Current Challenges in Neutrino Nucleus Scattering

What do we know about the kinematic region $W_H > M_\Delta$?

NuSTEC Workshop on SIS/DIS: https://indico.cern.ch/event/727283/overview

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Fermilab

Outline

$W^2 = M^2 + Q^2 (1 - x) / x$ is the Effective Mass of the Hadronic System

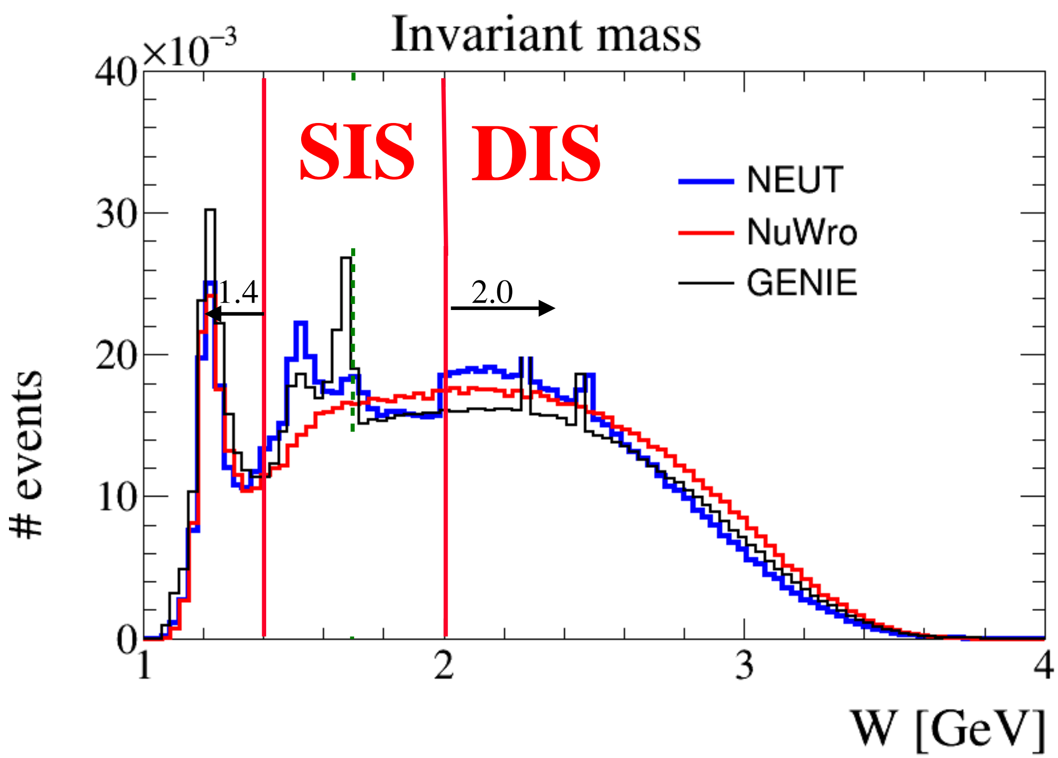
- ν Shallow Inelastic Scattering (SIS) - $M_\Delta < W < 2.0$ GeV
  - Higher W resonances
  - Duality
  - Non-perturbative / perturbative QCD Interface
- ν Deep Inelastic Scattering – $W > 2.0$ GeV & $Q^2 > 1$ GeV^2
  - Nuclear Parton Distribution Functions (nPDFs): ν +A vs. e/μ +A
  - "universal PDFs" and factorization

Inclusive SIS/DIS in Neutrino Event Generators

The General Landscape – Comparison of Generators

- By far the majority of contemporary studies in ν-nucleus interactions have been of Quasielastic and Δ production - that is W ≤ 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

Shallow-Inelastic Scattering: $M_\Delta < W < 2.0$ GeV

- Why study Shallow-Inelastic Scattering?
  - How does the physics (language) of quark/partons from DIS meet the physics of resonances - nucleons and pions. → **quark-hadron duality.**
  - Do the so-called "partonic" nuclear effects of DIS (shadowing, anti-shadowing & EMC effect) extend down into the SIS region or do they suddenly/slowly turn off.
  - **50 % of the expected events of the DUNE neutrino oscillation experiment, major HEP project, are in the SIS + DIS region (W > 1.4 GeV)!**

- How do we study it? **MINERvA starting the high-statistics experimental study of the following!**
  - Measure total and differential cross sections in the SIS region off **nuclei** and extract the corresponding "(nuclear) structure functions" $F_i(x,Q^2)$.
  - Compare cross sections and $F_i(x,Q^2)$ from the DIS with the SIS equivalents.
  - Determine bound nucleon (so-called "partonic") nuclear effects by ratios of σ or F_i off nuclei in the SIS region…

What About the Theory of Inclusive SIS studies? What is "Quark-Hadron Duality"?

- Quark–hadron duality is a general feature of strongly interacting landscape.
  - Relationships between meson–nucleon and quark–gluon degrees of freedom.

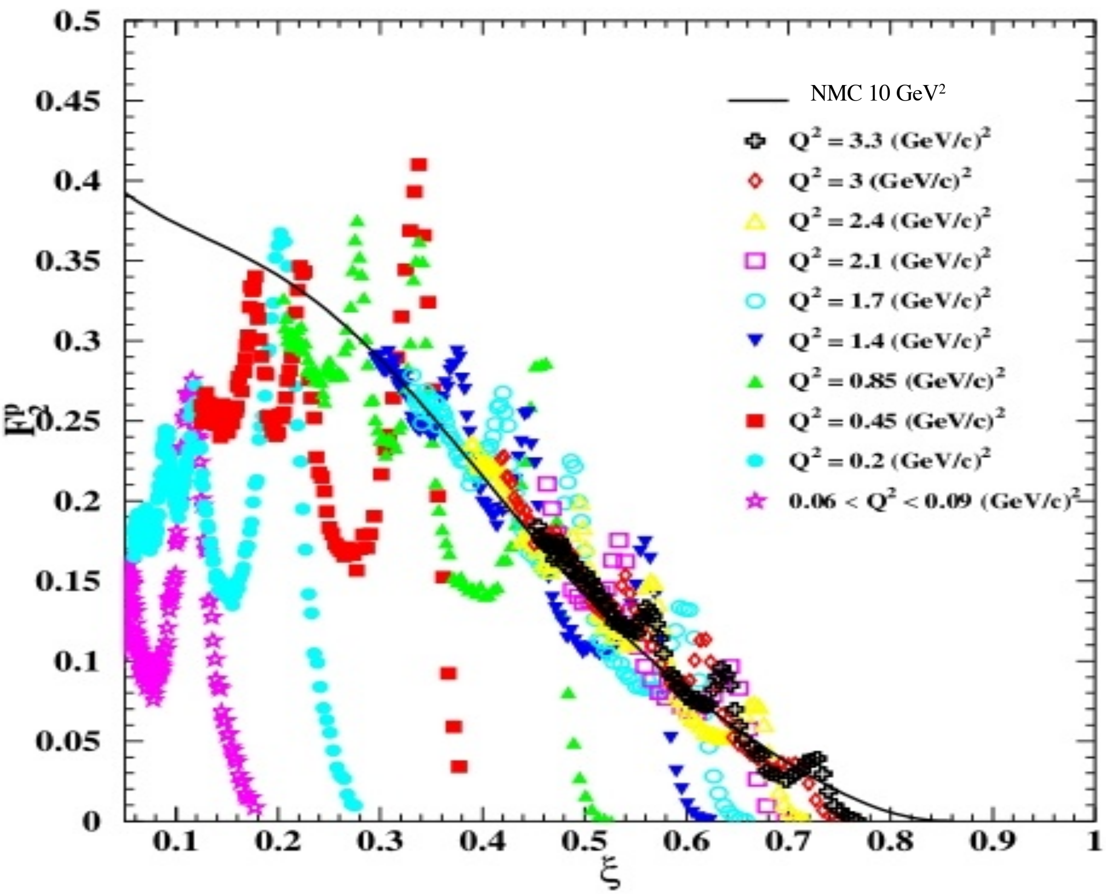
- Duality is an important concept for verifying the fundamental models that neutrino simulation generators employ (GENIE, NEUT and NuWro).
  - Quark-hadron duality originally studied and confirmed in e-N scattering – how about ν-N scattering?

- There is essentially no high-statistics ν-N/A experimental data with 1.4 < W < 2.0 GEV for tests!
  - **MINERνA is working to fix this for ν-A!**

- For now we rely on theoretical **models** of this region for an assessment of duality in ν-A scattering.

What does Q-H Duality "Look Like" Experimentally?

Early Jefferson Lab 6 GeV e-Nucleon Study



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

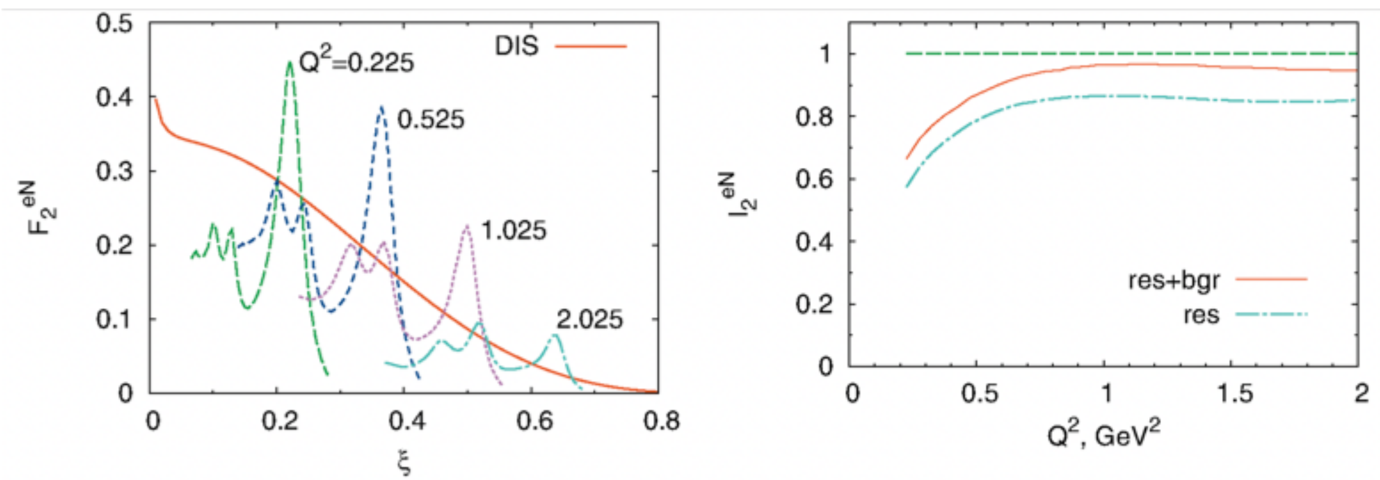
So-called Nachtmann variable to account for Target Mass Effects

