Open Issues in
Shallow-and Deep-Inelastic Scattering

NuFact18 WG2
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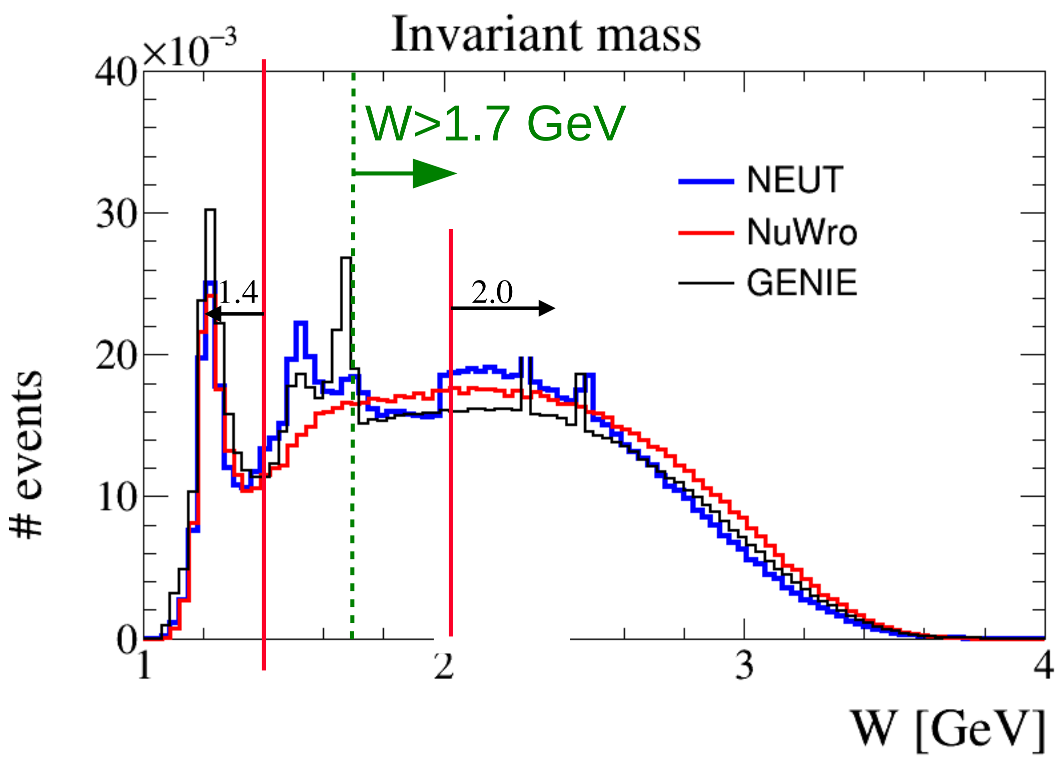
The General Landscape – Comparison of Generators

- We use the invariant mass of the hadronic system: $W^2 = M^2 + Q^2 (1 - x) / x$ to classify the type of interaction we are studying.
- By far the majority of contemporary studies in ν-nucleus interactions have been of QE and Δ production that is $W \leq 1.4$ GeV
- However, there is plenty of activity going on above this W cut! For example with a 6 GeV ν on Fe – excluding QE.



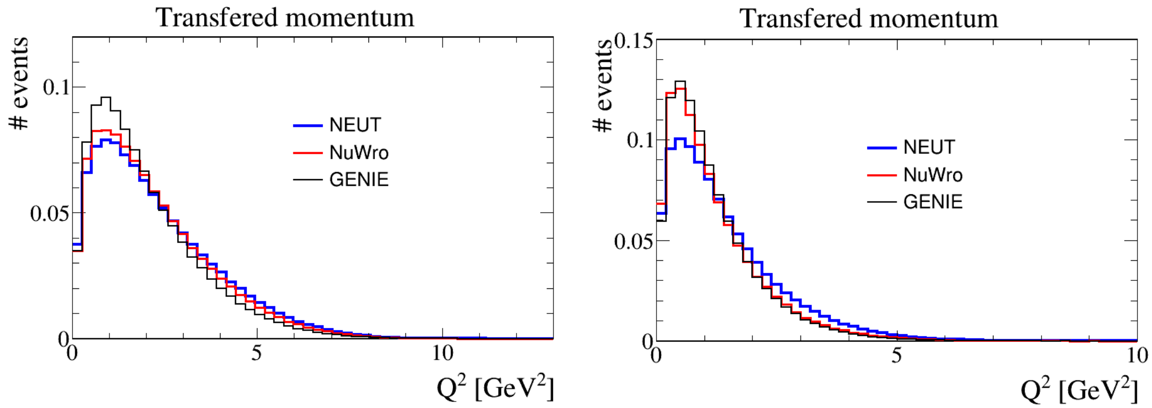
C. Bronner- 2016

The General Landscape - Comparison of Generators

- Since ***<u>over 50% of the DUNE events</u>*** have W greater than the Delta mass (W ≈≥ 1.4 GeV), we need to consider what we do(little)/do-not(big) know about this region!
- This region includes a series of higher mass resonances that dwindle in number as W increases. For example, if we take W > 1.7 GeV to be "above" a majority of these resonances then the Q^2 distributions for a 6 GeV ν on Fe are predicted to look like this. Corrections to NEUT and GENIE yield improved agreement.

2016

<u>Neutrino</u> <u>Anti-neutrino</u>



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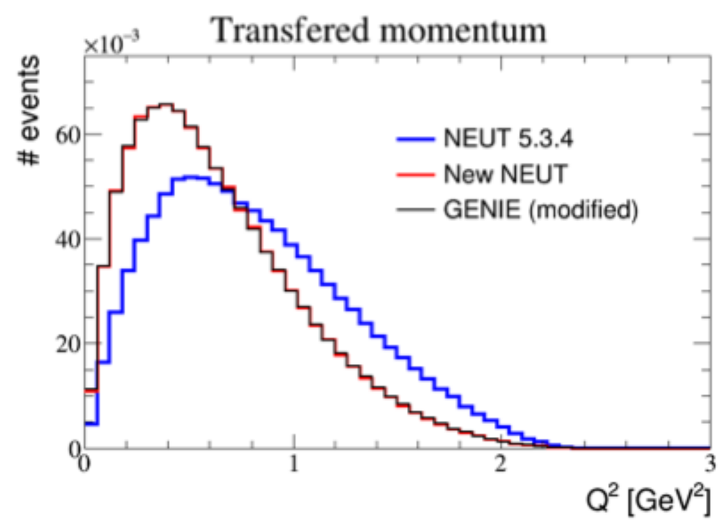
Neutrino - 2018



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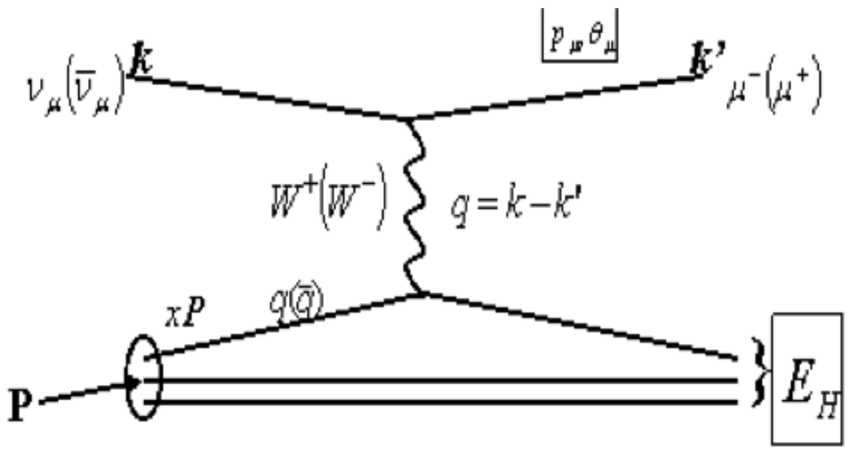
So let's start our examination of this region with Deep-Inelastic Scattering ($Q^2 > 1$ GeV^2 and $W > 2$ GeV)

- Why study Deep-Inelastic Scattering??
- Better understand the quark / parton structure of the free and bound nucleon.
- Test the predictions of (nuclear) Quantum Chromodynamics (QCD).
- How do we do study it?
  - Measure total and differential cross sections in x, Q^2 and W off various nuclei.
  - Extract the corresponding "nuclear structure functions" $F_i(x,Q^2)$ with i = 1,2 and 3.
  - Use the nuclear cross sections or nuclear F_i in global fits to determine **nuclear** parton distribution functions (nPDF).
  - Determine bound nucleon partonic nuclear effects by ratios of σ or F_i off a range of nuclei.
  - Determine quark hadronization by examining the make-up - multiplicities as function of $z \approx E_i / E_H$ and particle ID - of the hadron shower.
    - » Determine "hadron formation lengths" by comparing z distribution of various A.

The Fundamentals

Deep-Inelastic Scattering (Q² > 1 GeV² and W > 2 GeV)



$$Q^2 = 4E_\nu E_\mu \sin^2\frac{\theta}{2},$$ Squared 4-momentum transferred to hadronic system

$$x = \frac{Q^2}{2ME_{HAD}},$$ Fraction of momentum carried by the struck quark

$$y = \frac{\nu}{E_\nu} = \frac{E_{HAD}}{E_\nu},$$ Inelasticity

Differential cross section in terms of structure functions:

$$\frac{1}{E_\nu}\frac{d^2\sigma^{\nu(\bar{\nu})}}{dxdy} = \frac{G_F^2 M}{\pi\left(1+Q^2/M_W^2\right)^2}\left[(1-y)\,F_2^{\overset{(-)}{\nu}p}(x) + y^2 x F_1^{\overset{(-)}{\nu}p}(x) \pm y\left(1-\frac{y}{2}\right) x F_3^{\overset{(-)}{\nu}p}(x)\right]$$

Measuring Structure Functions F_2 and xF_3

F_2 (add σ's)

$$\left[\frac{d^2\sigma}{dx\,dy}^{\nu} + \frac{d^2\sigma}{dx\,dy}^{\bar{\nu}}\right]\frac{\pi}{G_F^2 ME} =$$

$$= 2\,\bar{F}_2\left(1 - y - \frac{Mxy}{2E} + \frac{y^2}{2}\frac{1+4M^2x^2/Q^2}{1+R}\right) + y\left(1 - \frac{y}{2}\right)\quad \Delta xF_3$$

- ΔxF_3 from a model
- $R \equiv \frac{\sigma_L}{\sigma_T} = \frac{F_2}{2xF_1}$ **Callan-Gross relation** $F_2 = 2xF_1$

xF_3 (subtract σ's)

$$\left[\frac{d^2\sigma}{dx\,dy}^{\nu} - \frac{d^2\sigma}{dx\,dy}^{\bar{\nu}}\right]\frac{\pi}{G_F^2 ME} =$$

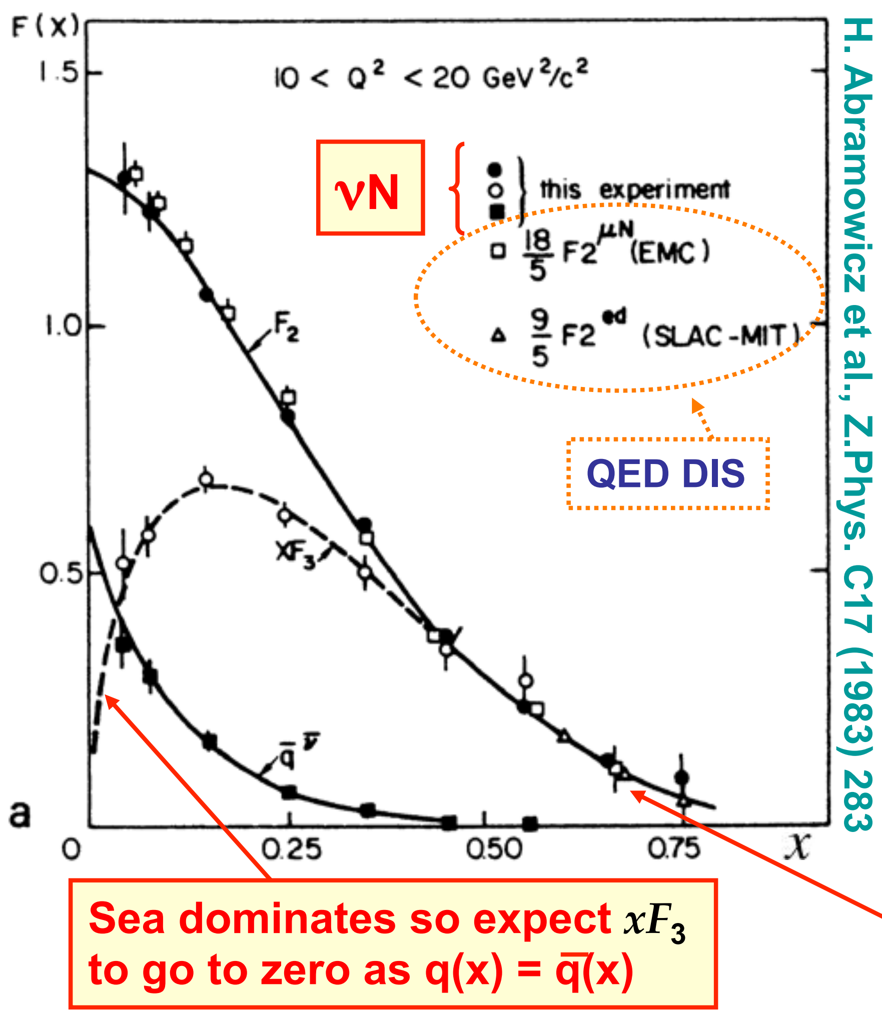
$$= \Delta F_2\left(1 - y - \frac{Mxy}{2E} + \frac{y^2}{2}\frac{1+4M^2x^2/Q^2}{1+R}\right) + 2\,y\left(1 - \frac{y}{2}\right)\quad x\bar{F}_3$$

- ΔF_2 is very small and is neglected

Measurements of F_2 and xF_3

Expressed in the language of quarks

•**CDHS Experiment** $\nu_\mu + \text{Fe} \rightarrow \mu^- + X$



$$F_2^{\nu N} = x[u(x) + d(x) + \overline{u}(x) + \overline{d}(x)]$$
$$xF_3^{\nu N} = x[u(x) + d(x) - \overline{u}(x) - \overline{d}(x)]$$

