Neutrino – Nucleus Scattering Physics with nuSTORM

What can a dedicated nuSTORM neutrino-nucleus scattering physics program deliver?

Jorge G. Morfín

nuSTORM Workshop
Virginia Tech
April, 2013
The nuSTORM Neutrino Beam

\[ \mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+ \quad \mu^- \rightarrow \nu_\mu + \bar{\nu}_e + e^- \]

- The νSTORM beam will provide a very well-known \( (\delta \phi(E) \leq 1\%) \) beam of ν and \( \bar{\nu} \).

- A high-intensity source of ν\(_e\) events for experiments.

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3.8 GeV \( \mu^+ \) stored, 150m straight, flux at 100m

Event rates per 1E21 POT -

100 tons at 50m

<table>
<thead>
<tr>
<th>Channel</th>
<th>( N_{evts} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \bar{\nu}_\mu ) NC</td>
<td>844,793</td>
</tr>
<tr>
<td>( \nu_e ) NC</td>
<td>1,387,698</td>
</tr>
<tr>
<td>( \bar{\nu}_\mu ) CC</td>
<td>2,145,632</td>
</tr>
<tr>
<td>( \nu_e ) CC</td>
<td>3,960,421</td>
</tr>
<tr>
<td>( \nu_\mu ) NC</td>
<td>709,576</td>
</tr>
<tr>
<td>( \nu_e ) CC</td>
<td>1,584,003</td>
</tr>
<tr>
<td>( \nu_\mu ) CC</td>
<td>1,784,099</td>
</tr>
<tr>
<td>( \nu_\mu ) CC</td>
<td>4,626,480</td>
</tr>
</tbody>
</table>

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νₑ Event Fractions in a νSTORM Near Detector

- νₑ produced by 3.8 GeV µ⁺ beam.

For νₑ sample, 52% resonant, 40% QE, 8% DIS.

out of the CC modes:

* 56% resonant
* 32% QE
* 12% DIS

For νₑ sample, 52% resonant, 40% QE, 8% DIS.)
The events we observe in our detectors are convolutions of:

\[ Y_{c\text{-like}} (E) \alpha \phi(E' \geq E) \bigotimes \sigma_{c,d,e..}(E' \geq E) \bigotimes \text{Nuc}_{c,d,e..} \rightarrow_c (E' \geq E) \]

\( Y_{c\text{-like}} (E) \) is the event energy and channel / topology of the event observed in the detector. It is called c-like since it appears to be channel c but may not have been channel c at interaction. The errors on the three components create a nasty, oozy morass!

nuSTORM takes one of these convoluted components \( \phi(E' \geq E) \) essentially out of the equation: a very well-known \( (\delta \phi(E) \approx 1\%) \) beam of \( \nu \) and \( \overline{\nu} \).

How well can nuSTORM help unravel the convolution of:

\[ \sigma_{c,d,e..}(E' \geq E) \times \text{Nuc}_{c,d,e..} \rightarrow_c (E' \geq E) \]
Neutrino Nucleus Scattering
What do we observe in our detectors?

- The events we observe in our detectors are convolutions of:
  \[ Y_{c\text{-like}}(E) \propto \phi(E' \geq E) \times \sigma_{c,d,e..}(E' \geq E) \times \text{Nuc}_{c,d,e.. \rightarrow c}(E' \geq E) \]

- \( \sigma_{c,d,e..}(E' \geq E) \) is the measured or the Monte Carlo (model) energy dependent neutrino cross section off a nucleon within a nucleus.

- Form factors are modified within a nucleus compared to a nucleon. Analogous to the difference between PDFs and nuclear nPDFs.

- \( \text{Nuc}_{c,d,e.. \rightarrow c}(E' \geq E) \) – Nuclear Effects
  - **Nuclear Effects** – a migration matrix that mixes produced/observed channels and energy
  - In general the interaction of a neutrino with energy \( E' \) creating initial channel d,e… can appear in our detector as energy \( E \) and channel c.
  - Particularly **fierce bias** when using the QE hypothesis to calculate \( E \) and \( Q^2 \)!
What are these Nuclear Effects $\text{Nuc}_{c,d,e..} \rightarrow c (E' \geq E)$ in Neutrino Nucleus Interactions? (Partial List)

- Target nucleon in motion – classical Fermi gas model or the superior spectral functions (Benhar et al.)

