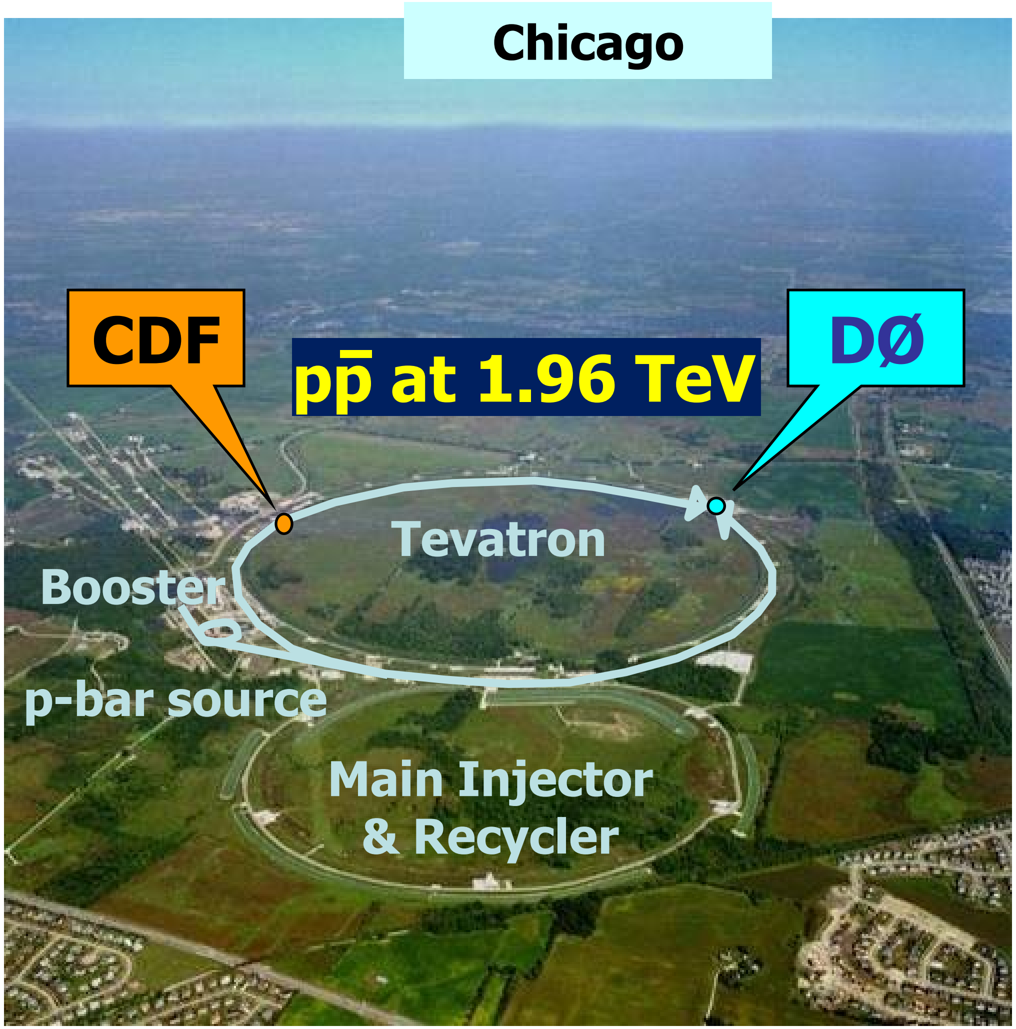
QCD Studies at the Tevatron

Results from the CDF and DØ Collaborations

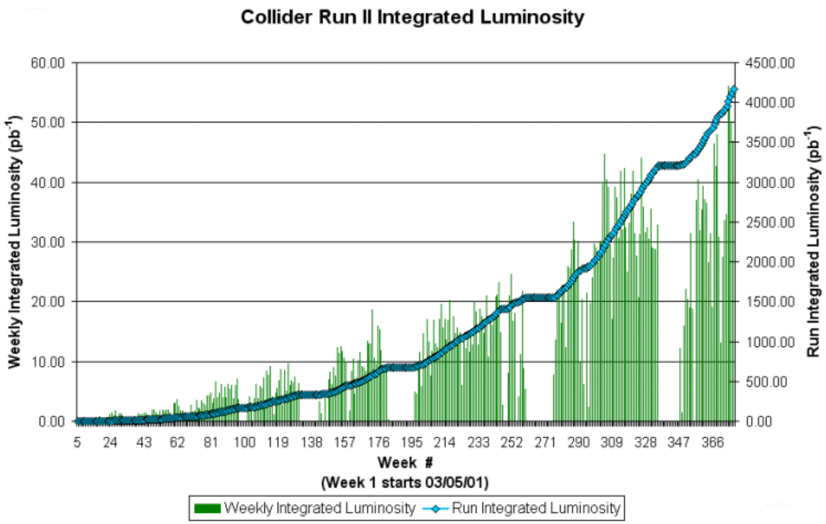
Markus Wobisch, Louisiana Tech University

DESY Seminar, June 24, 2008

Fermilab Tevatron - Run II



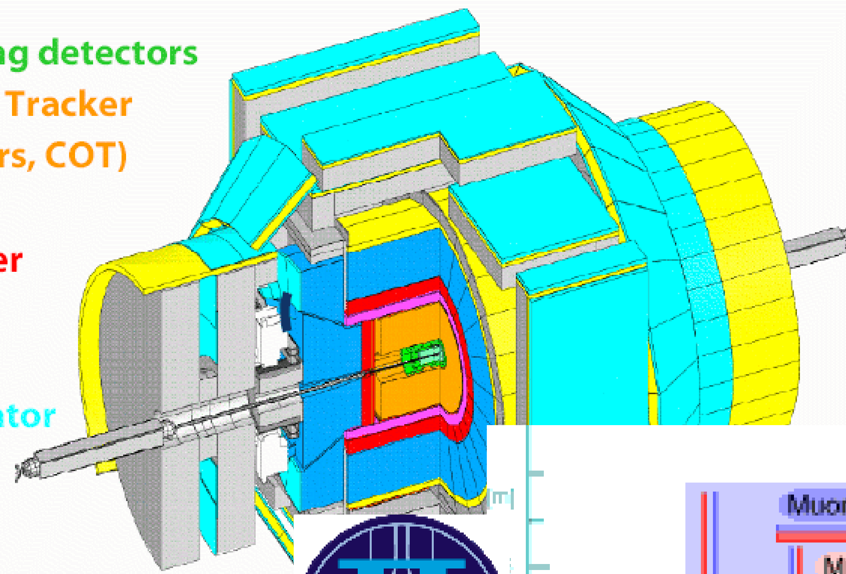
- 36x36 bunches
- bunch crossing 396ns
- Run II started in March 2001
- Peak Luminosity: 2.85E32 cm^{-2} sec^{-1}
- Run II delivered: >4.2 fb^{-1}



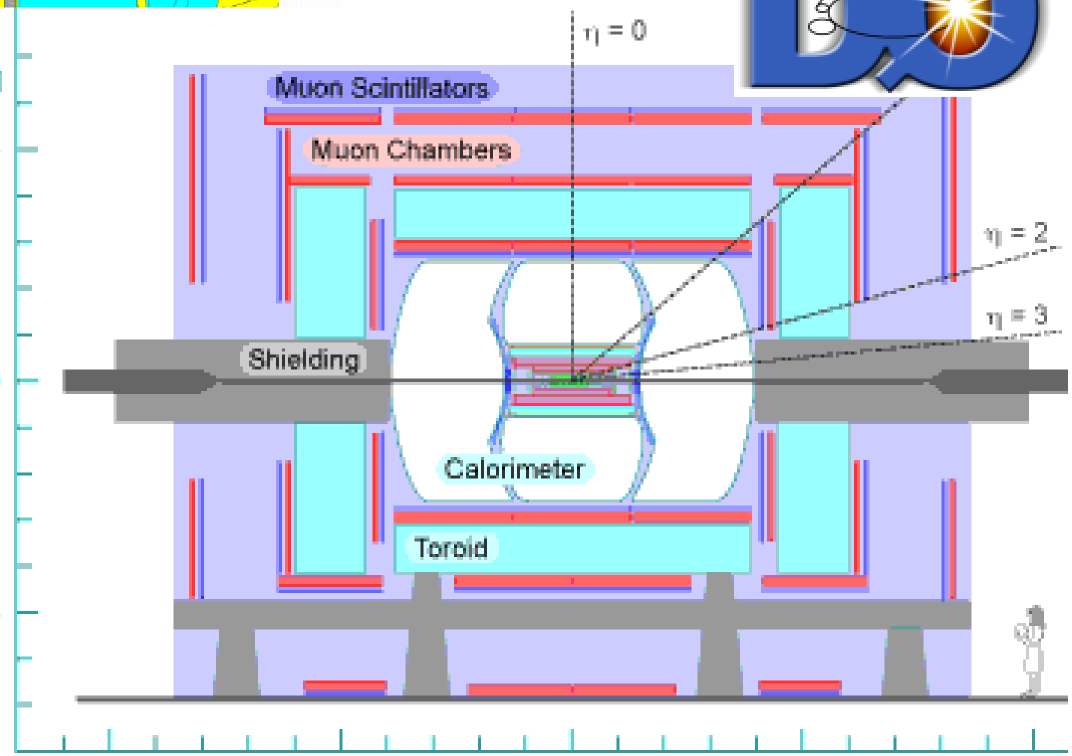
- Run II Goal: 8 fb^{-1} end of FY2010

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

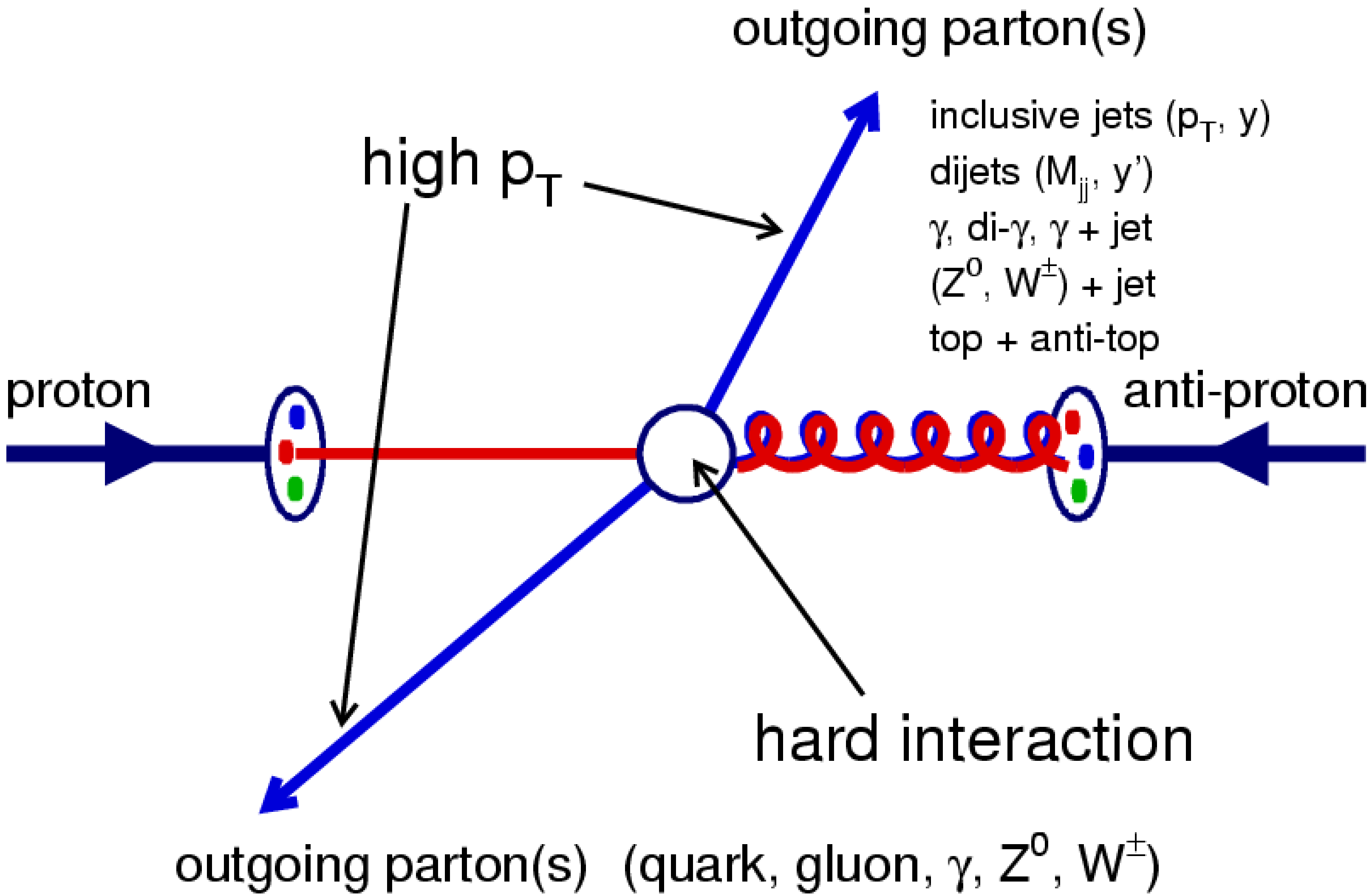
two high-energetic hadrons

Hadron-Hadron Collisions

partons inside the hadrons:
parton density functions (PDFs)

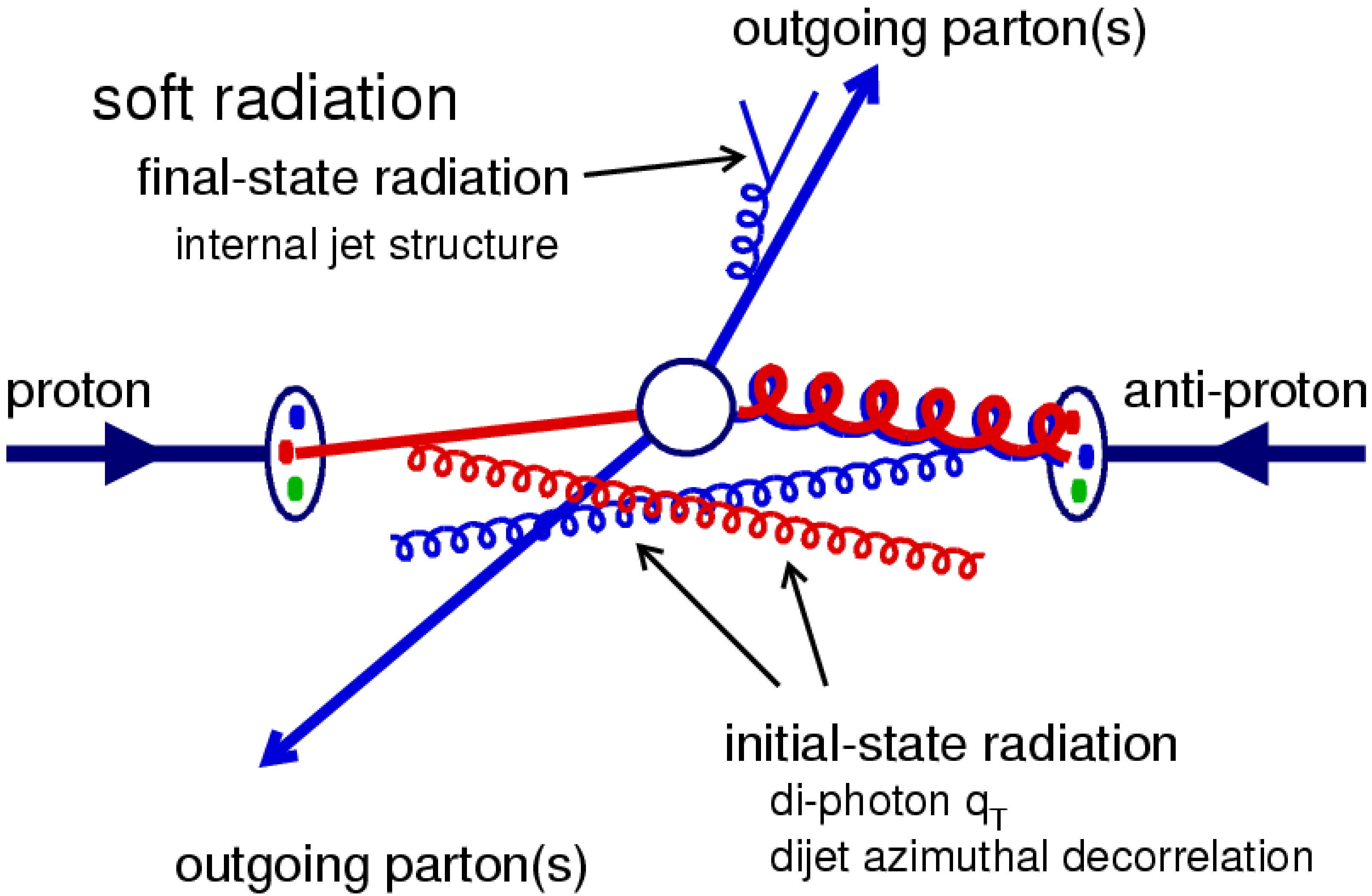
two high-energetic hadrons

Hadron-Hadron Collisions



MWos

Hadron-Hadron Collisions



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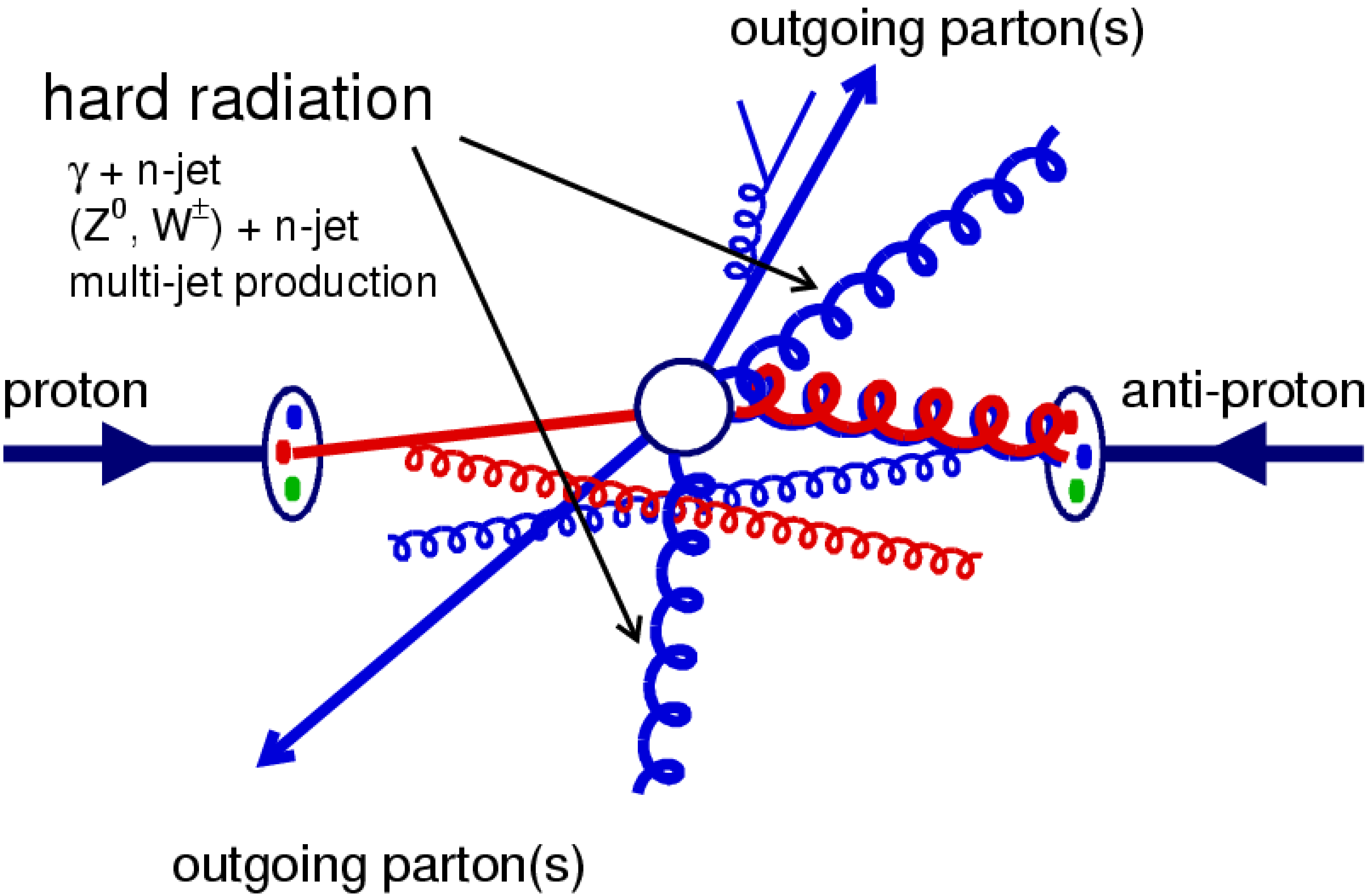
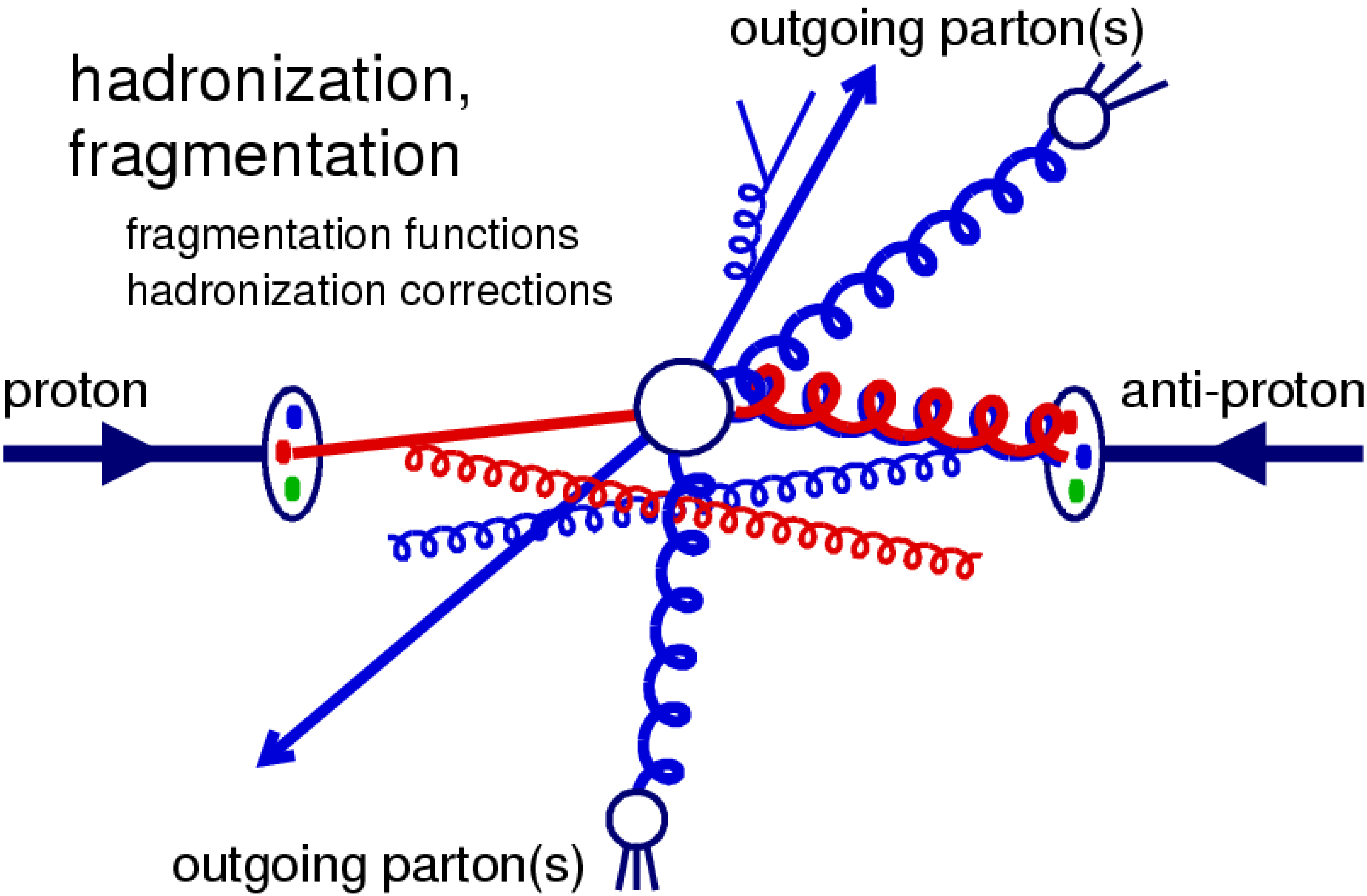