➡ $F_2^{\nu N} - xF_3^{\nu N} = 2x[\overline{u} + \overline{d}]$

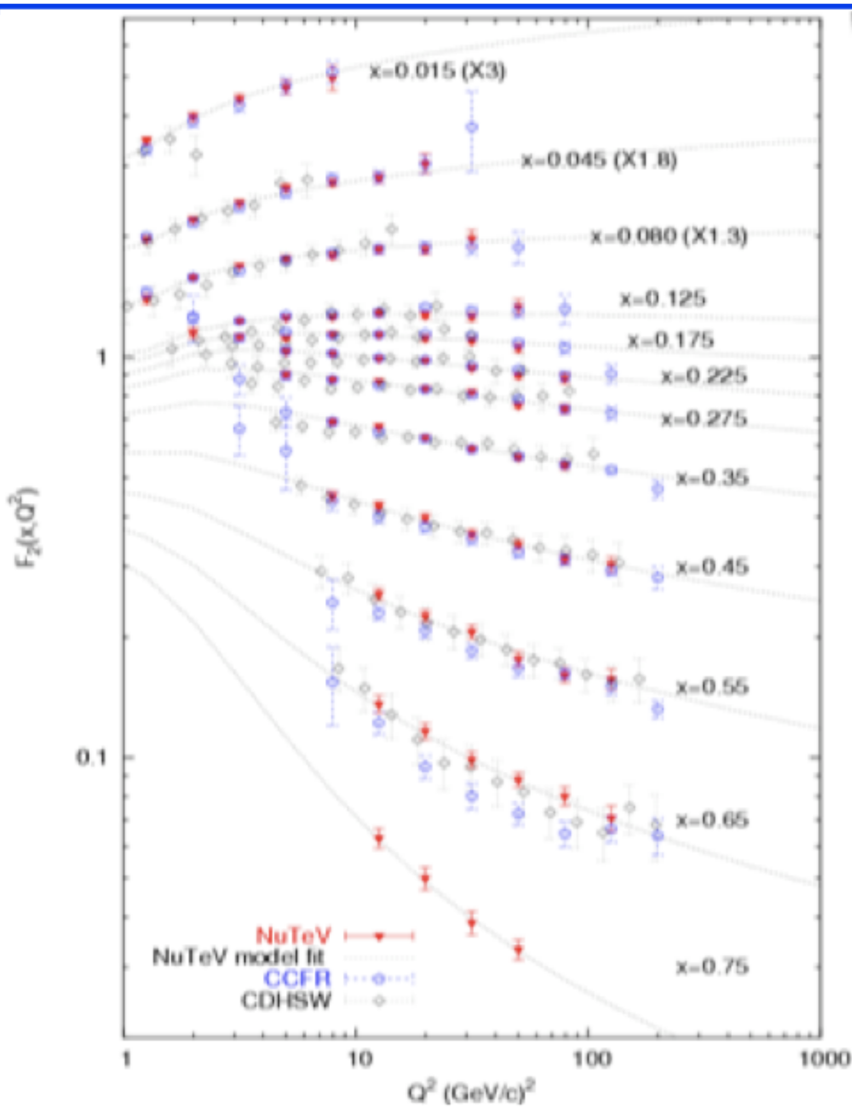
✶ **Difference in neutrino structure functions measures anti-quark (sea) parton distribution functions**

Most "Recent" DIS Experiments

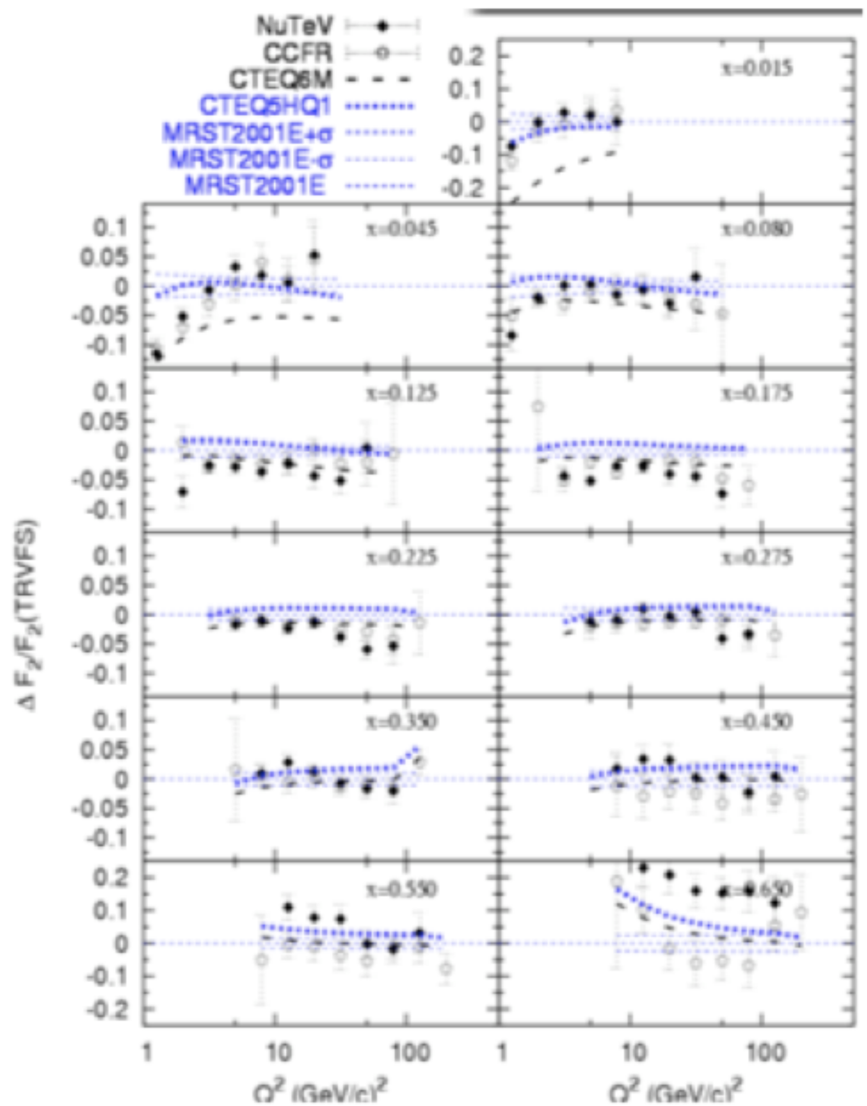
- There followed a long string of ν scattering experiments in US and Europe.
- **MINERvA is not a "DIS experiment"** but can/will contribute to DIS studies.

	E_ν range ($<E_\nu>$)(GeV)	Run	Target A	E_μ scale	E_{HAD} scale	Detector
NuTeV (CCFR)	30-360(120)	96-97	Fe	0.7%	0.43%	Coarse
NOMAD	10-200(27)	95-98	Various (mainly C)	--	---	Fine-grained
CHORUS	10-200(27)	95-98	Pb	2%	5%	Fine-grained
MINERvA	2 – 50(6)	10-20	He, C, O, CH, Fe, Pb	2.1-3.2%		Finer-grained

NuTeV F_2 Measurement on Fe

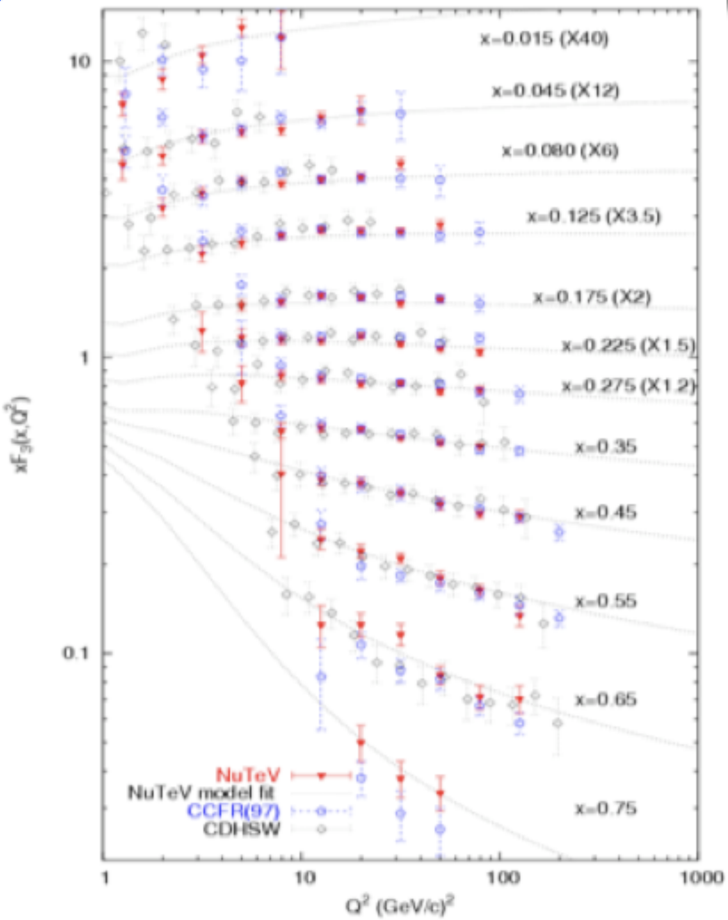


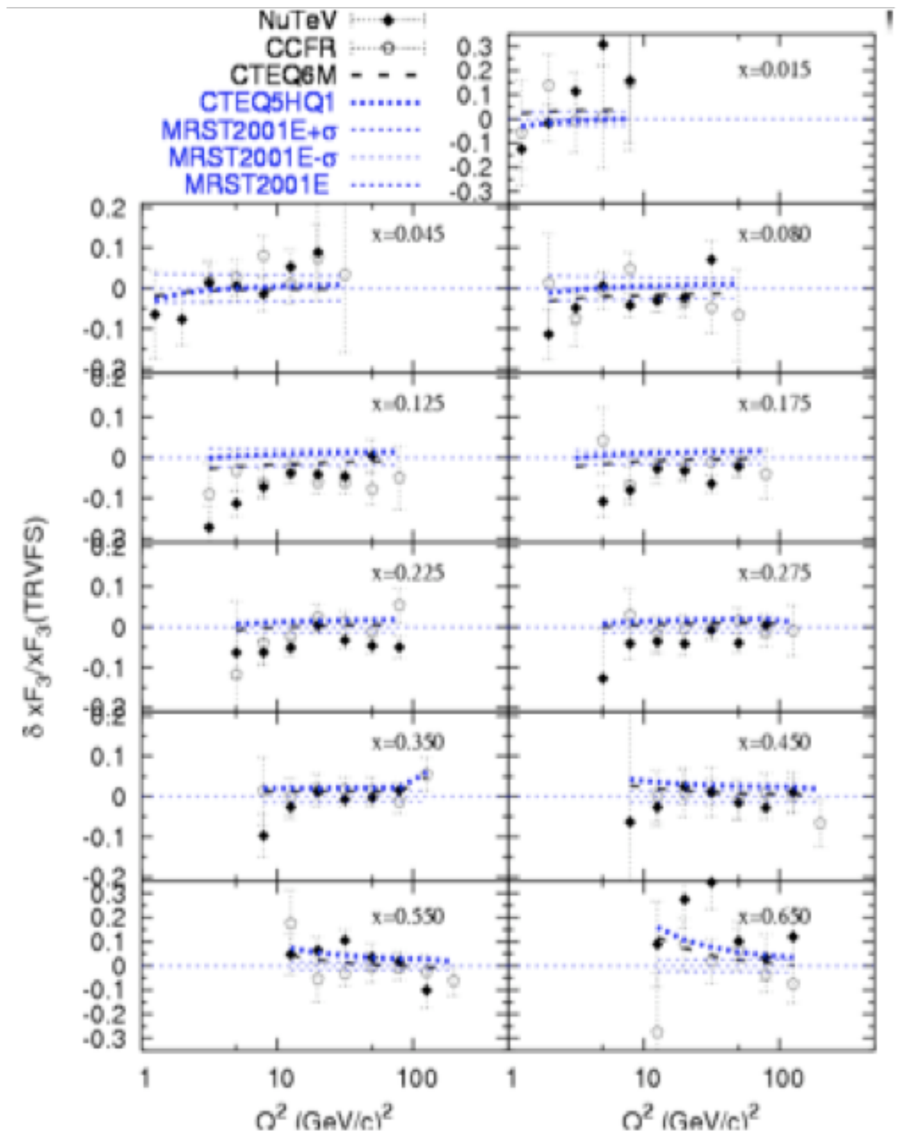
- Comparison of NuTeV F_2 with global fits



- At $x>0.4$ NuTeV is systematically higher than CCFR

NuTeV xF_3 Measurement





- At *x>0.5* NuTeV is systematically above CCFR
- NuTeV F_2 agrees with theory for medium x.
- At low x different Q^2 dependence.
- At high x (x>0.5) NuTeV is systematically higher.

Parton Distribution Functions:

What Can We Learn With All Six Structure Functions?

