Comparison of the F_2 Structure Function in Iron as Measured by Charged Lepton and Neutrino Probes

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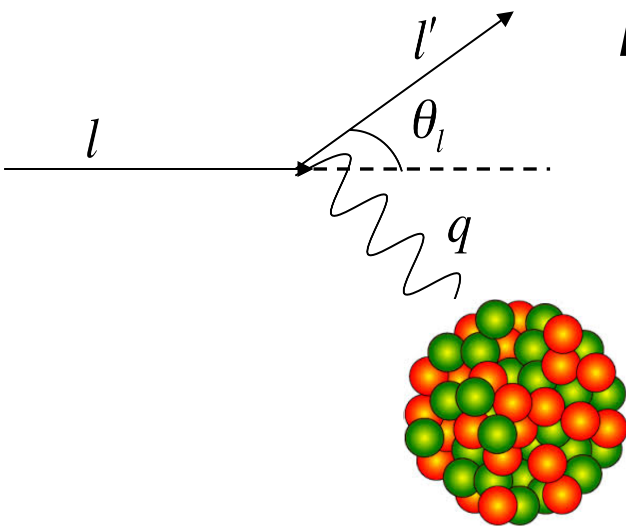
NuInt'15

November 19, 2015



Outline

- Motivation
- Lepton Scattering (Data)
- Analysis
- Results/Conclusions

Motivation

- How well do we understand nuclear structure on the quark-gluon scale?

  $< \sim 10^{-15}\ m$

- Understanding parton* distributions via F_2^{Fe} from DIS data.
- Confronting fitting with data: F_2^{Fe} from charged lepton and neutrino scattering experiments.
- How do data from charged lepton probes compare with neutrino probes ?

Charged Lepton vs. Neutrino Scattering

*only detecting the scattered lepton

Parity Violation

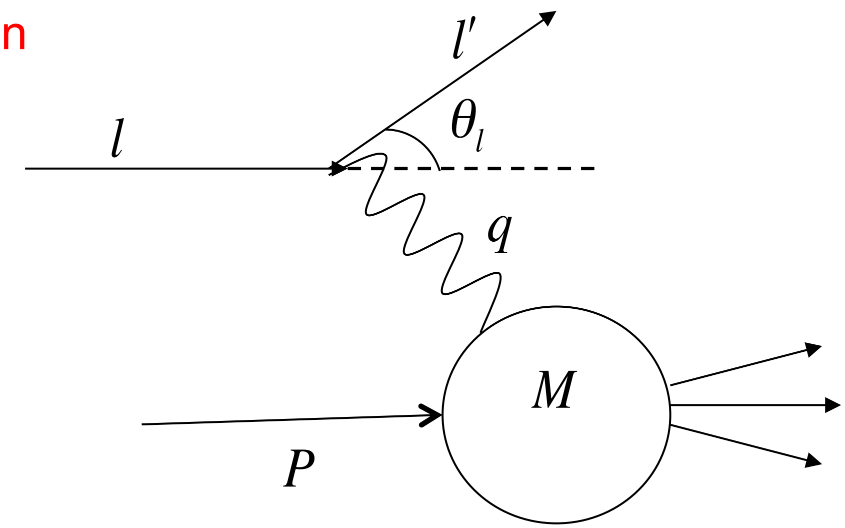
Charged Leptons:

$e^{+/-}, \mu^{+/-}$

q => ***EM*** coupling => γ, *Z*

Vector coupling (parity conserved)

Mono-energetic beam; fixed E_{beam}



Neutrinos:

ν, ν–bar

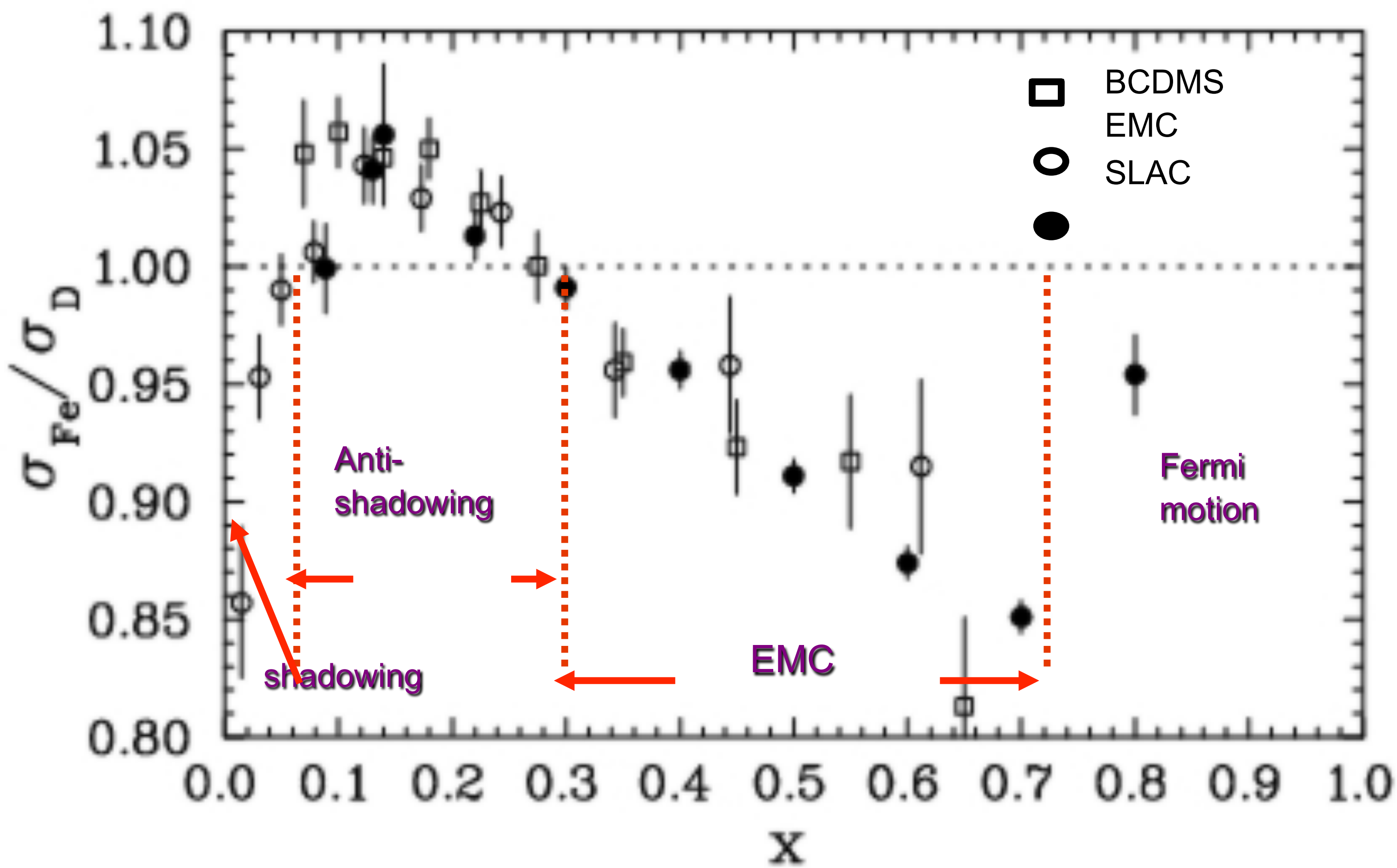
q => ***EW*** coupling => ***W+/-, Z*** (charged,neutral) current, respectively

Vector + *Axial* coupling (parity not necessarily conserved)

Beam is not mono-energetic; spectrum of E_{beam}

Nuclear Ratios

See something quite different -*definitely* not unity.



Charged lepton data

EMC Effect Reproduced (Many Times!)

EMC effect is simply the fact the ratio of DIS cross sections is not one

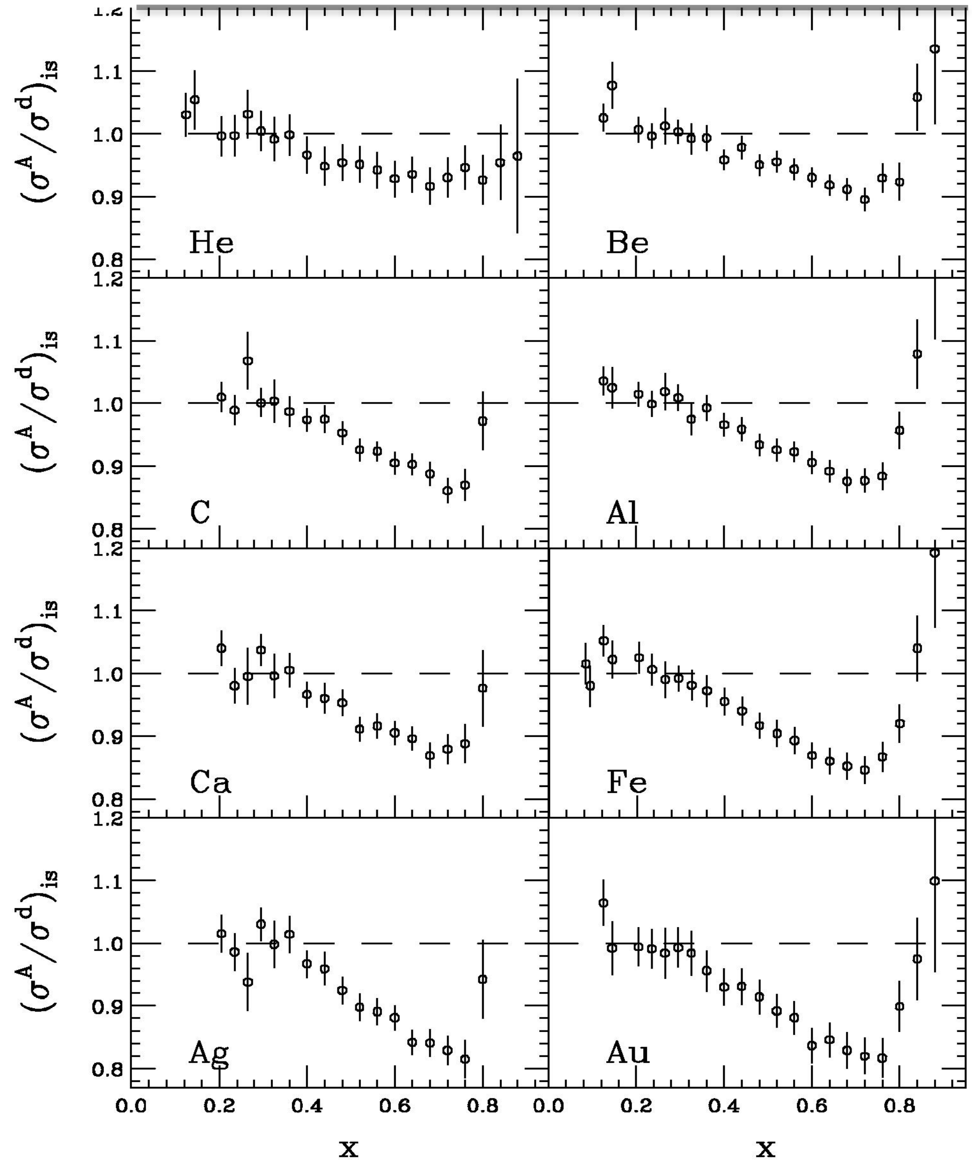
- PLB **123** (1983) 275.
- Simple Parton Counting Expects One
- **MANY Explanations**