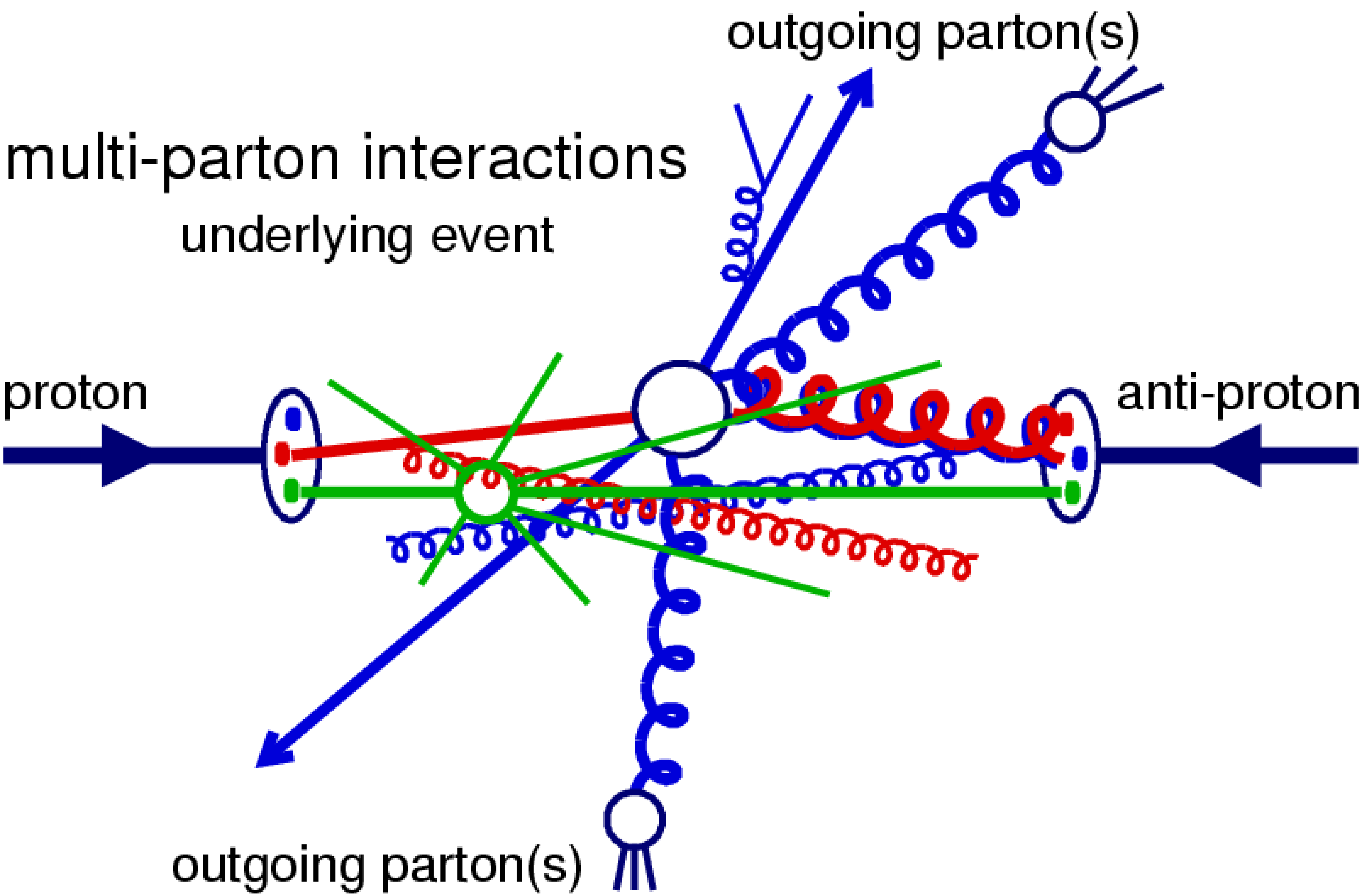
Hadron-Hadron Collisions

hadronization,
fragmentation

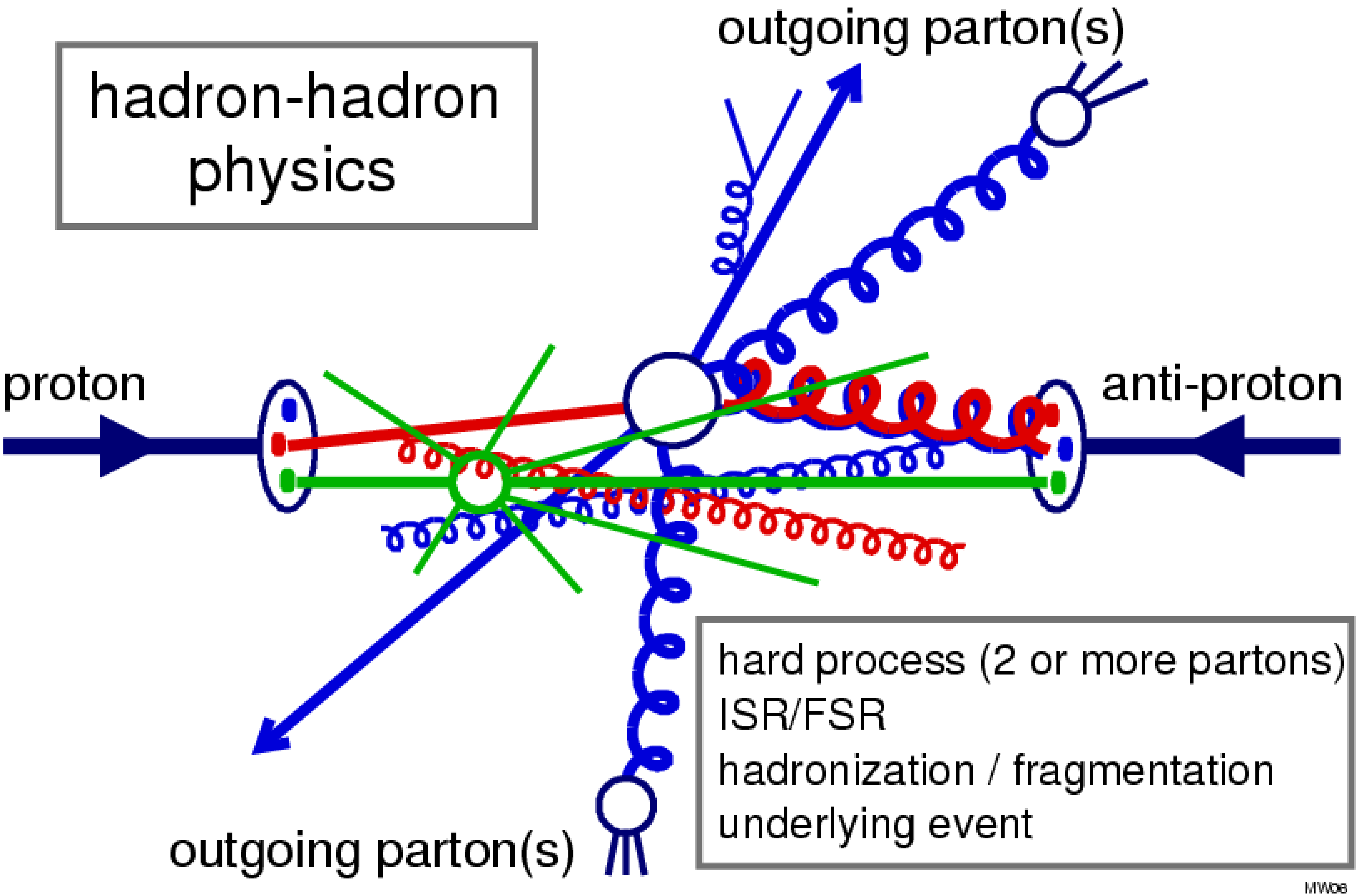
fragmentation functions
hadronization corrections



Hadron-Hadron Collisions



Hadron-Hadron Collisions



Outline

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

Not shown:

- Diffractive Results
- Underlying Event Studies

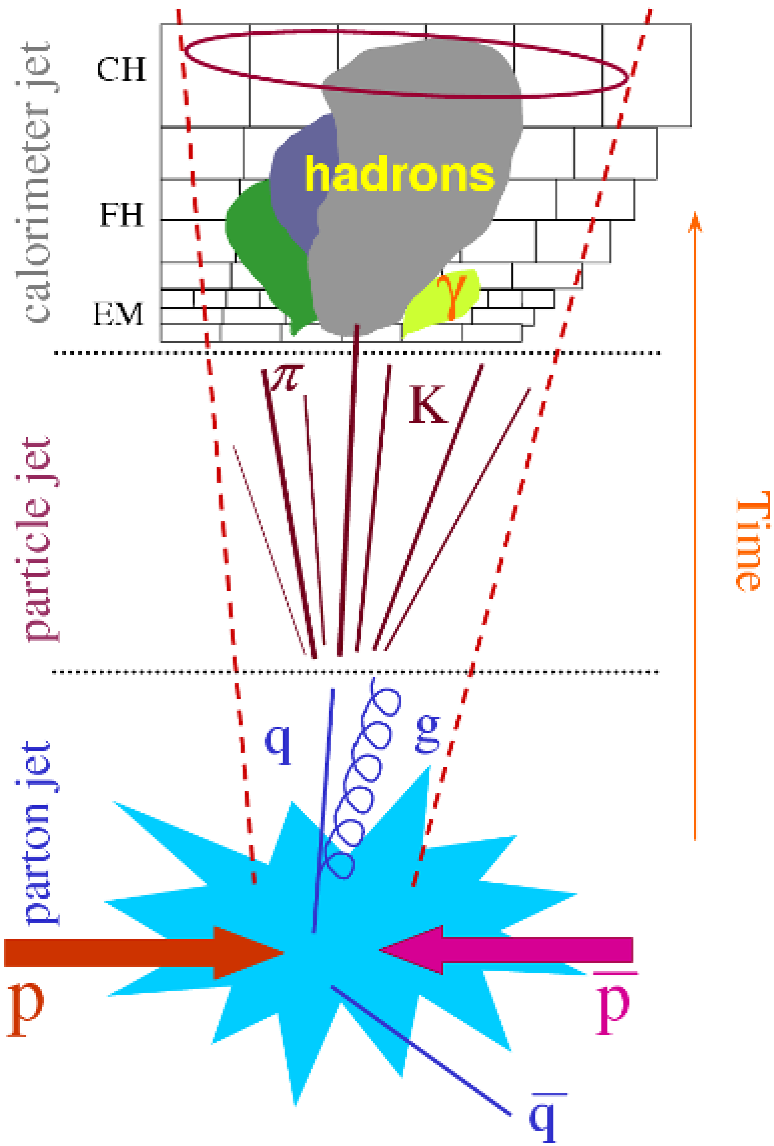
.

Jets

PDFs

QCD vs. "New Physics"?

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)
  only quantity to be predicted in pQCD

IR- and Collinear safe jet algorithms:
- TeV4LHC workshop
- Les Houches 2007 workshop

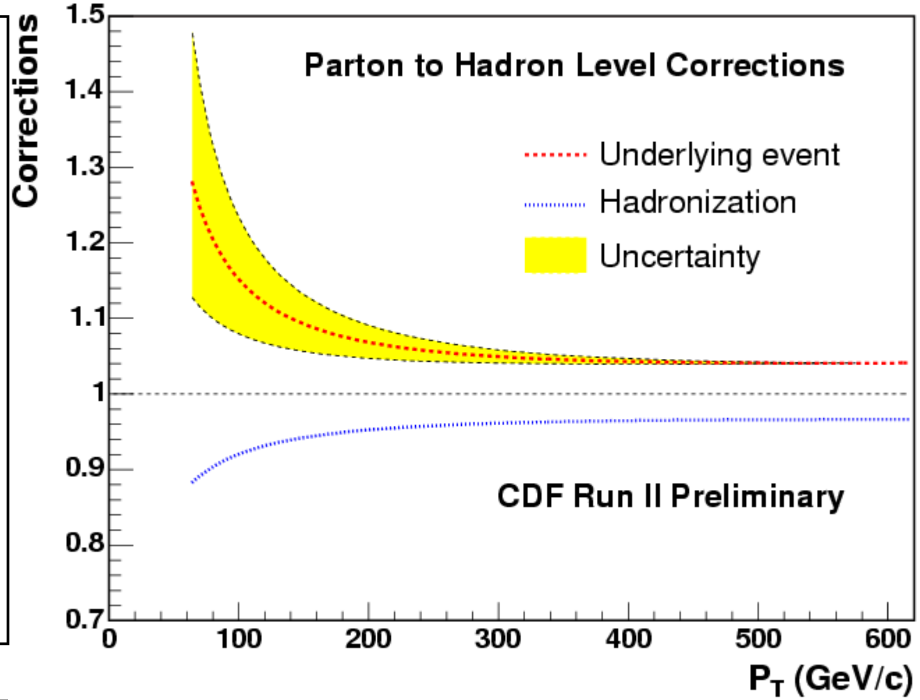
From Particle to Parton Level

- Measure cross section for pp-bar → Jets (on "Particle-Level")
  Corrected for Experimental Effects (Efficiencies, Resolution, …)

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



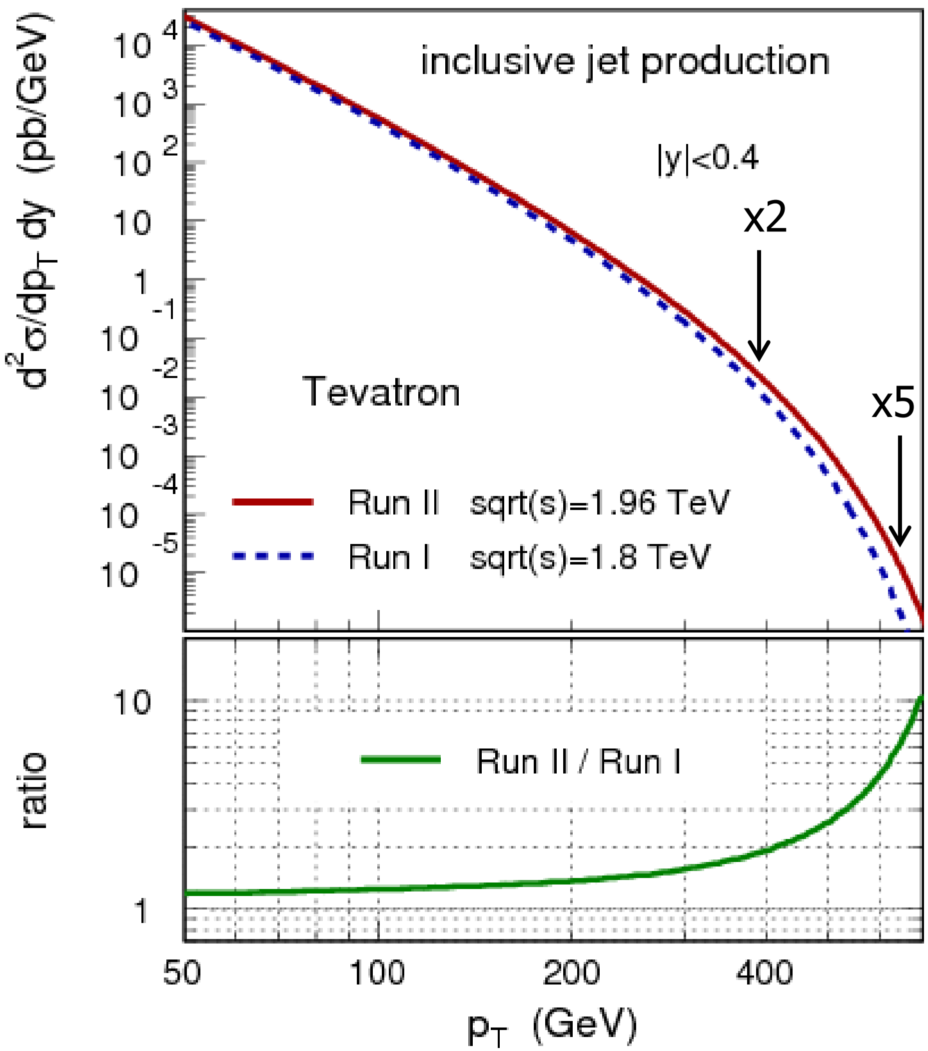
→ Apply this correction to the pQCD calculation

→ to be used for future MSTW/CTEQ PDF results

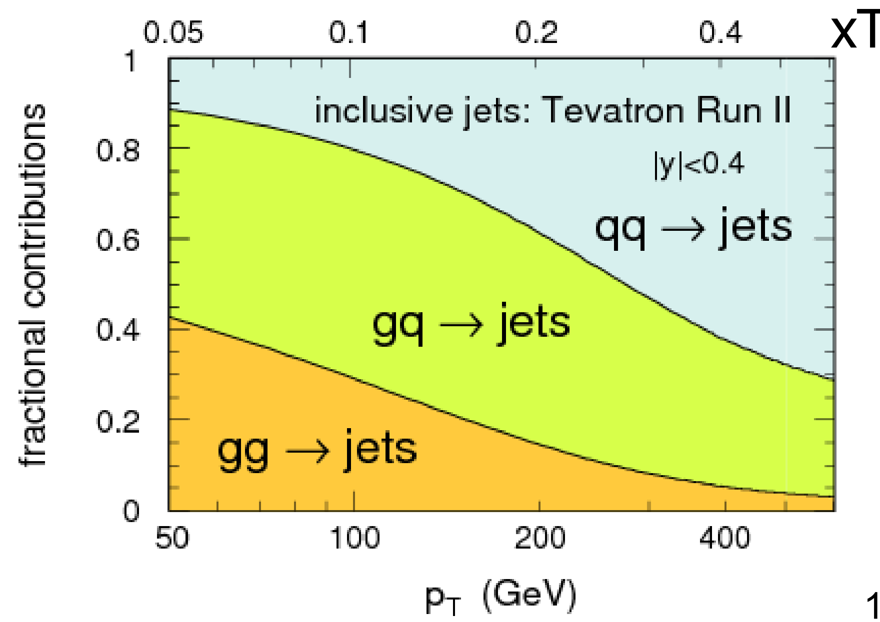
→ First time consistent theoretical treatment of jet data in PDF fits

New in Run II !!!

Inclusive Jet Production



- Run II: Increased x5 at pT=600GeV
  → sensitive to "New Physics":
  Quark Compositeness,
  Extra Dimensions, …(?)…
- Theory @NLO is reliable (10%)
  → sensitivity to PDFs
  → unique: high-x gluon



Inclusive Jet Cross Section

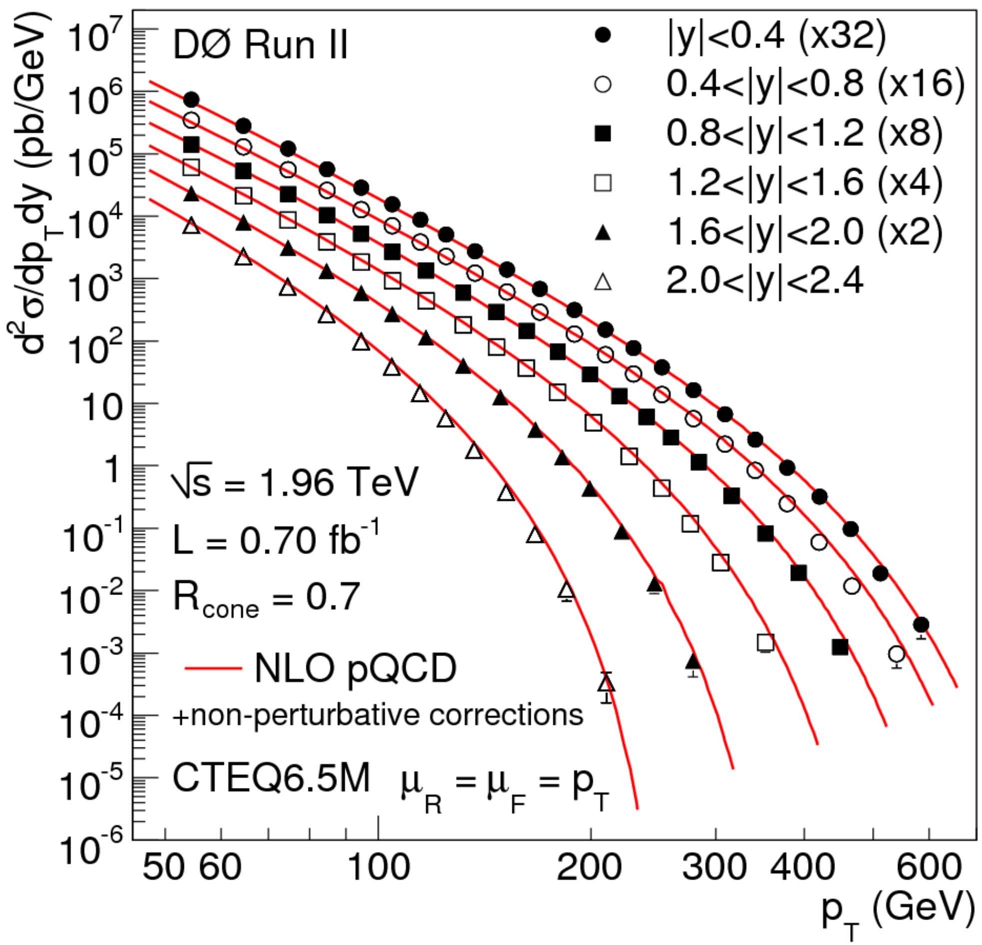
submitted to PRL arXiv:/0802.2400 [hep-ex]

Steeply falling pT spectrum:
1% error in jet energy calibration
→ 5—10% (10—25%)
central (forward) x-section

Benefit from
- Seven times more luminosity than in Run I
- Increased high pT cross section due to increased Run II cm energy
- Seven years of hard work on jet energy calibration

→ Result with largest rapidity coverage and highest precision!

