Introduction to the high p_T inclusives session

Matthew Wing (McGill University)

- Introduction.
- Advances in high p_T photon physics.
- Topics of relevance to high p_T inclusives.
  - "Non-photon" experiment (Tevatron) results.
  - "Non-photon" theoretical progress.
- Summary and the future.

Introduction.

- Talk focuses on advances in QCD $\rightarrow$ advances in the photon and "photon physics".

- Arbitrary LO cross section where incoming particle, I_1 resolves and collides with other incoming resolving particle, I_2:

$$d\sigma_{I_1 I_2 \rightarrow cd} = \sum_{ab} \int_{x_{I_2}} \int_{x_{I_1}} f_{I_2 \rightarrow b}(x_{I_2}, \mu^2_{I_2}) f_{I_1 \rightarrow a}(x_{I_1}, \mu^2_{I_1}) \mathcal{M}_{ab \rightarrow cd}$$

- Then have two or three "unknowns"; the perturbative cross section and one or two structure functions.

- Advances in understanding $\mathcal{M}_{ab \rightarrow cd}$ from e.g. Tevatron or theory essential for understanding the photon PDF.

Experimental advances in photon physics.

- **Photoproduction and $\gamma\gamma$ measurements starting to take on great importance.**

- **Many cross sections now available for theoretical comparison.**

- **Complimentary measurements of HERA and LEP? See later.**

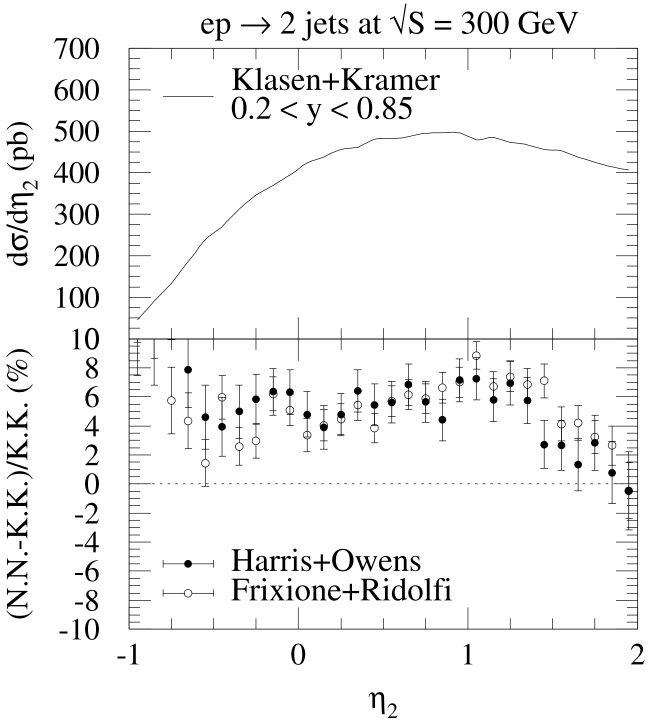
End of experimental photon physics review.

- **Problem is, results are harder to interpret:**
  - **Hadron $\leftrightarrow$ parton effects.**
  - **Understanding soft physics.**

- **Work needed and ongoing...**

Theoretical advances in photon physics.

- Frixione and Ridolfi, NPB 507 (1997) 315, NPB 507 (1997) 295. Subtraction method. Code freely available with web page.
- Harris and Owens, PRD 57 (1998) 5555, PRD 56 (1997) 4007. Phase space slicing method (δ_s, δ_c).
- Kleinwort, Klasen and Kramer, EPJC direct 1 (1998) 1, ZPC 76 (1997) 67. Phase space slicing method (y_{cut})



Calculations shown to be consistent to within 5 – 10 % (Harris, Klasen and Vossebeld, HERA MC proceedings, `hep-ph/9905348`)

- Aurenche et al., "Future Physics at HERA" (1996) 570. Phase space slicing method.
- `JetViP`: Kramer and Pötter, EPJC 5 (1998) 665, Pötter, EPJC 5 (1999) 1, CPC 119 (1999) 4. Code freely available with web page.

Shown to be consistent with Klasen et al. (Pötter, `hep-ph/9911221`)

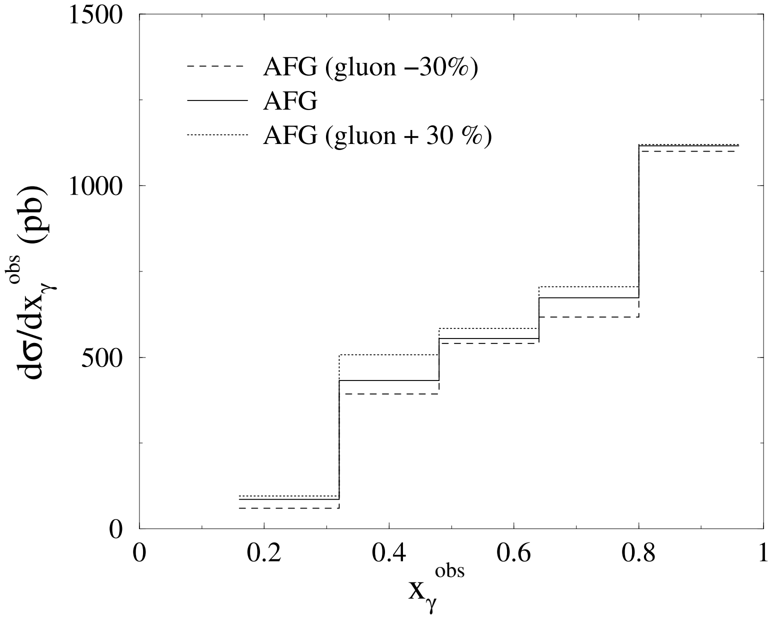
NLO Monte Carlo approach in 1 or 2 jets photoproduction.

P. Aurenche et al., `hep-ph/0006011`

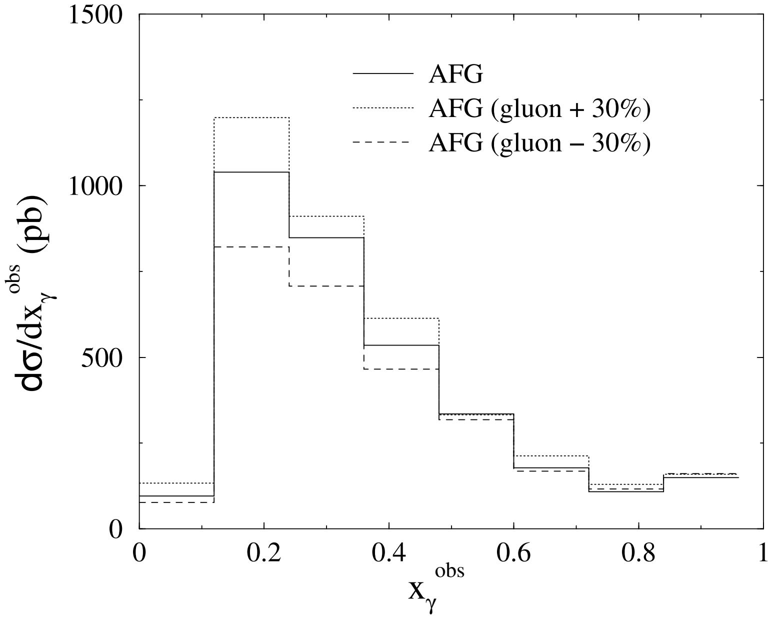
- **Paper shows NLO predictions for photoproduction data and compares to HERA data.**
- **Numerical comparisons with Klasen and Kramer were good.**
- **Focus is on constraining the gluon density in the photon and proton.**
- **Comparisons to dijet data made - some reviewed here.**

Sensitivity to the gluon in the photon.

