DIS with Neutrinos: Now and When

DIS12 Workshop
University of Bonn
March, 2012

Jorge G. Morfín
Fermilab

With thanks for the contributions of Trung Li (Rutgers), Rosen Matev(Sofia) and Martin Tzanov (LSU)
Studying Deep-Inelastic Scattering with $\nu/\overline{\nu}$

- Interacting with the weak current means a **much smaller interaction rate** than $e/\mu$ scattering
  - Need huge, higher-A detectors and/or intense neutrino beams to get reasonable statistics
- The incoming neutrino energy is not a priori known and even the neutrino energy dependent flux is difficult to predict – solution wait until end of talk!
- However **can select which set of quarks involved in the interaction via $\nu$ or $\overline{\nu}$**
- While $F_2$ is measured precisely by the charge lepton scattering, $xF_3$ is accessible by **neutrino DIS** and yields increased sensitivity to the **valence quark distributions**.
- Measuring charm production with $\nu$ and $\overline{\nu}$ also gives us insight into the $s$ and $\overline{s}$ quark distributions **within a nucleon in a nucleus**.
- **Measuring the difference between** $xF_3(\nu)$ and $xF_3(\overline{\nu})$ ($\Delta xF_3 = s - c$) gives information on heavy quarks
- Being forced to use heavy nuclear targets presents some challenges in disentangling nuclear effects from the study of nucleON PDFs. **Need to study nuclear effects with neutrinos** (as compared to charged lepton scattering) or use lighter targets, like $H_2/D_2$, .... or do both!
The Parameters of $\nu$ DIS

Differential cross section in terms of structure functions:

$$\frac{1}{E_\nu} \frac{d^2 \sigma^{\nu(\bar{\nu})}}{dx dy} = \frac{G_F^2 M}{\pi \left(1 + Q^2 / M_W^2\right)} \left[ \left(1 - \frac{y}{2} - \frac{M x y}{2 E_\nu} + \frac{y^2}{2} \left(1 + \frac{4 M^2 x^2}{Q^2} \right) \frac{1}{1 + R(x, Q^2)} \right) F_2^{\nu(\bar{\nu})} \pm \left(1 - \frac{y}{2} \right) x F_3^{\nu(\bar{\nu})} \right]$$

Structure Functions in terms of parton distributions (for $\nu$-scattering)

$$F_2^{\nu(\bar{\nu})} = \sum x q^{\nu(\bar{\nu})} (x) + x \bar{q}^{\nu(\bar{\nu})} (x) + 2 x k^{\nu(\bar{\nu})} (x)$$

$$xF_3^{\nu(\bar{\nu})} = \sum [x q^{\nu(\bar{\nu})} (x) - x \bar{q}^{\nu(\bar{\nu})} (x)] = x (d_\nu (x) + u_\nu (x)) \pm 2 x (s (x) - c (x)),$$

$$R = \frac{\sigma_L}{\sigma_T}$$
Parton Distribution Functions: 
What Can We Learn With All Six $\nu$ and $\bar{\nu}$ 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:

\[
F_{2 \bar{V}N}(x, Q^2) = x[u + \bar{u} + d + \bar{d} + 2s + 2c]
\]
\[
F_{2 \nu N}(x, Q^2) = x[u + \bar{u} + d + \bar{d} + 2s + 2c]
\]
\[
xF_{3 \bar{V}N}(x, Q^2) = x[u + d - \bar{u} - d - 2s + 2c]
\]
\[
xF_{3 \nu N}(x, Q^2) = x[u + d - \bar{u} - d + 2s - 2c]
\]

Taking combinations of the Structure functions

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

Most “Recent” ν DIS Experiments

<table>
<thead>
<tr>
<th>Detector</th>
<th>E_{ν} range (&lt; E_{ν}&gt;) (GeV)</th>
<th>Run</th>
<th>Target A</th>
<th>E_{μ} scale</th>
<th>E_{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>
**Old Style: The NuTeV Experiment: 800 GeV Protons**

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

---

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

Muon Spectrometer:
- Three toroidal iron magnets with five sets of drift chambers
  \[
  \langle B_\varphi \rangle \approx 1.7T, \ p_t \approx 2.4 \text{GeV/c}
  \]
  \[
  \delta \left(\frac{1}{p}\right) / \left(\frac{1}{p}\right) \sim 11\% \text{ MCS dominated}
  \]
- 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
Average $F_2$ Measurement

- Isoscalar $\nu\text{-Fe } F_2$
- NuTeV $F_2$ compared with CCFR and CDHSW results
- All systematic uncertainties are included
- All data sets agree for $x<0.4$.
- At $x>0.4$ NuTeV agrees with CDHSW.
- At $x>0.4$ NuTeV is systematically above CCFR.

