Neutrino Deep Inelastic Scattering and Nuclear Parton Distribution Functions

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Outline

- Introduction
- It all started with d/u ...
  - New data from E-866 ($pp(d) \rightarrow \mu^+\mu^- + X$)
  - New data from NuTeV and Chorus (νFe and νPb)
- Global Fitting Results
- NuTeV data and iron PDFs
- Conclusions

Global Fitting and Parton Distribution Functions - PDFs

PDFs are

- Key to perturbative QCD calculations in hadronic hard scattering processes
- Universal - independent of the hard scattering process
- The means for making the transition from hadronic to partonic beams and targets

Global Fits

Traditional tool for determining PDFs is global fitting

- Use a variety of data types
  - DIS: $l^\pm p$, $l^\pm d$, $\nu/\overline{\nu}A$
  - lepton pair: pp, pd, pA
  - W, γ, jets: pp, $\overline{p}p$
- Primary goal of *most* global fits is determining *nucleon* PDFs
- Need to account for nuclear effects in order to use data taken with nuclear targets
- Global fits updated as new data sets become available

Some forefront topics in PDF determination

- Flavor composition of the sea - $\overline{d}/\overline{u}$, $s \neq \overline{s}$, heavy flavors
- Behavior of PDFs at large values of x
  - d/u : nuclear effects often come into play here
  - large-x PDFs at low scales feed down to smaller values of x at larger scales
  - Neutrino data usually require nuclear corrections
  - Note: Some charged current data available from ep collisions at HERA
  - EIC could measure charged current neutrino structure functions and nuclear corrections would enter again
- Updated PDFs for LHC predictions

It all started with d/u...

At large values of x

$$F_2^{em} \sim 4u(x) + d(x) + ...$$

while for neutrino scattering

$$F_2^{CC} \sim u(x) + d(x) + ...$$

On the other hand, in lepton pair production

$$d\sigma/dM^2 dx_F \sim 4u(x_1)\overline{u}(x_2) + d(x_1)\overline{d}(x_2) + ...$$

where

$$x_{1,2} = \frac{\pm x_F + \sqrt{x_F^2 + 4M^2/s}}{2} \text{ or } x_1 \approx x_F \text{ and } x_2 \approx M^2/x_F s.$$

- All three observables are sensitive to different combinations of u and d
- Should be able to use these observables to constrain the d/u ratio.

New Data Sets

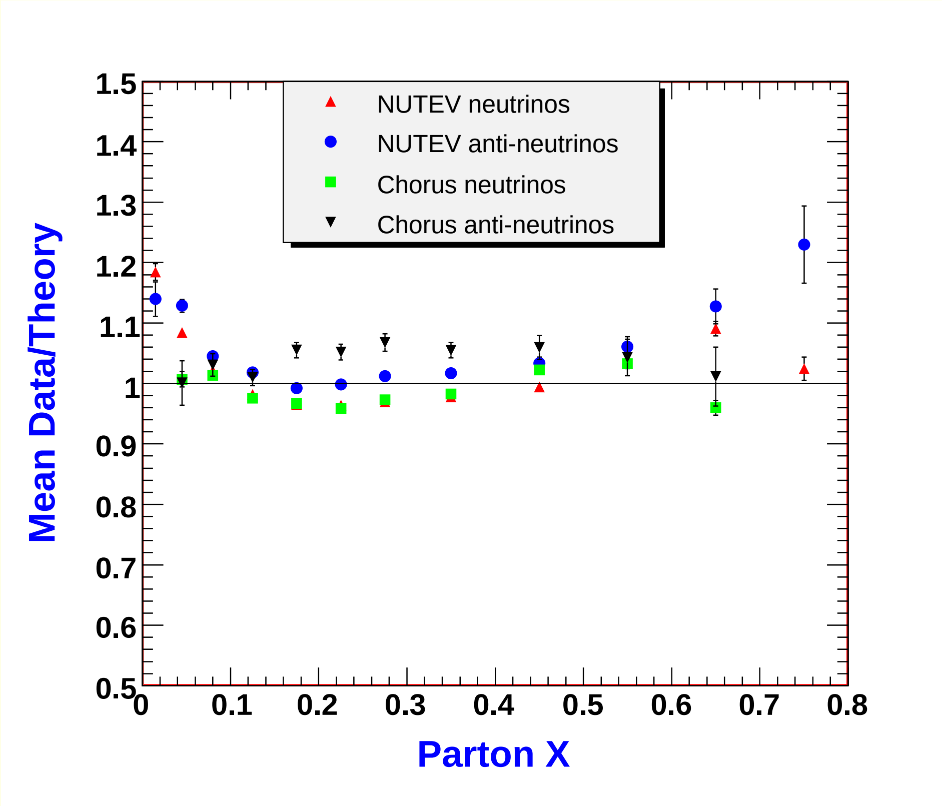
- E-866 $pp(d) \rightarrow \mu^+\mu^- + X$
  - Having both p and d targets helps constrain $\overline{d}/\overline{u}$
  - Also helps with d/u as mentioned previously
  - Nuclear effects measured to be small in the relevant x range for the target
- NuTeV $\nu(\overline{\nu})Fe \rightarrow \mu + X$
- Chorus $\nu(\overline{\nu})Pb \rightarrow \mu + X$
  - Both experiments provide constraints for d/u
  - Nuclear effects are important over the full x range

