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

10 April 2019

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Outline

\[ W^2 = M^2 + Q^2 \left(1 - \frac{1}{x}\right) / x \] is the Effective Mass of the Hadronic System

- \( \nu \) Shallow Inelastic Scattering (SIS) - \( M_\Delta < W < 2.0 \) GeV
  - Higher \( W \) resonances
  - Duality
  - Non-perturbative / perturbative QCD Interface

- \( \nu \) Deep Inelastic Scattering – \( W > 2.0 \) GeV & \( Q^2 > 1 \) GeV\(^2\)
  - Nuclear Parton Distribution Functions (nPDFs): \( \nu + A \) vs. \( e/\mu + A \)
  - “universal PDFs” and factorization
By far the majority of contemporary studies in $\nu$-nucleus interactions have been of Quasielastic and $\Delta$ 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 $\nu$ on Fe – excluding QE.
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. \textit{\textcolor{red}{\textbf{\Large 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.
  - \textbf{\textcolor{red}{\textit{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? \textbf{\textcolor{red}{\textit{MINERvA starting the high-statistics experimental study of the following!}}}
  - Measure total and differential cross sections in the SIS region off \textbf{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 $\sigma$ 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 $\nu$-N scattering?

- There is essentially no high-statistics $\nu$-N/A experimental data with $1.4 < W < 2.0$ GEV for tests!
  - MINERvA is working to fix this for $\nu$-A!

- For now we rely on theoretical models of this region for an assessment of duality in $\nu$-A scattering.
What does Q-H Duality “Look Like” Experimentally?
Early Jefferson Lab 6 GeV e-Nucleon Study

The most general scaling variable includes target mass correction and finite quark mass:

\[ \xi_B = Q^2 + q Q^4 + m_N^2 \left( \frac{1}{2} + \frac{Q^2}{m_N^2} \right) \]

Barbieri, Ellis, Gaillard, Ross

Nachmann scaling variable:

\[ \xi = \lim_{m_q \to 0} \xi_B = \frac{2Q^2}{2m_N \nu} \left( 1 + \frac{m_N^2}{Q^2} \right) \]

Expanding \( \xi \) in powers of \( \frac{1}{Q^2} \) at high \( Q^2 \) gives the variable found empirically in 1970 by Bloom and Gilman and used in their pioneer work on duality.

\[ \xi \approx \frac{1}{1 + \frac{m_N^2}{Q^2}} \]

At very high \( Q^2 \), neglecting \( m_N^2/Q^2 \), we get

\[ \xi \approx 2 \left( 1 + \frac{m_N^2}{Q^2} \right) \]

So-called Nachtmann variable to account for Target Mass Effects.

\[ \xi = \frac{2x}{1 + \sqrt{1 + 4m_N^2x^2/Q^2}} \]
Quantitative test of Q-H Duality: e Nucleon

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

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

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

- 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 \( Q^2 = 10 \text{ GeV}^2 \). 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** \(1.2 < W^2 < 3.0 \text{ GeV}^2\) and \(Q^2 = 4 \text{ GeV}^2\). 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 $Q^2 > 1 \text{ GeV}^2$ and $x < 0.65$??

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!!

◆ In early CTEQ free nucleon PDF fits – *terrible tension* - at low-x when including ν/¯ν corrected with e/µ NCF. Had to ignore ν / ¯ν !!

◆ 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 +

- **F₂ Structure Functions from NuTeV (ν Fe) and CHORUS (ν Pb) each compared to CCFR (ν Fe) and CDHSW (ν Fe)**
Comparison of NuTeV with Global Fits for $F_2$

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

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

- 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 $\nu$ and $\overline{\nu}$ independent?
Nuclear Parton Distribution Functions from $\nu$ DIS
(nCTEQ Global Fit to Neutrino Data)

◆ 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: $\nu Fe$, $\bar{\nu} Fe$
▼ NuTeV dimuon off Fe data: $\nu$ & $\bar{\nu}$
▼ CHORUS cross section data: $\nu Pb$, $\bar{\nu} Pb$
▼ CCFR dimuon off Fe data: $\nu$ & $\bar{\nu}$

◆ Directly determine Nuclear Correction Factors for $\nu$ & $\bar{\nu}$
Nuclear Correction Factors: $\nu$ and $\bar{\nu} - \frac{F_2(\nu \text{Fe})}{F_2[\nu(n+p)]}$

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

Could NOT find a compromise ($\chi^2$ with tolerance) fit with both $\nu$ and e/\(\mu\) 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 $\nu$ Fe compared directly to $e$ Fe. 15% effect.
We Now Have A New DIS Player - What does MINERvA see?
Reminder from NuTeV: The $Q^2$ distribution within an x bin is essential!
An nCTEQ low-$Q^2$ Prediction for MINERvA
What does MINERvA see? LE DIS Cross Section Ratios – dσ/dx. Much improved ME beam ratios soon to be released!

The Q² distribution within an x bin is essential!

- 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.

- nCTEQ fixed low-\( Q^2 \) (1.7 GeV²) points are shown as an example.
Can the **neutrino nuclear correction factors** be different than the charged lepton nuclear correction factor?

