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

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JLab Pizza Seminar

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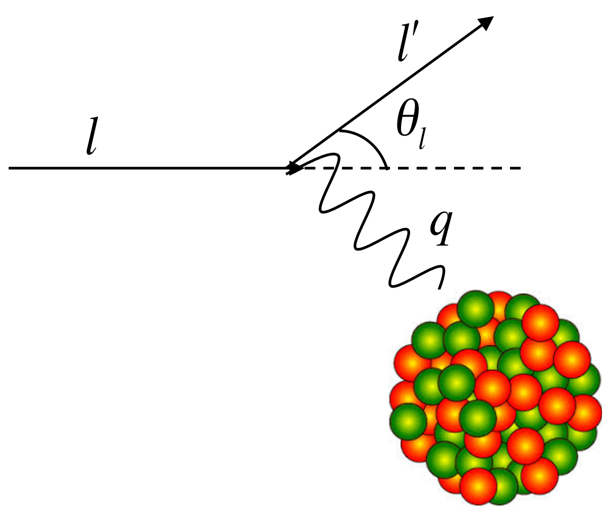


Outline

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

Motivation

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

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

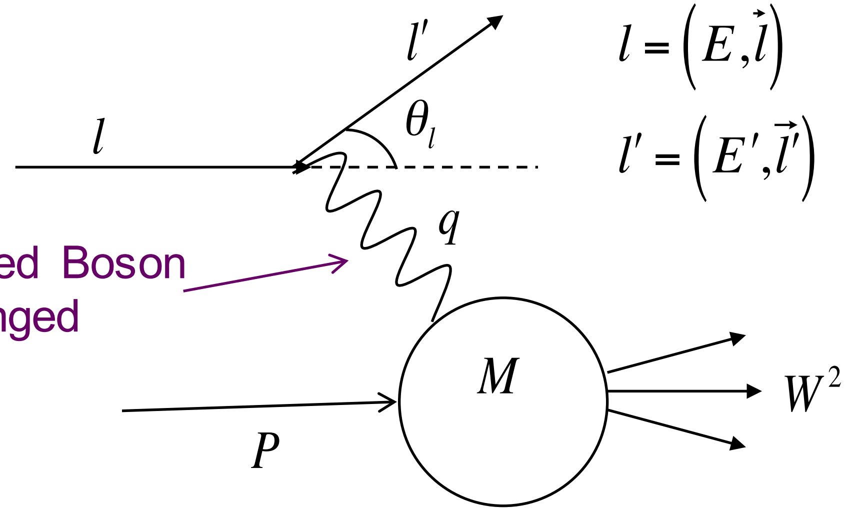
- Understanding parton* distributions via F_2^{Fe} from DIS data.
- Confronting fitting with data: F_2^{Fe} from charged lepton and neutrino scattering experiments.
- How do data from charged lepton probes compare with neutrino probes ?

*Quark-Parton Model (QPM): quarks treated as point-like objects

Inclusive Lepton Scattering

Only detecting the scattered lepton:

Physics Reports **406** 127 (2005)



$l = (E, \vec{l})$

$l' = (E', \vec{l}')$

Radiated Boson exchanged

Virtuality
(Resolving power) [GeV²]

$$q = l - l'$$

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

Bjorken scaling
variable *x*
(dimensionless)

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

Energy transferred to target

$$\nu = E - E'$$

Invariant mass
of final states [GeV²]

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

Inelasticity: $y = \dfrac{\nu}{E}$

Inclusive Lepton Scattering

Physics Reports **406** 127 (2005)

Incl. Cross-Section:
(QPM)

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

Mott: Scattering from a point particle:

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

Callan-Gross Relation:
Conservation of helicity spin ½
(Infinite momentum frame)

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

$f_q(x)$ Quark probability distribution
***i.e.* Parton Distr. Fn. (PDF)**

e_q Quark charge

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

Charged Lepton vs. Neutrino Scattering

*only detecting the scattered lepton

Parity Violation

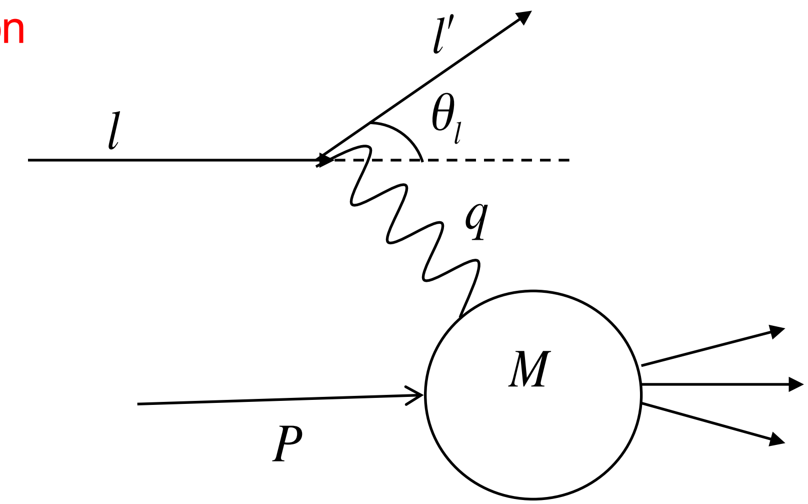
Charged Leptons:

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

q => ***EM*** coupling => γ, *Z*

Vector coupling (parity conserved)

Mono-energetic beam; fixed E_{beam}



Neutrinos:

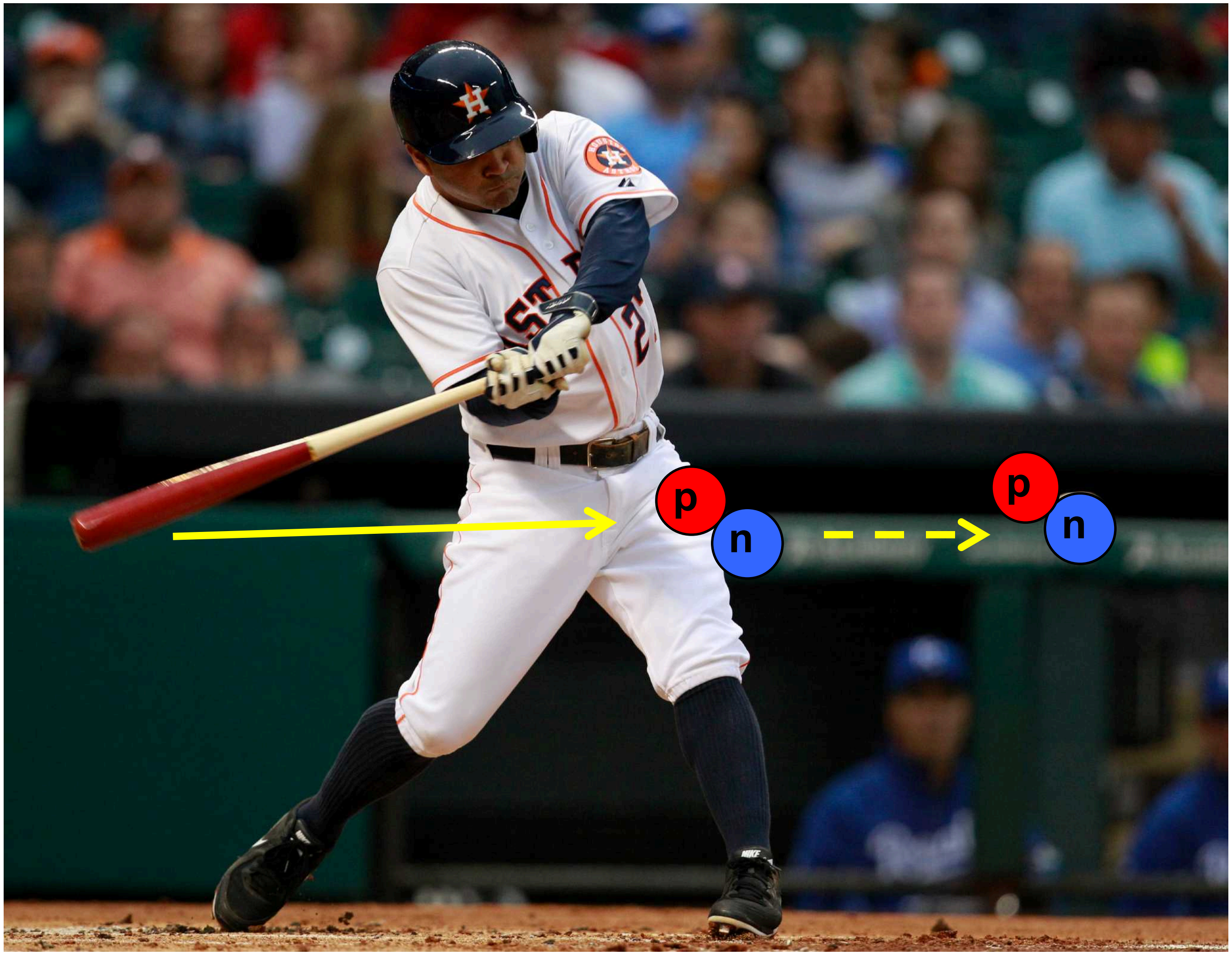
ν, ν–bar

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}

Elastic Scattering



Nucleons* stay together

$$x = \frac{Q^2}{2M\nu} = \frac{Q^2}{Q^2 + W^2 - M^2} = 1$$

$$W = M$$

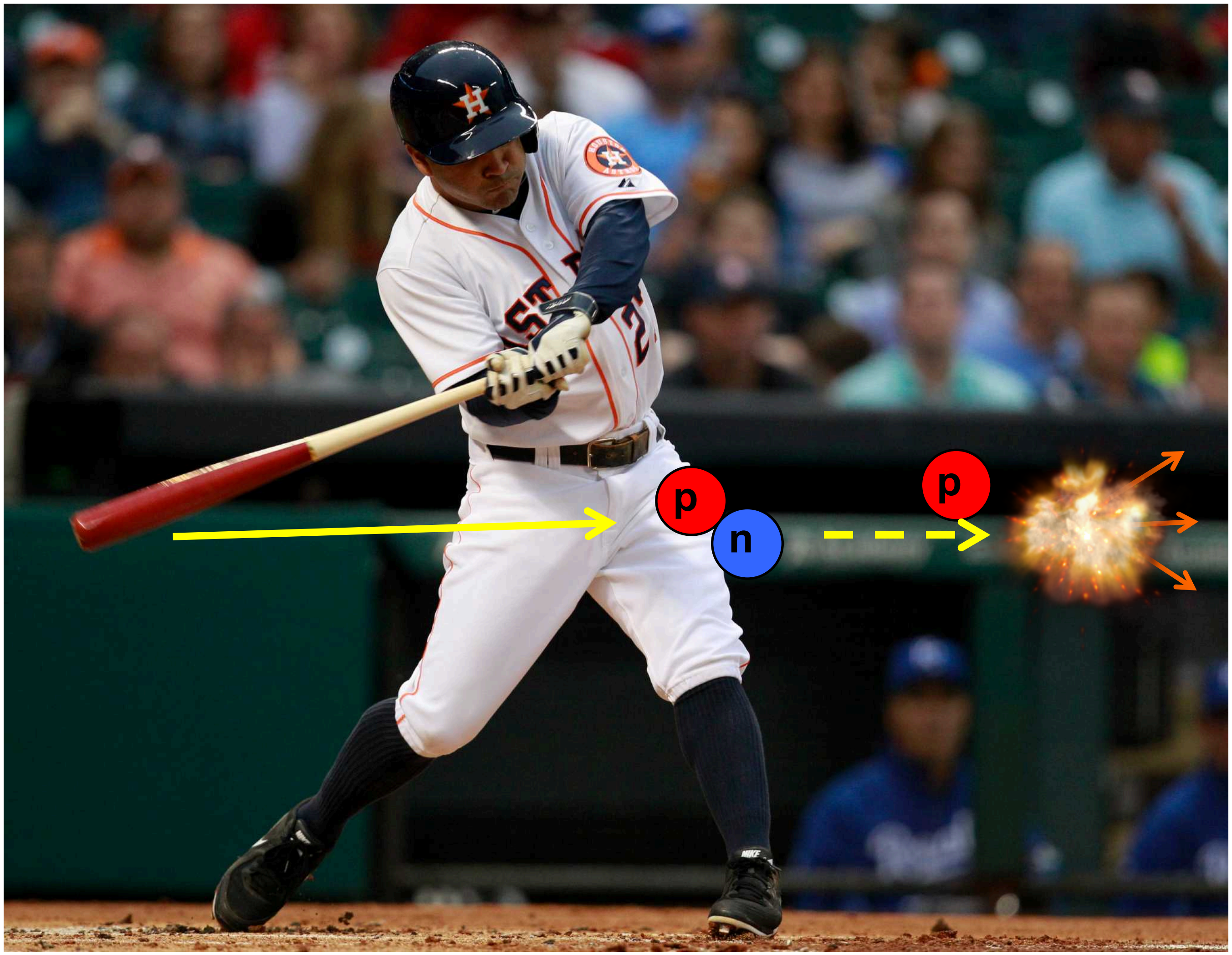
*Simple case of deuteron:
1 Proton (p), 1 Neutron (n)

Quasi-Elastic Scattering

1 Nucleon knocked out
Here: neutron carries momentum, proton "spectator"

*Simple case of deuteron:
1 Proton (p), 1 Neutron (n)

Deep Inelastic Scattering



Probing Partonic level.

Approaching Bjorken limit:

$$Q^2, \nu \rightarrow \infty$$

*Simple case of deuteron:
1 Proton (p), 1 Neutron (n)

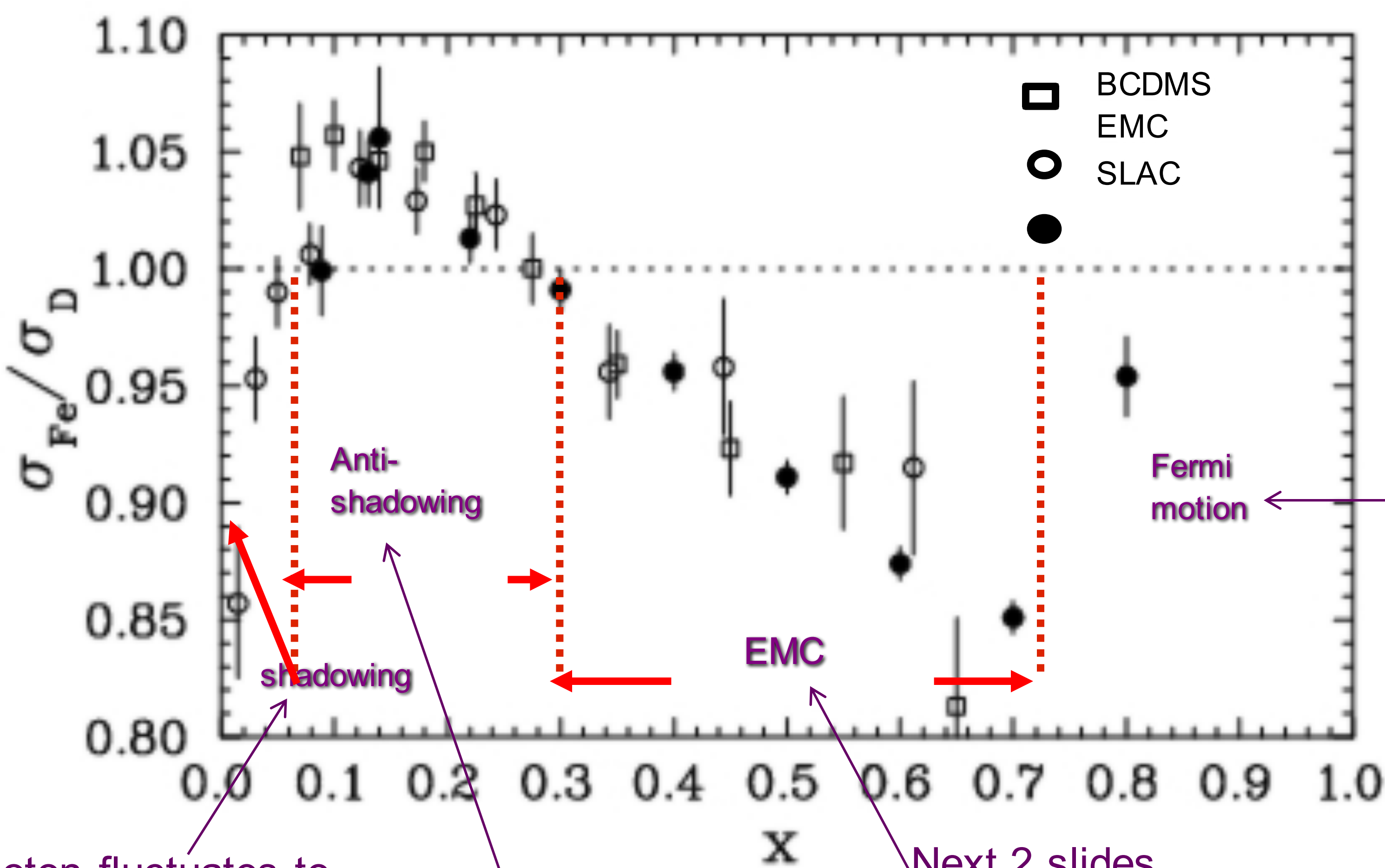
Nuclear Ratios

- Take the ratio of F_2 of a near isoscalar (#n = #p) target to simplest nucleus (deuteron).
- Are there changes in the medium?
- Is F_2 universal?
- If nuclei are (only) composed of neutrons and protons then, normalizing by nucleon number (A), such a ratio should be unity.

$$\frac{2}{A}\frac{F_2^A(x)}{F_2^d(x)} = 1$$

Nuclear Ratios

See something quite different -*definitely* not unity.



Charged lepton data

~ motion of nucleons in nucleus

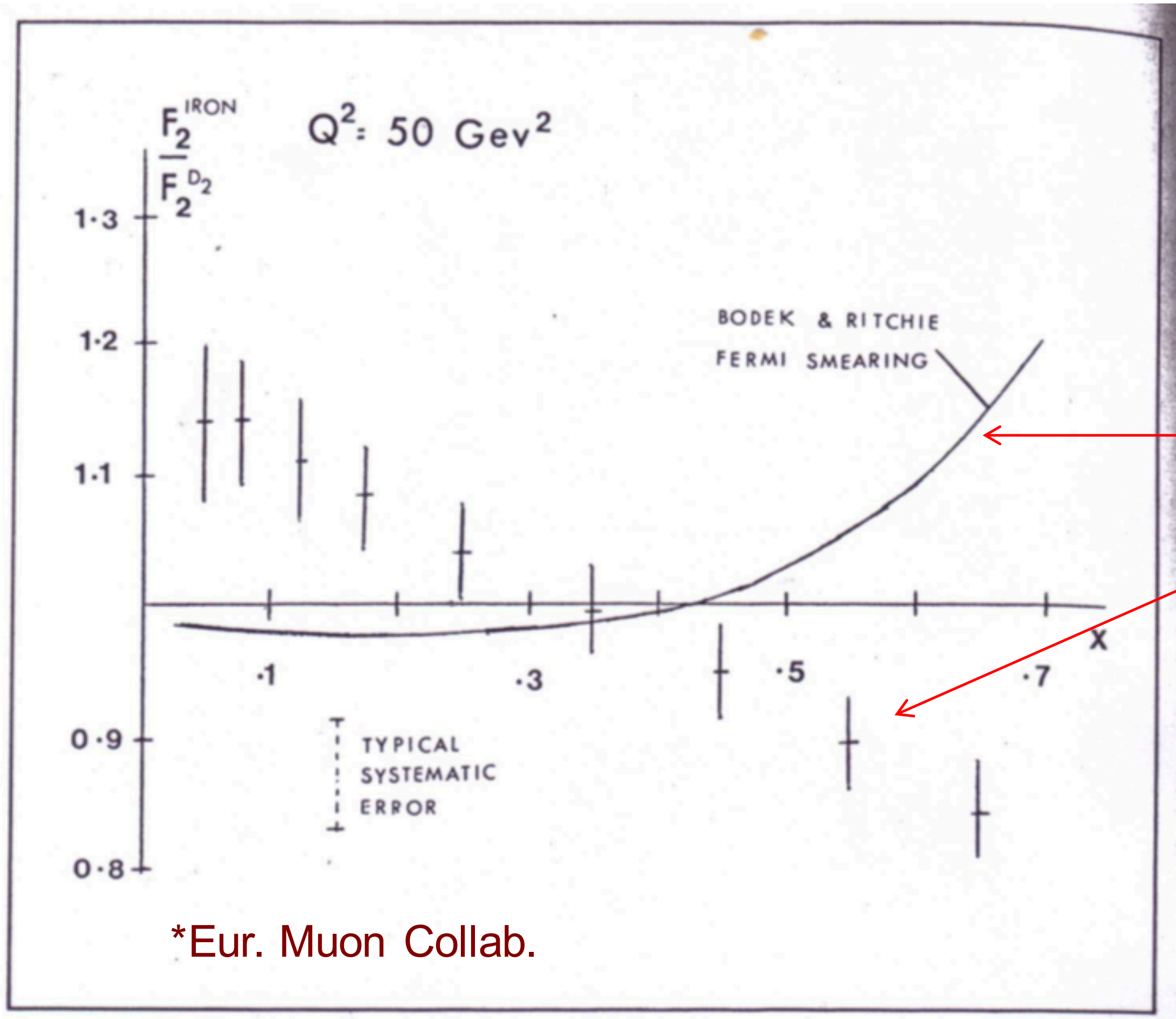
Photon fluctuates to meson sometimes

Extra mesons in nucleus

Next 2 slides

What is the EMC* Effect?