D0 Run II (L=0.7 fb-1)



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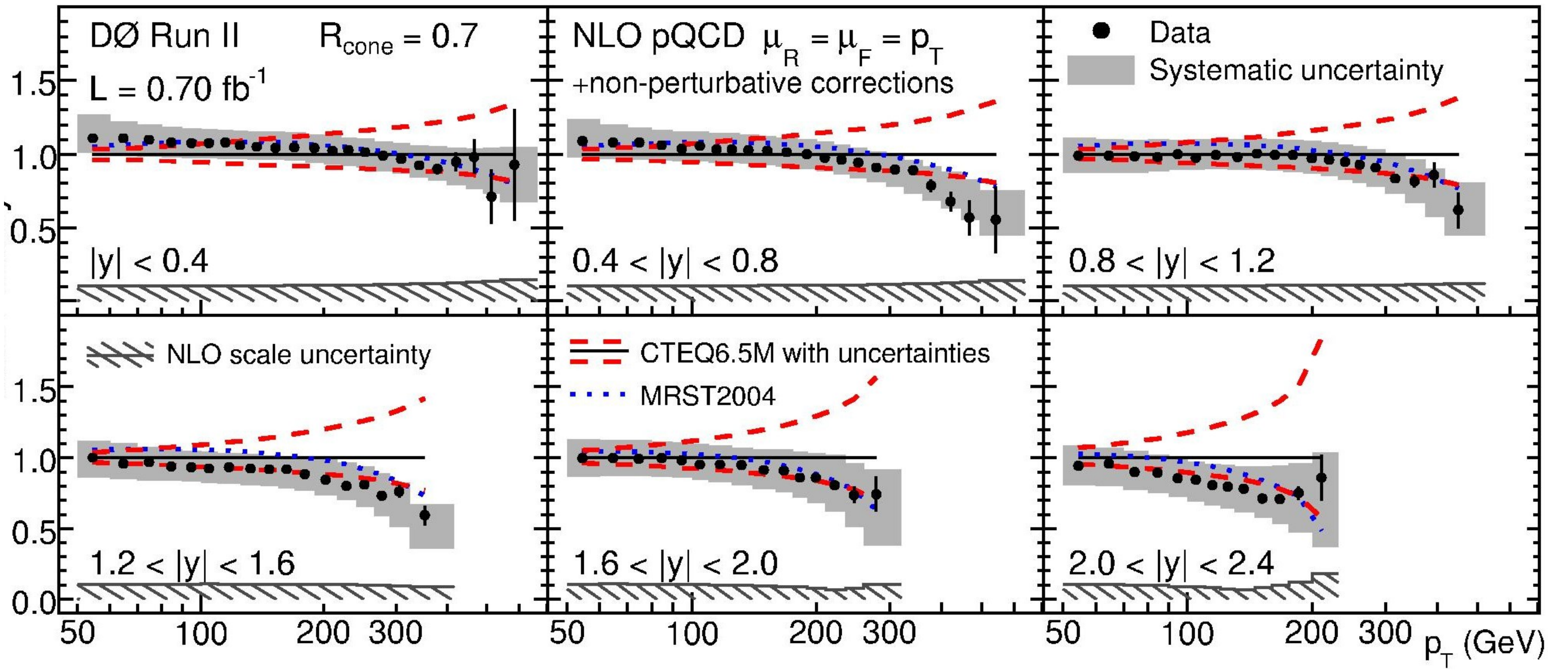
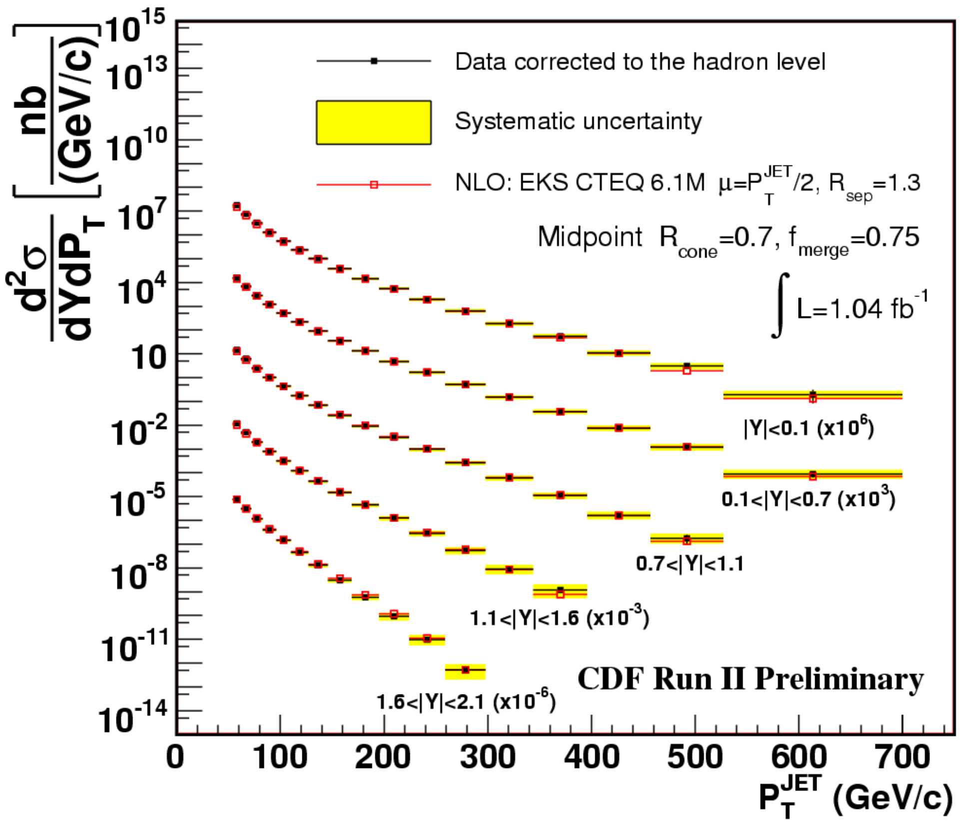


- data are well-described by NLO pQCD
- experimental uncertainties: smaller than PDF uncertainties!!
- data favor lower edge of CTEQ 6.5 PDF uncertainties at high p_T
- shape well described by MRST2004

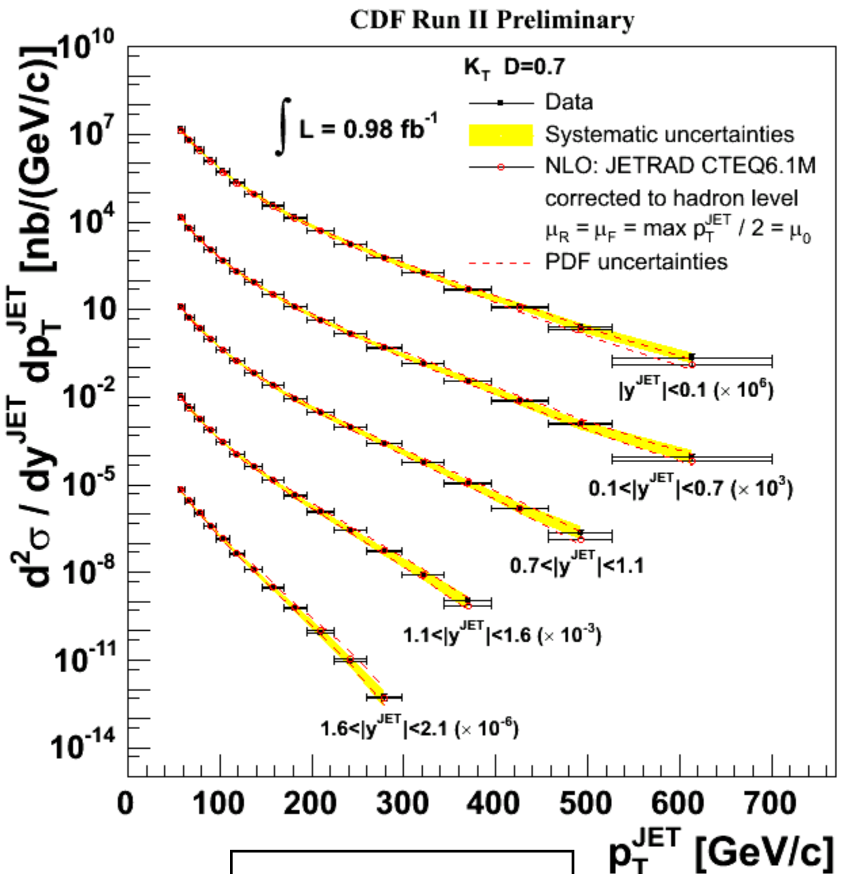
→ data are used in forthcoming MSTW2008 PDFs (→ talks at DIS2008)

Inclusive Jets
Cone and kT Algorithms

In 2005: published both central cone and kT jets with 400pb-1
Here: 2007/2006 results with large rapidity coverage for 1fb-1

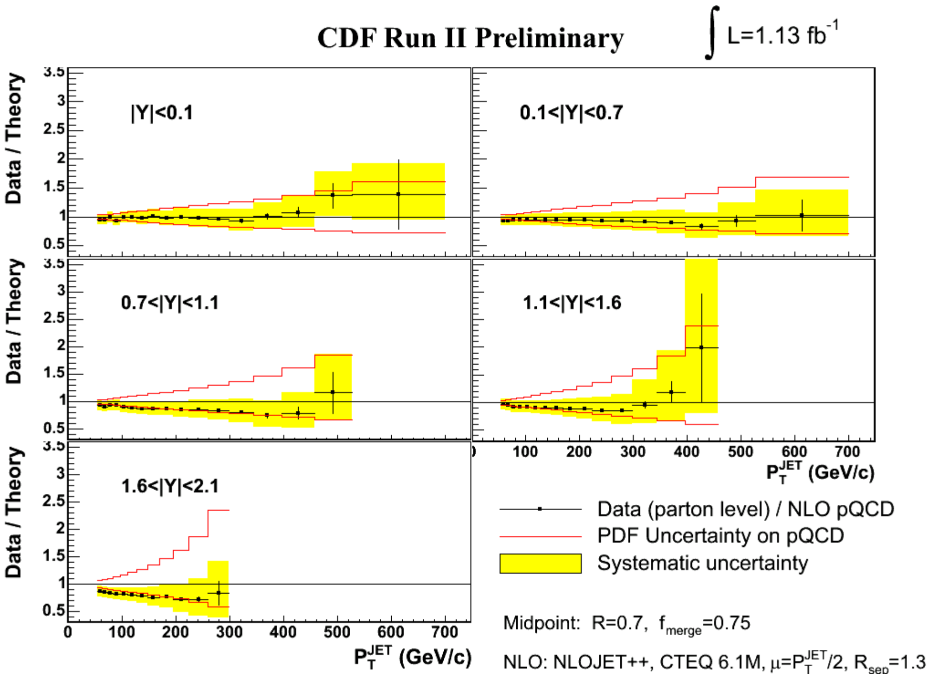


Midpoint Cone Algorithm



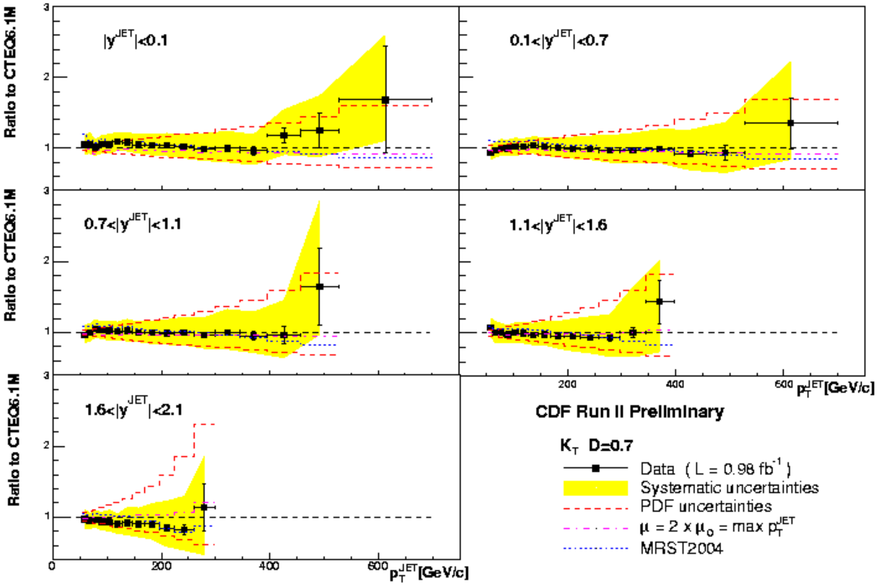
kT Algorithm

Inclusive Jets
Cone and kT Algorithms



Midpoint Cone Algorithm

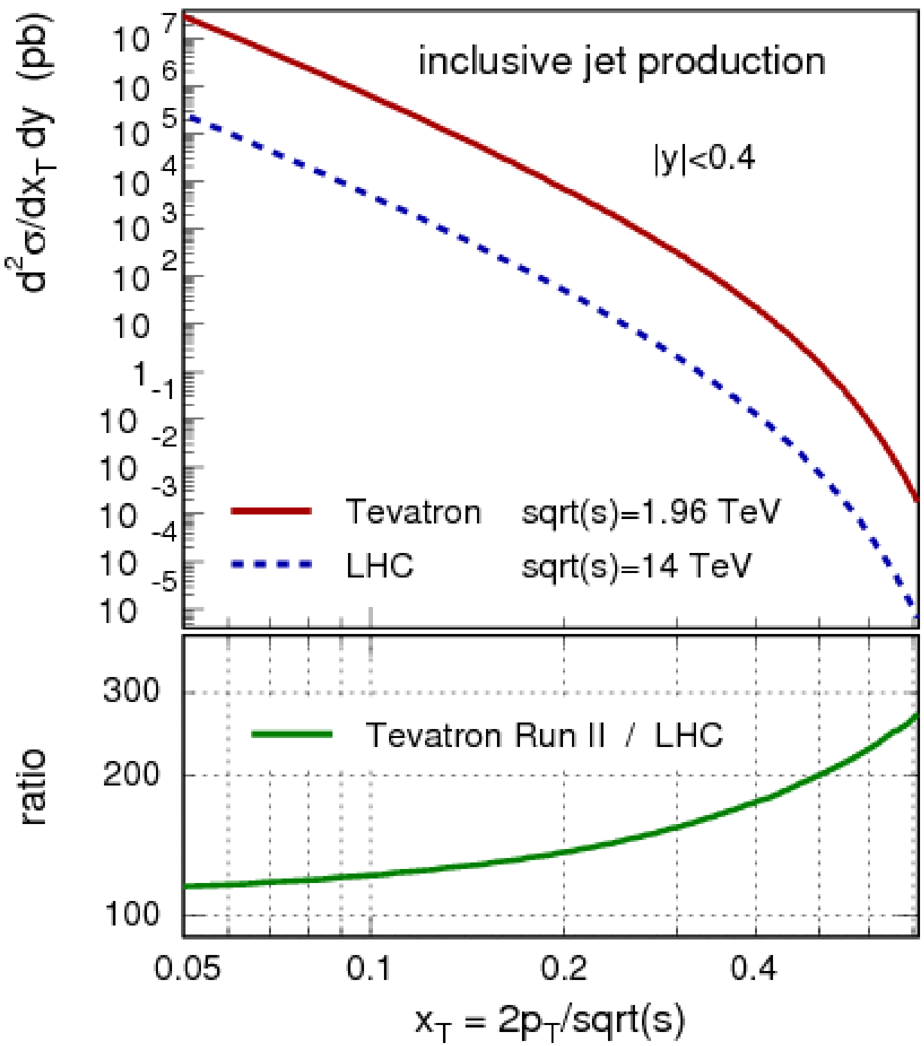
Phys. Rev. D 75, 092006 (2007)



kT Algorithm

Interpretations of CDF cone and kT jet results are consistent with D0 cone result

Inclusive Jets: Tevatron vs. LHC



PDF sensitivity:

→ Compare Jet Cross Section at fixed xT = 2pT / sqrt(s)

Tevatron (ppbar)

>100x higher cross section @ all xT

>200x higher cross section @ xT>0.5

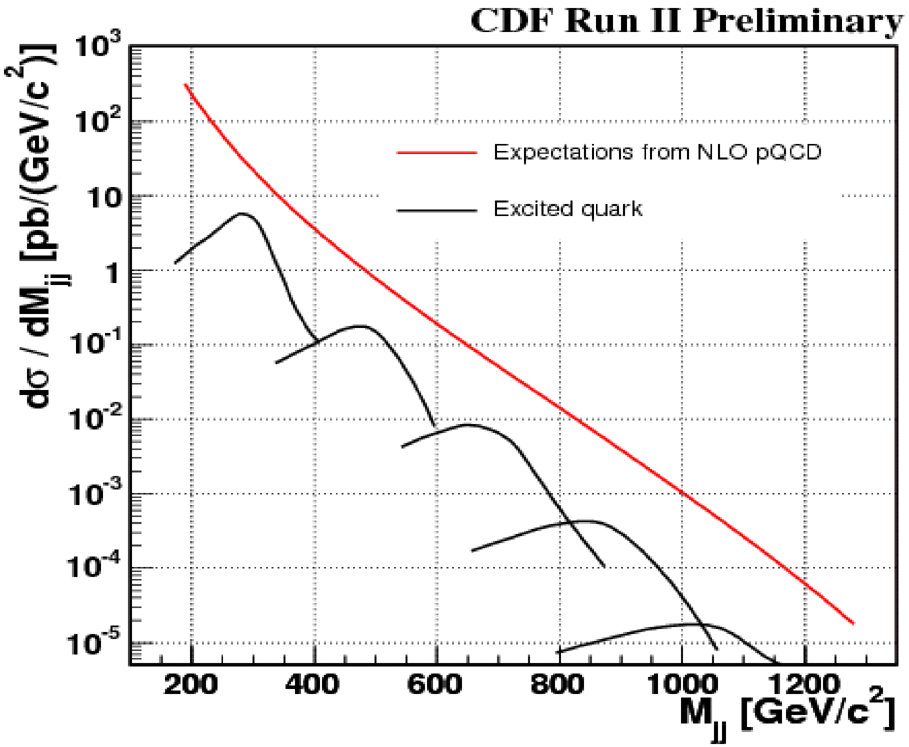
LHC (pp)

- need more than 1600fb-1 luminosity to compete with Tevatron@8fb-1
- more high-x gluon contributions
- but more steeply falling cross sect. at highest pT (=larger uncertainties)

→ Tevatron results will dominate high-x gluon for some time …

Dijet Mass Distribution

Central Dijet Production |y|<1
sensitive to new particles
decaying into dijets



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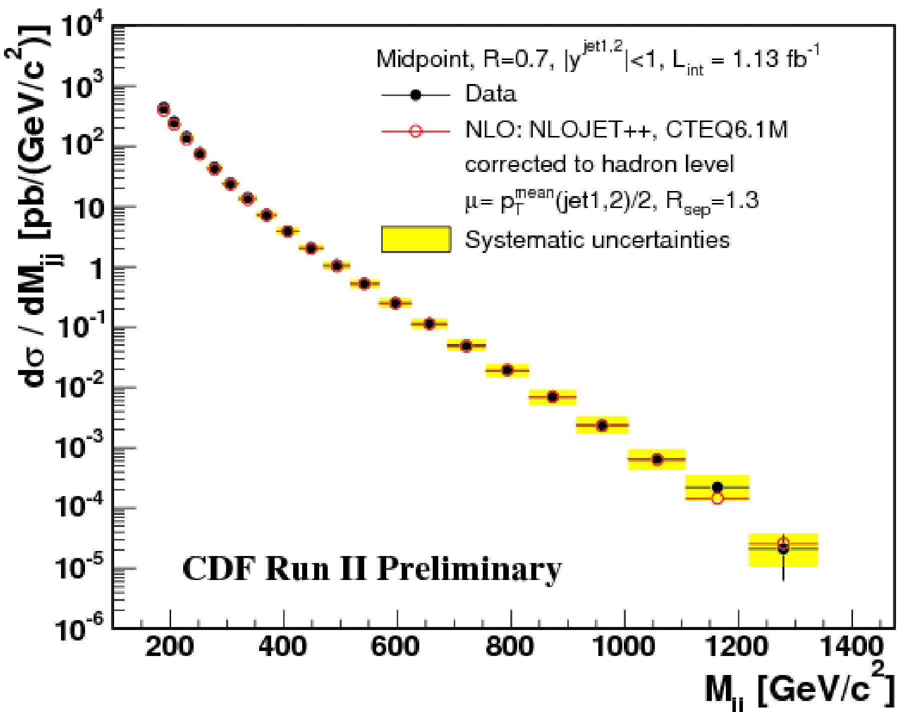
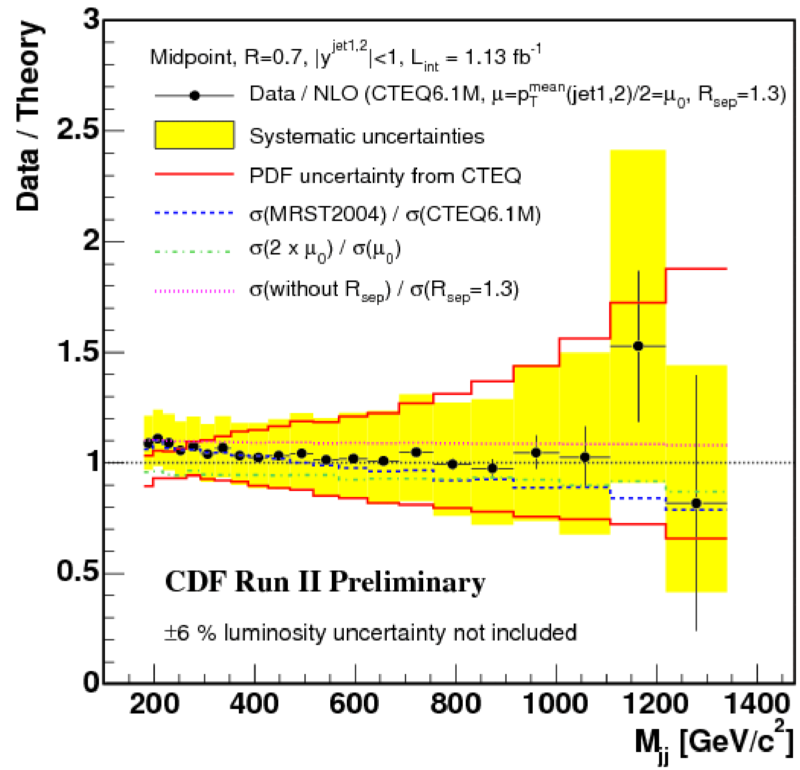




→ data above Mjj = 1.2TeV!
→ All described by NLO pQCD

→Limits on resonances:
excited quarks, massive gluons, Randall-Sundrum gravitons, Z′/W′

(see: http://www-cdf.fnal.gov/physics/exotic/r2a/20080214.mjj resonance 1b/)

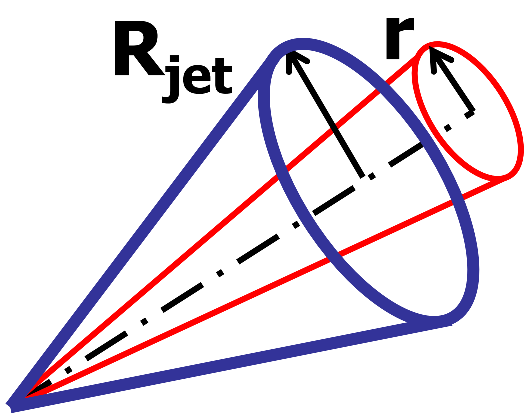
Jets beyond 2→2

- Internal Jet Structure
- Dijet Azimuthal Decorrelation
- Radius Dependence of Jet Cross Sections

