Theory Overview of Unpolarized PDFs

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Outline

1. Overview of PDF Global Fits
2. Issues at high-x
3. Impact of LHC Data
4. Treatment of heavy flavors
5. Strange Sea
6. Intrinsic Charm
7. Conclusions

State of the art for Global Fits of PDFs

Most analyses have many features in common

- DGLAP Evolution
- LO, NLO, and/or (partial) NNLO
- Dependence on α_S
- Target Mass Corrections and Dynamical Higher Twist, as needed
- Nuclear corrections, as needed

However, there are some areas of difference

- Treatment of flavors (fixed vs. variable schemes)
- Heavy quark treatments
- Parametrization dependence
- Treatment of PDF errors
- Choice of data sets
- Choice of kinematic cuts

These differences lead to variations in the resulting PDFs and their estimated errors. I will touch on a number of these in the following.

What are some issues of current interest in PDFs?

In a phrase - *flavor separation*

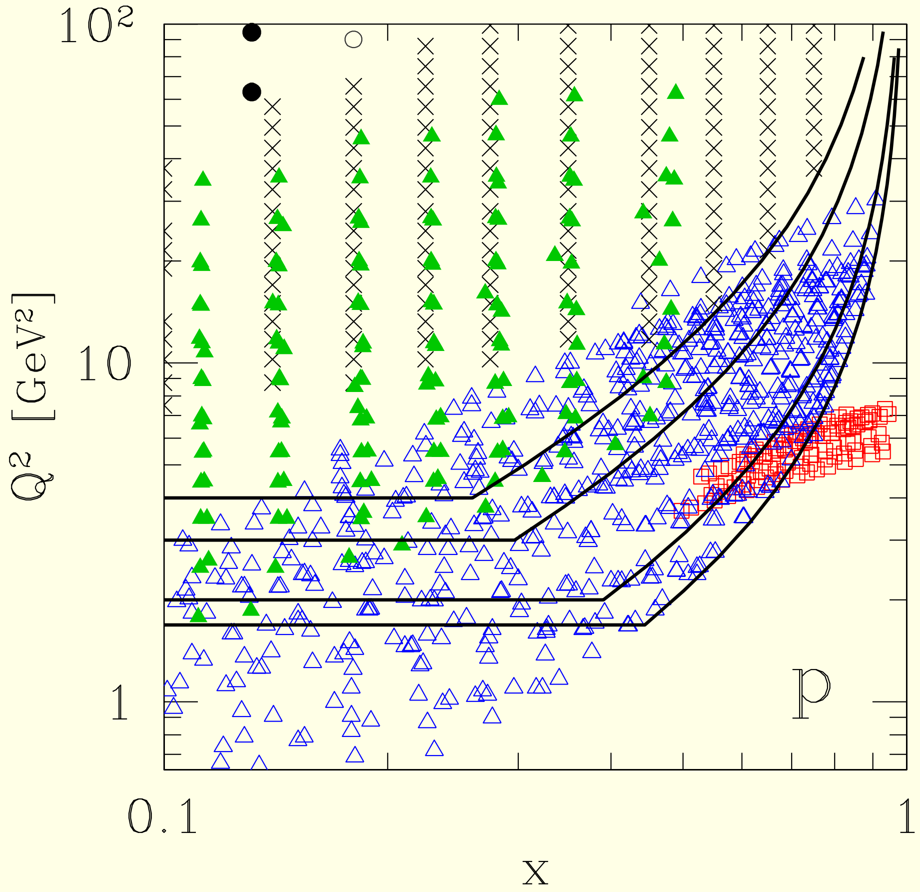
1. d/u behavior at large values of x
2. Determination of the $s \pm \bar{s}$ PDFs
3. Heavy quarks
   - Effects of different flavor schemes
   - Intrinsic Charm?
4. Constraints on the gluon PDF

Exploration of the large-x region

- If one wants to explore the large-x region, then cuts on Q^2 and W^2 must be lowered from conventional values since

$$W^2 = m^2 + Q^2(\frac{1}{x} - 1)$$

- Lower the Q^2 cut to get access to more data from lower energy experiments
- Must also then lower the W^2 cut in order to get to high x values

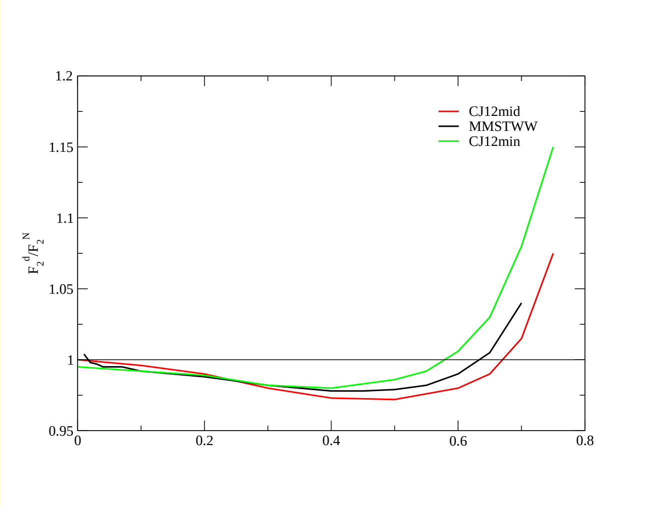


This requires including power-suppressed contributions and nuclear corrections (see talks by W. Melnitchouk and A. Accardi)

Nuclear Corrections

Several approaches

- Explicit calculation of deuterium Fermi motion smearing using existing nucleon wavefunctions as well as models for off-shell corrections and screening (*e.g.*, CJ)
- Use of models such as that of Kulagin and Petti, especially for heavier nuclei such as Fe (*e.g.*, ABM)
- Parametrize deuteron corrections without an explicit model (*e.g.*, MSTW)
- For the deuterium case the two different methods (explicit model vs. parametrization) yield compatible results