Why there is δF_2 and δxF_3 in expressions for F_2 and xF_3

- Scattering off proton:

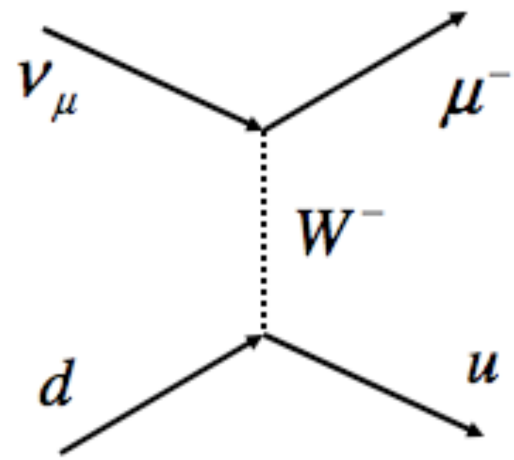
$$\frac{d\sigma_{CC}(\nu_\mu p)}{dxdy} = \frac{G_F^{\,2} ME}{\pi} 2x\left\{\left[d(x)+s(x)\right]+\left[\bar{u}(x)+\bar{c}(x)\right](1-y)^2\right\}$$

$$\frac{d\sigma_{CC}(\bar{\nu}_\mu p)}{dxdy} = \frac{G_F^{\,2} ME}{\pi} 2x\left\{\left[u(x)+c(x)\right](1-y)^2+\left[\bar{d}(x)+\bar{s}(x)\right]\right\}$$

- Structure functions:

  Callan-Gross relationship: $2xF_1(x) = F_2(x)$

$$F_2^{\nu p}(x) = 2x\left[d(x)+\bar{u}(x)+s(x)+\bar{c}(x)\right]$$
$$xF_3^{\nu p}(x) = 2x\left[d(x)-\bar{u}(x)+s(x)-\bar{c}(x)\right]$$
$$F_2^{\bar{\nu} p}(x) = 2x\left[u(x)+c(x)+\bar{d}(x)+\bar{s}(x)\right]$$
$$xF_3^{\bar{\nu} p}(x) = 2x\left[u(x)+c(x)-\bar{d}(x)-\bar{s}(x)\right]$$



- Neutron (isospin symmetry):

$$F_2^{\nu n}(x) = 2x\left[u(x)+\bar{d}(x)+s(x)+\bar{c}(x)\right]$$
$$xF_3^{\nu n}(x) = 2x\left[u(x)-\bar{d}(x)+s(x)-\bar{c}(x)\right]$$

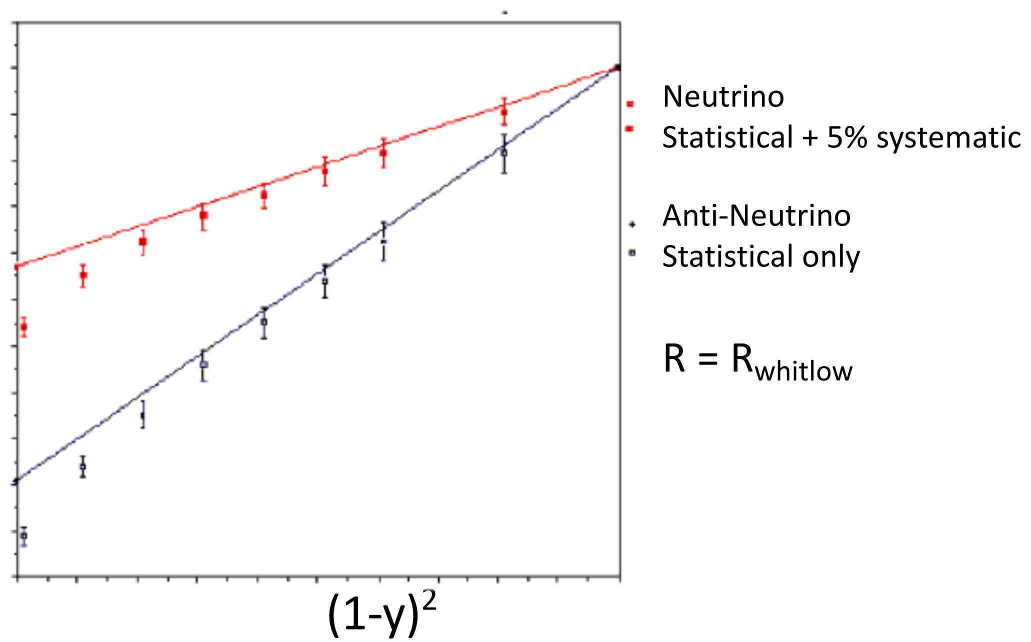
Parton Distribution Functions:
What Can We Learn With All Six Structure Functions?

Neutrinos have the ability to directly resolve flavor of the nucleon's constituents:
ν interacts with d, s, $\overline{u}$, and $\overline{c}$ while $\overline{\nu}$ interacts with u, c, $\overline{d}$ and $\overline{s}$.

$$\frac{d^2\sigma^\nu}{dxdQ^2} = \frac{G_F^2}{2\pi x}\Big[\frac{1}{2}\left(F_2^\nu(x,Q^2) + xF_3^\nu(x,Q^2)\right) + \frac{(1-y)^2}{2}\left(F_2^\nu(x,Q^2) - xF_3^\nu(x,Q^2)\right) - 2y^2 F_L^\nu x, Q^2)\Big].$$

X = 0.1 - 0.125
Q^2 = 2 - 4 GeV^2

Meant to give an impression only!
Kinematic cuts in (1-y) not shown.



Summary of NuTeV ν Scattering Results

NuTeV accumulated over 3 million neutrino / antineutrino events with $20 \leq E_\nu \leq 400$ GeV.

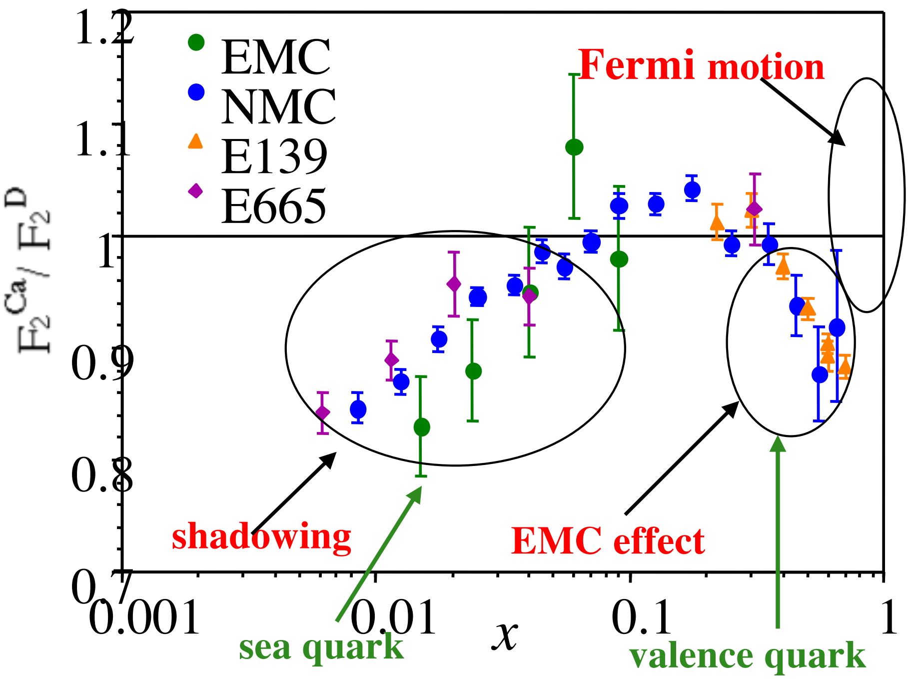
NuTeV considered over 20 systematic uncertainties.

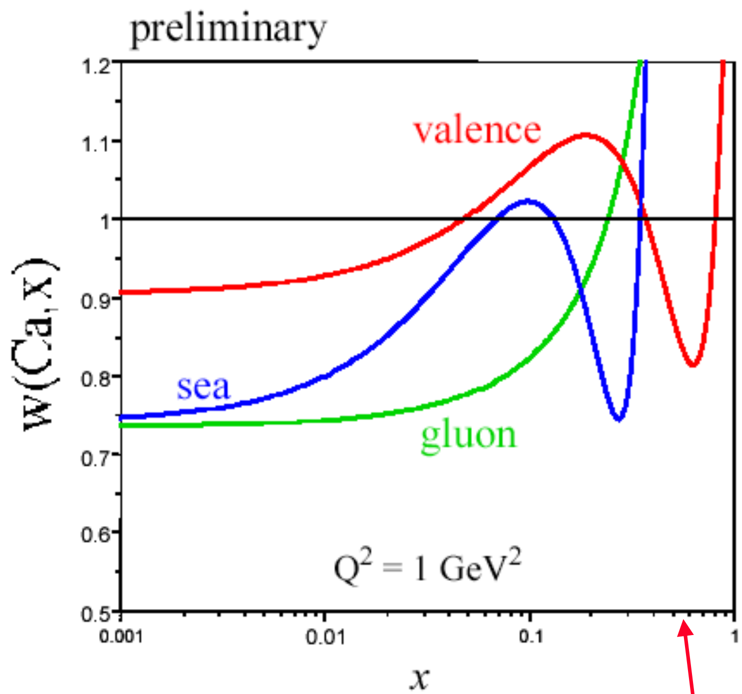
NuTeV σ agrees with other ν experiments and theory for medium x.
At low x different Q^2 dependence.
At high x (> 0.5) NuTeV is systematically higher.

NuTeV extracts the **strange quark** distribution via charm production using both ν and $\bar{\nu}$ and gets a value of S(x)

All of the NuTeV Results are for ν – Fe interactions and where necessary have assumed the nuclear corrections for neutrino interactions are the same as $l^\pm$. Is this really the case?

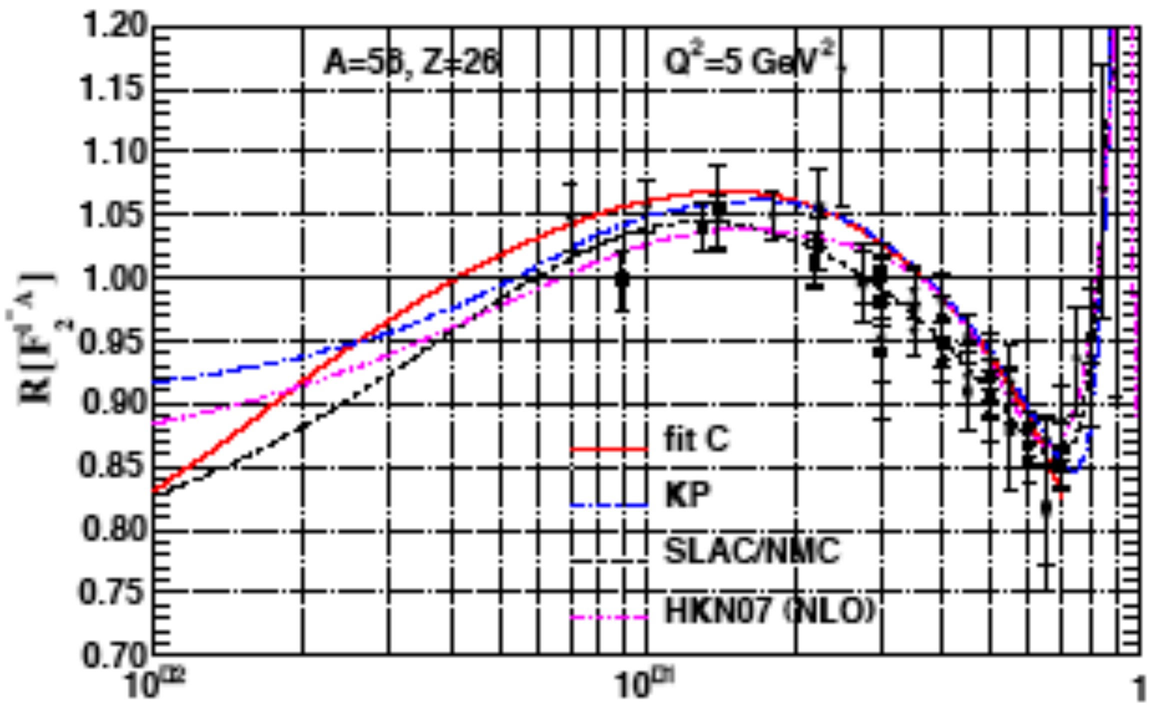
Knowledge of Nuclear Effects with Neutrinos: essentially NON-EXISTENT





- F_2 / nucleon changes as a function of A. Measured in μ/e - A **not in ν – A**
- **Good reason to consider nuclear effects are DIFFERENT in ν - A.**
  - **Presence of axial-vector current.**
  - **SPECULATION: Much stronger shadowing for ν -A but somewhat weaker "EMC" effect.**
  - **Different nuclear effects for valance and sea --> different shadowing for xF_3 compared to F_2.**
  - **Different nuclear effects for d and u quarks.**

Nuclear Structure Function Corrections $\ell^{\pm}$ (Fe/D_2)



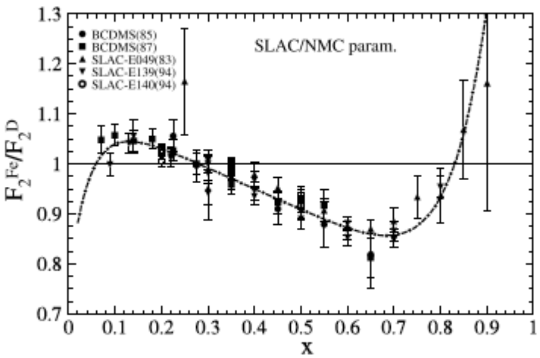
- **Good reason to consider nuclear effects are DIFFERENT in ν - A.**
  - **Presence of axial-vector current.**
  - **Different nuclear effects for valance and sea --> different shadowing and antishadowing for xF_3 compared to F_2.**

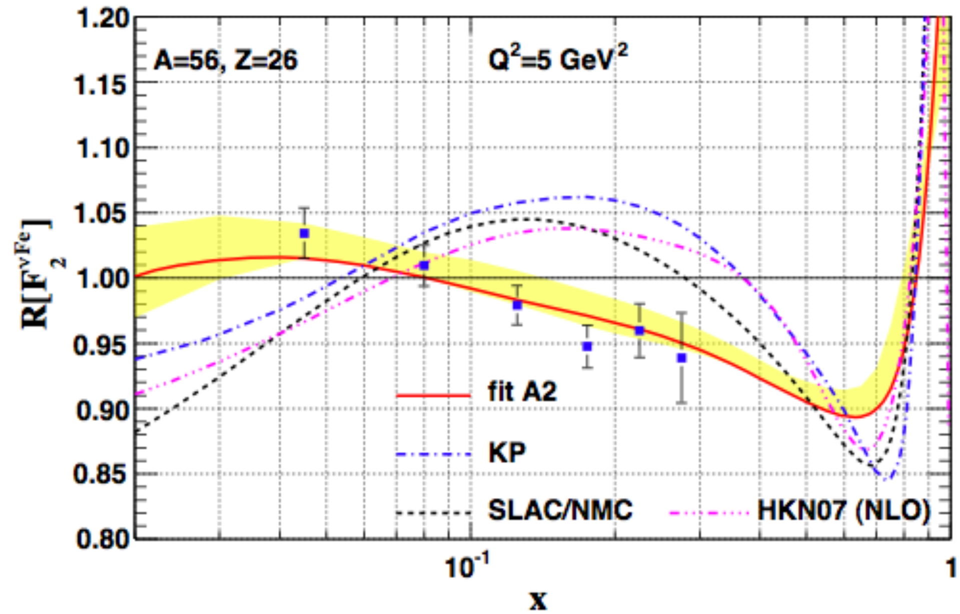
Nuclear PDFs from neutrino deep inelastic scattering

