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

Narbe Kalantarians
Hampton University
JLab Pizza Seminar
April 20, 2016
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)

Virtuality (Resolving power) [GeV$^2$]

\[ q = l - l' \]

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

Bjorken scaling variable $x$ (dimensionless)

\[ x = \frac{Q^2}{2M\nu} \]

Invariant mass of final states [GeV$^2$]

\[ W^2 = M^2 + 2M\nu - Q^2 \]

Radiated Boson exchanged

\[ l = (E, \vec{l}) \]
\[ l' = (E', \vec{l}') \]

Energy transferred to target

\[ \nu = E - E' \]

Inelasticity:

\[ y = \frac{\nu}{E} \]
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:
\[
\sigma_{Mott} = \frac{4x^2 E_f^2}{Q^4} \cos^2 \frac{\theta}{2}
\]

Callan-Gross Relation:
Conservation of helicity spin \( \frac{1}{2} \)
(Infinitesimal momentum frame)
\[
F_2(x) = 2xF_1(x) = x \sum_q e_q^2 f_q(x)
\]

* using natural units: \( h-bar = c = 1 \)
Charged Lepton vs. Neutrino Scattering

**Charged Leptons:**

\[ e^{+/-}, \mu^{+/-} \]

\[ q \rightarrow EM \text{ coupling} \rightarrow \gamma, Z \]

Vector coupling (parity conserved)

Mono-energetic beam; fixed \( E_{beam} \)

**Neutrinos:**

\[ \nu, \nu-\overline{\nu} \]

\[ q \rightarrow EW \text{ coupling} \rightarrow W^{+/-}, Z \text{ (charged,neutral) current, respectively} \]

Vector + Axial coupling (parity not necessarily conserved)

Beam is not mono-energetic; spectrum of \( E_{beam} \)
Elastic Scattering

Nucleons* stay together

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

[Image of a baseball player swinging a bat]  

\[ W = M \]

*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.

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


*Eur. Muon Collab.
Effect Reproduced (Many Times!)

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


Simple Parton Counting Expects One

MANY Explanations

SLAC E139


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

Neutrino Ratio Data


Nuclear PDF fits done on charged lepton data. (nCTEQ)
A-dependent PDFs then used to extract ratios.

NuTeV Fe data, deuteron constructed using PDFs.
\(\nu - A\) dependence different from \(e/\mu - A\)

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

Theory Predictions


- Predict sizeable effect in (anti)shadowing region. Phys. Report 512 255 PRL 81 4075 => CSV(?)
- 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 ($e/\mu$)
BCDMS, EMC, E140, E139
slac.stanford.edu/exp/e139/
NMC
18/5 Rule

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

Holds at leading order.

\[ F_2^{VN}(x) \leq \frac{18}{5} F_2^{eN}(x) \]
Isoscalar Corrections

- 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.

Fig. 4. World data of the dependence of the cross section ratio $\sigma(vn)/\sigma(pp)$ 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].
Isoscalar Corrections

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

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

For $\sigma_n/\sigma_p = 3$

$\frac{^{56}\text{Fe}}{}: \frac{A}{Z} = \frac{56}{26} = 2.154$

$f = 0.965$

(30% ratio uncertainty)

For $\sigma_n/\sigma_p = 3*1.3$

$f = 0.959$

*For neutrinos

How well do we know $\sigma_n/\sigma_p$?
Charged Lepton Uncertainties for $F_{n_2}^{n_2}/F_{p_2}^{p_2}$

→ Data is from BONuS

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

→ $x \approx 0.6$ uncertainty < 8%

Assuming same uncertainty and for neutrino $n/p \sim 3$

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

Much smaller correction for $x < 0.6$
$F^{Fe_2}$ Data and Fits

Some spread in the charged lepton data.
$F^{Fe}_2$ Data and Fits

Some spread in the charged lepton data.

Difference between Charged lepton and neutrino data at $x < \sim 0.15$

“CJ12min fit”

“MaGHiC”
Recent Minerva Result

PRL 112 231801 (2015)

- Low Energy Data
- See A-dependence, enhancement at lowest x-bin
- Data at low $Q^2 (< 1 \text{ GeV}^2)$
- High Energy Data will be important!
$F^{Fe_2}$ Scaling with $Q^2$

- 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 / CJ (CC neutrino).

Common $Q^2 = 8 \, [\text{GeV}^2]$

See discrepancy between neutrino and charged lepton data; (~>15%)

More than predicted by nCTEQ; (~5%)

NuTeV/CJ $\sim 1$
Both EMC & NMC data/CJ drops down as $x \to 0.$

Systematics $\sim<9\%$.
Comparing with Prediction

\[ 2 < Q^2 < 20 \text{ [GeV}^2\text{]} \]

- Seem to be beyond systematics (not shown). NuTeV’s \( \leq 9\% \) in regions of shadowing and anti-shadowing.
- Deuteron seems to make difference. nCTEQ predicted \( \sim 5\% \) (absence of nuclear effects \( Fe/d \sim 1 \)); seeing \( \sim 15-20\% \).
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!
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.
Parton Distribution Function

- $f_q(x)$ - 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 $x$. 

hep-ph/0703242
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.
For Charged Leptons and Neutrinos

\[ F_{2}^{ep}(x) = x \left\{ \frac{4}{9} [u(x) + \bar{u}(x)] + \frac{1}{9} [d(x) + \bar{d}(x) + s(x) + \bar{s}(x)] \right\} \]

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

\[ F_{2}^{eN}(x) = x \left\{ \frac{5}{18} [u(x) + \bar{u}(x) + d(x) + \bar{d}(x)] + \frac{1}{9} [s(x) + \bar{s}(x)] \right\} \]

Neutrino charged couplings: \( \nu_\mu d \rightarrow \mu^- u, \ \nu_\mu \bar{u} \rightarrow \mu^- \bar{d} \)

\( \bar{\nu}_\mu u \rightarrow \mu^+ d, \ \bar{\nu}_\mu \bar{d} \rightarrow \mu^+ \bar{u} \)

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

\[ F_{2}^{\nu N}(x) = x \left[ u(x) + d(x) + \bar{u}(x) + \bar{d}(x) \right] \]

Equate for charged leptons and neutrinos:

\[ F_{2}^{\nu N}(x) \leq \frac{18}{5} F_{2}^{eN}(x) \]