# Recent Tevatron Jet, W/Z+Jet and b-Jet Results

Shin-Shan Yu

*Fermi National Accelerator Laboratory*

*for the CDF and D0 Collaborations*

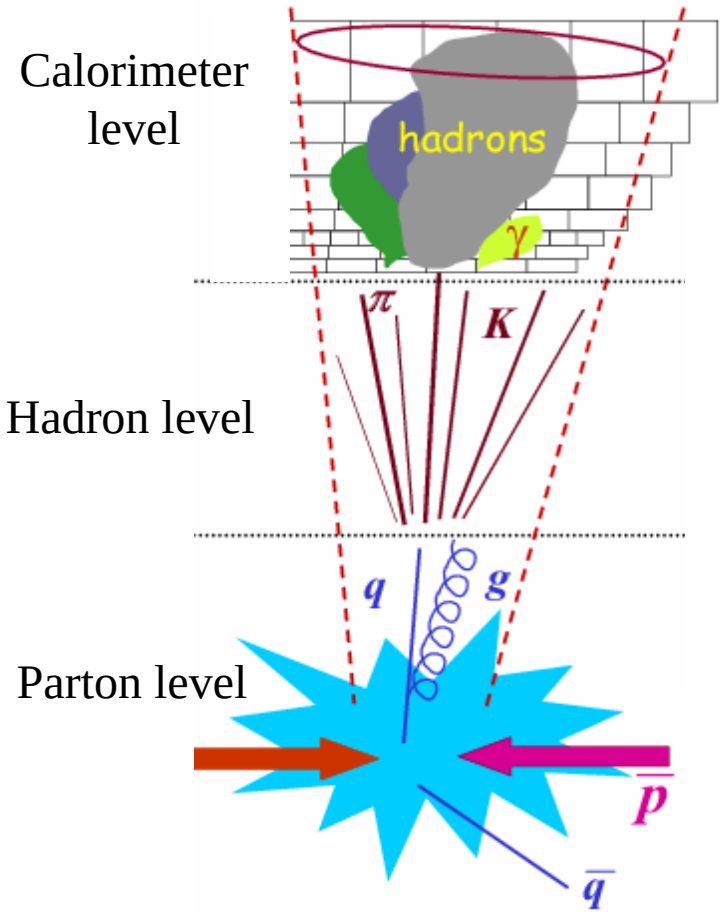
Photon 2009, May 11-15, 2009, DESY

# Outline

- Introduction
- Inclusive Jet Production X-section
- Dijet X-section
- Dijet Angular Distribution
- W + Jet Production
- Z + Jet Production
- W + Heavy Flavor (Wc, Wbb)
- Z + Heavy Flavor (Zb)
- b-jet Shape
- Conclusion

*See talks by Dan Krop and Ashish Kumar for photon results from Tevatron.*

# What is Jet?

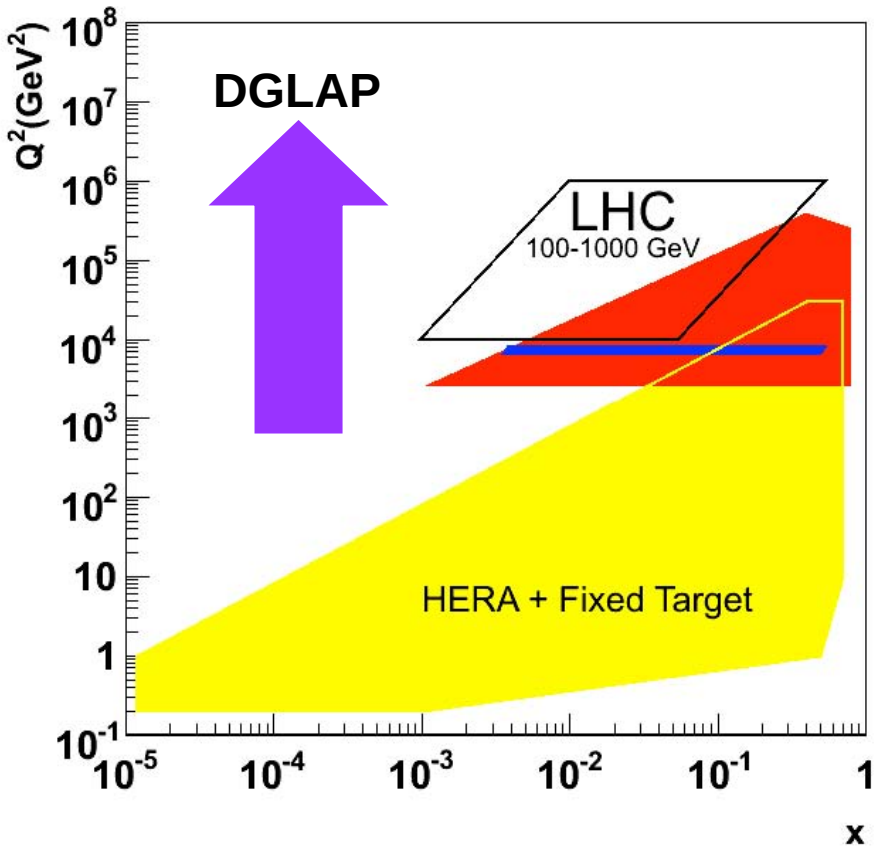



- Jets are collimated sprays of hadrons originating from quarks or gluons
- Energy correction from the calorimeter to the hadron level
  - 10% to 50%

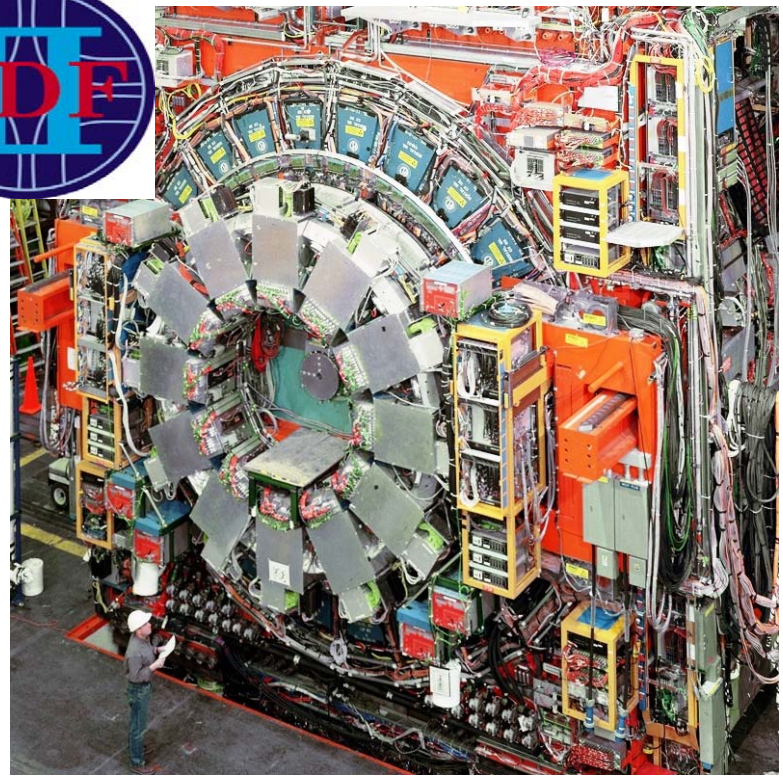
# Motivation

- Test perturbative QCD (pQCD) calculation
  - Jet production has the highest reach of energy and rapidity
- Constrain PDF at large $Q^2$ and medium-to-large x
  - Similar to LHC $Q^2$
  - PDFs of gluon, b, and s quarks
- Backgrounds to new physics
  - Wbb: low-mass SM Higgs
  - W/Z+jets: SUSY, 4th generation
- Search for new physics

**Tevatron Inclusive jet x-section**
**Tevatron W/Z rapidity shape**



# Detectors

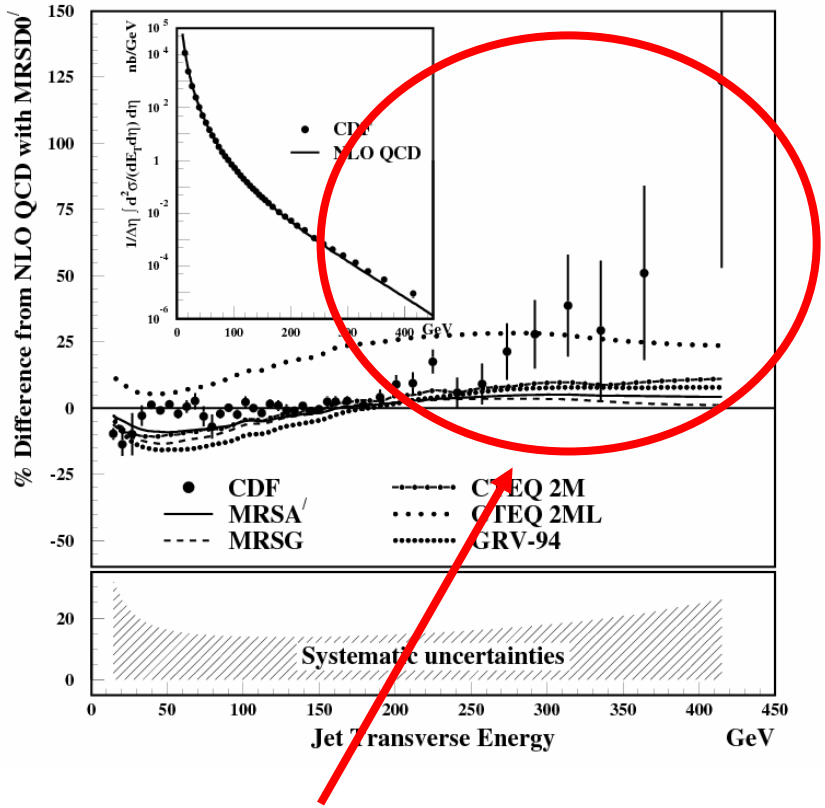


Each experiment has collected > 5/fb on tape

0.3-2.5/fb results in this talk, 17 analyses in total

# Inclusive Jet X-section

- Test pQCD calculation
- Constrain high-x gluon PDF
- Improvements compared to Run I
  - Increase energy by 150 GeV
  - Extend to wider rapidity region
  - Use cone (R=0.7) and kT (D=0.7) algorithms




Excess > 160 GeV in CDF Run 1 data (1%)
*Phys. Rev. Lett. 77, 438 (1996)*
Results included in CTEQ6, MRST2001

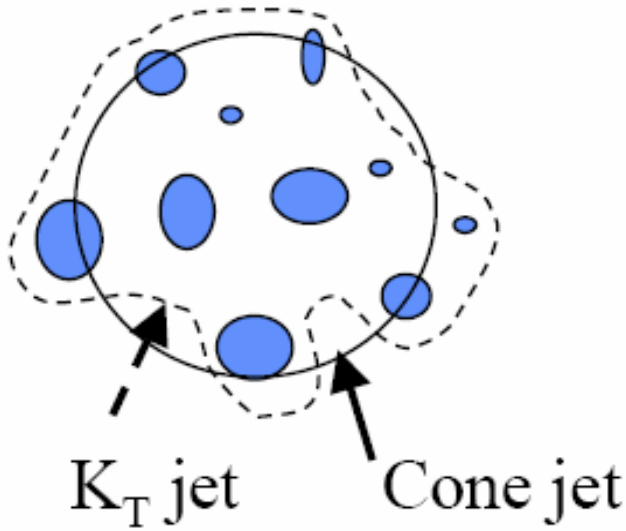
# Jet Algorithms

*Prog. Part. Nucl. Phys., 60, 484 (2008)*

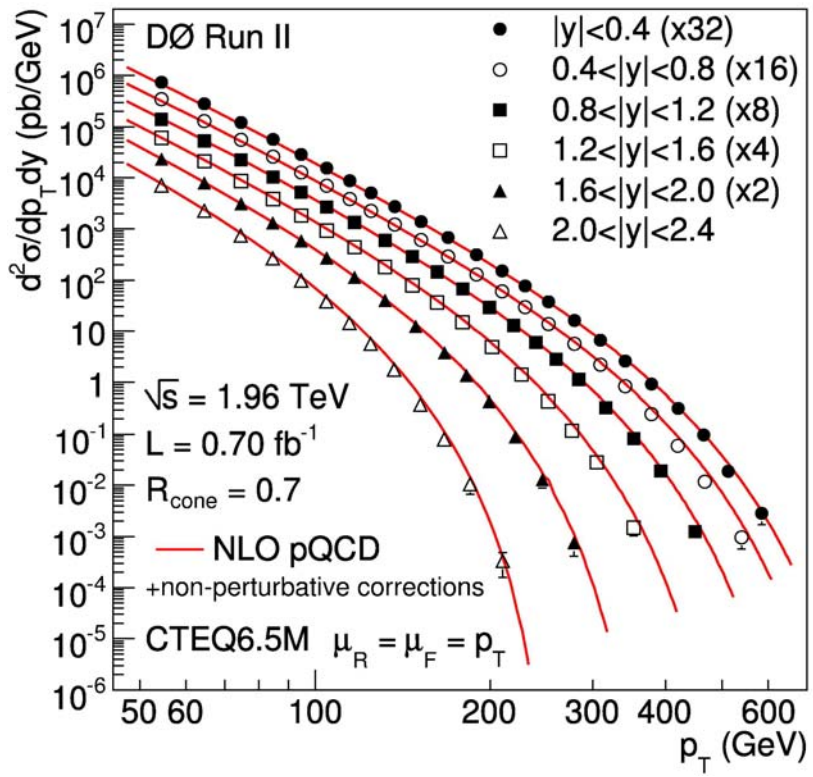
- Cone algorithm (most analyses)
  - Cluster objects based on their proximity in y-$\phi$ ($\eta$-$\phi$) space
  - Starting from seeds, iteratively cluster particles in cones of radius $R_{CONE}$ and look for stable cones (geometrical center = $p_T$-weighted centroid)
  - Uses midpoints between pairs of stable cones as additional seeds

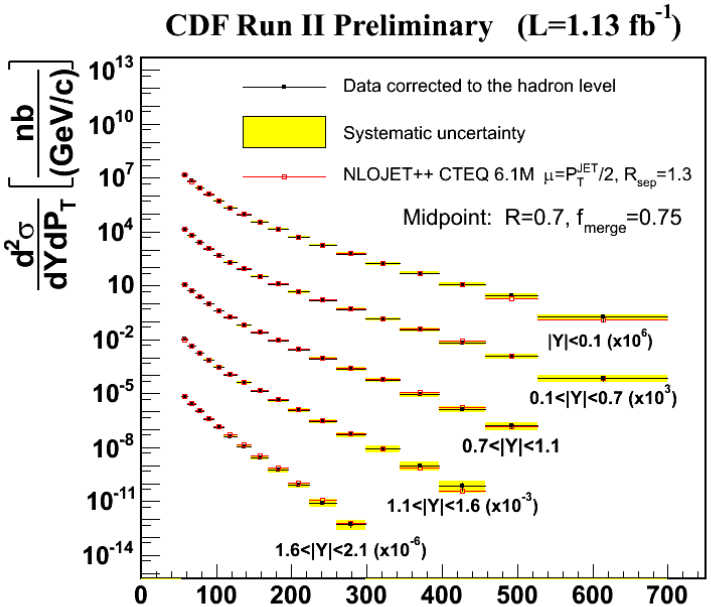
  → Infrared safe to NNLO
- Inclusive kT algorithm
  - Cluster objects based on their relative pT
  - D parameter controls merging termination and characterizes size of resulting jets

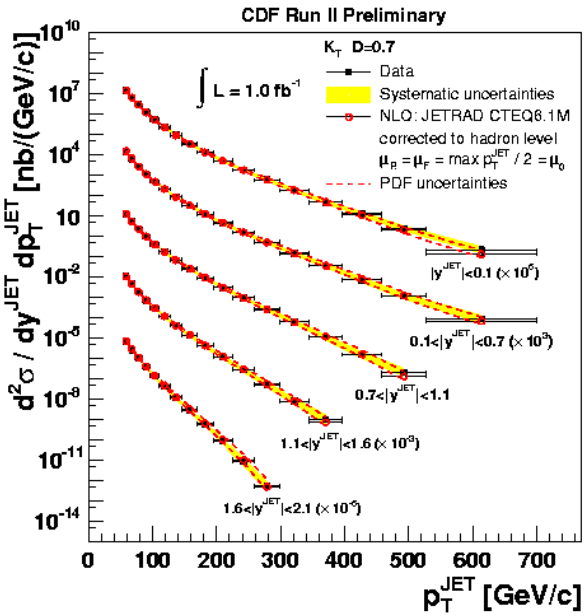
  → Infrared safe to all orders, more difficult to model UE or MI



# Run 2 Results



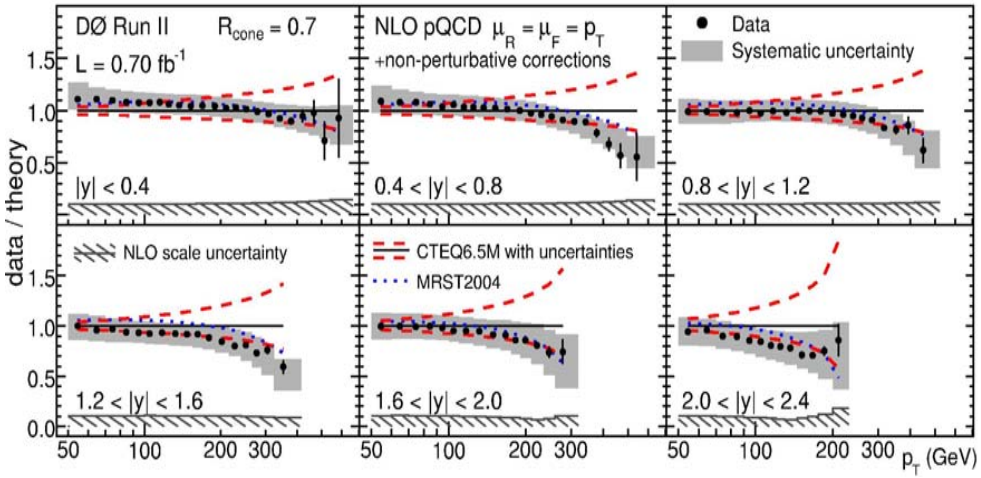



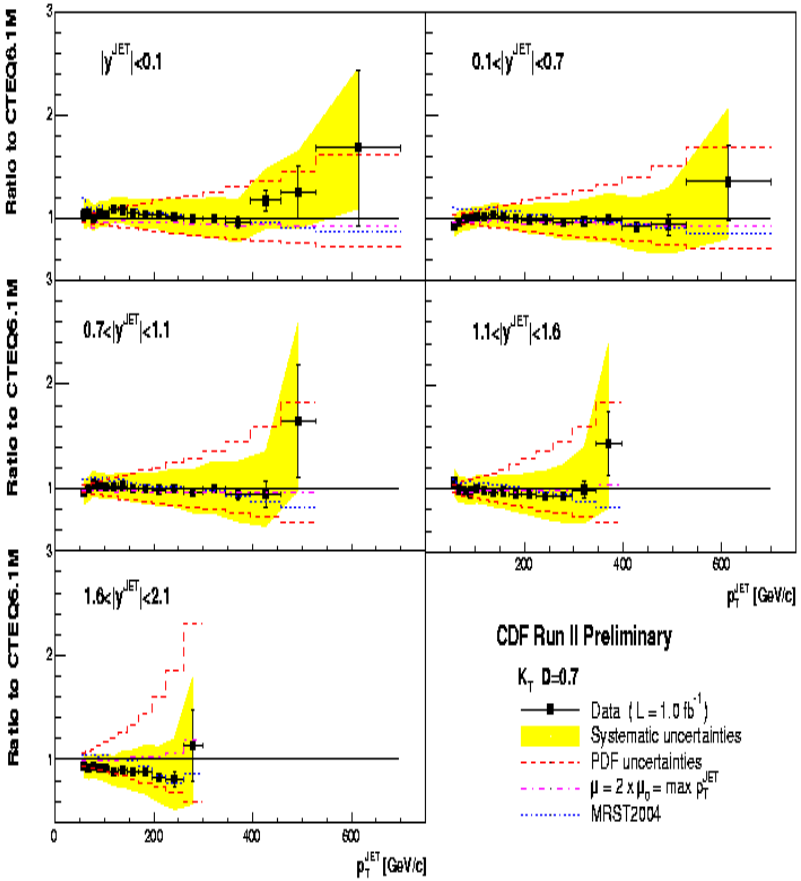




*CDF Cone: Phys. Rev. D 74, 071103(R) (2006)*
*Phys. Rev. D 78, 052006 (2008)*
*CDF kT: Phys. Rev. Lett. 96, 122001 (2006)*
*Phys. Rev. D 75, 092006 (2007)*
*D0 Cone: Phys. Rev. Lett. 101, 062001 (2008)*