SLAC E139

- Phys. Rev. D **49** (1994) 4348.
- Precise large-x data
- Nuclei from A=4 to 197

Conclusions from SLAC data

- Nearly Q^2-independent
- Universal x-dependence (shape)
- Magnitude varies with A
- Recent Jefferson Lab results consistent with this; PRL **103** (2009) 202301.



Neutrino Nucl. Ratio Data

Phys. Rev. D **77**, 054013 (2008)
Phys. Rev. D **80**, 094004 (2009)
Phys. Rev. Lett. **106**, 122301 (2011)

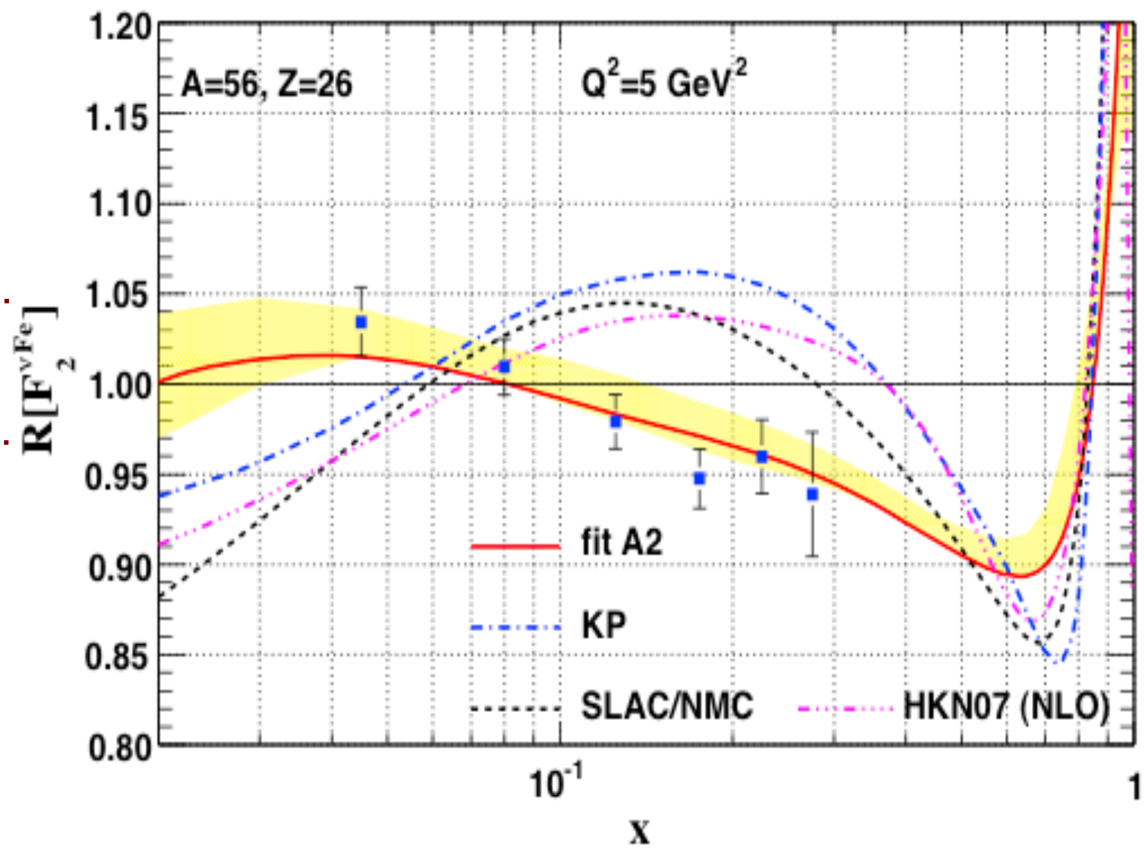
Nuclear PDF fits done on charged lepton data. (nCTEQ): predicts ~5% difference.

A-dependent PDFs then used to extract ratios.

NuTeV Fe data, deuteron constructed using PDFs.

ν–A dependence different from *e/μ-A*

How about looking at the Fe data, itself? (next slide)



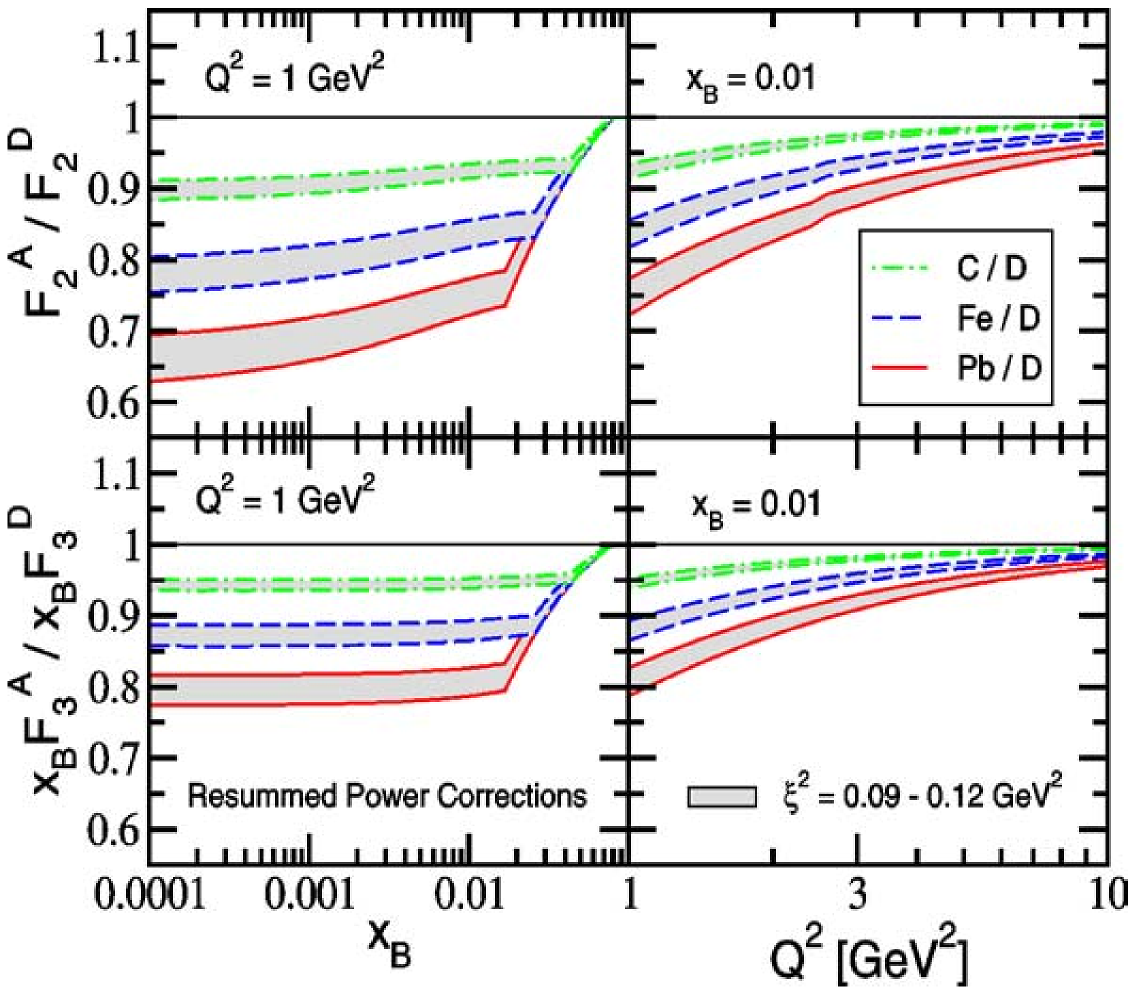
HKN07: Phys. Rev. C **76**, 065207 (2007)
KP: Phys. Rev. D **76**, 094023 (2007)

