HQ–correct PDFs: CTEQ6.5

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Dallas CTEQ meeting Dec 1–2, 2006

Recent work by Tung, Stump, Pumplin, Yuan, Lai, Belyaev hep-ph/0611254

- CTEQ6.5 PDFs
  - Improved theory: Zero Mass (ZM) $\rightarrow$ General Mass (GM) formalism.
  - Improved data: all HERA run I data using measured cross sections instead of extracted F_2, F_3; NuTeV dimuon data.
- Uncertainty of $d(x)/u(x)$ – background for Jeff's talk
- Shape of $\bar{d}(x)$ and $\bar{u}(x)$
- Study of $c(x)$ and $\bar{c}(x)$ (Intrinsic Charm)
- Study of $s(x)$ and $\bar{s}(x)$ – Liang

The "Global Analysis" paradigm

1. Parameterize the x-dependence of each flavor at $\mu_0 = 1.3\,\mathrm{GeV}$ with $\sim$20 free parameters

2. Compute PDFs $f_a(x, \mu)$ at all $\mu > \mu_0$ by DGLAP

3. Compute cross sections for Deep Inelastic Scattering, Drell-Yan, Inclusive Jets,... using QCD perturbation theory

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

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

5. Vary the parameters in $f_a(x, \mu_0)$ to minimize χ^2, yielding Best Fit PDFs.

6. Find eigenvectors that diagonalize χ^2 as a function of the fitting parameters in the neighborhood of the minimum, where it can be approximated by a quadratic form. Move along each of those directions until the fit becomes unacceptable, to estimate uncertainties (the "40 sets").

New Global Analysis: CTEQ6.5

Theory update:

- Remove Zero-Mass approximation for c and b quarks by implementing Collins' General Mass (GM) formalism (Tung, Lai, Yuan)
- Simplified parametrizations at $Q_0 = 1.3\,\text{GeV}$.
- Code cleaned up using f90 features.

Experimental update:

- Full DIS data sets from HERA I (1994–2000).
- Include Charged Current ($e\,p \to \nu X$) data.
- Fit measured cross sections instead of F_2.
- Include correlated systematic errors as always.
- Include NuTeV dimuon data

Still to be included (for CTEQ7)

- NuTeV and Chorus (nuclear corrections and consistency issues) – see Jeff's talk

- E866 – see Jeff's talk

- Fermilab Run II Jets, Wasy (with cuts?)

- HERA DIS + Jet data

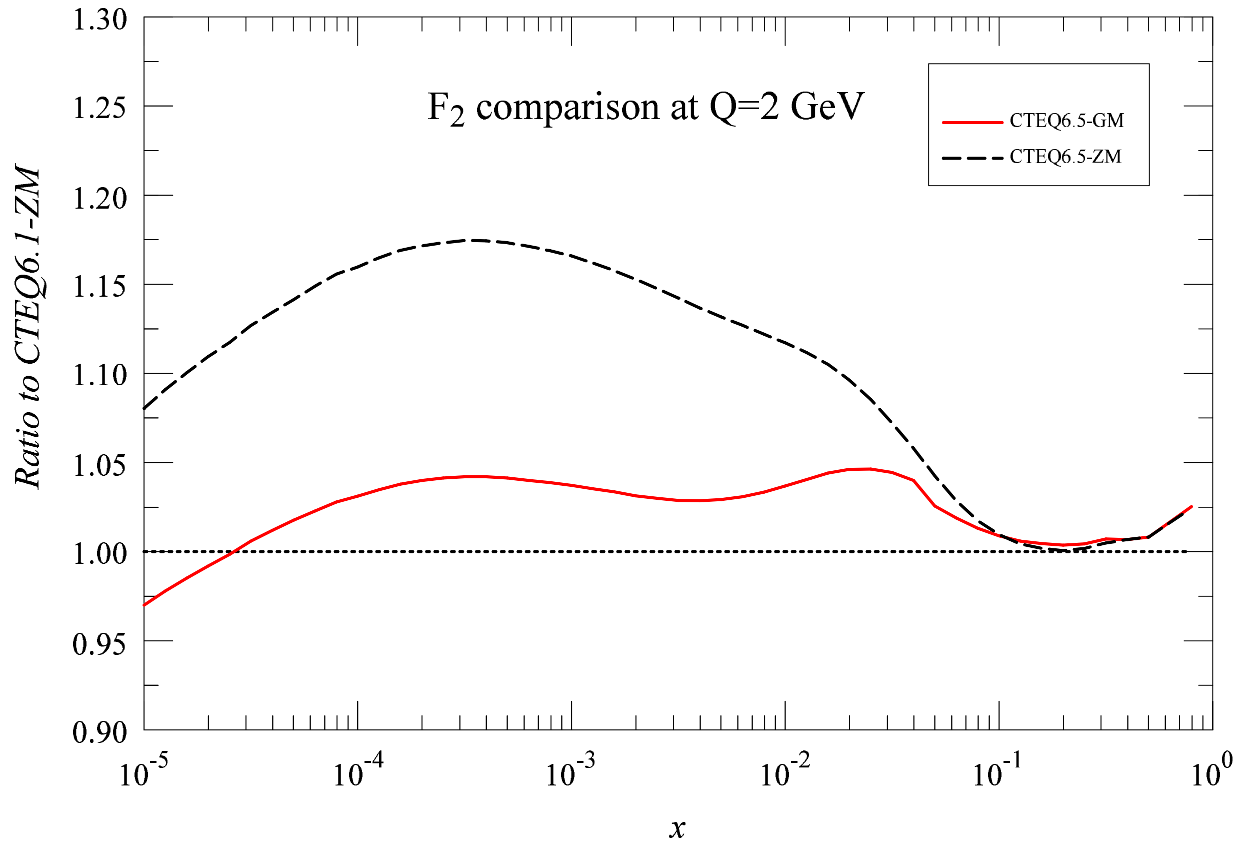
- HERA run II data?

- Other Fermilab data? Z^0 inclusive? W inclusive? $\gamma +$jet?

Quark mass effects

New code that implements Collins' General Mass pQCD formalism.

ACOT χ variable – kinematic suppression.

