CTEQ

Global Fitting Project

and

the Impact of PDF's at Large-x

J.F. Owens
Physics Department, Florida State University

Jefferson Laboratory
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Outline

- Introduction
- Global Fitting
  - procedures
  - observables and kinematic coverage
  - errors
- Current Projects - new data sets
- Large-x
  - Treatment in current fits
  - Possible future directions
- Conclusions

PDF's - Parton Distribution Functions

- Essential ingredient for any perturbative calculation for a hadron-induced large momentum transfer process
- Required for comparison between perturbative standard model calculations and data

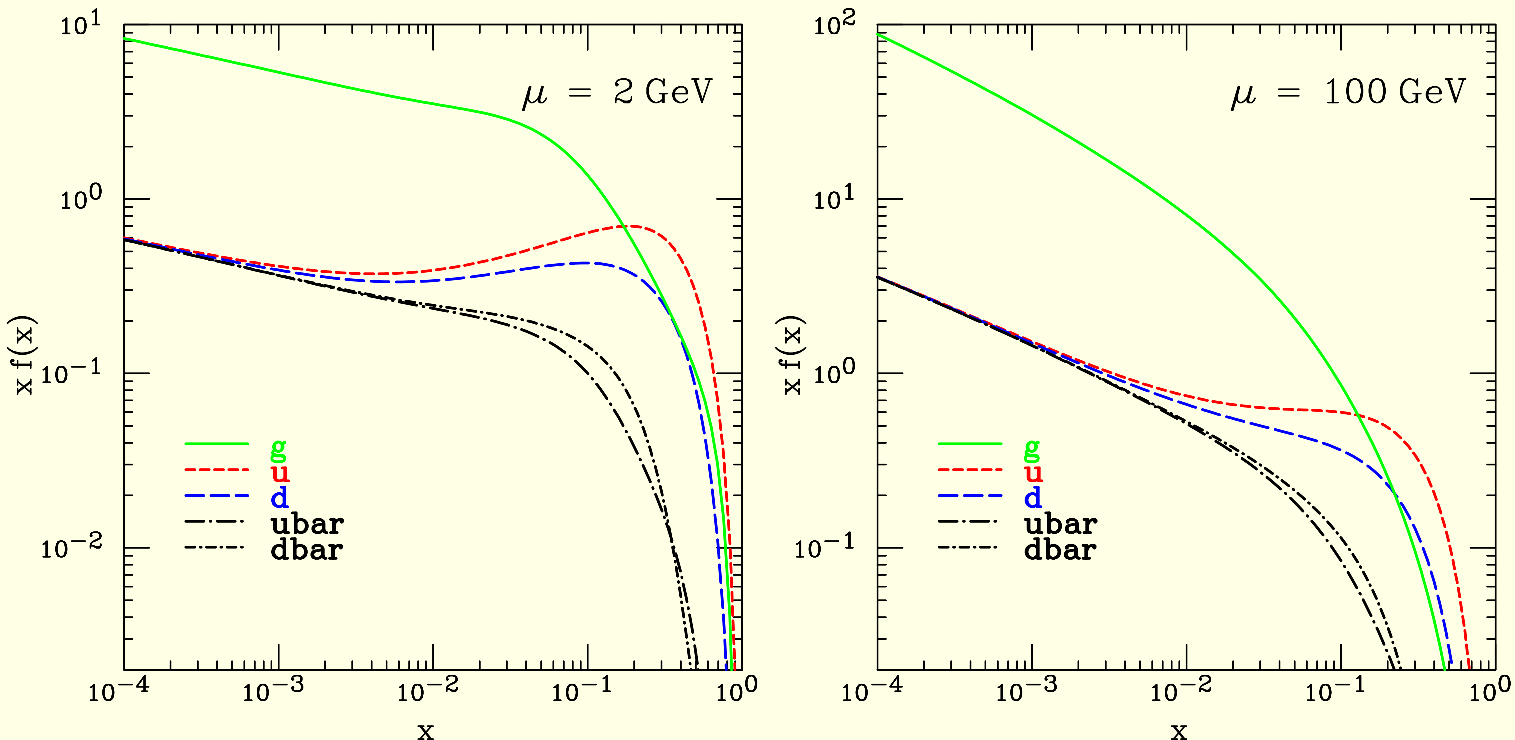
$$\sigma(AB \to M + X) \sim \int dx_a \, dx_b \, G_{a/A}(x_a, \mu^2) G_{b/B}(x_b, \mu^2) \hat{\sigma}(ab \to M + X)$$

- μ is the factorization scale which is used to separate the long- and short-distance parts of the calculation
- μ dependence is calculable in QCD
- Need pdf's over a large kinematic region
- Need reliable flavor separation

  Solution has been to do Global Fits to a variety of data in order to constrain the various pdf's

Status of PDF's

- u and d valence distributions reasonably well described over a significant range in x
- Flavor dependence of the sea quark distributions becoming better know $(\overline{u} \neq \overline{d},\ s \neq \overline{s})$
- Gluon distribution becoming better constrained, especially at medium- to large-x
- Error estimates available for newer pdf's

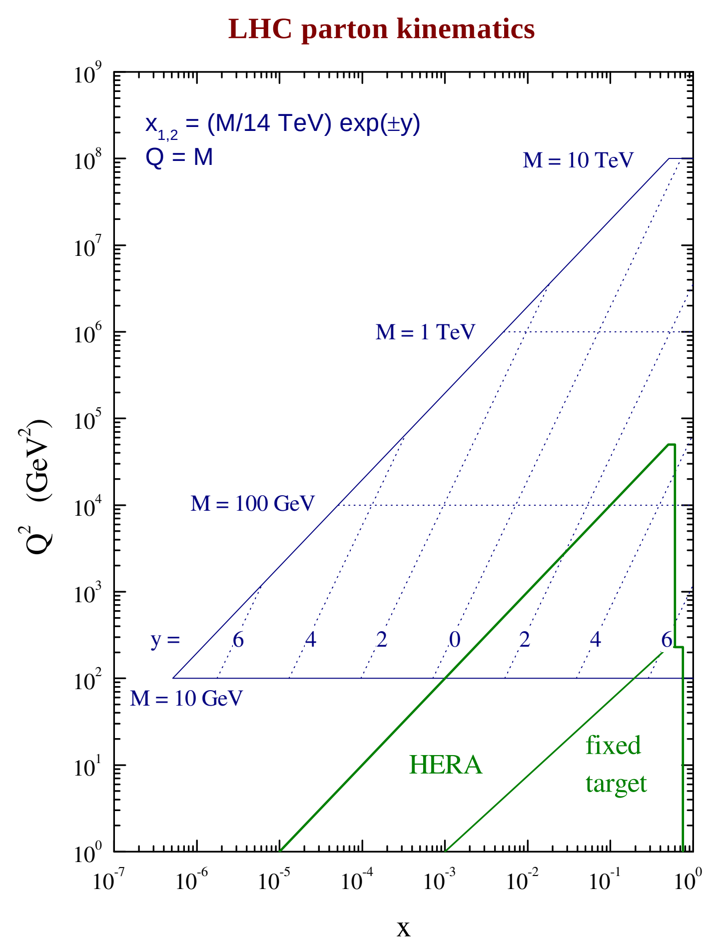


Current areas of investigation

- Behavior of u and d distributions as $x \rightarrow 1$
- Further work on $s \neq \overline{s}$
- More work on the gluon distribution at large-x
- Area of large-x is key to further refining our knowledge of pdf's