CERN Courier, Nov. 1982 (shown) and then Phys. Lett. B **123** (1983) 275.



*Eur. Muon Collab.

Effect Reproduced (Many Times!)

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

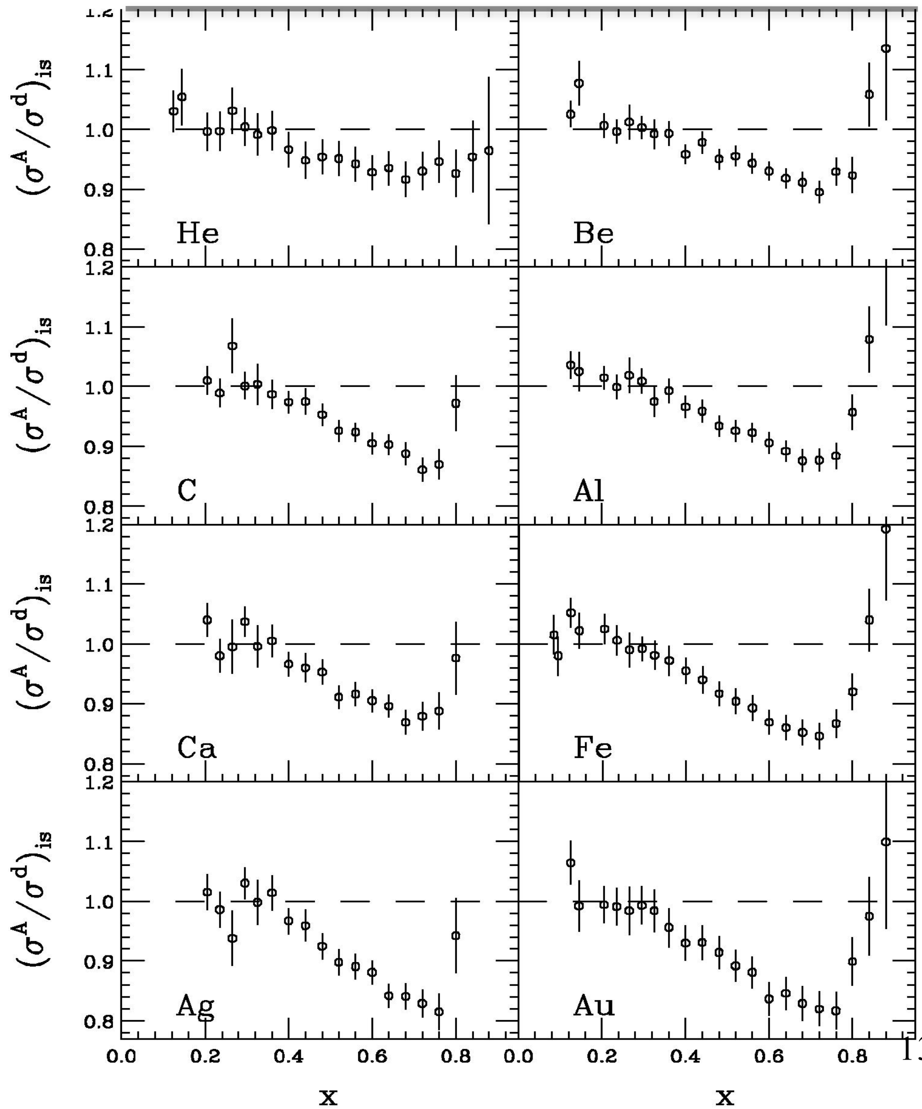
- PLB **123** (1983) 275.
- Simple Parton Counting Expects One
- **MANY Explanations**

SLAC E139

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

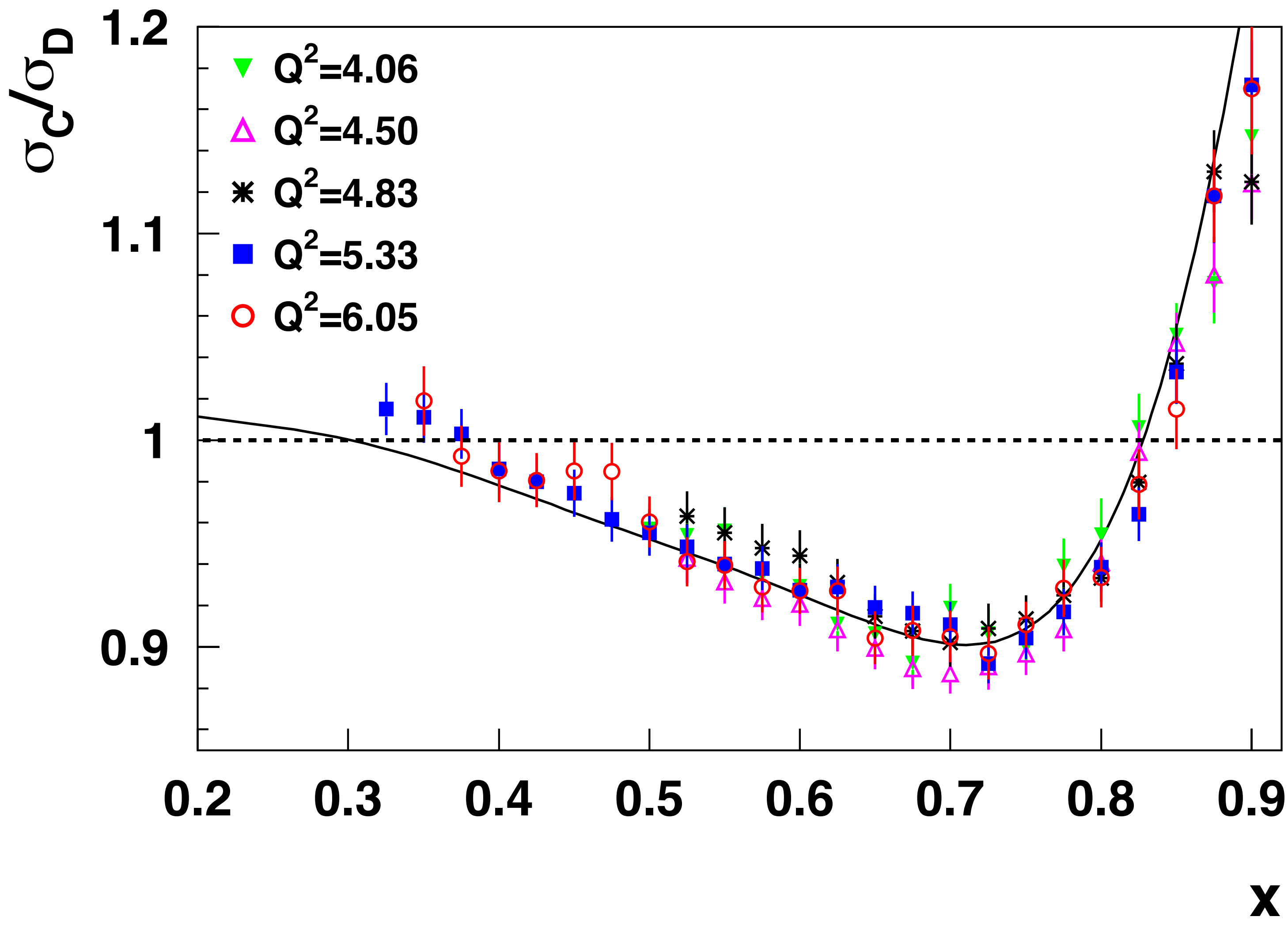
Conclusions from SLAC data

- Nearly Q^2-independent
- Universal x-dependence (shape)
- Some A dependence



Recent Jlab EMC Data

Phys, Rev. Lett. **103** (2009) 202301.



Neutrino Ratio Data

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

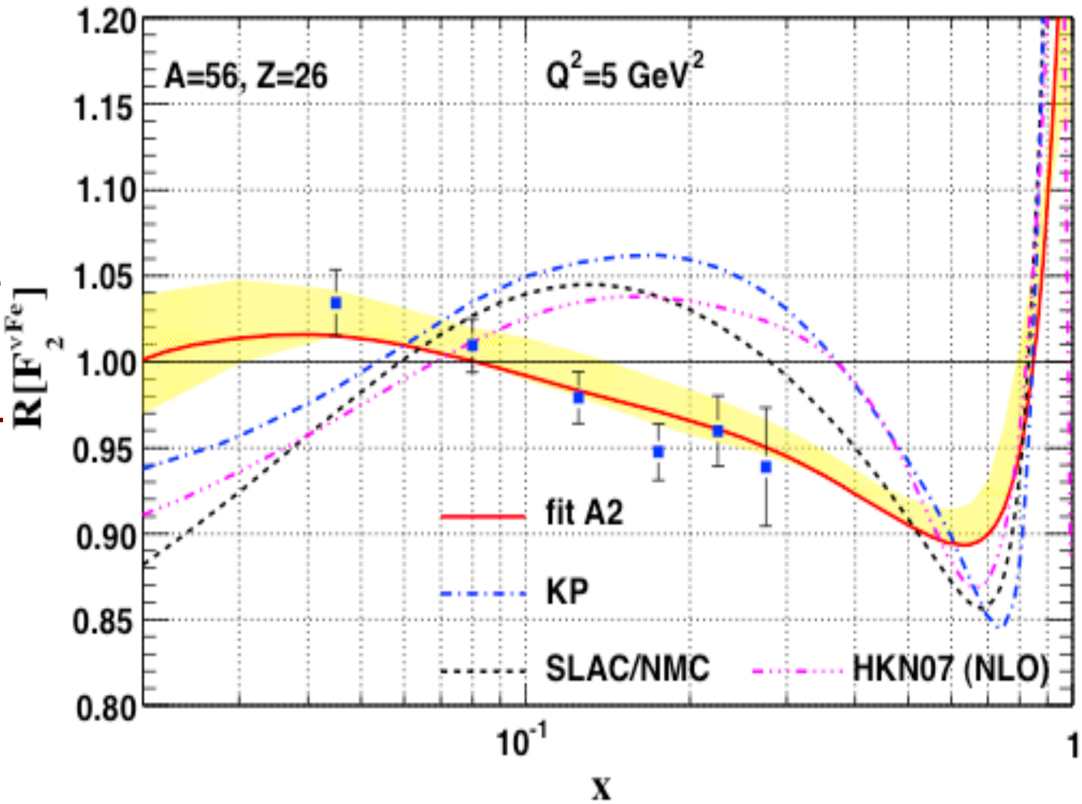
Nuclear PDF fits done on charged lepton data. (nCTEQ)

A-dependent PDFs then used to extract ratios.

