Inclusive Jets at the Tevatron

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1. Jets at CDF and D0
2. The Inclusive Jet Cross Section versus E_T at $\sqrt{s} = 1800$ GeV
3. The Inclusive Jet Cross Section versus E_T at $\sqrt{s} = 630$ GeV
4. The Ratio of the Dimensionless Cross Sections versus x_T

The motivation:

Jet distributions at colliders can:

- signal new particles + interactions
- test QCD predictions
- check parton distribution functions

The complementary Tevatron detectors D0 and CDF have studied the inclusive jet cross section at

$$\sqrt{s} = 1800 \text{ and } 630 \text{ GeV} \ldots$$

Common features of the two detectors:

•Luminosity monitors near beamline to monitor collision products. At each site,

$$L = \frac{\text{monitor event rate}}{\text{portion of } p\bar{p} \text{ cross section accepted}}.$$

CDF + D0 use slightly different $p\bar{p}$ cross sections → the CDF jet cross section ends up 2.7% higher.

•Both calorimeters have projective towers that point to the nominal IP.

•The p beam is $\hat{z}$, θ is measured relative to $\hat{z}$, + azimuth φ is measured from the Tevatron plane.

D0 in Run 1:

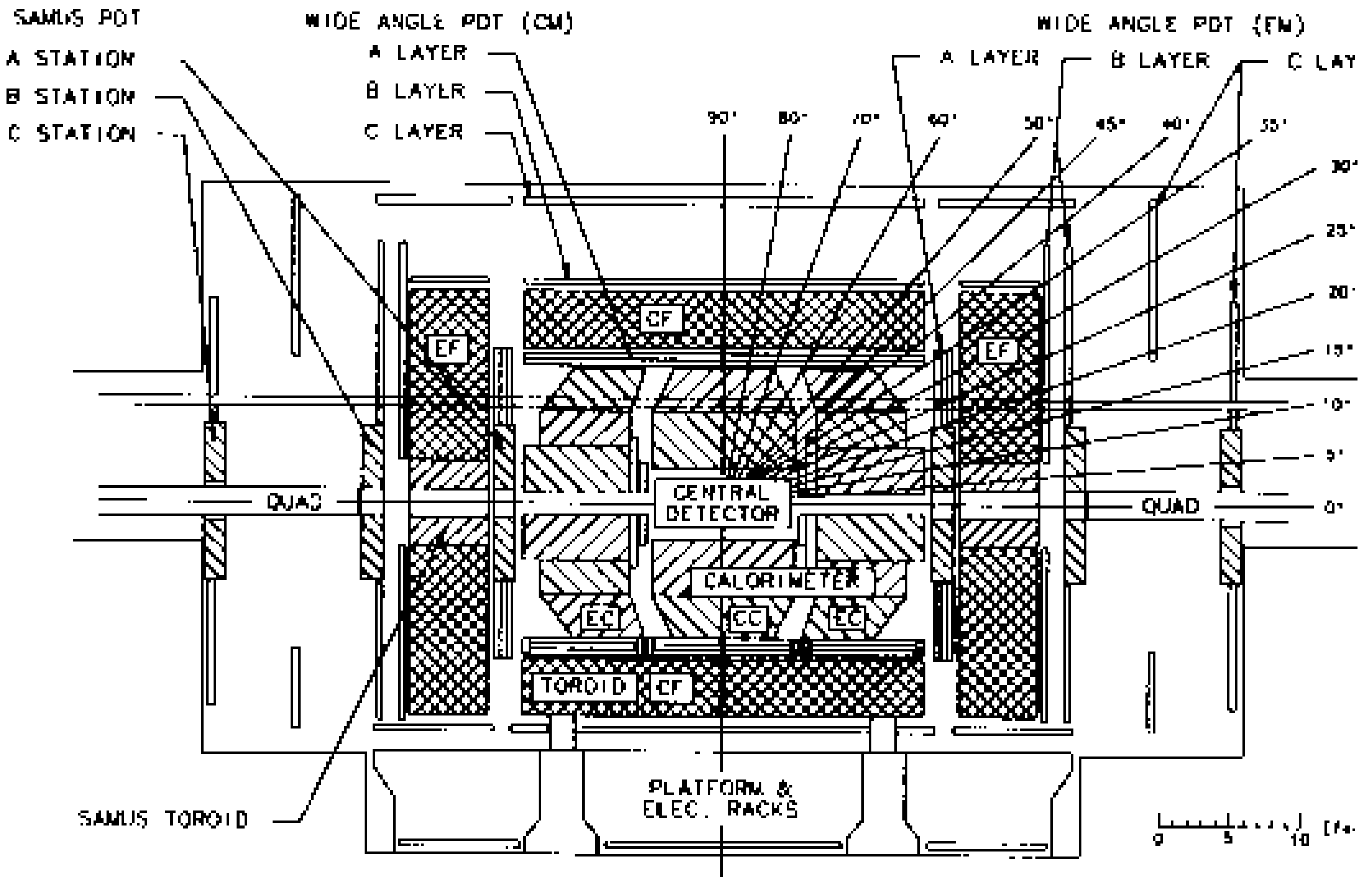


Fig. I ELEVATION OF DQ/DETECIOR

- Central Tracking (radius to 75 cm, 270 cm length, $|\eta| \leq 2$), to find vertices:
  - vertex drift chamber
  - transition radiation detector
  - 3-barrel central + 2 forward drift chambers
- Calorimetry, to find jets:
  - thick, uniform, finely segmented, unit gain LAr with U + Cu absorbers; ~compensating (Gaussian response, $\sigma_E/E = 5 - 7\%$)
  - central calorimeter: $|\eta| \leq 1.2$
    - 32 EM (U; 4 samples),
      16 fine HA (U; 3 samples),
      16 coarse HA (Cu, 1 sample) modules
    - 7.2 absorption lengths @ $\eta = 0$
    - $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$ (0.05×0.05 @ shower max)

- $\frac{\sigma_E(e)}{E} = \frac{14.8\%}{\sqrt{E}} \oplus 0.3\%$; $\frac{\sigma_E(had)}{E} = \frac{47.0\%}{\sqrt{E}} \oplus 4.5\%$

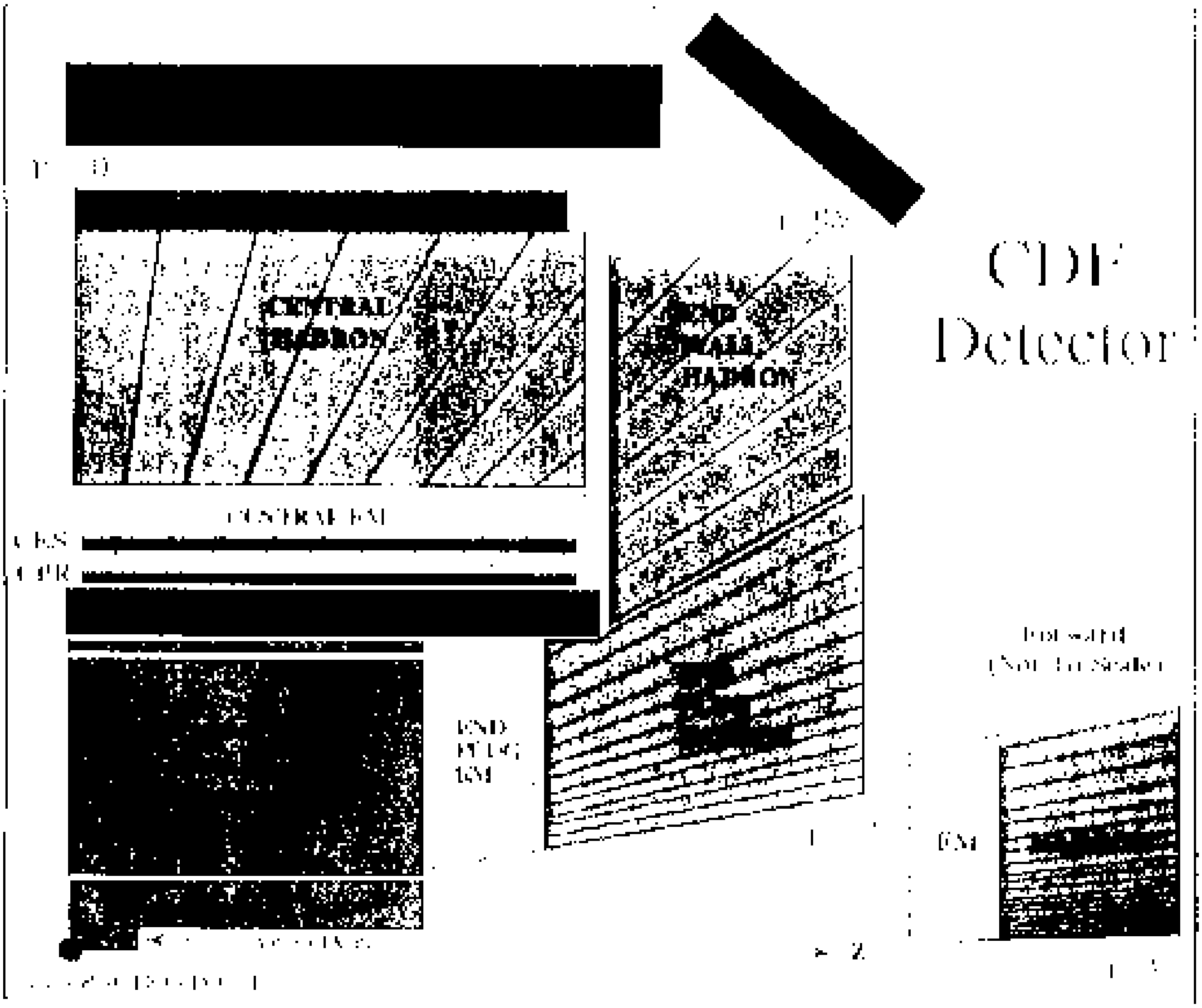
- Endcap calorimeter: $|\eta| \leq 4.4$
  - inner EM (U), inner HA (U), middle HA (U + stainless), outer HA (stainless)
  - 10 λ_0, 8–9 segments @ $\eta = 2$
  - $\frac{\sigma_E(e)}{E} = \frac{15.7\%}{\sqrt{E}} \oplus 0.3\%$; $\frac{\sigma_E(had)}{E} = \frac{44.6\%}{\sqrt{E}} \oplus 3.9\%$

D0 jet energy calibration procedure corrects for:

- calorimeter hadronic response
- electromagnetic showering out of the reconstruction cone (see below)
- offsets due to instrumental effects, multiple event pile-up, multiple interactions, underlying event

- EM response calibrated with $Z \rightarrow ee$ and $\pi^0 \rightarrow \gamma\gamma$
- HA response calibrated from central γ-jet events by E_T balancing
- Calibration of jets
  - w/ $E_T < 150$ GeV: directly from events w/central γ, jet
  - w/ $E_T < 300$ GeV: with central γ + high-η jet
  - Extend to $E_T > 300$ GeV by simulation

CDF in Run 1:


CENTRAL HADRON
END WALL HADRON
CDF Detector
CENTRAL EM
CES
CPR
END PLUG EM
EM

- Central tracking ($|\eta| \leq 1$):
    - 4-layer Si strip vertex chamber for r-ϕ
    - vertex drift chamber for r-z + IP
    - 3.2 m central drift chamber @ $31 \leq r \leq 132$ cm
    - all inside 1.5 T B field
    - $\frac{\delta p_T}{p_T^2} = 0.0009\, p_T \oplus 0.0066$; p_T in GeV/c
- Calorimeters :
    - Central Calorimeter
        - EM (scintillator + Pb, $|\eta| \leq 1.1$); HA (scintillator + Fe, $|\eta| \leq 1.3$)
        - $\Delta\varphi \times \Delta\eta = 15° \times 0.1$
        - 4.5 absorption lengths
        - $\frac{\sigma_E}{E}(e) = \frac{13.7\%}{\sqrt{E}} \oplus 2\%$

- $\left(\frac{50\%}{\sqrt{E}} \oplus 3\%\right) \le \frac{\sigma_E}{E}(had) \le \left(\frac{75\%}{\sqrt{E}} \oplus 4\%\right)$

- Plug + forward calorimeters ($2.2 \le |\eta| \le 4.2$)
  - gas proportional chambers
  - $\Delta\eta \times \Delta\varphi \approx 0.1 \times 5^\circ$

CDF jet energy calibration corrects for:

- calorimeter response
- multiple interactions
- neutrinos + muons
- underlying event

Corrections are based on

- Monte Carlo tuned on test beam (for $10\ \text{GeV} \leq E_{beam} \leq 227\ \text{GeV}$).
- CTC (drift chamber) tracks w/ $400\ \text{MeV/c} \leq p_T \leq 10\ \text{GeV/c}$.

MC fragmentation parameters tuned to match observed particle momenta + numbers.

Calorimeter resolution: $\sigma = 0.1E_T + 1\text{GeV}$.

Forward + plug calorimeter response calibrated by balancing dijets in which 1 jet of the pair is central.

The data:

CDF + D0 reconstruct jets using an *iterative cone algorithm* with cone radius

$$R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2} = 0.7$$

A typical jet crosses 40 calorimeter cells in CDF + 100 cells in D0.

Both experiments use algorithms based on the Snowmass one, which says: if *i* indexes all towers within cone radius *R*,

$$E_T^{jet} \equiv \sum_i E_T^i$$

$$\eta^{jet} \equiv \left(\sum_i E_T^i \eta_i \right) \Big/ E_T^{jet}$$

$$\varphi^{jet} \equiv \left(\sum_i E_T^i \varphi_i \right) \Big/ E_T^{jet}$$

The *D0 iterative cone algorithm*:

•Examine all calorimeter towers with $E_T > 1$ GeV.

•Begin w/ highest E_T tower, form preclusters by adding all neighboring towers within $R = 0.3$.

•Calculate jet direction (η,φ) for each precluster.

•Sum all energy within $R = 0.7$ about precluster jet direction; recalculate (η,φ).

•Iterate until jet direction is stable.

If two jets overlap –

Merge them if ≥ 50% of the smaller jet's E_T is in the overlap region; otherwise assign the overlap energy to the nearest jet.

Then recalculate (η,φ).

