Light Front physics and Parton Distributions

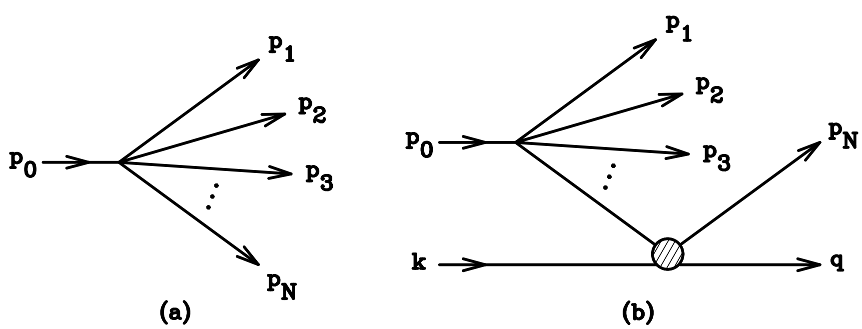
Jon Pumplin

LC2006 Minneapolis May 17, 2006

1. Light Front models for Intrinsic Charm
   - Diffractive Charm thought experiment
   - Brodsky-Hoyer-Peterson-Sakai model
   - Other models are similar to BHPS
2. Parton Distribution Functions (PDFs)
   - Introduction to PDFs
   - Global Fitting to measure PDFs
   - Typical results
3. Combine 1. + 2.
   - PDF limits on Intrinsic Charm
   - Predictions for large x charm
4. Nonperturbative theory and PDFs

Light-Cone Models for Intrinsic Charm

Derive light-cone probability distributions from Feynman rules by a thought experiment: Tickle the Fock state onto mass shell by small momentum transfer diffractive scattering.
(Works for real to calculate the "$A^{2/3}$" component of J/ψ diffractive production on nuclei.)



For simplicity, assume spin 0 particles with point coupling. Find

$$dP \propto \prod_{j=1}^{N} d^2p_{j\perp}\, dx_j/x_j\, \delta^{(2)}(\sum_{j=1}^{N} p_{j\perp})\, \delta(1-\sum_{j=1}^{N} x_j)\, \frac{g^2}{(s-m_0^2)^2}$$

where

$$s = \sum_{j=1}^{N} (p_{j\perp}^2 + m_j^2)/x_j\, .$$

High-mass Fock states are suppressed by the energy denominator $s - m_0^2$. Further suppression is needed to make the integrated probability finite — it is natural to assume a factor $[F(s)]^2$. Or LC wave functions??

Brodsky-Hoyer-Peterson-Sakai model

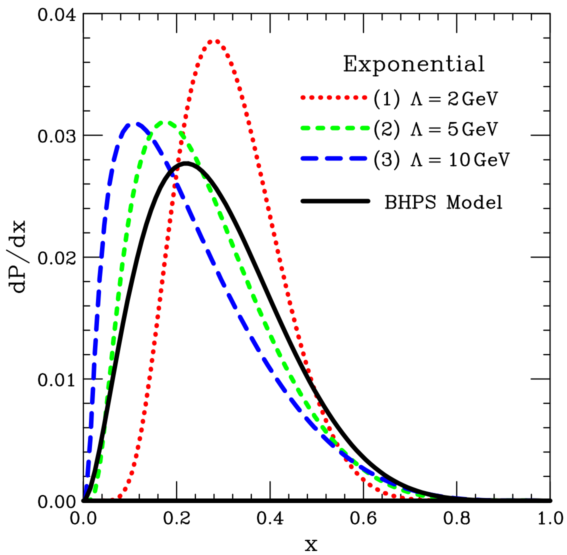
Simple model for x-dependence of $uudc\bar{c}$ state in proton: neglect the $p_\perp$ content, the $1/x_j$ factors, $F^2(s)$, and all masses except m_c yields

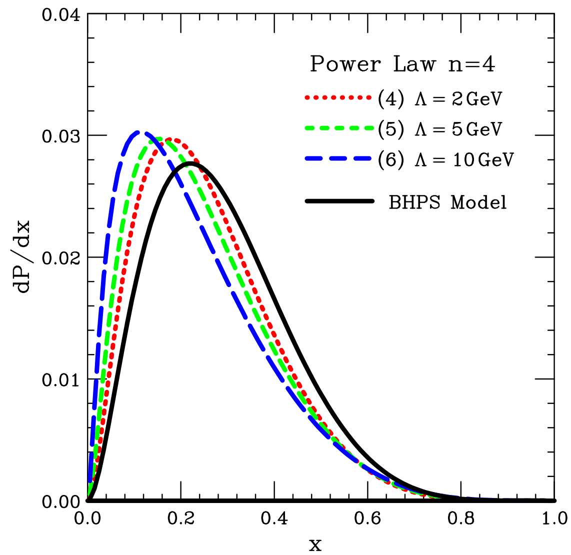
$$dP \propto \prod_{j=1}^{5} dx_j \, \delta(1 - \sum_{j=1}^{5} x_j) \, (1/x_4 + 1/x_5)^{-2} \, .$$

Carrying out all but one of these integrals and normalizing to an assumed total probability of 1% yields the BHPS model

$$\frac{dP}{dx} = 6\, x^2 \left[6\, x\, (1+x) \ln x + (1-x)(1+10x+x^2) \right]$$

Avoiding the crude approximations and trying a wide variety of reasonable choices for $F^2(s)$, produces very similar predictions, e.g.,





Models with meson+baryon dissociation such as $p \to \overline{D}^0 \Lambda_c^+$ (analogous to $p \to K^+ \Lambda^0$ for strangeness) are also similar except $c(x) \neq \bar{c}(x)$.