NuTeV Fe data, deuteron constructed using PDFs.

ν–*A* dependence different from *e*/μ-*A*

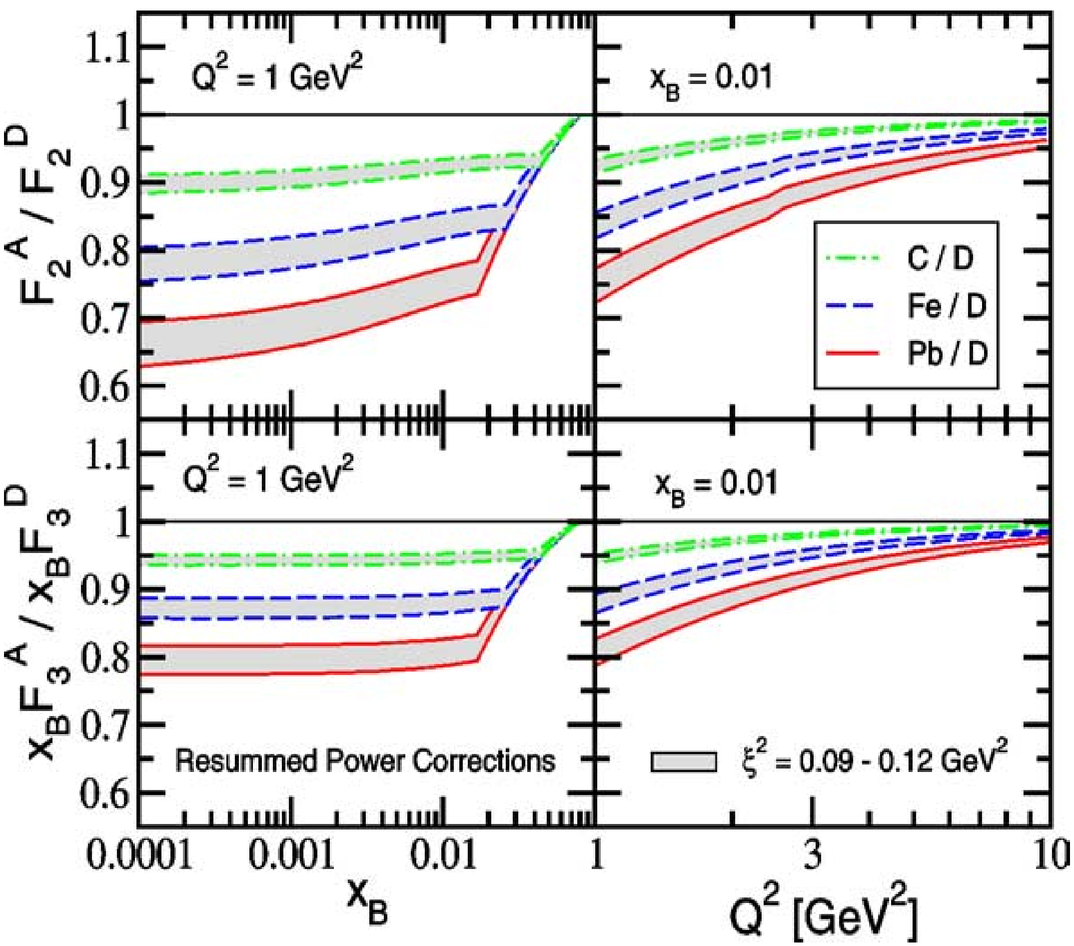
***How about looking at the Fe data, itself? Reduce the model-dependence.**



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

Theory Predictions

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



- Predict sizeable effect in (anti)shadowing region.
  Phys. Report **512** 255
  PRL **81** 4075 =>CSV(?)
- 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).
- Nuclear corrections taken into account.

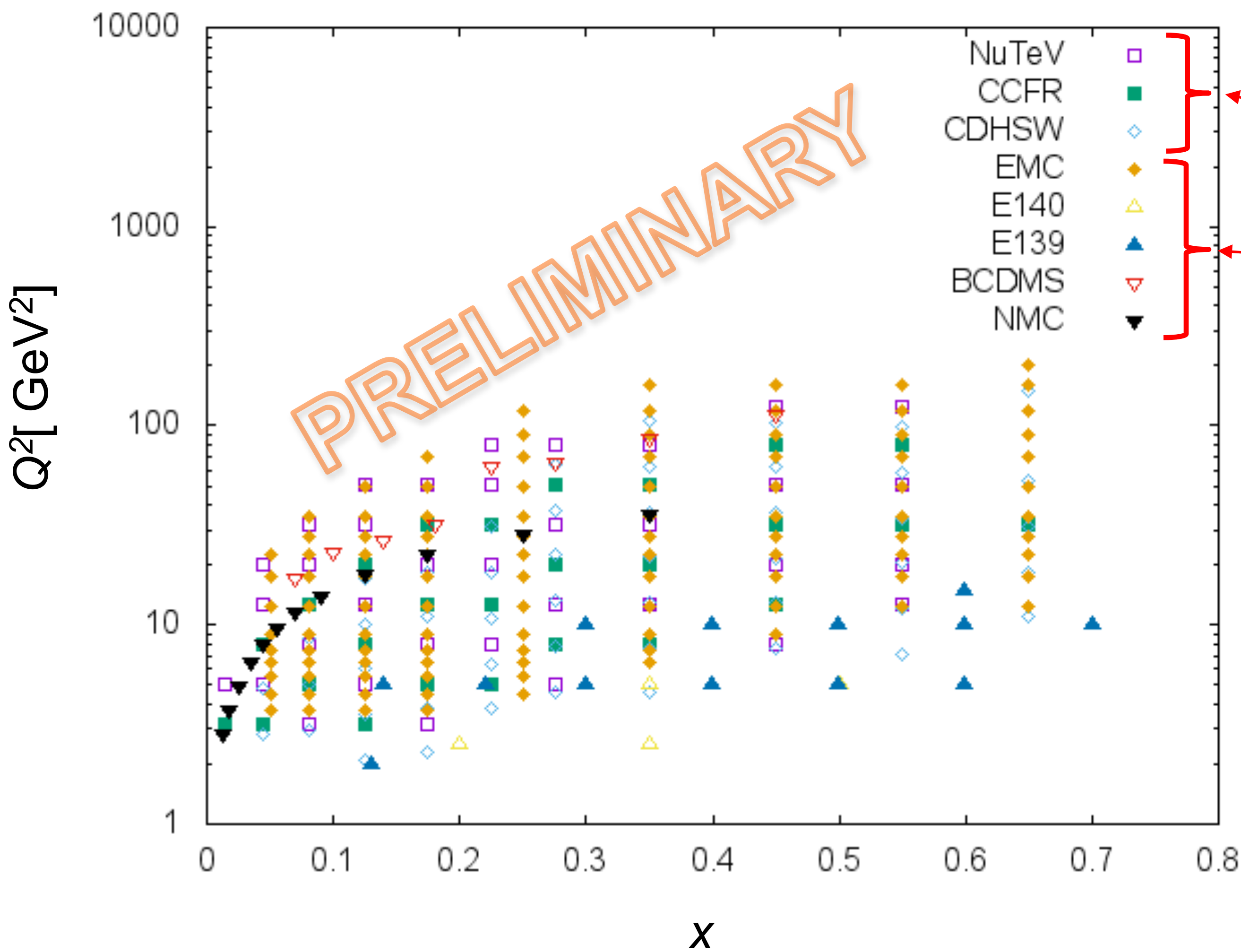
Analysis

- Apply DIS cuts; $Q^2 > 2$, $W^2 > 4$ [GeV^2].
- Set F^{Fe}_2 data to a common Q^2; 8 [GeV^2] (average bin-centering).
- For cases of data being SF ratio F^{Fe}_2/F^d_2; use reliable F^d_2 parameterization (*NMC*) to multiply and extract F^{Fe}_2.
- Plot (and compare) data with fits (ratios)
- Neutrino data normalized to account for quark charges: ~5/18.
- 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