Comments

- Comparison with predictions using existing data sets suggested that the E-866 data would pull the valence distributions down at large values of x.
- Similar comparisons with the NuTeV data suggested that they would pull the valence distributions up at large values of x
- NuTeV data at large values of x lie above the previously obtained CCFR data - some of the discrepancy is understood
- Nuclear corrections in this region will increase the “free nucleon” structure functions and, therefore, increase the upward pull on the valence PDFs

Procedure

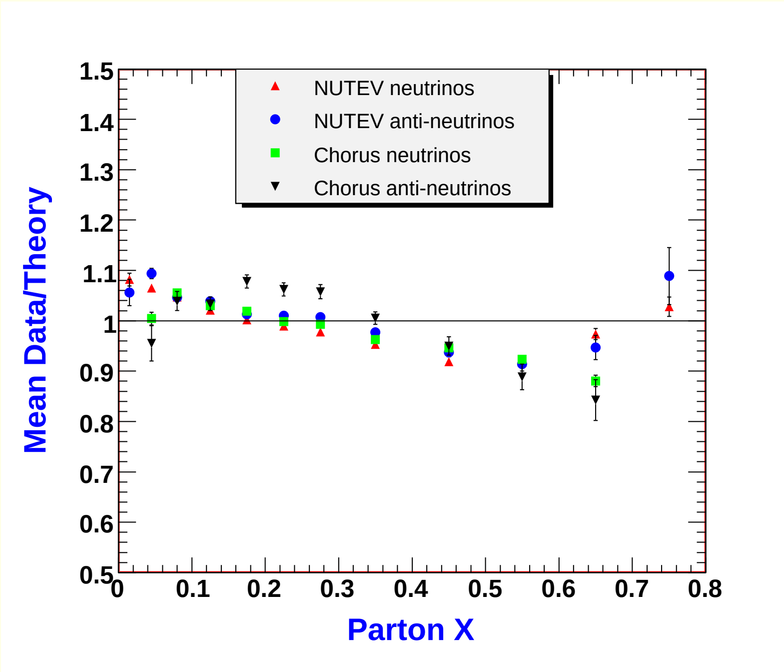
- Start with a Reference Fit - CTEQ6.1M with heavy target data sets (CCFR $\nu/\overline{\nu}$) removed and (model dependent) deuteron corrections included where appropriate
- Compare to new Chorus and NuTeV cross section data for $\nu/\overline{\nu}$ on Fe and Pb, respectively.
- Examine fits both with and without nuclear corrections



Comparison of Reference Fit (no heavy targets) to Chorus and NuTeV data

- Plot shows weighted average of data/theory integrated over Q^2 for each bin in x
- Only normalizations have been fit - these data were not included in the fit
- Kulagin-Petti nuclear corrections included