Looking at the Fe Data itself

- The neutrino data assume a model deuteron (little to no neutrino-deuteron scattering data available).
- Can F^{Fe}_2 show if there is a difference between the charged lepton and neutrino data?
- There are abundant Fe data, from both charged lepton and neutrino, covering a wide range of *x.*

Theory Predictions

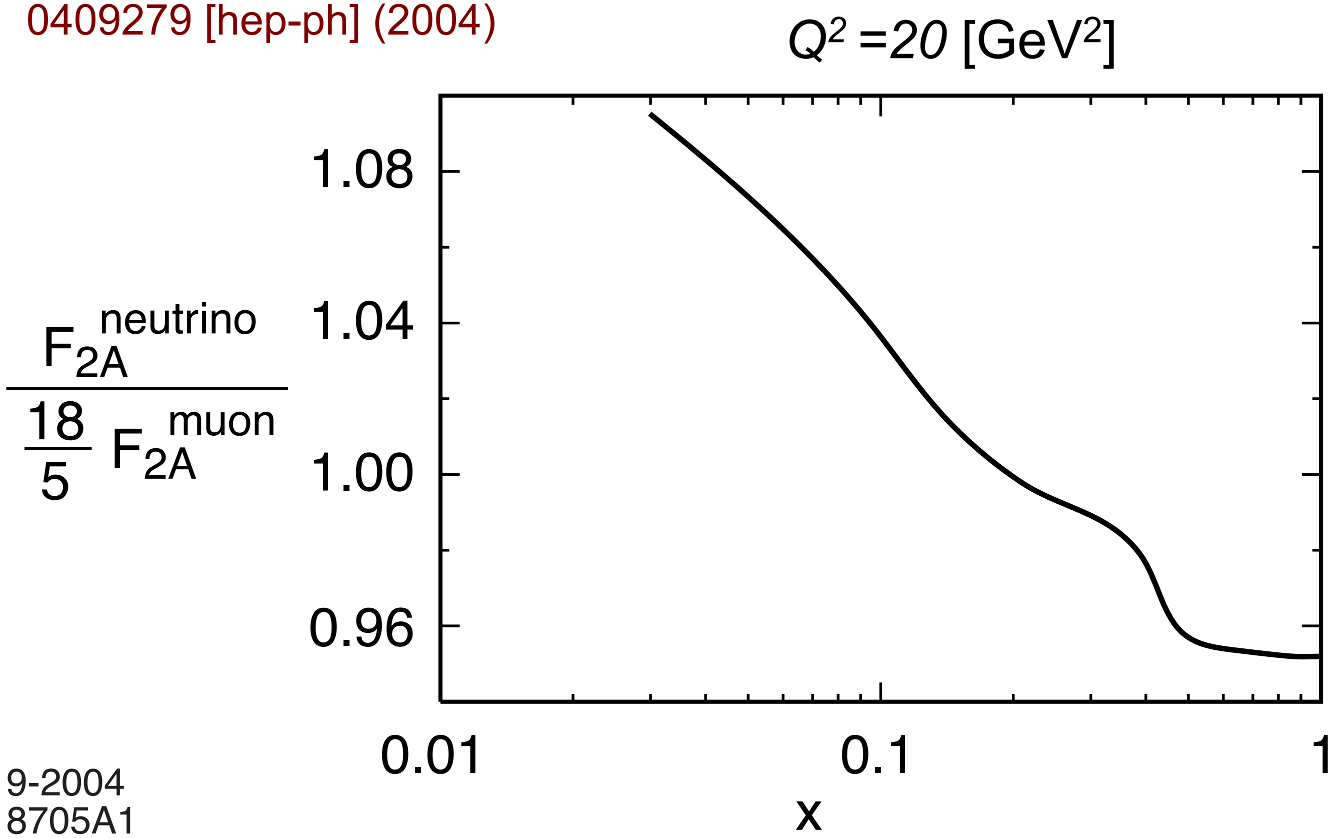
Phys. Lett. B **587**, 52 (2004)



- Predict sizeable effect in shadowing region.
- Nuclear corrections taken into account.
- Nucleon binding and Fermi motion not enough. Off-shell effects. (Nucl. Phys. A **765** 126).
- Nuclear medium effect important. Meson cloud contributions (Phys. Rev. C **84** 054610).
- Some predict that charged lepton and neutrino data similar and matter of analysis technique (PRL **110** 212301).

Theory Predictions

0409279 [hep-ph] (2004)



- Prediction for difference between charged lepton and neutrino scattering data due to nuclear effects.
- Based in good part on data analysis; Phys. Rev. Lett. **86** 2742 (2001)

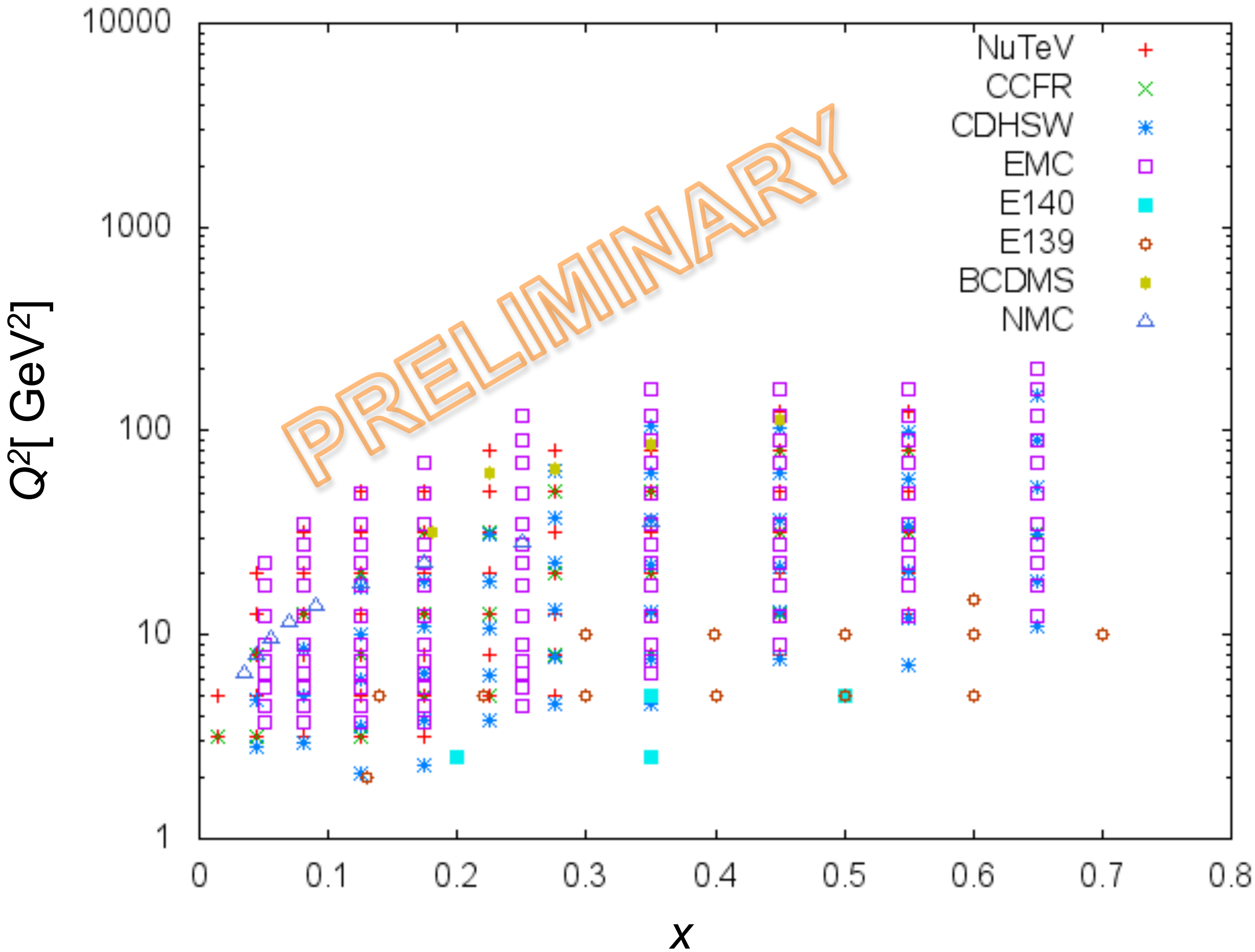
Analysis

- Apply DIS cuts; $Q^2 > 2$, $W^2 > 4$ [GeV^2].
- Set F^{Fe}_2 data to a common Q^2 (average bin-centering).
- For cases of data being SF ratio F^{Fe}_2/F^d_2 (charged lepton); use reliable F^d_2 parameterization (*NMC*) to multiply and extract F^{Fe}_2.
- Plot (and compare) data with fits (ratios)
- Current algebra of applying 8/15 to neutrino data to account for quark charges.
- Data are isoscalar corrected.