Example of kinematic coverage - heavy particle production

- Mass M, center-of-mass energy $\sqrt{s}$, rapidity Y
- $x_a = \frac{M}{\sqrt{s}}\, e^{Y} \qquad x_b = \frac{M}{\sqrt{s}}\, e^{-Y} \qquad x_a\, x_b = \frac{M^2}{s}$
- $\frac{M^2}{s} \leq x_i \leq 1$
- Factorization scale ("Q") $\sim M$
- Large Y with large M means one x is small, the other large.
- For a $q\overline{q} \rightarrow M + X$ subprocess at the LHC one would have a $\overline{q}$ at small x with a valence q at large x
- Understanding small x means understanding large x



- Figure from hep-ph/0507015, Thorne et al.
- Illustrates wide kinematic range over which pdf's must be known
- Fortunately, DGLAP evolution allows high Q pdf's to be generated from those at lower Q

PDF Evolution

$$\frac{dq_i(x,t)}{dt} = \frac{\alpha_s(t)}{2\pi}\int_x^1 \frac{dy}{y}\left[P_{qq}\left(\frac{x}{y}\right) q_i(y,t) + P_{qg}\left(\frac{x}{y}\right) g(y,t)\right]$$

$$\frac{dg(x,t)}{dt} = \frac{\alpha_s(t)}{2\pi}\int_x^1 \frac{dy}{y}\left[\sum_{i=1}^{n_f} P_{gq}\left(\frac{x}{y}\right) q_i(y,t) + P_{gg}\left(\frac{x}{y}\right) g(y,t)\right]$$

with $t = \ln(Q^2/\Lambda^2)$.

Several comments are in order

- Evolution at a value x_0 only requires knowledge of the pdf's at values of $x \geq x_0$
- As a result, high-x, low-Q feeds lower-x, higher-Q
- Knowledge of the pdf's at some starting value Q_0 is, in principle, sufficient to calculate the pdf's at all higher values of Q

Processes currently used in global fits

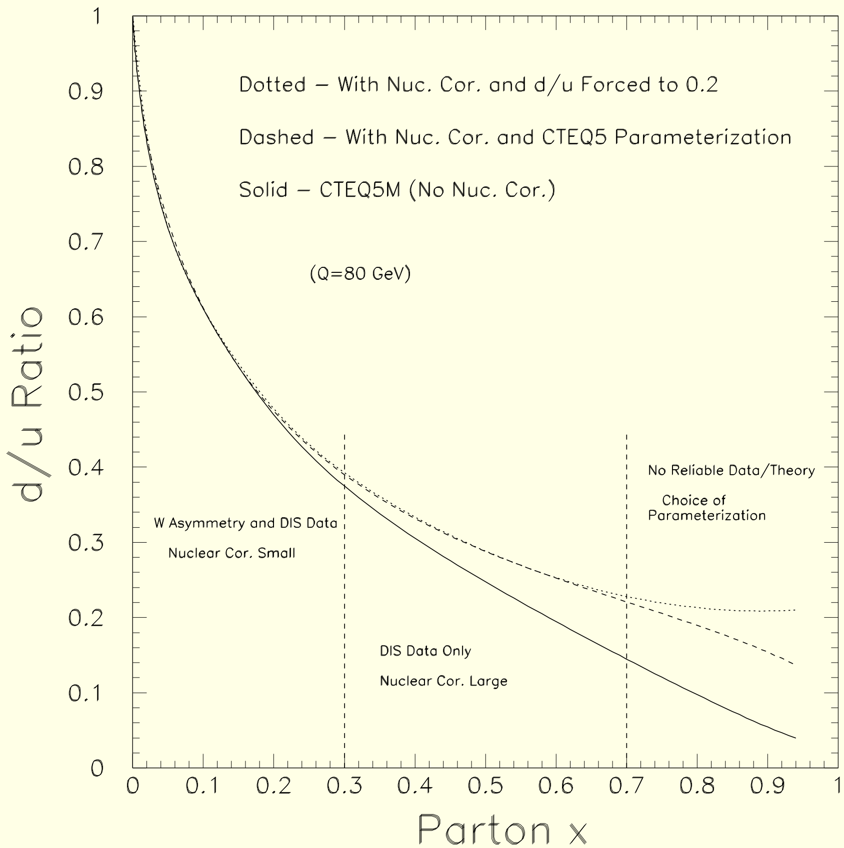
- DIS: (μp, μd, νFe, $\overline{\nu} Fe$, $e^{\pm}p$) – constrain $q, \overline{q}$, and, indirectly, g
- $\mu^+\mu^-$: (pN, pp, pd) – constrain $q, \overline{q}$
- $W^{\pm}$: $(\overline{p}p)$ – constrain d/u
- jets: $(\overline{p}p)$ – constrain g
- Approximately 2000 data points

W Lepton Asymmetry

- Lowest order subprocesses are

$$u\overline{d} \to W^+ \to l^+\nu_l$$
$$d\overline{u} \to W^- \to l^-\overline{\nu}_l$$

- For $\overline{p}p$ collisions, one expects the W^+ (W^-) to go preferentially in the direction of the p $(\overline{p})$
- Shape of the asymmetry between the $W^\pm$ at a fixed rapidity gives information of the d/u ratio
- Leptonic decay reduces the sensitivity somewhat, but the principle remains



- W asymmetry data constrains d/u out to $x \approx .30$ from Run I TeVatron data
- DIS data provide constraints at higher x, but with uncertainties due to nuclear corrections

Lowest order kinematics for W production and decay - have x_a, x_b, and the lepton decay angle θ in the W rest frame

Fixing the W mass and the lepton rapidity y leaves one variable to integrate

Result is

$$\frac{M_W}{\sqrt{s}} e^{(y-\xi)} \leq x \leq \frac{M_W}{\sqrt{s}} e^{(y+\xi)}$$

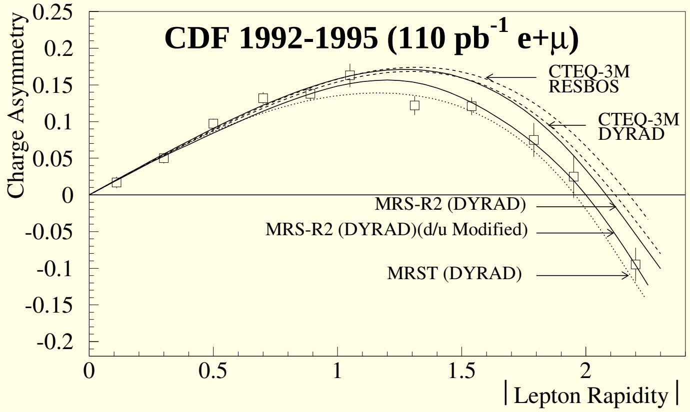
with

$$\xi = \ln\left(\frac{M_W}{2p_{Tmin}} + \sqrt{\left(\frac{M_W}{2p_{Tmin}}\right)^2 - 1}\right)$$

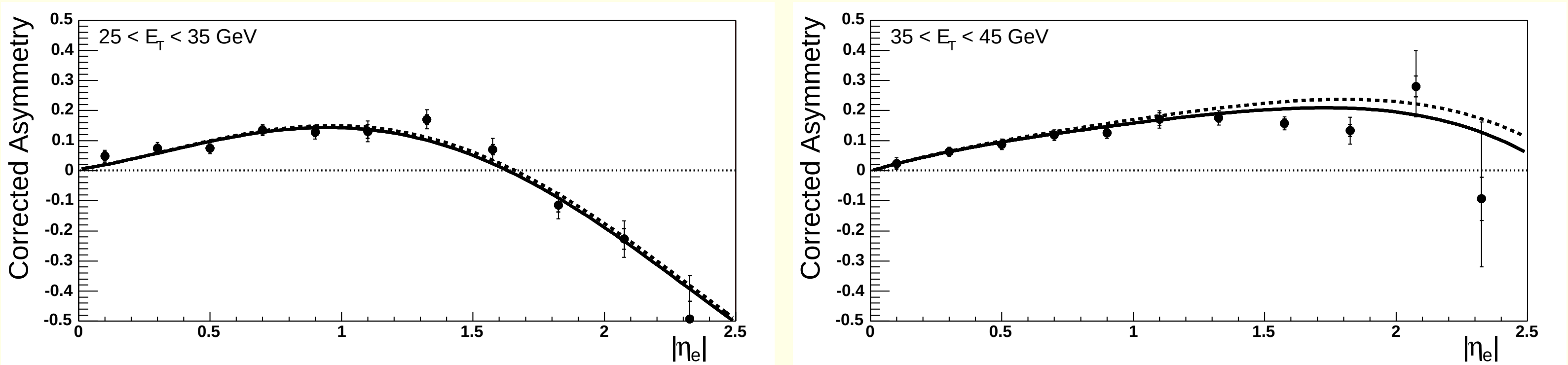
where p_{Tmin} is the minimum lepton transverse momentum