- Black curve is the parametrized results from MSTW arXiv:1211.1215
- Colored curves are from CJ12_min and CJ12_mid arXiv:1212.1702
- Note: this agreement was found after MSTW switched the forms of the parametrizations used for the PDFs
- These corrections primarily affect the d PDF at large values of x
- Simple way to think of this - in a sense, one divides the deuterium data by the above function(s) to get the corrected "isoscalar data"
- If the curve is below one (above one), the d PDF will be increased (decreased)

- The d PDF can compensate for changes in the model used for nuclear corrections
- Need other observables that constrain the d PDF without nuclear corrections
  - Lepton pair production
  - Jet cross sections
- Interplay between fixed target DIS experiments on deuterium and collider data needing no nuclear corrections can help discriminate between different nuclear models
- Similar conclusions about the role of nuclear corrections in PDF global fits have been presented in arXiv:1303,1189[hep-ph], R.D. Ball *et al.*,

Parametrization Dependence

- If a parametrization is used for the PDF boundary conditions it is often of the form

$$f_i(x, Q_0^2) = a_0 x^{a_1} (1-x)^{a_2} P(x)$$

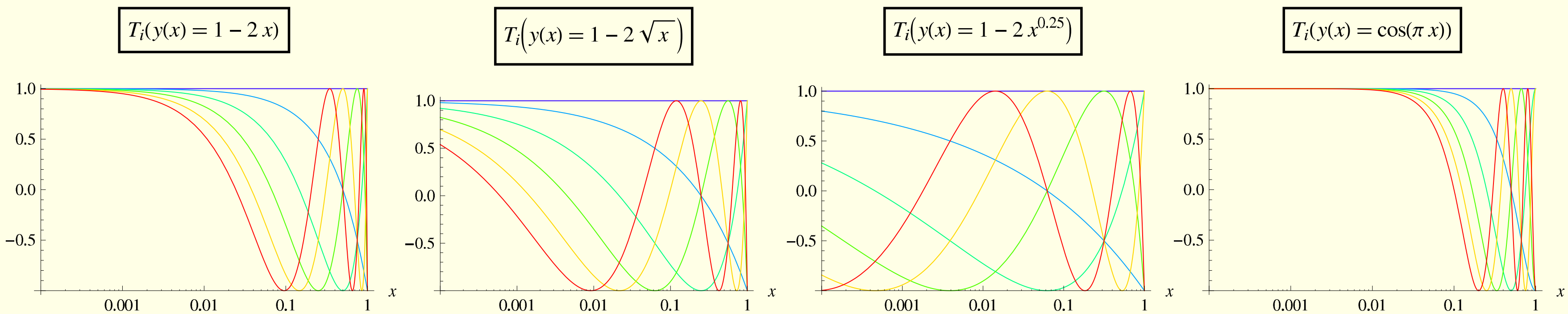
where $P(x)$ is often chosen to be a polynomial in x or $\sqrt{x}$

- MSTW (arXiv:1211.1215) chose to use

$$P(x) = 1 + \sum_1^n T_i(1 - 2\sqrt{x})$$

where the T_i are Chebyshev polynomials

- They find
  - Improved χ^2
  - More realistic nuclear corrections
  - Some changes in $u_v - d_v$ resulting from the more flexible parametrization
- Note: the argument of the Chebyshev polynomials is arbitrary
- The choice of $1 - 2\sqrt{x}$ spreads the effects of the polynomials over the full x range



Another Example

- Region dominated by u and d PDFs
- d/u falls roughly as $1 - x$
- Precise behavior of d/u is of interest to the study of the nonperturbative structure of the nucleon, for example
- If both PDFs fall as powers of $(1 - x)$ then as $x \to 1$ d/u must either go to zero or infinity
- Try a modification of the d PDF where

$$d \to d + c_1 u x^{c_2}$$

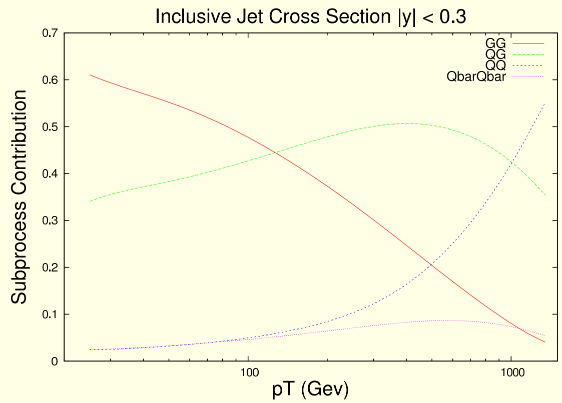
- Then as $x \to 1$ $d/u \to c_1$
- Parametrization allows d/u to take any value

Gluon at large values of x

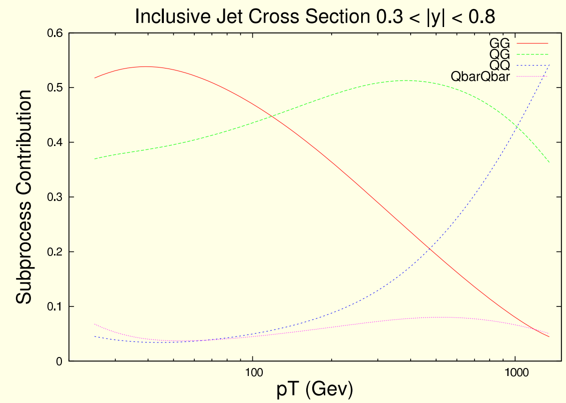
- Traditionally the large-x gluon PDF has been constrained by hadronic jet data from colliders
- Using LO kinematics, the relevant momentum fractions depend on the jet rapidities

