Jets at the Tevatron

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Fermilab

Overview

Testing pQCD via:

- Inclusive Jet Cross Sections @ 1800 and 630 GeV (D0 & CDF)
  - Results and Comparisons to NLO QCD
- Inclusive Jet Cross Section @ 1800 vs Jet Cone Size (D0)
- Dijet Mass Distribution (D0 & CDF)
  - Results and Comparisons to NLO QCD
- Dijet Angular Distribution (D0 & CDF)
  - Results and Comparisons to LO & NLO QCD
  - Search for Quark Substructure
- Search for BFKL (D0)
  - Measurement of dijet azimuthal decorrelation
  - Comparisons to Herwig, NLO QCD, and BFKL predictions

Conclusions

Inclusive Jet Production

$$\frac{1}{\Delta\eta}\int d\eta \frac{d^2\sigma}{dE_T d\eta}$$

- Powerful challenge of pQCD
- The large statistics of the CDF and D0 high-E_T data provide a unique probe searching for new physics of distances $\sim 10^{-17}$ cm
- NLO predictions are available
  - Ellis,Kunszt,Soper, Phys.Rev.D, **64**, (1990)
  - Aversa,Greco,Chiappetta,Guillet, Phys.Rev.Lett.,**65**, (1990)
  - Giele,Glover,Kosower, Phys.Rev.Lett., **73**, (1994)

Inclusive Jet Production

Data Sets

Collider Run	D0 Luminosity	CDF Luminosity
1992-93 @ 1800 GeV	13 pb^{-1}	19 pb^{-1}
1994-95 @ 1800 GeV	91 pb^{-1}	87 pb^{-1}
Dec 1995 @ 630 GeV	0.5 pb^{-1}	0.6 pb^{-1}

Event & Jet Selection

- Eliminate events with large $\not\!\!E_T$
- Apply Standard Jet Quality Cuts
- $|z| < 50$ cm (D0); $|z| < 60$ cm (CDF)
- $|\eta| < 0.5$ (D0); $0.1 < |\eta| < 0.7$ (CDF)
- R = 0.7 Jet Cone Algorithm

Jet Cone Algorithm

- Iterate until stable solution is found
- Determine jet variables as follows:

D0

$$E_T = \Sigma E_{Ti}\,,\ E_{Ti} = (E^2_{x\,i} + E^2_{y\,i})^{1/2}$$

$$E_x = \Sigma E_{x\,i}\,,\ E_y = \Sigma E_{y\,i}\,,\ E_z = \Sigma E_{z\,i}$$

$$\cos\theta_0 = E_z/(E^2_x + E^2_y + E^2_z)^{1/2}$$

$$\eta = -\ln(\tan\theta_0/2)$$

CDF

$$E = \Sigma E_i\,,\ E_T = E\sin\theta$$

$$P_x = \Sigma P_{x\,i}\,,\ P_y = \Sigma P_{y\,i}\,,\ P_z = \Sigma P_{z\,i}$$

$$\sin\theta = (P^2_x + P^2_y)^{1/2}/(P^2_x + P^2_y + P^2_z)^{1/2}$$

$$\eta = 0.5 \ln [(P + P_z)/(P - P_z)]$$

- Two jets are merged if they share >50% (75%) of the smaller jet E_T
- Two jets are split if the share <50% (75%) of the smaller jet E_T. Towers are assigned to the closest jet.

Corrections to Jet Cross Section

- Energy Scale

D0

Corrections determined from data and applied on a jet by jet basis:

$$E_{jet} = (E_{measured} - O) / [(1 - S) R_{had}]$$

O = offset due to uranium noise, pileup, and underlying event.

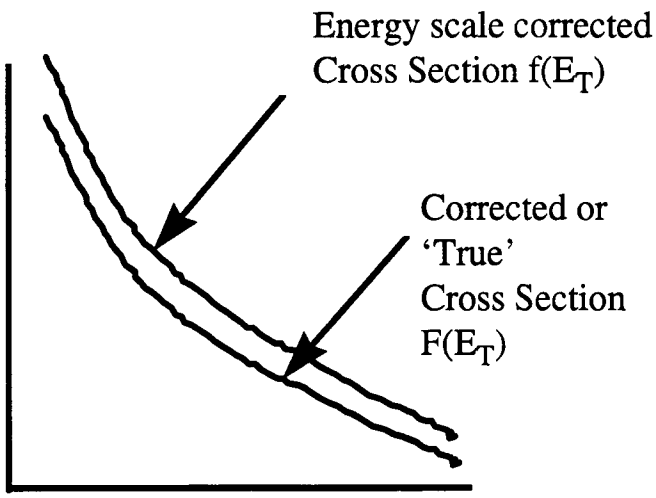
S = showering losses. Negligible for 0.7 cone.

R_{had} = correction for hadron response. Determined from the missing transverse energy balance of photon-jets events.

EM calibration was established via Z, J/ψ, and π^0 resonances

- Jet Energy Resolution & Unsmearing

After jet energy scale corrections the cross section must be corrected for jet energy resolution effects



D0

Jet σ_{ET}/E_T resolution is measured from data using the dijet E_T balance method.

$$A = (E_{T1}-E_{T2}) / (E_{T1}+E_{T2})$$

In the limit of no soft radiation, both jets of nearly equal E_T and rapidity:

$$\sigma_A = \sigma_{ET}/(\sqrt{2}\, E_T)$$

Dijet events are selected with no additional jets above 10 GeV. (An extrapolation to zero is performed to account for the third jet threshold.)

The observed E_T spectrum is corrected for resolution smearing by assuming a "physics curve," $F(E'_T)$, smearing it with the measured resolution, and comparing the smeared result with the measured cross section.

$$f(E_T) = \int F(E'_T)\, R(E'_T - E_T, E'_T)\, dE'_T$$

where

$$F(E'_T) = (AE'^{-B}_T)(1 - 2E'_T/\sqrt{s})^C$$

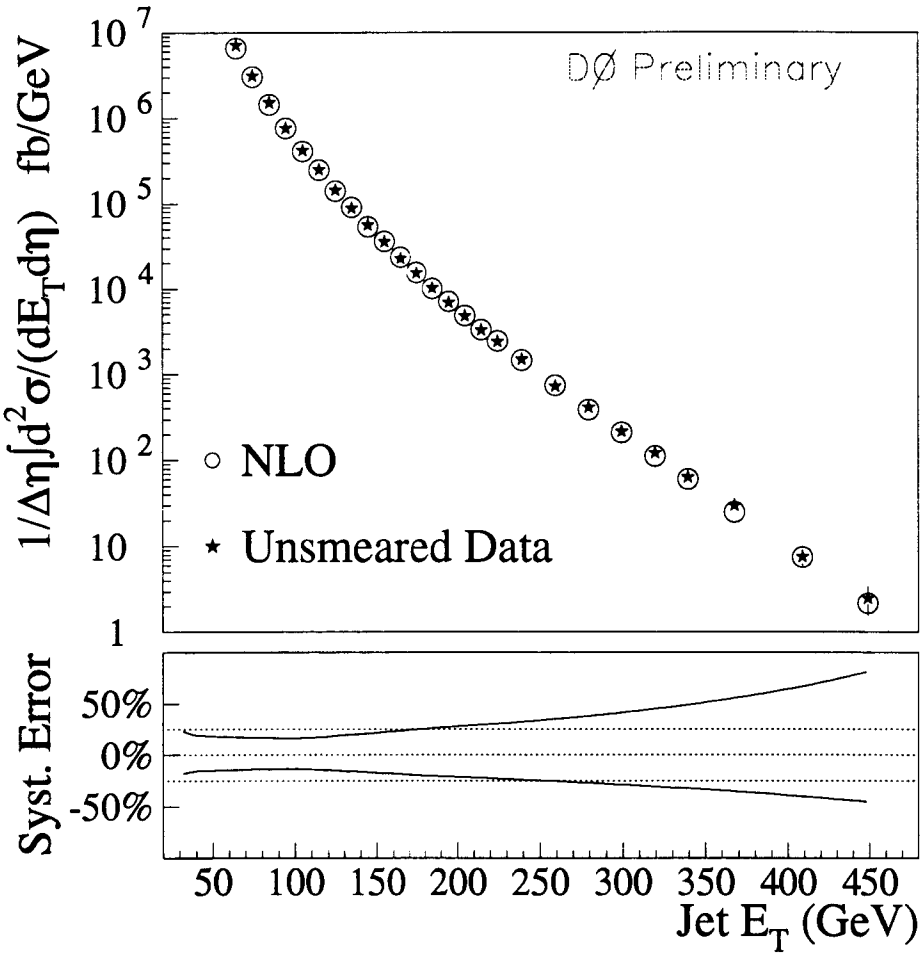
CDF

Measured jet energy is corrected for offset due to underlying event.

No showering loss correction applied.

Detector energy response and smearing effects are determined from data-tuned Monte Carlo simulations and applied together in an iterative process to correct the measured cross section.

DØ Inclusive Jet Cross Section

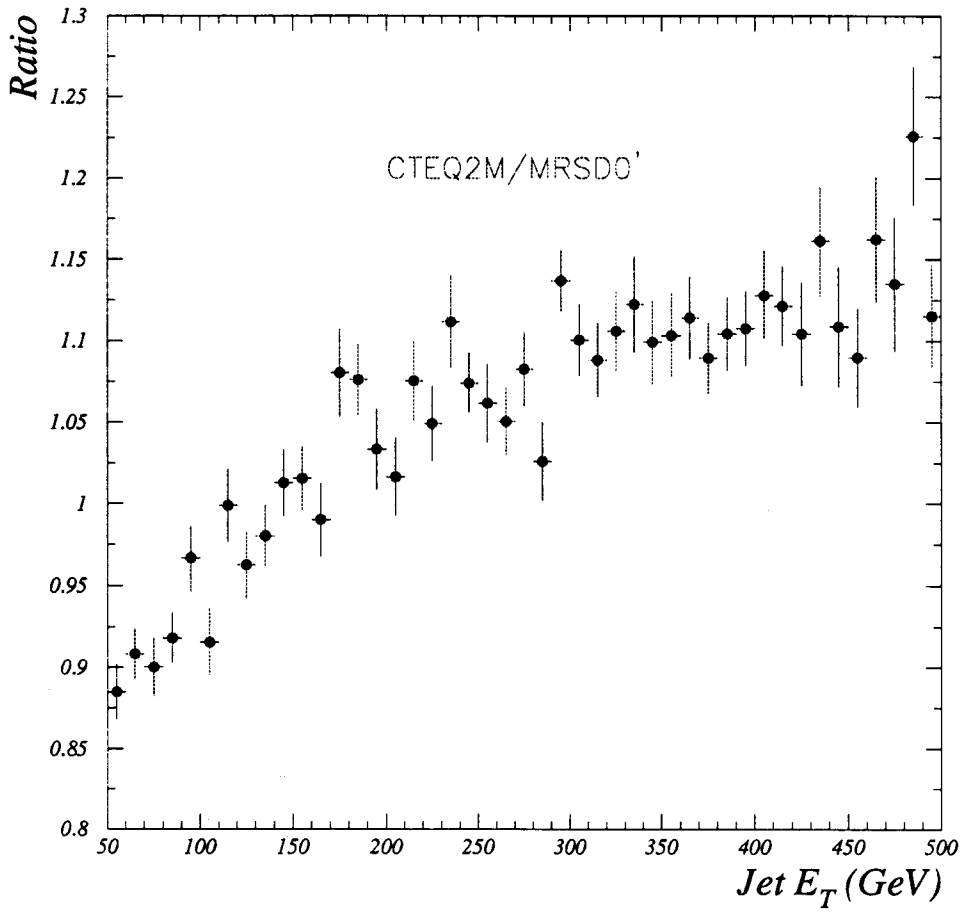


Source	Percentage Error
Jet Selection	1
Event Sel.	1
Luminosity	8
Lum. Match	1,2,2
Unsmearing	3 - 7 (for 100 - 400 GeV)
Energy Scale	15 - 45 (for 100 - 400 GeV)

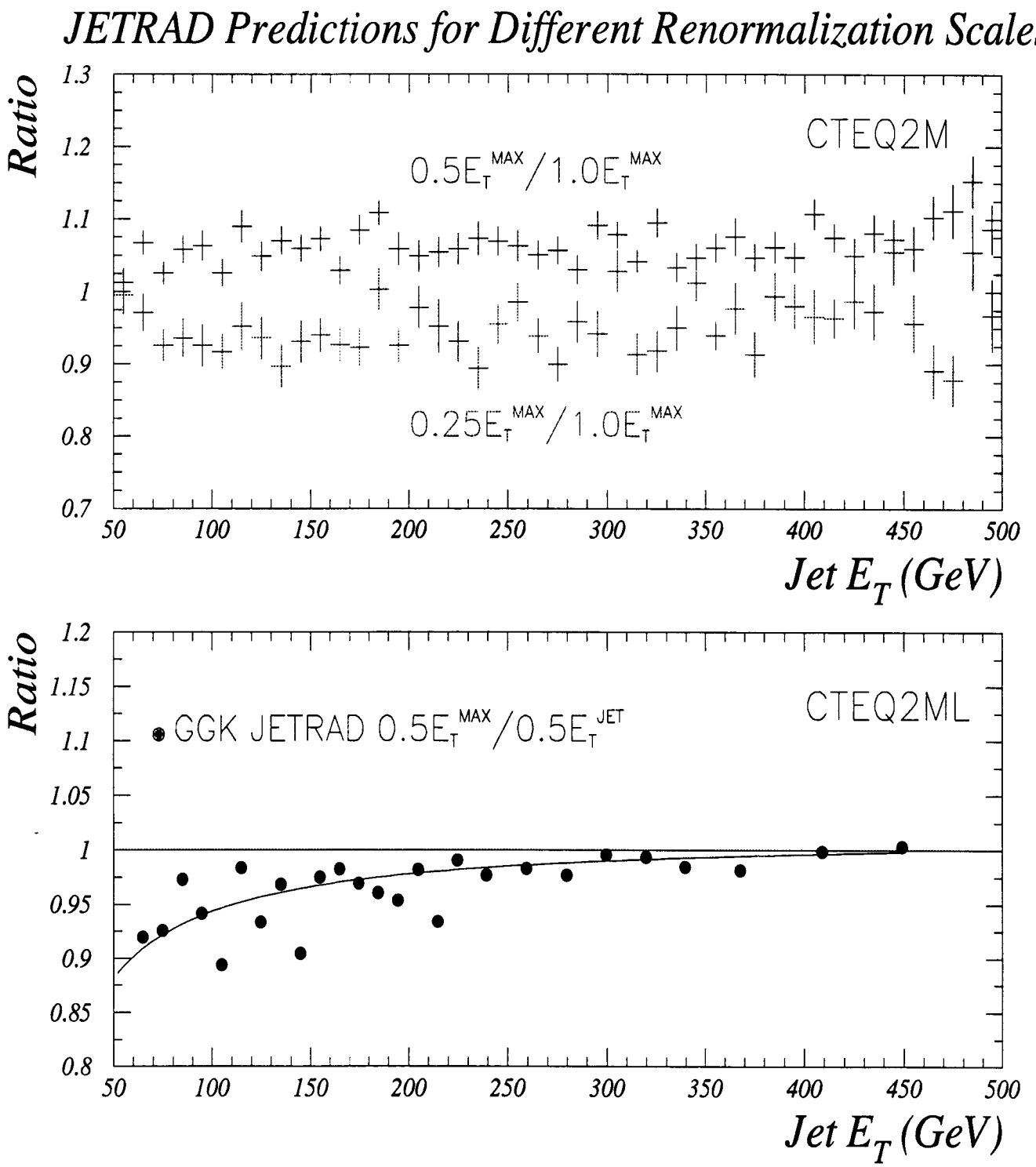
Theory

- NLO predictions:
  - **E**llis,**K**unszt,**S**oper, Phys.Rev.D, **64**, (1990)
  - Aversa,et al.,Phys.Rev.Lett.,**65**, (1990)
  - Giele,Glover,Kosower, Phys.Rev.Lett., **73**, (1994) - **JETRAD**
- Choices:
  - PDFs (~20%)
  - Renormalization/Factorization Scale (~10%)
  - Clustering Algorithms (~5%)
  - Model (e.g., EKS vs JETRAD) (~10%)

