Parton Distributions

Jon Pumplin – DIS2005

Parton distribution functions describe the quark and gluon content of a hadron when all of the spin structure and correlations are integrated out.

Because of Asymptotic Freedom, this is the only aspect of initial-state hadron structure needed to calculate short-distance hard scattering.

PDFs are

- **A Fundamental Measurement**
  — A challenge to understand by non-perturbative QCD.

- **A Necessary Evil**
  — Essential input to perturbative calculations of signal and background at hadron colliders.

Outline of talk

1. Introduction
   - Fundamentals
   - Kinematics and Evolution
   - Global Analysis paradigm
   - Typical results
2. Uncertainties
   - Sources of Uncertainty
   - Eigenvector sets
   - Comparison of results from different groups
3. W cross section at LHC
4. New Physics from PDF fitting?
5. Outlook
   - What's Next?
   - New Measurements
   - Key Applications

Solid theoretical basis

PDFs are extracted by Global Analysis of data from many experiments that probe short distance.

- Asymptotic freedom
  $\Rightarrow$ Interactions weak at short distance
  $\Rightarrow$ Perturbative QCD useful

- Factorization theorems
  $\Rightarrow$ PDFs are same for all processes.

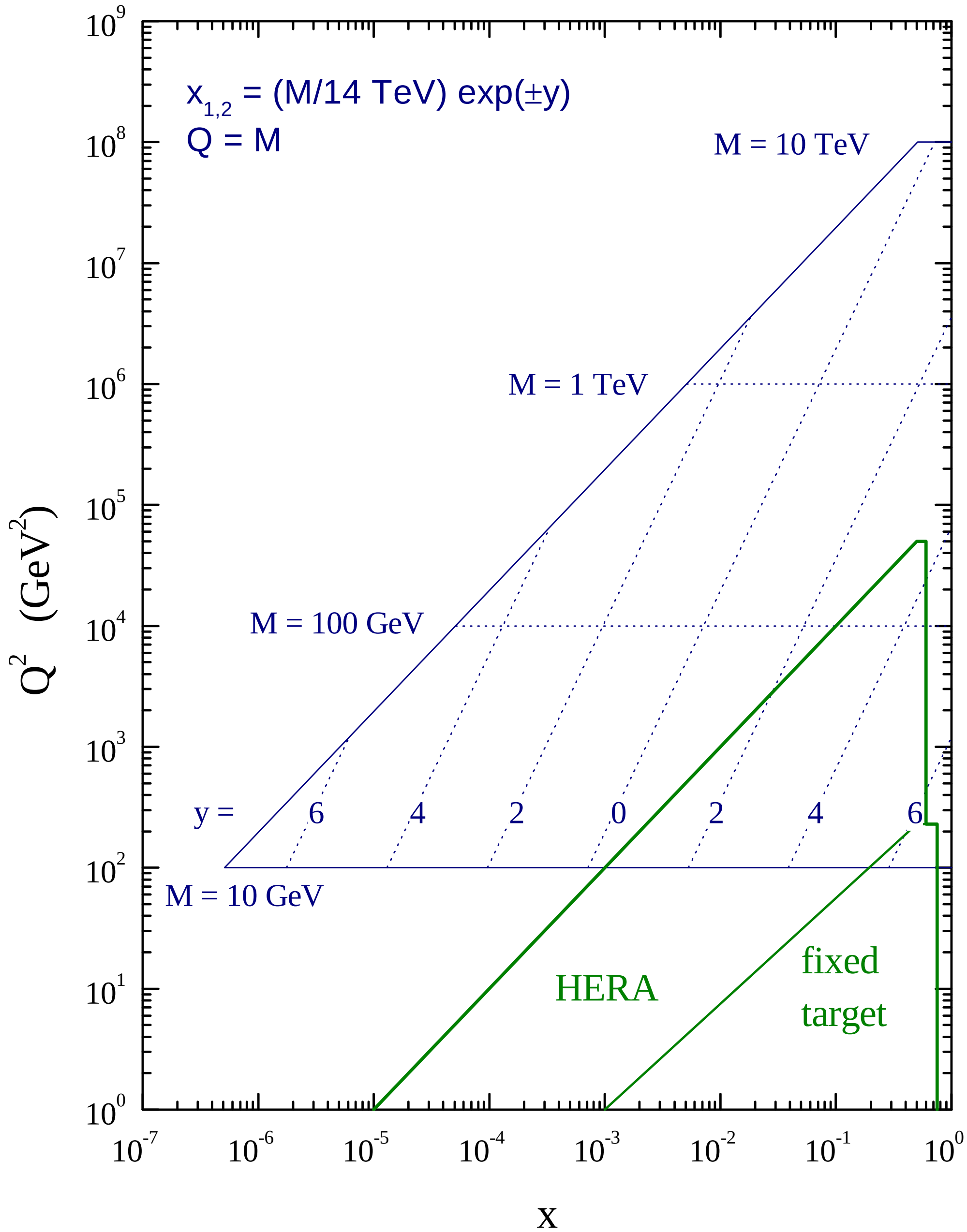
- DGLAP evolution
  $\Rightarrow$ dependence of $f_a(Q,x)$ on momentum scale Q is perturbatively calculable
  $\Rightarrow$ only the dependence on light-cone momentum fraction x for flavor a at fixed small Q_0 needs to be measured

Constant Battles

- Systematic Errors
  Unquantified experimental and theoretical errors make trouble when data from diverse experiments are combined.

- “Parametrization Dependence”
  Extracting continuous functions from a finite set of measurements is mathematically unclean. PDFs at Q_0 are modeled by smooth functions with parameters to be determined from experiment. The choice of functions is a possible source of bias.