Run I data had $p_{Tmin} = 25$ GeV whereas Run II data have two p_T bins

Improved constraints on d/u ratio



Run II data from CDF



New data with additional statistics have the potential to provide better constraints on d/u

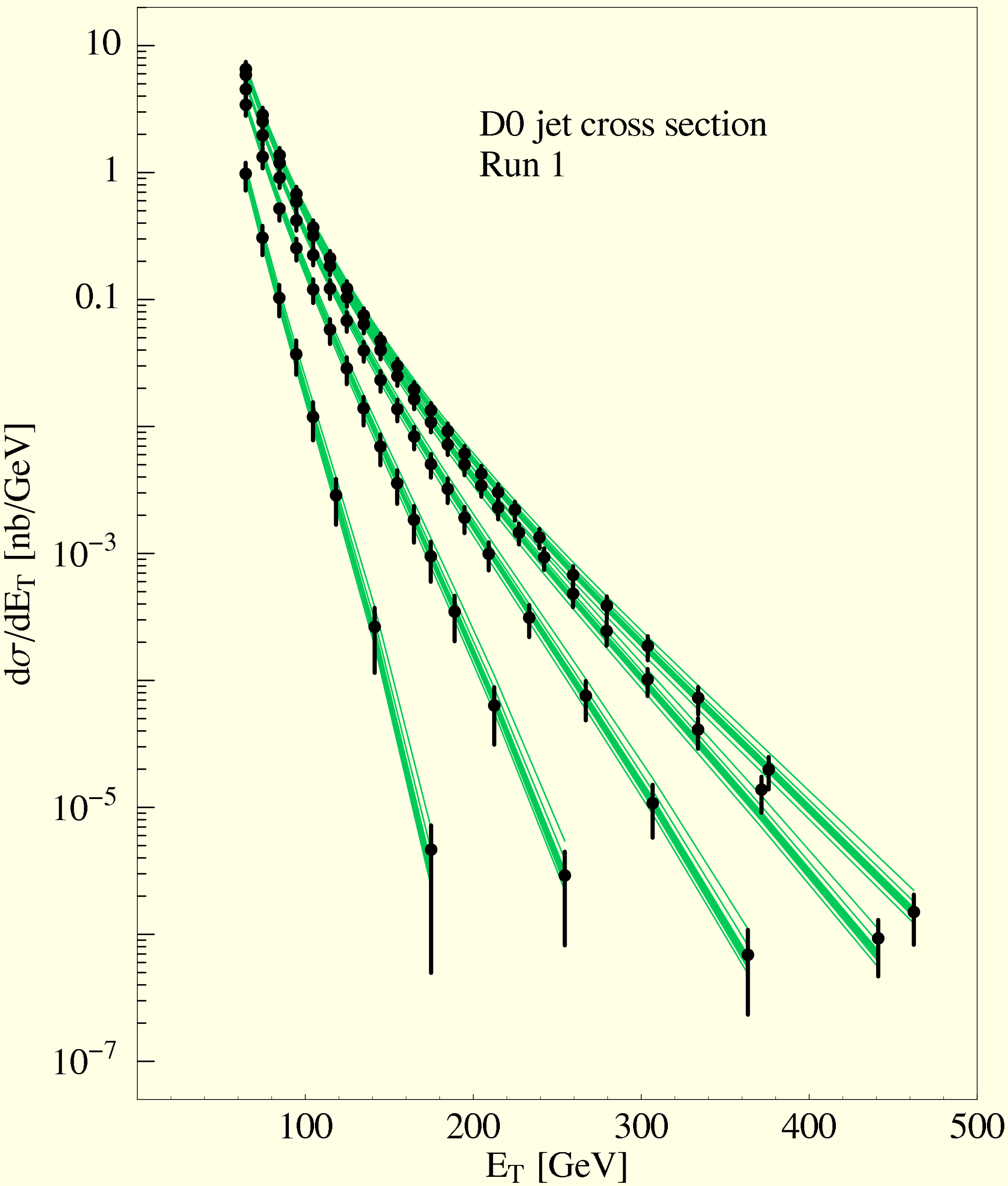
Jet Data

- DØ jet data in five rapidity bins out to $\eta = 3$
- Using lowest order kinematics

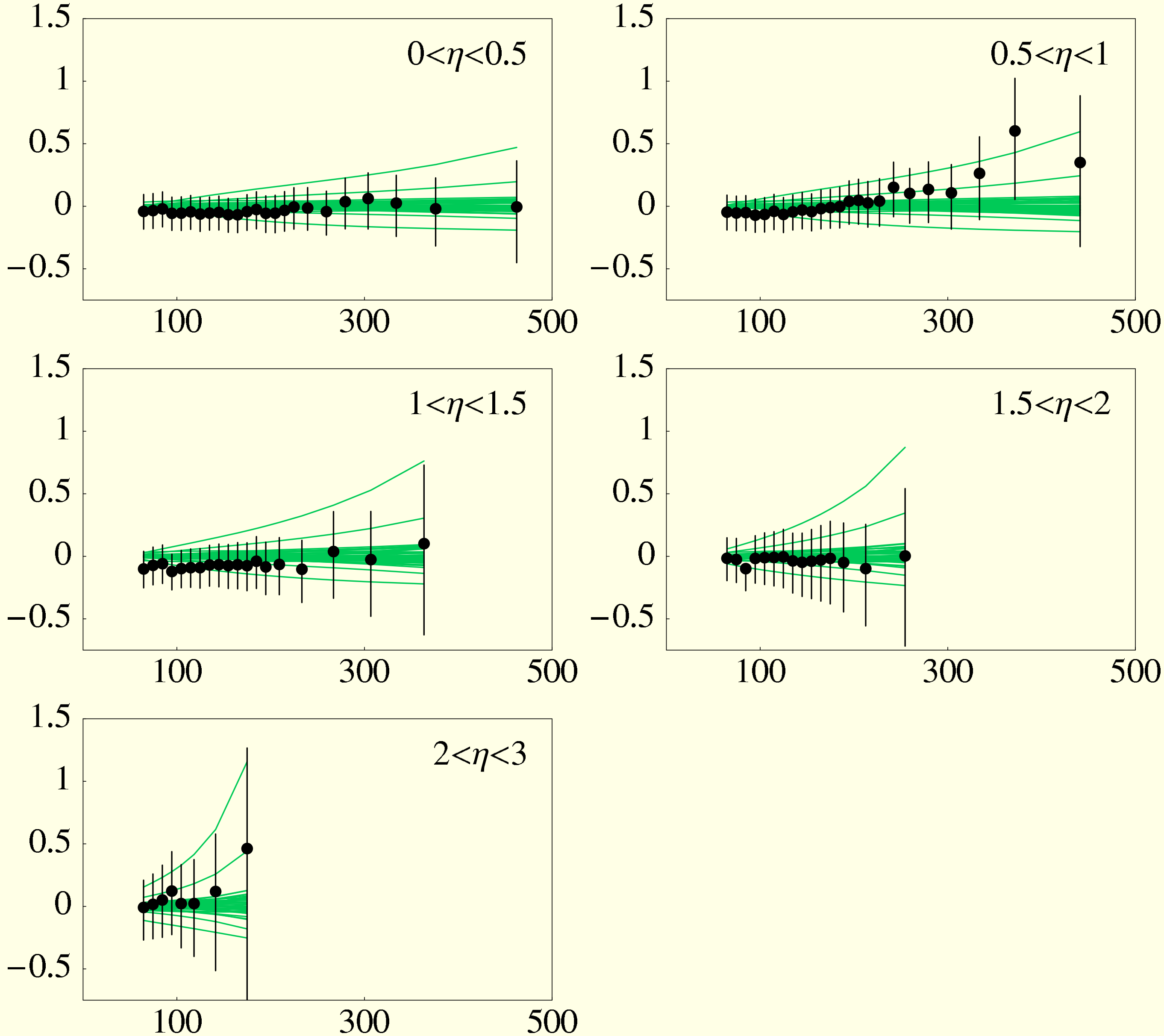
$$x_b = x_a x_T e^{-\eta}/(2x_a - x_T e^{\eta}) \quad \text{and} \quad x_{amin} = x_T e^{\eta}/(2 - x_T e^{-\eta})$$