*This work done with M. E. Christy and C. Keppel; Draft in progress

World F^{Fe}_2 Data

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



Neutrino Expt's:
CCFR, CDHSW, NuTeV

Charged Lepton (e/μ)
BCDMS, EMC, E140,
E139
slac/stanford.edu/exp/e139/
NMC
Nucl. Phys. B **441** 3 (1995)
Nucl. Phys. B **481** 3 (1996)

18/5 Rule

Perkins

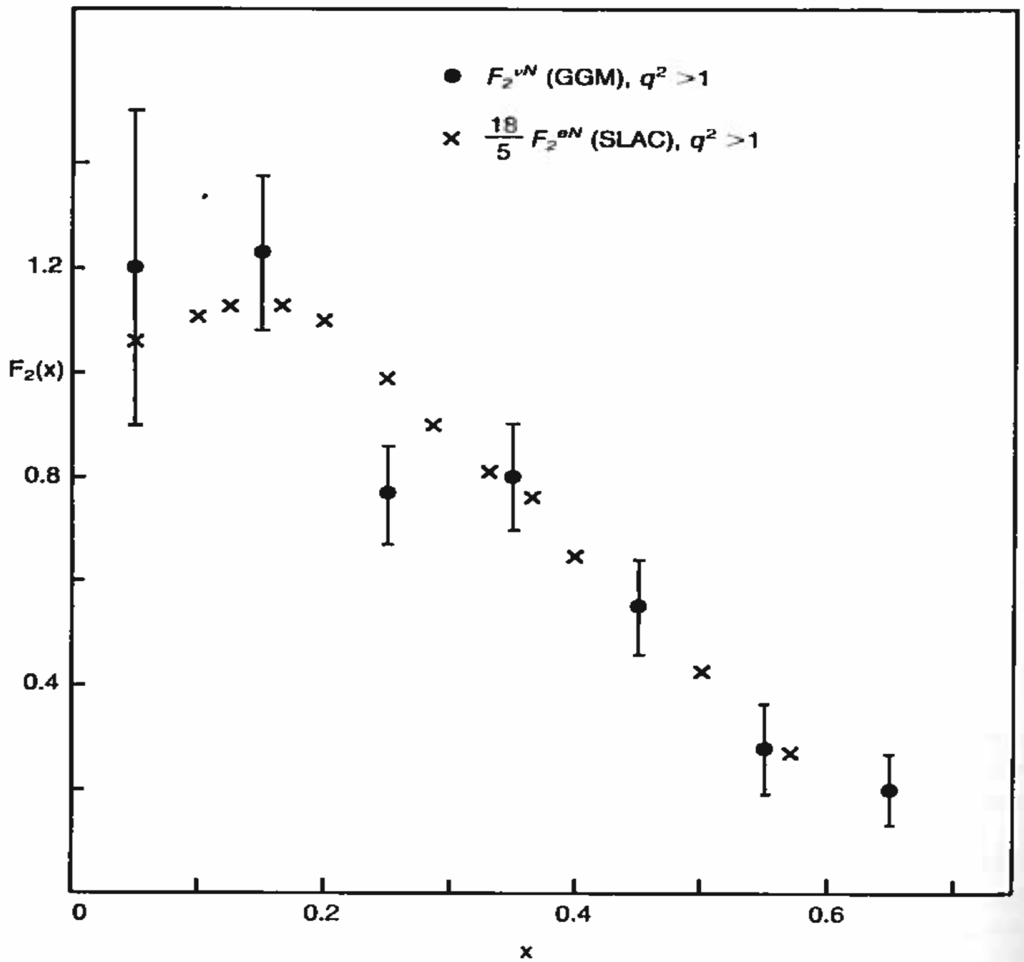


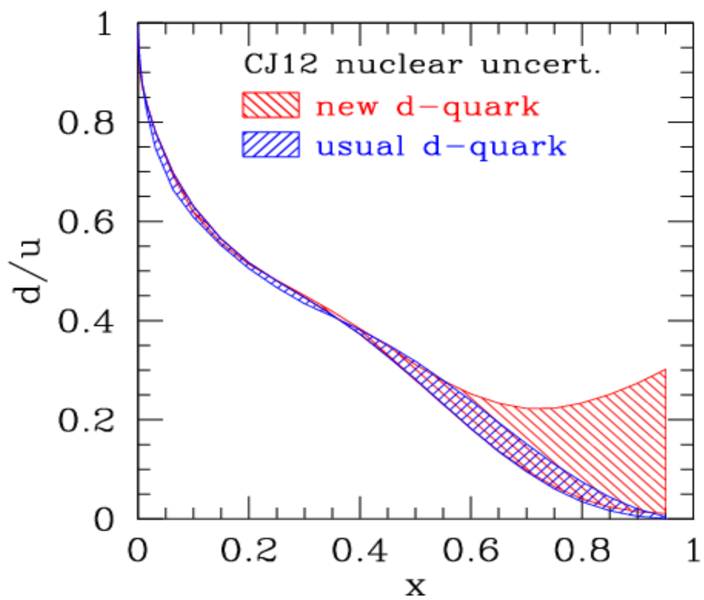
Figure 8.12 (a) First comparison of $F_2^{\nu N}$ measured in neutrino-nucleon scattering in the Gargamelle heavy-liquid bubble chamber in a PS neutrino beam at CERN, with SLAC data on F_2^{eN} from electron-nucleon scattering, in the same region of q^2. The two sets of data agree when the electron points are multiplied by the factor $\frac{18}{5}$, which is the reciprocal of the mean squared charge of u- and d-quarks in the nucleon. This is a confirmation of the fractional charge assignments for the quarks. Note that the total area under the curve, measuring the total momentum fraction in the nucleon carried by quarks, is about 0.5. The remaining mass is ascribed to gluon constituents, which are the postulated carriers of the interquark color field.

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

Holds at leading order.

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

Isoscalar Corrections



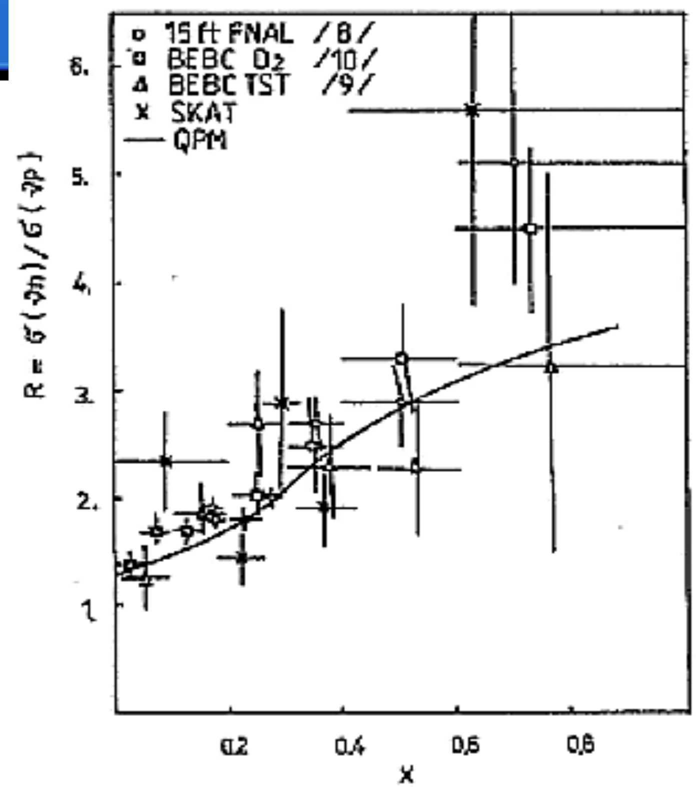


Fig. 4. World data of the dependence of the cross section ratio $\sigma(\nu n)/\sigma(\nu p)$ on Bjorken-x measured in neutrino bubble chamber experiments. The full line gives the prediction of the quark parton model [1, 2] using the parametrisation of the quark distributions by Feynman-Field [5]

- 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.

Isoscalar Corrections

Assuming unmodified free nucleon cross sections, the isoscalar correction for a target with atomic number A and Z protons is:

$$f^{A}_{ISO} = \frac{\sigma_{iso} = A/2^{*}(\sigma_p + \sigma_n)}{\sigma = Z\,\sigma_p + (A-Z)\,\sigma_n} = \frac{A/2Z * (1 + \sigma_n/\sigma_p)}{1 + (A/Z-1)^{*}\sigma_n/\sigma_p}$$

(30% ratio uncertainty)

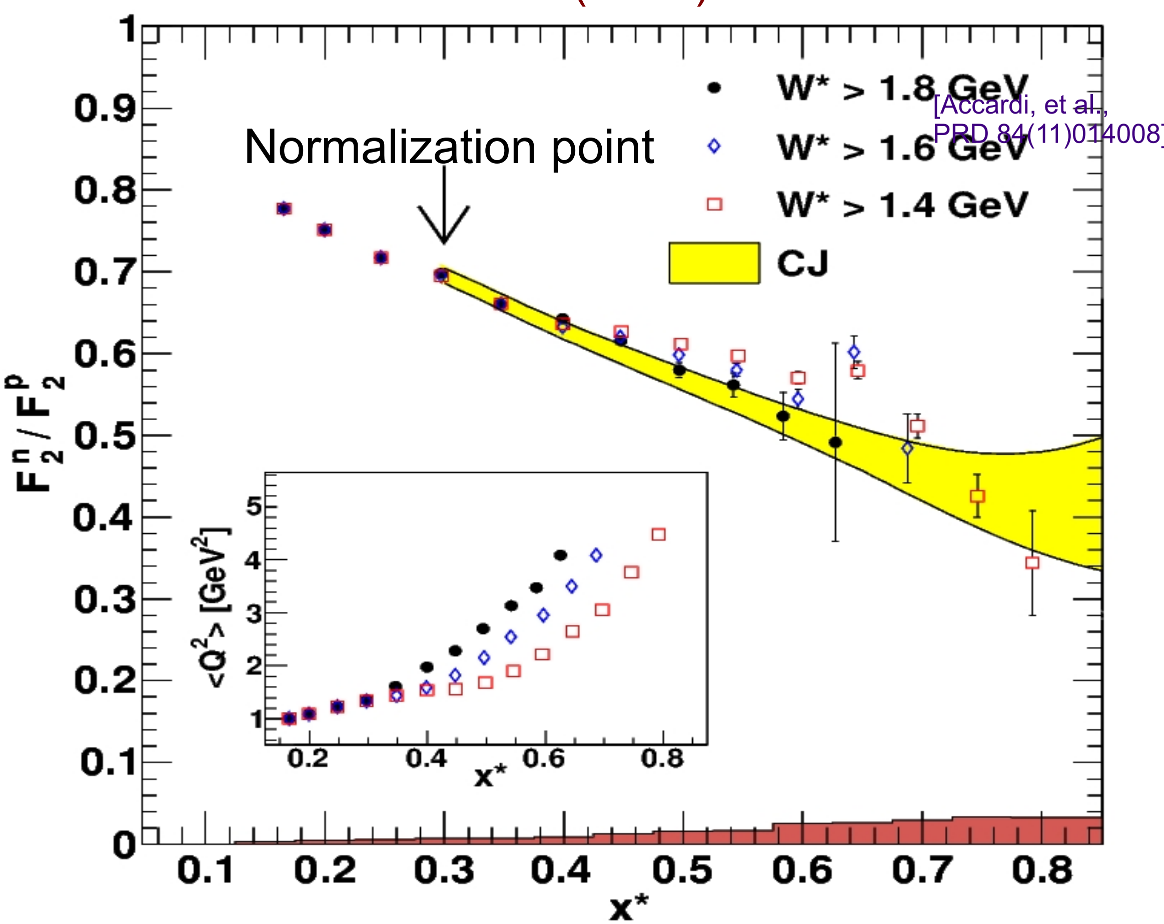
	For $\sigma_n/\sigma_p = 3$	For $\sigma_n/\sigma_p = 3^{*}1.3$
^{56}Fe : A/Z = 56/26 = 2.154	f = 0.965	f = 0.959