$$x_{\frac{1}{2}} = \frac{p_T}{\sqrt{s}}(e^{\pm y_1} + e^{\pm y_2})$$

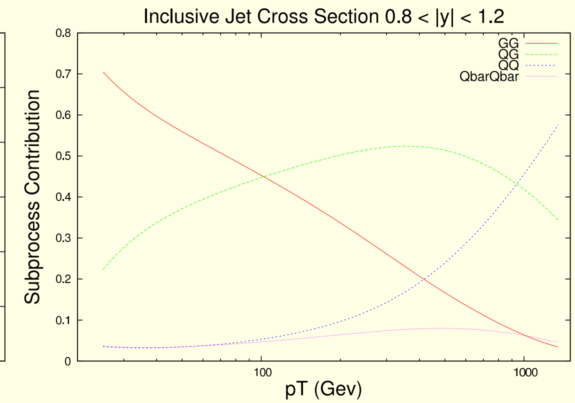
- Nice figure from Watt, Motylinski, and Thorne arXiv:1311.5703 shows the relative importance of different subprocesses



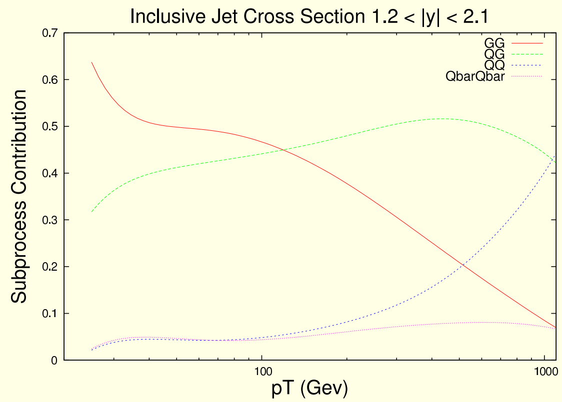
(a) $|y| < 0.3$



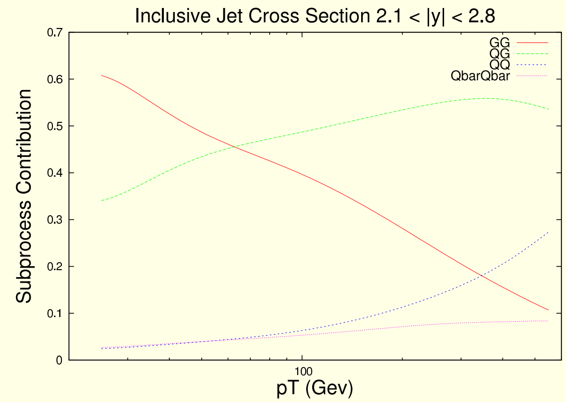
(b) $0.3 < |y| < 0.8$



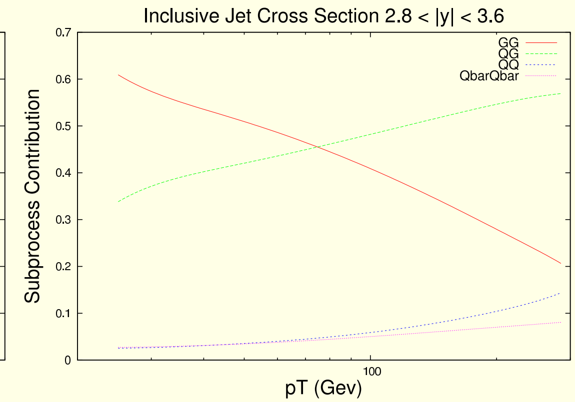
(c) $0.8 < |y| < 1.2$



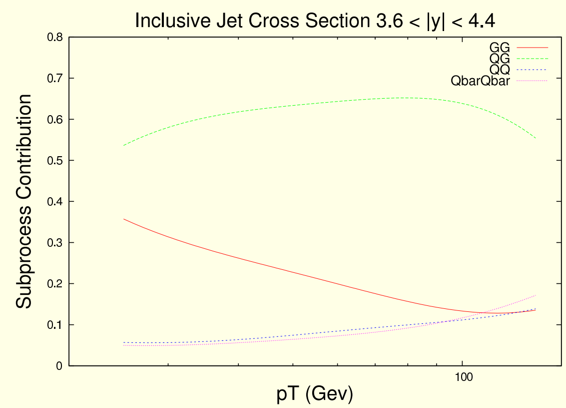
(d) $1.2 < |y| < 2.1$



(e) $2.1 < |y| < 2.8$



(f) $2.8 < |y| < 3.6$



(g) $3.6 < |y| < 4.4$

- Shows that the large rapidity region is dominated by the $gq \rightarrow gq$ subprocess, so high rapidity jet production can help constrain the gluon at high values of x
- Direct photon production, especially from fixed target experiments, has the potential to constrain the large-x gluon PDF
- Problems with the theoretical interpretation of the data and some data inconsistencies has resulted in this source of information being largely ignored
- Threshold resummation applied to both the pointlike and the fragmentation components of the process holds promise for a better theoretical description (see talk by N. Sato)

Impact of LHC Data

- Initial interest was in testing the extrapolation of existing PDF sets to the newly opened kinematic regions. Some of this is still going on.