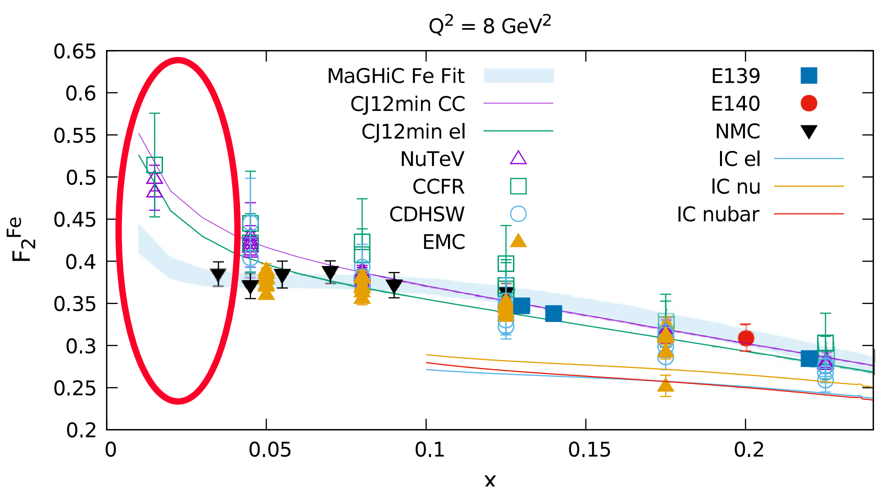
I. Schienbein (SMU & LPSC-Grenoble, J-Y. Yu (SMU)
C. Keppel (Hampton & JeffersonLab) J.G.M. (Fermilab),
F. Olness (SMU), J.F. Owens (Florida State U)
(nCTEQ)

Phys.Rev. D80 (2009) 094004

F_2 Structure Function Ratios: ν-Iron

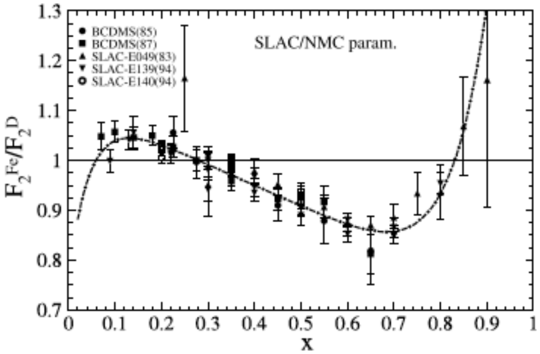


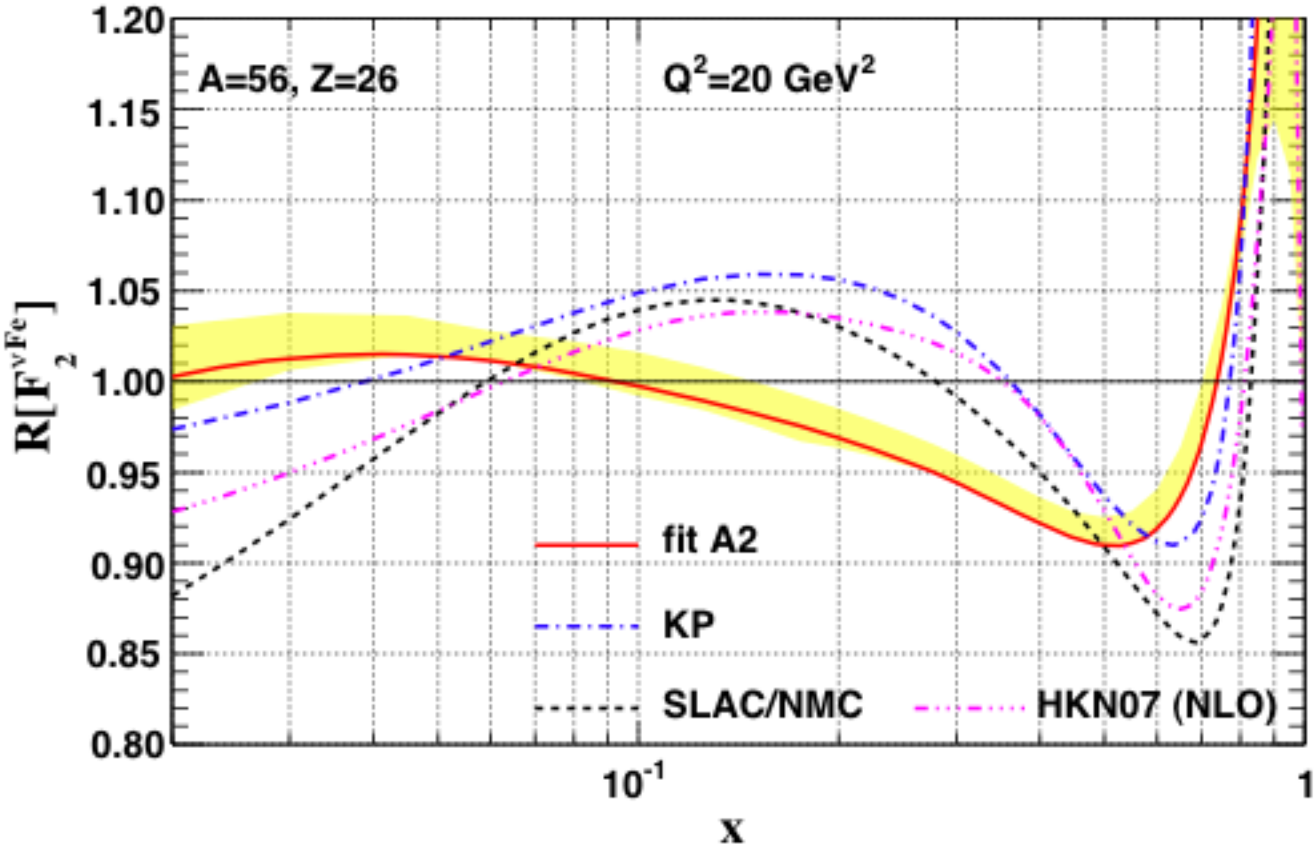




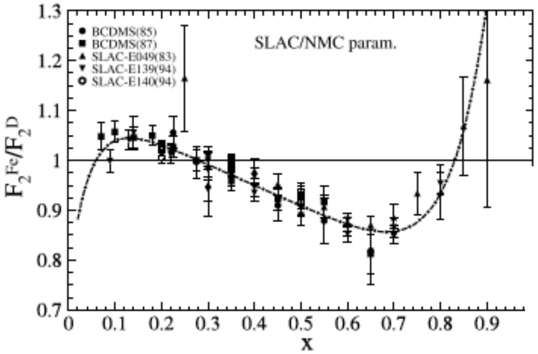
Recent Jlab analysis of F_2 from muon + Fe compared to F_2 from neutrino + Fe scaled by 5/18 to account for quark charges

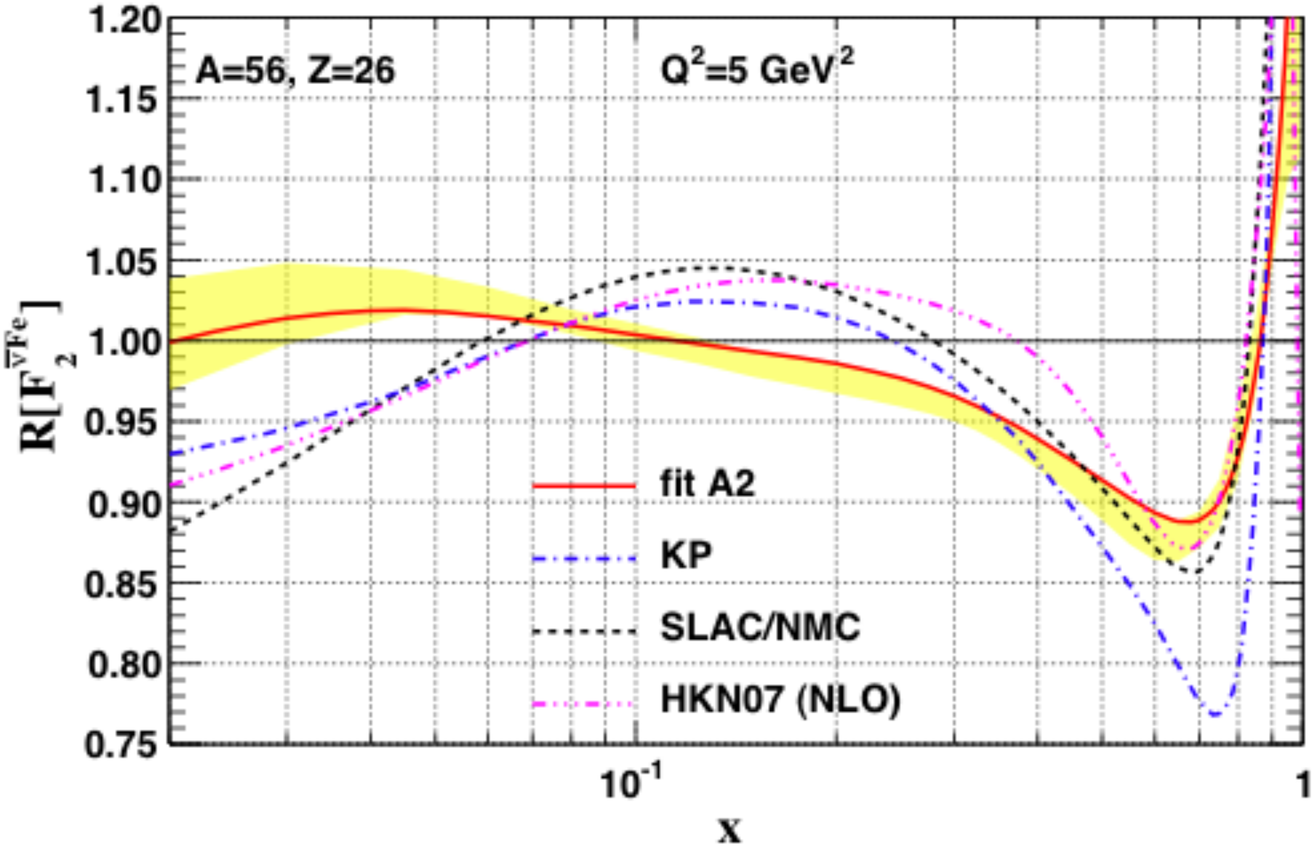
F_2 Structure Function Ratios: ν-Iron



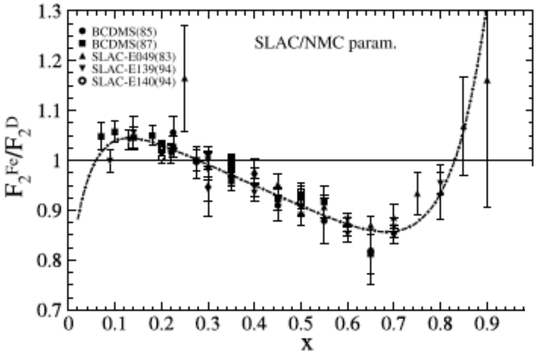


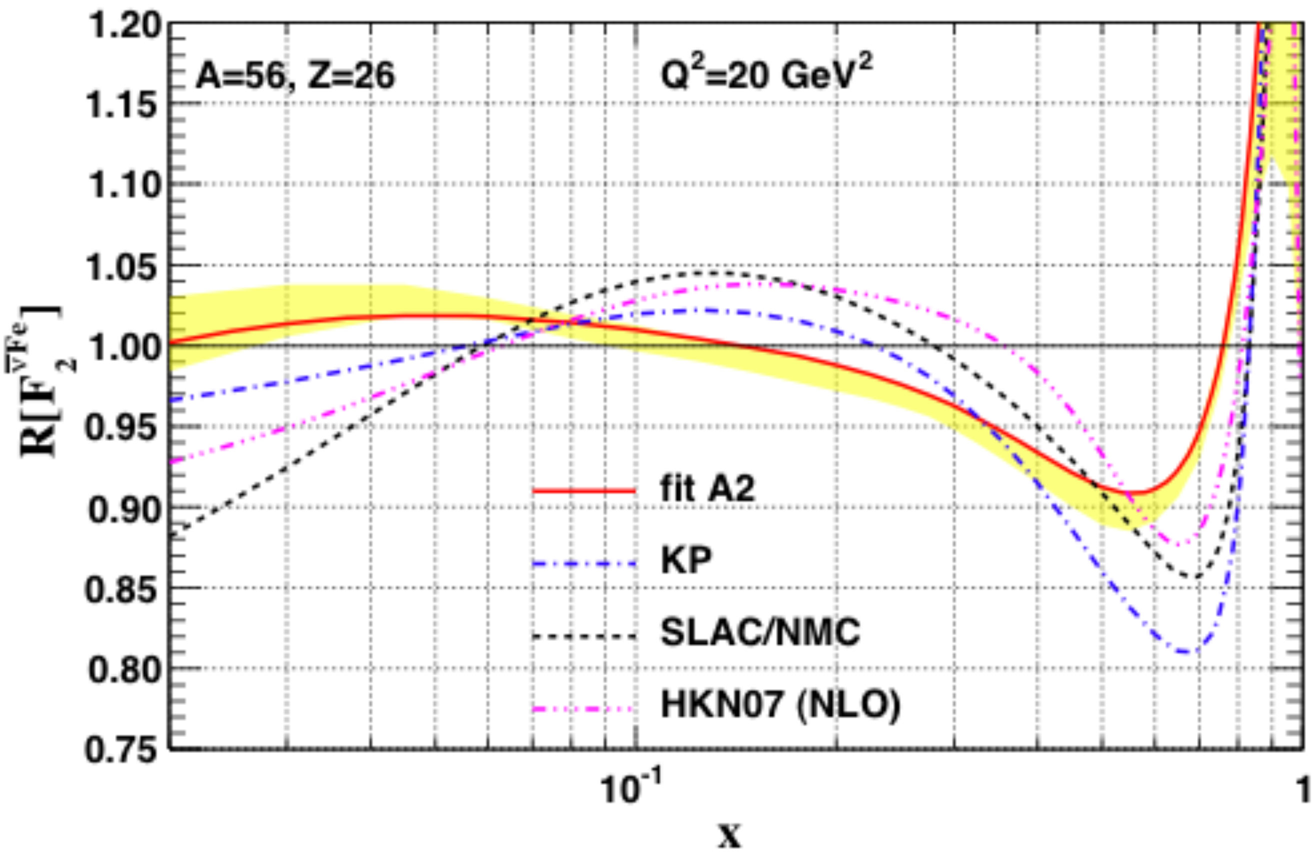
F_2 Structure Function Ratios: $\overline{\nu}$-Iron





F_2 Structure Function Ratios: $\bar{\nu}$-Iron





Conclusions DIS

- All high-statistics neutrino data is off nuclear targets. Need nuclear correction factors to include data off nuclei in global fits with nucleon data to determine nucleon PDFs.