Notice the $Q^2$ range!

Martin Tzanov
Comparison with Global Fits for $F_2$

- Baseline is TRVFS(MRST2001E)
- NuTeV and CCFR $F_2$ are compared to TRVFS(MRST2001E)
- Theoretical models shown are:
  - ACOT(CTEQ6M)
  - ACOT(CTEQ5HQ1)
  - TRVFS (MRST2001E)
- Theory curves are corrected for:
  - target mass
  (H. Georgi and H. D. Politzer, Phys. Rev. D14, 1829)
  - nuclear effects – parameterization from charge lepton data, assumed to be the same for neutrino scattering (no $Q^2$ dependence added) nuclear effects parameterization is dominated by SLAC (lower $Q^2$ in this region) data at high-$x$
- 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.
Comparison with Charge Lepton Data for $x>0.4$

- Baseline is NuTeV model fit
- data points are $\frac{F_2^{D\text{ATA}} - F_2^{BG}}{F_2^{BG}}$
- charge lepton data is corrected for:
  - $F_2^\nu$ using CTEQ4D
  - heavy target $\frac{F_2^N}{F_2^D}$

• NuTeV agrees with charge lepton data for $x=0.45$.
• NuTeV is higher than BCDMS($D_2$), different $Q^2$ dependence
  - 7% at $x=0.55$, 12% at $x=0.65$, and 15% at $x=0.75$
• NuTeV is higher than SLAC($D_2$) (bottom 4 plots)
  - 4% at $x=0.55$, 10% at $x=0.65$, and 17% at $x=0.75$

“Perhaps the nuclear correction is smaller for neutrino scattering at high $x$.”

Martin Tzanov

• the nuclear correction is dominated by SLAC data, which is at lower $Q^2$ than NuTeV in this region
Charm Production by Neutrinos
a direct look at strange sea.

- Charm quark is produced from CC neutrino interaction with s(d) quark in the nucleon. d-quark interaction is CKM suppressed
- Detect charm via the semi-leptonic decay which yields a very clear signature – two opposite sign muons
- It is sensitive to $m_c$ through $E_\nu$ dependence.
- With high-purity $\nu$ and $\bar{\nu}$ beams, NuTeV made high statistics separate s and $\bar{s}$ measurements: 5163 $\nu$ and 1380 $\bar{\nu}$
- Could then make a measurement of $s \rightarrow \bar{s}$.

This is an analysis of strange quarks in an Fe nucleus!
Summary \( \nu \) Scattering Results – NuTeV

NuTeV accumulated over 3 million neutrino / antineutrino events with \( 20 \leq E_\nu \leq 400 \text{ GeV} \). Most accurate results available until NOMAD.

NuTeV considered multiple correlated systematic uncertainties.

NuTeV agrees with other \( \nu \) experiments and theory for medium \( x \).

NuTeV has a different \( Q^2 \) dependence at low \( x \).

NuTeV is systematically higher at high \( x \) (\( x > 0.6 \)).

How do we now incorporate these NuTeV results in the analysis of nucleon structure?

We need to understand neutrino nuclear correction factors (NCF) to bring \( \nu / \bar{\nu} - \text{Fe} \) to \( \nu / \bar{\nu} - \text{N} \)!
Knowledge of Nuclear Effects with Neutrinos: Very sparse

- $F_2$ / nucleon changes as a function of $A$. Measured in $\mu/e - A$ **not in $\nu - A$**
- **Good reason to consider nuclear effects are DIFFERENT in $\nu - A$.**
  - Presence of axial-vector current.
  - SPECULATION: Much stronger shadowing for $\nu - A$ 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 PDFs from neutrino deep inelastic scattering
Karol Kovarik Presentation – this afternoon in SF session

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)

F₂ Structure Function Ratios: ν-Iron and ν-Iron

This would suggest that the nuclear parton distribution function
for ν are different than those found by ℓ
Where are we now: Conclusions

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

◆ Nuclear correction factors (R) seems to be different for $\nu$-Fe scattering compared to $\ell^\pm$-Fe.

