QCD Processes at Fermilab

Pierrick Hanlet
Northeastern University

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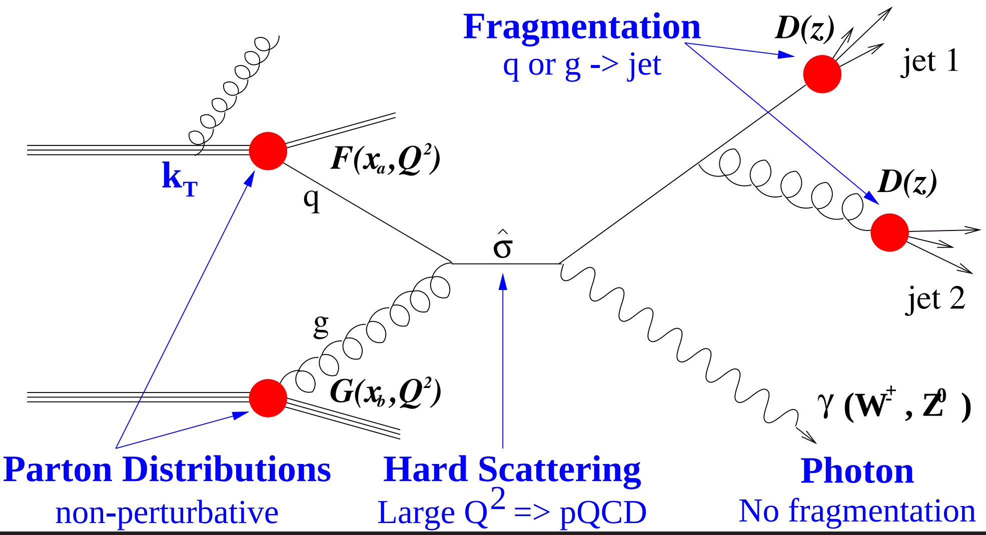
QCD Processes



I. Hard Scattering

CDF: inclusive jets (630 GeV, 1.8 TeV), inclusive di–jets, W+jets, α_s, *DPS*
DØ: inclusive jets (630 GeV, 1.8 TeV), inclusive di–jets
NuTeV: α_s

II. Structure Functions (see P. Reimer: *QCD Bound States*)

CDF: W–asymmetry, direct–γ
NuTeV: F_2,F_3, $R = \sigma_L/\sigma_T$
E706: direct photons
DØ: b–quark excess, direct–γ
NuSea: $\overline{d}/\overline{u}$ asymmetry in the sea

III. Fragmentation/Hadronization (see J. Russ: *Charm Physics*)

E791: $D - \pi$ production correlations, D_s^+/D_s^- asymmetry

IV. k_T Effects

DØ: di–photons
E706: direct photons

V. Diffractive

CDF: diffractive W's and di–jets
E665: diffractive ρ^0
DØ: *CSE*, hard single diffraction, double gaps

VI. High Q^2: New Physics? Quark Compositeness?

CDF: inclusive jets, di–jet angular distributions
DØ: inclusive jets, di–jet angular distributions, di–jet mass

Hard Scattering (pQCD): Inclusive Jets

Motivation for Studies of Inclusive Jet Production

- Test of NLO pQCD calculations:
  - Aversa et al. *Nuc. Ph. B327 (1989)*
  - Ellis et al. *PRL 64 (1990)*
  - Giele et al. *Nuc. Ph. B403 (1993)*
- Test of PDF models
- Search for new physics (CDF and DØ probe distance scales of $\approx 10^{-19}$ m)
- At different $\sqrt{s}$ energies (1.8 TeV and 630 GeV):
  - Comparison of $\sqrt{s}=630$ GeV results with CERN results
  - Use di–jets to study BFKL pomeron parameter α_P
  - Use $\sqrt{s}$ depedence to study double pomeron exchange
  - Study low x_T discrepancy between direct photon data and theory
  - Ratio of $\sigma(630)/\sigma(1800)$ vs x_T is more sensitive to pQCD than either independent measurement

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Results Since Last Year:

- Inclusive Differential Jet Cross Sections:
  $\partial^2\sigma_j/\partial E_T \partial\eta$ ($\sqrt{s}$=1800, 630 GeV)
- Inclusive Differential Di–jet Mass:
  $\partial^3\sigma_{jj}/\partial M_{jj}\partial\eta_1\partial\eta_2$
- Inclusive Differential Di–jet Angular:
  $\partial^3\sigma_{jj}/\partial\chi\partial\eta_1\partial\eta_2$
- Inclusive Triple–Differential Di–jet:
  $\partial^3\sigma_{jj}/\partial E_T^1\partial\eta_1\partial\eta_2$
- $\sigma_{(W+\geq 1_{jet})}/\sigma_W$
- α_s

Hard Scattering (pQCD): DØ Jets

DØ Jet Energy Scale (NIM)

Determined mostly from DØ data and applied on a *jet–by–jet basis*

$$E_{\mathrm{jet}} = \frac{E_{\mathrm{measured}} - O}{(1 - S)R} \qquad (1)$$

Where:

- **O:** Offset due to noise, pileup and underlying event
- **R:** Calorimeter response.
  Determined from event E_T balance ($\not{E}_T$ projection fraction method) using a γ-jet sample. (EM calibration established with Z, J/Ψ, π^0 resonances)
- **S:** Showering losses. Small for jets reconstructed with a $\mathcal{R} = 0.7$ fixed cone algorithm

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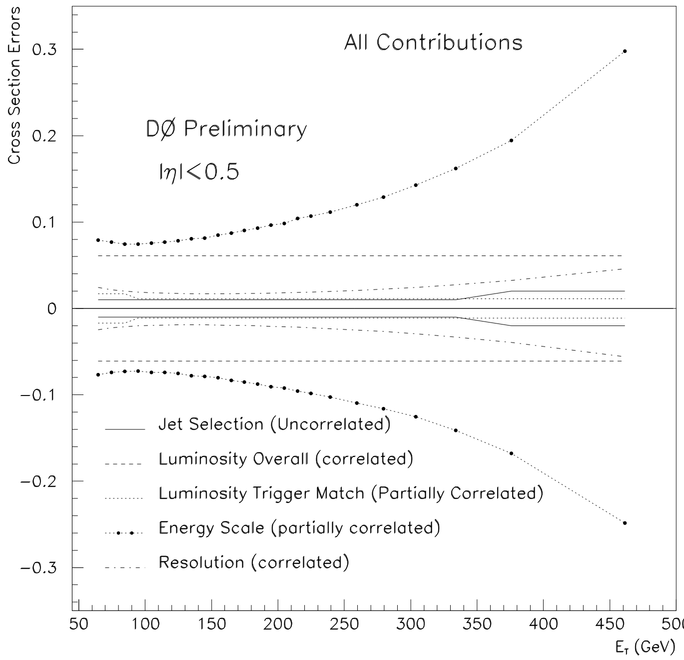
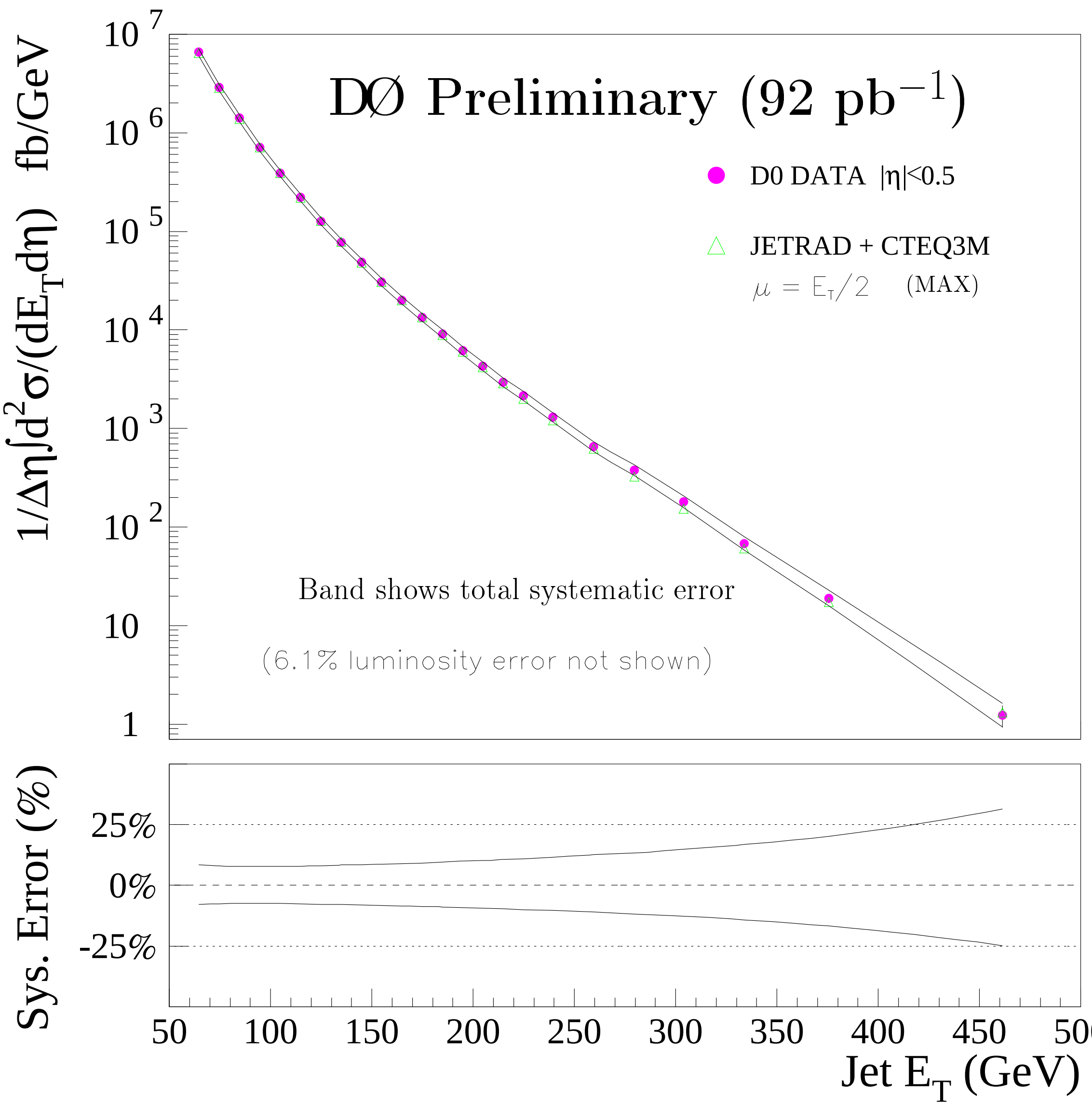
DØ Full Systematic Error Correlation Analysis