- Current nuclear correction factors in GENIE use B-Y model that gives only ν-isoscalar Fe correction factor that is then then used for ALL nuclei.

- Nuclear correction factors (R) and, consequently, the nuclear parton distribution functions are found to be **different** for neutrino-Fe scattering compared to charged lepton-Fe. **One experiment and one nucleus.**

- **There is now fresh evidence that these so-called DIS partonic nuclear effects (EMC effect) continue down into the SIS region with W < 2.0 GeV!** (Low-Q scaling, duality, and the EMC effect – Arrington et al.)

Approach the SIS region

Unknown Experimentally and Theoretically!!

- Let's now approach the SIS region by first keeping W > 2 GeV and lowering Q then lowering W as well.
- $1/Q^2$ effects - when Q is even smaller than M_N then there are non–perturbative QCD effects that come into play.
- Called dynamic and kinematic "higher twist" terms such as the (kinematic) target mass effect. These often represent the interaction of multiple quarks or sensitivity to the p_t of quarks. These dynamic higher twist terms are challenging in ν-nucleon and even more complicated in ν-nucleus scattering.
- We can estimate them by assuming a form:
  - Where the terms H_4 and H_6 can be fit experimentally but only calculated non—perturbatively.

QCD

$$F_i(x,Q^2) = F_i^{LT}(x,Q^2)\left[1 + \frac{H_4(x,Q^2)}{Q^2} + \frac{H_6(x,Q^2)}{Q^4} + \cdots\right]$$

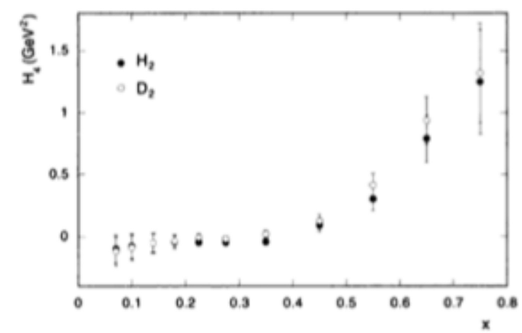


Fig. 5.6.1 Higher twist coefficients $H_4(x)$ determined from charged-lepton scattering on hydrogen (full circles) and deuterium (open circles).

- Continuing down in W we eventually hit resonances and instead of speaking of quarks and gluons we start speaking of nucleons and pions! The physics is continuous so there should be a common **"quark language = hadron language" → quark-hadron duality!**

Enter: Shallow-Inelastic Scattering

- Why study Shallow-Inelastic Scattering? (Q^2 > ? GeV and W > Δ res)
  - How does the physics (language) of quark/partons from DIS meet the physics of hadrons (resonances) → **quark-hadron duality**
  - Do the partonic nuclear effects of DIS extend down into the SIS region or do they suddenly/slowly turn off.
  - Oh – by the way – **50 % of the DUNE events in the SIS + DIS region!**
- How do we do study it? **MINERvA starting this study!**
  - Measure total and differential cross sections with x, Q^2 and W in the SIS region off various nuclei.
  - Extract the corresponding "nuclear structure functions" $F_i(x,Q^2)$ with i = 1,2 and 3 but now with W and Q^2 in the SIS region.
  - Compare the (W) cross sections and $F_i(x,Q^2)$ derived in the DIS with the SIS equivalents.
  - Determine bound nucleon partonic nuclear effects by ratios of σ or F_i off nuclei in the SIS region…

What is "Duality"

- Relationships between meson–hadron and quark–gluon degrees of freedom.
- Quark–hadron duality is a general feature of strongly interacting landscape.
- There exist examples where low-energy hadronic phenomena, averaged over appropriate energy intervals, closely resemble those at higher energies, calculated in terms of quark-gluon degrees of freedom.
- Duality is an important ingredient for the Bodek-Yang model that GENIE, NEUT, NuWro employ.
- Originally studied and confirmed in e-N scattering – how about ν-N scattering? There is essentially no high-statistics ν-N experimental data with W>1.4 GEV for tests! Rely on **models** for resonances and essentially **ONE** theoretical look at duality in ν-N scattering.
  - $F_2^{ep\ en}$: Duality HOLDS in electron–nucleon scattering
  - $F_2^{\nu p\ \nu n}$: In neutrino–nucleon scattering duality does NOT hold for proton and neutron individually
  - $F_2^{\nu p\ \nu n}$: Duality HOLDS for the averaged structure functions. Need equal number of neutrons and protons…

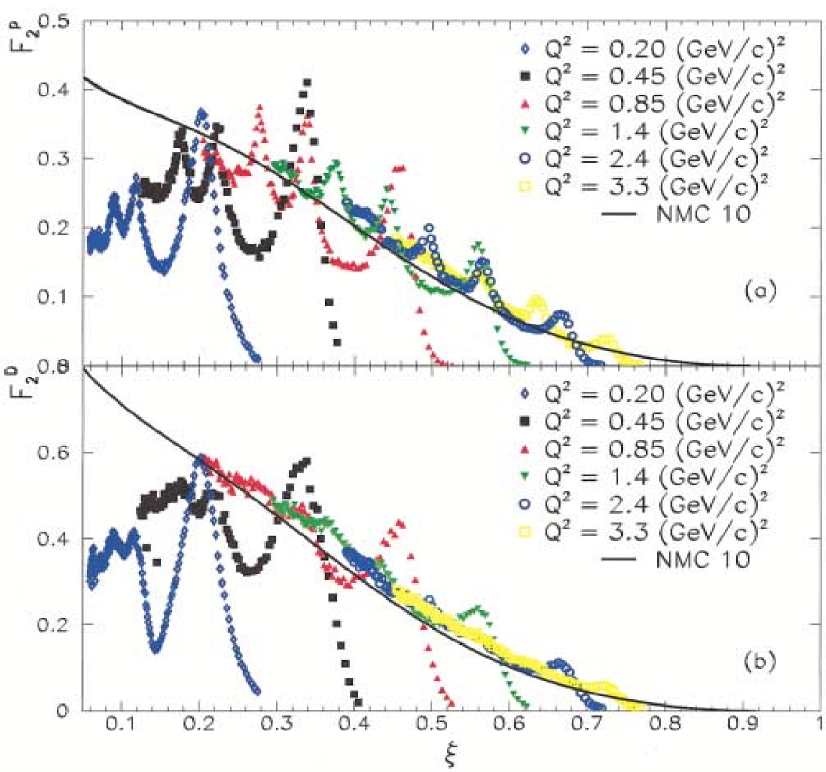
Duality HOLDS in electron–nucleon scattering!

What does that mean?

- If you take F_2 determined from a QCD fit to DIS data and extrapolate down in ξ

- a form of x_{Bj} that compensates for low-Q phenomena. The extrapolation runs approximately through the middle of the resonances.

$$\xi = \frac{2x}{\left(1 + \sqrt{1 + 4m_N^2 x^2 / Q^2}\right)}$$

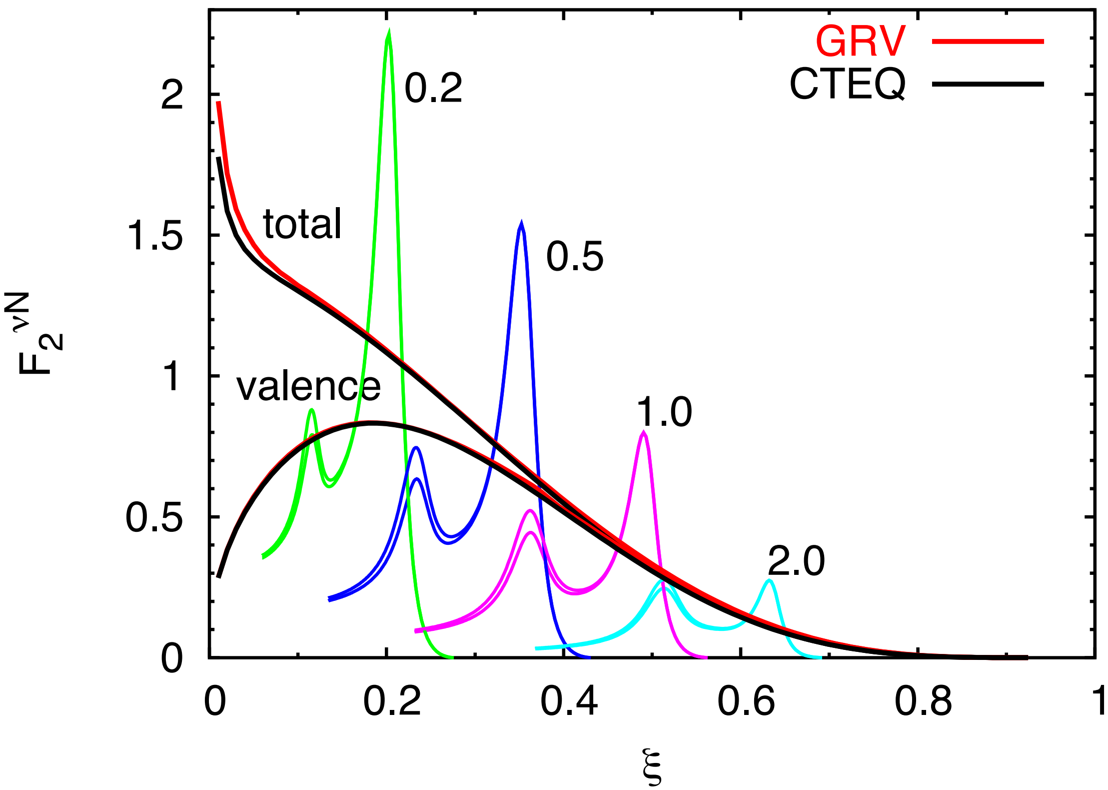


JLAB: recent experimental data on F_2 of the reactions $ep \to eX$, $eD \to DX$ in the resonance region

solid curve — global fit to the world's DIS data by NMC collaboration

The data at various values of Q^2 and W average to a smooth curve if expressed in terms of ξ.

From work of Olga Lalakulich – **the one real expert on ν-N duality who left the field – (Manny Paschos retired and Wally Melnitchouk busy)** –
Duality supposedly holds for the averaged neutrino $F_2^N = (F_2^n+F_2^p) / 2$



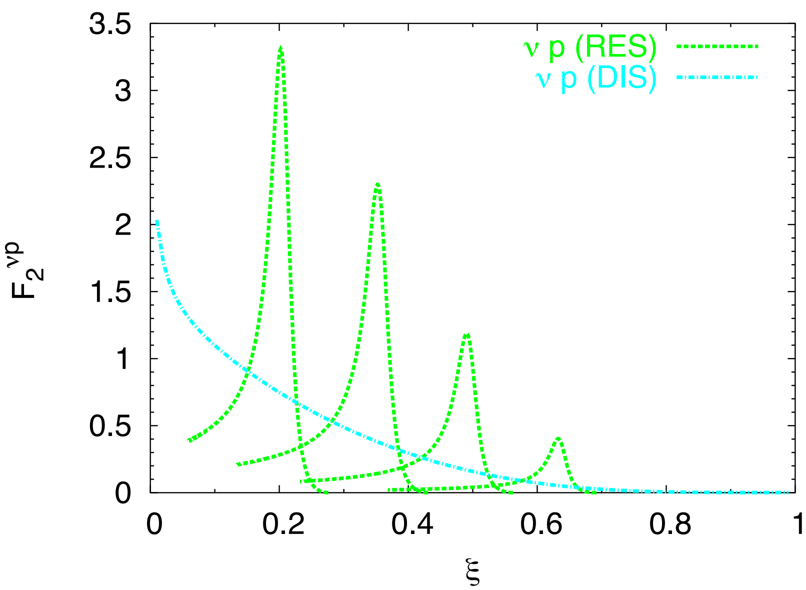
What about individually ν-n and ν-p scattering?

Resonance estimates from Lalakulich, Melnitchouk and Paschos

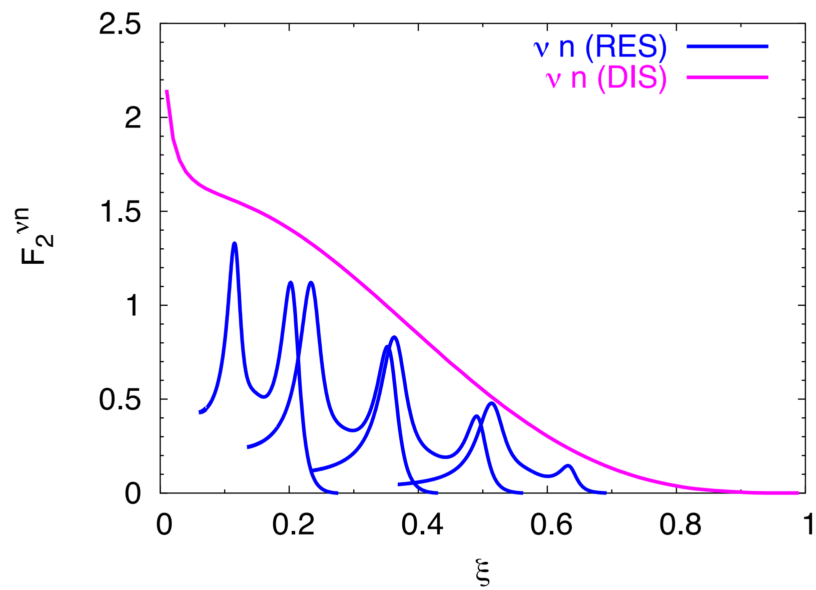
Oops!