- Some sets are now being updated to include LHC data in the fits, *e.g.*, NNPDF 3.0, arXiv:1410.8879

- Some clear examples to be discussed below
  - Jet cross sections extend to lower x and, potentially, to higher x, at higher values of the scale.
  - W and Z production data have the potential to assist in flavor separation of the sea PDFs
  - W + charm data are useful in this regard, too
  - LHC data has the potential to reduce the uncertainties on the PDFs in a variety of ways

- See arXiv:1311.5703, Watt, Motylinski, and Thorne for an analysis of the impact of the LHC jet data - generally consistent with the MSTW08 PDFs, but including the data in the fits somewhat shifts the central values (especially for the gluon PDF) and reduces the size of the error bands

New Results on the Strange PDF

See Alekhin *et al.*, arXiv:1404.6469[hep-ph]

- Traditional constraints on the strange PDF have come from the NuTeV/CCFR dimuon data

$$\nu_\mu s \rightarrow \mu^- c \rightarrow \mu^- s \mu^+ \nu_\mu \quad (1)$$

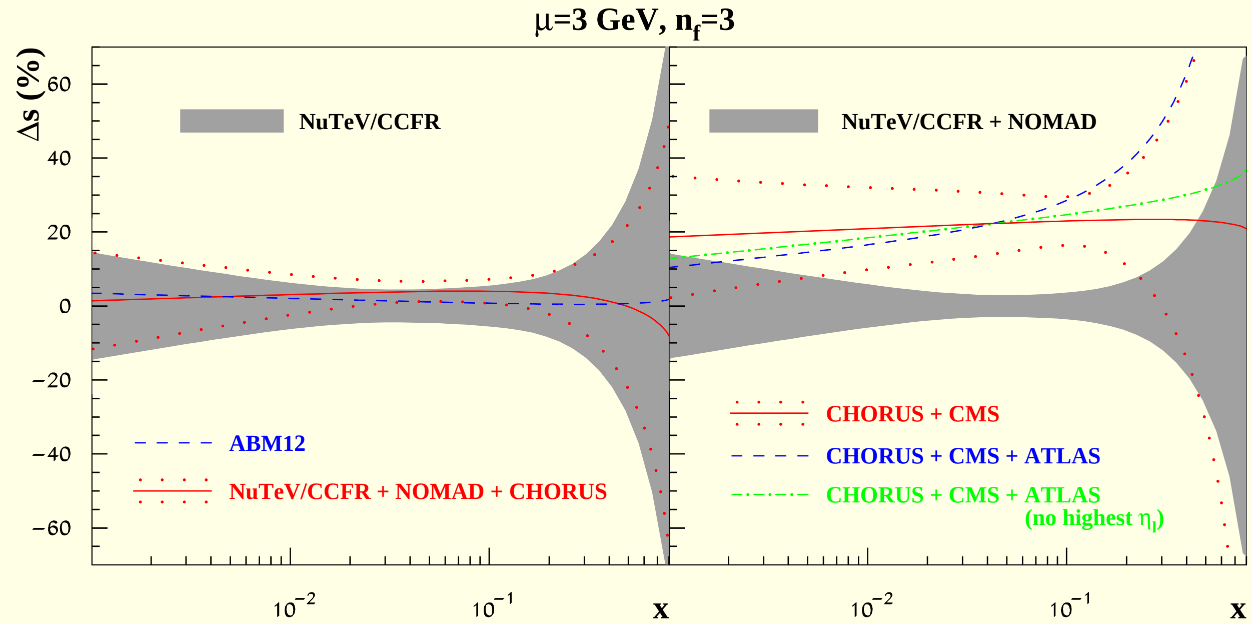
$$\bar{\nu}_\mu \bar{s} \rightarrow \mu^+ \bar{c} \rightarrow \mu^+ \bar{s} \mu^- \bar{\nu}_\mu \quad (2)$$

  - Both reaction end with an opposite sign muon pair in the final state
  - Measurements of both can constrain $s \pm \bar{s}$
  - Current analysis adds NOMAD and CHORUS data on dimuon pairs
  - Need to include nuclear corrections due to the use of heavy targets
  - Constraints are indirect due to the necessity of modeling the decay of the charm hadrons

- Associated $W + c$ production at the LHC

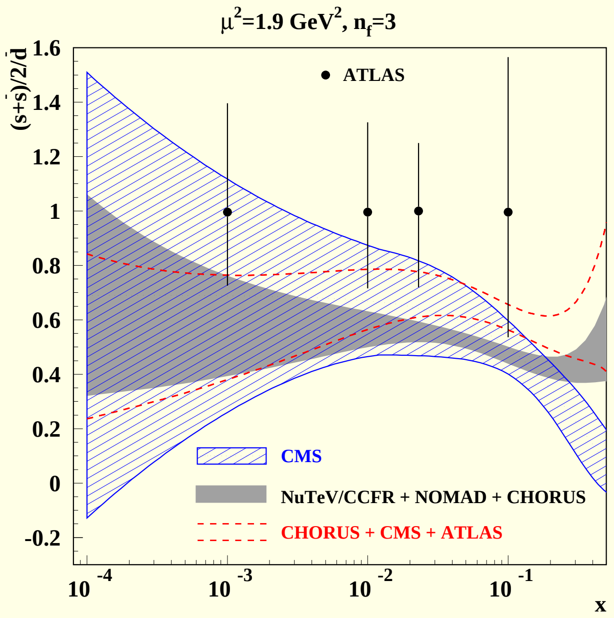
$$gs \rightarrow W + c$$

- Driven by a generalized QCD Compton subprocess
- Data from both ATLAS and CMS
- No nuclear corrections needed
- Constraints on $s + \bar{s}$ evaluated for various combinations of fixed target neutrino data and collider data
- Can separately see the constraints coming from the new neutrino data and from the collider data



- Left hand side shows the effects of adding the new neutrino data to the NuTeV/CCFR data sets - generally quite compatible

- The right hand side shows the effects of adding in the W + charm collider data - CMS and ATLAS both favor a somewhat larger strange PDF



- This plot shows the ratio $\frac{s+\bar{s}}{2\bar{d}}$
- The bands highlight the effect of combining the different data sets (fixed target and collider)
- Notice that above $x \approx .02$ the bands are roughly consistent with a ratio of about 0.5
- ATLAS (arXiv:1203.4051[hep-ex]) found a ratio near 1 at $x \approx .02$ when using data on the W lepton and Z rapidity distributions

