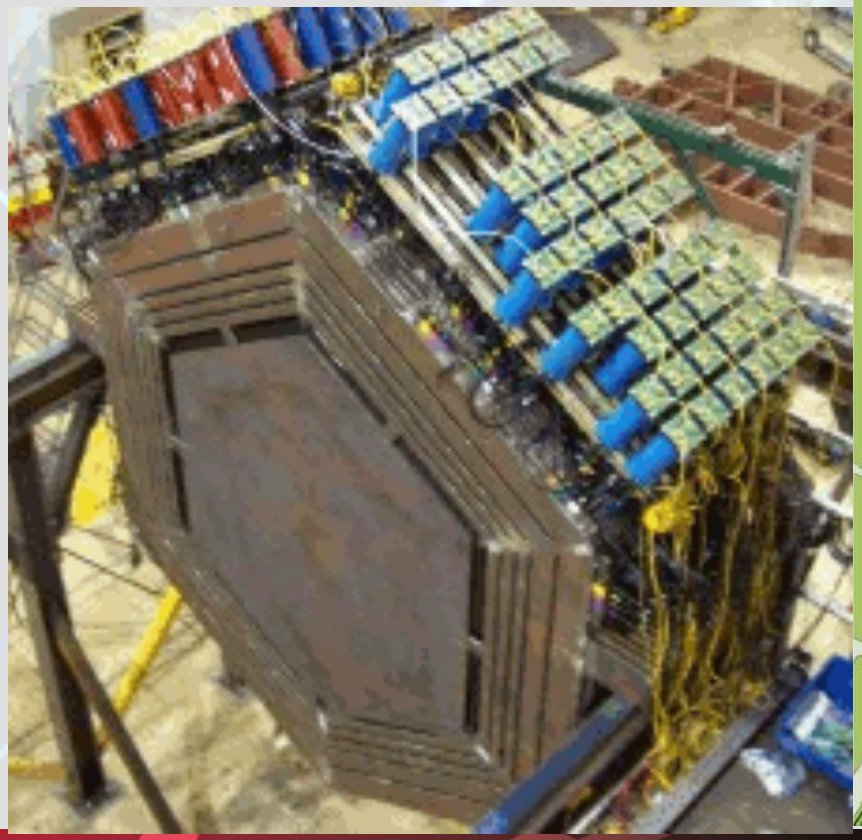
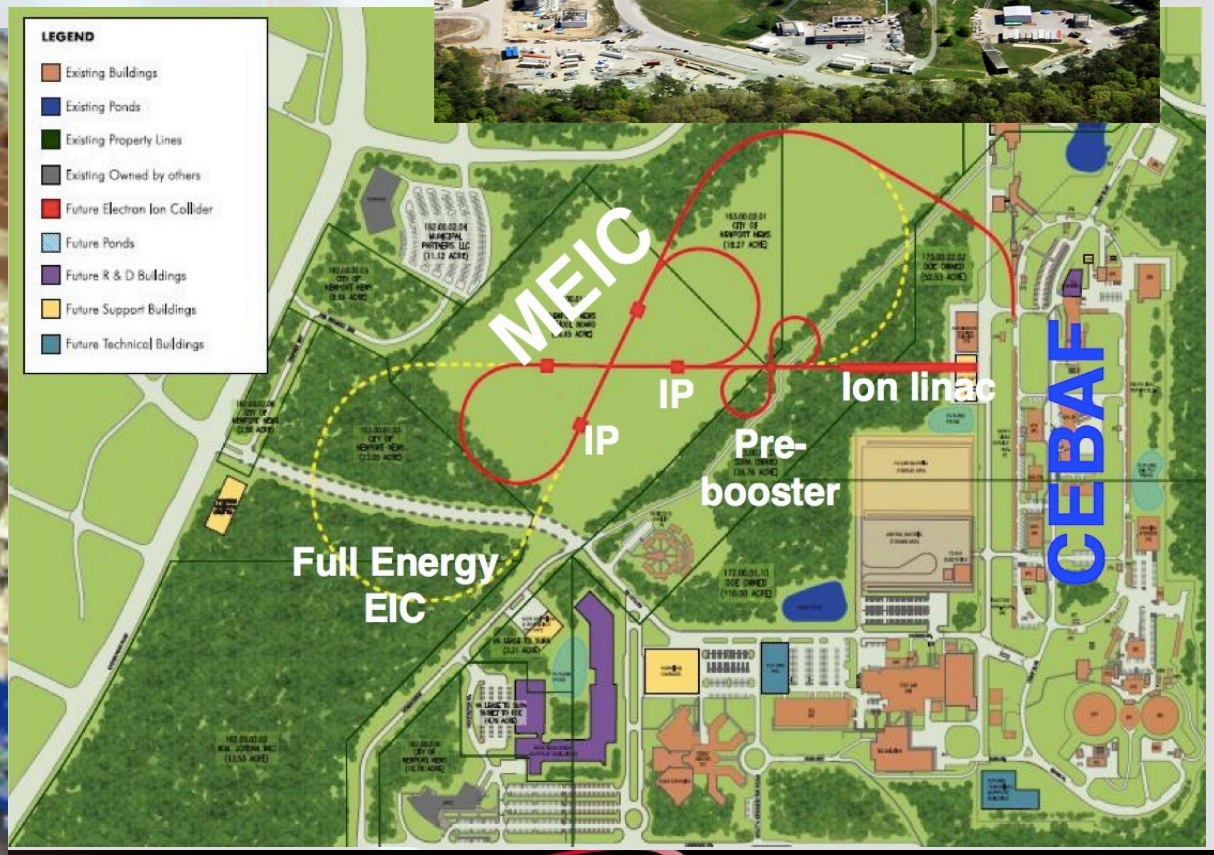
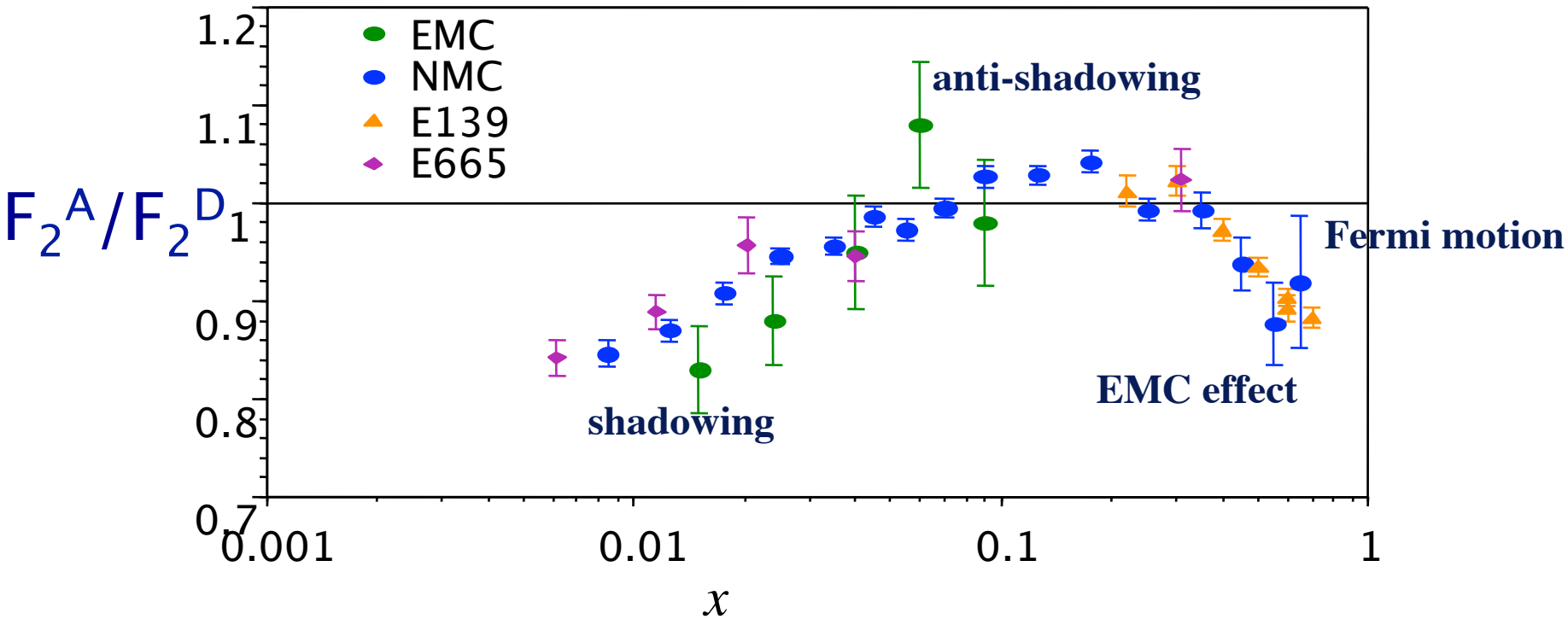
Comparison of F_2^{Fe} as Measured by Charged Leptons and Neutrinos