**Shin-Shan Yu**

# Run 2 Jet X-section Data/Theory



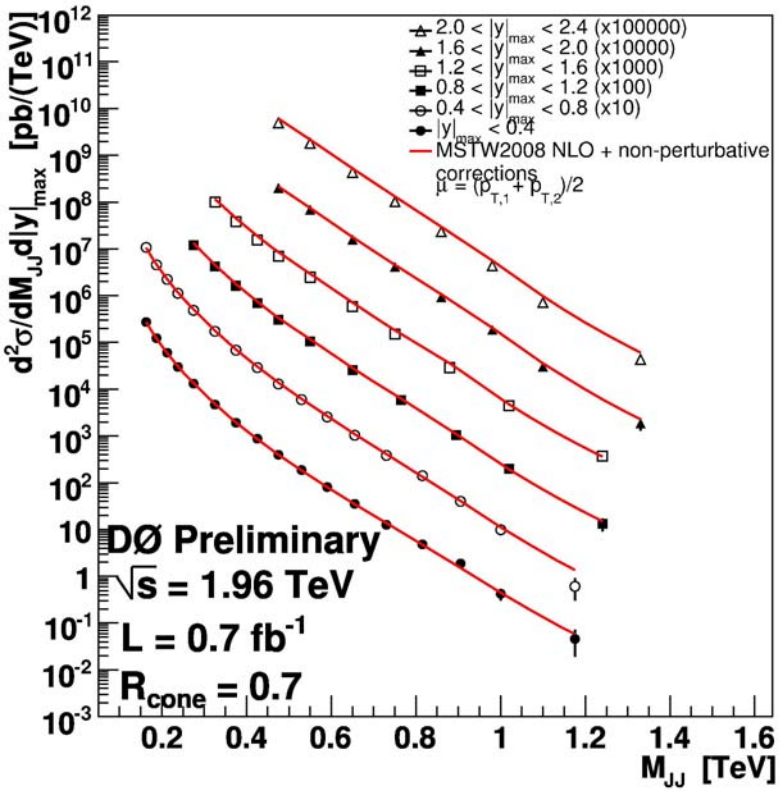



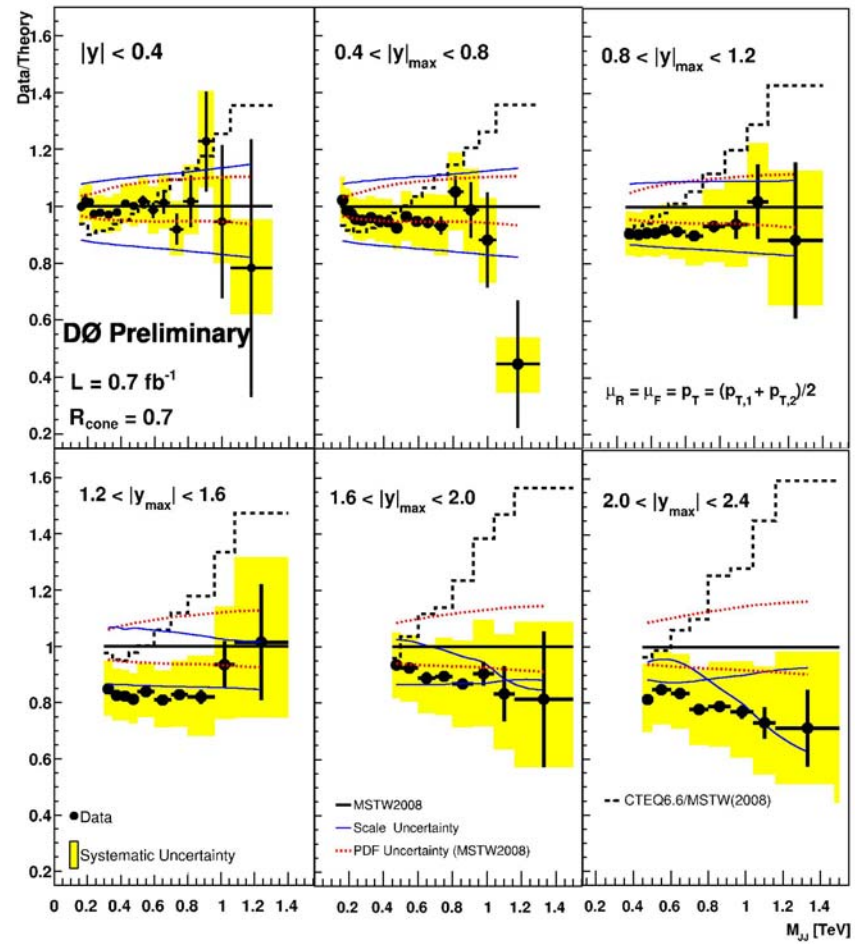

- Dominant sources of uncertainties
  - Data: jet energy scale (2-3% for CDF, 1.2-2% for D0)
  - Total uncertainties on $\sigma$: CDF (15-50%) and D0 (15-30%)
- Provide input to PDF
  - MSTW2008 uses CDF kT and D0 cone results
  - Reduced gluon PDF uncertainties
  - Data prefer lower gluon PDF at high-x

*See backup slides for CDF cone data/theory ratios*

# Dijet Mass X-Section

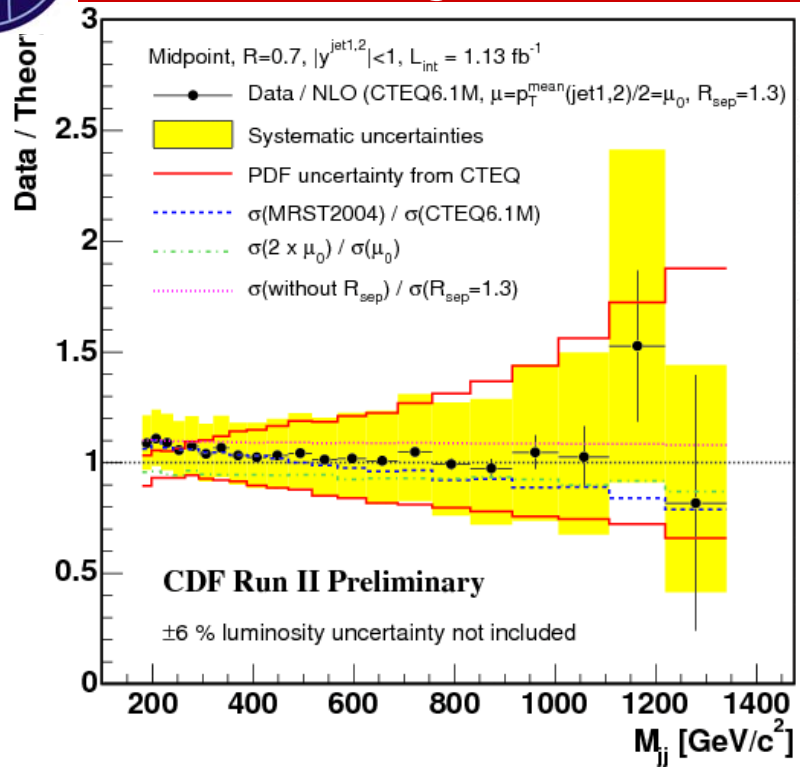
NEW!!

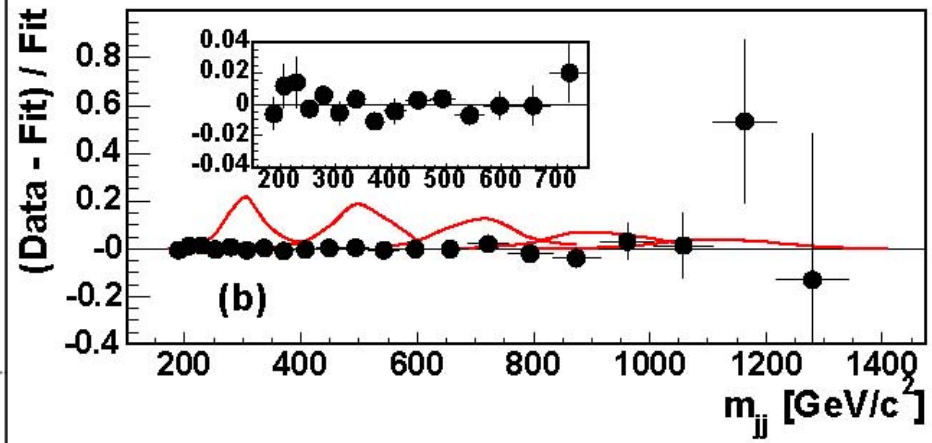



- Use MSTW 2008 NLO PDF!
- Limits on new physics work in progress

# Dijet Mass X-Section




| Model | Excluded mass GeV |
|---|---|
| axigluon, coloron | 260-1250 |
| E6 diquark | 260-630 |
| Color octet Techni- ρ | 260-1100 |
| Excited q | 260-870 |

- Concentrate on central jets
- Good agreement between data and NLO prediction
- Best limits on resonance X→dijets

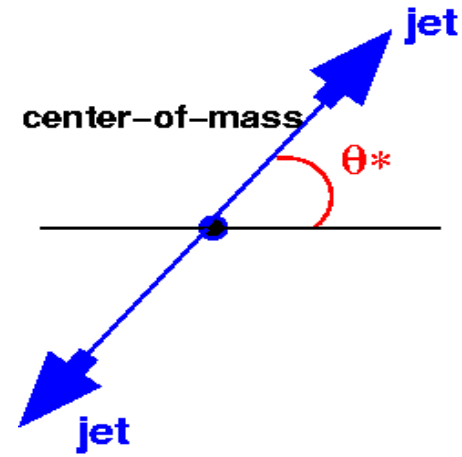
*arXiv:0812.4036*

# Dijet Angular Distribution

- Run 1 jet x-section best fit of compositeness scale $\Lambda$ at 1.6 TeV (PDF or new physics?)

$$\sigma_{ij\to k} = \int dx_1 \int dx_2 f_i(x_1) f_j(x_2) \hat{\sigma}_{ij\to k}$$

- Shape of the dijet angular distributions as a function of dijet mass
  - Previous best $\Lambda$ limits 2.7 TeV(2.4 TeV) for $\lambda$=+1(-1)

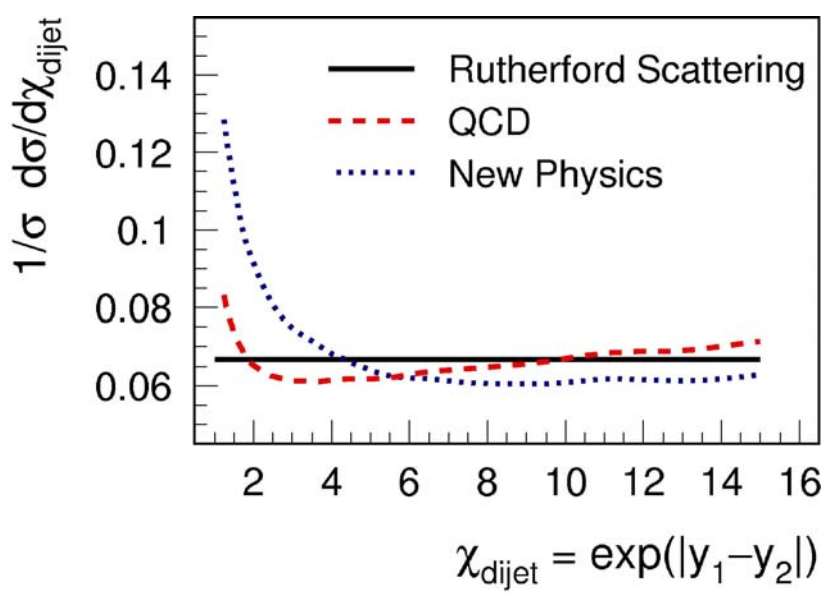



$$\cos\theta^* = \tanh(y^*),$$

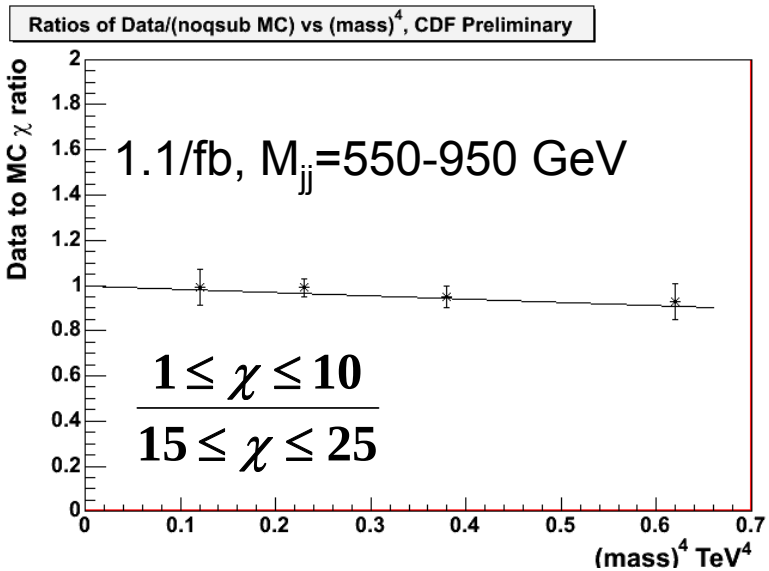
$$y^* \equiv \frac{1}{2}(y_1 - y_2)$$

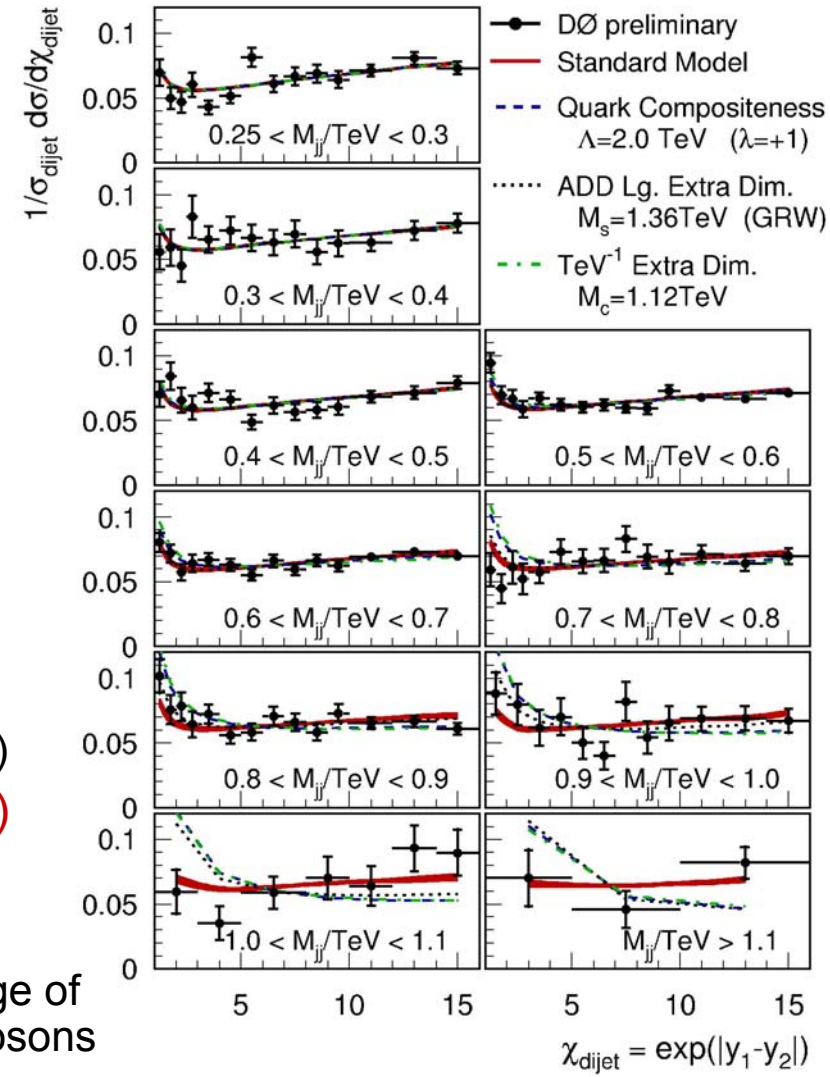
$$\chi_{dijet} = \exp(|y_1 - y_2|)$$

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



# Run 2 Results

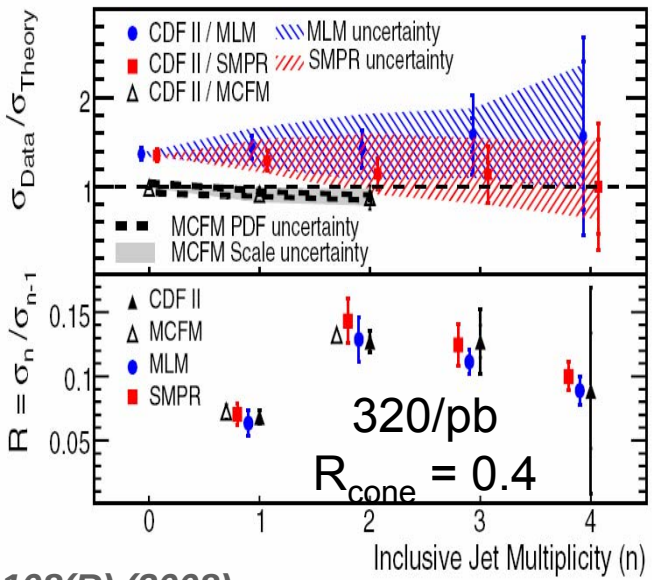


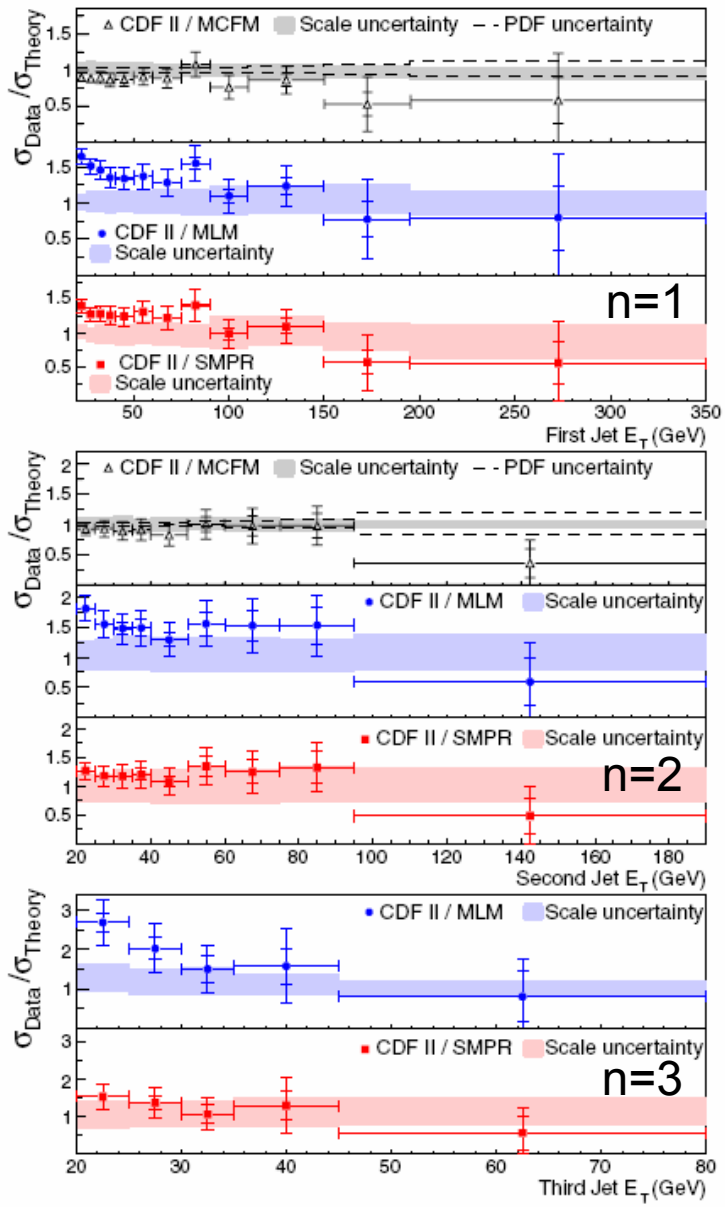

- Quark Compositeness ($q^* \rightarrow qg$)
  - CDF: $\Lambda$ > 2.4 TeV for $\lambda$ = -1
  - D0: $\Lambda$ > 2.73 (2.64) TeV for $\lambda$ = +1 (-1)
- ADD Large Extra Dimension (D0 only)
  - GRW: $M_s$ > 1.56 TeV
- TeV$^{-1}$ Extra Dimension (D0 only)
  - X-section modified due to the exchange of virtual KK excitations of SM Gauge Bosons
  - Compactification scale $M_c$ > 1.42 TeV

# W(→eν)+ ≥ n Jet Production

Restricted
W phase space
$E_T(e) > 20$ GeV
$|\eta(e)| < 1.1$,
$E_T(\nu) > 30$ GeV
$m_T(W) > 20$ GeV



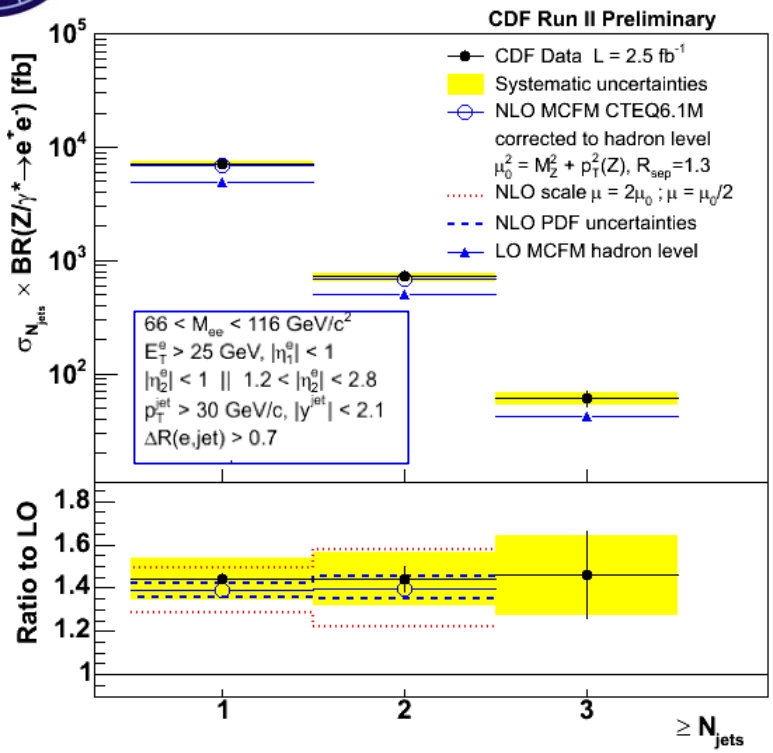

*Phys. Rev. D 77, 011108(R) (2008)*

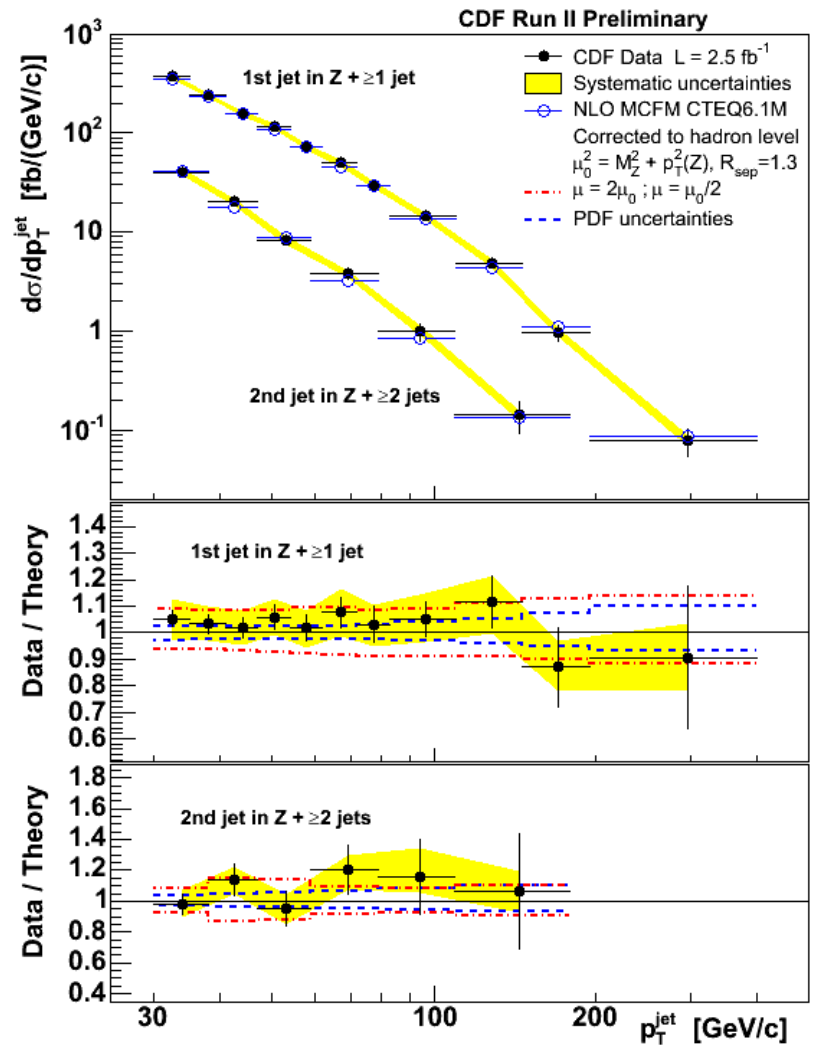



- Background 10% (40%) to 90% for n=1(4)
  - Systematic uncertainties 15% to 50%(20%)
- Jet energy scale (low pt) and background (high pt) are dominant uncertainties
- Comparison
  - NLO: MCFM
  - MLM (LO): ALPGEN+ HERWIG+ MLM
  - SMPR (LO): MADGRAPH + PYTHIA+ CKKW