Photoproduction; $E_T^{\text{jet1}} > 12$ GeV, $E_T^{\text{jet2}} > 10$ GeV



$0 < \eta^{\text{jet}} < 1$



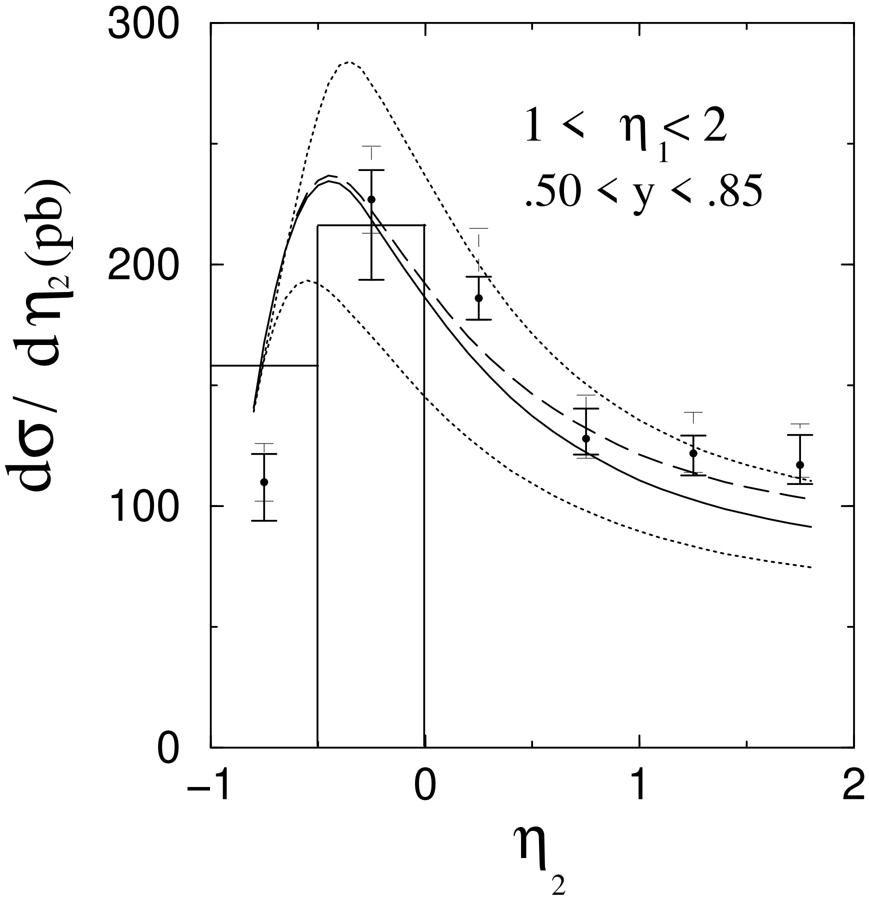
$1 < \eta^{\text{jet}} < 2$

- **Forward η^{jet} and low$-x_\gamma^{\text{obs}}$ show sensitivity to the gluon content for similar kinematic region under study at HERA.**

- **At $x_\gamma^{\text{obs}} = 0.2$, increase of 30% in gluon density $\rightarrow 25\%$ increase in cross-section.**

Comparison with HERA data I

ZEUS data*, $Q^2 < 1$ GeV^2, $E_T^{\text{jet1}} > 14$ **GeV**, $E_T^{\text{jet2}} > 11$ **GeV**



Solid line: central value

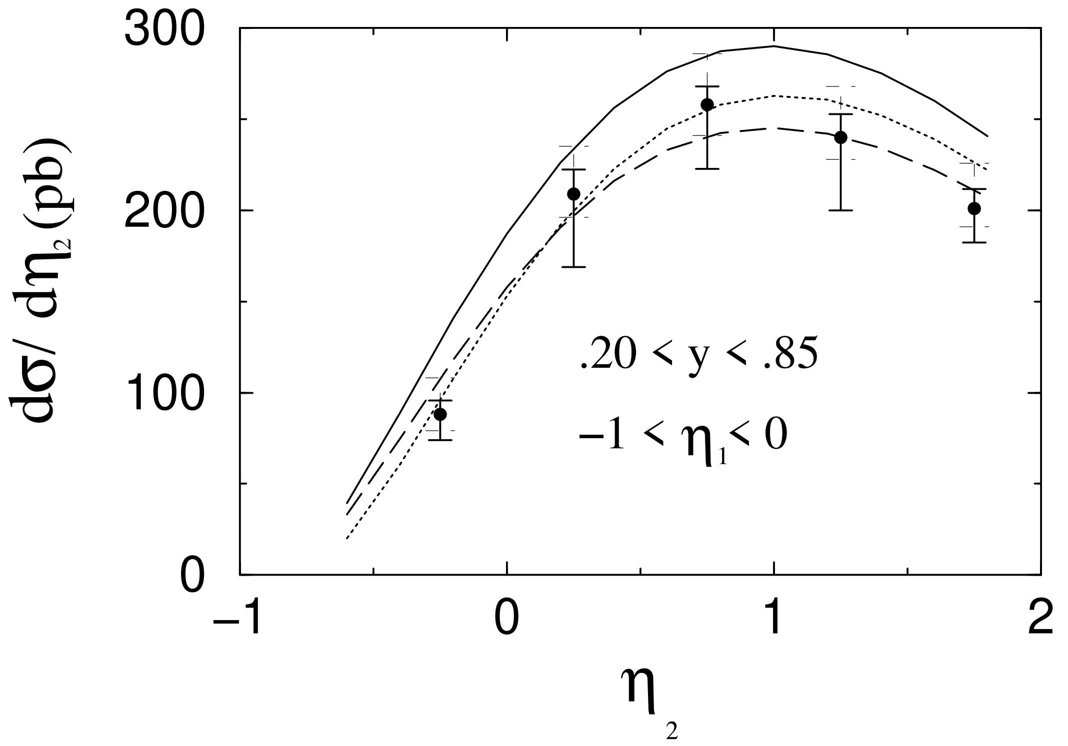
Dashed line: g/γ **increased by** 20%

- **Increase in the gluon density improves the description.**
- 20% **increase in** $g/\gamma \rightarrow$ **up to** 10% **increase in cross section.**
- **Change in the forward direction; negative** η^{jet} **remains the same.**
- **Negative** η^{jet} **affected strongly by hadronisation.**

*J. Breitweg et al., Euro. Phys. J., C11 (1999) 35.

Comparison with HERA data II

ZEUS data, $Q^2 < 1\ \mathrm{GeV}^2$**,** $E_T^{\mathrm{jet1}} > 14$ **GeV,** $E_T^{\mathrm{jet2}} > 11$ **GeV**



Solid line: central value
Dashed line: g/P **reduced by** 20%

- **Central theory prediction lies above the data.**
- **Decrease in the gluon density in the proton improves the description.**
- **BUT, negative** η^{jet} **affected strongly by hadronisation.**
- **Errors of measurement as large as variation of the gluon content.**

- **HERA data indicates roughly** 20% **increase in** g/γ **and** 20% **decrease in** g/P**.**
- **Improved measurements to come...**

Physics at the Tevatron

- HERA/LEP test QCD in complimentary way to Tevatron.

- Proton PDF better constrained than photon PDF.

- Where we finish, $E_T^{\text{jet}} \sim 50$ GeV, $M_{jj} \sim 200$ GeV, Tevatron starts, providing overlap between experiments.

