Constraints on Parton Distribution Functions
from
Charged Current Deep Inelastic Scattering

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International Workshop on Physics with Positrons at Jefferson Lab

September 12-15, 2017

Jefferson Lab

Outline

1. Overview of PDF Global Fits
2. Issues at high-x
3. Flavor Separation
   (a) d/u
   (b) $s, \overline{s}$
4. Conclusions

Parton Distribution Functions

PDFs are important for

- Precision calculations of large momentum transfer hadronic processes
- Understanding the internal structure of hadrons

Hadronic observables may involve single PDFs

$$\sigma_A(x) = \sum_a \int dy\, G_{a/A}(x/y, Q)\, \hat{\sigma}(y)$$

or

$$\sigma_{AB}(x) = \sum_{a,b} \int dy \int dz\, G_{a/A}(y, Q)\, G_{b/B}(z, Q) \hat{\sigma}(y, z) \delta(x - yz)$$

Challenge is to obtain data for appropriate observables in order to constrain the PDFs over as large a kinematic region as possible.

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
- Inclusion of nuclear corrections and the method used

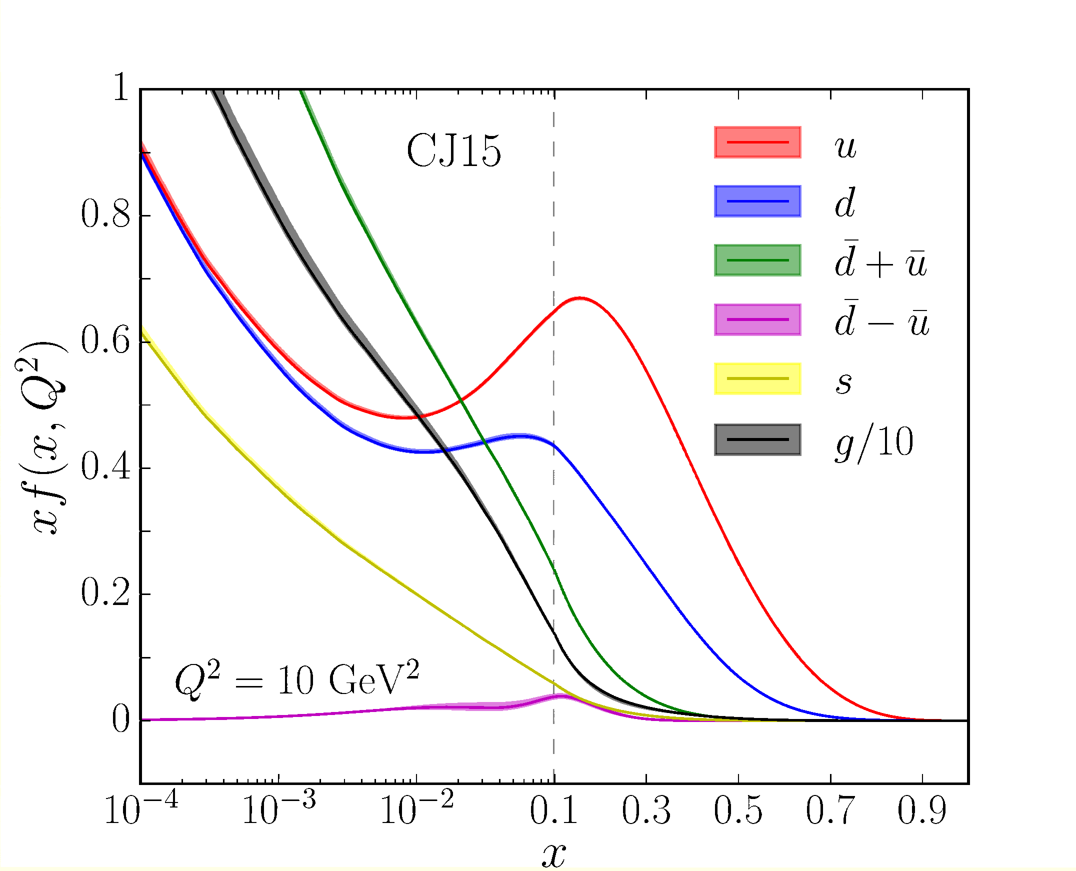
These differences lead to variations in the resulting PDFs and their estimated errors. I will touch on a number of these in the following.

What are some issues of current interest in PDFs?