JETRAD Predictions for Different PDFs



Inclusive Jet Cross Section

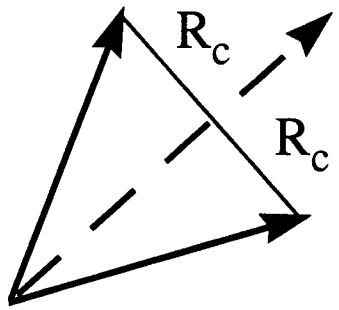


Clustering of Partons at NLO

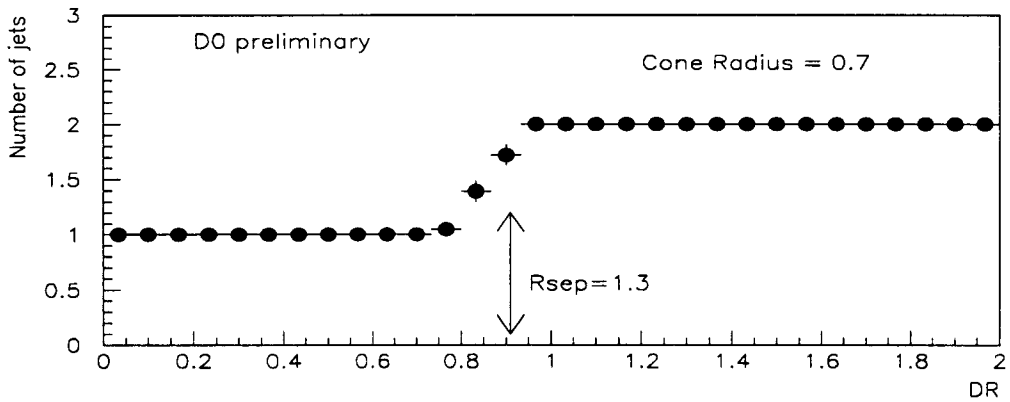
1) Each Parton must be within $R_c = 0.7$ of centroid.
2) The two partons must be within Rsep*R_c of one another where Rsep varies from 1 - 2.

CDF: Rsep = 2

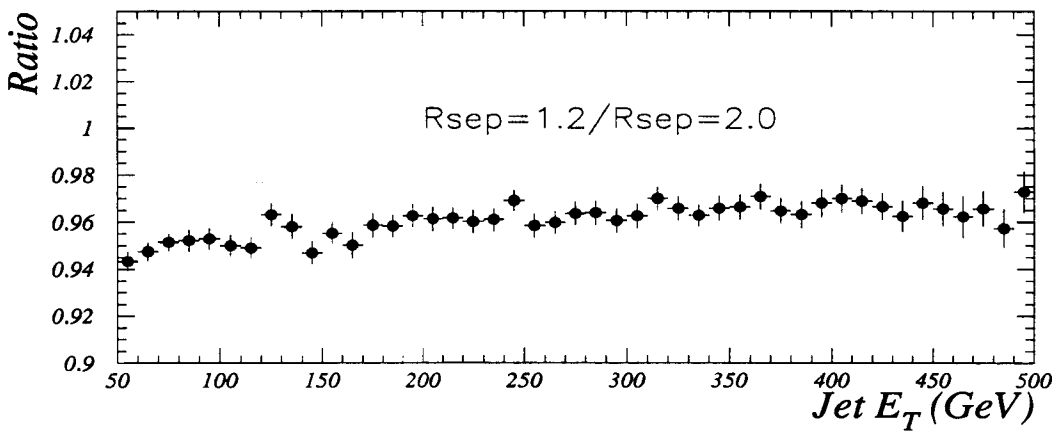
D0:



If jets from separate events are overlaid then they can be distinguished at (1.2-1.3)R_c or 0.9 for 0.7 cones:



JETRAD Predictions for Different Rsep values



NLO QCD Programs

D0 Model

NLO Program: **Jetrad**

μ-scale value: $\mathbf{E_T^{max}/2}$

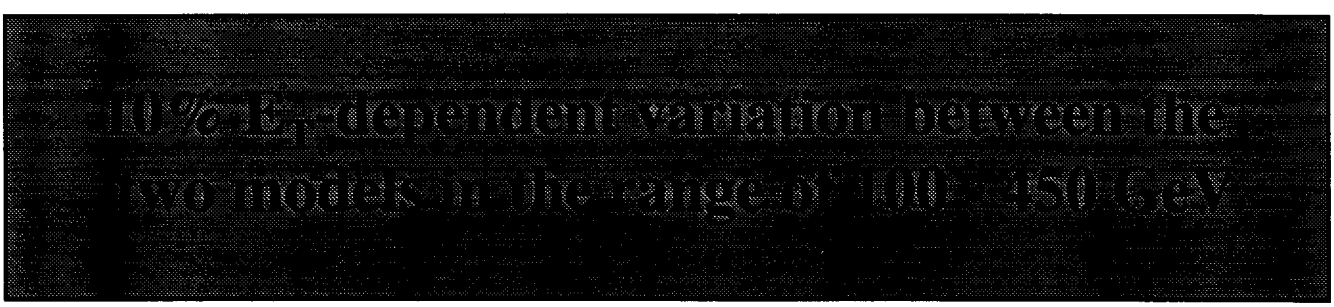
Rsep value: **1.2**

CDF Model

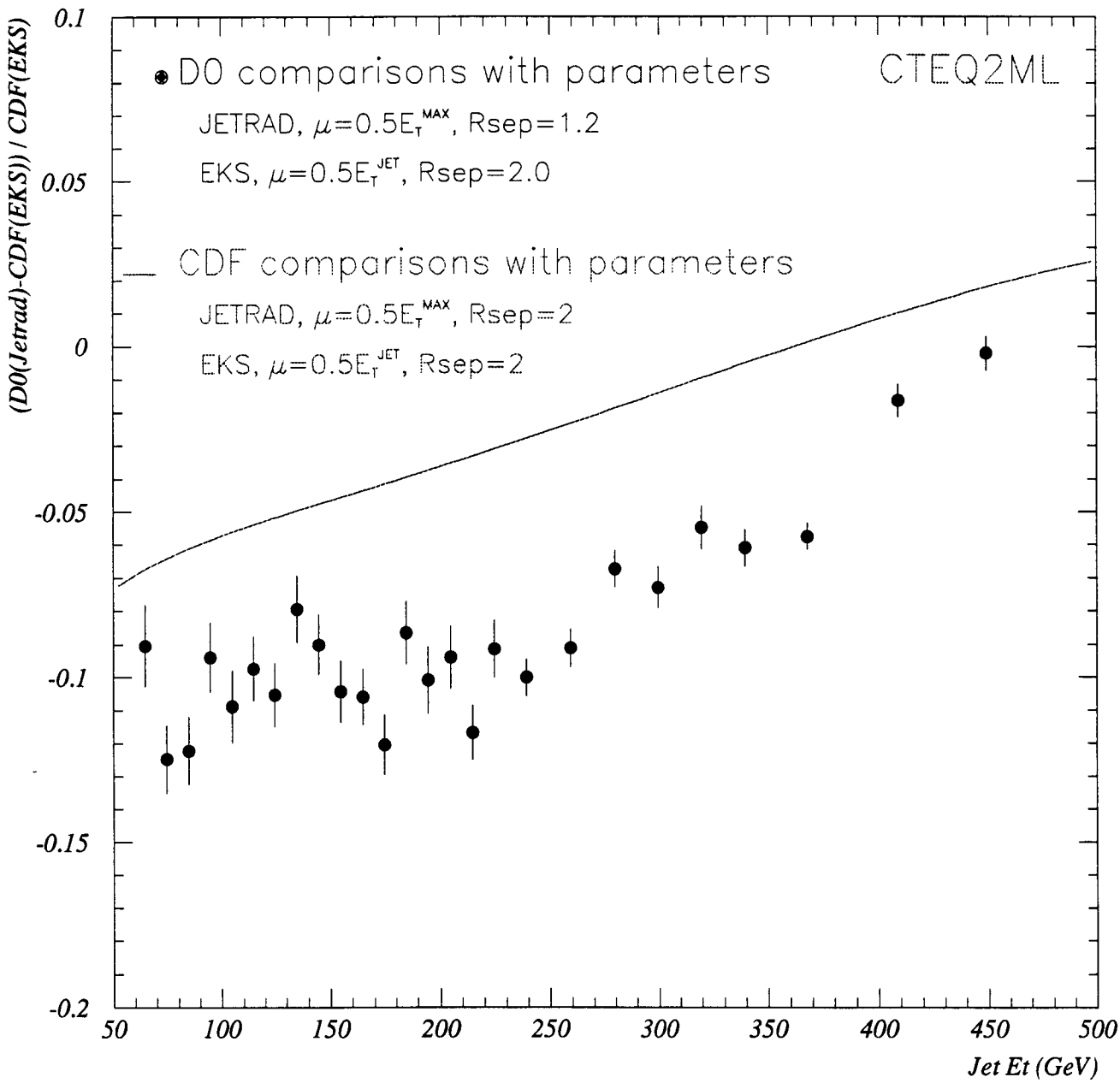
NLO Program: **EKS**

μ-scale value: $\mathbf{E_T^{jet}/2}$

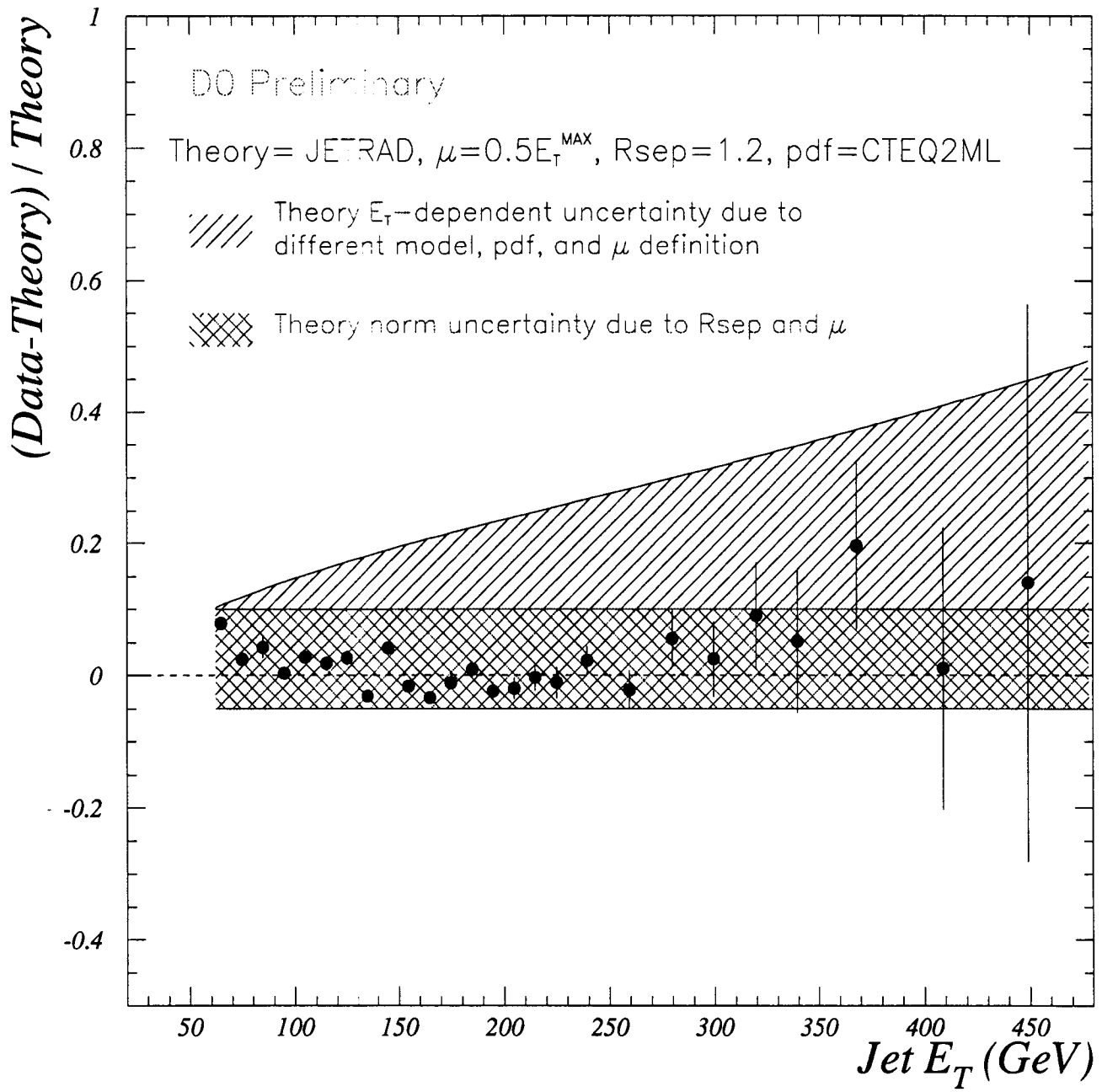
Rsep value: **2**



D0(JETRAD) vs CDF(EKS) Predictions @1800 GeV

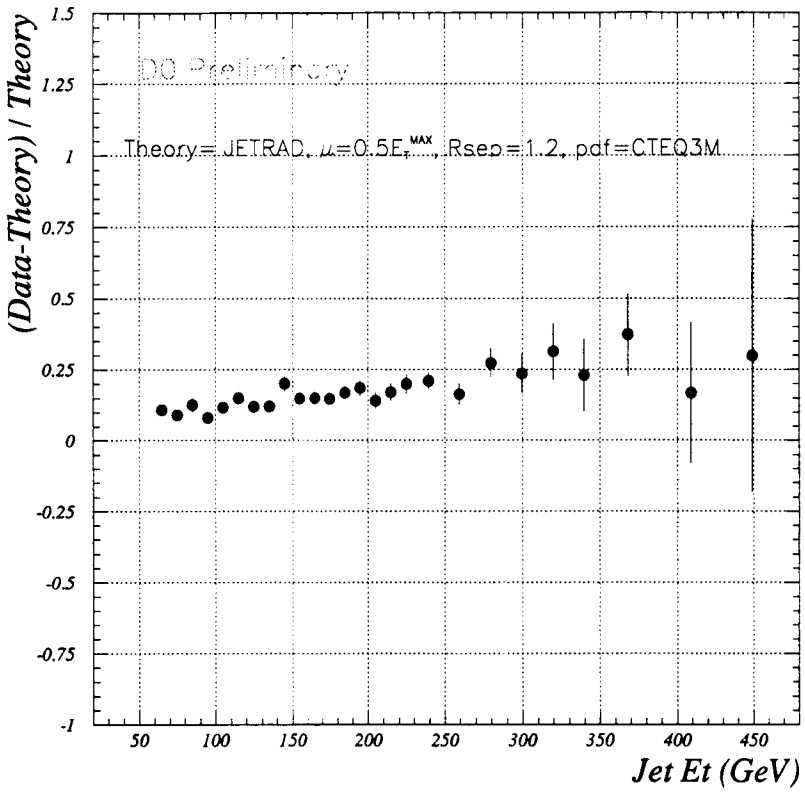


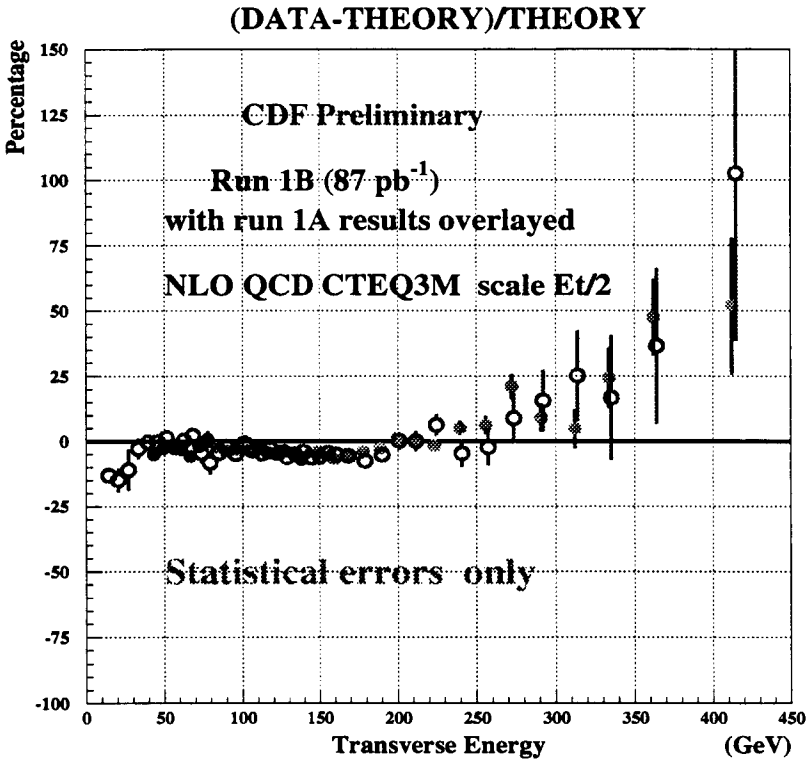
NLO/PDF Uncertainties



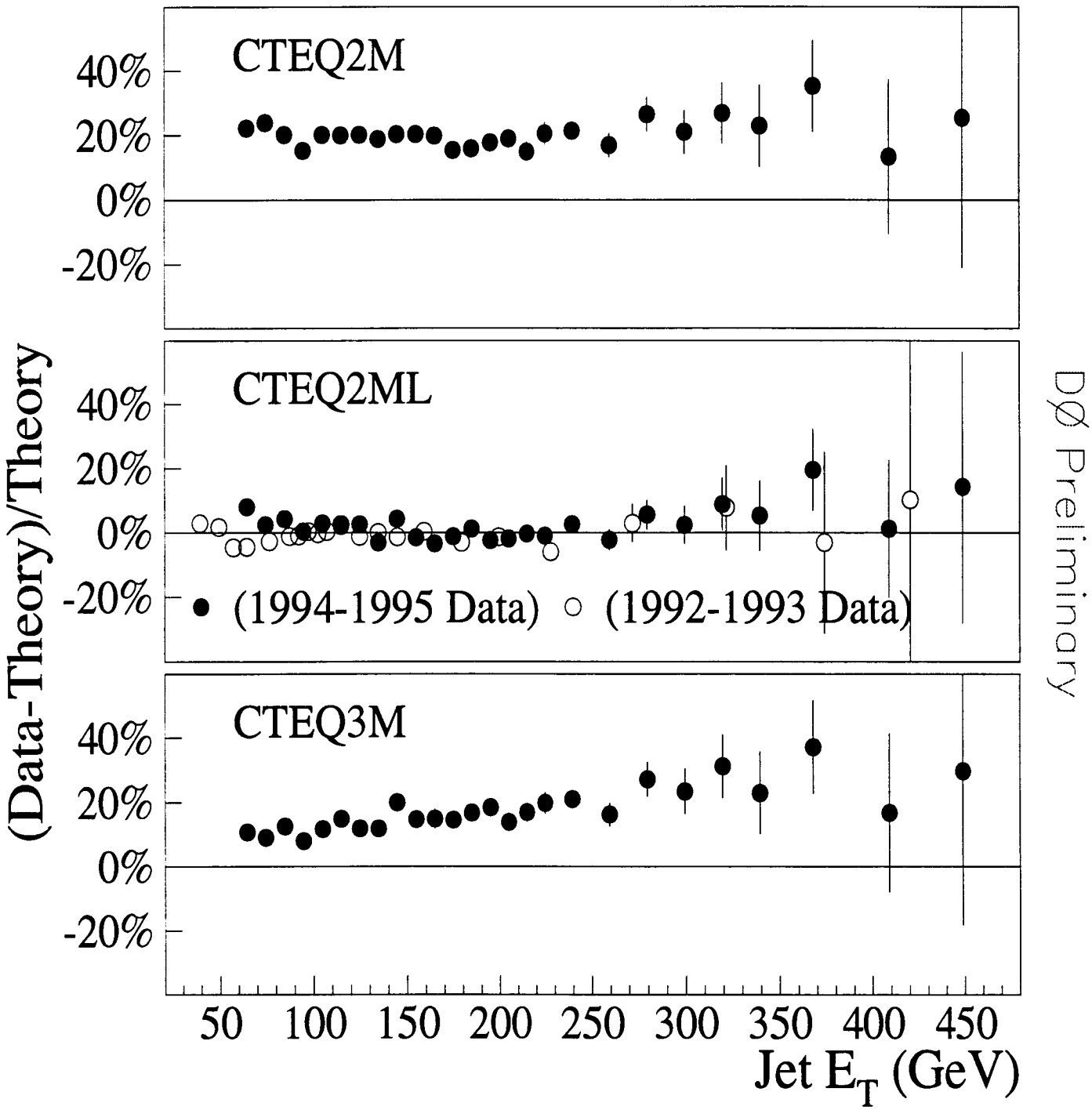
Theory uncertainties ~ Experimental uncertainties

Data vs Theory



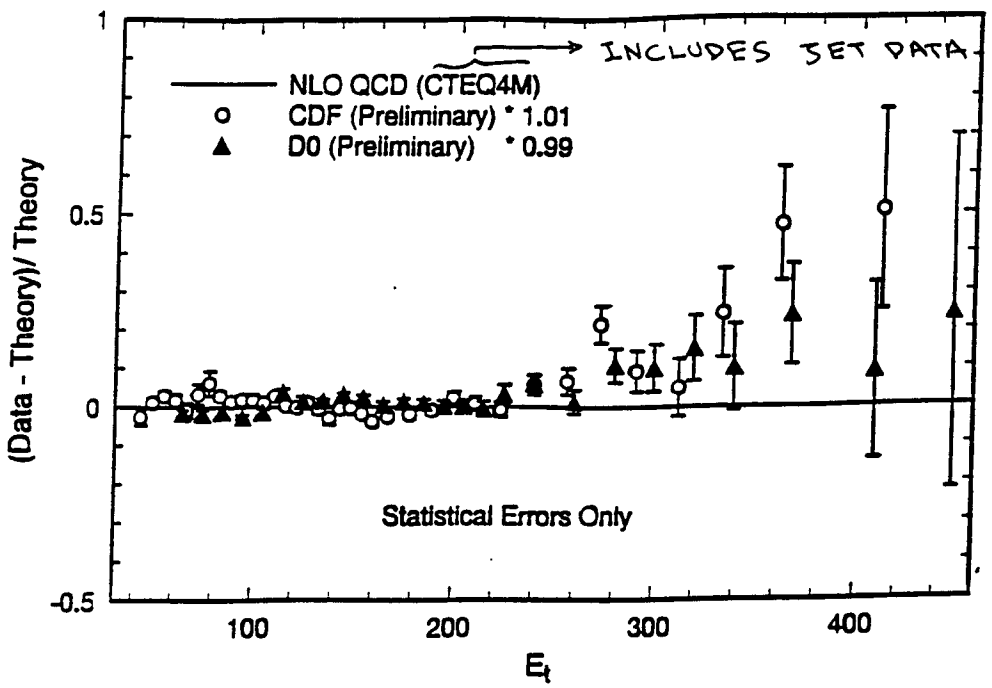


DØ Inclusive Jet Cross Section



conclusion: good agreement with pQCD

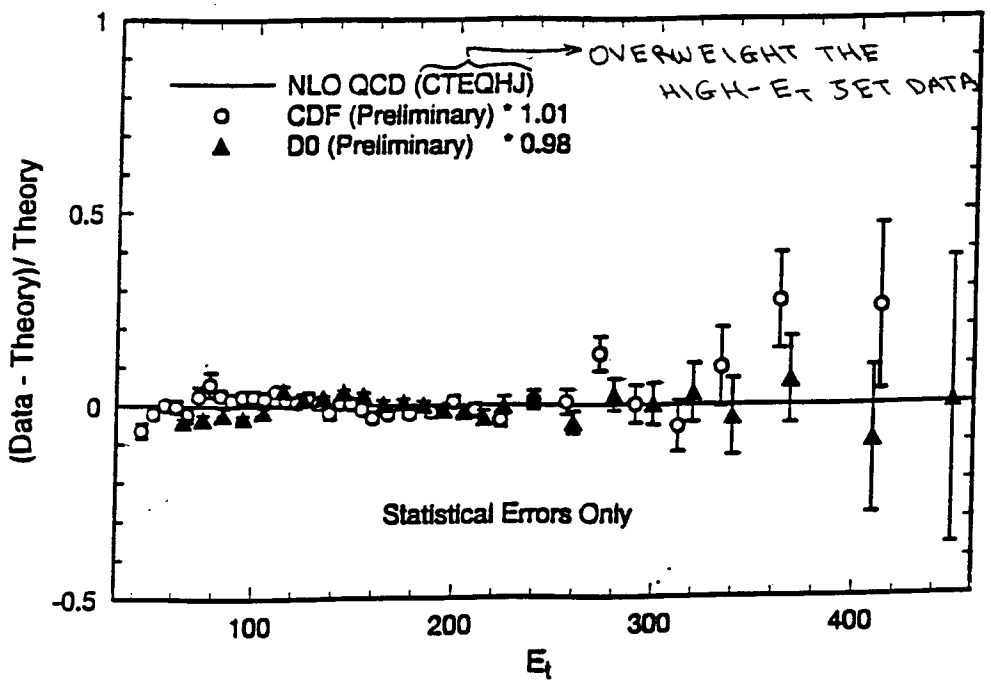
How about these high-x gluons?



GLOBAL FIT

$\frac{\chi^2}{dof} = \frac{1320}{1297}$

FIG. 3. The preliminary CDF and D0 Run Ib data compared to NLO QCD using CTEQ4M parton distributions. Experimental points normalized as indicated.