Quantitative test of Q-H Duality: e Nucleon

- Ratio of the strength of the SIS to DIS region. Ideal Duality I = 1.0

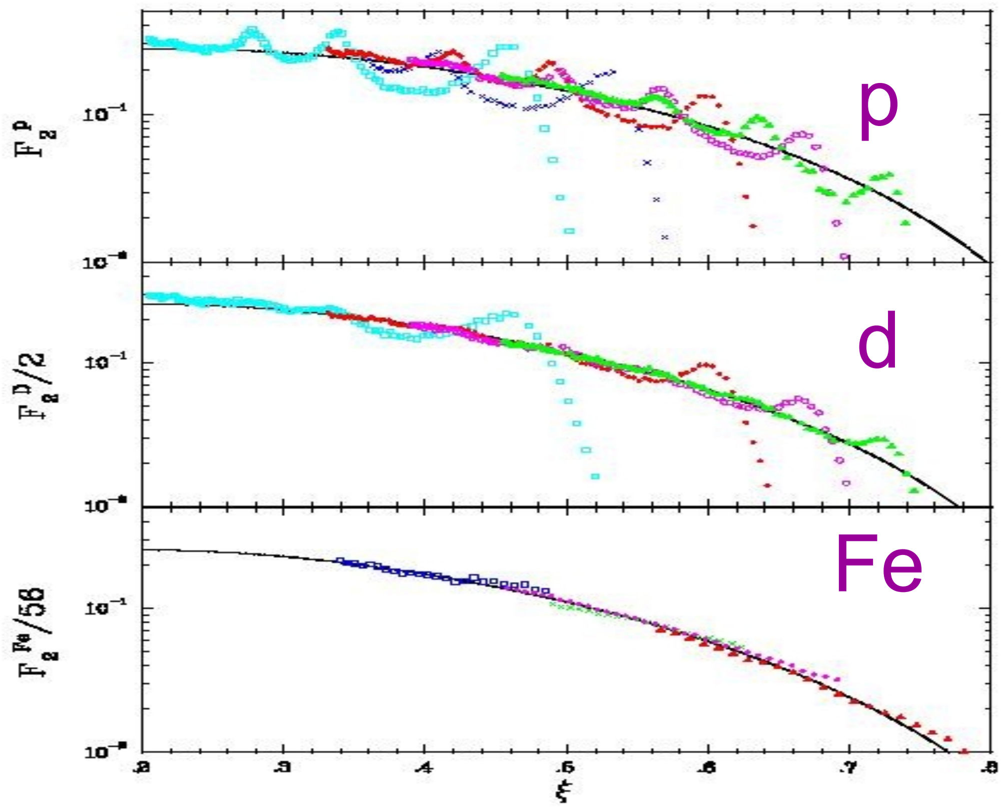
$$\mathcal{I}_{|}(Q^2, Q^2_{DIS}) = \frac{\int_{\xi_{min}}^{\xi_{max}} d\xi F_j^{RES}(\xi, Q^2)}{\int_{\xi_{min}}^{\xi_{max}} d\xi F_j^{DIS}(\xi, Q^2_{DIS})} \qquad \xi = \frac{2x}{(1+\sqrt{1+4m_N^2 x^2/Q^2})}$$

- Using Giessen fit to e-N scattering – $F_2^{eN}(\xi)$ for values of Q^2 indicated on spectra compared to LO DIS QCD fit at Q^2 = 10 GeV^2. Value of integral I(Q^2).



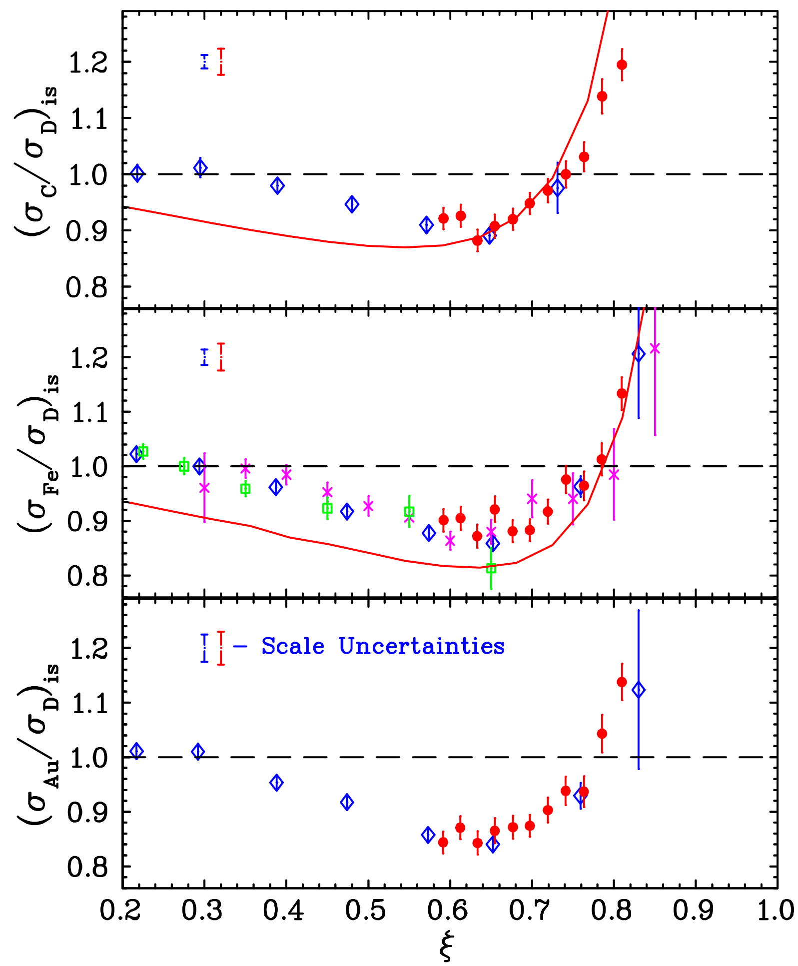
Now Nucleus not Nucleon
Qualitative look at Q-H Duality: e A

- Now e-**nucleus** – individual resonances visible in e-P, somewhat less in e-D and mostly smeared out by e-Fe. Curved line is from MRST global **DIS fits** with **EMC effect** for Fe applied.



Speaking of the EMC Effect….
Found in the eA **Resonance Region**
Further evidence of Quark-Hadron Duality?

- The solid red circles are Jefferson Lab data taken in the **resonance region 1.2 < W2 < 3.0 GeV and Q^2 = 4 GeV^2**. All other data points from DIS region.

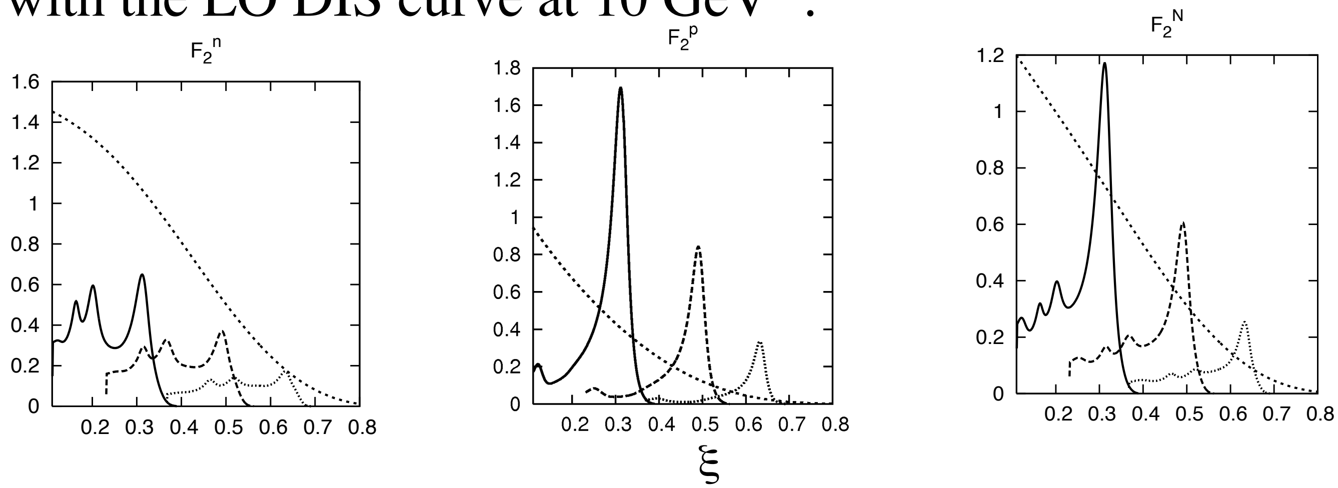


Now for **Neutrinos**

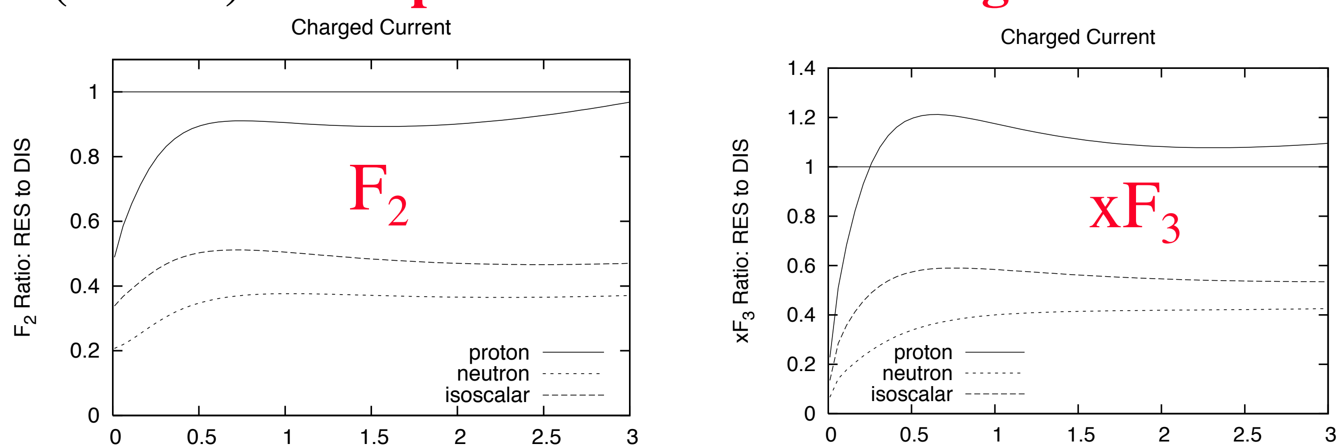
NO high-statistics Experimental Data available - turn to Theory

When using the Rein-Sehgal Model for **ν-N** Resonances (J. Sobczyk et al.-NuWro)

- Comparison to Rein-Sehgal structure functions for n, p and N at $Q^2 = 0.4$, 1.0 and 2.0 GeV^2 with the LO DIS curve at 10 GeV^2 .