- High E_T and high η cover the large x region
- Example: $x_{amin} = 1$ at $\eta = 2.5$, $p_T \approx 150$ GeV
- $2 \to 3$ kinematics in NLO calculations are less restrictive, but the above is a good starting point
- The jet data provide the strongest gluon constraints at large x

CTEQ6.1 compared to D0 jet data



CTEQ6.1 comparison on a linear scale



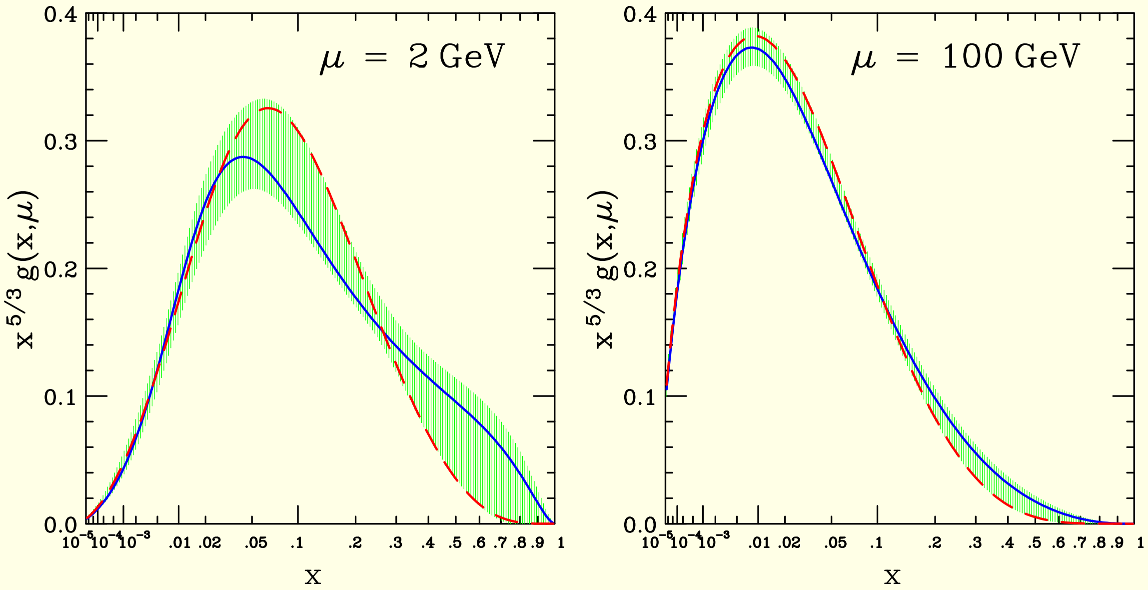
PDF Errors

- Would like to be able to estimate errors on pdf's in order to estimate errors on observable quantities
- Errors come from many sources
  - Experimental statistical and systematic errors
  - Truncation of perturbation series
  - Scale dependence
  - Choice of parametrizations for pdf's
  - Choices for cuts on experimental data sets
  - Neglect of target mass and higher twist corrections
  - Uncertainties in nuclear corrections
- Only the errors due to the first item have been included thus far

Miscellaneous Comments on Errors

- Errors tend to decrease as Q increases -"convergent evolution"
  - Steep distribution tends to evolve more slowly (decrease) than a flatter distribution due to the size of the derivative from the evolution equations

- Illustrated by the decrease of the fractional gluon errors in CTEQ6.1 (see J. Pumplin hep-ph/0507093)



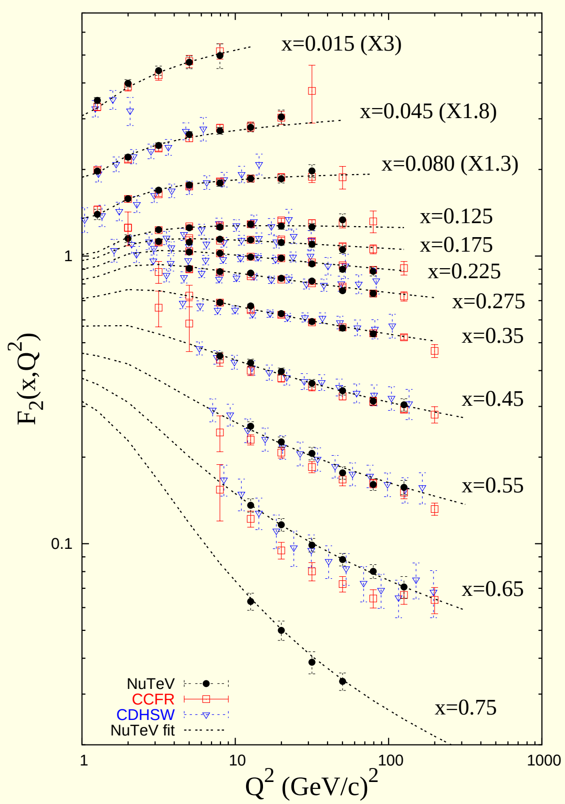
Shape dependence and NLO Stability

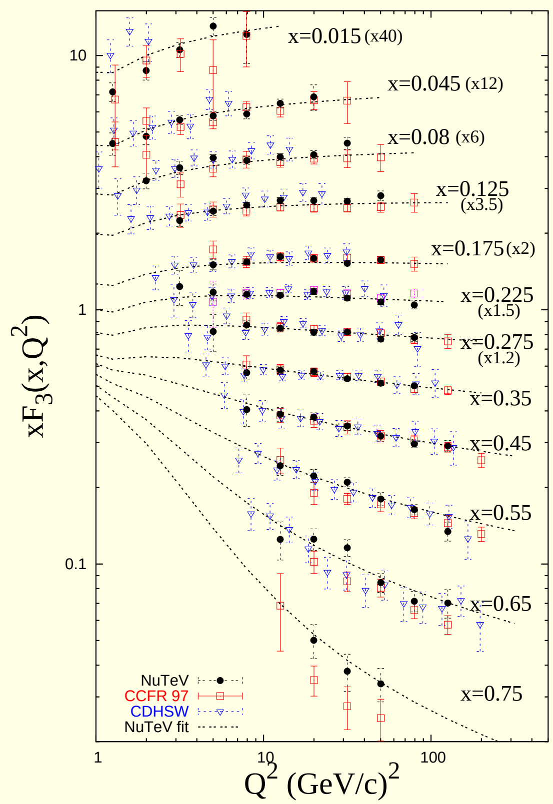
- Choice of parametrization can affect χ^2 if it is not sufficiently flexible, e.g., gluon parametrization and high-E_T jets
- Poor χ^2 results from "tension" between different data sets
- Can induce sensitivity to choice of cuts on data as specific data points are included/excluded (see discussion in Huston et al., hep-ph/0502080)
- Overly restrictive high-x gluon parametrization causes compromise between small/medium-x DIS and high-E_T data
- As (x, Q) cuts are increased on the DIS data the fits change dramatically in order to better accommodate the jet data
- Classic example of the interplay between choice of data sets, choice of cuts, and choice of parametrizations
- Resulting uncertainties are difficult to quantify and require extensive exploration of the various choices