*For neutrinos

How well do we know σ_n/σ_p?

Charged Lepton Uncertainties for $F^n{}_2/F^p{}_2$

PRL **108** 199902 (2012)



→ Data is from BONuS

→ Yellow area is nuclear corrections uncertainty band from CJ PDFs.

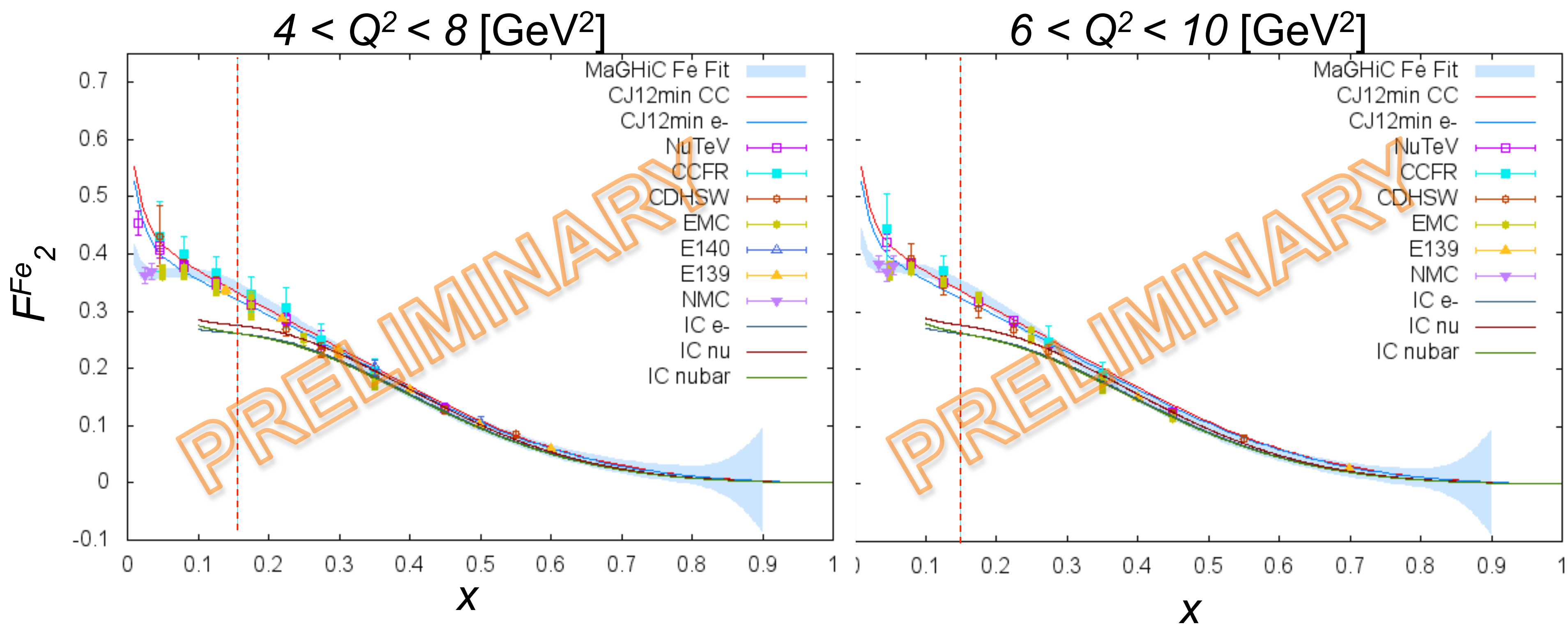
→ x~0.6 uncertaintiy < 8%

Assuming **same** uncertainty and for neutrino n/p ~ 3

→ 56Fe isoscalar correction known much better than 1% (for charged lepton)

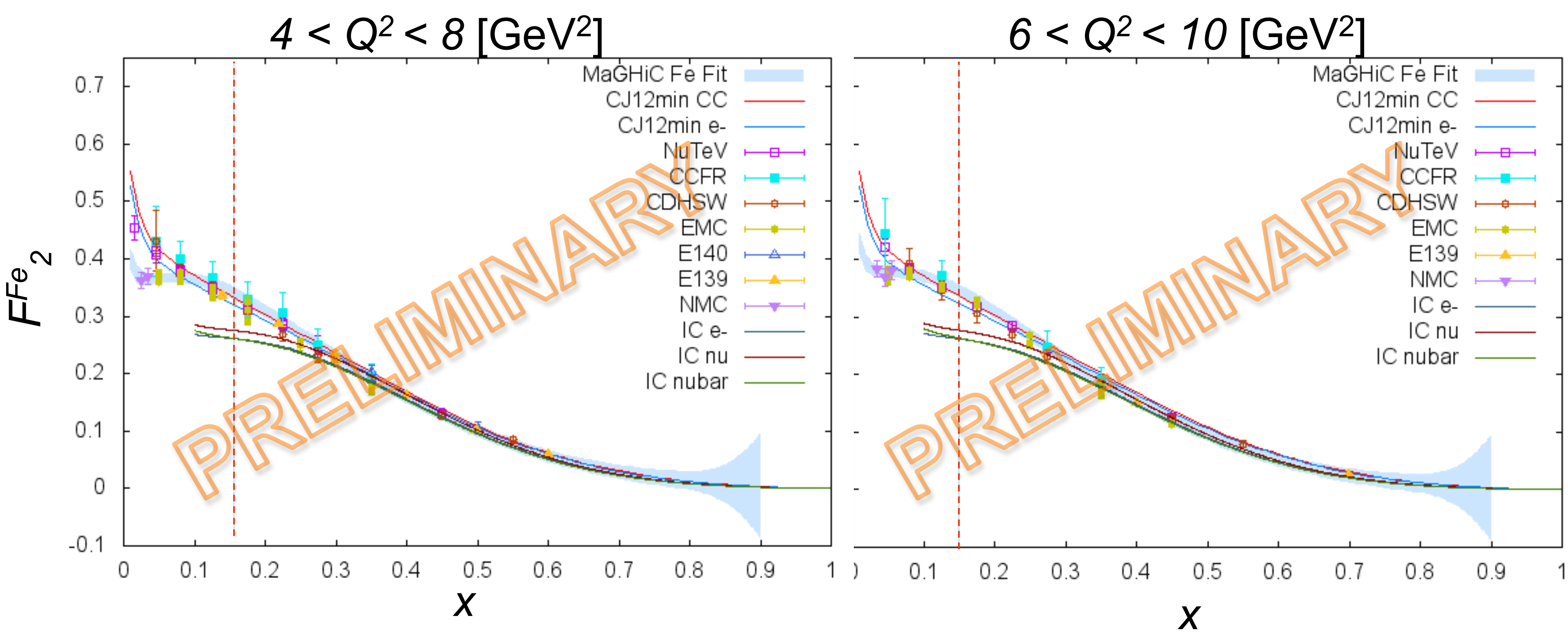
Much smaller correction for x < 0.6

F^{Fe}_2 Data and Fits



- "CJ12min fit" Phys.Rev. D **87** 094012 (2013)
- "MaGHiC" Intl. Journ. Mod. Phys. E **23** 1430013 (2014)
- Difference between Charged lepton and neutrino data at $x < \sim 0.15$
- Neutrino data seems to be in agreement with CJ -CJ has no nuclear effects taken in to account.