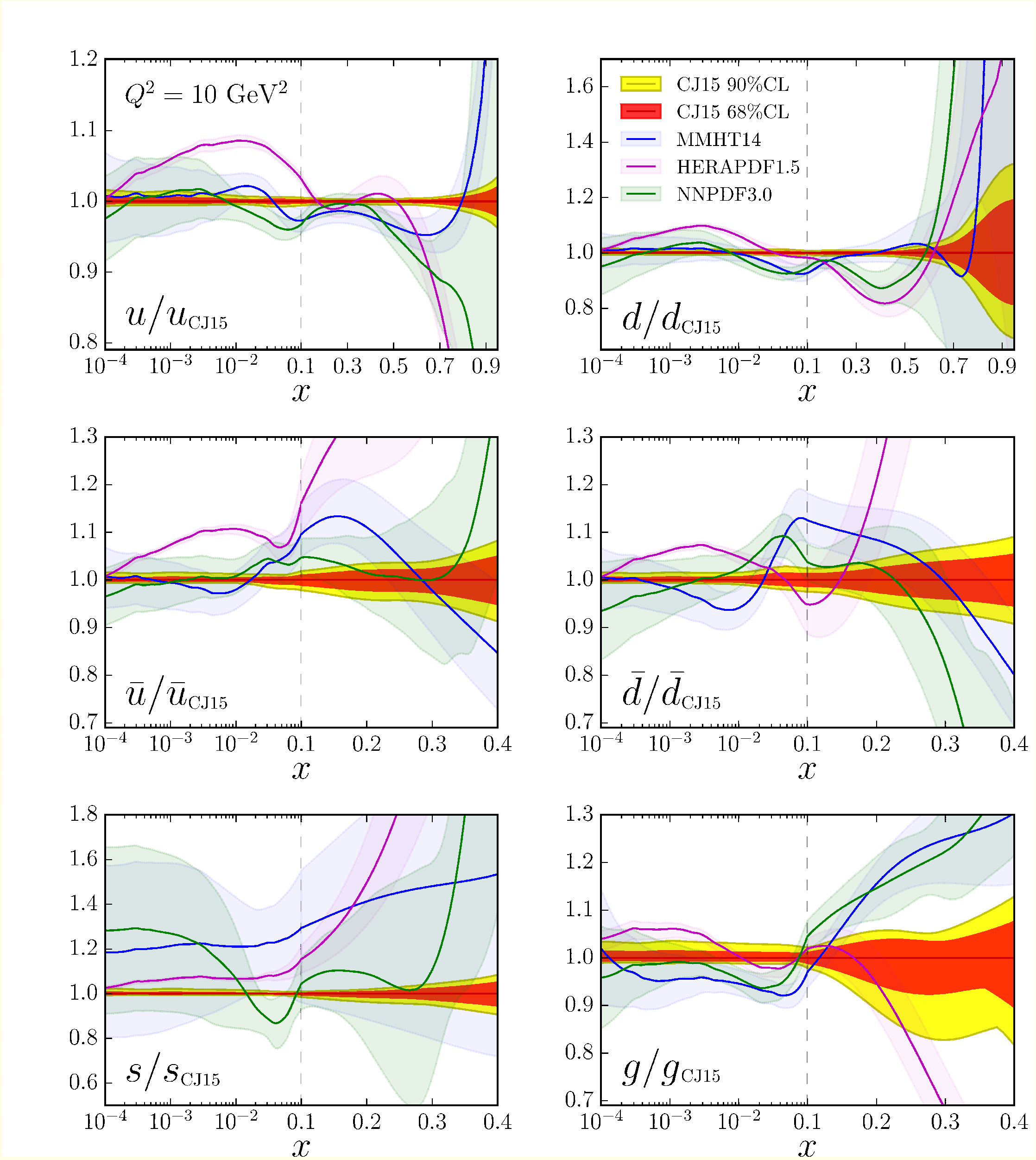
In a phrase - *flavor separation*

1. d/u behavior at large values of x
2. Determination of the $s \pm \bar{s}$ PDFs
3. Constraints on the gluon PDF

To start with, here is a typical set of PDFs (CJ15 in this case)



- It looks as if the PDFs are well determined, but a linear scale can hide important details.
- Look instead at ratios



See significant uncertainties in all of the PDFs,

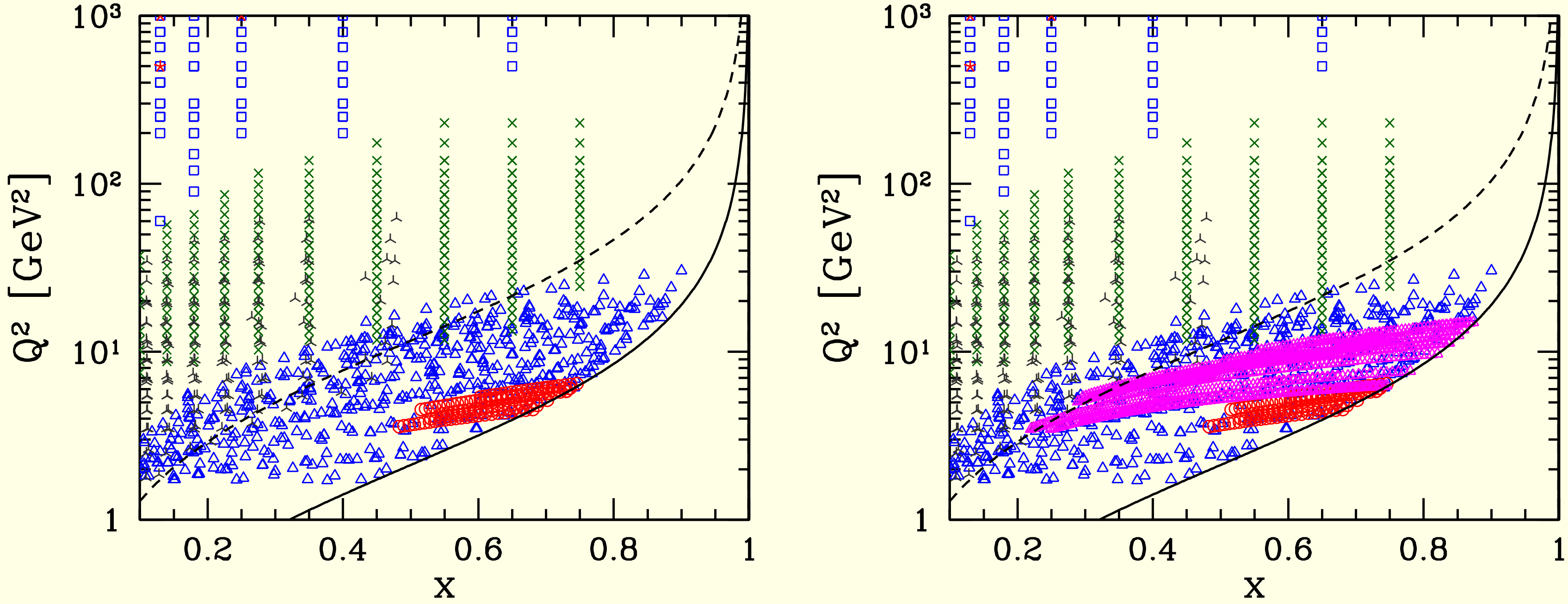
$\Longrightarrow$ **especially the d PDF at large values of x**