280 Perkins Quark-Quark Interactions: The Parton Model and QCD

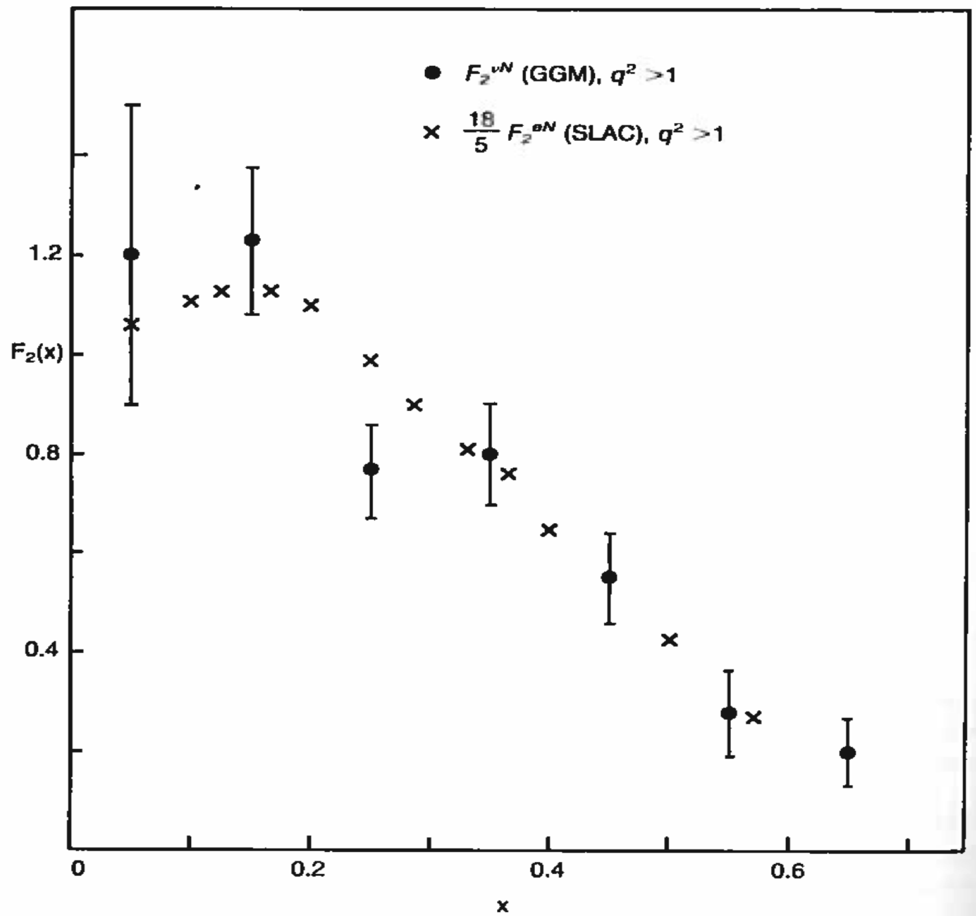


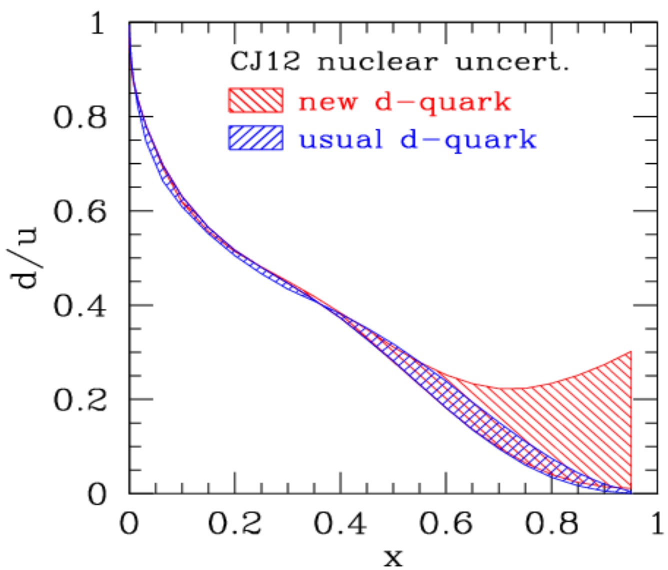
Figure 8.12 (a) First comparison of $F_2^{\nu N}$ measured in neutrino-nucleon scattering in the Gargamelle heavy-liquid bubble chamber in a PS neutrino beam at CERN, with SLAC data on F_2^{eN} from electron-nucleon scattering, in the same region of q^2. The two sets of data agree when the electron points 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



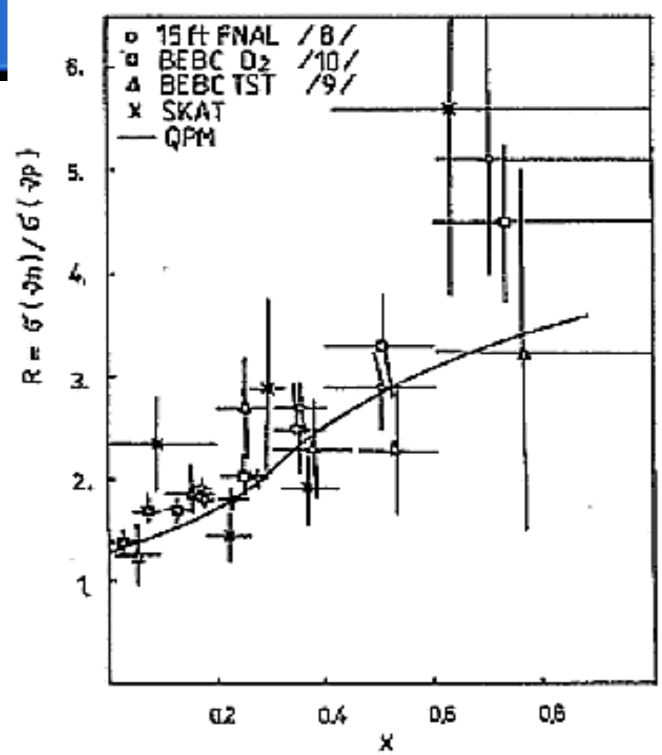


Fig. 4. World data of the dependence of the cross section ratio $\sigma(\nu n)/\sigma(\nu p)$ on Bjorken-x measured in neutrino bubble chamber experiments. The full line gives the prediction of the quark parton model [1, 2] using the parametrisation of the quark distributions by Feynman-Field [5]

- 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:

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

(30% ratio uncertainty)

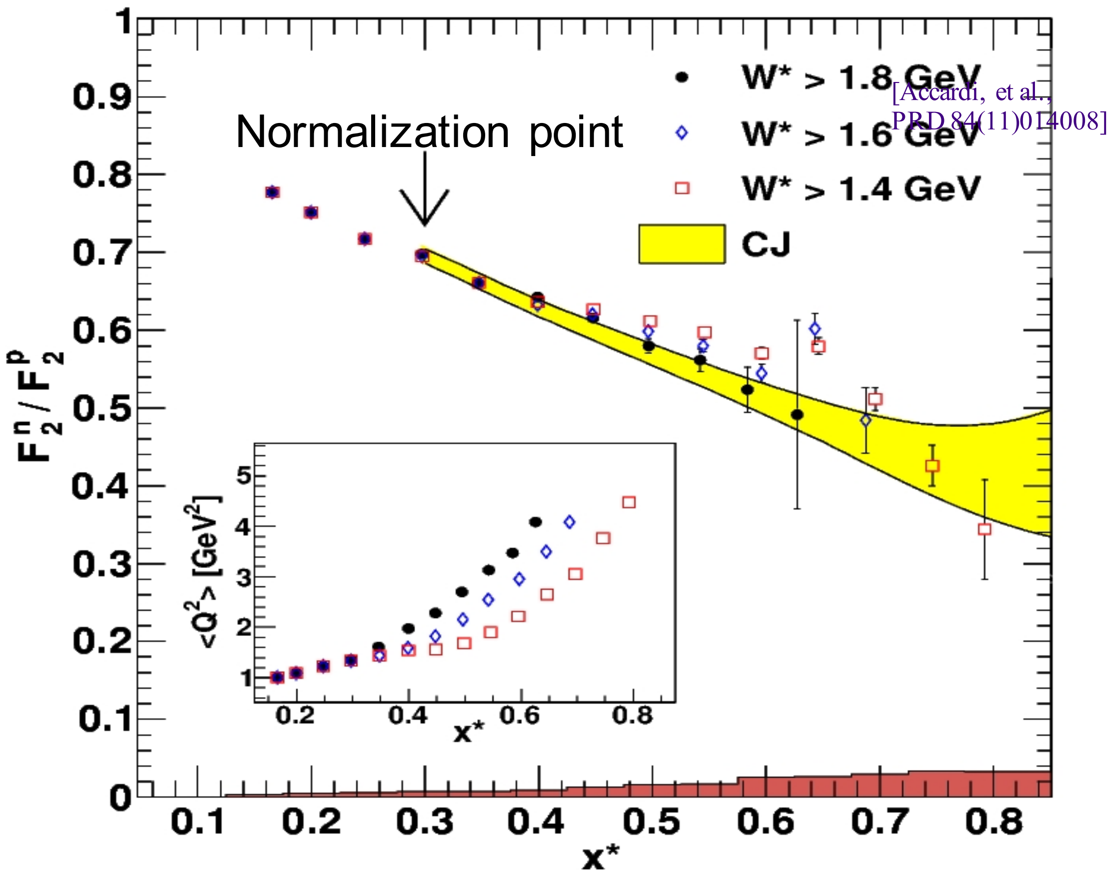
	For $\sigma_n/\sigma_p = 3$	For $\sigma_n/\sigma_p = 3*1.3$
^{56}Fe : $A/Z = 56/26 = 2.154$	$\boxed{f = 0.965}$	$\boxed{f = 0.959}$

*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.