**Shin-Shan Yu**

# Z(→ee)+ ≥ n Jet Production

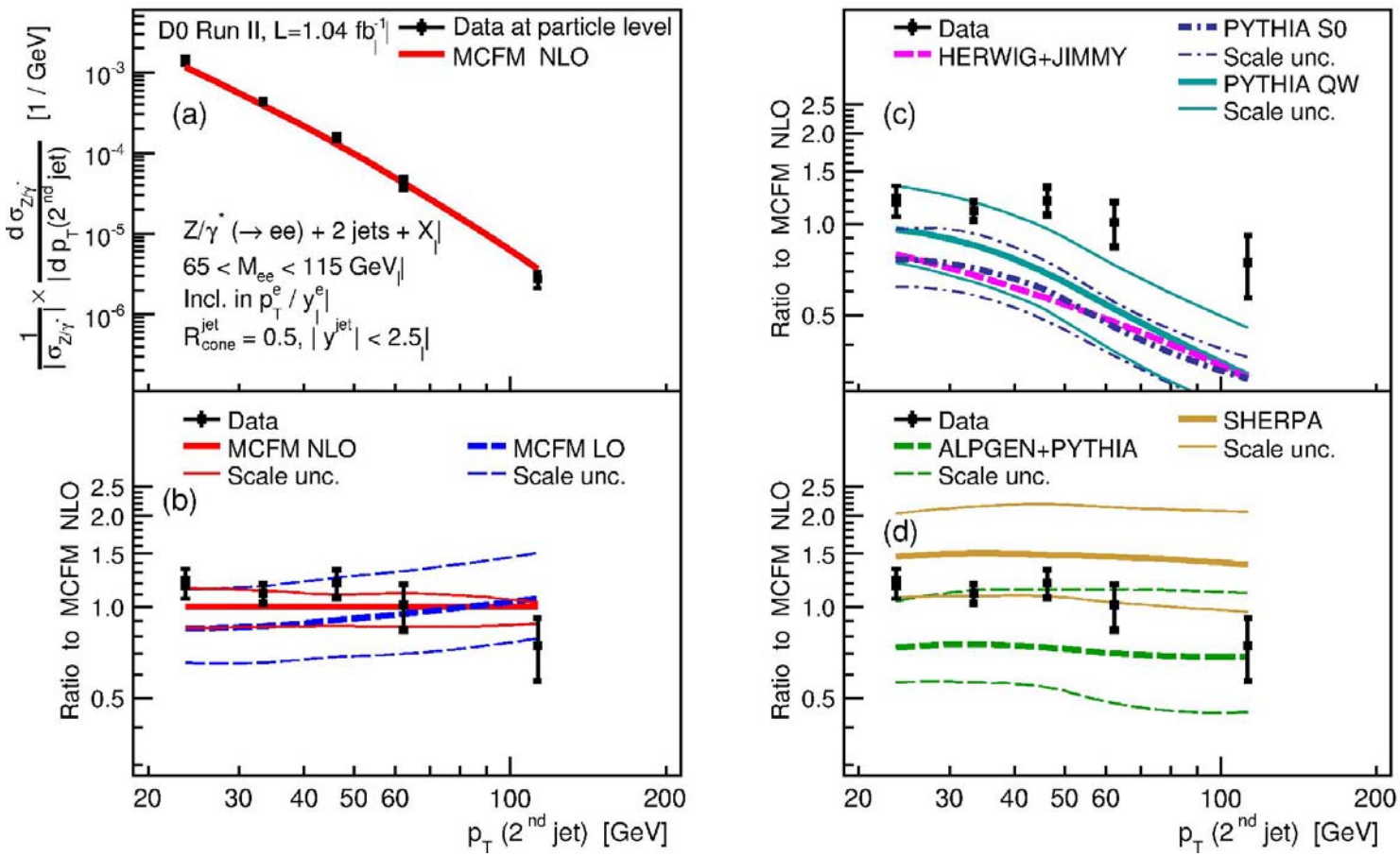



- Much cleaner compared to W+jets
  - 12(17)% background for n>=1(3)
- Good agreement with NLO MCFM
  - Systematic uncertainties 8 to 13%

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

# Z(→ee)+ ≥ n Jet Production

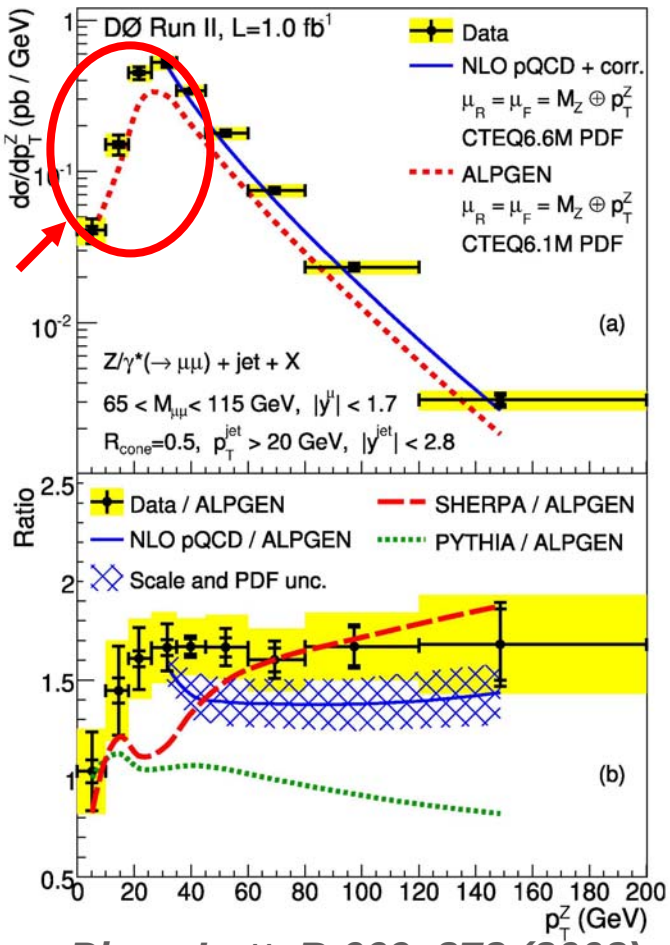



*arXiv:0903.1748*

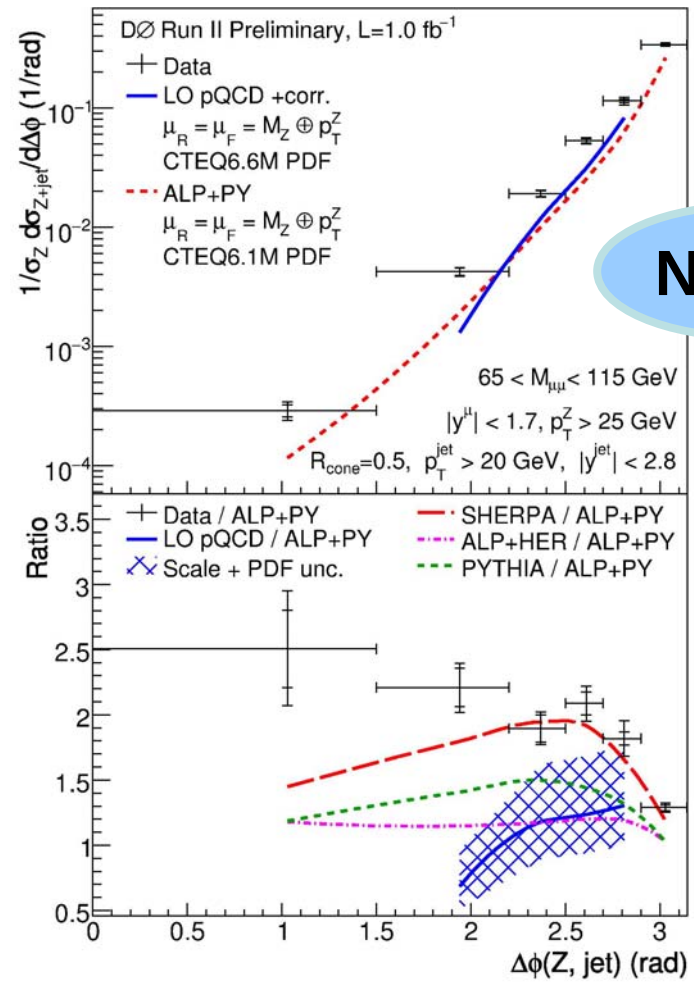
- Also check several LO predictions
  - Parton-shower based generator disagree in shapes and normalization
  - Matrix element + Parton-shower generators describe shape better

# Z(→μμ)+ ≥ n Jet Production

Dominated by non-pQCD




*Phys. Lett. B 669, 278 (2008)*

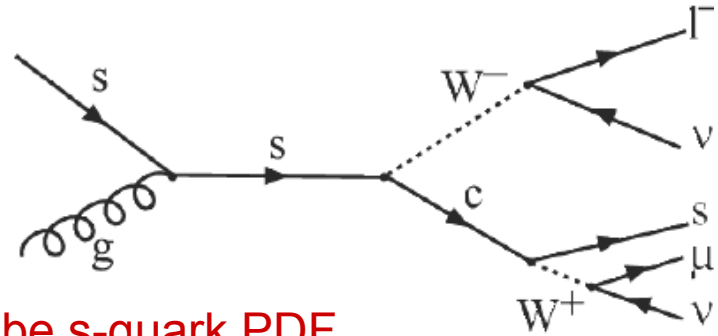


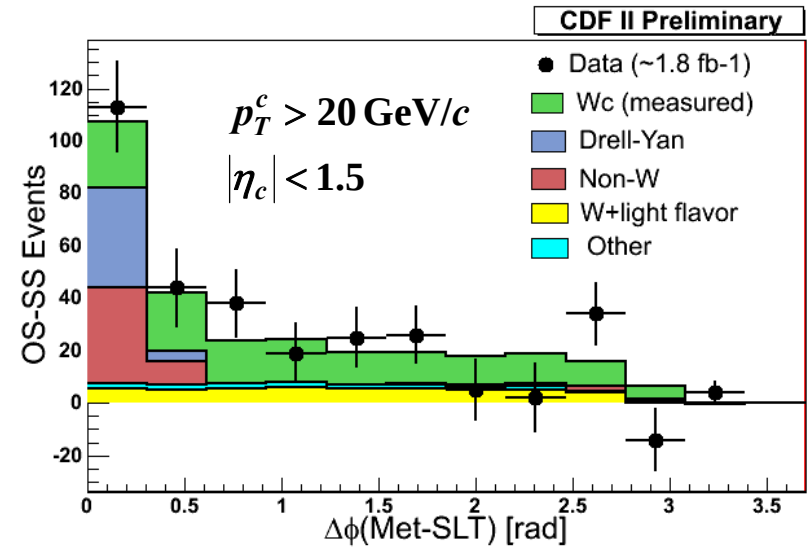

**NEW!!**

- Good agreement with NLO in $p_T$(jet), y(jet), $p_T$(Z), y(Z)

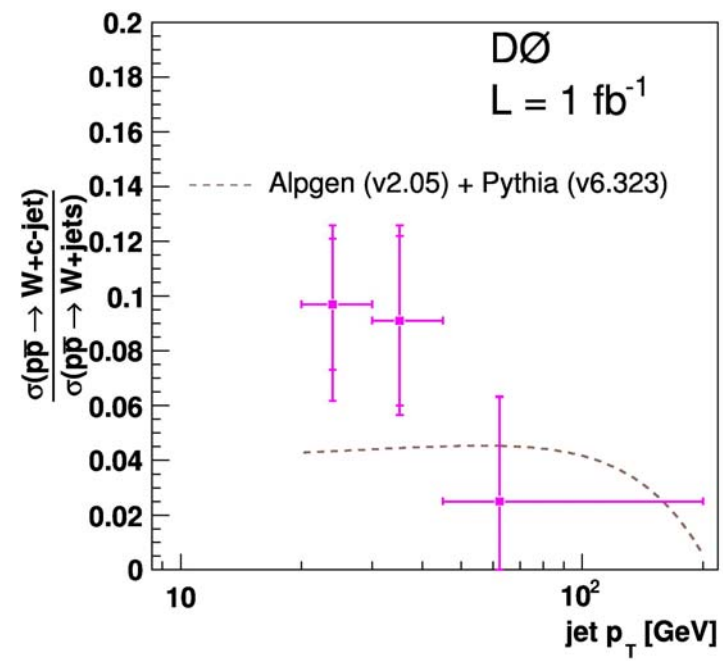
$\Delta\phi$: Only LO, not good agreement in shapes and normalization

# W + c Production




- Probe s-quark PDF
- Use soft-muon-tag to tag c
  - 90-60% (55%) efficiency for CDF (D0)
- Wc production have more OS than SS events
- Results
  - CDF: σ = **9.8 ± 2.8 (stat) + 1.4-1.6 (sys) ± 0.6 (lum) pb**, agree with NLO 11.0+1.4-3.0 pb
  - D0 σ ratio: **0.074 ± 0.019 (stat) + 0.012-0.014 (sys)**, agree with LO 0.044 ± 0.003

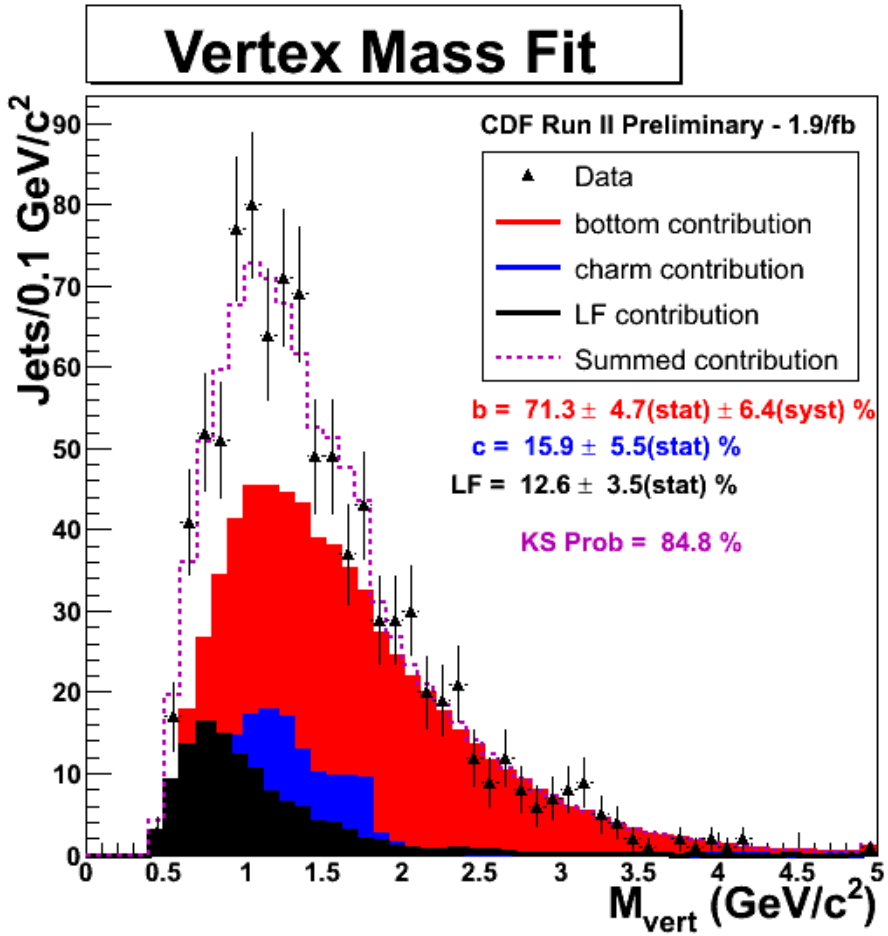



*CDF: Phys. Rev. Lett. 100, 091803 (2008)*
*D0: Phys. Lett. B 666, 23 (2008)*

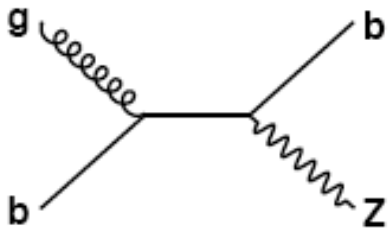
**Shin-Shan Yu**

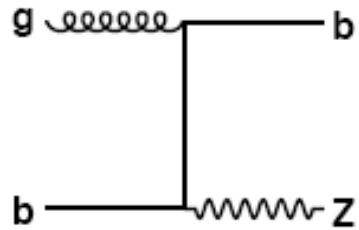
# W + b Production (Per Jet)

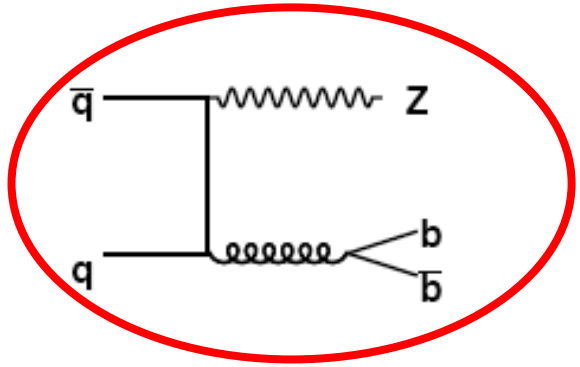
- Tag b-jets by looking for secondary vertex contained in jets
- Fit the secondary vertex mass to obtain b purity
  - Largest uncertainty in modeling of b mass shape
- Results: $\sigma$ = 2.74 ± 0.27 (stat) ± 0.42 (sys) pb, 3.5 times larger than ALPGEN prediction (0.78 pb)
  - NLO predictions will help



# Z + Inclusive b Production



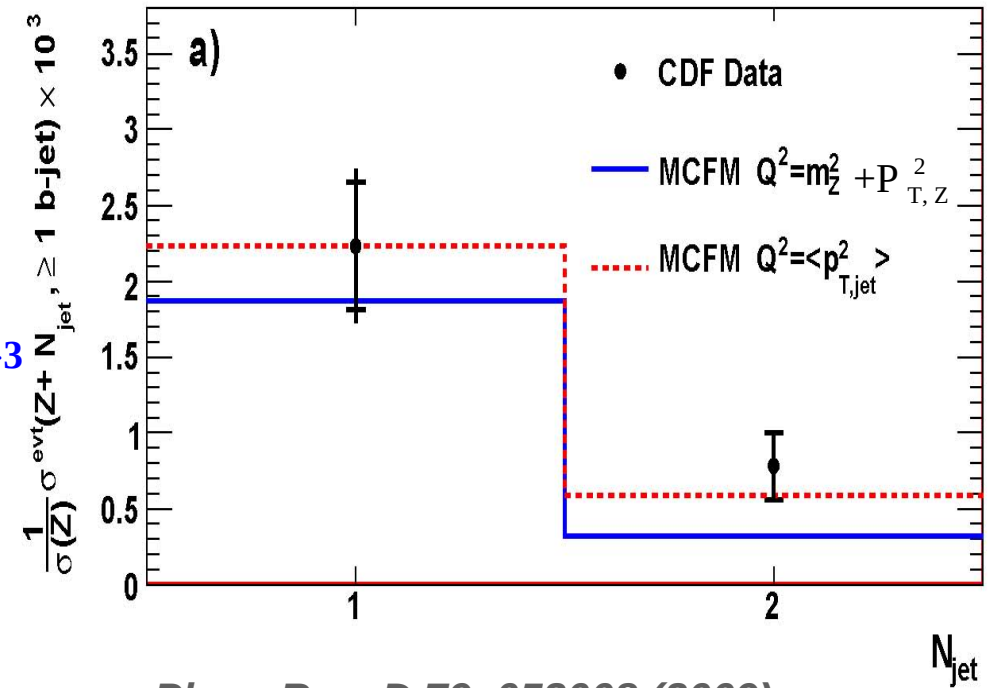




- Large dependence on scales
  - Lower scale preferred
- MCFM Zbb diagram not available for NLO

$$\frac{\sigma^{jet}(Z+b)}{\sigma(Z)} = (3.32 \pm 0.53 \pm 0.42) \times 10^{-3}$$

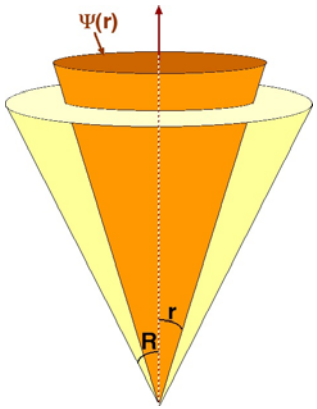
$$MCFM: 2.3 \times 10^{-3} \ (Q^2 = M_Z^2 + P_{T,Z}^2)$$