- Multi-nucleon initial states: Short-range correlations, meson exchange currents.

- Form factors, structure functions, resonance widths, parton distribution functions and, consequently, cross sections are modified within the nuclear environment. (Butkevich / Kulagin, Tsushima et al., Kovarik et al.)

- Produced topologies are modified by final-state interactions modifying topologies and possibly reducing detected energy and increasing wrong-sign background. 
  ▼ Convolution of $\delta\sigma(n\pi) \times$ formation zone uncertainties $\times$ $\pi$-charge-exchange/absorption probabilities and nuclear density uncertainties.

- Systematics associated with each of these effects.
  - Monte Carlos – like GENIE – try to include all these effects. 
    GENIE needs improvements! GENIE group needs additional help from the community.

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How well off are we with $\nu_\mu$ Cross sections: Range of Existing Model (MC) Predictions off C

NuInt09 – Steve Dytman
Example Model Uncertainties

### Cross Section Model Uncertainties

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>1 σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_A$ (Elastic Scattering)</td>
<td>± 25%</td>
</tr>
<tr>
<td>$F_{1A}$ (Elastic scattering)</td>
<td>± 30%</td>
</tr>
<tr>
<td>$M_A$ (CCQE Scattering)</td>
<td>+25% -15%</td>
</tr>
<tr>
<td>CCQE Normalization</td>
<td>± 20%</td>
</tr>
<tr>
<td>CCQE Vector Form factor model</td>
<td>± 15%</td>
</tr>
<tr>
<td>CC Resonance Normalization</td>
<td>± 20%</td>
</tr>
<tr>
<td>$M_A$ (Resonance Production)</td>
<td>± 20%</td>
</tr>
<tr>
<td>$M_V$ (Resonance Production)</td>
<td>± 10%</td>
</tr>
<tr>
<td>1π production from $V_p$/$V_R$ non-resonant interactions</td>
<td>± 50%</td>
</tr>
<tr>
<td>1π production from $V_n$/$V_p$ non-resonant interactions</td>
<td>± 50%</td>
</tr>
<tr>
<td>2π production from $V_p$/$V_R$ non-resonant interactions</td>
<td>± 50%</td>
</tr>
<tr>
<td>2π production from $V_n$/$V_p$ non-resonant interactions</td>
<td>± 50%</td>
</tr>
<tr>
<td>Mobility Factor blocking (CCQE+) at low $Q^2$ (change PB momentum threshold)</td>
<td>± 30%</td>
</tr>
</tbody>
</table>

### Intranuclear Rescattering Uncertainties

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>1 σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pion mean free path</td>
<td>± 20%</td>
</tr>
<tr>
<td>Nucleon mean free path</td>
<td>± 20%</td>
</tr>
<tr>
<td>Pion fates - absorption</td>
<td>± 30%</td>
</tr>
<tr>
<td>Pion fates - charge exchange</td>
<td>± 50%</td>
</tr>
<tr>
<td>Pion fates - Elastic</td>
<td>± 10%</td>
</tr>
<tr>
<td>Pion fates - Inelastic</td>
<td>± 40%</td>
</tr>
<tr>
<td>Pion fates - pion production</td>
<td>± 20%</td>
</tr>
<tr>
<td>Nucleon fates - charge exchange</td>
<td>± 50%</td>
</tr>
<tr>
<td>Nucleon fates - Elastic</td>
<td>± 30%</td>
</tr>
<tr>
<td>Nucleon fates - Inelastic</td>
<td>± 40%</td>
</tr>
<tr>
<td>Nucleon fates - absorption</td>
<td>± 20%</td>
</tr>
<tr>
<td>Nucleon fates - pion production</td>
<td>± 20%</td>
</tr>
<tr>
<td>AGKY hadronization model - $x_F$ distribution</td>
<td>± 20%</td>
</tr>
<tr>
<td>Delta decay angular distribution</td>
<td>On/off</td>
</tr>
<tr>
<td>Resonance decay branching ratio to photon</td>
<td>± 50%</td>
</tr>
</tbody>
</table>

What do we observe in our detectors?