   ▼ Results from one experiment on one nuclear target… careful.

◆ We need $\nu$-experiments to measure these nuclear correction factors!
   ▼ For the cleanest study of nucleon structure, $\nu/\bar{\nu}$ - H$_2$/D$_2$ experiment would be excellent!

◆ Aside from the question of nuclear correction factors, there are differences between the highly accurate NuTeV results and results from other neutrino experiments and theory we need to understand.

◆ How do we answer these questions?
The MINERνA Experiment – First of the New Style High-Statistics Neutrino Detectors

Joel Mousseau (Univ. Florida) - just described this

Cryotarget: ready for H₂/D₂ fill

Fully Active Fine Segmented Scintillator
Target: 8.3 tons, 3 - 5 tons fiducial

Nuclear Targets with Pb, Fe, C, H₂O, CH
Simultaneous in the same neutrino beam reduces systematic errors between nuclei

The ME beam peaks at 7 GeV rather than the LE beam peak of 3.5 GeV. Not exactly designed for DIS
Where do we go after MINERνA?

- With MINERνA and the ME exposure, we will begin to resolve the question of neutrino nuclear correction factors… however:
  - Will know the neutrino flux to within (5 – 10)%
  - Was designed to understand the low-\(E_\nu\), low multiplicity QE \(\rightarrow\) transition resonance region.
  - Even with the ME beam cannot investigate the full x range at high-\(Q^2\)

- To make significant advances in DIS studies with neutrinos we have to work on lowering the systematics (there’s that word again!)
  - Beam: Need a higher energy beam and to understand the neutrino flux to within 1% or so.
  - Detector: Need a detector with excellent acceptance over full \(Q^2\) range.
  - Detector: Need a detector with improved measurement accuracy of \(E_\mu\) and \(\theta_\mu\).
  - Detector: Need to reduce the error on the \(E_{\text{hadron}}\) shower measurement.
What’s Next…. LBNE (but we have to wait awhile!)

- Beam energy lower than ME!
- Uses same double-horn, pion-decay source neutrino beam – not much help there same flux errors!
- However has the beam power (0.7 MW) and the time is right to employ a new type of neutrino detector to reduce systematics.
  - 7 ton interaction volume
- DIS event rates: 5 year $\nu$ and 5 year $\bar{\nu}$ yields 20 M $\nu$ and 4 M $\bar{\nu}$.
  - Statistics fine – **systematics**!
Straw-tube Tracker Design
S. Mishra – Univ. S. Carolina

High resolution magnetised detector (HiResMy) – LBNE Standard Near detector
Builds on NOMAD experience, ATLAS TRT and COMPASS detector designs

Transition Radiation ↔ e-/+e+ ID ⇒ γ (w. Kinematics)
dE/dx ↔ Proton, π+/–, K+/– ID
Magnet/Muon Detector ↔ μ+/–
HiResMv design parameters

- **Space point resolution** better than 200 $\mu m$ (in ATLAS 130 $\mu m$).

- **Momentum resolution** for $\rho = 0.1 g/cm^3$ and $B = 0.4T$:
  - Multiple scattering contribution $0.05$ for $L = 1m$ ($B = 0.4T$, default radiator)
  - Measurement error ($B = 0.4T$)
    \[
    \frac{\sigma(p)}{p} = \frac{\sigma(x)p}{0.3BL^2} \sqrt{\frac{720}{N + 4}}
    \]
    which gives $0.006$ for $L = 1m$ and $p = 1$ GeV/c ($N = 50$ if along beam direction)

- **Full reconstruction of charged particles and $\gamma$’s**

- **Identify $e, \pi, K, p$ from $dE/dx$. Use Transition Radiation for electron identification in the whole fiducial volume with Xe filling.**

- **Reconstruction of electrons down to 80 MeV from curvature in magnetic field ($B = 0.4T$)**