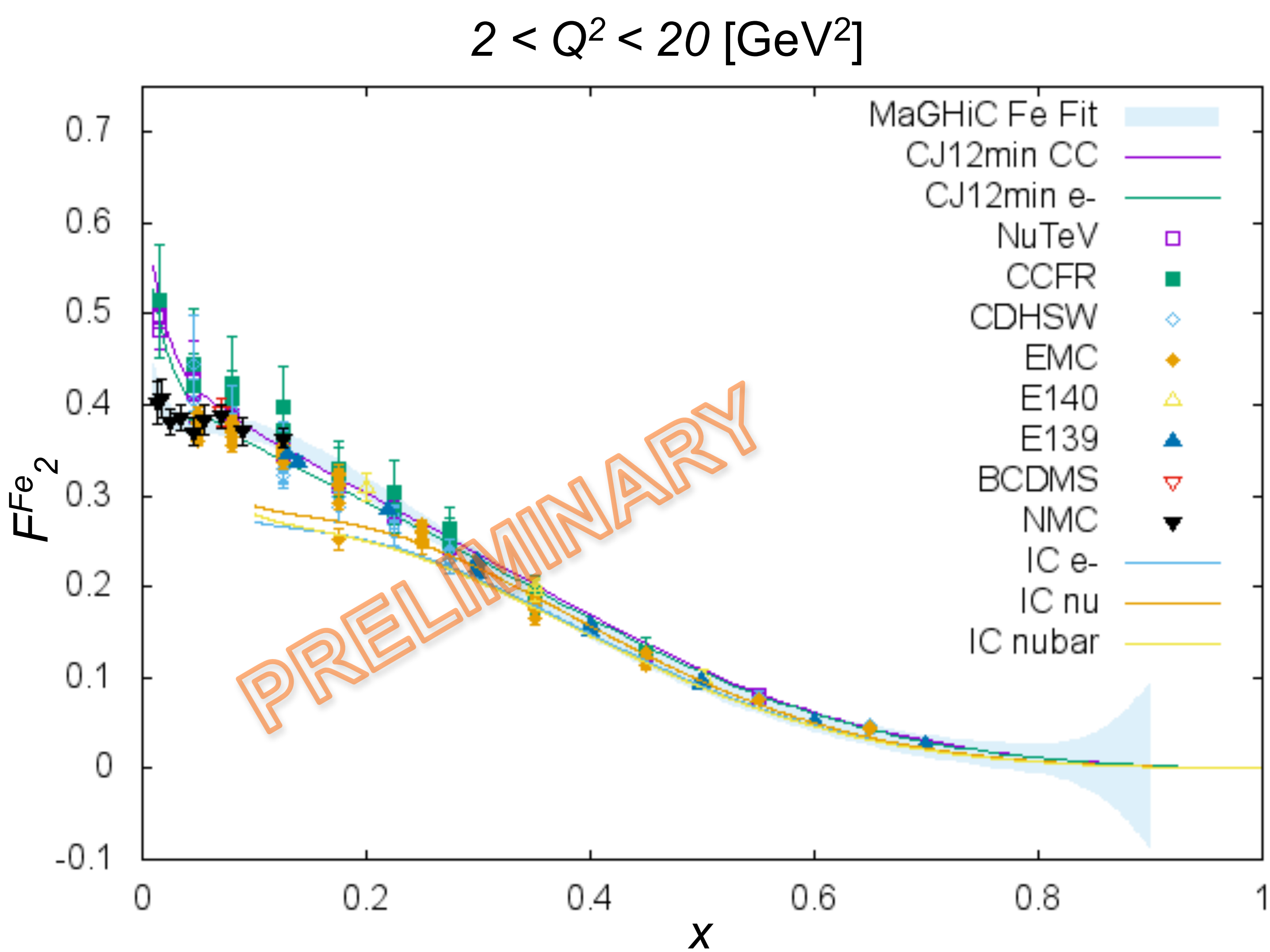
→ x~0.6 uncertaintiy < 8%

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

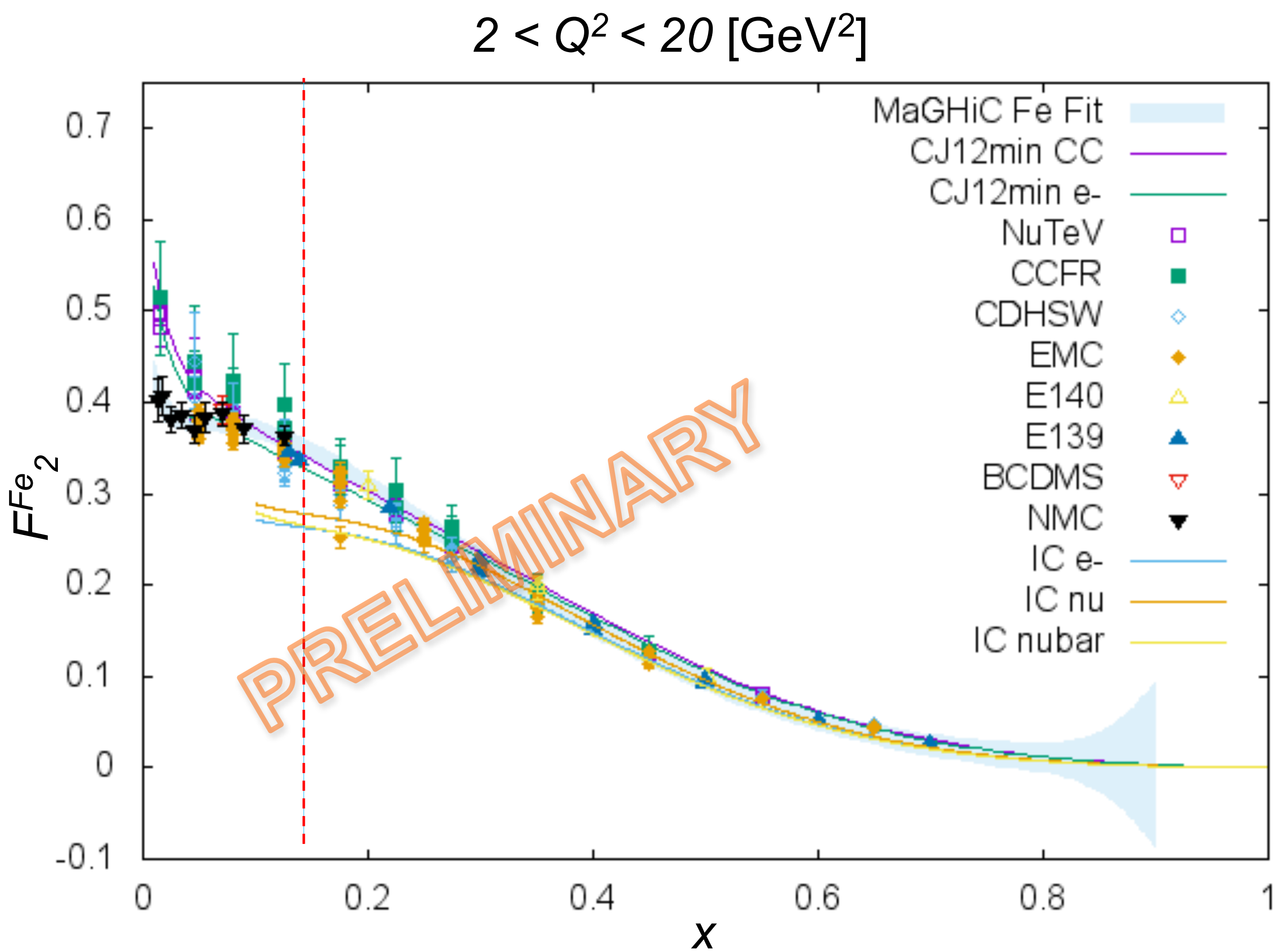


"CJ12min fit"
Phys.Rev. D **87** 094012 (2013)

"MaGHiC"
Intl. Journ. Mod. Phys. E **23** 1430013 (2014)

Some spread in the charged lepton data.

F^{Fe}_2 Data and Fits



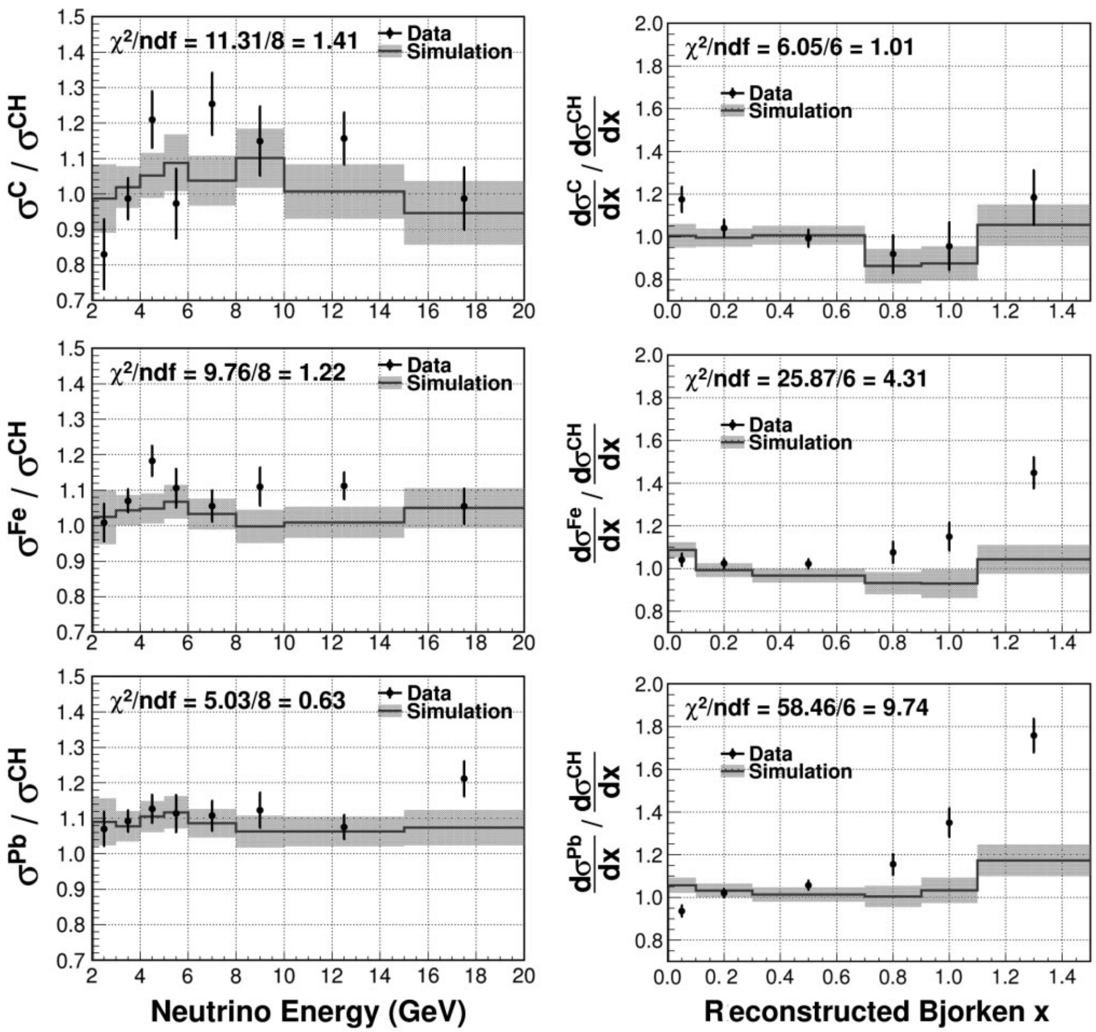
"CJ12min fit"
Phys.Rev. D **87** 094012 (2013)

"MaGHiC"
Intl. Journ. Mod. Phys. E **23** 1430013 (2014)

Some spread in the charged lepton data.

Difference between Charged lepton and neutrino data at x < ~0.15

Recent Minerνa Result

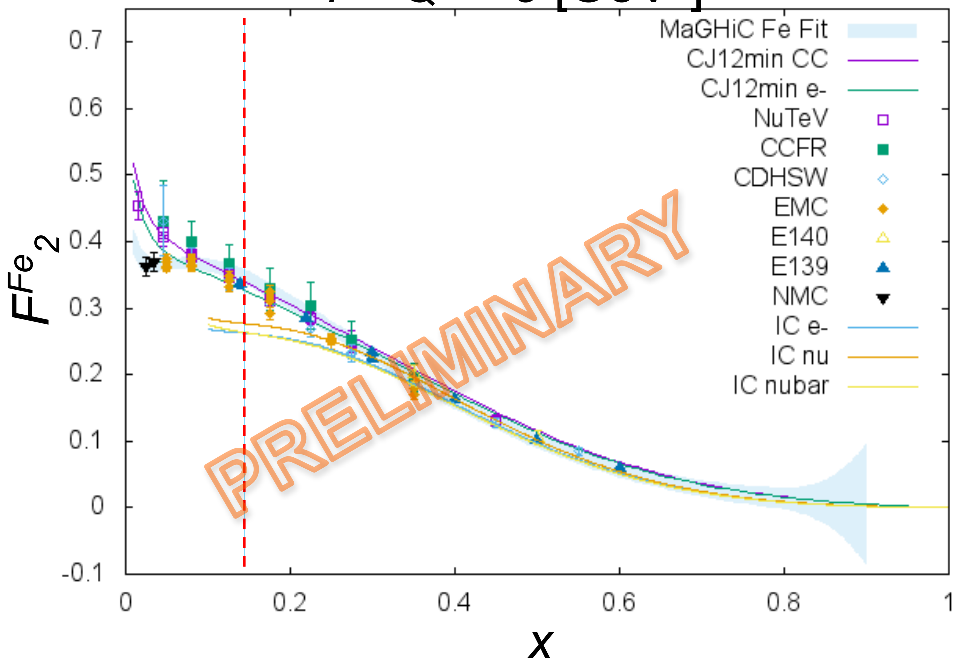


PRL **112** 231801 (2015)