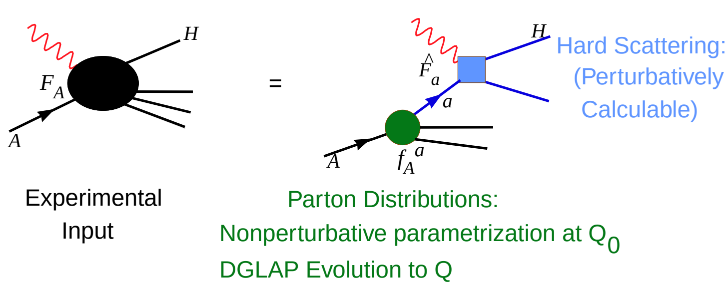
Parton Distribution Functions

Hadrons interact at high energy through their quark and gluon constituents. Short distance interactions can be calculated perturbatively because of Asymptotic Freedom.

The nonperturbative long-distance properties needed to calculate inclusive processes are the Parton Distribution Functions (Parton Densities) $f_a(x, \mu)$. These functions are universal according to Factorization Theorems.

The parton distributions are functions of light-cone momentum fraction x and momentum transfer scale μ for each flavor $a = g, d, \bar{d}, u, \bar{u}, \ldots$. But the evolution in μ is determined perturbatively by the QCD renormalization group (DGLAP equations), so the $f_a(x, \mu)$ are completely determined by functions $f_a(x, \mu_0)$ of x alone.

$$F_A^\lambda\left(x, \frac{m}{Q}, \frac{M}{Q}\right) = \sum_a f_A^a\left(x, \frac{m}{\mu}\right) \otimes \hat{F}_a^\lambda\left(x, \frac{Q}{\mu}, \frac{M}{Q}\right) + \mathcal{O}\left(\left(\frac{\Lambda}{Q}\right)^2\right)$$



The PDF "Global Analysis" paradigm

1. Parameterize the x-dependence of each flavor at $\mu_0 = 1.3\,\text{GeV}$ 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 "χ^2" measure of agreement between predictions and measurements:

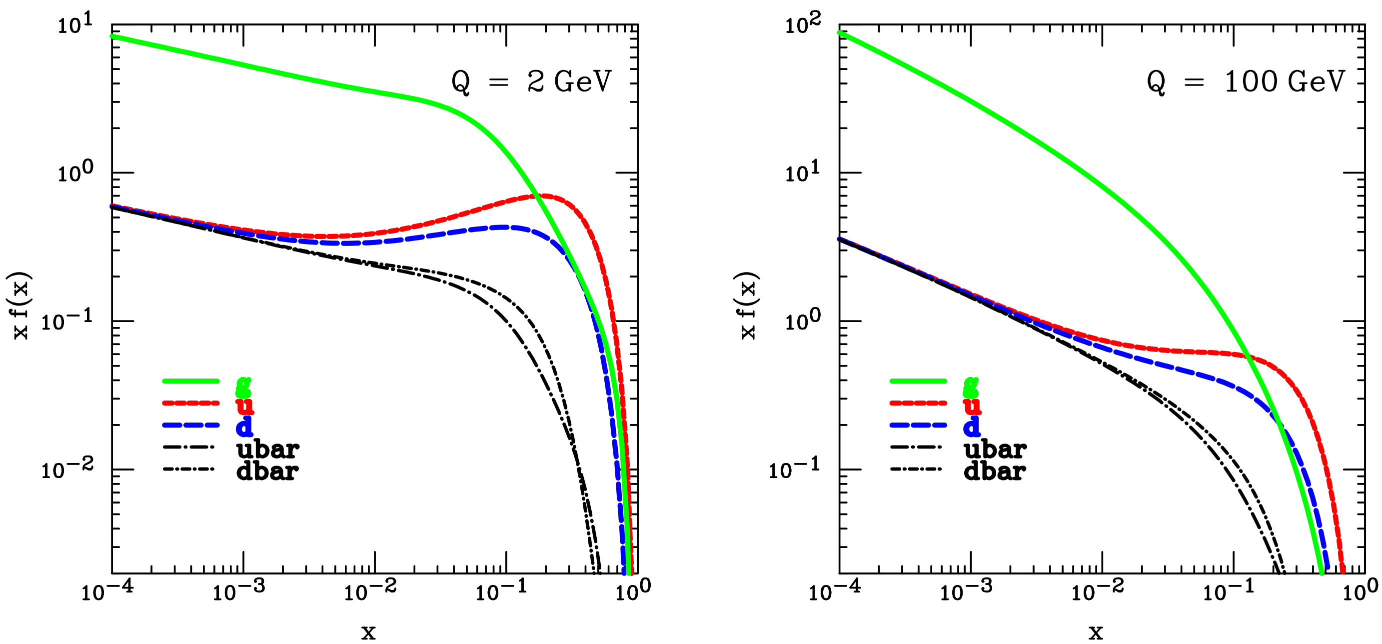
$$\chi^2 = \sum_i \left(\frac{\text{data}_i - \text{theory}_i}{\text{error}_i} \right)^2$$

5. Vary the parameters in $f_a(x, \mu_0)$ to minimize χ^2, yielding Best Fit PDFs: CTEQ6.1, MRST,. . .

The resulting PDFs are critical for all phenomenology at hadron colliders. Continued improvements are needed to fully understand New Physics and Standard Model backgrounds at the LHC.