~~*Thia Keppel*~~ *Jorge G. Morfín*





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



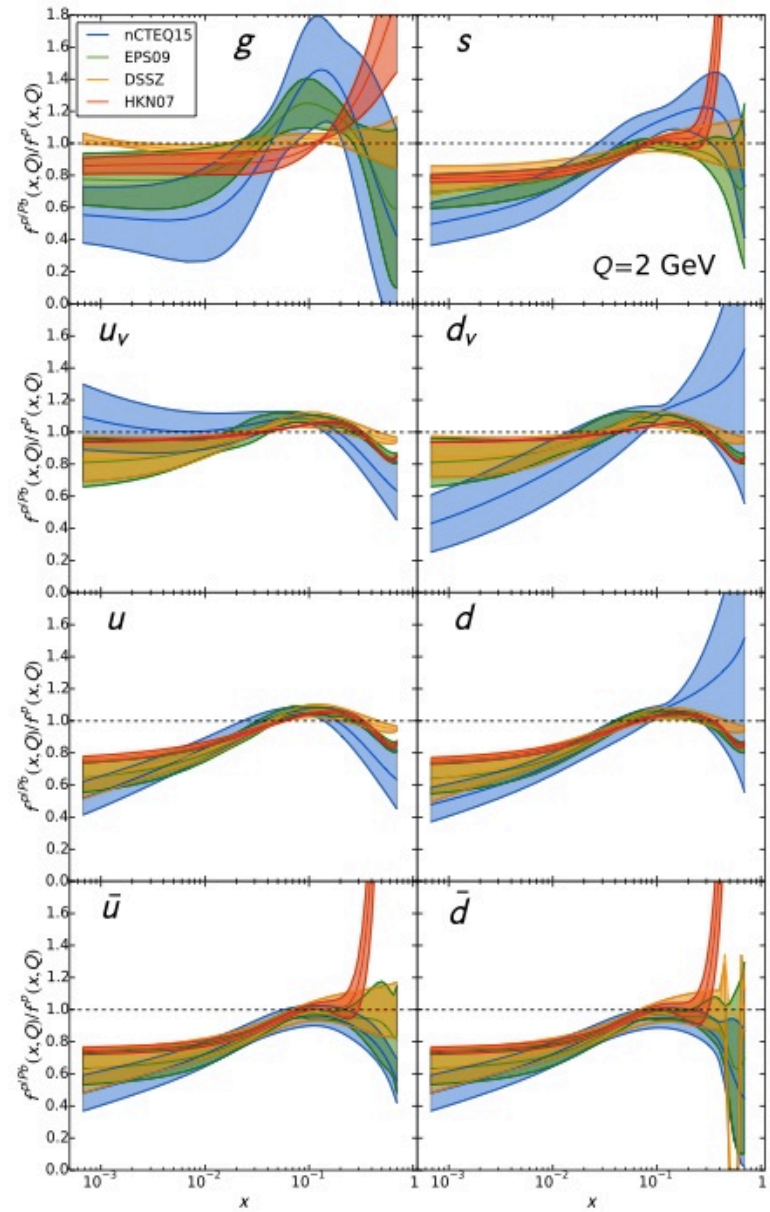
General and once surprising statement:

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

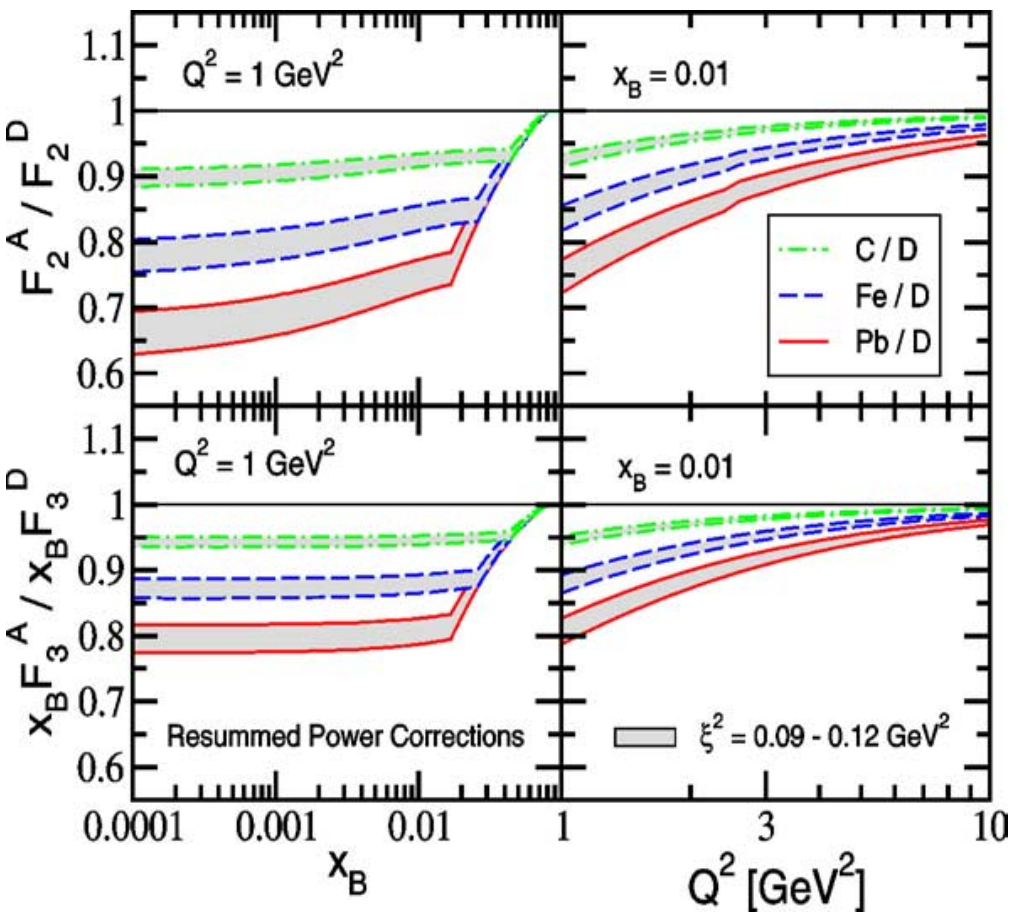


nCTEQ15 *– F p(Pb) / F (p)*

A variety of theory predictions…

Many Theory Predictions…

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



- The axial-vector current allows shadowing *at higher x_{BJ}* than the vector current (B. Kopeliovich, J.G. Morfin and I. Schmidt) Prog.Part.Nucl.Physics 68 314 (2013)
- Sizeable, A-dependent effects in shadowing region (Frankfurt, V. Guzey, M. Strikman, Phys. Rept. 512, 255 (2012)
- 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!*

Challenge for Neutrino Experiments

Although nuclear effects in neutrino and charged lepton scattering are expected to be different, the effects *observed in charged lepton scattering* are still today 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

Neutrino vs. Charged Lepton 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), Phys. Rev. D **93** (2016) 085037

1) Q > 2.0 GeV, W > 3.5 GeV
2) A-dependence introduced directly into distributions at input scale Q = 1.3 GeV
3) Use ACOT – heavy quark mass in NLO QCD

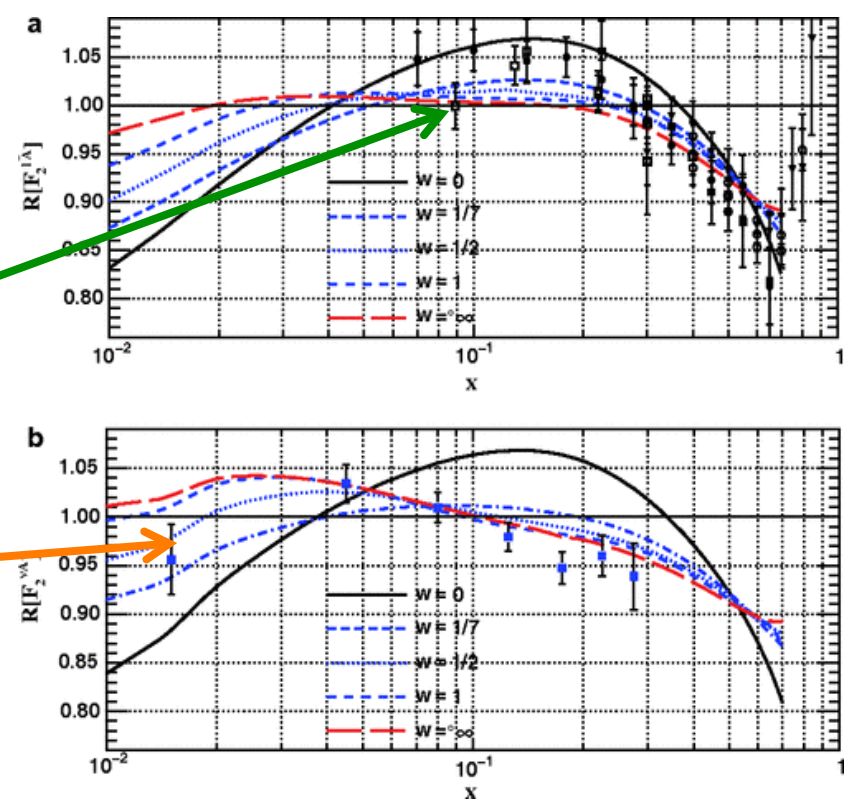
Charged lepton data

Neutrino data

ν–A dependence different from e/μ–A

$Q^2 = 5\ \mathrm{GeV}^2$

Fits with different weighting of neutrino data



BUT…

- Conclusions from different groups are contradictory, ranging from a violation of the universality up to a good agreement. Not all groups use cross sections (as opposed to structure functions) and the full covariant error matrix in the analysis

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!

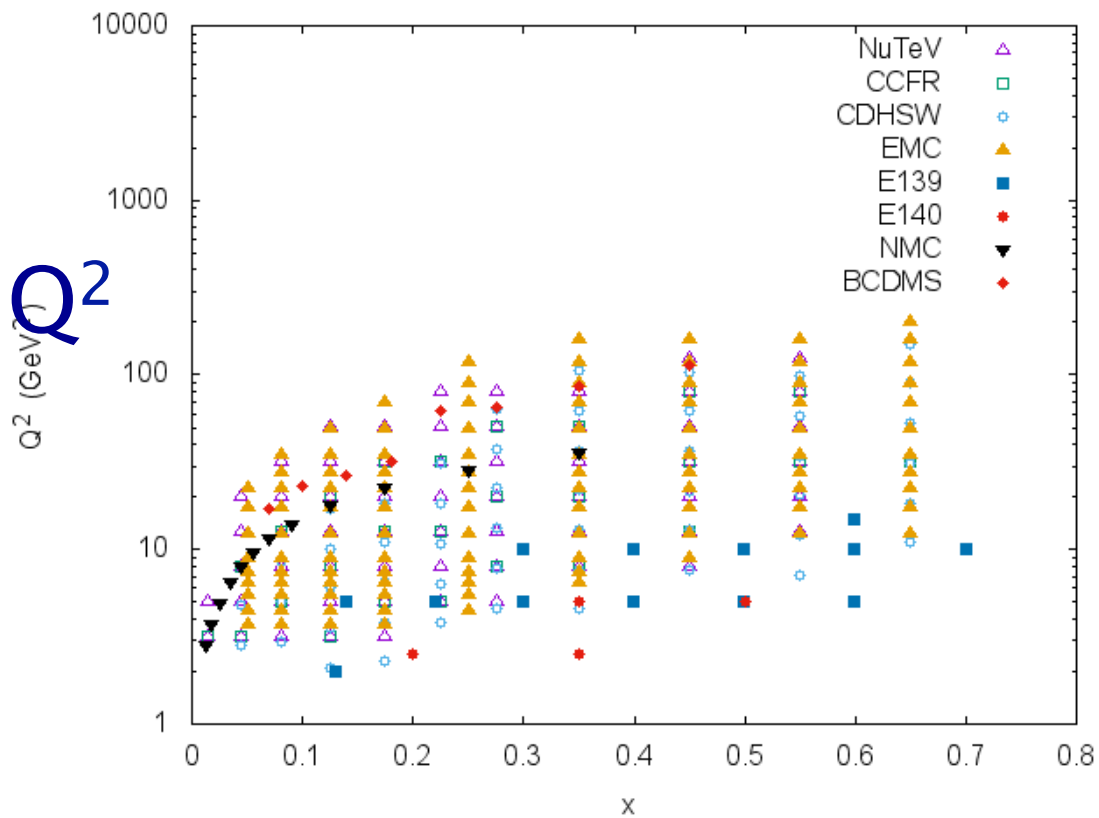
Comparisons are necessarily to *modeled* denominator using PDFs determined from free nucleon data.