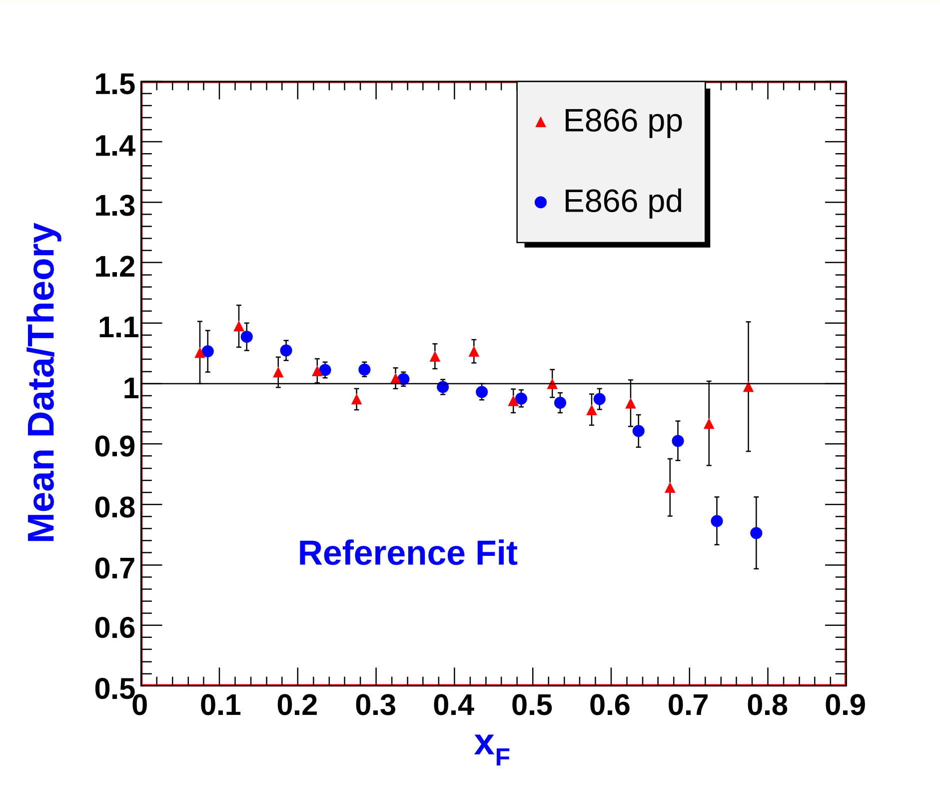
Now, what if the nuclear corrections are removed?



- Different data sets are now more consistent, even if they do not agree totally with the Reference Fit
- Differences at large values of x look like the expected pattern of nuclear effects as seen in $l^{\pm}$ A DIS but reduced in magnitude
- Results suggest that the nuclear corrections for both ν and $\overline{\nu}$ cross sections may be rather similar
- Results also suggest the absence of a screening correction at low-x

Effects of new data sets on PDF fitting

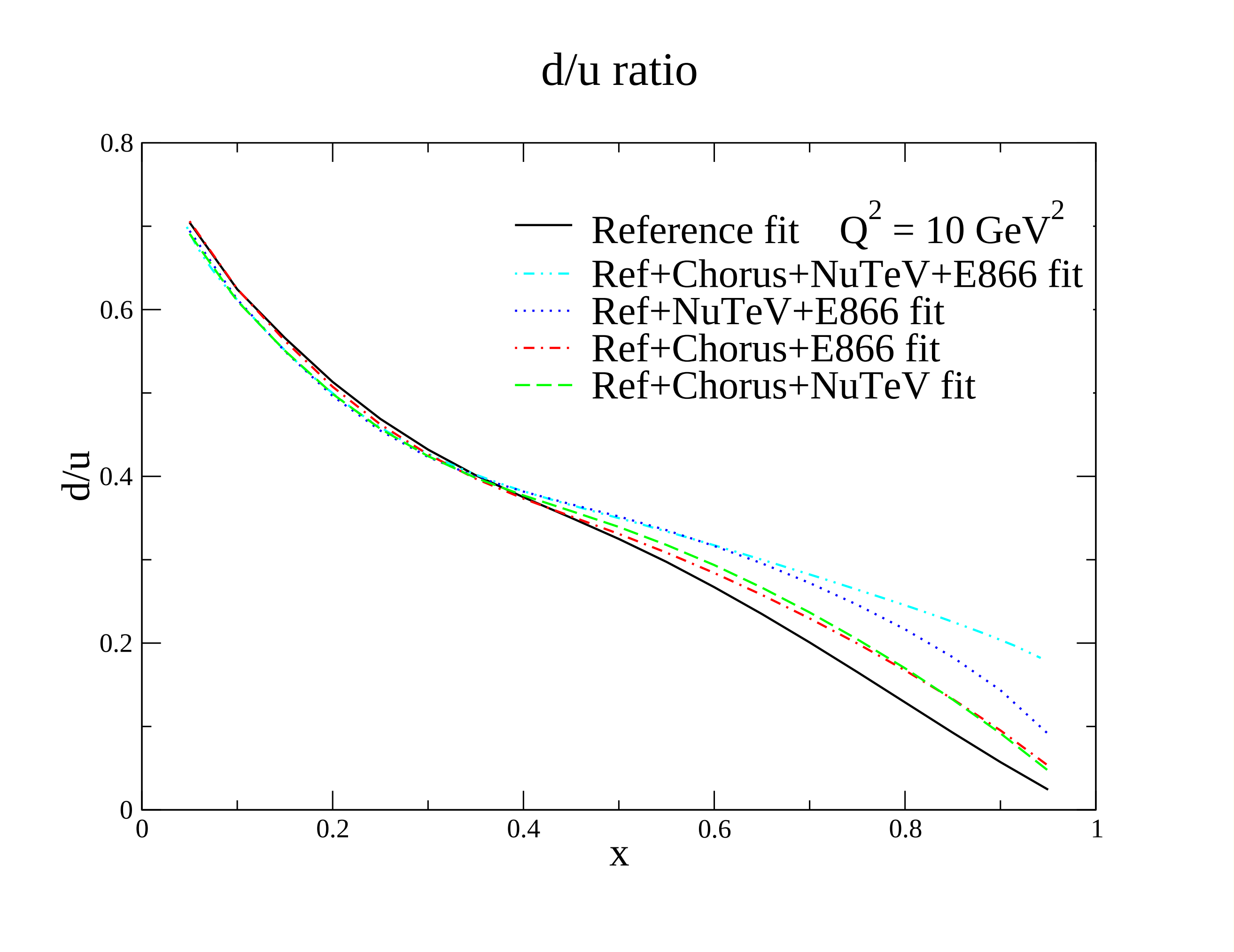
- Add to the Reference Fit data from
  - E-866 pp and pd dimuon production
  - NuTeV
  - Chorus
- Add data sets singly, in pairs, and all at once
- Goal is to see how the various data sets pull the PDFs
- Kulagin-Petti nuclear corrections are used for both the NuTeV and Chorus data sets
- Use the fitted d/u ratio as in indicator of what is going on
- Easier to understand than lengthy chi square tables