	Energy Scale	Energy Resolution	Luminosity
100 GeV	$+7.7/-7\%$	$\pm 2\%$	$\pm 6.1\%$
400 GeV	$+22/-19\%$	$+3.5/-4.5\%$	$\pm 6.1\%$

DØ Inclusive Jet Cross Section

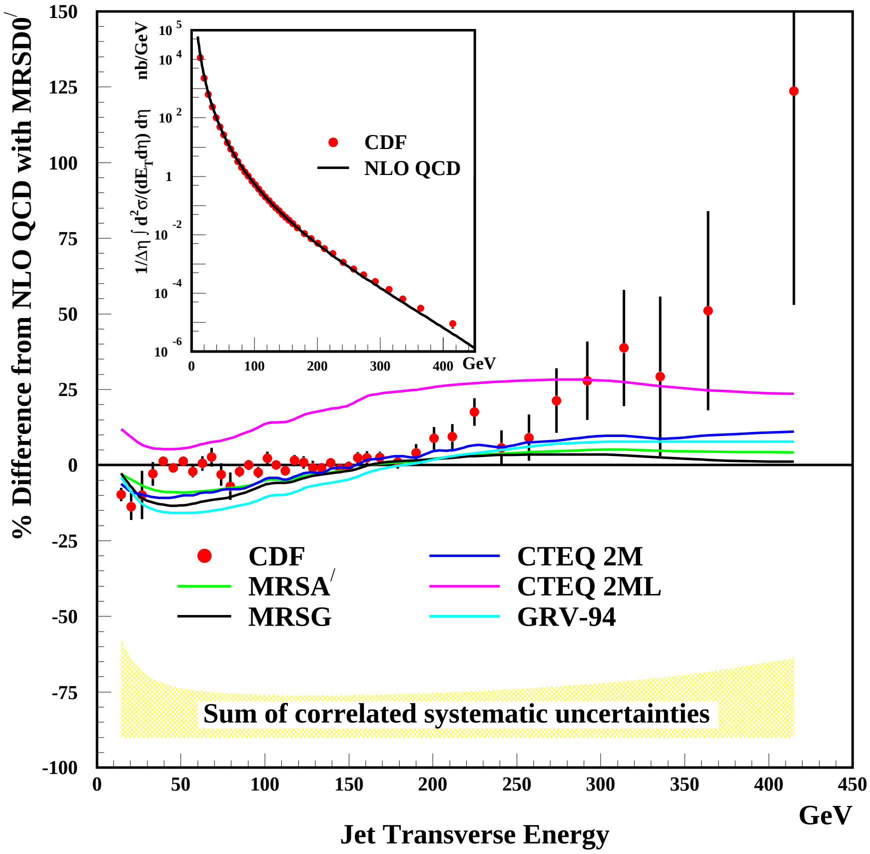
$|\eta| < 0.5$



$\pm 8\%$	$+12\%$	$+24\%$
	-10%	-20%

CDF Inclusive Jet Cross Section
(1992-93 data) PRL 77, 438 (1996)

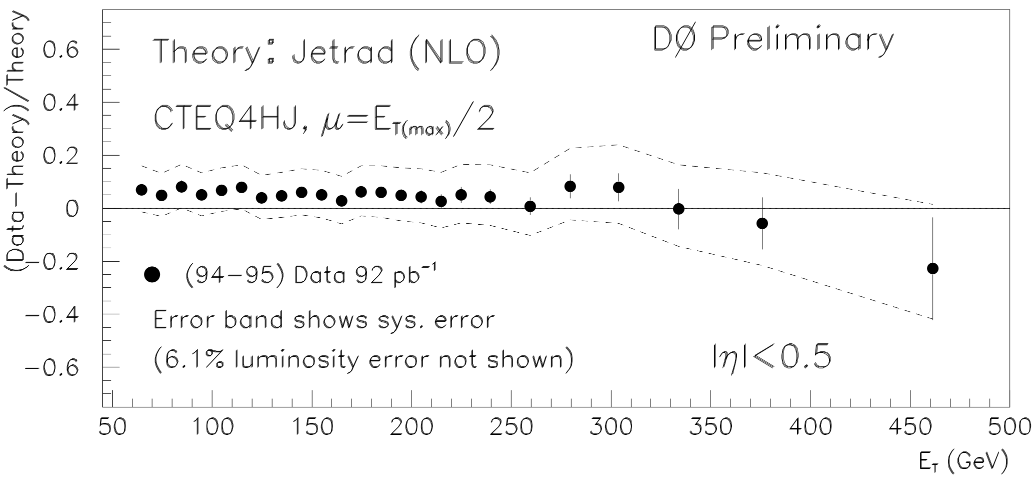
$0.1 < |\eta| < 0.7$

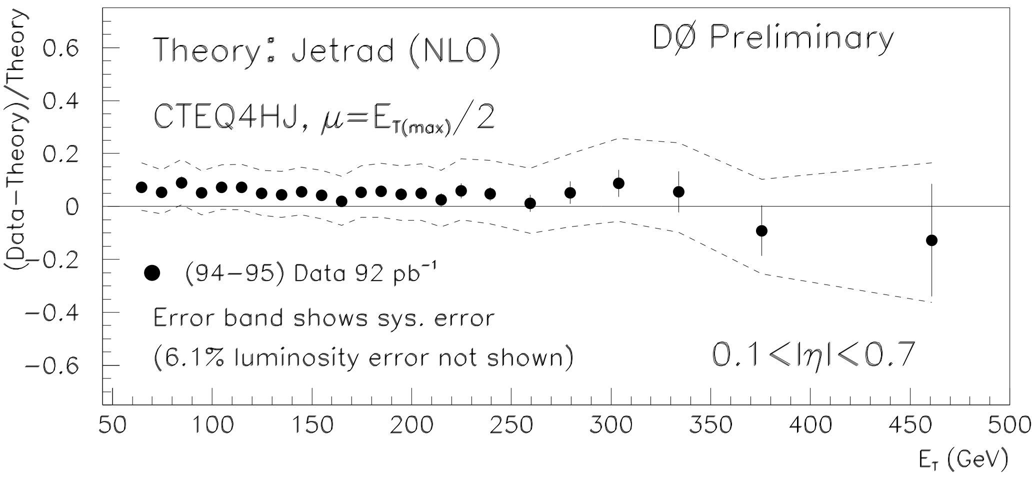


100 GeV $\rightarrow \pm 15\%$ 400 GeV $\rightarrow \pm 25\%$

- Good agreement with QCD < 200 GeV
- Significant excess > 200, not fully accounted for by systematic errors
- Excess accommodated with a modification of the gluon PDF at high x

DØ Inclusive Jet Cross Section (1994-95 data) Preliminary

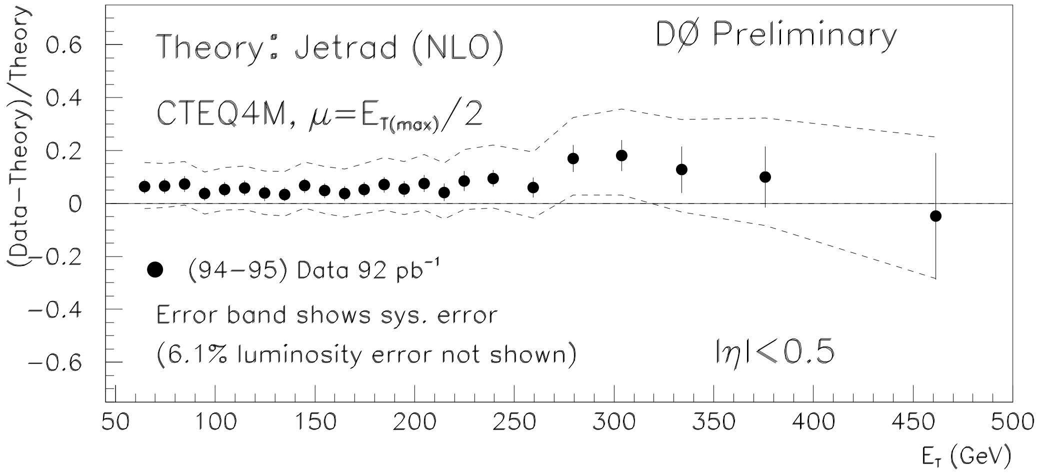


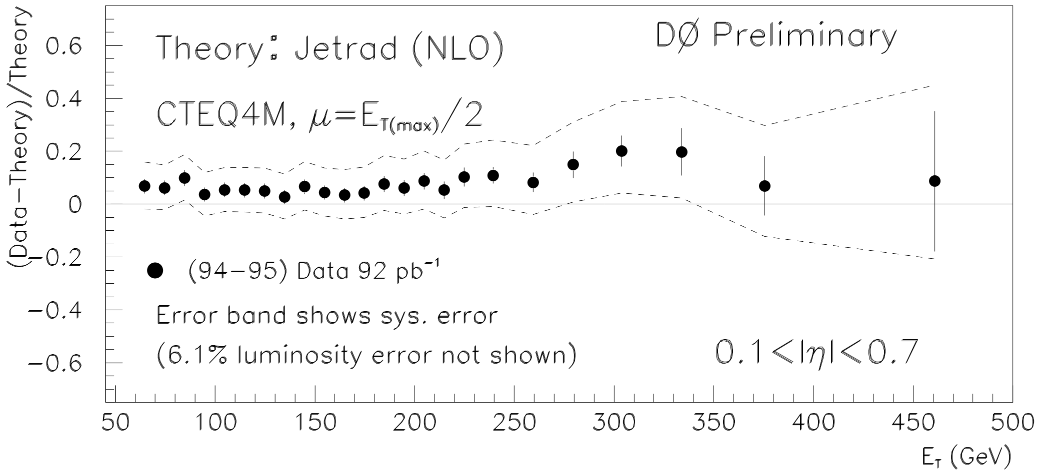


CTEQ4HJ is the same as CTEQ3M plus the high E_T (1992-93) jet results from CDF (older than CTEQ4M)