Low-lying resonances: $F_2^{\nu n(res)} < F_2^{\nu p(res)}$, DIS: $F_2^{\nu n(DIS)} > F_2^{\nu p(DIS)}$

$F_2^{\nu p(res-3/2)} = 3 F_2^{\nu n(res-3/2)}$
$F_2^{\nu p(res-1/2)} \equiv 0$



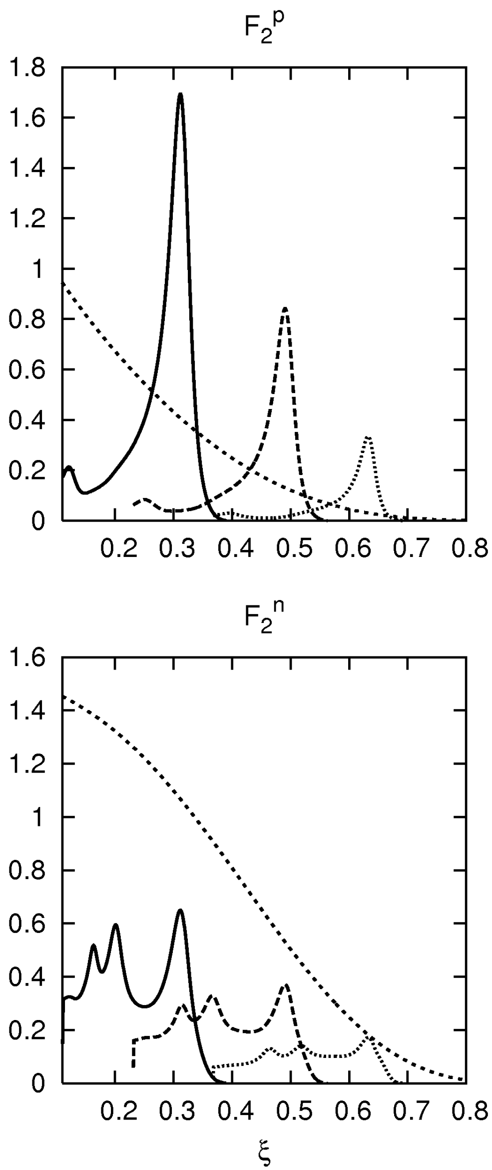
$F_2^{\nu n(res)}$: finite contributions from isispin-3/2 and -1/2 resonances



Also does not hold for n and p individually

when using the Rein-Sehgal Model for ν-N Resonances

WARNING: R-S model questionable



Similar results in the framework of Rein–Sehgal Model Graczyk, Juszczak, Sobczyk, Nucl Phys A781 (19 resonances included in the model)

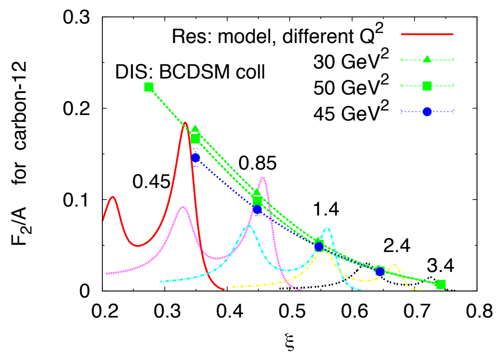
$P_{33}(1232)$,
$P_{11}(1440)$, $D_{13}(1520)$, $S_{11}(1535)$,
$P_{33}(1600)$,
$S_{11}(1650)$, $D_{15}(1675)$, $F_{15}(1680)$

Interplay between the resonances with different isospins:

isospin-3/2 resonances give strength to the proton structure functions, while isospin-1/2 resonances contribute to the neutron structure function only

However, it is a different story when talking of NUCLEI not NUCLEON
Even with the carbon nucleus (equal p and n) duality with both incoming electrons and neutrinos has challenges

For nuclei, the Fermi motion and other medium effects broaden resonances, thus performing averaging



Resonance structure functions: isobar model with phenominological form factors OL,Paschos, PRD 71, 74 includes the first four low-lying baryon resonances $P_{33}(1232)$, $P_{11}(1440)$, $D_{13}(1520)$, $S_{11}(1535)$

Preliminary!

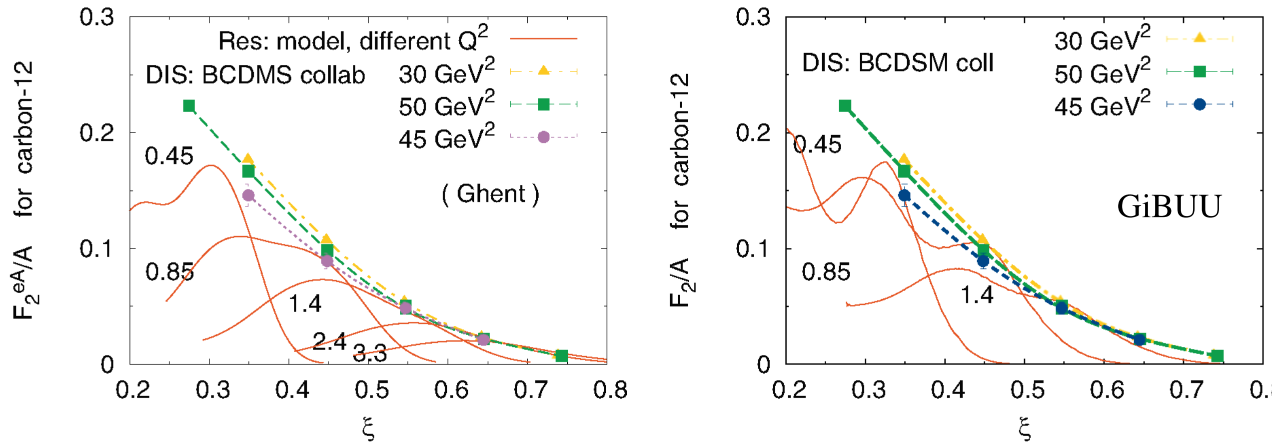


FIGURE 3. (Color online) Resonance curves $F_2^{e^{12}C}/12$ as a function of ξ, for $Q^2 = 0.45, 0.85, 1.4, 2.4$ and 3.3 GeV^2 (indicated on the spectra), obtained within Ghent (left) and Giessen (right) models, compared with the experimental data [23, 24] in the DIS region at $Q^2_{DIS} = 30$, 45 and 50 GeV^2.

However, it is a different story when talking of NUCLEI not NUCLEON – now Fe

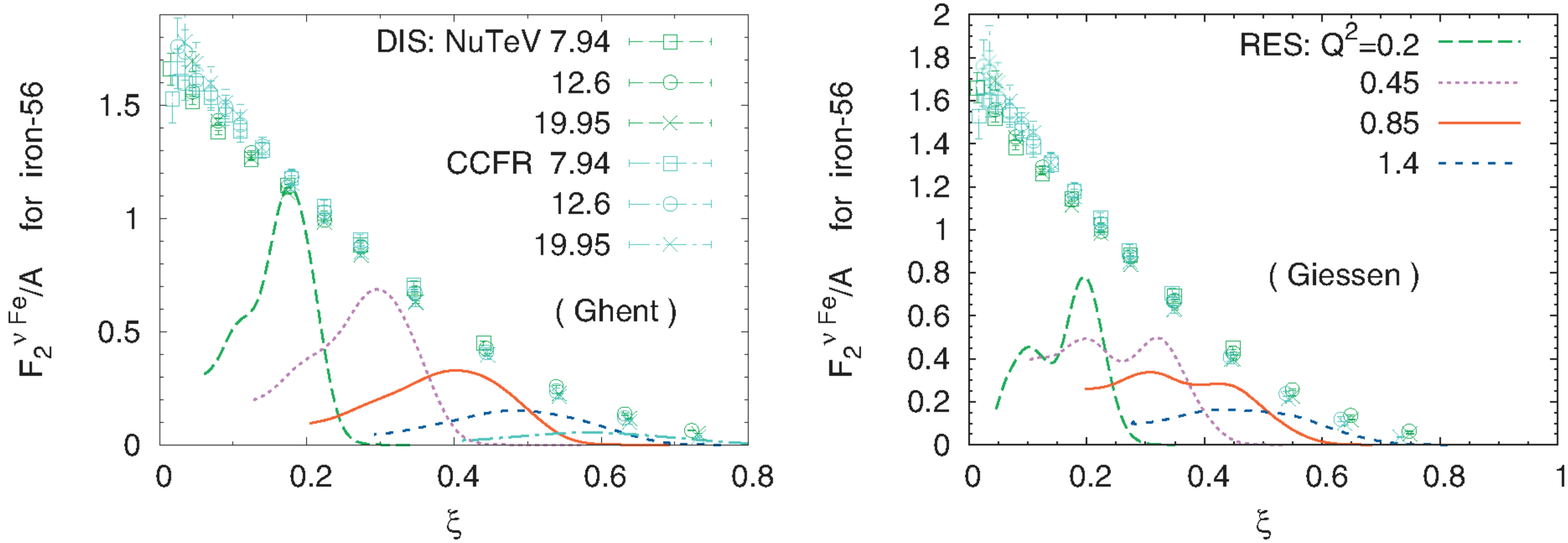


FIGURE 5. (color online) The computed resonance curves $F_2^{\nu^{56}Fe}/56$ as a function of ξ, calculated within Ghent(left) and Giessen (right) models for $Q^2 = 0.2, 0.45, 0.85$, 1.4, and 2.4 GeV^2. The calculations are compared with the DIS data from Refs. [26, 27]. The DIS data refer to measurements at $Q^2_{DIS} = 7.94$, 12.6 and 19.95 GeV^2.

Still Curious about SIS and DIS Scattering?

NuSTEC Workshop on Shallow- and Deep- Inelastic Scattering –

Just before (11-13 October) and in same location as NuInt18

https://indico.cern.ch/event/727283/

NuSTEC Workshop on Shallow- and Deep-Inelastic Scattering
11-13 October, Gran Sasso Science Institute, L'Aquila, Italy

1) General introduction and considerations from non-neutrino communities.
   A) Introduction to SIS/DIS Theory and Models
   B) e-A community studies of the SIS/DIS region

2) Generator / Transport treatments of the SIS and DIS region.
   A) Improved Rein-Sehgal Model above the Delta
   B) Status of the Bodek-Yang Model
   C) Generator/Transport Treatments:
      GiBUU, GENIE, NEUT, NuWRO
   D) Generator Comparison of SIS/DIS treatment- Overview

3) Sensitivity of oscillation parameters to the SIS and DIS region.
   A) NOvA
   B) Atmospheric Neutrino Studies, SK and HK

4) Resonant and non-resonant contributions with W > Delta
   A) Isobar models of resonance production
   B) Dynamical coupled-channel models
   C) pi-nucleon scattering community studies
   D) Experimental nu-A higher-W pion production studies

5) The transition from SIS to DIS
   A) Duality in e-nucleon / nucleus scattering
   B) Duality in neutrino nucleus scattering
   C) Higher Twist and Duality in the SIS/DIS transition
   D) Chiral Field and Regge theory in the transition region

6) Nuclear modifications of structure functions and nuclear PDFs
   A) Nuclear Medium Effects on Structure Functions I
   B) Nuclear Medium Effects on Structure Functions II
   C) nPDFs from e/mu-A and nu-A scattering I
   D) nPDFs from e/mu-A and nu-A scattering II
   E) MINERvA results of Inclusive and DIS on nuclear targets

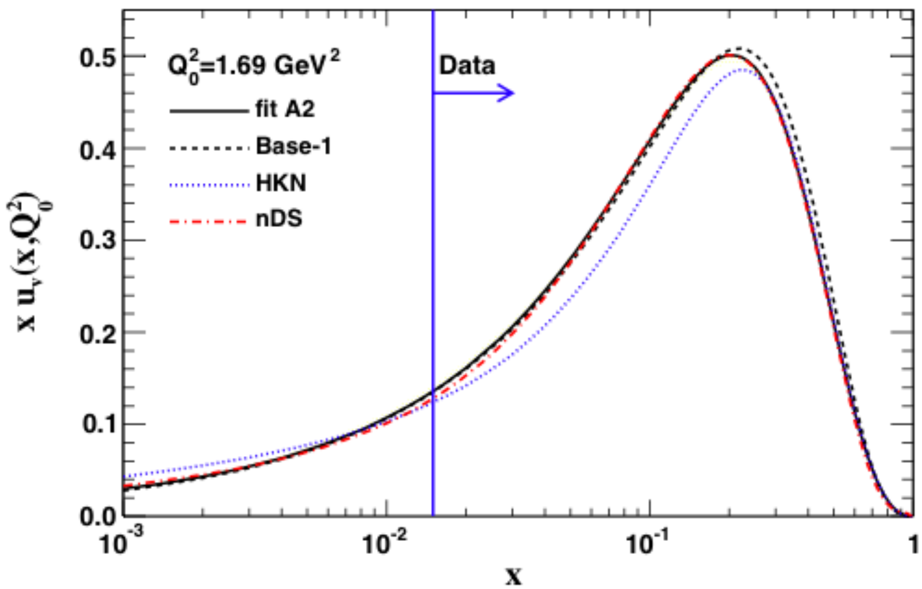
7) Hadronization in the nuclear environment
   A) Hadronization studies from the e/mu-A community
   B) The AGKY hadronization model
   C) Hadronization in FLUKA and DPMJET
   D) NOMAD Hadronization Studies