The *CDF iterative cone algorithm*:

- Examine all towers with $E_T > 1$ GeV.
- Form preclusters from continuous groups of towers with monotonically decreasing E_T.
- If a tower is outside a window of 7 x 7 towers from the seed of its cluster, start a new precluster with it.
- For each precluster, find the E_T-weighted centroid for all towers with $E_T > 100$ MeV within $R = 0.7$.
- Define the centroid to be the new cluster axis.
- Iterate until the tower list is stable.

If 2 jets overlap –

Merge them if ≥ 75% of the smaller jet's E_T is in the overlap region; otherwise assign overlap energy to the nearest jet.

Recalculate (η, φ).

For D0, $E_T^{jet} = \sum_i E_T^i$

For CDF, $E_T^{jet} = E \sin\theta^{jet}$, where

$$\theta^{jet} = \tan^{-1}\left[\frac{\sqrt{\left(\sum_i E_x^i\right)^2 + \left(\sum_i E_y^i\right)^2}}{\sum_i E_z^i}\right]$$

….the D0 jets are massless ($p_T = E_T$) whereas the CDF jets have mass.

The Inclusive Jet Cross Section, $E \cdot d^3\sigma/dp^3$

- For jet transverse energies achievable at the Tevatron, this probes distances down to 10^{-17} cm.
- For massless jets + 2π acceptance in φ,

$$E\frac{d^3\sigma}{dp^3} = \left(\frac{1}{2\pi E_T}\right)\left(\frac{d^2\sigma}{dE_T\,d\eta}\right)$$

$$\uparrow$$

$$\frac{N}{\Delta E_T \cdot \Delta\eta \cdot L}$$

This is what we measure.

CDF (D0) begin with similar data quality requirements:

- $|z_{vertex}| < 60$ (50) cm to maintain projective geometry of calorimeter towers.
- $0.1\ (0.0) \leq |\eta_{detector}| \leq 0.7\ (0.5)$ for full containment of energy in central barrel.
- (CDF only:) $E_{total} < 1800$ GeV to reject accelerator loss events.
- To reject cosmic rays + misvertexed events, define $\not{E}_T$ = missing E_T. Require

$$\frac{\not{E}_T}{\sqrt{\sum_{all} E_T}} < 6 \qquad \text{(CDF)}$$

$\not{E}_T < (30$ GeV or $0.3 E_T^{\text{leading jet}}$, whichever is larger). (D0)

- Apply EM/HA + jet shape cuts to reject noise fakes.

Both next correct for

•Pre-scaling of triggers.

•Detection efficiencies (typically 94 –100%).

•underlying event + multiple interactions.

•"Smearing": energy mismeasurement + detector resolution.

**No correction is made for jet energy deposited outside the cone by the fragmentation process, as this is included in the NLO calculation to which the data are ultimately compared.*

The CDF Unsmearing Procedure:

Simultaneous correction for detector response + resolution produces a result that is independent of binning but preserves the statistical uncertainty on the measured cross section.

•A smooth function is proposed representing a trial "pre-detector" cross section. This is called the "physics function." For the inclusive cross section, the physics function has the form:

$$\frac{d\sigma(E_T^{true})}{dE_T^{true}} = P_0(1-x_T)^{P_6} \times 10^{F(E_T^{true})},$$

where:

$$F(x) = \sum_{i=1}^{5} P_i[\ln(x)]^i,$$

$$x_T = 2E_T^{true}/\sqrt{s},$$

E_T^{true} is in GeV + the P_i are fitted parameters.

•The physics function is convoluted with measured E_T-loss and resolution functions and binned in E_T. The response functions have long tails due to uninstrumented regions. The response function is parameterized by an exponential combined with a Gaussian and depends on the choice of cone opening angle. The response function requires

•Gaussian mean $M = C_1 E_T^3 + C_2 E_T^{\frac{1}{3}} + C_3 E_T^2 + C_4 E_T^{\frac{1}{2}} + C_5 E_T + C_6$,

•Gaussian standard deviation $\sigma = C_7 (E_T + C_8)^{C_9} - C_{10}$, and

•Exponential decay constant $S = C_{11} E_T + C_{12}$ (where C_{11} and C_{12} depend upon the E_T range).

The C_i are determined by comparing measured calorimeter jet response to jets in Monte Carlo simulation. The Monte Carlo is based on single particle response from test beam data and isolated tracks from minimum bias events.

•The result of the convolution is compared with the measured cross section.

•The parameters of the physics function are iterated to obtain the best match between the convoluted function and the data.

•The ratio of (data):(physics function) for each E_T bin is tabulated. The correction factors (typically 10%) are subsequently applied to data to obtain the "unsmeared physics cross section."

The D0 Unsmearing Procedure:

This procedure corrects for detector response and resolution sequentially.

- Correct the E_T of each measured jet for the average response of the calorimeter.
- Assume an ansatz function of the form

$$\frac{d\sigma(E_T)}{dE_T} = A \cdot E_T^{-B} \cdot (1 - x_T)^C,$$

where :

E_T is the corrected transverse energy and

$x_T = 2E_T / \sqrt{s}$.

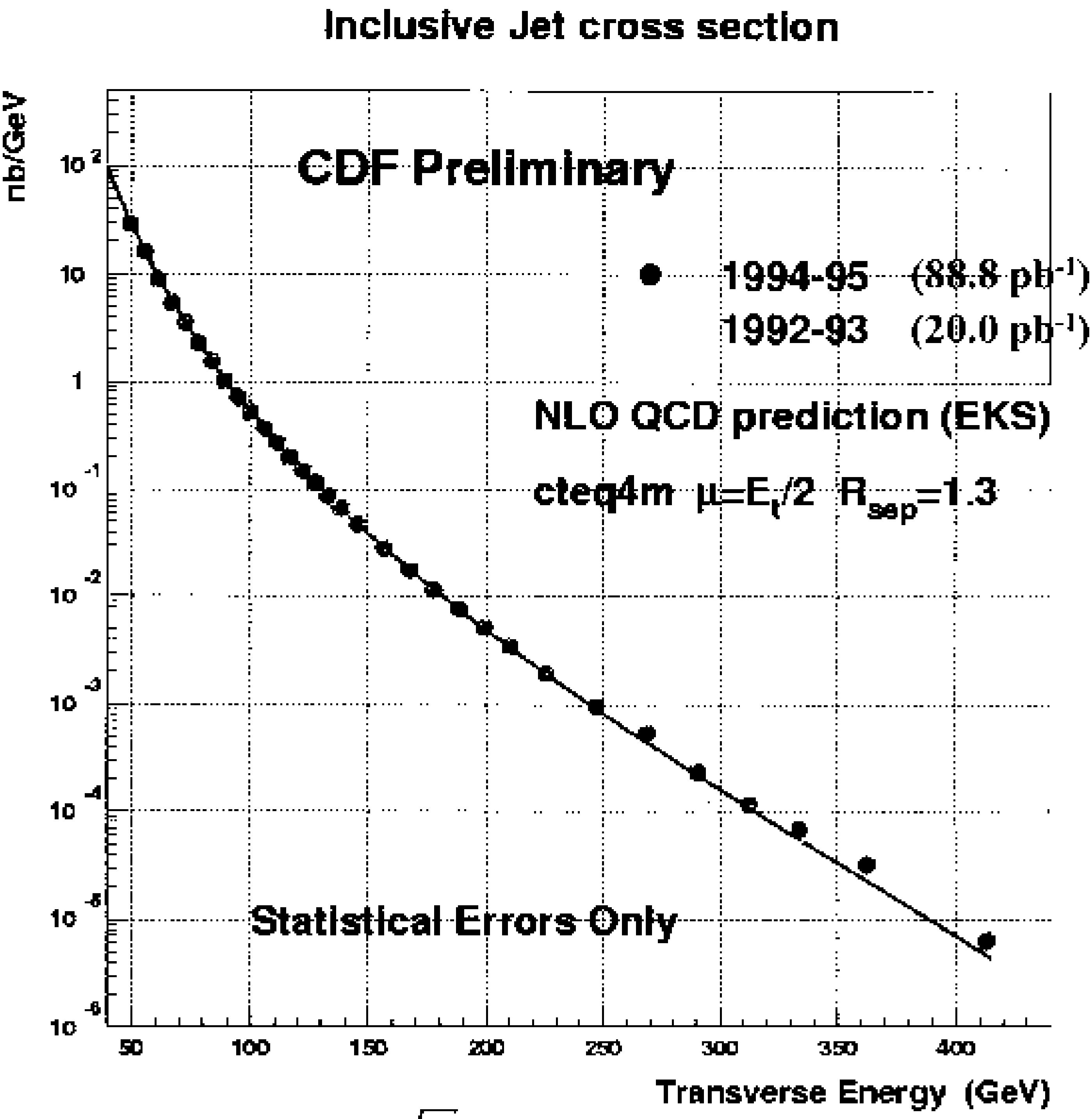
Convolute this with the (E_T-dependent, Gaussian) measured resolution function. Compare the result with the measured cross section.

- Iterate to optimize A, B, and C.
- Tabulate ratio (initial physics function) : (smeared physics function) for each E_T bin + apply it to the cross section.

The inclusive jet cross section results, for

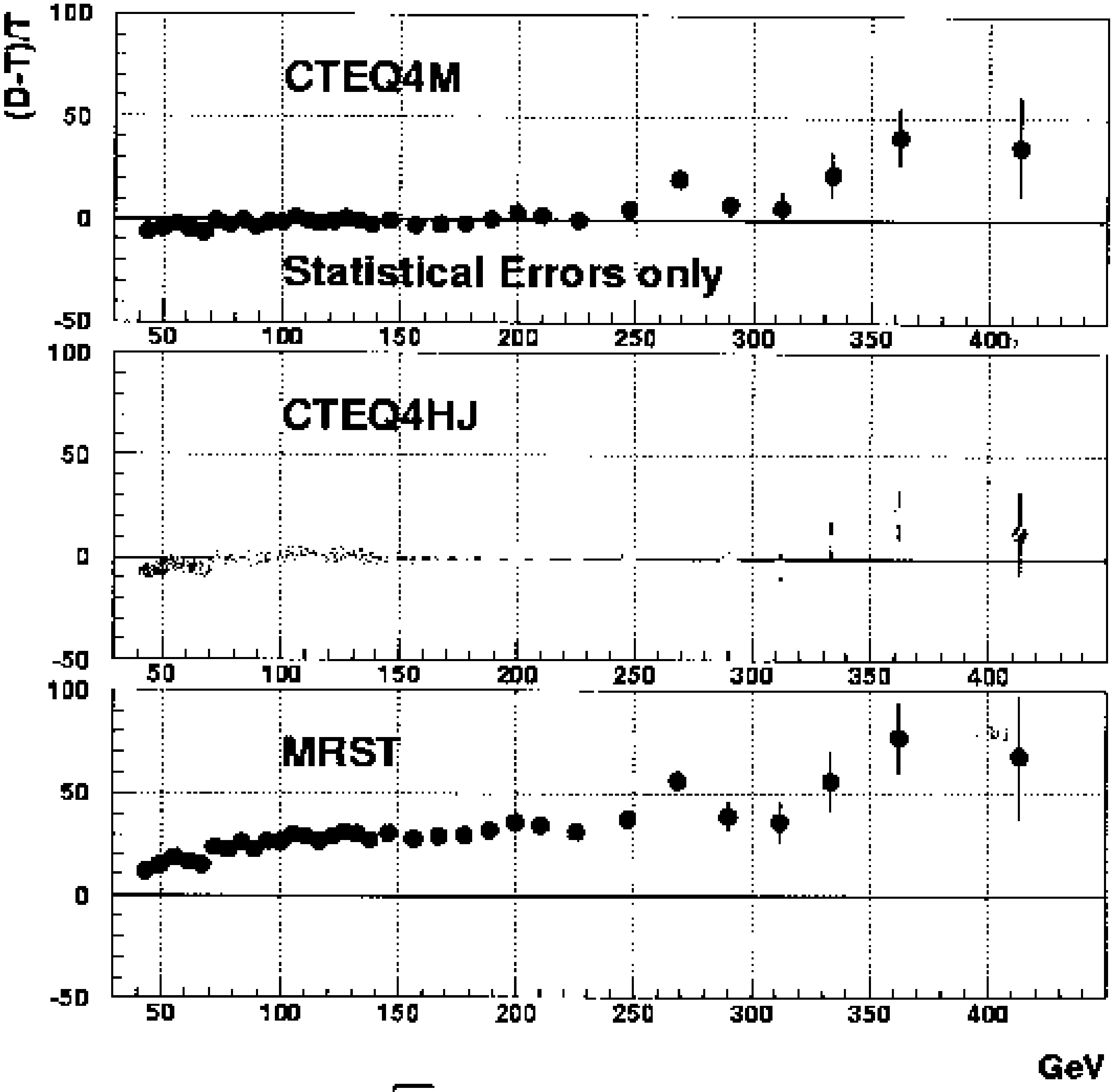
$\sqrt{s} = 1800\,\mathrm{GeV}$...