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



- Requires including power-suppressed terms and nuclear corrections
- Red symbols are existing JLab data
  (more available - database in preparation with Shujie Li)
- For the 12 GeV program the max Q^2 value will nearly double
  (pink is E12-10-002 – see also MARATHON and BONuS12)
- Lowest curve shows the limit for $Q^2 > (1.3\ \text{GeV})^2$ and $W^2 > 3\ \text{GeV}^2$
- Kinematic coverage will get close to $x \simeq 0.85$

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

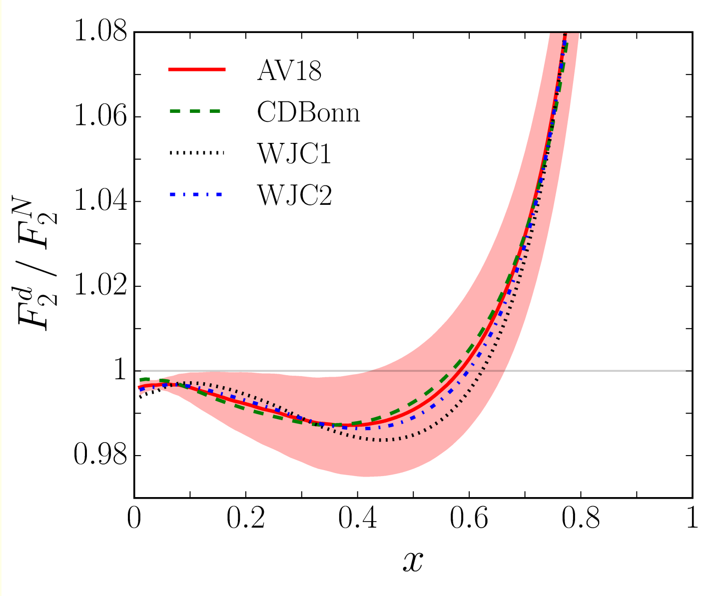
So why does the error on the d PDF grow so large as $x \to 1$?

Lowest order ep neutral current DIS at large values of x - use as a guide

$$F_2^{ep} = \frac{x}{9}(4u + d) \qquad F_2^{en} = \frac{x}{9}(4d + u)$$

- At large values of x, the d PDF falls faster than the u PDF
- F_2^{ep} dominated by the u PDF and the errors on u are relatively small
- F_2^{en} dominated by the d PDF - If you had data for F_2^{en}, then you could separate the d and u PDFs at large values of x
- Extract F_2^{en} from data taken on deuterium at large values of x

- The large-x region is where the nuclear corrections become large due to Fermi motion corrections