- When quoting a ratio both the numerator and denominator have to be under control

- The numerator comes from the data sets just discussed while the $\bar{d}$ PDF in the denominator is separated from the $\bar{u}$ PDF on the basis of the FNAL E-866 lepton pair production data

- FNAL E-866 measured lepton pair production in pp and pd reactions over a wide range of x_F

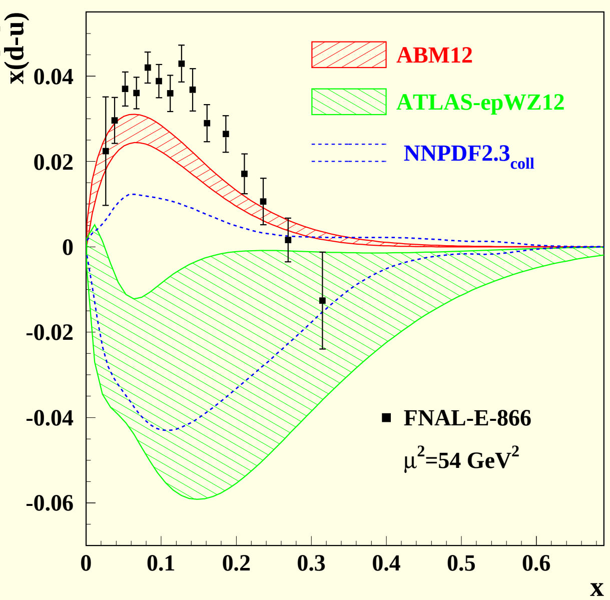
- The ratio of the two cross sections can, at lowest order, be expressed as

$$\frac{\sigma_{pd}}{2\sigma_{pp}} = \frac{1}{2}\frac{(1+\frac{1}{4}R_{du}(x_1)}{(1+\frac{1}{4}\bar{R}_{du}(x_2)R_{du}(x_1))}(1+\bar{R}_{du}(x_2))$$

where $\bar{R}_{du}(x_2)$ is the $\bar{d}/\bar{u}$ ratio at x_2 while $R_{du}(x_1)$ is the d/u ratio at x_1 with $x_{\frac{1}{2}} = \frac{M}{\sqrt{s}}e^{\pm y}$

- For large values of x_1 $R_{du} \ll 1$ so this result simplifies to approximately $\frac{1}{2}(1+\bar{R}_{du}(x_2))$

- Alekhin *et al.*, point out that the ATLAS analysis results in too small a $\bar{d}$ PDF when compared to the E-866 lepton pair production results



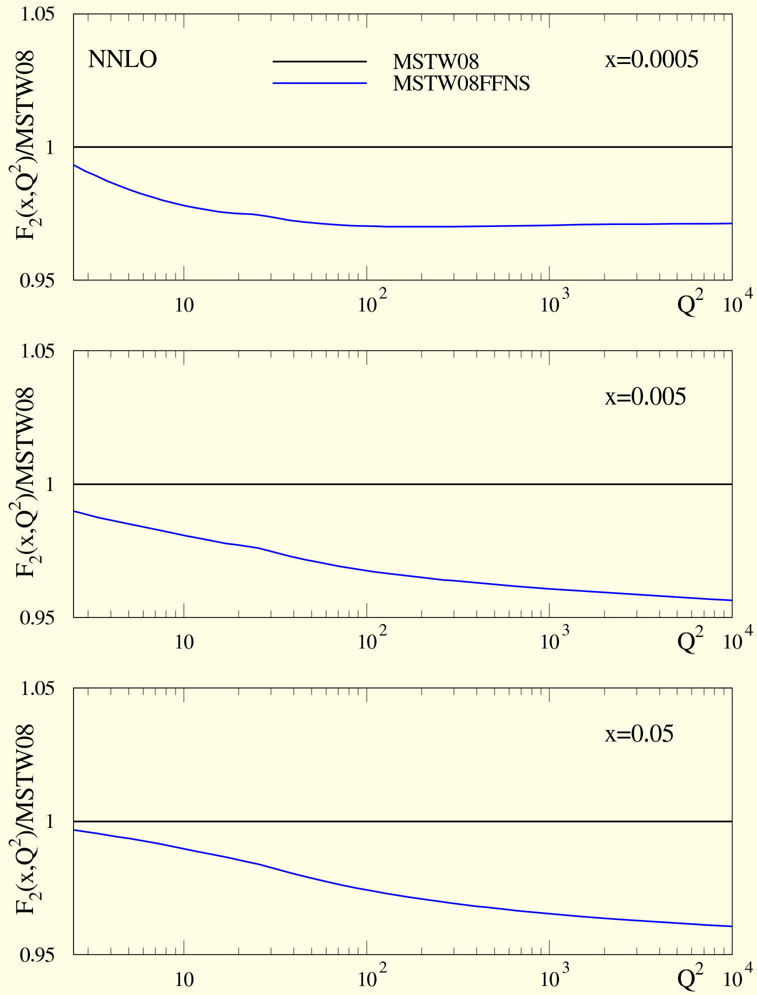
- Underestimating the $\bar{d}$ PDF leads to an overestimate of the $\frac{s+\bar{s}}{2\bar{d}}$
- Really need more information on the $\bar{d}/\bar{u}$ ratio over a larger x range – SeaQuest Experiment FNAL E-906
- Expect much higher statistics in an x range out to about 0.45