- Comparison to the Reference Fit suggests that the E866 data will pull the high-x valence distributions downward
- Previous plots suggest that the NuTeV data will pull the high-x valence distributions upward
- Expect tension between the two

Basic results

- Can get reasonable fits when any single data set is added, although adding NuTeV does cause the chi squares to increase for other DIS experiments
- Adding NuTeV and Chorus or E-866 and Chorus in pairs results in acceptable fits
- Adding E-866 and NuTeV results in a poorer fit and a d/u ratio which differs from the usual results



- See significant increase in d/u when NuTeV and E-866 are both included in the fit
- Results from the tension between the conflicting demands of the NuTeV and E-866 data sets

Explanation

- For large values of x $\sigma^{\nu N} \propto u + d$
- $\sigma(pp \to \mu\mu + X) \propto 4u(x_1)\overline{u}(x_2) + d(x_1)\overline{d}(x_2)$
- $\sigma(pd \to \mu\mu + X) \propto [4u(x_1) + d(x_1)](\overline{u}(x_2) + \overline{d}(x_2))$
- NuTeV wants an increase in the high-x valence distributions while E-866 wants a decrease
- Can achieve both by increasing d and decreasing u (decrease of u is weighted by 4 in the dimuon process)
- Explains the increase in the d/u ratio

Note: Variations of the d/u ratio for large values of x are likely well within the range allowed by the PDF errors. These are not meant to represent error bands. It is simply an easy way to see how the PDFs respond to the conflicting demands of the data sets.

Interim Conclusions

- Nuclear corrections in $\nu/\overline{\nu}$ A DIS may be similar to or less than the corrections in $l^{\pm}$ A DIS
- Including NuTeV (with Kulagin-Petti nuclear corrections) and E-866 results in relatively poor chi squares overall
- Shift in d/u results are indicative of the tension between the two data sets
- Can't use high statistics nuclear DIS data to constrain *nucleon* PDFs without a better understanding of the nuclear corrections
- New results from BONUS at Jefferson Lab expected to constrain the d/u ratio and not be dependent on nuclear effects
- May be able to turn the problem around and use the neutrino data to study nuclear effects once d/u is better known.
- For additional details see J.F. Owens *et al.*, hep-ph/0702159, Phys. Rev. D75:054030,2007.

