Exploring Nucleon Spin Structure through Neutrino Neutral-Current Interactions in MicroBooNE

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μBooNE

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Elastic Neutrino-Proton Scattering

The elastic neutrino-proton cross section depends on the axial, electric, and magnetic form factors, $G_{A}^{NC}$, $G_{E}^{NC}$, and $G_{M}^{NC}$

- Represent the spin, electric, and magnetic distributions of the nucleon
- All three can be written in terms of individual quark contribution

At low $Q^2$, get net quark contribution to spin, electric charge, or magnetic moment

- Individual quark contributions to $G_{E}^{NC}$ and $G_{M}^{NC}$ at low $Q^2$ ($< 1 \text{ GeV}^2$) have been determined in electron-neutron scattering
Neutral-Current Elastic $\nu p$ Scattering

NC elastic $\nu p$ cross section:

$$
\left( \frac{d\sigma}{dQ^2} \right)^{NC}_\nu = \frac{G_F^2}{2\pi} \left[ \frac{1}{2} y^2 (G_M^{NC})^2 + \left( 1 - y - \frac{M}{2E} y \right) \frac{(G_E^{NC})^2 + \frac{E}{2M} y (G_M^{NC})^2}{1 + \frac{E}{2M} y} \right. \\
+ \left. \left( \frac{1}{2} y^2 + 1 - y + \frac{M}{2E} y \right) (G_A^{NC})^2 + 2y \left( 1 - \frac{1}{2} y \right) G_M^{NC} G_A^{NC} \right]
$$

• Can get net spin contribution from all three quarks from axial form factor when $Q^2 \rightarrow 0$

$$G_A^{NC}(Q^2 = 0) = -\Delta u + \Delta d + \Delta s$$

• $\Delta u - \Delta d$ has been determined in neutron decay

$s$ was expected to be zero

• Found to be negative in polarized, charged-lepton, inclusive DIS
  • Assumes flavor $SU(3)$ symmetry
  • Analyses give range $\Delta s = -0.08$ to $-0.24$ [1]

Neutrino-Based Experimental Measurements of $\Delta s$

NC elastic measurement from the E734 neutrino scattering experiment at BNL

- Measured NC elastic $\nu - p$ interactions down to $Q^2 = 0.45 \text{ GeV}^2$
- Found $-0.31 \leq \Delta s \leq -0.04$ [2]
  - Sensitive to choice of form factor

NC elastic $\nu p$ signal is a single, isolated proton

- Difficult to measure at low momentum transfer
- Kinematics determined by proton energy: $Q^2 = 2Tm_p$

Need a dense, high-resolution detector

$\Rightarrow$ Liquid argon time projection chamber

Liquid Argon TPCs

- Large liquid argon target for neutrino interactions
- Charged particles produced in interaction ionize the argon
- Ionization electrons drift to anode wire plane due to electric field

- Signal from electrons on wires is read out
- Reconstruct images of events
MicroBooNE LArTPC

MicroBooNE Detector:

- 170 tons of liquid argon (89 tons active)
- \(10 \times 2.5 \times 2.3 \, \text{m}^3\)
- 3 planes of \(\sim 3000\) wires each
- 3 mm wire spacing combined with time information allows high-resolution 3D reconstruction
- 32 PMTs detect argon scintillation light with ns timing resolution

Status:

- Installed in detector hall summer 2015
- Commissioned and started taking neutrino data fall 2015
- First year of running: collected \(3.6 \times 10^{20}\) protons on target
  - \(\sim 100,000\) neutrino events

Photo: Fermilab
Measuring $\Delta s$ in MicroBooNE

Measuring $\Delta s$:

- Measure the ratio of neutral-current elastic to charged-current quasi-elastic events
  - Reduce uncertainty from beam flux, detector efficiency, nuclear effects, and final state interactions

$$R_{NC/CC} = \frac{\left( \frac{d\sigma}{dQ^2} \right)_{NC}}{\left( \frac{d\sigma}{dQ^2} \right)_{CC}} \rightarrow \frac{N(\nu p \rightarrow \nu p)}{N(\nu n \rightarrow \mu^- p)}$$

- Will be able to detect protons that traverse as few as five wires (1.5 cm)
  - Corresponds to a NC elastic interaction with $Q^2 = 0.08 \text{ GeV}^2$
Neutral-Current Elastic $\nu p$ events in MicroBooNE

We expect 10,000 NC elastic proton events above during MicroBooNE’s three year run

- Makes up $\sim$5% of neutrino interactions in MicroBooNE
- Large cosmic background
- Need automated reconstruction and selection!
  - Hasn’t been done before in a LArTPC

Simulated 70 MeV proton from NC elastic event $(Q^2=0.13 \text{ GeV}^2)$
LArSoft Reconstructed Tracks

We first get reconstructed TPC tracks from LArSoft (Liquid Argon Software)

- There is a series of algorithms that create these tracks

1. **Hit finding:** Fit gaussians to de-noised waveform peaks

2. **Neutrino track finding:**
   - Combine hits from step (1) into tracks
   - Return set of neutrino event-like tracks
   - The current neutrino-finding algorithm finds \( \sim 50\% \) of simulated proton tracks — this efficiency is rapidly improving

- The next step is to identify which tracks are protons
Gradient-Boosted Decision Trees

**Decision tree:**
series of if/else statements

- Input an event
  (collection of track features)
- Output a class
  (proton, muon, cosmic, etc.)