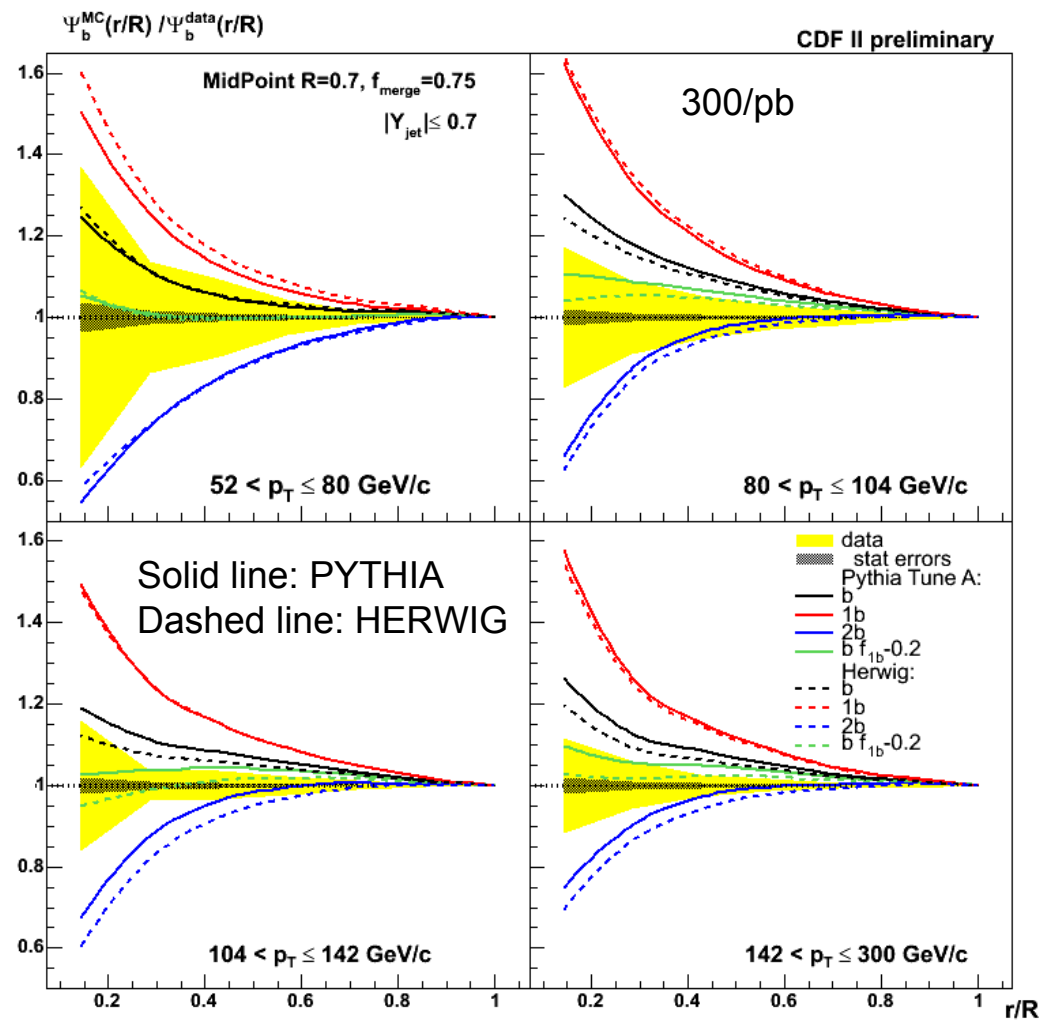
$$: 2.8 \times 10^{-3} \ (Q^2 = < P_{T,Jet}^2 >)$$




*Phys. Rev. D 79, 052008 (2009)*

# b-jet Shape



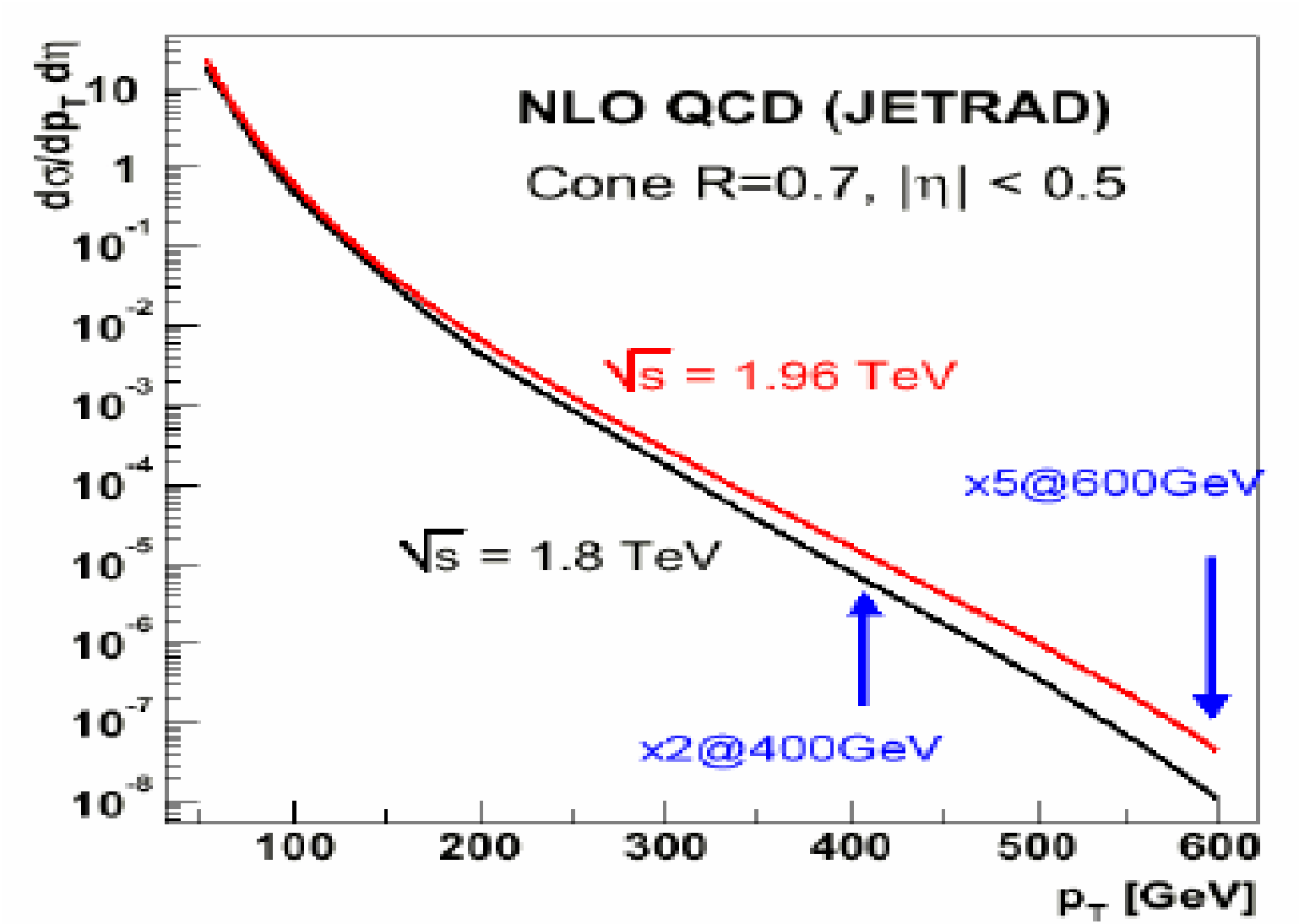

- Fraction of momentum carried by particles within cone of r
- Indirectly probe the contribution of gluon-splitting
  - More 2-b quarks in a jet
  - 2-b jet broader than 1-b jet
  - Complimentary to $\Delta\phi$ method
- Prefer 0.2 less than the default value of 1-b fraction in LO generator

*Phys. Rev. D 78, 072005 (2008)*

# Conclusion

- Tevatron jet and W/Z+jet results provide stringent tests of pQCD
  - Dijet, W/Z + jets, W + c results agree with NLO predictions
  - Need full NLO of W/Z+b to be implemented in MCFM
- b-jet shapes indicate that smaller 1-b jet fraction is preferred
- Tevatron Run 2 Jet X-section results constrain gluon PDF at high-x
  - Less gluon density preferred by data
- Dijet mass and angular variables used to search for new physics
  - World's best limits on excited quark, E6 diquark, coloron, axigluon, coloron, compositeness scale
- More data always help. More reach to higher energy and jet multiplicity. Expect 8-10/fb by the end of Run 2.
  - W/Z + heavy flavor production
- Better understanding of QCD will enhance the discovery of new physics!

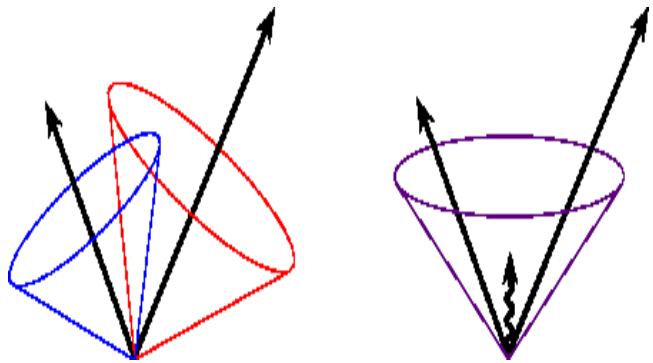
# Backup Slides

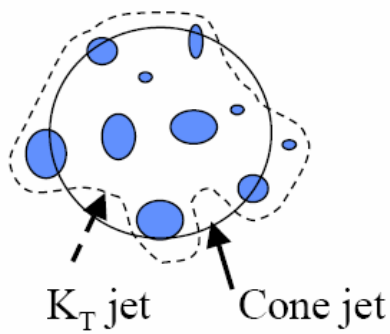

NLO QCD (JETRAD)
Cone R=0.7, |η| < 0.5
√s = 1.96 TeV
√s = 1.8 TeV
x5@600GeV
x2@400GeV
dσ/dp_T dη
p_T [GeV]
10
1
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
100
200
300
400
500
600

# Jet Algorithms

- Midpoint cone algorithm (most analyses)
  - Cluster objects based on their proximity in y-$\phi$ ($\eta$-$\phi$) space
  - Starting from seeds, iteratively cluster particles in cones of radius $R_{CONE}$ and look for stable cones (geometrical center = $p_T$-weighted centroid)
  - Uses midpoints between pairs of stable cones as additional seeds $\rightarrow$ Infrared safe to NNLO
- Inclusive kT algorithm
  - Cluster objects based on their relative pT
  - D parameter controls merging termination and characterizes size of resulting jets

  $\rightarrow$ Infrared safe to all orders, more difficult to model UE or MI





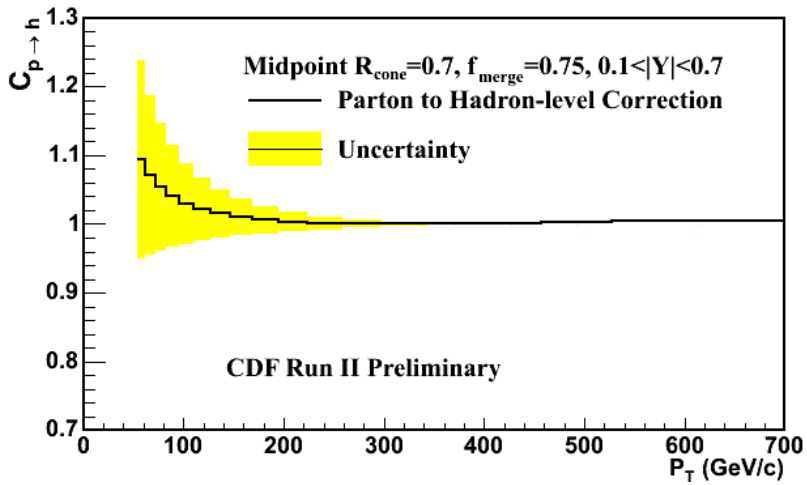

$$d_{ij} = \min(p_{T,i}^2, p_{T,j}^2)\,\frac{\Delta R^2}{D^2}$$

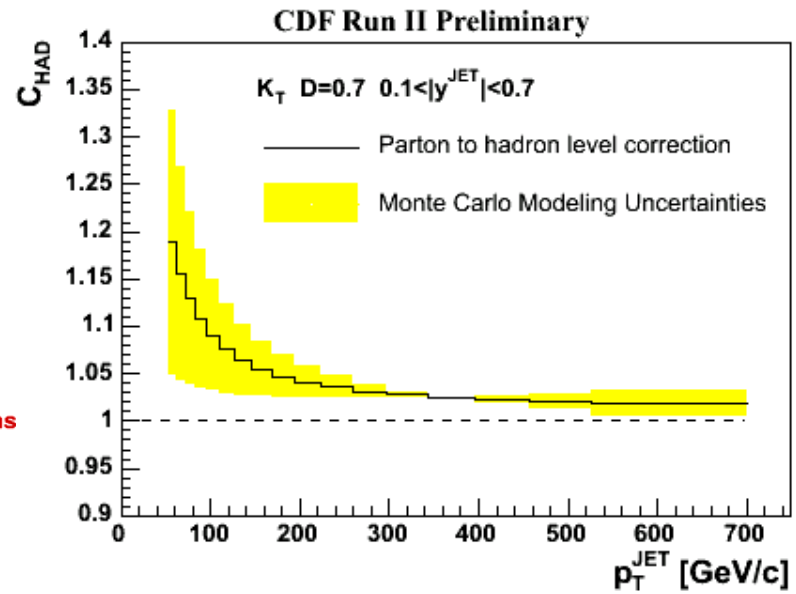
$$d_i = p_{T,i}^2$$

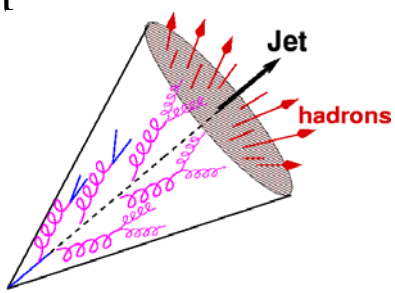
*Prog. Part. Nucl. Phys., 60, 484 (2008)*

# Jet Energy Correction

- Correct measured jet energy from the calorimeter level to the hadron level
  - Non-linear response of calorimeter
  - Non-uniform geometric acceptance of calorimeter
  - Extra energy from multiple ppbar interactions
- Unfolding
  - Smearing, efficiency
- Correct theory predictions for the non-perturbative effect
  - Underlying event
  - Hadronization

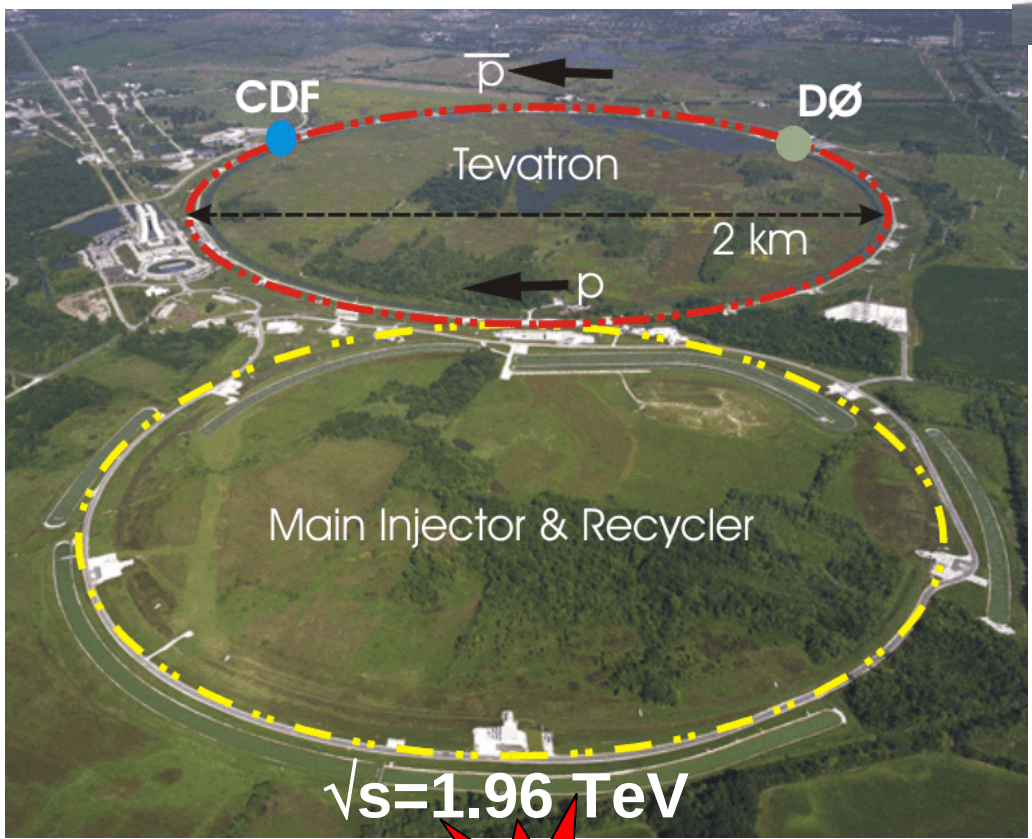


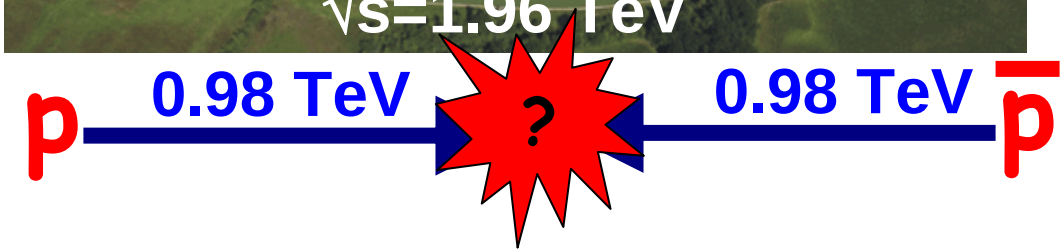



# Fermilab Tevatron

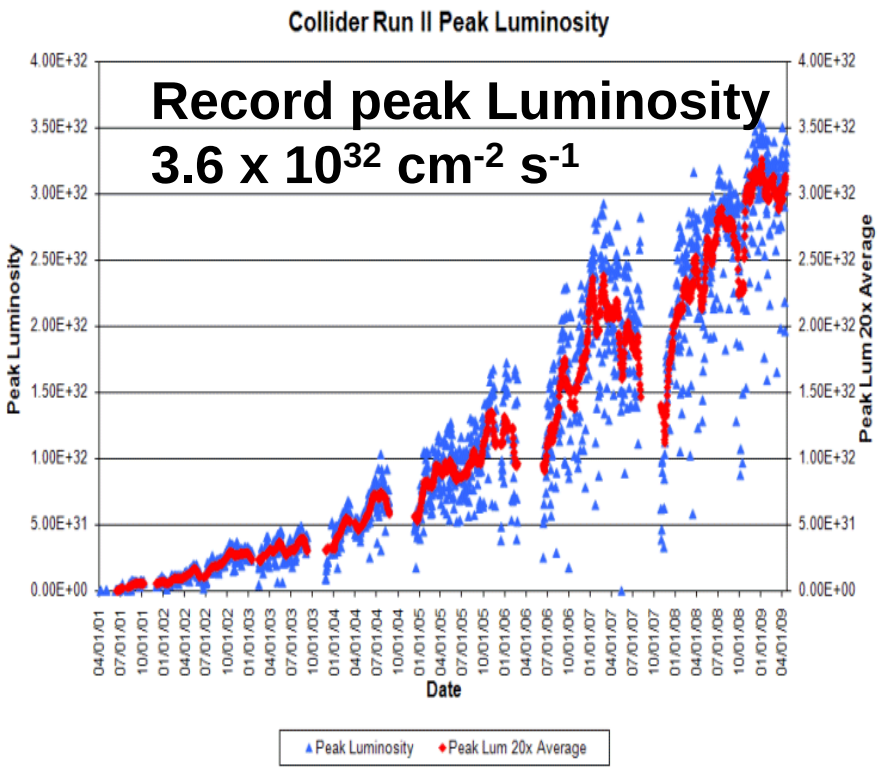
**~70 km west of Chicago**

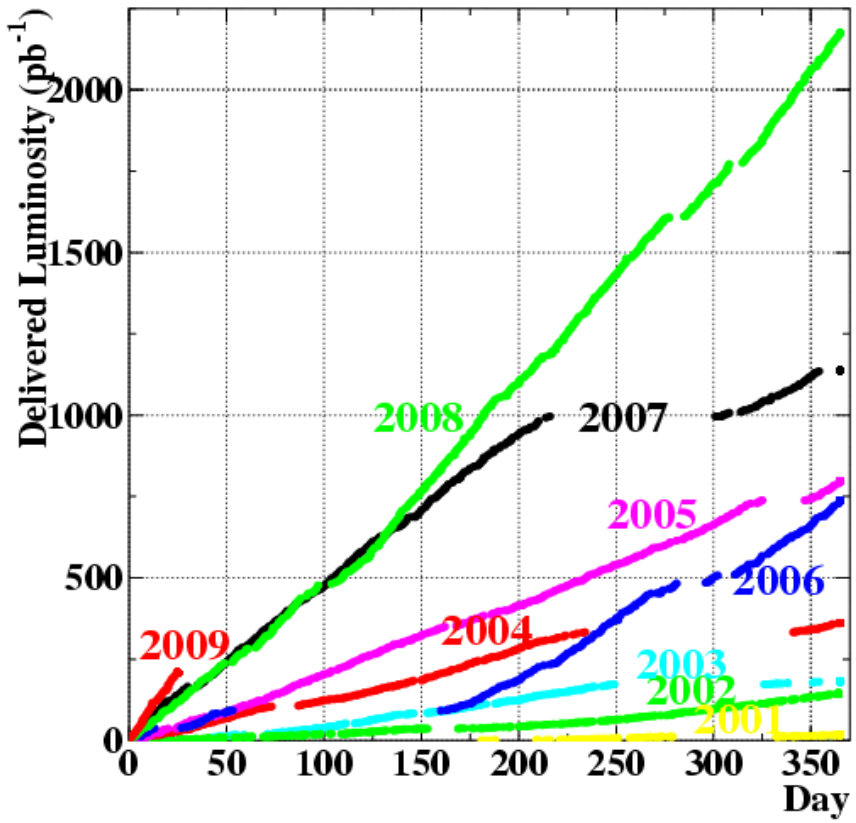



**√s=1.96 TeV**



# Tevatron Performance

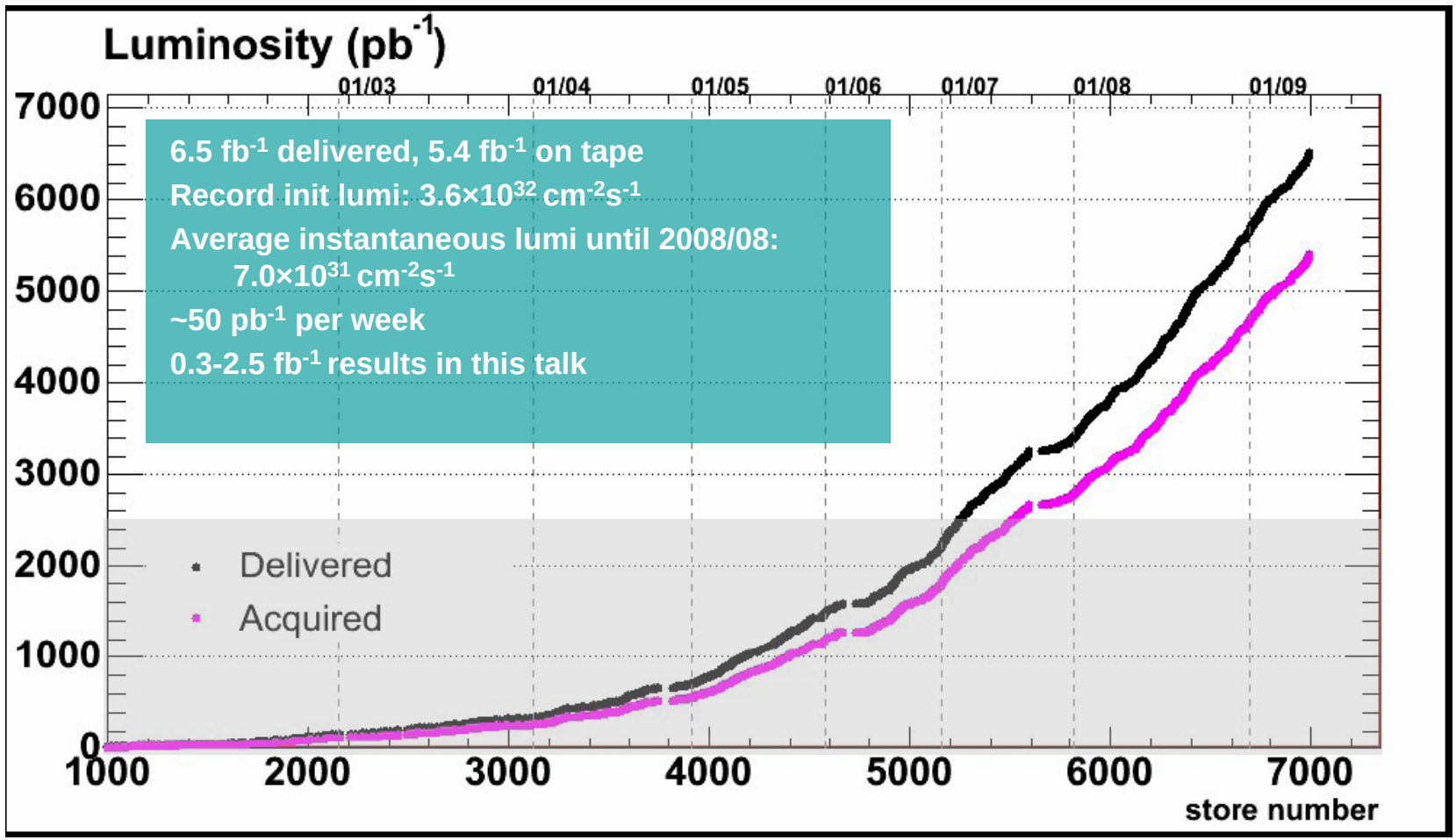



Tevatron delivered > 6.5 $fb^{-1}$
(8 $fb^{-1}$ expected by end FY09)