F^{Fe}_2 Data and Fits (cont'd)

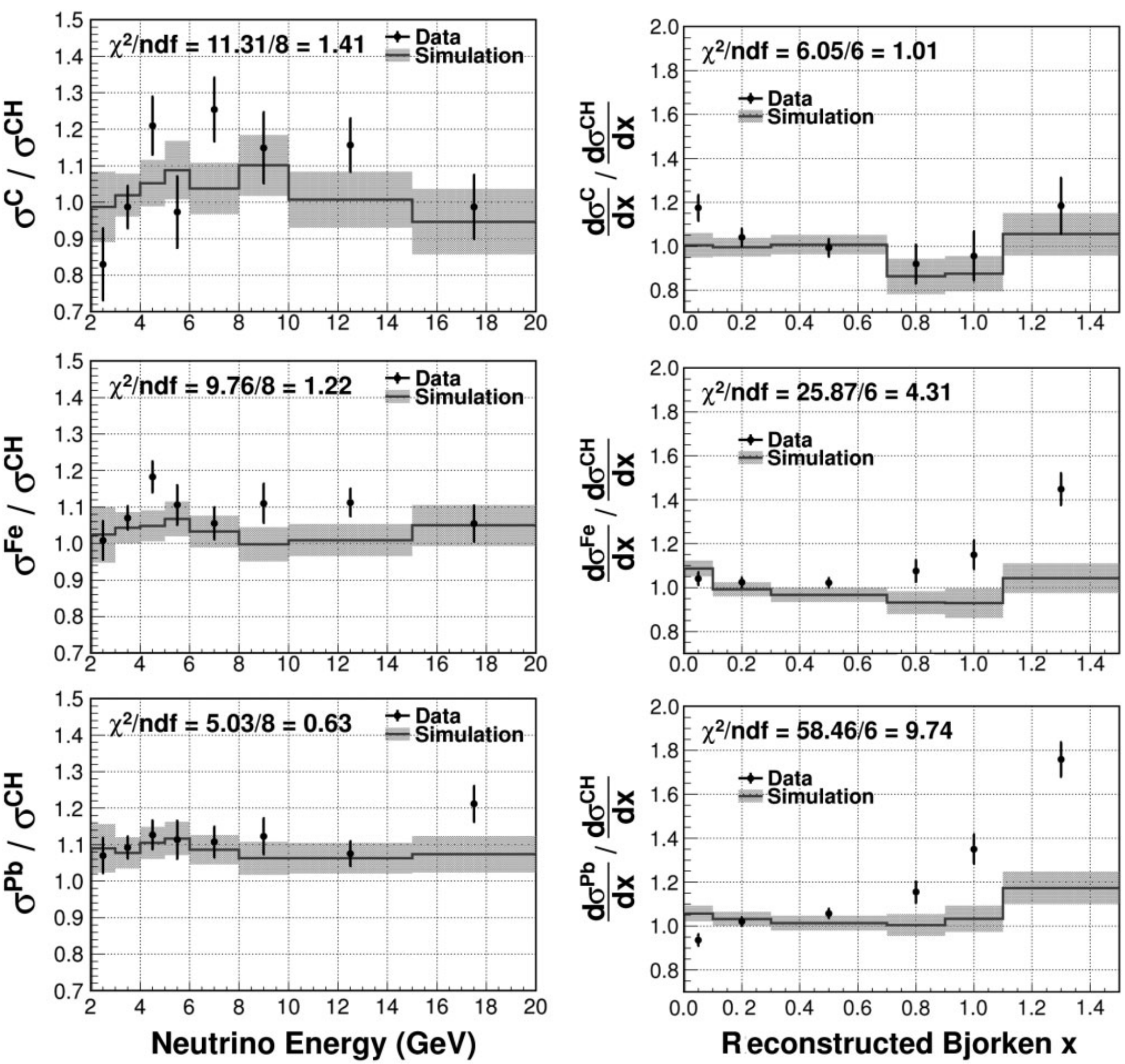


- Remarkable agreement at $x > 0.3$.
- "IC" curves provided by I. Cloet. Valence quark picture; anti-quark and gluon contributions not taken into account.

MaGHiC Fit

- S. Malace, D. Gaskell, D, Higinbotham, I. Cloet; ” Intl. Journ. Mod. Phys. E **23** 1430013 (2014)
- EMC Ratio, Charged Lepton Data Fit on wide range of nuclei: ^{3}He – ^{207}Pb.
- Heavier and lighter nuclear ratios that go to even lower *x* than Fe; continued turnover in charged lepton fit not artifact or extrapolation.

Recent Minerνa Result

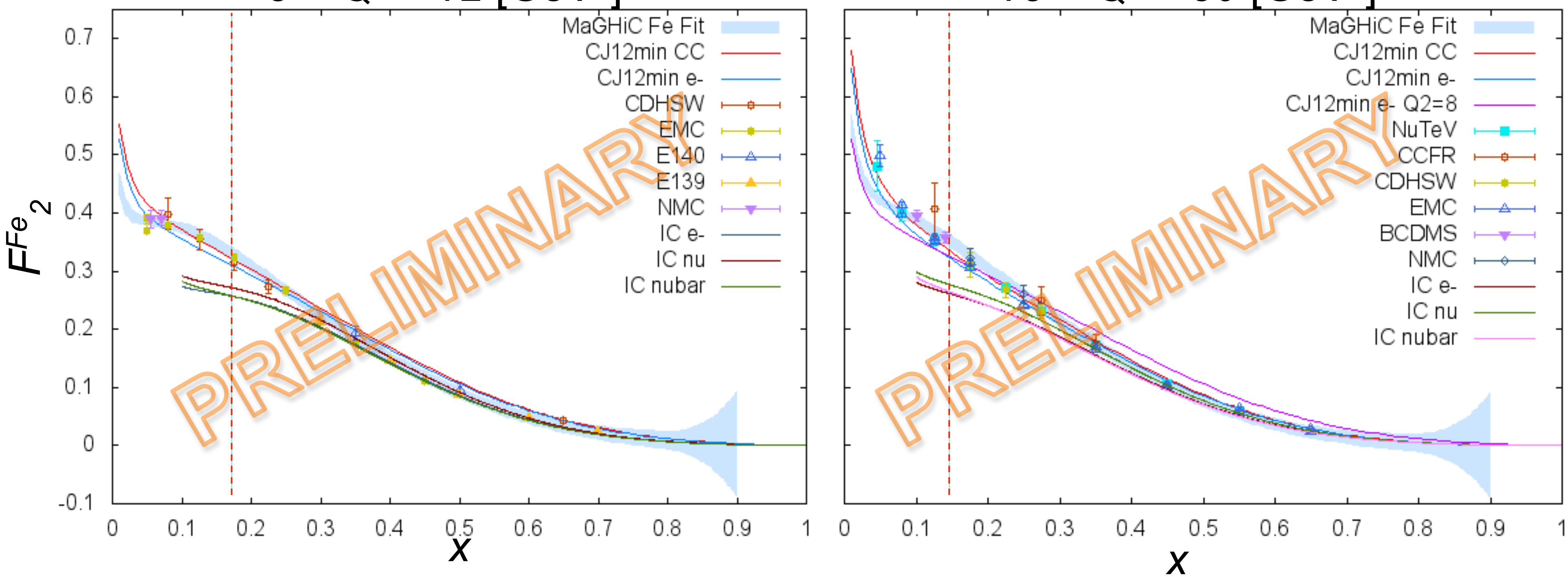


PRL **112** 231801 (2015)

- Low Energy Data
- See *A*-dependence, enhancement at lowest *x*-bin
- Data at low Q^2 (< 1 GeV^2)
- High Energy Data will be important!

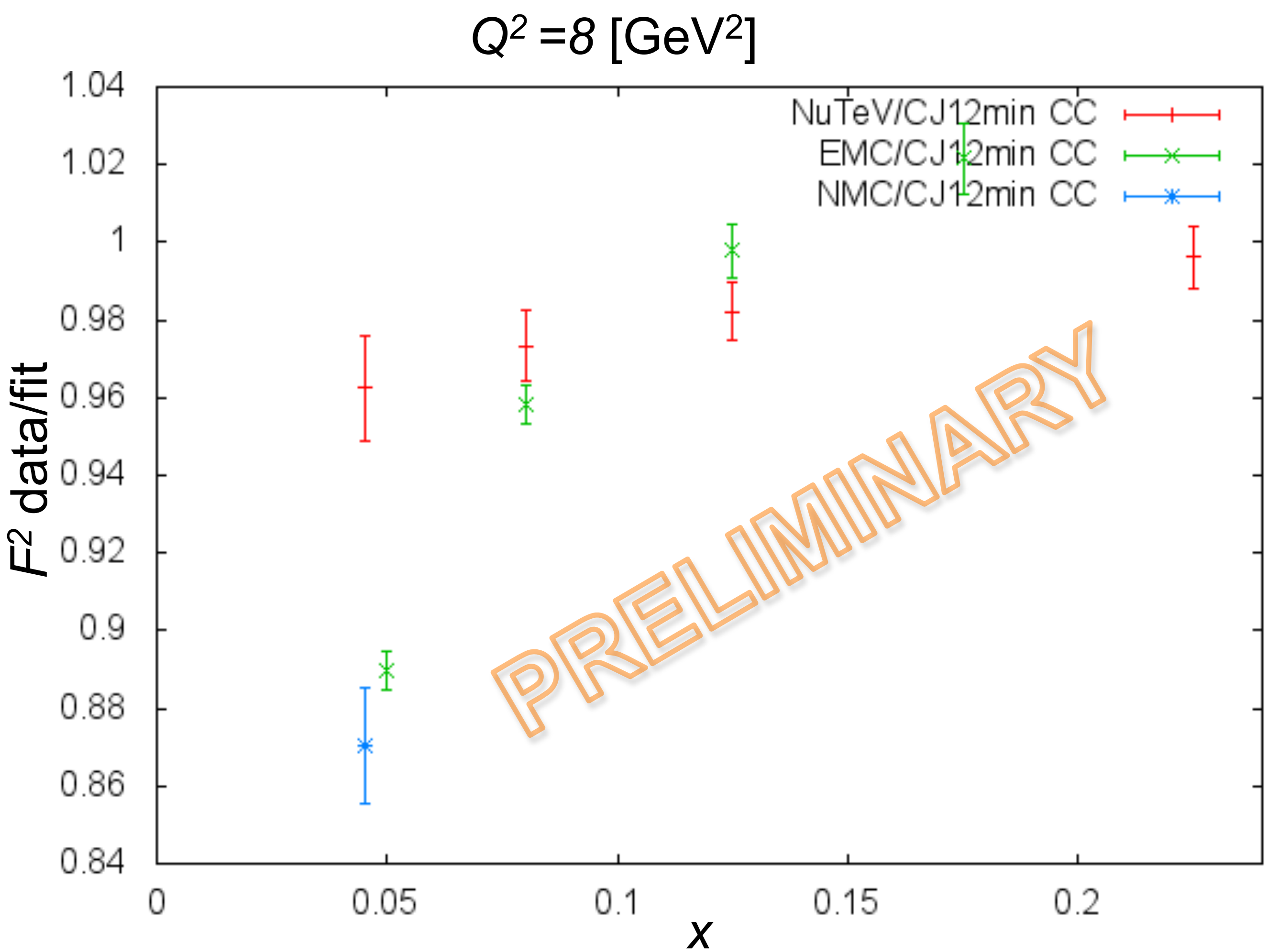
F^{Fe}_2 Scaling with Q^2

$8 < Q^2 < 12$ [GeV^2] $\quad$ $18 < Q^2 < 30$ [GeV^2]