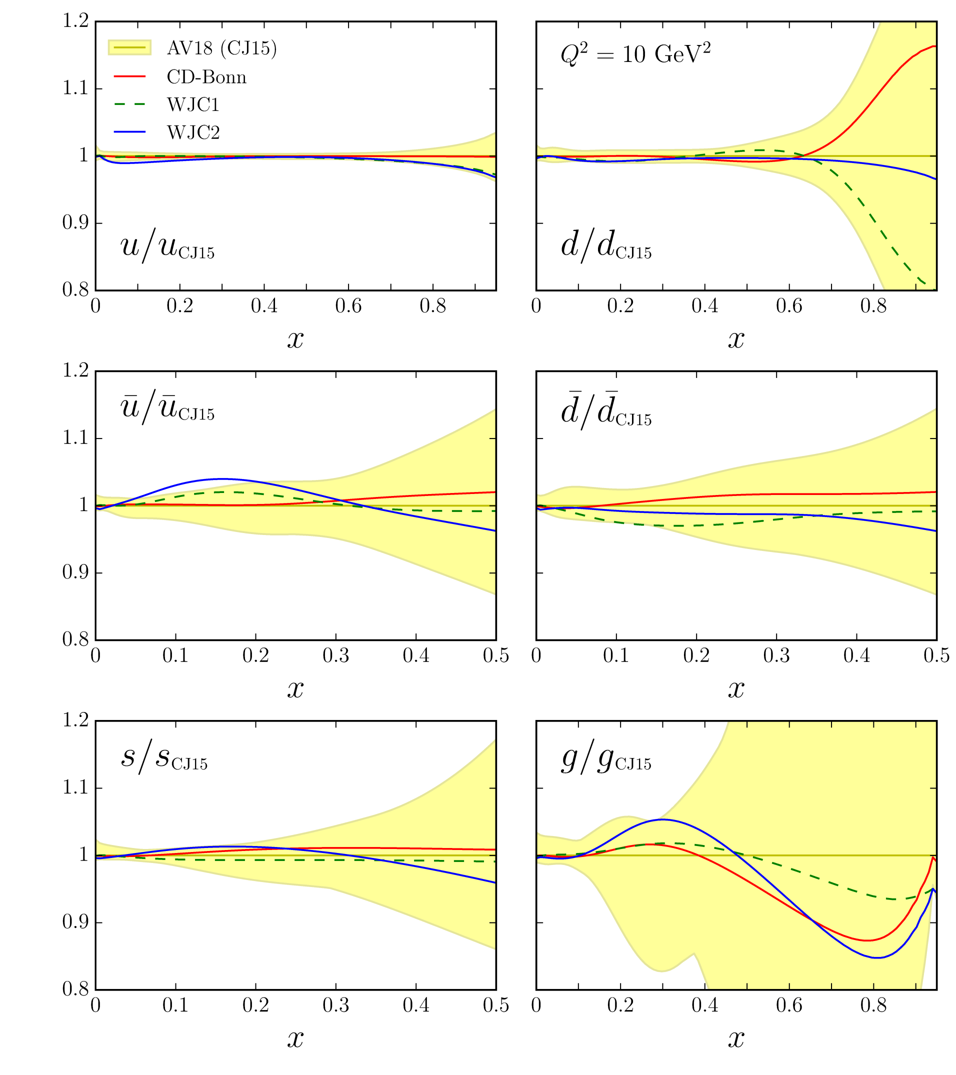


- The ratio of F_2^d to the isoscalar structure function F_2^N exceeds 10% once you go past $x \simeq 0.75$

- Note that the dependence on the wavefunction used is relatively small compared to the overall error band for this ratio of structure functions

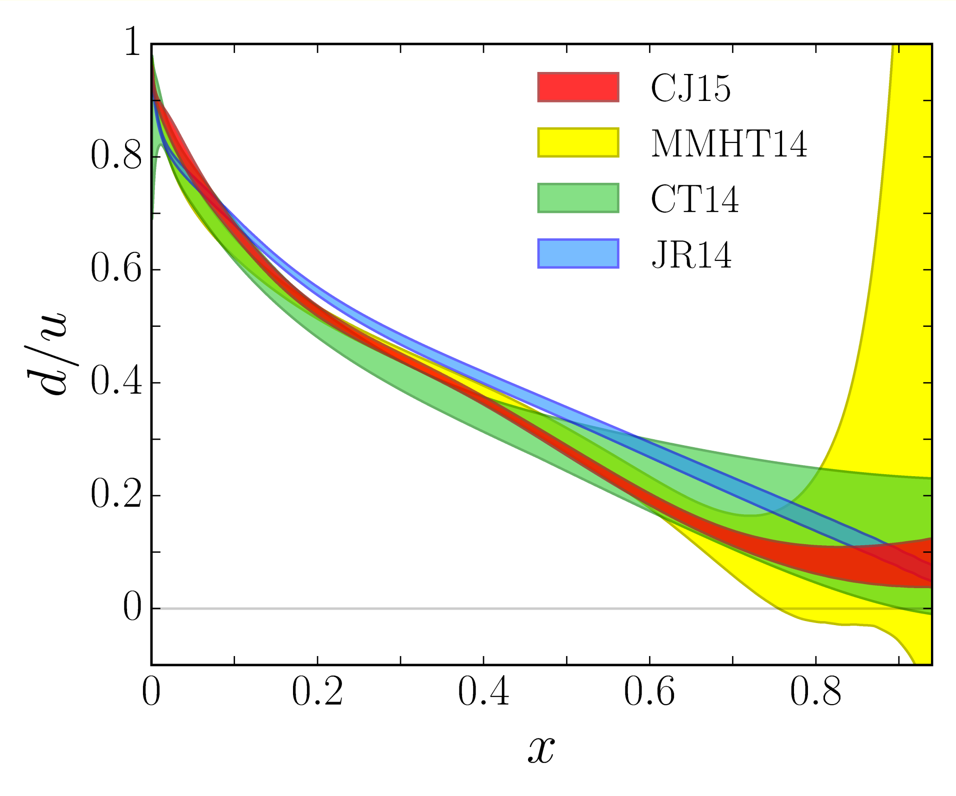
- The d PDF changes to compensate for different nuclear smearing so the resulting error band on the d PDF itself grows in the region where the smearing gets large