Ongoing discussion for FY2010
(up to 10 $fb^{-1}$)

# Integrated Luminosity (Per Experiment)




6.5 fb$^{-1}$ delivered, 5.4 fb$^{-1}$ on tape

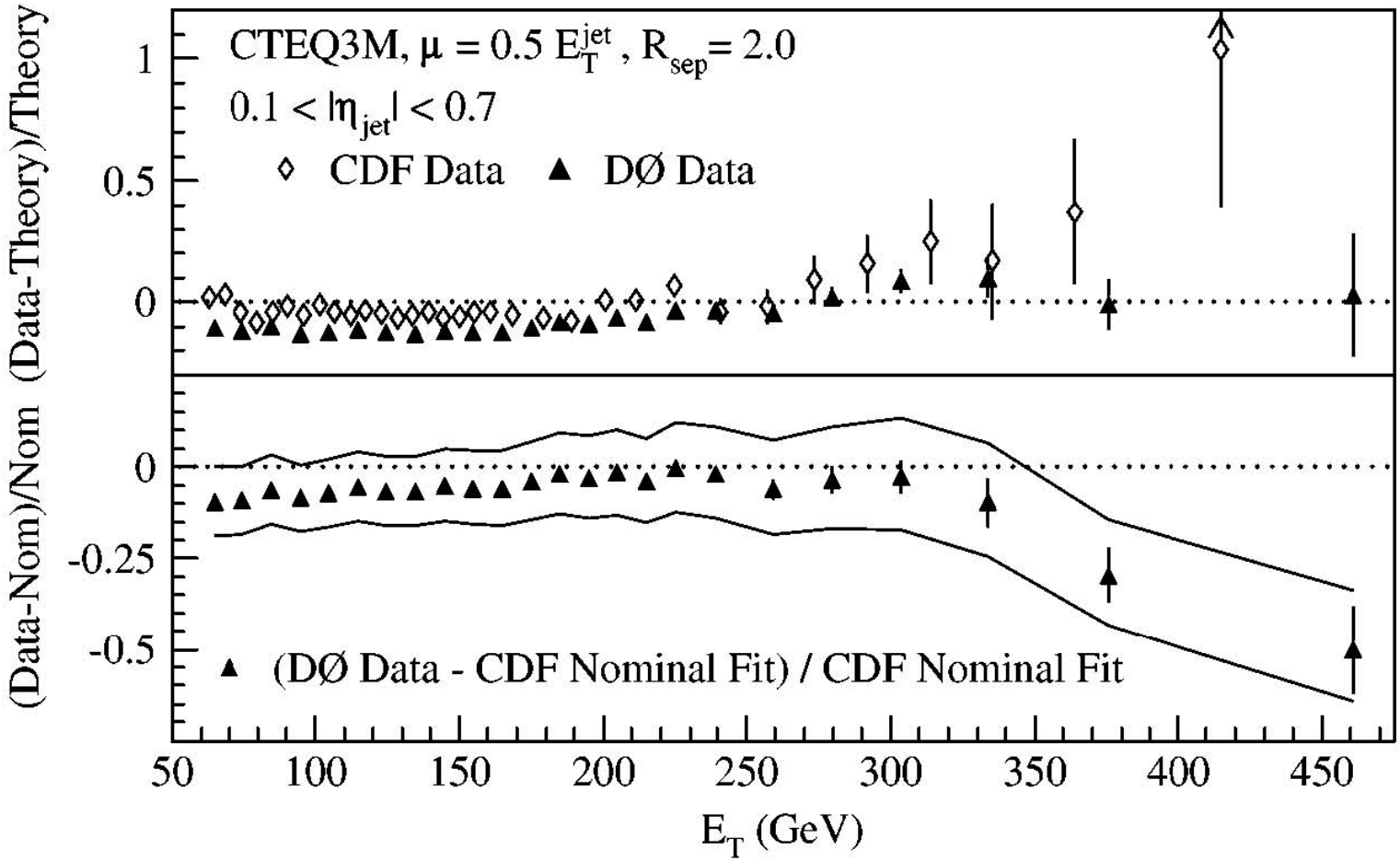
Record init lumi: 3.6×10$^{32}$ cm$^{-2}$s$^{-1}$

Average instantaneous lumi until 2008/08: 7.0×10$^{31}$ cm$^{-2}$s$^{-1}$

~50 pb$^{-1}$ per week

0.3-2.5 fb$^{-1}$ results in this talk

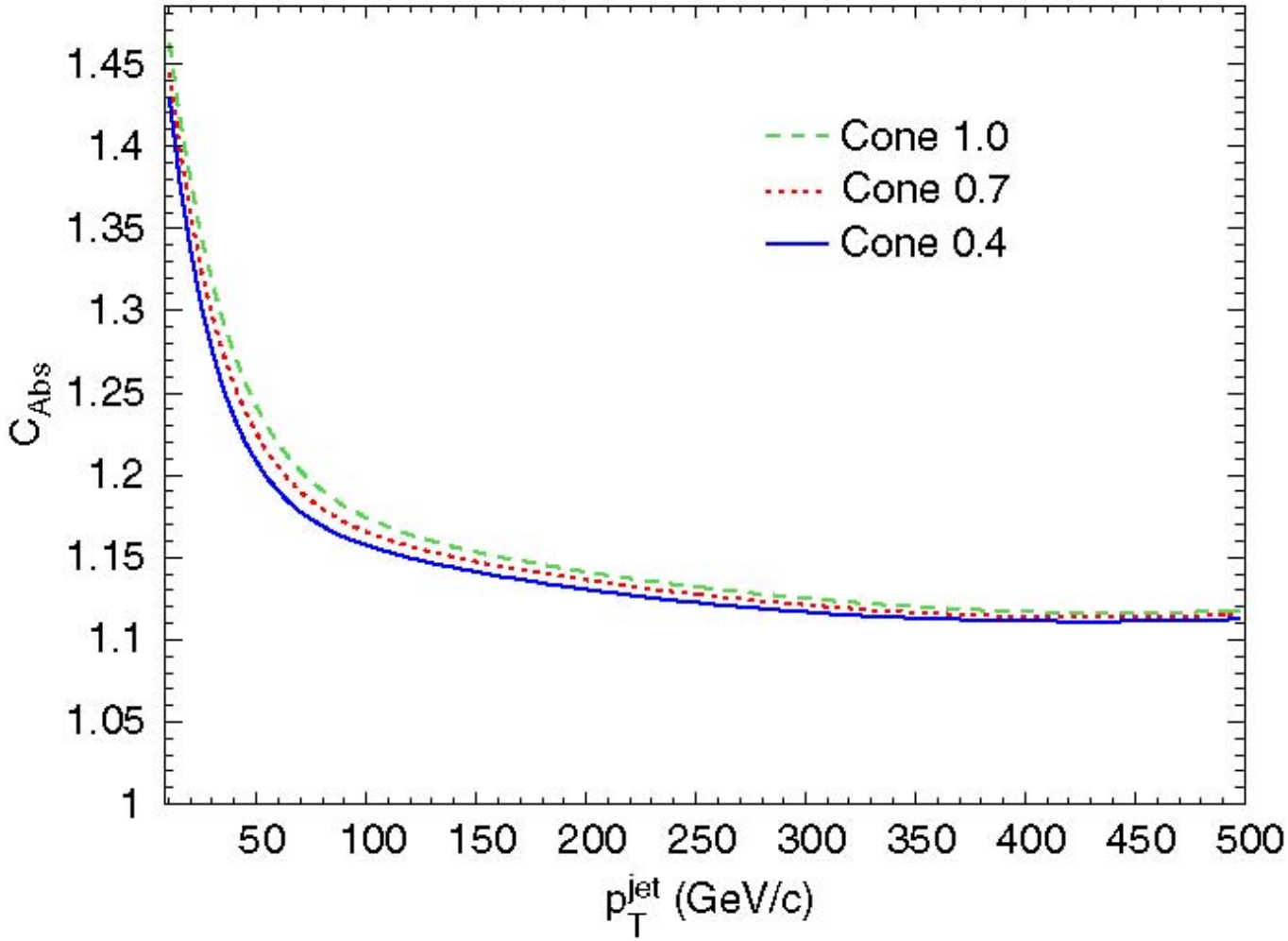
# CDF and D0 Run 1 Jet X-Section



# Jet Energy Correction

- Jet energy correction
  - CDF cone: 15%(12%) for 50(400) GeV
  - CDF kT: 9%
  - D0 cone: 50%(20%) for 50(400) GeV
- Jet energy resolution
  - CDF cone: 12%(10%) for 50(400) GeV
  - CDF kT: 10%
  - D0: 13%(7%) for 50(400) GeV in CC and EC, 16%(11%) in the ICR
- Threshold of seeds or protojets
  - Cone: 1 GeV
  - kT: 0.1 GeV
- Energy added by extra ppbar collisions per vertex
  - Cone: 1.1 GeV
  - kT: 1.9 GeV

# CDF Cone Absolute Energy Scale



# Unfolding of CDF Cone Results

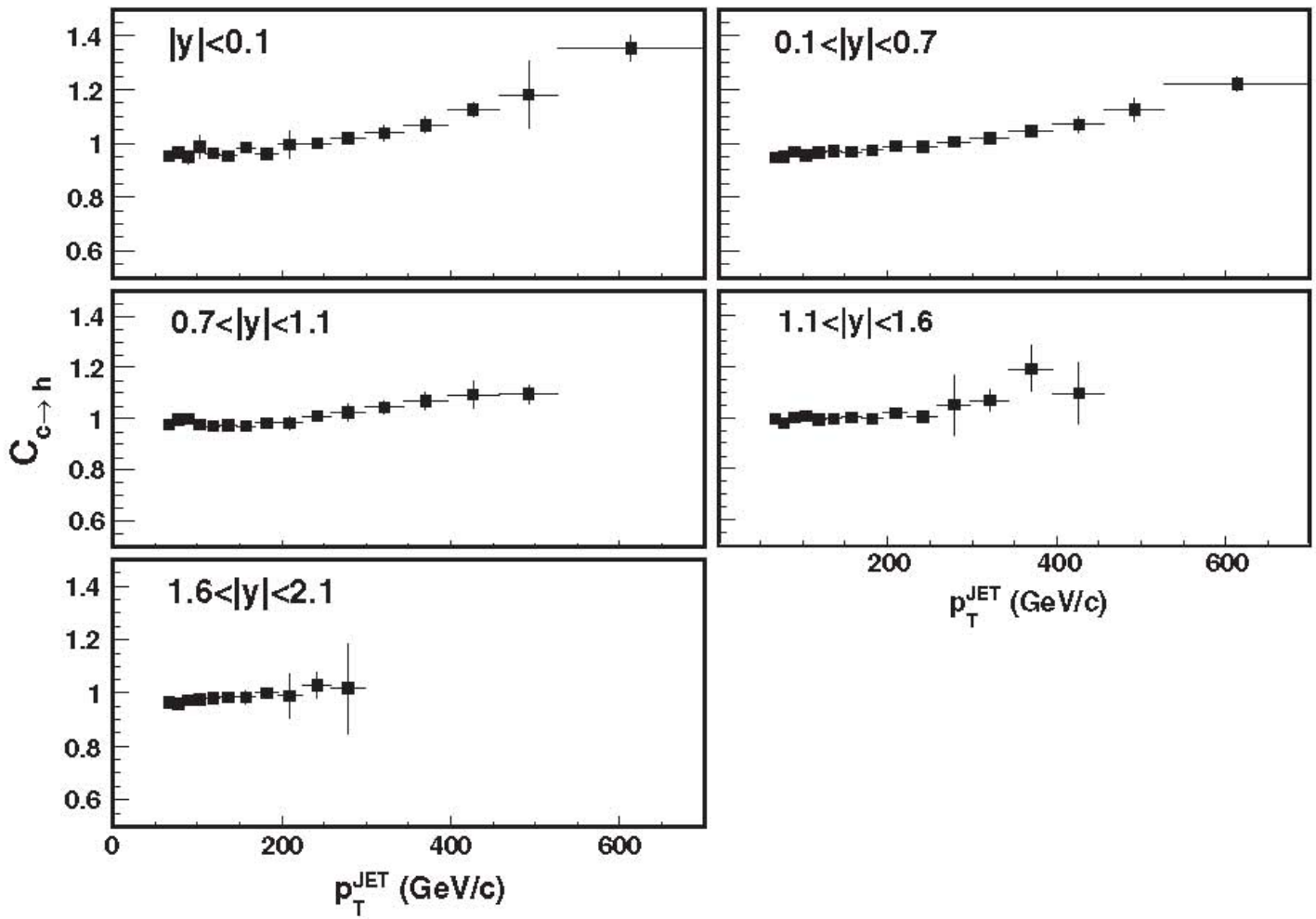
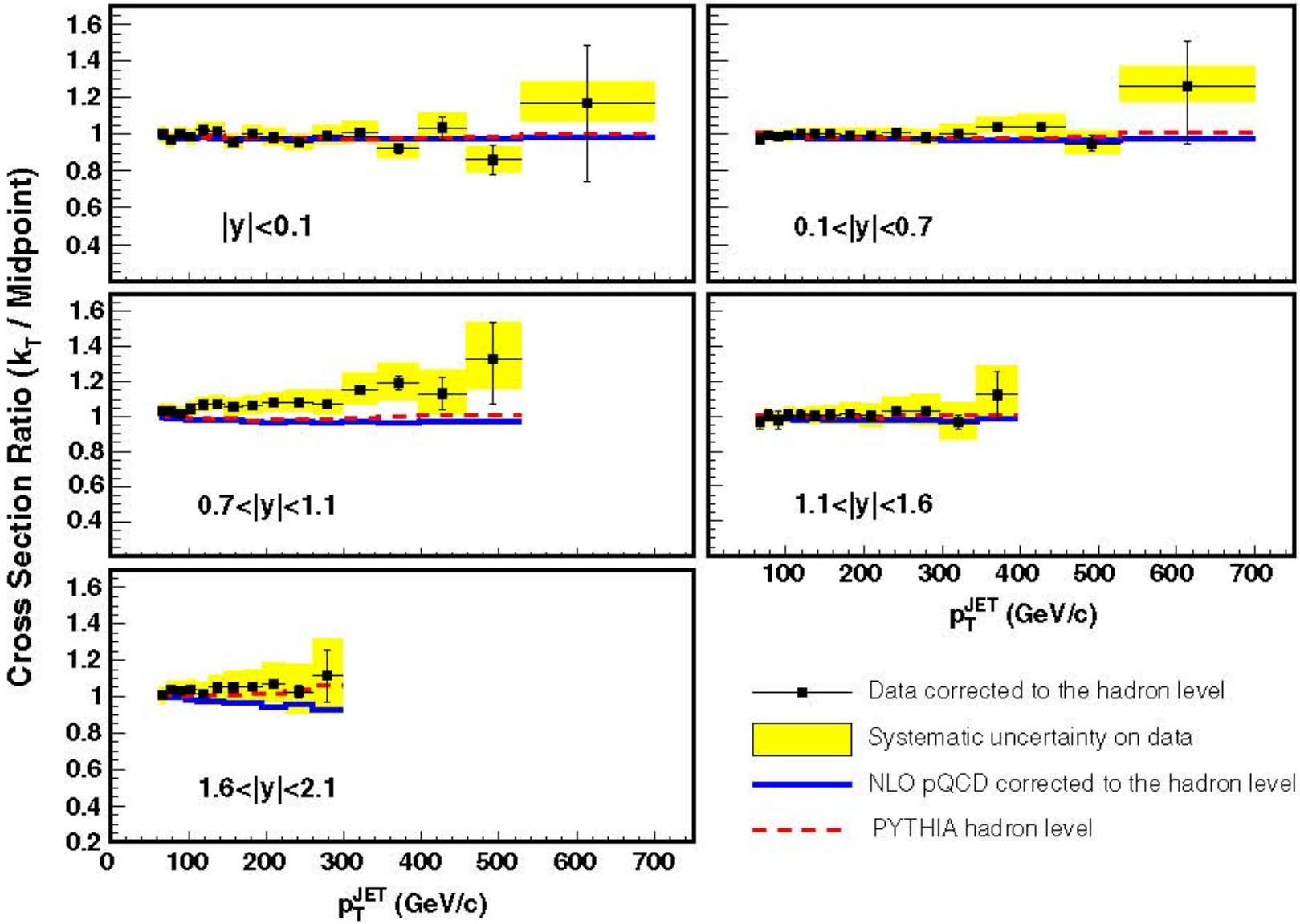
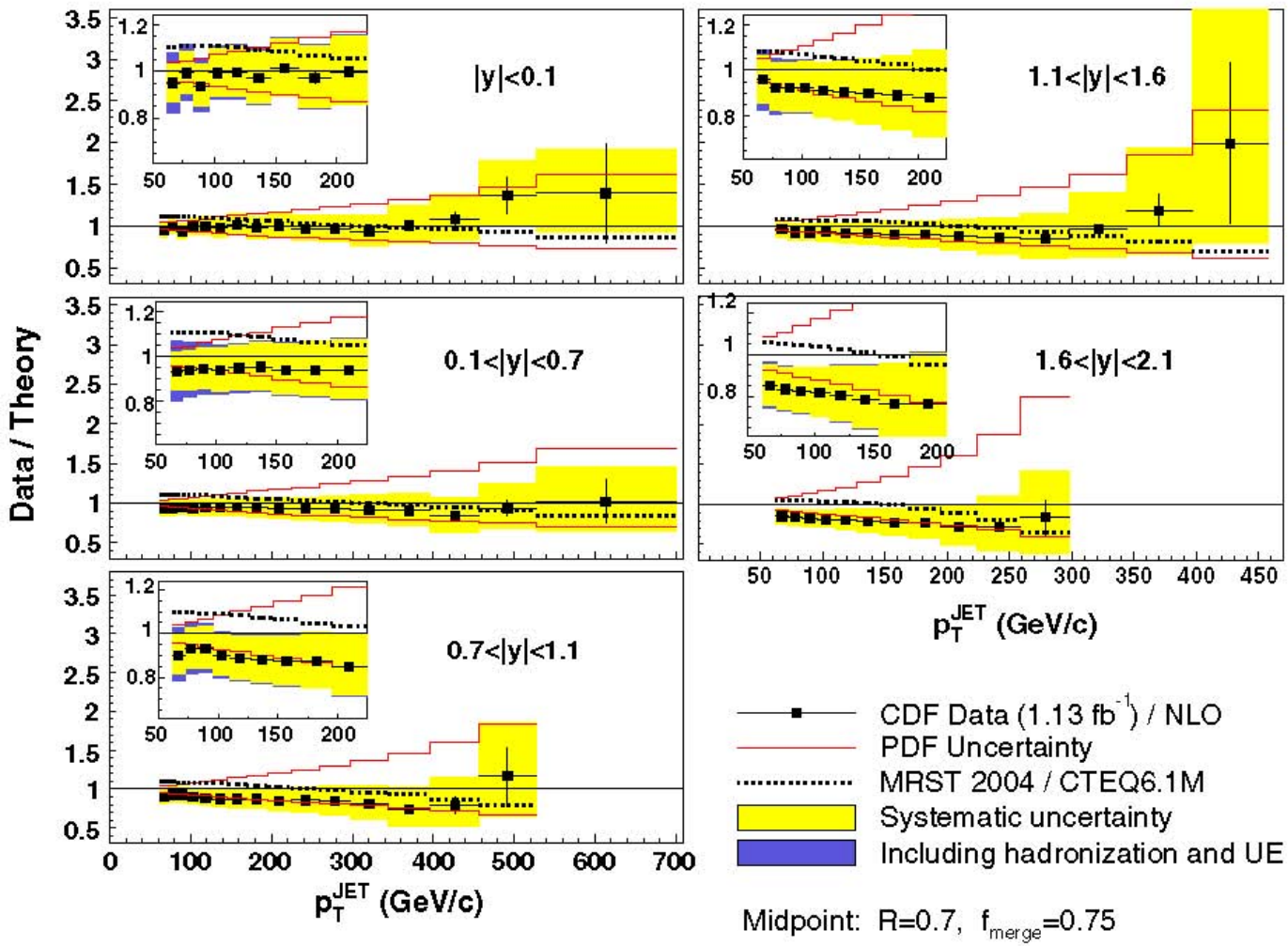



FIG. 10. The unfolding correction factors as functions of jet $p_T$ in five rapidity regions