Good agreement with QCD over the whole range of measured E_T and pseudorapidity

DØ Inclusive Jet Cross Section (1994-95 data) Preliminary

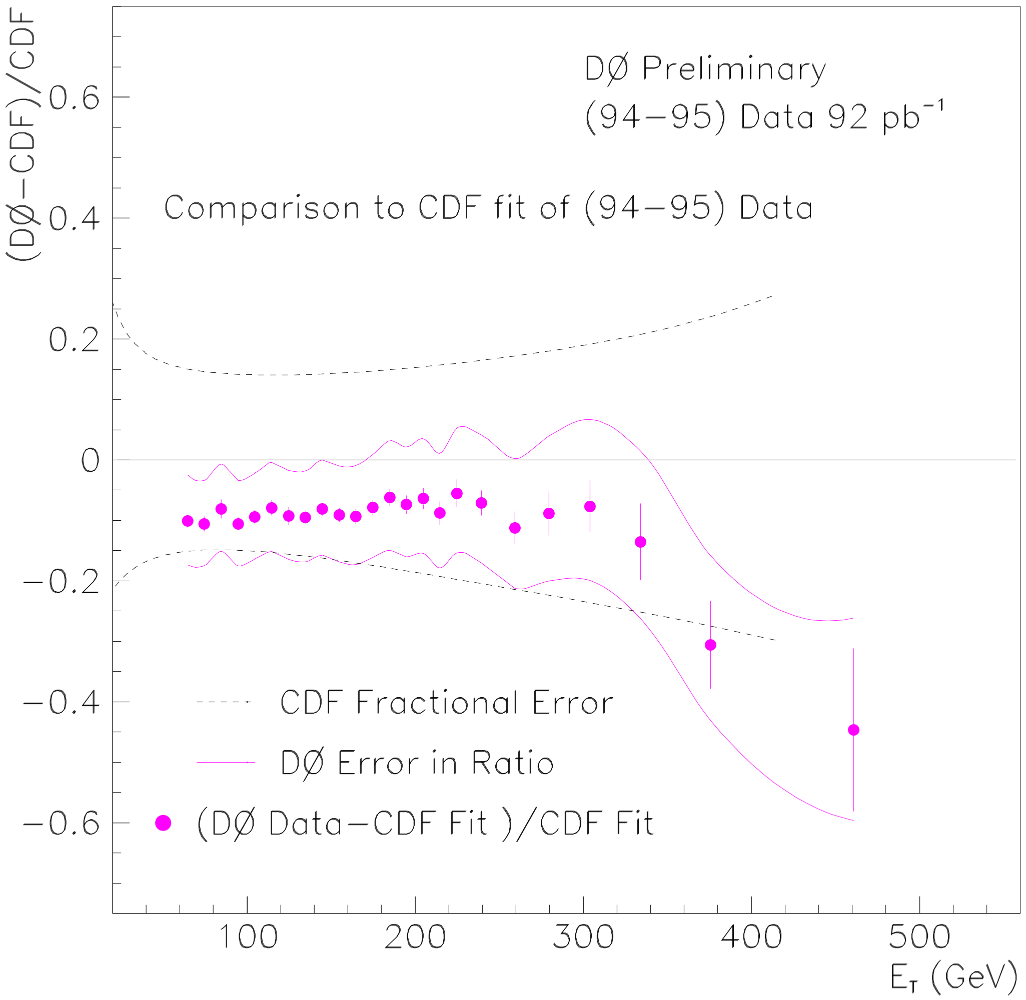




CTEQ4M includes data from HERA, NMC, E665, and the CDF and DØ (1994-95) inclusive jet cross section measurements

Good agreement with QCD over the whole range of measured E_T and pseudorapidity

DØ-CDF Comparison



DØ and CDF error bands overlap in the measured E_T range

There is good agreement between the two experiments below $E_T \approx 300$ GeV

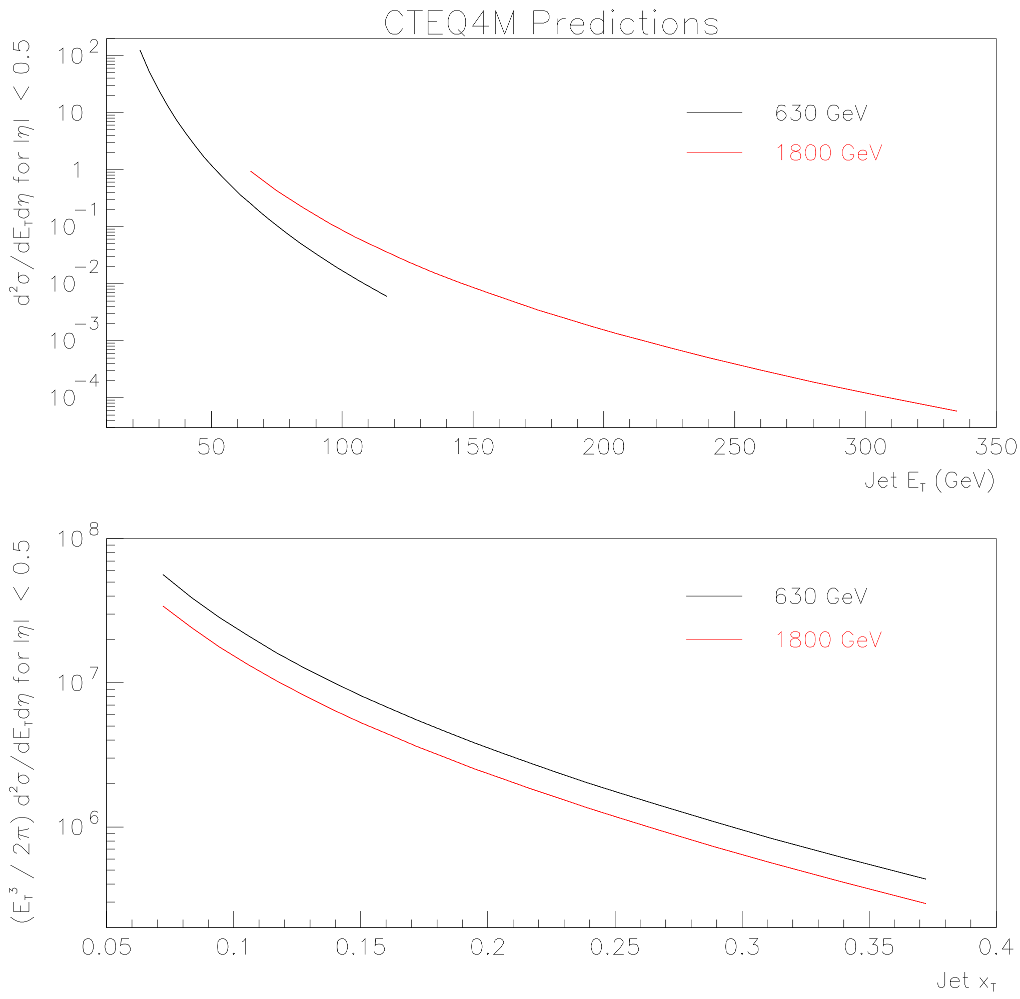
Hard Scattering (pQCD): Why x_T?

Compare the QCD predictions and experimental results from the 630 and 1800 GeV analyses directly:

Study the dimensionless cross section as a function of the the fraction of E_T available to a jet, x_T:

$$\frac{E_T^3}{2\pi}\frac{d^2\sigma}{dp_T d\eta} \text{ vs. } x_T \tag{2}$$

where $x_T = 2E_T/\sqrt{s}$. This puts both measurements on the same scale for direct comparison.



Hard Scattering (pQCD): Ratio and Scaling

Motivation for Studying the Ratio $\frac{\sigma_{630}(x_T)}{\sigma_{1800}(x_T)}$:

I. Theoretical uncertainties in pdfs are dramatically reduced

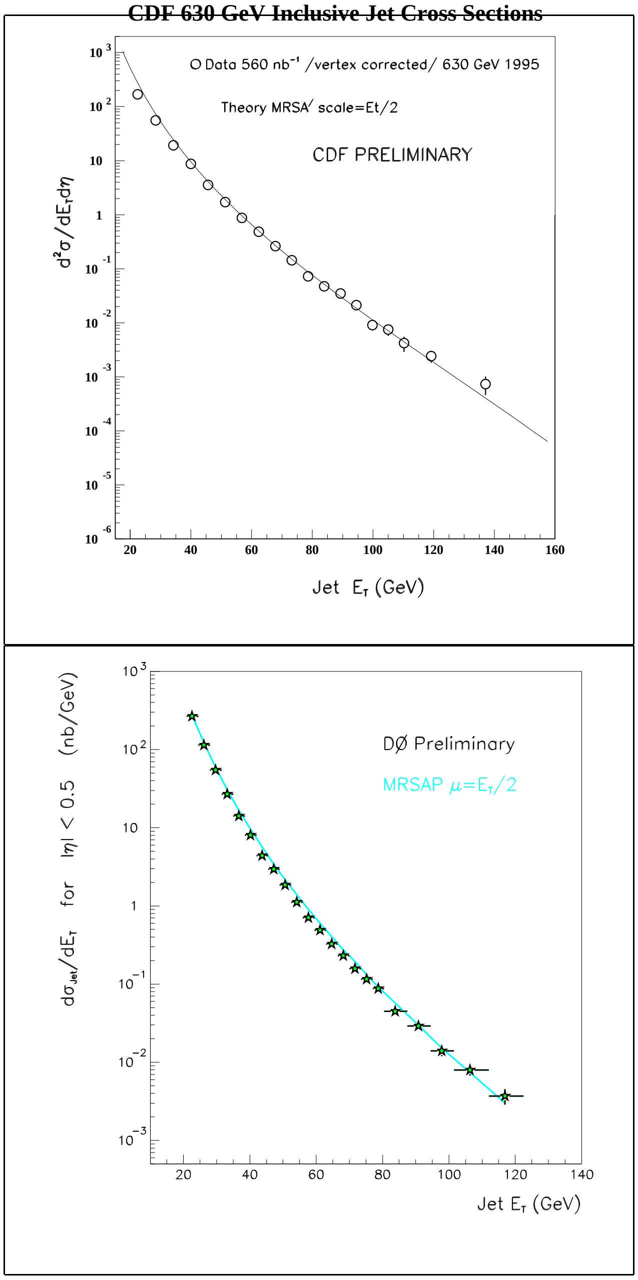
II. Many experimental uncertainties are reduced: (DØ Example)