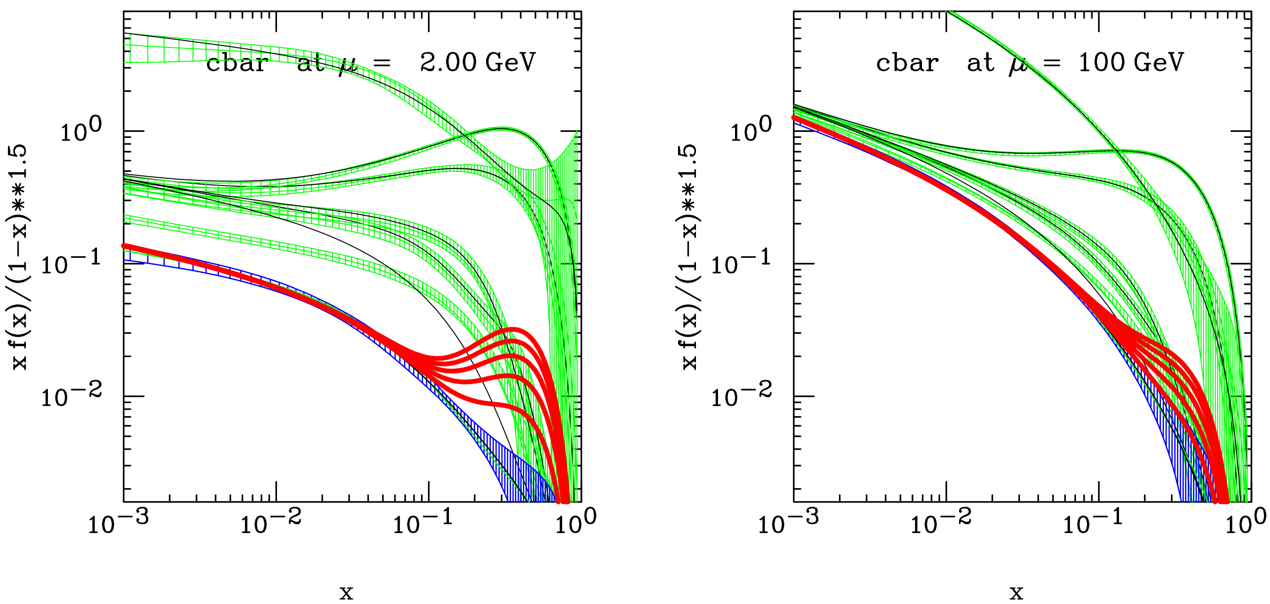
This work has been my day job (+ lots of nights) for the past 5 years. The effort at Michigan State has been led by Wu-Ki Tung.

Sample Parton Distributions results



- Valence quarks dominate for $x \to 1$
- Gluon dominates for $x \to 0$, especially at large Q

PDFs with Intrinsic Charm



Green: g, u, d, $\bar{u}$, $\bar{d}$, $s = \bar{s}$

Black: Candidate for new "Best Fit" (Prefers $s(x) = \bar{s}(x)$ equal to $\bar{u}(x) = \bar{d}(x)$ (built in) at $x \to 0$.)