Underlying Event
Parton Shower
Matched Predictions
3-Jet NLO

Internal Jet Structure

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

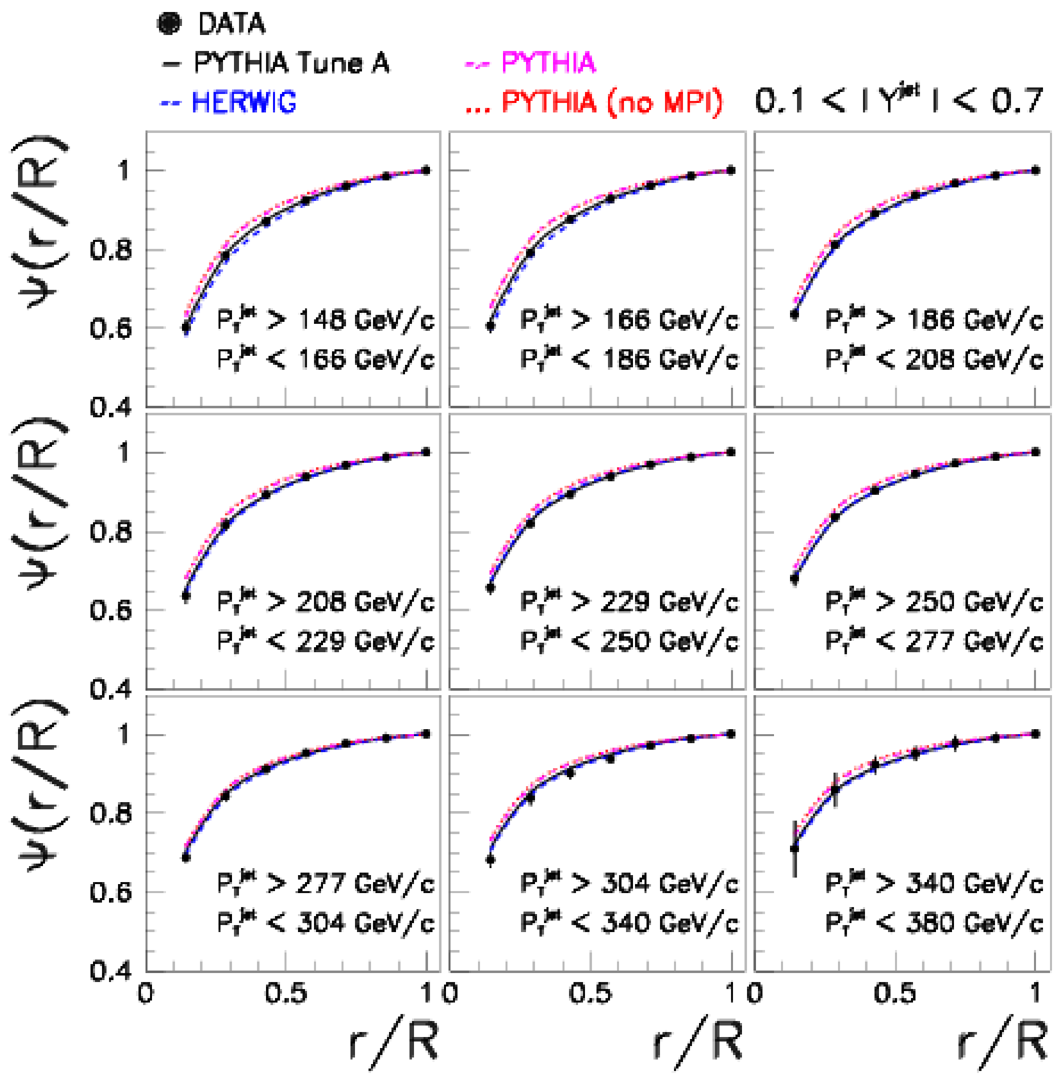


Integrated Jet Shape:

Fractional pT in Subcone vs.(r/R)

Sensitive to Soft and Hard Radiation – and UE

Well-Described by (tuned) MCs



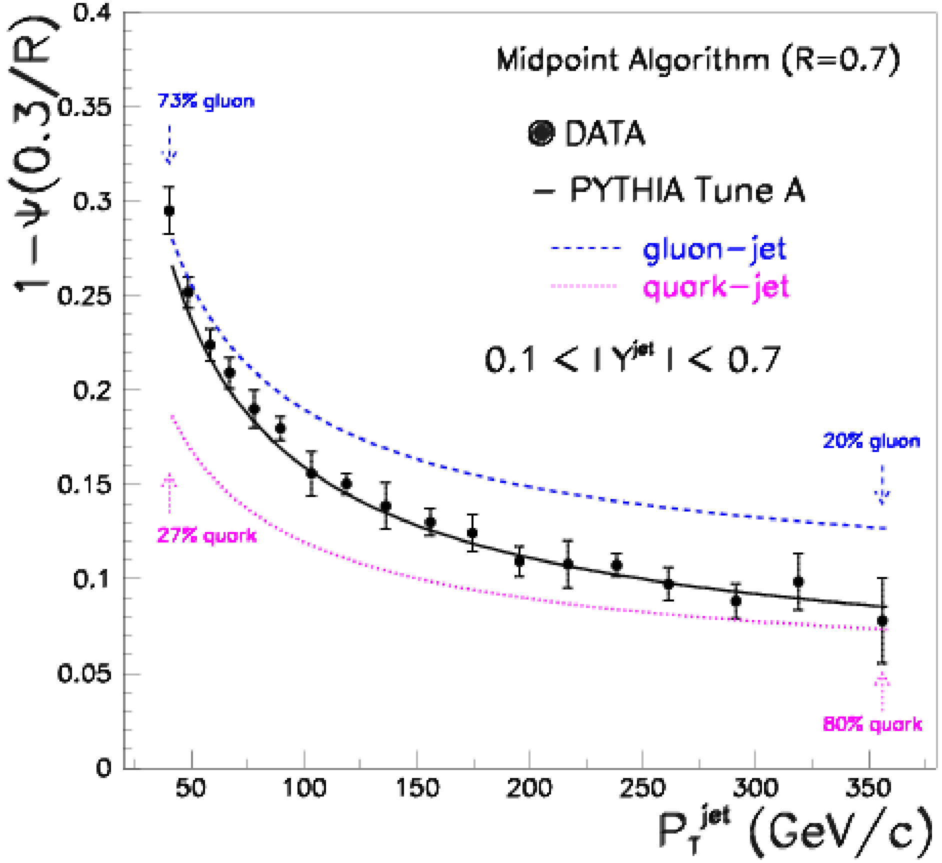
Internal Jet Structure

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 tuned PYTHIA gives good description of data



Radius Dependence of Jet Cross Sections

Jet cross section depends on radius in jet definition
→ Important testing ground

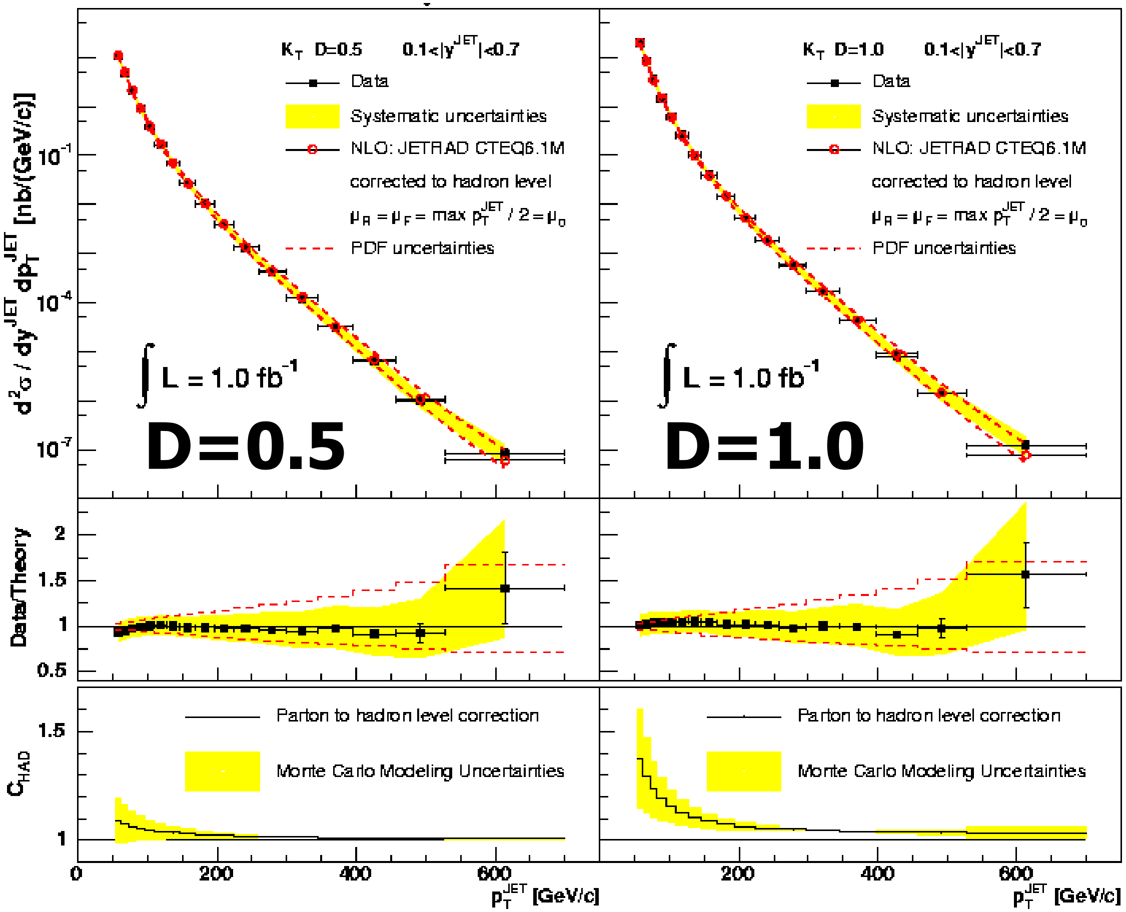
CDF: radius dependence for incl. jets (kT jet algorithm) for D (=radius) parameter D = 0.5, 0.7, 1.0

→ Results for each D value are compared to NLO pQCD calculation + non-pert corr.

→ agreement for all D values

(similar analysis in DIS by ZEUS)

Phys. Rev. D 75, 092006 (2007)



→ … but effectively only a LO test of radius dependence
→ better: study **ratios** and compute at true NLO (using 3-jet NLO)

Radius Dependence of Jet Cross Sections @NLO

Ratio of cross sections: $$R(D) = \frac{\sigma(D)}{\sigma(D_0)} = 1 + c_1\alpha_s + c_2\alpha_s^2 + \mathcal{O}(\alpha_s^3)$$

- Jet cross section at **LO** → **no** radius dependence
- Jet cross section at **NLO** → **LO** contribution to radius dependence

$$\frac{[\sigma(D)]_{\mathrm{NLO}}}{[\sigma(D_0)]_{\mathrm{NLO}}} = \left[\frac{\sigma(D)}{\sigma(D_0)}\right]_{\mathrm{LO}} = R_{\mathrm{LO}}(D)$$

- Jet cross section at **NNLO** → **NLO** contribution to radius dependence

NNLO calculation not available → missing: 2-loop virtual corrections

→ but: 2-loop virtual correction don't depend on radius (2→2 kinematics)

→ contributions from 2-loop corrections cancel in difference

Use **three-jet NLO calculation** to compute **difference**

→ obtain **NLO** result for ratio:

$$\frac{[\sigma(D) - \sigma(D_0)]_{\mathrm{NLO}}}{[\sigma(D_0)]_{\mathrm{NLO}}} + 1 = \left[\frac{\sigma(D)}{\sigma(D_0)}\right]_{\mathrm{NLO}} = R_{\mathrm{NLO}}(D)$$

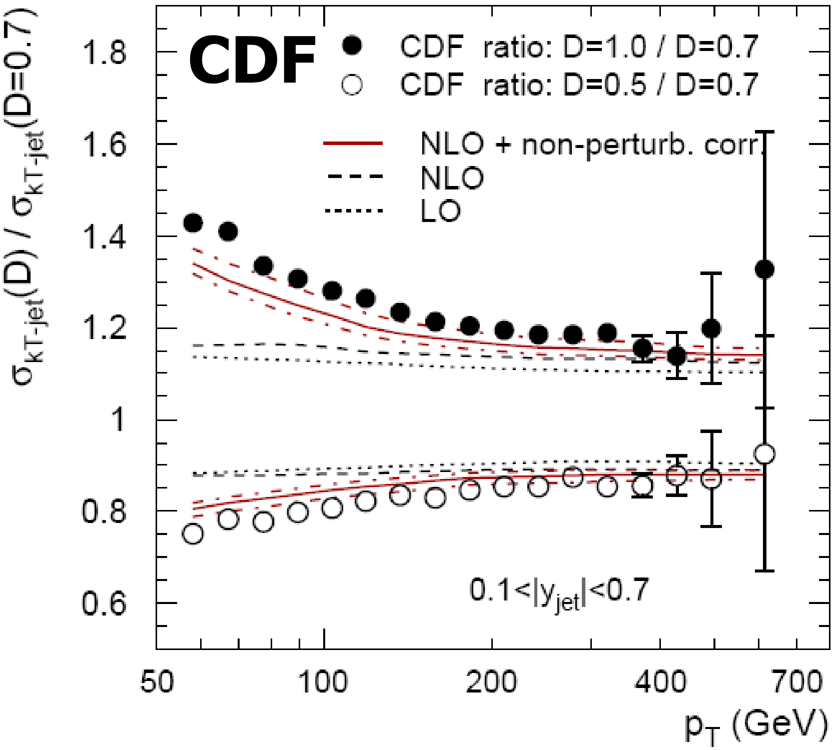
→ use for first NLO study of radius dependence of jet cross sections

Radius Dependence of Jet Cross Sections @NLO

Study cross section **ratios**:

T. Kluge, M.W. – work in progress

(D=1.0/D=0.7) and (D=0.5/D=0.7) and compare with true NLO calculation



scales: mu=pT (0.5pT, 2pT)

only at highest pT:

→ agreement at the edge of scale dependence

disagreement at lower pT:

→ larger radius dependence in data

→ NLO corrections are <20% for Tevatron

→ most of pT range: dominated by non-pert. corrections

Radius Dependence of Jet Cross Sections @NLO

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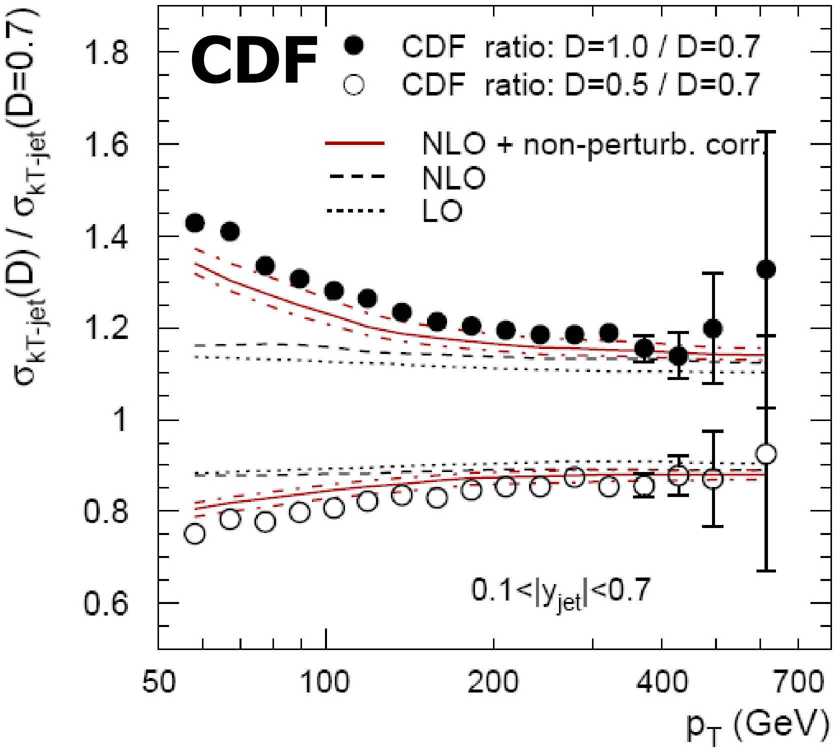
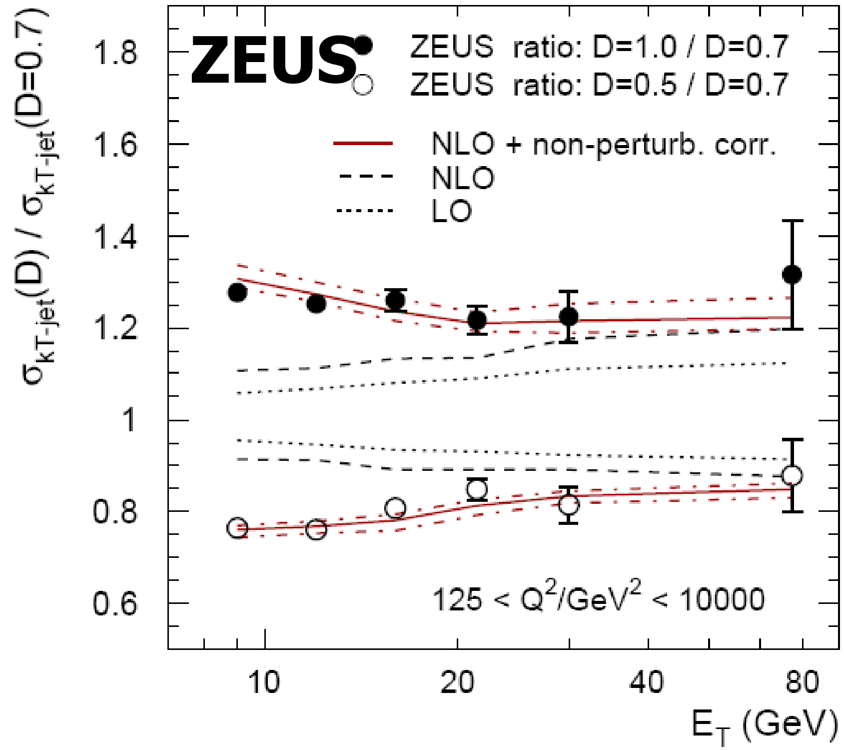




→ NLO corrections are <20% for Tevatron ~60-100% for HERA

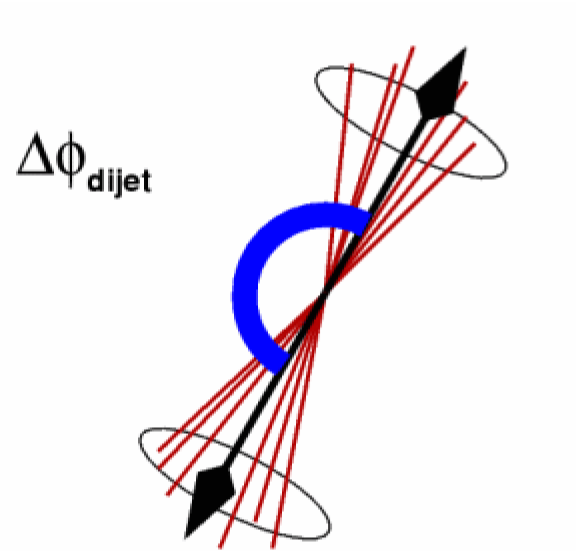
→ most of pT range: dominated by non-pert. corrections

→ HERA data described / Tevatron data not → underlying event???

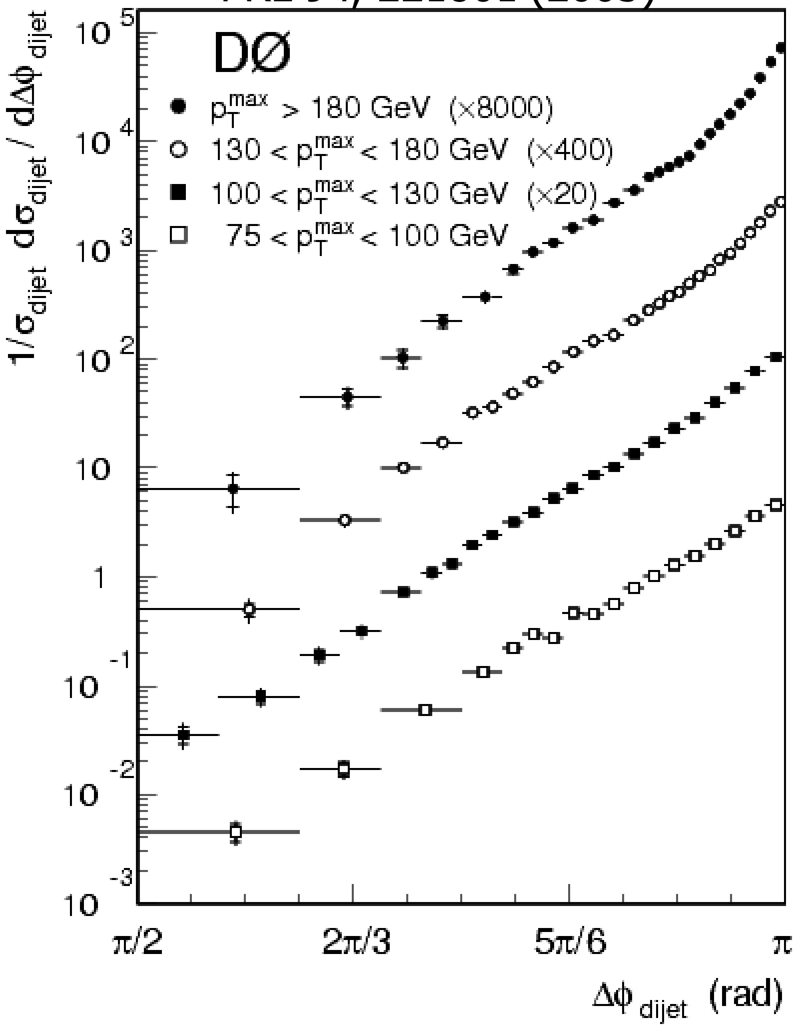
Dijet Azimuthal Decorrelation

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

- Test Parton-Shower
- Test 3-Jet NLO



PRL 94, 221801 (2005)



Dijet Azimuthal Decorrelation

Compare with theory:

- LO has Limitation >2pi/3
  & Divergence towards pi

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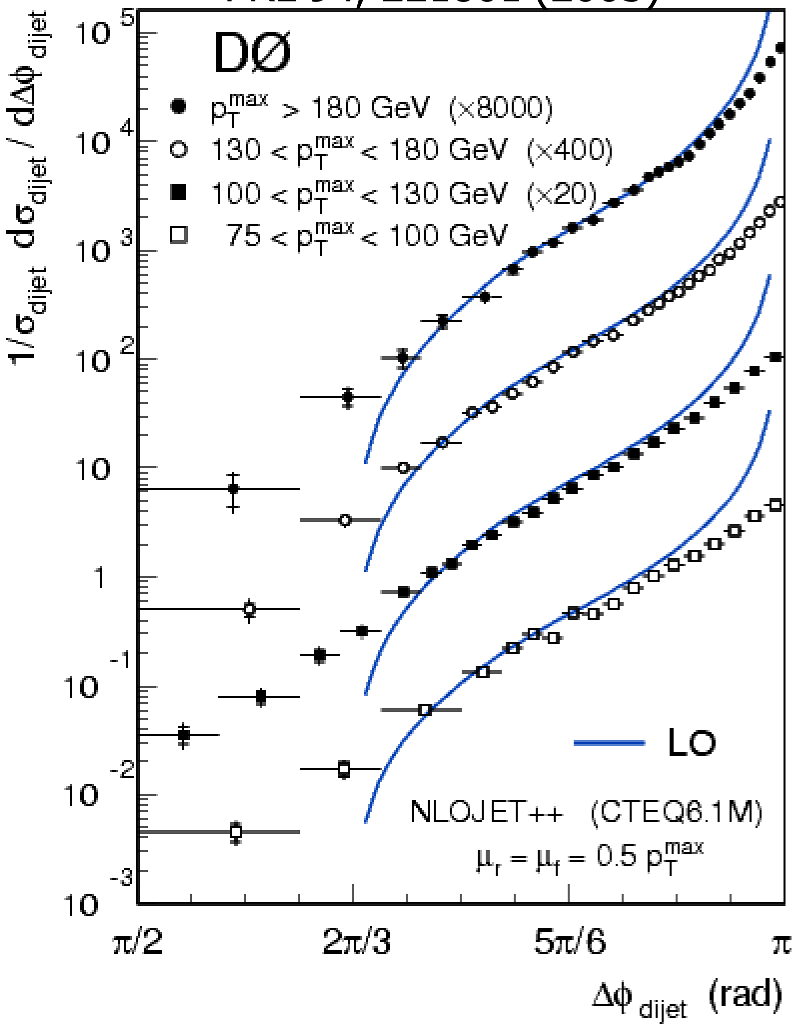

Dijet Azimuthal Decorrelation

Compare with theory:

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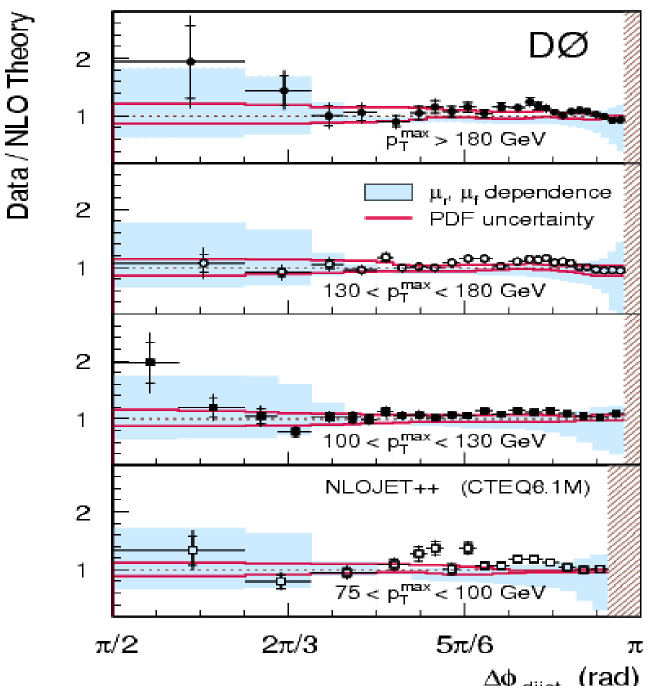
- NLO is very good – down to pi/2
  & better towards pi
  … still: resummation needed



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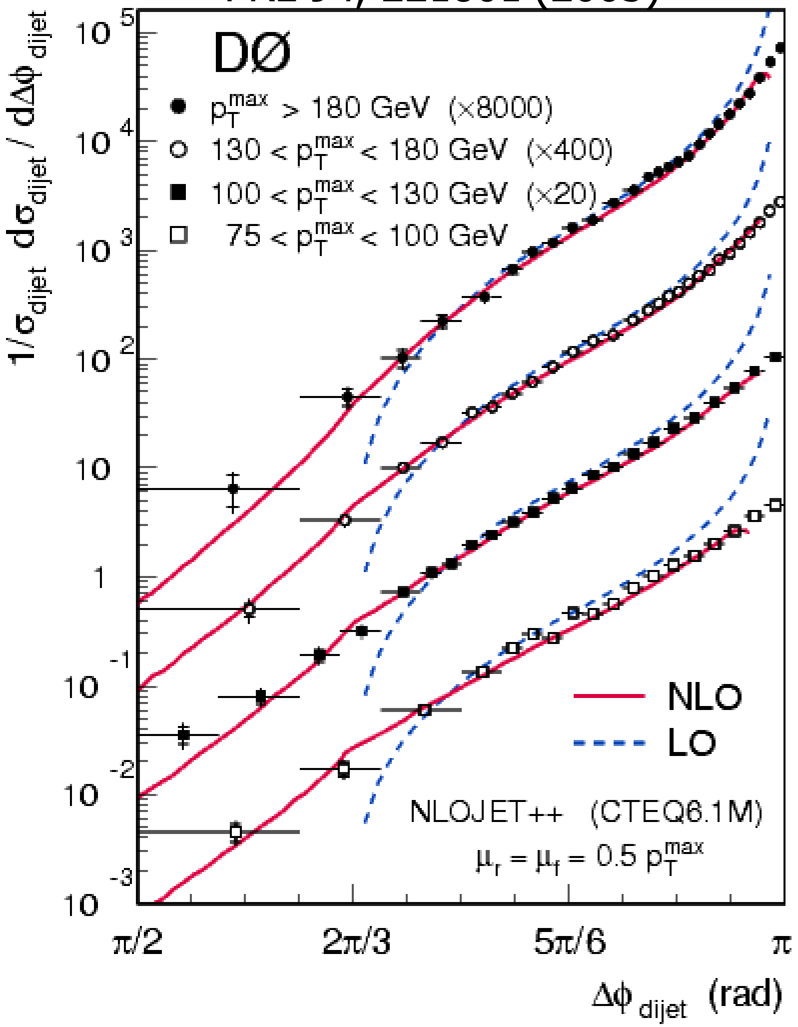

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- HERWIG is perfect “out-the-box”
- PYTHIA is too low in tail …

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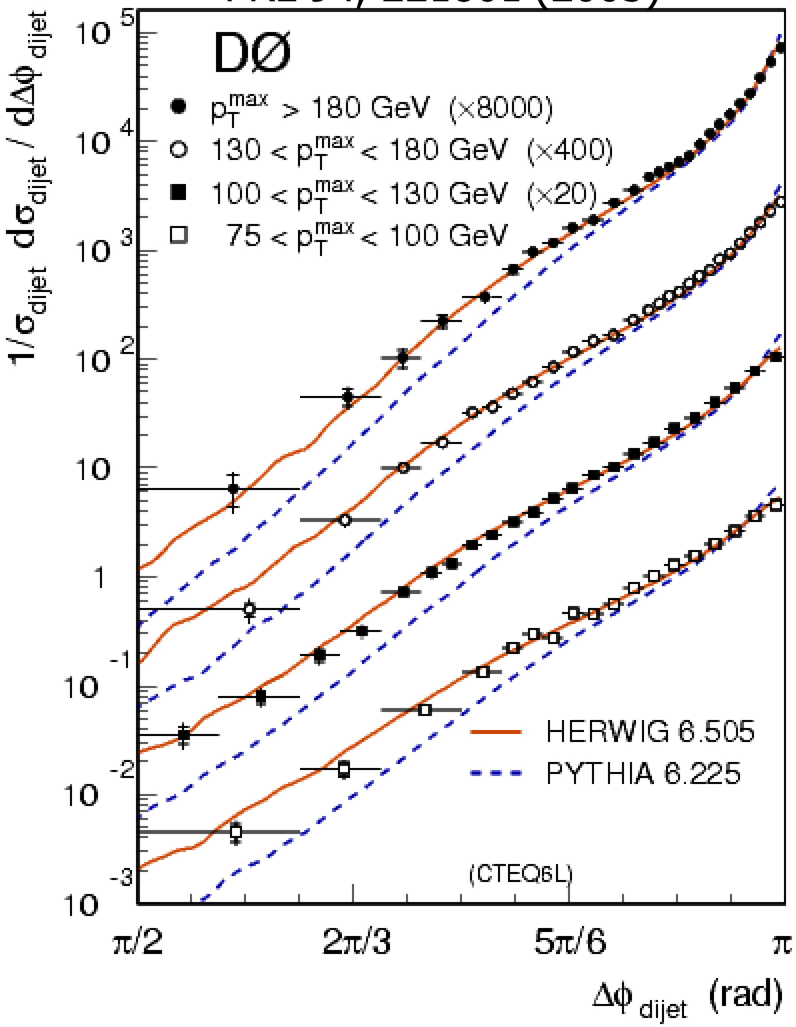

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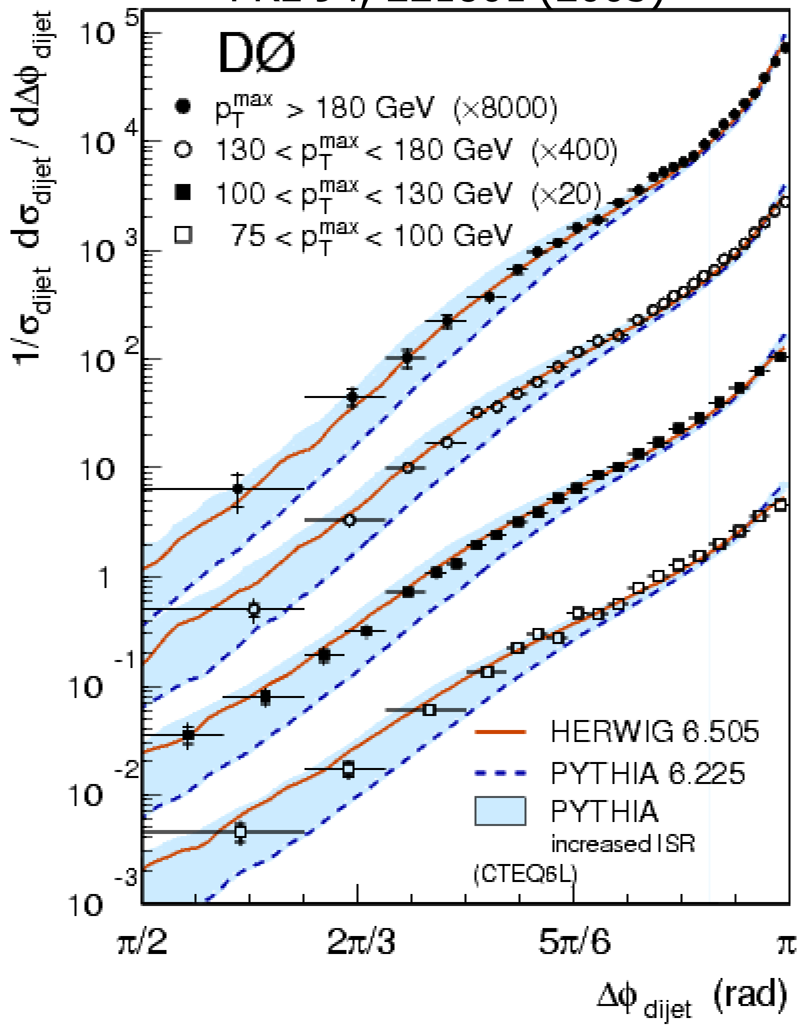
  … but it can be tuned (tune DW)

  (“tune A” is too high!)

PRL 94, 221801 (2005)



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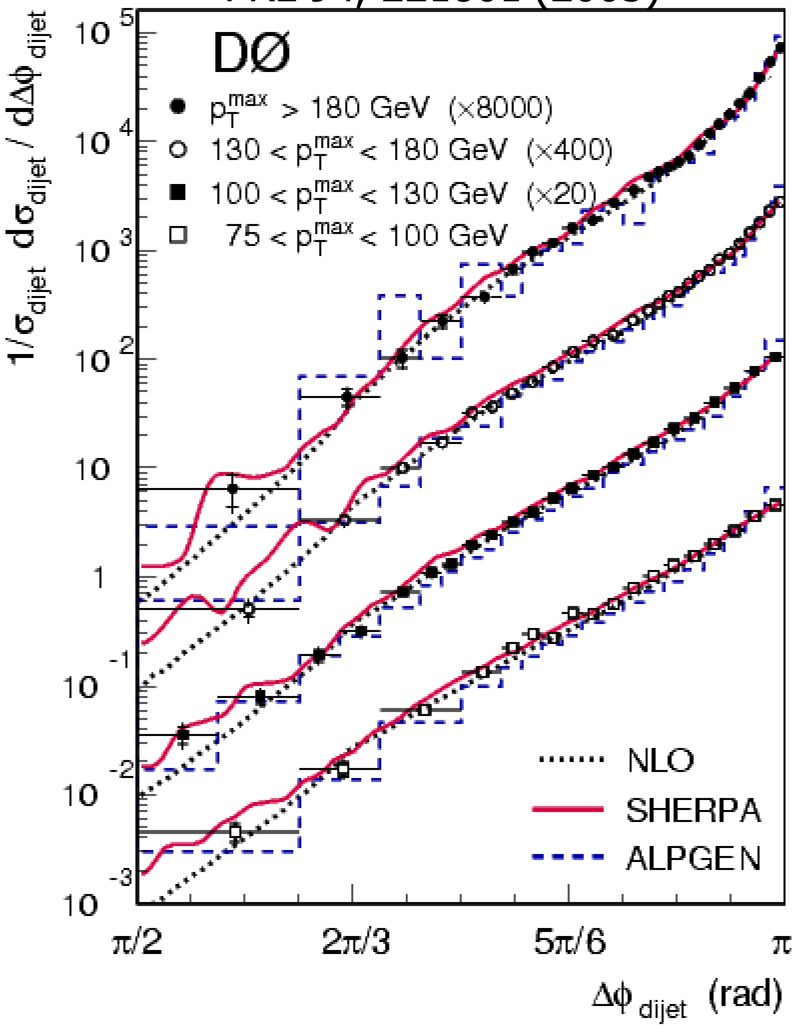
- HERWIG is perfect "out-the-box"
- PYTHIA is too low in tail …
  … but it can be tuned (tune DW)
  ("tune A" is too high!)
- SHERPA is great
- ALPGEN looks good – but low efficiency → large stat. fluctuations

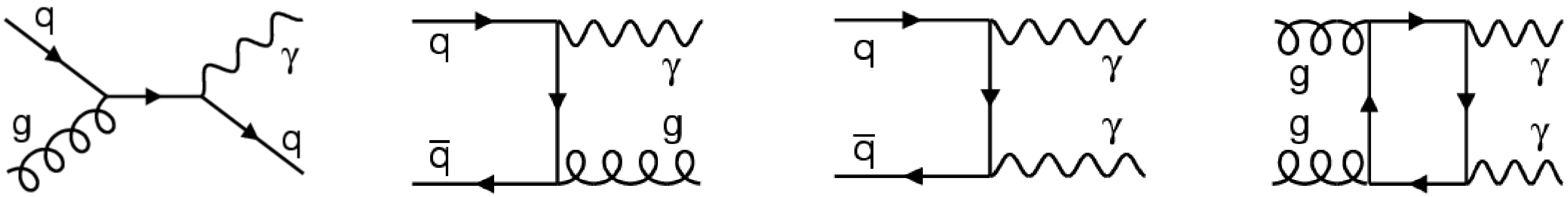
PRL 94, 221801 (2005)



Photons

Fixed-Order: NLO (?)
Resummation
… PDFs ?

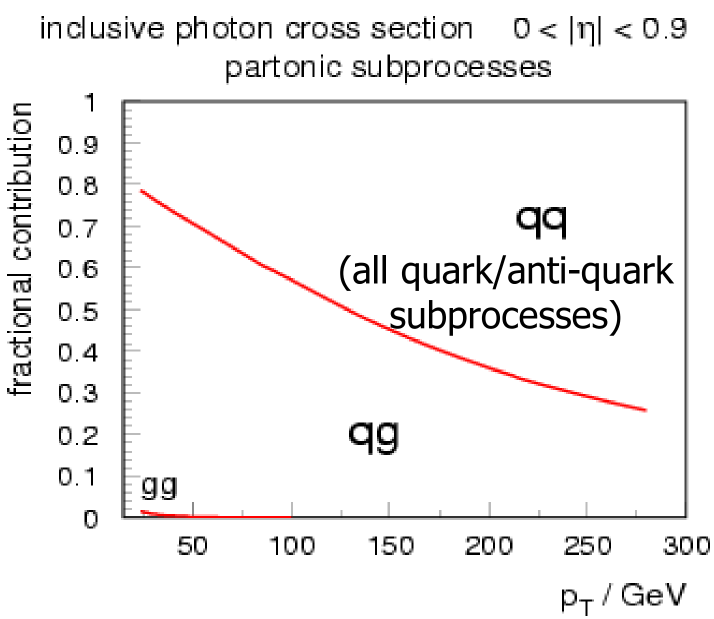
Direct Photon Production



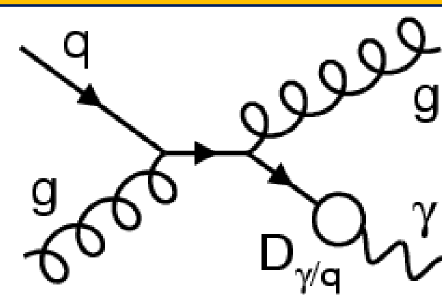
Direct Photons come unaltered from the Hard Subprocess

→ Direct Probe of the Hard Scattering Dynamics

→ Sensitivity to PDFs (…but only if we understand theory)



also fragmentation contributions:



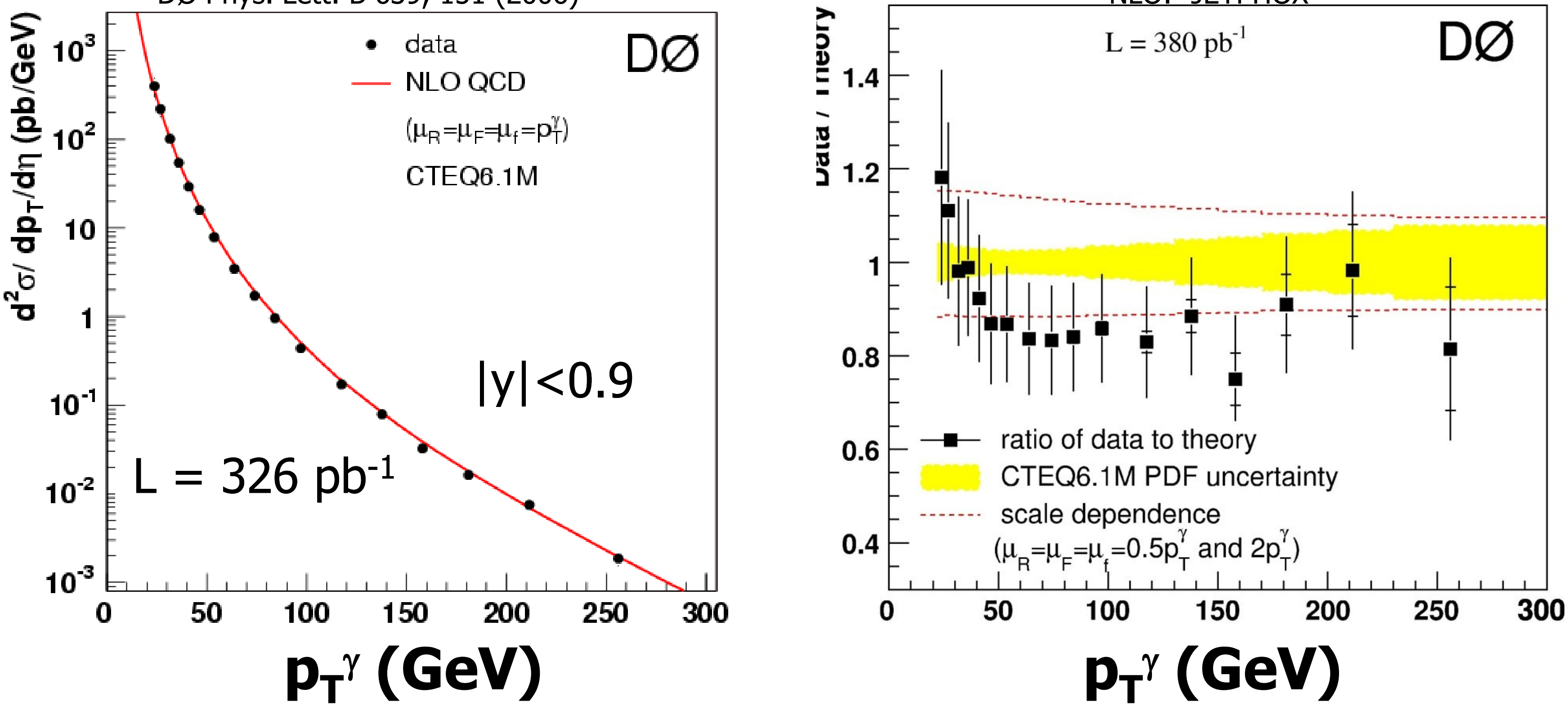
suppress by isolation criterion

→ Observable: **isolated** photons

Isolated Photon Cross Sect.

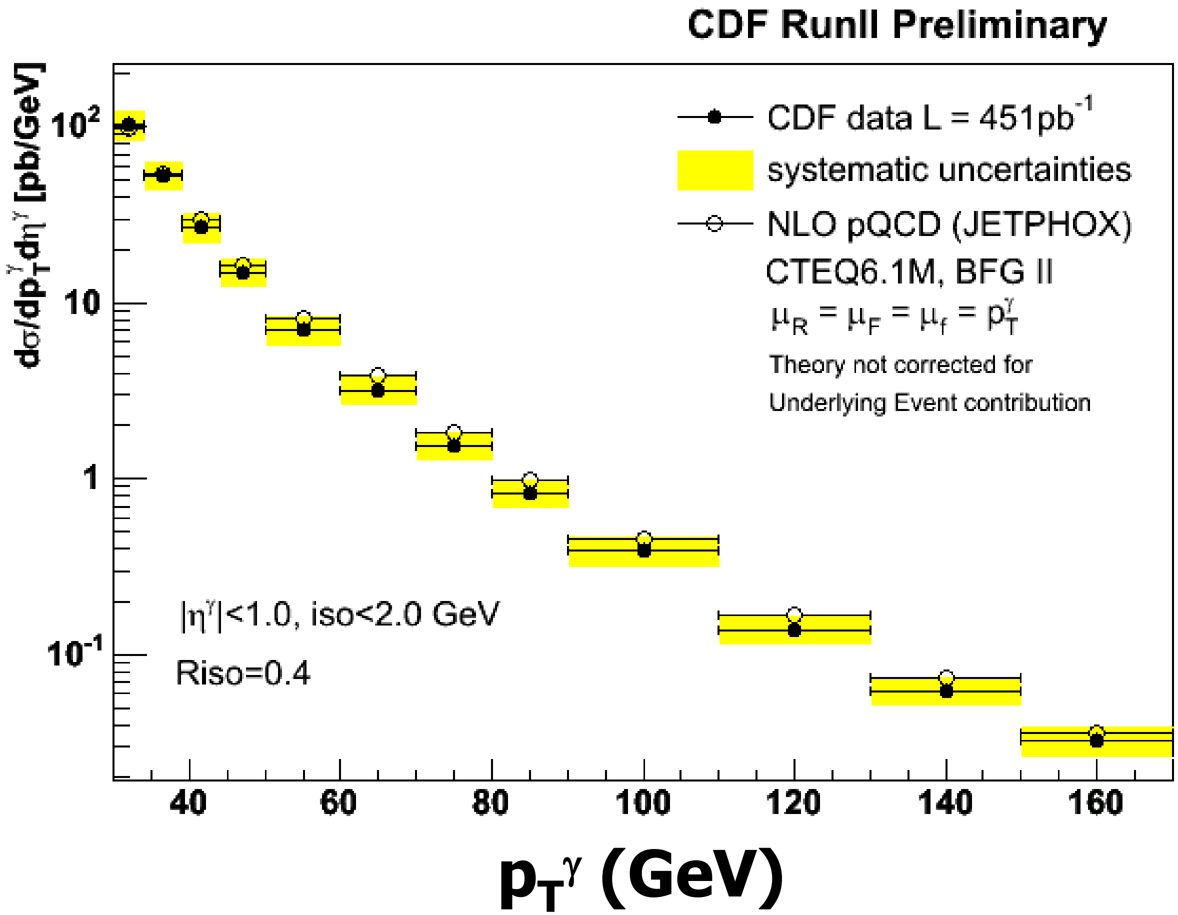
DØ Phys. Lett. B 639, 151 (2006)

NLO: JETPHOX



- data/theory: reasonable agreement over 23<pT<300GeV
- different shape at low pT
- experimental and theory uncertainties > PDF uncertainty
  → no PDF sensitivity (need improvements in exp. and thy.)

Isolated Photon Cross Sect.