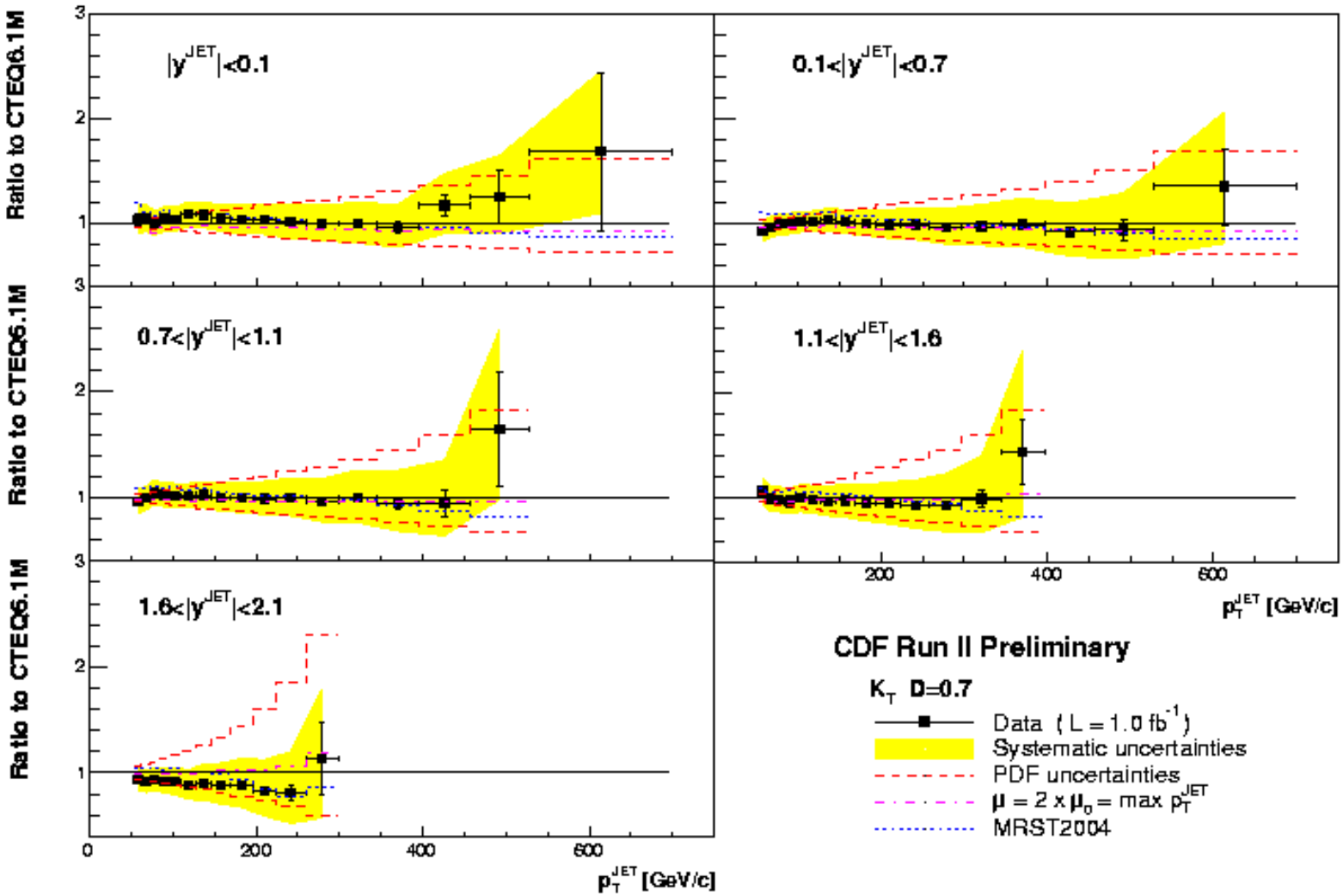
# Cone vs. kT


Cross Section Ratio ($k_T$ / Midpoint)
|y|<0.1
0.1<|y|<0.7
0.7<|y|<1.1
1.1<|y|<1.6
1.6<|y|<2.1
$p_T^{JET}$ (GeV/c)
Data corrected to the hadron level
Systematic uncertainty on data
NLO pQCD corrected to the hadron level
PYTHIA hadron level

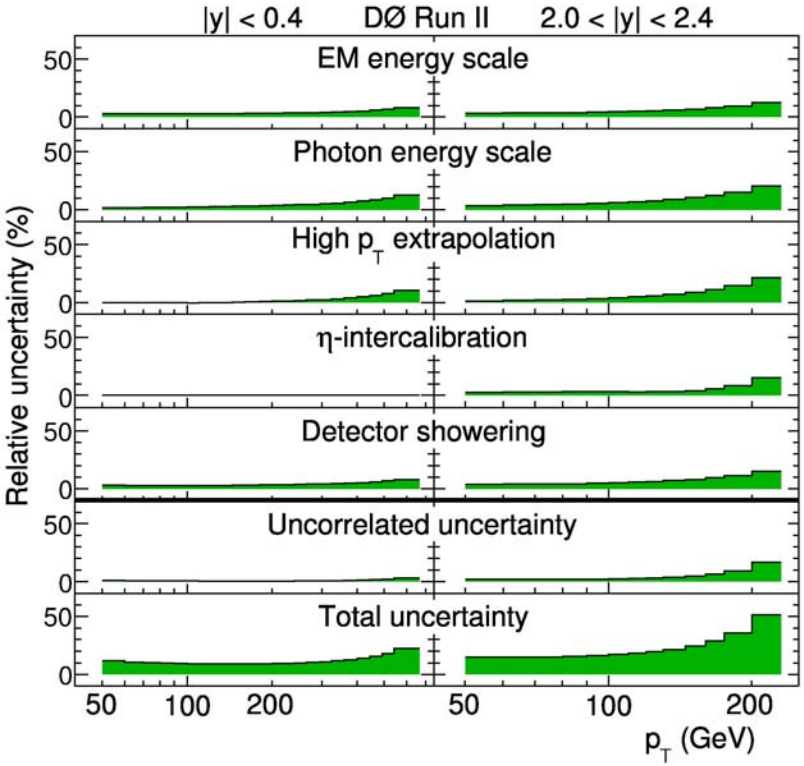
# Close Look of CDF Cone Results

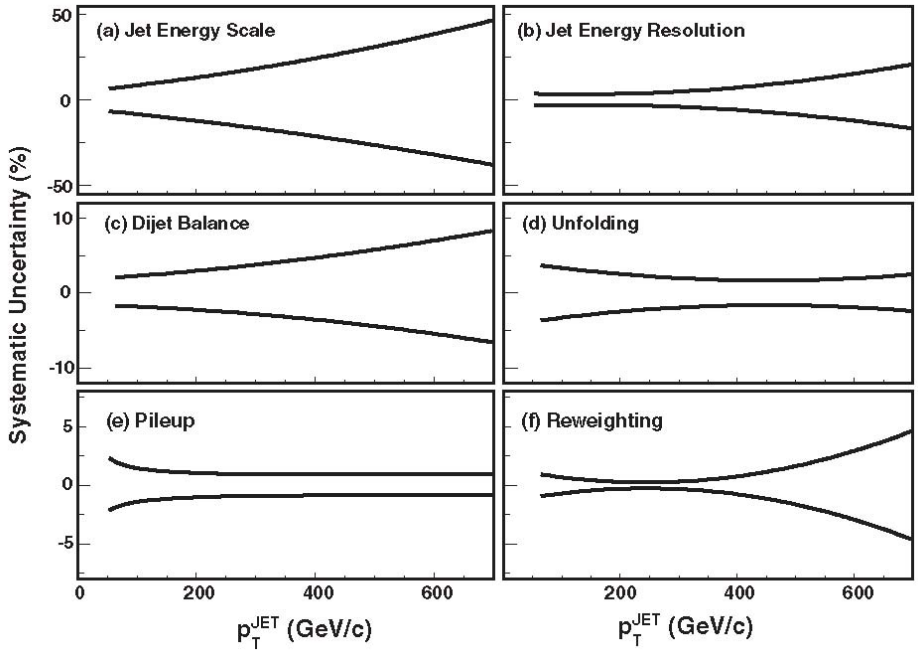


# Close Look of CDF kT Results

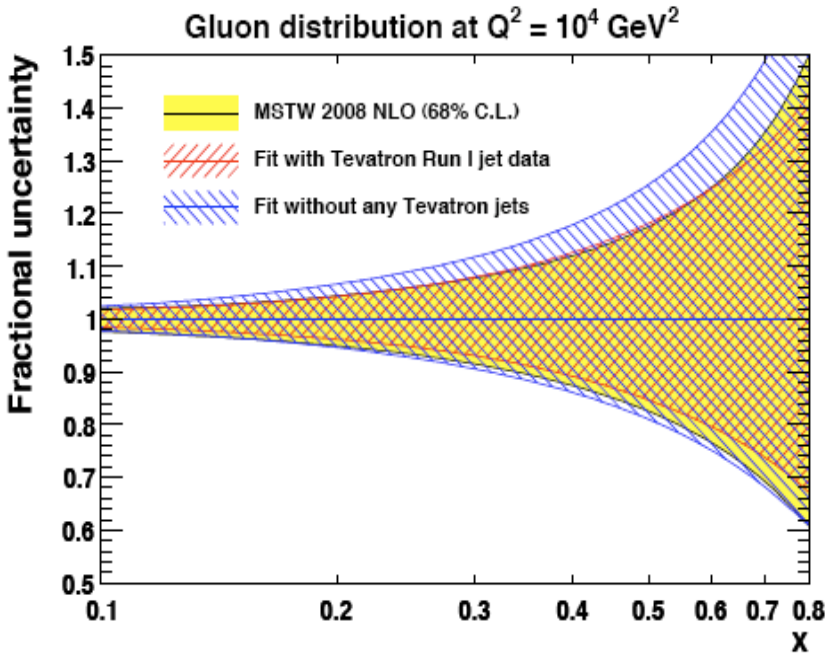


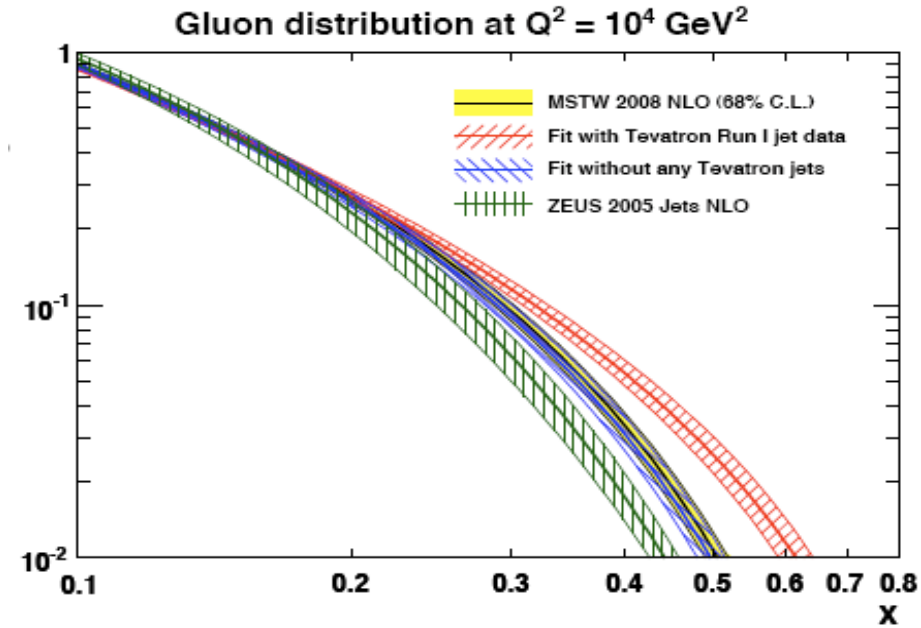
# Systematic Uncertainty

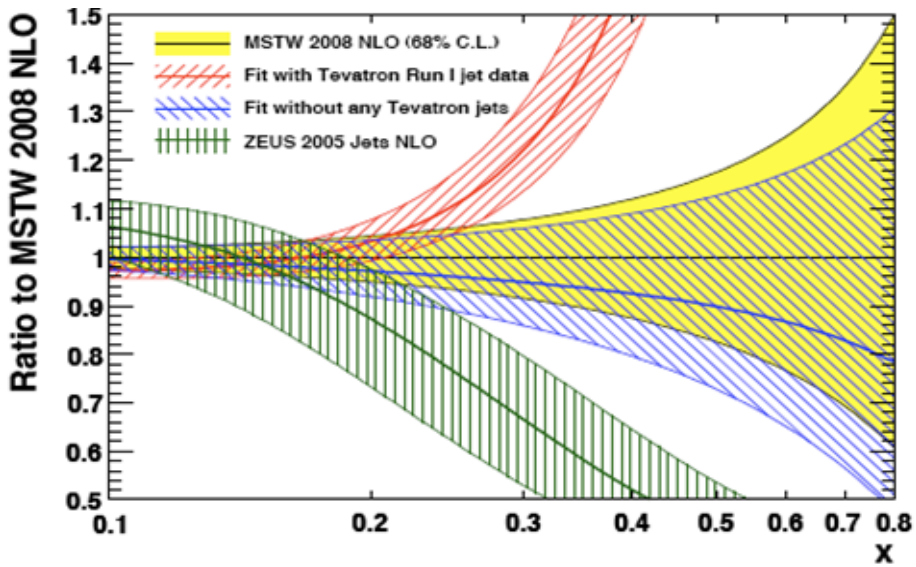


# Input to MSTW Gluon PDF



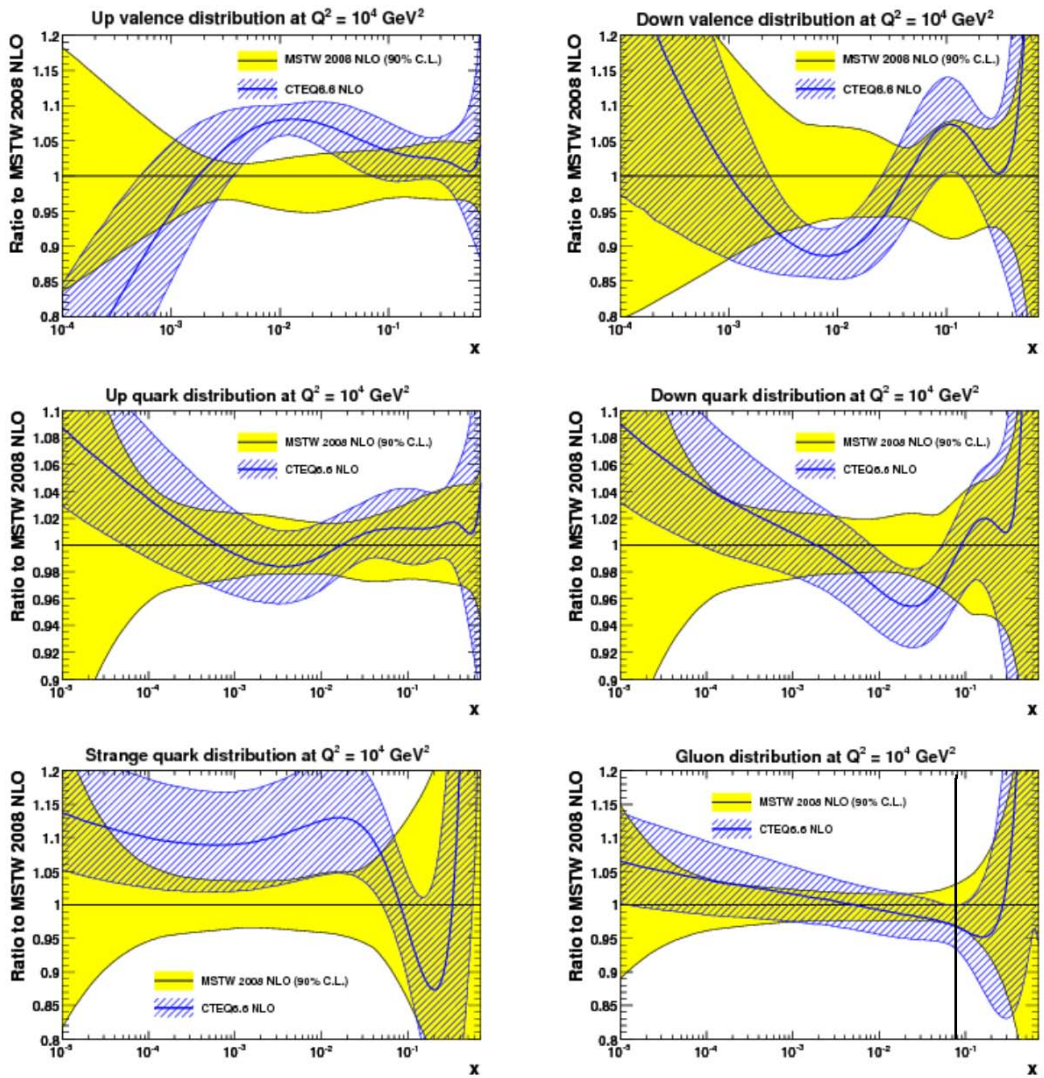



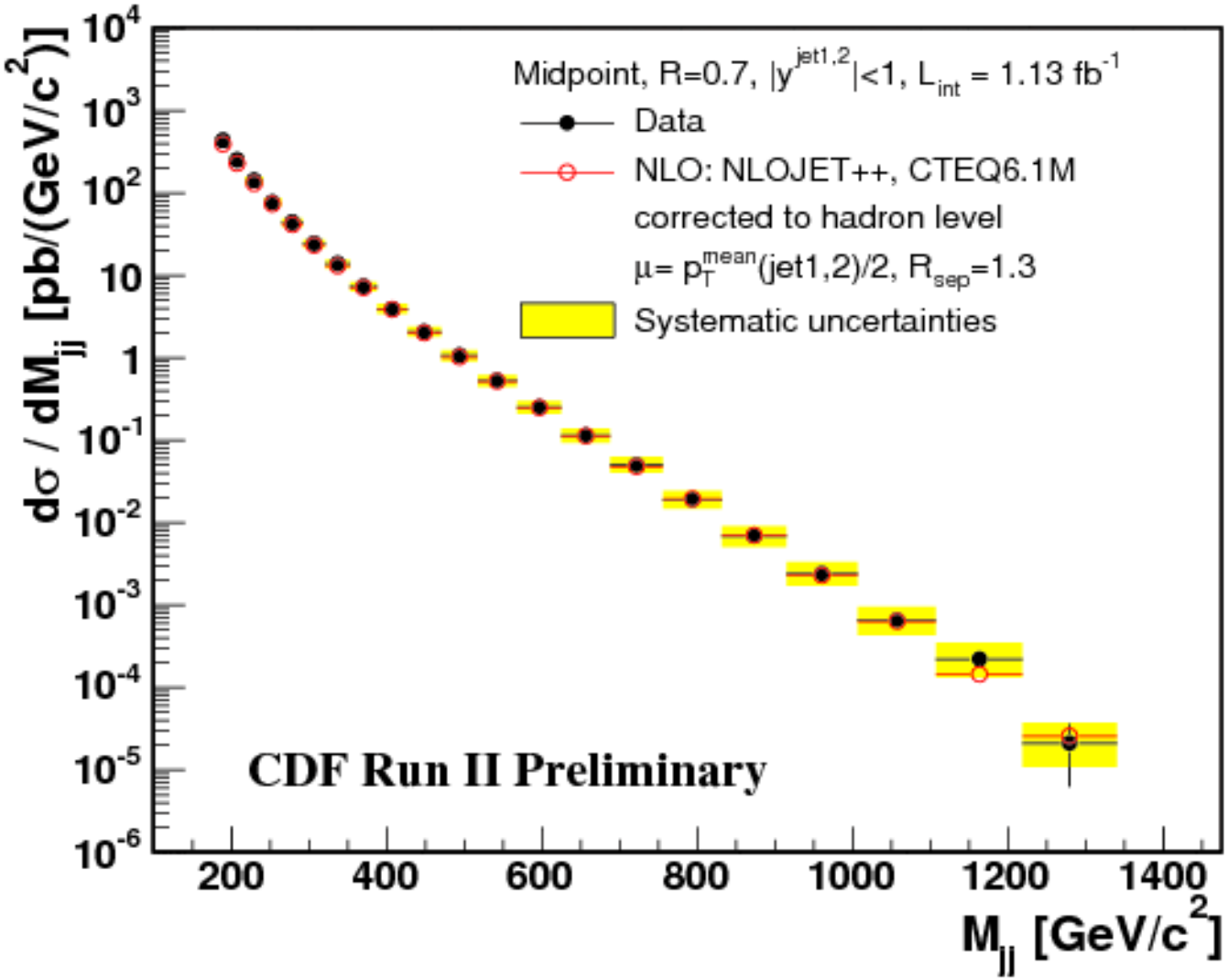

- MSTW2008 uses CDF kT and D0 cone results
- Data prefer lower gluon PDF at high-x
- Reduced gluon PDF uncertainties