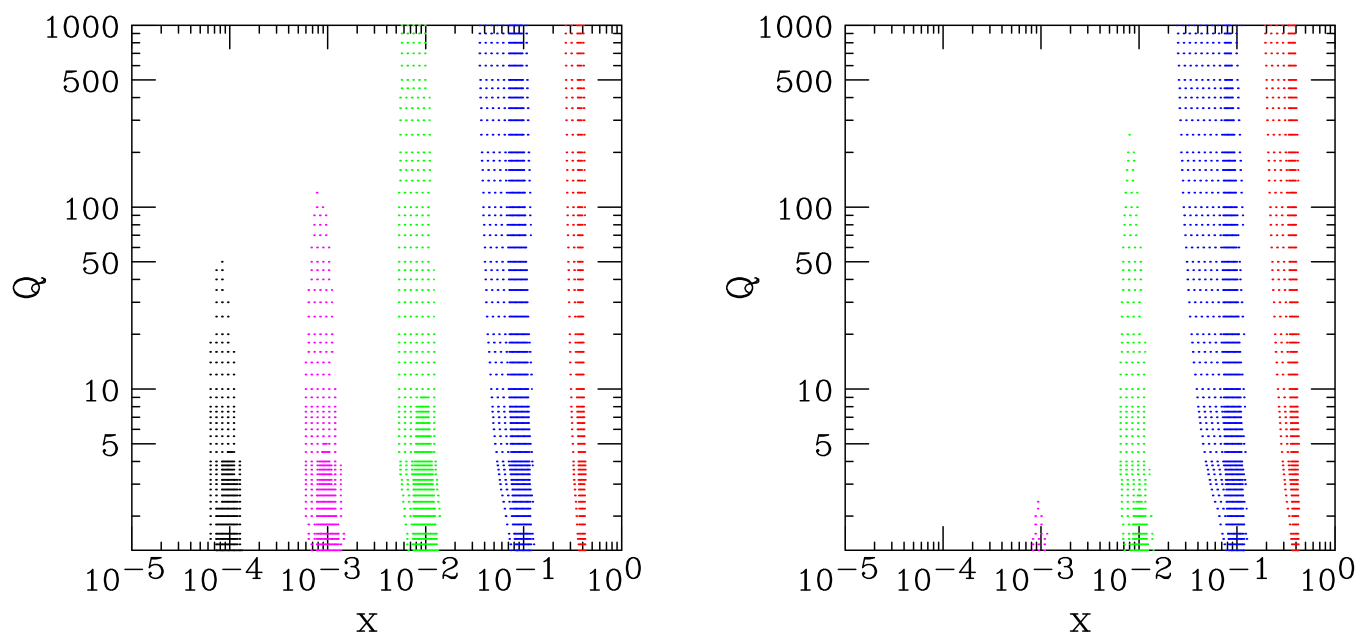
Kinematic Map



- Large range of scales connected by DGLAP
- LHC will dramatically extend the range

Direction of Evolution

Regions of PDF change $>0.2\,\%$ (solid) or $>0.05\,\%$ (dotted) caused by $1\,\%$ change at $Q_0 = 1.3\,\mathrm{GeV}$ in a narrow band of x:

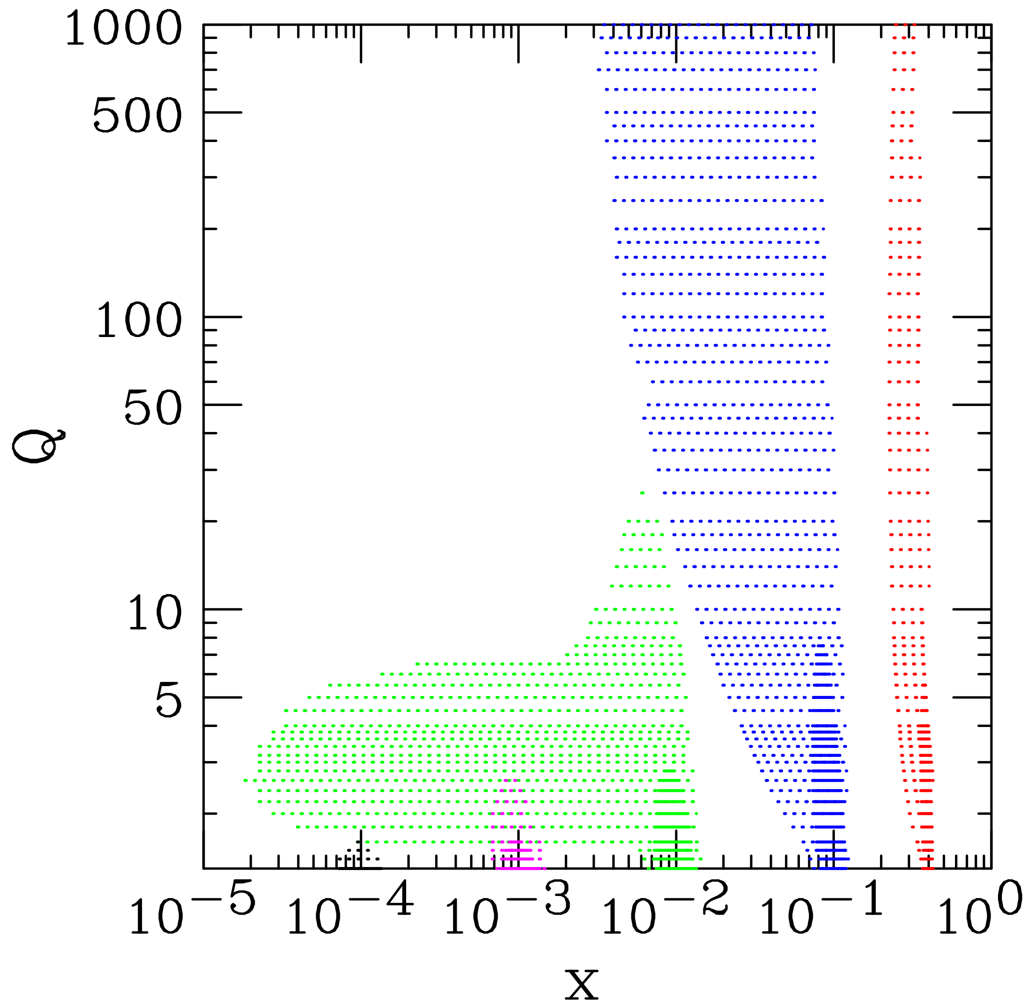


$\bar{d} + \bar{u}$ $\qquad$ u_v

- Valence quarks unimportant at small x as expected

- Quark evolution is effectively at constant x.

Evolution of gluon



- Influence of input $g(x)$ spreads in x much more than quarks

- Small-x gluon at $Q_0 = 1.3\,\text{GeV}$ has little direct influence $\Rightarrow$ gluons at moderate and high Q are radiatively generated

The PDF Paradigm

1. Parameterize x-dependence of each flavor at fixed small Q_0 (parameters $A_1, \ldots, A_N$)

2. Compute PDFs $f_a(x, Q)$ at $Q > Q_0$ by DGLAP

3. Compute cross sections for DIS(e,μ,ν), Drell-Yan, Inclusive Jets,... by perturbation theory

4. Compute "χ^2" measure of agreement between predictions and measurements:

$$\chi^2 = \sum_i \left(\frac{\text{data}_i - \text{theory}_i}{\text{error}_i} \right)^2$$

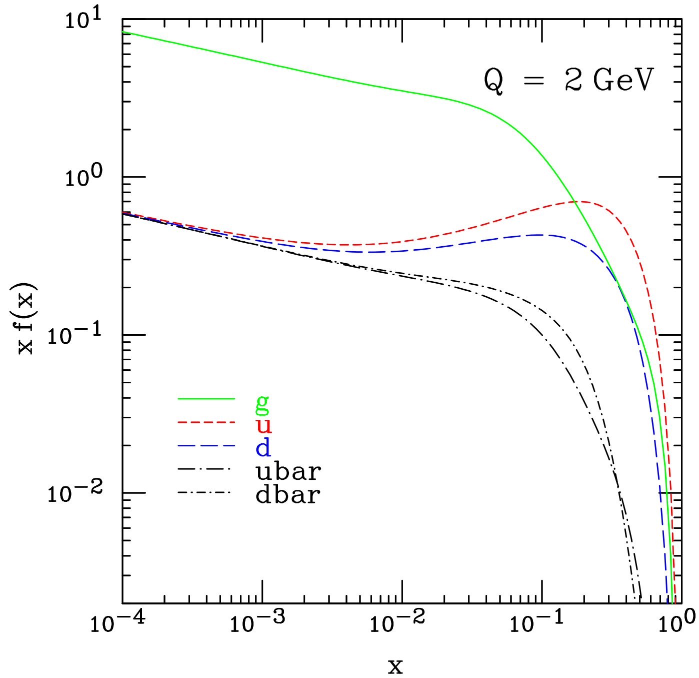
   or generalizations to include correlated systematic errors.