The CDF Result:



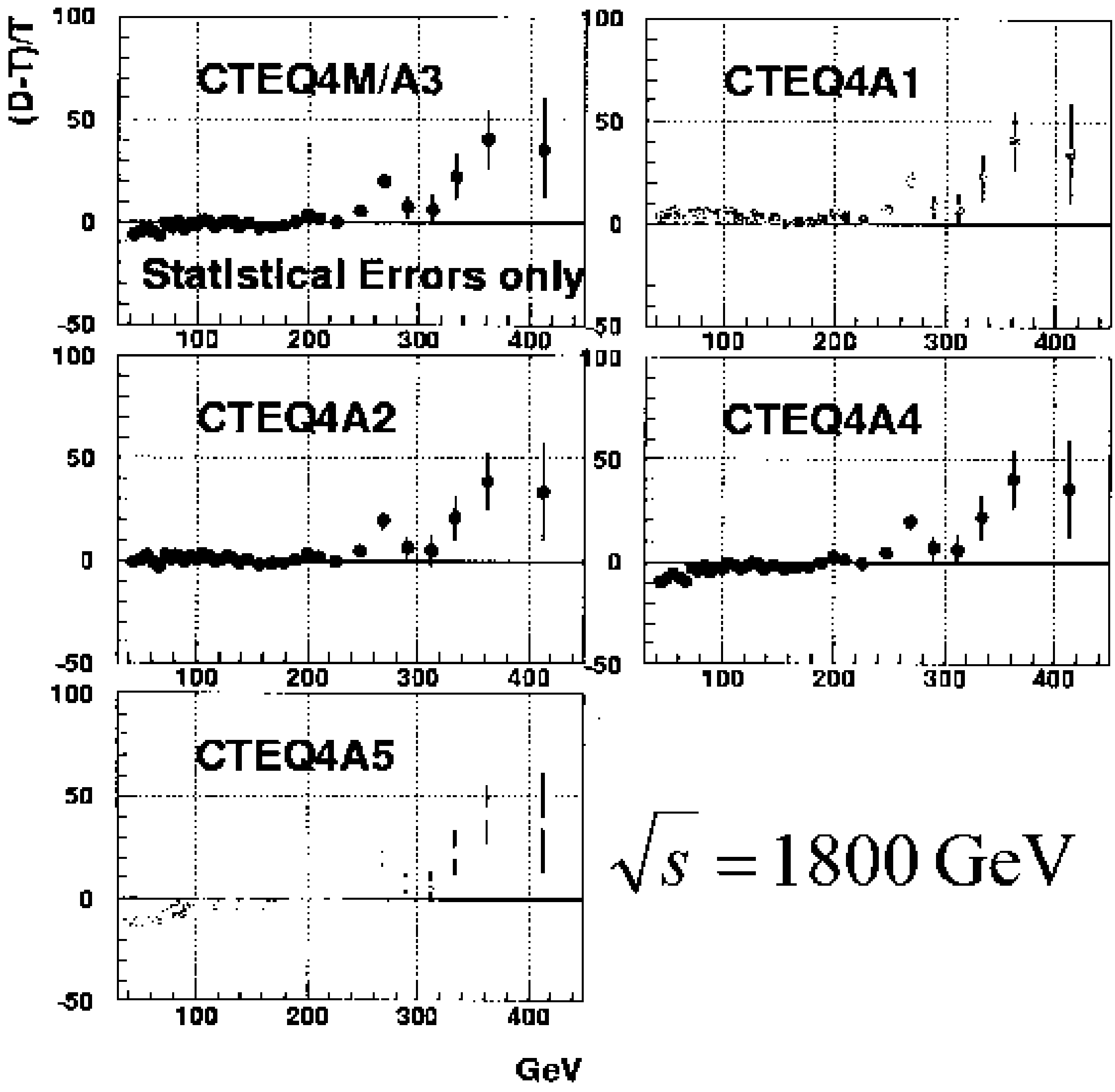
$$\sqrt{s} = 1800\,\text{GeV}$$

Inclusive Jet Cross Section (CDF Preliminary)



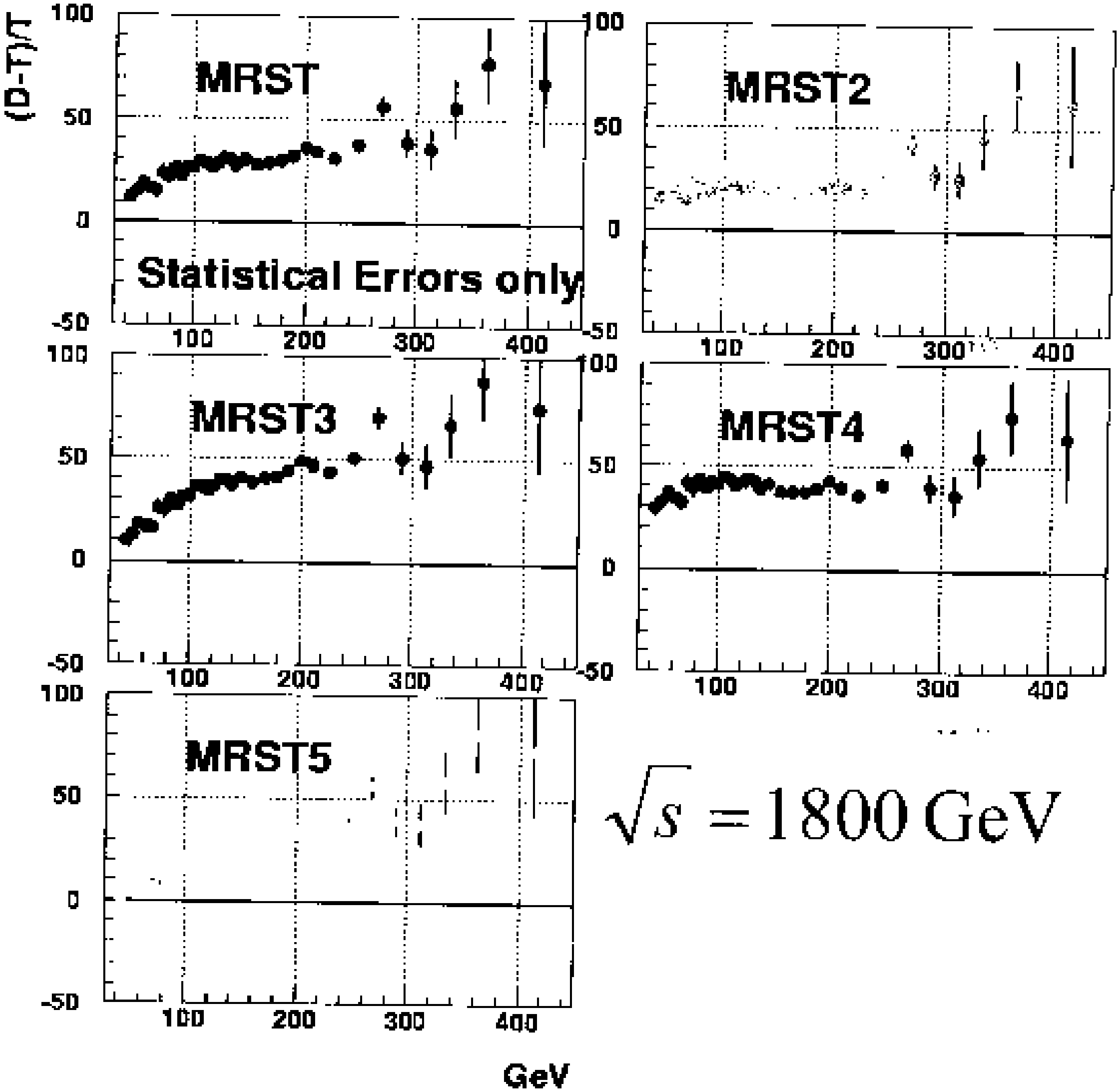
$$\sqrt{s} = 1800\,\text{GeV}$$

Inclusive Jet Cross Section (CDF Preliminary)



$\sqrt{s} = 1800\,\mathrm{GeV}$

Inclusive Jet Cross Section (CDF Preliminary)



$$\sqrt{s} = 1800\,\mathrm{GeV}$$

Systematic uncertainties (all uncorrelated) on the CDF inclusive jet cross section:

i. Calorimeter response to high-p_T charged hadrons

ii. Calorimeter response to low-p_T charged hadrons

iii. Energy scale stability (±1%)

iv. Jet fragmentation model used in the simulation

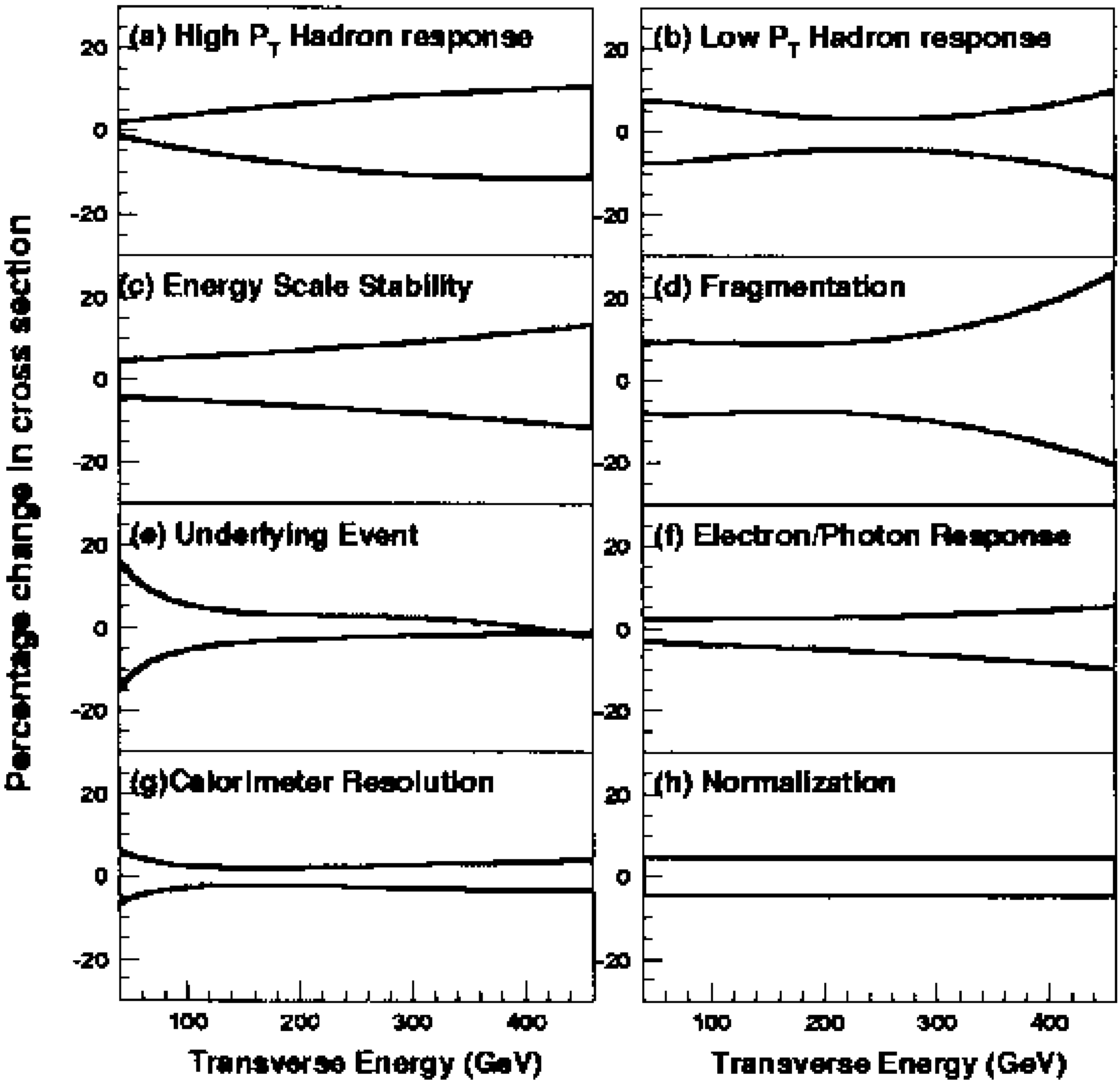
v. Energy of the underlying event in the jet cone (±30%)

vi. Calorimeter response to electrons + photons

vii. Modelling of the jet energy resolution function

viii. Normalization (3.8%)

Systematic uncertainties (CDF Preliminary)



The high-E_T excess present in the Run 1b data is consistent with what was previously observed in the Run 1a data. No single experimental source of systematic uncertainty can account for the excess. The significance of the excess was analyzed after Run 1a with 4 normalization-independent, shape-dependent statistical tests:

- signed Kolmogorov-Smirnov
- unsigned Kolmogorov-Smirnov
- Smirnov-Cramer-VonMises
- Anderson-Darling

The MRSD0' PDF was used since it describes the low-E_T data best. All 8 sources of systematic error + the effect of finite binning was included. Two E_T ranges were tested independently:

For $40 < E_T < 160$ GeV:

All 4 tests show > 80% agreement between data + theory.

For $E_T > 160$ GeV:

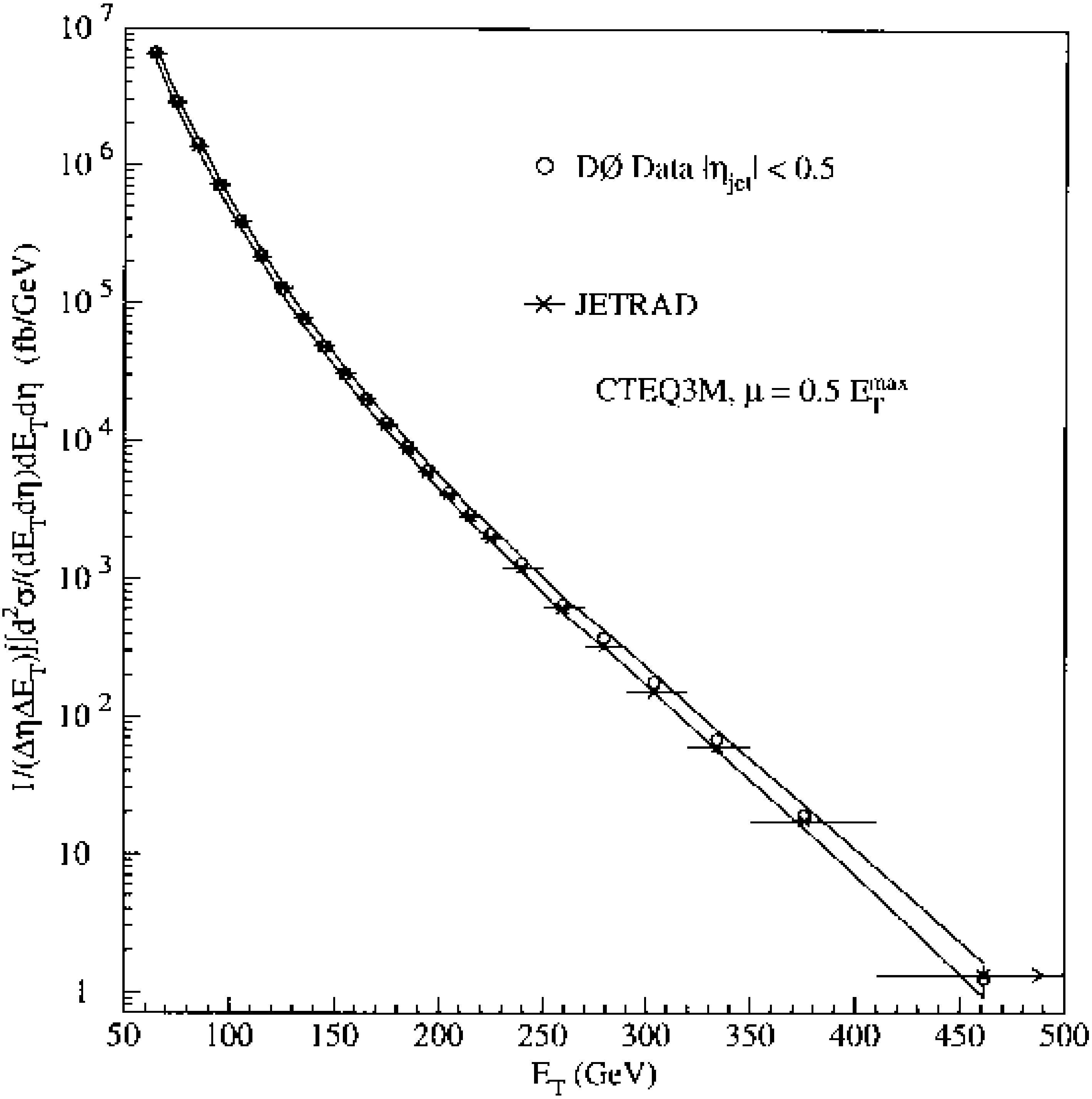
Each test indicates that the probability that the excess is due to fluctuation is 1% .