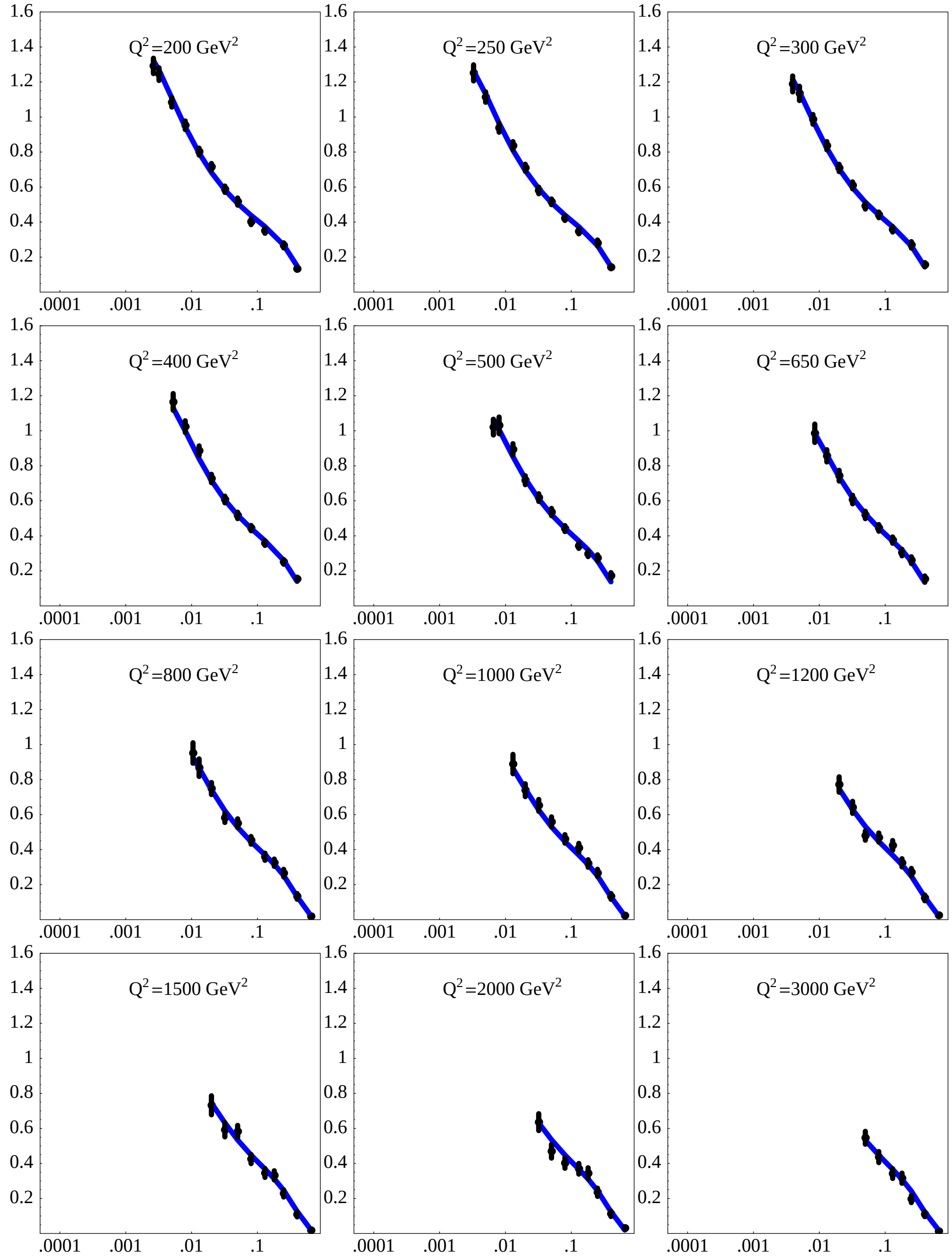


Calculated F_2 relative to CTEQ6.1.

Solid red curve is CTEQ6.5 – close to 1 because lots of HERA F_2 data which both CTEQ6.1 and CTEQ6.5 were fitted to.

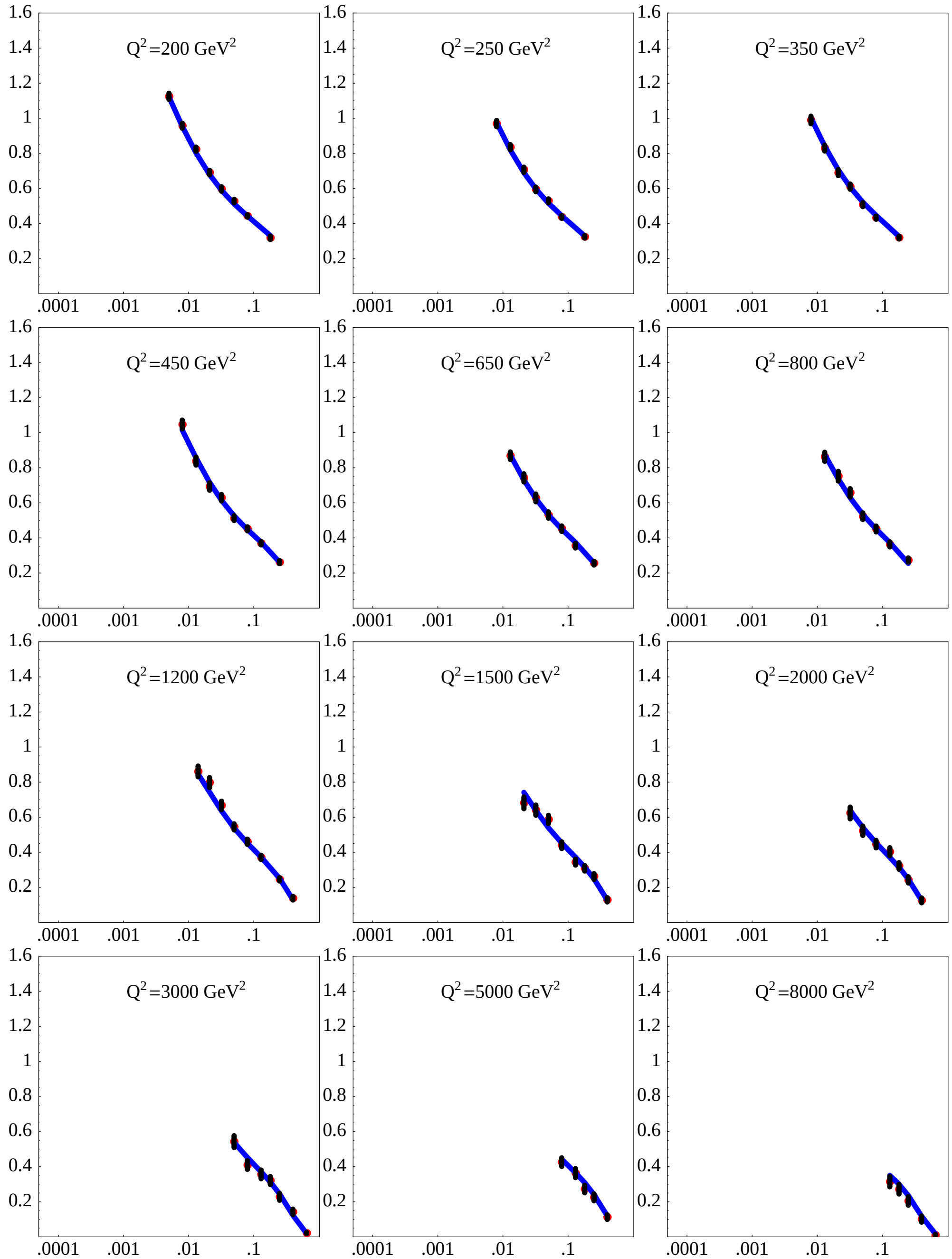
Dashed black curve is CTEQ6.5 PDFS but Zero Mass approximation for F_2 – jumps up because mass effects reduce F_2.

Agreement of CTEQ6.5 with typical DIS input data



CTEQ6.5 fit to H1 (1999-2000 e^+p NC reduced cross section)

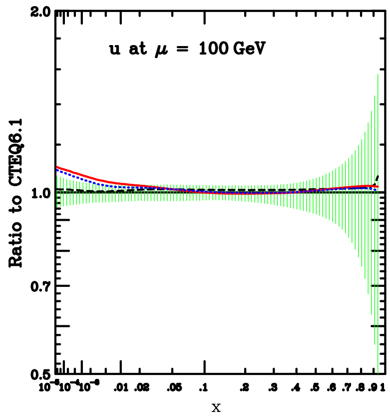
Agreement of CTEQ6.5 with typical DIS input data

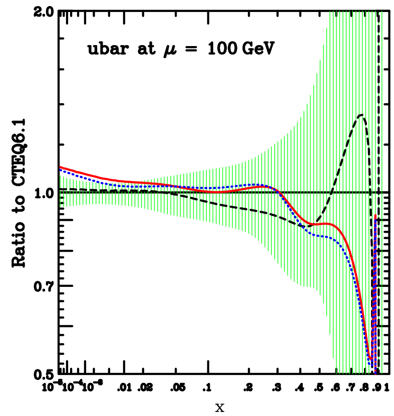


CTEQ6.5 fit to ZEUS (1999-2000 e^+p NC reduced cross section)

(From my talk at ANL last May)