- The I integral for the R-S model for resonances off neutron (dotted), proton (solid) and isoscalar (dashed). **Real problems for A with large neutron excess!**

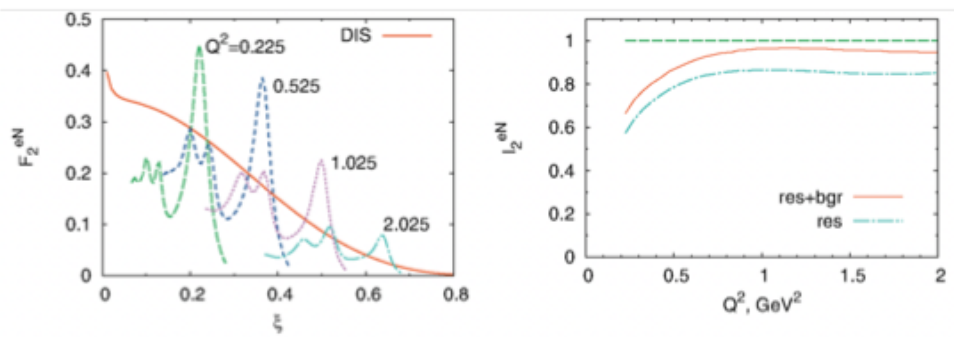


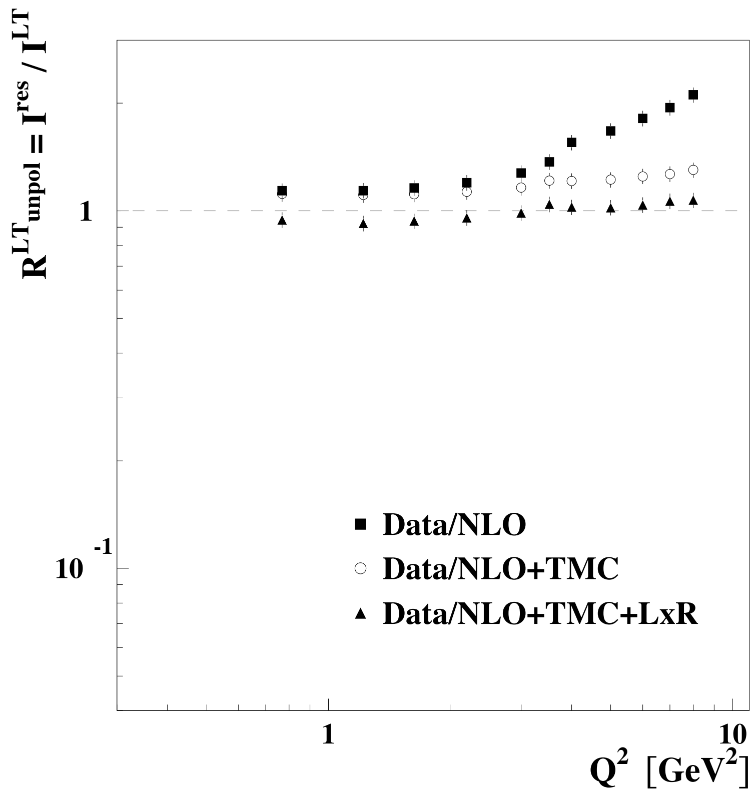
Summary: Quark-Hadron Duality for e-N/A and ν-N/A

- $F_2^{ep\ en}$: Qualitative and quantitative duality HOLDS in electron–nucleon scattering.
- $F_2^{\nu p\ \nu n}$: In neutrino–nucleon scattering, using the R-S model, duality roughly holds for proton but NOT for neutron and NOT for isoscalar $F_2^{\nu N}$.
- F_2^{eA} : Very different story, looks good but quantitative duality check in e – A not as good as the nucleon.
- **$F_2^{\nu A}$: Not at all clear how duality works here, particularly in nuclei with an excess number of neutrons.**
- In general for neutrinos, the resonance structure functions for **proton are much larger than for neutrons** and in the case of DIS structure functions **the situation is opposite.** Although to some extent model dependent, a general tendency is that for larger W, DIS structure functions are much larger than the resonance contribution at lower W.
- 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!**
- MINERvA's goal is to make the first experimental measurement of inclusive production in the SIS region.

Duality and Higher Twist

- Does the fact that duality holds so well for e N resonance scattering compared to LO, **leading twist** DIS results suggest there is little room for higher twist contributions for $Q^2 > 1$ GeV^2 and x < 0.65??
- Multiple studies of this available in the literature and all seem to agree with the above statement. For example from: A. Fantoni, N. Bianchi, and S. Liuti. Quark-hadron duality and higher twist contributions in structure functions. *AIP Conf. Proc.*, 747(1):126–129, 2005.

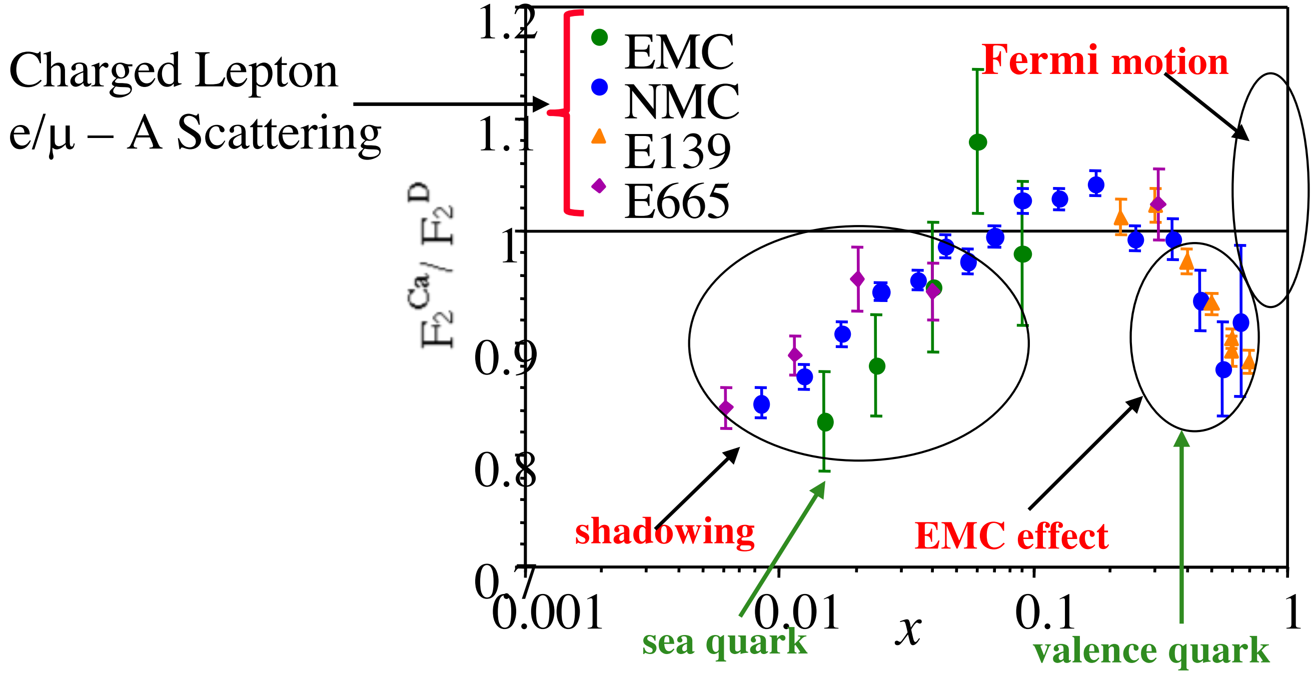




Deep-Inelastic Scattering (Q^2 > 1 GeV^2 and W > 2 GeV)

Studied for decades with **e/μ + Nucleons and Nuclei** Scattering

→ **PDFs for bound nucleon NOT the same as for free nucleon!!**



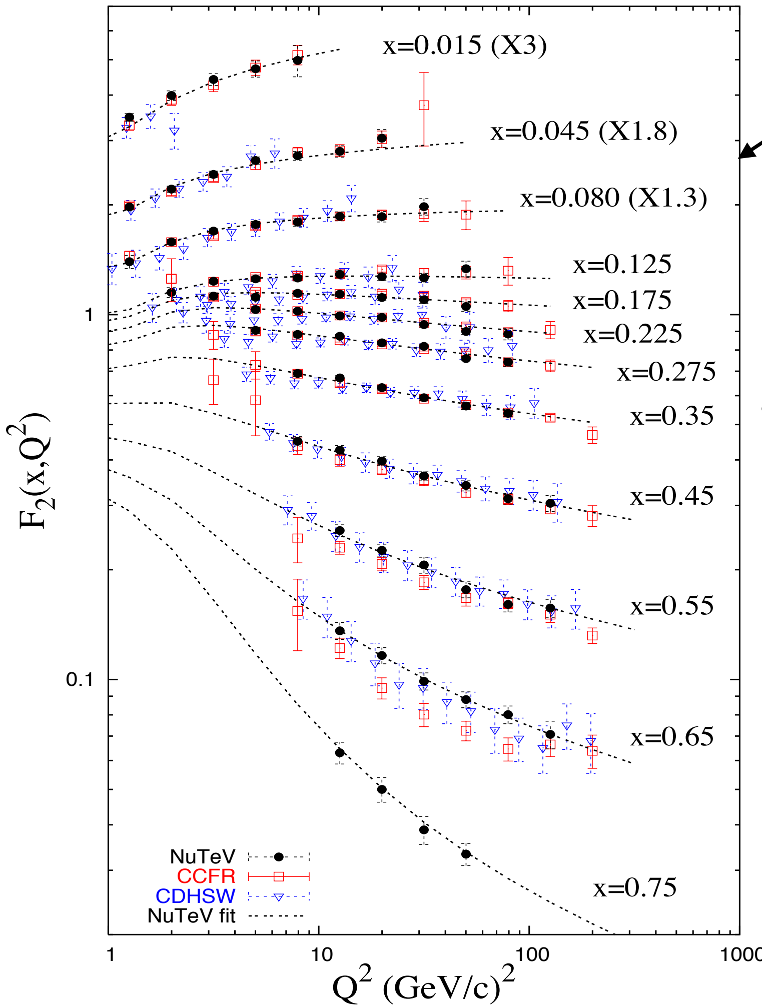
Nuclear Correction Factor
to bring e/μ A to e/μ N
for fitting free N PDFs

- **In early CTEQ free nucleon PDF fits – *terrible tension* - at low-x when including ν/$\bar{\nu}$ corrected with e/μ NCF. Had to ignore ν / $\bar{\nu}$!!**

- Hmmm - are the **neutrino nuclear correction factors** **different** than the charged lepton nuclear correction factor?