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^2

* ***N. Kalantarians, M.E. Christy, C. Keppel, arXiv:1706:02002 (2017)***

World F_2^{Fe} Data



Wide range in x, Q^2!

Neutrino Expts **(OPEN SYMBOLS):**
CCFR, CDHSW, NuTeV

Charged Lepton (e/μ) Expts **(CLOSED SYMBOLS):**
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

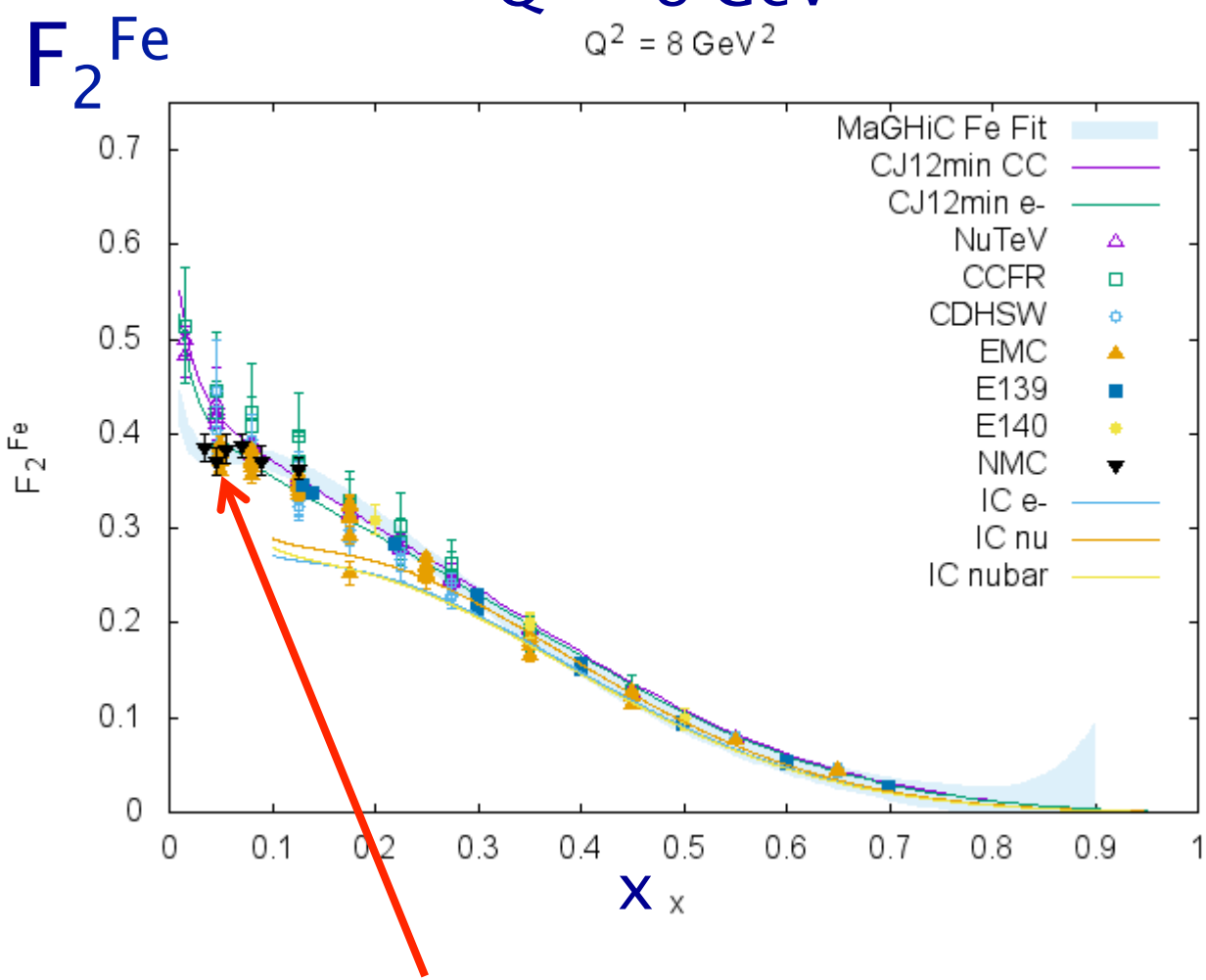
Analysis

- 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_2^{Fe} 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!

$Q^2 = 8\ GeV^2$



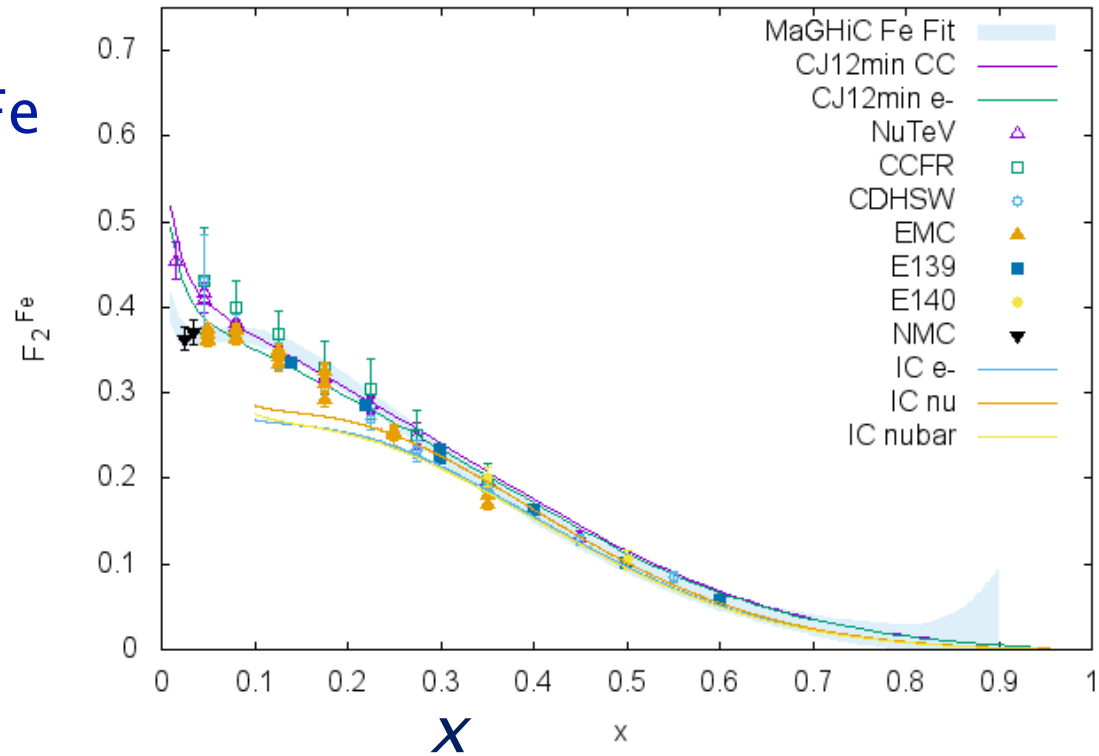
LARGE discrepancy at small x between neutrino and charged lepton data

- All data in range **$2 < Q^2 < 20$** 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)
  - Lower x constrained by data from other nuclei
- Cloet calculation is *valence quark only*
  - good agreement!
- Charged lepton data agree with charged lepton and neutrino with neutrino
- Remarkable agreement of all data at $x > 0.1$
  - **18/5 works within ~5%**

Check different/smaller binning in Q^2

$Q^2 = 6\ \mathrm{GeV}^2$ $Q^2 = 8\ \mathrm{GeV}^2$

F_2^{Fe}



Data now from range
$4 < Q^2 < 8$ GeV^2

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

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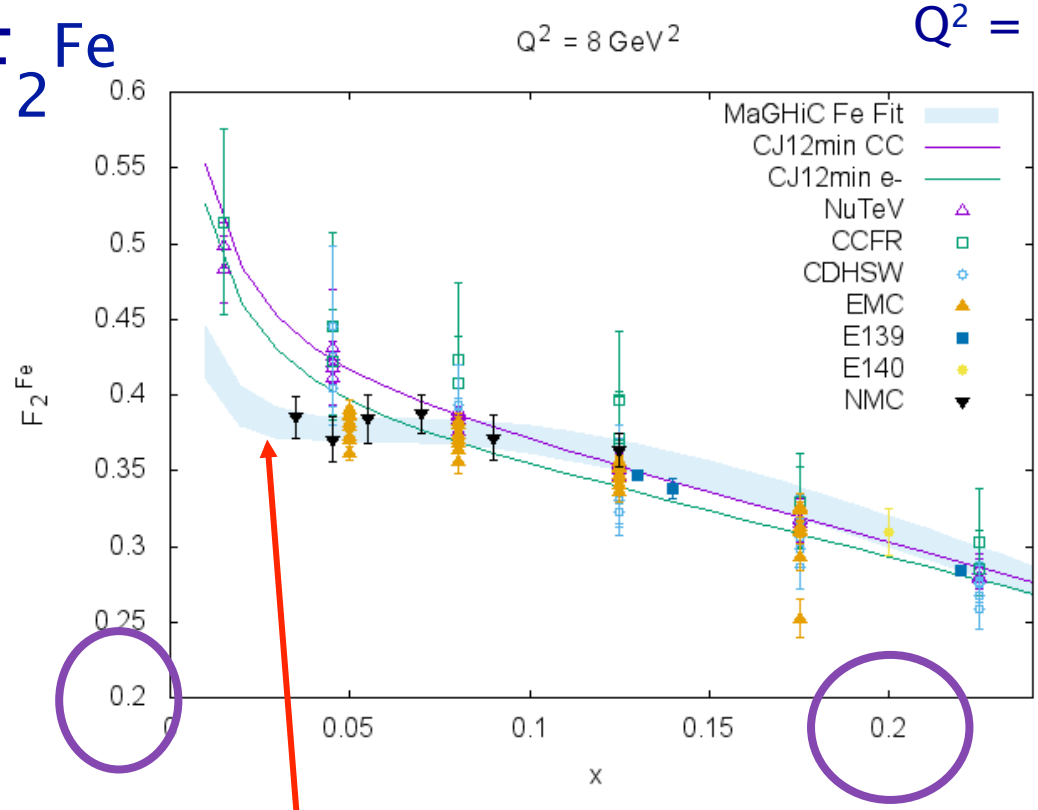
Look closer, zoom in at low x