Comparison with CTEQ6.1





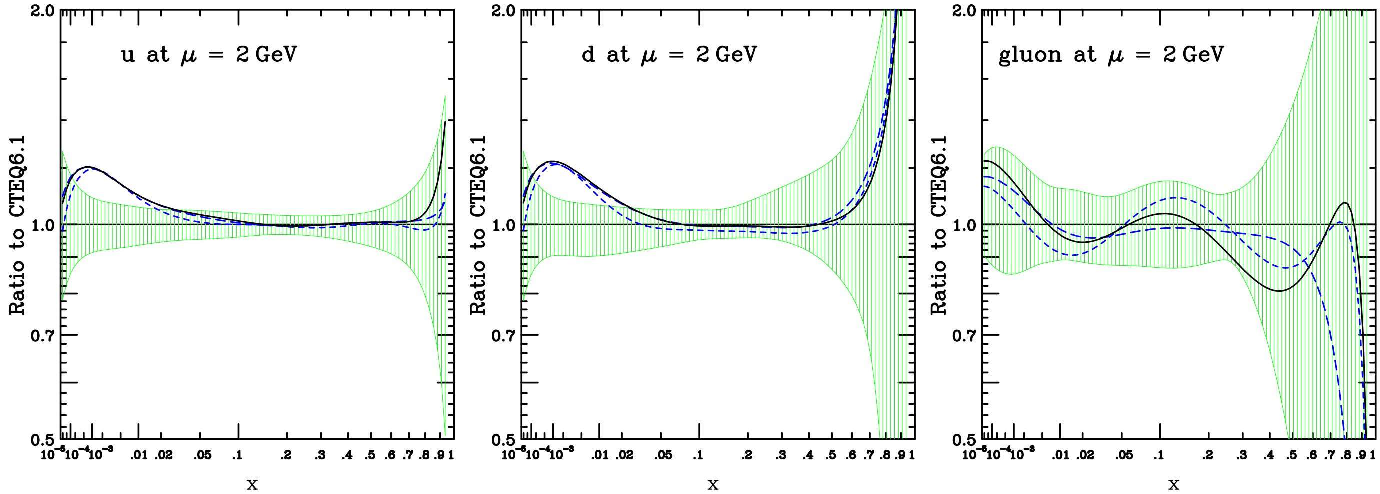
Green: Uncertainty from CTEQ6.1 40 ev sets.
Black: CTEQ6A118
Red, Blue: Candidates for new "Best Fit"

- PDFs are somewhat larger at small $x \Rightarrow$ somewhat larger cross sections predicted for LHC. (Because heavy-quark mass effects reduce the predicted DIS cross sections at smaller Q, so PDFs rise to maintain agreement at HERA.)

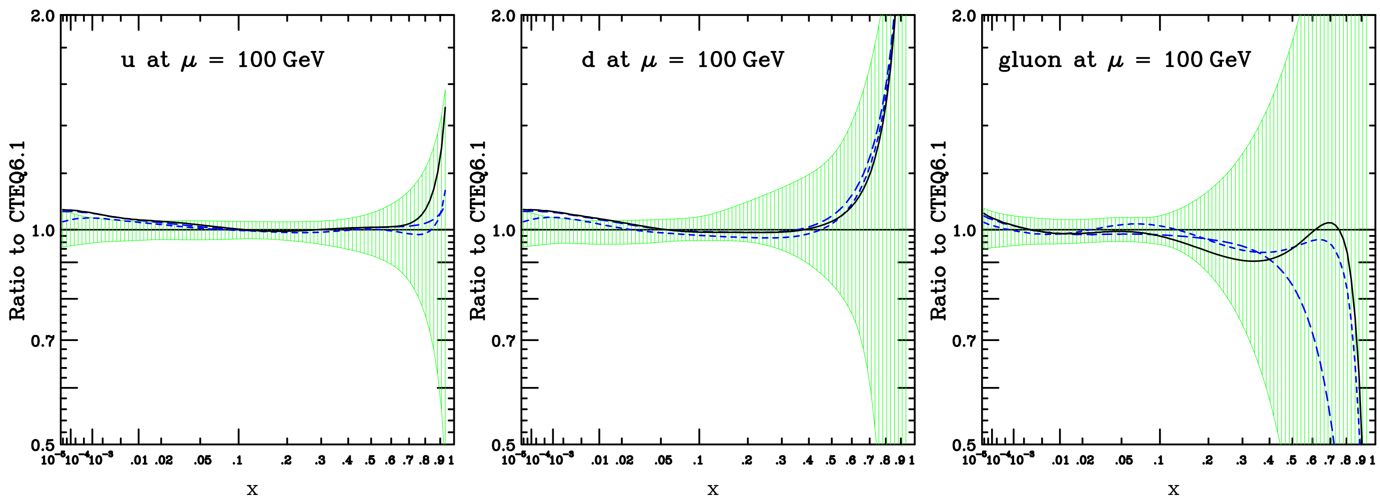
- CTEQ6.1 uncertainty estimate was otherwise about right: the new PDFs are more-or-less within the expected (90% confidence) range.

- Gluon smaller (well within old errors) at $x \to 1$ by choice of parametrization: $(1-x)^{A_2}$ with A_2 moved from ~ 1.9 to 3.0 based on quark counting. (A_2 moved further to 4.0 in CTEQ6.5)