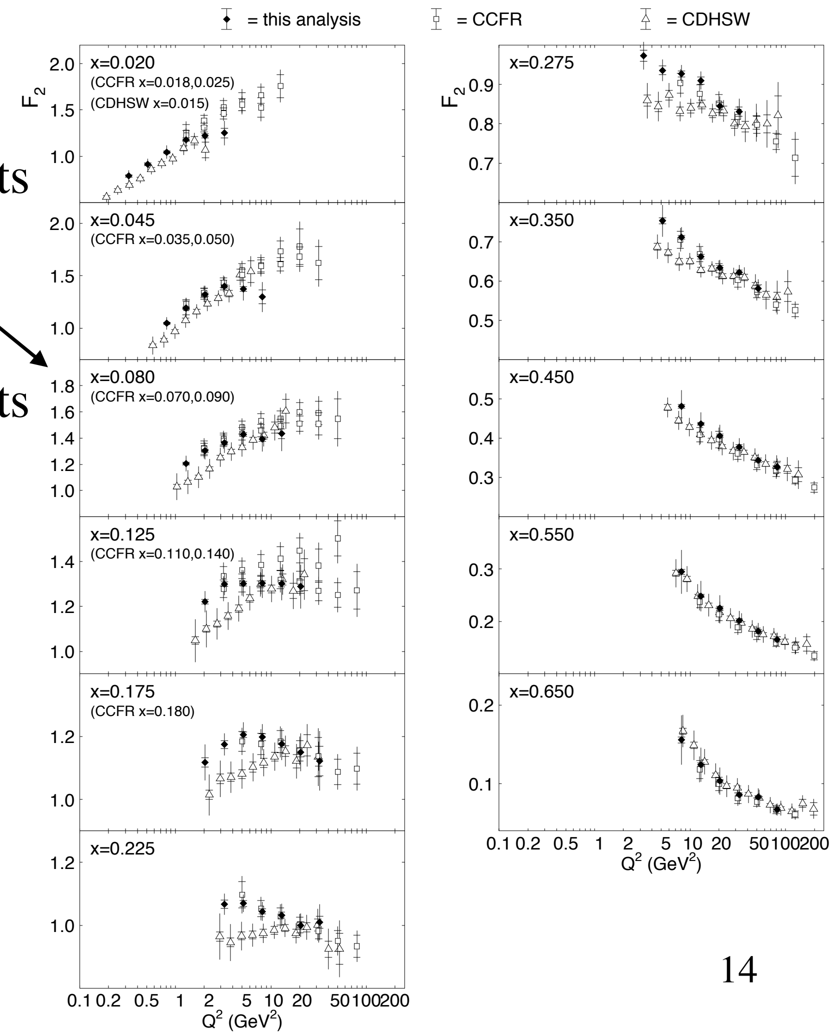
nCTEQ: Determine the neutrino nuclear correction factors using NuTeV and CHORUS <F_2> ($\nu + \bar{\nu}$) Structure Functions +

- F_2 Structure Functions from NuTeV **(ν Fe)** and CHORUS **(ν Pb)** each compared to CCFR **(ν Fe)** and CDHSW **(ν Fe)**

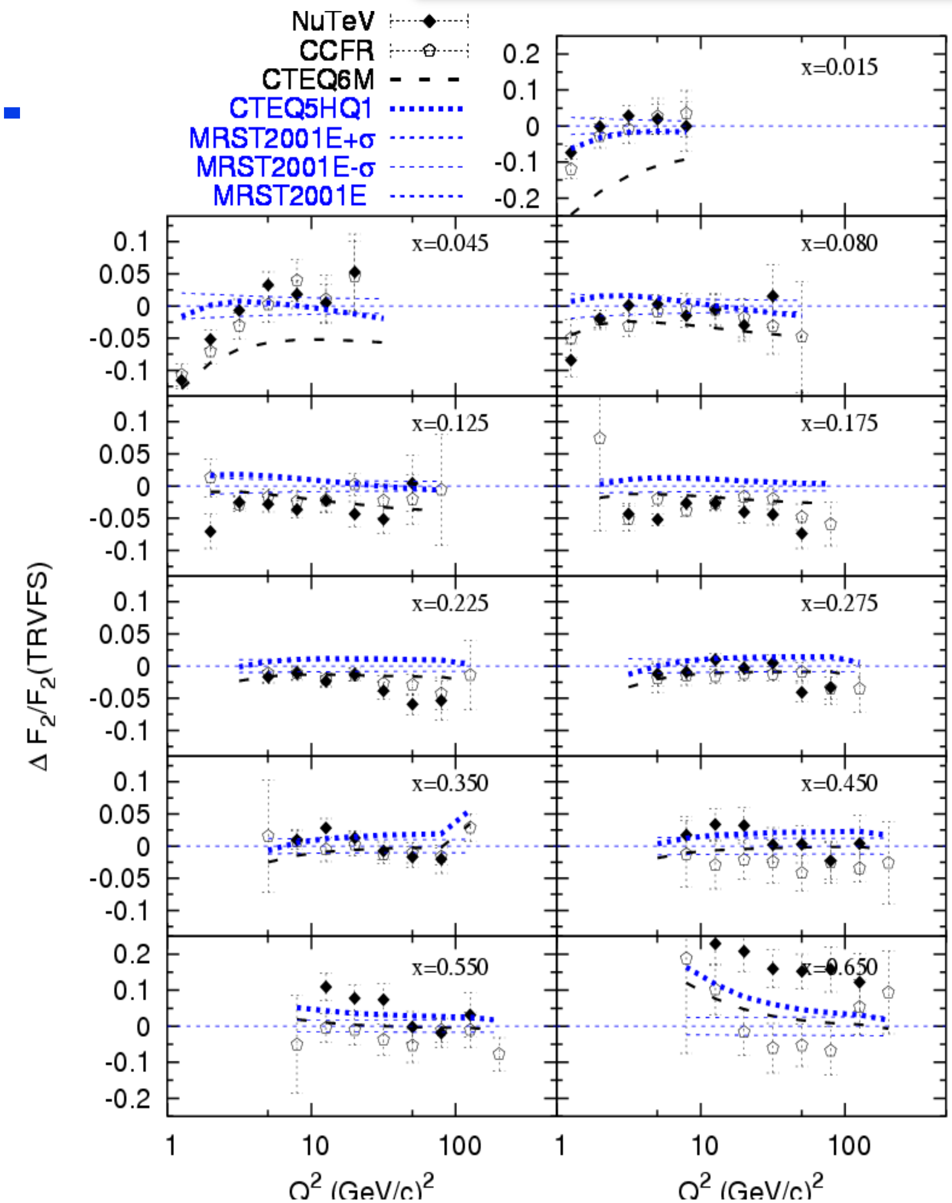


NuTeV
3 Million Events

CHORUS
1 Million Events



Comparison of NuTeV with Global Fits for F_2



- Baseline is TRVFS(MRST2001E)

- NuTeV and CCFR F_2 are compared to TRVFS(MRST2001E)

$$\frac{F_2^{NuTeV} - F_2^{TRVFS}}{F_2^{TRVFS}}$$

- Theoretical models, corrected for Target Msss, shown are:
  - ACOT(CTEQ6M)
  - ACOT(CTEQ5HQ1)
  - TRVFS (MRST2001E)

- **F_2 somewhat lower than theory at mid-x.**
- **At low-x very different Q^2 dependence.**
- **At high-x (x>0.5) NuTeV is systematically higher.**

Let's extract (neutrino) nuclear parton distributions to determine ν and $\bar{\nu}$ independent ?

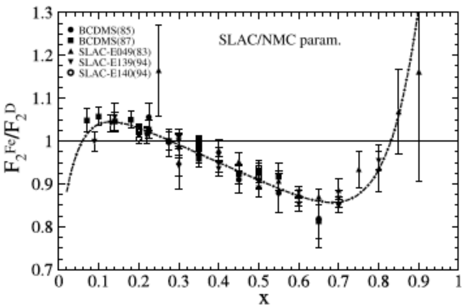
Nuclear Parton Distribution Functions from ν DIS

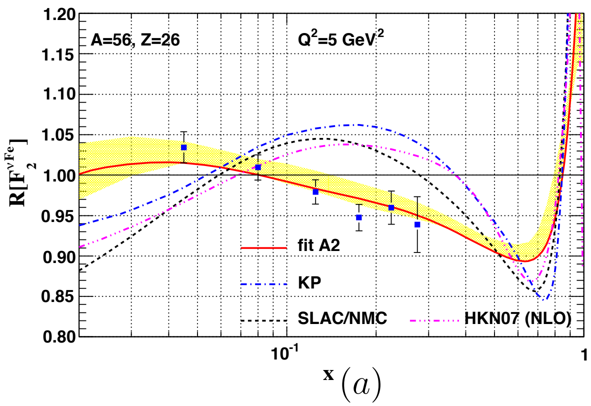
(nCTEQ Global Fit to Neutrino Data)

Phys.Rev. D77 (2008) 054013

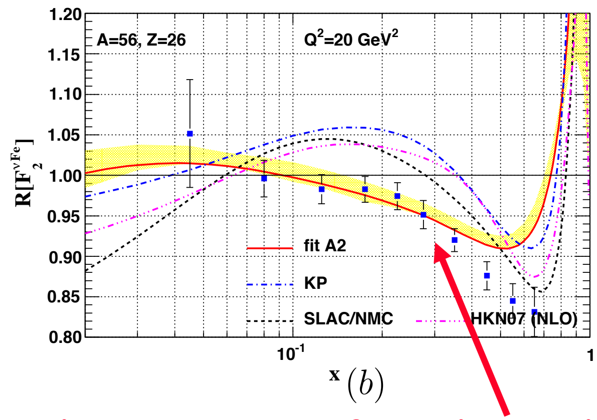
- nCTEQ uses:
  - the NuTeV **double differential cross sections NOT the structure functions** F_2 and xF_3 that require additional theoretical assumptions to extract.
  - **the full NuTeV covariant error matrix**
- nCTEQ uses **8 Neutrino data sets**
  - NuTeV cross section data: νFe, $\bar{\nu} Fe$
  - NuTeV dimuon off Fe data: ν & $\bar{\nu}$
  - CHORUS cross section data: νPb, $\bar{\nu}\ Pb$
  - CCF*R* dimuon off Fe data: ν & $\bar{\nu}$
- **Directly determine Nuclear Correction Factors for ν & $\bar{\nu}$**

Nuclear Correction Factors: ν and $\overline{\nu}$ – $F_2(\nu Fe)$ / $F_2[\nu(n+p)]$