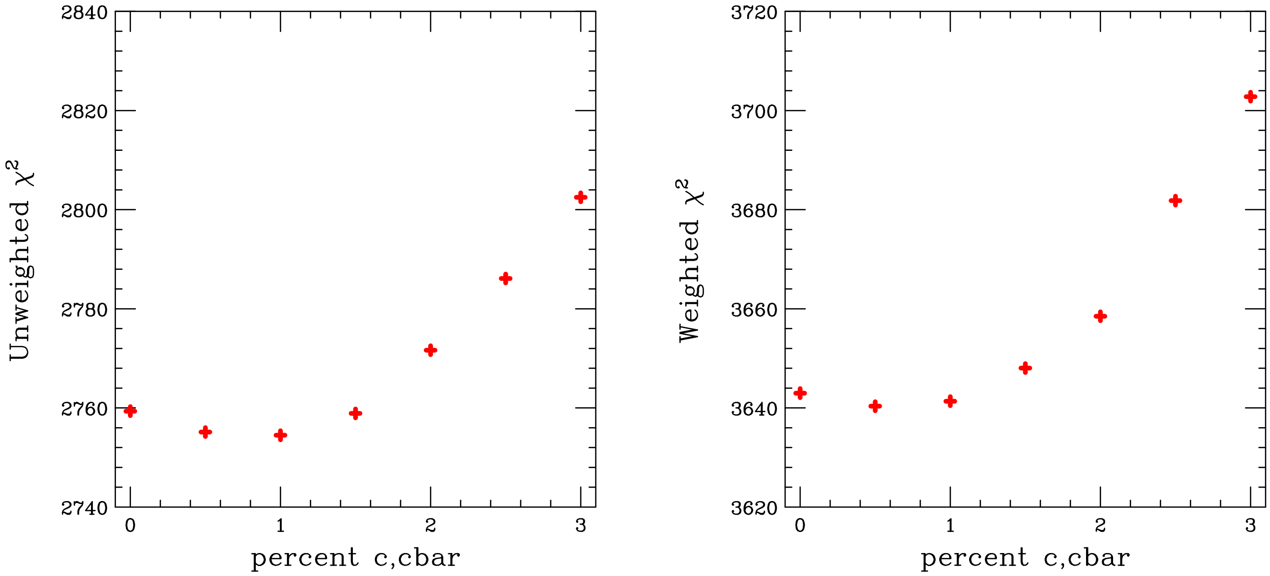
Blue: Charm from gluon splitting

Red: Intrinsic Charm using BHPS 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%; up to 2.5% allowed by Global Fit.

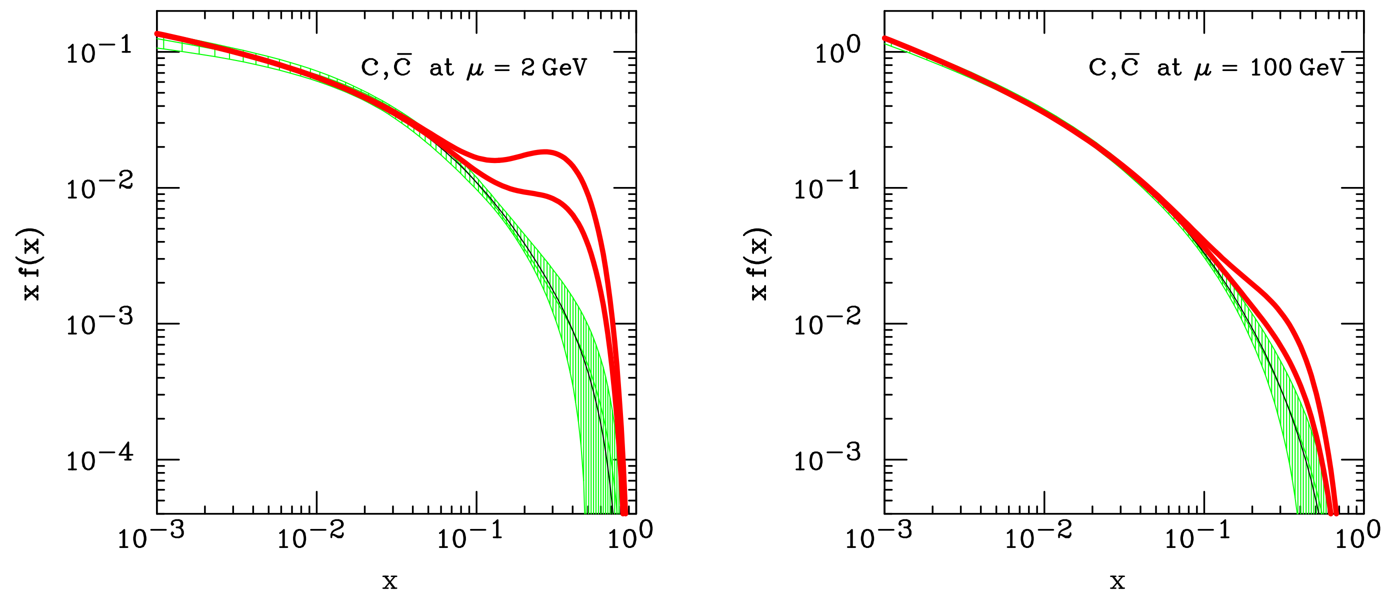
- IC may be "large" ($\bar{c} > \bar{u}, \bar{d}$) for $x > 0.2$. How to observe??