Can see this by looking at the dependence of the PDF on the wavefunction used



d PDF shows the most dependence on the choice of the deuteron wavefunction

d/u ratio shows significant variations between various PDF sets



- Some is due to parametrization bias
- Some is due to Q and W cuts that effectively limit x to $x \sim 0.7$ so the large x region is an extrapolation
- Some is due to different treatments of nuclear corrections

Need a way to constrain the d PDF in the absence of nuclear corrections

Classic solution is to use neutrino DIS. Again, at lowest order at large values of x

$$F_2^{\nu p} = 2x(d + s + \bar{u} + \bar{d}) \xrightarrow[x \to 1]{} 2xd$$

and

$$F_2^{\bar{\nu} p} = 2x(u + c + \bar{d} + \bar{s}) \xrightarrow[x \to 1]{} 2xu$$

so that at large values of x

$$F_2^{\nu p} / F_2^{\bar{\nu} p} = d/u$$

However

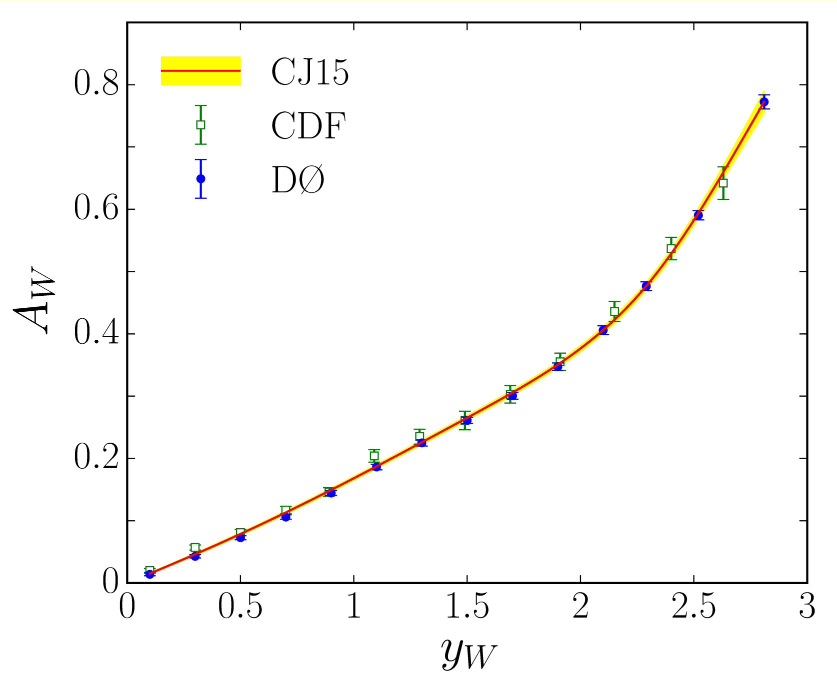
- Data on proton targets from early bubble chamber experiments had low statistics and provided little constraint on d/u at large values of x
- High statistics experiments used nuclear targets
  - Results give information on *nuclear* PDFs
  - Need to account for nuclear model dependent corrections to extract d/u for the proton
  - Highly unlikely to get data from a hydrogen target using modern high intensity neutrino beams due to safety concerns

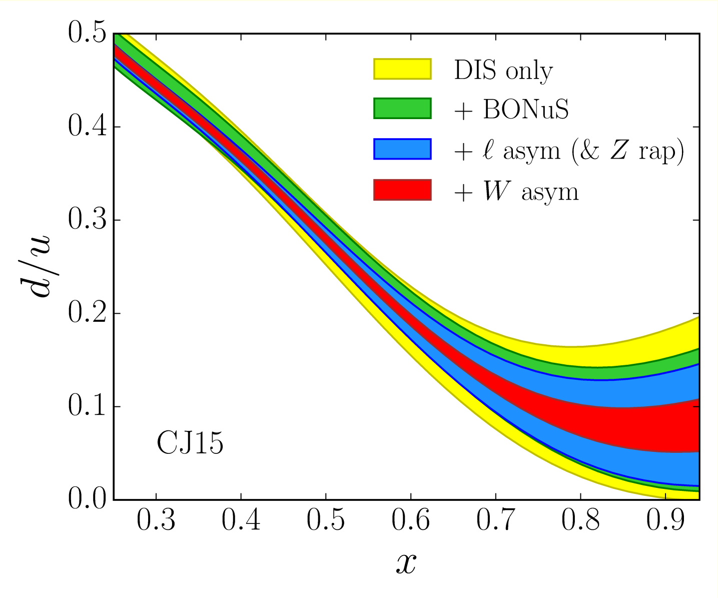
One solution is to use the charged current interaction in the form of W production from the Tevatron

The charged W asymmetry

$$A(y) = \frac{\sigma(W^+) - \sigma(W^-)}{\sigma(W^+) + \sigma(W^-)} \approx \frac{1 - d/u(x_1)}{1 + d/u(x_1)} \quad \text{with} \quad x_1 \approx \frac{M_W}{\sqrt(s)} e^{\eta_W}$$

at large W rapidity is sensitive to the d/u ratio





- Can see the effect of adding various data sets to a series of fits
- Can see the decrease in the d/u error bands
- No nuclear corrections needed
- Can help select amongst the various treatments of nuclear corrections