- The events we observe in our detectors are convolutions of:
  \[ Y_{c\text{-like}}(E) \alpha \phi(E' \geq E) \bigotimes \sigma_{c,d,e..}(E' \geq E) \bigotimes \text{Nuc}_{c,d,e..} \rightarrow_c (E' \geq E) \]

- Experimentally, the last two terms convoluting the initial nucleon (within a nucleus) cross section and nuclear effects are combined into an effective cross section \( \sigma_c^A(E) \).

- Note that the effective cross section \( \sigma_c^A(E) \) measured depends on the incoming neutrino energy spectrum and the involved nuclear effects that populate the yield \( Y_c^A(E) \).

- This implies that, for example, the effective \( \sigma_{\pi^+}^C(1 \text{ GeV}) \) measured in the MiniBooNE Booster beam will be different than the same effective \( \sigma_{\pi^+}^C(1 \text{ GeV}) \) observed by MINERvA in the higher energy NuMI beam due to, for example, more feed down from multi-pi events via pion absorption in the NuMI beam.

What is a “standard candle” in neutrino-nucleus scattering?
Significant Implications for Oscillation Experiments

- Can not simply plug in effective $\sigma^A_{\pi}$ from experiments using a different beam.

- In a two-detector oscillation experiment the neutrino flux entering the far detector is different than the neutrino flux at the near detector due to source geometry and oscillations.

- The $\sigma^A_c(E)$ effective that should be applied to expectations (Monte Carlo) at the far detector is NOT the same as that which we would measure at the near detector. However, the near detector results give us an excellent starting point for calculating the difference.

- Particular problems using the QE hypothesis for calculating $E$ and $Q^2$

- The convoluted $\phi(E' \geq E) \times \sigma(E) \times \text{Nuc}(E' \geq E)$ systematics need to be correctly incorporated in determining the systematics of oscillation parameter measurements.
How well do we know cross sections: $\nu_e$ vs. $\nu_\mu$?

Definite advantage of nuSTORM

- The events we observe in our detectors are convolutions of:
  $$ Y_{c\text{-like}}(E) \propto \phi(E' \geq E) \times \sigma_{c,d,e..}(E' \geq E) \times Nuc_{c,d,e..} \rightarrow E' \geq E $$

- When the three terms are for $\nu_\mu$ then we have experiments currently measuring these cross sections on relevant nuclear targets but with limited knowledge of the incoming flux and with good but not outstanding resolution detectors. Will review shortly.

- When the terms are for $\nu_e$ then we have no higher energy experimental measurements of these cross sections.

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What do we know about $\sigma_{\nu_e}(E)$? Mostly very low energy results.

- Reactor neutrinos studying Inverse Beta Decay
- Solar neutrino off deuterium (SNO)
- Stopping $\pi/\mu$ decay neutrinos off higher $A$ targets

One of few measurements of spectral shape of $\sigma$ reflects the upper limit of most existing measurements, $E \leq 50$ MeV.

$\nu_e^{12}\text{C} \rightarrow e^-^{12}\text{N}_{\text{g.s.}}$

NO WHERE! Need to measure the $\sigma_{\nu\text{e}}(E)$ of multiple channels to fully predict a spectrum at a far detector for LBL experiments.

We infer them from $\sigma_{\nu\mu}(E)$ results. The validity of this inference directly impacts the uncertainty of the measurements.
What are the Differences $\sigma_{\nu\mu}(E)$ and $\sigma_{\nu e}(E)$?

**Quasi-elastic Scattering**


- QE scattering dominates at low energies (2nd oscillation maxima)
- Sources of possible differences and uncertainties - obvious:
  - Kinematic limits from $\mu / e$ mass difference.
  - Radiative Corrections. **This may be overestimated. Need full calculation.**

\[ (\sigma_{\mu e} - \sigma_{e e}) / \sigma_{e e} \]
Paschos-Schalla predicts the following differences in cross sections where only the lepton mass term contributions are shown and any differences in form factors are not yet included.