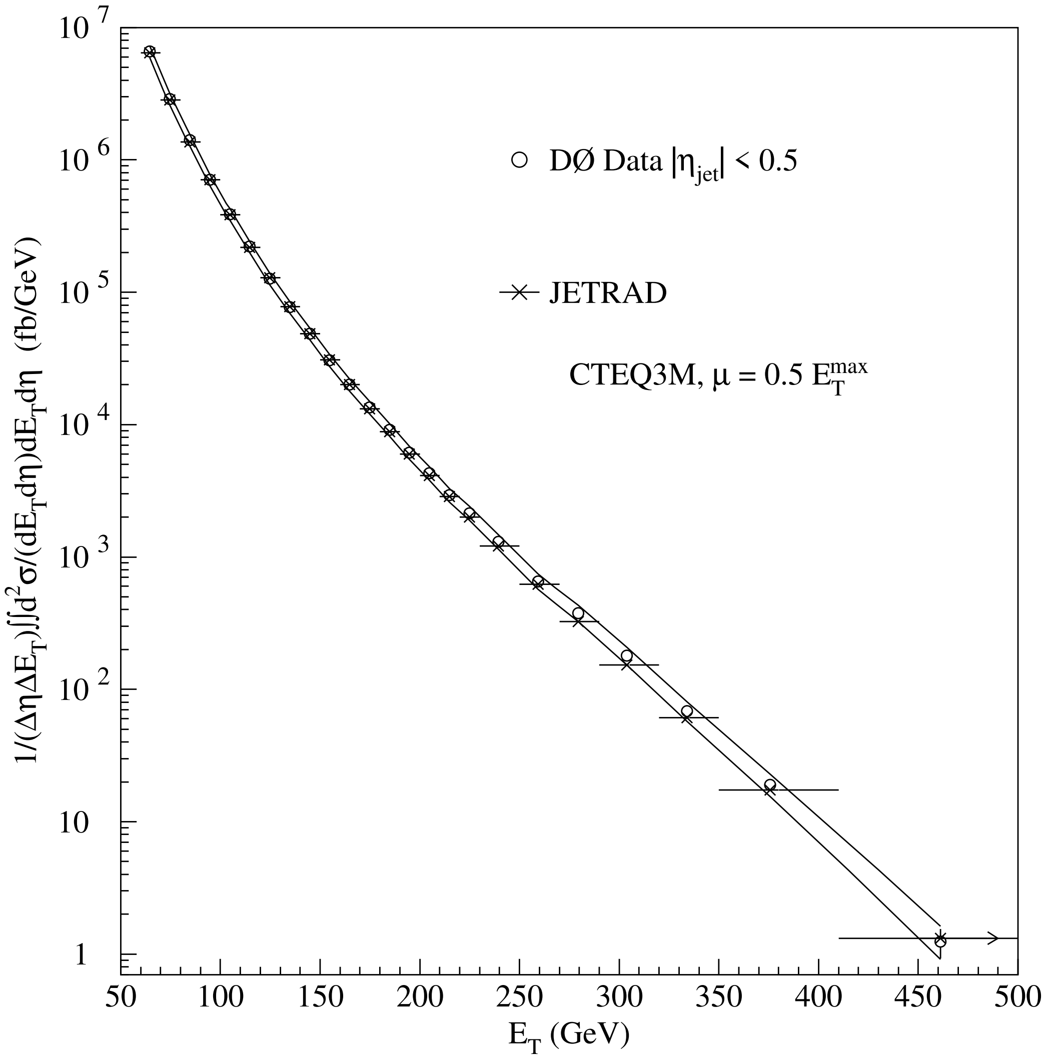
  – High$-E_T$ jet production.

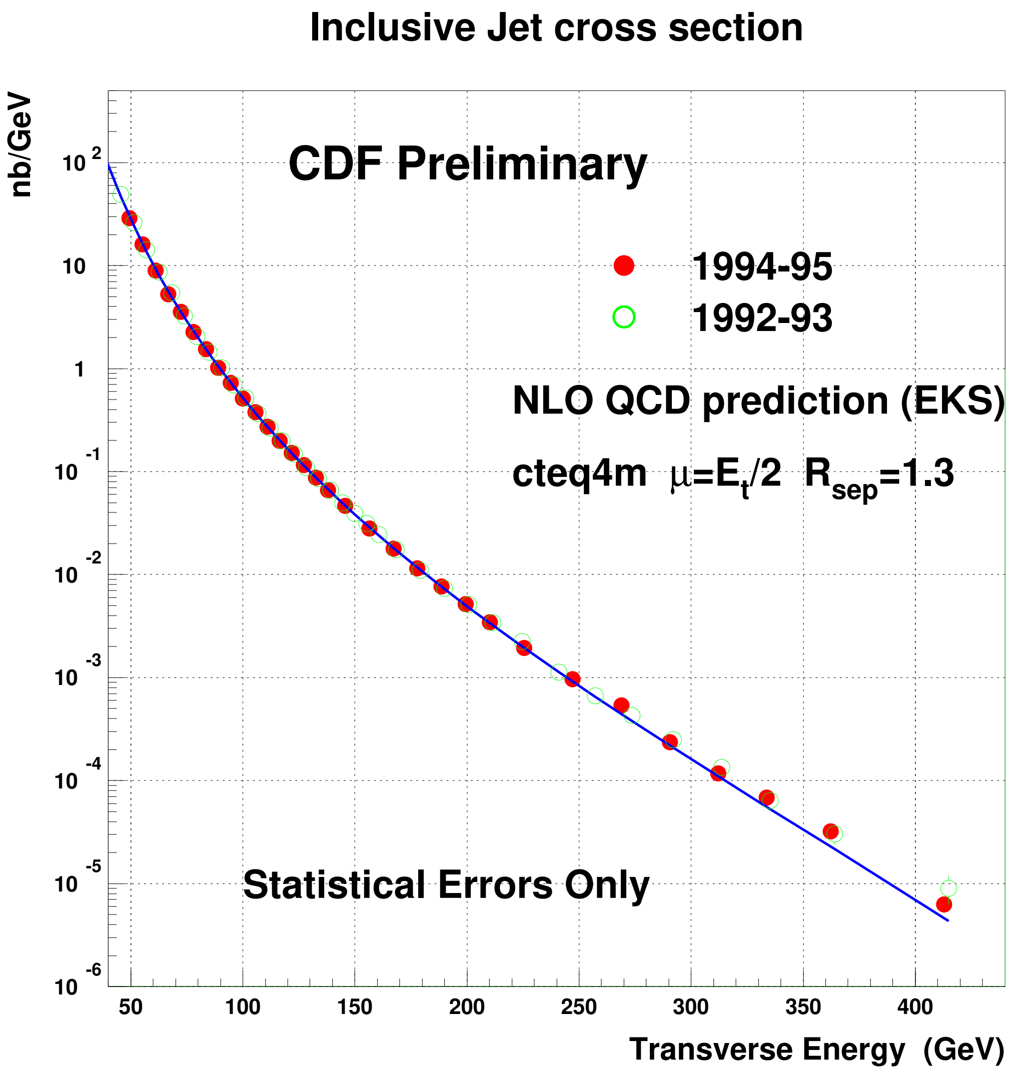
  – Jet substructure.

  – Direct photon events.

- Selection of interesting measurements (some old) of relevance.