For other PDF's (CTEQ2M, CTEQ2ML, GRV94, MRSA', + MRSG), agreement at low E_T is reduced if the agreement at high E_T is improved.

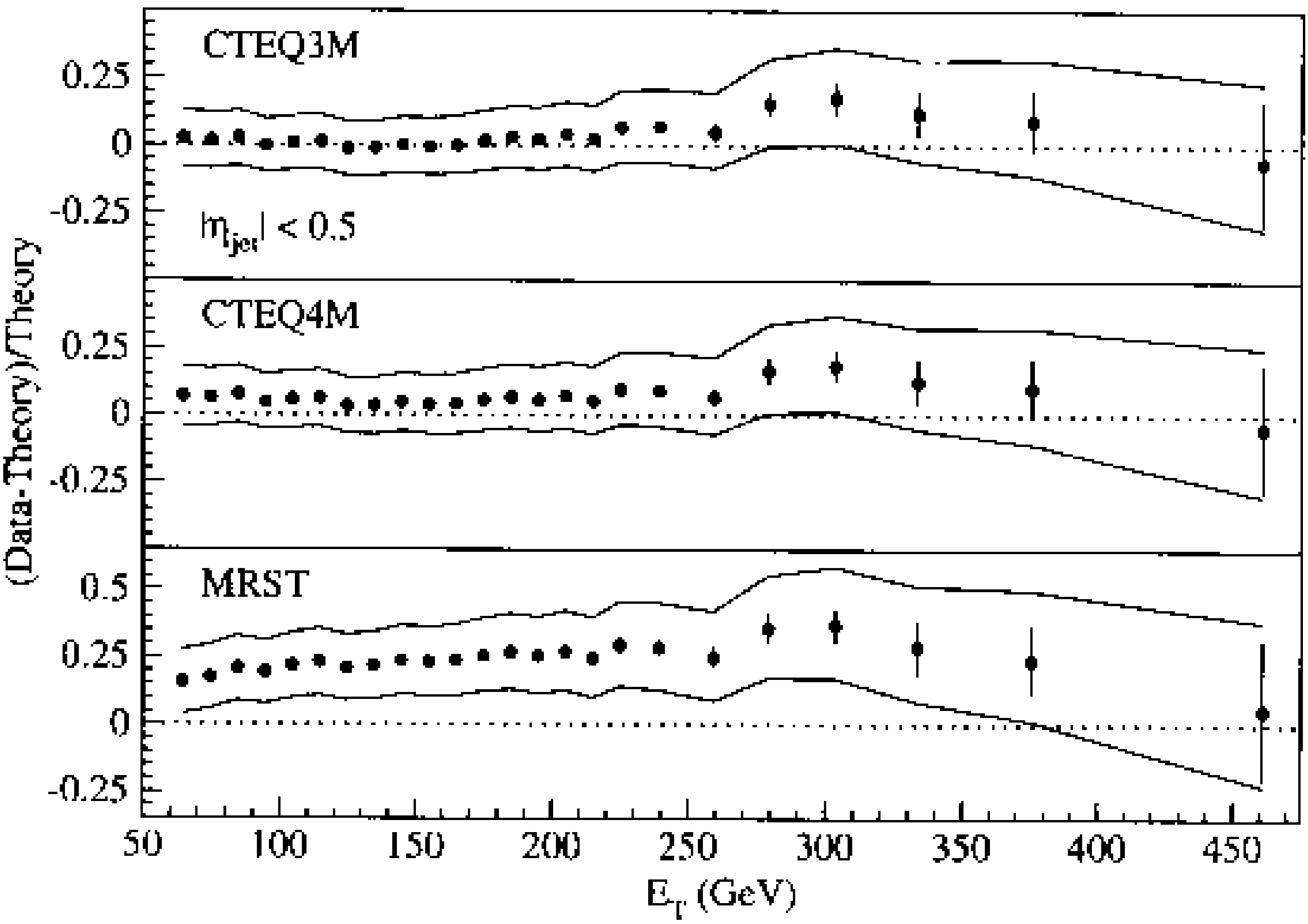
The best agreement at high E_T is for CTEQ2M: 8% likelihood for high E_T but only 23% for low E_T.

Quantitative comparison of the CDF Run 1b result with theory is now underway.

The D0 result:



$$92\ \text{pb}^{-1}\ @\ \sqrt{s} = 1800\ \text{GeV}$$



$$\sqrt{s} = 1800\,\text{GeV}$$

Systematic uncertainties on the D0 inclusive jet cross section:

i. The calorimeter energy scale (including response + corrections).

ii. The jet selection procedure (including jet, $\not{E}_T$, and vertex cut efficiencies).

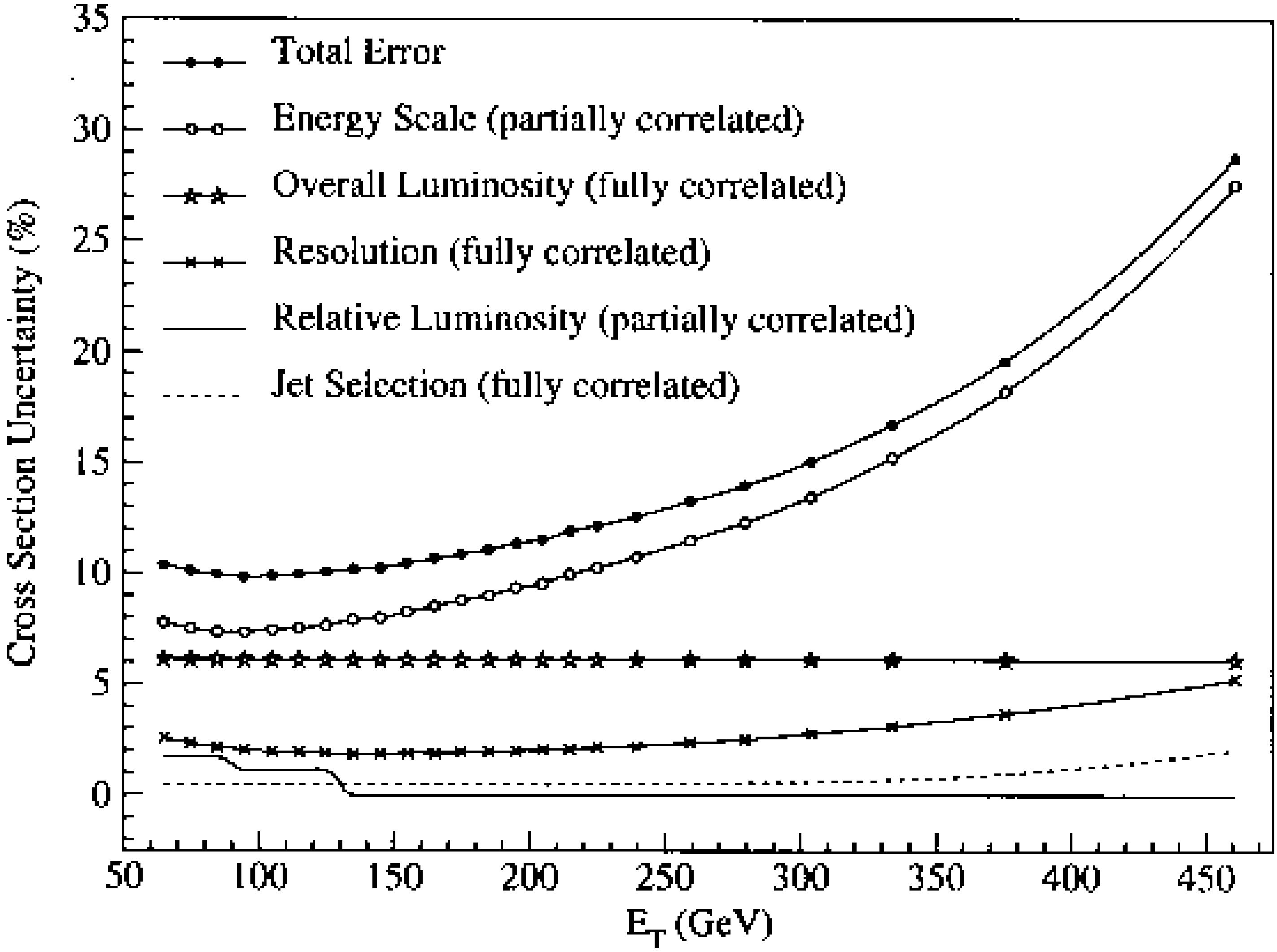
iii. Relative luminosity (uncertainties on prescale values of component triggers).

iv. Determination of the jet energy resolution function needed for unsmearing (including fitting + choice of q-g fractions).

v. Luminosity (including hodoscope acceptance, Level 0 hardware efficiency, and $\sigma_{inel}(\bar{p}p)$ uncertainty).

D0 systematic uncertainties

$@\ \sqrt{s} = 1800\,\text{GeV}:$



χ^2 Comparison of the D0 data and theory:

i.) Define

$$\chi^2 = \sum_{i,j} (D_i - T_i)(C^{-1})_{ij}(D_j - T_j),$$ where

i = bin #

D = number of jets observed in the data

T = number of jets predicted by the theory

C = uncertainty covariance matrix

ii.) Construct the C_{ij} by analyzing the correlation of uncertainties between each pair of E_T values. (Bin-to-bin correlations for representative E_T bins are ~ 40% + positive.)

iii.) There are 24 d.o.f.

iv.) Compare the data to JETRAD with 5 PDF's:

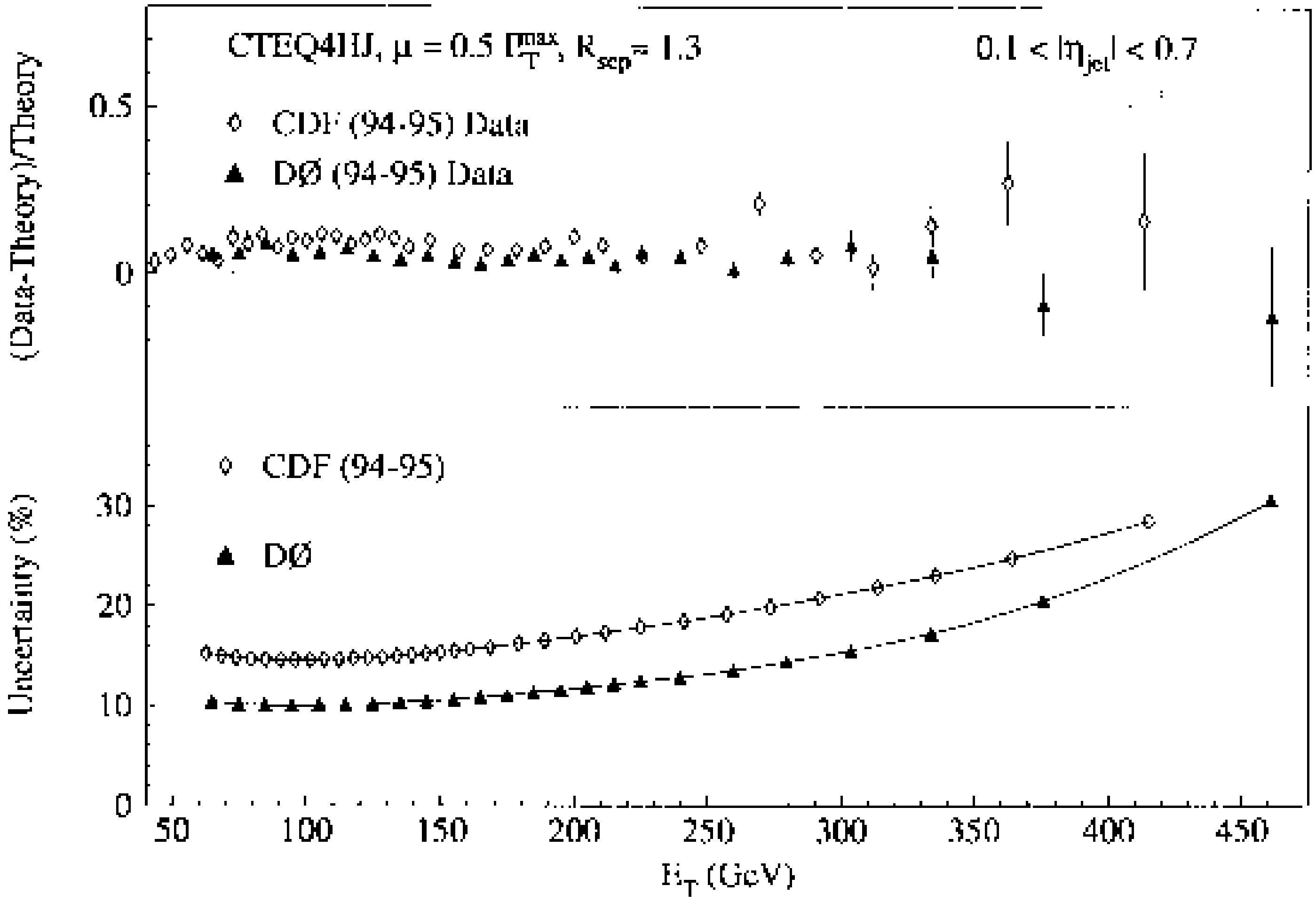
- χ^2/dof = 0.65 – 1.0 (Prob. 47 – 90%) for data in range $|\eta| \leq 0.5$.
- χ^2/dof = 0.8 – 1.0 (Prob. 24 – 72%) for data in range $0.1 \leq |\eta| \leq 0.7$.

v.) Compare the data to EKS using CTEQ3M, $R_{sep} = 1.3R$, and scale $\mu = cE_T^{max}$ or $\mu = cE_T^{jet}$ (c = 0.25, 0.5, or 1.0):

- Prob. ≥ 57% in all cases.