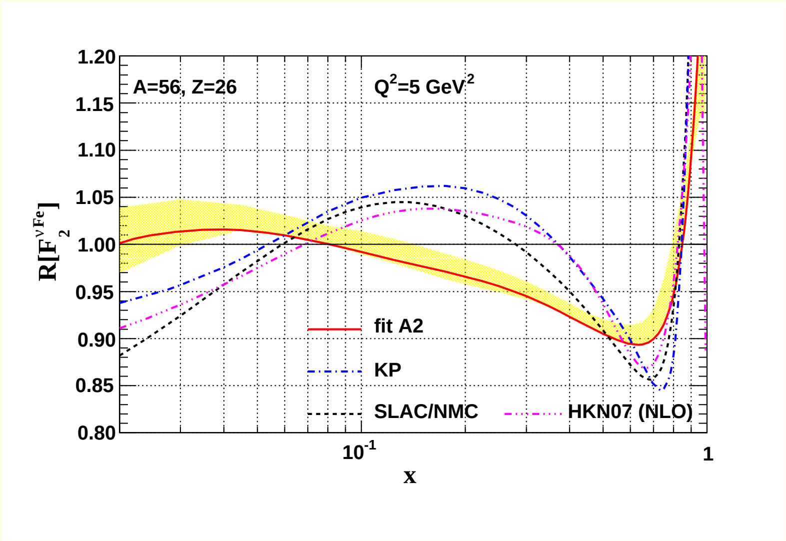
Nuclear PDFs from Neutrino Scattering

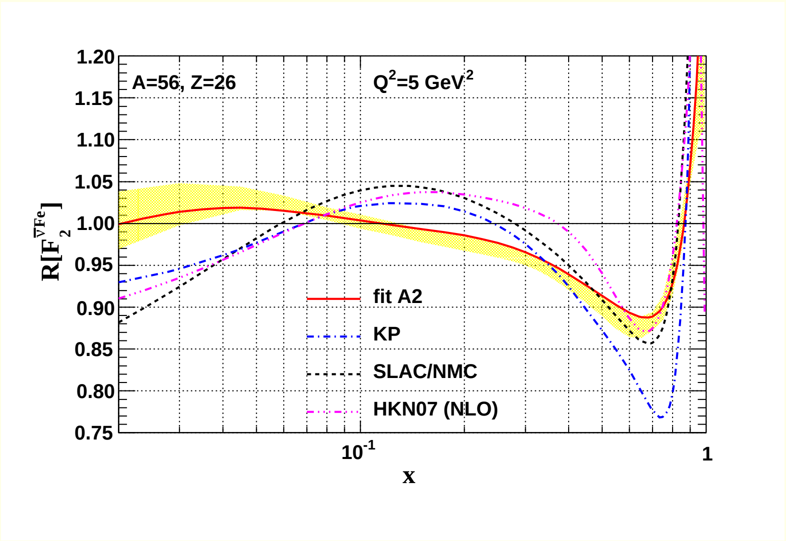
Basically, turn the problem around ...

- Start with the previously described Reference Fit
- Compare with PDFs fitted to the NuTeV data without nuclear corrections, *i.e.*, iron PDFs
- Basically deduce what the nuclear corrections look like
- More detailed look than using the ratios presented earlier
- More details in I. Schienbein et al., arXiv:0710.4897[hep-ph], Phys. Rev. D77, 054013 (2008)

Procedural details

- Use the same parametrization as for CTEQ6M1
- Use next-to-leading order formalism
- Include target mass corrections and heavy quark effects (ACOT scheme)
- Gluon parameters not varied (little sensitivity since only the NuTeV data are being fitted)
- $\overline{d}/\overline{u}$ ratio fixed to free nucleon results for the same reason
- After the fitting is complete, calculate nuclear correction factors as the ratio – Observable (using iron PDFs)/Observable (using free nucleon PDFs)