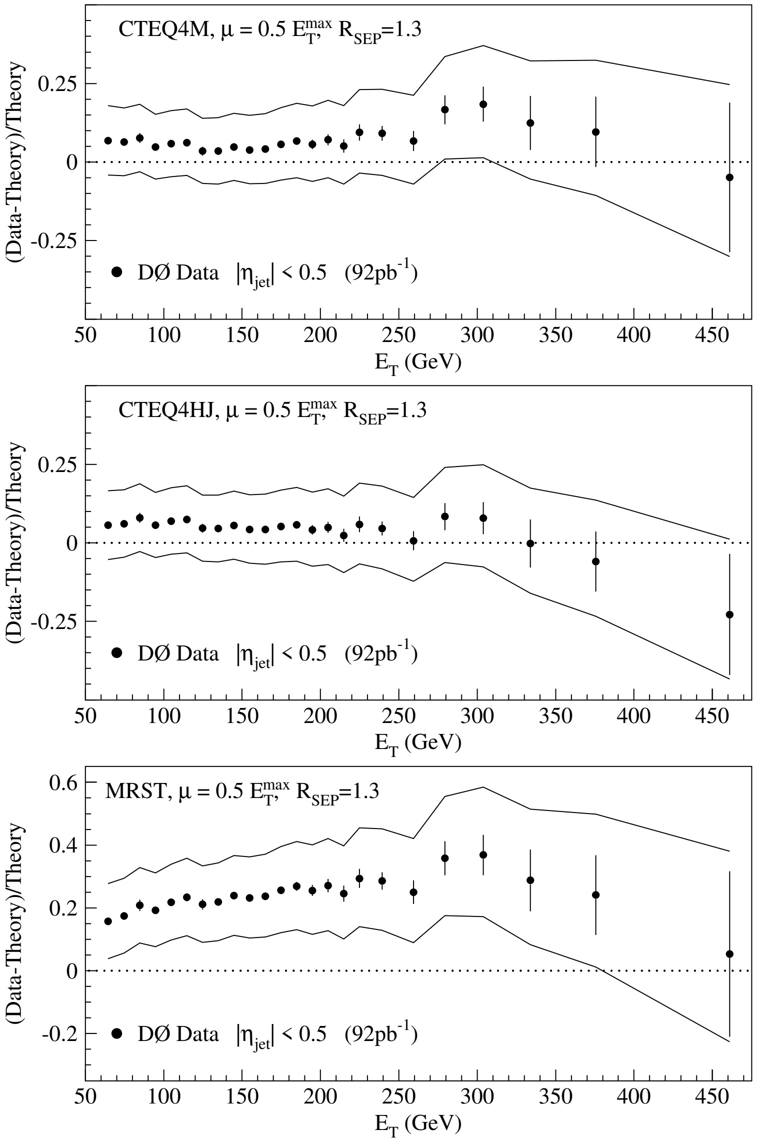
Inclusive jet cross sections

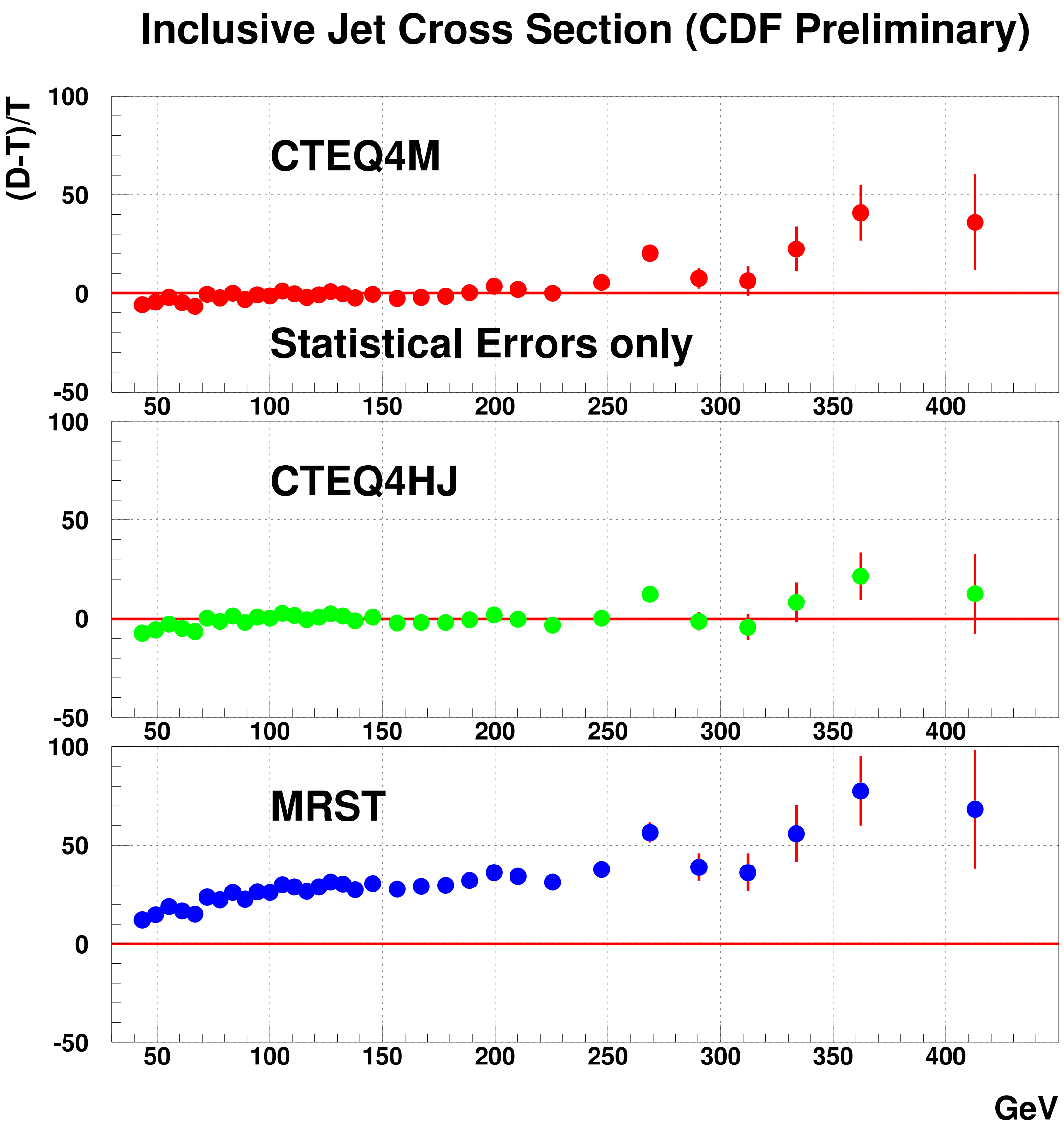




- **Cross section measurements fall by $\sim$ 7 orders of magnitude.**
- **CDF data above at high E_T.**

Comparison to different PDF's

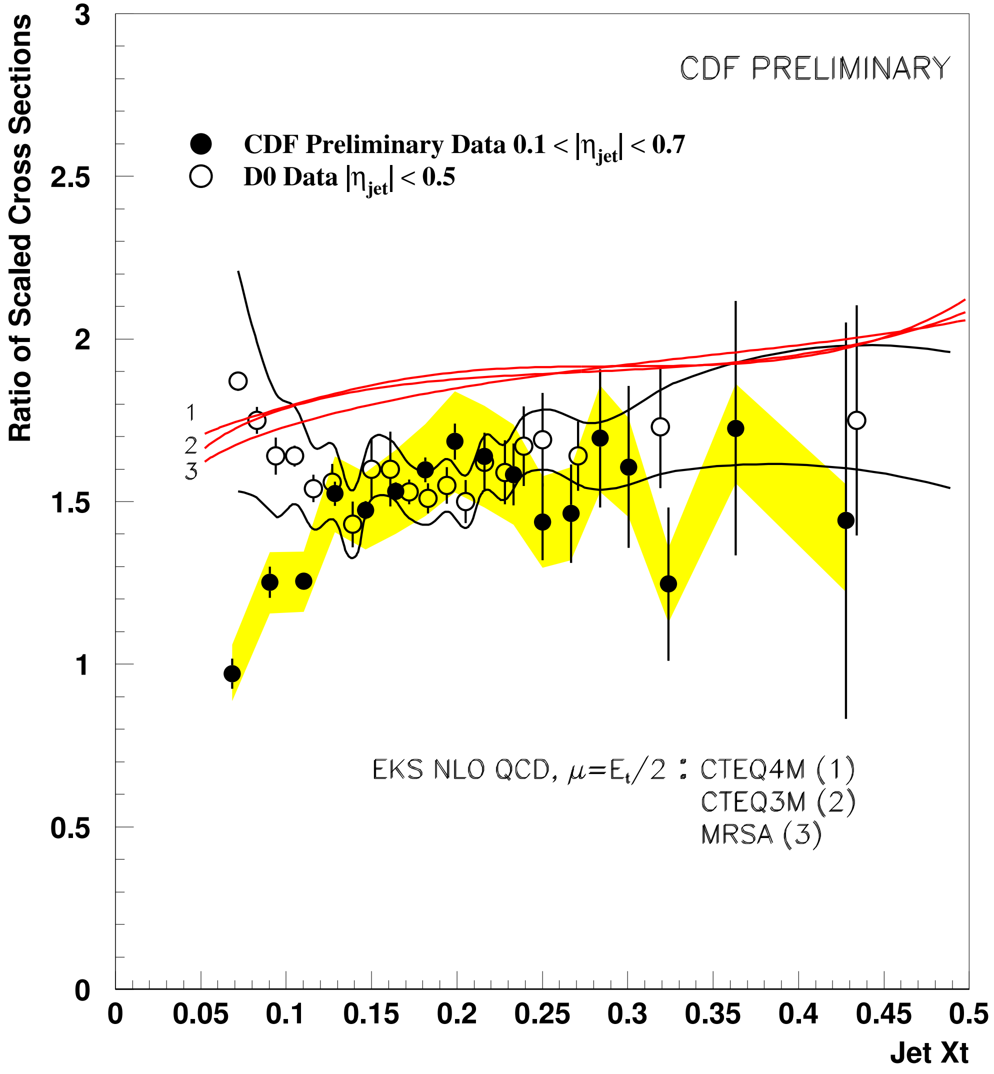




Note, CTEQ4HJ includes CDF 1A data.