Intrinsic Charm: BHPS model

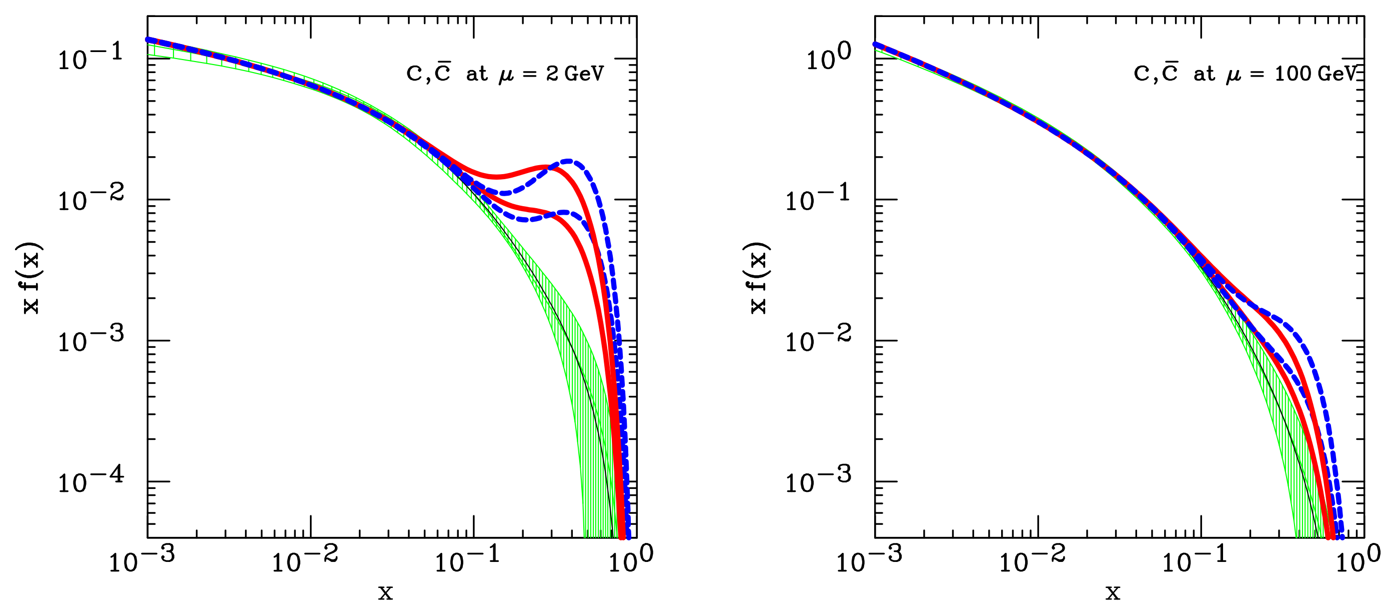


- Allowing 1% intrinsic charm improves the fit by an insignificant amount.
- Roughly 0–3% can be tolerated by the global fit.
- Since only large x matters, the charm momentum fraction is a better measure of the IC content.