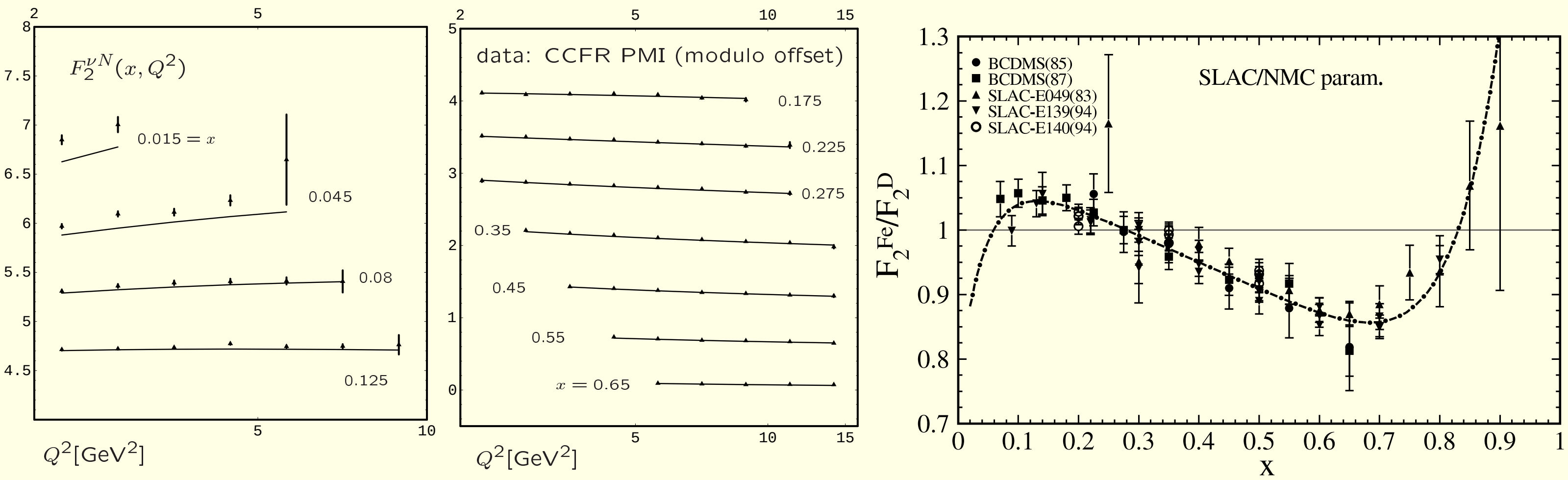
- Nuclear correction factors for F_2 for neutrinos (left) and antineutrinos (right)
- nuclear corrections are similar for both
- Again, see no evidence for screening at low values of x
- Corrections are generally smaller than for F_2^{em} and for the Kulagin-Petti calculation
- No evidence for antiscreening in the x range from .1-.3

Screening - another clue

ACOT heavy quark scheme addresses the disagreement between μN and νN structure functions - charm is produced via different mechanisms

$$\gamma^* g \to c\bar{c} \quad \text{vs} \quad W s \to c$$

(see S. Kretzer et al., Phys. Rev. D**69**, 114005(2004.) Yet even when these differences are taken into account, there is a disagreement with the CCFR ν data at low values of x. CCFR data have been corrected for nuclear effects using a parametrization of SLAC/NMC data.



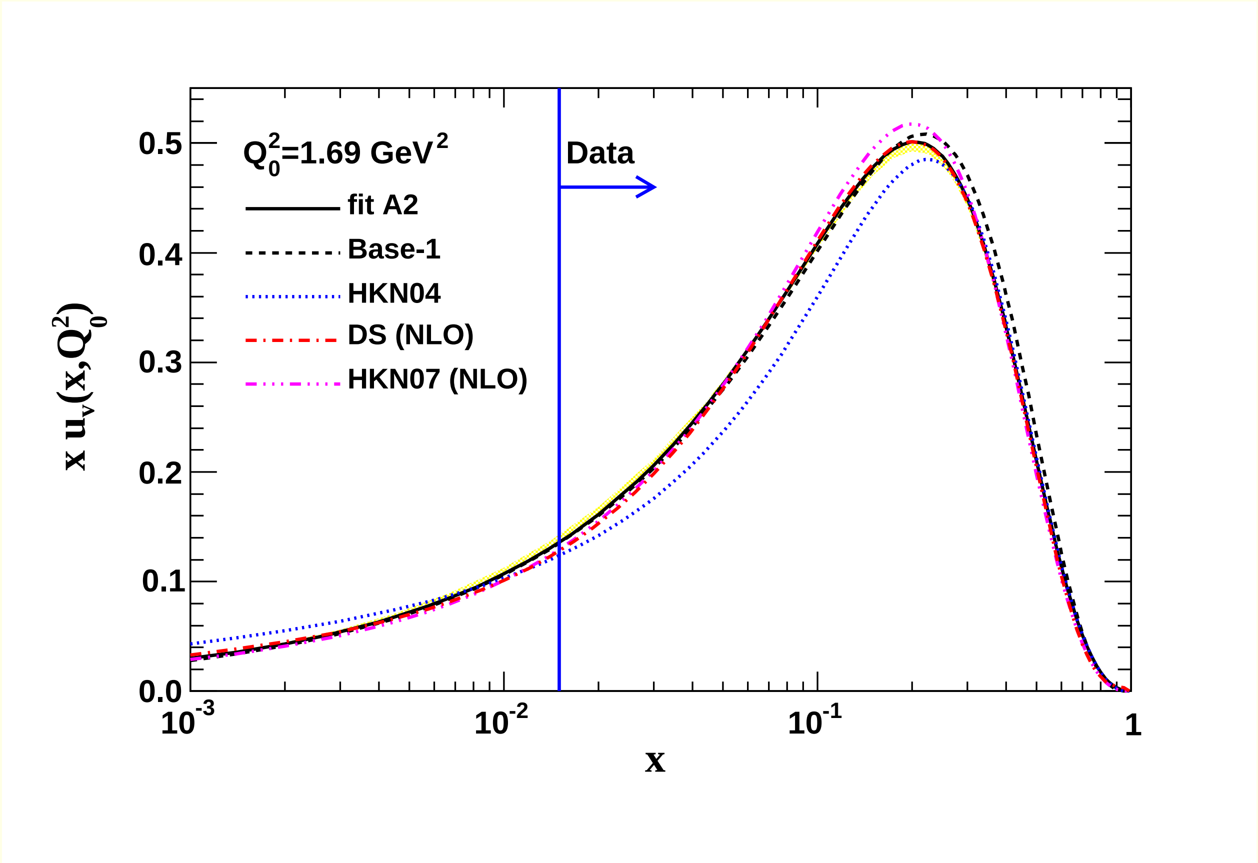
Discrepancy would be reduced if nuclear corrections without screening were used.