$\frac{\chi^2}{dof} = \frac{1343}{1297}$

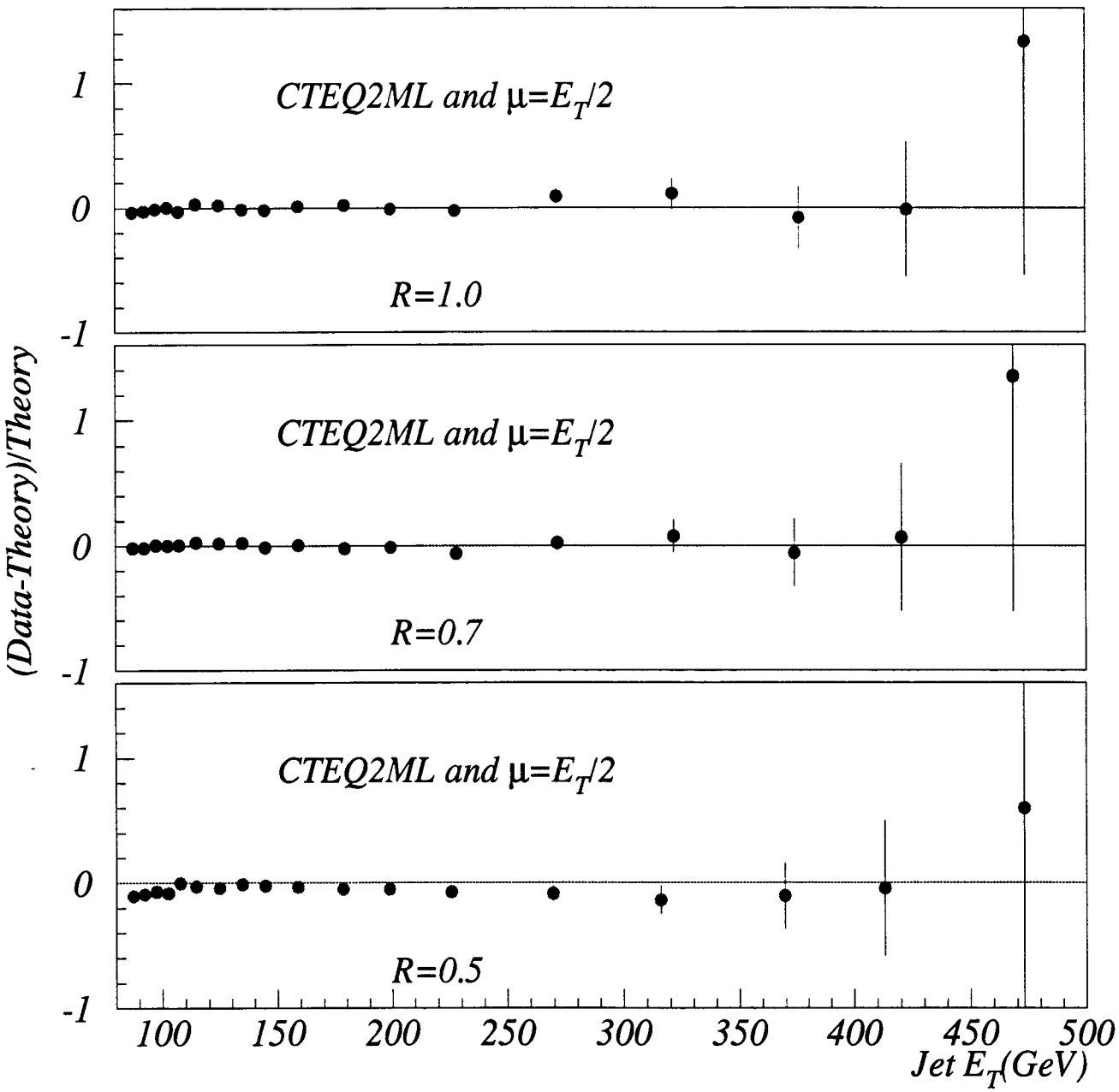
FIG. 4. The preliminary CDF and D0 Run Ib data compared to NLO QCD using CTEQHJ parton distributions. Experimental points normalized as indicated.

H.L. Lai and W.K. Tung
MSU-HEP-60508

DØ Inclusive Jet Cross Section

Inclusive Jet Production vs Jet Cone Size

D0 Preliminary (1992-93 Data)



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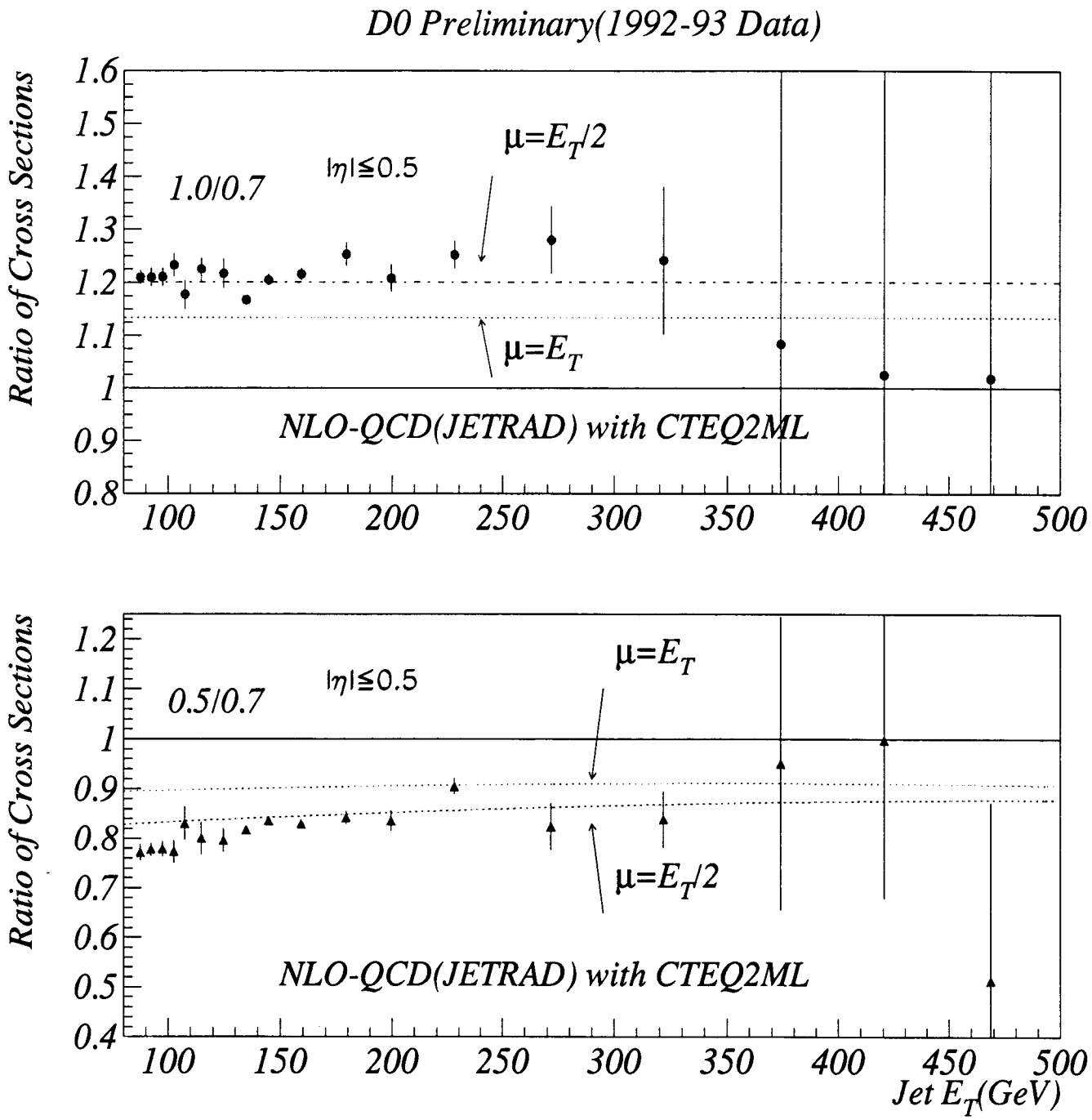
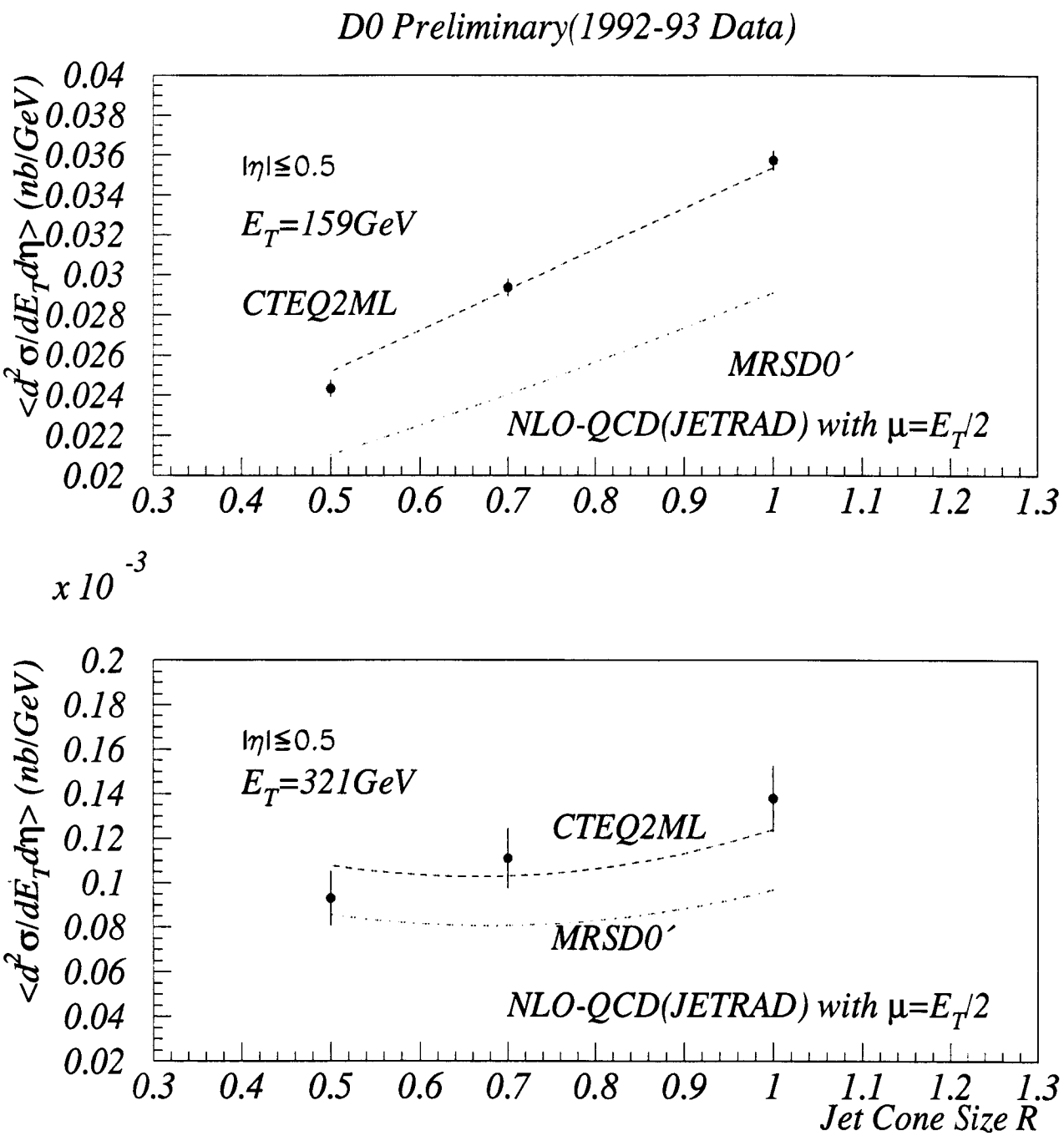
DØ Inclusive Jet Cross Section