Compare CTEQ6.5 with CTEQ6.1

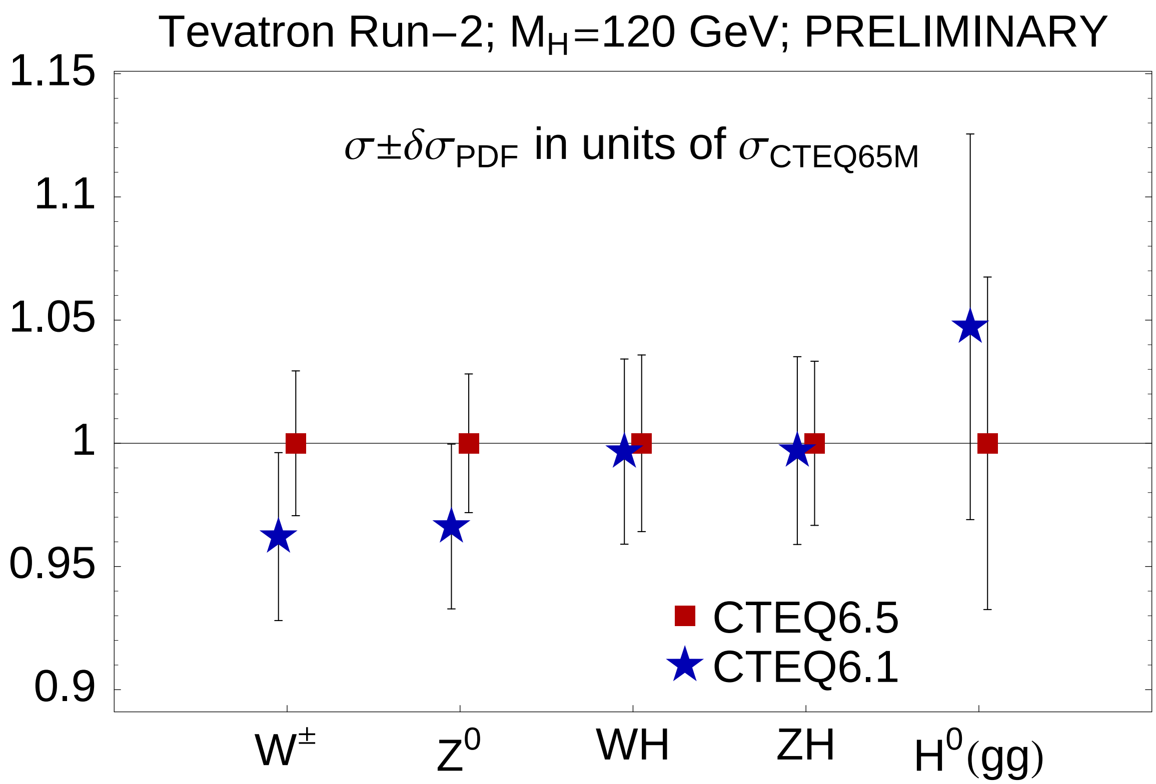


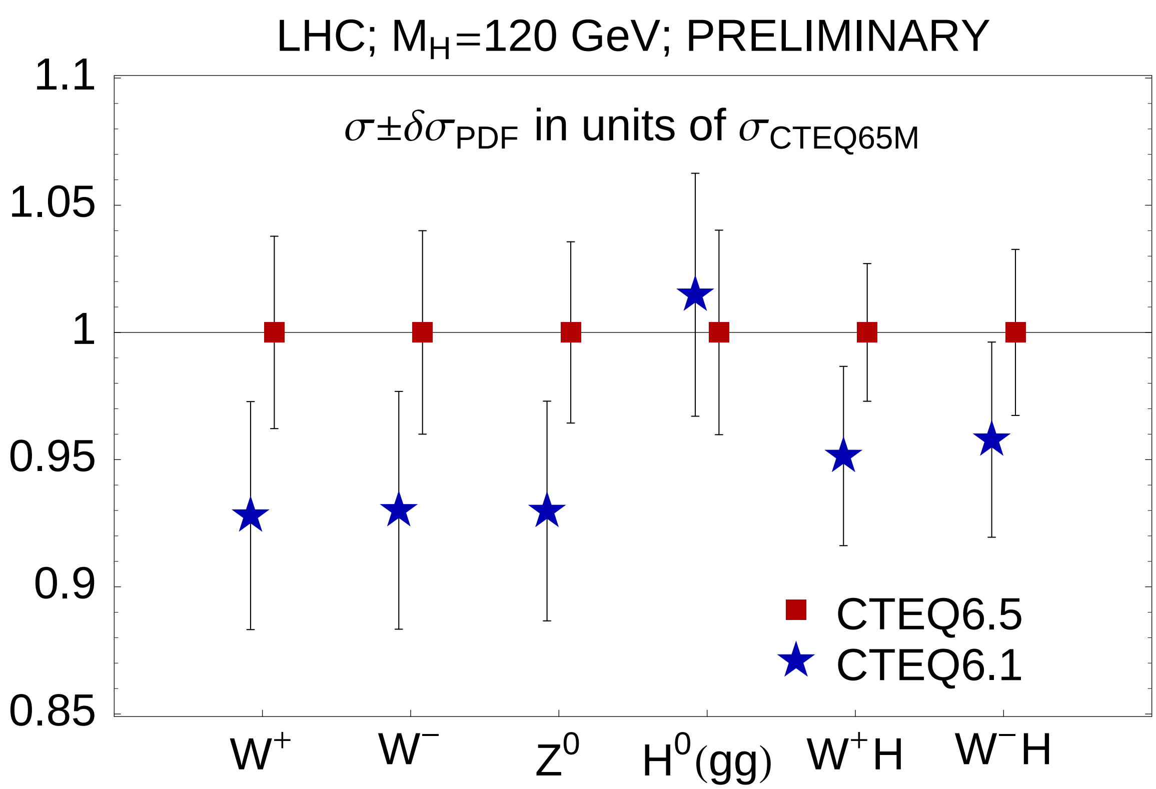
CTEQ6.5/CTEQ6.1 for u, d, g at $Q = 2\,\text{GeV}$. Shaded area is uncertainty estimate from CTEQ6.1. Dashed curves represent alternative candidates for Best Fit obtained by different parametrizations.



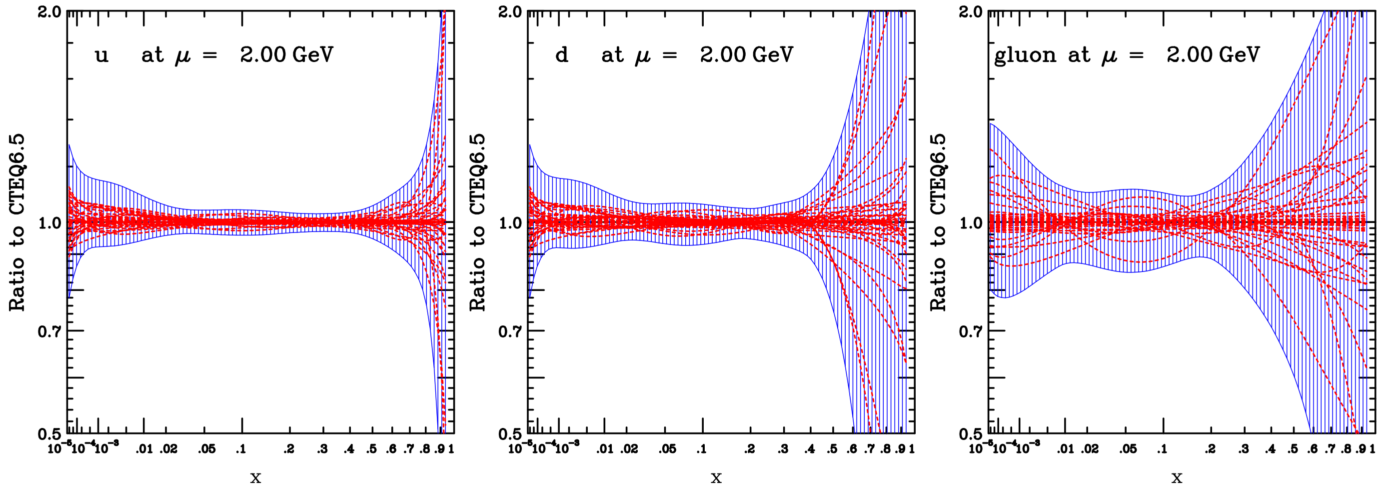
Same except scale $Q = 100\,\text{GeV}$. The difference persists, so predict higher cross sections at LHC (e.g., 8 % increase for inclusive W production.)

