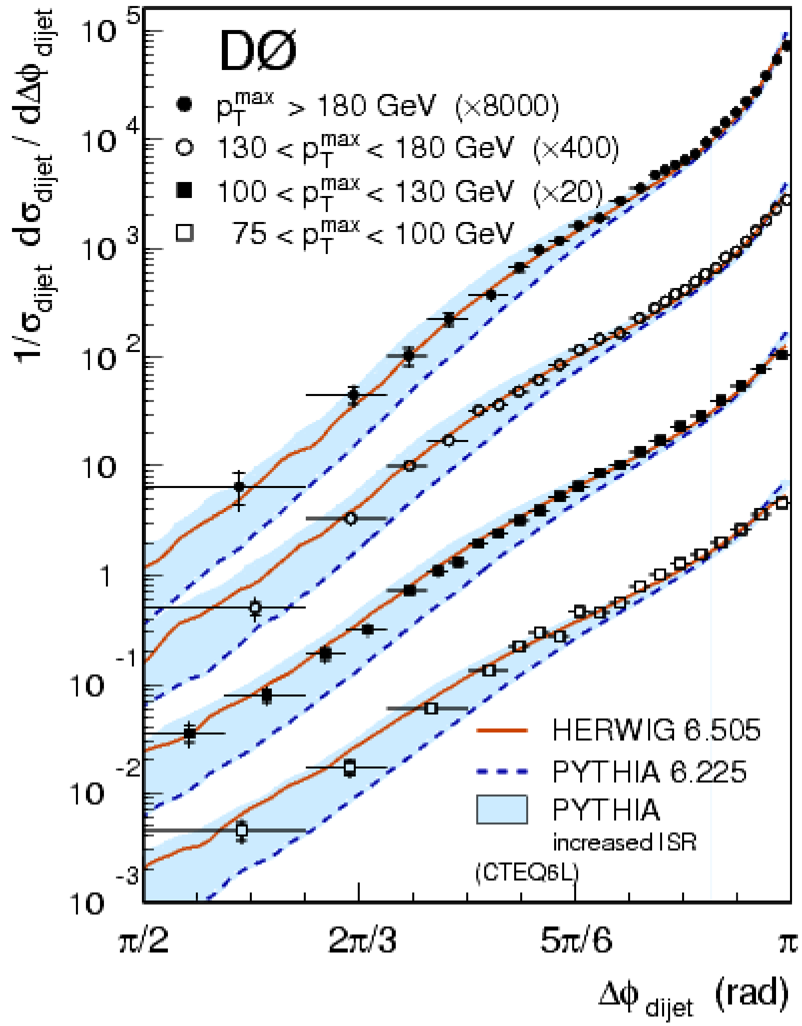

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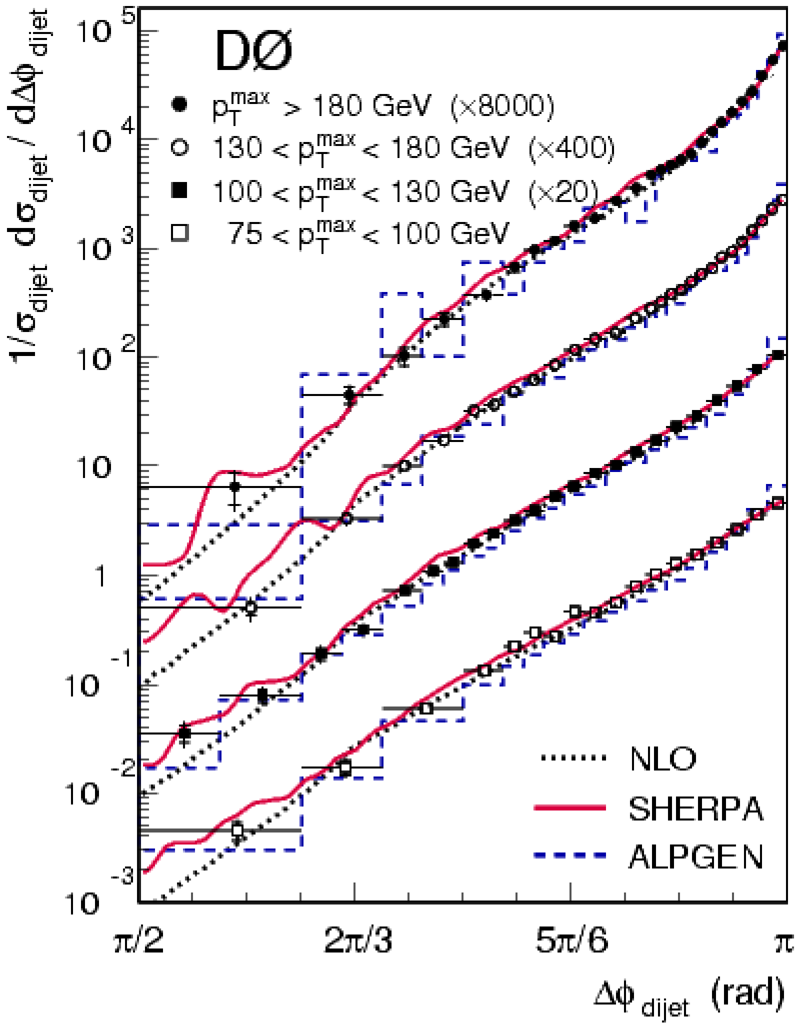
- HERWIG is perfect “out-the-box”
- PYTHIA is too low in tail ...
  ... but it can be tuned
  (“tune A” is too high!)
- SHERPA is great
- ALPGEN looks good – but low efficiency → large stat. fluctuations



Summary

- Tevatron is more than “the Place to Develop Tools for the LHC”
- This Presentation: Broad Spectrum of Processes
  Jets, Photons, W-Asymmetry, Vector-Boson + Jets,
  Heavy-Flavor Jets, Jet Production at higher Orders
- “Bread-and-Butter Physics”:
  Precision Measurements of Fundamental Observables @2TeV
- Successfully Testing various Approximations of QCD
- Significant Impact in Constraining Proton PDFs

Run IIb has just started!!