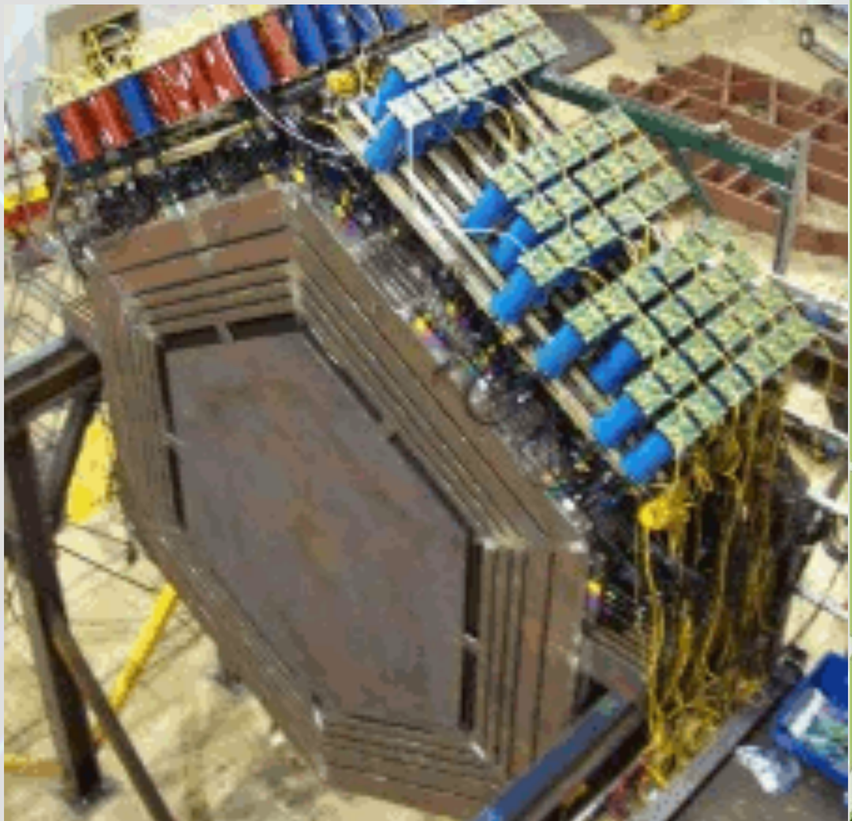
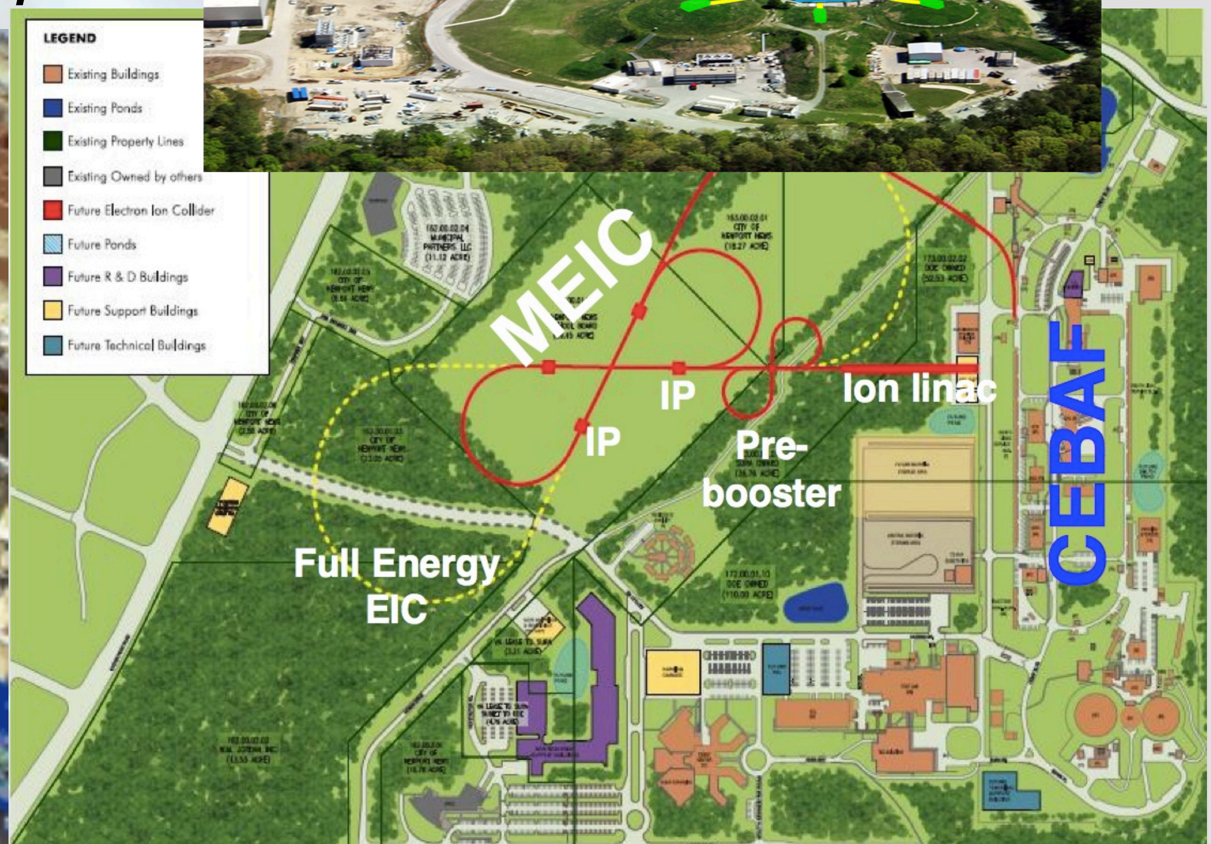
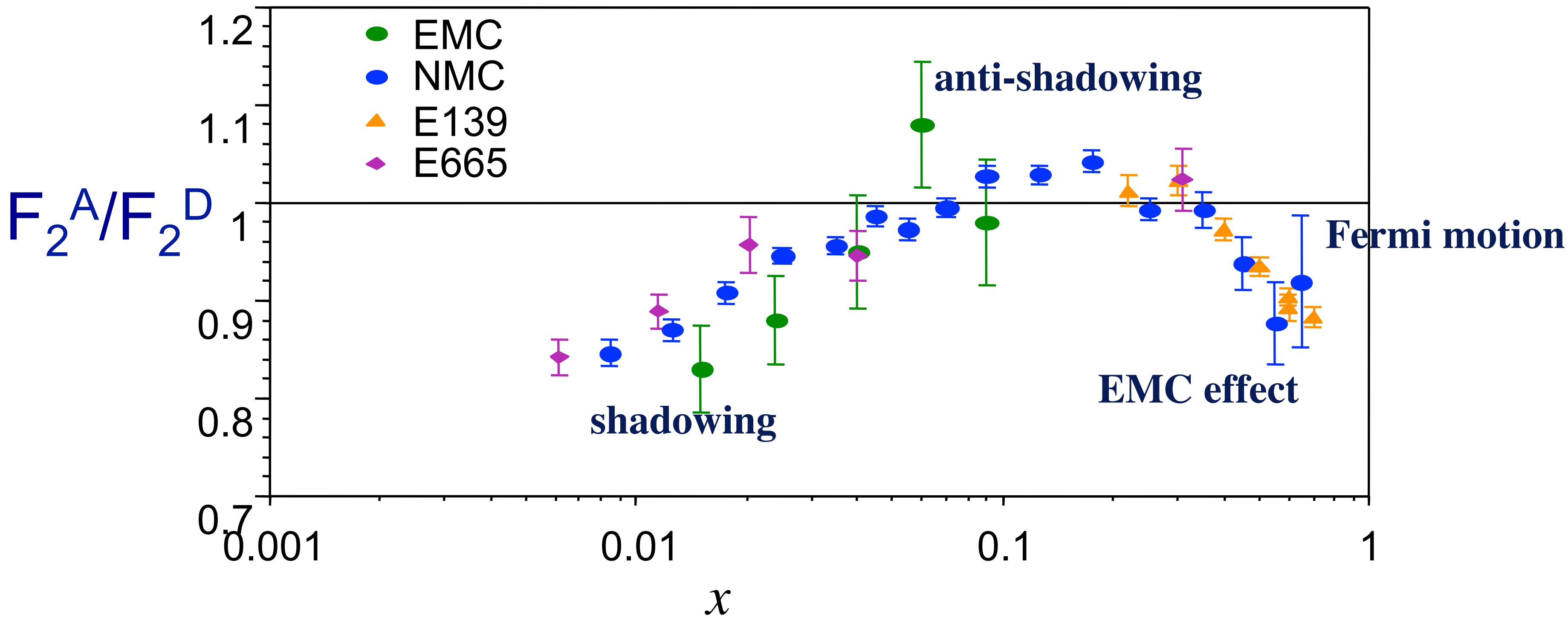
Comparison of F_2^{Fe} as Measured by Charged Leptons and Neutrinos

Thia Keppel





Experimental Studies of Nuclear Effects with Structure Functions - *what do we really know?*



General and once surprising statement:

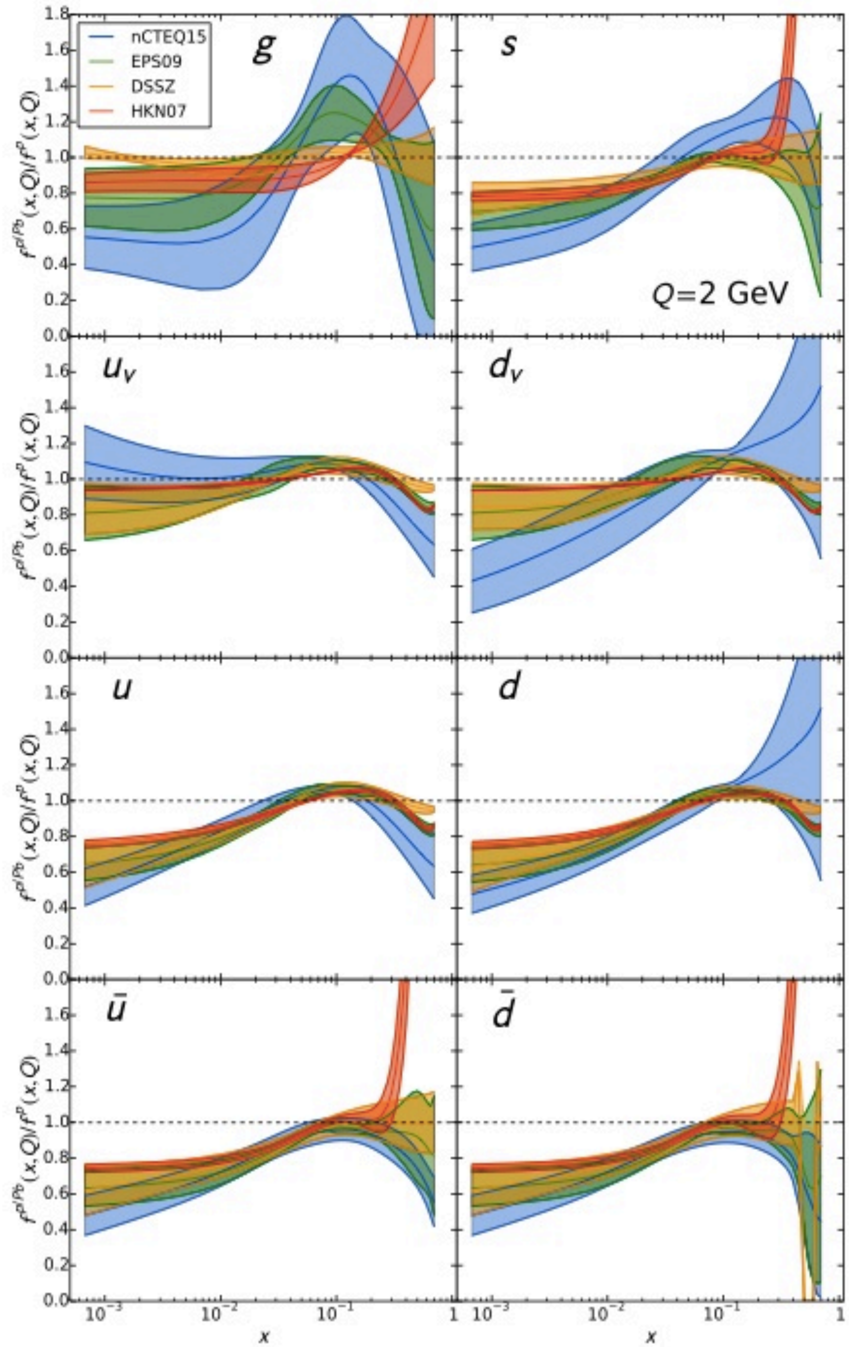
F_2 structure function modified in nuclear environment