Various Light-Cone models for IC

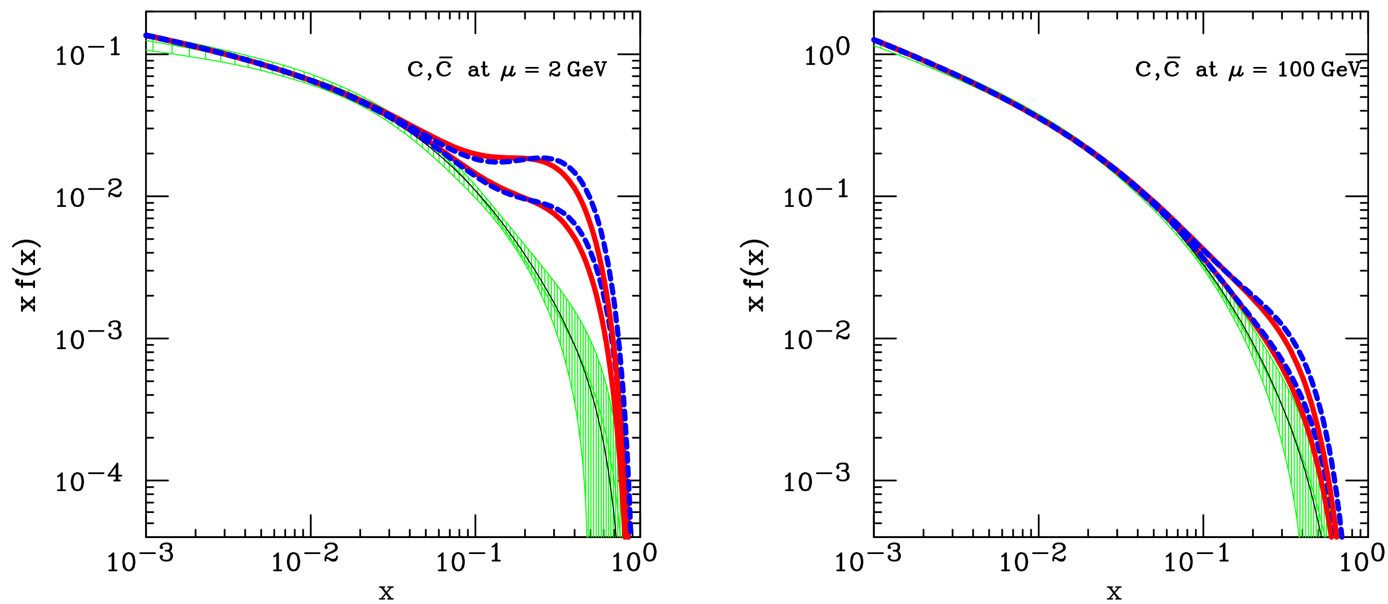


BHPS model with $c, \bar{c}$ probability 1.0%, 2.5%



$\bar{D}_0 \, \Lambda_c^+$ model

Yet another Light-Cone model



$(udc)(u\bar{c})$ model

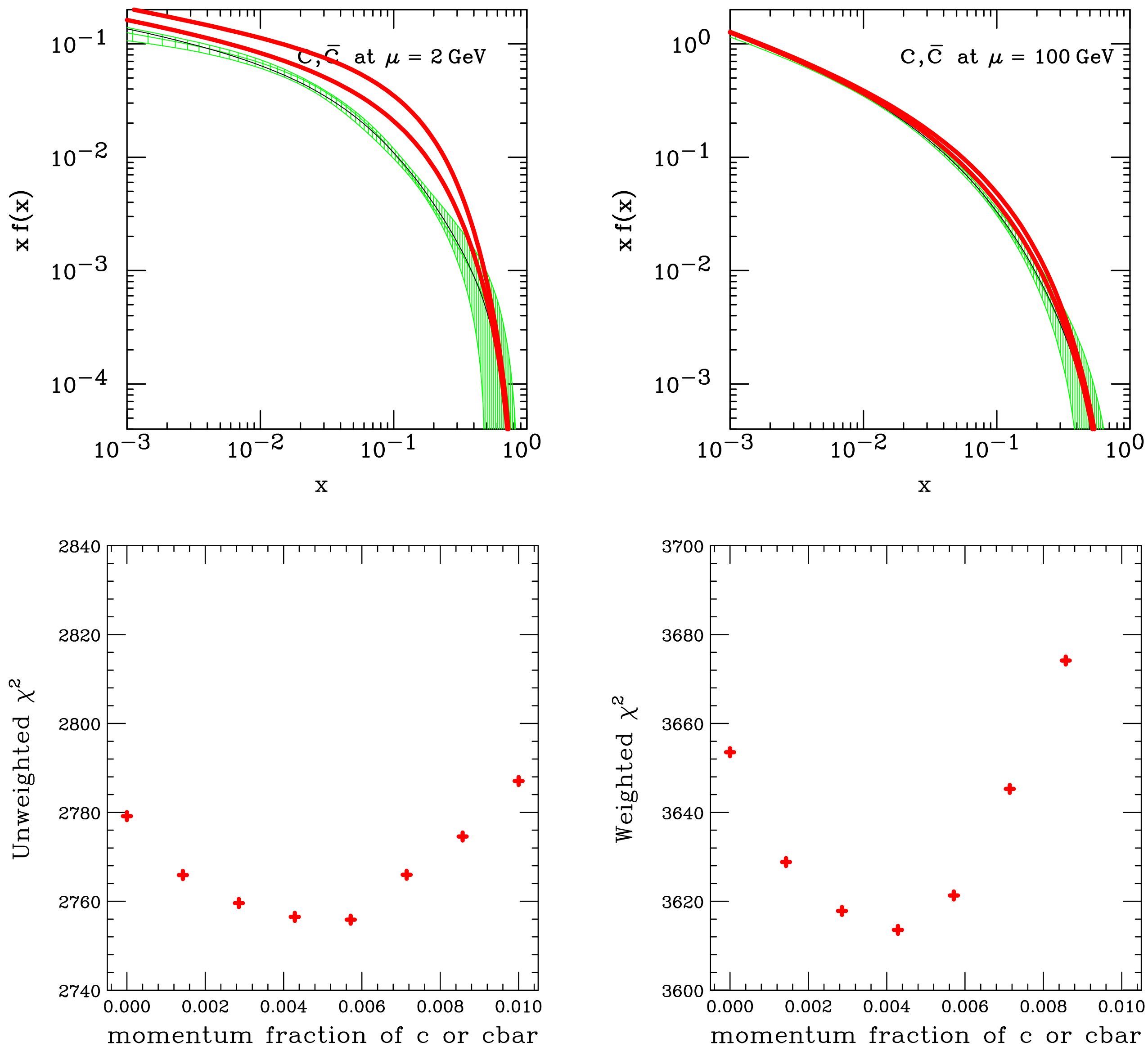
- $c + \bar{c}$ momentum fraction up to 0.015 allowed by Global Fit.

- IC may be large compared to $\bar{d}$, $\bar{u}$ at $x > 0.2$.

- Difference between $c(x)$ and $\bar{c}(x)$ is not large. (Sign is $\bar{c}(x) > c(x)$ at $x \rightarrow 1$)

- All Light-Cone models are similar to BHPS.

Intrinsic Charm at small x?



$$c(x) = \bar{c}(x) \propto [s(x) + \bar{s}(x)]$$

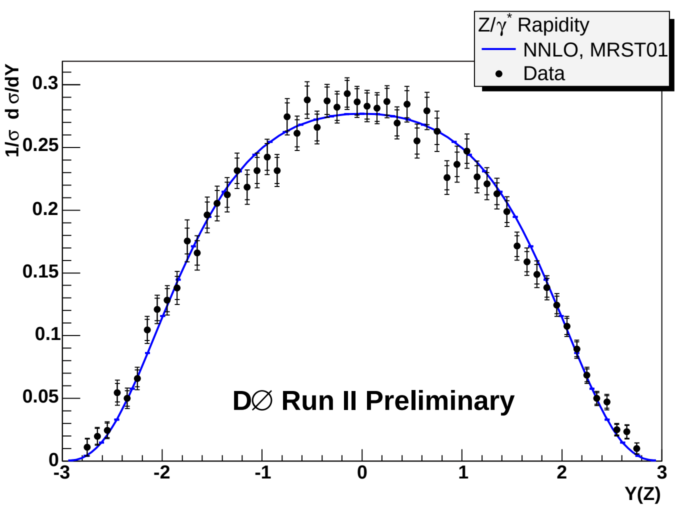
Not motivated by Light-Cone arguments, but allowed by data at this level.