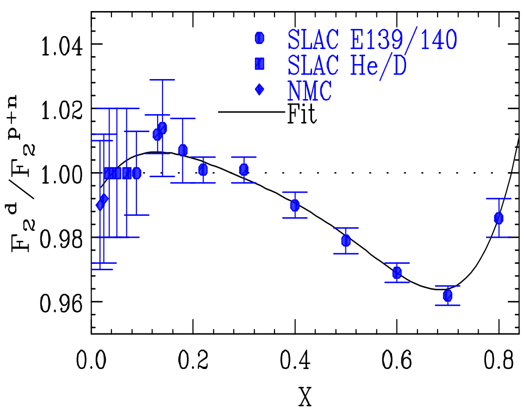


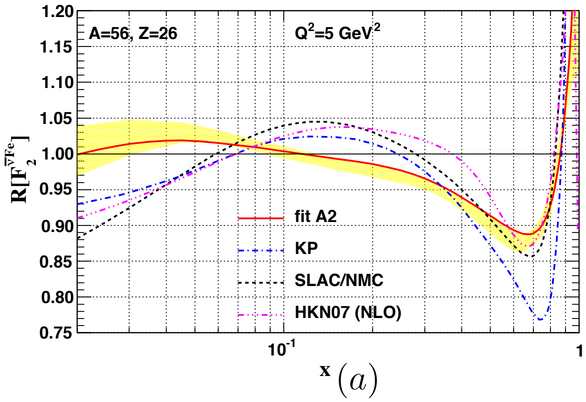


ν

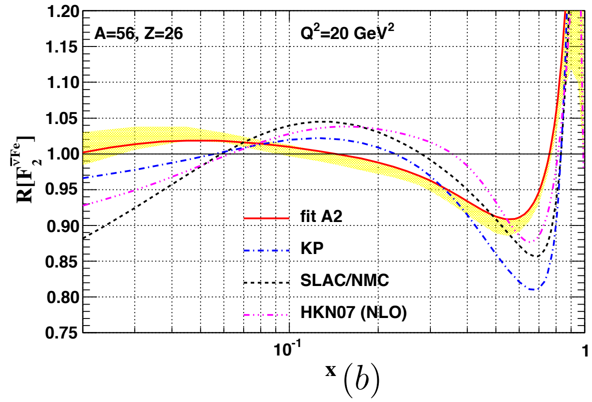


More intense study of medium- high-x region in current round of fits





$\overline{\nu}$

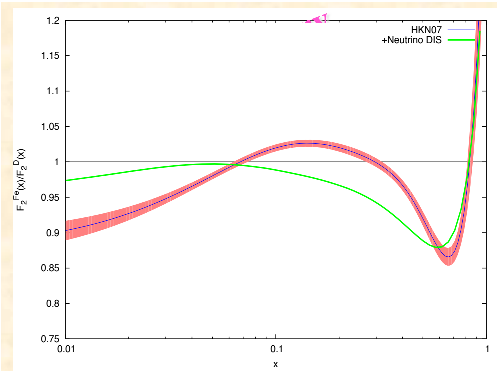


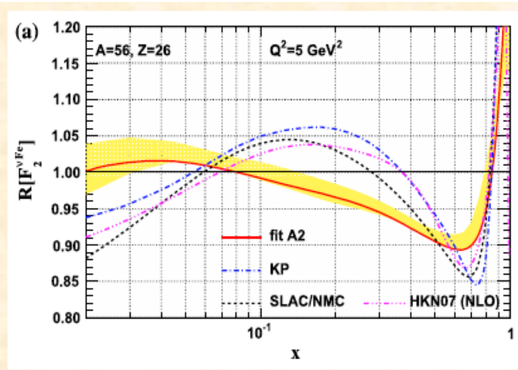
Could NOT find a compromise (χ^2 with tolerance) fit with both ν and e/μ results using cross sections and NuTeV covariant errors.

Other Groups find similar results!

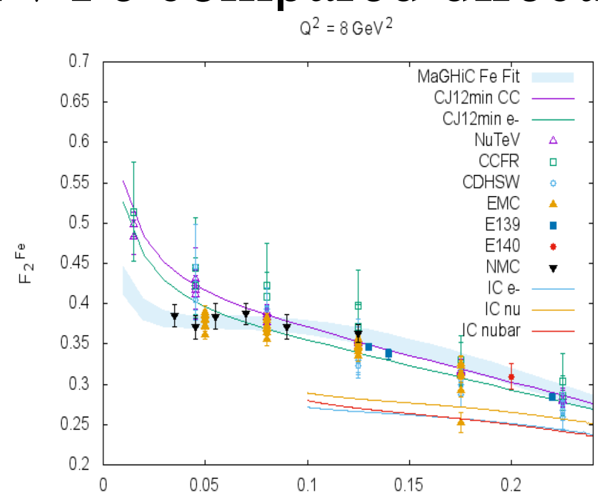
Also there are global fitting groups that do NOT find this result.

- Same NCF determined by Japanese Collaboration: Kumano et al.





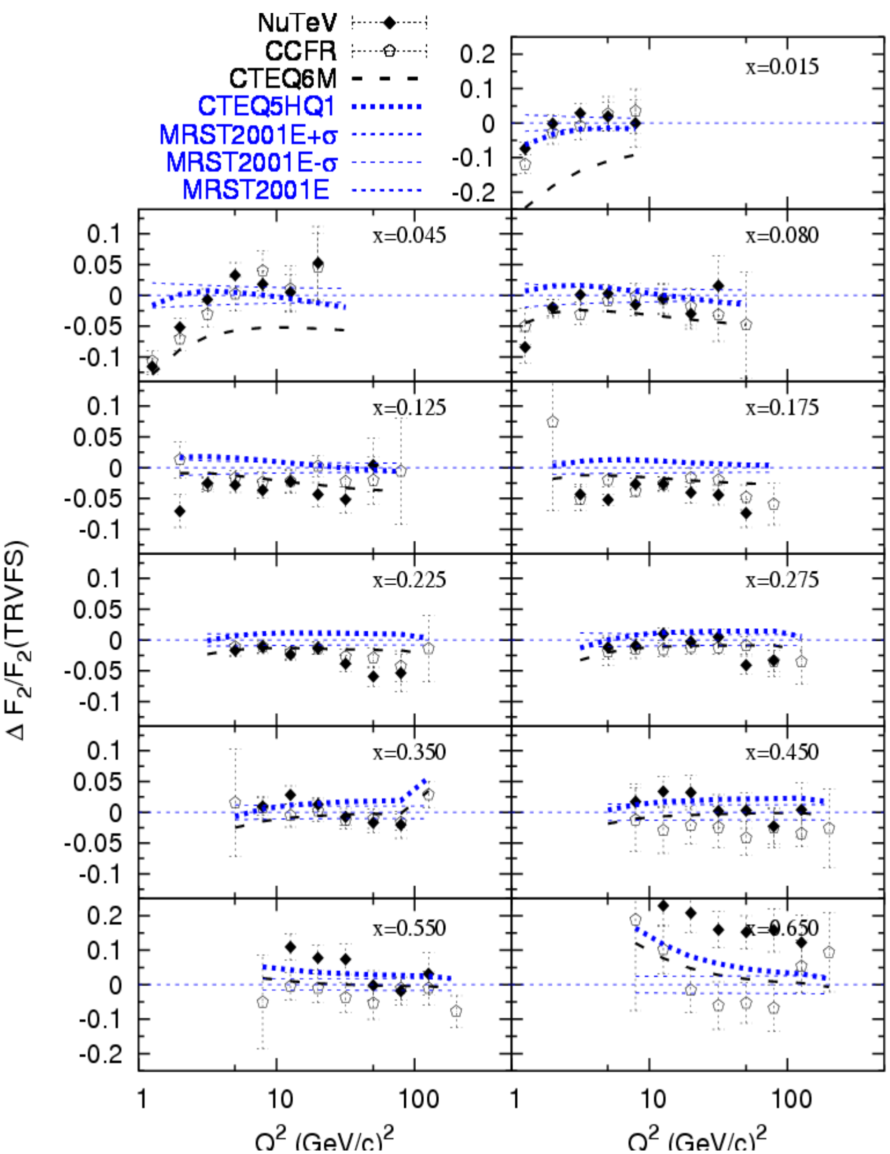
- JLab Centered Collaboration sees same effect looking at measured F_2 (not ratios) from ν Fe compared directly to e Fe. 15% effect.

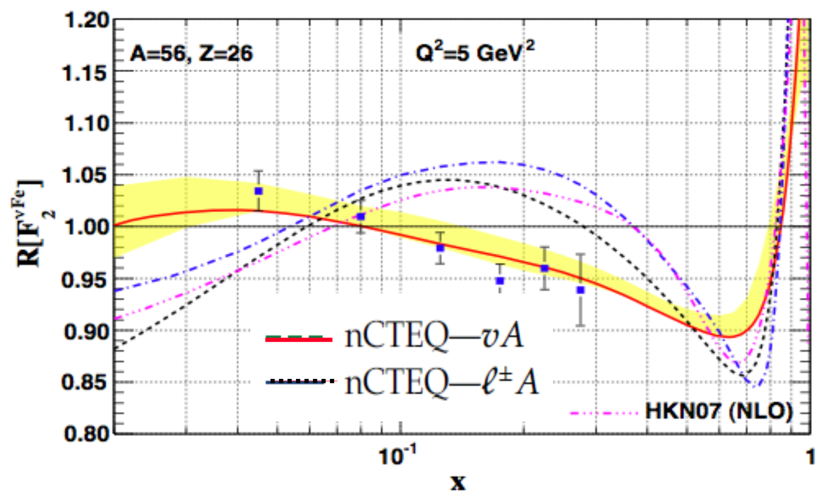


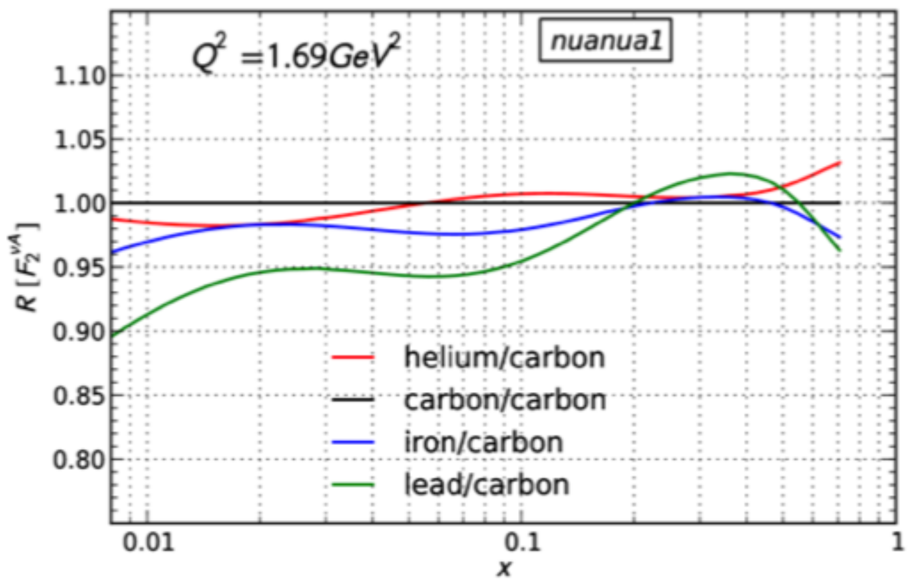
We Now Have A New DIS Player - What does MINERνA see?

Reminder from NuTeV: The Q^2 distribution within an x bin is essential!