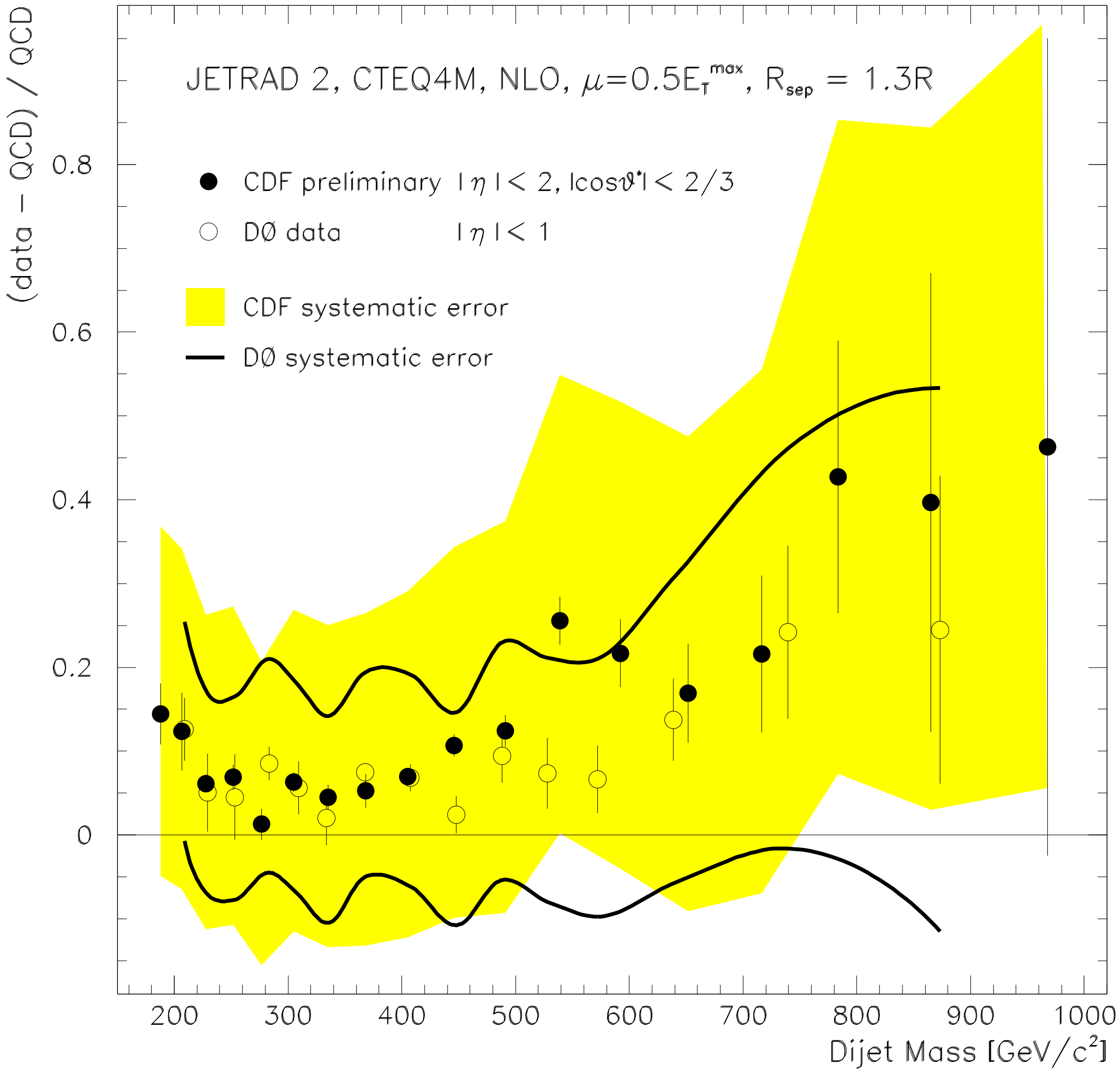
Ratio of cross sections

Ratio of cross sections at 630 GeV and 1800 GeV.



- **Reduction in PDF uncertainty.**
- **Data consistent with each other at moderate and high$-E_T$ but not at low$-E_T$.**
- **Data $10-15\%$ below the theory.**
  - **Different renormalisation scales at different $\sqrt{s}$?**
  - **Other effects, experimental, intrinsic k_T, ...?**

Dijet mass spectrum

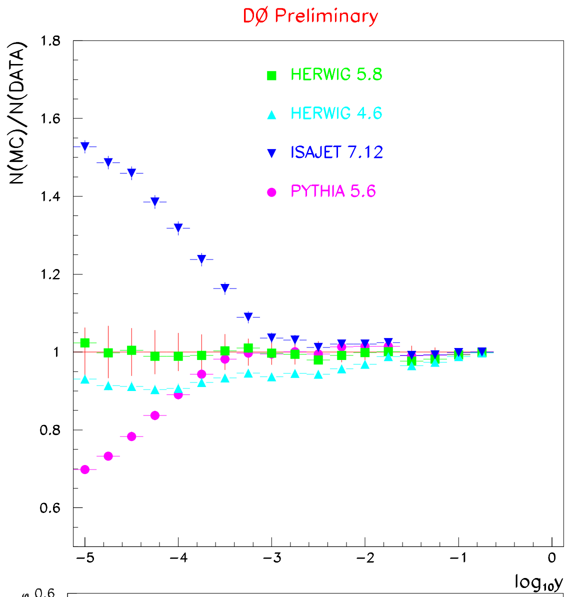


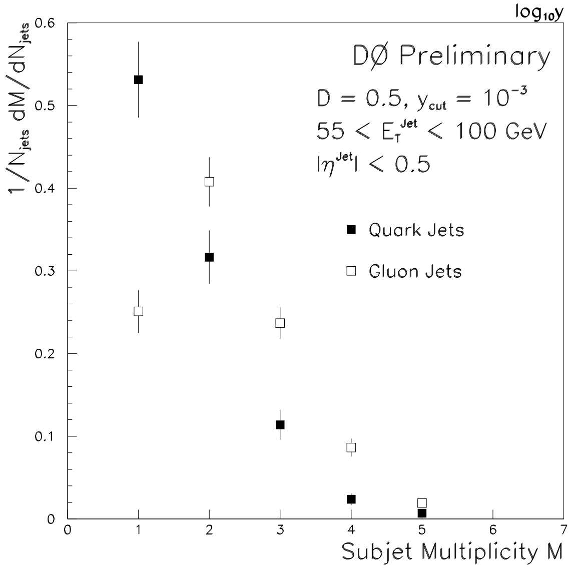
- **Experiments agree very well (different η range).**
- **Reasonable description from theory.**
- **Trend towards high masses?**
- **Large systematic errors.**

Inclusive jet summary

- Systematic uncertainties at high$-E_T$ need to be better understood.
- More statistics needed $\rightarrow$ Run II
- Ratio of cross sections at 630 GeV and 1800 GeV differ drastically with theory.
- Have we seen this at HERA?
  - Potentially easy to do, many centre-of-mass energies.
  - Hampered by photon structure function uncertainty.