Summary and Conclusions

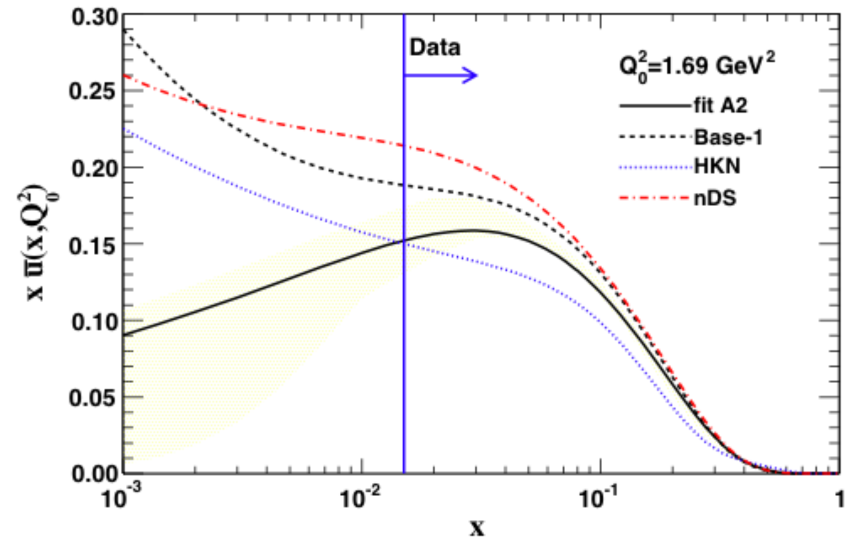
- Neutrino scattering can provide an important look at the free and bound nucleon from a different (and complimentary) point of view than electro-production.
  - The ability of neutrinos and anti-neutrinos to taste particular flavors of quarks can help isolate nPDFs
- There are significant differences in the measurement of DIS (nuclear) structure functions by different experiments that must be resolved.
- There are indications from **one** experiment using **one** nucleus that **ν and $\bar{\nu}$ -induced partonic nuclear effects are different** than found by $\ell^{\pm}$-A experiments.
- Need a systematic **experimental** study of **ν-induced partonic nuclear effects.**
- Need careful **experimental and theoretical** examination of higher W (above the Δ) **single and multi-pion production.**
- **Need to carefully understand the concept of "duality" as exhibited by ν and $\bar{\nu}$ on nuclei and how this co-exists with non-perturbative QCD effects! Generator behavior in the SIS region uses this concept.**

Additional Details

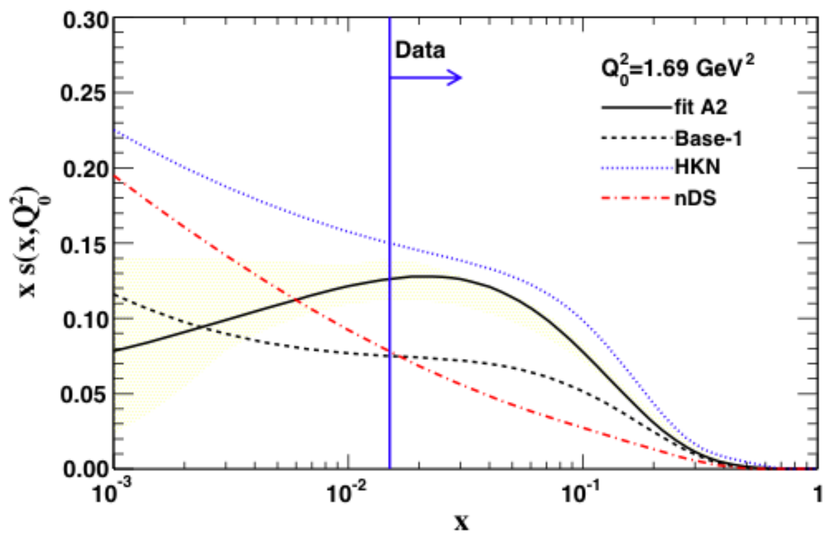
Iron PDFs



Q_0^2=1.69 GeV^2
Data
fit A2
Base-1
HKN
nDS
$x\,u_v(x,Q_0^2)$
x

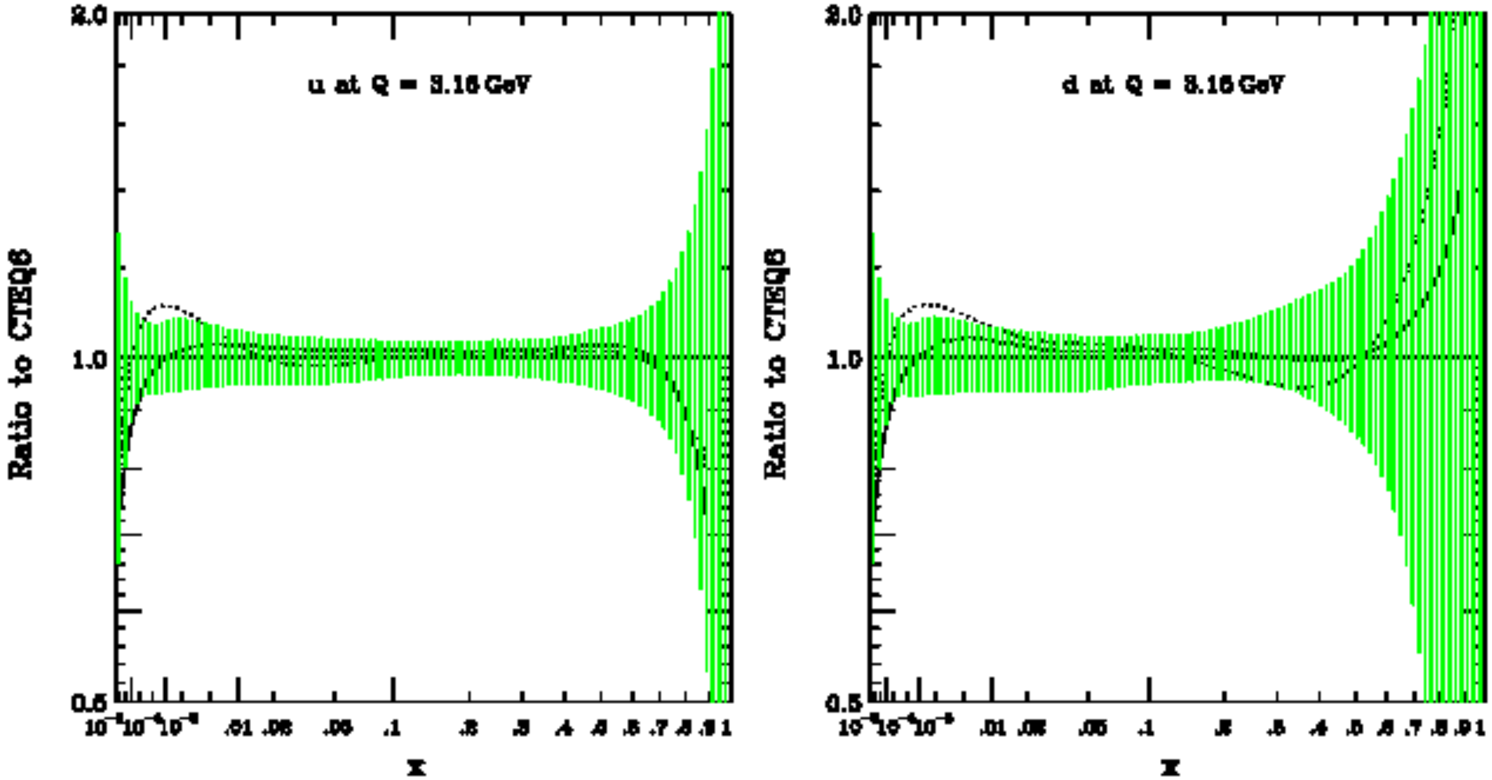


Q_0^2=1.69 GeV^2
Data
fit A2
Base-1
HKN
nDS
$x\,\bar{u}(x,Q_0^2)$
x



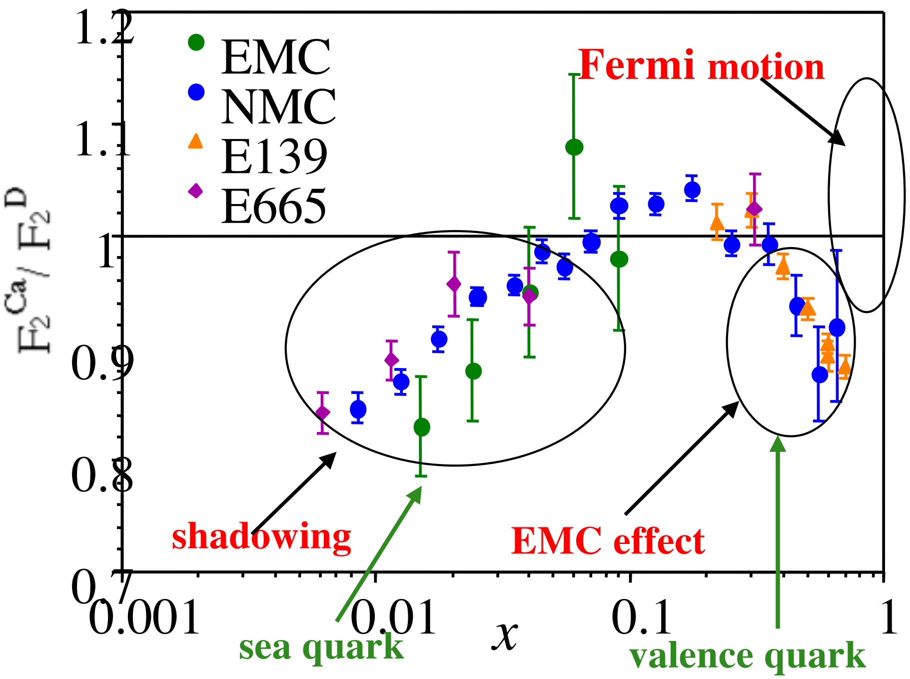
Q_0^2=1.69 GeV^2
Data
fit A2
Base-1
HKN
nDS
$x\,s(x,Q_0^2)$
x

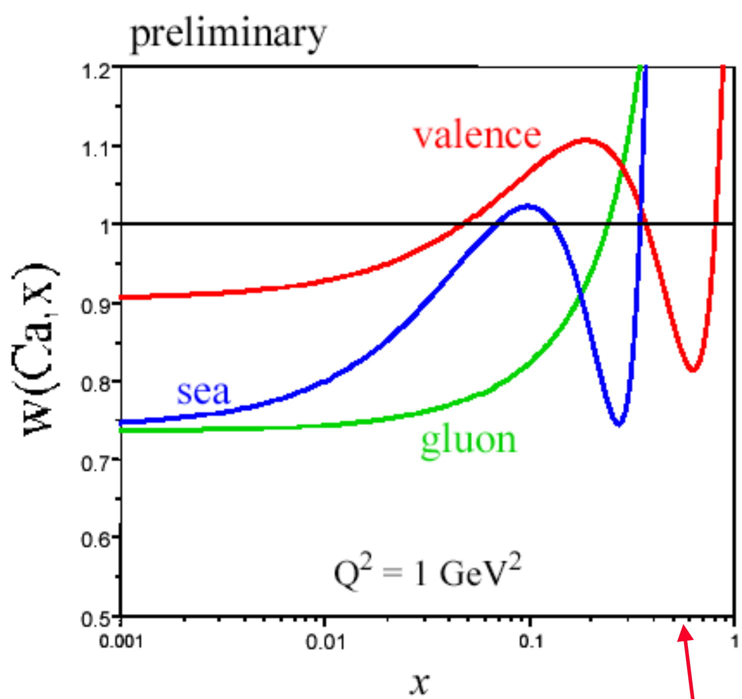
Present Status: ν-scattering High x_{Bj} parton distributions



- Ratio of CTEQ5M (solid) and MRST2001 (dotted) to CTEQ6 for the u and d quarks at $Q^2 = 10$ GeV^2. The shaded green envelopes demonstrate the range of possible distributions from the CTEQ6 error analysis.
- CTEQ / MINERνA working group to investigate high-x_{Bj} region.

Knowledge of Nuclear Effects with Neutrinos: essentially NON-EXISTENT





- F_2 / nucleon changes as a function of A. Measured in μ/e - A **not in ν – A**
- **Good reason to consider nuclear effects are DIFFERENT in ν - A.**
  - **Presence of axial-vector current.**
  - **SPECULATION: Much stronger shadowing for ν -A but somewhat weaker "EMC" effect.**
  - **Different nuclear effects for valance and sea --> different shadowing for xF_3 compared to F_2.**
  - **Different nuclear effects for d and u quarks.**

Formalism

- PDF Parameterized at Q_0 = 1.3 GeV as

$$xf_i(x,Q_0) = \begin{cases} A_0 x^{A_1}(1-x)^{A_2} e^{A_3 x}(1+e^{A_4}x)^{A_5} & : i = u_v, d_v, g, \bar{u}+\bar{d}, s, \bar{s}\,, \\ A_0 x^{A_1}(1-x)^{A_2} + (1+A_3 x)(1-x)^{A_4} & : i = \bar{d}/\bar{u}\,, \end{cases}$$