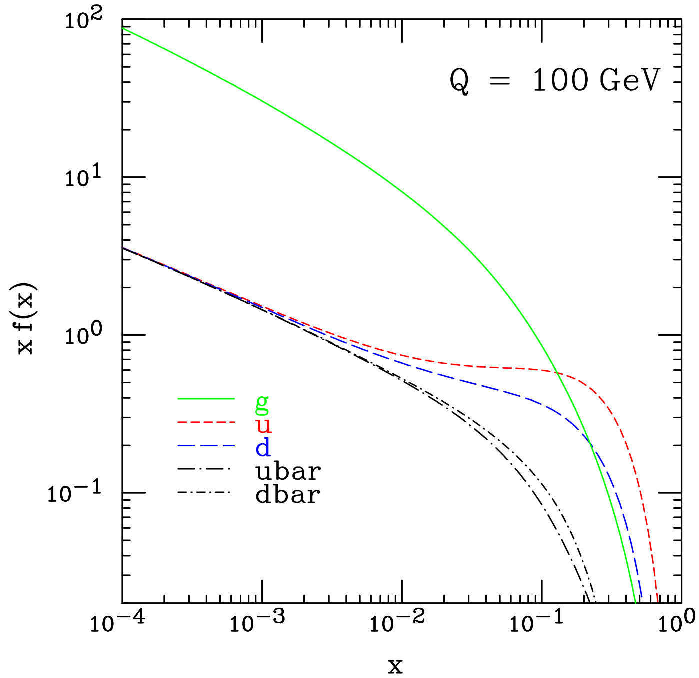
5. Minimize χ^2 with respect to the shape parameters $\{A_i\}$ to find Best Fit PDFs: MRST, Alekhin, CTEQ, H1, MRST, Zeus,...

6. PDF Uncertainty Range is the region in $\{A_i\}$ space where χ^2 is sufficiently close to minimum

7. Make Best Fit and Uncertainty Sets available: http://durpdg.dur.ac.uk/HEPDATA/

Typical results





- Valence quarks dominate at $x \to 1$

- Gluon dominates at $x \to 0$, especially for large Q
  $\Rightarrow$ Gluons crucial for LHC

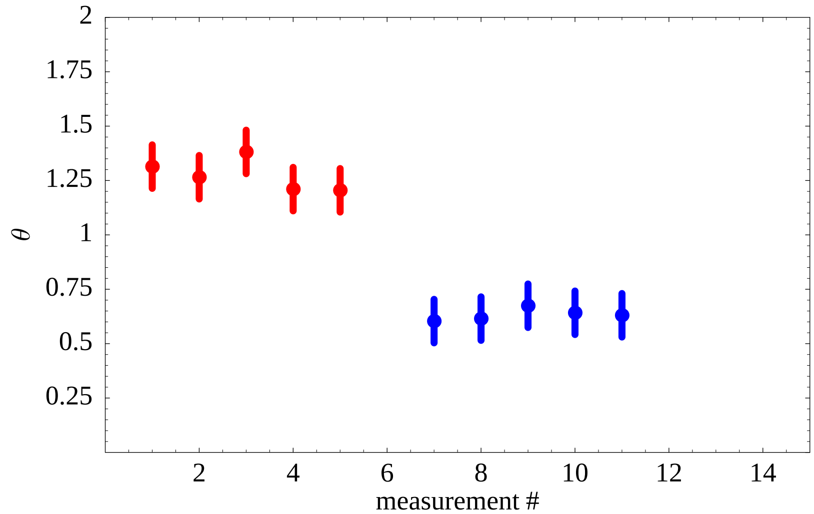
Sources of uncertainty:

- Experimental errors included in χ^2
- Unknown experimental errors
- Higher-order QCD corrections + Large Logs
- Power Law QCD corrections ("higher twist")
- Parametrization dependence

Essential Difficulties

- Experiments run until systematic errors dominate
  $\Rightarrow$ remaining systematic errors involve guesswork
- Systematic errors of the theory and their correlations are even harder to guess
- Some combinations are unconstrained
  — like $s - \bar{s}$ before NuTeV data

The Uncertainty Issue



Suppose θ is measured in two different experiments. What do you quote as Best Fit and Uncertainty?

(Perhaps you expand the errors so the uncertainty range covers both data sets. Or perhaps you expand it even more, using the difference between experiments as a measure of the uncertainty.)

What happens to the Best Fit value when the relative weight of the two experiments is varied?

That is the method used to assess uncertainties of the PDF Global Fit: We vary weights of the experiments to estimate a range of acceptable $\Delta\chi^2$ above the minimum value, in place of the classical $\Delta\chi^2 = 1$.