We need to measure these $\nu_e$ cross sections. nuSTORM should do it.
Illuminate Potential nuSTORM Contributions via a $\nu_\mu$ Channel-by-Channel Survey:
The (published) situation today

- ~30% difference between low and high energy QE measurements

- MB QE $\sigma$ normalization can be matched by increasing $M_A$ … or adding np-nh effects.

- These np-nh effects have been known for a decade (NuInt01)
A Sample of Recent Measurements

- several experiments fit QE data (often excluding problematic low $Q^2$)
- most favor $M_A > 1.0$ GeV,
- In contrast to early BC experimental results: $M_A = 1.016 \pm 0.026$ GeV
- Also $M_{Aep}= 1.069 \pm 0.016$ GeV = 1.014 after corrections at low $Q^2$

- The one exception is the higher $E_\nu$

NOMAD data with low $M_A$.

(J. Sobczyk, NuInt11)
**Quasi-elastic Scattering: History**

- **problem of low $Q^2$**
  - $\kappa$ parameter (MiniBooNE); RPA modeling of CC $\pi$ backgrounds which contribute at low $Q^2$

- **problem of axial mass**

- **problem of np-nh (multi-nucleon targets - more complex nuclear effects: SRC + MEC**
QE History

**Very important for nuSTORM**

- problem of low $Q^2$

- problem of axial mass

- problem of np-nh
  (more complex nuclear effects: SRC + MEC)

- $M_A$ provides a convenient tool to describe exp. data in shape & normalization with Fermi Gas

  Have they got the flux wrong? nuSTORM could tell us? Distinction between Fermi Gas and Spectral Functions? With accurate $d\phi / dE$ – maybe nuSTORM could help.

- However there is an alternative path involving a more sophisticated nuclear models. MEC implies extra tracks and energy at vertex, nuSTORM could help. **Time to retire impulse approximation with RFG!**
Have these experiments really measured $M_A$?

- Just as we have noted, we are observing an effective $\sigma_c^A(E)$ in our detectors…
  - What has been measured is a parameter $M_a^{\text{eff}}$.
  - It depends on the use of RFGM or Spectral Functions.
  - It depends on the nucleus used and…
  - It depends on the incoming flux.
  - It also depends on number of initial nucleons involved.

- Need nuSTORM with its accurate flux and series of nuclear targets with high-resolution detector(s).

- Also need at least a good model for pion production which, through FSI, is the main background for QE.

- (QE) measurements calculating $E$ and $Q^2$ via the muon are in trouble!
Nuclear Effects can Change the Energy Reconstruction for “QE” Events

- In pure QE scattering on nucleon at rest, the outgoing lepton can determine the neutrino energy:

\[ E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos \theta_\mu)} \]

However, not on nuclei. Reco. energy shifted to lower values for all processes other than true QE off nucleon at rest. Can nuSTORM with excellent (\(\delta\phi(E) \approx 1\%\)) and a precision detector use measured final hadron state?

\[ E_\nu (\text{GeV}) \]

\[ \text{flux} \times \sigma_{\text{target}}/c \text{GeV}^{-1} \text{cm}^{-2} \text{sr}^{-1} \text{GeV}^{-1} \]

U. Mosel GiBUU

Jorge G. Morfín - Fermilab
Nuclear Effects and Oscillation Measurements

Ulrich Mosel using his Giessen Boltzmann-Uehling-Uhlenbeck (GiBUU) Transport Model looking at T2K
Differences between $\nu_e$ or $\nu_\mu$. Mainly QE Scattering
Meson-exchange Current Contributions – Marco Martini

- Hadronic part (nuclear response functions) is the same for $\nu_e$ or $\nu_\mu$ cross section.
- However, the lepton tensor changes → the relative weight of the nuclear responses in the several channels may change.
- The double ratio suggests the effect on the $\nu_e/\nu_\mu$ cross section ratio is $\leq 5\%$
- Can nuSTORM measure this difference $\nu_e$ vs. $\nu_\mu$
Pion Production
Some Recent Theoretical Work

- $\pi$ production in GiBUU (O. Lalakulich, Mosel)

- low $Q^2$ PCAC based pion production model (Paschos, Schalla)

- N-$\Delta$ weak transition (K. Gradzyk)