- Measured over 20<pT<170GeV
- data/theory → consistent with D0 result

Isolated Photon + Jet

investigate source for disagreement in data/theory incl. photon pT shape:

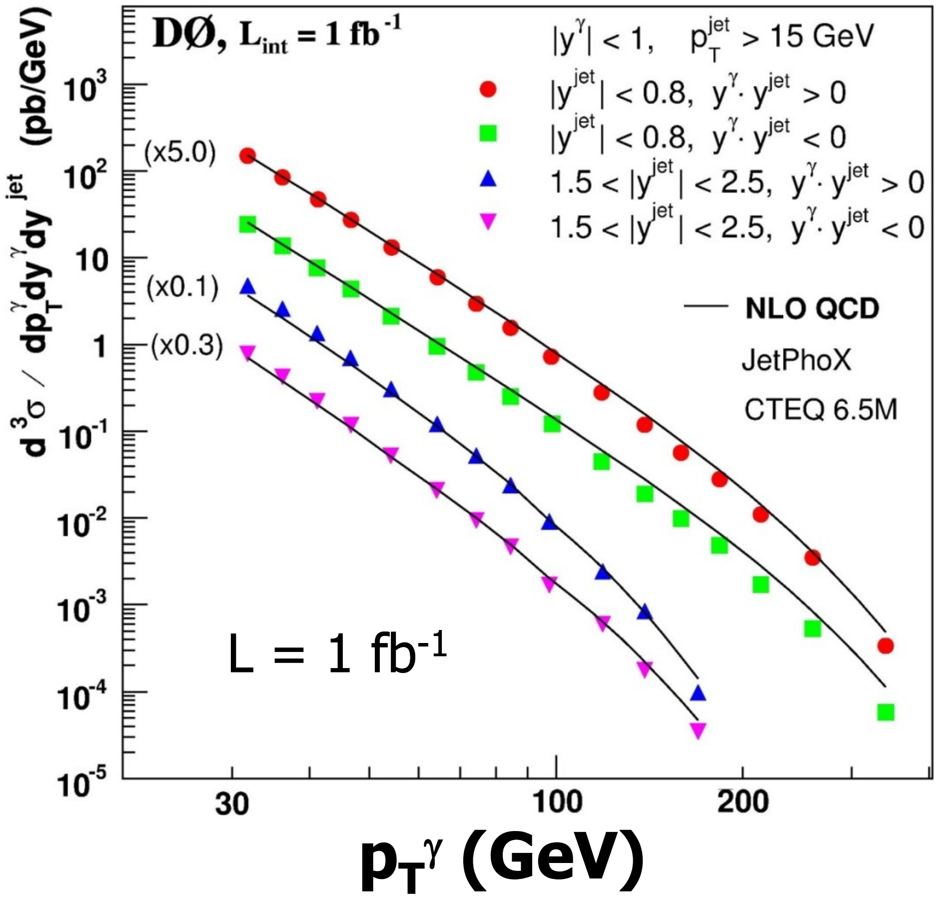
measure more differential:

- tag **photon and jet**
  → reconstruct full event kinematics

- measure in 4 regions of y^{γ} / $y^{\mathbf{jet}}$
  - photon: central
  - jet: central / forward
  - same side / opposite side

- different PDF sensitivity in different y^{γ} / $y^{\mathbf{jet}}$ regions

DØ, arXiv: 0804.1107 [hep-ex]



→ look at ratios for quantitative statement …

Isolated Photon + Jet

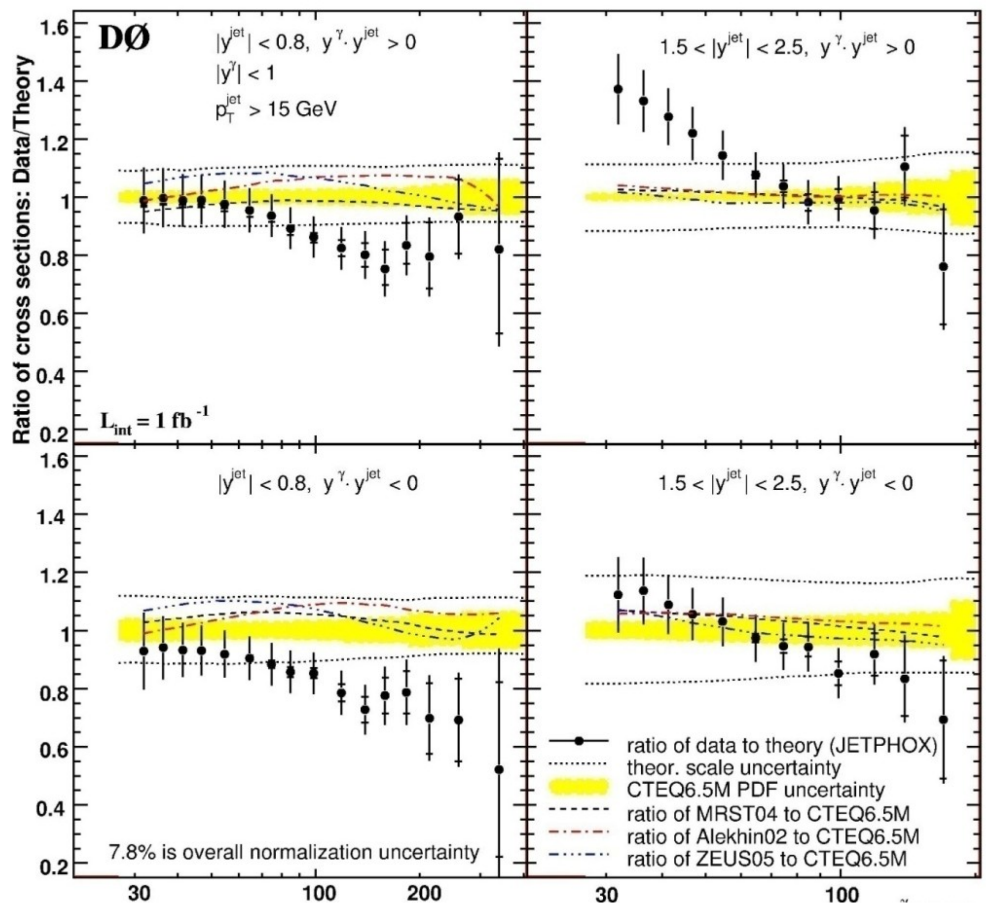
DØ, arXiv: 0804.1107 [hep-ex]

Observe:

- different shape discrepancies in different y^{γ} / y^{jet} regions

Checked that effect is **not due** to

- scale choice
- PDF uncertainty/variation
- fragmentation contributions



p_T^{γ} **(GeV)**

Isolated Photon + Jet

Study ratios of cross sections in different y^{jet} regions

- cancelation of correlated uncertainties
- stronger sensitivity to differences in different regions

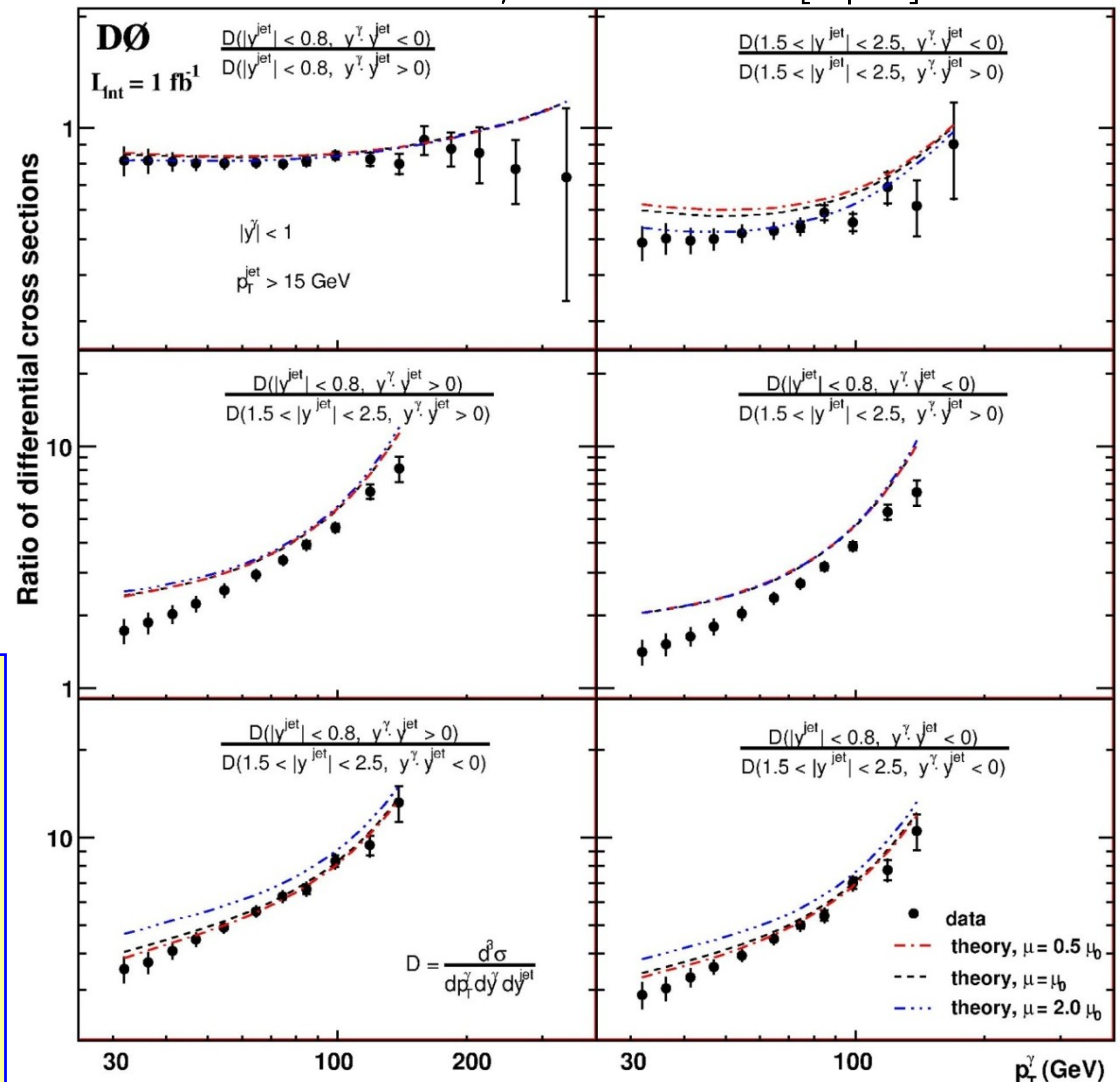
→ biggest problems for central / forward-opposites

need improved theory challenge:

→ find out what is missing…

- higher orders?
- resummation?
- …???

DØ, arXiv: 0804.1107 [hep-ex]

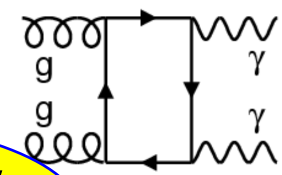


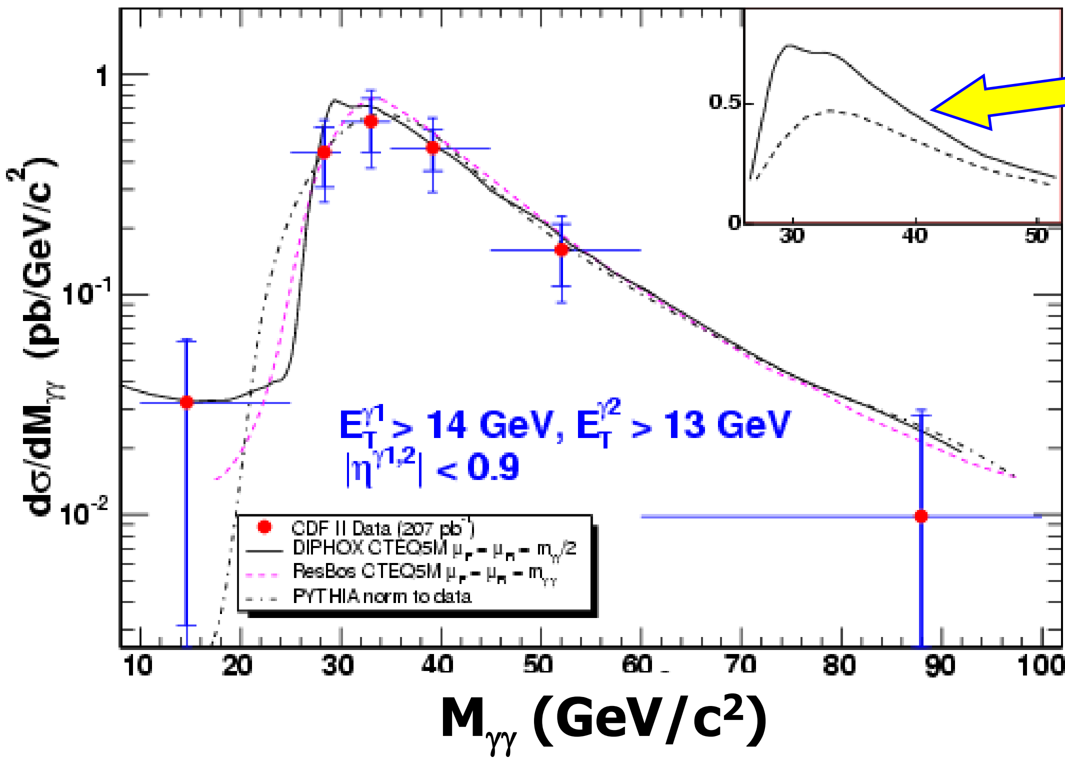
p_T^{γ} (GeV)

Di-Photon Cross Section

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

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

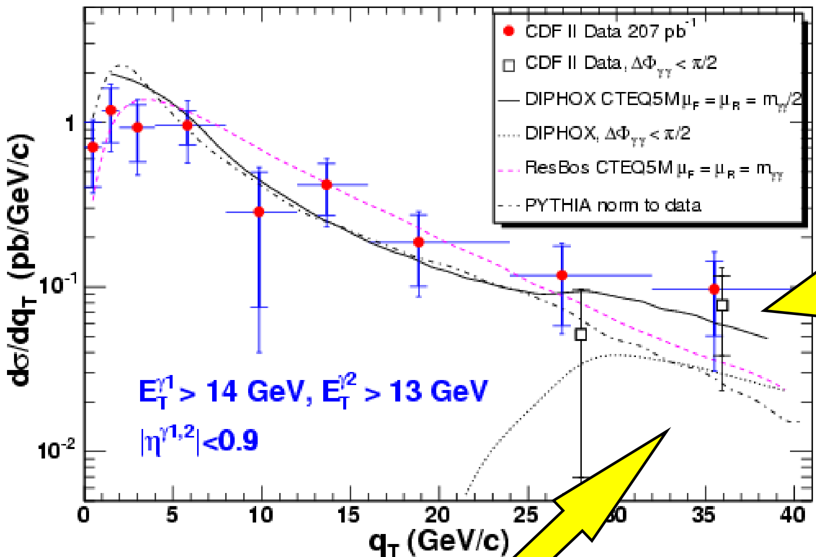


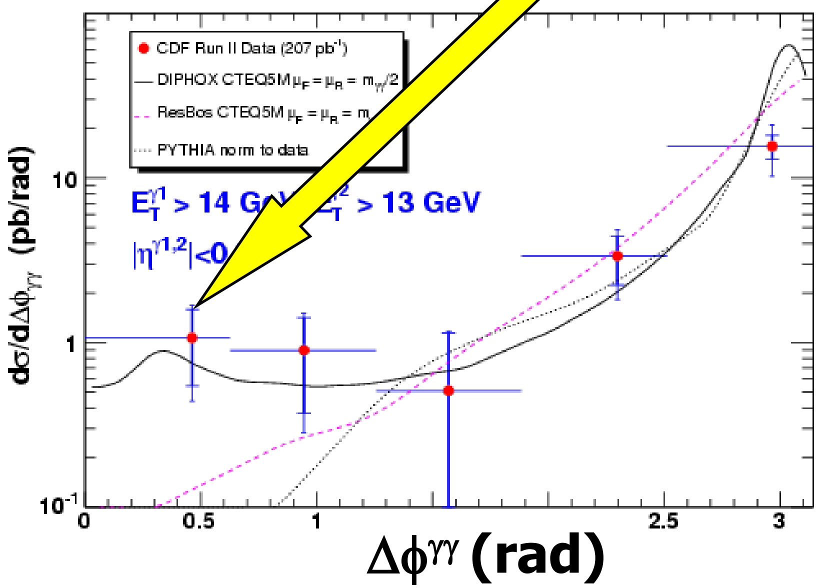


DIPHOX: with and w/o NNNLO gg-diagram

- **DIPHOX**:
  - NLO prompt di-photons
  - NLO fragmentation (1 or 2 γ)
  - NNNLO gg→γγ corrections
- **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>

need combined calculation with NLO fragmentation & initial state resummation

.

Vector Boson + Jets

Fixed-order: NLO

LO + Parton Shower

Matched Tree-Level + PS (CKKW/MLM)

Backgrounds to New Physics

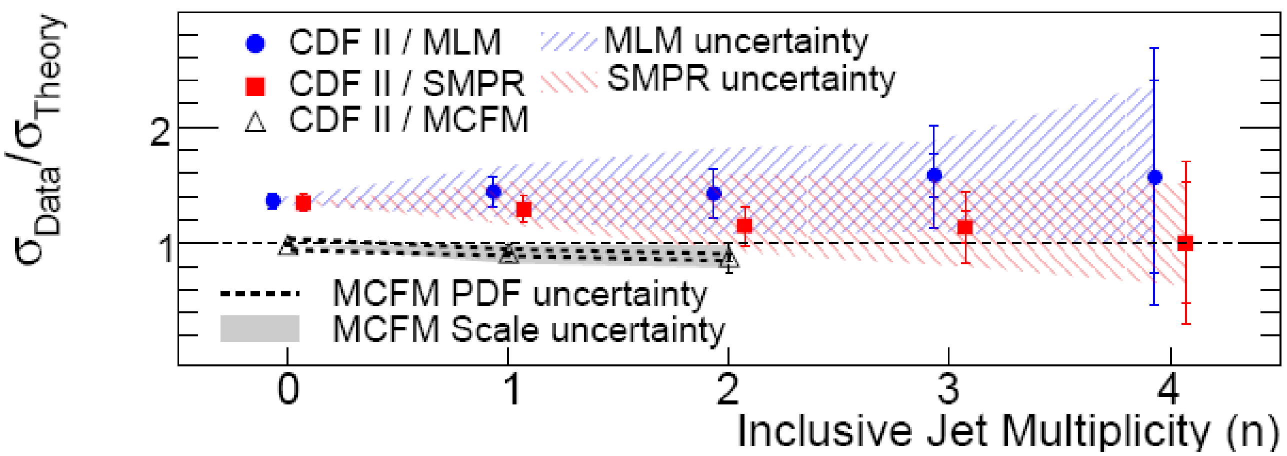
W + n Jets inclusive

PRD 77, 011108(R) (320pb-1)

Total cross section for jet multiplicity, *n* :

$$\sigma_n = \sigma\left(W \to e\nu + \geq n - \text{jet}; E_T^n > 25, |\eta| < 2.0\right)$$

JETCLU cone algorithm



"MCFM": NLO up to W+2 jets
here: no non-pert. corrections applied

"MLM":
ALPGEN (LO) +
Herwig (shower) +
MLM matching

"SMPR":
MadGraph (LO) +
Pythia (shower) +
CKKW matching

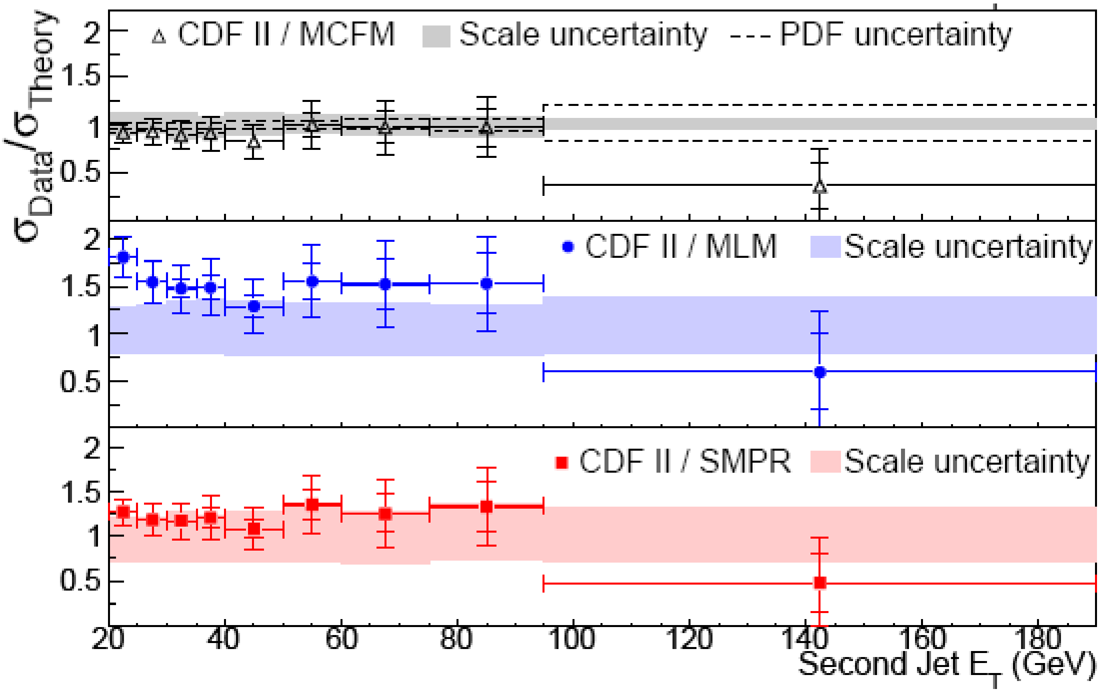
→ NLO predictions look good / questionable: JETCLU & ignore non-pert. corrections

→ matched calc.: up to 40% too low / SMPR: slightly different shape

W + 2 Jets inclusive

PRD 77, 011108(R) (320pb-1)

Differential jet ET distributions: **Second Jet**



"MCFM": NLO

No non-pert. corrrections applied

"MLM":

ALPGEN (LO) +

Herwig (shower) +

MLM matching

"SMPR":

MadGraph (LO) +

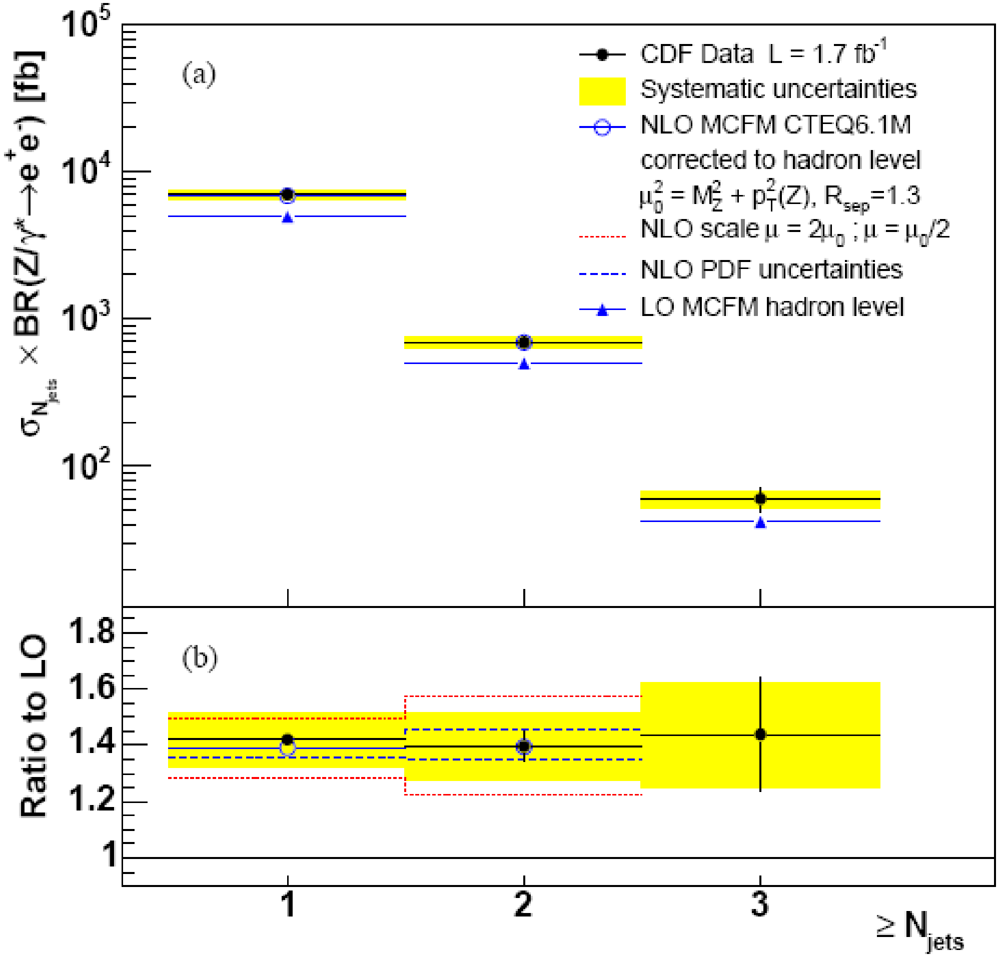
Pythia (shower) +

CKKW matching

→ NLO predictions look good / questionable: JETCLU & ignore non-pert. corrections