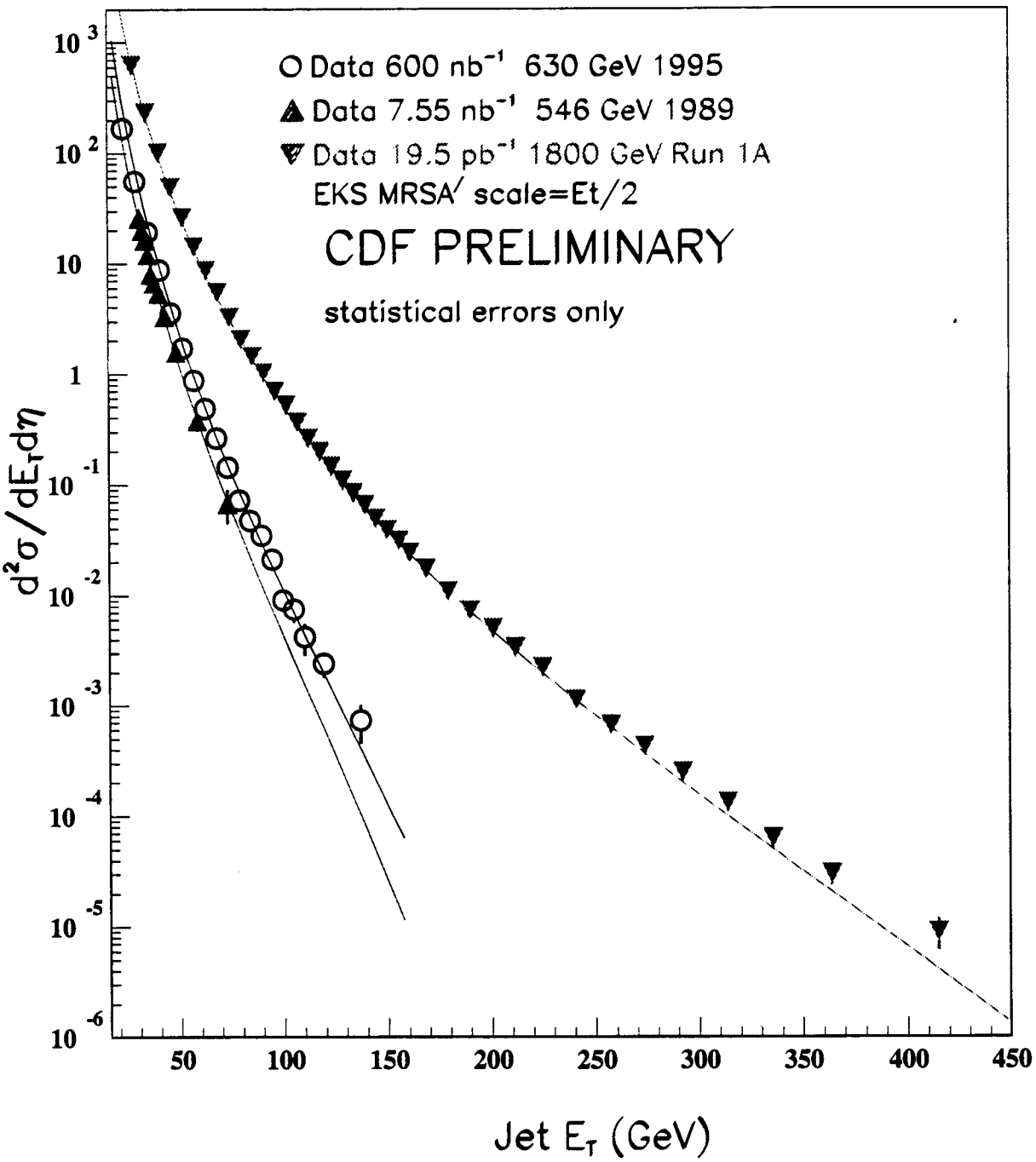


DØ Inclusive Jet Cross Section

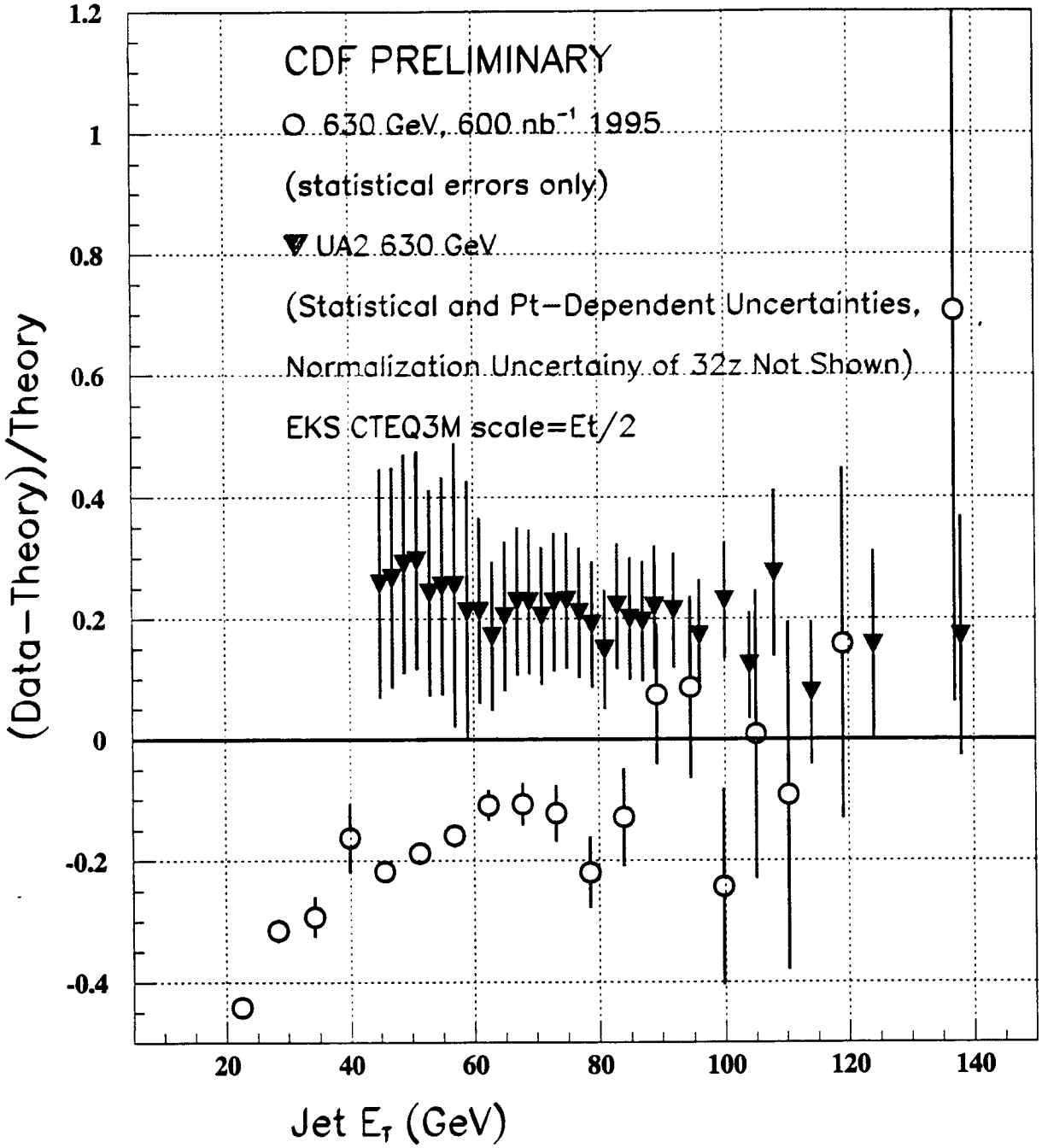


conclusion: good agreement with pQCD

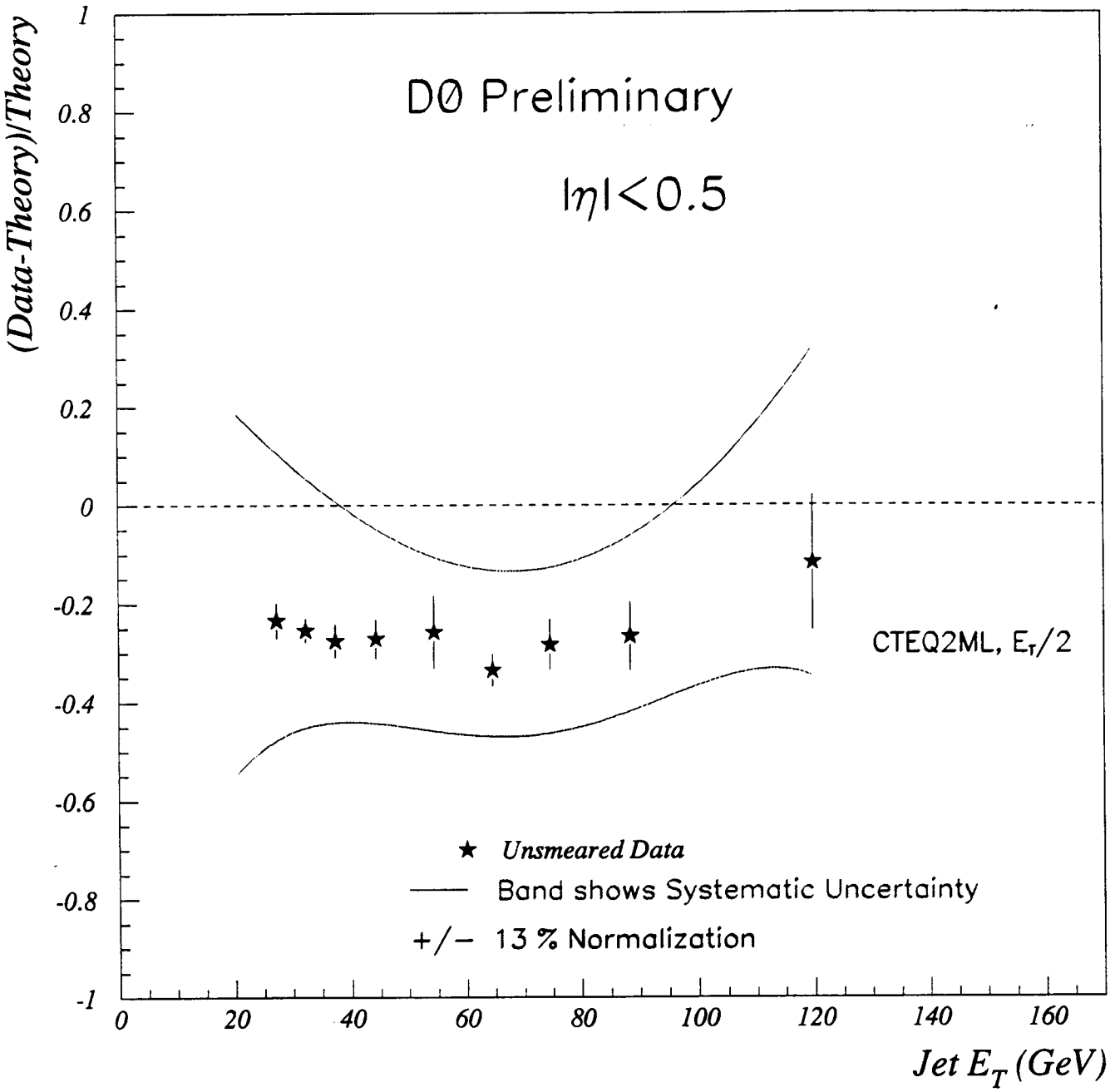
CDF Inclusive Jet Cross Sections



CDF and UA2 Inclusive Jet Cross Sections at 630 GeV

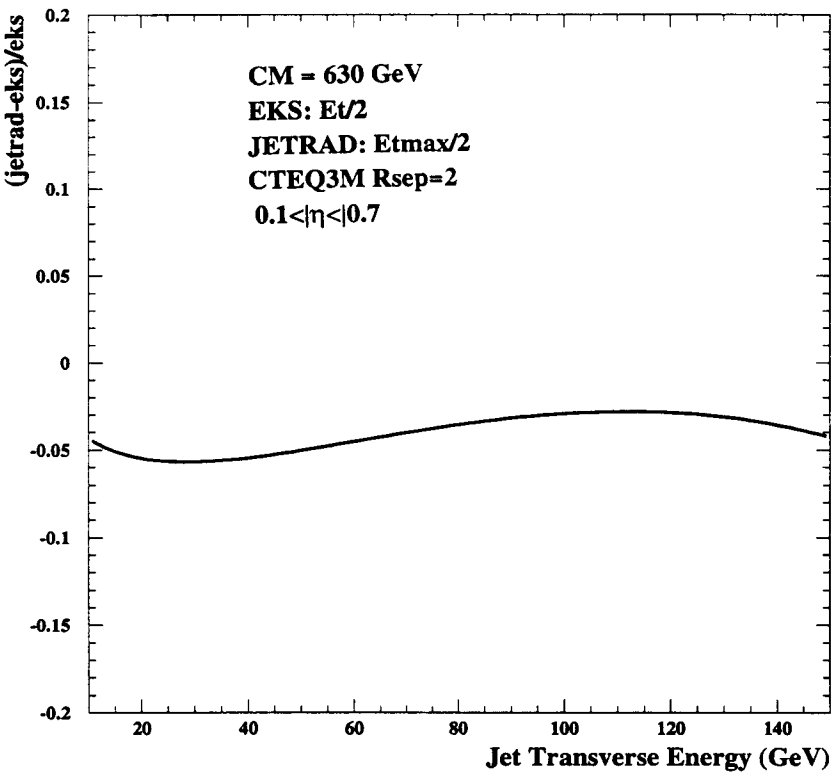


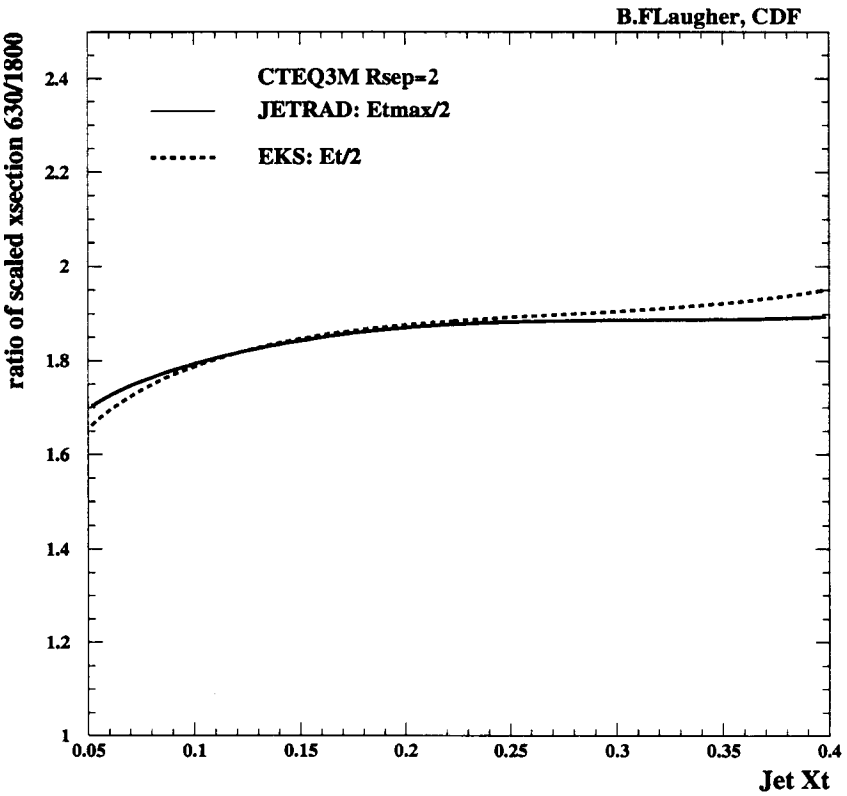
Data (630 GeV CM Energy) and NLO QCD



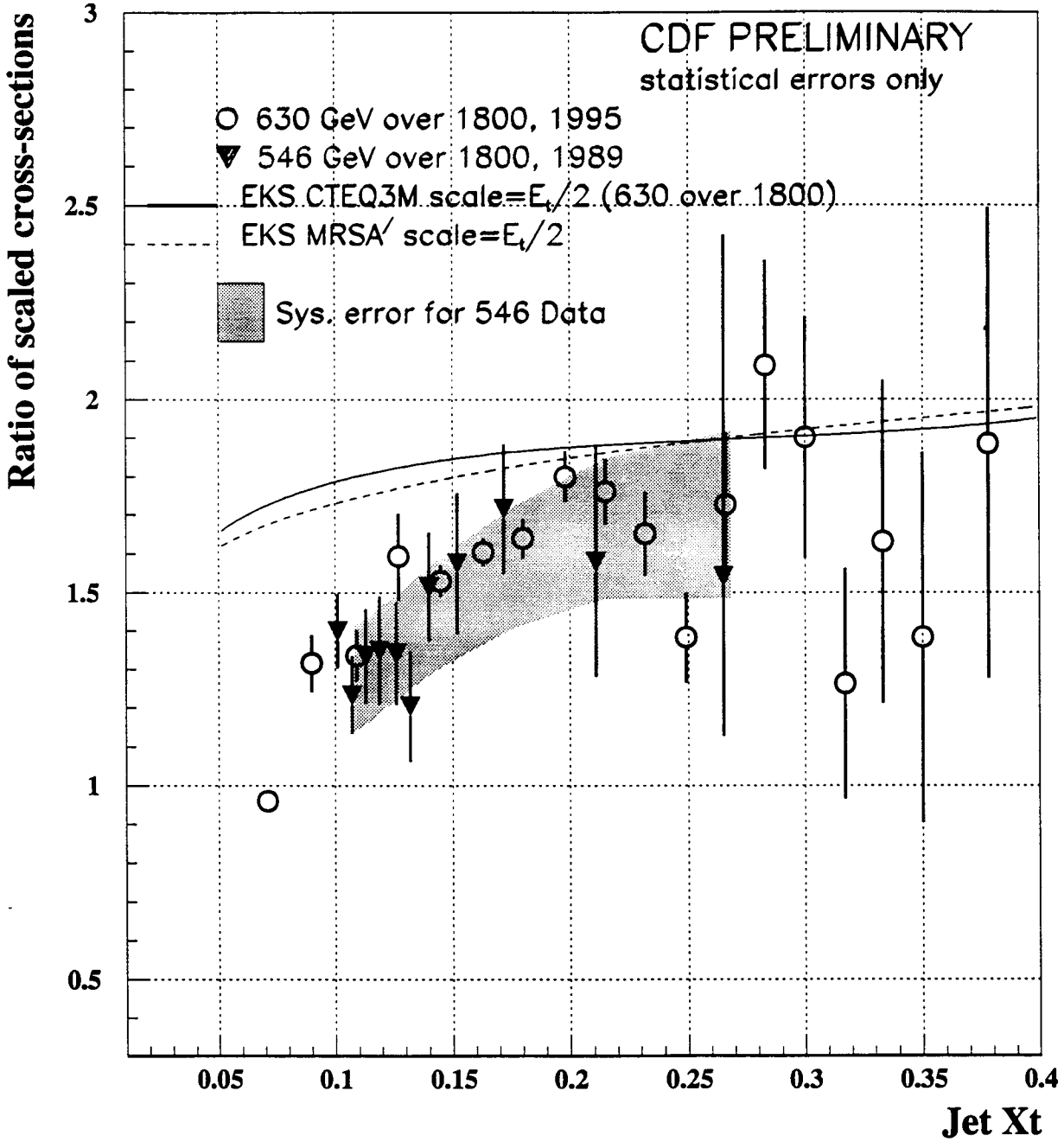
D0(JETRAD) vs CDF(EKS) Predictions @630 GeV