F_2^{Fe}

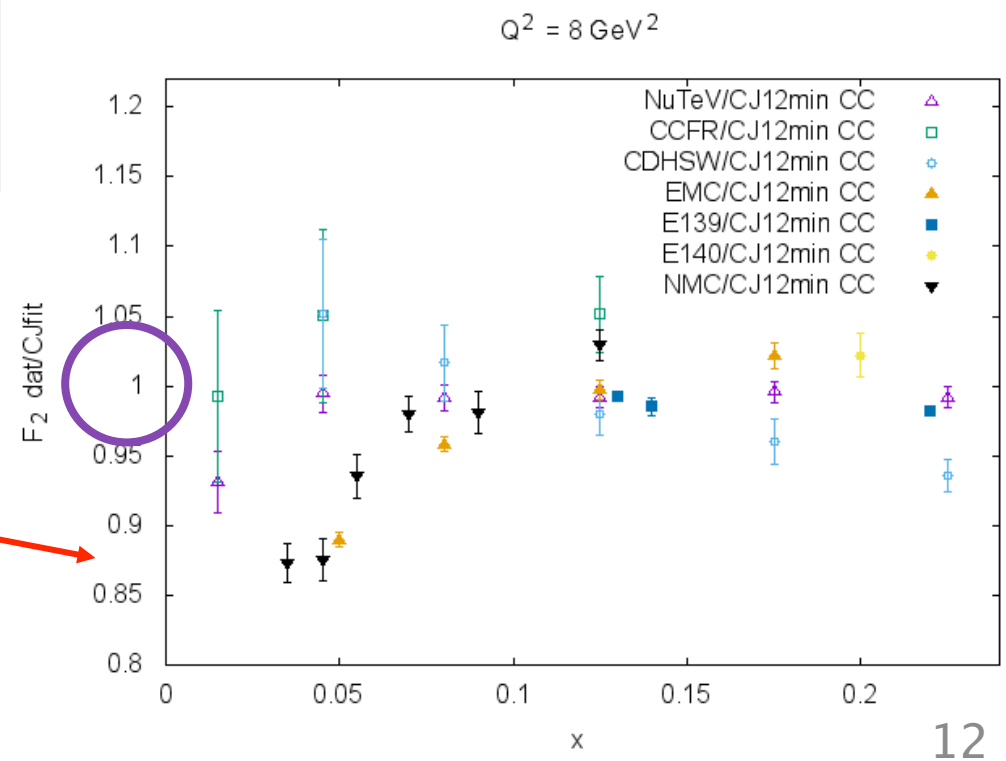
$Q^2 = 8\ GeV^2$



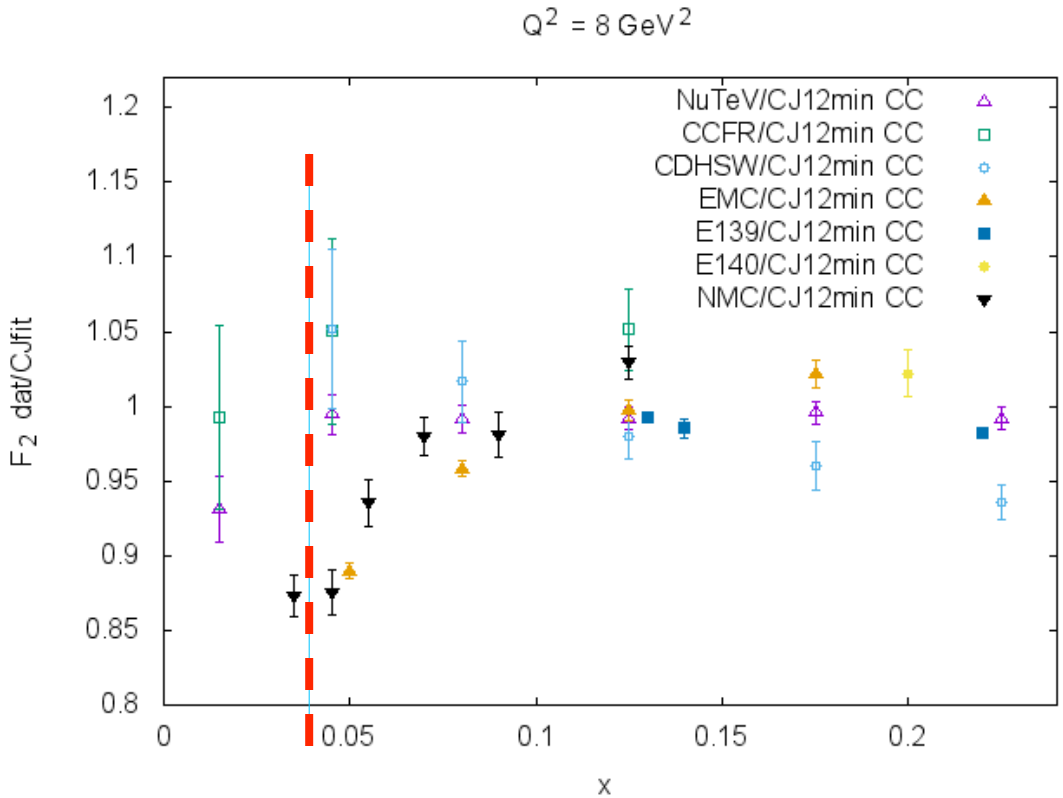
Ratio to CJ electron, at lowest x:

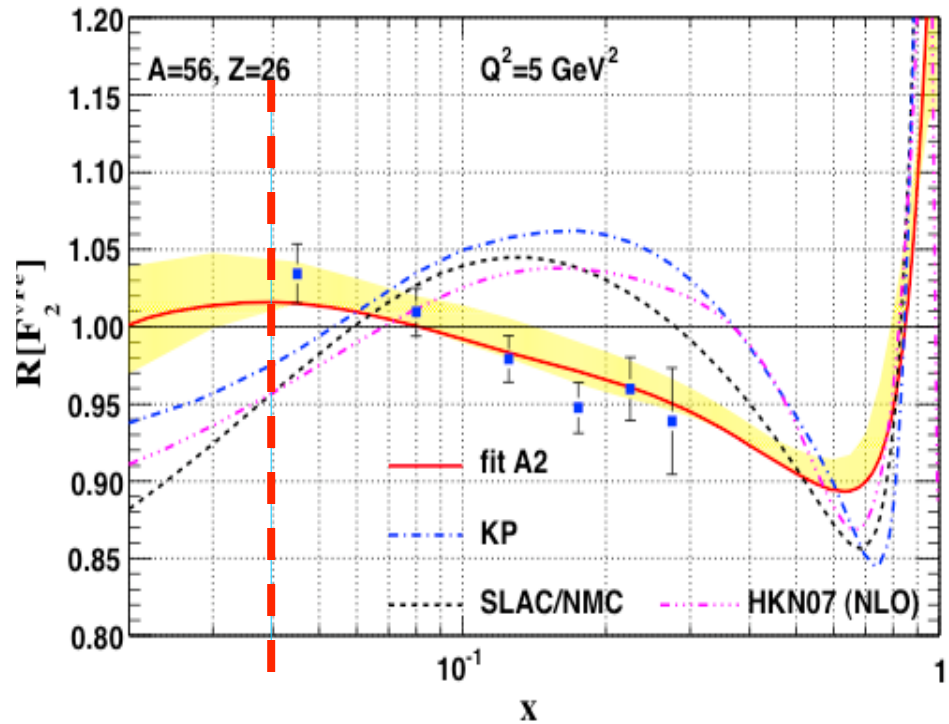
- Neutrino data ratio ~1
- Charged lepton ratio ~0.85

Looks to be ~15% effect



Compare with nCTEQ





- Same trend, perhaps somewhat larger effect in data
- May just be a relative shift toward low x rather than no nuclear dependence in the neutrino data

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..

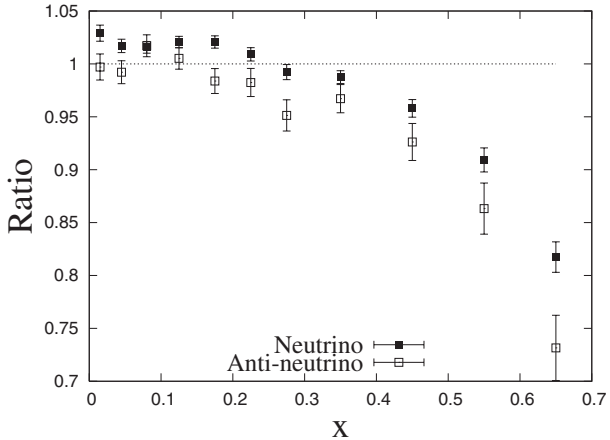
- C. Boros, J.T. Londergan, A.W. Thomas, Phys.Rev.Lett. 81 4075 *(1998!)*
- Similar observation comparing CCFR and NMC only, smaller data set
- *Ascribed discrepancy to CSV*

Possible Explanations Continued
Extraction of NuTeV F_2 (ν–Fe)

- Challenging to extract F_2 from measured cross sections:
  - Need $R = \sigma_L / \sigma_T$ certainly different for neutrino compared to charged lepton. However neutrino experiments use charged lepton R when determining F_2 .
  - Need ΔxF_3 for the extraction of F_2 that is also a theoretical construct since it is not yet measured.
  - Much superior to compare ratios of measured cross sections!