Flavor scheme dependence

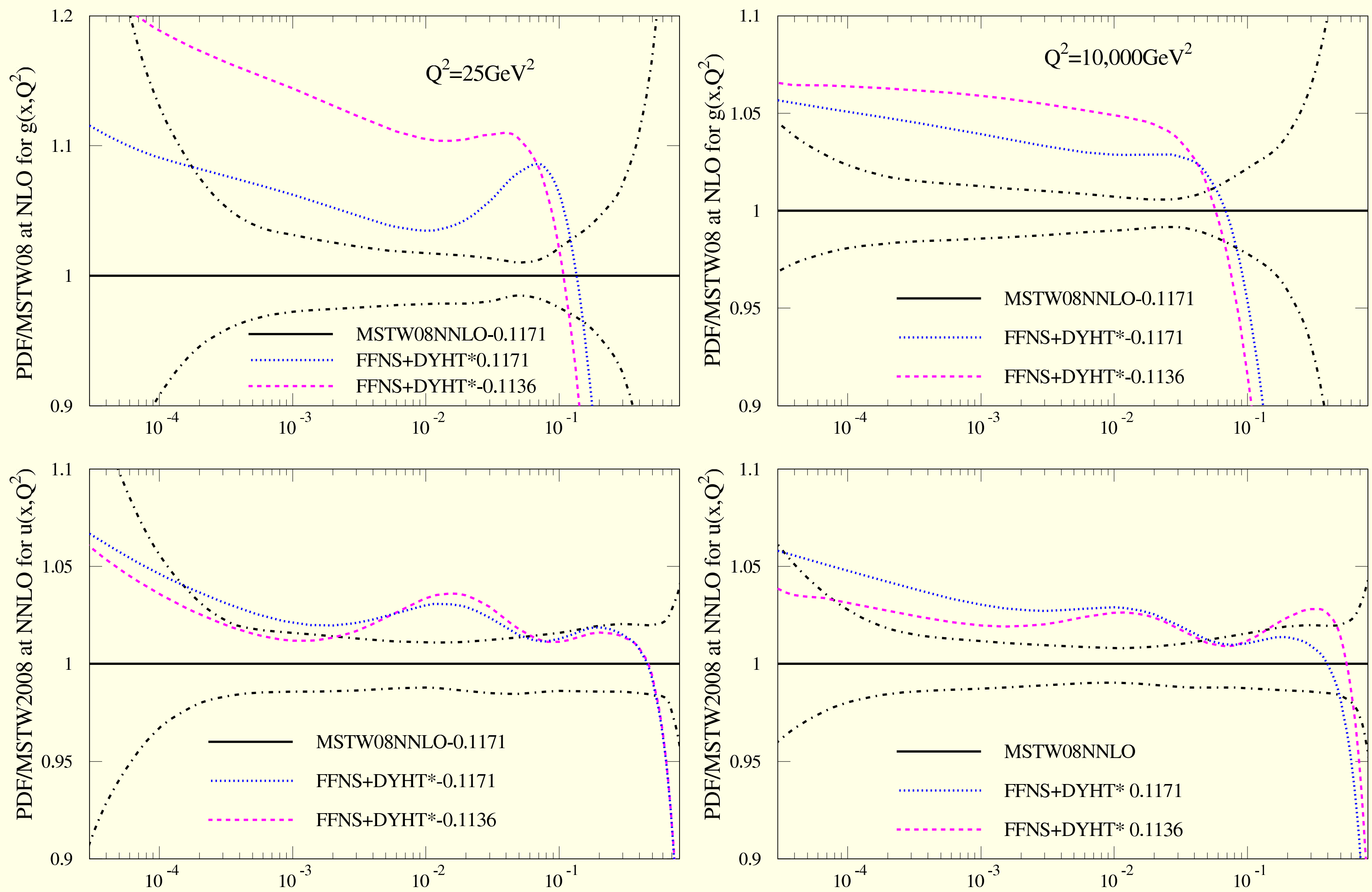
arXiv:1402.3536[hep-ph] R.S. Thorne

also see arXiv:1303.1189[hep-ph] R.D. Ball *et al.*

- Studied the effects of using a general mass variable flavor number scheme (GM-VFNS) versus a Fixed Flavor Scheme (FFS)
- Differences
  - FFS more accurate near the heavy quark threshold
  - Usual DGLAP evolution resums $\log(M_Q/Q)$ terms
  - GM-VFNS basically interpolates between the two
- Studied the impact on different PDFs and on α_s
- Also studied the effect of reducing cuts on Q and on W



- Shows the differences between the two schemes for F_2 as a function of both x and Q^2
- FFS results are below the GM-VFNS results with the differences increasing with Q^2
- These differences propagate into the other PDFs



- Gluon PDF is larger at small x and smaller at high x
- Light quark PDFs are larger over most of the x range
- Also found that α_s is slightly smaller in the FFS
- Also showed the leading twist PDFs were stable as the minimum cuts on Q and W were lowered as long as a sufficiently flexible higher twist contribution was included

Intrinsic Charm

- An idea that goes way back to the relatively early days of QCD
- Usual scheme (at LO or NLO) is to assume that the charm content of the proton is zero at and below threshold
- All charm is radiatively generated, driven by the $g \to c\bar{c}$ splitting process
- Intrinsic charm replaces this hypothesis by a non-zero value for the charm PDF at threshold.
- Recent analysis by Dulat *et al.*, arXiv:1309.0025[hep-ph] in the CT10 NNLO context

Three models

1. Standard radiatively generated charm
2. BHPS (Brodsky, Hoyer, Peterson, and Sakai) Phys. Lett B93, 451 (1980), "valence-like" input