Subjet multiplicity at the Tevatron †

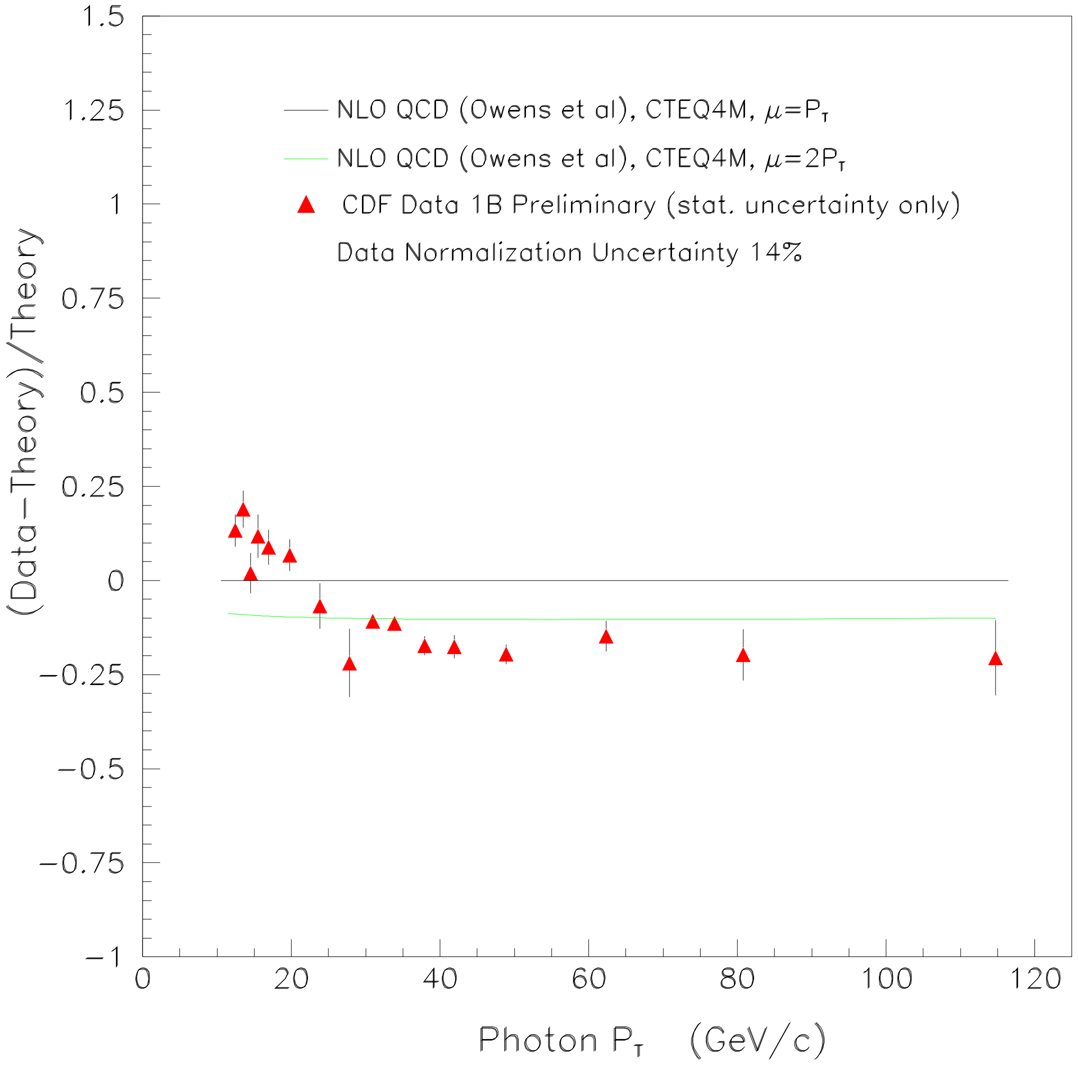




- **Studying 250 GeV jets starting at scales of $\sim$ 1 GeV.**
- **Description by HERWIG is excellent.**
- **Study for separate quark and gluon jet samples.**
- **Assume q and g events independent of $\sqrt{s}$ for fixed E_T.**
- **Statistical separation for $\sqrt{s} = 630$ GeV and $\sqrt{s} = 1800$ GeV**
- **Gluon jets contain more activity than quark jets.**
- **Distributions also well described by HERWIG.**
- $R = \dfrac{<M_g>-1}{<M_q>-1} \approx 1.9 \pm 0.2$

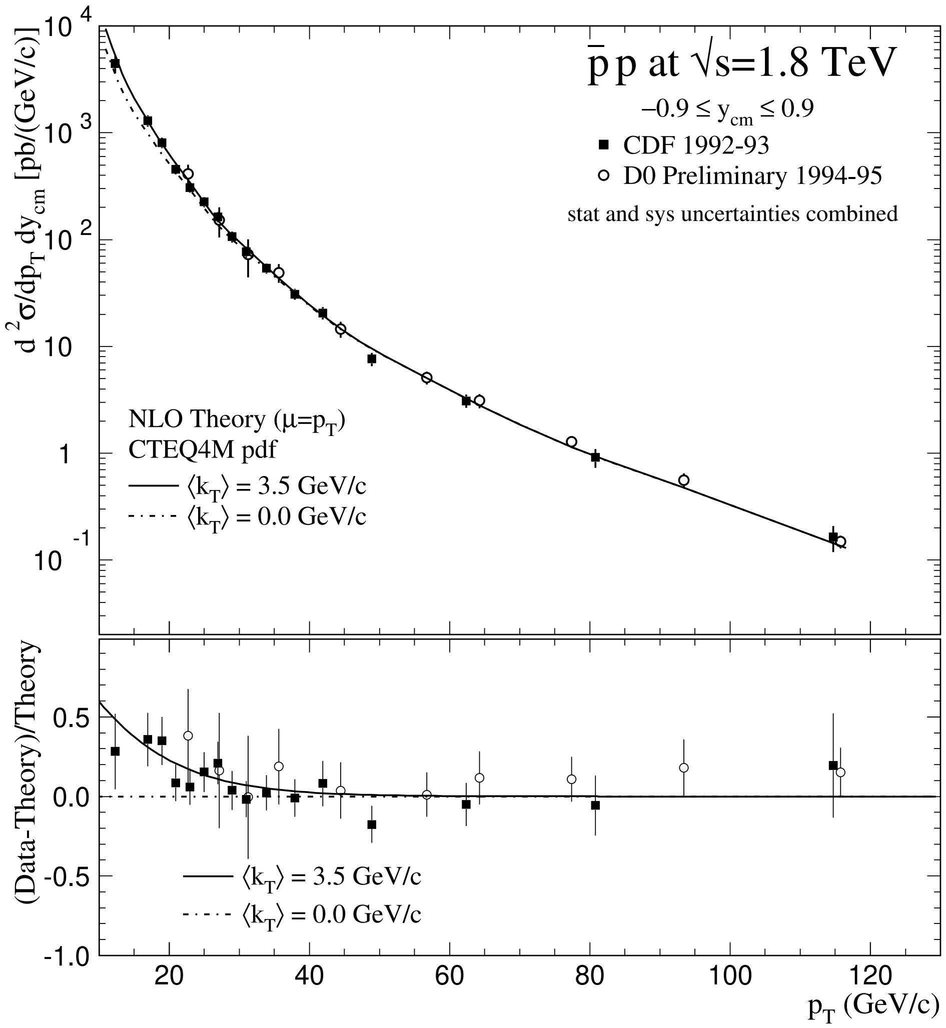
†R. V. Astur, Proc. 10th Topical Workshop on $p\bar{p}$ Collider Physics (1995) 598.
D0 Collab., Nucl. Phys. Proc. Suppl. **79** (1999) 494, `hep-ex/9907059`