- W asymmetry has more constraining power than the W-lepton asymmetry
- Leptonic $V - A$ decay limits the reach in rapidity $\Rightarrow$ less constraint on the d PDF
- On the other hand, the W asymmetry extraction is model dependent

Another solution - use the line-reversed DIS processes, again for large x

$$e^+p \rightarrow \bar{\nu} + X \quad F_2^{e^+p,cc}(x,Q) \propto xd$$

and

$$e^-p \rightarrow \nu + X \quad F_2^{e^-p,cc}(x,Q) \propto xu$$

- Allows direct extraction of d/u at large values of x
- These processes have been measured at HERA out to $x \simeq 0.4$
- Need good statistics at larger x values if one wants to extract d/u directly

Progress on antiquark PDFs

- $g \to q\bar{q}$ vertex is flavor independent so one might expect all antiquark PDFs to be the same
- This ignores various nonperturbative effects
- $\bar{d} \neq \bar{u}$ based on meson cloud model

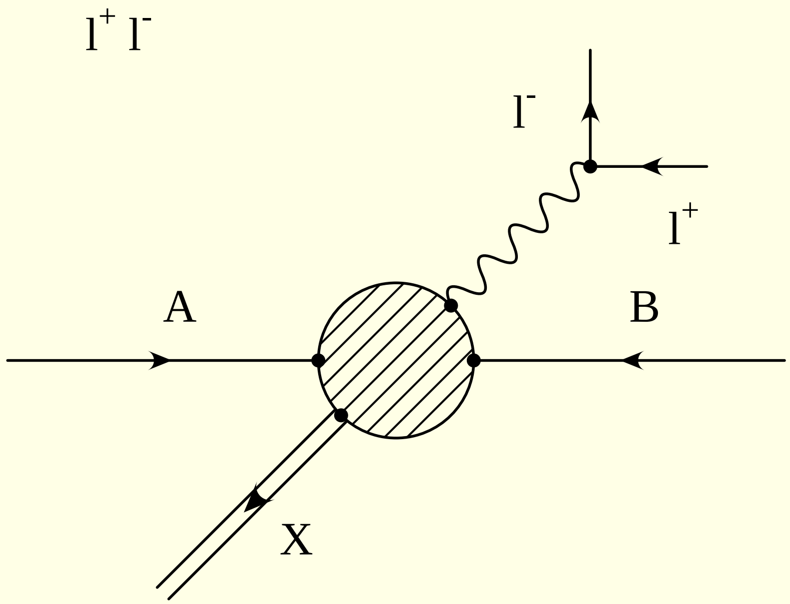
$$p \to \pi^+ n \text{ versus } p \to \pi^- \Delta^{++}$$

$$uud \to (u\bar{d})(ddu) \quad uud \to (d\bar{u})(uuu)$$

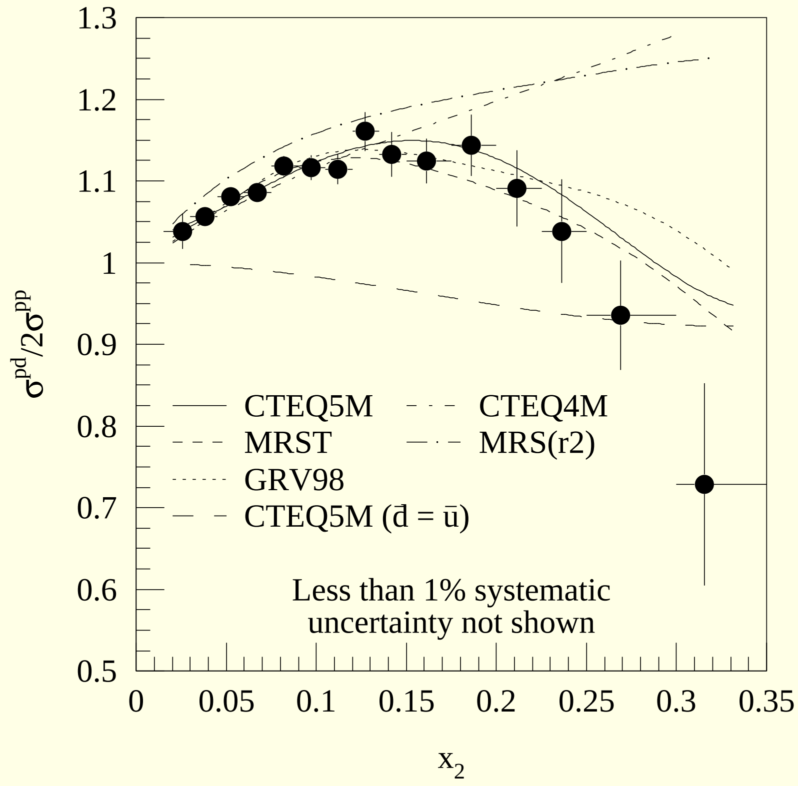
- Latter is suppressed relative to the former so one might expect $\bar{d} > \bar{u}$
- Confirmed by Gottfried Sum Rule

$$\int_0^1 \frac{dx}{x}(F_2^p(x) - F_2^n(x)) \approx \frac{1}{3} - \frac{2}{3}\int_0^1 dx(\bar{d}(x) - \bar{u}(x)) = 0.234 \pm 0.026$$