**Now - How do we improve the BEAM?**
Ultimate $\nu$ – DIS Experiment: Neutrino Factory

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

Muon Storage Ring

O(10^{21}) Muon Decays/year

Beam

(target, π, ..., μ, e, μ, ...)

storage

proton acceleration
hadron production
focusing
decay
absorption of e's
cooling
acceleration

Muon decay

$\nu_\mu, \nu_e$

50%, 50%

detector
Example Event Energy Distribution
25 GeV $\mu^-$

Inverse Muon Decay Threshold
Near Detector Design Requirements

• Determination of the neutrino flux (through the measurement of neutrino-electron scattering) to < 1%!

• Magnetic field for muon momentum ($\delta p/p \sim 1\%$)

• Muon catcher and capability for and $e^+/e^-$ identification

• Good resolution on neutrino energy – goal $\delta E/E \sim 1\%$
Neutrino Factory Near Detector(s)

$E_\mu = 25 \text{ GeV} \pm 80 \text{ MeV}$

Straight section length = 600 m

Muon angular spread 0.5 mrad

Event Rates

$2.5 \times 10^{20}$ $\mu$-decays/year

3 Years of $\mu^+$ and $\mu^-$

Fid. Mass 3.5 Tons

$\mu^+$:

$\nu_u$-CC: $1.8 \times 10^9$ Events

IMD: $1.3 \times 10^6$ Events

$\nu_u e$ QE: $1.1 \times 10^6$ Events

$\mu^-$:

$\bar{\nu}_u$-CC: $0.9 \times 10^9$ Event

$\nu_u e$ QE: $1.3 \times 10^6$ Event
Currently the most accurate measurement of neutrino DIS scattering is the NuTeV $\nu/\bar{\nu}$ – Fe results.

There are inconsistencies between NuTeV and other $\nu/\bar{\nu}$ – Fe results.

Absolute rates limited by neutrino flux determinations.

Attempts to extract neutrino nuclear correction factors yield a different NCF for $\nu/\bar{\nu}$ – Fe than for $\ell^\pm$ - Fe.

Current generation experiments (MINERvA) can measure NCF off different A. Pb / C could be a few %

Next generation detectors can reduce detector systematics to the percent level.

Need Neutrino Factory beams to reach < 1% errors on the flux.

It could be a bit of a wait for the next great $\nu$ DIS experiment.
Additional Details
Formalism

- PDF Parameterized at $Q_0 = 1.3$ GeV as

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

- 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:

\[
\frac{d^2 \sigma^{(\bar{\nu})}}{dx \, dy} = \frac{G^2 M E}{\pi} \left[ (1 - y - \frac{M x y}{2E}) F_2^{(\bar{\nu})} + \frac{y^2}{2} 2x F_1^{(\bar{\nu})} \pm y(1 - \frac{y}{2}) x F_3^{(\bar{\nu})} \right]
\]
Neutrino Beamlines

- Intense proton beam on a target and collect $\pi$ and $K$ and focus into a decay space.
- Absorb hadrons and muons leaving only neutrinos.
- Do not know individual $E_\nu$ a priori and absolute flux known to 5-10%.
**F\textsubscript{2} and xF\textsubscript{3} Measurement**

\[ F\textsubscript{2} = 2 \bar{F}_2 \left( 1 - \frac{M_{xy}}{2E} + \frac{y^2}{2} \frac{1 + 4M^2x^2/Q^2}{1 + R} \right) + y \left( 1 - \frac{y}{2} \right) \Delta xF_3 \]

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

- Perform 1-parameter fit for F\textsubscript{2}
- ΔxF\textsubscript{3} model
- RL model
- Perform 1-parameter fit for xF\textsubscript{3}
- ΔF\textsubscript{2} is very small and is neglected

- Radiative corrections applied
- Isoscalar correction applied
**$xF_3$ Measurement**

- **NuTeV** $xF_3$ compared to CCFR and CDHSW
- All systematic uncertainties are included
- All data sets agree for $x<0.4$.