- Energy scale: dominant error in measurement at high E_T (25%) is reduced to 5%
- Luminosity errors are reduced by ≈ 2
- Resolution errors are *not* appreciably reduced

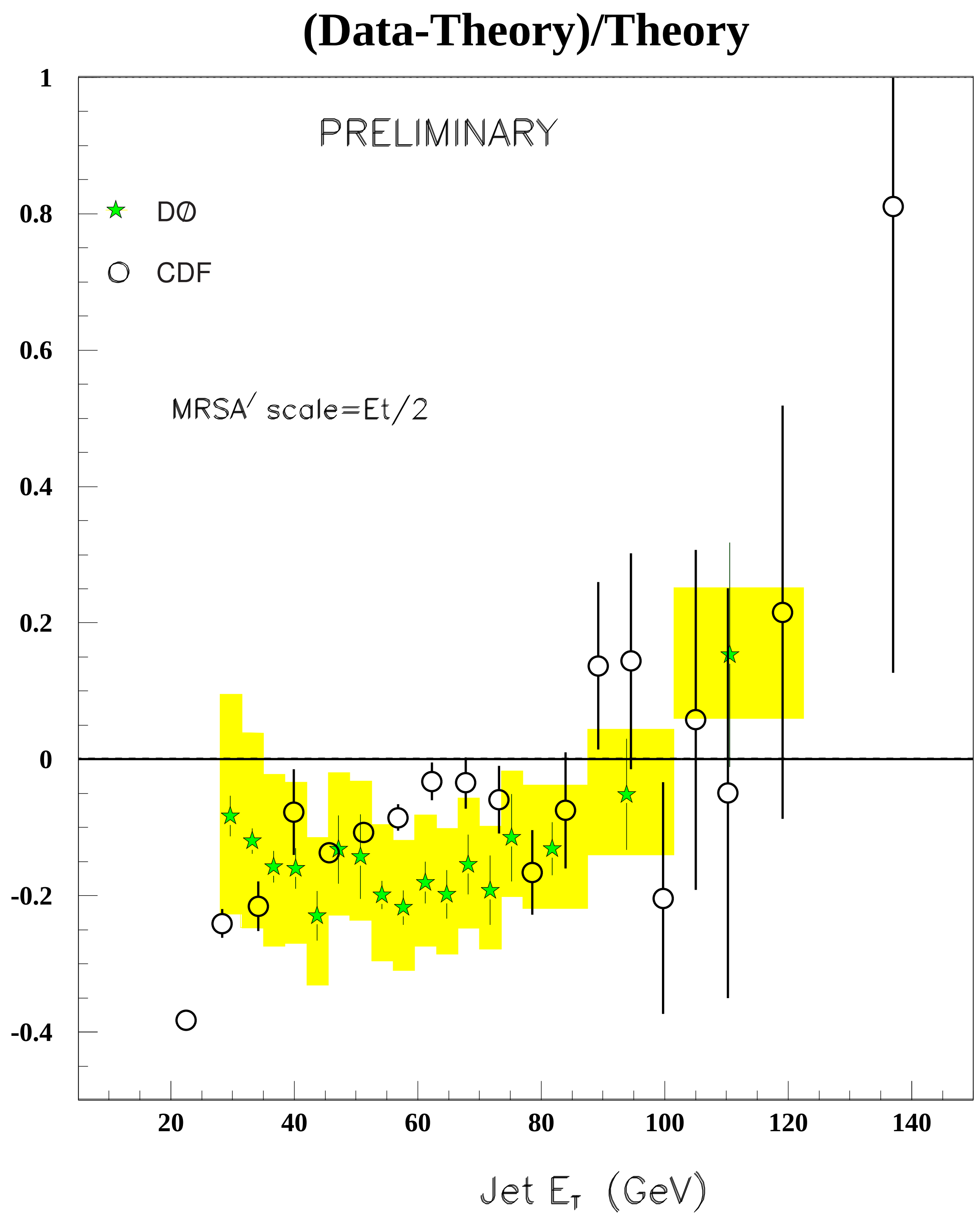
Cross Section Scaling vs NLO QCD

- At NLO in QCD the prediction of the ratio $\frac{\sigma_{630}(x_T)}{\sigma_{1800}(x_T)}$ is roughly flat around 1.8-1.9
- Naive "Scaling" $\Rightarrow$ dimensionless cross section is independent of $\sqrt{s}$; however in QCD:
  - structure function evolution
  - running of α_s
  - gluon radiation

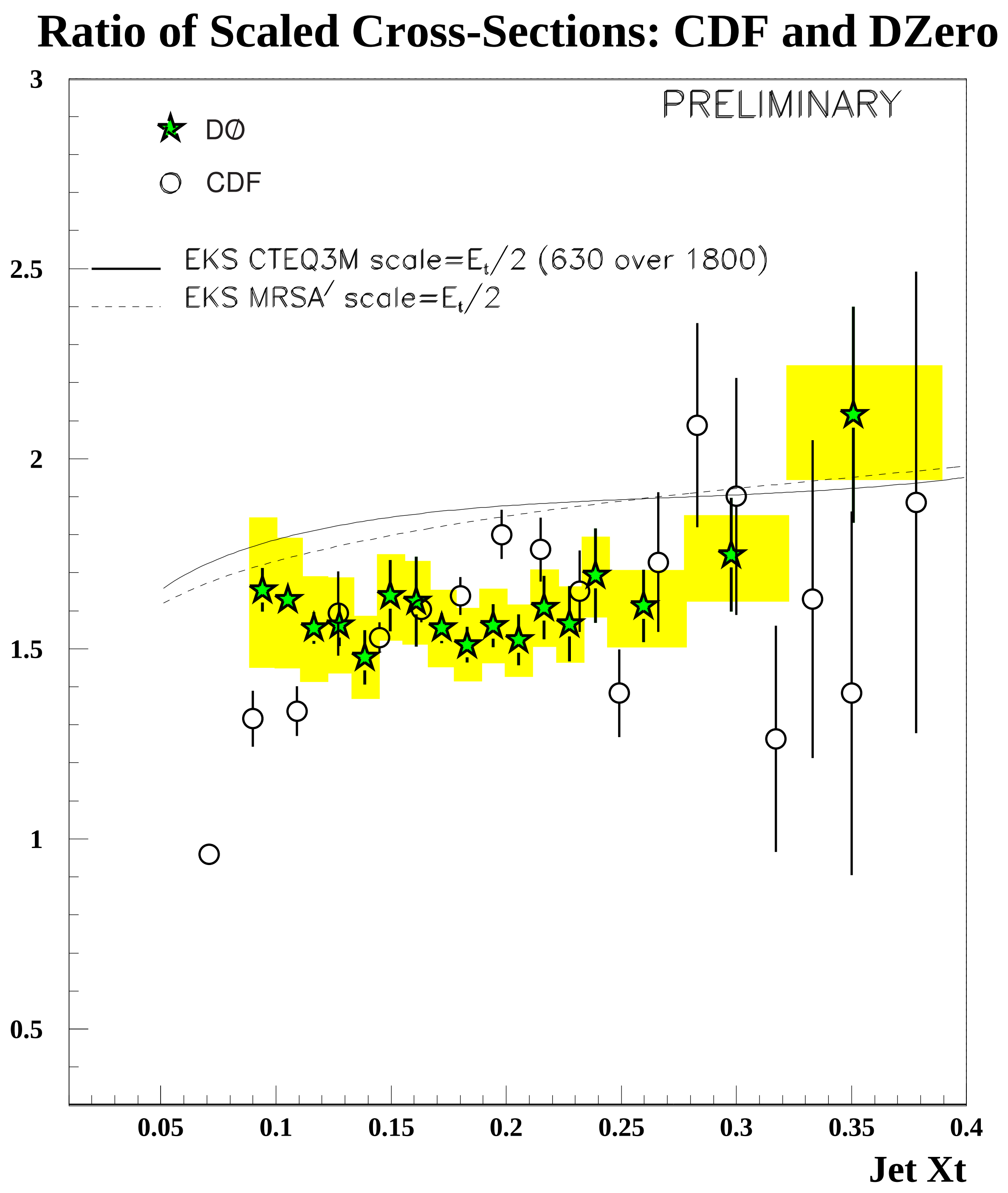
Hard Scattering (pQCD): $\sqrt{s} = 630$ GeV



Hard Scattering (pQCD): $\sqrt{s} = 630$ GeV



Hard Scattering (pQCD): $\sqrt{s} = 630$ GeV



- CDF and DØ are consistent
- Both CDF and DØ are consistently below the theory for $x_T < 0.25$

Hard Scattering (pQCD): Jets Conclusions

$\sqrt{s} = 1.8$ TeV

I. The CDF and DØ systematic uncertainties are of the same order or smaller than the uncertainties in NLO QCD predictions.

II. The DØ (1994–1995) improved preliminary measurement (reduced uncertainties and complete error correlation analysis) is in excellent agreement with NLO QCD.

III. CDF published data (1992–1993) and the preliminary 1994–1995 result are consistent with NLO QCD predictions for $E_T < 200$ GeV. The excess above 200 GeV can be accommodated with a modification in the gluon distribution function at high x.

IV. CDF and DØ are in very good agreement for $E_T < 300$ GeV. The systematic error bands overlap in the entire measured range.