**Gradient-boosting:**
Each new tree trains on the error of the previous tree

- Input an event (collection of track features)
- Each tree votes
- Output probability of track being from each class
- Using XGBoost software package [3]

[3] Tianqi Chen and Carlos Guestrin. 22nd SIGKDD Conference on Knowledge Discovery and Data Mining (2016)
Building the Gradient-Boosted Decision Trees

We are using a multi-class classifier
- Identify protons, muons, pions, electrons/photons, and cosmics
  - Protons, muons, pions, electrons, and photons are neutrino-event like
  - Cosmics are any type of cosmic induced tracks

Each input is a collection of reconstructed track features:

- Geometric: length, angle, ...
- Calorimetric: total charge, ...
- Optical: distance to flash, ...

<table>
<thead>
<tr>
<th>Feature Importance</th>
<th>MicroBooNE Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>PIDA</td>
<td></td>
</tr>
<tr>
<td>Theta</td>
<td></td>
</tr>
<tr>
<td>Phi</td>
<td></td>
</tr>
<tr>
<td>$\chi^2$ PID</td>
<td>MicroBooNE “In Progress”</td>
</tr>
<tr>
<td>Ave. dQ/dx</td>
<td></td>
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<tr>
<td>Length</td>
<td></td>
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<tr>
<td>Flash Dist.</td>
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<tr>
<td>Tot. dQ/dx</td>
<td></td>
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<tr>
<td>Start dQ/dx</td>
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<tr>
<td>Start Y Pos.</td>
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<tr>
<td>End dQ/dx</td>
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<tr>
<td>End Y Pos.</td>
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<tr>
<td>Start Z Pos.</td>
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<tr>
<td>Straightness</td>
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<tr>
<td>dQ/dx Ratio</td>
<td></td>
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<tr>
<td>End Z Pos.</td>
<td></td>
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<tr>
<td>dQ/dx Diff.</td>
<td></td>
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<tr>
<td>Num. Hits</td>
<td></td>
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<tr>
<td>Cosmic Score</td>
<td></td>
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<tr>
<td>Cont. Score</td>
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Performance on Training Set

To train, we used $\sim 700,000$ simulated neutrino events and cosmic data events in MicroBooNE

- “Proton Score” is the log-odds of a track being from a proton
  \[ S_i = \ln \left( \frac{p_i}{1 - p_i} \right) \]
- $S = 0$ corresponds to 50% probability
Performance on Test Set

Tested the trained classifiers on an independent set of 200,000 simulated neutrino and simulated cosmic events

- Greater than 50% proton probability is considered a classification for these plots
- Efficiency is not very dependent on proton kinetic energy
- Most of background tracks are cosmic-induced protons
Example Protons from Data

Ran classifier on small subset of MicroBooNE data
- Found both neutral and charged-current elastic candidate events
- Can select neutral-current by requiring the proton be isolated
Impact on Form Factors and $\Delta s$

Predictions based on $2e20$ POT and 100% efficiency
- Reduce uncertainty on $\Delta s$ in global fit by factor of 10

Global Fit from Currently Available Data

MicroBooNE: Projected Impact on Nucleon Form Factor Measurements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fit to Existing Data</th>
<th>Including MicroBooNE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_s$</td>
<td>$\pm 0.09 \pm 0.03$</td>
<td>$\pm 0.08 \pm 0.02$</td>
</tr>
<tr>
<td>$\mu_s$</td>
<td>$\pm 0.029 \pm 0.022$</td>
<td>$\pm 0.023 \pm 0.017$</td>
</tr>
<tr>
<td>$\Delta s$</td>
<td>$\pm 0.42 \pm 0.19$</td>
<td>$\pm 0.036 \pm 0.003$</td>
</tr>
<tr>
<td>$\Lambda_d$</td>
<td>$\pm 1.0 \pm 1.1$</td>
<td>$\pm 0.42 \pm 0.03$</td>
</tr>
<tr>
<td>$S_A$</td>
<td>$\pm 0.5 \pm 0.2$</td>
<td>$\pm 0.05 \pm 0.02$</td>
</tr>
</tbody>
</table>

Not much effect on vector form factors (no surprise)
BIG effect on axial form factor (expected!)

$G_E^s = \rho_s \tau \quad G_M^s = \mu_s \quad G_A^s = \frac{\Delta s + S_A Q^2}{1 + Q^2 / \Lambda_A^2}$

Stephen Pate, Dennis Trujillo
Strangeness Vector and Axial-Vector Form Factors of the Nucleon.
August 2013
Conclusion

- MicroBooNE can measure low $Q^2$ neutral-current elastic neutrino-proton events
  - The signal is a single short proton track

- A combination of LArSoft algorithms for track reconstruction and boosted decision trees for particle I.D. is being developed for event selection

- May be able to reduce uncertainty on $\Delta s$ by an order of magnitude

Thank you!