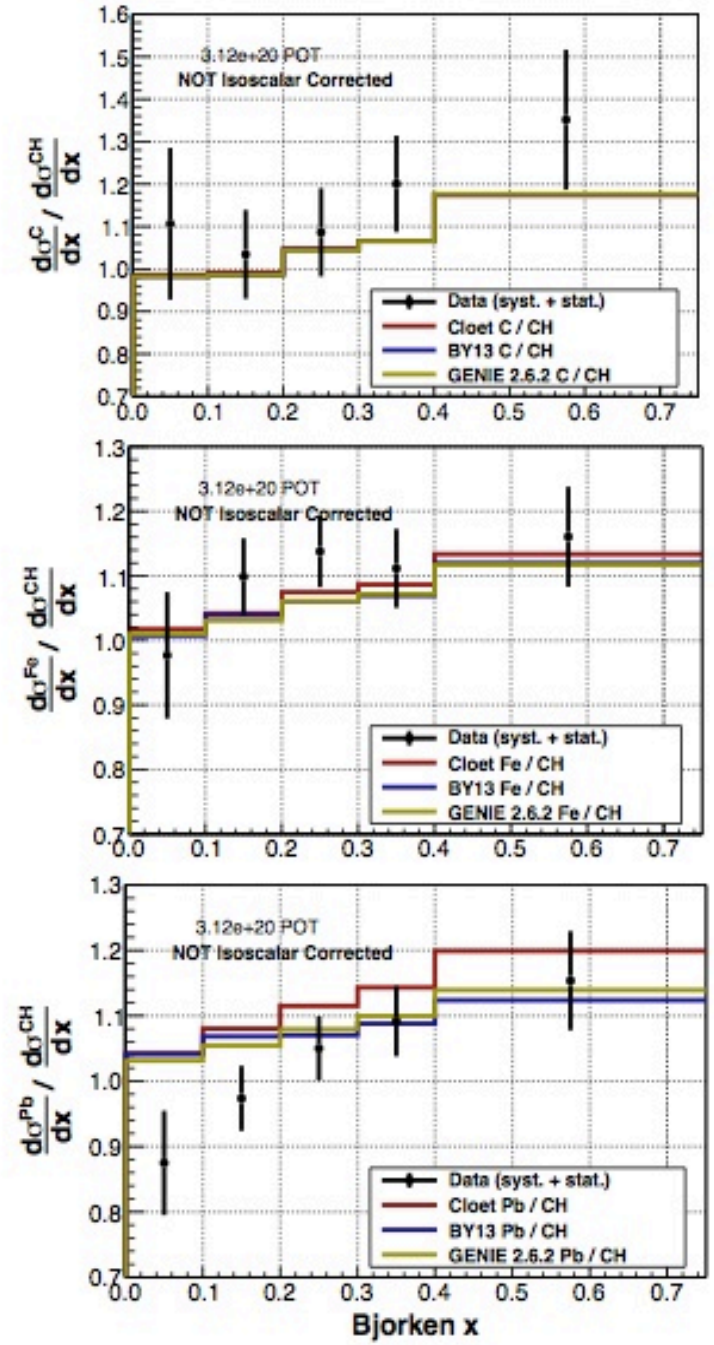
- For details **NuSTEC White Paper: Status and Challenges of Neutrino–Nucleus Scattering – arXiv:1706:03621**
  Section VIII – Shallow and Deep Inelastic Scattering.

- Ratio of cross sections shows large differences between CCFR and NuTeV at larger x not clearly seen in ratios of F_2 !



Important to test with 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 in the DIS region ($Q^2 > 1$ GeV^2 and W > 2 GeV)

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

- For Pb: note drop at low x & Cloet predictions at higher x
- Data at $Q^2 \approx 2$ GeV^2 in lowest x bin
- Not yet isoscalar corrected
- **We are taking much increased statistics at higher energy this year.**

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 suppression
- *On to Pb and nuclear ratios next….*
- Looking forward to new data!

See *N. Kalantarians, M.E. Christy, CK, arXiv:1706:02002 (2017)*

Thank You, Jorge!

Backups

Nuclear PDFs

BUT…

- Conclusions from different groups are contradictory, ranging from a violation of the universality up to a good agreement. Not all groups use cross sections (as opposed to structure functions) and the full covariant error matrix in the analysis

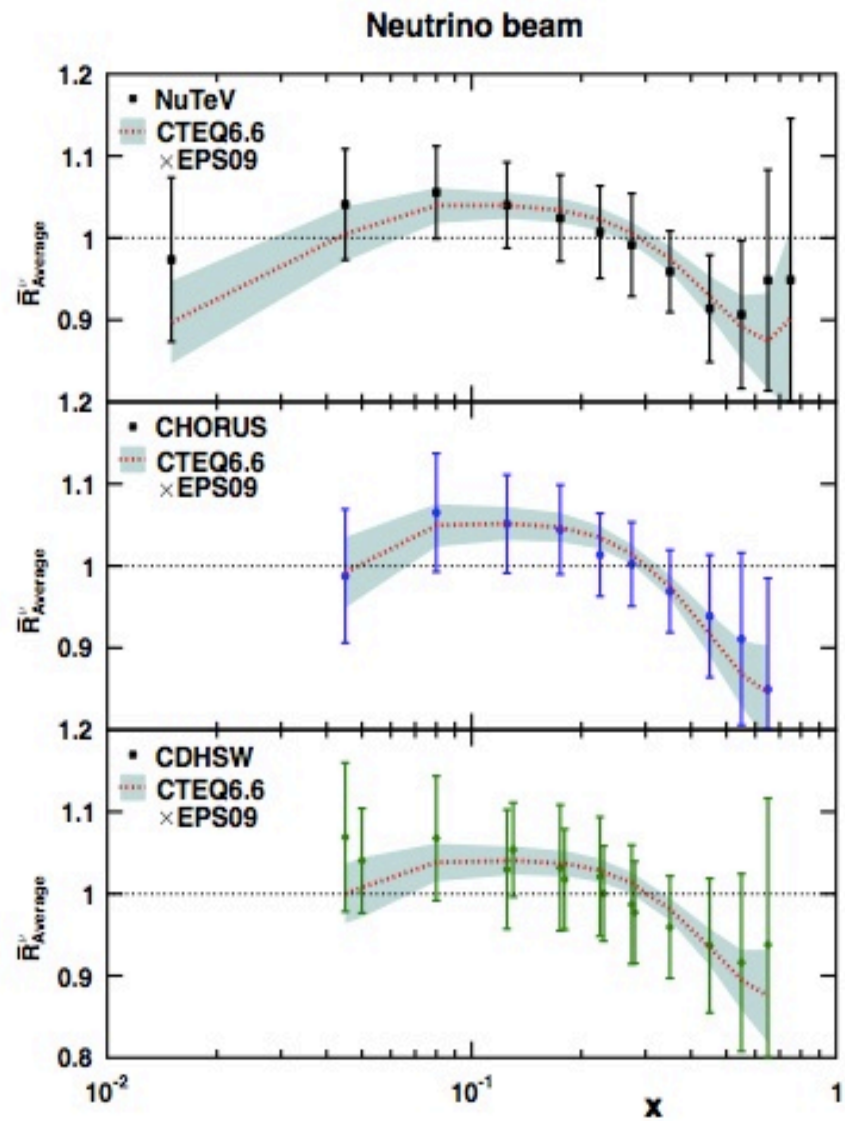
Example:

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



Different probes sensitive to different partons (V. Guzey)

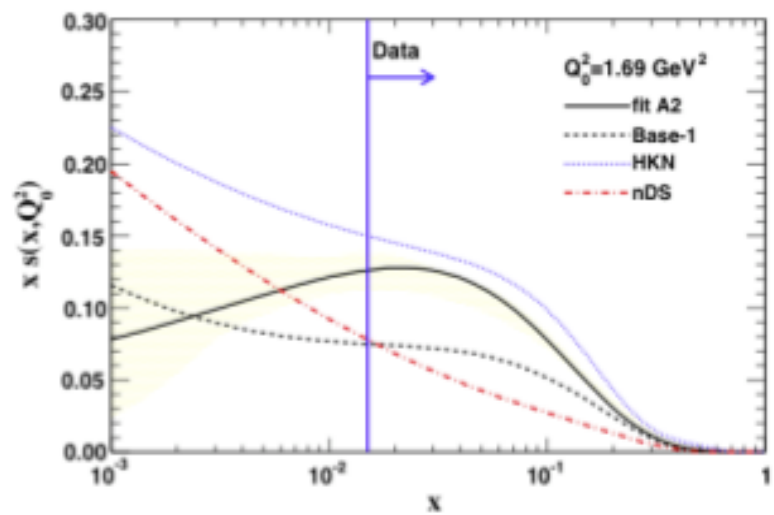
• In leading order:

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

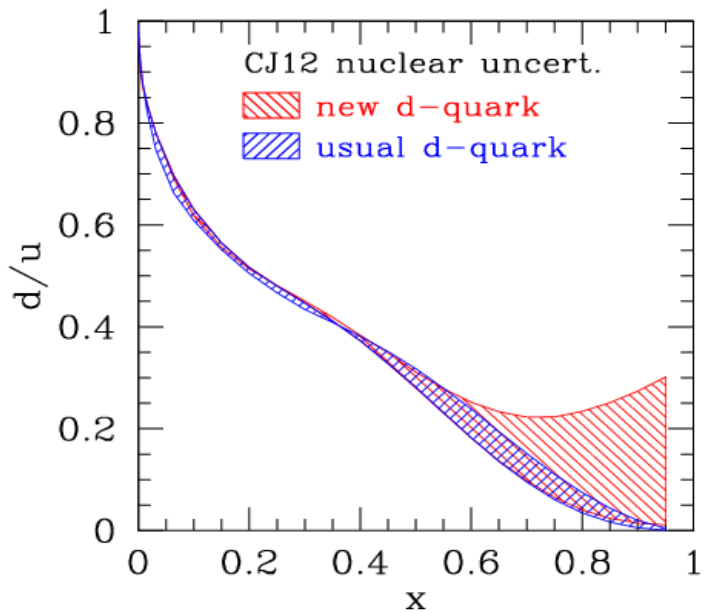
• In the shadowing region at low-x, y is large and the σ are primarily probing the d- and s-quarks.