Eigenvector PDF sets

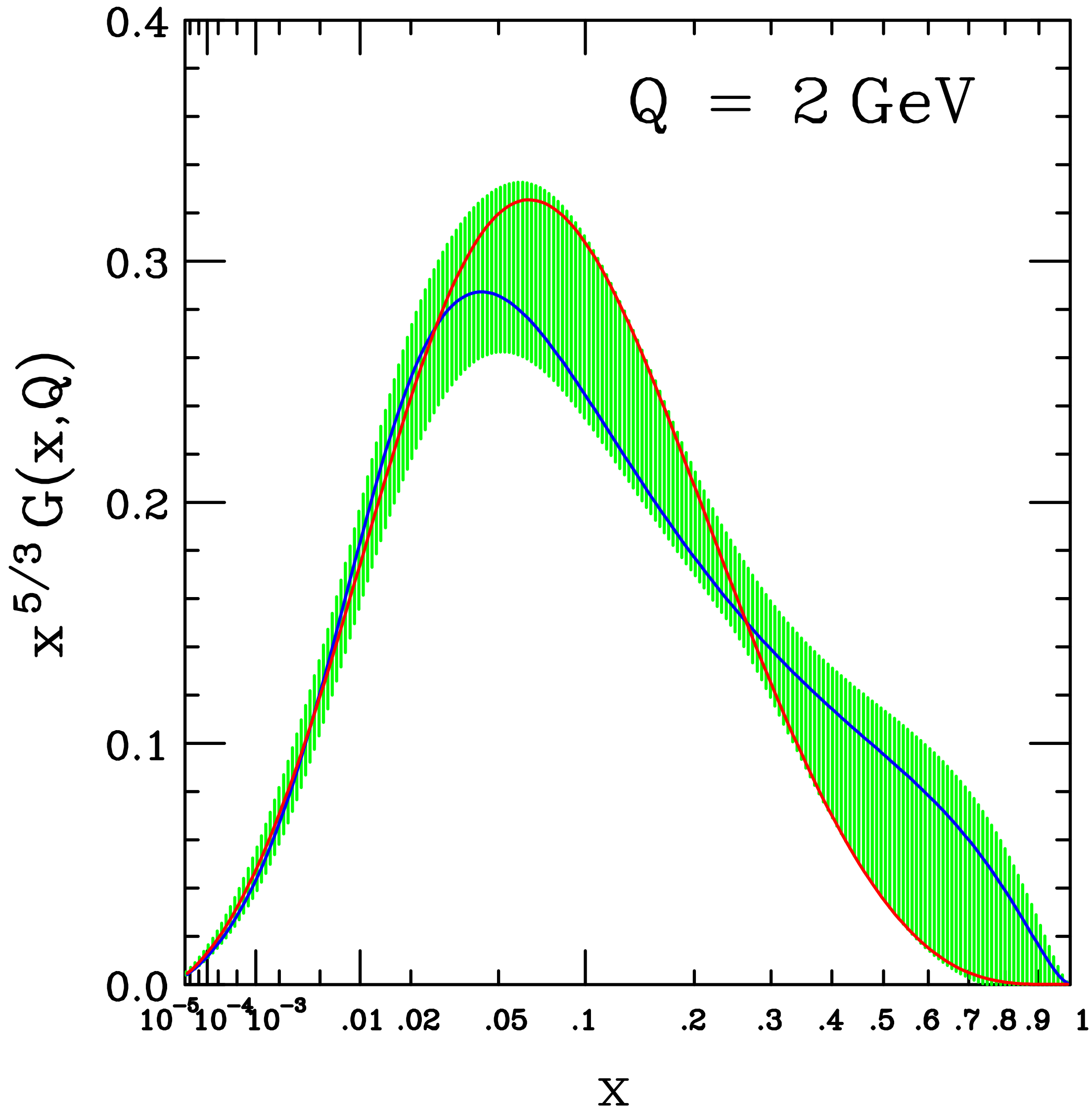
The uncertainty of PDFs can be characterized by a collection of fits that are created by stepping away from the minimum of χ^2 along each eigenvector direction of the local quadratic form (Hessian matrix).

The PDF uncertainty for any quantity is obtained by evaluating that quantity with each of the eigenvector sets and then applying a simple formula; or more crudely just by the spread in eigenvector predictions.

Uncertainty sets should be regarded as an essential part of any general-purpose PDF determination.

CTEQ has developed an iterative procedure to compute the eigenvector sets in spite of numerical difficulties associated with the large range in eigenvalues of the Hessian. Other PDF groups have adopted this method as well, and/or they avoid the numerical difficulties by keeping substantially fewer free parameters — at a cost of greater of parametrization bias.

Consistency Check

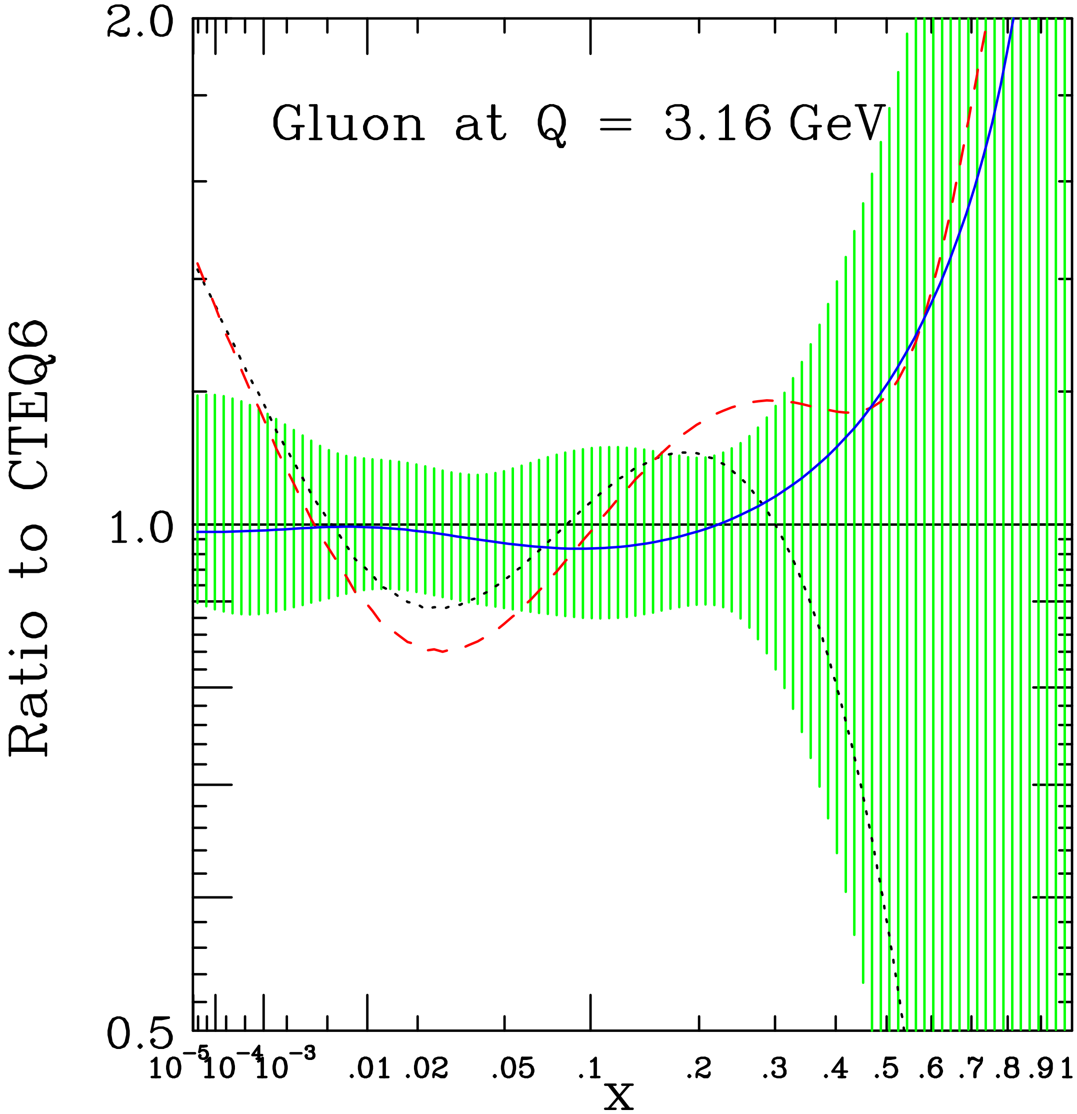


Curves show the effect of reweighting data to emphasize CDF or DØ inclusive jets.

Estimated uncertainty is comparable to the difference between the "pull" of similar experiments
$\Rightarrow$ Eigenvector method is working correctly

Interesting that similar experiments pull so differently.