- F_2 ratios measured in μ/e - A, but ***not in ν − A***

Good reasons to consider nuclear effects may be DIFFERENT in ν - A:

- Shadowing effects ~similar in Drell-Yan and DIS for x < 0.1, *BUT,* no Anti-Shadowing in Drell-Yan (in DIS 5-8% effect)
- Different probes sensitive to different partons
  - Global nuclear PDF fits suggest different nuclear effects for valence and sea
  - Isospin-dependent nuclear forces lead to flavor-dependence of nuclear PDFs (Cloet, Bentz, Thomas, Phys.Rev.Lett. 109 (2012) 182301)
  - F_L dominance in low Q neutrino, vanishes for charged lepton
  - Presence of axial-vector current
  - Coherence length differences for vector, axial vector masses

A variety of theory predictions...



nCTEQ15 PDFs

ν Nuclear Effects: The Axial-Vector Current and Shadowing

A weakly interacting particle may develop a strongly interacting fluctuation - small probability but, if it's lifetime is longer than the time of propagation through the nucleus, this fluctuation experiences nuclear shadowing

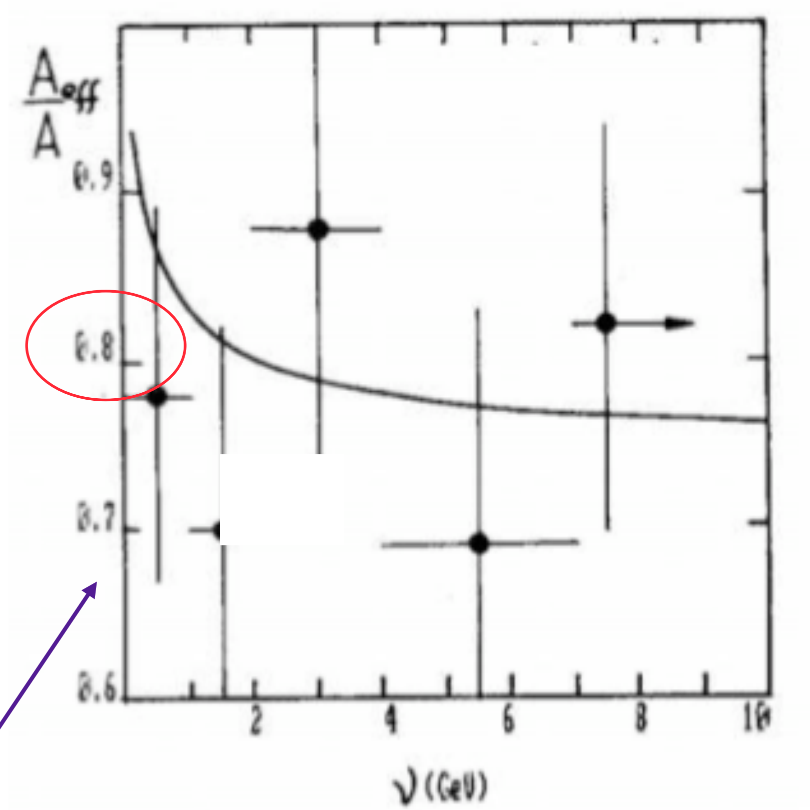
The axial-vector current allows shadowing *at lower ν* than the vector current (B. Kopeliovich, Nucl. Phys. Proc. Suppl. 139:219-225, 2005):

The coherence length, that governs when shadowing commences, is different for the axial-vector current compared to the vector current. Two scales:

$L_c = 2\nu / (m_\pi^2 + Q^2) \geq R_A$

L_c is ~100 times shorter* for heavier axial vector states, m_A^2, *allowing low ν, low Q^2 shadowing

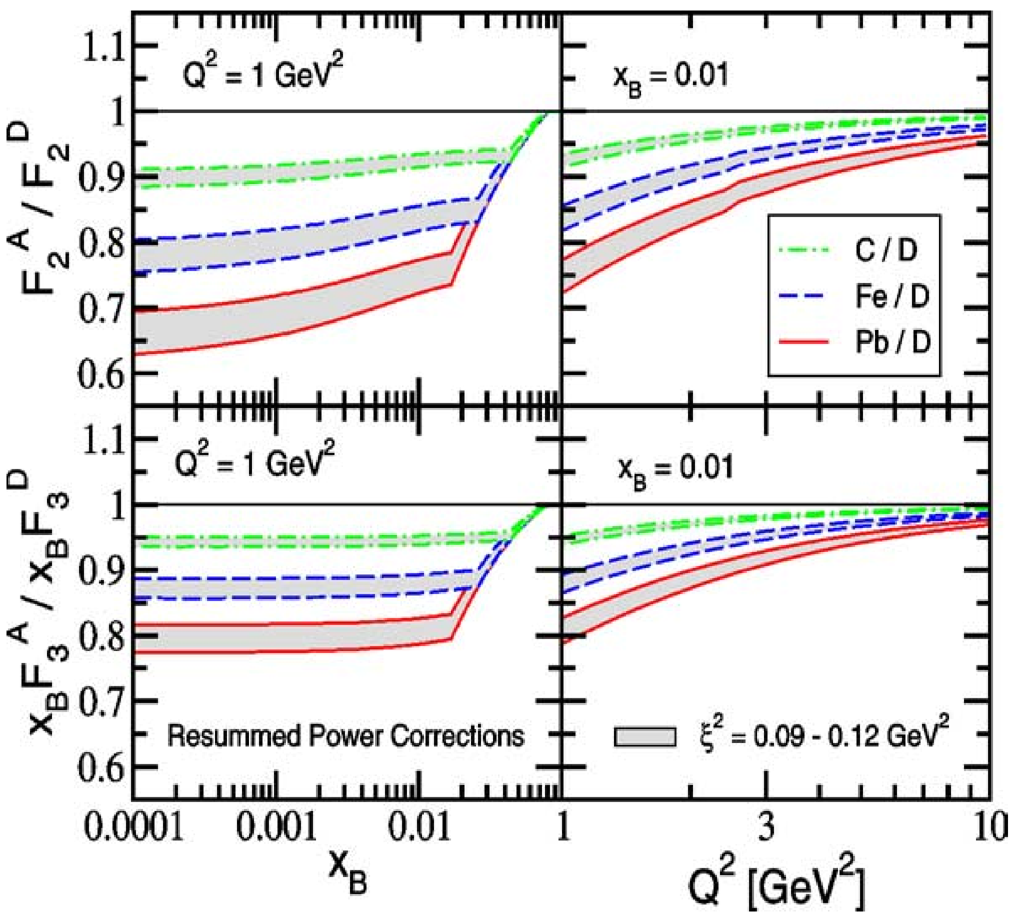
….seems to be borne out by existing (scant!) data



neon to proton ratio from BEBS for $x < 0.2$ and $Q^2 < 0.2$ GeV^2

More/Many Theory Predictions…

Qiu and Vitev, Phys. Lett. B **587**, 52 (2004)



- Sizeable, A-dependent effects in shadowing region (Frankfurt, V. Guzey, M. Strikman, Phys. Rept. 512, 255 (2012)
- Nuclear medium effects important, meson cloud contributions (Haider, Simo, Athar, and Vacas, Phys. Rev. C 84, 054610 Phys. Rev. C **84** 054610 (2011))
- Global analysis including nucleon binding, Fermi motion, off-shell effects,.. (Kulagin and Petti, Phys. Rev. D76:094023 bal 2007; Phys. Rev. C 90, 045204)
- More… *please accept my apologies for not mentioning all!*

Although nuclear effects in neutrino and charged lepton scattering are expected to be different, the effects ***observed in charged lepton scattering*** are applied directly to:

- neutrino interaction models and Monte Carlos.
  - Can effect neutrino oscillation experiments
- neutrino data as used in some global nuclear "nPDF" fits. The nPDFs are:
  - Sometimes input for the above
  - Employed regularly for numerous studies, such as p-A benchmarking [H. Honkanen, M. Strikman, V. Guzey]
  - Critical tool for studying nuclear medium modifications

Nuclear PDFs

The compatibility of neutrino and charged lepton nuclear DIS data within the universal, factorizable nuclear parton distribution functions has been studied independently by several groups.

nCTEQ:

Phys. Rev. D **77**, 054013 (2008)

Phys. Rev. D **80**, 094004 (2009)

Phys. Rev. Lett. **106**, 122301 (2011)

K. Kovarik et al., arXiv:1509.00792v2 (2015, accepted for publication)

Q > 2.0 GeV, W > 3.5 GeV
(standard CTEQ cuts)

A-dependence introduced directly into distributions at input scale Q = 1.3 GeV

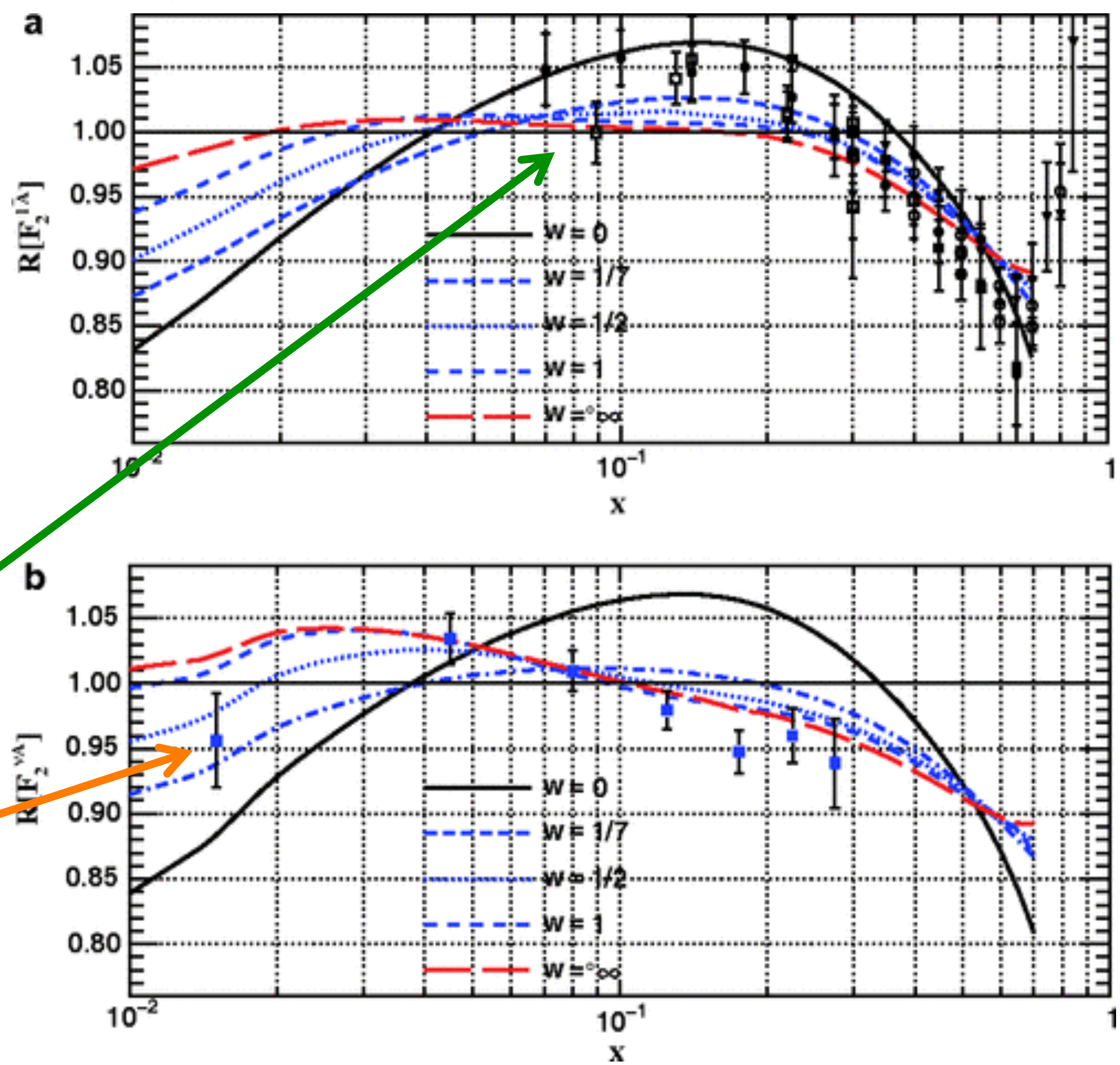
Use ACOT - heavy quark mass effects - in NLO QCD