- PDFs for a nucleus are constructed as:

$$f_i^A(x,Q) = \frac{Z}{A}\, f_i^{p/A}(x,Q) + \frac{(A-Z)}{A}\, f_i^{n/A}(x,Q)$$

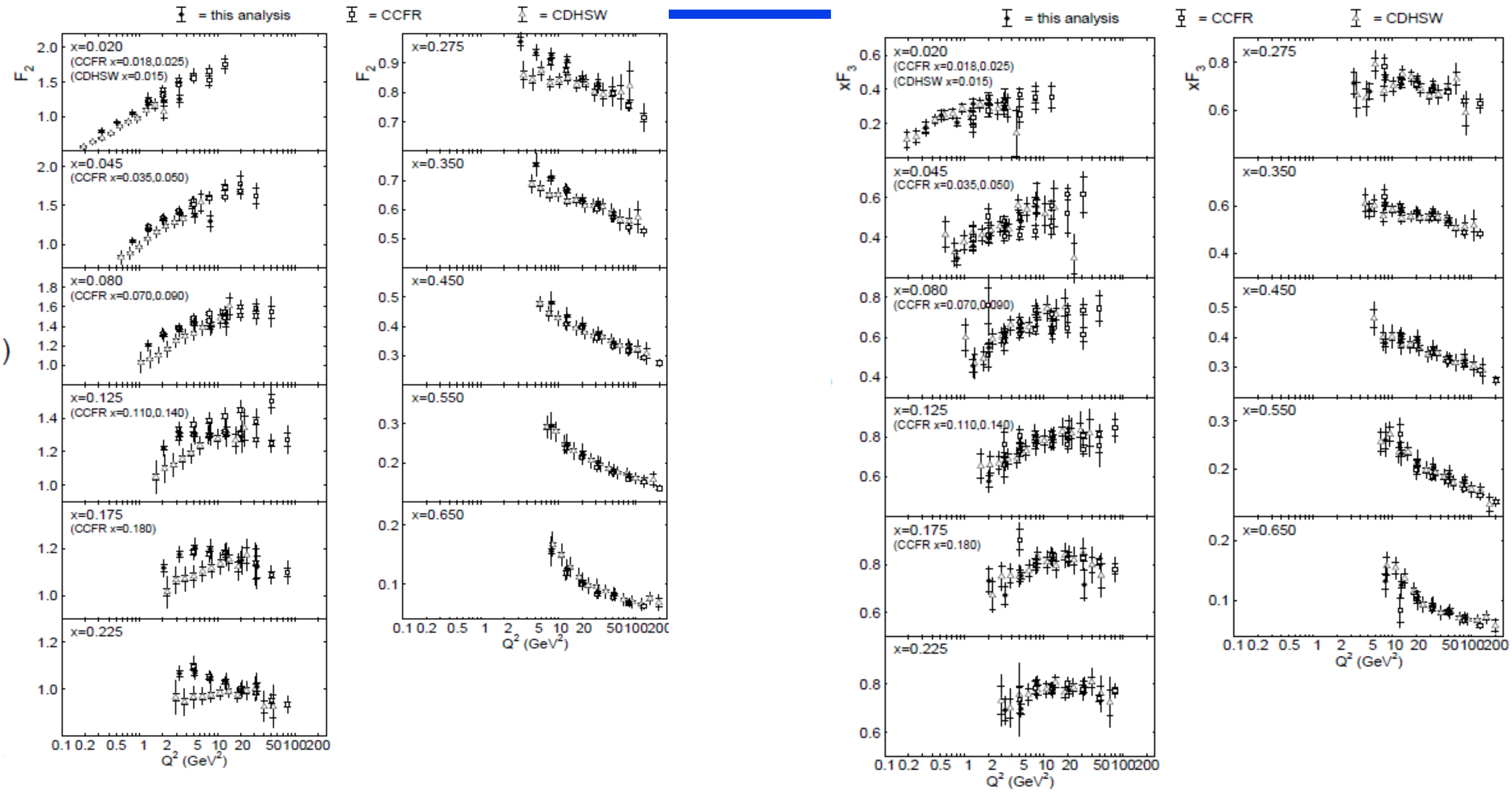
- Resulting in nuclear structure functions:

$$F_i^A(x,Q) = \frac{Z}{A}\, F_i^{p/A}(x,Q) + \frac{(A-Z)}{A}\, F_i^{n/A}(x,Q)$$

- The differential cross sections for CC scattering off a nucleus::

$$\frac{d^2\sigma}{dx\,dy}^{\overset{(-)}{\nu}A} = \frac{G^2 M E}{\pi}\left[(1-y-\frac{Mxy}{2E})F_2^{\overset{(-)}{\nu}A} + \frac{y^2}{2}2xF_1^{\overset{(-)}{\nu}A} \pm y(1-\frac{y}{2})xF_3^{\overset{(-)}{\nu}A}\right]$$

CHORUS Structure Functions: ν Pb



- First ν-Pb differential cross section and structure functions
- CHORUS measurement somewhat favors CCFR over NuTeV
- Much larger systematic errors than the NuTeV experiment

Kulagin-Petti Model of Nuclear Effects

hep-ph/0412425

- Global Approach -aiming to obtain quantitative calculations covering the complete range of x and Q^2 available with thorough physics basis for fit to data.
- Different effects on structure functions (SF) are taken into account:

$$F_i^A = F_i^{p/A} + F_i^{n/A} + F_i^{\pi/A} + \delta F_i^{\mathrm{coh}}$$

  - $F_i^{p(n)/A}$ bound proton(neutron) SF with Fermi Motion, Binding (FMB) and Off-Shell effect (OS)
  - $F_i^{\pi/A}$ nuclear Pion excess correction (PI)
  - $\delta F_i^{\mathrm{coh}}$ contribution from coherent nuclear interactions: Nuclear Shadowing (NS)

- **Fermi Motion** and **Binding** in nuclear structure functions is calculated from the convolution of nuclear spectral function and (bound) nucleon SFs:
- Since bound nucleons are off-mass shell there appears dependence on the nucleon virtuality $\kappa^2 = (M + \varepsilon)^2 - k^2$ where we have introduced an **off-shell structure function $\delta f_2(x)$**

$$F_2(x, Q^2, k^2) = F_2(x, Q^2)\left(1 + \delta f_2(x)(k^2 - M^2)/M^2\right)$$

- Leptons can scatter off mesons which mediate interactions among bound nucleons yielding a **nuclear pion correction**

CTEQ study: The Impact of new neutrino DIS (NuTeV and Drell-Yan data on large-x parton distributions

Joey Huston - MSU, Cynthia Keppel - Hampton, Steve Kuhlmann - ANL,
JGM - Fermilab, Fred Olness - SMU, Jeff Owens - Florida State,
Jon Pumplin and Dan Stump - MSU

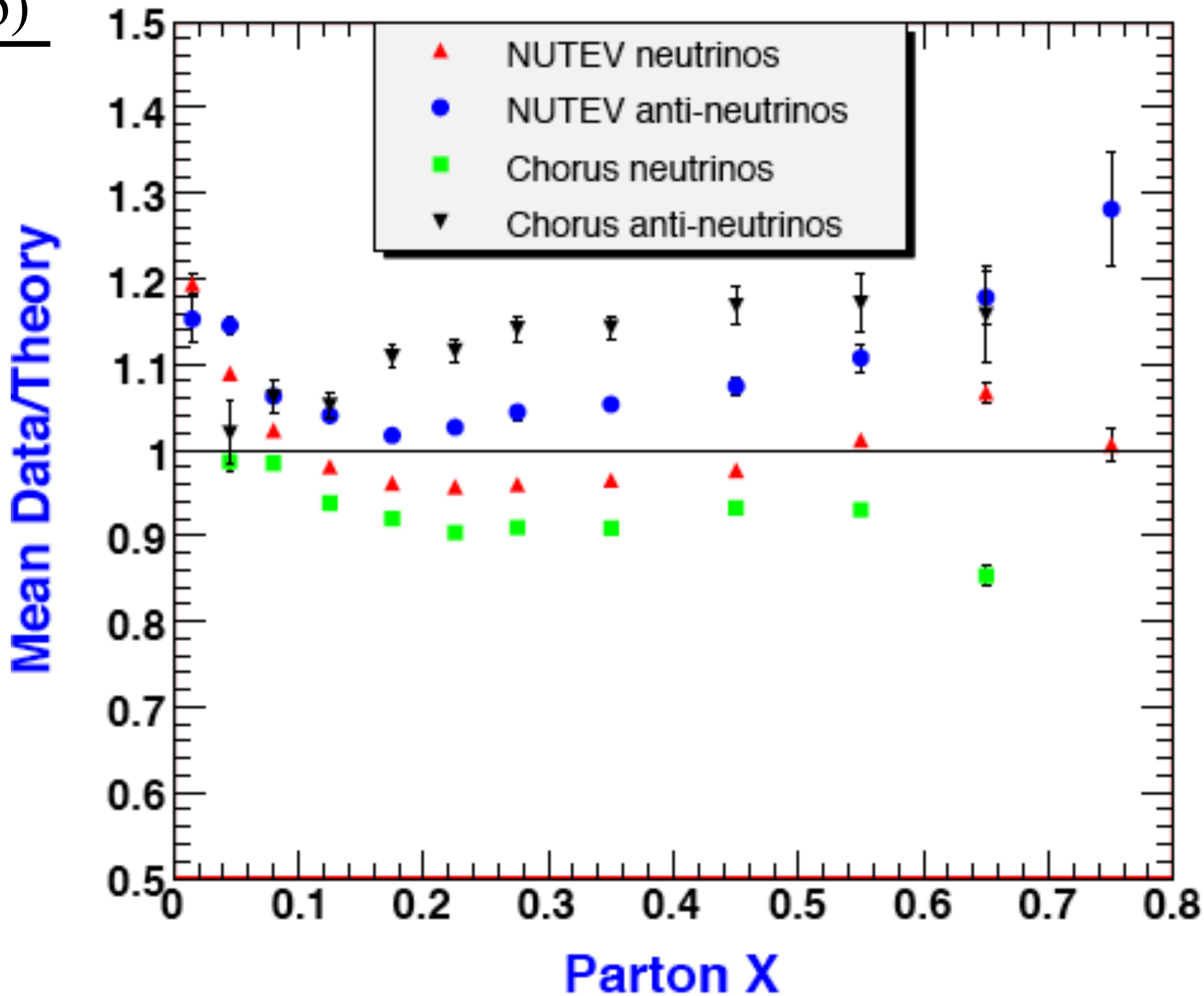
Published in **Phys.Rev.D75:054030,2007**.
e-Print: **hep-ph/0702159**

Had to use $l^{\pm}$-Fe correction factors to combine NuTeV ν-Fe results with E866 p-H and p-D Drell-Yan results.
Tension between NuTeV and E866 started us on a rather convoluted path to extracting **nuclear effects from neutrino interactions**.

NuTeV σ(Fe) & CHORUS σ(Pb) ν scattering (un-shifted) results compared to reference fit

Kulagin-Petti nuclear corrections for neutrinos

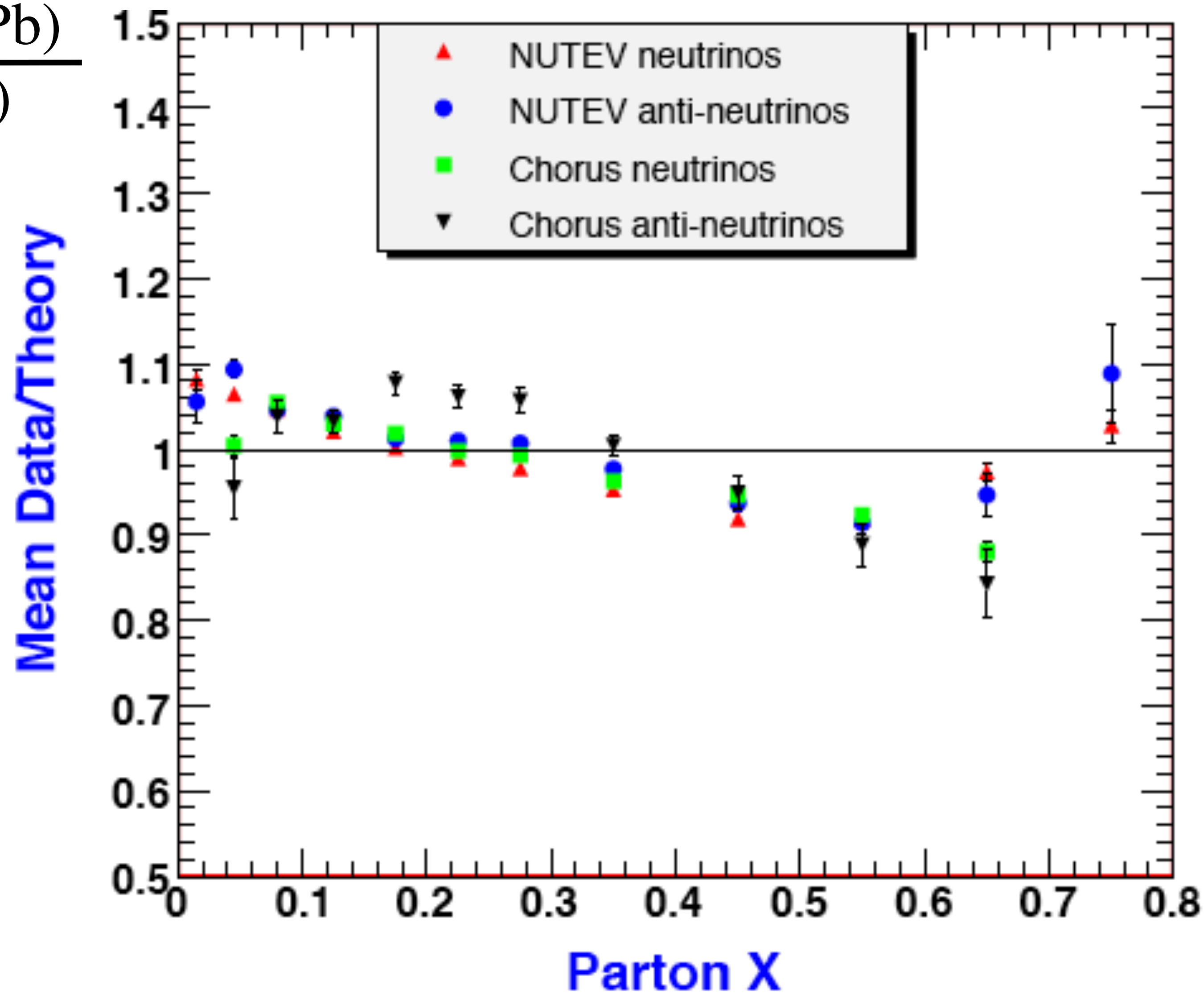
$$\frac{\sigma(\text{Fe or Pb})}{\sigma(D_2)}$$



NuTeV(Fe) and CHORUS (Pb) ν scattering (unshifted) σ results compared to reference fit

no nuclear corrections

$$\frac{\sigma(\nu\text{Fe or }\nu\text{Pb})}{\sigma(\nu\square D_2\square)}$$



NuTeV σ(Fe) & CHORUS σ(Pb) ν scattering (shifted) results compared to reference fit

Kulagin-Petti nuclear corrections for neutrinos

$$\frac{\sigma(\text{Fe or Pb})}{\sigma(\square D_2 \square)}$$