$\sqrt{s} = 630$ GeV

I. The inclusive jet cross section as a function of E_T for preliminary CDF measurement agree with NLO QCD predictions within errors

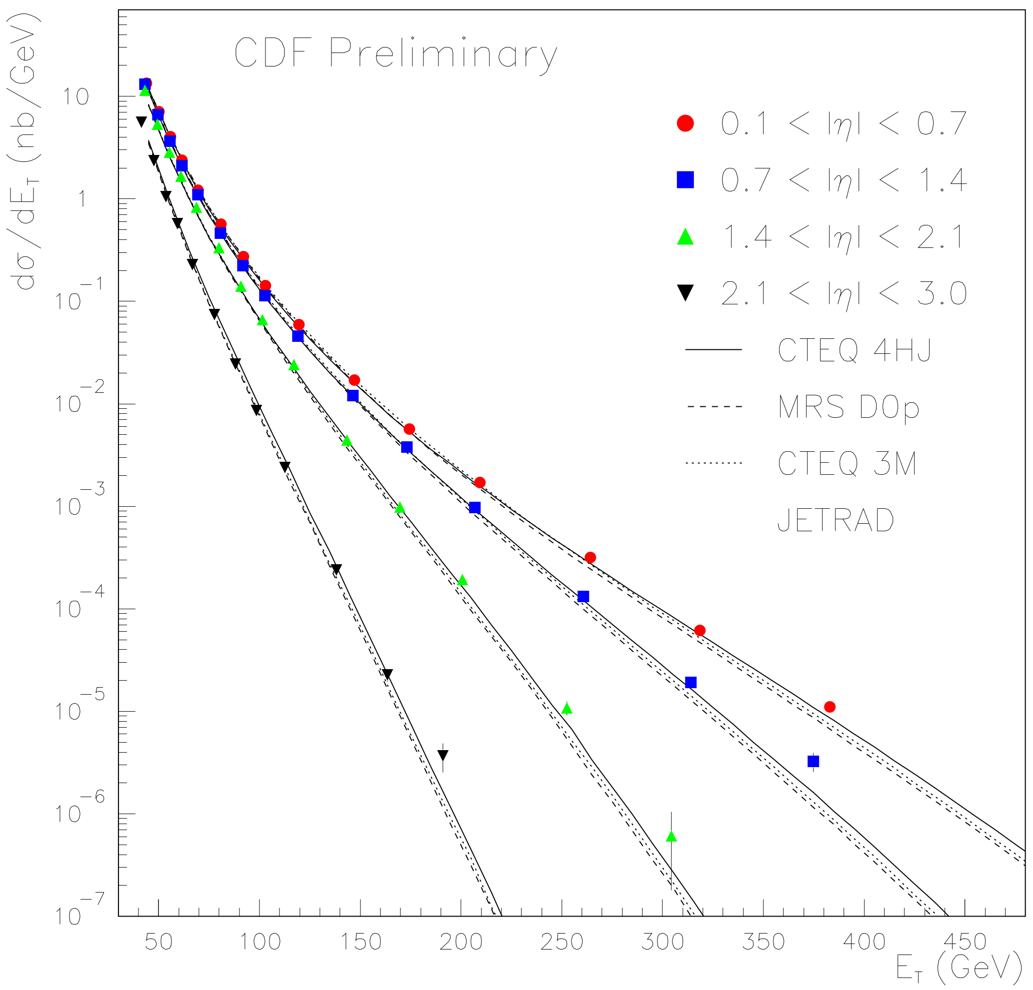
II. The NLO QCD predictions for the inclusive jet cross section as a function of E_T tends to lie higher than the preliminary DØ measurement

III. The inclusive jet cross section ratio as a function of x_T:

- both preliminary CDF and DØ measurements are consistent within systematic errors
- the theoretical prediction is consistently higher than both experimental measurements

Perhaps higher order calculations in pQCD are required!

Hard Scattering (pQCD): CDF Di–jets



Comparison is made to NLO QCD using Jetrad.

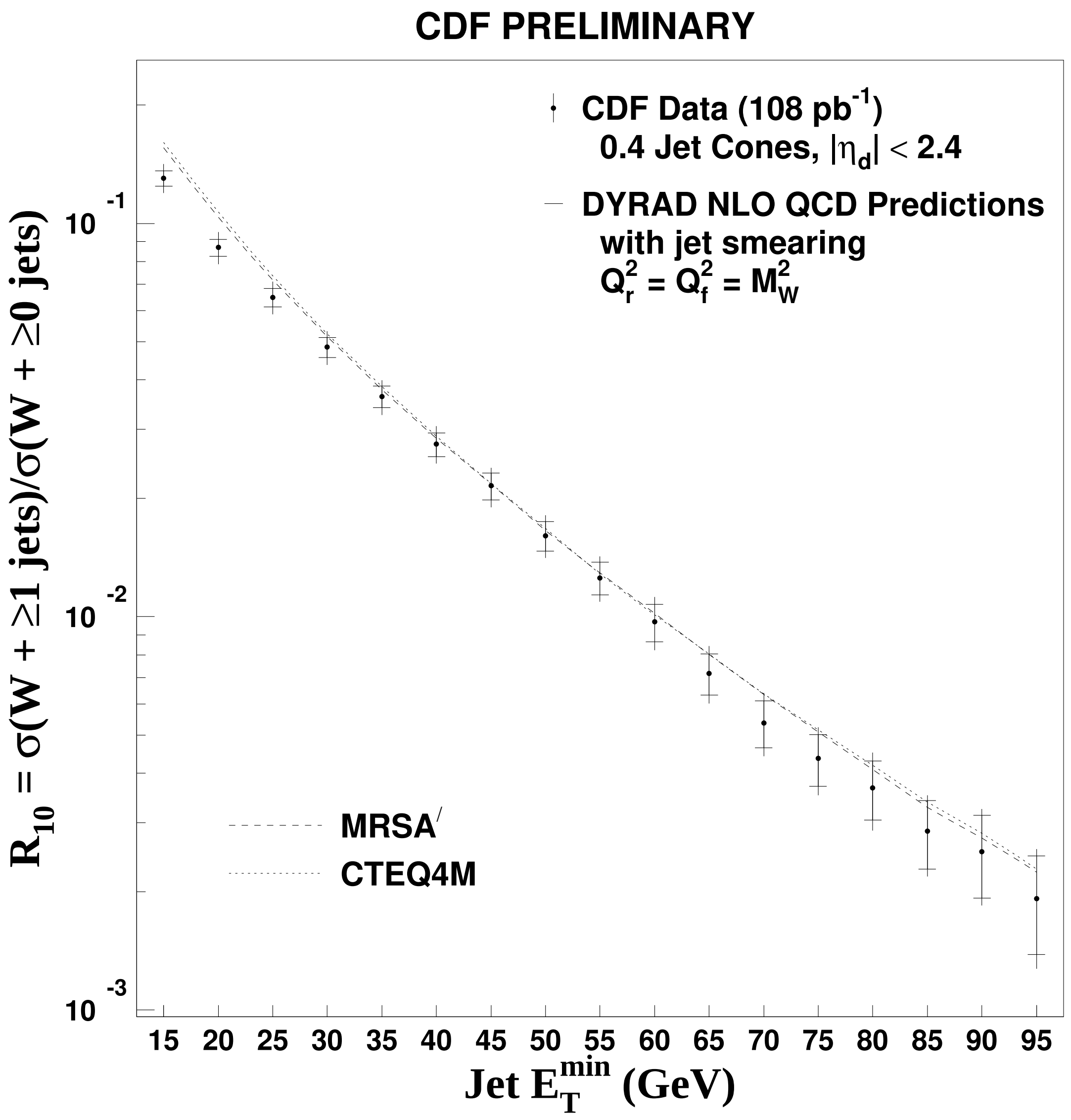
- no systematic errors
- consistent with inclusive jet
- di–jet data lies higher than theory for higher values of E_T in each rapidity bin for different PDF's

Hard Scattering (pQCD): CDF W + jets

Why?

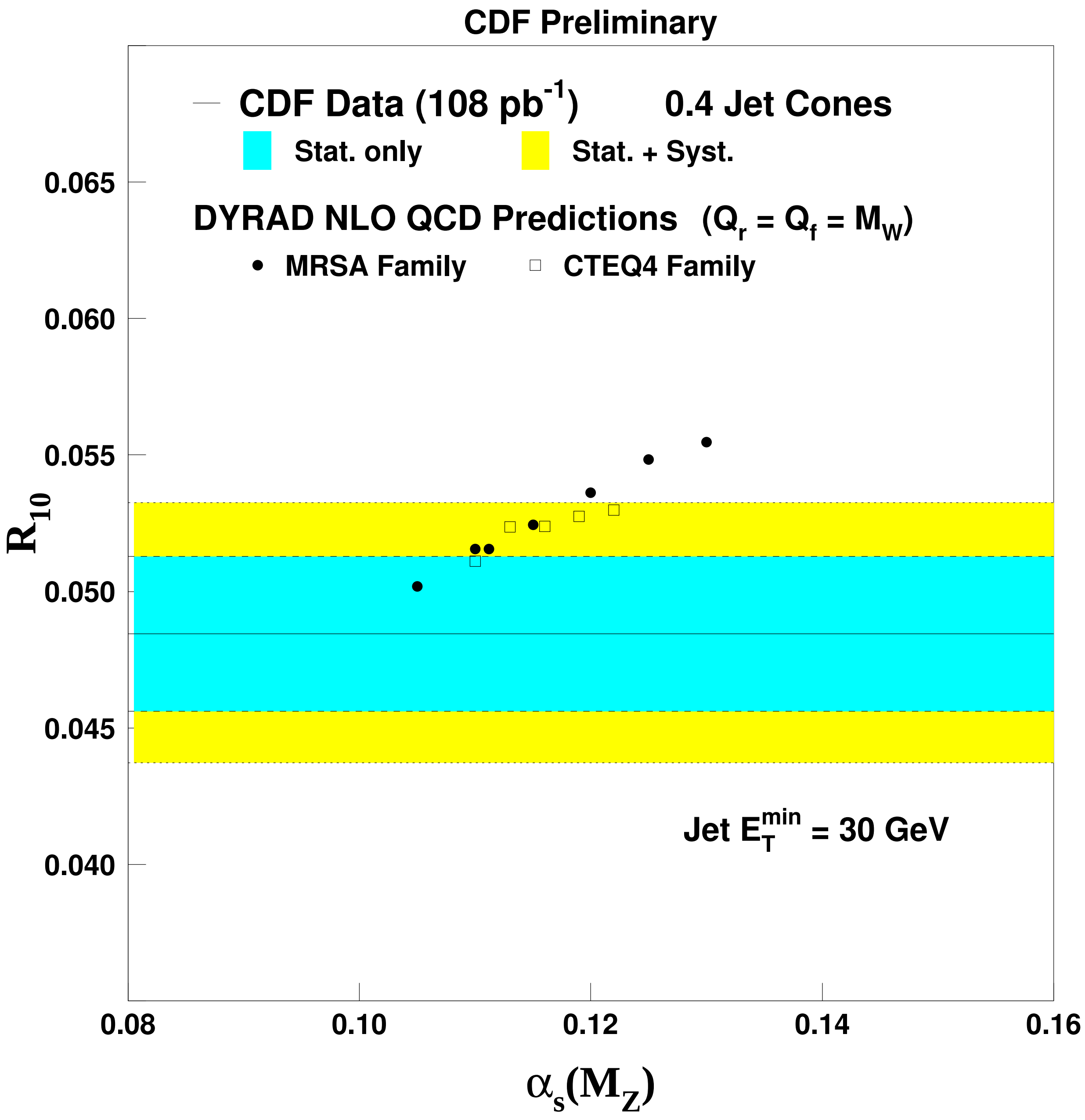
• To test NLO QCD predictions of associated jet production in W–boson events.