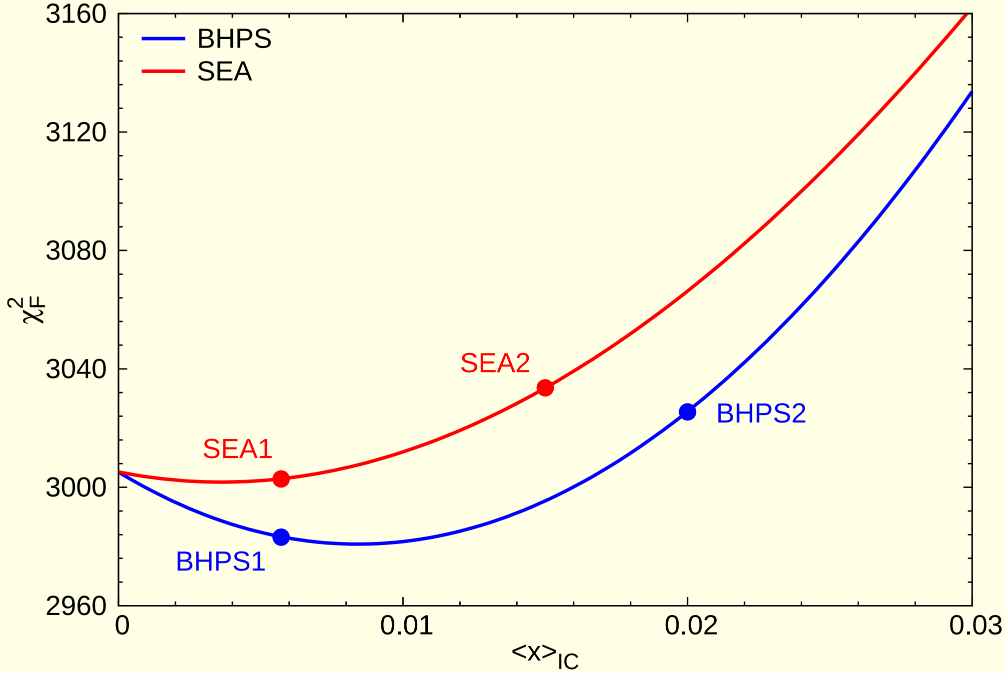
$$c(x) = Ax^2[6x(1+x)\ln x + (1-x)(1+10x+x^2)]$$

3. SEA - sea like input

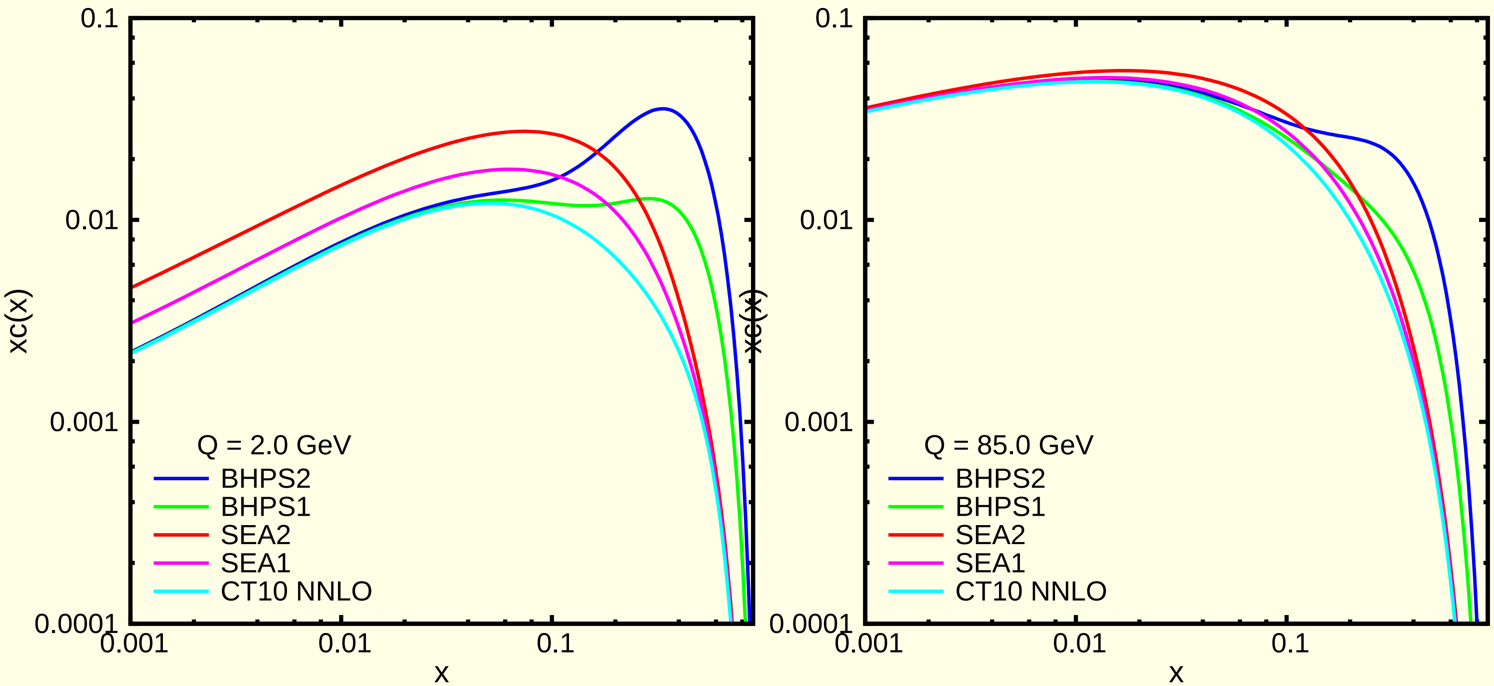
$$c(x) = A(\bar{d}(x, Q_0^2) + \bar{u}(x, Q_0^2))$$

- $Q_0 = 1.295\mathrm{GeV}$, Charm threshold $Q_c = 1.3\mathrm{GeV}$
- Charm PDF size quoted in terms of