"The art of global fitting..." – Wu-Ki Tung

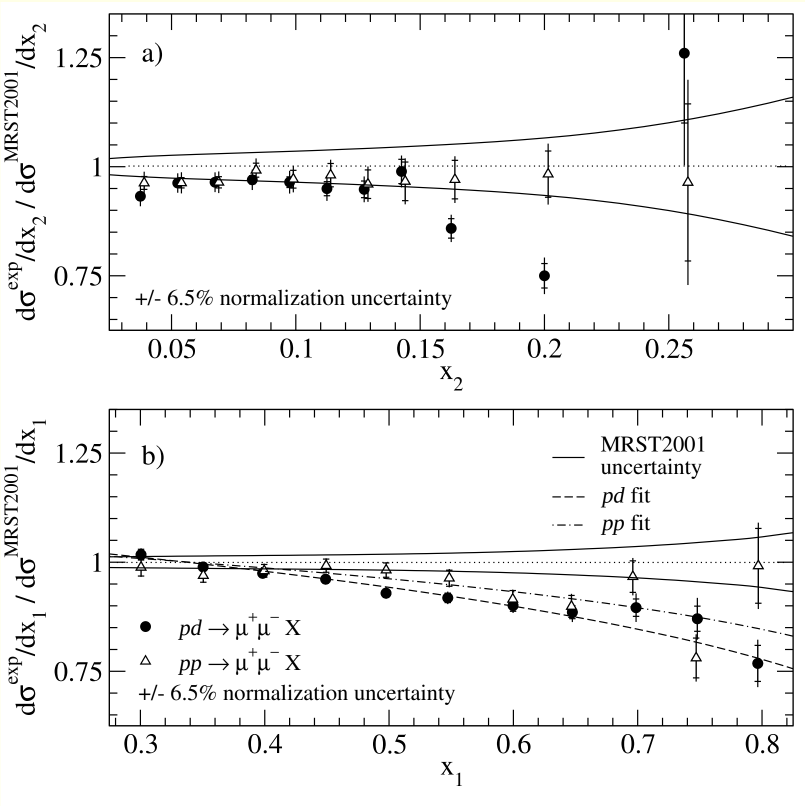
Current Projects

- Incorporate new NuTeV data
  - higher than older CCFR data above $x \approx 0.55$
  - Will affect valence distributions at high x
  - Need to incorporate NuTeV-style systematic errors





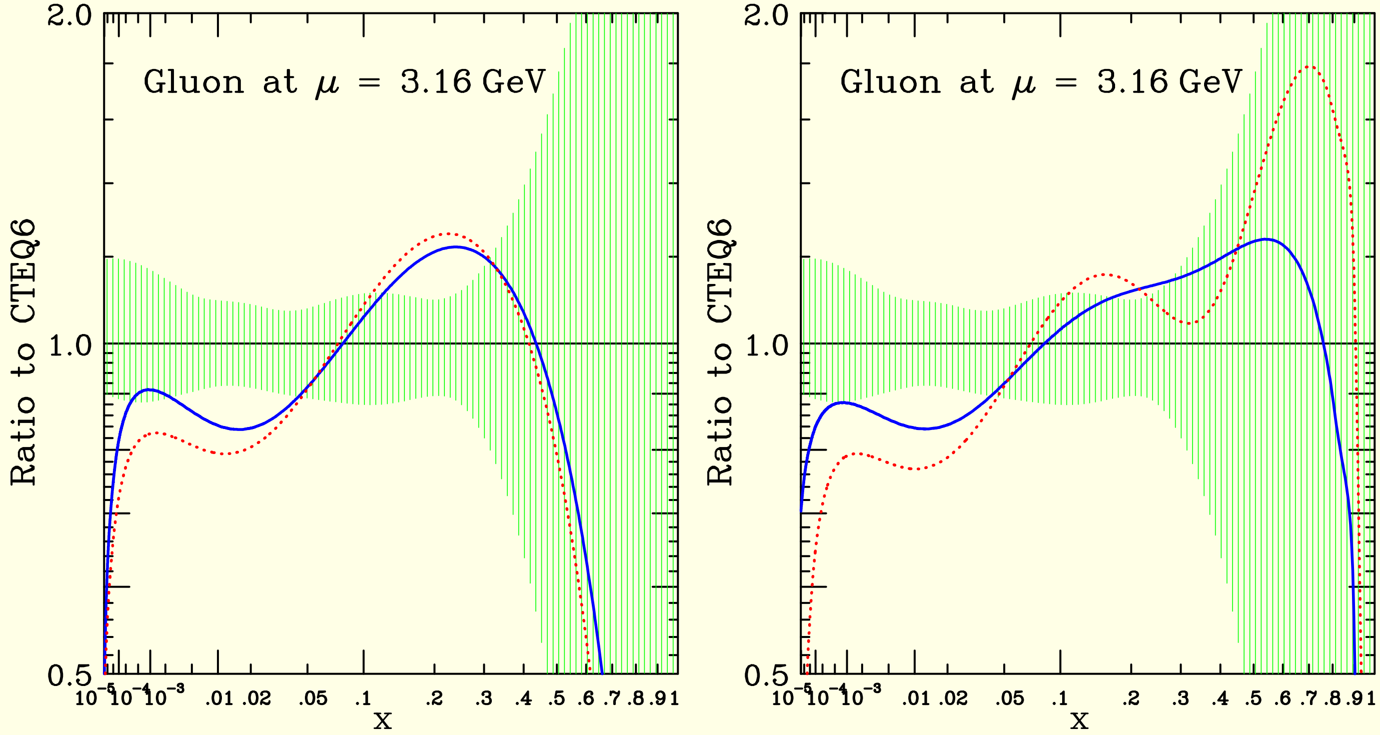
- E-866 $pp, pd \to \mu\mu + X$
  - Waiting for final radiative corrections
  - early indications suggested that the valence distributions were too high at high x
  - Opposite to what is suggested by NuTeV and JLAB data



- Add new data for jet production, $W^{\pm}$ asymmetry
- Deuterium corrections at high x
    - studying effects of various parametrizations of the deuterium corrections
    - large theoretical errors from nuclear calculations
    - trying to use data to constrain the corrections

- NNLO
  - Required to check convergence of perturbation series and reduce scale dependence
  - Three-loop splitting functions - exist and have been installed in several evolution packages
  - Need to incorporate the nnlo coefficient functions for DIS and the nnlo hard scattering subprocess expressions for lepton pair and jet production
  - In progress...