- dynamical models of $\pi$ production (S. Nakamura)

- also, strange particle production (S. Athar)
Pion Production

• there has been a steady stream of pion measurements that have been published over the years:

- K2K: NC $1\pi^0$/CC ratio (2005)
- K2K: CC coherent $\pi^+/CC$ ratio (2005)
- K2K: CC $\pi^+/QE$ ratio (2008)
- SciBooNE: CC coherent $\pi^+/CC$ ratio (2008)
- MiniBooNE: NC coherent $\pi^0$ fraction (2008)
- SciBooNE: NC $\pi^0$/CC ratio (2009)
- NOMAD: NC coherent $\pi^0$ (2009)
- MiniBooNE: CC $\pi^+/QE$ ratio (2009)
- SciBooNE: NC coherent $\pi^0$/CC ratio (2010)
- K2K: CC $\pi^0$/CC (2010)
- MiniBooNE: NC $\pi^0$ (2010)
- MiniBooNE: CC $\pi^0$ (2011)
- MiniBooNE: CC $\pi^+$ (2011)
Pion Production Challenges

- State of the art calculations describe better the data without FSI
NC $\pi^0$ Production

- what about FSI?

- Need to measure $M_a^{\text{res}}$ as well. Very poorly measured and needed to constrain $C_5^A$.

- suggestion of np-nh effects

possible origins:
- elementary cross section too small
- neutrino-flux prediction (cf. discrepancy in QE channel)
- “data” contains “MC”: model dependence

(U. Mosel, NuInt11)
Coherent $\pi$ Production Puzzle

- do we see this process or not? NC/CC differences

| $\nu$ NC coherent $\pi^0$ | $\nu$ CC coherent $\pi^+$
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>• K2K</td>
<td>• K2K $\nu$</td>
</tr>
<tr>
<td>• MiniBooNE</td>
<td>• SciBooNE $\nu$</td>
</tr>
<tr>
<td>• NOMAD</td>
<td>• SciBooNE $\bar{\nu}$</td>
</tr>
<tr>
<td>• SciBooNE</td>
<td>• MINOS (D. Cherdak, new!)</td>
</tr>
</tbody>
</table>

all see some level of non-zero NC coherent $\pi^0$

<table>
<thead>
<tr>
<th>$\bar{\nu}$ CC coherent $\pi^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>• no evidence</td>
</tr>
<tr>
<td>• set limits</td>
</tr>
</tbody>
</table>

- indication of signal via angle cuts.

- Very strange experimental ratio of NC coherent to CC Coherent pion production.
Total CC Inclusive

• 1\textsuperscript{st} measurement of CC inclusive $\sigma$ on $^{12}\text{C}$ at low energy from SciBooNE

• important because measures combination of:
  + QE
  + np-nh
  + $\Delta, N^* \rightarrow \pi$
  + $\Delta, N^* \rightarrow 1\pi, \text{multi-}\pi$
  + DIS …

(Y. Nakajima, \textit{NuInt11})
Total CC Inclusive

- provides an important **starting point** (before get to exclusive modes)
- already being used by theorists …

Next steps:

- \( \frac{d^2\sigma}{dT_\mu d\theta_\mu} \)
- A dependence
  (how evolves with nuclear target)

Nieves et al., arXiv:1102.2777

(L. Alvarez-Ruso, **NuInt11**)
ν DIS – skip for now

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

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

\[ y = \frac{\nu}{E_\nu} = \frac{E_{HAD}}{E_\nu}, \quad \text{Inelasticity} \]

Differential cross section in terms of structure functions:

\[
\frac{1}{E_\nu} \frac{d^2 \sigma^{\nu(\bar{\nu})}}{dx dy} = \frac{G_F^2 M}{\pi \left(1 + Q^2 / M_W^2 \right)} \left[ \left(1 - y - \frac{Mxy}{2E_\nu} + \frac{y^2}{2} \frac{1 + 4M^2x^2/Q^2}{1 + R(x,Q^2)} \right) F_2^{\nu(\bar{\nu})} \pm \left(y - \frac{y^2}{2} \right) xF_3^{\nu(\bar{\nu})} \right]
\]