B.FLaugher, CDF

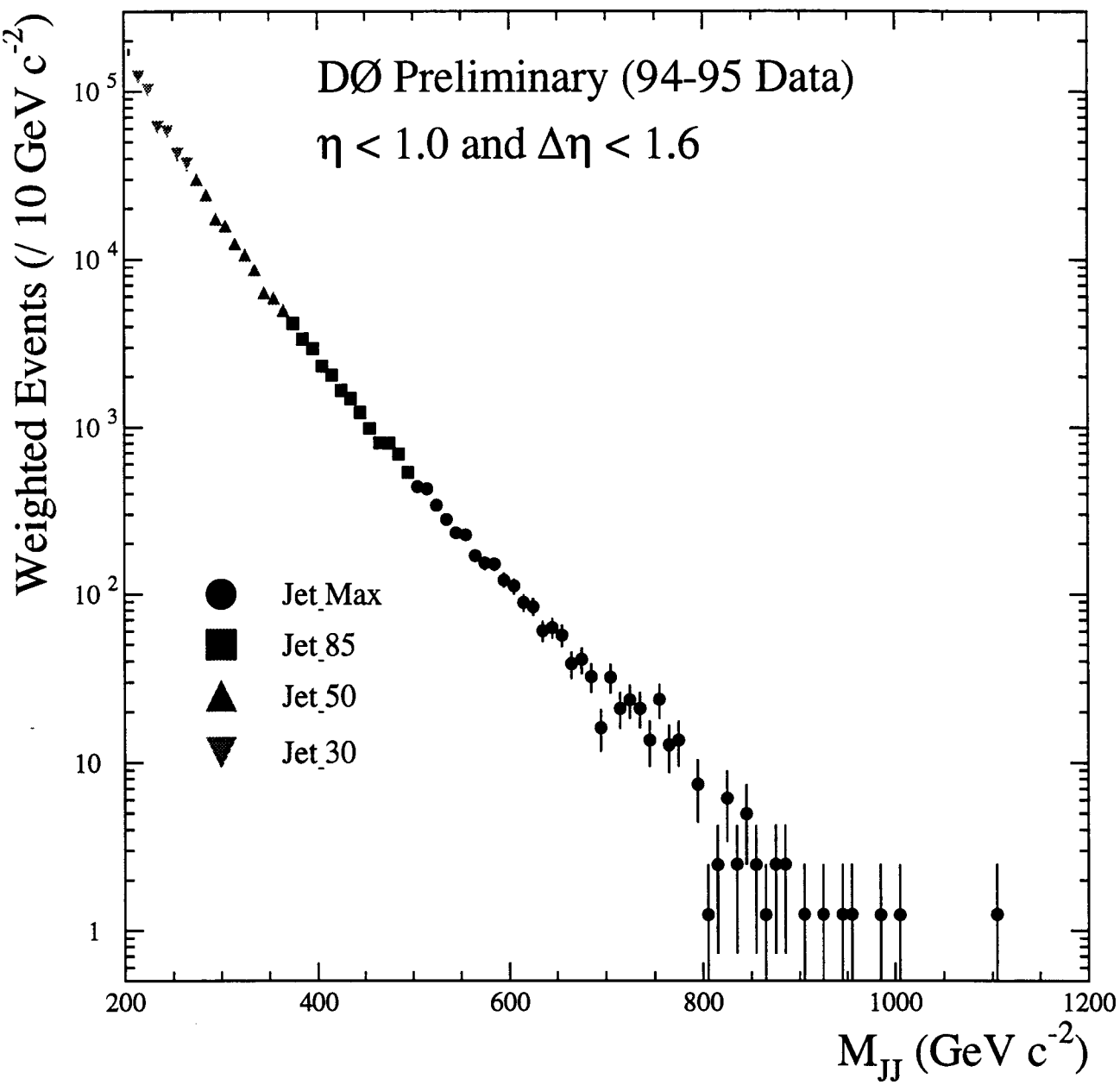




Ratio of Scaled Cross-Sections: 630 and 546 over 1800



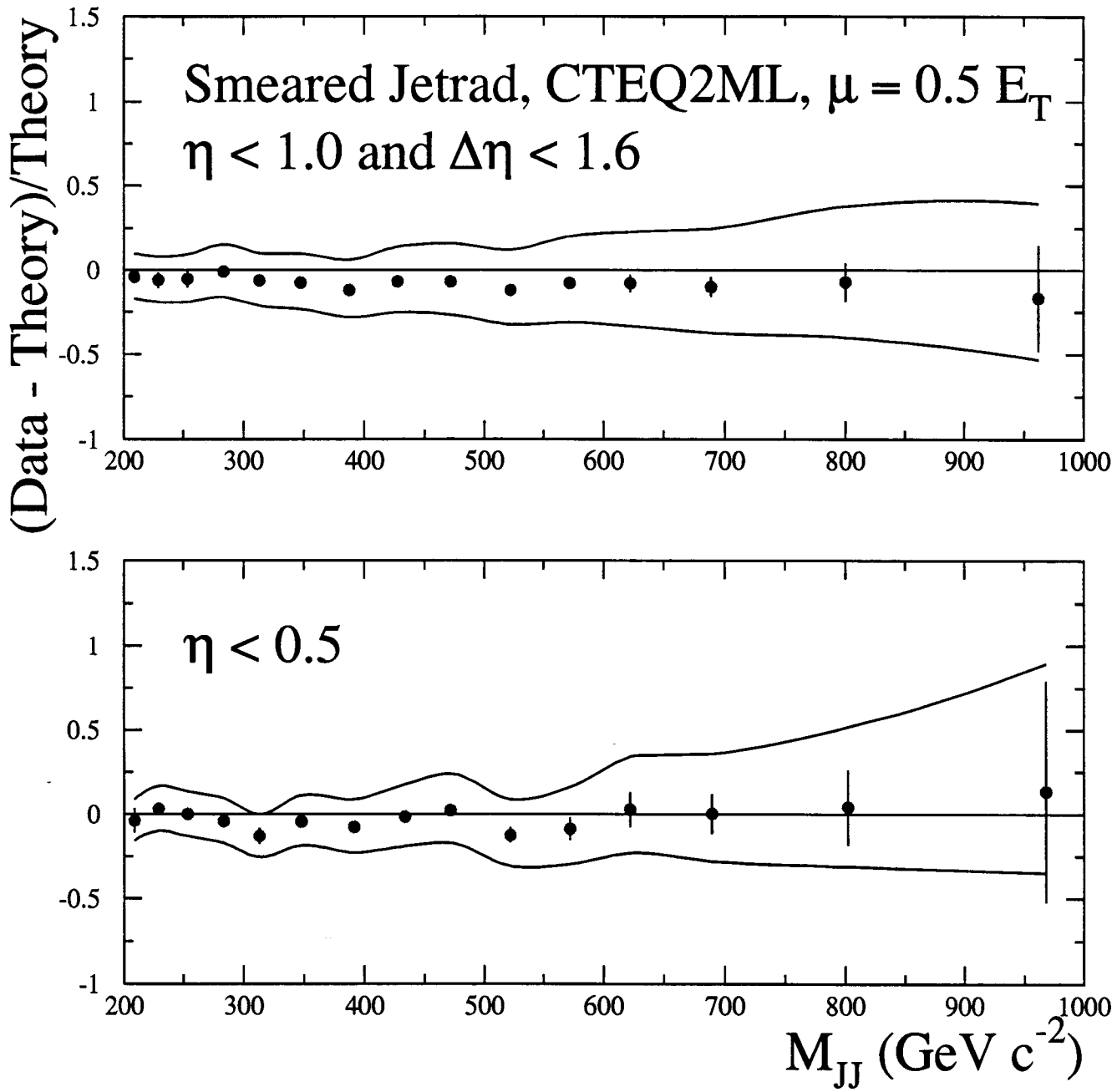
Dijet Mass Spectrum



DØ Dijet Mass

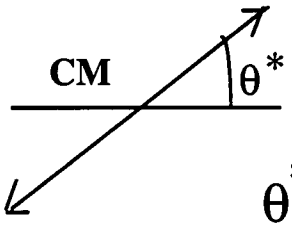
Data vs. Theory

DØ Preliminary (94-95 Data)



conclusion: good agreement with pQCD

Dijet Angular Distribution



$$\theta^* \in \left[0, \frac{\pi}{2}\right]$$

for small CM angles: t-channel gluon exchange dominates → Rutherford scattering

$$\frac{d\hat{\sigma}}{d\cos\theta^*} \propto \frac{1}{\sin^4\left(\frac{\theta^*}{2}\right)}$$

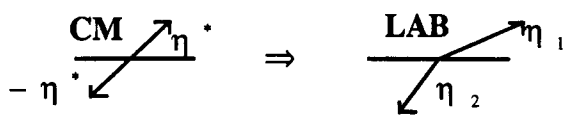
flatten out the $\cos\theta^*$ distribution by plotting $dN/d\chi$

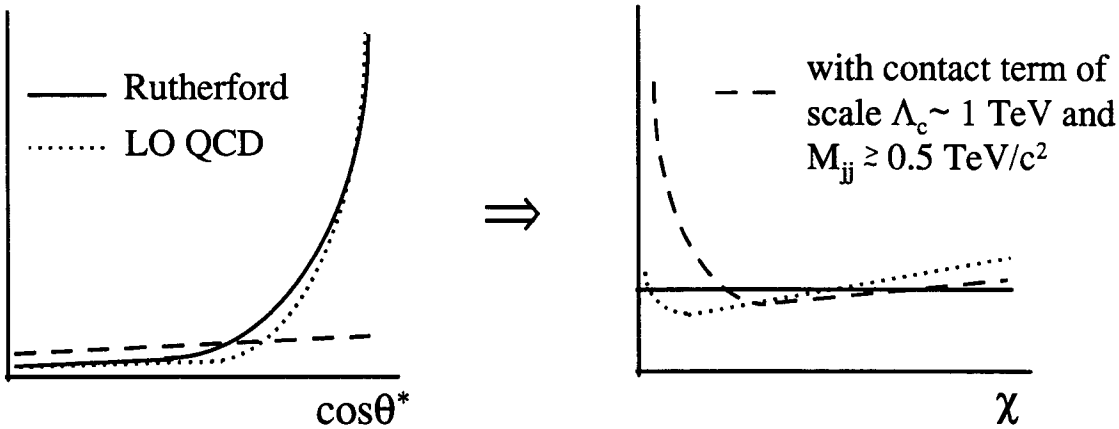
$$\chi = e^{2|\eta^*|} = \frac{1+\cos\theta^*}{1-\cos\theta^*}$$

$$\eta^* = \frac{1}{2}(\eta_1 - \eta_2)$$

$$\cos\theta^* = \tanh\eta^*$$

$$\eta_{boost} = \frac{1}{2}(\eta_1 + \eta_2)$$





$dN/d\chi$ sensitive to contact interactions for quark compositeness

$dN/d\chi$ insensitive to parton distribution functions

- Shape of angular distribution unaffected by boost of system
- $gg \rightarrow gg$, $gq \rightarrow gq$, $qq \rightarrow qq$ produce similar angular distributions

$1/N\ dN/d\chi$ insensitive to overall energy scale, but

- very sensitive to η dependent quantities (like: η-dependence of the jet energy scale and multiple interactions)

Measure the relative response of the calorimeters vs η by using an E_T-balancing method