Charged lepton data

Neutrino data

Fits with different weighting of neutrino data

$Q^2 = 5\ GeV^2$



ν-A dependence different from e/μ-A

Nuclear PDFs

BUT…

- Conclusions from different groups are contradictory, ranging from a violation of the universality up to a good agreement

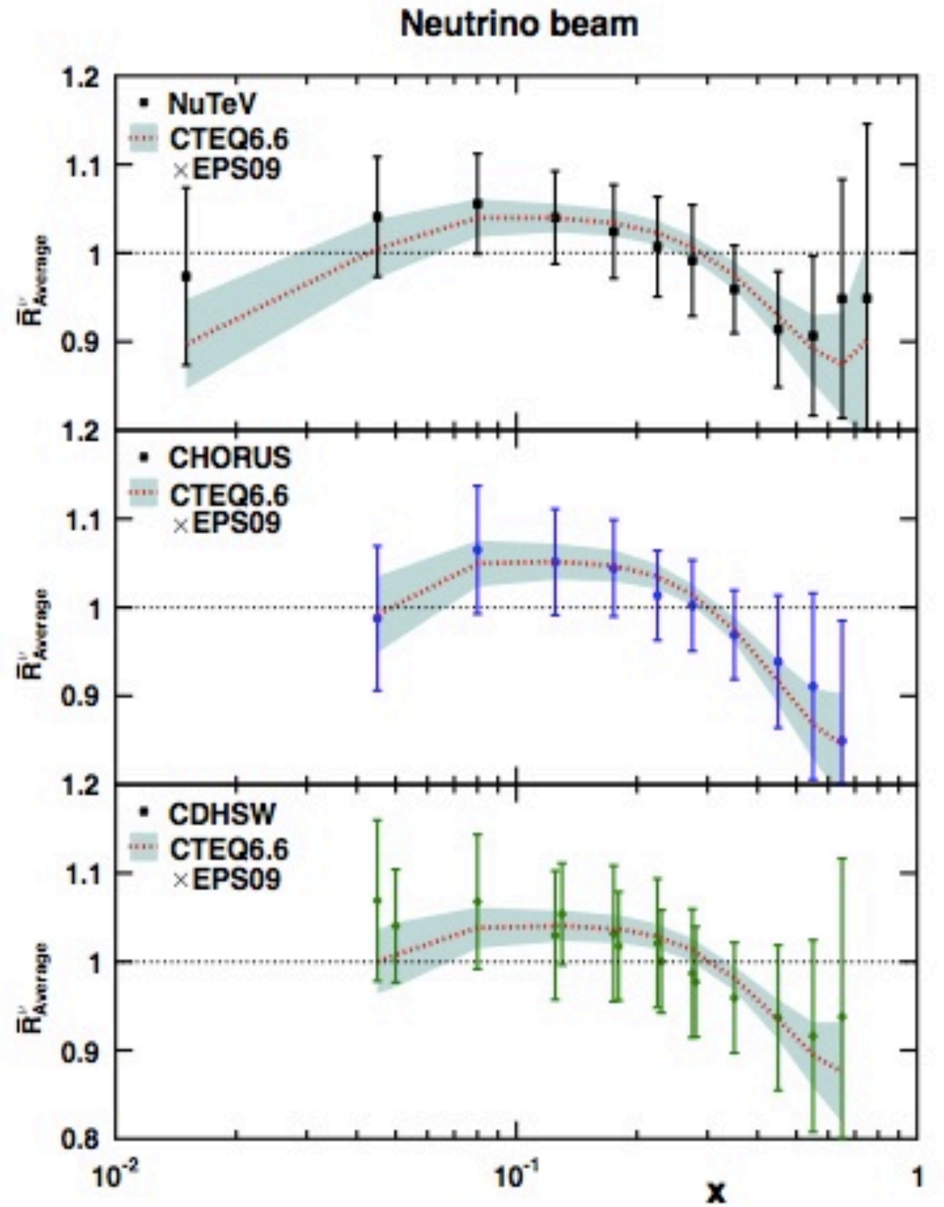
Example:

H. Paukkunen, C. Salgado, Phys.Rev.Lett.110:212301 (2013)

Consider non-negligible differences in the absolute normalization between different neutrino data sets… procedure to accommodate this.

With the normalization procedure, the NuTeV data seem to display tension with the other neutrino data.

ν-A dependence **compatible** with *e/μ-A*



What's going on?

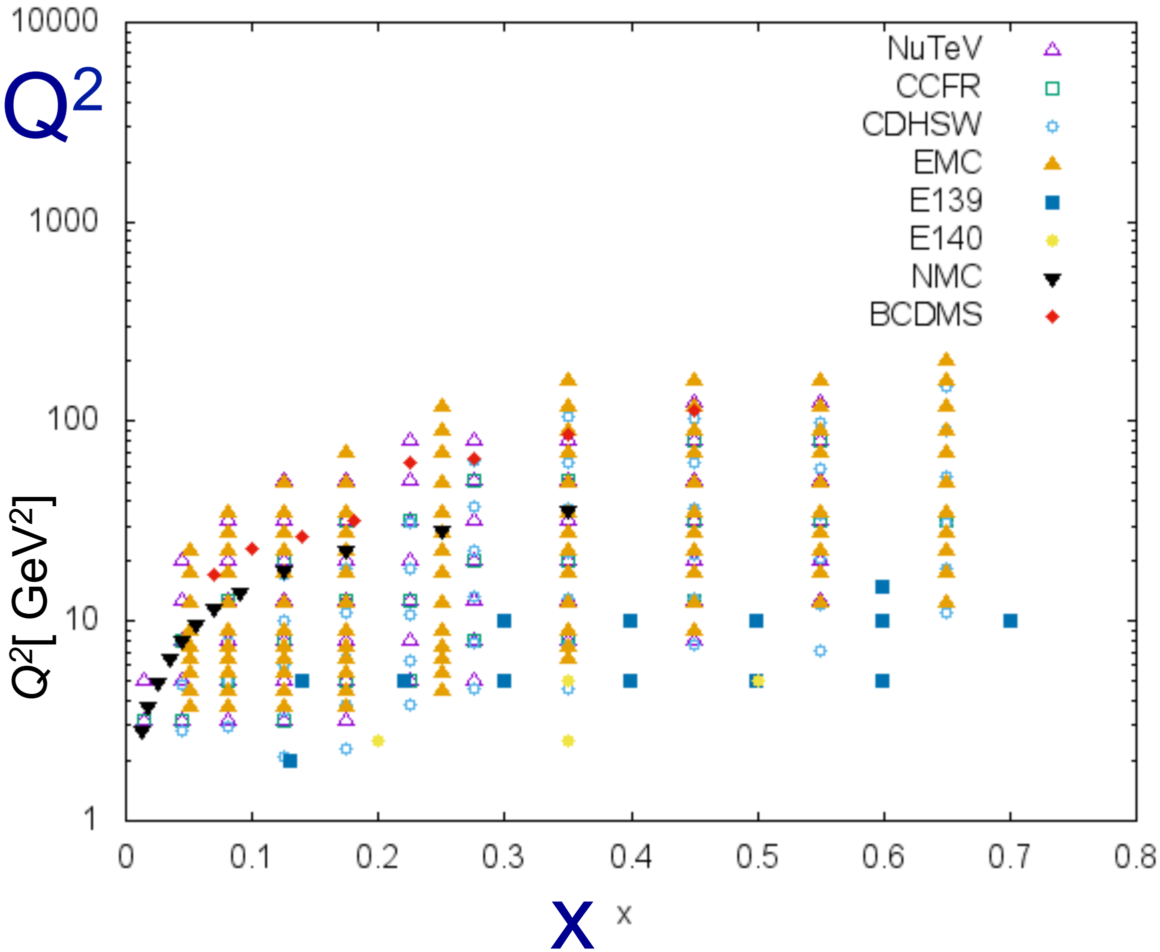
The nPDF efforts fit nuclear effects using the canonical F_2^A/F_2^D ratios as a function of x

However, there are essentially NO neutrino F_2^D data!

Comparisons are necessarily to *modeled* deuterium data

*We decided to try and compare **only** F_2^A data*
- starting with Fe, largest data set covering both charged lepton and neutrino data over a range of x,Q….

World F^{Fe}_2 Data



Wide range in x, Q^2!

Neutrino Expts ***(open symbols)***: CCFR, CDHSW, NuTeV

Charged Lepton (e/μ) Expts: BCDMS, EMC, E140, E139,NMC

Most available at Durham data base:

http://hepdata.cedar.ac.uk/review/f2/

E139 cross sections available at: slac/stanford.edu/exp/e139/

- used parameterization of R to get F_2

BCDMS and NMC were available in ratios of Fe to D

- used fit of F_2^D from NMC to obtain F_2^{Fe}

Evaluated model dependence of the above

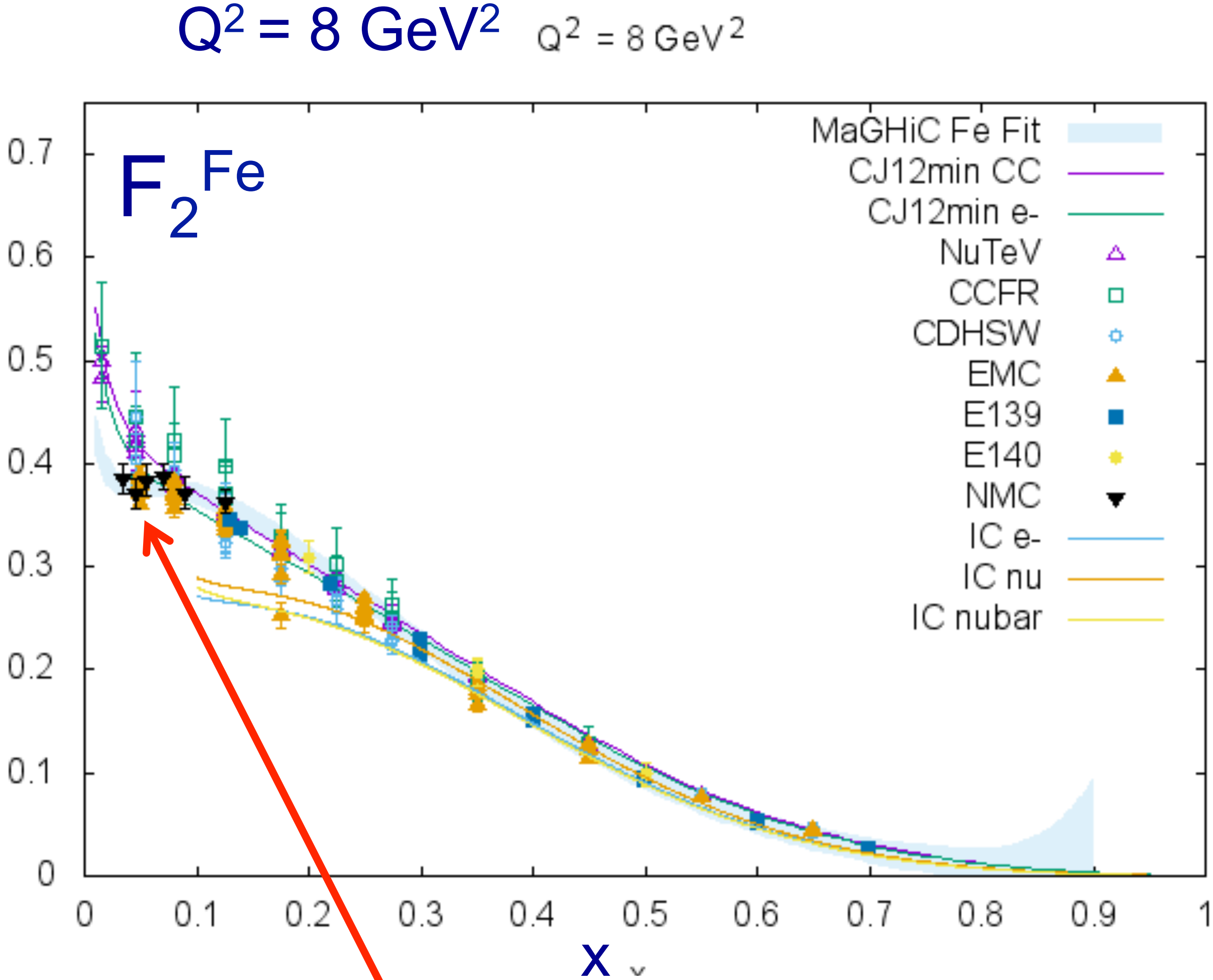
Analysis

- All data used were iso-scalar corrected when published. We did not alter these corrections, used data as presented.
  - Large at small *x* for neutrino, and large x for charged leptons
  - Correction is SMALL for Fe
- Applied "DIS" cuts; $Q^2 > 2$, $W^2 > 4$ GeV^2
- Set F^{Fe}_2 data to a common Q^2 (bin-centering) using NMC fit*, checked for dependence on this fit
- Neutrino data are a flux-weighted average of nu, nubar data
- Multiply neutrino data by 5/18 to account for quark charges.

*H.Abramowicz, A.Levy, hep-ph/9712415,
Q^2 dependent, with F2n/F2p added by A. Bruell

Results: F_2^{Fe} Data – NOT a ratio to deuterium!

$Q^2 = 8$ GeV^2



LARGE discrepancy at small x between neutrino and charged lepton data

Neutrino data open symbols, charged lepton closed

$2 < Q^2 < 20$ GeV^2, bin-centered to 8 GeV^2

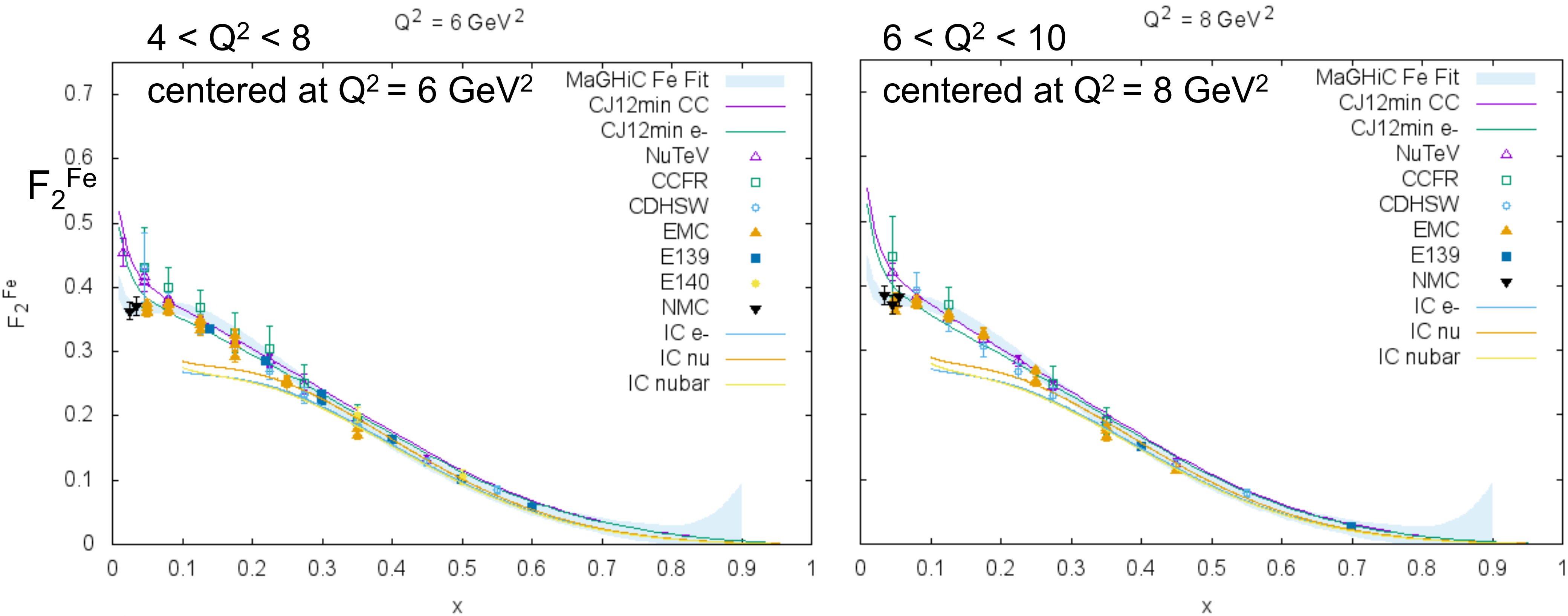
MaGHiC fit is to charged lepton data (Malace, Gaskell, Higinboham, Cloet, Int. J. Mod. Phys. E 23 (2014) 1430013)

Cloet fit is valence only
 - good agreement!

Charged lepton data agree with charged lepton and neutrino data with neutrino

Remarkable agreement of all data at x > 0.1, 18/5 works within ~5%

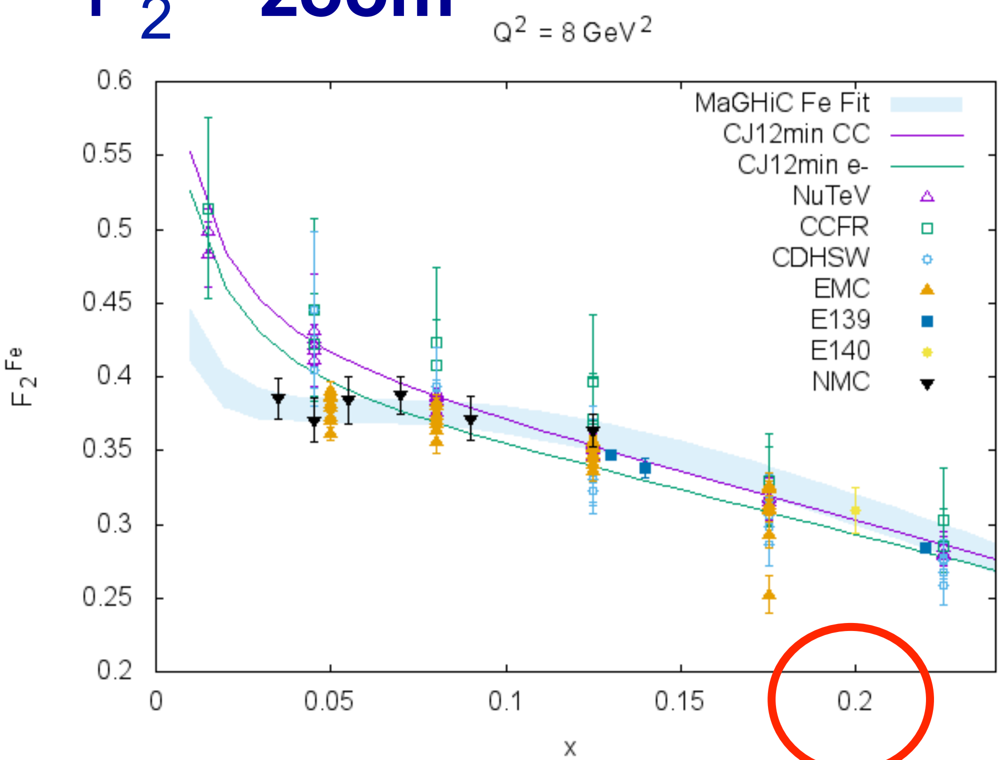
Smaller bins in Q^2



- Same observations:
  - remarkably good agreement of neutrino, charged lepton at large x
  - surprisingly bad at small x
- Both CJ and Cloet theory curves are shown with both electron and CC
  - Should depict size of strangeness difference
  - Does not account for large discrepancy at low x
- Charged lepton data agree with MaGHiC fit – not surprising
- Neutrino data seem to be in agreement with CJ12min fit (Phys. Rev. D **87** 094012 (2013))
  - no nuclear effects taken in to account, just add free neutrons and protons

Look closer

F_2^{Fe} zoom

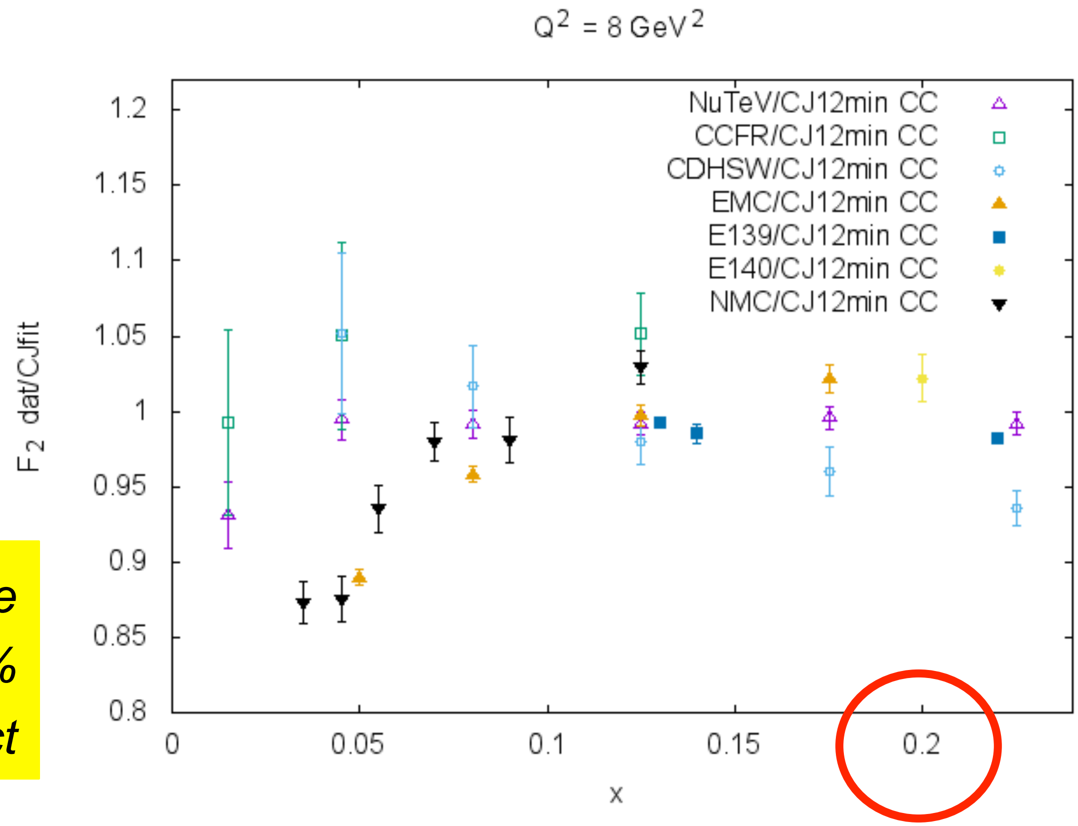


Note relatively good agreement of neutrino data sets (open symbols) – *no normalization factors applied*