From J. Pumplin, hep-ph/0507093



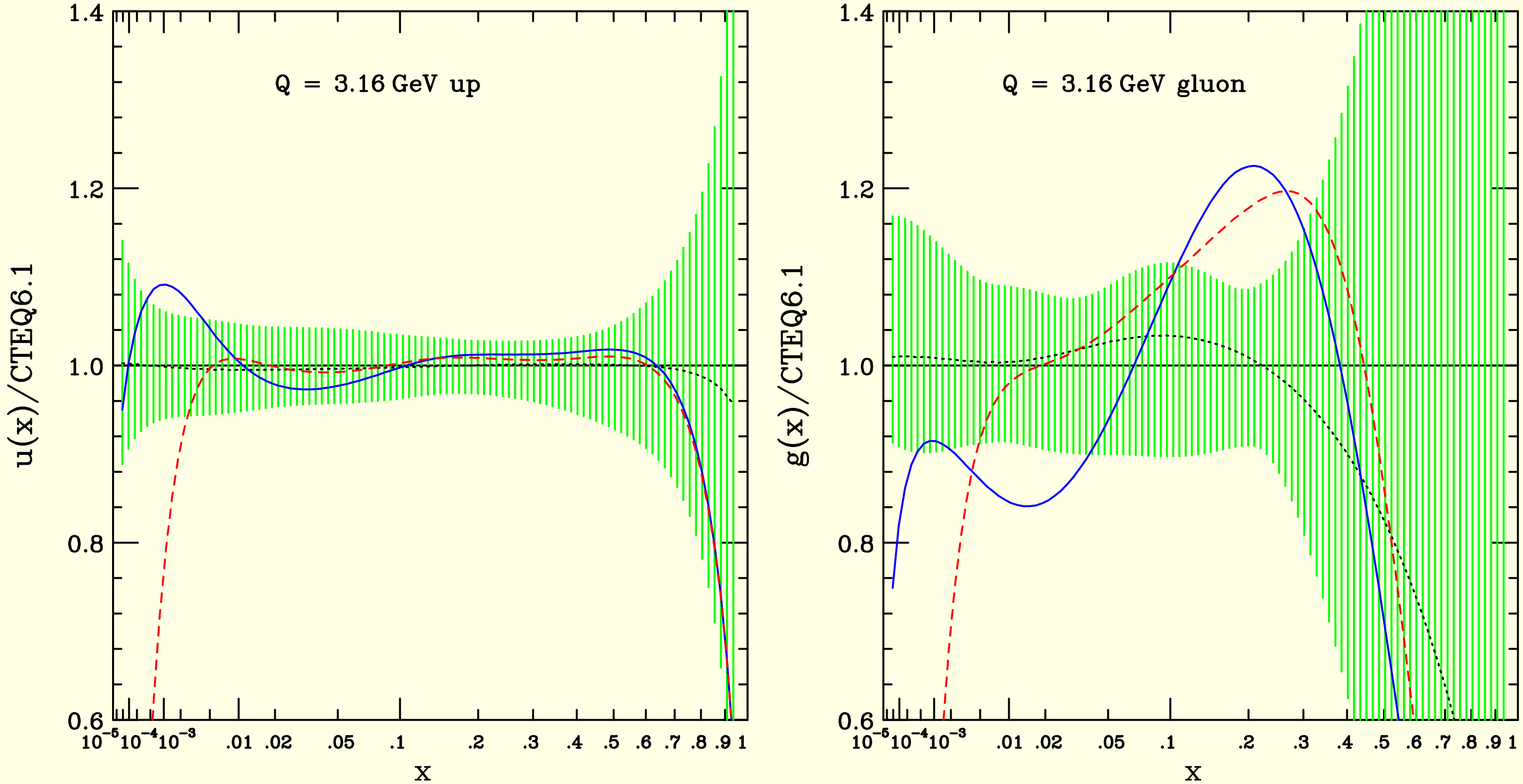
Left is MRST2002 and right is MRST2004 relative to CTEQ6

NLO(solid) and NNLO(dashed)

Large-x PDF's

- Current global fit procedures
  - For DIS use $Q > 2$ GeV and $W > 3.5$GeV
  - Basically eliminates most DIS data above $x \approx 0.65$
- Information on high-x comes via
  - Sum rules constrained by low/mid-x
  - High-E_T jet data
  - Extrapolation of fitted parametrizations
- Results in large error bands at large-x since the parametrizations there are not well constrained by data
- To put it another way, we are fitting data which cover $\sim 65\%$ of the x range – 35% is unconstrained!

Example Uncertainty Bands - CTEQ6.1

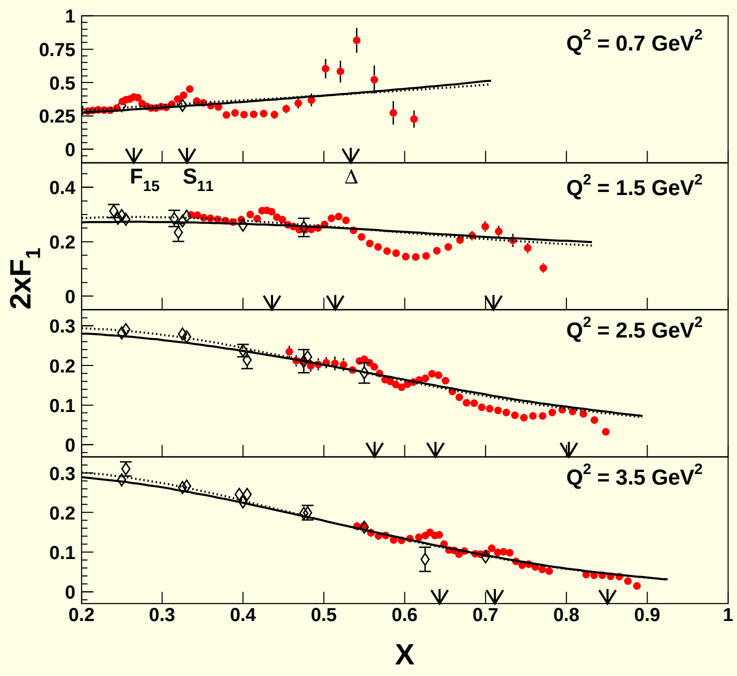


Dotted: CTEQ6M   Solid: MRST2002   Dashed: MRST2003c

Alternatives

Use of scaling variables à la Bodek and Yang (hep-ph/0508007)

- Can provide an efficient and useful parametrization of data
- Difficult to match to perturbative evolution of pdfs
- Doesn't necessarily provide new information on pdf's in region below existing cuts