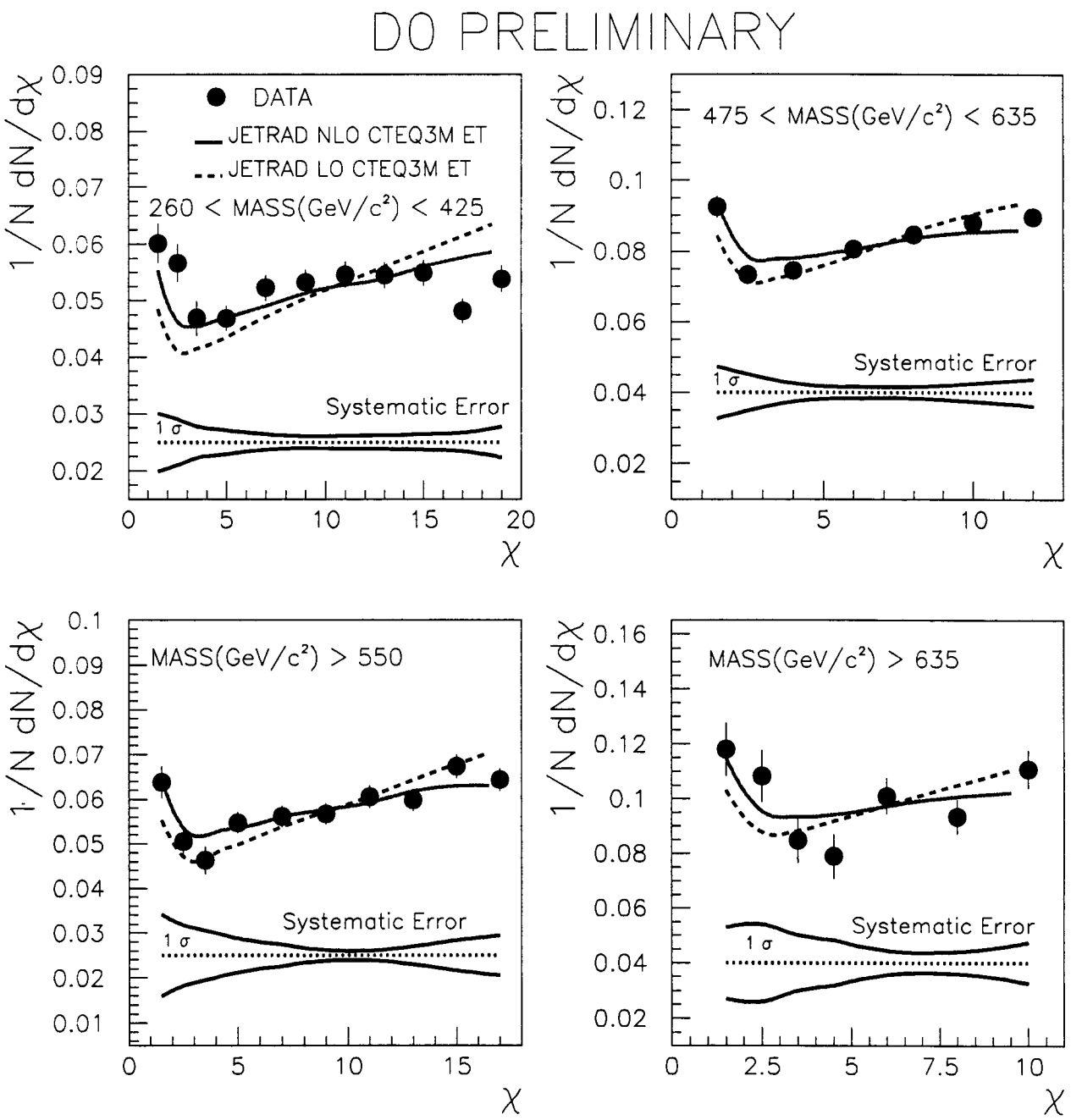
Event Selection

- 1994-95 Inclusive jet data sample
- The two leading-E_T jets were required to have $|\eta_{max}| < 3$
- The mass bins and χ_{max} were chosen to ensure 100% trigger efficiency
  $M^2 = 2E^2{}_T{}^{leading}[\cosh(\ln\chi)+1]$
- Once the χ_{max} was chosen then the η_{boost} cut was determined to ensure uniform acceptance
  $|\eta^*| + |\eta_{boost}| < 3$

Min E_{T1}	Dijet Mass	χ_{max}	$\lvert\eta^*_{max}\rvert$	$\lvert\eta_{boost\ max}\rvert$
55	260 - 425	20	1.5	1.5
120	475 - 635	13	1.3	1.5
120	550 -	18	1.45	1.5
175	635 -	11	1.2	1.5

DØ Dijet Angular Distribution

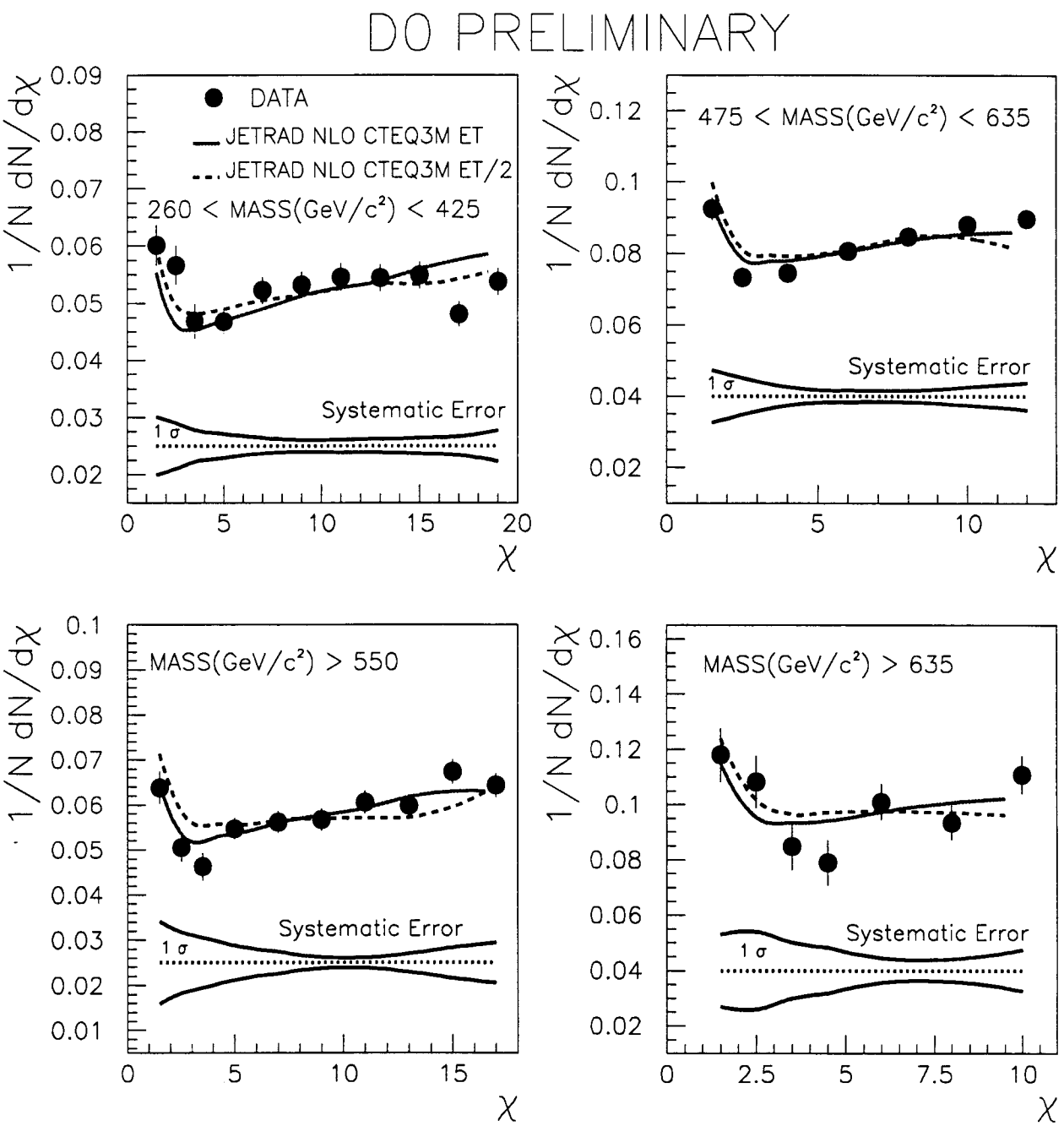
Leading Order vs. Next-To-Leading order pQCD



conclusion: good agreement with NLO

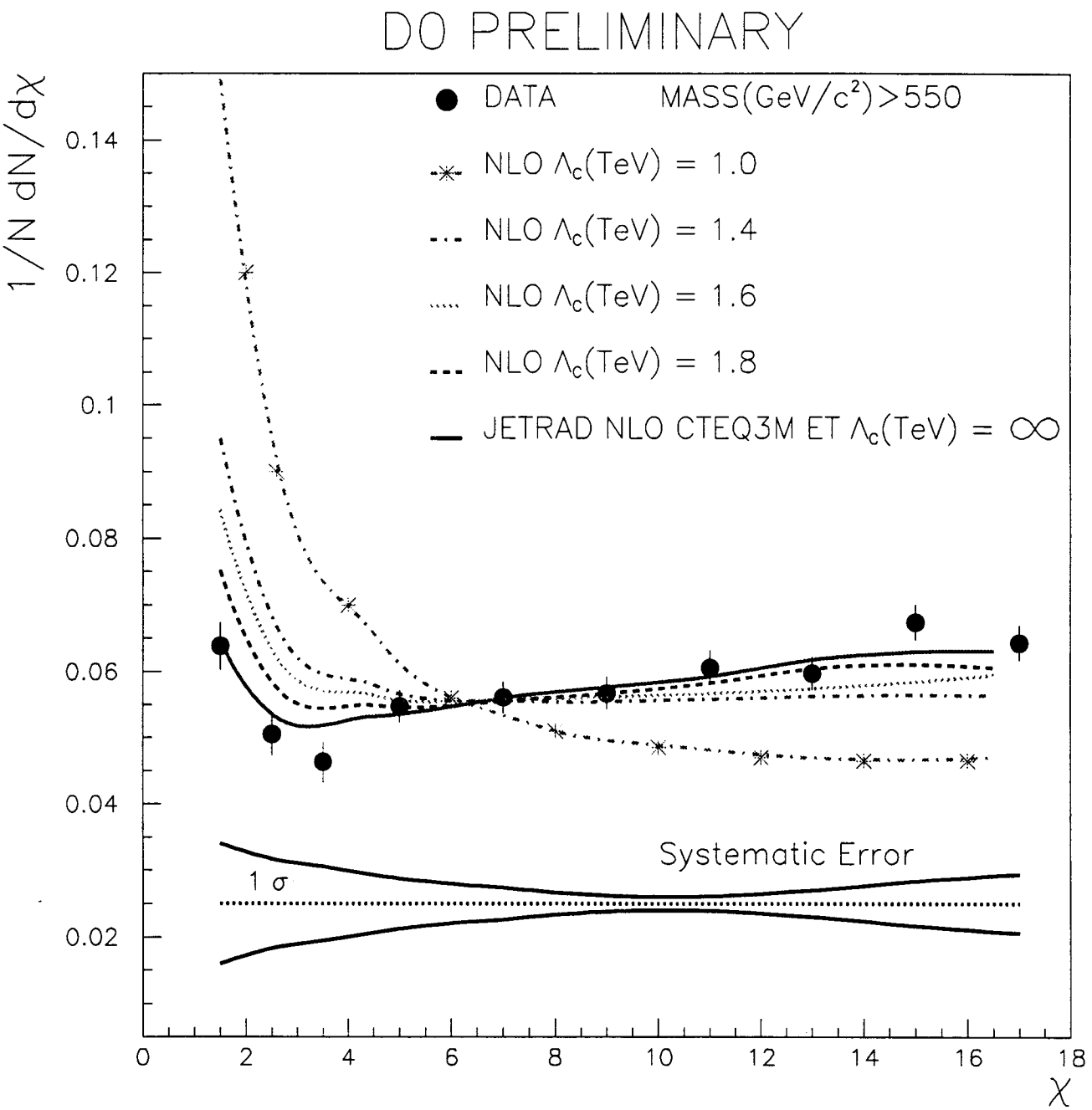
DØ Dijet Angular Distribution

renormalization scale dependence (NLO)



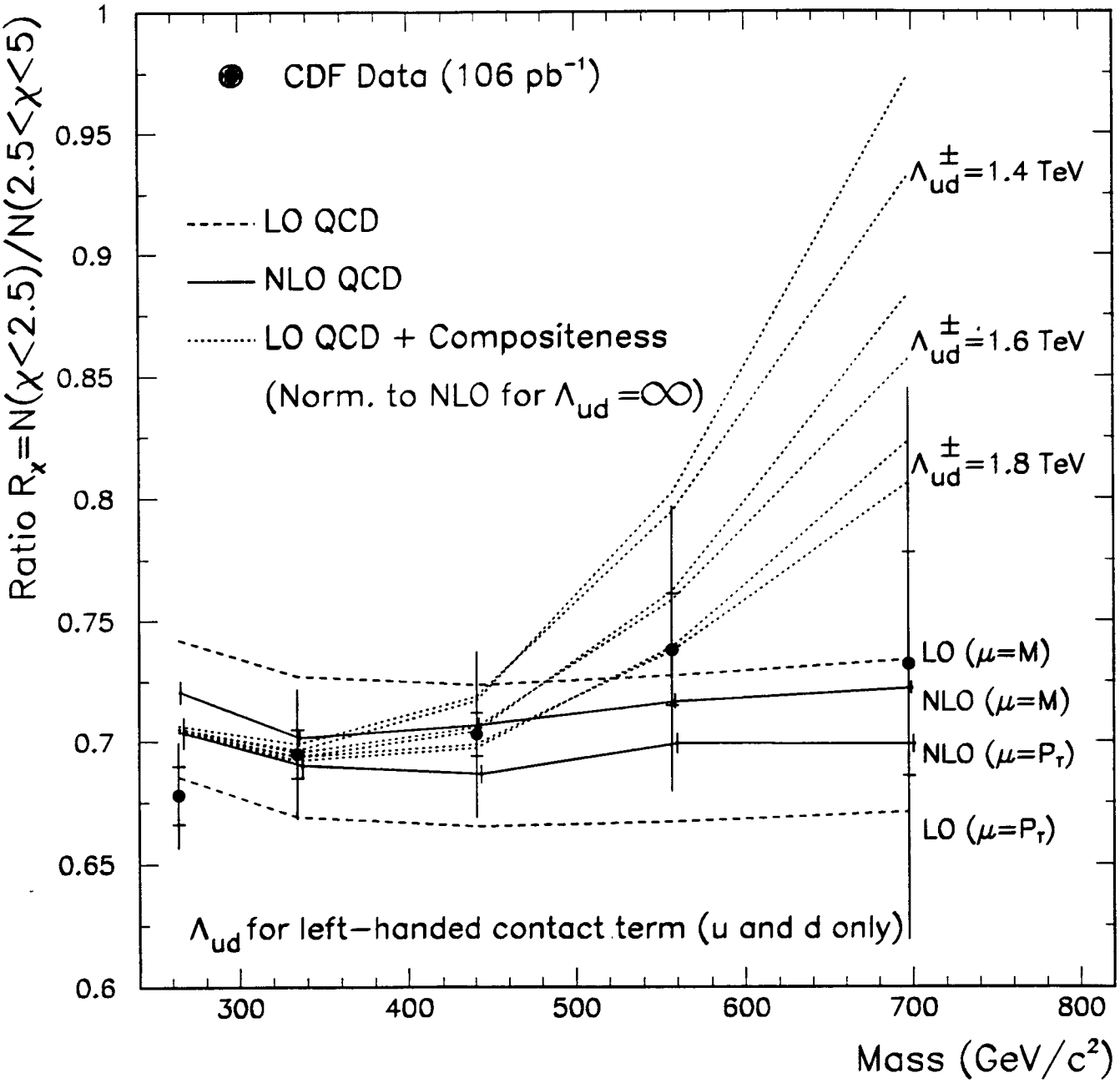
DØ Dijet Angular Distribution

Comparison with NLO w/ added LO contact term



NLO with added contact term is unavailable. Effect of contact term was calculated using LO Papageno*. NLO was multiplied by the ratio of LO with and without a contact term.