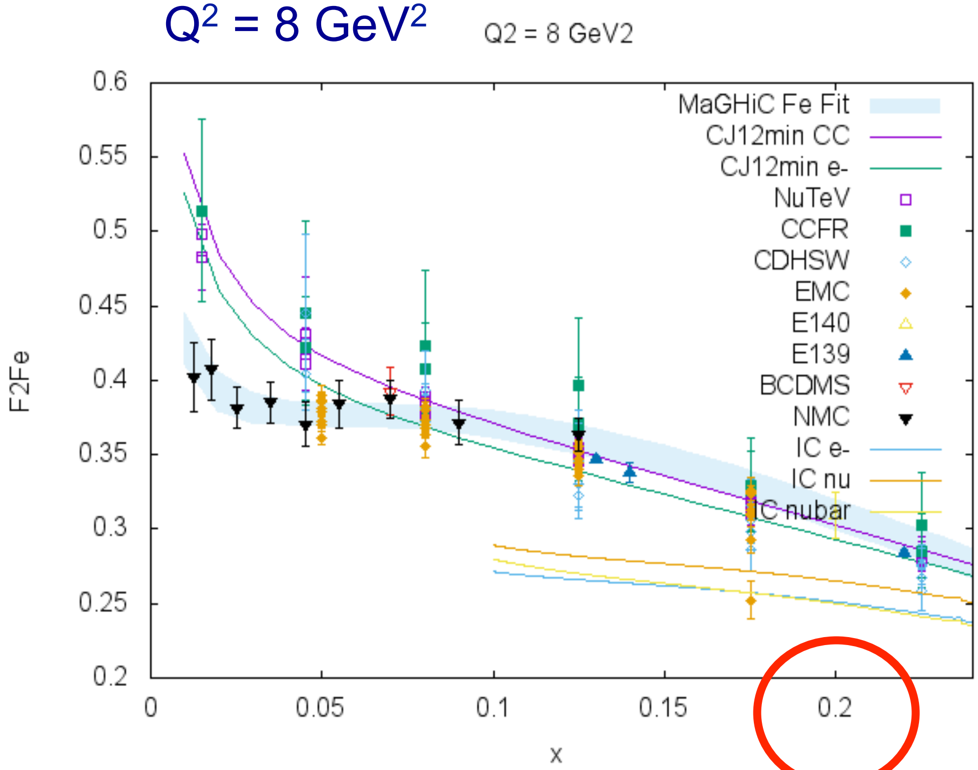
Looks to be ~10-15% effect

Ratio to CJ electron, at lowest x:

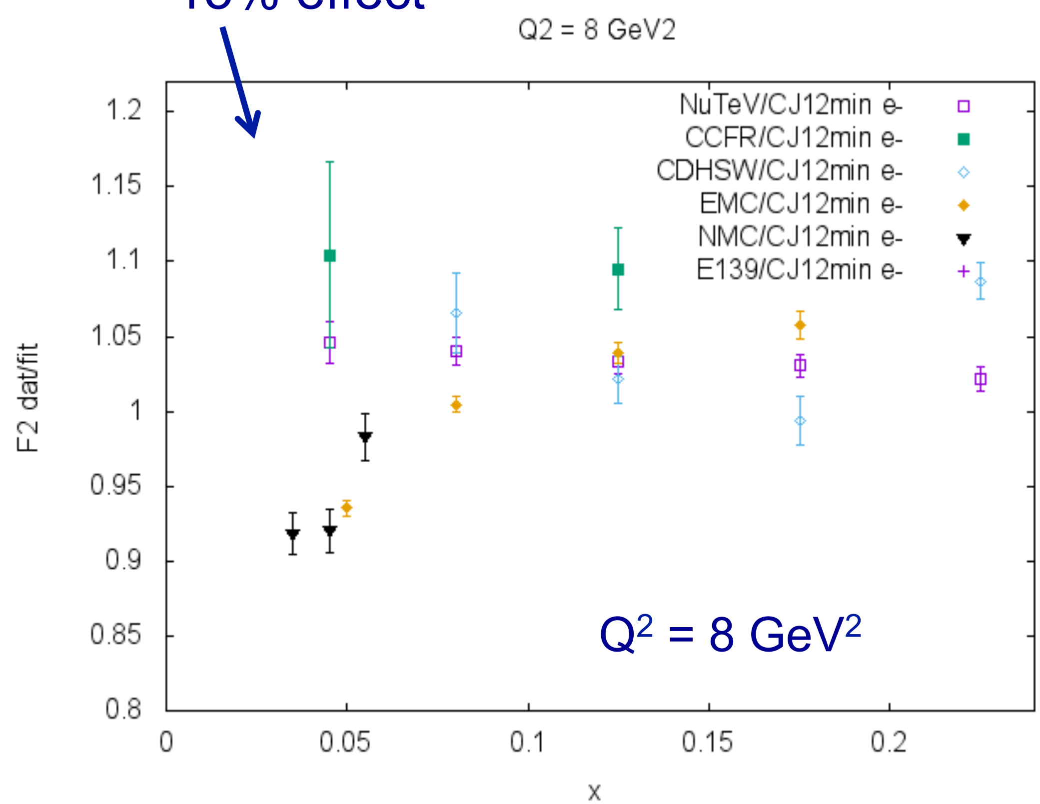
- Neutrino data ratio ~1
- Charged lepton ratio < 0.9

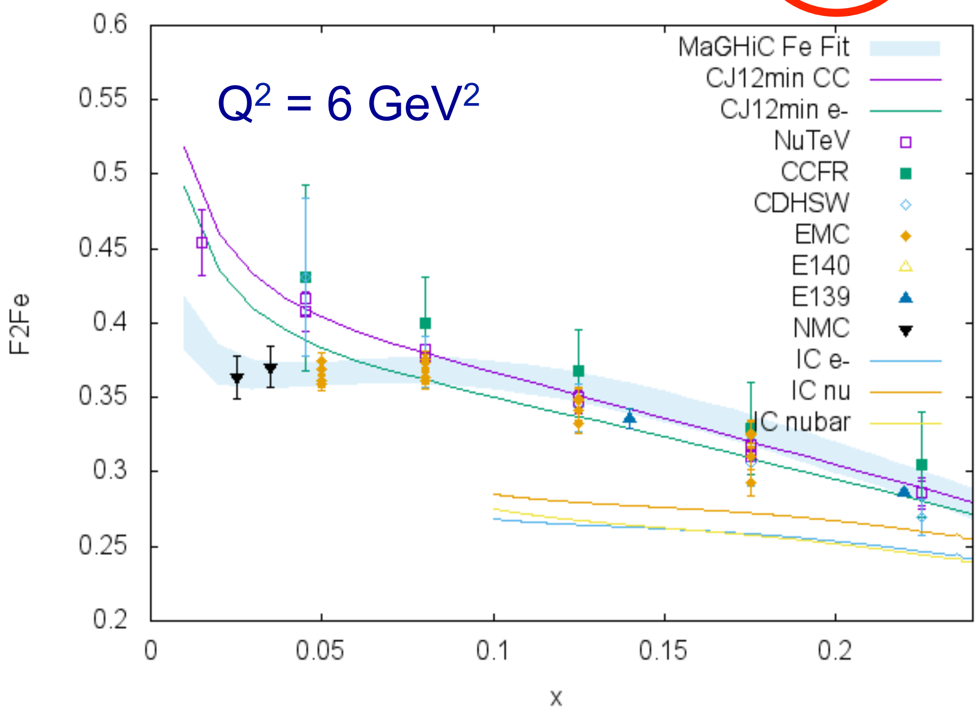


$Q^2 = 8\ GeV^2$

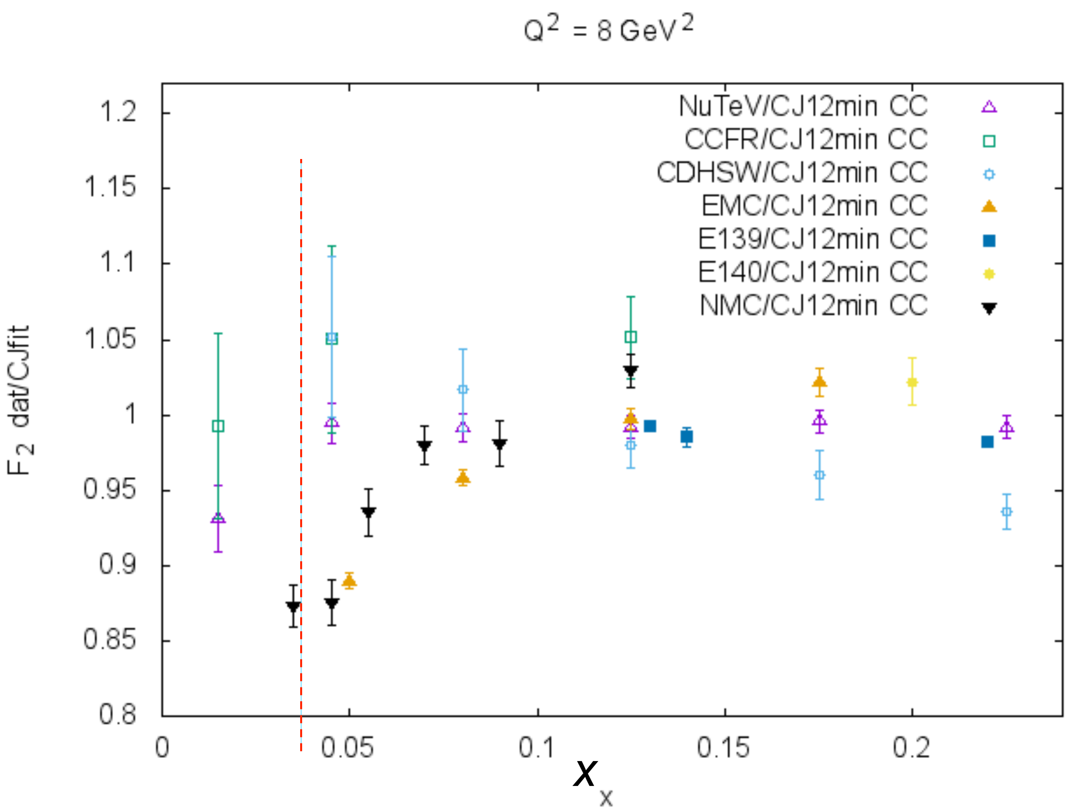


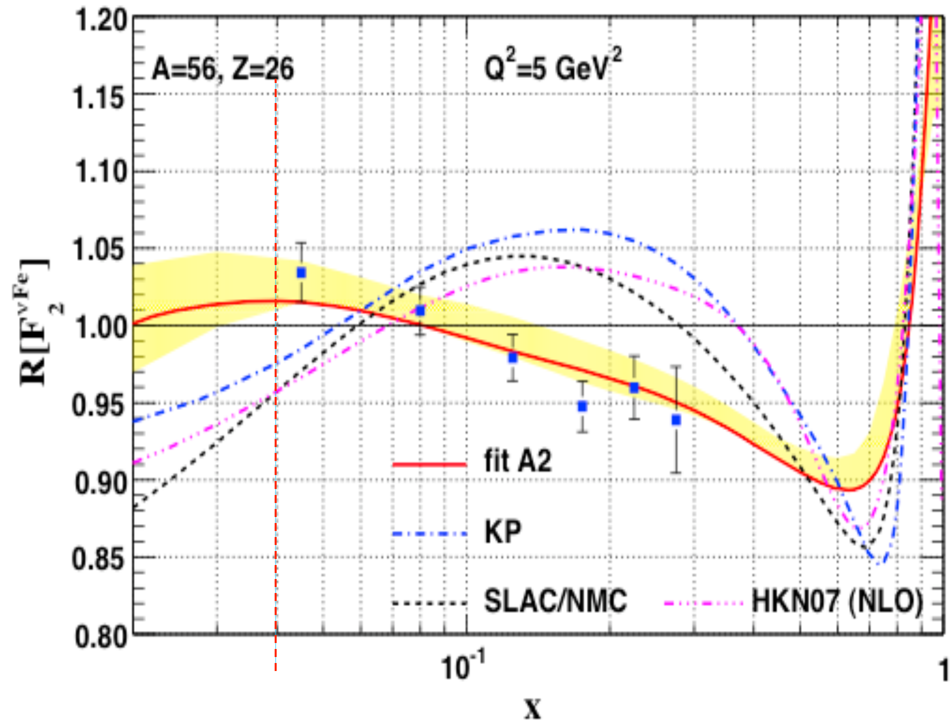
- Still working on final Q^2 binning choices
- Studied higher Q also, same effect but harder to see on steeply rising low x curve
- Ratio to CJ electron, consistent ~15% effect





Compare with nCTEQ





- *Same trend*, perhaps somewhat larger effect in data
- Deuteron model in nCTEQ could make some difference

Possible Explanations

Strangeness contribution?