CTEQ Gluon distributions

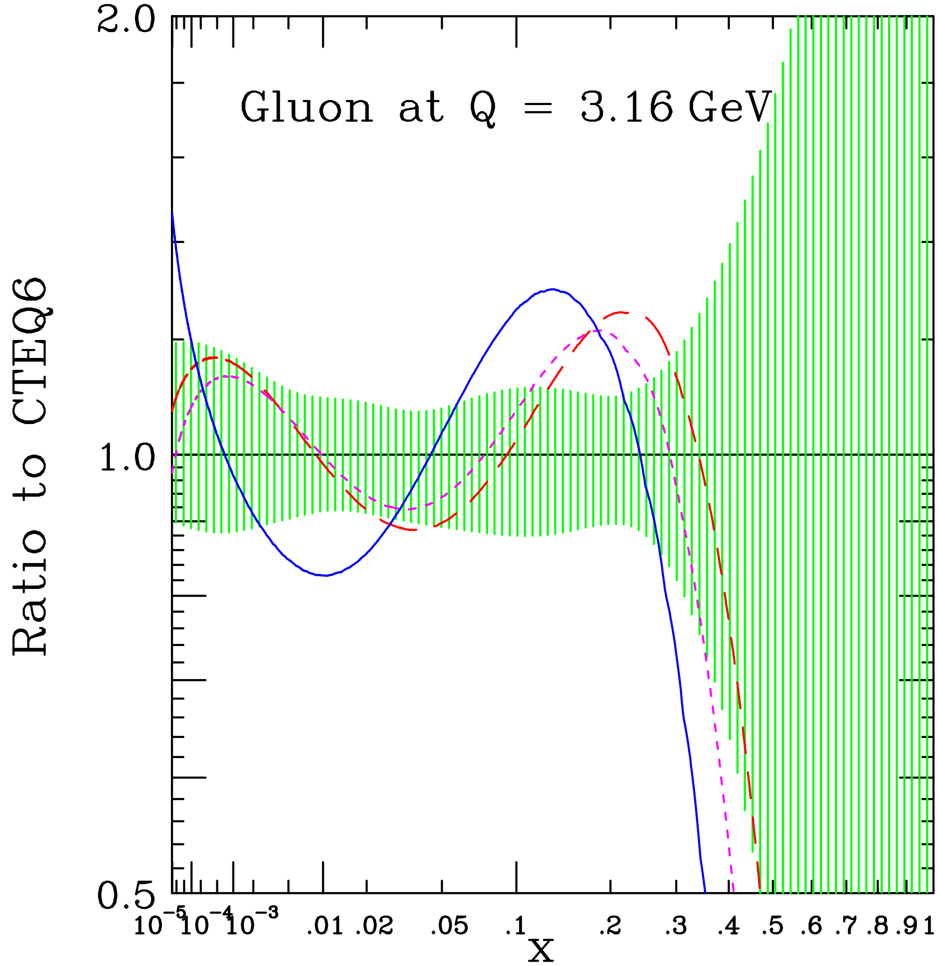


CTEQ5, CTEQ5HJ, CTEQ6.1

CTEQ5HJ was an early milestone in the PDF uncertainty game: large inclusive jet cross section from CDF explained by PDF uncertainty.

CTEQ6.1 very similar to CTEQ6.0

Zeus and Alekhin gluons

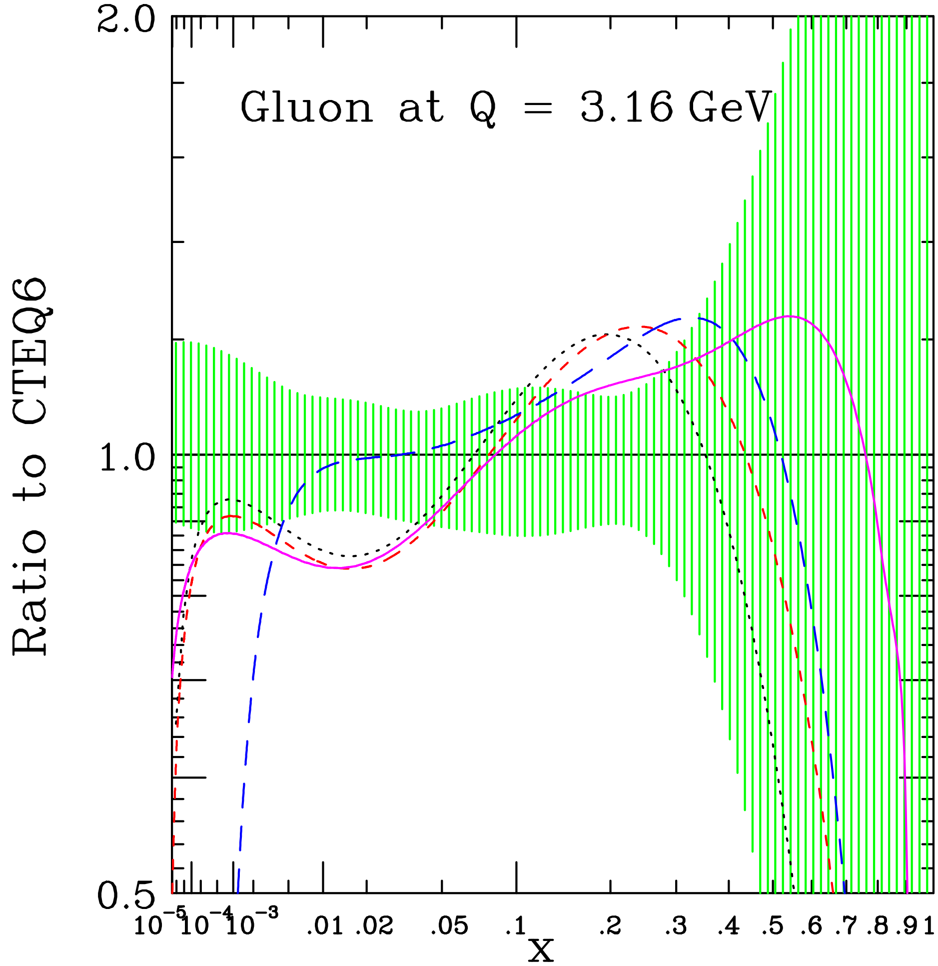


Zeus2005zj, Alekhin02NLO, Alekhin02NNLO

- Fits based on a subset of the available data lie outside the CTEQ uncertainty bands.

- Difference between NLO and NNLO is small compared to the PDF uncertainty.