• 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



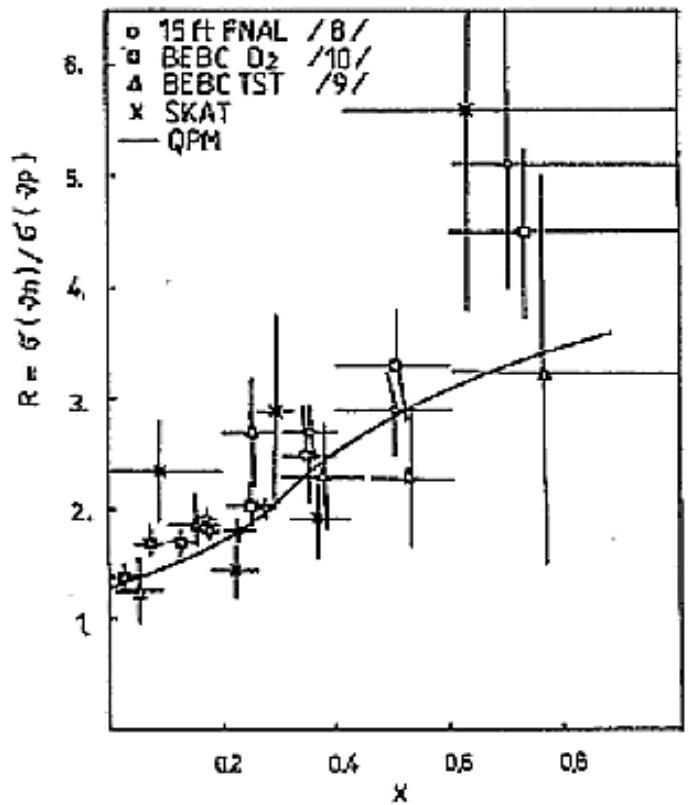


Fig. 4. World data of the dependence of the cross section ratio $\sigma(\nu n)/\sigma(\nu p)$ on Bjorken-x measured in neutrino bubble chamber experiments. The full line gives the prediction of the quark parton model [1, 2] using the parametrisation of the quark distributions by Feynman-Field [5]

- 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.

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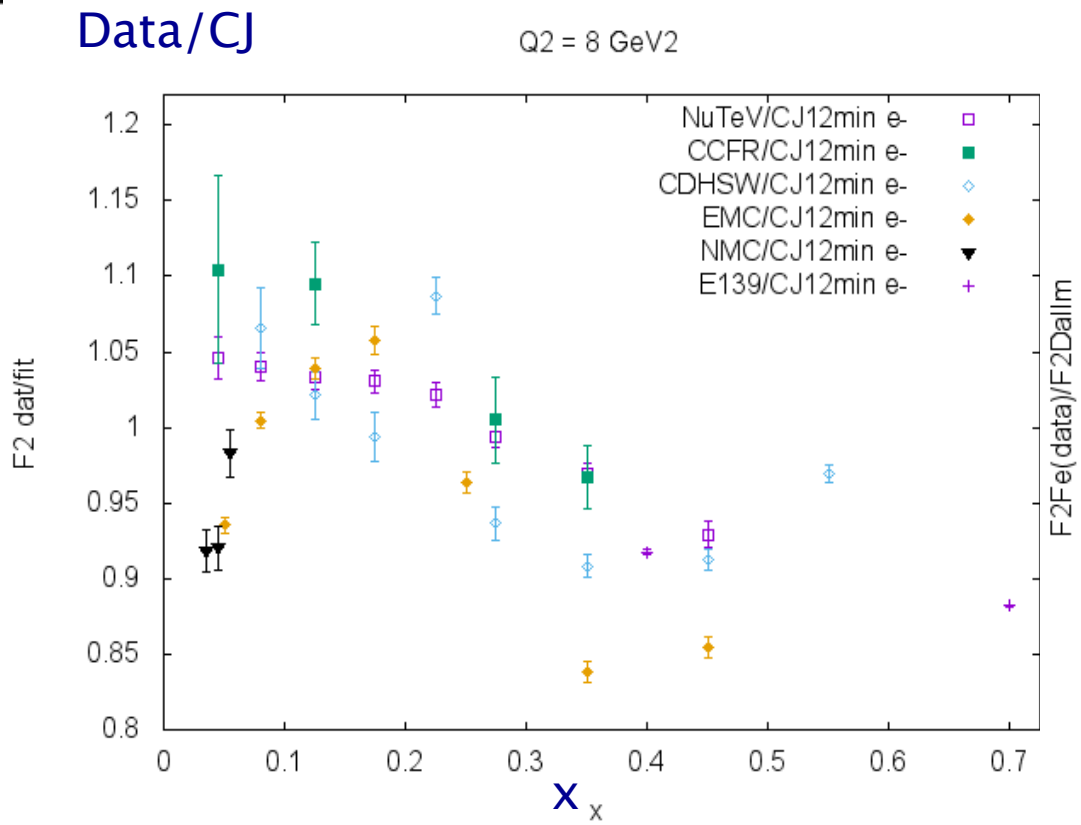
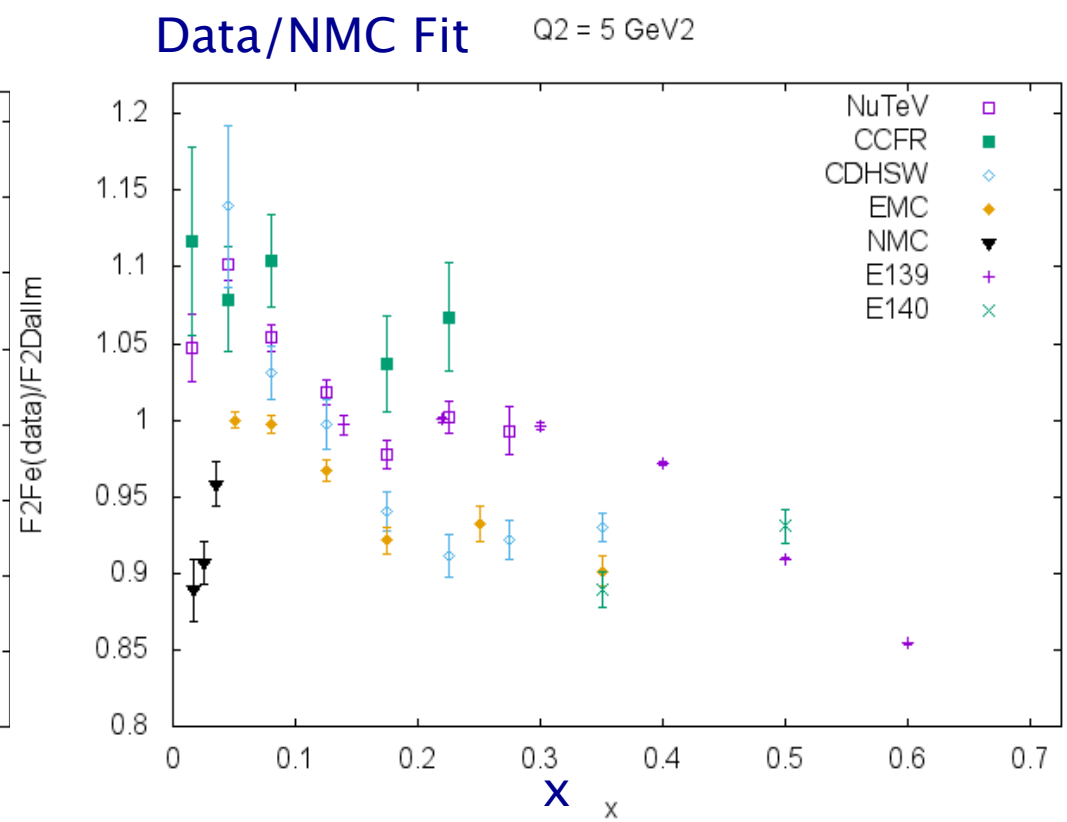
Look closer – large x

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!

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Charged lepton scattering:

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

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

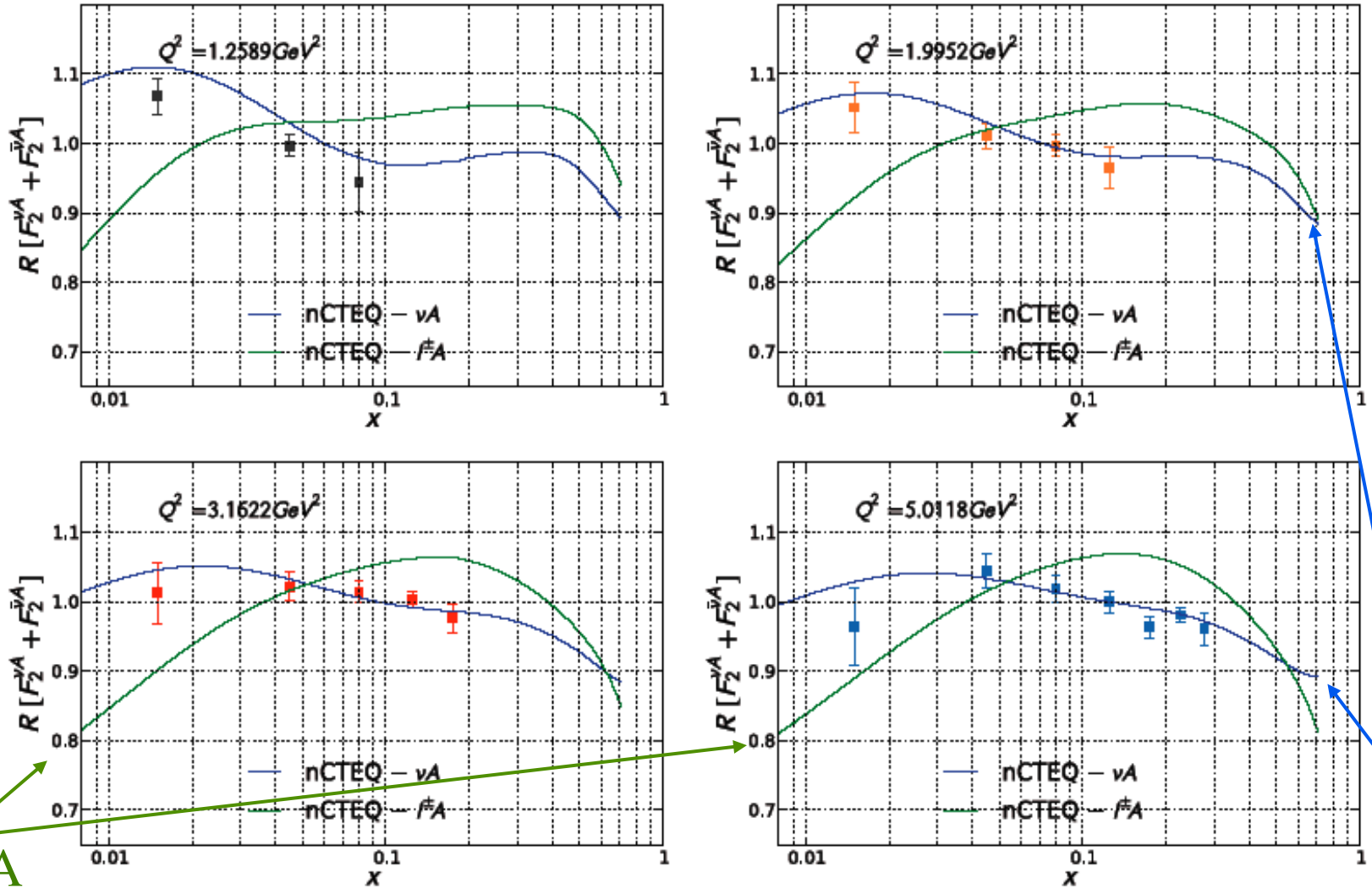
Neutrino scattering:

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

- 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

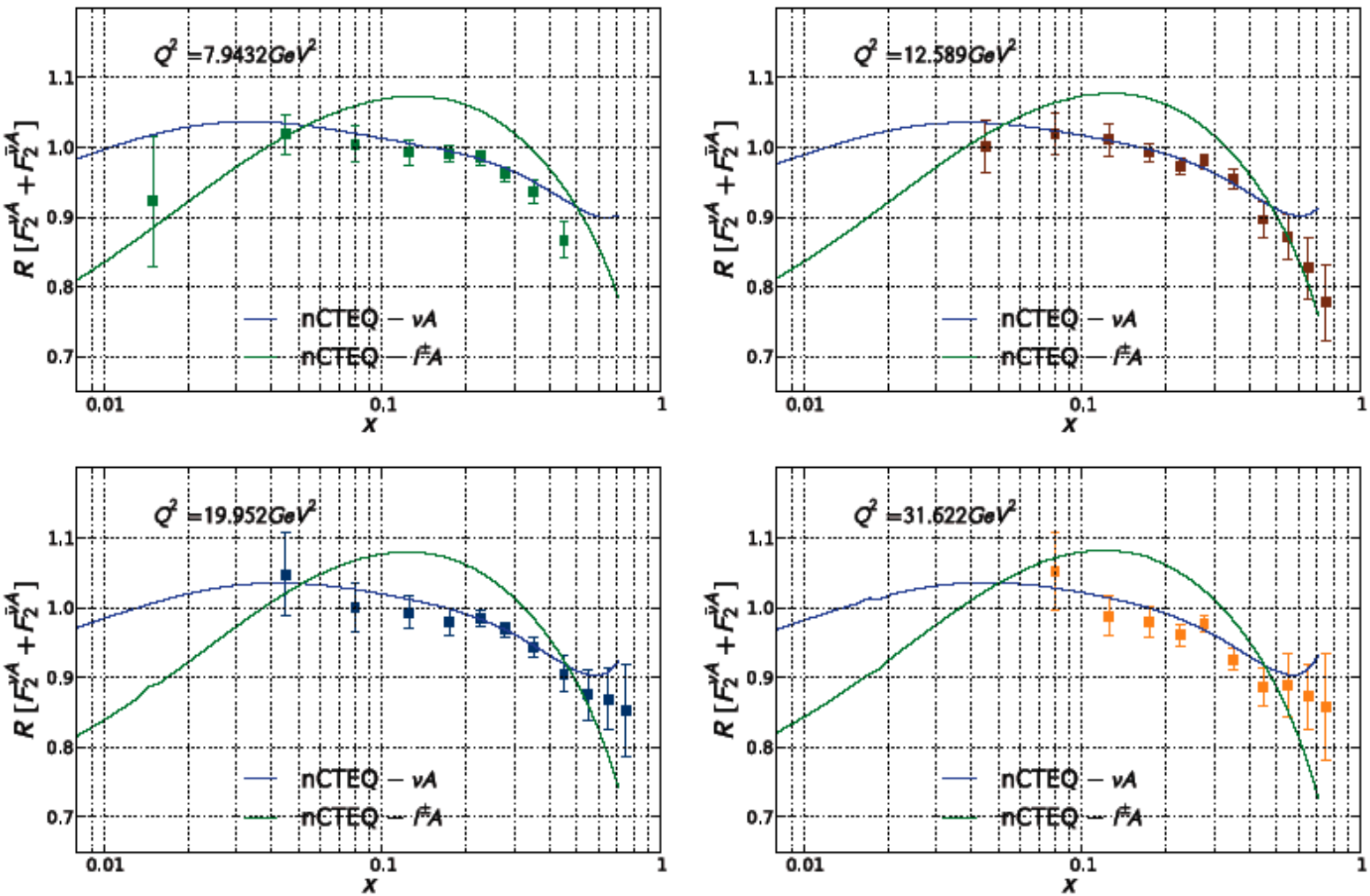


e,μ - A

ν - A

- 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

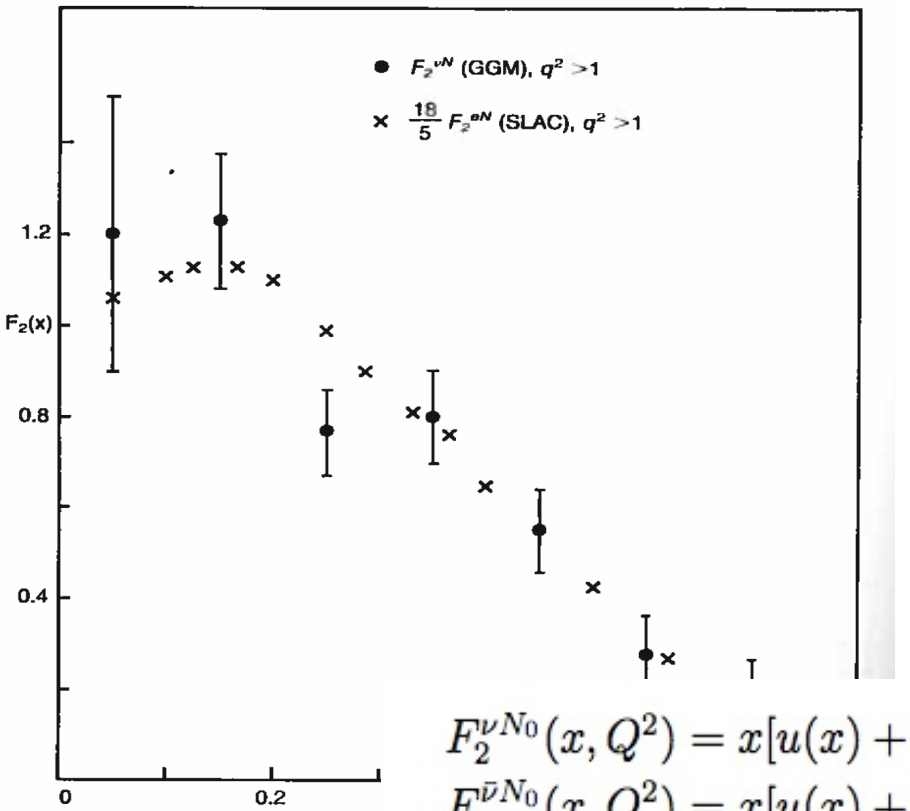


Figure 8.12 (a) First comparison of F Gargamelle heavy-liquid bubble chamber F_2^{eN} from electron-nucleon scattering, in tl the electron points are multiplied by the f charge of u- and d-quarks in the nucle assignments for the quarks. Note that t momentum fraction in the nucleon carri ascribed to gluon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

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

Holds at leading order

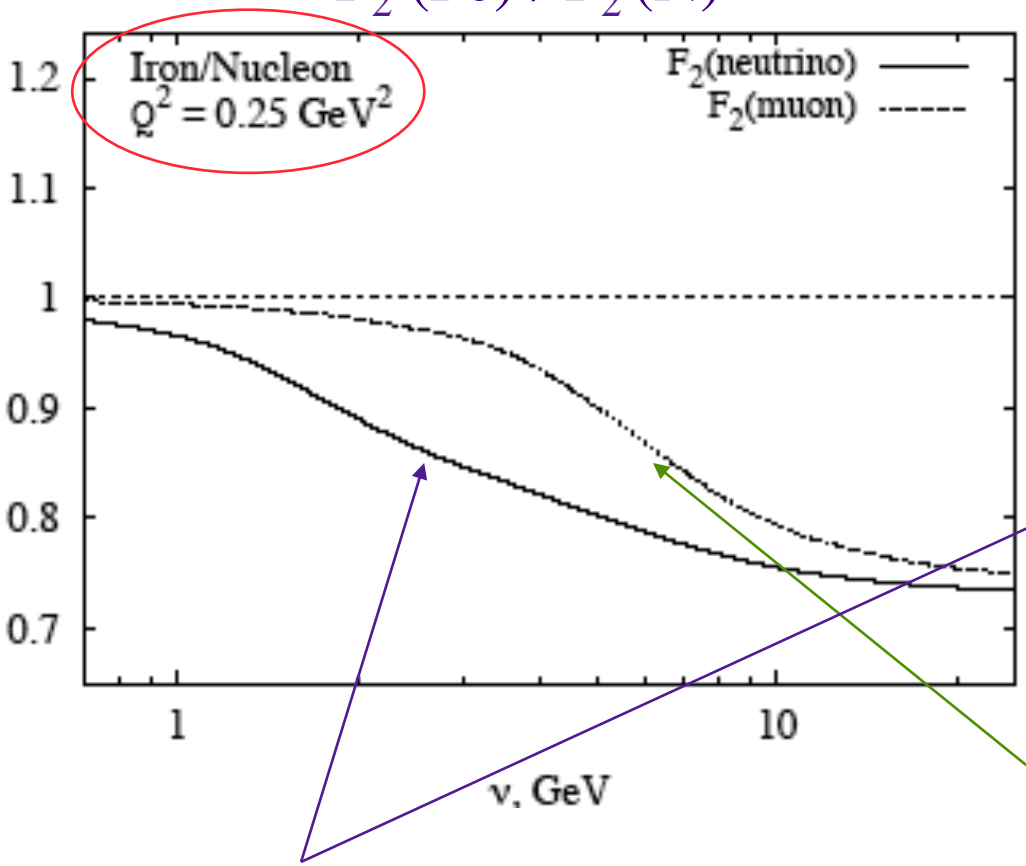
$$F_2^{\nu N}(x) \leq \tfrac{18}{5} F_2^{eN}(x)$$