→ matched calculations: "SMPR" better than "MLM" (under investigation)

Z + n Jets inclusive



Phys. Rev. Lett. 100, 102001 (2008)

- ***$Z/\gamma^* \to e^+e^-$***
  - Two E_T > 25 GeV electrons
  - 66 < M_{ee} < 116 GeV
- **Midpoint Cone algorithm:**
  - p_T > 30, |y| < 2.1
  - R=0.7

Integrated cross sections for n=1,2,3

Non-pert. corrections: 1.1–1.4

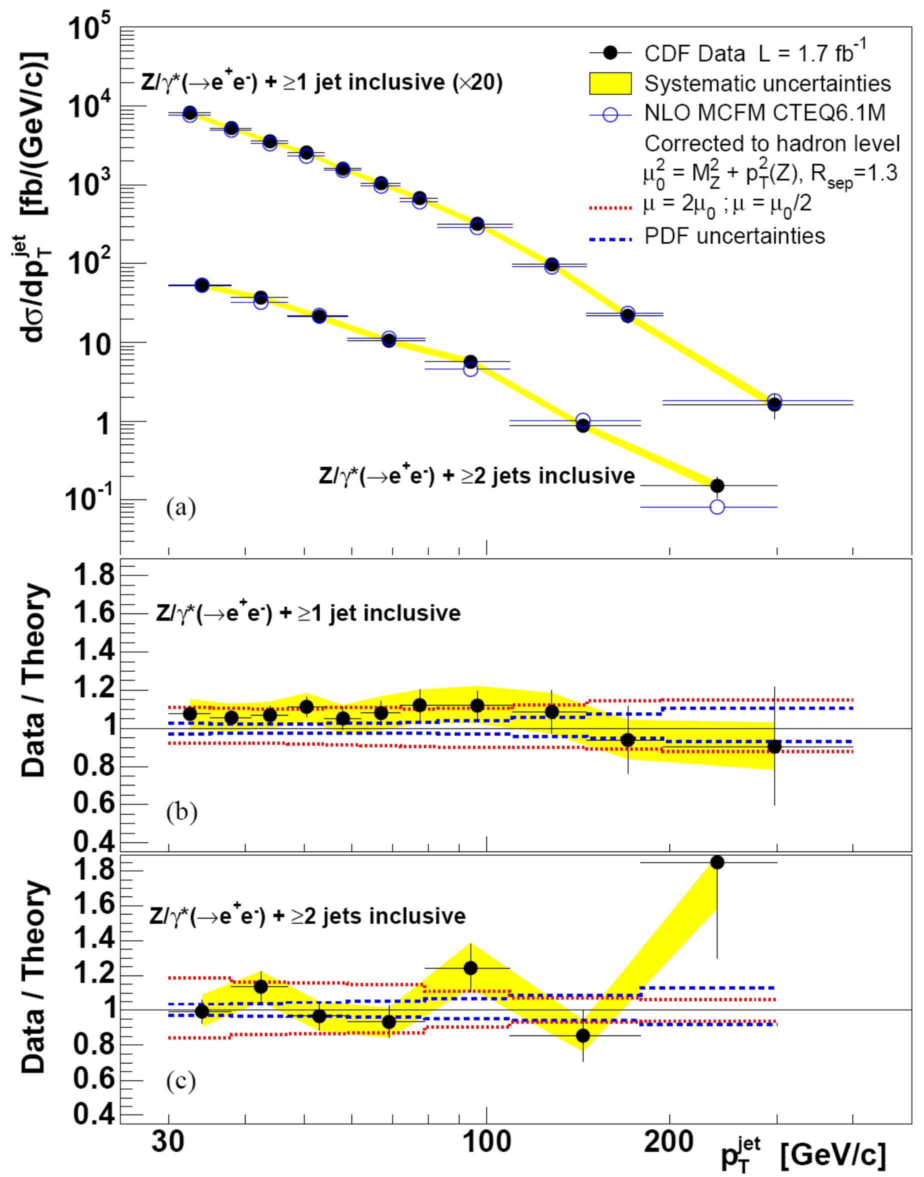
→ NLO prediction + non-pert corrections describe data for n=1,2

→ same deviation from LO for n=1,2,3 (success, if k-factor is constant)

Z + n Jets inclusive

Phys. Rev. Lett. 100, 102001 (2008)

differential jet pT distributions
for n=1,2



As for W+jets:

→ NLO describe n-th jet differential pT distribution for n=1,2

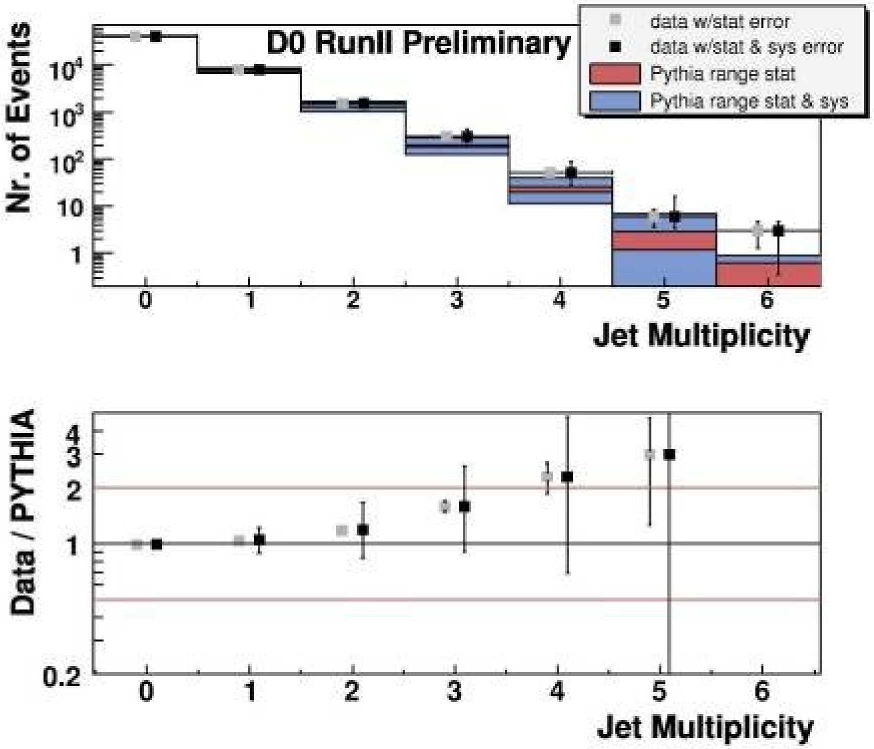
Z+2 jet sample would benefit from more statistics

Z + n Jets

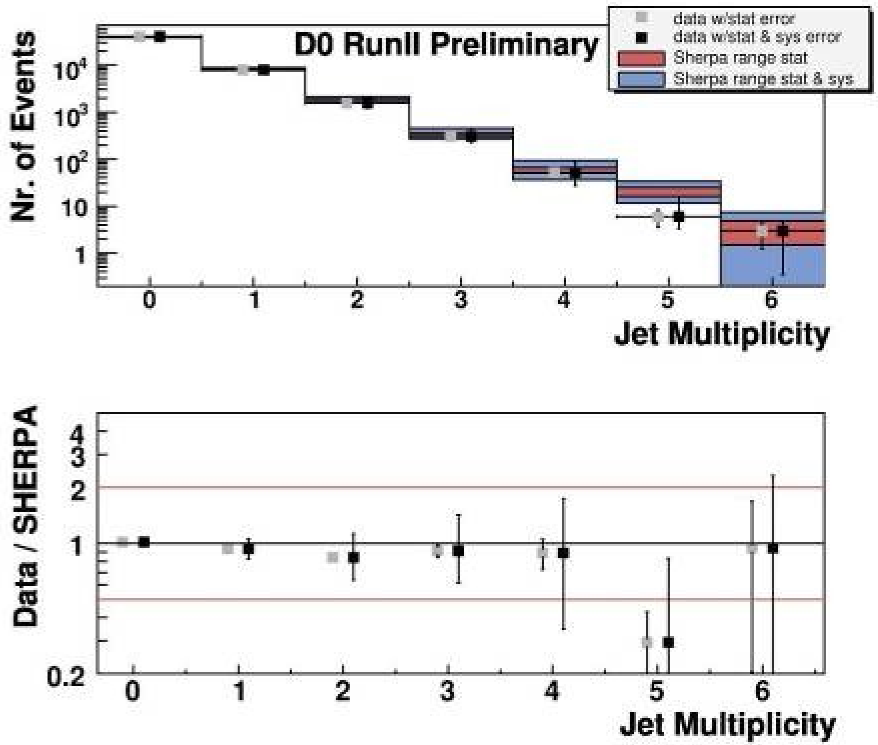
D0 preliminary (950pb-1)

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

PYTHIA does not describe Higher Jet Multiplicities



SHERPA is pretty good!



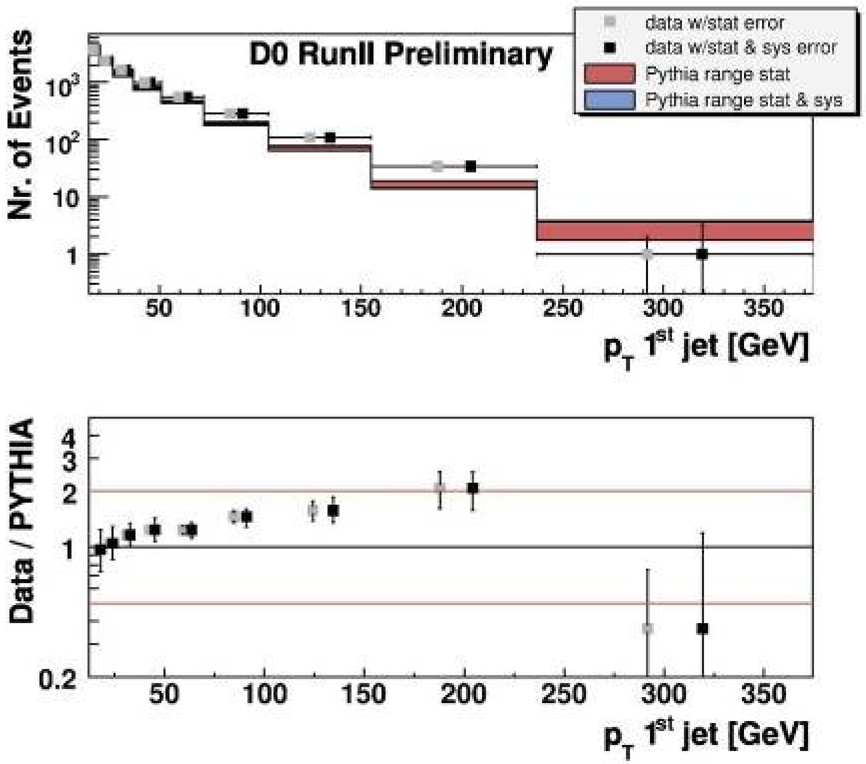
Z + 1 Jet inclusive

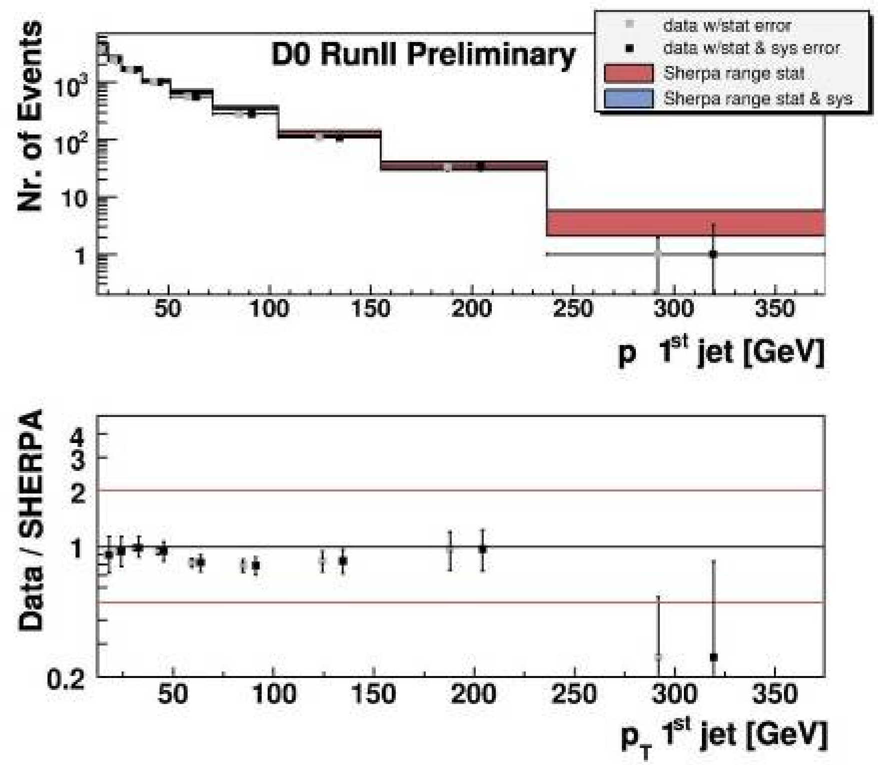
D0 preliminary (950pb-1)

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

PYTHIA does not describe Leading Jet pT Spectrum

SHERPA is pretty good!

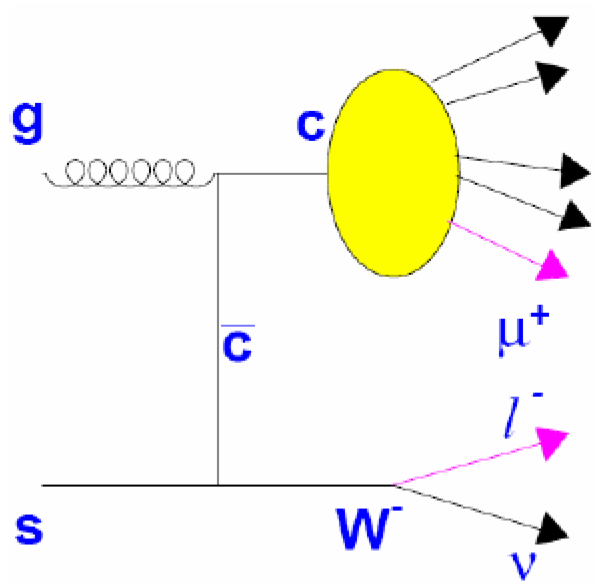




Heavy Flavor Jets

Heavy Flavor PDFs
Fixed-Order: NLO
LO + Parton Shower

$W^{\pm}$ + single c-jet



- probe strange quark PDF at rather large Q^2
  - PDF fits so far: no direct input on the strange quark density
  - strange quark-PDF errors are small because: s=(u-sea +d-sea)/2
  - this small uncertainty is fake
    → does not reflect true uncertainty
- sensitive to $|V_{cs}|$
- Part of W+jets bkgd to top, Higgs searches

Event selection similar to *W*+jets: $W \rightarrow e/\mu\ \nu$

Exploit feature of $W^{\pm}$ +single c :

→ Opposite charge of W and semileptonic daughter of charm hadron

→ almost no charge correlation for backgrounds

Here: First Measurements of $W^{\pm}$+c

$W^{\pm}$ + single c-jet

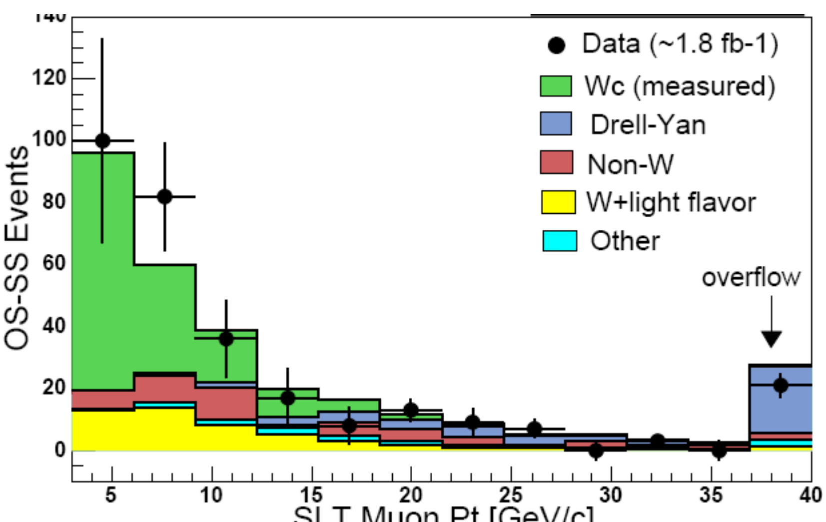
Phys. Rev. Lett. 100, 091803 (2008)

Subm. to Phys. Lett. B - arXiv:/0803.2259 [hep-ex]

$$\sigma_{Wc} \times \mathrm{BR}(W \to \ell \nu) = \frac{N^{\mathrm{OS-SS}}_{\mathrm{Tot}} - N^{\mathrm{OS-SS}}_{\mathrm{Bkg}}}{A \cdot \mathcal{L}}$$

σ x BR

- **CDF:** for $p_T^c > 20$ GeV, $|\eta^c|<1.5$
  9.8 ± 2.8 (stat) $^{+1.4}_{-1.6}$(syst) ± 0.6 (lum) pb
- NLO prediction (MCFM):
  σ x BR = 11.0 $^{+1.4}_{-3.0}$ pb

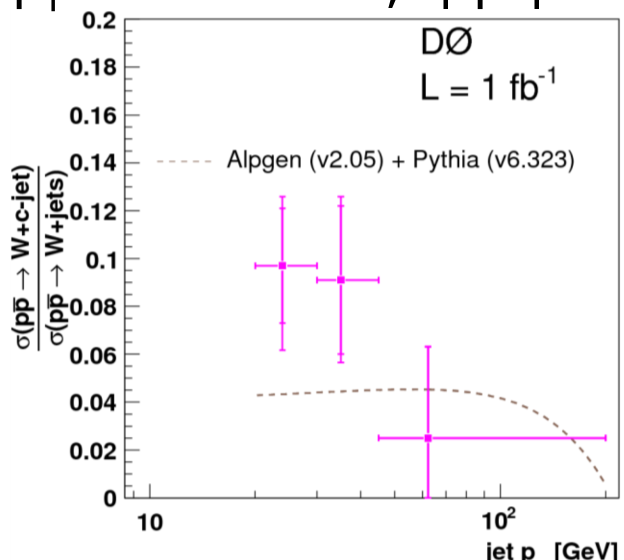


D0: measure ratio

W+c-jet / W+jet vs. jet pT

→partial cancelation of syst. uncert.

$p_T^{\mathrm{lepton}} > 20$ GeV, $|\eta^{\mathrm{jet}}|<2.5$



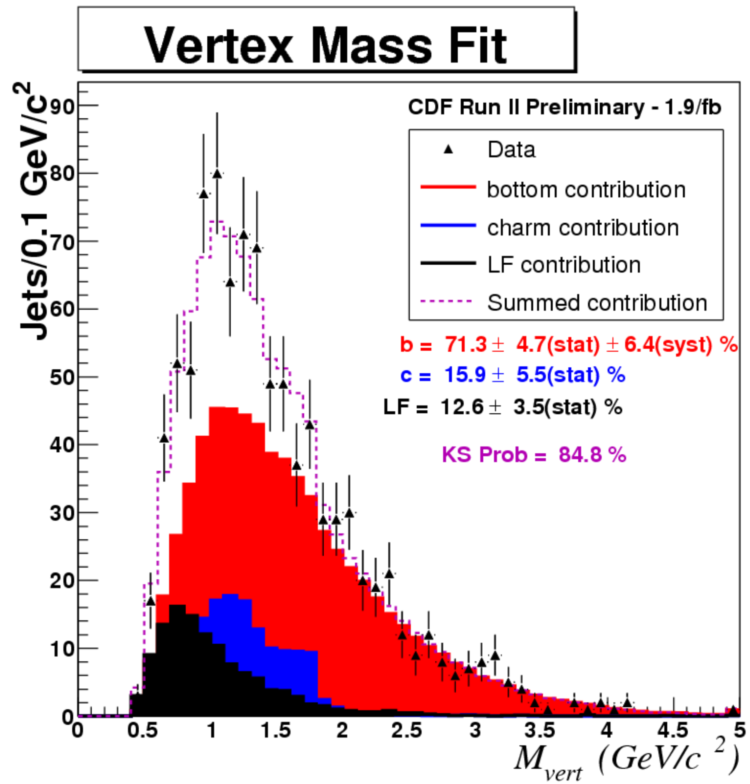
$$\frac{\sigma(W + \text{single - }c)}{\sigma(W + jets)} = 0.071 \pm 0.017$$

LO prediction: 0.040 ± 0.003 (PDF)

W + b-jet

Measure cross section for *W+b*-jet production
in events
with a high p_T central lepton,
high p_T neutrino and 1 or 2 total jets

improve background estimate for Higgs search



- ~1000 tagged jets
- among which ~700 are consistent with coming from a *b* quark

CDF: $\sigma_{b\text{-jets}}$(*W+b*-jets) x BR($W \to l\nu$) = 2.74 ± 0.27 (stat) ± 0.42 (syst) pb

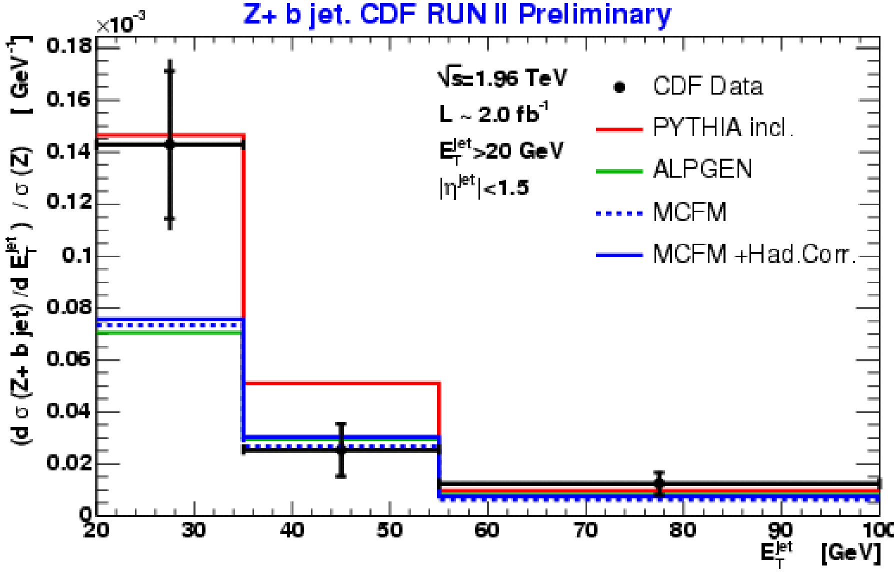
Default ALPGEN: σ x BR = 0.78 pb

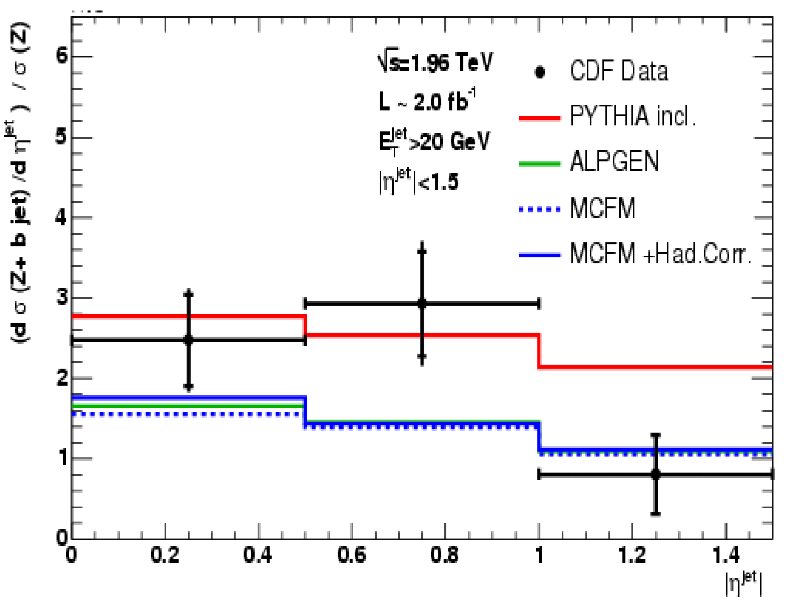
→ Difference by factor of 3.5 - under investigation (other predictions?)