Plots from Pavel Nadolsky

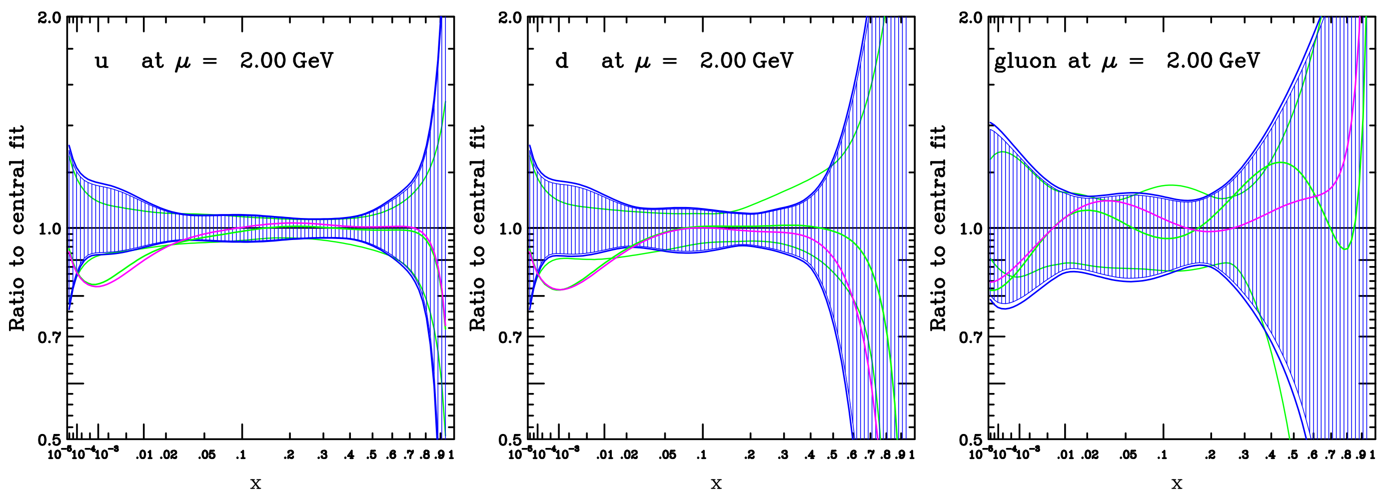




Uncertainties in CTEQ6.5



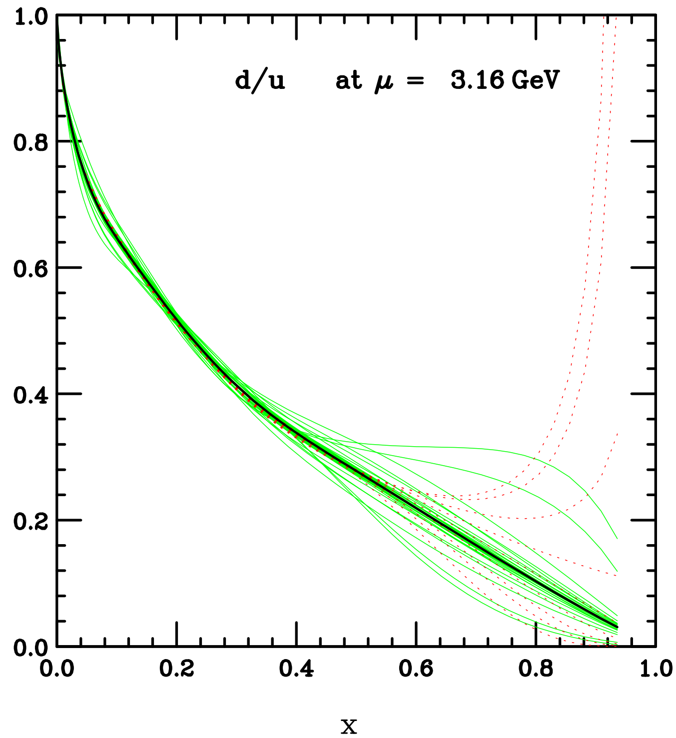
CTEQ6.5 uncertainty bands and eigenvector sets used to generate them by adding in quadrature.



CTEQ6.5 PDF uncertainty bands compared to those of CTEQ6.1. Estimated uncertainty has stayed about the same.

(The CTEQ6.1M and CTEQ6A00 sets are represented by the central solid green and magenta lines.)

Uncertainty of $d(x)/u(x)$ at large x



Black: CTEQ6.5 central fit
Green: The 40 CTEQ6.5 eigenvector uncertainty sets

In CTEQ6.5, we assumed $d_v(x) \sim (1-x)^{a_d}$ and $u_v(x) \sim (1-x)^{a_u}$ at $x \to 1$, with constraint $a_d - a_u = +1$. This constraint was imposed (for the best fit and for all eigenvector sets) because $a_d - a_u$ is very weakly constrained by χ^2 ("flat direction")

Red dotted curves are fits made with a variety of choices for $a_d - a_u$. They are all very good fits, so the behavior of d/u is completely unconstrained by the experiments included here for $x > 0.8$.

(See Jeff's talk!)

Conclusions on CTEQ6.5

1. Improved Input
   - HQ formalism implemented
   - Use HERA measured cross sections directly
   - Include HERA CC data and NuTeV dimuon data (weight=2.0)

2. Gives better fit (χ^2 lower by ~ 200), suggesting that the physics is better! :)

3. CTEQ6.1 uncertainties were not unreasonable

4. Little or no decrease in estimated uncertainty – though the agreement with CTEQ6.1 (except where difference is expected) inspires increased confidence.

5. Larger q and $\bar{q}$ distributions at $x \sim 10^{-3}$ from correcting the former ZM approximation implies larger cross sections at LHC.

Parametrizations

Parametrization of PDFs at Q_0 in CTEQ5 and CTEQ6.1 had 5 "shape parameters" (in addition to normalization) for each flavor.

However, the data were insufficient to constrain all of them, so some parameters were frozen at arbitrary values.

In CTEQ6.5, we use a simpler 4-parameter form for $u_v(x)$, $d_v(x)$, $g(x)$:

$$f(x) = a_0\, x^{-a_1}\, (1-x)^{a_2}\, \mathrm{e}^{a_3 x + a_4 x^2} .$$

This is a plausible generalization of the conventional minimal form

$$f_0(x) = a_0\, x^{a_1}\, (1-x)^{a_2} ,$$

which combines Regge behavior at $x \to 0$ and spectator counting behavior at $x \to 1$ in an economical way.

The minimal form has

$$\phi_0(x) = -x\,(1-x)\,\frac{d \ln f_0}{dx} = -a_1 + a_2 x ,$$

We simply extend the right hand side to a higher-order polynomial in the spirit of using a polynomial to approximate an unknown functions with no known singularities.

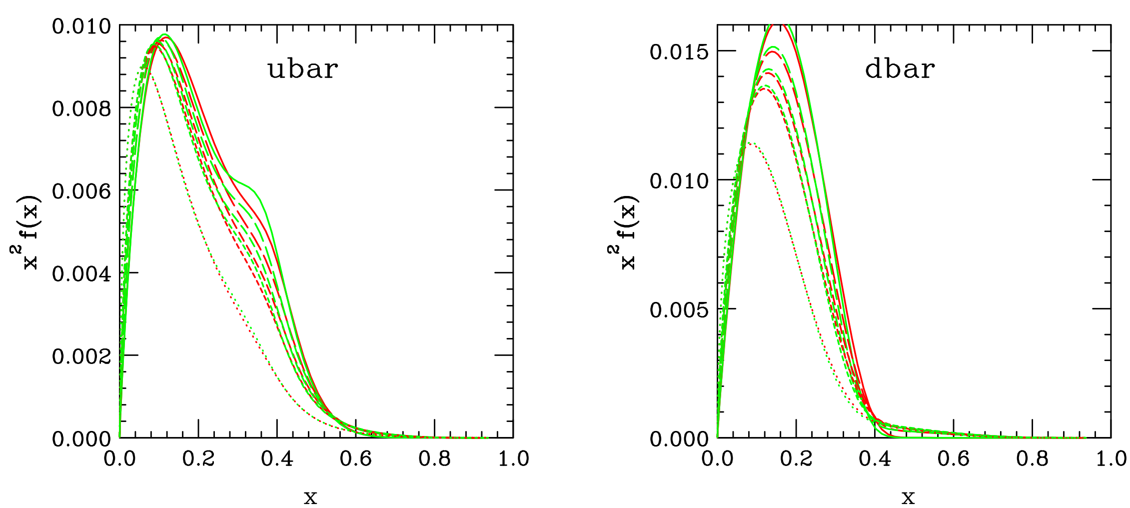
Study of $\bar{d}(x)$ and $\bar{u}(x)$

In CTEQ6.0-6.5, parametrize $\bar{d}(x) + \bar{u}(x)$ and $\bar{d}(x)/\bar{u}(x)$. Form needed for $\bar{d}(x)/\bar{u}(x)$ is oddball, and has rapid variations. Is this telling something?

When parametrize $\bar{d}(x)$ and $\bar{u}(x)$ separately, neither of the forms used in CTEQ6.1 or CTEQ6.5 achieve good fits. What do good fits look like?

Answer: $\bar{u}(x)$ has a shoulder (second peak), and both $\bar{u}(x)$ and especially $\bar{d}(x)$ are suppressed much more strongly than $(1-x)^{5(?)}$ would predict.