MRST gluon distributions

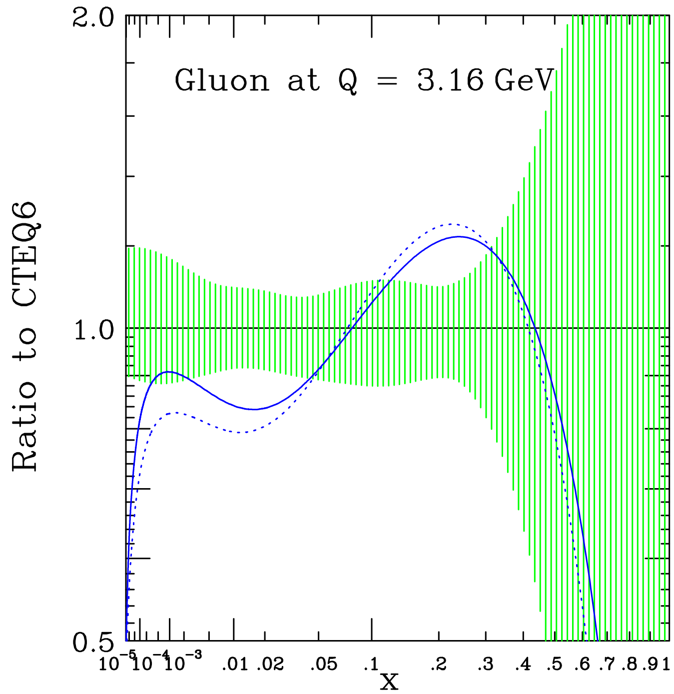


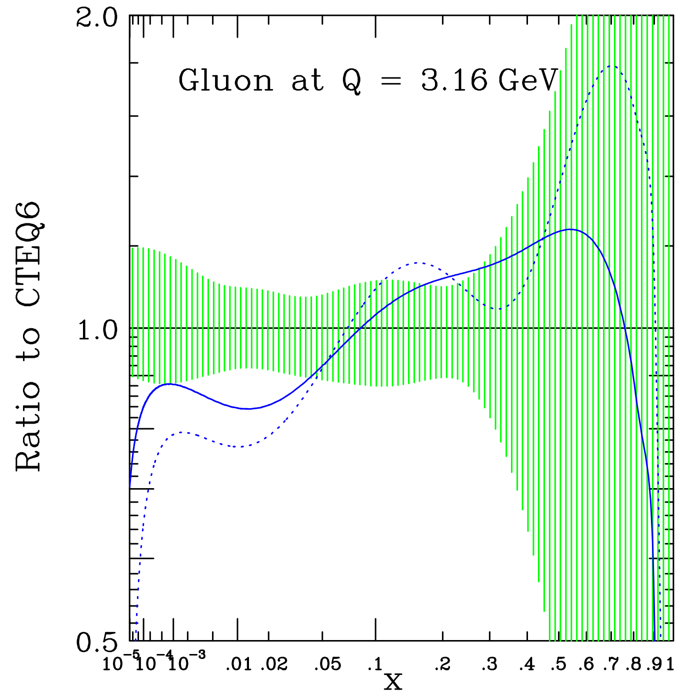
mrst2001, mrst2002, mrst2003, mrst2004

Differences between MRST and CTEQ are comparable to the estimated uncertainty

(Ironic because original motive to study uncertainty was the danger that comparing groups using same basic method would underestimate the uncertainty!)

NLO vs. NNLO





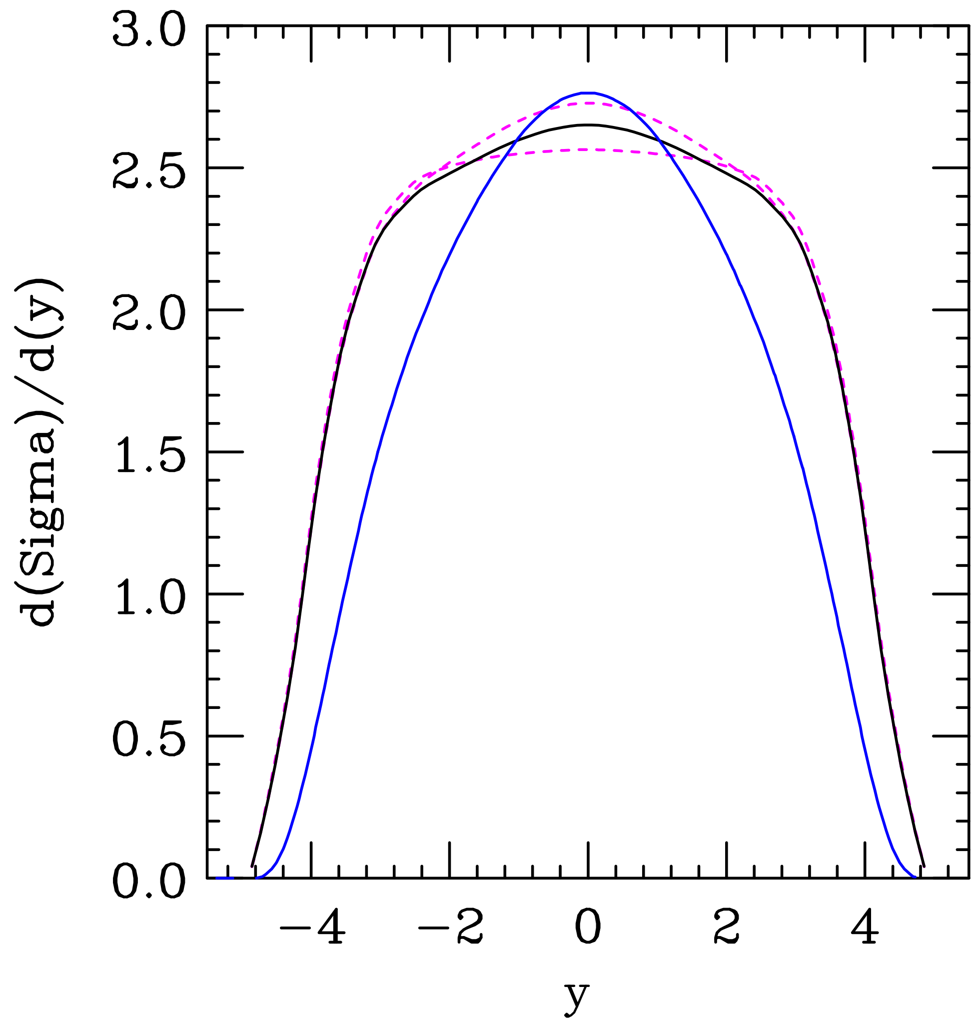
MRST2002NLO, NNLO MRST2004NLO, NNLO

Difference between NLO and NNLO analysis is small compared to current PDF uncertainty.

Hence full NNLO fitting – while of course desirable – is not urgent.