✓ Good agreement.

Comparison between D0 + CDF measurements, both relative to JETRAD:



- Excellent agreement between nominal values for $E_T \leq 350$ GeV.

- To quantify the level of agreement over the full E_T range, D0 carried out a χ^2 comparison between D0 data + the nominal curve describing the central values of the CDF Run 1b data:

  - $\chi^2 = 41.5$ for 24 d.o.f.

  - To approximate a "statistical error only" comparison, find the value of the CDF curve at the D0 E_T points, multiply the D0 stat errors by $\sqrt{2}$ to make them equivalent to CDF's, + remove the 2.7% relative normalization difference… $\chi^2 = 35.1$ (prob. 5.4%).

  - Add syst. error info by expanding the covariance matrix to include both D0 + CDF… $\chi^2 = 13.1$ (prob. 96%).

The Ratio of Dimensionless Cross Sections

Consider $x_T \equiv 2E_T/\sqrt{s}$.

Consider the dimensionless cross section,

$$\sigma_d \equiv E_T^4\left(E\frac{d^3\sigma}{dp^3}\right)$$

Again for massless partons, this can be written as

$$\sigma_\mathrm{d} \equiv \left(\frac{E_T^3}{2\pi}\right)\left(\frac{d^2\sigma}{dE_T d\eta}\right)$$

$$\uparrow$$

$$\frac{N}{\Delta E_T \cdot \Delta\eta \cdot L}$$

•The Naïve Parton Model hypothesis that σ_d is independent of $\sqrt{s}$, when plotted versus x_T, is called "scaling."

•QCD predicts scaling violation due to the energy-scale dependence of the probability for gluon radiation from a primary parton in the collision.

→ This energy scale dependence leads to the running of α_s + the evolution of the PDF's.

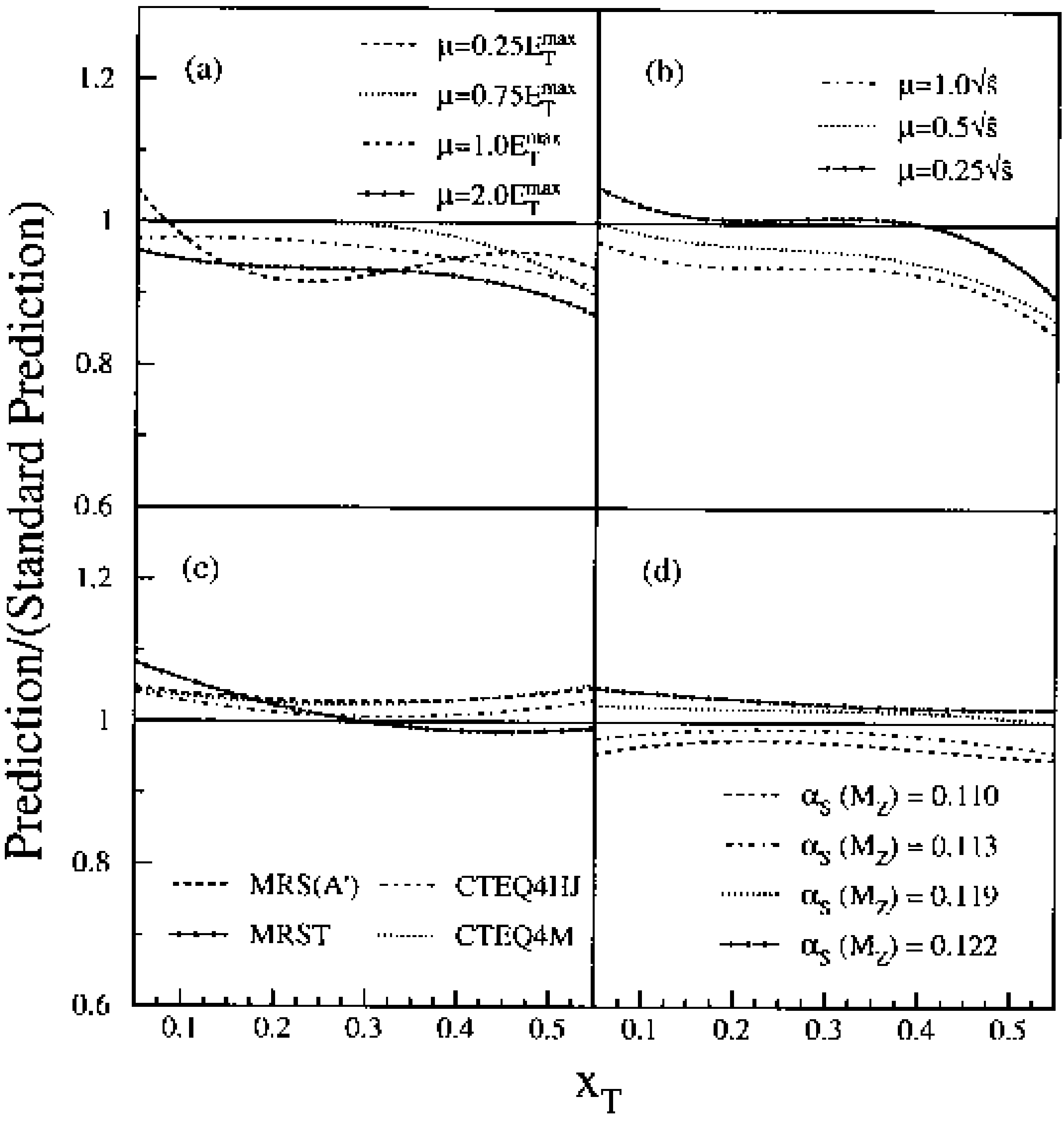
• Comparison of σ_d measured at 2 different energies by the same experiment suppresses many theoretical + experimental uncertainties.

Suppression of theoretical uncertainties:

$$\frac{\sigma_d\left(\sqrt{s} = 630\,\mathrm{GeV}\right)}{\sigma_d\left(\sqrt{s} = 1800\,\mathrm{GeV}\right)}$$

was calculated by JETRAD, for the case of $\mu = 0.5E_T^{max}$ and CTEQ3M, then compared to a range of other options for μ, PDF, + α_s:

the result of this study on the dependence of the calculation on input parameters:



All show ≤ 10% variation for $x_T < 0.4$.

•D0 + CDF each collected ≈600 nb^{-1} of data @ $\sqrt{s} = 630$ GeV in Dec. ‘95.

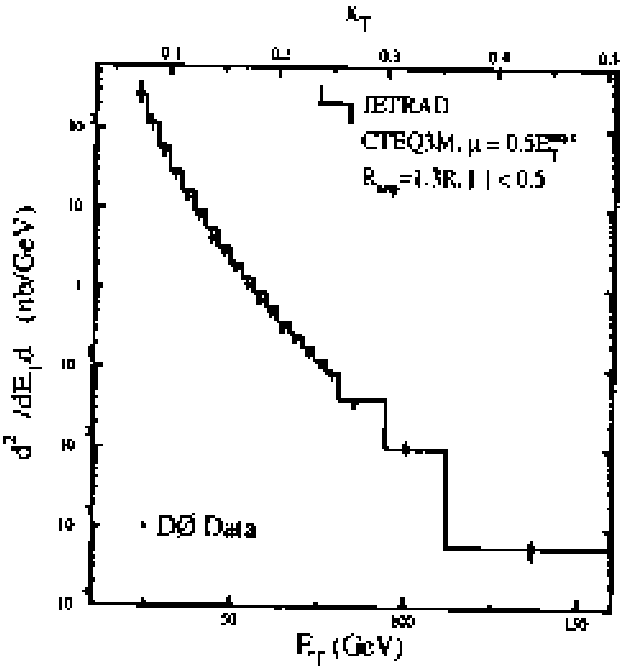
•Results for a previous data set of 8.6 nb^{-1} @ $\sqrt{s} = 546$ GeV had been published by CDF in ‘93.

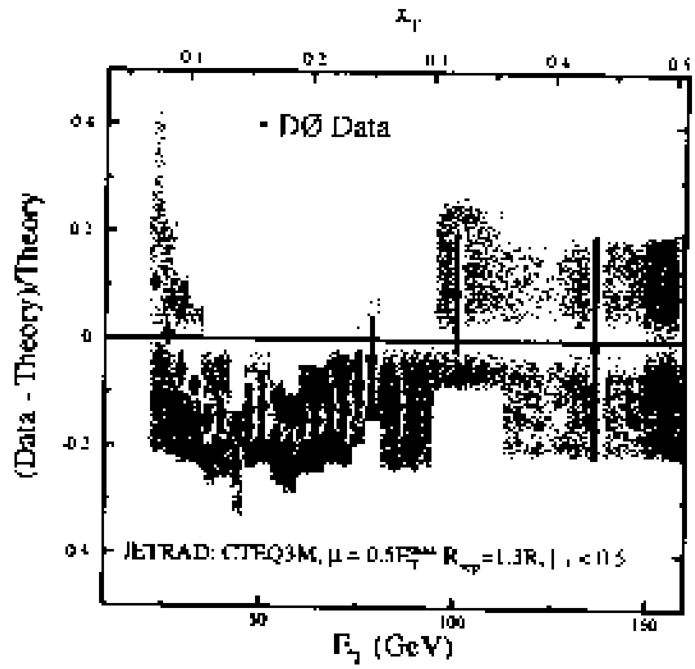
•These data were analyzed like the 1800 GeV sample + compared to JETRAD w/ MRSA′ + $\mu = 0.5E_T^{jet}$.

* Principal difference between the treatment of the 630 GeV + 1800 GeV data sets is the underlying event correction, which increases by 50% as $\sqrt{s}$ increases from 630 to 1800 GeV.