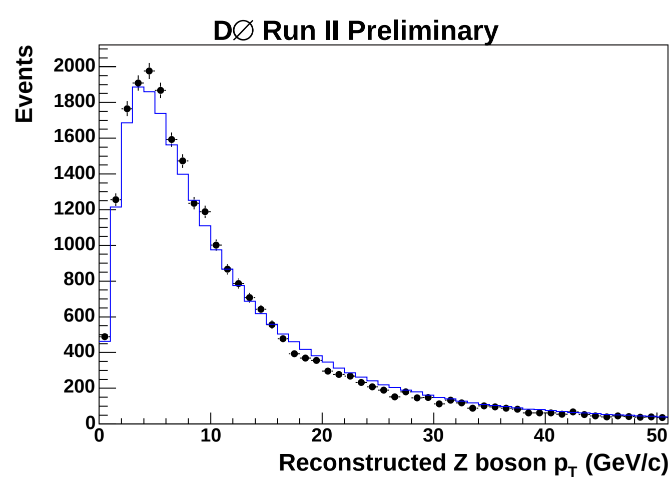
Seeing Intrinsic $c\bar{c}$ at the TeVatron?

Intrinsic charm is predicted to be at large x, especially if both c and $\bar{c}$ can participate.

Look in inclusive Z^0 production $p\bar{p} \to Z^0 + X$, where the dominant color octet intrinsic $c\bar{c}$ component in one of the hadrons absorbs a gluon from the other hadron and is thereby converted to Z^0.

Analogous to diffractive dissociation, but has gluon exchange, so no rapidity gap. (Could also have a second gluon exchange to neutralize color and produce a gap.)





One can imagine a small excess at large $|y|$; the experiment will eventually show p_T distributions in bins of $|y|$ which should be definitive: IC predicts a very steep p_T component in the $|y| > 2.5$ bin.

Would be nice to make an explicit prediction for the the IC component of Z^0 production — before the data come out!

Prediction should have just one free parameter: the probability of the IC component.

The momentum distribution of IC given by the BHPS model for $c + \bar{c}$ is simply

$$\frac{dP}{dx} = \frac{3}{5} x^3 (1 - x)^2$$

normalized to 1% probability. Maximum at $x = 0.6$ will make Z^0 at large rapidity:

$$y = \ln(x\sqrt{s}/m_Z) = 2.6 \pm 0.3$$

Intuitively, the Z^0 made this way will have very small p_T. However, the kinematics for producing Z^0 at large y by combining a low-mass high-x ($c\bar{c}$) from the beam with a low-x g from the target is not different from the Drell-Yan kinematics in which the Z^0 is created by combining a high-x q from the beam with a low-x $\bar{q}$ from the target; so perhaps the low-x parton provides similar p_T in the two cases.

The p_T distribution of the Standard Model pQCD "background" can be computed using the soft gluon resummation program RESBOS.

Stan: let's do it!

The Non-perturbative Connection

Measuring the PDFs and estimating their errors is a Big Deal: essential to interpreting results from hadron collider experiments; essential to understanding Standard Model backgrounds to new physics at LHC.

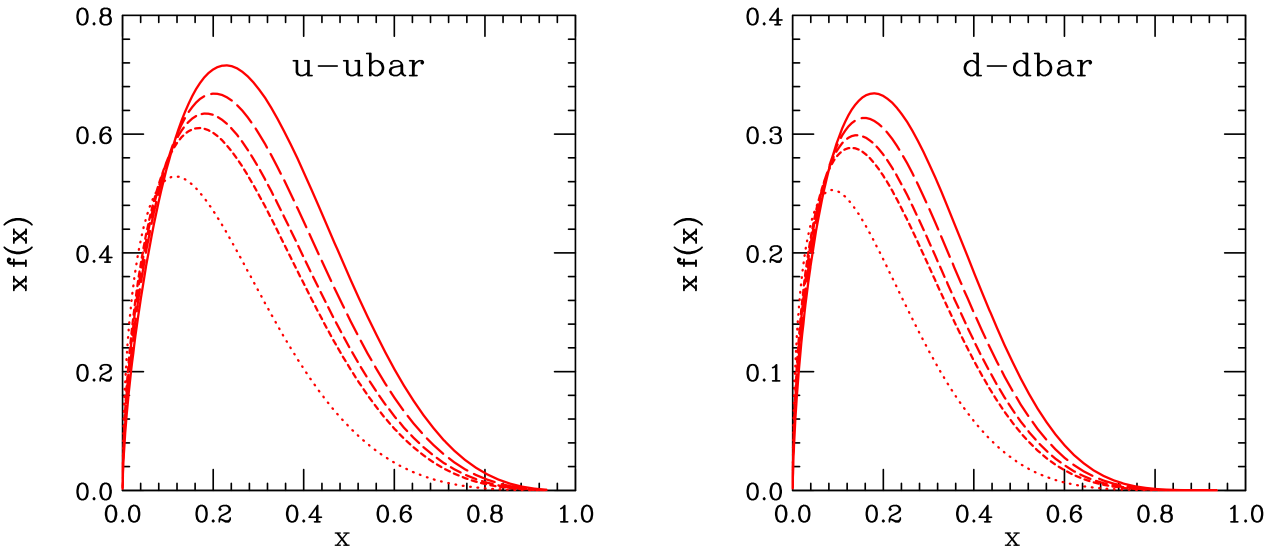
The success of this PDF program is a beautiful test of large parts of Perturbative QCD.

Questions for LC2006:

- What can Light Front and other non-perturbative methods tell us about the parametrization forms – or the parameters – for the $f_a(x, \mu_0)$ functions?

- Are the measurements of $f_a(x, \mu_0)$ from Global Analysis useful information for attendees of LC2006?