Structure Functions in terms of parton distributions (for ν-scattering)

\[
F_2^{\nu(\bar{\nu})N} = \sum \left[ xq^{\nu(\bar{\nu})N}(x) + \bar{xq}^{\nu(\bar{\nu})N}(x) + 2xk^{\nu(\bar{\nu})N}(x) \right]
\]

\[
xF_3^{\nu(\bar{\nu})N} = \sum \left[ xq^{\nu(\bar{\nu})N}(x) - xq^{\nu(\bar{\nu})N}(x) \right] = x(d_\nu(x) + u_\nu(x)) \pm 2x(s(x) - c(x))
\]

\[ R = \frac{\sigma_L}{\sigma_T} \]

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What could a nuSTORM Scattering analysis add?

Provide significant input to knowledge of electro-weak physics.

- Use the unique qualities of the nuSTORM beam meaning the flux of $\nu_e$ and the fantastic knowledge of absolute and relative flux.
- Need an experiment that has a track sensitive H and D target (bubble chamber) upstream of a high-resolution near detector with multiple nuclear targets to provide detailed studies of the final states including the vertex (multiplicities and energy flow).
- nuSTORM, providing a beam with a large sample of $\nu_e$ events and knowledge of the flux to $\leq 1\%$, to such a suite of near detectors would provide an outstanding neutrino-nucleus scattering experiment addressing both electroweak and nuclear physics questions.
- Need theorists to extend the energy range of np-nh calculations.
- Need Monte Carlo masters to keep the generators updated with most recent ideas and results.
νSTORM Near Detectors

HighRes -
High Resolution Straw-tube Magnetized Detector
Presented by Sanjib Mishra

- A 1-2 ton fiducial liquid hydrogen/deuterium track sensitive target upstream of HiRes for normalization. This could be a bubble chamber.
Conclusions: What does nuSTORM bring to Neutrino-nucleus Interaction Physics?

- Obvious benefit in measuring $\nu_e$ events
- Goal is to make maximum use of vastly improved nuSTORM neutrino flux (absolute and energy dependence).
- There are many physics topics that will be awaiting the precision of a high-resolution detector in the accurate nuSTORM flux to give us the results we need!
- However, this is no longer the $260\mathrm{M}$ nuSTORM. Add $70\mathrm{M}$ for Hi Res, add $\approx 70\mathrm{M}$ more for H/D Bubble Chamber.

- Need a muon-sourced, neutrino interaction workshop in the Fall leading to an independent collaboration for nuSTORM facility?
**F₂ and xF₃ Measurement**

\[ F_2 \]
\[
\left[ \frac{d^2 \sigma}{dx \, dy} \right] \frac{\pi}{G_F^2 M E} = 2 \bar{F}_2 \left( 1 - y - \frac{M_{xy}}{2E} + \frac{y^2}{2} \frac{1 + 4 M^2 x^2/Q^2}{1 + R} \right) + y \left( 1 - \frac{y}{2} \right) \Delta xF_3
\]

\[ xF_3 \]
\[
\left[ \frac{d^2 \sigma}{dx \, dy} \right] \frac{\pi}{G_F^2 M E} = \Delta F_2 \left( 1 - y - \frac{M_{xy}}{2E} + \frac{y^2}{2} \frac{1 + 4 M^2 x^2/Q^2}{1 + R} \right) + 2 y \left( 1 - \frac{y}{2} \right) x\bar{F}_3
\]

- Perform 1-parameter fit for F₂
- ΔxF₃ model
- R_L model

- Perform 1-parameter fit for xF₃
- ΔF₂ is very small and is neglected

- Radiative corrections applied
- Isoscalar correction applied
Summary $\nu$ Scattering Results – NuTeV

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

NuTeV considered 23 systematic uncertainties.

NuTeV $\sigma$ agrees with other $\nu$ experiments and theory for medium $x$.
   At low $x$ different $Q^2$ dependence.
   At high $x$ ($x > 0.6$) NuTeV is systematically higher.