**Shin-Shan Yu**

# Uncertainties on PDF



# Close Look of CDF Dijet X-section



# LED GRW and HLZ Models

$$[M_{Pl}]^2 = 8\pi \times R^{n_d} [M_D]^{n_d+2}$$

$$\sigma_{NP} = f_{SM} + \left(\frac{F}{M_S^4}\right) f_{\text{int}} + \left(\frac{F}{M_S^4}\right)^2 f_{NP}$$

$$F = 1 \text{ (GRW)}$$

$$F = \ln\left(\frac{M_S^2}{\hat{s}}\right) \text{ for } n_d = 2 \text{ (HLZ)}$$

$$F = \frac{2}{n_d - 2} \text{ for } n_d > 2 \text{ (HLZ)}$$

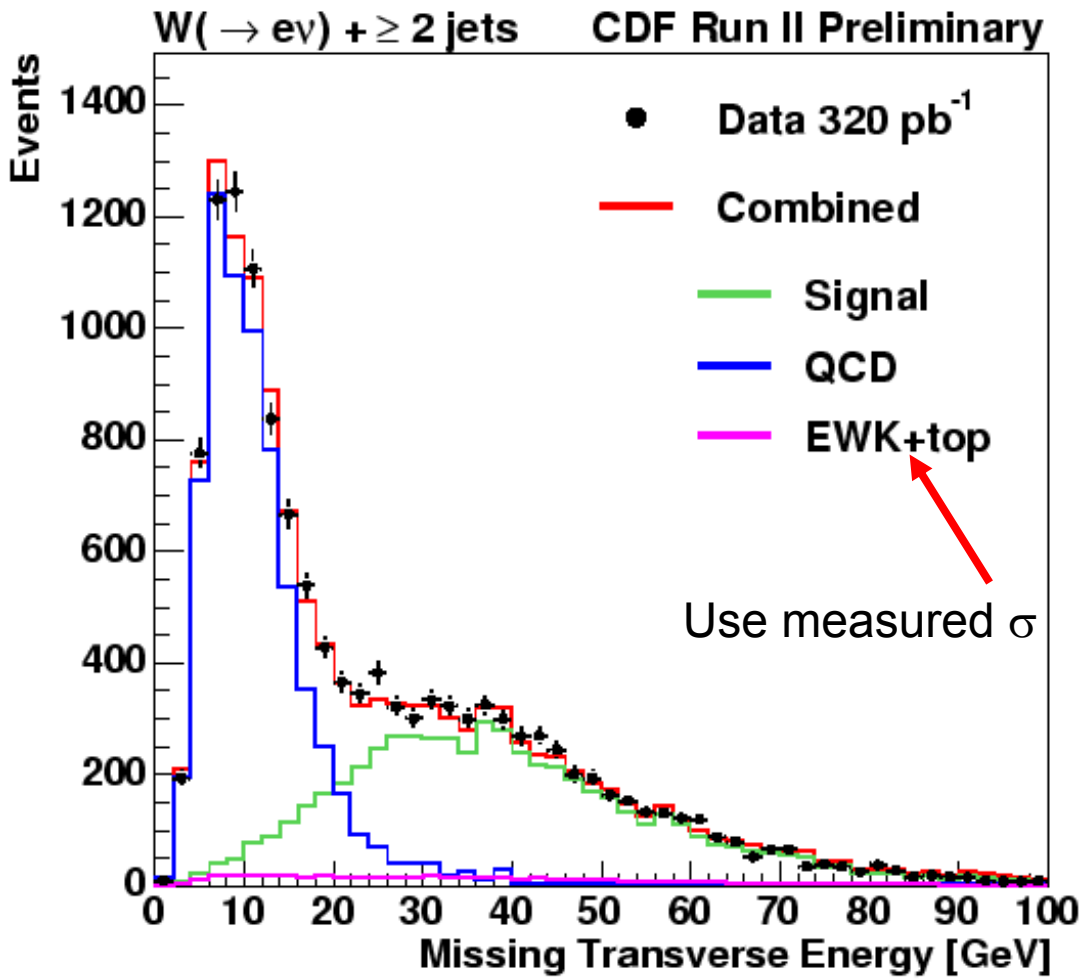
$$M_{pl}^2 = 8\pi\, M_D^{n+2} R^n$$

# LED and Compositeness Limits in jj

DØ preliminary
95% CL limits on New Physics models from the dijet angular distribution (in TeV)

| model (parameter) | $\chi^2$ minimum position | $\chi^2$ minimum depth | Bayesian prior flat in $\eta$ expected | Bayesian prior flat in $\eta$ found | Bayesian prior flat in $\eta^2$ expected | Bayesian prior flat in $\eta^2$ found | frequentist $\chi^2 - \chi^2_{\min} = 3.84$ expected | frequentist $\chi^2 - \chi^2_{\min} = 3.84$ found | previous limit |
|---|---|---|---|---|---|---|---|---|---|
| Quark Composit. ($\Lambda$) | | | | | | | | | |
| $\lambda = +1$ | 5.10 | 0.02 | $2.75^{+0.43}_{-0.35}$ | 2.58 | $2.58^{+0.28}_{-0.29}$ | 2.39 | $2.65^{+0.42}_{-0.35}$ | 2.46 | 2.73 [10] |
| $\lambda = -1$ | 5.22 | 0.02 | $2.78^{+0.36}_{-0.41}$ | 2.54 | $2.55^{+0.31}_{-0.33}$ | 2.35 | $2.65^{+0.45}_{-0.39}$ | 2.42 | 2.49 [10] |
| $\mathrm{TeV}^{-1}$ ED ($M_C$) | 2.17 | 0.66 | $1.64^{+0.23}_{-0.25}$ | 1.42 | $1.51^{+0.16}_{-0.19}$ | 1.33 | $1.57^{+0.33}_{-0.24}$ | 1.35 | 1.12 [27] |
| ADD LED ($M_S$) | | | | | | | | | |
| GRW | $\infty$ | | $1.49^{+0.12}_{-0.14}$ | 1.56 | $1.44^{+0.10}_{-0.10}$ | 1.48 | $1.47^{+0.16}_{-0.14}$ | 1.54 | 1.62 [26] |
| Hewett $\lambda = +1$ | $\infty$ | | $1.33^{+0.11}_{-0.12}$ | 1.39 | $1.28^{+0.09}_{-0.09}$ | 1.32 | $1.31^{+0.14}_{-0.12}$ | 1.37 | 1.22 [25] |
| Hewett $\lambda = -1$ | $\infty$ | | $1.28^{+0.11}_{-0.09}$ | 1.35 | $1.23^{+0.09}_{-0.08}$ | 1.29 | $1.25^{+0.13}_{-0.09}$ | 1.33 | 1.10 [25] |
| HLZ n=3 | $\infty$ | | $1.77^{+0.14}_{-0.16}$ | 1.85 | $1.71^{+0.11}_{-0.12}$ | 1.76 | $1.74^{+0.19}_{-0.16}$ | 1.83 | 1.94 [26] |
| HLZ n=4 | $\infty$ | | $1.49^{+0.12}_{-0.14}$ | 1.56 | $1.44^{+0.10}_{-0.10}$ | 1.48 | $1.47^{+0.16}_{-0.14}$ | 1.54 | 1.62 [26] |
| HLZ n=5 | $\infty$ | | $1.35^{+0.11}_{-0.12}$ | 1.41 | $1.30^{+0.09}_{-0.09}$ | 1.34 | $1.32^{+0.14}_{-0.12}$ | 1.39 | 1.46 [26] |
| HLZ n=6 | $\infty$ | | $1.25^{+0.11}_{-0.10}$ | 1.31 | $1.21^{+0.08}_{-0.09}$ | 1.25 | $1.22^{+0.14}_{-0.11}$ | 1.29 | 1.36 [26] |
| HLZ n=7 | $\infty$ | | $1.19^{+0.09}_{-0.11}$ | 1.24 | $1.14^{+0.08}_{-0.08}$ | 1.18 | $1.17^{+0.13}_{-0.11}$ | 1.22 | 1.29 [26] |

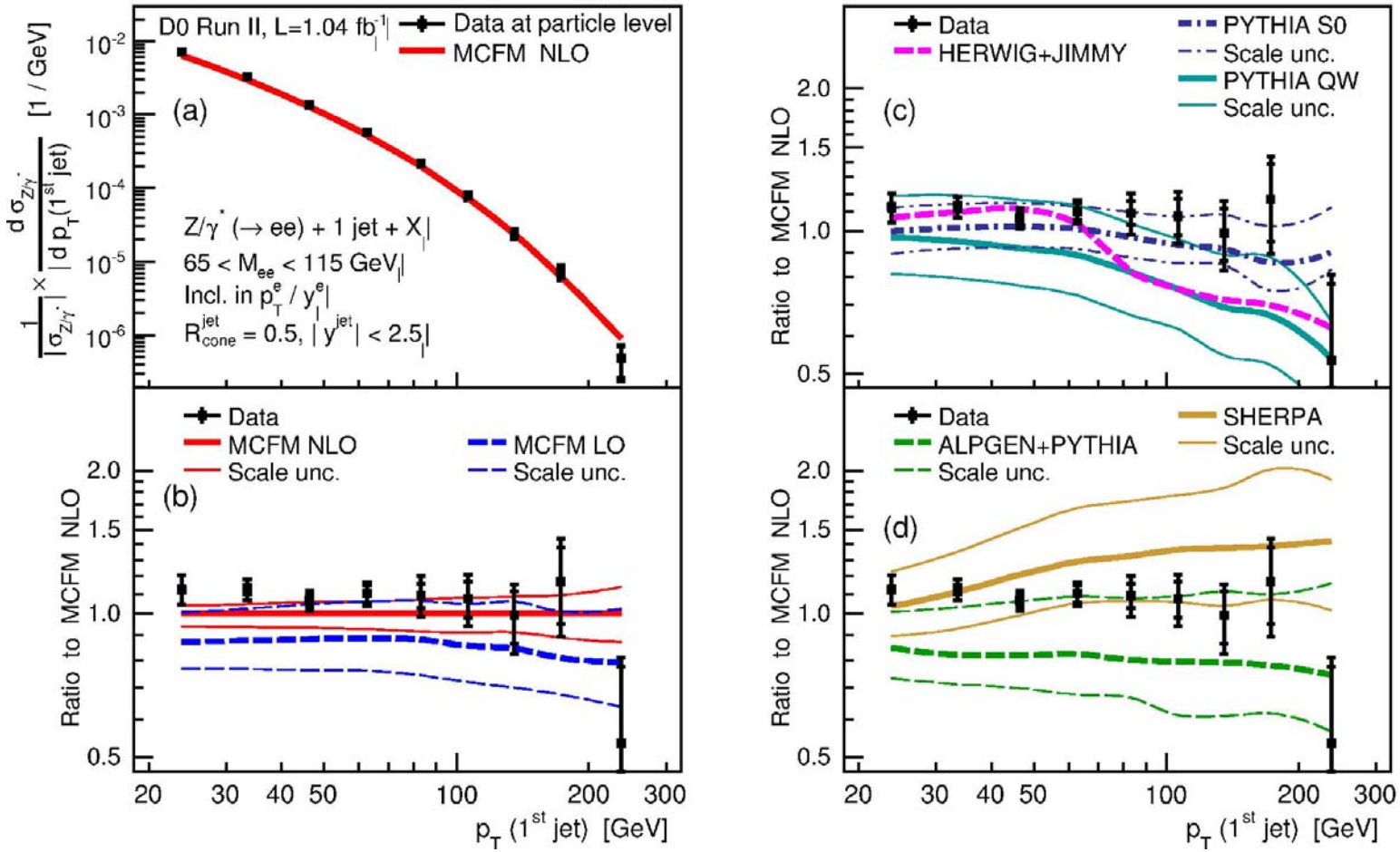
# CDF W+njet MET Fit



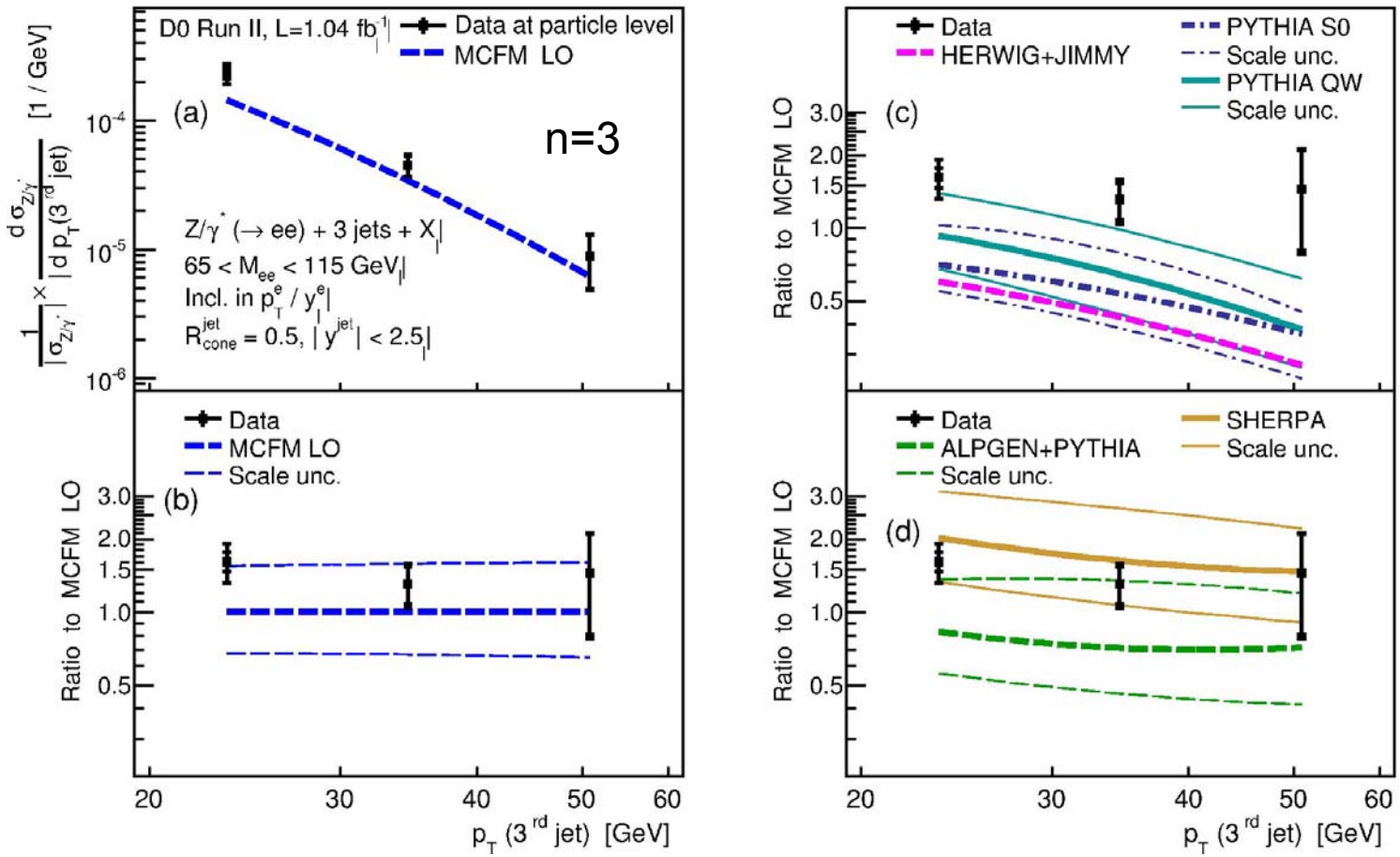
# Difference of Event Generators

- PYTHIA: 2 to 2 in matrix element, parton showering ordering in Q2, parton shower to hard scattering increases Q2 (includes b quark PDF)
- HERWIG: 2 to 2 in matrix element, parton showering ordering in angle, parton shower to hard scattering increases angle, hadronization model slightly different, no good modeling of underlying events
- ALPGEN: 2 to n<=6 in matrix element, use MLM to do matching, assume massive bquark (no b PDF)
- SHERPA: 2 to n<=6 in matrix element, use CKKW, kT in parton showering
- JIMMY: Underlying events
- Each of this model may have different scales

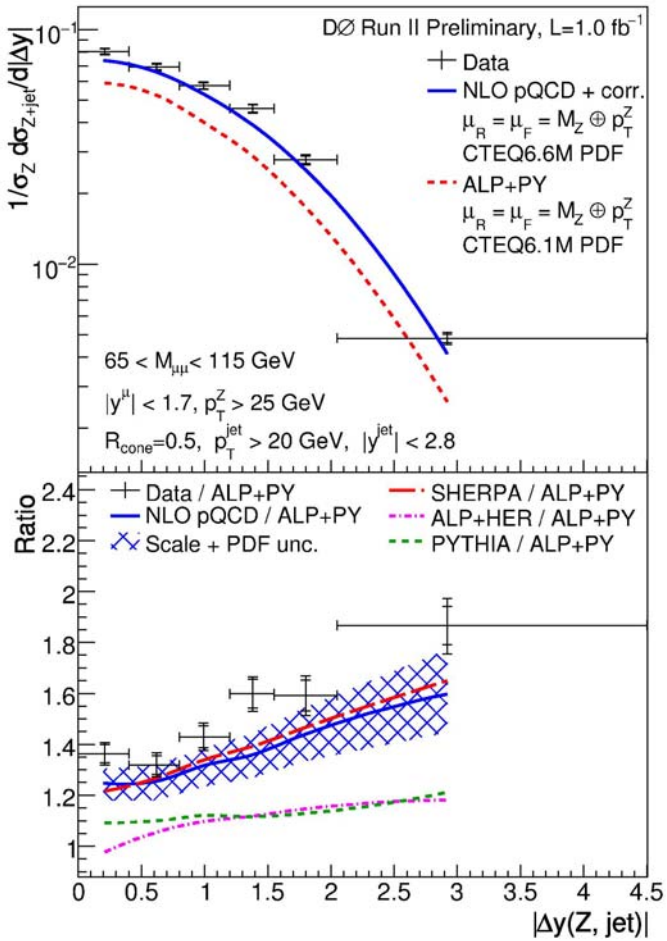
# D0 Z(ee)+njet (n=1)

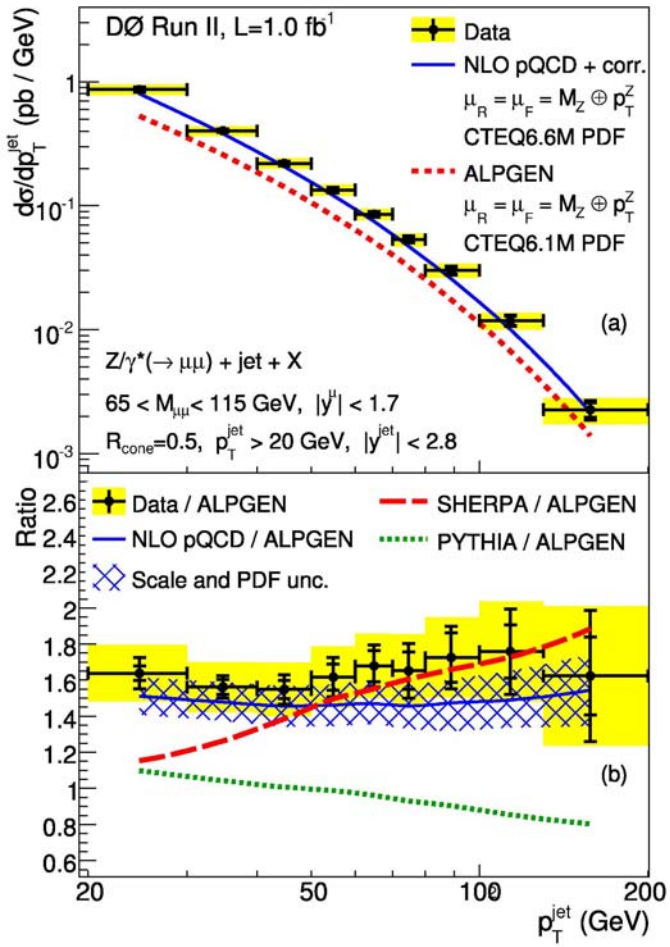


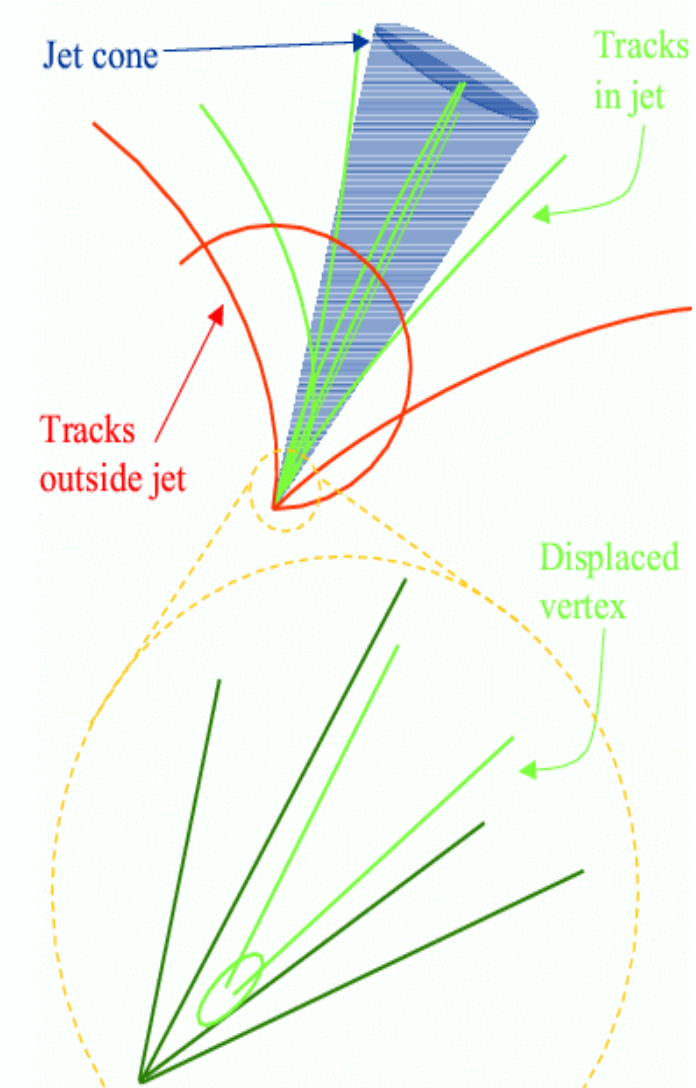
# Z(→ee)+ ≥ n Jet Production

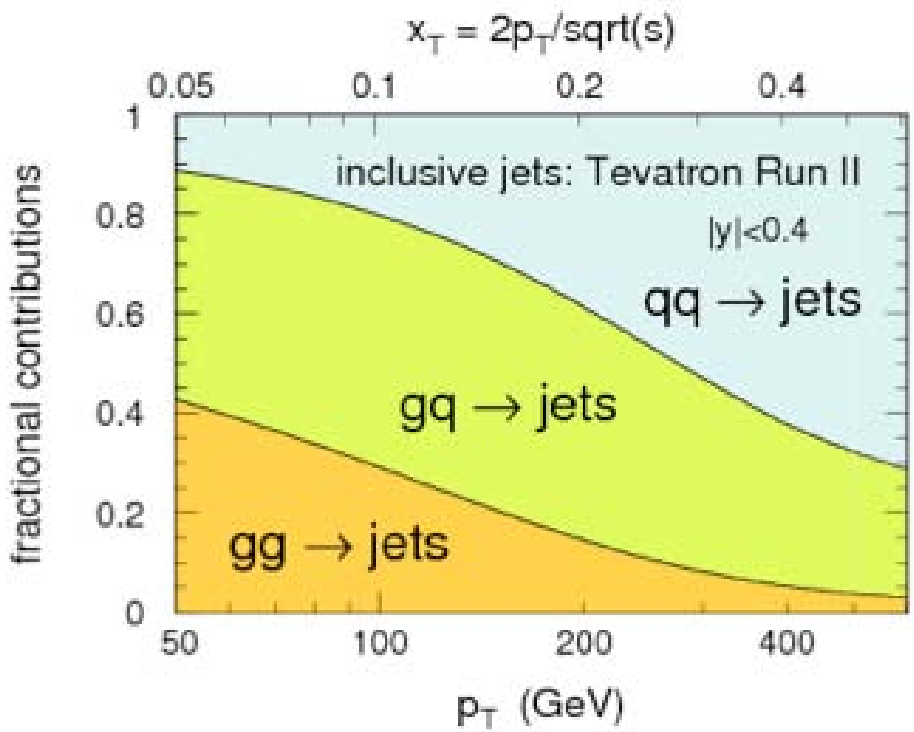


# D0 Z (μμ) + n jet

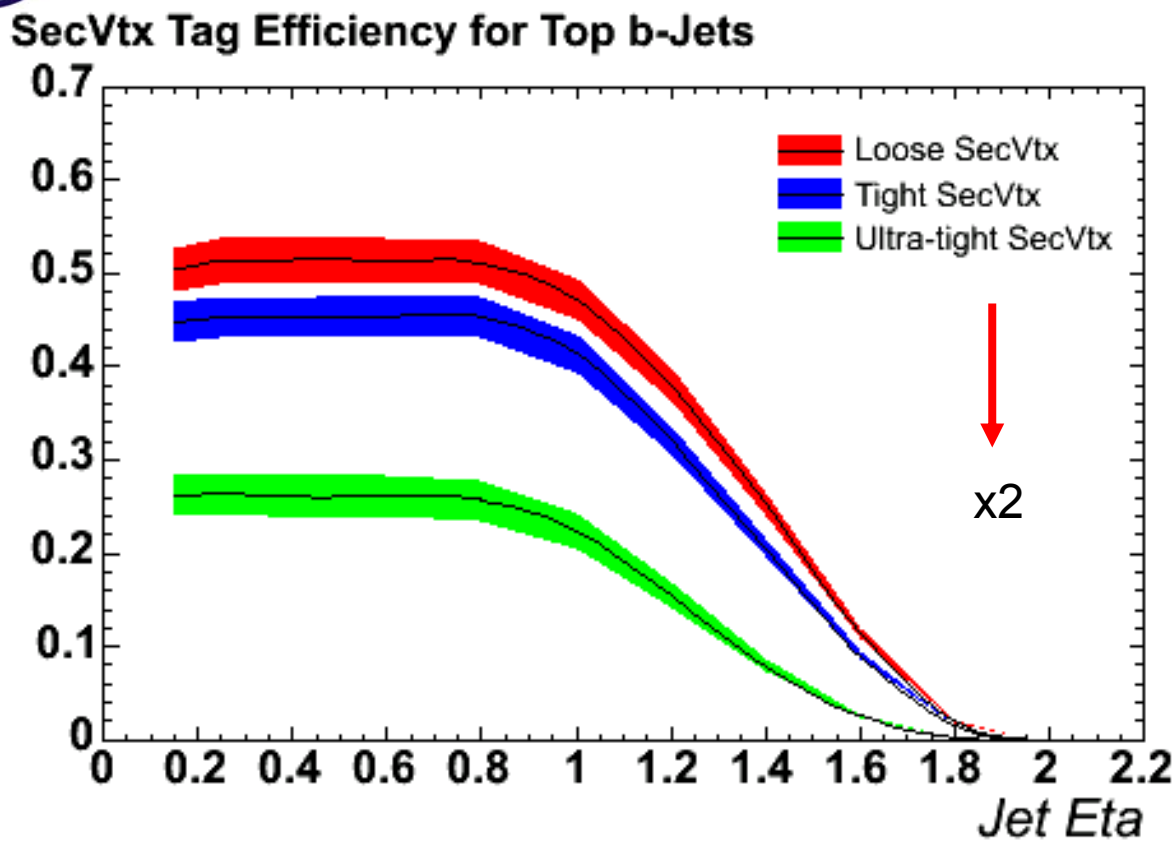

DØ Run II Preliminary, L=1.0 fb$^{-1}$
Data
NLO pQCD + corr.
$\mu_R = \mu_F = M_Z \oplus p_T^Z$
CTEQ6.6M PDF
ALP+PY
$\mu_R = \mu_F = M_Z \oplus p_T^Z$
CTEQ6.1M PDF
$65 < M_{\mu\mu} < 115$ GeV
$|y^\mu| < 1.7$, $p_T^Z > 25$ GeV
$R_{cone}=0.5$, $p_T^{jet} > 20$ GeV, $|y^{jet}| < 2.8$
$1/\sigma_Z\, d\sigma_{Z+jet}/d|\Delta y|$
Ratio
Data / ALP+PY
NLO pQCD / ALP+PY
Scale + PDF unc.
SHERPA / ALP+PY
ALP+HER / ALP+PY
PYTHIA / ALP+PY
$|\Delta y(Z, jet)|$