The ratio $\mathcal{R}_{10} = \sigma(W+ \geq 1jet)/\sigma(W)$ was determined from 51,437 $W^{\pm} \rightarrow e^{\pm}\nu$ events with $\mathcal{L} = 108$ pb^{-1}.



For a jet threshold of $E_T^{min} > 25$ GeV, the theory agrees with the data to within 1σ over the measured range.

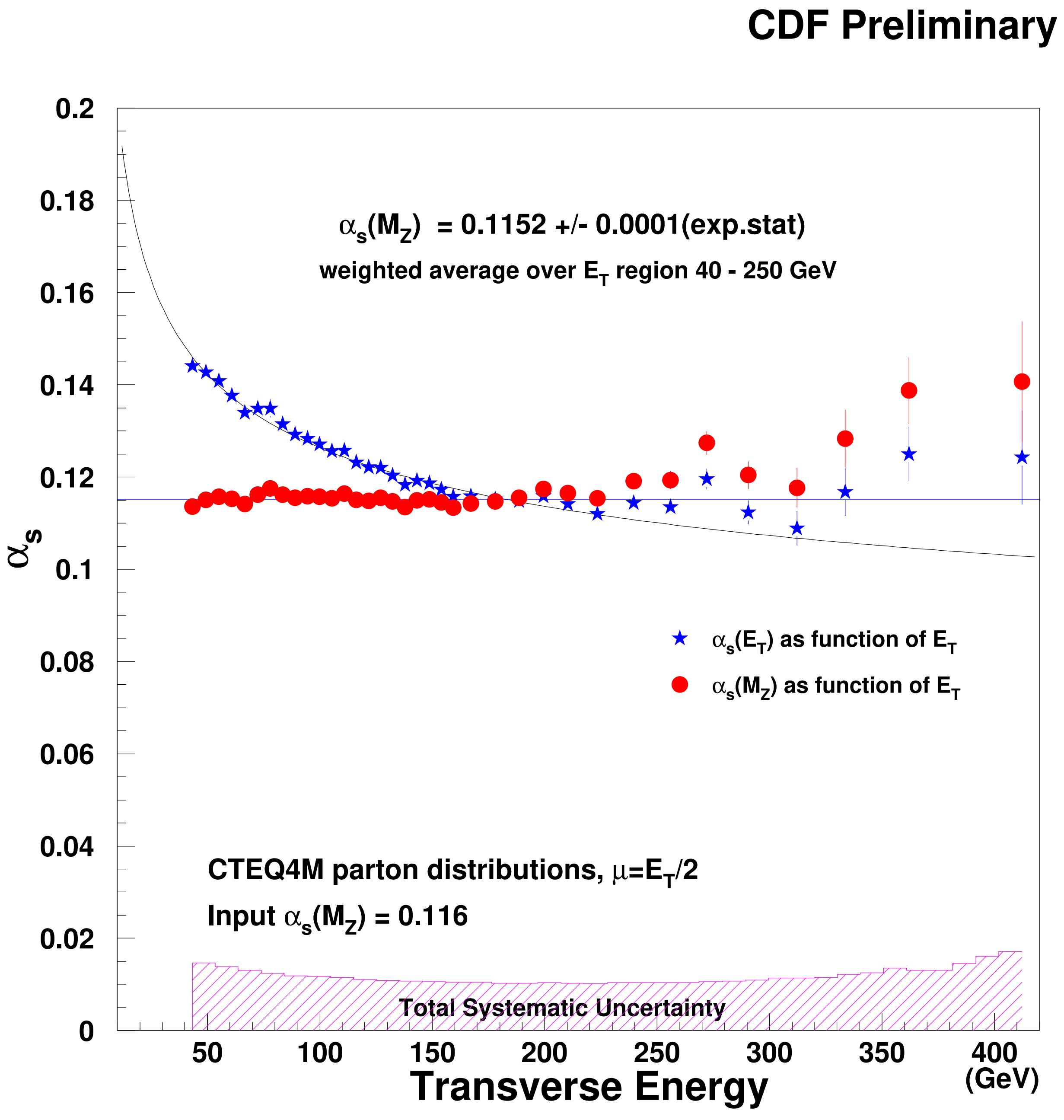
Hard Scattering (pQCD): CDF W + jets



Because of the small dependence of $\mathcal{R}_{10}$ to variations in α_s, no extraction of α_s can be made from this measurement.

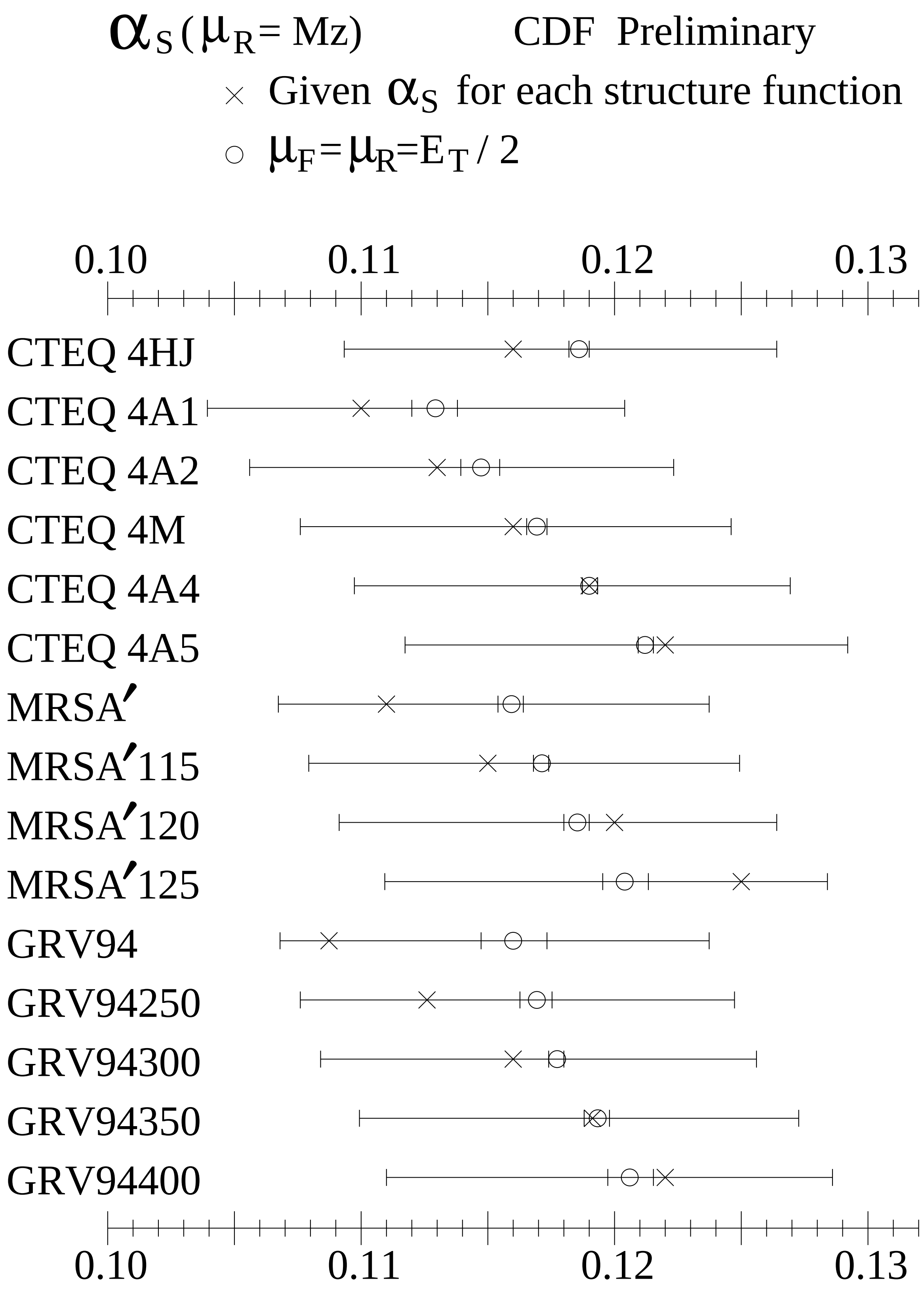
Hard Scattering (pQCD): CDF α_s

CDF Inclusive Jet Data



- Initialize α_s
- Compute theoretical prediction for given PDF
- Fit prediction to theory and extract α_s

Hard Scattering (pQCD): CDF α_s

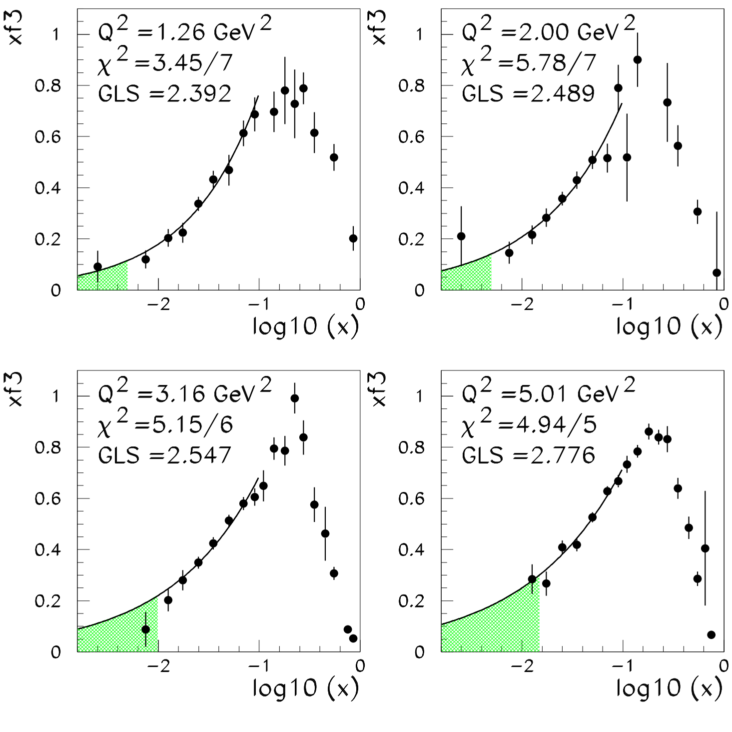


CCFR: Gross Llewellyn Smith Sum Rule

$$\int_0^1 xF_3(x,Q^2)\frac{dx}{x} = 3(1-\frac{\alpha_s}{\pi}-a_2(n_f)(\frac{\alpha_s}{\pi})^2-a_3(n_f)(\frac{\alpha_s}{\pi})^3)-\frac{\Delta HT_{GLS}}{Q^2}$$