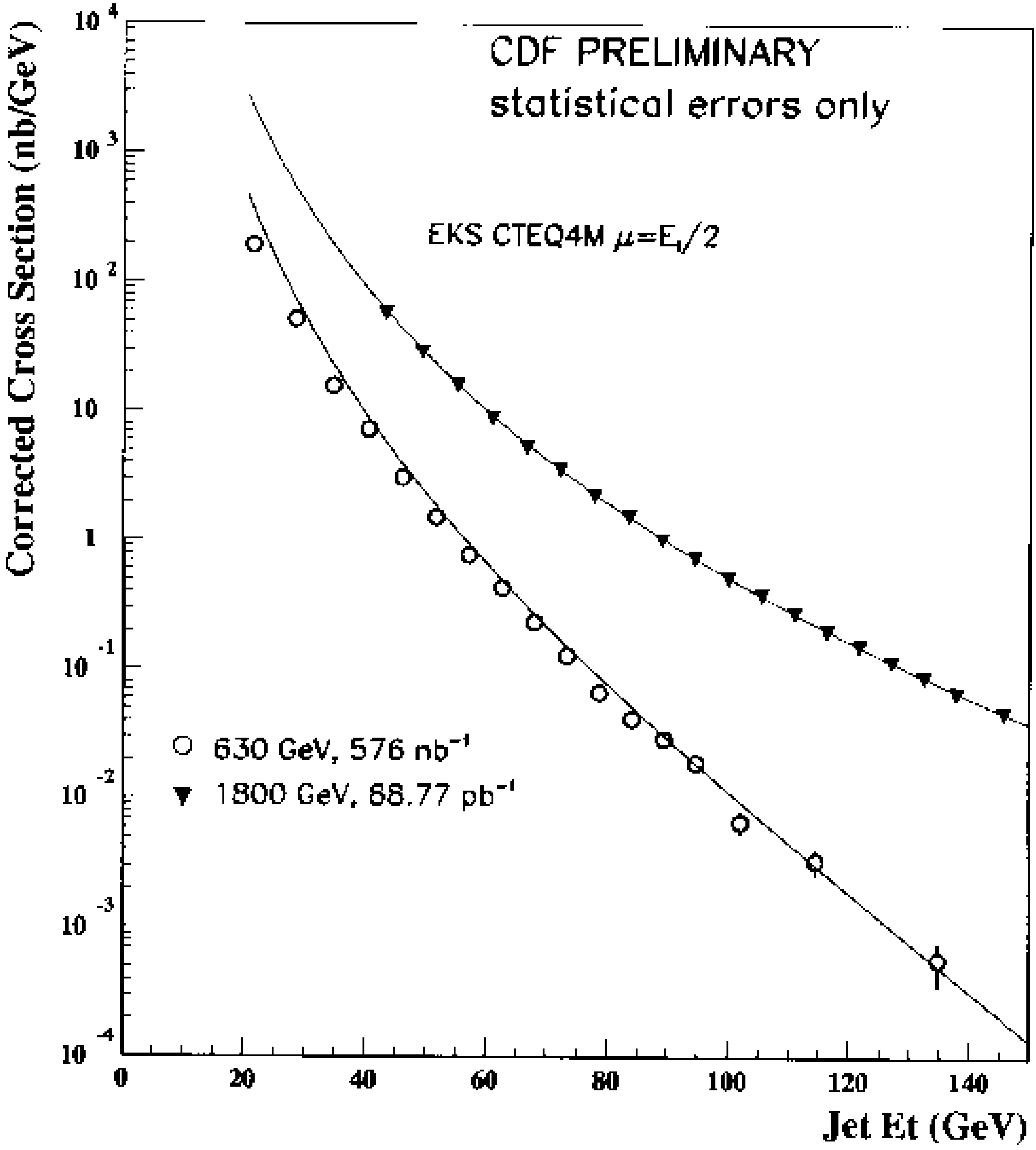
The D0 cross section result, for

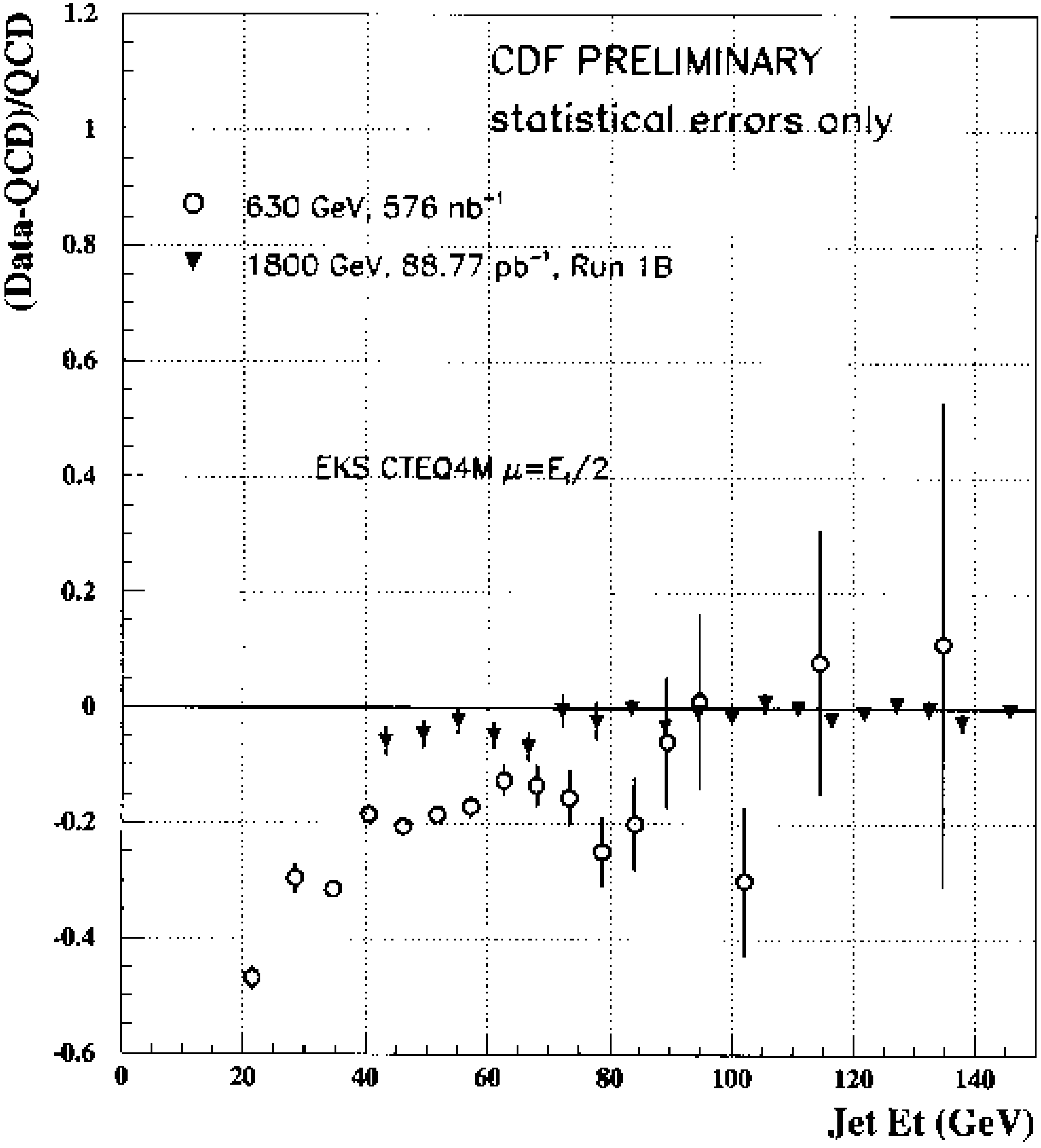
$537\ nb^{-1}$ @ $\sqrt{s} = 630$ GeV :



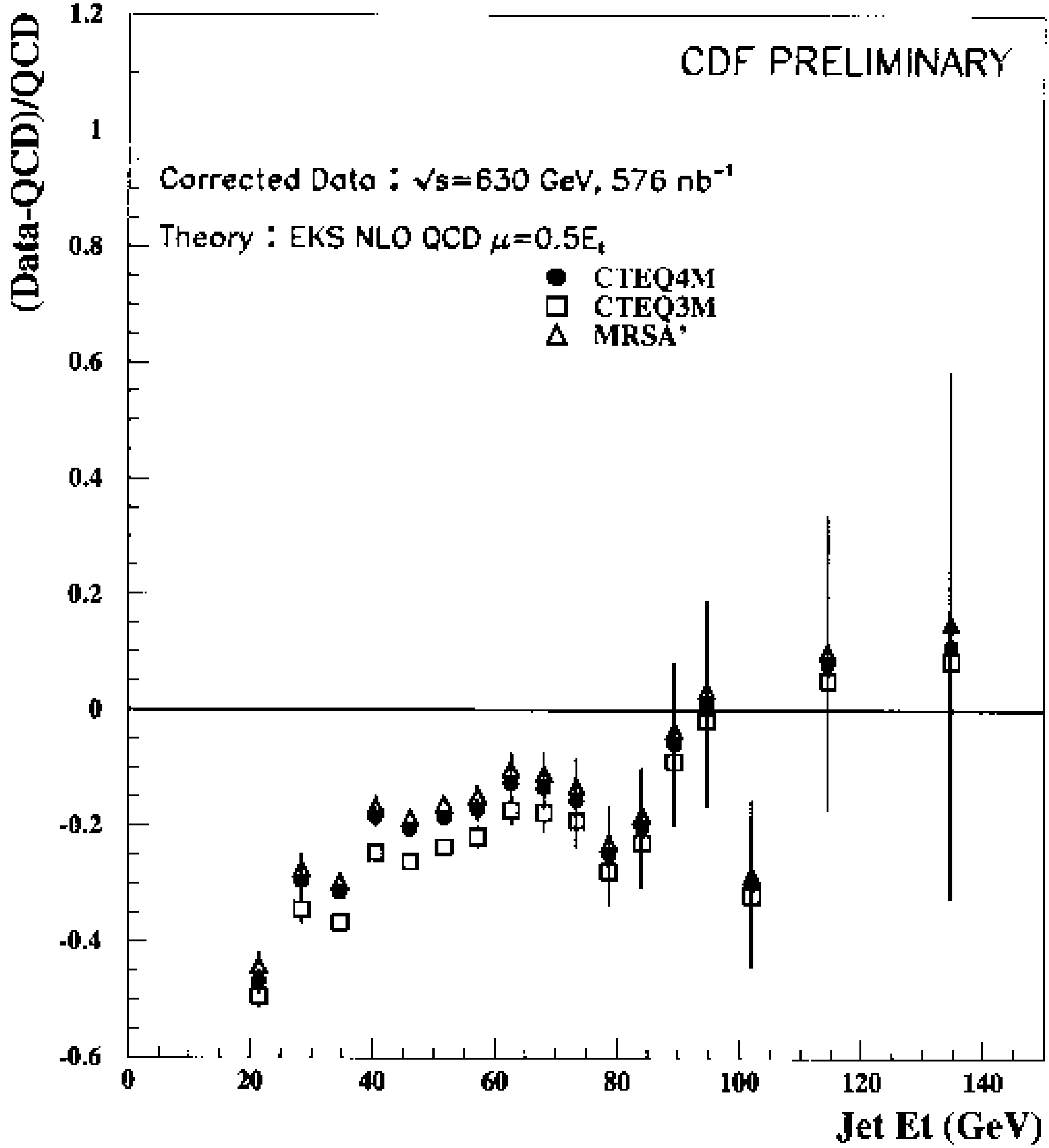


The CDF Result:



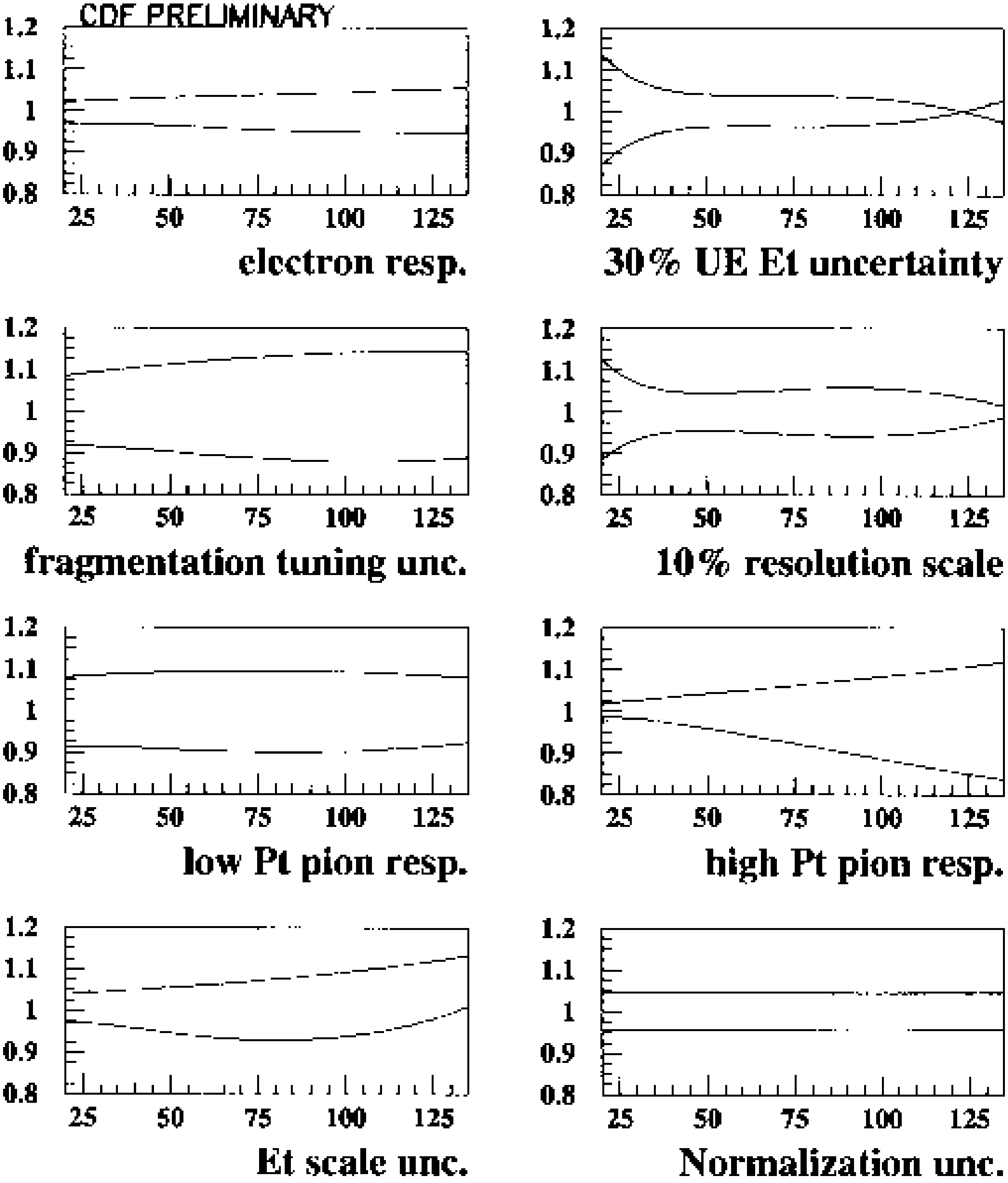


CDF PRELIMINARY
statistical errors only
630 GeV, 576 nb⁻¹
1800 GeV, 88.77 pb⁻¹, Run 1B
EKS CTEQ4M μ=E_t/2
(Data-QCD)/QCD
Jet Et (GeV)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0
20
40
60
80
100
120
140