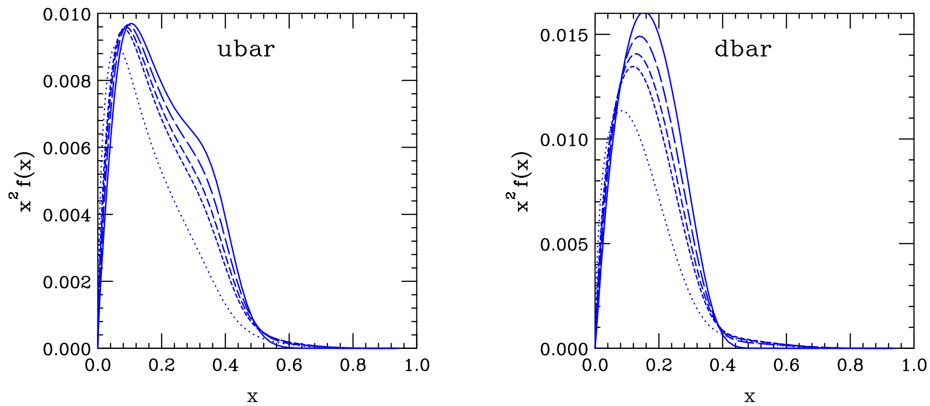
$\bar{d}(x)$ and $\bar{u}(x)$ at $Q = 1.3$, 2, 3.16, 5, 100 GeV



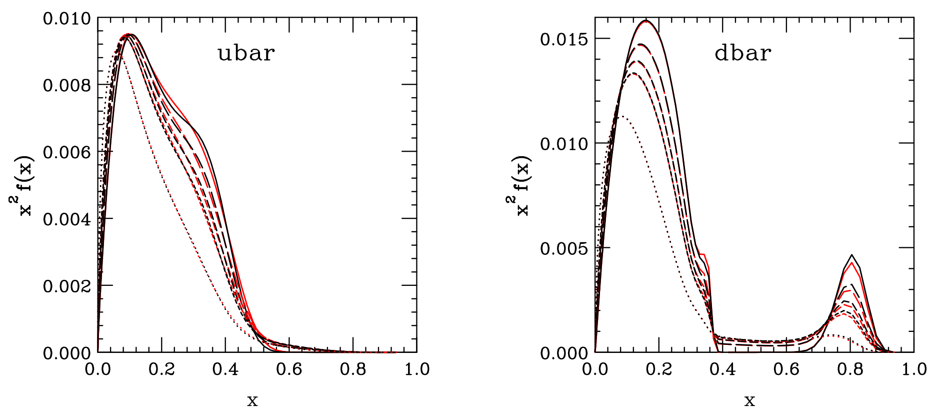
Red=parametrization used in the new strangeness study ($\chi^2_{\text{weighted}} = 3371$

Green = "$\sinh P \rightarrow P$" modification (χ^2_{wghtd} lower by 15.

Study of $\bar{d}(x)$ and $\bar{u}(x)$ - ctd



More elaborate parametrizations of $\bar{d}(x)/\bar{u}(x)$ (χ^2_{weighted} lower by 50)



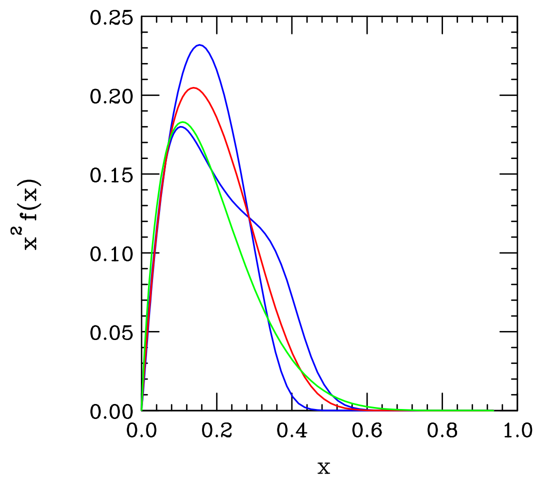
Odd-looking parametrizations of $\bar{d}(x)$, $\bar{u}(x)$ (χ^2_{weighted} lower by 70)

- Sharp drop in $\bar{d}(x)$ at $x = 0.4$ caused by iteraction with specific data points??

- Peak at large x a surrogate for $(1 - x)^8$ tail??

Implications for s and $\bar{s}$

In these studies of $\bar{u}$ and $\bar{d}$, assumed simple $s(x) = \bar{s}(x) = a_0\, x^{a_1}\, (1-x)^{a_2}$ form to avoid confusing the issue by tying it to $\bar{u} + \bar{d}$.

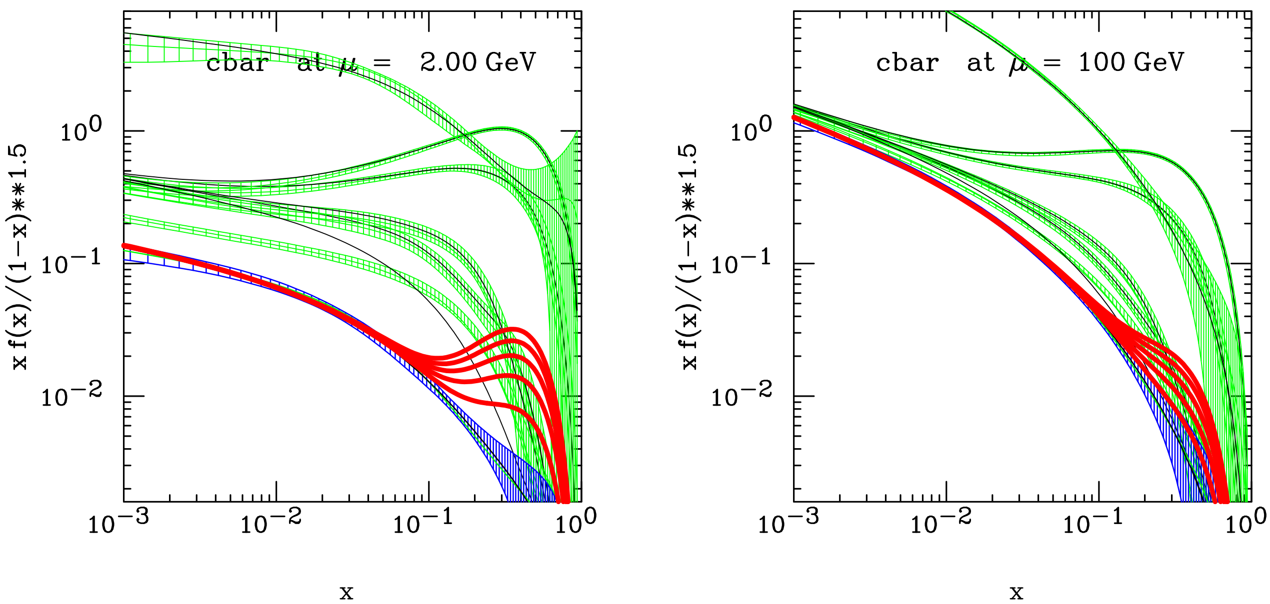


Blue: $\bar{u}(x)$ and $\bar{d}(x)$ from above.
Red: $\bar{u}(x) + \bar{d}(x)$
Green: $s(x) = \bar{s}(x) = a_0\, x^{-0.124}\, (1-x)^{7.13}$ from fitting simple form.

All 3 curves normalized to same total momentum

Conclude: the two choices for $s(x) = \bar{s}(x)$ for the study of strangeness are quite similar.

PDFs with Intrinsic Charm



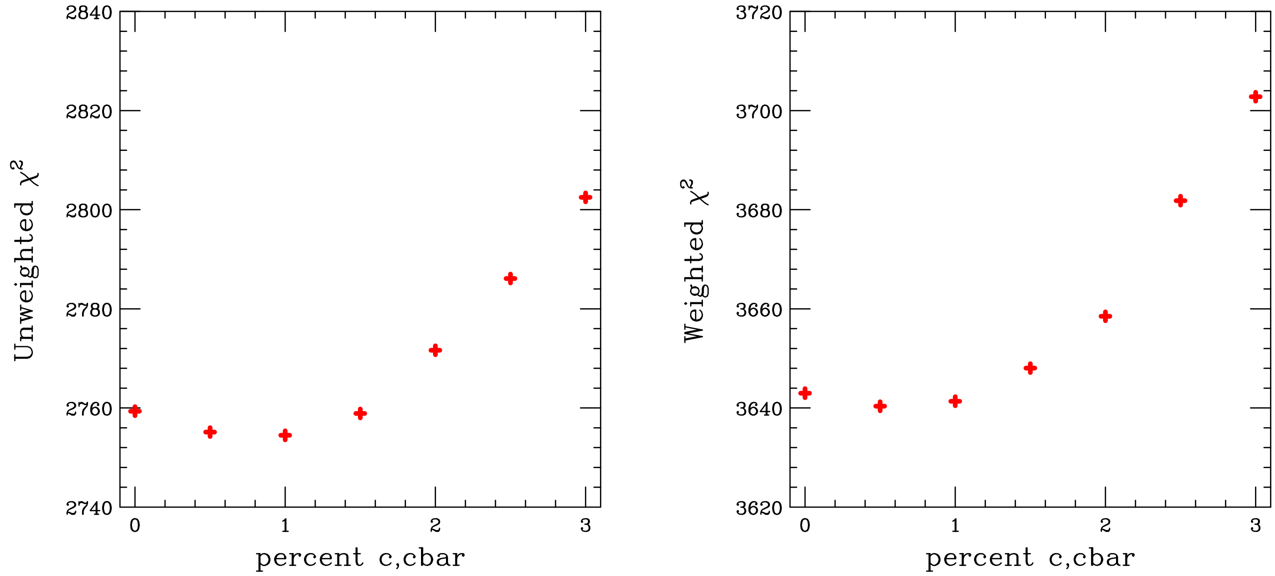
Green: g, u, d, $\bar{u}$, $\bar{d}$, $s = \bar{s}$
Black: Proto-CTEQ6.5
Blue: Charm from gluon splitting
Red: Intrinsic Charm using Brodsky (BHPS) Light-Cone form at $Q_0 = 1.3\,\mathrm{GeV}$, normalized to probability 0.5%, 1.0%, 1.5%, 2.0%, 2.5% for $c\bar{c}$.