An nCTEQ low-Q^2 Prediction for MINERνA

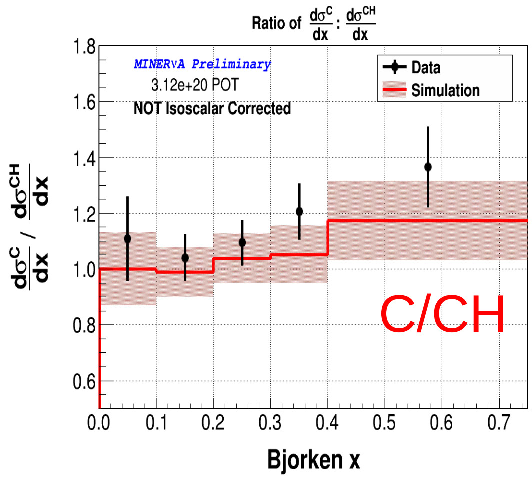


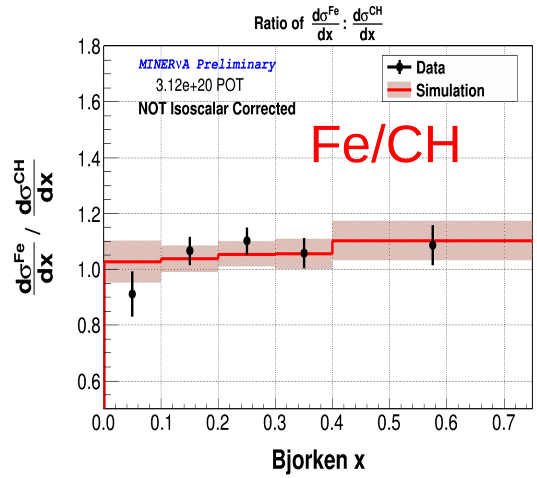


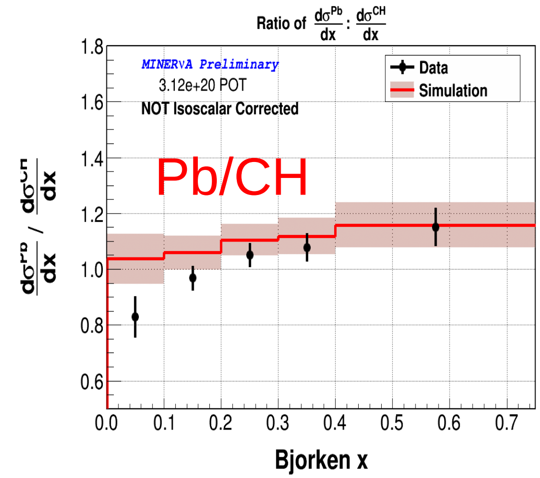


What does MINERvA see? LE DIS Cross Section Ratios – dσ/dx. Much improved ME beam ratios soon to be released!

The Q^2 distribution within an x bin is essential!

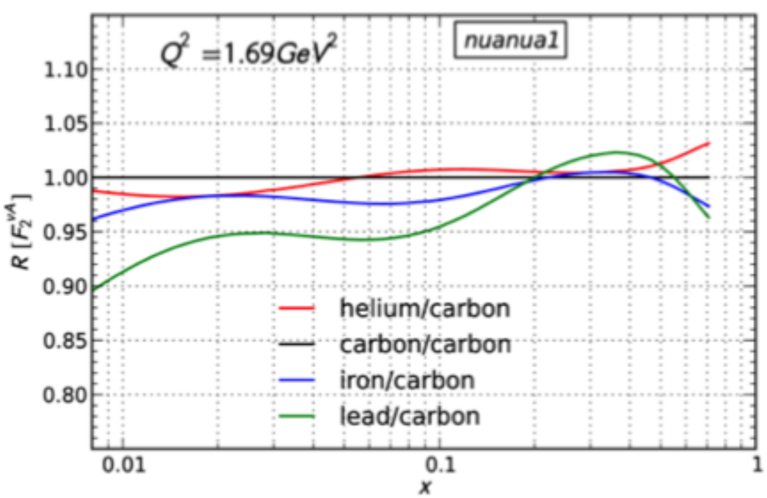


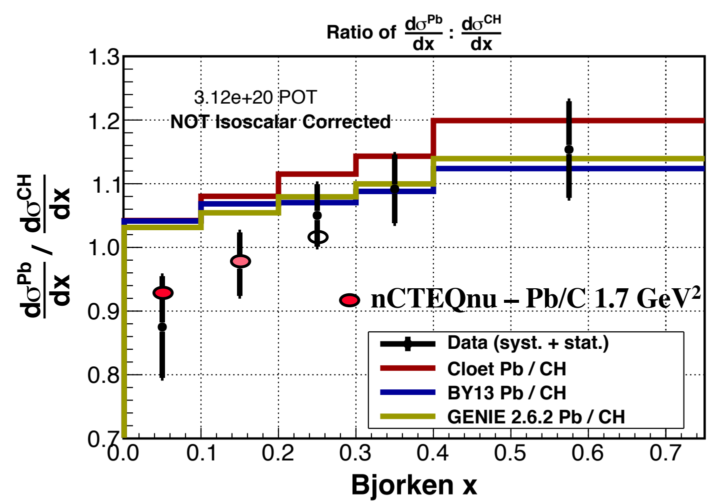




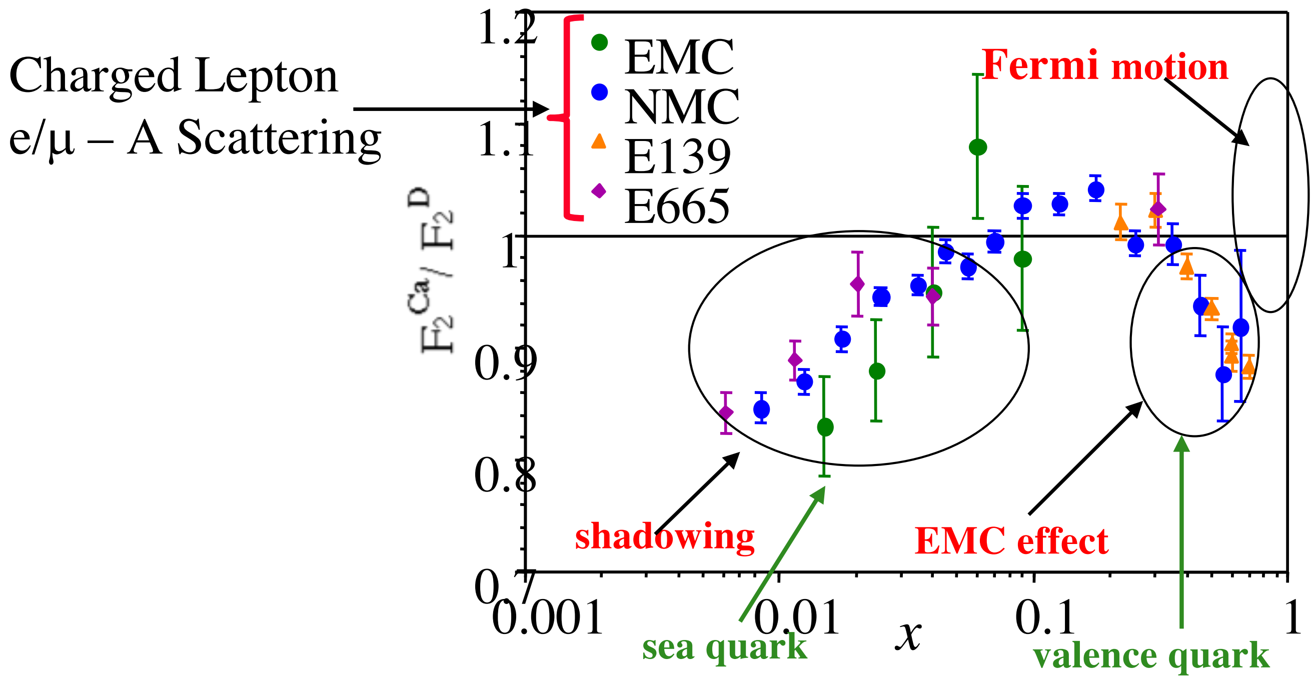
J. Mousseau

- The shape of the data at low x, especially with lead is consistent with nuclear shadowing **at <x> = (0.07)** - **where negligible shadowing is expected with e/μ Fe.**
- <u>**nCTEQ fixed low-Q^2 (1.7 GeV^2) points are shown as an example.**</u>





Can the **neutrino nuclear correction factors be <u>different</u>** than the charged lepton nuclear correction factor?



- **<u>Good reason to consider nuclear effects are DIFFERENT in ν - A</u>.**
  - Presence of axial-vector current. Different nuclear effects for valance and sea --> different shadowing for xF_3 compared to F_2.
- **<u>Models predicting a difference between ν A and e/μ A</u>**
  - S. Brodsky, I. Schmidt, J. Yang PRD 70 (2004) 116003
  - J. Qiu, I. Vitev PLB 587 (2004) 52
  - S. Kulagin, R. Petti PRD 76 (2007) 094023

Overall Summary and Conclusions

- **Need to carefully understand the concept of "quark-hadron duality" seemingly NOT exhibited by ν and $\bar{\nu}$ on nuclei in the same way as e and μ on nuclei! <u>Neutrino event generator assumed behavior in the SIS region uses this concept for verification.</u>**

- There are indications from experiments on Fe and Pb that ν and $\bar{\nu}$ – nuclear parton distributions **are different** than those determined by **e/μ – Fe/Pb** experiments. **Also found by Kumano's group and Jlab studies of F_2 in e-Fe compare to ν-Fe.**

- **Soon to be a higher energy, much reduced statistical and systematic error result for these neutrino nuclear correction factor ratios from the <u>MINERνA</u> ME beam DIS analysis.**

- Most clearly, different shadowing / antishadowing effects in **ν-A** compared to **e/μ–A → different nPDFs for ν-A** compared to **e/μ–A.**

No universal nPDFs??