All of the NuTeV Results are for $\nu$ – Fe interactions and where necessary have assumed the nuclear corrections for neutrino interactions are the same as $l^\pm$. Is this really the case?
Nuclear Structure Function Corrections
\( \mathcal{L}^{\pm} (\text{Fe}/D_2) \)

- \( F_2 / \) nucleon changes as a function of A. Measured in \( \mu/\text{e} - A \), **not in** \( \nu - A \).
- **Reason to consider nuclear effects are DIFFERENT in** \( \nu - A \).
  - Presence of axial-vector current.
  - Different nuclear effects for valance and sea --> different shadowing for \( xF_3 \) compared to \( F_2 \).
Addressing the lack of $F_2$ Neutrino Nuclear Effects Analyses

Nuclear PDFs from neutrino deep inelastic scattering

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

Also analyses by:
K. Eskola, V. Kolhinen and C. Salgado
and
D. de Florian, R. Sassot, P. Zurita and M. Stratmann
F₂ Structure Function Ratios: ν-Iron

\[ \frac{F_2(\nu + Fe)}{F_2(\nu + [n+p])} \]
F₂ Structure Function Ratios: $\bar{\nu}$-Iron

\[ \frac{F_{2}(\nu + Fe)}{F_{2}(\nu + [n+p])} \]
A More-Detailed Look at Differences

- NLO QCD calculation of \( \frac{F_2^\nu A + F_2^\nu A}{2} \) in the ACOT-VFN scheme
  - charge lepton fit undershoots low-x data & overshoots mid-x data
  - low-\( Q^2 \) and low-x data cause tension with the shadowing observed in charged lepton data
A More-Detailed Look at Differences

- NLO QCD calculation of $\frac{F_2^\nu A + F_2^{\nu A}}{2}$ in the ACOT-VFN scheme
  - charge lepton fit undershoots low-$x$ data & overshoots mid-$x$ data
  - low-$Q^2$ and low-$x$ data cause tension with the shadowing observed in charged lepton data
BACKUP
Neutrino Experiments have been studying QCD for about 40 years

- For example, Gargamelle made one of the first measurements of $\Lambda_{ST}$ in the early 1970’s using sum rules and the $x-Q^2$ behavior of the structure functions $F_2$ and $xF_3$ measured off heavy liquids.
- BEBC followed with QCD studies using $\nu + p$ and $\nu + D$ scattering.
Most “Recent” DIS Experiments

- There followed a long string of $\nu$ scattering experiments with increasing statistics and decreasing systematic errors ....

<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>Fine-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>MINOS</td>
<td>3-15</td>
<td>05-10</td>
<td>Fe</td>
<td>2.5%</td>
<td>5.6%</td>
<td>Coarse</td>
</tr>
</tbody>
</table>
NuTeV CC Differential Cross Section
\(d\sigma/dy\) for different \(E_\nu\)

- NuTeV has increased statistics compared to other \(\nu\)-Fe experiments.
- Significant reduction in the largest systematic uncertainties: \(-E_\mu\) and \(E_{\text{HAD}}\) scales

<table>
<thead>
<tr>
<th></th>
<th>(E_\mu) scale</th>
<th>(E_{\text{HAD}}) scale</th>
<th>(E_\nu) range (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDHSW</td>
<td>2%</td>
<td>2.5%</td>
<td>20-200</td>
</tr>
<tr>
<td>CCFR</td>
<td>1%</td>
<td>1%</td>
<td>30-360</td>
</tr>
<tr>
<td>NuTeV</td>
<td>0.7%</td>
<td>0.43%</td>
<td>30-360</td>
</tr>
</tbody>
</table>
Estimated systematic error: $E_\mu$ scale

NuTev achieved 0.7%

Effect of $E_\mu$ scale uncertainty 2%

$F_2(x)$ vs $x$

$Q^2 = 2\text{Gev}^2$
Estimated systematic error: $E_{\text{had}}$ scale

NuTev achieved 0.43%
NuTeV $F_2$ Measurement

- Comparison of NuTeV $F_2$ with global fits

- At $x>0.4$ NuTeV is systematically above 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.
First $\nu$-Pb differential cross section and structure functions

CHORUS measurement favors CCFR over NuTeV

Much larger systematic errors than the NuTeV experiment

CHORUS Structure Functions: $\nu$ Pb
Parton Distribution Functions: What Can We Learn With All Six Structure Functions?