The Valence Quarks in the Nucleon

- Fundamental Prediction of QCD
- Theoretically Robust low Q^2 Prediction
- Independent of Gluon Distribution
- Calculated to $\mathcal{O}({\alpha_s}^3)$, estimated to $\mathcal{O}({\alpha_s}^4)$



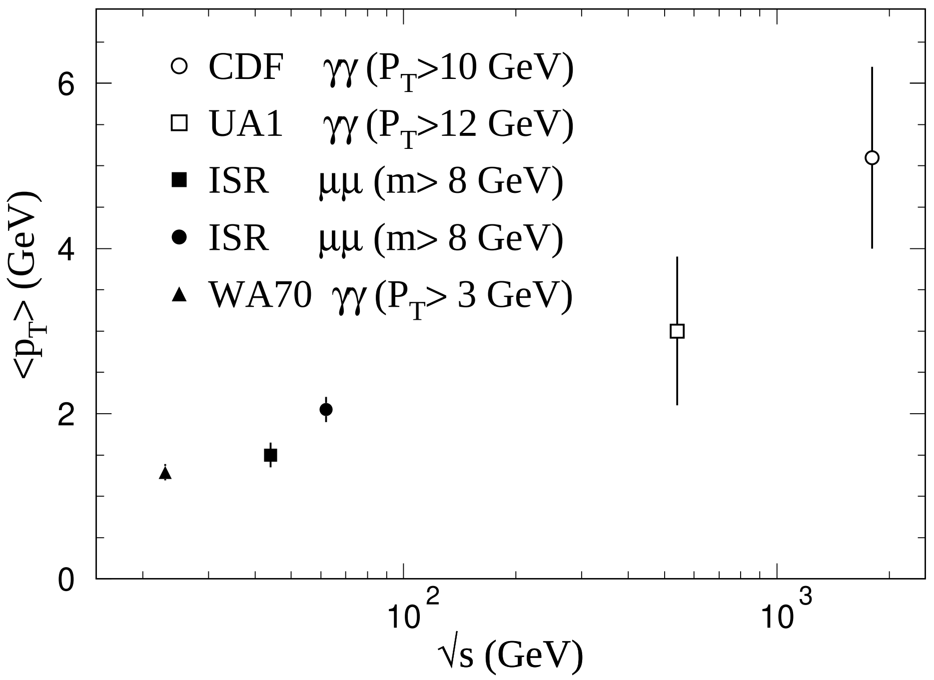
$$\alpha_s(M_Z^2) = 0.114 \pm^{.005}_{.006} (stat) \pm^{.007}_{.009} (syst) \pm^{.004}_{.005} (theory)$$

J.H.Kim, D.A.Harris *et al*, Submitted to PRL

QCD Processes: k_T Effects

- k_T refers to the transverse momenta of partons within the colliding particles before the hard scattering
- Average $< k_T >$ values significantly larger than expected from non-perturbative hadron–size effects have been observed in di–muon and di–photon production. This has been interpreted as resulting from multiple soft gluon emissions.

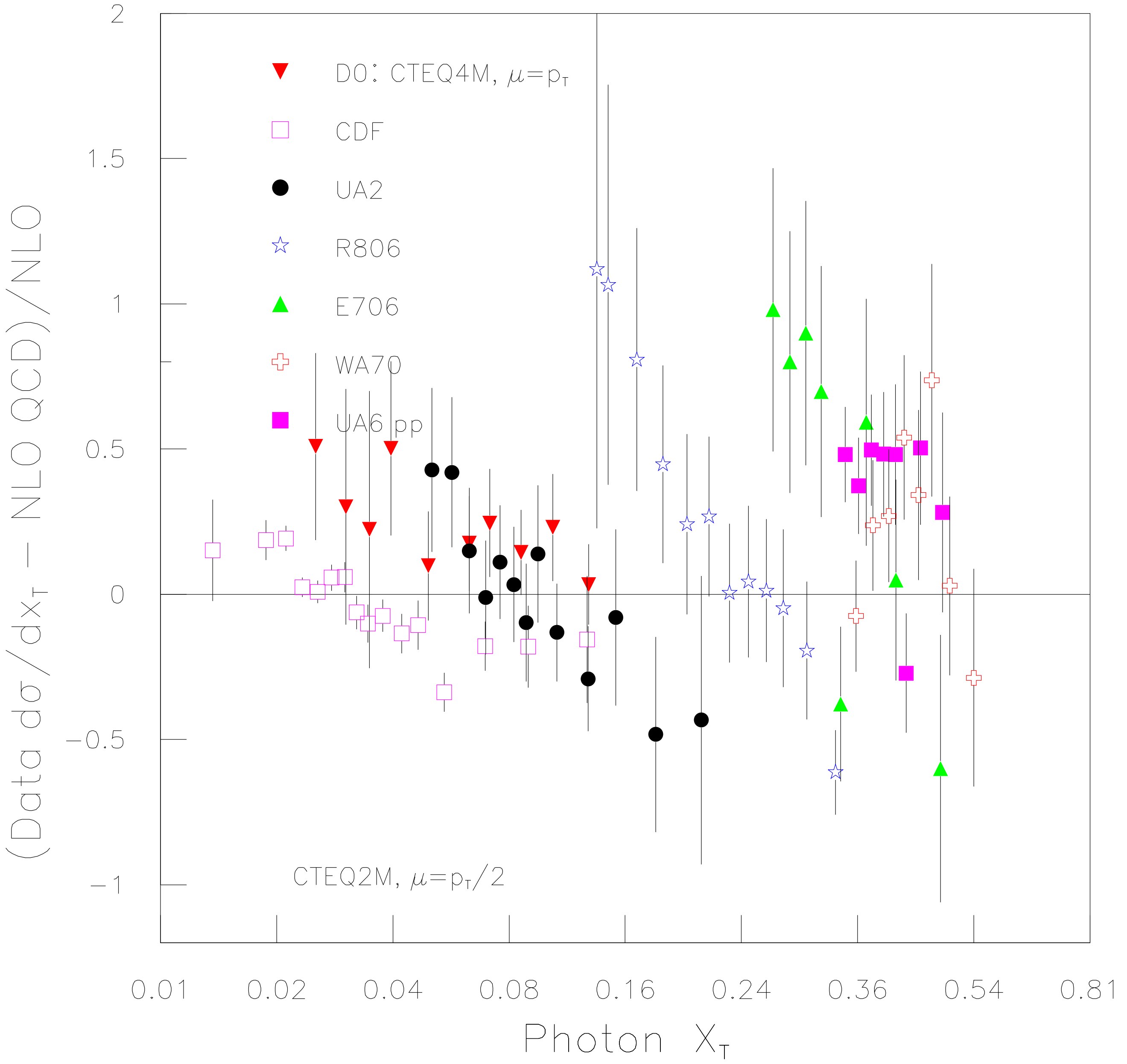
Phys. Rev. Lett. 70, 2232 (1993)



- k_T is expected to modify:
  I. the magnitude and shape of steeply falling high p_T inclusive cross sections
  II. fragmentation distributions observed in jets recoiling against high p_T triggers
- Current NLO calculations of inclusive high p_T photon and light hadron production neglect such soft gluon effects

QCD Processes: k_T Effects

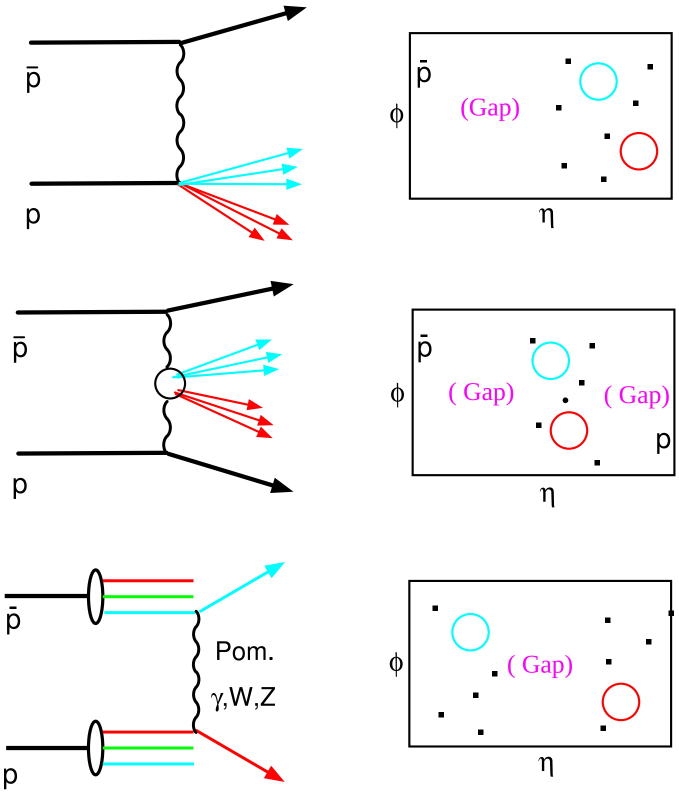
From inclusive photon data, numerous experiments have reported excesses at lower values of x_T than what is predicted by NLO QCD.



QCD Processes: Rapidity Gaps

Rapidity Gaps and Color-Singlet Exchange

Hard Processes (jet production):



Hard Single Diffraction

Hard Double Pomeron

Hard Color-Singlet

Pomerons are color singlet objects which mediate some diffractive interactions. By the nature of their not carrying color charge, no soft radiation is emmitted in regions of phase space. This leaves low multiplicity regions which appear in the detector, and are referred to as **rapidity gaps**.

Definitions of the pomeron vary from a theoretical definition:

> "the highest Regge trajectory with quantum numbers of the vacuum, responsible for the growth in the hadronic cross section with $\sqrt{s}$",

to an experimental one:

> "the thing that causes rapidity gaps". (DØ TDR)

Rapidity Gaps: CDF Hard Single Diffraction

CDF has published measurements of Hard Single Diffractive events.