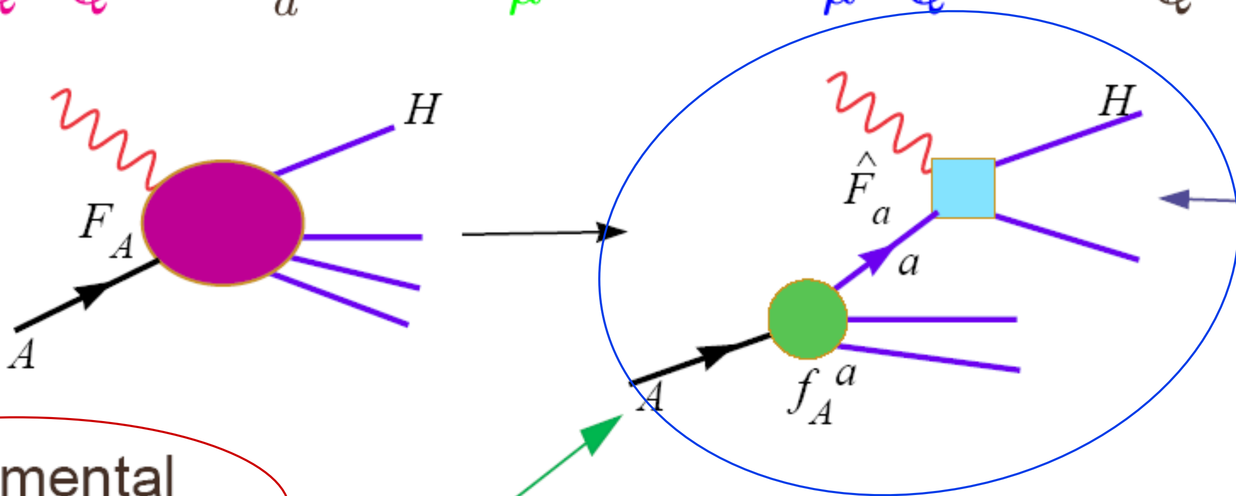
Global QCD Analysis in a Nutshell

Master Equation for QCD Parton Model – the Factorization Theorem

???

$$F_A^{\lambda}\left(x,\frac{m}{Q},\frac{M}{Q}\right)=\sum_a f_A^a\left(x,\frac{m}{\mu}\right)\otimes\widehat{F}_a^{\lambda}\left(x,\frac{Q}{\mu},\frac{M}{Q}\right)+\mathcal{O}\left(\left(\frac{\Lambda}{Q}\right)^2\right)$$

+ term for the nuclear environment?



Experimental Input

Theoretical Calculations

Hard Cross-section perturbative calculable (may contain $\alpha_s^n \mathrm{Log}^n(M/Q)$)

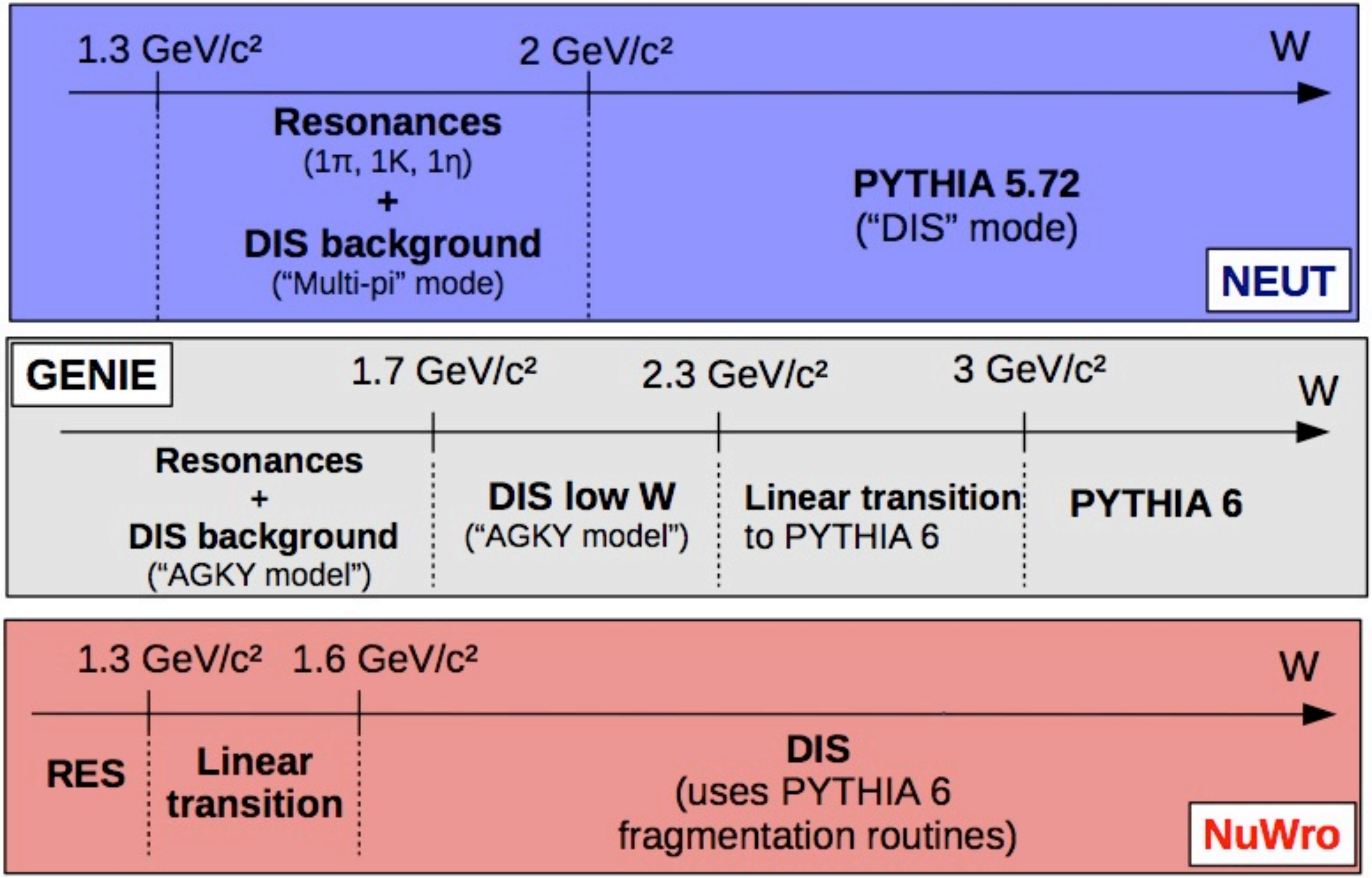
universal Parton Dist. Fn.
Non-Perturbative Parametrization at Q_0
GLAP Evolution to Q

extracted by applying global analysis methods

What do the concepts of “factorization” and “universal (nuclear) parton distributions” mean in the nuclear environment?

Additional Details

SIS/DIS Regions in Generators



Neutrino interactions in resonance region beyond $\Delta(1232)$ is much more difficult to understand than in $\Delta(1232)$ region

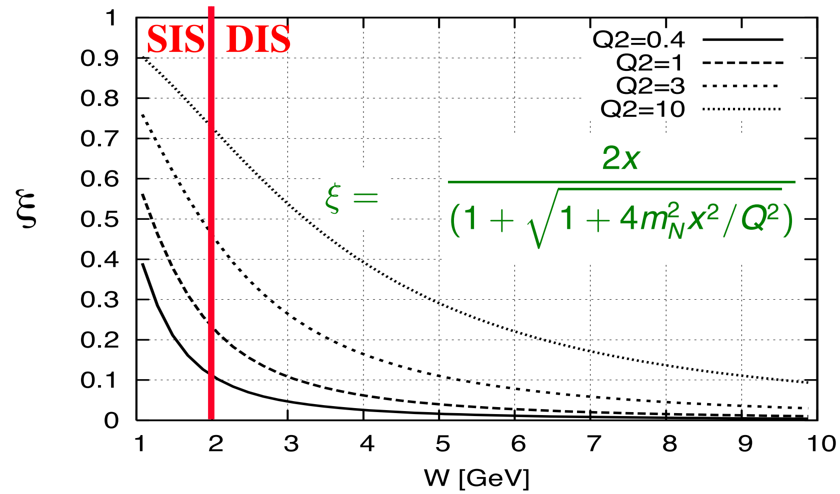
- Experimentally we are limited to the low-statistics & considerable systematics of early bubble chamber exposures from the 70's and 80's. **We need a modern high-statistics ν - H/D scattering experiment covering the SIS/DIS regions!**
- Theoretically: Predominantly use the Rein-Sehgal model from early 80's for this region. Modern take S. Nakamura, "Dynamical coupled-channels approach to Resonance Region beyond Δ(1232)"

	$\Delta(1232)$ region	Beyond $\Delta(1232)$ region ($W \lesssim 2$ GeV)
Resonance	$\Delta(1232)$ dominates No other resonances	No single resonance dominate Several comparable resonances overlap
Non-resonant	Much smaller than $\Delta(1232)$ ChPT works → well-controlled	Comparable to resonant contributions ChPT not work
Relative phases among mechanisms	(fairly) well-controlled	Crucially important but not easy to control
Coupled-channels	Only πN	πN and $\pi\pi N$ are comparable and strongly coupled ηN, $K\Lambda$, $K\Sigma$ channels are also coupled

Quantitative test of Q-H Duality: e Nucleon

- Ratio of the strength of the SIS to DIS region. Ideal Duality I = 1.0

$$\mathcal{I}_{|}(Q^2, Q^2_{DIS}) = \frac{\int_{\xi_{min}}^{\xi_{max}} d\xi F_j^{RES}(\xi, Q^2)}{\int_{\xi_{min}}^{\xi_{max}} d\xi F_j^{DIS}(\xi, Q^2_{DIS})}$$



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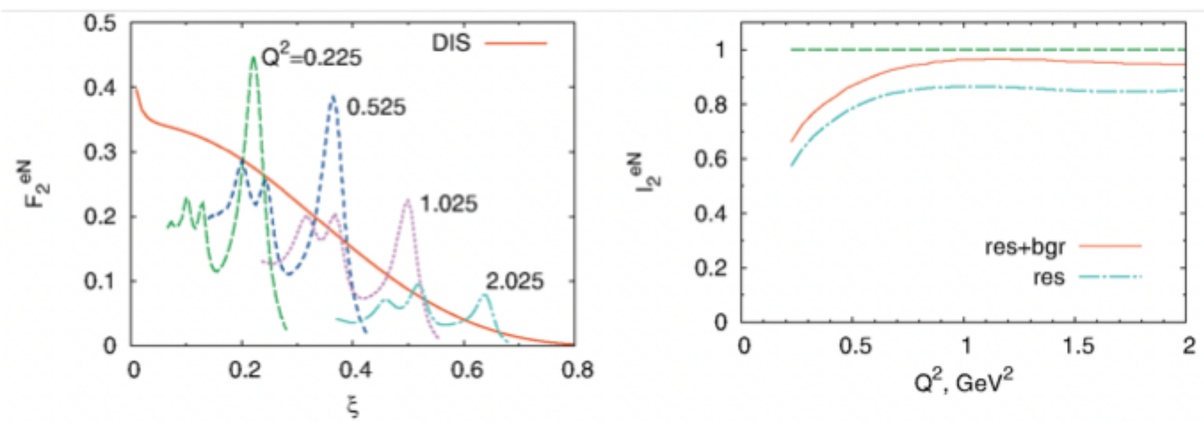