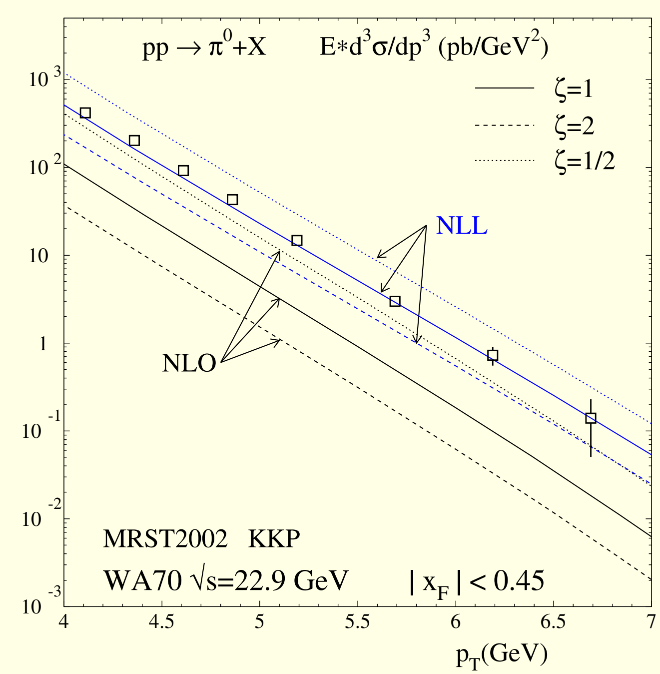
Traditional Approach

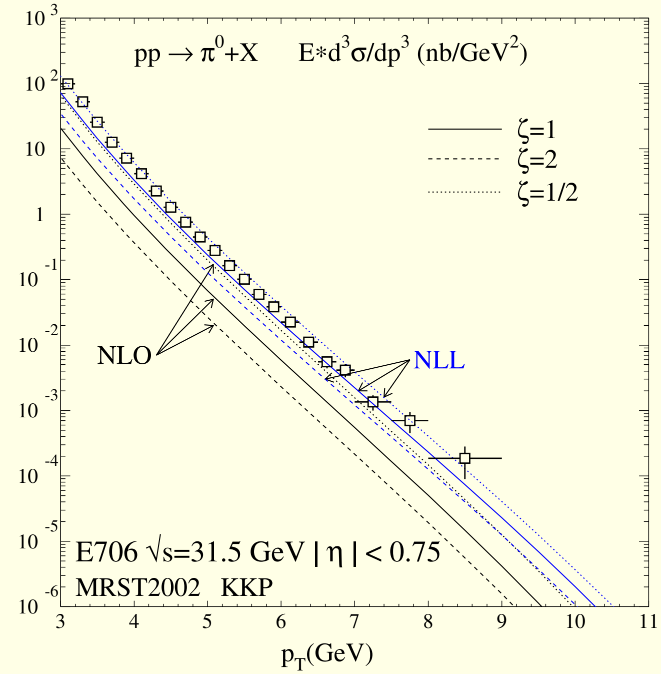
- Parametrize higher twist terms
- Include target mass corrections
- Relax cuts on Q, W
- Pdf's become model dependent in the region below the cuts
- Haven't done this yet - have concentrated on determining the pdf's in the leading twist region

No reason in principle not to do this, but more work is needed to reduce the dependency of the resulting pdf's on the choices made for the higher twist terms

Large-x Resummation

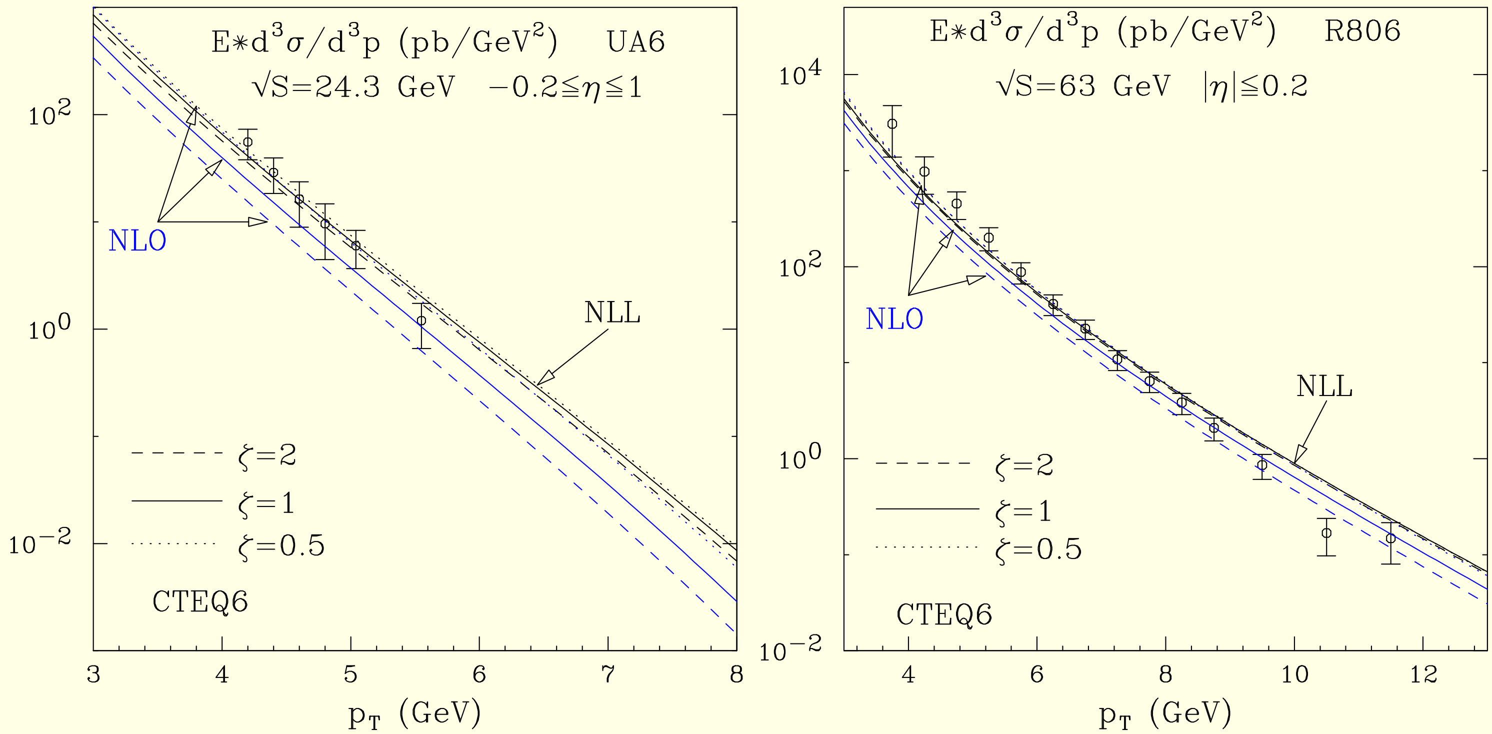
- Soft-gluon resummation important for processes near the partonic subprocess threshold
- Large mass particle production, high-E_T hadron or jet production, fixed target direct photon production, ...





From DeFlorean and Vogelsang, hep-ph/0501258

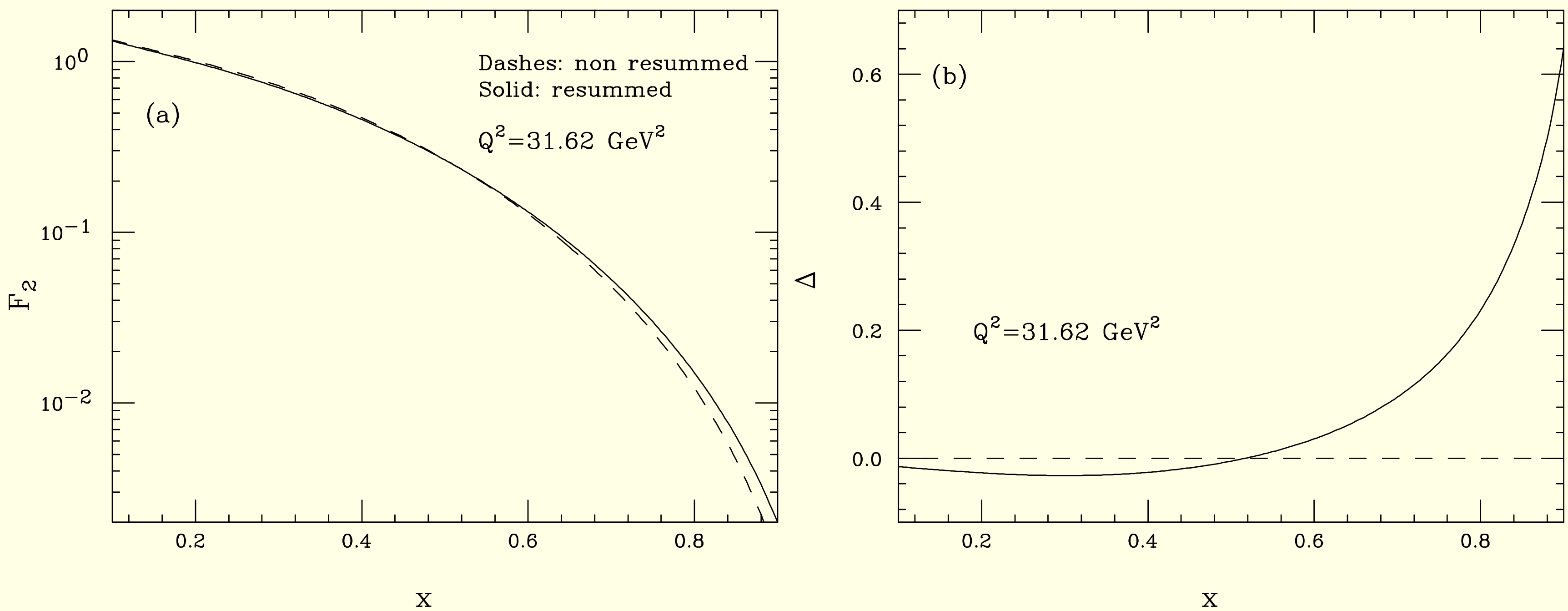
May also provide an explanation of the long-standing puzzle of direct photon production (from DeFlorean and Vogelsang, hep-ph/0506150)