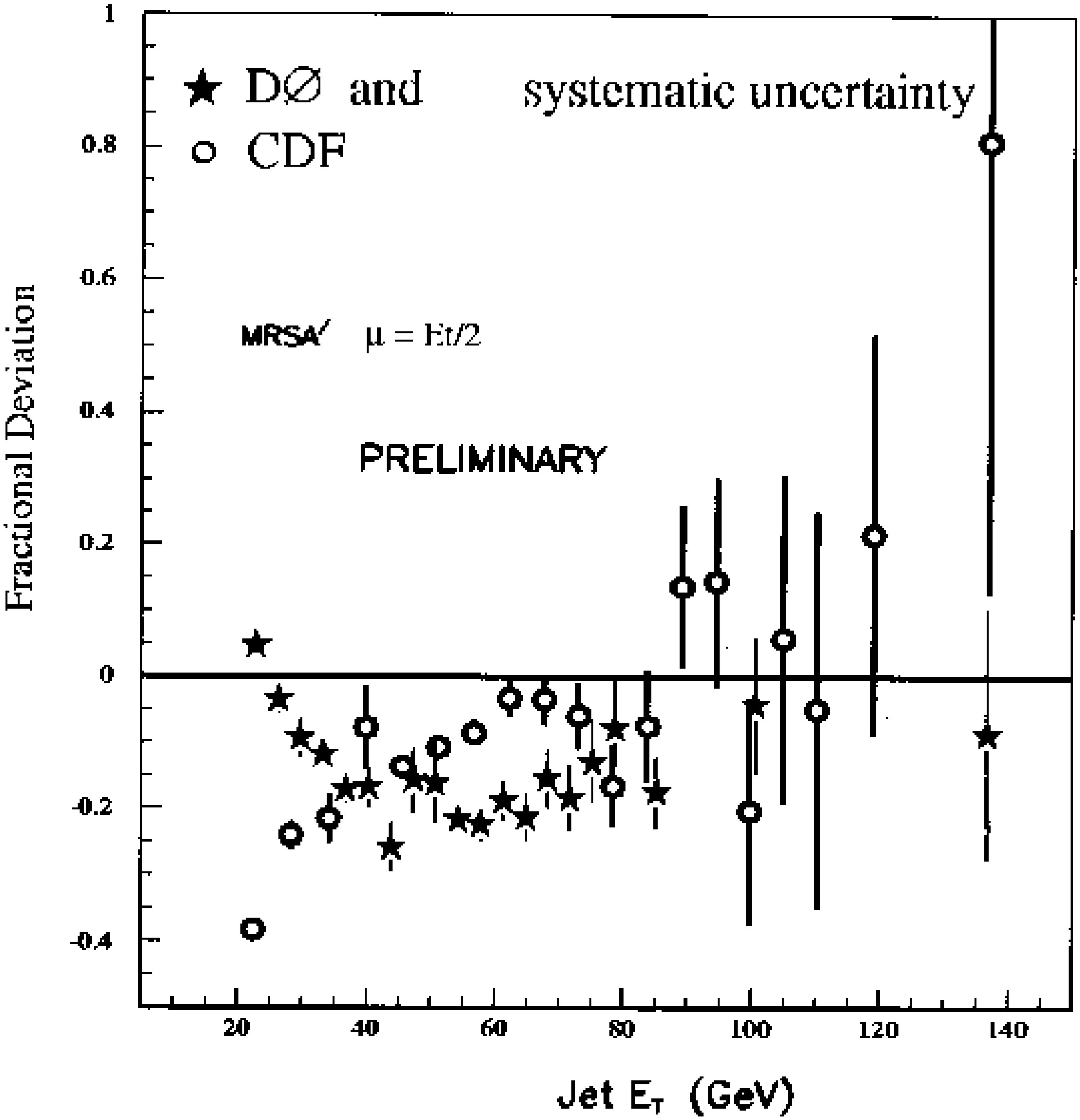


CDF PRELIMINARY
Corrected Data : √s=630 GeV, 576 nb⁻¹
Theory : EKS NLO QCD μ=0.5Eₜ
CTEQ4M
CTEQ3M
MRSA'
(Data-QCD)/QCD
Jet Et (GeV)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0
20
40
60
80
100
120
140

Systematic Errors on the CDF 630 GeV measurement:



Comparison of CDF + D0 measurements of the cross section @ 630 GeV:



Result + Preliminary Conclusions:

- CDF + D0 measurements of the cross section @ 630 GeV agree with each other above ~ 80 GeV.

- Conclusions about agreement between the 2 experiments below 80 GeV cannot be drawn yet; pending further studies of systematic errors, the data may diverge in the lowest few E_T bins.

- Both measurements are consistent w/theory above ~ 80 GeV; theory somewhat higher below.

...additional studies are needed for energy scale determination @ low E_T.

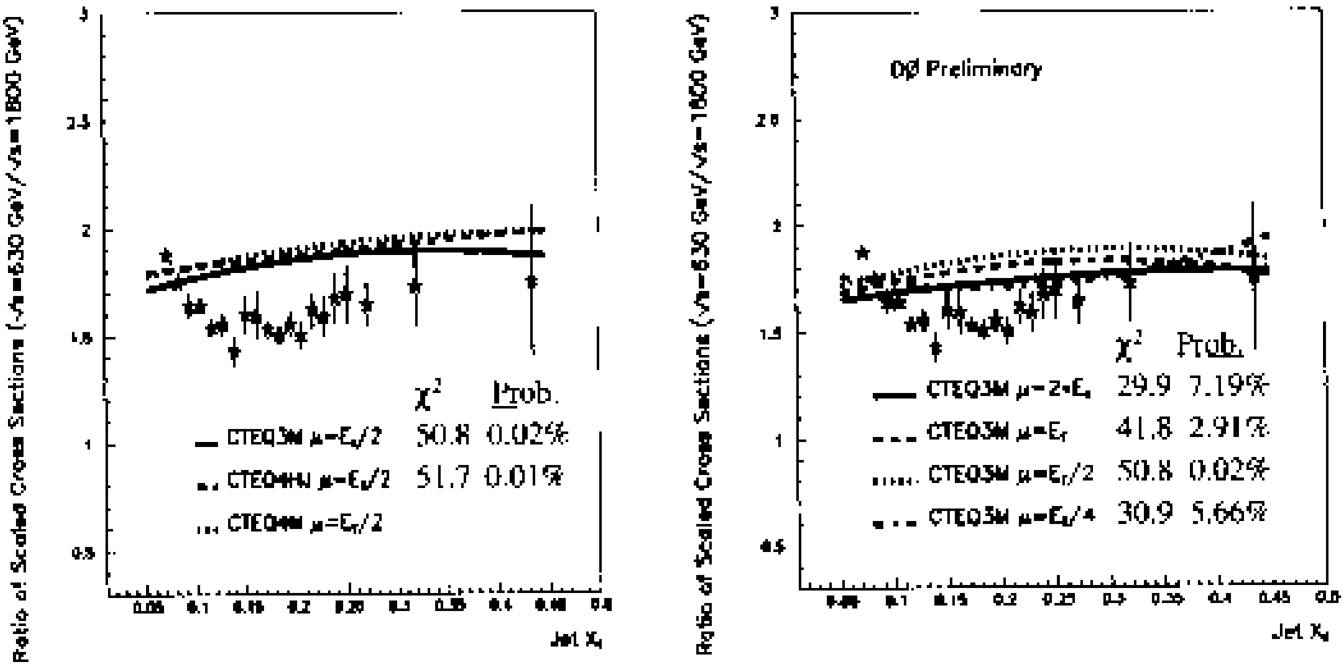
The cross section ratio,

$$\frac{\sigma_d(630\,\mathrm{GeV})}{\sigma_d(1800\,\mathrm{GeV})}$$

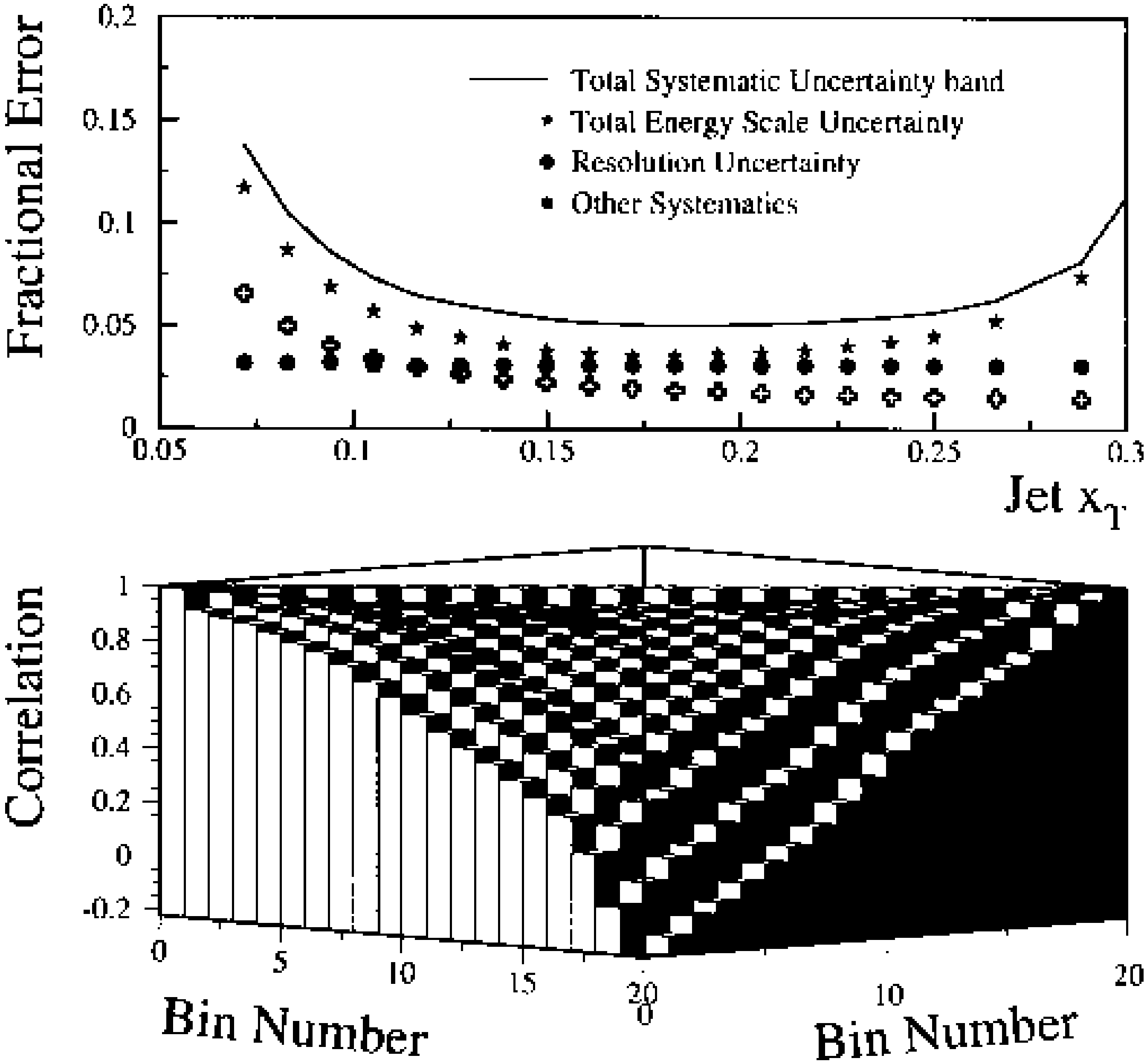
for D0 + CDF, is then formed + compared to

- JETRAD w/ 3 pdf's, and
- EKS w/ 2 pdf's:

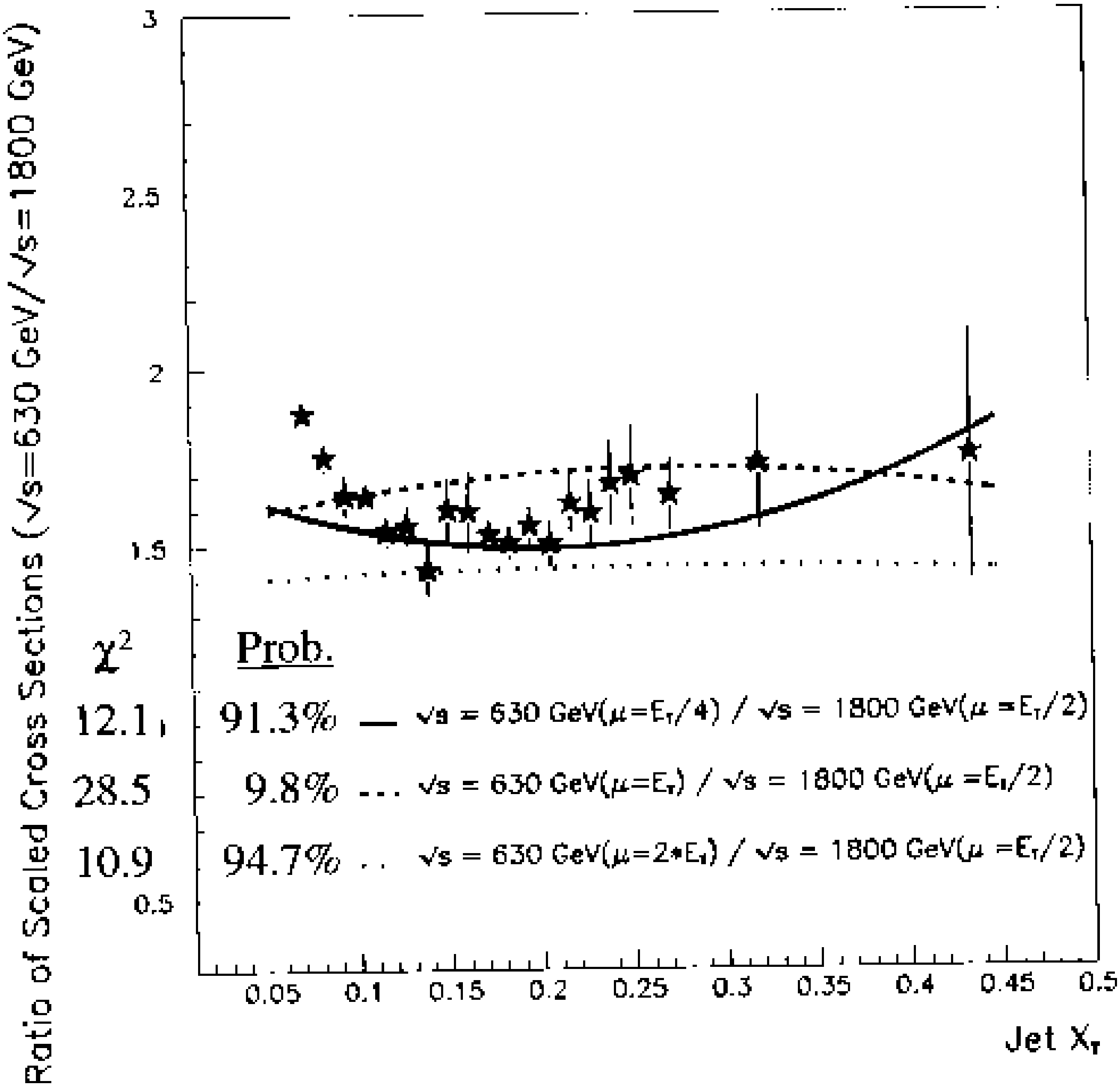
The D0 result for the cross section ratio:



Uncertainties on the D0 cross section ratio:

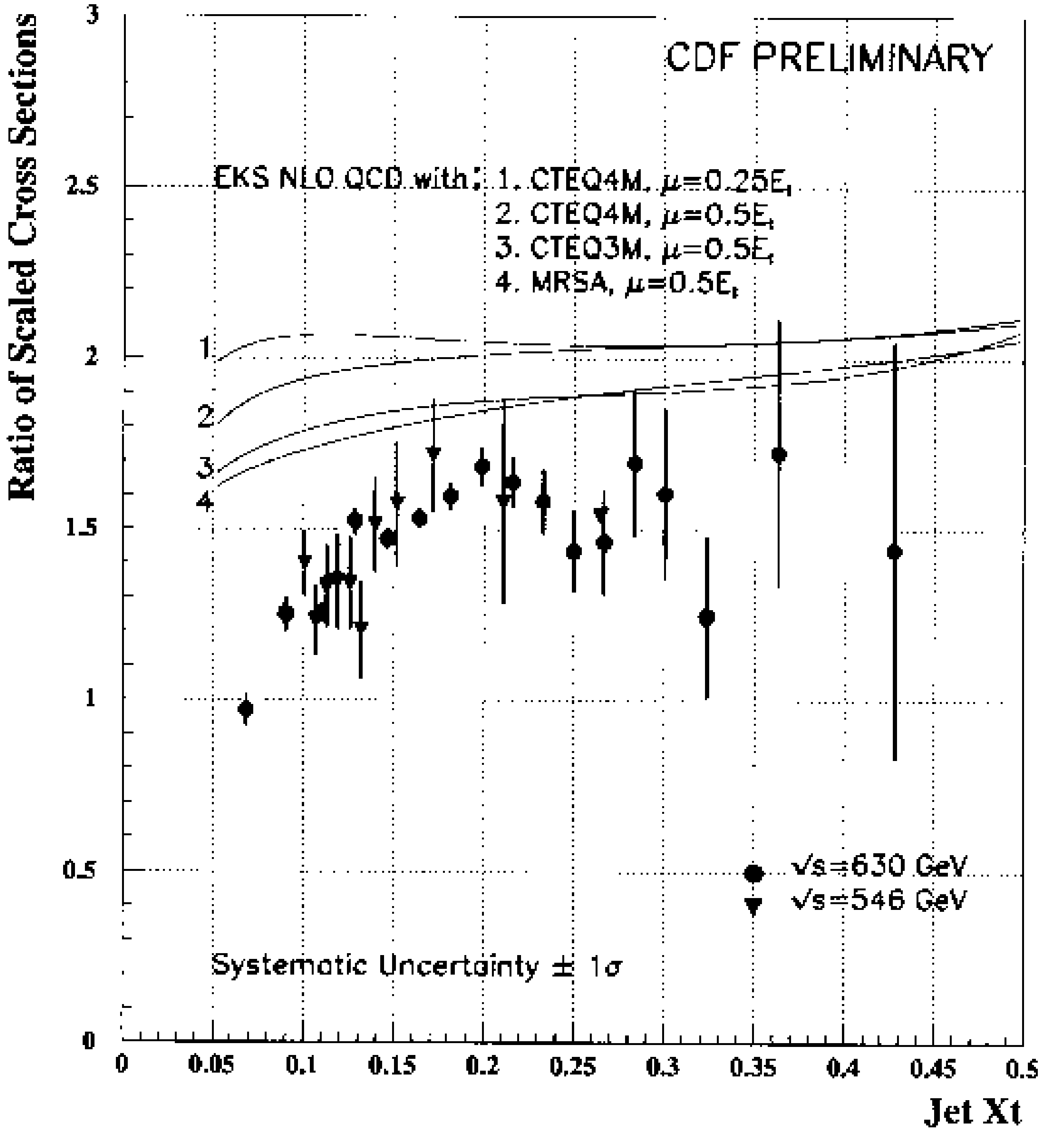


D0 has considered the case in which the scale μ is $\sqrt{s}$-dependent. Using CTEQ3M:



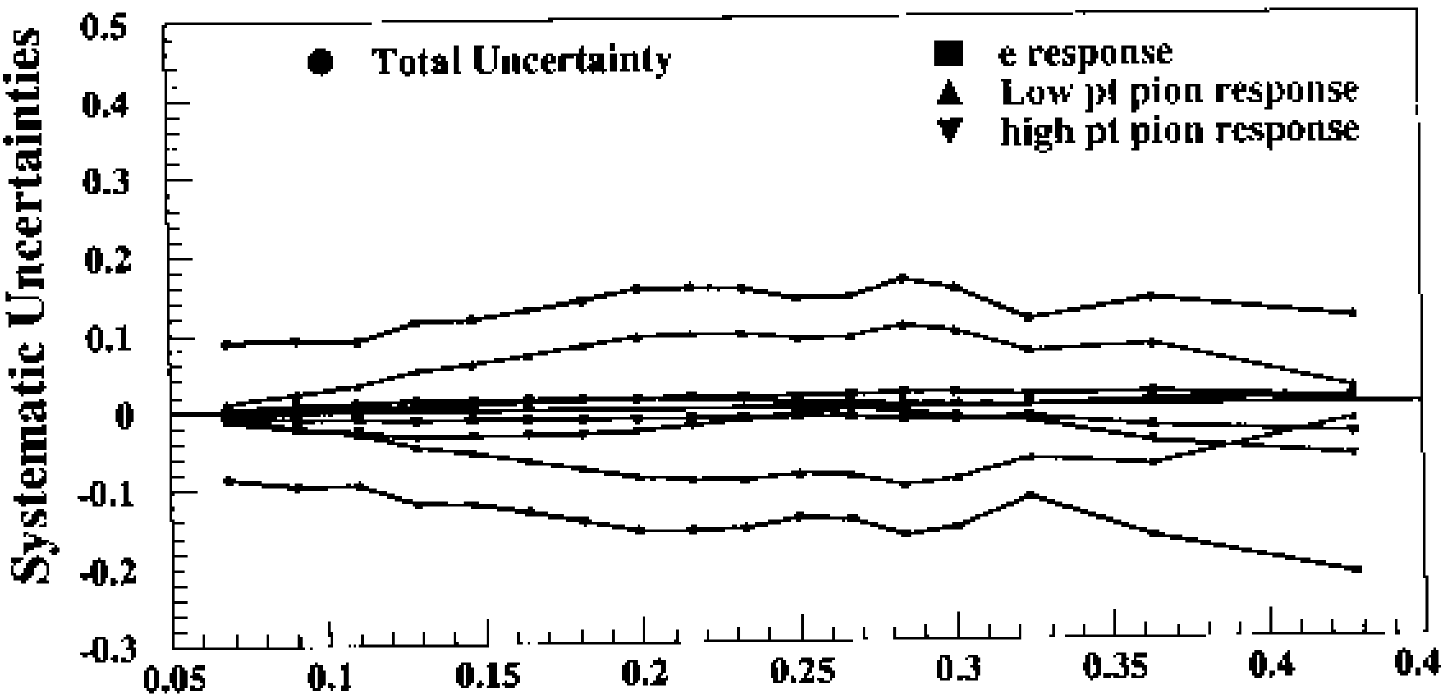
The apparent preference for different scales may indicate that the NNLO terms, when calculated, will not be negligible.

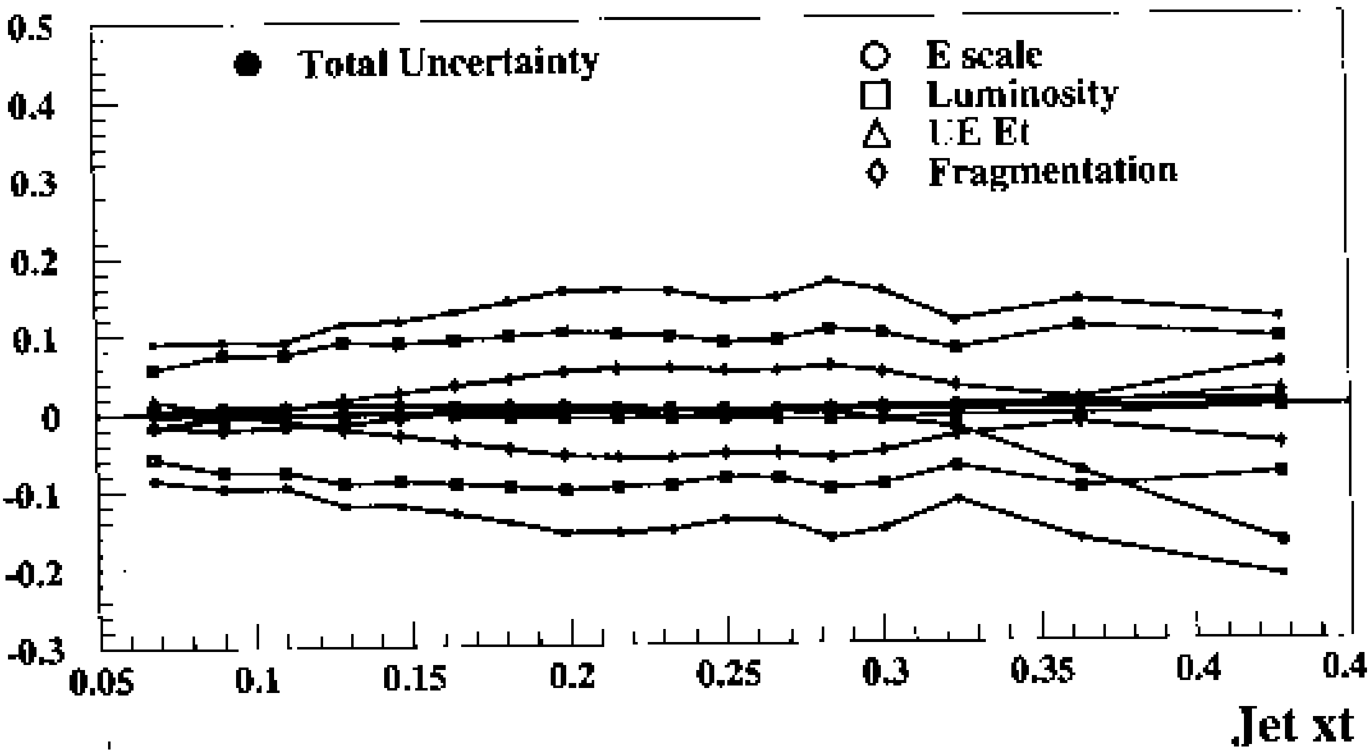
The CDF measurement of the cross section ratio, compared to EKS:



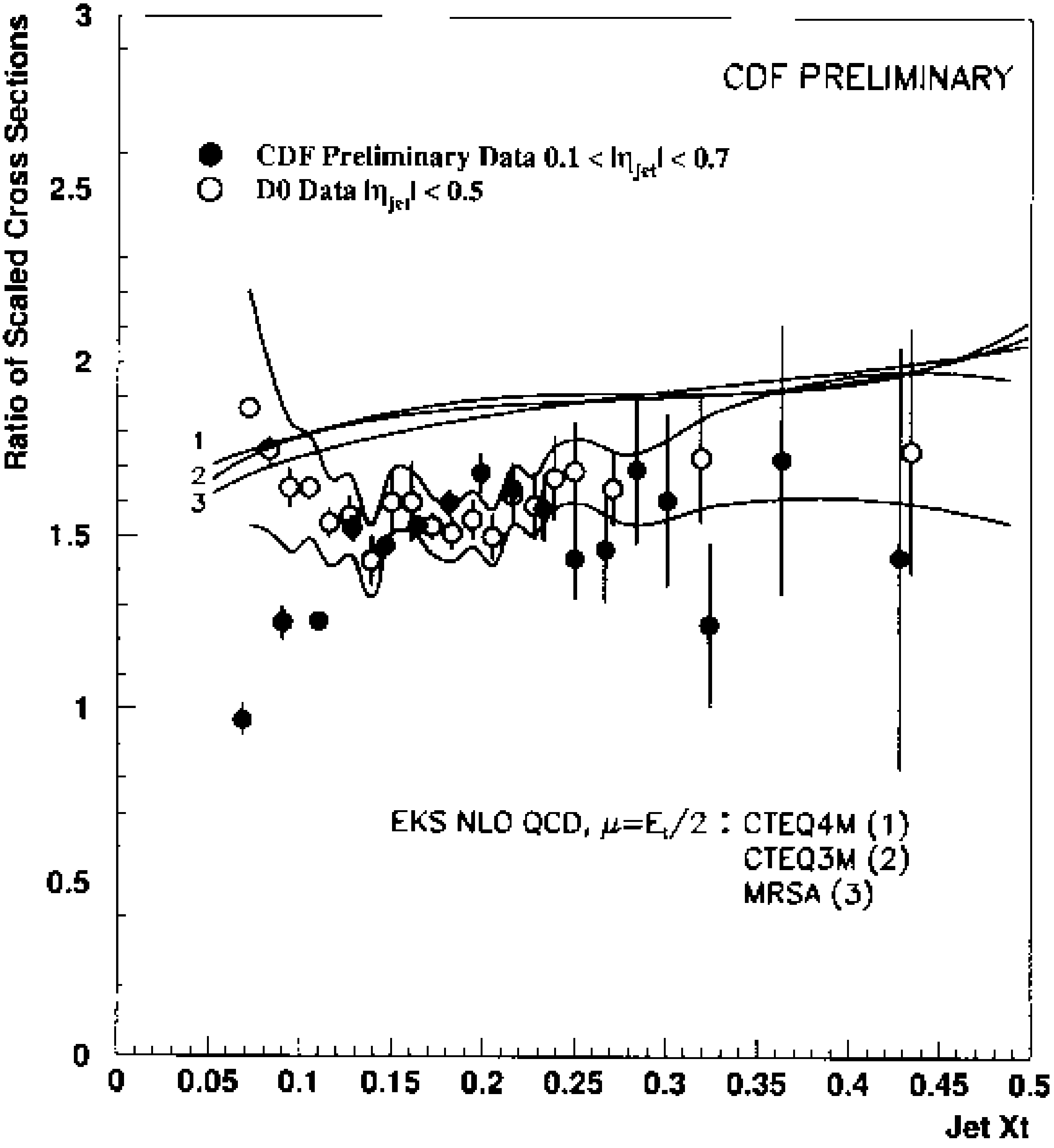
CDF Systematics:

Systematic Uncertainties on Ratio





Comparison of CDF + D0 Results:



- The ratio measurements are consistent for $x_T \geq 0.1$.
- Discrepancy below $x_T = 0.1$ may be traced to the σ_d(630 GeV) results + was also seen in the 546 GeV data.
- $\text{Theory} / \text{D0 data} \approx 1.2.$
- Variation among theoretical predictions is small unless μ is $\sqrt{s}$-dependent.
- The theoretical uncertainty on the ratio is 1/2 what it is on the inclusive cross section.