Lepton Pair Production

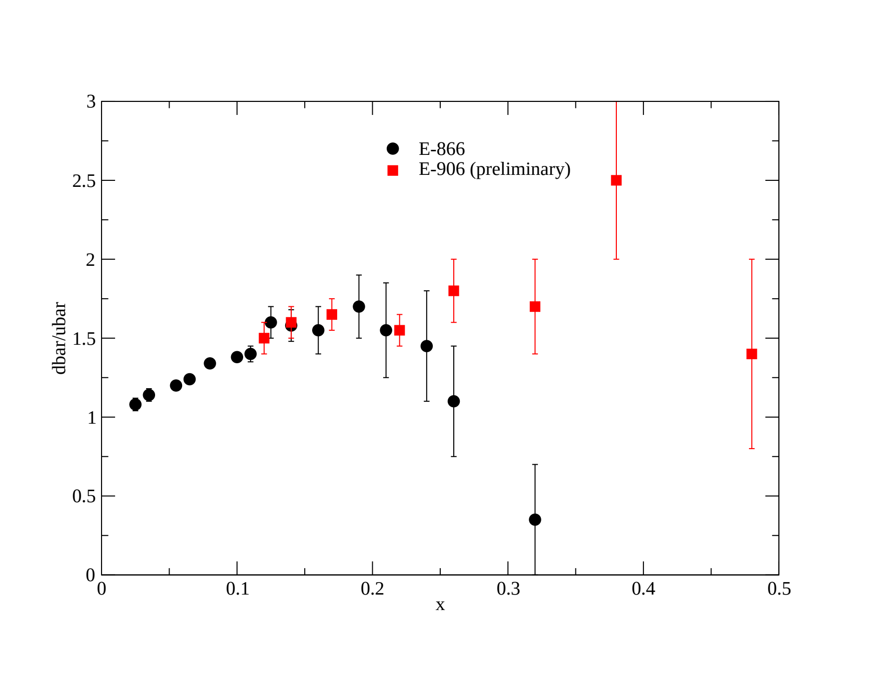


- $pp \to \mu^+\mu^- + X$ driven by the subprocess $\bar{q}q \to \mu^+\mu^-$
- Yields information on the antiquarks at small values of x and the valence quarks at large values of x
- E866 at Fermilab measured this process with both proton and deuteron targets
- $\frac{\sigma^{pd}}{2\sigma^{pp}} \approx \frac{1}{2}(1 + \frac{\bar{d}}{\bar{u}})$
- Results showed $\bar{d} > \bar{u}$ over much of the measured range in x



- Data indicate that $\bar{d} > \bar{u}$ for most of the x range
- Last few points suggest that $\bar{d} < \bar{u}$ for $x > 0.2$
- Hard to accommodate in any physical picture of the nonperturbative inputs

- New experiment E-906 (SeaQuest) at Fermilab will have improved statistics and kinematic coverage
- Preliminary data suggests $\bar{d} > \bar{u}$ out to at least $x \approx 0.5$
- Additional data being taken, acceptance and efficiency corrections being finalized.



Again, consider the charged current structure functions in lowest order

$$F_2^{e^+p,cc}(x,Q) = 2x(d + s + \bar{u} + \bar{c})$$

and

$$F_2^{e^-p,cc}(x,Q) = 2x(u + c + \bar{d} + \bar{s})$$

- If $xF_3^{e^-p,cc} = 2(u - \bar{d} - \bar{s} + c)$ and $xF_3^{e^+p,cc} = 2(d - \bar{u} - \bar{c} + s)$ can be extracted, one can separate the quark and antiquark PDFs
- If the charm PDF is perturbative, *i.e.* there is no intrinsic charm, then $c = \bar{c}$
- Can get information on $\bar{d}/\bar{u}$