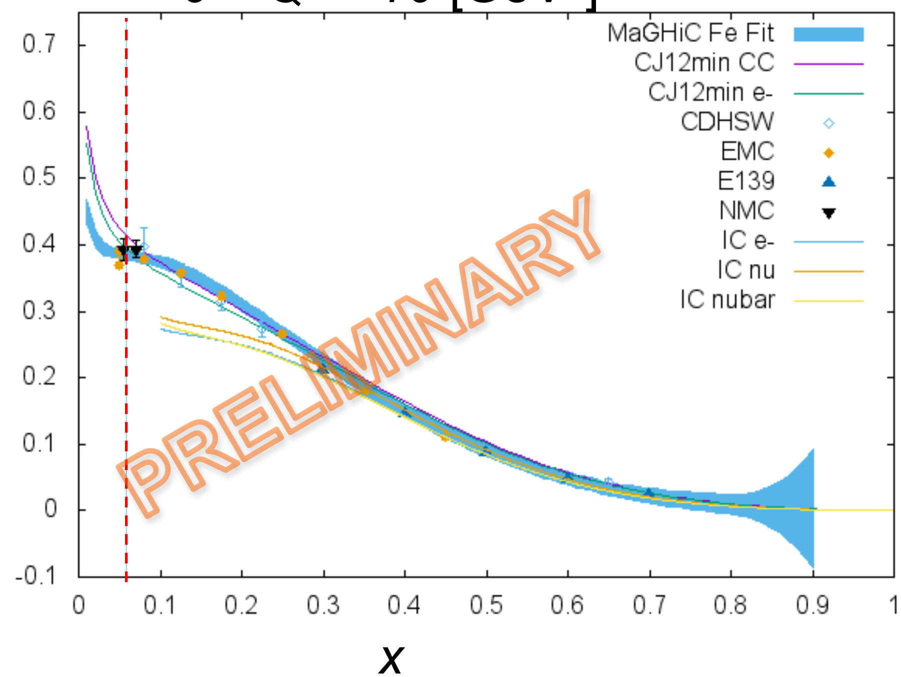
- Low Energy Data
- See *A*-dependence, enhancement at lowest *x*-bin
- Data at low Q^2 (< 1 GeV^2)
- High Energy Data will be important!

F^{Fe}_2 Scaling with Q^2

$4 < Q^2 < 8$ [GeV^2]

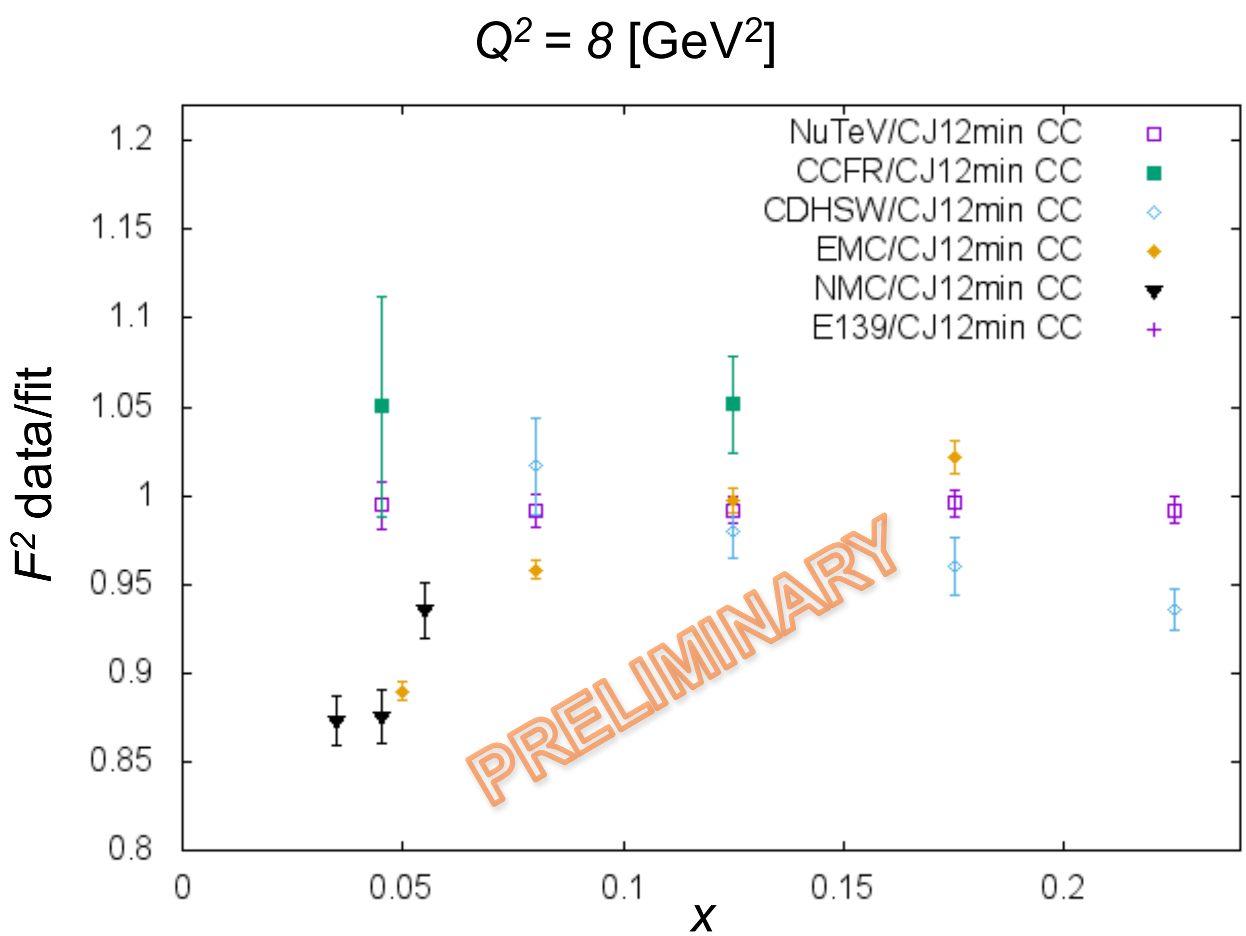


$6 < Q^2 < 10$ [GeV^2]



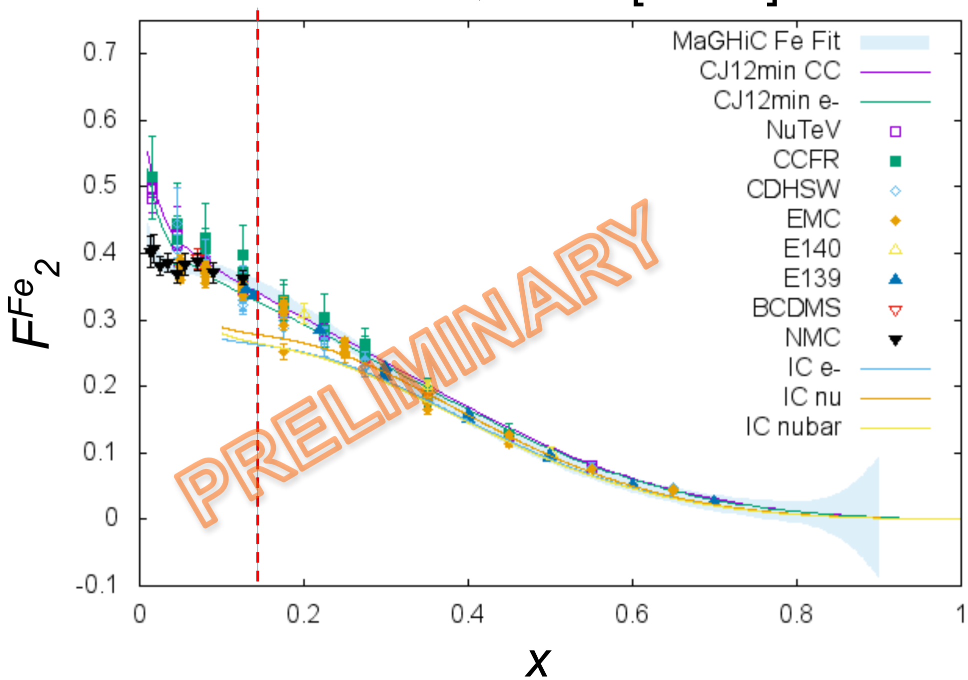
- Trend seems to remain. Study in progress; looking at higher Q^2.
- $Q^2 = 8$ [GeV^2] for fits
- nCTEQ predicted different shadowing between neutrino and charged lepton scattering.

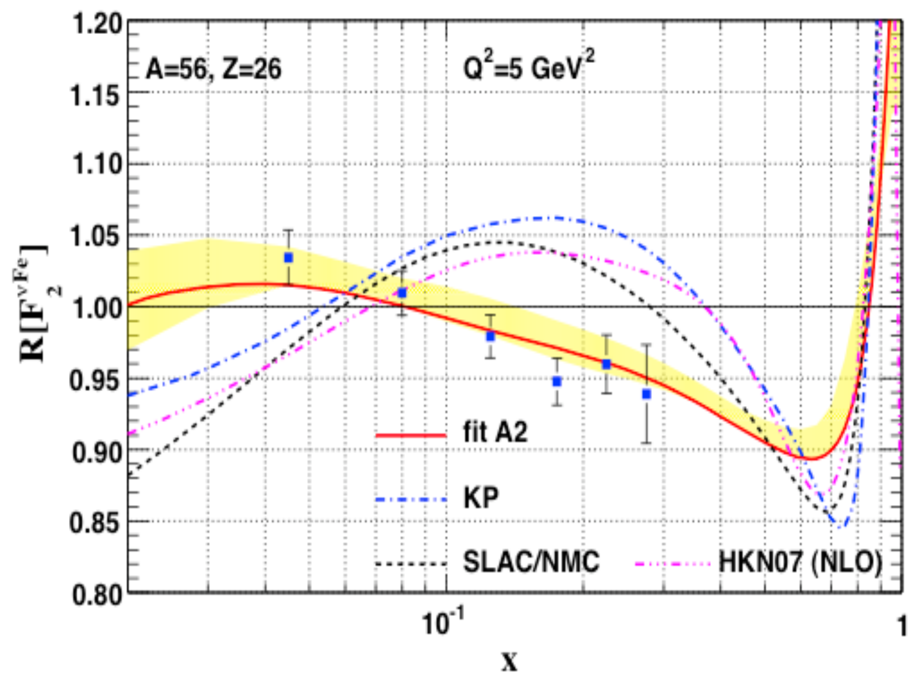
Data/Fit



- Data / CJ (CC neutrino).
- Common $Q^2 = 8$ [GeV^2]
- 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 $x \to 0$.
- Systematics ~< 9 %.