- At $x>0.4$ NuTeV agrees with CDHSW
- At $x>0.4$ NuTeV is systematically above CCFR
Comparison with Global Fits for $x F_3^3$

- Baseline is TRVFS(MRST2001E).
- NuTeV and CCFR $x F_3^3$ are compared to TRVFS(MRST2001E)

$$\frac{x F_3^{\text{NuTeV}} - x F_3^{\text{TRVFS}}}{x F_3^{\text{TRVFS}}}$$

- Theoretical models shown are:
  - ACOT(CTEQ6M)
  - ACOT(CTEQ5HQ1)
  - TRVFS (MRST2001E)

- Theory curves are corrected for:
  - target mass
  (H. Georgi and H. D. Politzer, Phys. Rev. D14, 1829)
  - nuclear effects – parameterization from charge lepton data, assumed to be the same for neutrino scattering (no $Q^2$ dependence added) nuclear effects parameterization is dominated by SLAC (lower $Q^2$ in this region) data at high-$x$

- NuTeV $x F_3^3$ agrees with theory for medium $x$.
- At low $x$ different $Q^2$ dependence.
- At high $x$ ($x>0.6$) NuTeV is systematically higher.

Martin Tzanov
Comparison with Theory at Low $x$

- both NuTeV and CCFR agree in level with theory in the shadowing region (except CTEQ6M)

- the red curve is TRVFS(MRST) using the following model for nuclear correction:

  *NUCLEAR SHADOWING IN NEUTRINO NUCLEUS DEEPLY INELASTIC SCATTERING.*


  Published in Phys.Lett.B587:52-61,2004

  e-Print Archive: hep-ph/0401062

Martin Tzanov
CHORUS (using Pb targets and nuclear emulsions), NuTeV and CCFR $F_2$ Comparison

- CHORUS is not as precise,
- CHORUS agrees well with NuTeV and CCFR over the whole range,
- hint of a different $Q^2$ shape at low-x
- This comparison assumes nuclear corrections similar for Fe and Pb.
Estimated systematic error: \( E_\mu \) scale

NuTeV achieved 0.7%
A leading systematic error: $E_{\text{had}}$ scale

NuTev achieved 0.43%
$F_2$ Structure Function Ratios: $\nu$-Iron
F₂ Structure Function Ratios: $\bar{\nu}$-Iron
NuTeV(Fe) and CHORUS (Pb) $\nu$ scattering (unshifted) results compared to reference fit

no nuclear corrections
Broad Range of Nuclear Targets
Acceptance for $\mu$’s in MINOS from the nuclear targets…complicated!

- 5 nuclear targets + water target
- He target upstream of detector
- Near million-event samples
  $(4 \times 10^{20}$ POT LE beam + $12 \times 10^{20}$ POT in ME beam

<table>
<thead>
<tr>
<th>Target</th>
<th>Mass in tons</th>
<th>CC Produced Events (Million)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scintillator</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>He</td>
<td>0.2</td>
<td>0.6</td>
</tr>
<tr>
<td>C (graphite)</td>
<td>0.15</td>
<td>0.4</td>
</tr>
<tr>
<td>Fe</td>
<td>0.7</td>
<td>2.0</td>
</tr>
<tr>
<td>Pb</td>
<td>0.85</td>
<td>2.5</td>
</tr>
<tr>
<td>Water</td>
<td>0.3</td>
<td>0.9</td>
</tr>
</tbody>
</table>
High-$x$ Structure Functions & PDFs

$\nu - p$ Scattering

\[
\begin{align*}
F_2^{\nu p} &= 2x (d + \bar{u} + s) \\
F_2^{\bar{\nu} p} &= 2x (\bar{d} + u + \bar{s})
\end{align*}
\]

At high $x$

\[
\frac{F_2^{\nu p}}{F_2^{\bar{\nu} p}} \approx \frac{d}{u}
\]

Add in…

\[
\begin{align*}
xF_3^{\nu p} &= 2x (d - \bar{u} + s) \\
xF_3^{\bar{\nu} p} &= 2x (-\bar{d} + u - \bar{s})
\end{align*}
\]

\[
\begin{align*}
F_2^{\nu p} - xF_3^{\nu p} &= 4x\bar{u} \\
F_2^{\bar{\nu} p} + xF_3^{\bar{\nu} p} &= 4xu
\end{align*}
\]