Too small… can glean by comparing CJ CC and CJ e-

Isoscalar Corrections?

Too small in Fe to account for this (~1-few %)

Fit/Theory predictions?

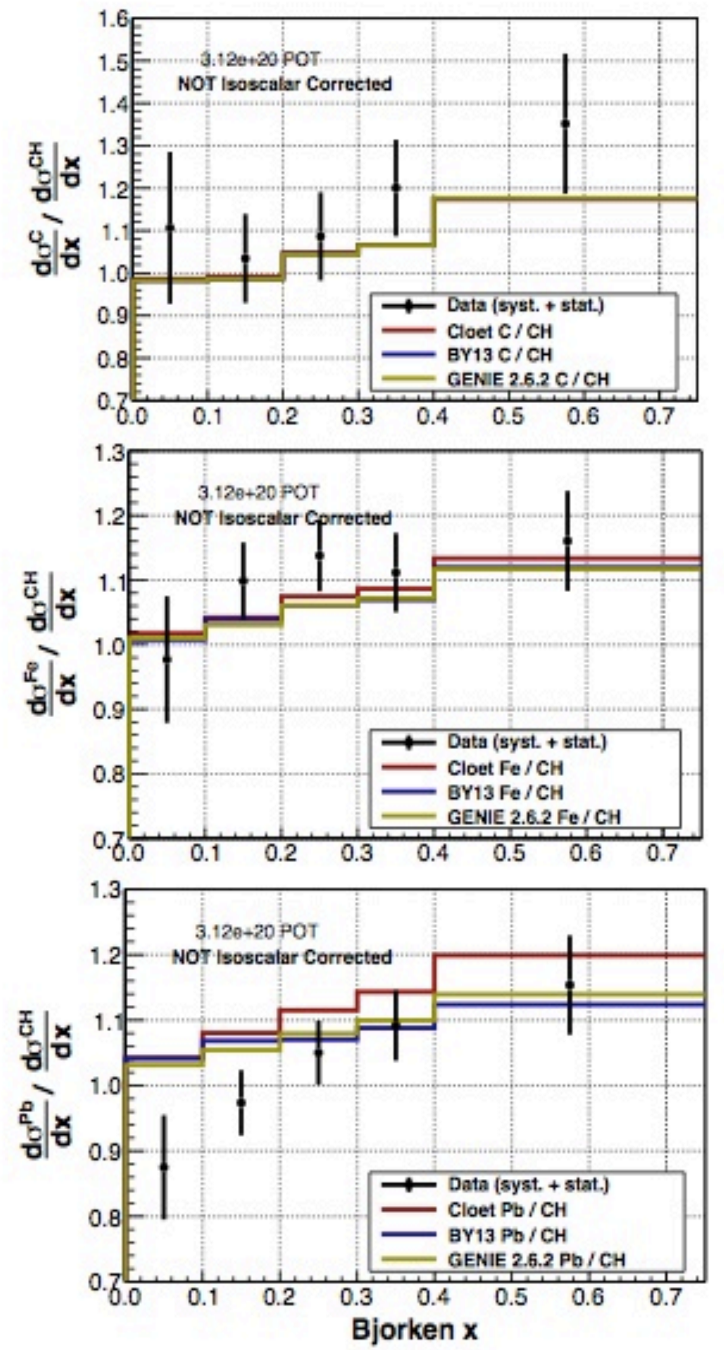
- Many predictions (earlier slides), most predict enhanced shadowing for neutrinos
- Shadowing onset could be at lower x for neutrinos
- Some qualitatively predict this

Not completely new..

- C. Boros, J.T. Londergan, A.W. Thomas, Phys.Rev.Lett. 81 4075 *(1998!)*
- CCFR and NMC only, smaller data set available
- *Ascribed discrepancy to CSV*

Need more low *x* nuclear DIS data!....

Experimental Studies of Nuclear Effects with Neutrinos: *until recently essentially NON-EXISTENT*



J. Mousseau et al., PRL **112** 231801 (2015)

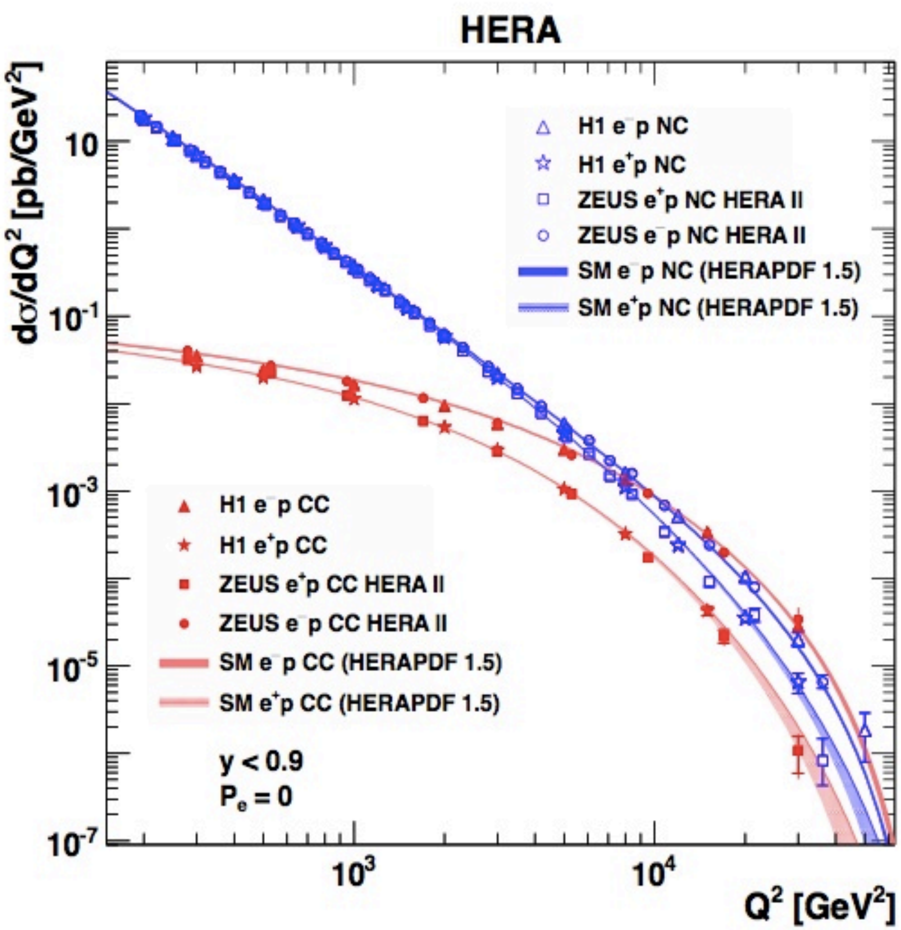
Data now coming from MINERvA experiment at Fermilab:

- Neutrino-nucleus scattering
- Cross section measurements possible
- Nuclear ratios

Note *A*-dependence at lowest *x*-bin

- A drop in x for Pb?
- Data at low Q^2 (< 1 GeV^2)
- Not yet isoscalar corrected
- Taking higher energy data this year

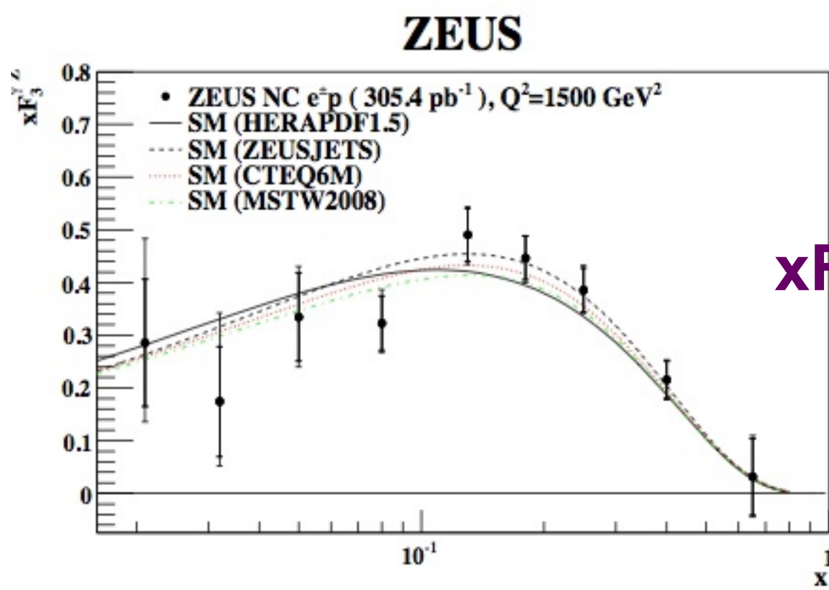
EIC should be uniquely able to help



Charged current red

Neutral current blue

- All of the $x < .05$ charged lepton data are from NMC – will be important to check with another experiment
- Too low in x, high in Q for JLab12
- Simulations just started, EIC x,Q range is optimal
- Should be able to distinguish neutral and charged current events a la HERA
- Straightforward e-A experiment



xF_3

Summary

- Studied Structure Function F_2 in Iron by comparing available global data from charged lepton and neutrino probes
- Good agreement of data sets at large x (above x ~ 0.1) achieved with simple 18/5 current algebra
- Observe disparate behavior between the 2 types of data below x ~ 0.1:
  - Neutrino data consistent with CJ no nuclear medium modifications
  - ~15% different from charged lepton, which displays shadowing suppression
- Publication draft prepared, to be submitted soon
- On to Pb and nuclear ratios next
- Looking forward to MINERvA and the EIC!

This work done with N. Kalantarians

Thanks!