W cross section at LHC

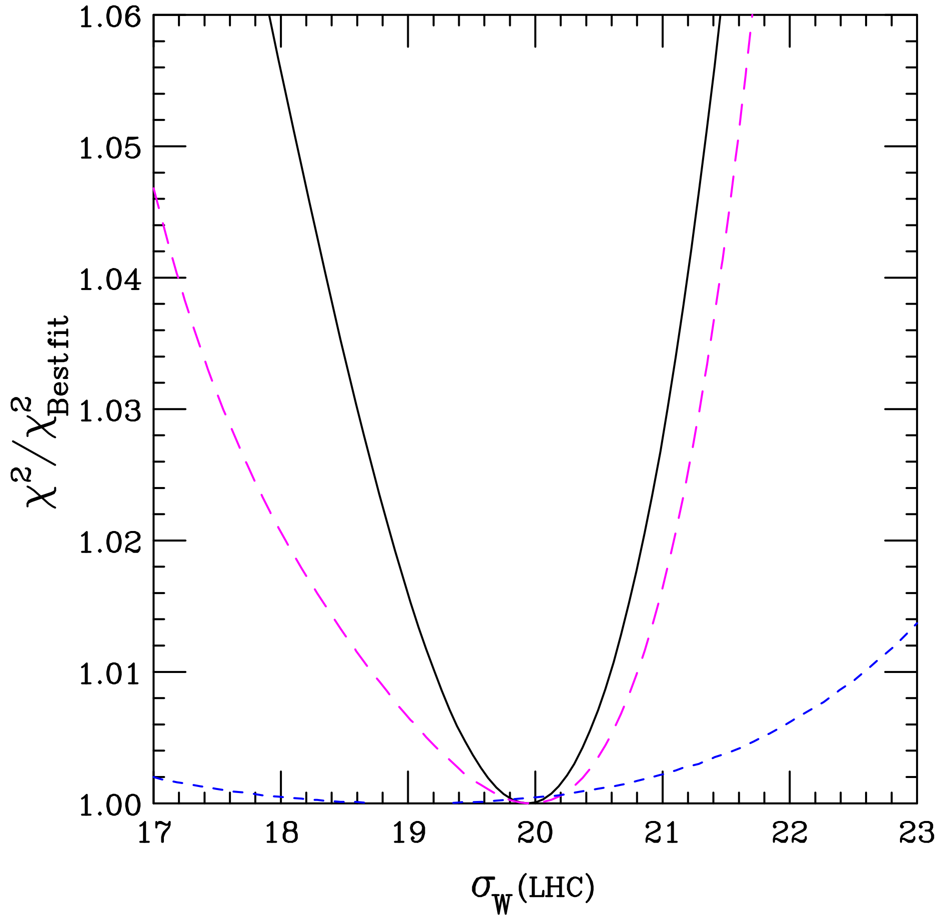
Can we use σ_W as a "Standard Candle" parton luminosity measure at LHC?



CTEQ6.1 and Extreme eigenvector sets predict similar $d\sigma/dy$ for $(W^+ + W^-)$ at LHC.

MRST2003c "conservative" fit is radically different — much smaller integrated cross section!

Can CTEQ reproduce small σ_W?



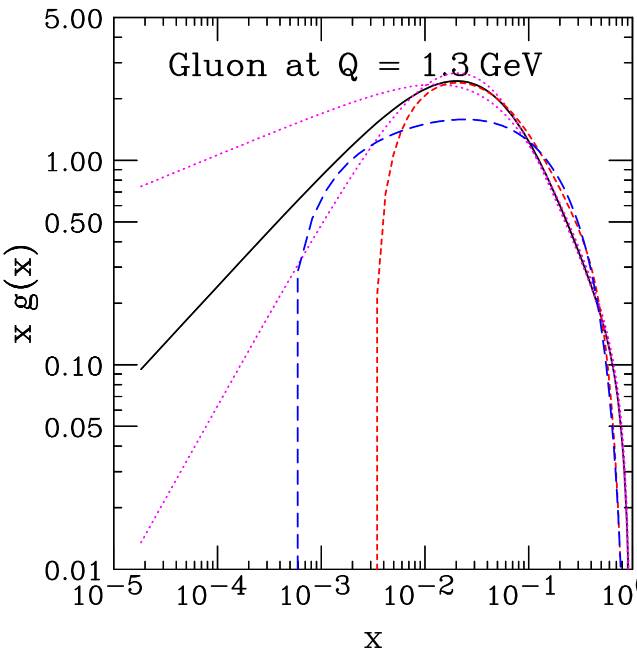
Standard cuts ($Q > 2$),
Intermediate cuts ($Q > 2.5$, $x > 0.001$),
Strong cuts ($Q > 3.16$, $x > 0.005$)

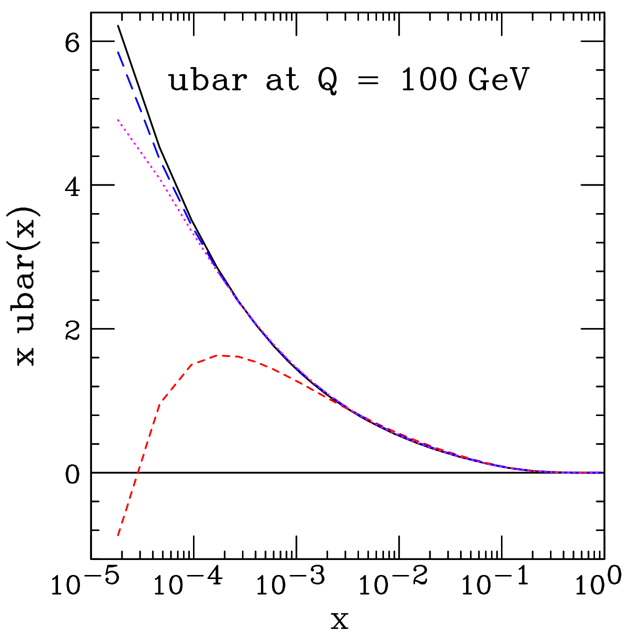
CTEQ finds in agreement with MRST that (Strong cuts) + (Negative gluon) $\Rightarrow$ (small σ_W allowed)

CTEQ finds in disagreement with MRST that the NLO fit is stable with respect to the cuts, and hence provides no motivation to make the strong "conservative" cuts. (see Dan Stump's talk.)

Small x gluons and quarks

The gluon distribution needed to get small σ_W is also so strongly negative that it drives quark distributions negative at large Q.