- Typical estimate 1.0%; $>$ 2.5% ruled out by Global Fit.

- IC could be "large" $(\bar{c} > \bar{u}, \bar{d})$ for $x >$ 0.2.

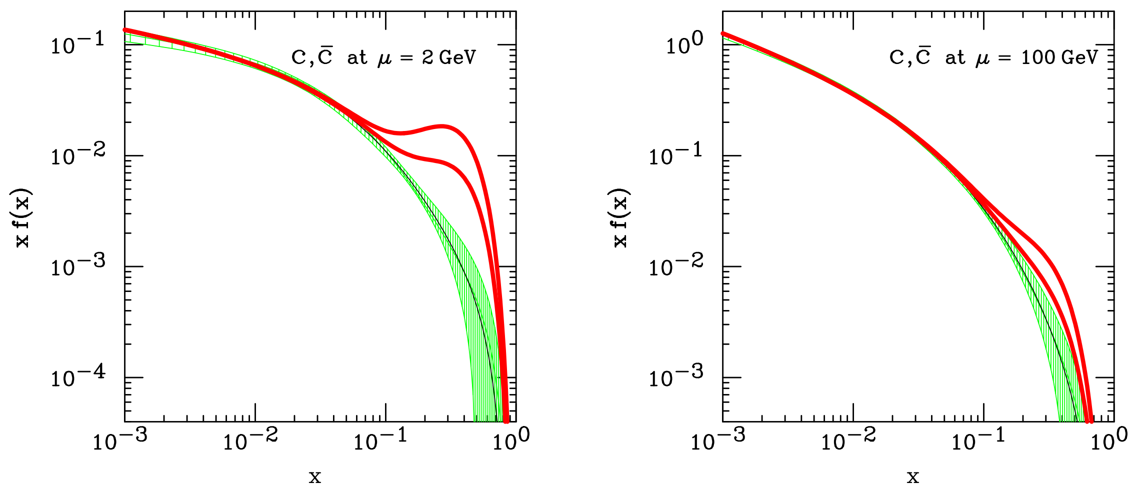
These figures were shown last May at the ANL CTEQ meeting.
The fits have been updated to use the CTEQ6.5 Heavy Quark formalism at data sets, and a draft of the paper is in progress.

Intrinsic Charm: BHPS model

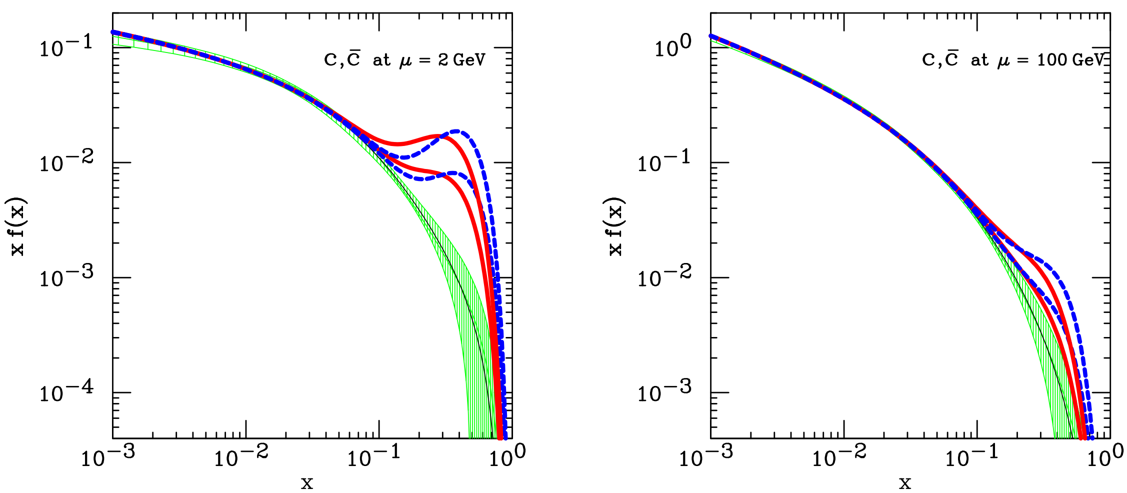


Allowing 1% intrinsic charm improves the fit by an insignificant amount. Roughly 0–3% can be tolerated by the global fit.

Light-Cone models for IC



BHPS model with $c, \bar{c}$ probability 1.0% or 2.5%.