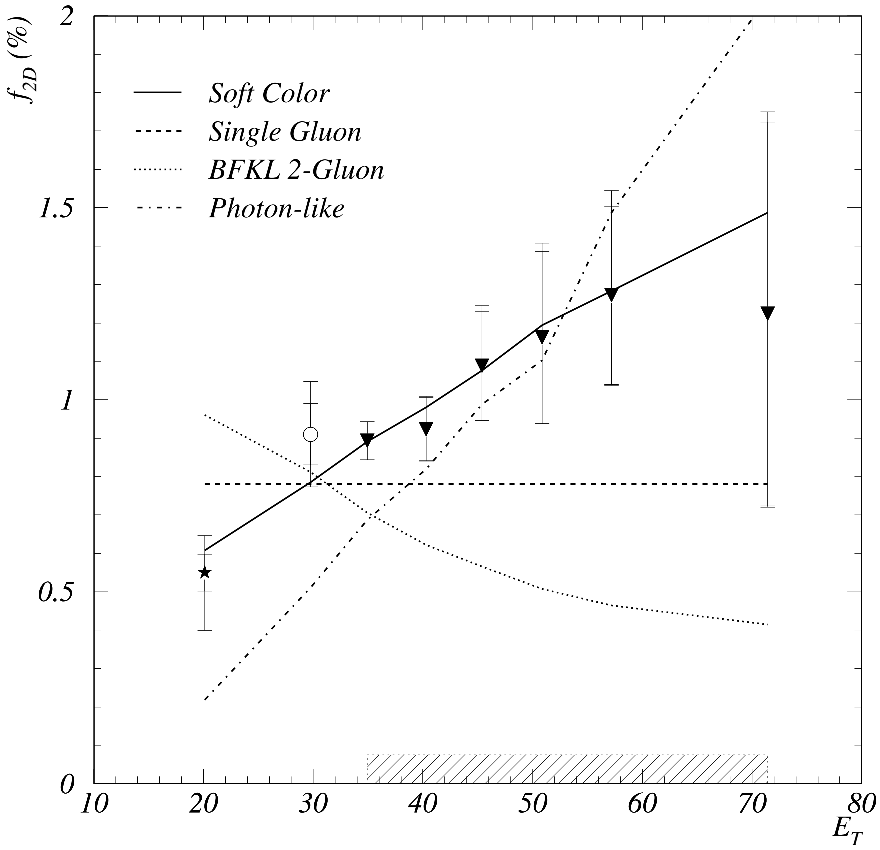
In diffractive di–jet production at $\sqrt{s} = 1.8$ TeV, the measured gap fraction was reported to be $0.75 \pm 0.05(stat) \pm 0.09(syst)\%$.

CDF has first observation of diffractively produced W bosons in hard single diffractive events. The diffractive to non-diffractive W production ratio was reported to be $1.15 \pm 0.55\%$.

Using the previous results, the pomeron gluon fraction was determined to be $f_g = 0.7 \pm 0.2$.

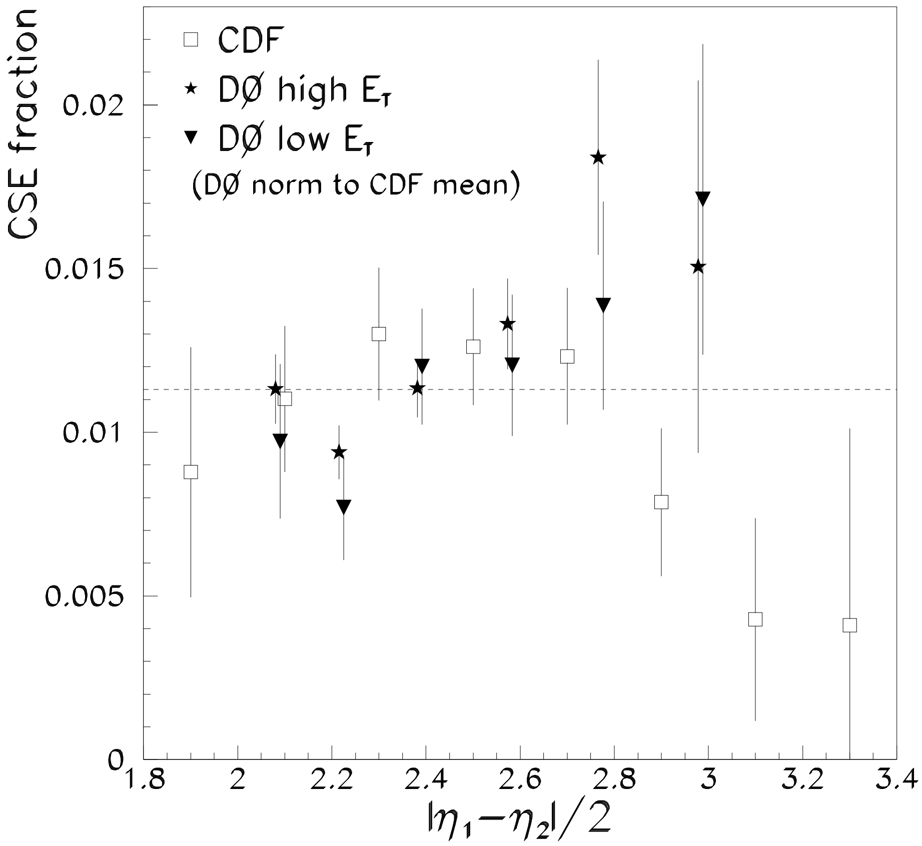
Hard Color Singlet Exchange

DØ Preliminary



Though the systematic errors are consistent with a flat distribution, the data favors a quark–initiated color singlet process; aka soft color rearrangement.

Hard Color Singlet Exchange

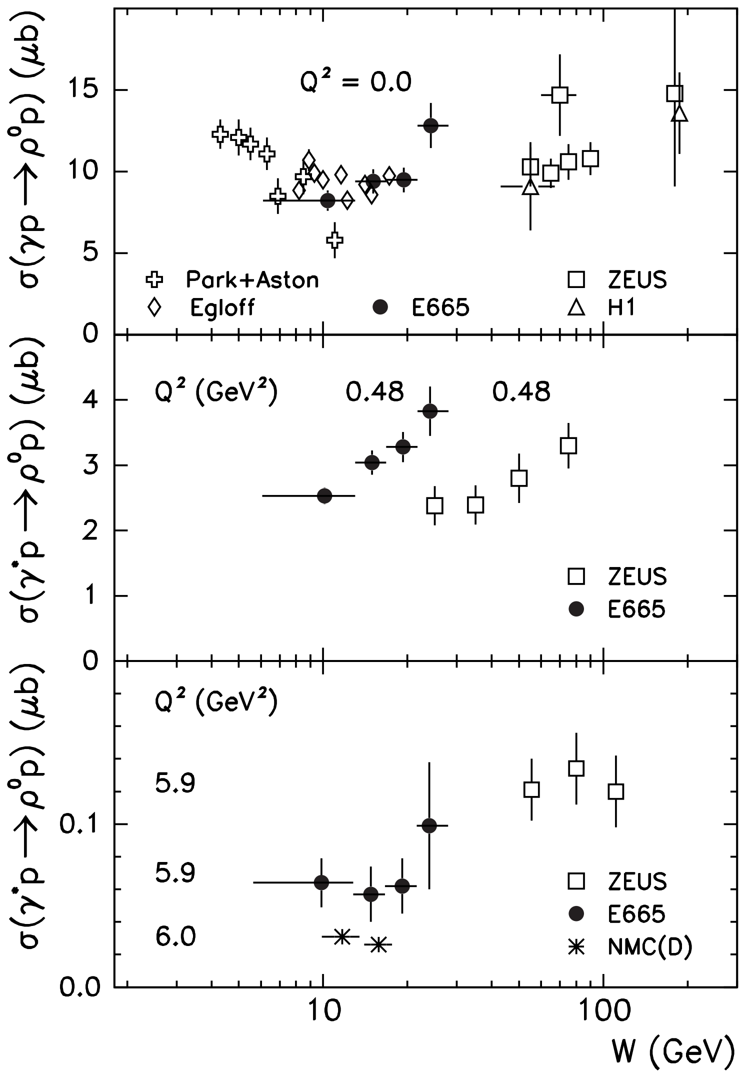


DØ : Though the systematic errors are consistent with a flat distribution, there is indication of a rise with $\Delta\eta$

CDF: Data consistent with flat distribution

E665: Diffractive ρ^0 Production

$$\mu^+ p \to \mu^+ p \rho^0$$



- E665 data are consistent with Zeus and H1 data at $Q^2 = 0$ and $Q^2 = 5.9$ GeV^2
- E665 lie aboe the trend of the Zeus data at $Q^2 = 0.48$ GeV^2 and above the NMC data at 5.9 GeV^2.
- Although the E665 results assume a smaller double-diffractive contamination, this effect is not large enough to explain the large discrepancy between the NMC and E665 measurements.

Rapidity Gaps: Conclusions

- Both CDF and DØ have published results of measurements of Jet Production in Hard Single Diffractive events. CDF(DØ) measures a gap fraction of $\simeq 0.75 \pm 0.05 \pm 0.09\%$ $(0.76 \pm 0.04 \pm 0.07\%)$
- DØ has preliminary results for Jet Production in Hard Single Diffractive events at $\sqrt{s} = 630$ GeV. The measured gap fraction is $1.11 \pm 0.11 \pm 0.20\%$
- CDF has also observed W–boson production in Hard Single Diffractive events. The diffractive to non-diffractive W production ratio was reported to be $1.15 \pm 0.55\%$
- CDF used the diffractive W and diffractive jet results to determine the pomeron gluon fraction to be 0.7 ± 0.2
- CDF and DØ each observe events with gap–jets–gap topology which are consistent with double pomeron exchange
- CDF and DØ have measured the dependence of the gap fraction for Hard Color Singlet Exchange (jet–gap–jet) on $\sqrt{s}$, E_T, and $\Delta\eta$. DØ data favor quark initiated color singlet processes

QCD Processes: Conclusions

- Many new QCD results have been presented.
- Many tests of QCD are in good agreement with the theory.
- Several of the experimental measurements are now of high enough precision to drive theory.
- Several results indicate the need for higher order theoretical predictions.

QCD IS ALIVE AND WELL AT FERMILAB!!!