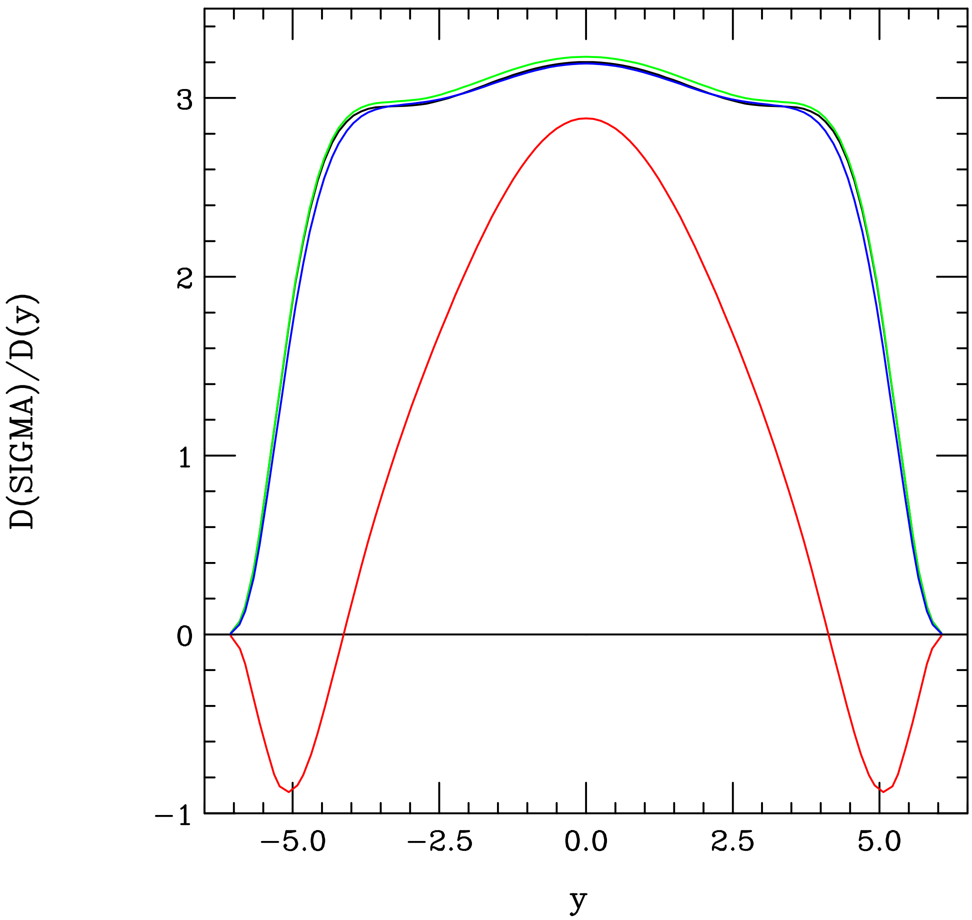
CTEQ6.1, MRST2002, MRST2003c

Gluon: Magenta curves are the extremes from among the 40 eigenvector sets.

Quark: Magenta curve is CTEQ best fit with $g(x) < 0$

MRST2003c has negative u, $\bar{u}$, d, $\bar{d}$ at $Q = 100\,\text{GeV}$ at small x — e.g., leads to negative $d\sigma_W/dy$ at $\sqrt{s} = 40\,\text{TeV}$.

Predicted $d\sigma_{W+}/dy$ at 40 TeV

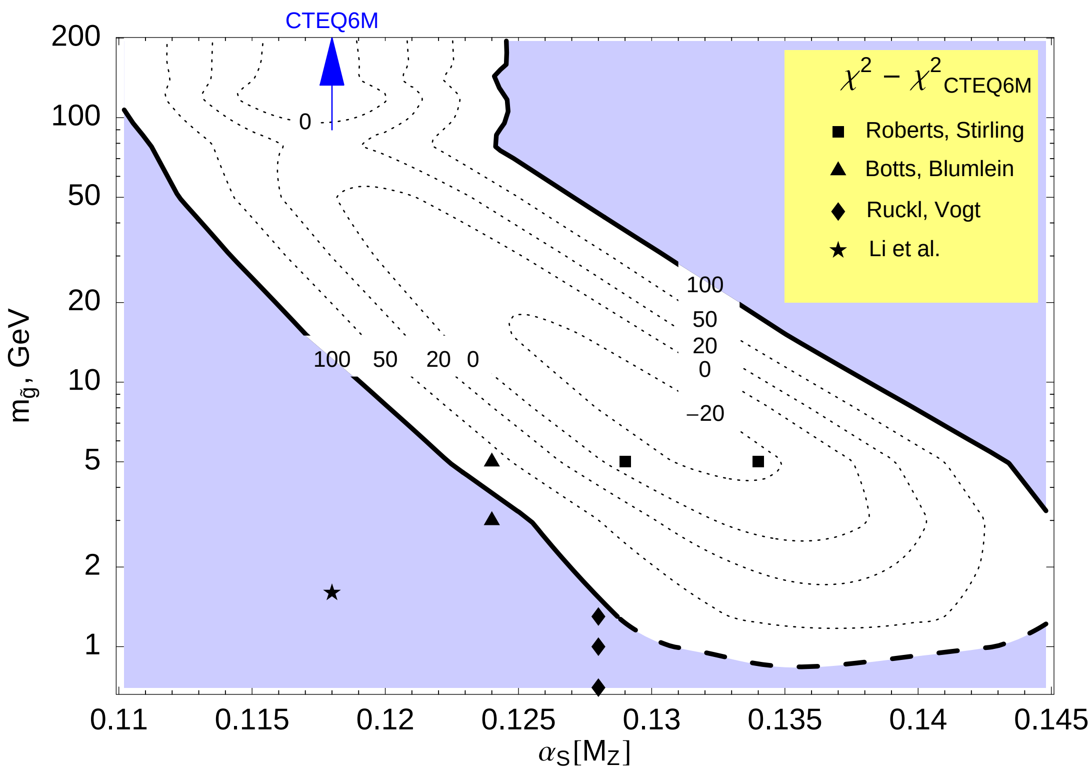


CTEQ6.1, CTEQ6, MRST2002, MRST2003c

New Physics from PDF fits?

Global fit for PDFs relies on lots of Standard Model QCD $\Rightarrow$ deviations sensitive to New Physics.

Example: Light gluino could modify evolution and jet production (Nadolsky, Olness, Berger, JP).
Contour plot of $\chi^2 - \chi^2_{\text{CTEQ6}}$ vs. $M_{\tilde{g}}$ and $\alpha_s(M_Z)$



- Valley with $5\,\text{GeV} < M_{\tilde{g}} < 20\,\text{GeV}$ has $\Delta\chi^2 \approx -25$ $\Rightarrow \sim 1\,\sigma$ "suggestion" of a light gluino.

- Can interpret this as confirmation that the global fit is consistent with QCD, and a reminder that $\Delta\chi^2 = 25$ is within acceptable range.

What's Next?

Improvements from theory:

- Improved treatment of heavy quarks
- Weaker input assumptions:
  - s, $\bar{s}$ free (currently assume $s + \bar{s} \propto \bar{d} + \bar{u}$)
  - Allow non-radiatively generated ("intrinsic") $c, \bar{c}$ and $b, \bar{b}$
- Stronger input assumptions: Nonperturbative models, lattice
- NNLO

Improvements from old experiments:

- H1, Zeus
- NuTeV
- E866 – where are you??
- CDF, DØ (Inclusive Jets, lepton y-asymmetry from W decay)

New Measurements?

- HERA: F_L, $e^{\pm} + d$ (any chance??)
- CDF and DØ: inclusive Z^0 and $W^{\pm}$
- CDF and DØ: $\gamma/Z^0/W^{\pm}$ + jet with c- or b-tag
- CDF and DØ: inclusive jet with c- or b-tag (?)

(see HeraLHC and TeV4LHC workshops)

Key Applications

- Systematics of W mass measurement
- All things LHC – Standard Model and beyond

Extensions

- Spin-dependent PDFs
- Generalized PDFs