**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 for xF_3 compared to F_2.

**Models predicting a difference between ν A and e/μ A**

- J. Qiu, I. Vitev PLB 587 (2004) 52
Overall Summary and Conclusions

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

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

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

* Most clearly, different shadowing / antishadowing effects in $\nu$-A compared to $e/\mu$–A $\rightarrow$ different nPDFs for $\nu$-A compared to $e/\mu$–A. No universal nPDFs??
What do the concepts of “factorization” and “universal (nuclear) parton distributions” mean in the nuclear environment?
Additional Details
SIS/DIS Regions in Generators

- **GENIE**
  - 1.7 GeV/c²: Resonances + DIS background ("AGKY model")
  - 2.3 GeV/c²: DIS low W ("AGKY model")
  - 3 GeV/c²: Linear transition to PYTHIA 6

- **Pythia 5.72**
  - "DIS" mode

- **NuWro**
  - 1.3 GeV/c²: RES
  - Linear transition
  - DIS (uses PYTHIA 6 fragmentation routines)
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 $\nu$ - 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 $\Delta(1232)$”

<table>
<thead>
<tr>
<th>Resonance</th>
<th>$\Delta(1232)$ dominates</th>
<th>No single resonance dominate</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>No other resonances</td>
<td>Several comparable resonances overlap</td>
</tr>
</tbody>
</table>

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<tr>
<th>Non-resonant</th>
<th>Much smaller than $\Delta(1232)$</th>
<th>Comparable to resonant contributions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ChPT works $\Rightarrow$ well-controlled</td>
<td>ChPT not work</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Relative phases among mechanisms</th>
<th>(fairly) well-controlled</th>
<th>Crucially important but not easy to control</th>
</tr>
</thead>
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<thead>
<tr>
<th>Coupled-channels</th>
<th>Only $\pi N$</th>
<th>$\pi N$ and $\pi\pi N$ are comparable and strongly coupled</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\eta N$, $K\Lambda$, $K\Sigma$ channels are also coupled</td>
</tr>
</tbody>
</table>
Quantitative test of Q-H Duality: e Nucleon

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

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

- 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 $I(Q^2)$. 

![Graph showing the ratio of strength and scaling variable](image)
Duality with $\nu$ Fe Scattering

**FIGURE 5.** (color online) The computed resonance curves $F_2^{^{56}\text{Fe}}/A$ as a function of $\xi$, 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$^2$. 

- **DIS: NuTeV**
- **CCFR**
- **RES: $Q^2$**
  - 0.2
  - 0.45
  - 0.85
  - 1.4
- **(Ghent)**
- **(Giessen)**

![Graph showing resonance curves and DIS data comparison](image)

**Notes:**
- **Resonances** are included in the calculations.
- **Fe Scattering** elementar.
- **T磁场**

**Referenced Data**
- **Ref**
- **E, E**
- **Recall**
- **Duality**
- **Resonances**
- **Free nucleon**
- **Ghent**
- **Giessen**
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!

Target Calorimeter:
- Steel-Scintillator Sandwich (10 cm)
  $$\frac{\delta E}{E} \approx 0.86 \sqrt{E}$$ -resolution
- Tracking chambers for muon track and vertex

Muon Spectrometer:
- Three toroidal iron magnets with five sets of drift chambers
  $$\langle B_\varphi \rangle \approx 1.7 T, \ p_t \approx 2.4 GeV / c$$
  $$\delta(1/ p)/(1/ p) \sim 11\%$$ MCS dominated
- Always focusing for leading muon

1170 $\nu$ 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 \((Q^2 > 1 \text{ GeV}^2 \text{ and } W > 2 \text{ GeV})\)

Most “Recent” DIS Experiments

<table>
<thead>
<tr>
<th></th>
<th>(E_\nu) range (&lt; (E_\nu)&gt;)(GeV)</th>
<th>Run</th>
<th>Target A</th>
<th>(E_\mu) scale</th>
<th>(E_{\text{HAD}}) scale</th>
<th>Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>NuTeV CCFR</td>
<td>30-360(120)</td>
<td>96-97</td>
<td>Fe</td>
<td>0.7%</td>
<td>0.43%</td>
<td>Coarse</td>
</tr>
<tr>
<td>NOMAD</td>
<td>10-200(27)</td>
<td>95-98</td>
<td>Various (mainly C)</td>
<td>--</td>
<td>--</td>
<td>Finest-grained</td>
</tr>
<tr>
<td>CHORUS</td>
<td>10-200(27)</td>
<td>95-98</td>
<td>Pb</td>
<td>2%</td>
<td>5%</td>
<td>Fine-grained</td>
</tr>
<tr>
<td>MINERvA</td>
<td>2 – 50(6)</td>
<td>10-19</td>
<td>He, C, O, CH, Fe, Pb</td>
<td>2.1-3.2%</td>
<td></td>
<td>Finer-grained</td>
</tr>
</tbody>
</table>

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

\[
\frac{d^2\sigma^{\nu(\bar{\nu})A}}{dx\,dy} = \frac{G^2ME}{\pi} \left[ (1-y-\frac{Mxy}{2E})F_2^{\nu(\bar{\nu})A} + y^2xF_1^{\nu(\bar{\nu})A} \pm y\left(1-\frac{y}{2}\right)x F_3^{\nu(\bar{\nu})A} \right]
\]

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?

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.