*Hinchliffe



95% Limits : $\Lambda_{ud}^{+} > 1.6$ TeV (u and d only)

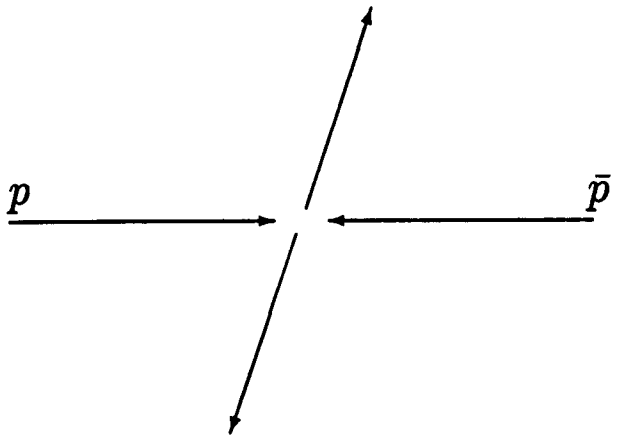
$\Lambda_{ud}^{-} > 1.4$ TeV

$\Lambda^{+} > 1.8$ TeV (all quarks)

$\Lambda^{-} > 1.6$ TeV

Jets at Large Rapidity Intervals

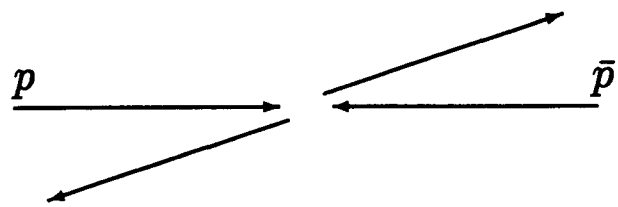
- *Hard Region - Small y $(y \equiv y_1 - y_2)$*



$Q \sim p_T \sim \sqrt{\hat{s}}$

– conventional perturbative QCD has been quite successful describing the experimental data

- *Semihard Region - Large y*

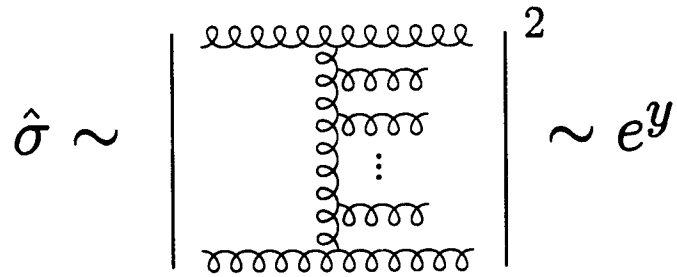


$Q \sim p_T \ll \sqrt{\hat{s}}$

When $y \gg 1 \Rightarrow y \sim \ln(\frac{\hat{s}}{Q^2})$

– large logarithms $\ln(\frac{\hat{s}}{Q^2})$ may appear in the partonic cross section and ruin the calculation

– these logarithms can be resummed by using the Balitsky-Fadin-Kuraev-Lipatov (BFKL) formalism



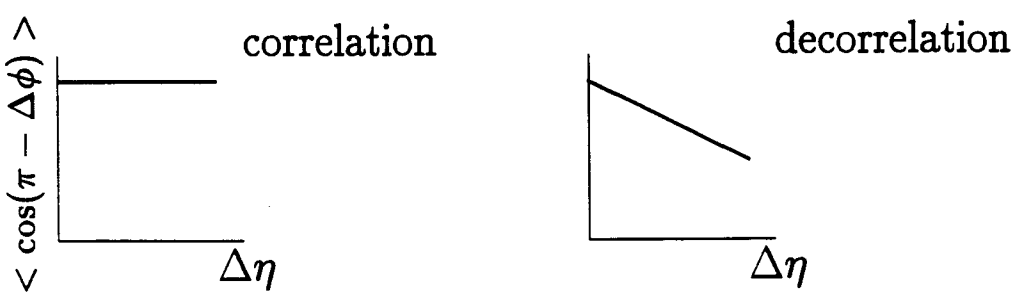
– BFLK resummation technique can also be applied at *ep* deep inelastic scattering at very low x

- *Study of jet-jet decorrelations can provide important insights into testing the BFKL resummation theories and the significance of higher order processes*

- *Measure the decorrelation in ϕ as a function of $\Delta\eta$*

  – plot $< \cos(\pi - \Delta\phi) >$ vs $\Delta\eta$ for the two jets with the largest rapidity separation

  where $\Delta\phi = | \phi_1 - \phi_2 |$ and $\Delta\eta \equiv y$ (massless partons)

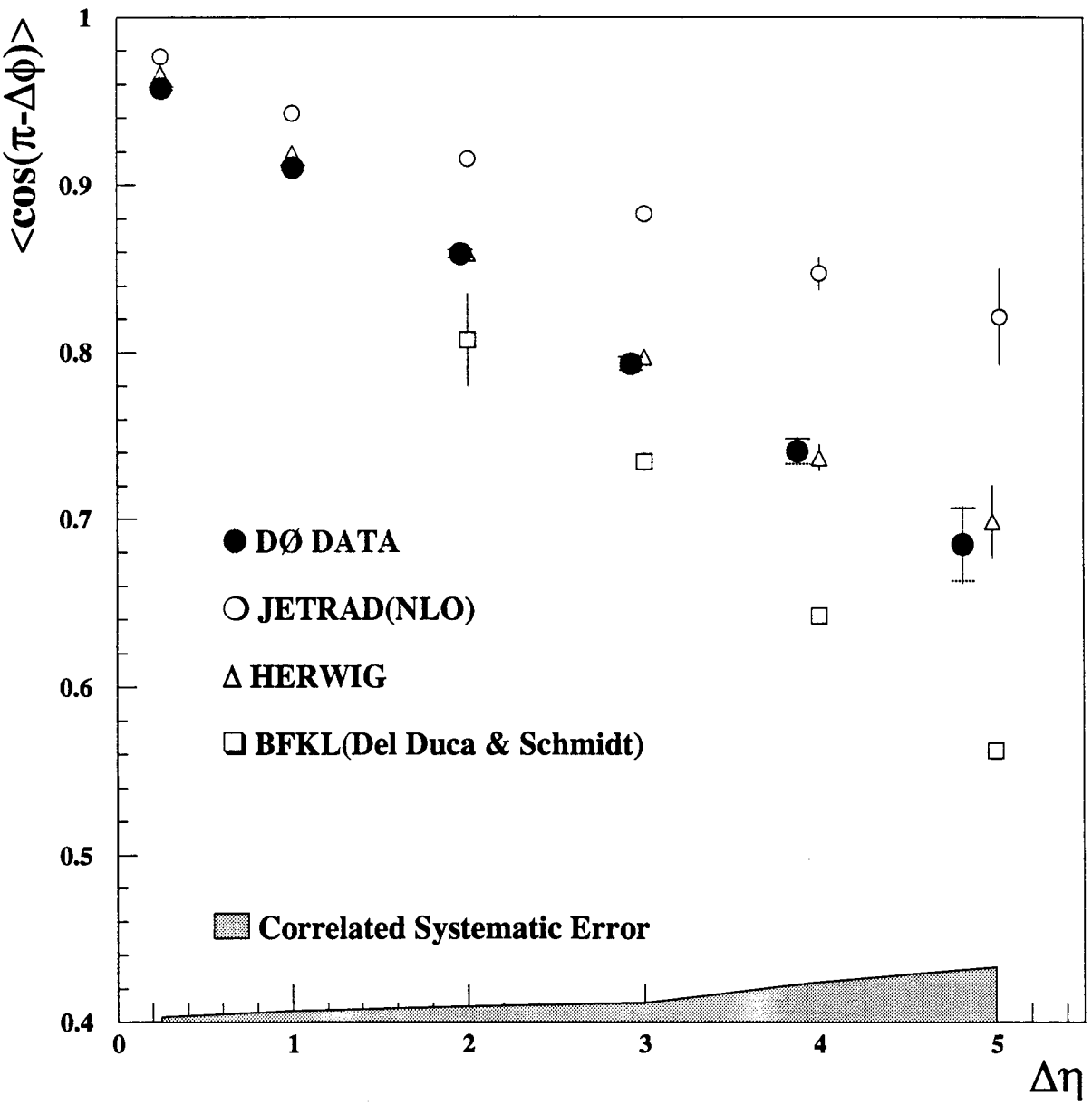


– compare DATA to HERWIG, JETRAD and BFKL predictions

Run1A Measurement

Require one of the tagged jets to have $E_T > 50$ GeV and the other $E_T > 20$ GeV

$\langle \cos(\pi - \Delta\phi) \rangle$ vs. $\Delta\eta$



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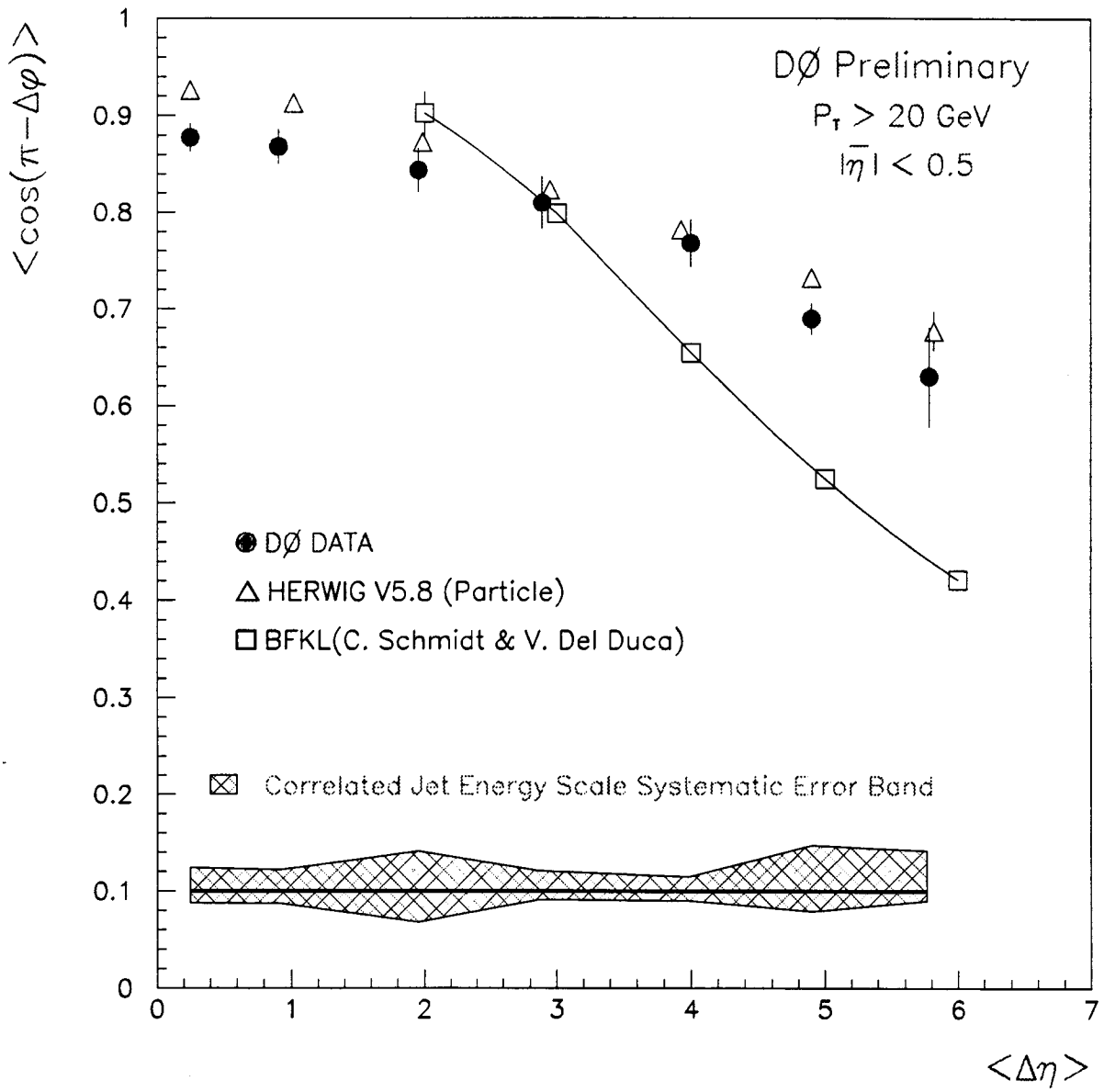
Run1B Measurement

Require both tagged jets to have $E_T > 20$ GeV

$\langle \cos(\pi - \Delta\phi) \rangle$ vs. $\Delta\eta$



Conclusions

- The Tevatron high-E_T jet data @ 1800 and 630 GeV are challenging the theory
- Inclusive jet cross section has been measured vs ET and jet cone size
- Theoretical predictions are uncertain to 15-25% level with an additional 20% from PDFs
- Enough flexibility on the gluon distribution to accommodate the high-E_T jet data
- The dijet angular distributions disfavor new physics of scale $\Lambda_c \sim$ 1.8 TeV. Excellent agreement with NLO predictions
- No direct sign of BFKL yet...

Wish List &Questions...

- Can the uncertainty on the current PDFs be quantified? (e.g. μ-scale, Theory Model, exp systematics etc ...)
- Which μ scale should we be using? $E_T^{max}/2$ vs $E_T^{jet}/2$?
- What relationship exists among μ scales as a function of cm energy and cone size?
- Need for NLO predictions with added contact term
- What does K_T do to jets?
- NLL BFKL Predictions ?