Conclusions

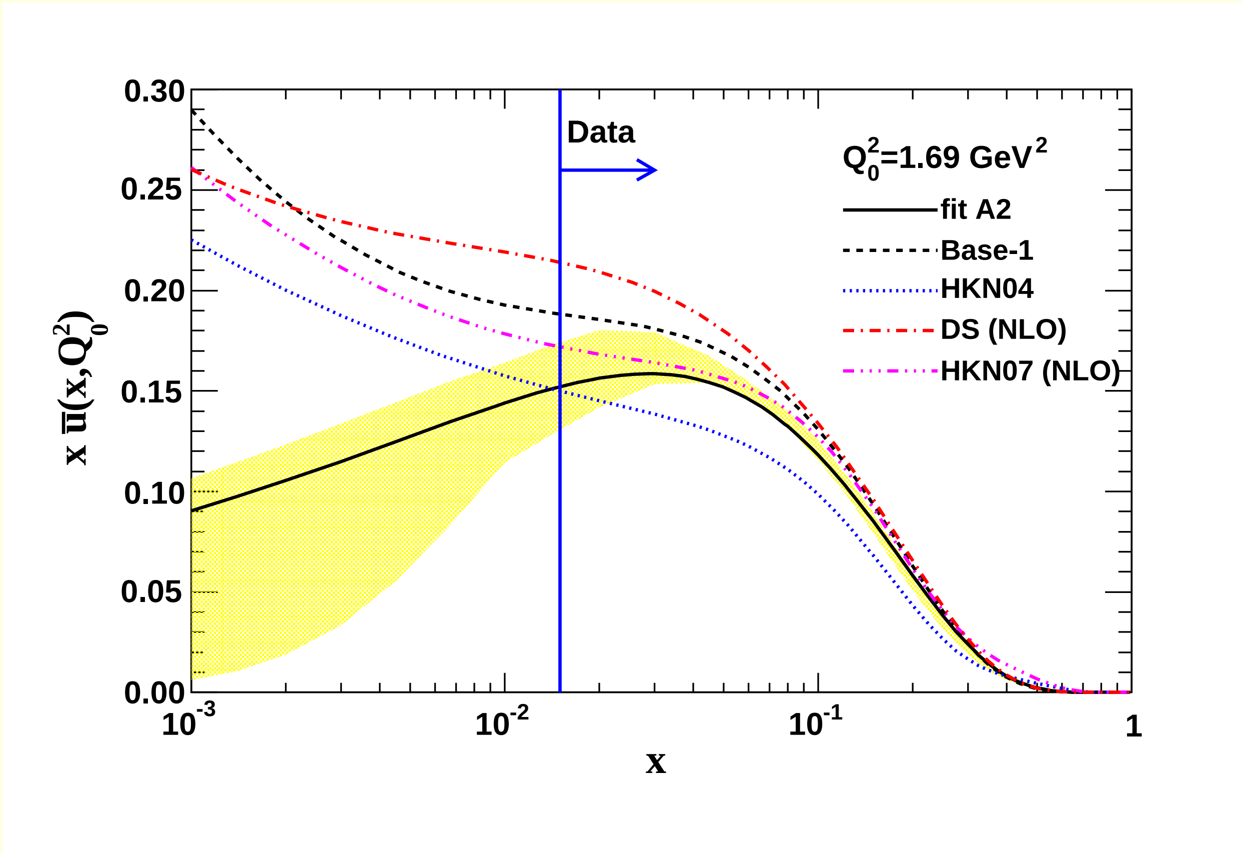
Two different approaches using neutrino data were used to study nuclear effects on PDFs.