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

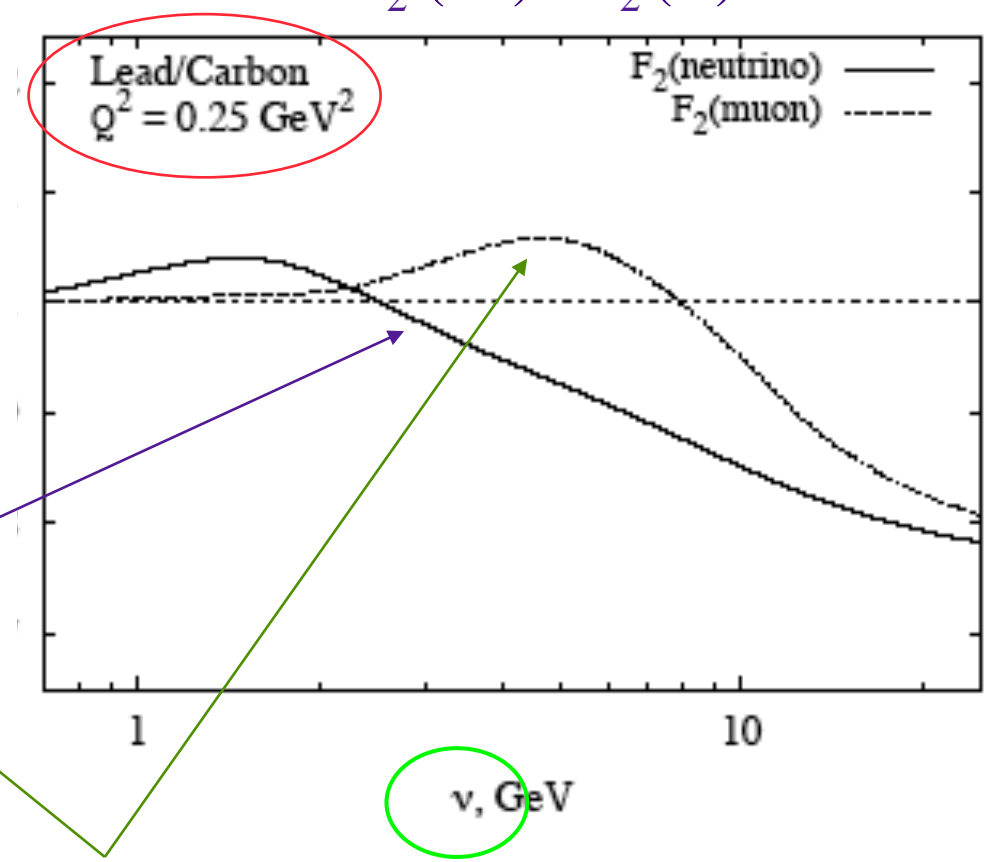
Nuclear Effects: Global analysis also predicts differences

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)

F_2 (Fe) / F_2 (N)



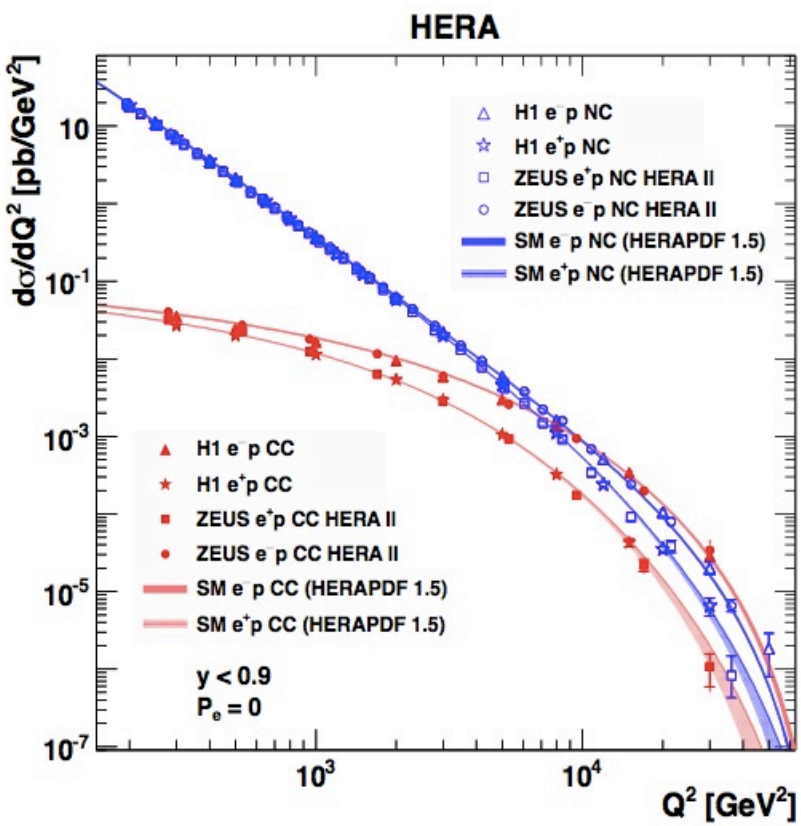
F_2 (Pb) / F_2 (C)



neutrino

muon

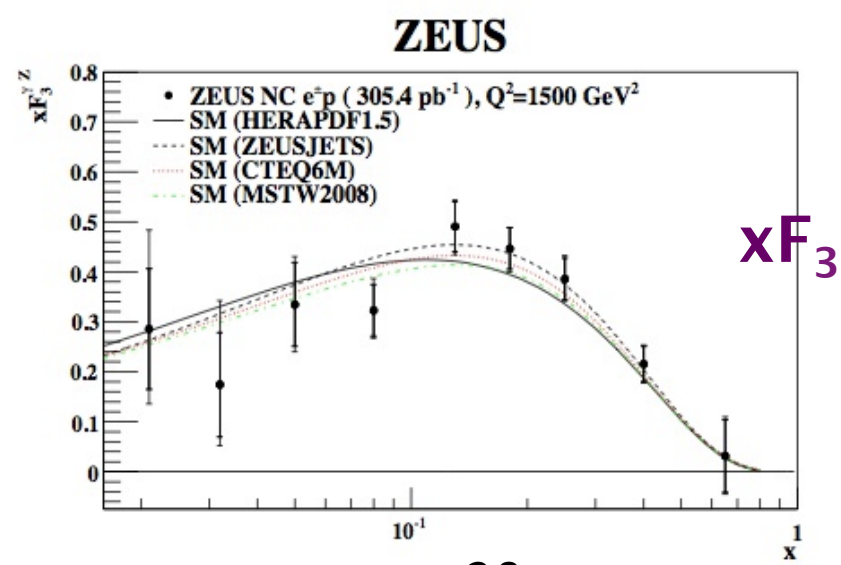
EIC should be uniquely able to help



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
- Didn't run simulations yet, but the EIC x,Q range is optimal
- Should be able to distinguish neutral and charged current events a la HERA
- Straightforward e-A experiment



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

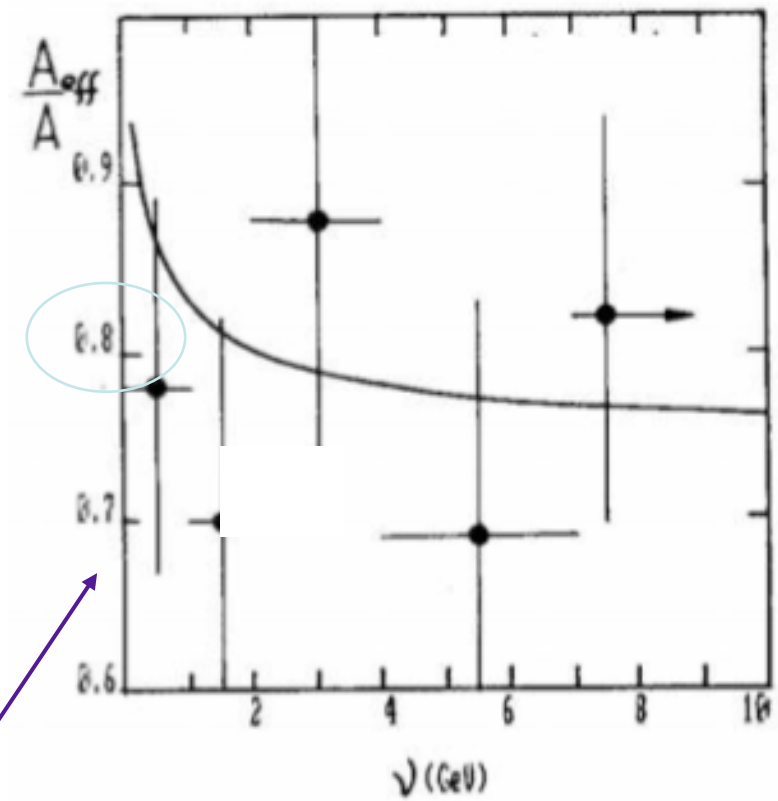
The axial-vector current allows shadowing *at lower ν* than the vector current (B. Kopeliovich, Nucl. Phys. Proc. Suppl. 139:219-225, 2005):

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 longer for* axial vector states than vector, *allowing shadowing at higher x for the same Q^2

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



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