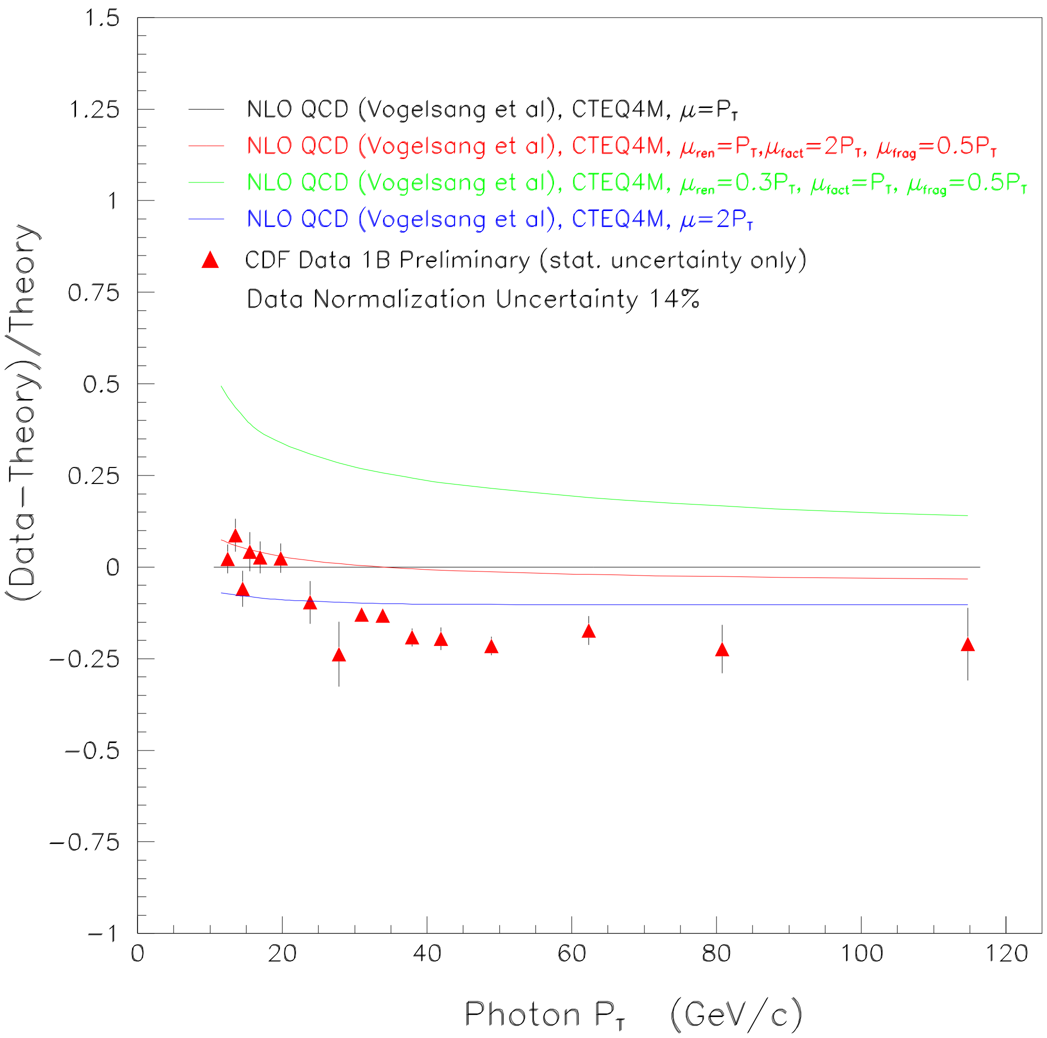
Photon production at the Tevatron



- Rise of data at low E_T.
- Effect not reproduced from NLO of Owens et al.
- Scale change results in a normalisation difference, but no change in shape.
- Prompt photon production (at lower energies) at HERA

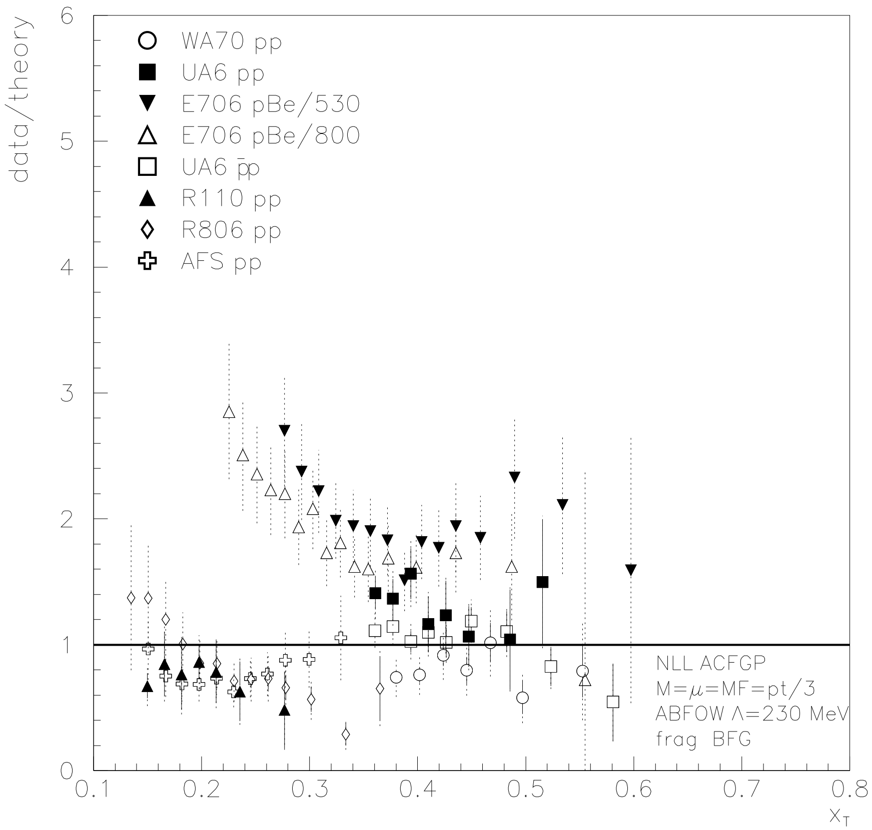
Two interpretations

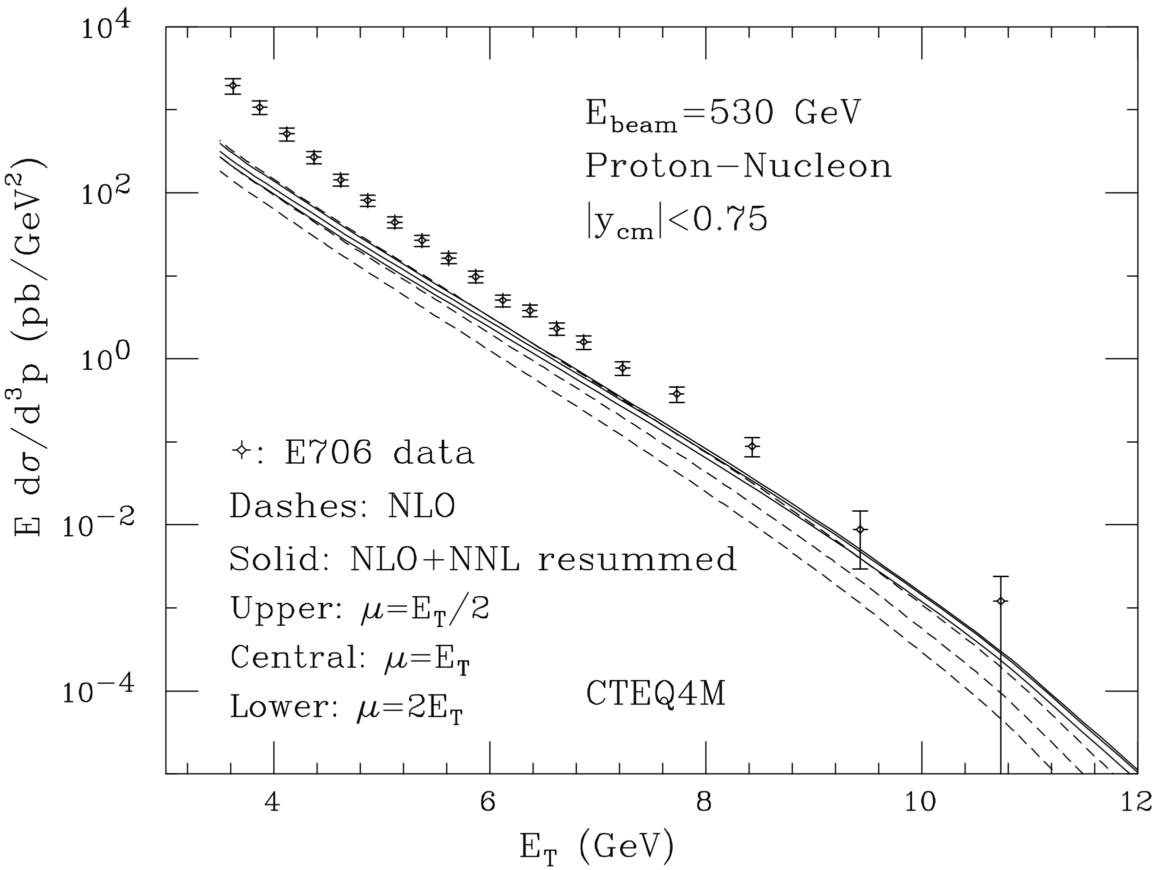




- k_T **smearing in the proton** `hep-ph/9808467` **- better description.**
- **Range of scales,** $\mu_R \neq \mu_F$**.**

Fixed target data compared to theory





Aurenche et al [Eur.Phys.J. C9 (1999) 107] do not use k_T.