Duality with ν Fe Scattering

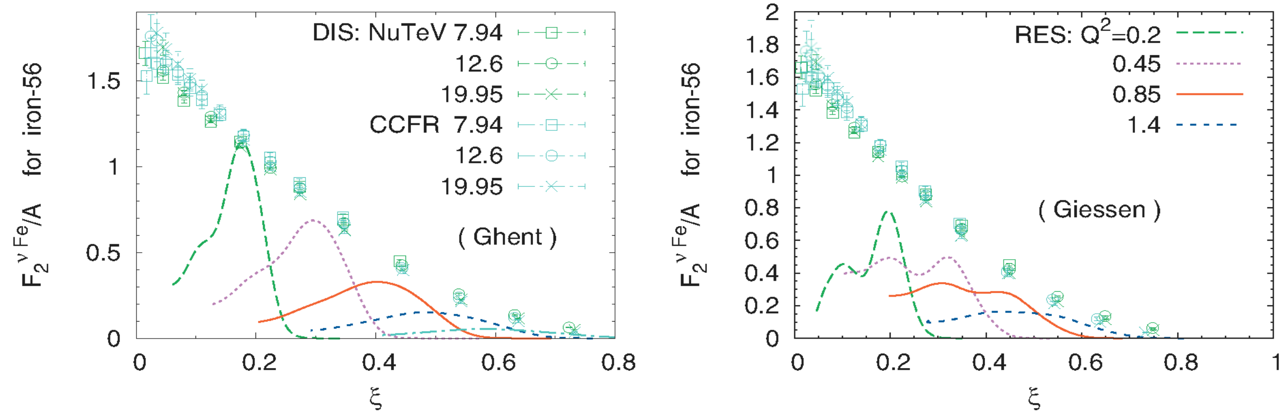
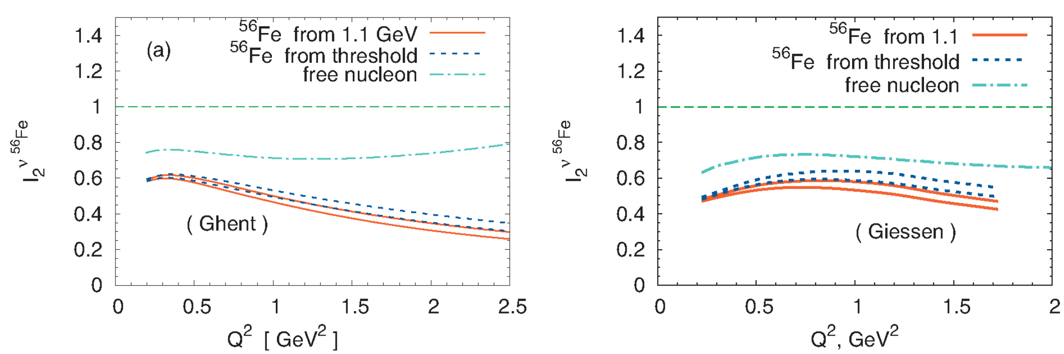


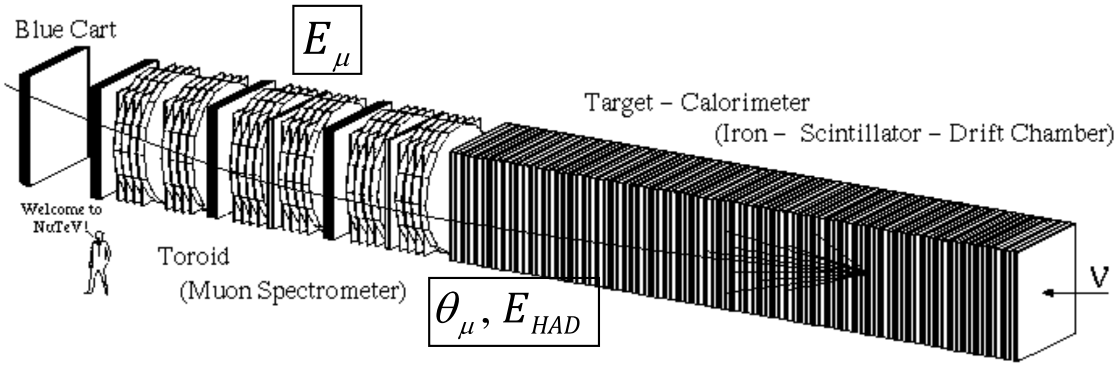
FIGURE 5. (color online) The computed resonance curves $F_2^{\nu\,^{56}Fe}/56$ as a function of ξ, calculated within Ghent(left) and Giessen (right) models for $Q^2 = 0.2, 0.45, 0.85,\ 1.4$, and 2.4 GeV^2. The calculations are compared with the DIS data from Refs. [26, 27]. The DIS data refer to measurements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

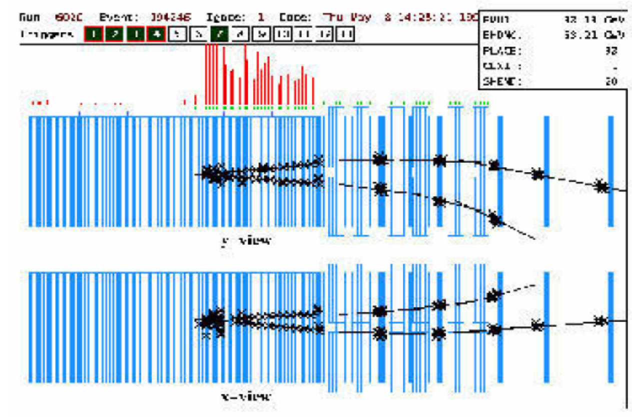


Neutrino DIS - The NuTeV Experiment: 800 GeV Protons

> 3 million neutrino/antineutrino events with $20 \leq E_\nu \leq 400$ GeV

Also CCFR, CDHSW and CHORUS Data sets – NuTeV smallest (correlated) errors!





Refurbished CCFR detector in a quite different neutrino beam

Target Calorimeter:

- Steel-Scintillator Sandwich (10 cm)

$$\frac{\delta E}{E} \approx \frac{0.86}{\sqrt{E}}$$ -resolution

- Tracking chambers for muon track and vertex

- Muon Spectrometer:

  Three toroidal iron magnets with five sets of drift chambers

$$\langle B_\varphi \rangle \approx 1.7T,\ p_t \approx 2.4 GeV/c$$

$$\delta(1/p)/(1/p) \sim 11\%$$ MCS dominated

- Always focusing for leading muon

1170 ν and 966 $\bar{\nu}$ data points with seven correlated systematic errors.

To confront leading systematic errors, there was a continuous calibration beam

nCTEQ: Determine the neutrino nuclear correction factors using Deep-Inelastic Scattering ($Q^2 > 1$ GeV^2 and $W > 2$ GeV)

Most "Recent" DIS Experiments

	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)	--	---	Finest-grained
CHORUS	10-200(27)	95-98	Pb	2%	5%	Fine-grained
MINERvA	2 – 50(6)	10-19	He, C, O, CH, Fe, Pb	2.1-3.2%		Finer-grained

MINERvA is not a "DIS experiment" but we are contributing to DIS studies.

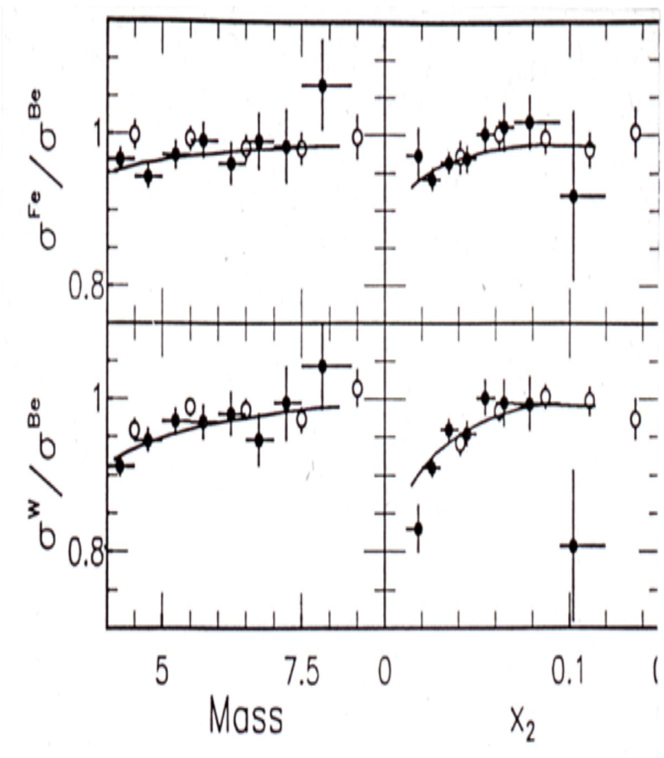
$$\frac{d^2\sigma^{\nu(\bar{\nu})A}}{dx\,dy} = \frac{G^2ME}{\pi}\left[\left(1-y-\frac{Mxy}{2E}\right)F_2^{\nu(\bar{\nu})A} + y^2 xF_1^{\nu(\bar{\nu})A} \pm y\left(1-\frac{y}{2}\right)xF_3^{\nu(\bar{\nu})A}\right]$$

Measured F_2 from neutrino experiments is really $<F_2>$ ($\nu + \bar{\nu}$)

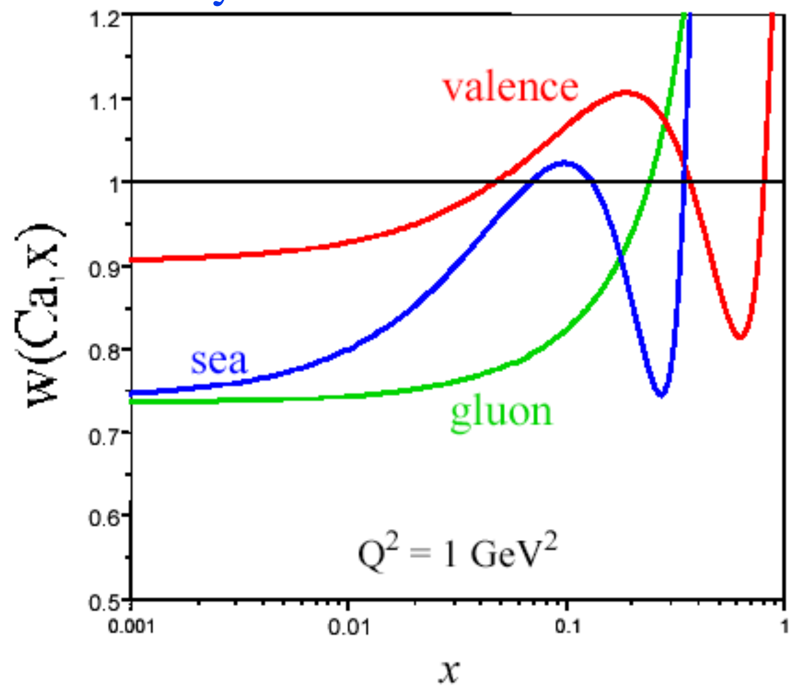
Nuclear Effects

A Difference in Nuclear Effects of Valence and Sea Quarks?

Drell-Yan



Maybe nPDFs looks like this?



- Nuclear effects similar in Drell-Yan and DIS for x < 0.1. Then no "anti-shadowing" in D-Y while "anti-shadowing" seen in DIS.