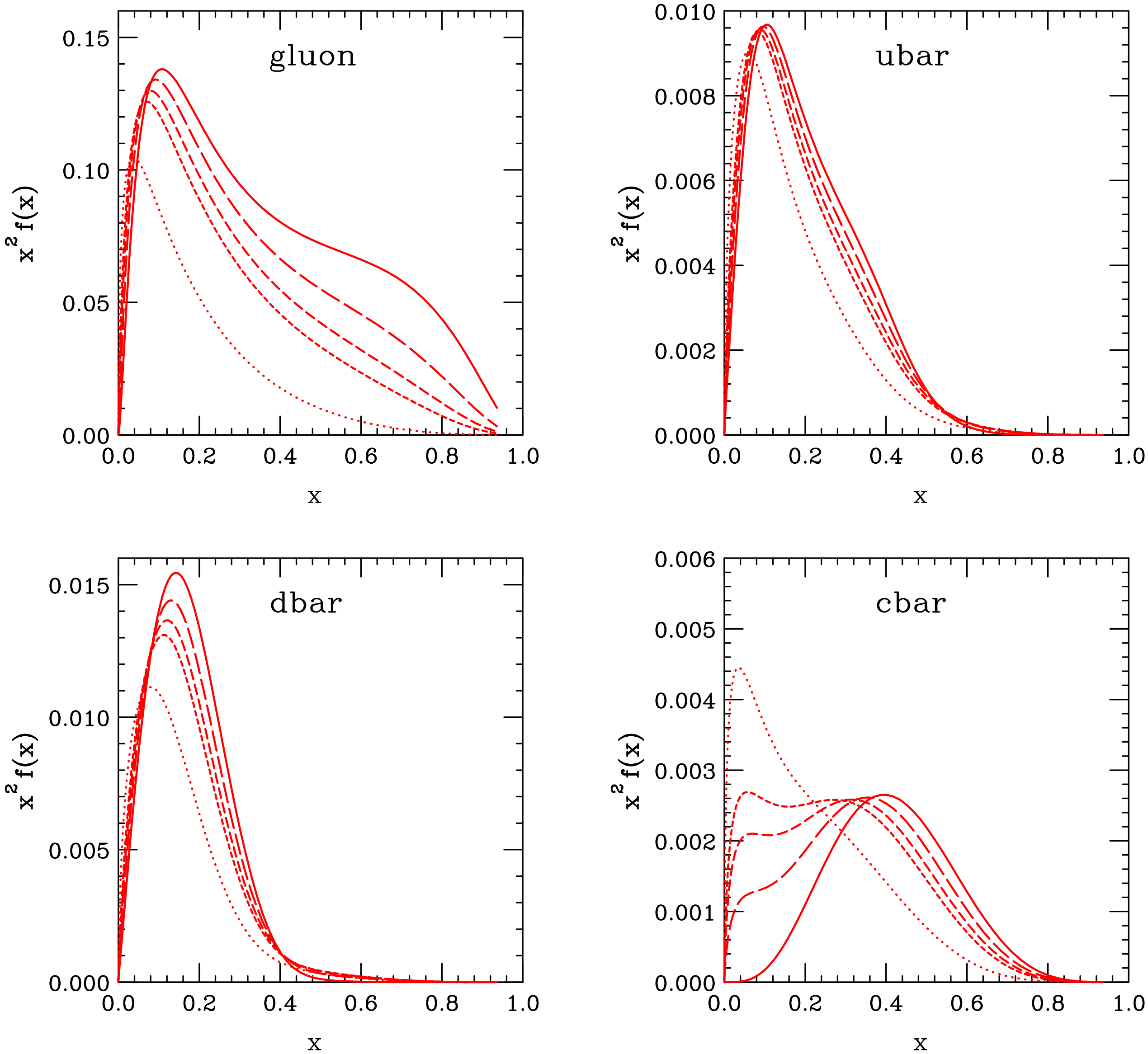
PDFs at smallish μ



Valence $u_v = u - \bar{u}$ and $d_v = d - \bar{d}$ distributions at $Q = 100$, 5, 3.16, 2, and 1.3 GeV = as low as I can go.

Valence quark distribution evolves with increasing μ because quarks lose momentum to gluons when shorter distance scales are probed; while number sum rule $\int_0^1 u_v(x)\, dx = 2$ keeps one moment of the distribution constant.

More "Movies"


gluon
ubar
dbar
cbar
$x^2 f(x)$
x
0.00
0.05
0.10
0.15
0.000
0.002
0.004
0.006
0.008
0.010
0.005
0.015
0.001
0.003
0.0
0.2
0.4
0.6
0.8
1.0

Outlook: Connecting PQCD parton distributions to low-energy physics

Parton distributions in the perturbative region are critical to progress in short-distance hadronic and electroweak physics.

Can physicists who are interested in the Roper baryon be of help to physicists who are primarily interested in the Higgs boson?

At present, the only non-perturbative physics taken as input to the PDF analyses are

1. Number sum rules $\int [u(x) - \bar{u}(x)]\, dx = 2$, etc.

2. Regge behavior e.g., $g(x) \propto x^a$ at $x \to 0$, but with a free parameter.

3. Spectator counting behavior, e.g., $g(x) \propto (1-x)^b$ at $x \to 1$, but with b free parameter.

Are the PDF results at short distances ($\mu \gtrsim 1.3$ GeV of any use to those who study low energies?

- You tell me!