All calculations done to date have used standard pdf's

- Resummation is also important for large-x DIS
- Gives significant increase to existing pdf's above $x \approx 0.6$
- For consistency, should incorporate resummation in the global fits to have a set of pdf's to be used when calculating other processes using resummation
- Certainly necessary if one wants to compare extracted pdf's at large$-x$ with model calculations, e.g., from lattice, etc.

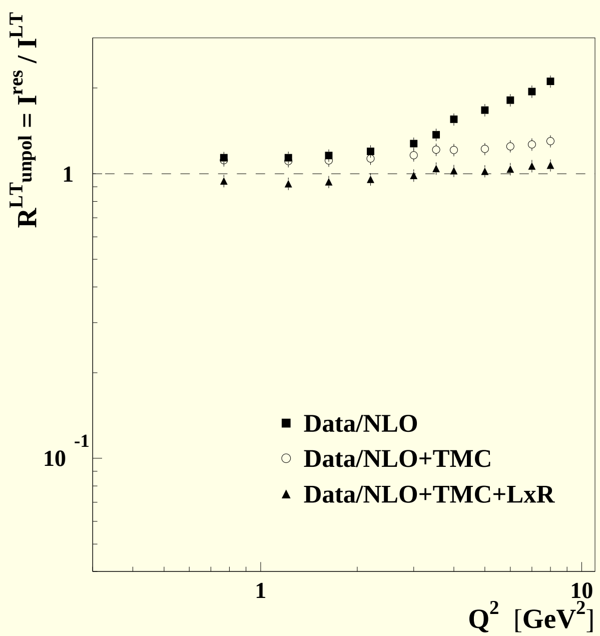
From Corcella and Magnea, hep-ph/0507042

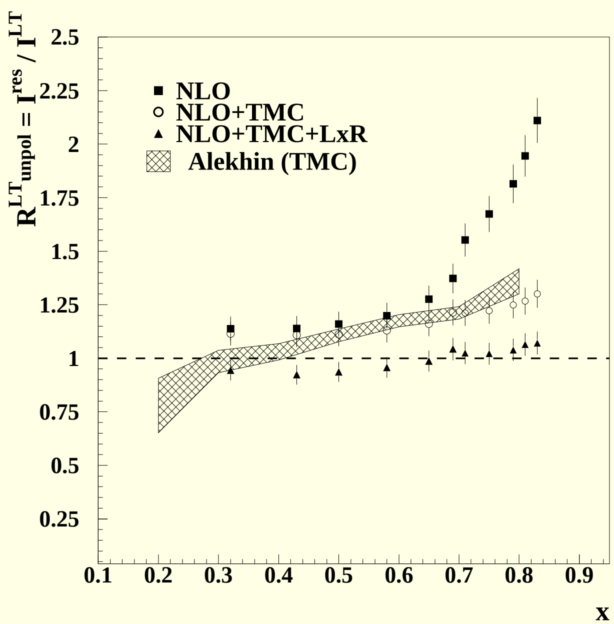


- Demonstrates large fractional increase of F_2 at large-x when threshold resummation is taken into account in the coefficient functions while using CTEQ6M pdf's
- Suggests that resummation effects must be included if the large-x region is to be included in global fits
- Corcella and Magnea claim about a 10% decrease in the valence pdf's at large-x when doing a trial fit

Interesting observation for large-x PDF's

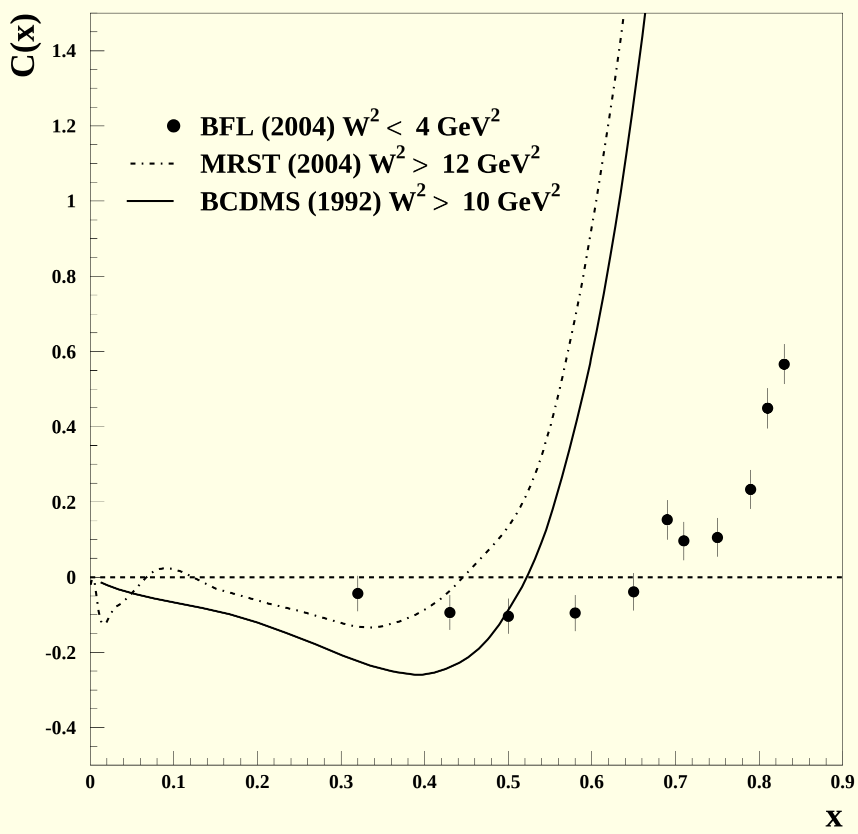
- Extrapolations of pdf's fitted at high-Q^2 down to the low-Q^2 region tend to underestimate the data
- Discrepancies traditionally ascribed to target mass corrections and higher twist effects
- But, the more physics that is included, the smaller the discrepancies...
- Including large-x resummation leads to reduced need for higher twist terms (Fantoni, Bianchi, and Liuti: hep-ph/0501180, 0308057)





Implications for Global Fits

- Less need for parametrized higher twist terms as compared to older analyses



- Could mean less model dependency for global fits

Summary and Conclusions

- Global analysis of pdf's still is an important activity required for making precision predictions of large momentum transfer processes
- New data promises to help further refine our knowledge of the u, d, g, and various sea quark distributions
- Properties of these distributions in the large-x region need to be better understood
- Theoretical advances, *e.g.,* large-x resummation, will help the global fits to be extended to higher values of x
- Data at large-x will be crucial for the further refinement of our knowledge of pdf's