- Nuclear corrections seem to be similar for ν amd $\overline{\nu}$ interactions
- No evidence is seen for shadowing at small values of x
- No evidence is seen for antishadowing in the range in x of .1-.3
- The overall magnitude of the corrections seems to be less than in neutral current charged lepton deep inelastic scattering
- Similar studies will soon be carried out on neutrino data sets taken with other targets (but smaller statistics).
- A proposed neutrino fixed target experiment at Fermilab - NuSOnG - NeUtrinoS On Glass - will have higher statistics than NuTeV and is proposed to have a variety of nuclear targets.

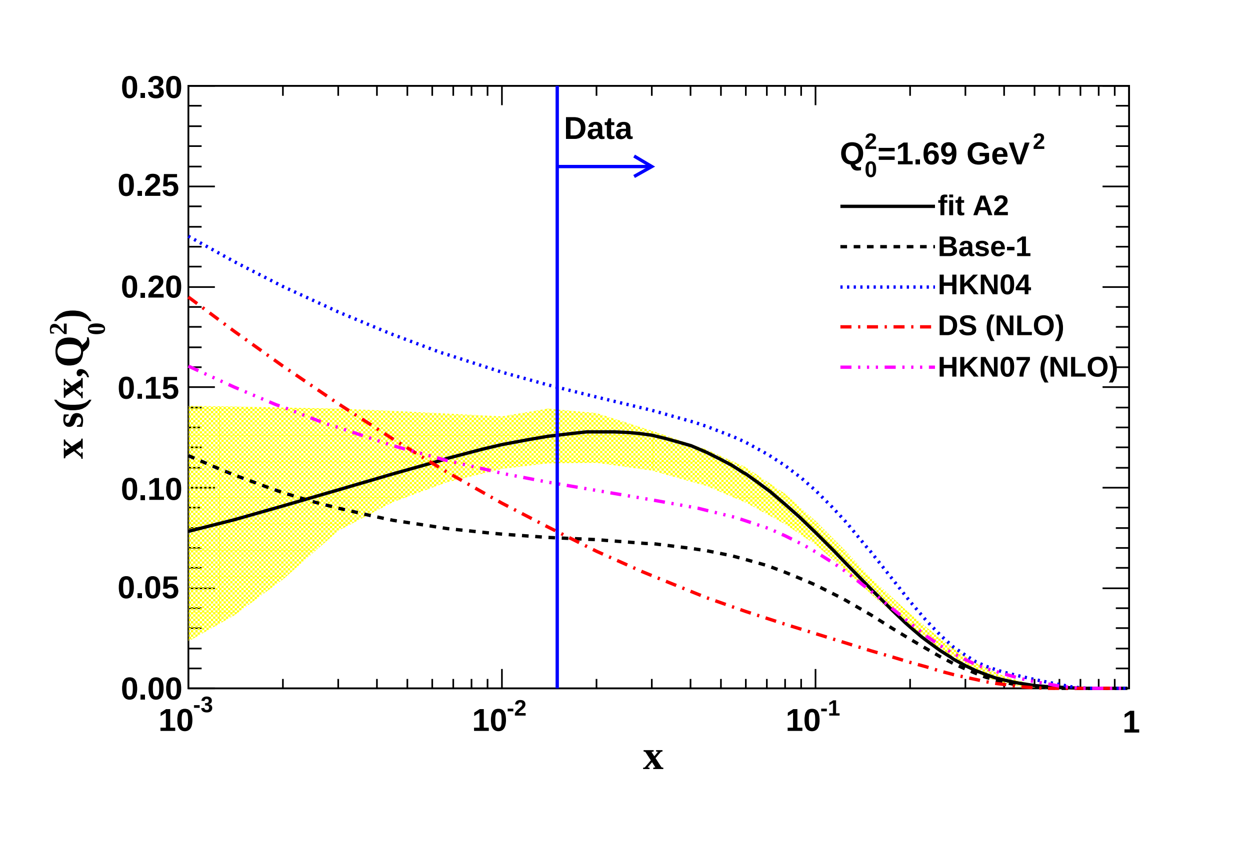
Some Backup Slides



This is a comparison of the fitted u distribution with some other determinations



Here is a similar comparison for the $\overline{u}$ distribution. The $\overline{u}$ distribution in fit A2 is reduced because the s distribution is increased in order to better fit the low-x data (next slide).



And here is one for the s distribution. Note the relative increase of the s distribution compared to the base-1 (Reference) fit. But the results are still consistent with the NuTeV/CCFR dimuon data which were included in the fit.