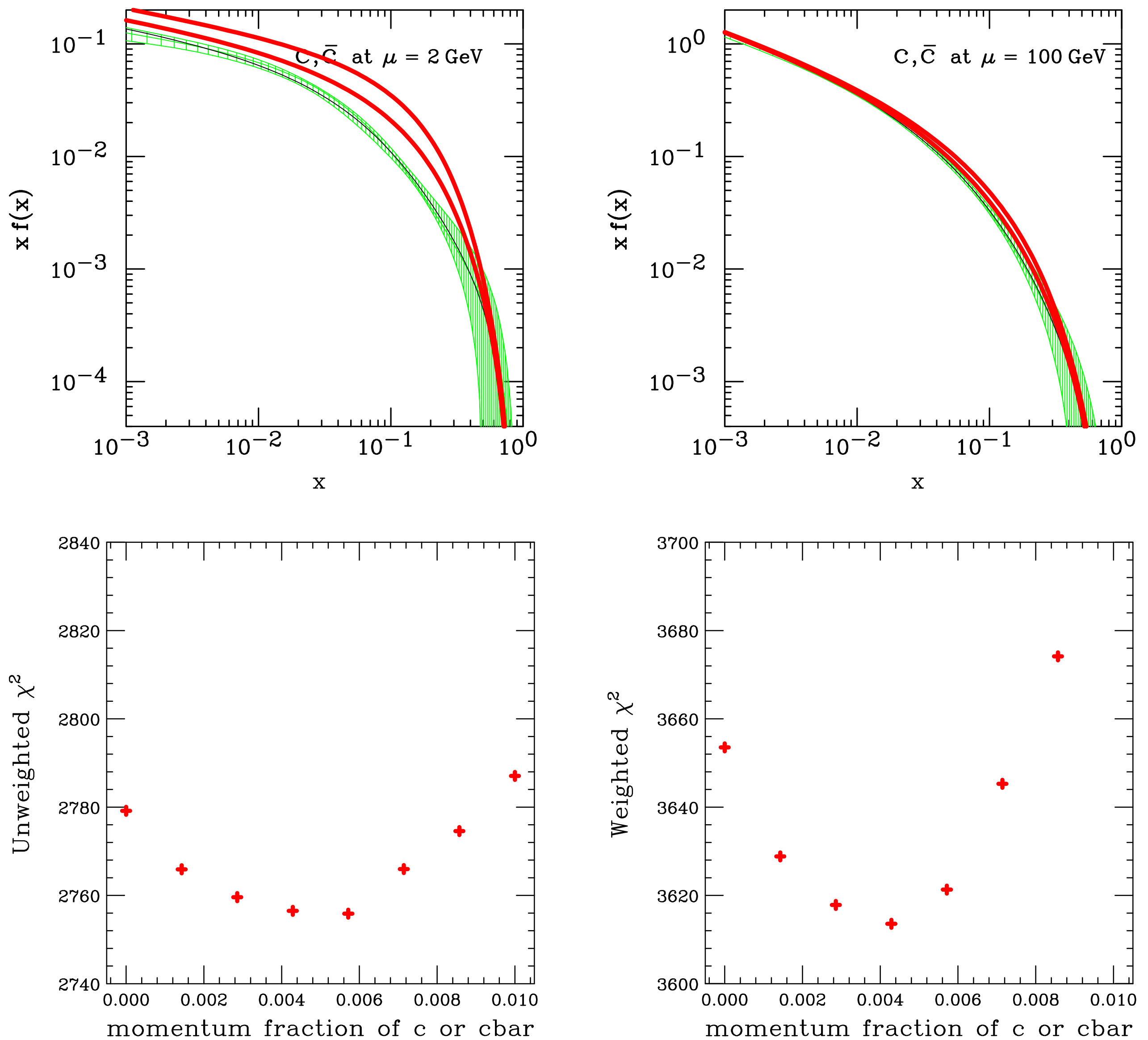


$D_0 \, \Lambda_c^+$ model – Predicts $c(x)$ .ne. $\bar{c}(x)$

Light-cone off-shell distance favors IC at large x:
$(p_\perp^2 + m^2)/x$

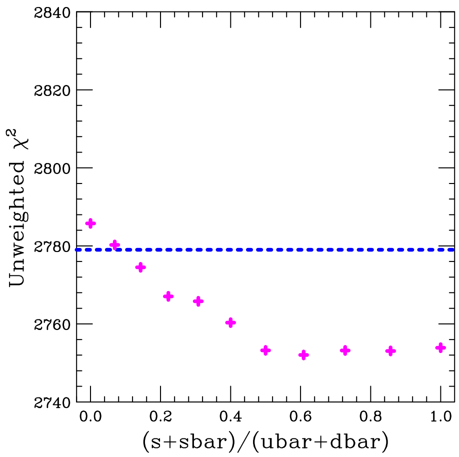
Intrinsic Charm at small x?

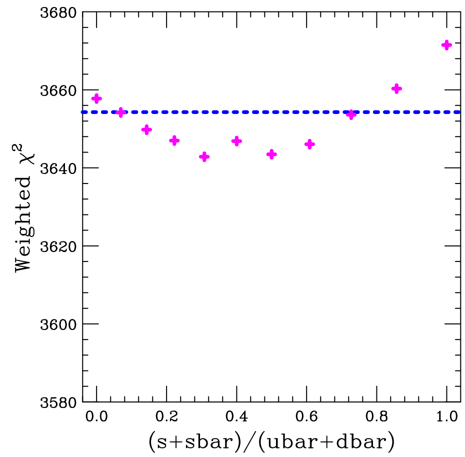
Assume $c(x) = \bar{c}(x) \propto [s(x) + \bar{s}(x)]$ and use global fit to find limits on the magnitude.



(Slide from my talk at ANL last May)

Kappa series





χ^2 of Global Fit vs.
$\kappa = \int_0^1 [s(x) + \bar{s}(x)]\, x\, dx \;/\; \int_0^1 [\bar{d}(x) + \bar{u}(x)]\, x\, dx$

- Very little constraint on $s(x) + \bar{s}(x)$, even with the CC DIS data emphasized by weight factor 5.

- Still consistent with $s(x) + \bar{s}(x) \propto \bar{u}(s) + \bar{d}(s)$ (dashed constant values).

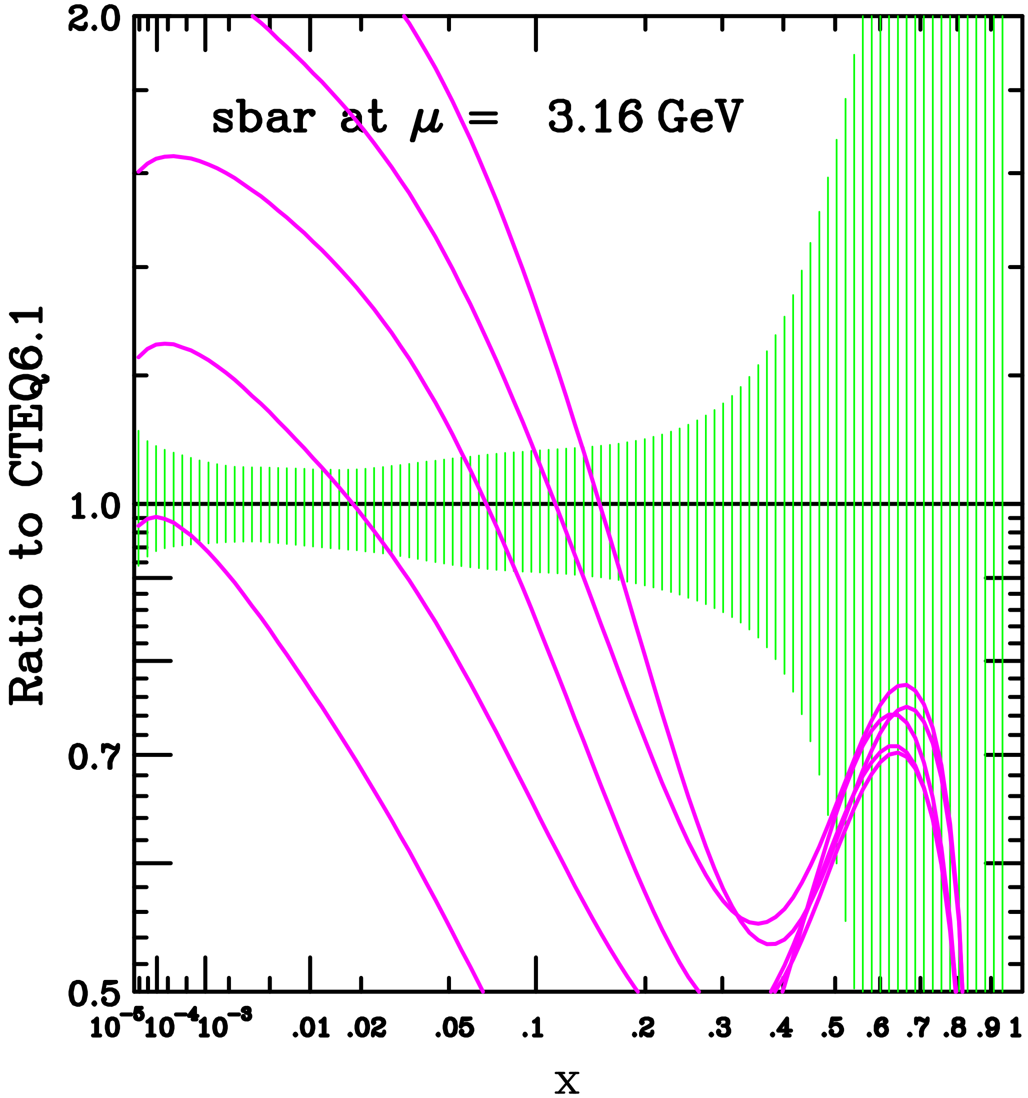
- Need to include more dimuon data!

- Have not investigated $s(x) - \bar{s}(x)$ with the new data set.

The above was done without NuTeV dimuon or Chorus data. Adding these gives much more information – Liang will report on what happens when they are included.

(Slide from my talk at ANL last May)

Fits with a variety of strangeness fractions



Green: Uncertainty from CTEQ6.1 40 ev sets.
Magenta: "Kappa series"