Backups

Different probes sensitive to different partons (V. Guzey)

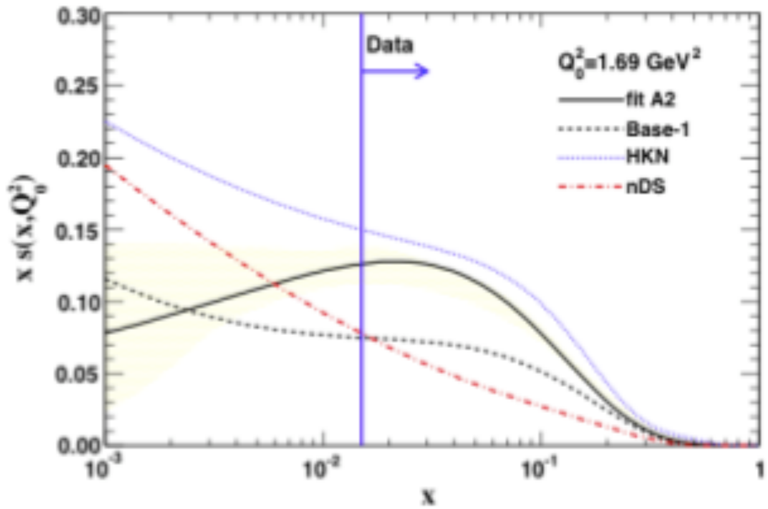
- In leading order:

$$\frac{d\sigma^{\nu A}}{dxdy} = \frac{G_F^2 M_W^4}{(Q^2+M_W^2)^2}\frac{ME}{\pi}2x\left[d^A + s^A + (1-y)^2(\bar{u}^A + \bar{c}^A)\right]$$

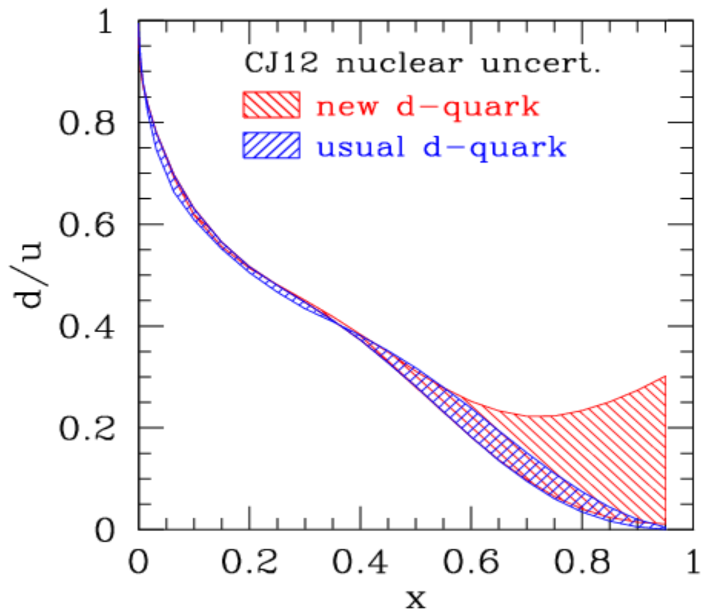
$$\frac{d\sigma^{\bar{\nu} A}}{dxdy} = \frac{G_F^2 M_W^4}{(Q^2+M_W^2)^2}\frac{ME}{\pi}2x\left[\bar{d}^A + \bar{s}^A + (1-y)^2(u^A + c^A)\right]$$

- In the shadowing region at low-x, y is large and the σ are primarily probing the d- and s-quarks.
- This is very different from charged lepton scattering where the d- and s-quarks are reduced by a factor of 4 compared to the u- and c-quarks.

- Negligible shadowing of the d- or s-quark consistent with the NuTeV results.



Isoscalar Corrections



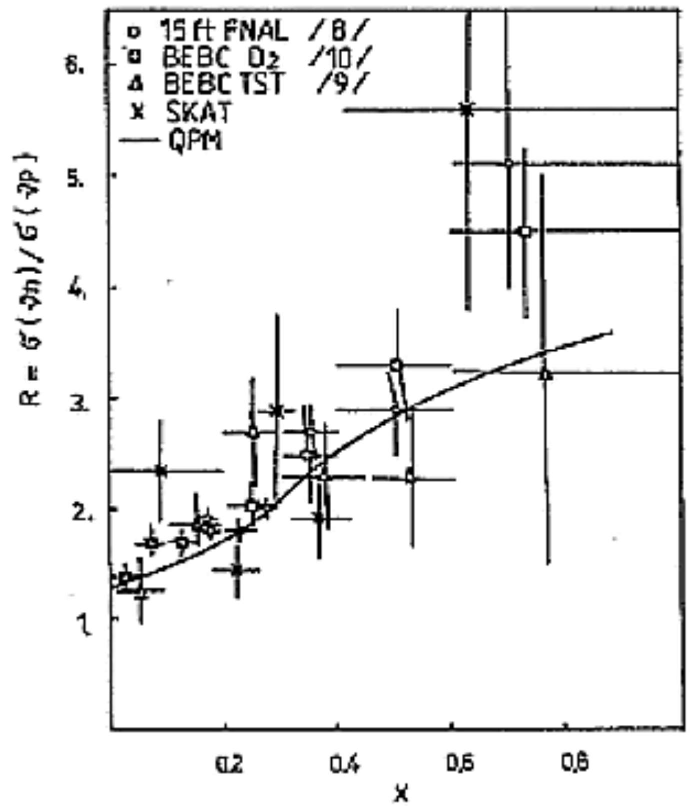
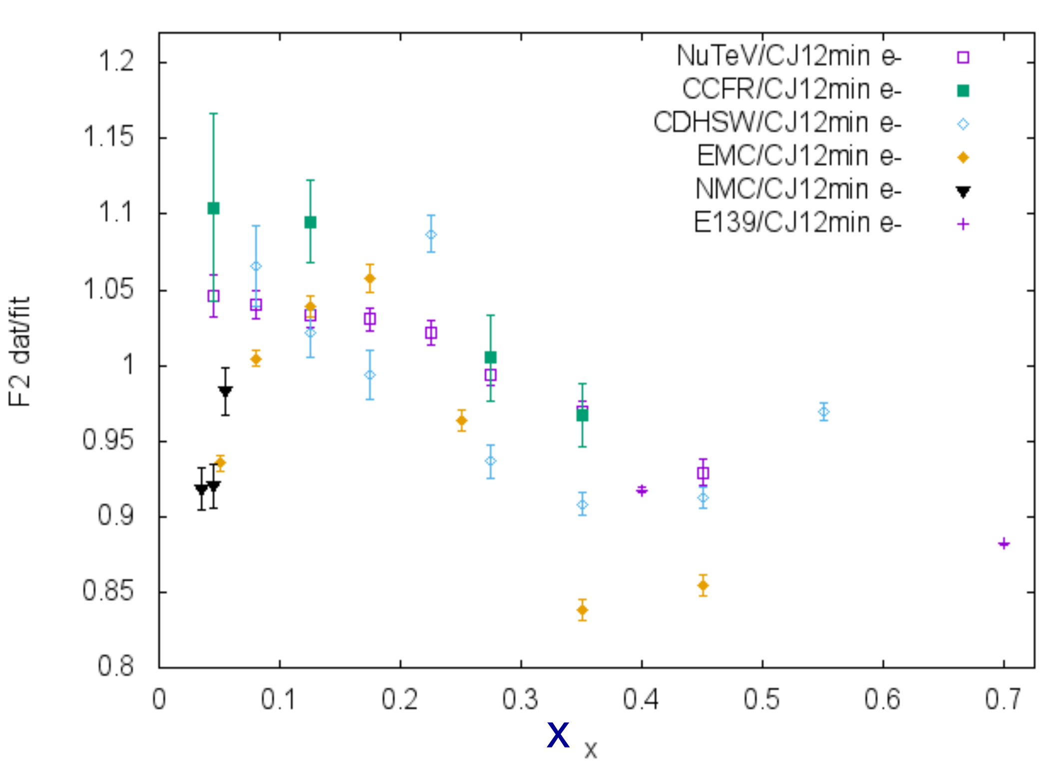


Fig. 4. World data of the dependence of the cross section ratio $\sigma(\nu n)/\sigma(\nu p)$ on Bjorken-x measured in neutrino bubble chamber experiments. The full line gives the prediction of the quark parton model [1, 2] using the parametrisation of the quark distributions by Feynman-Field [5]

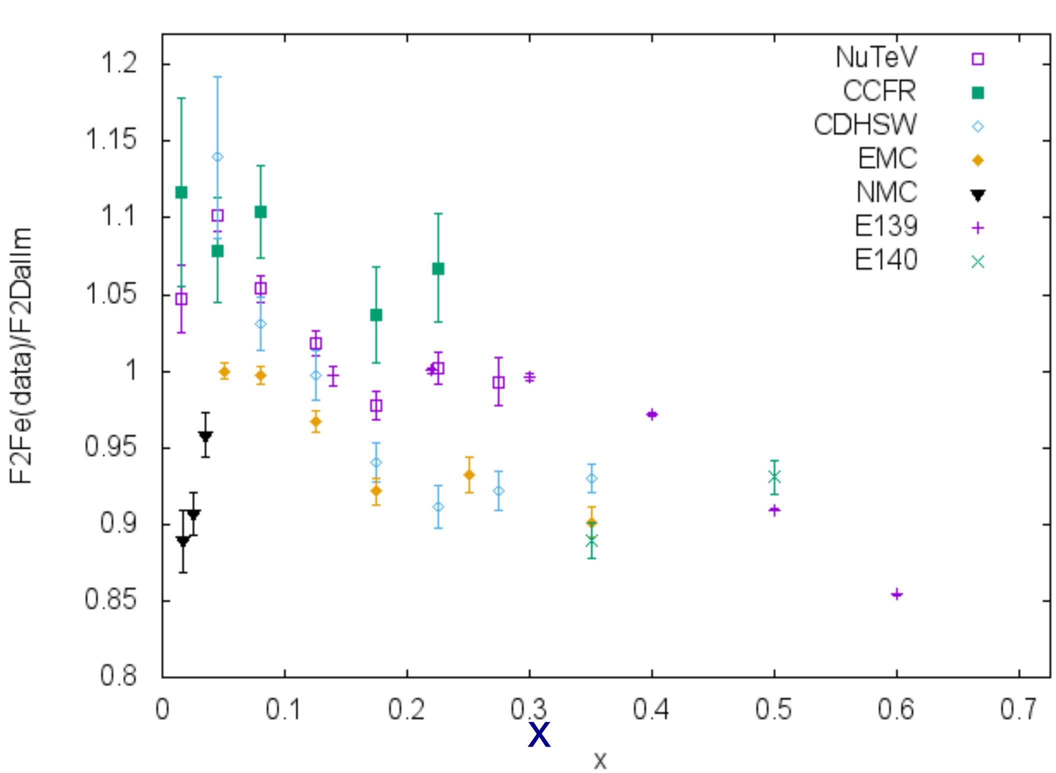
- Phenomenologically different for charged lepton and neutrino scattering.
- Large at small *x* for neutrino, and large x for charged leptons.
- Neutrinos prefer to couple to u or d via $W^{+/-}$, charged leptons couple to either and have to account for quark charge.

Look closer – large x

Data/CJ



Data/NMC Fit



- Data/CJ is nuclear/(n + p), using CJ electron
- Data/NMC is over fit to NMC deuterium data
- Should NOT look as clean as ratios we are used to
  – F_2^A has Q^2 dependence that F_2^A/F_2^D doesn't
- That said, we can see the EMC effect at large x
  - It's just small!

Charged lepton scattering:

$$\frac{d^2\sigma^{e^\pm p}}{dxdy} = \frac{4\pi\alpha^2 s}{Q^4}\left[(1-y)F_2(x,Q^2) + y^2 x F_1(x,Q^2)\right]$$