Strange antiquarks

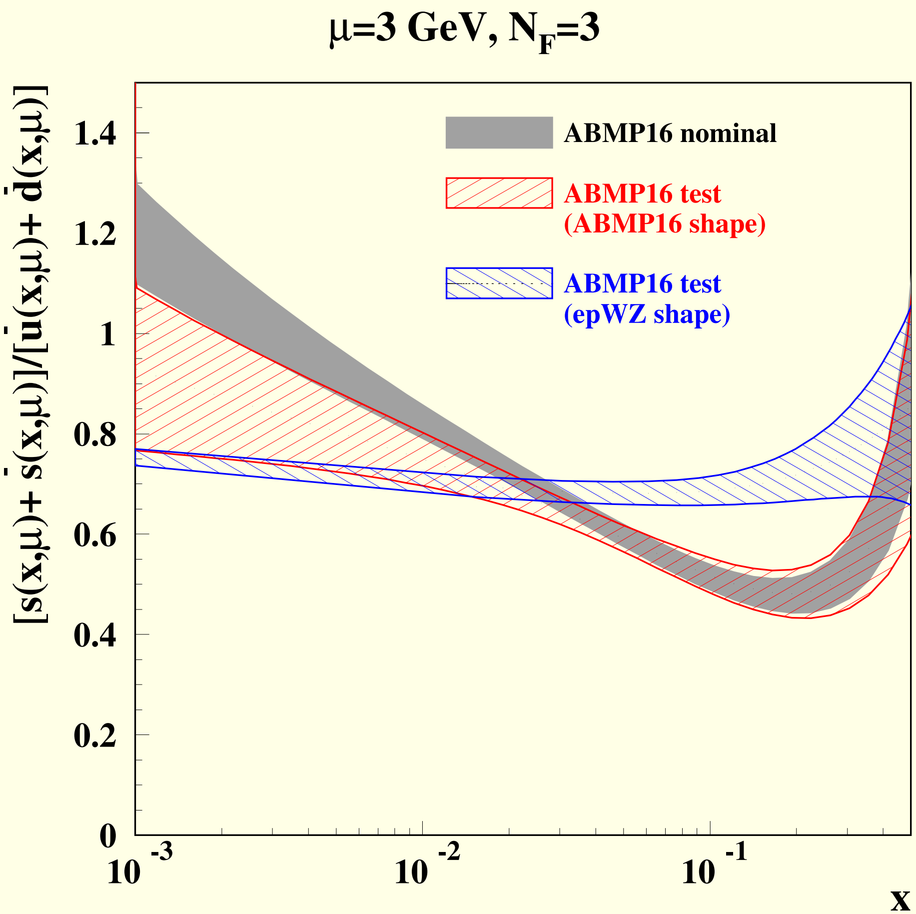
- Best constraint has come from neutrino production of muon pairs

$$\nu_\mu s \to \mu^- c \ \text{ followed by } \ c \to s\mu^+\nu_\mu$$

- Opposite sign dimuon cross section sensitive to the s PDF.
- Using a $\bar{\nu}_\mu$ beam gives sensitivity to the $\bar{s}$ PDF
- CCFR and NuTeV results suggest

$$\kappa = \frac{s+\bar{s}}{\bar{u}+\bar{d}} \approx 0.4$$

- But some collider results for $W^{\pm}, Z$ production suggest a ratio closer to one (ATLAS Collaboration, M. Aaboud *et al.*, arXiv:1612.03016)
- Alekhin, Blümlein, and Moch (arXiv:1708.01067) attribute at least some of the difference to a less flexible paramtrization in the ATLAS analysis



Would a meson cloud approach say something about this?

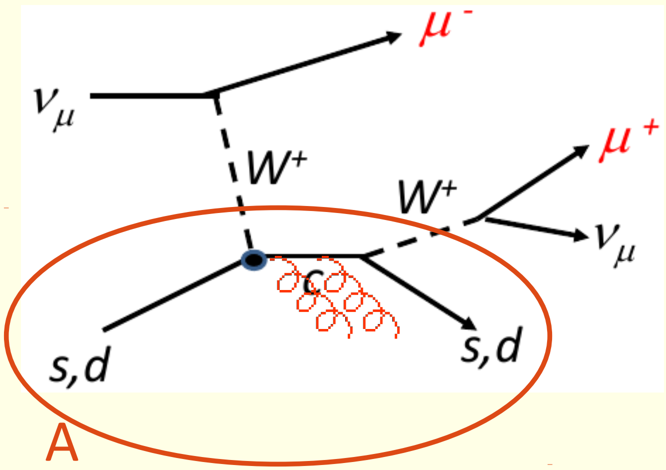
$$p \to K^+\Lambda$$

$$uud \to (u\bar{s})(sud)$$

- Intermediate state is heavier that $\pi^+ n$ or $\pi^- \Delta^{++}$
- Suggests a nonperturbative $s\bar{s}$ contribution that is suppressed relative to the $\bar{d}$ and $\bar{u}$ PDFs

Caveats

- Neutrino measurements are on iron targets so one is really sensitive to iron PDFs, not those of the free proton
- There are uncalculated (and unknown) nuclear corrections for the propagation of the produced charm meson through the nucleus
- One could also have induced energy loss in the final state



- Would like a process free of nuclear corrections/effects

Measure charged current cross sections with a muon tag to select charm final states

$$e^+ s \to \bar{\nu} c \quad \text{followed by} \quad c \to s \mu^+ \nu_\mu$$

and

$$e^- \bar{s} \to \nu \bar{c} \quad \text{followed by} \quad \bar{c} \to \bar{s} \mu^- \bar{\nu}_\mu$$

- Note that the sign of the muon is the same as the sign of initial state lepton
- Potentially capable of separating s from $\bar{s}$

Conclusions

Charged current measurements in $e^{\pm}p$ DIS are potentially capable of improving our knowledge of PDFs by providing:

- Better constraints on d/u in the large x region
- Additional constraints on $\bar{d}/\bar{u}$ to complement information from lepton pair production
- Constraints on $\frac{s+\bar{s}}{\bar{u}+\bar{d}}$ without the need for nuclear corrections

Studies at EIC kinematics are under way to quantify this potential

[Accardi, Ent, Furletova, Keppel, Park, Yoshida – EICUG Trieste, Jul'17]

- Help is welcome
- What's possible at JLab12?