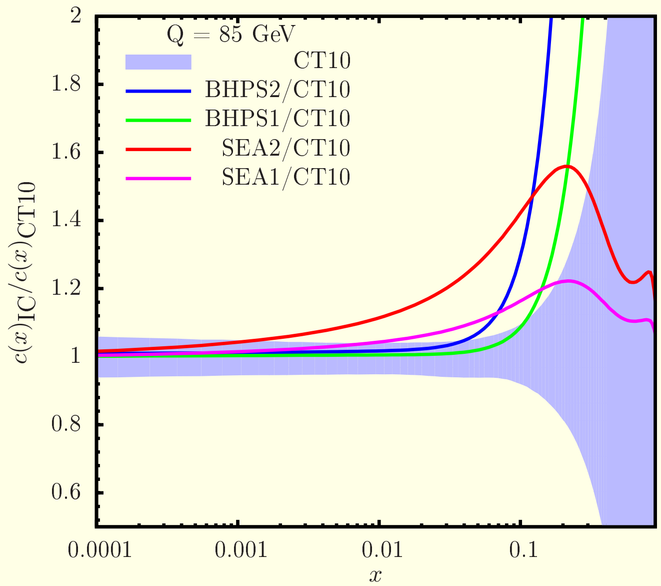
$$< x >_{IC} = \int_0^1 x[c(x) + \bar{c}(x)]dx$$



- χ^2 curves from many runs with different valuse of $< x >_{IC}$
- Upper limits for reasonable fits (90% confidence level) are quoted as 1.5% (SEA) and 2.5% (BHPS)
- Note: Standard CT10 result at $< x >_{IC} = 0$



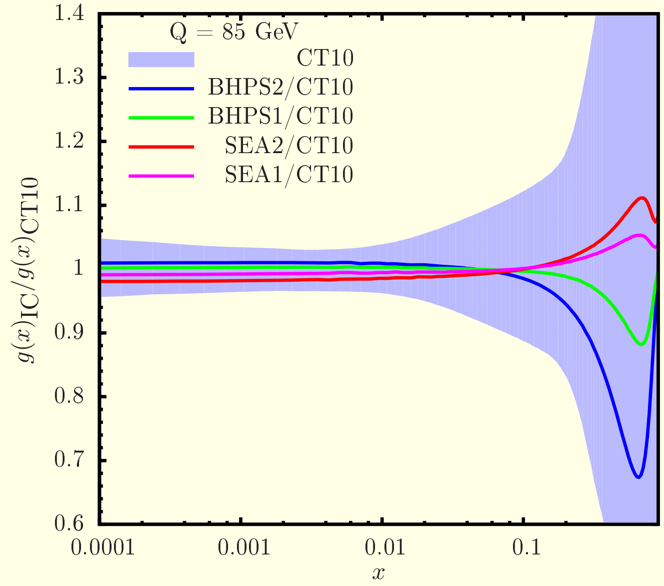
- SEA 1 (2) 0.57% (1.5%)
- BHPS 1 (2) 0.57% (2.0%)
- Can see the SEA solutions dominantly at low x
- See the BHPS solutions peaking at higher x

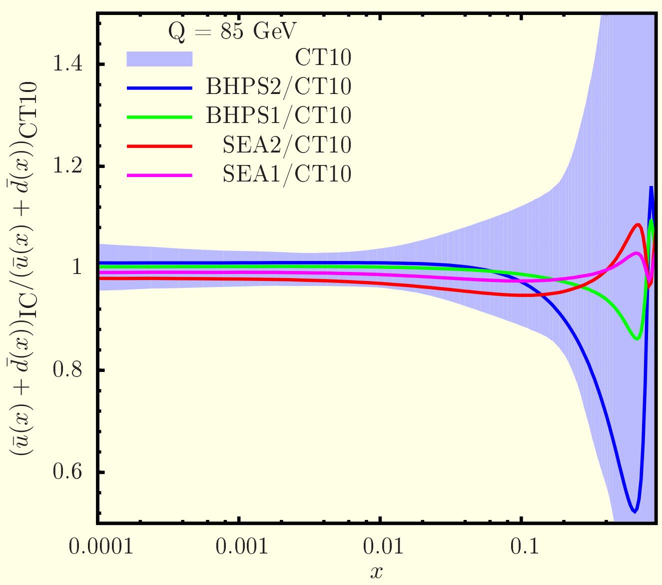


- Another view showing the IC results versus the standard CT10 results
- Can see the SEA results peaking around $x = 0.1$
- Can see the BHPS results continuing to grow at large values of x

Data Set dependence

- HERA data sensitive to charm at very low values of x – places strong constraint on the SEA model
- The SEA model has very little contribution at large values of x, so one doesn't get a significant improvement
- BCDMS data receives an improved description in the BHPS model – here the improvement is at larger values of x where the BHPS model has most of its contribution
- However, this is insufficient to claim the need for an IC component





- Variations of the gluon and $\bar{u}+\bar{d}$ PDFs are within the original error bands
- The data can tolerate a small amount of IC ($< 1.5\%$ for SEA, 2.5% for BHPS)
- Other PDFs are not adversely affected
- Doesn't prove that IC is there

Another recent analysis: arXiv:1408.1708[hep-ph], Jimenez-Delgado, Hobbs, Londergan, and Melnitchouk

- Use lower Q and W cuts that allow the use of SLAC data in the analysis
- They find a much lower limit on the allowed IC content with $< x >_{IC} < 0.1\%$
- One might worry about the treatment of hadronic thresholds versus partonic thresholds in the charm contribution at low values of W
- See talk by W. Melnitchouk

Summary and Conclusions

- Flavor separation is being improved by the advent of new fixed target and collider data
- Precision of the PDFs will also improve with he continued addition of LHC data and also some fixed target data *e.g.*, SeaQuest (lepton pair production)
- Nuclear corrections are necessary both for neutrino processes and deuterium target DIS
- Collider data together with fixed target deuterium DIS can help constrain nuclear models
- Constraints on $s + \bar{s}$ are being provided by new collider data
- Definitive evidence for Intrinsic Charm, is still lacking. While the idea is interesting and may be in the data, improved PDF precision is needed