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 ~15-20%.

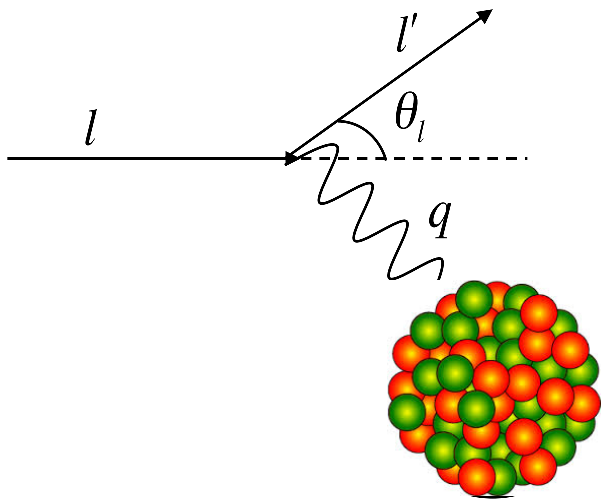
Possible Explanations

- 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

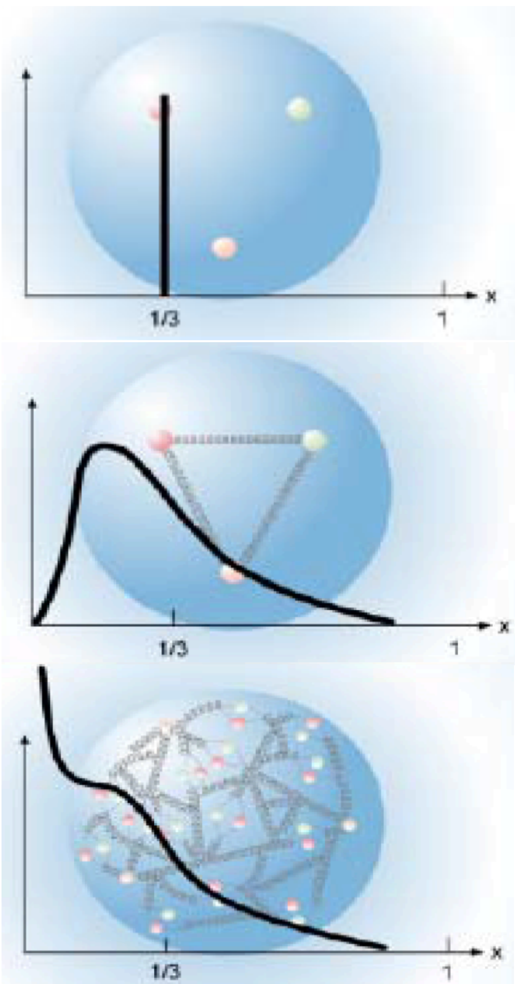
- Lepton scattering provides an opportunity to study nuclear structure.
- Structure Functions give fundamental information of the partonic structure of nucleons and nuclei.
- Charged lepton and neutrino data have shown some surprises.
- Studied Structure Function F_2, in Iron, by comparing data from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

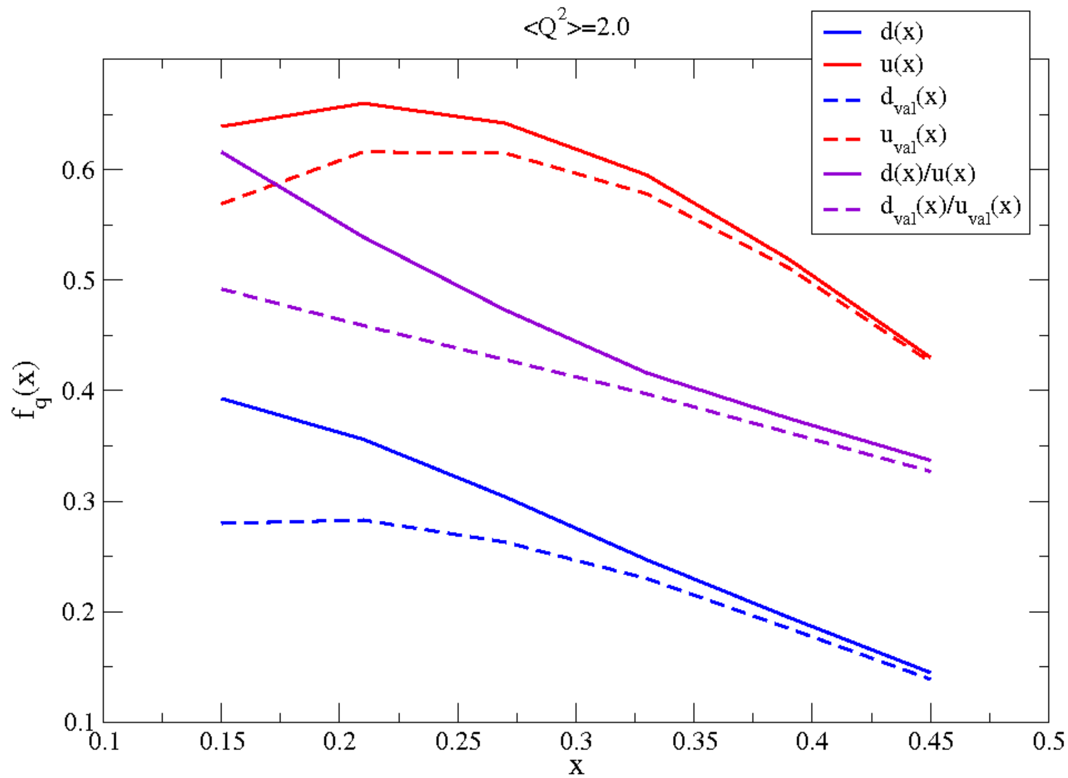
Back-Up Slides



Parton Distribution Function

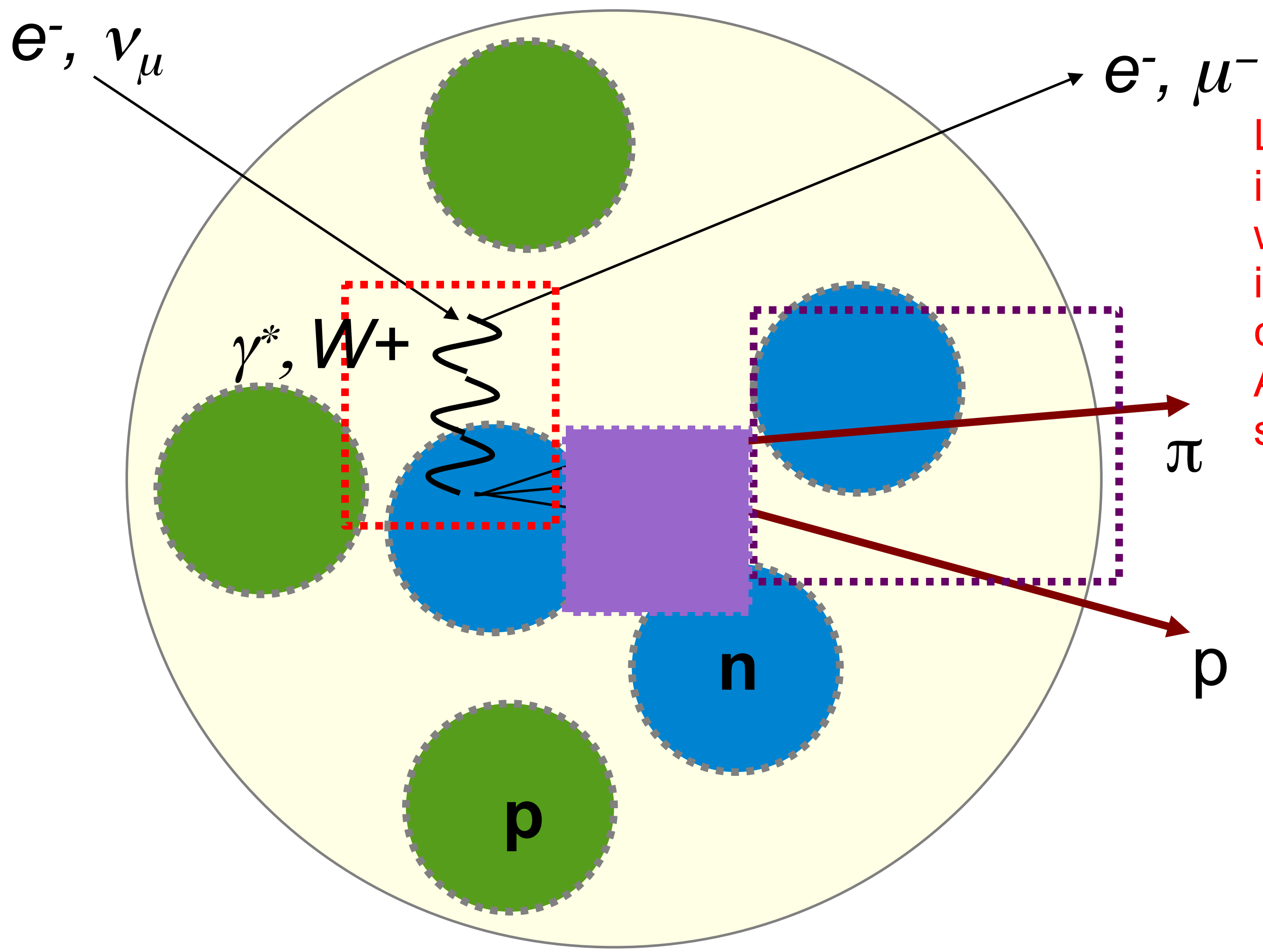
hep-ph/0703242





- $f_q(x)$ - Probability of finding a quark *q* with a fraction of momentum *x*.
- Contributions from sea quarks become negligible at x>0.3.
- u-quark dominates at higher *x*.

Nuclei Structure



Lepton scatters from
independent nucleons.
which have momentum
in the rest frame of the nucleus,
can be off-shell,
And have modified
structure

Hadron formation
From quarks

Hadron propagation
through nucleus

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:

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