DØ Run II, L=1.0 fb$^{-1}$
Data
NLO pQCD + corr.
$\mu_R = \mu_F = M_Z \oplus p_T^Z$
CTEQ6.6M PDF
ALPGEN
$\mu_R = \mu_F = M_Z \oplus p_T^Z$
CTEQ6.1M PDF
(a)
$Z/\gamma^*(\rightarrow \mu\mu)$ + jet + X
$65 < M_{\mu\mu} < 115$ GeV, $|y^\mu| < 1.7$
$R_{cone}=0.5$, $p_T^{jet} > 20$ GeV, $|y^{jet}| < 2.8$
$d\sigma/dp_T^{jet}$ (pb / GeV)
Ratio
Data / ALPGEN
NLO pQCD / ALPGEN
Scale and PDF unc.
SHERPA / ALPGEN
PYTHIA / ALPGEN
(b)
$p_T^{jet}$ (GeV)


Jet cone
Tracks
in jet
Tracks
outside jet
Displaced
vertex

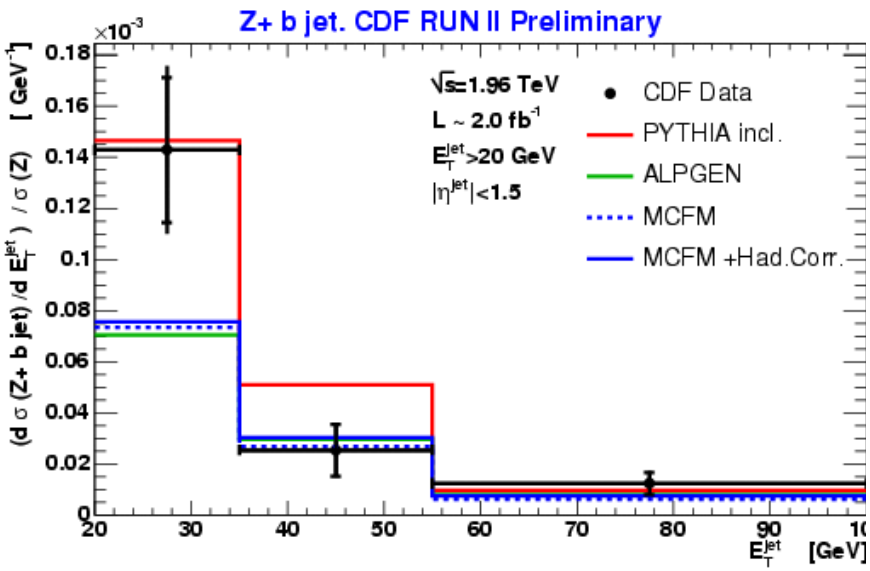

$x_T = 2p_T/\mathrm{sqrt}(s)$
0.05
0.1
0.2
0.4
inclusive jets: Tevatron Run II
|y|<0.4
qq → jets
gq → jets
gg → jets
fractional contributions
1
0.8
0.6
0.4
0.2
0
50
100
200
400
$p_T$ (GeV)

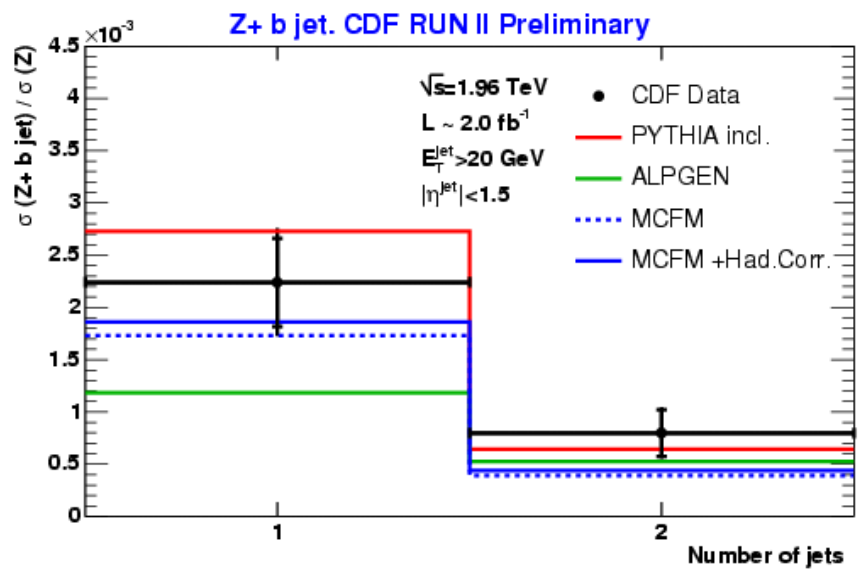
# W + b Production (Per Jet)




- Use ultra-tight SecVtx algorithm
  - Mistag rate is about 0.1%, x10 (4) reduction for light (charm) flavor
  - Data/MC scale factor 0.88±0.05

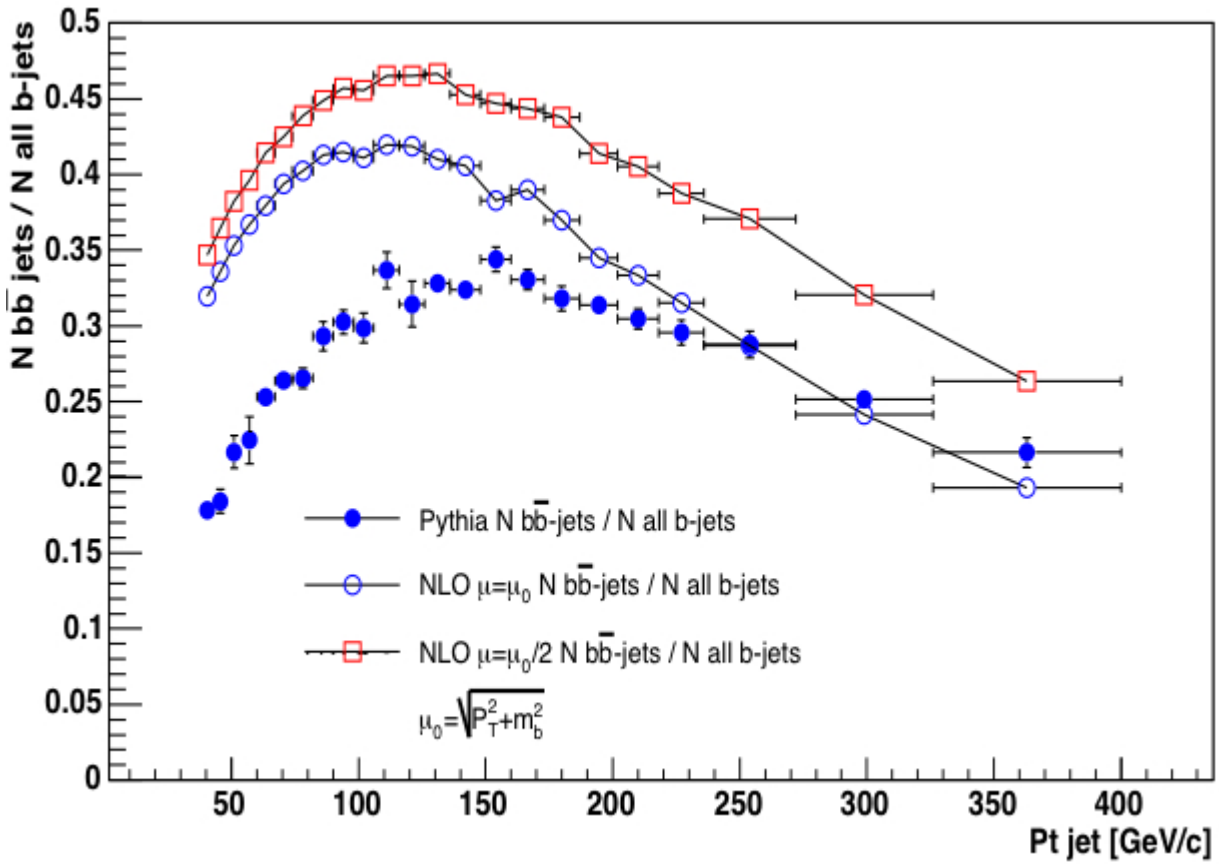
# Z + Inclusive b Production



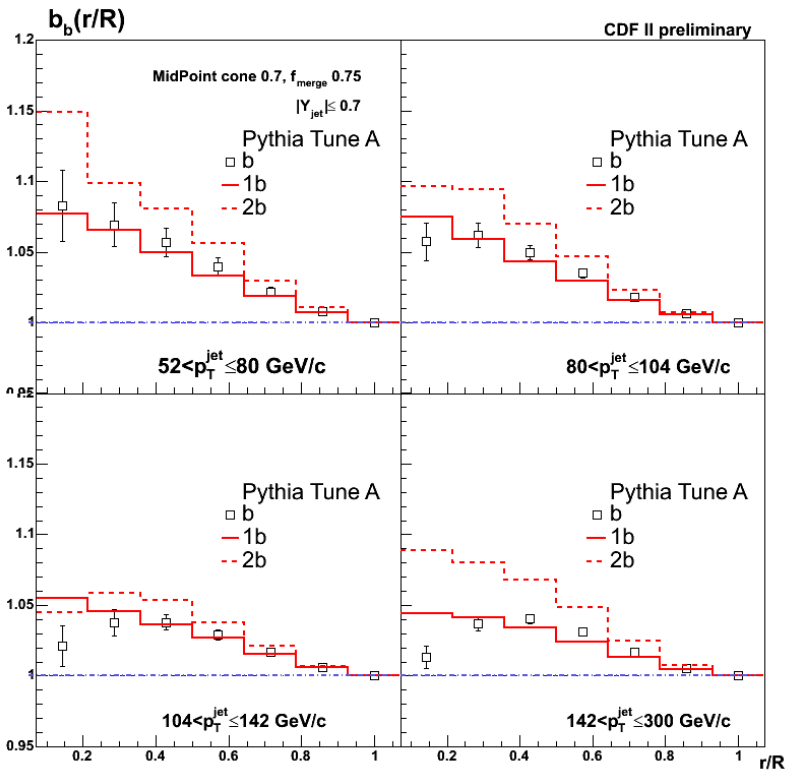

- Use tight SecVtx algorithm
- Fit the secondary vertex mass to obtain b purity
- Largest uncertainty in modeling of b Et and mass shape
- MCFM and ALPGEN scales $\mu_0^2 = M_Z^2 + p_{T,Z}^2$
- PYTHIA scale $\mu_0^2 = \langle p_{T,jet}^2 \rangle$

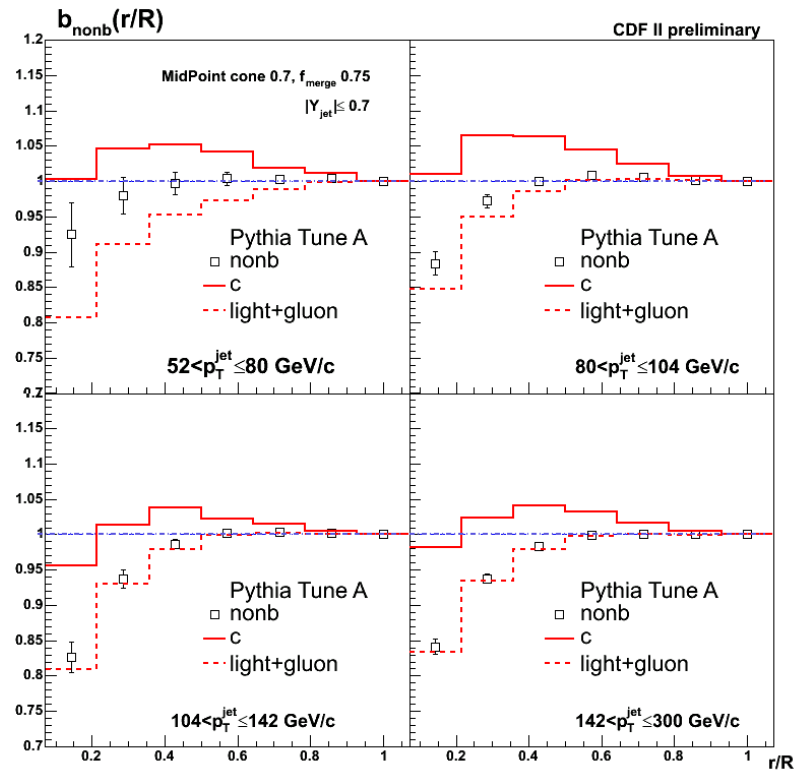
# 1-b Fraction in NLO and LO



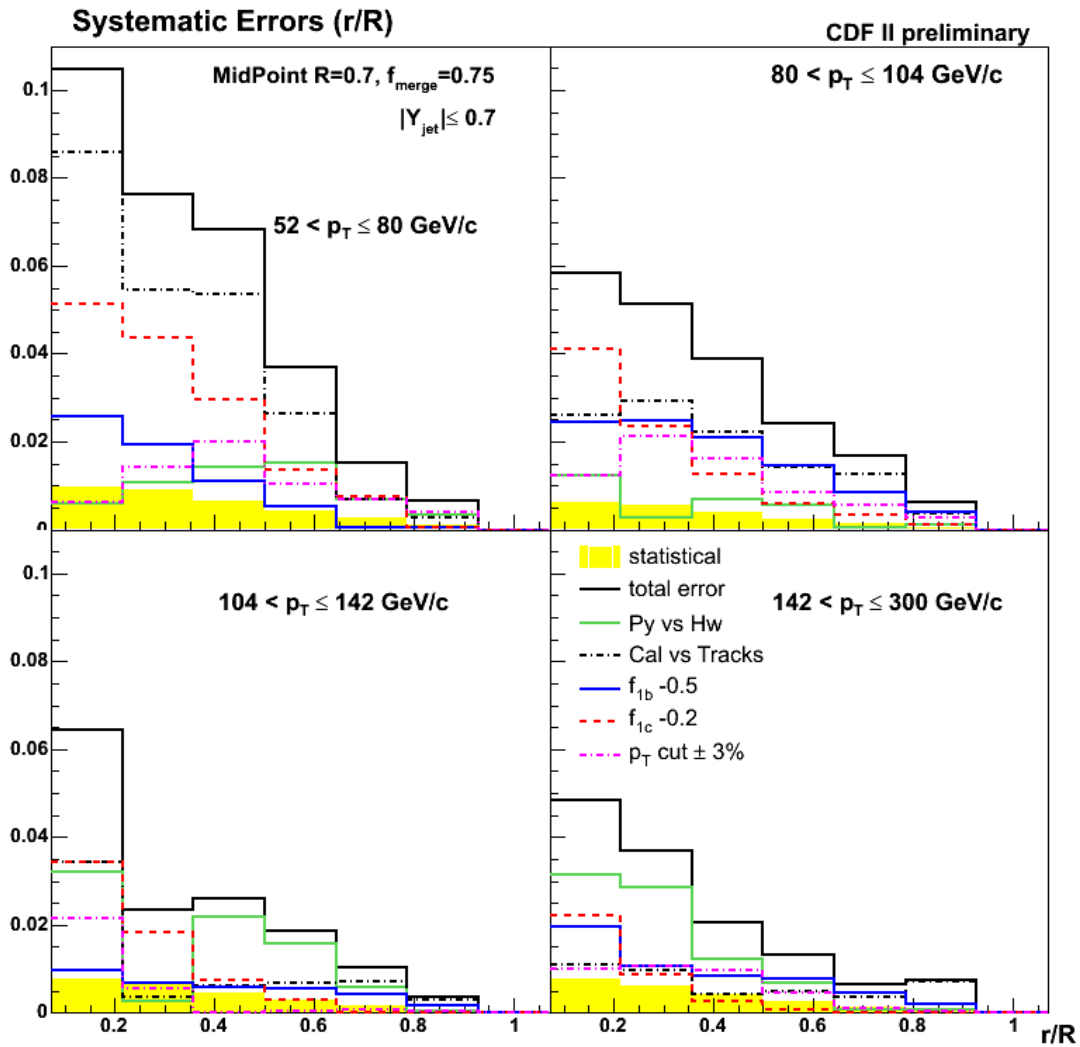
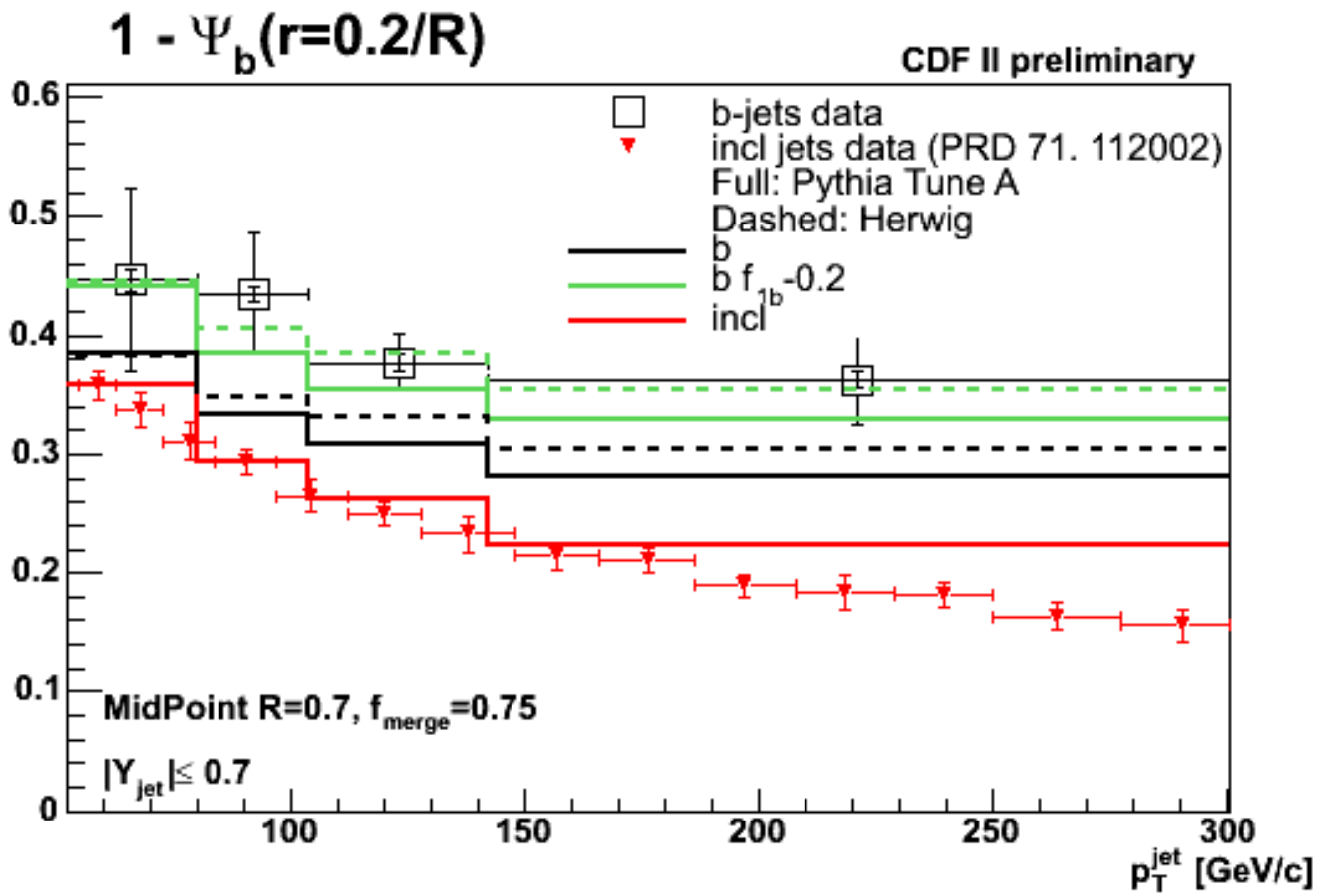
# Bias on Tagged b-Jets and Non-b Jets

$$\Psi^{\mathrm{b}}_{\mathrm{had}}(r) = C_{\mathrm{had}}(r)\frac{\Psi_{\mathrm{meas}}(r) - (1-p_{\mathrm{b}})b^{\mathrm{nonb}}(r)\Psi^{\mathrm{nonb}}_{\mathrm{det}}(r)}{p_{\mathrm{b}}b^{\mathrm{b}}(r)}$$



# b-jet Systematic Uncertainties



# b-jet Shape vs. pt