$F_2 = (F_L + 2xF_1)/(1+\nu^2/Q^2)$, $R = F_L / 2xF_1$

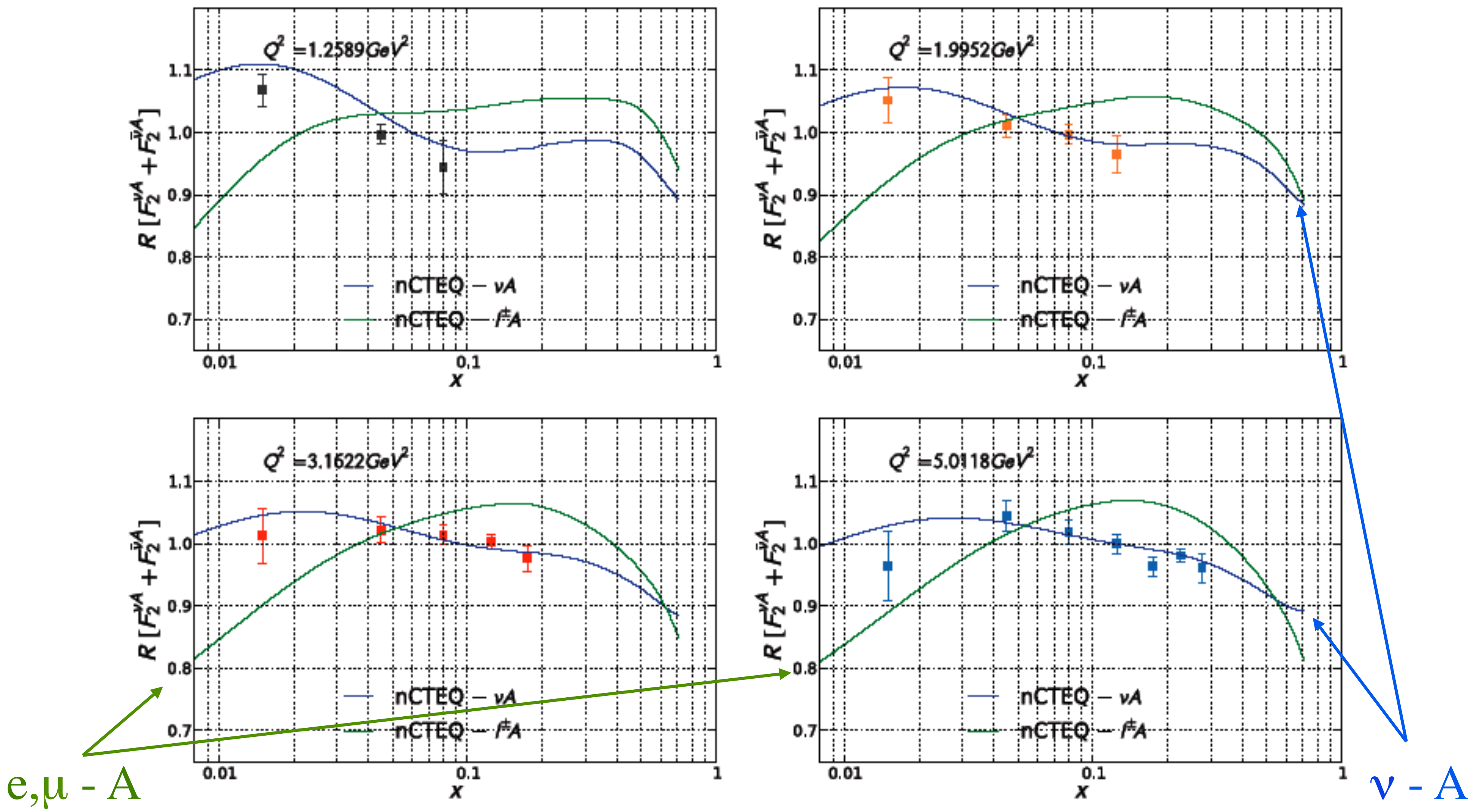
Neutrino scattering:

$$\frac{d^2\sigma^{\nu(\overline{\nu})}}{dxdy} = \frac{G_F^2 ME}{\pi}\left(\left[1 - y\left(1+\frac{Mx}{2E}\right) + \frac{y^2}{2} \times \left(\frac{1+\left(\frac{2Mx}{Q}\right)^2}{1+\mathcal{R}}\right)\right]\mathcal{F}_2 \pm \left[y - \frac{y^2}{2}\right]x\mathcal{F}_3\right)$$

- In (anti) neutrino scattering, cross sections at low Q^2 are dominated by F_L
  - F_L driven by axial current interactions
  - Divergence of axial-vector current proportional to pion field (PCAC)

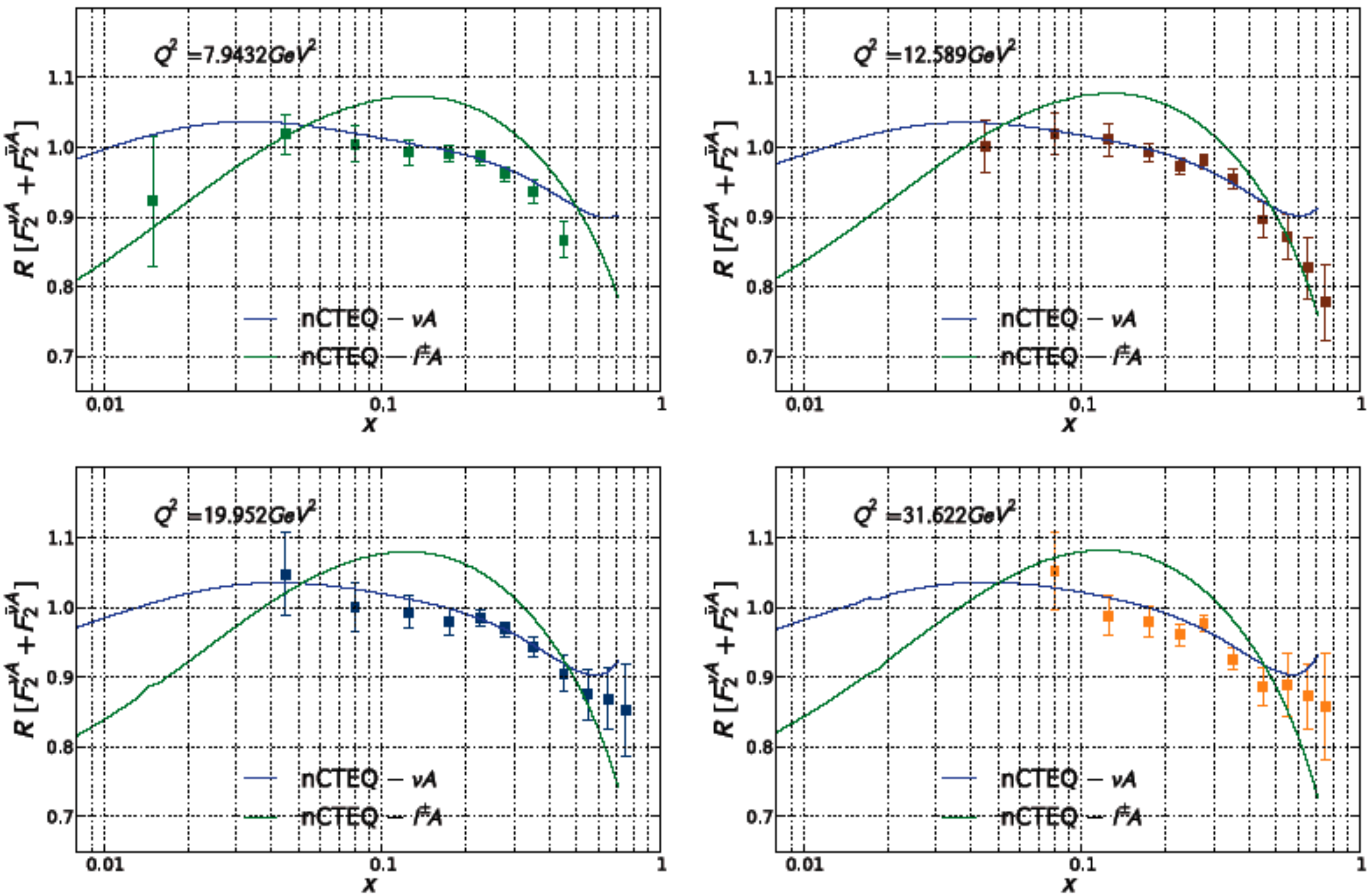
BUT…..R (and hence F_L) is difficult to measure….

A more detailed look at nCTEQ fit differences



- NLO QCD calculation of $(F_2^{\nu A} + F_2^{\nu barA})/2$ in the ACOT-VFN scheme
  - Charged lepton fit undershoots at low x and overshoots at moderate x
  - Compared here with NuTeV data

A more detailed look at differences - higher Q^2



- Neutrino data cause tension with the shadowing, anti-shadowing, EMC regions of charged lepton data

Multiply neutrino data by 5/18 to plot with charged lepton

280 Quark-Quark Interactions: The Parton Model and QCD

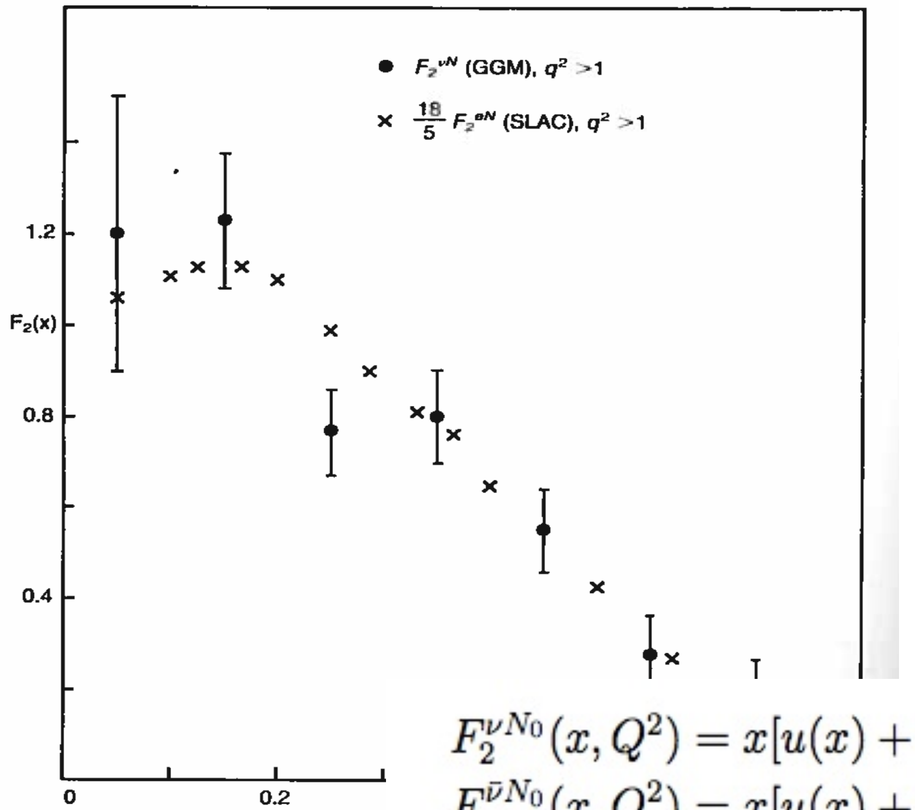


Figure 8.12 (a) First comparison of F
Gargamelle heavy-liquid bubble chamber
F_2^{eN} from electron-nucleon scattering, in th
the electron points are multiplied by the f
charge of u- and d-quarks in the nucle
assignments for the quarks. Note that t
momentum fraction in the nucleon carri
ascribed to gluon constituents, which are

Accounts for quark charge coupling present in charged lepton scattering but not in neutrino scattering.

Holds at leading order

$$F_2^{\nu N}(x) \leq \tfrac{18}{5} F_2^{eN}(x)$$

$$F_2^{\nu N_0}(x,Q^2) = x[u(x) + \bar{u}(x) + d(x) + \bar{d}(x) + 2s(x) + 2\bar{c}(x) - \delta u(x) - \delta\bar{d}(x)]$$
$$F_2^{\bar{\nu} N_0}(x,Q^2) = x[u(x) + \bar{u}(x) + d(x) + \bar{d}(x) + 2\bar{s}(x) + 2c(x) - \delta d(x) - \delta\bar{u}(x)]$$
$$xF_3^{\nu N_0}(x,Q^2) = x[u(x) + d(x) - \bar{u}(x) - \bar{d}(x) + 2s(x) - 2\bar{c}(x) - \delta u(x) + \delta\bar{d}(x)]$$
$$xF_3^{\bar{\nu} N_0}(x,Q^2) = x[u(x) + d(x) - \bar{u}(x) - \bar{d}(x) - 2\bar{s}(x) + 2c(x) - \delta d(x) + \delta\bar{u}(x)]$$
$$F_2^{\ell N_0}(x,Q^2) = \frac{5}{18} x[u(x) + \bar{u}(x) + d(x) + \bar{d}(x) + \frac{2}{5}(s(x) + \bar{s}(x)) + \frac{8}{5}(c(x) + \bar{c}(x)) - \frac{4}{5}(\delta d(x) + \delta\bar{d}(x)) - \frac{1}{5}(\delta u(x) + \delta\bar{u}(x))]$$

Nuclear Effects: Global analysis also predicts differences

Includes nucleon binding and Fermi motion, off-shell effects – sea vs valence
(Kulagin and Petti, Phys. Rev. D76:094023 2007; Phys. Rev. C 90, 045204)