Z + b-jet

- Use $Z \rightarrow ee$ and $\mu\mu$
- jet reconstruction
  - Cone algorithm with R=0.7
  - Secondary vertex tags
  - Corrected E_T > 20 GeV, $|\eta|$ < 1.5

Normalize by inclusive Z cross sect.
→ Helpful to compare to LO and NLO





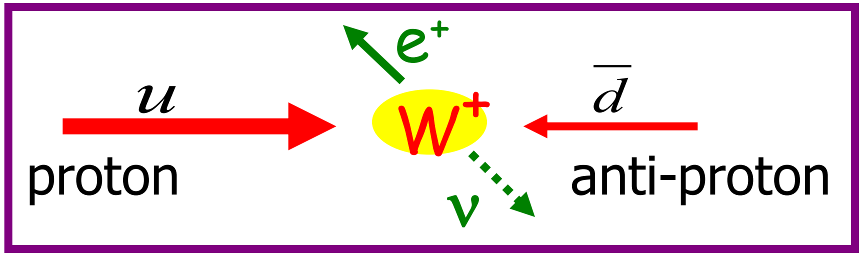
- PYTHIA good at low ET
- ALPGEN (LO) and MCFM (NLO) undershoot data in several bins

W-Asymmetry

↕

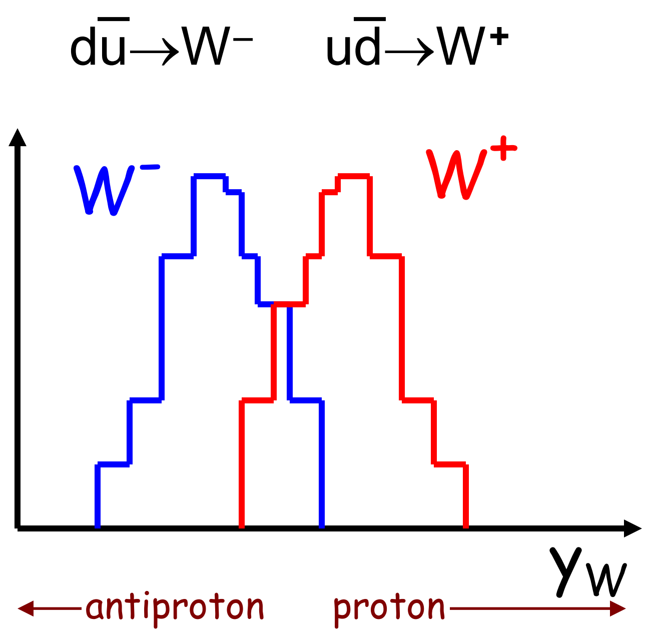
PDFs

W-Asymmetry



valence-quarks dominate

constrain ratio of d/u PDFs



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

W decay: longitudinal neutrino momentum not measured

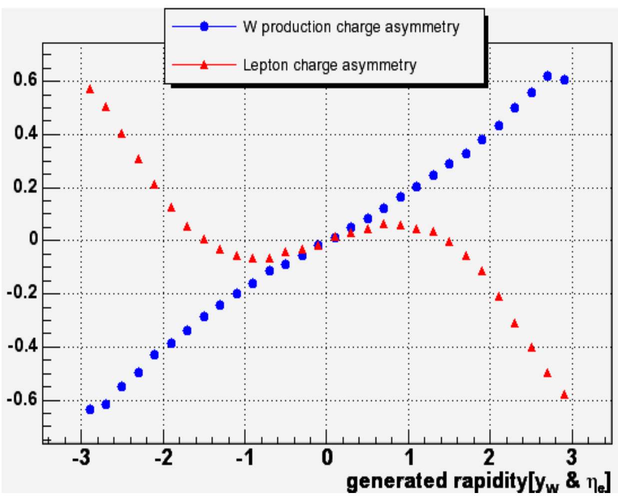
→ can’t reconstruct W rapidity

Lepton Charge Asymmetry

W decay: longitudinal neutrino momentum not measured
→ can't reconstruct W rapidity

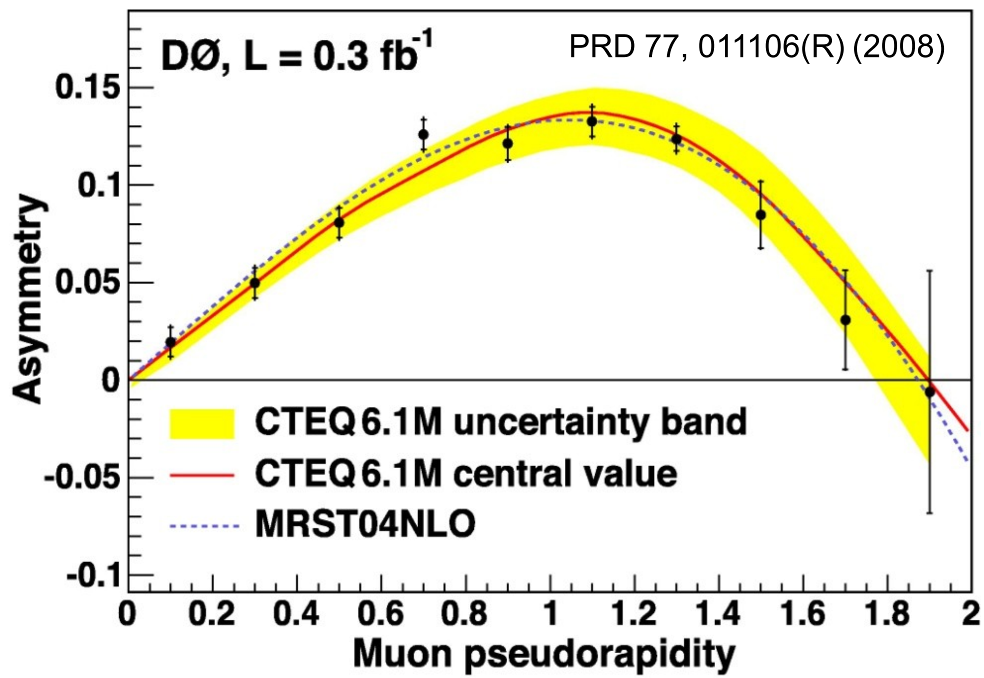
$$A_l(\eta) = \frac{d\sigma(e^+)/d\eta - d\sigma(e^-)/d\eta}{d\sigma(e^+)/d\eta + d\sigma(e^-)/d\eta} \simeq \frac{d(x)}{u(x)}$$

V-A structure of $W^{+(-)}$ decay favors backward (forward) charged lepton



0.3 fb^{-1} DØ measurement

~190,000 $W \rightarrow \mu\nu$ events with $|\eta_\mu|<2$



Lepton Charge Asymmetry

▼

W-Asymmetry

Direct Extraction of $A(y_W)$

- determine p_L^{ν} by constraining M_W = 80.4 GeV
  $\rightarrow$ two possible solutions for y_W

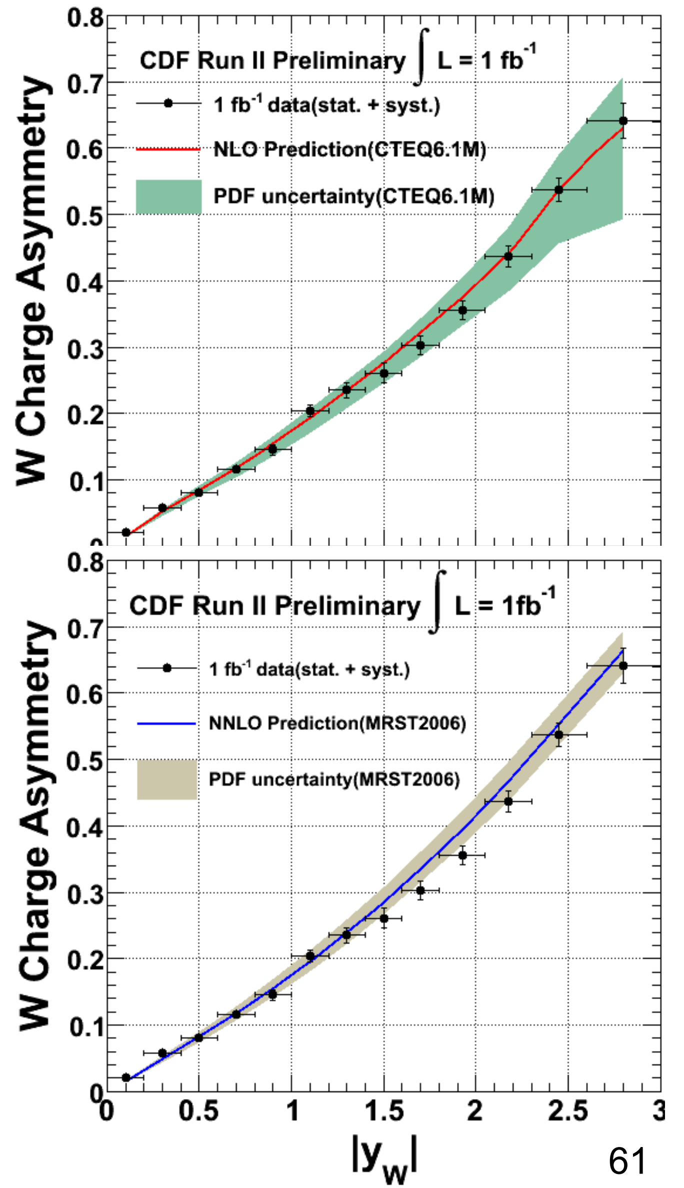
- Each solution receives a weight probability according to:
  - V-A decay structure
  - W cross-section: $\sigma(y_W)$

- Process iterated since $\sigma(y_W)$ depends on asymmetry

  Analysis method: arXiv:hep-ph/0711.2859

- preliminary CDF measurement (1 fb^{-1})
  (~715,000 $W \rightarrow e\nu$ events with $|\eta_e|<2.8$)

→ Compared to CTEQ6.1 and MRST2006 PDFs



Summary

- This Presentation: Broad Spectrum of Processes
  Jets, Photons, W-Asymmetry, Vector-Boson + Jets,
  Heavy-Flavor Jets, Jet Production at higher Orders
- Tevatron is more than "the Place to Develop Tools for the LHC"
- "Bread-and-Butter Physics":
  Precision Measurements of Fundamental Observables @2TeV

- PDF knowledge (for searches at Tevatron and LHC)
  → Inclusive Jets, W Asymmetry → strong PDF constraints
- Testing QCD at higher orders & transition soft → hard QCD
  Internal jet structure, jet radius dependence, dijet azimuthal decorrelation → novel QCD tests and MC tuning
- Differential Measurements of Vectorboson+Jet production
  to test predictions for "New Physics" backgrounds & model tuning
- Provide data to identify theory shortcomings: photons, HF jets

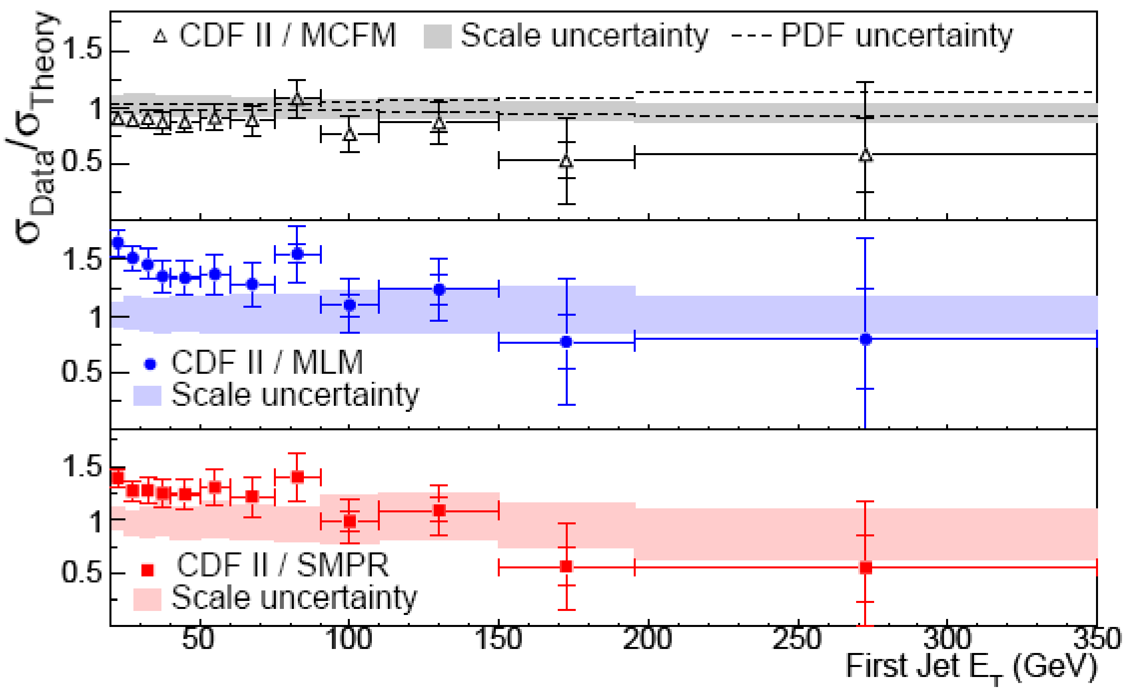
→ Significant improvements with 8fb-1

Backup

W + 1 Jet inclusive

PRD 77, 011108(R) (320pb-1)

Differential jet ET distributions: **First Jet**



"MCFM": NLO
No non-pert. corrrections applied

"MLM":
ALPGEN (LO) +
Herwig (shower) +
MLM matching

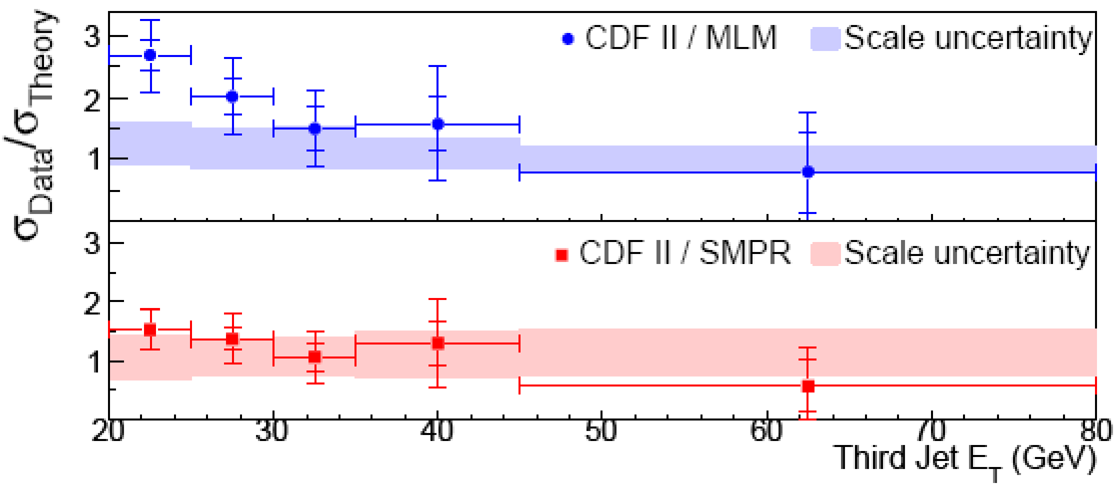
"SMPR":
MadGraph (LO) +
Pythia (shower) +
CKKW matching

→ NLO predictions look good / questionable: JETCLU & ignore non-pert. corrections
→ matched calculations: don't describe ET dependence

W + 3 Jets inclusive

PRD 77, 011108(R) (320pb-1)

Differential jet ET distributions: **Third Jet**



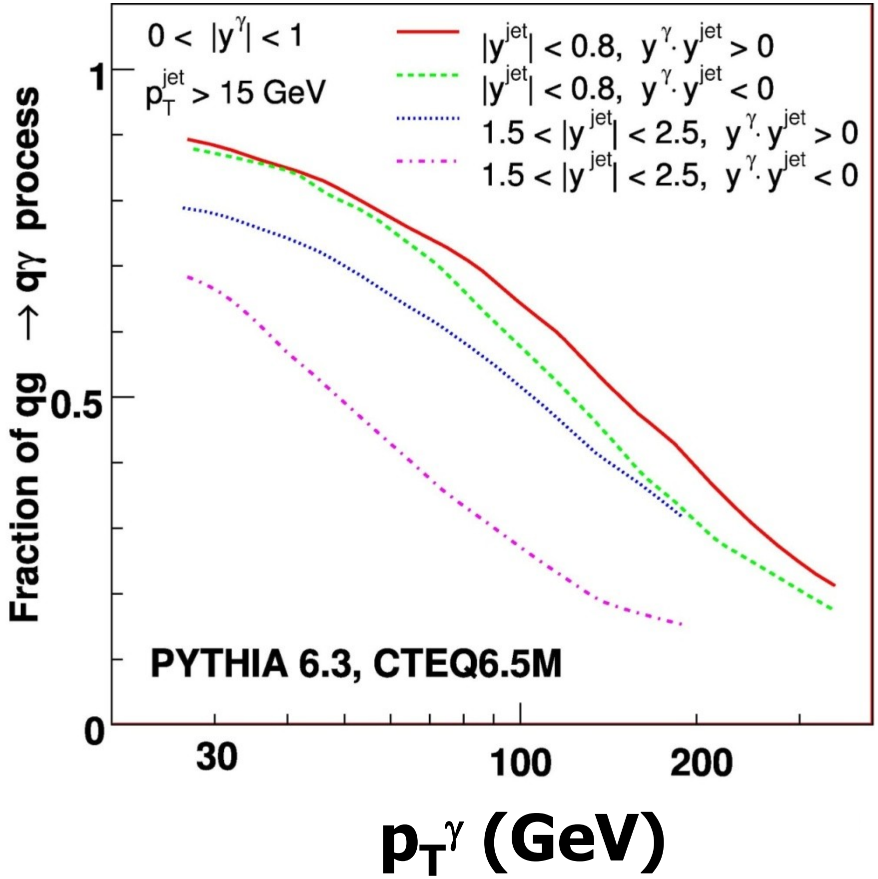
"MLM":
ALPGEN (LO) +
Herwig (shower) +
MLM matching

"SMPR":
MadGraph (LO) +
Pythia (shower) +
CKKW matching

→ not computed to NLO

→ matched calculations: "SMPR" better than "MLM"   (under investigation)

Isolated Photon + Jet

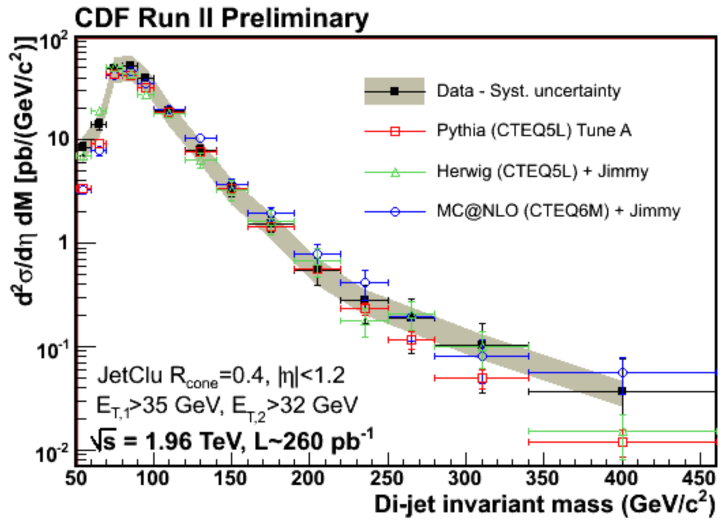


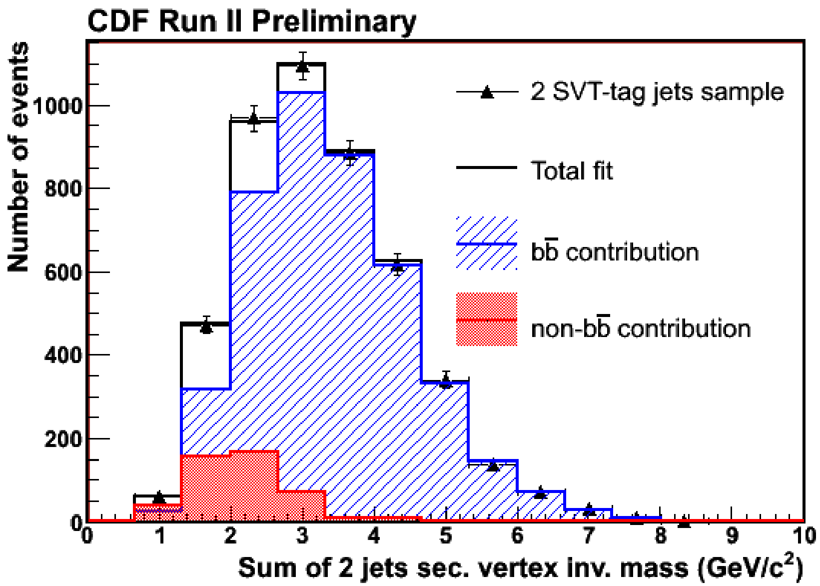
quark-gluon subprocess fraction in different rapidity regions versus pT

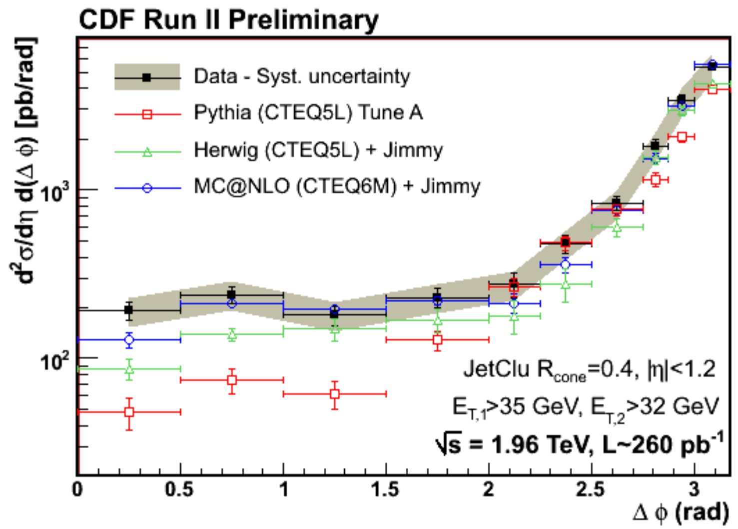
bbar Dijet Production (using SVT)

Dedicated silicon vertex trigger data
- Displaced tracks with IP > 120 μm
- Secondary vertex b-tagging algorithm

Fit signal+bkd template to mass distribution of tracks from secondary vertices to extract heavy flavor contribution







Data/theory agreement improves as we go from LO to Herwig or MC@NLO + Jimmy