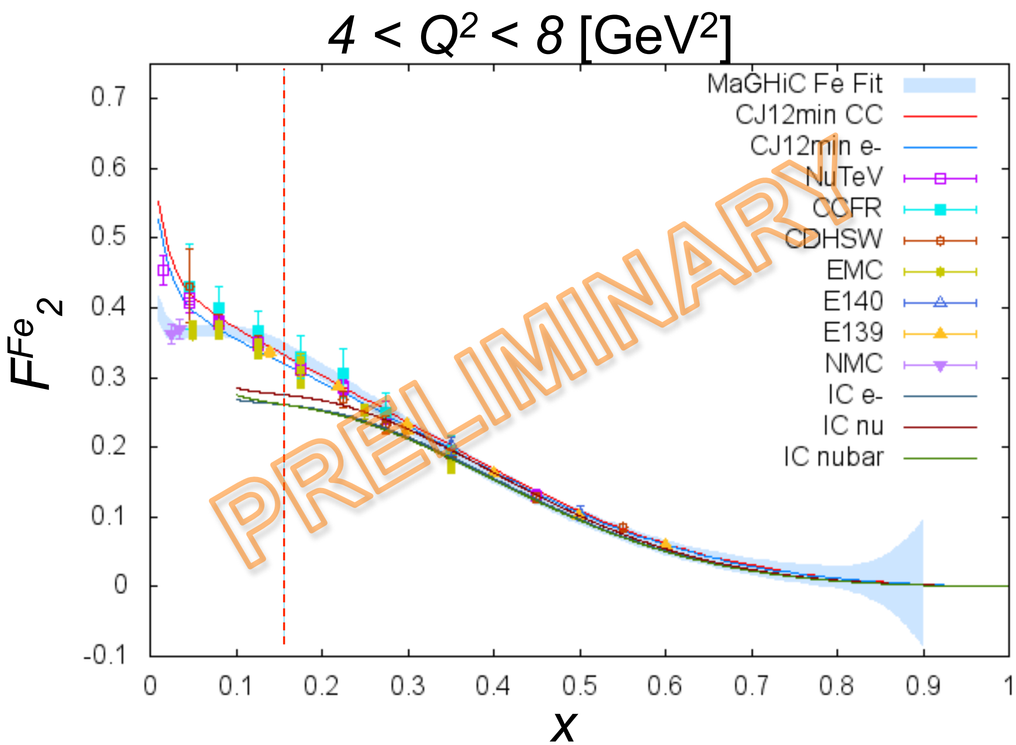
- Trend seems to remain. Study in progress; looking at higher Q^2.
- nCTEQ predicted different shadowing between neutrino and charged lepton scattering.

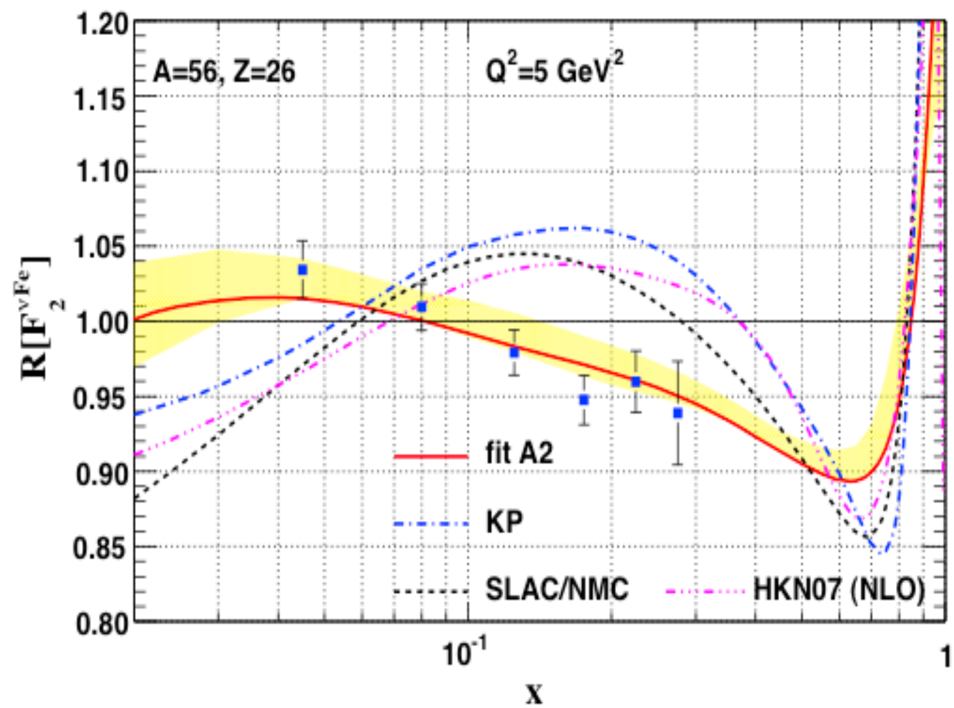
Data/Fit



- Data / CJ (CC neutrino).
- See discrepancy between neutrino and charged lepton data; (->~15%)
- More than predicted by nCTEQ; (~5%)
- NuTeV/CJ ~ 1
  Both EMC & NMC data/CJ drops down as *x -> 0*.
- Systematics ~ few %.

Comparing with Prediction





- Seem to be beyond systematics (not shown). NuTeV’s </~ 9% in regions of shadowing and anti-shadowing.
- Deuteron seems to make difference. nCTEQ predicted ~5% (absence of nuclear effects *Fe/d ~1*); seeing ->~15%.

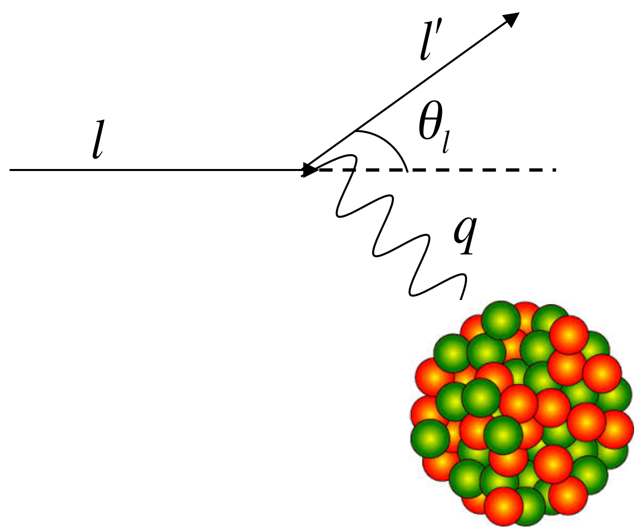
Possible Explanations

- Strangeness contribution? Can glean by comparing CJ CC and CJ e-.
- Radiative Corrections? Not same for charged lepton and neutrinos and do not seem to be large enough.
- Isoscalar Corrections? Too small to account for this (~1-few %)
- Fit/Theory predictions? Many proposed explanations (earlier slide). Deuteron seems to make difference.
- Need more low x (DIS) data!