- **Describe all data except E706.**
- **Low energy ($E_T \sim 4$ GeV) data not used as results unstable.**

Catani et al. [JHEP 9903 (1999) 25] have a resummed calculation.

- **Scale dependence reduced**
- **E706 data still not described**

Do these calculations describe the Tevatron data?

Tevatron summary

- Tevatron is (clearly a) good testing ground for QCD and is done so over a wide kinematic region.

- Broadly QCD describes the data well.

- Some discrepancies seen - more so than at HERA/LEP?

- Systematic errors often large - experimentally and theoretically.

- QCD pretty much describes everything!

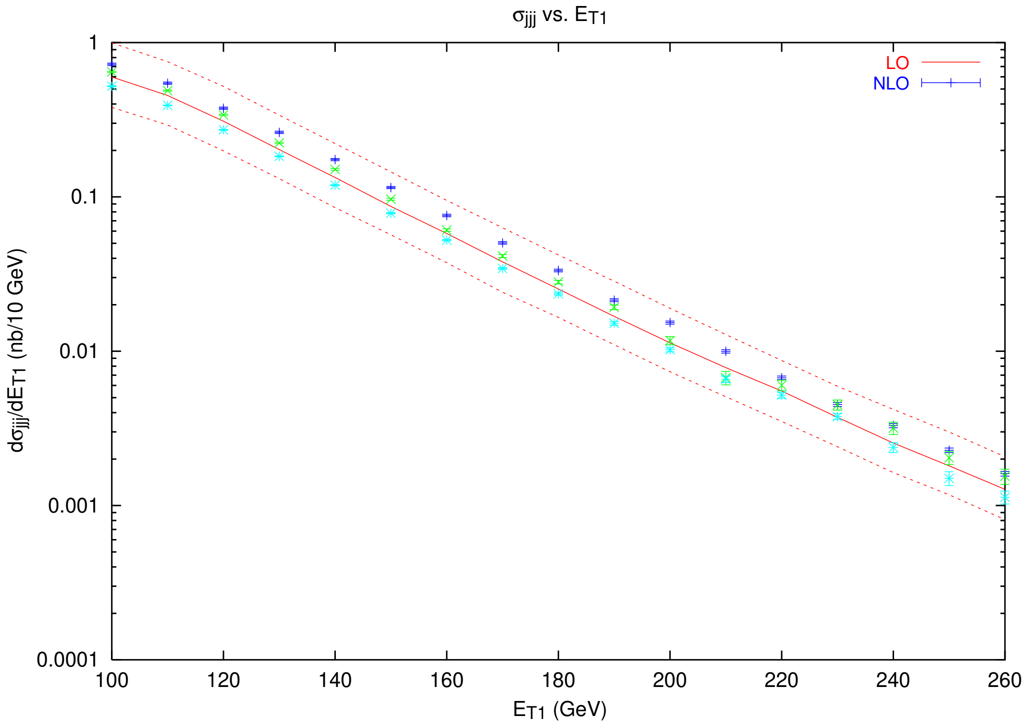
NLO 3-jet production [‡]

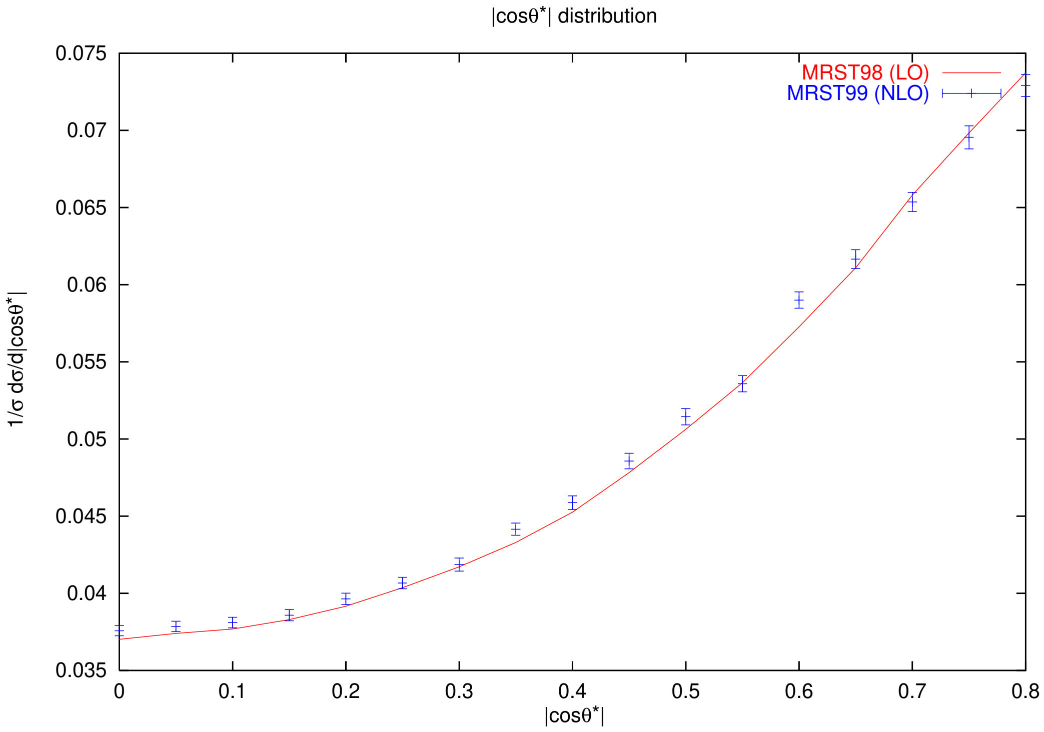
Why do NLO 3-jet production?

- **Measure α_s - 3-jet/2-jet production ratio.**
- **Testing QCD.**
- **Understanding backgrounds to new physics.**
- **Step towards calculating NNLO 2-jet production**

[‡]W. Kilgore, W. Giele

Results of NLO 3-jet production





$\sqrt{s} = 1800$ **GeV,** $\mu = E_T^{\text{jet1}}$

LO (CTEQ-3L), NLO (CTEQ-3M)

k_T **algorithm:**

- $E_T^{\text{jet1}} > 100$ **GeV**
- $E_T^{\text{jet2,3}} > 50$ **GeV**
- $|\eta^{\text{jet}}| < 4$

$\sqrt{s} = 1800$ **GeV**

EKS algorithm:

- $E_T^{\text{jet1}} > 60$ **GeV**
- $E_T^{\text{jet2,3}} > 20$ **GeV**
- $|\eta^{\text{jet}}| < 4$

The Next-to-Leading Order Monte Carlo Calculation is working and producing results.

NNLO jet production [§]

The advantage of each following order:

- **LO gives an order of magnitude estimate.**
- **NLO gives a reliable estimate of σ.**
- **NNLO gives a reliable estimate of $\Delta\sigma$.**

$$
\begin{aligned}
\sigma_{\mathrm{NNLO}}(n\,\mathrm{jet}) \;\sim\; & \int |A^{\mathrm{tree}}_{n+2}|^2 dPS_{n+2} \\
+ & \int \left(A^{1,\mathrm{loop}}_{n+1} A^{\dagger\,\mathrm{tree}}_{n+1} + A^{\dagger 1,\mathrm{loop}}_{n+1} A^{\mathrm{tree}}_{n+1} \right) dPS_{n+1} \\
+ & \int \left(A^{2,\mathrm{loop}}_{n} A^{\dagger\,\mathrm{tree}}_{n} + A^{\dagger 2,\mathrm{loop}}_{n} A^{\mathrm{tree}}_{n} + |A^{1,\mathrm{loop}}_{n}|^2 \right) dPS_{n}
\end{aligned}
$$

“I anticipate NNLO monte carlo for $2 \to 2$ in 5 years”

N. Glover, RAL Xmas meeting 1998.

[§] Many people, Glover et al., Bern et al., ...

Summary and the future.

- General basis of NLO QCD works well.

- NNLO will be available "soon" and NLO 3-jets is developed.

- Some work on understanding HERA data with respect to the gluon content of the photon has been done.

- More work needed on measuring the photon PDF from HERA/LEP (two photon).

- Theory and experiment converging to more detailed picture of QCD
  $\rightarrow$ detailed picture of the photon.

- Further photon physics at future ep machine and NLC.