Recall Neutrinos have the ability to directly resolve flavor of the nucleon’s constituents: \( \nu \) interacts with \( d, s, \bar{u}, \) and \( \bar{c} \) while \( \bar{\nu} \) interacts with \( u, c, \bar{d} \) and \( \bar{s} \).

Using Leading order expressions:

\[
F_2^\nu (x, Q^2) = x [u + \bar{u} + d + \bar{d} + 2s + 2c] \\
F_2^{\bar{\nu}} (x, Q^2) = x [u + \bar{u} + d + \bar{d} + 2s + 2c] \\
xF_3^\nu (x, Q^2) = x [u + d - \bar{u} - \bar{d} - 2s + 2c] \\
xF_3^{\bar{\nu}} (x, Q^2) = x [u + d - \bar{u} - \bar{d} + 2s - 2c]
\]

Taking combinations of the Structure functions

\[
F_2^\nu - xF_3^\nu = 2(\bar{u} + \bar{d} + 2\bar{c}) \\
F_2^{\bar{\nu}} - xF_3^{\bar{\nu}} = 2(\bar{u} + \bar{d} + 2\bar{s}) \\
xF_3^\nu - xF_3^{\bar{\nu}} = 2[(s + \bar{s}) - (c + \bar{c})]
\]
CTEQ High-x Study: nuclear effects ratio $A/D_2$
No high-statistics $D_2$ data – “make it” from PDFs

- Form reference fit mainly nucleon (as opposed to nuclear) scattering results:
  - BCDMS results for $F_2^p$ and $F_2^d$
  - NMC results for $F_2^p$ and $F_2d/F_2^p$
  - H1 and ZEUS results for $F_2^p$
  - CDF and DØ result for inclusive jet production
  - CDF results for the $W$ lepton asymmetry
  - E-866 results for the ratio of lepton pair cross sections for pd and pp interactions
  - E-605 results for dimuon production in pN interactions.

- Correct for deuteron nuclear effects
What are the Differences $\sigma_{\nu\mu}(E)$ and $\sigma_{\nu e}(E)$?

Quasi-elastic Scattering


- Sources of possible differences: form factor uncertainties entering through lepton mass alterations - much more subtle:
  - Form factor contributions – both Axial and Pseudoscalar
  - Second class current contributions to vector and axial-vector form factors
- Possible contribution to CP uncertainties: effect on the FF could be different for $\nu$ and $\bar{\nu}$

$(\sigma_{\mu} - \sigma_e)/\sigma_e$ (v-\nu difference)

$pseudo$-scalar form factor and second class currents

Energy(GeV)

What are the Differences? Δ Production

- Manny and his student have investigated $\nu_\mu$ and $\bar{\nu}_\mu$ differences in Δ production in the low-Q ($Q^2 \approx m_\pi^2$) region where PCAC dominates the axial contribution.
- At E = 1-2 GeV, V part and V/A interference same size → cancel for $\nu$
- Use the Adler-Nussinov-Paschos model for nuclear corrections.
MINERνA

- Taking data in NuMI beam since March 2010
- Has “grown up” with NuInt series
$\bar{\nu}_\mu$ CCQE Analysis (L. Fields- NuInt12)

Neutrino energy and Q2 in the final sample:

\[ E_\nu = \frac{m_\mu^2 - (m_p - E_b)^2 - m_\mu^2 + 2(m_p - E_b)E_\mu}{2(m_p - E_b - E_\mu + p_\mu \cos \theta_\mu)} \]

\[ Q^2 = 2E_\nu(E_\mu - p_\mu \cos \theta_\mu) - m_\mu^2 \]

"Area Normalized" used here (and throughout this talk) to denote comparisons of shapes between data and MC.

24/10/12
$\bar{\nu}_\mu$ CCQE Analysis (L. Fields- NuInt12)

Shown for the first time at NuInt a shape-only comparison of data/models
2-Track $\nu_\mu$ CCQE in Fe, Pb and C (L. Fields- NuInt12)

$Q^2$ distributions for candidates passing all cuts:

Q2 shapes match GENIE relatively well at this level of statistics.

Coming soon: background subtraction, target ratios.