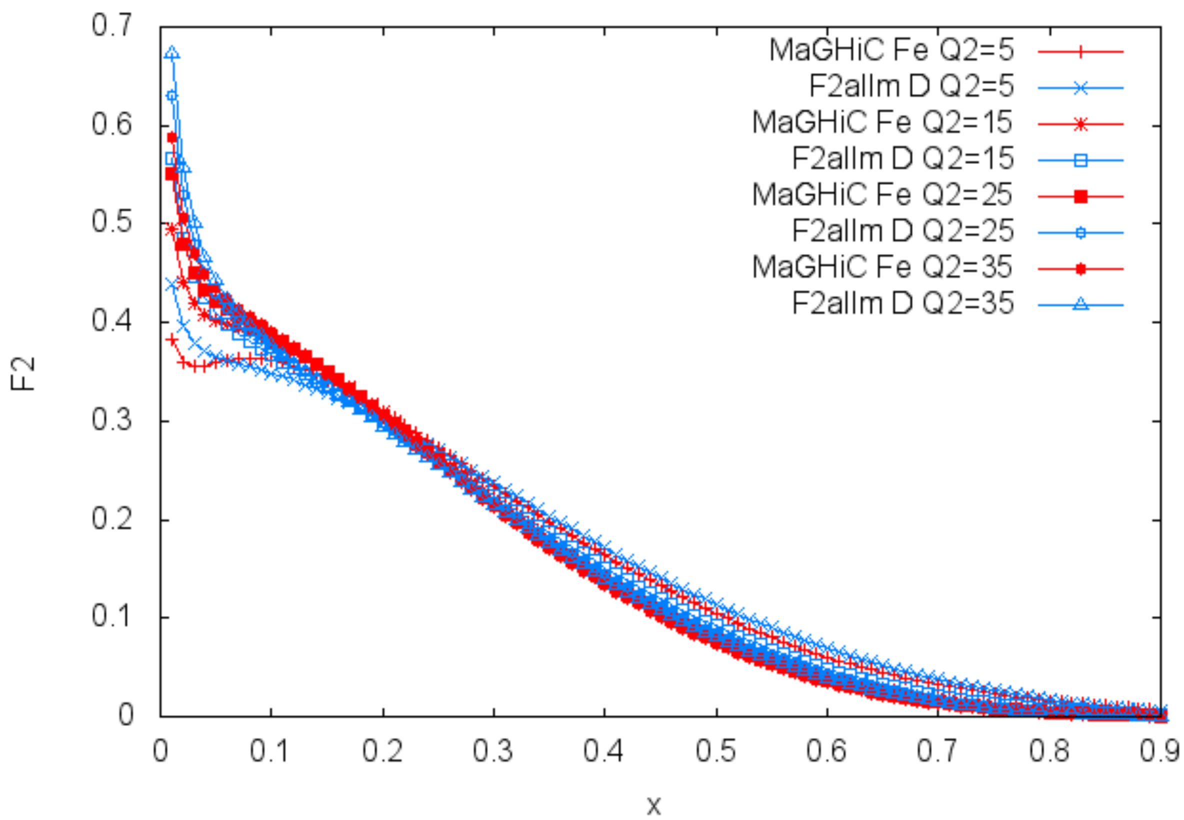
Summary

- Lepton scattering provides an opportunity to study nuclear structure.
- Structure Functions give fundamental information of the partonic structure of nucleons and nuclei.
- Charged lepton and neutrino data have shown some surprises.
- Studied Structure Function F_2, in Iron, by comparing data from charged lepton and neutrino probes.
- Observe that there seems to be different behavior between these 2 types of data in the shadowing region, perhaps more than expected.
- Minerνa high energy (low x) data will be important.

Back-Up Slides

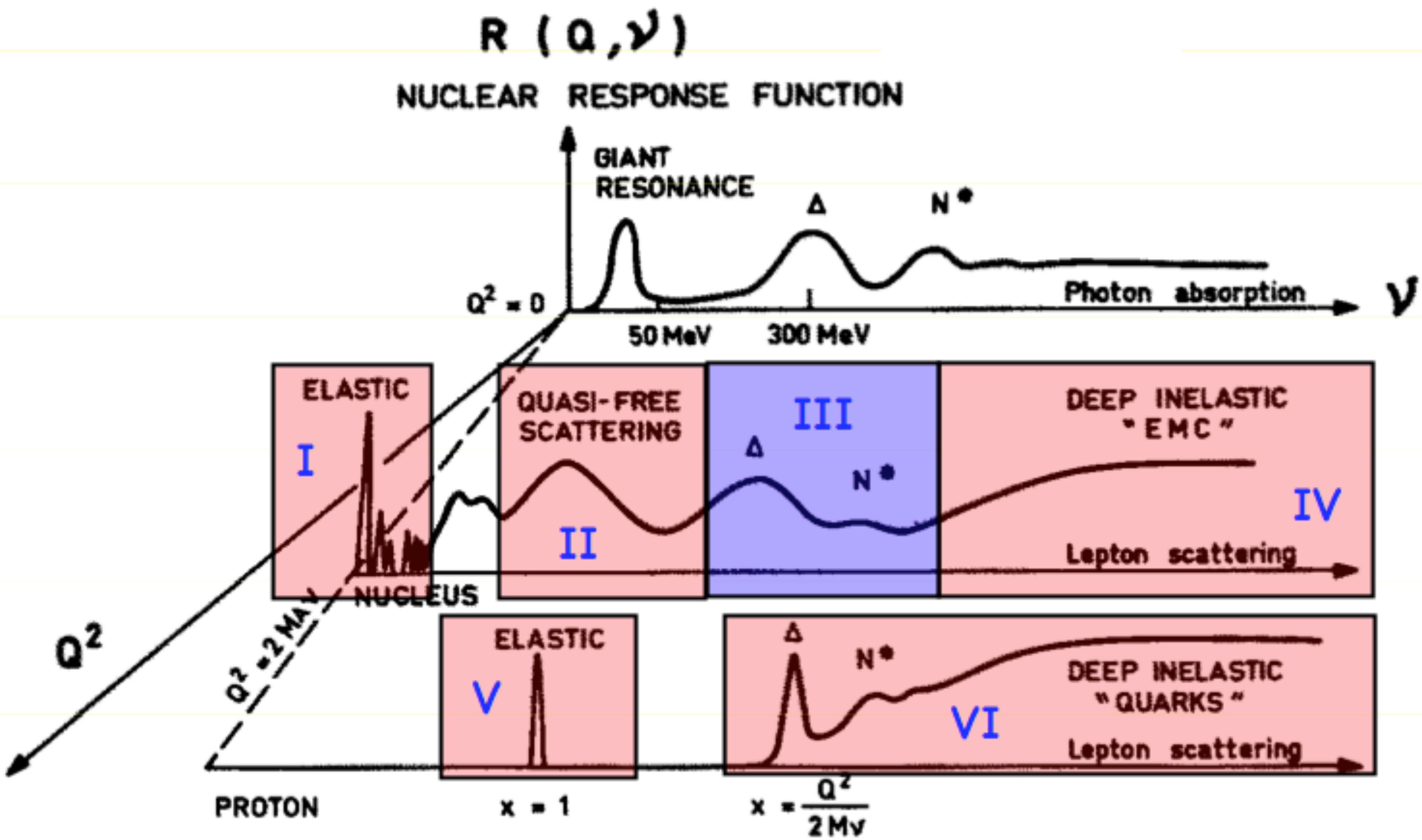


F_2^{Fe} From MaGHiC



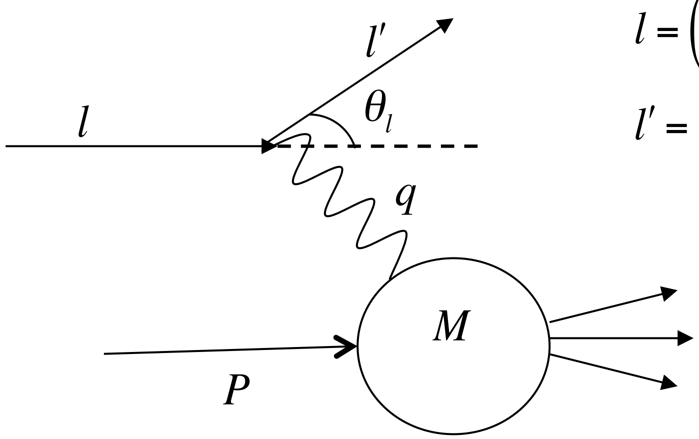
- MaGHiC integrates over Q^2.
- F2allm utilizes F_2^n/F_2^p parameterization, which is Q^2 dependent.

Lepton Scattering on a Nucleus



Inclusive* Lepton Scattering

*only detecting the scattered lepton



$$l = \left(E, \vec{l}\right) \qquad q = l - l'$$

$$l' = \left(E', \vec{l}'\right) \qquad Q^2 = -\vec{q}^{\,2} = 4EE'\sin^2\left(\frac{\theta_l}{2}\right)$$

$$x = \frac{Q^2}{2M\nu} \qquad y = \frac{\nu}{E}$$

$$\nu = E - E'$$

$$W^2 = M^2 + 2M\nu - Q^2$$

$$\sigma_{Mott} = \frac{4x^2E'^2}{Q^4}\cos^2\frac{\theta}{2}$$

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{Q^4}\frac{E'}{E}L_{\mu\nu}W^{\mu\nu}$$

$$F_2(x) = 2xF_1(x) = x\sum_q e_q^2 f_q(x)$$

$$F_1(x,Q^2) = MW_1(\nu,Q^2)$$

$$F_2(x,Q^2) = \nu W_2(\nu,Q^2)$$

$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_{Mott}\left[\frac{1}{y}F_2(x,Q^2) + \frac{2}{M}F_1(x,Q^2)\tan^2(\theta/2)\right]$$

*using natural units: *h-bar = c = 1*

F_2 For Charged Leptons and Neutrinos

Perkins

$$F_2^{ep}(x) = x\left\{\tfrac{4}{9}\left[u(x)+\bar{u}(x)\right]+\tfrac{1}{9}\left[d(x)+\bar{d}(x)+s(x)+\bar{s}(x)\right]\right\}$$

Isospin invariance in strong reactions: $u(x)^n = d(x),\, d(x)^n = u(x)$

$$F_2^{eN}(x) = x\left\{\tfrac{5}{18}\left[u(x)+\bar{u}(x)+d(x)+\bar{d}(x)\right]+\tfrac{1}{9}\left[s(x)+\bar{s}(x)\right]\right\}$$

Neutrino charged couplings: $\nu_\mu d \to \mu^- u, \quad \nu_\mu \bar{u} \to \mu^- \bar{d}$

$$\bar{\nu}_\mu u \to \mu^+ d, \quad \bar{\nu}_\mu \bar{d} \to \mu^+ d\bar{u}$$

$$F_2^{\nu p}(x) = 2x\left[d(x)+\bar{u}(x)\right], \quad F_2^{\nu n}(x) = 2x\left[u(x)+\bar{d}(x)\right]$$

$$F_2^{\nu N}(x) = x\left[u(x)+d(x)+\bar{u}(x)+\bar{d}(x)\right]$$

Equate for charged leptons and neutrinos:

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