Studying Neutral Current Elastic Scattering and the Strange Axial Form Factor in MicroBooNE

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The NC elastic cross section and strange nucleon spin

One of the least constrained parts of the neutral current elastic cross section is the strange quark contribution to the axial form factor, $G_A^s(Q^2)$

- The strange axial form factor is equal to the net strange quark spin contribution to the nucleon spin, Δs, at $Q^2 = 0$

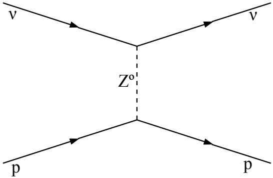
$$G_A^s(Q^2 = 0) = \Delta s = \int_0^1 [s^\uparrow(x) + \bar{s}^\uparrow(x)] - [s^\downarrow(x) + \bar{s}^\downarrow(x)]dx$$

Δs was found to be negative in polarized, charged-lepton, DIS

- Experiment analyses give ranges $\Delta s = -0.08$ to -0.14
  - Ellis-Jaffe sum rule assumes SU(3) flavor symmetry is valid and $\Delta s = 0$
  - Δs should be checked using alternate methods not assuming SU(3)
- Attempts to measure Δs in semi-inclusive DIS scattering of charged-leptons off of protons gave results consistent with zero
  - These measurements require assumptions involving fragmentation functions

The elastic neutrino scattering cross section

Elastic cross section (both CC and NC) off free nucleons:



$$\frac{d\sigma}{dQ^2} = \frac{G_F^2 M^2}{8\pi E_\nu^2}\left[A \mp \frac{(s-u)}{M^2}B + \frac{(s-u)^2}{M^4}C\right]$$

- $\mp$ is for (anti)neutrino scattering
- $s - u = 4ME_\nu - Q^2 - m^2$
- G_F is the Fermi coupling constant, E_ν is the incoming neutrino energy, M is the nucleon mass, m is the outgoing lepton mass

$$A = \frac{m^2 + Q^2}{M^2}\Big[(1+\tau){G_A}^2 - (1-\tau)({F_1}^2 + \tau {F_2}^2) + 4\tau F_1 F_2$$
$$-\frac{m^2}{4M^2}\left((G_A + F_2)^2 + G_A + 2F_P)^2 - (\frac{Q^2}{M^2} + 4)F_P^2\right)\Big]$$

$$B = \frac{Q^2}{M^2} G_A (F_1 + F_2)$$

$$C = \frac{1}{4}({G_A}^2 + {F_A}^2 + \tau {F_2}^2)$$

- Terms containing m drop out in NC scattering
- The only other CC/NC difference is the form factors, F_1, F_2, and G_A

The neutral current elastic cross section

We know how the CC and NC form factors are related:

- F_1 and F_2 are the Dirac and Pauli form factors
  - They are linear combinations of the Sachs form factors G_E and G_M which represent the electric and magnetic structure of the nucleon
  - They have been determined experimentally in electron-nucleon scattering

$$F_{1,2}^{NC} = \frac{1}{2} F_{1,2}^{CC}$$

- G_A is the axial form factor
  - It encodes the longitudinal spin structure of the nucleon
  - The charged current part only contains contributions from the up and down quarks

$$G_A^{NC} = \pm\frac{1}{2}(G_A^d - G_A^u) + \frac{1}{2}G_A^s$$
$$G_A^{NC} = \pm\frac{1}{2}G_A^{CC} + \frac{1}{2}G_A^s$$

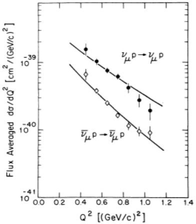
  - $\pm$ is for proton (neutron) scattering

We can use our knowledge of the charged current elastic neutrino-proton cross section to determine $G_A^s(Q^2)$ and Δs

Previous neutrino measurements of $G_A^s(Q^2)$

BNL E734 (1987)

PRD 35.000785



Brookhaven E734 measured $\nu p \to \nu p$

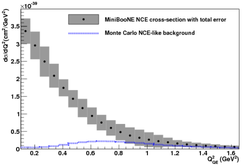
- Included interactions down to $Q^2 = 0.45$ GeV^2
- Found $\Delta s = -0.12 \pm 0.07$

MiniBooNE measured $(\nu p \to \nu p)/(\nu N \to \nu N)$

- Included interactions down to $Q^2 = 0.7$ GeV^2
- Found $\Delta s = 0.08 \pm 0.26$

MiniBooNE (2010)

PRD 82.092005



The previous measurements of G_A^s have assumed a dipole form for both the charged current and the strange axial form factor:

$$\begin{aligned}
G_A^{NC}(Q^2) &= \pm\frac{1}{2}G_A^{CC}(Q^2) + \frac{1}{2}G_A^s(Q^2) \\
&= \pm\frac{1}{2}\frac{g_A}{(1+Q^2/M_A^2)^2} + \frac{1}{2}\frac{\Delta s}{(1+Q^2/M_A^2)^2} \\
&= \pm\frac{1}{2}\frac{g_A}{(1+Q^2/M_A^2)^2}(1 \pm \eta)
\end{aligned}$$

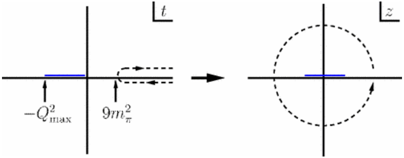
- M_A is the "axial mass" and $\eta = \Delta s/g_A$
- $g_A = \Delta d - \Delta u$ is the weak coupling constant determined in neutron decay

A more general form factor model

Form factor z expansion parameterization:

$$G(z) = \sum_{k=0}^{k_{\mathrm{max}}} a_k z^k$$

Map Q^2 onto the complex plane where the form factor is analytic:



$$z(Q^2, t_{cut}, t_0) = \frac{\sqrt{t_{\mathrm{cut}} + Q^2} - \sqrt{t_{\mathrm{cut}} - t_0}}{\sqrt{t_{\mathrm{cut}} + Q^2} - \sqrt{t_{\mathrm{cut}} - t_0}}$$

- z is a small parameter so the Taylor expansion of the form factor will converge
  - t_{cut} is the limit where the form factor is analytic
  - t_0 is an arbitrary value optimized to the range of Q^2
- G can be any of the electromagnetic and axial form factors
  - a_k are coefficients that are determined by fitting to data

Boyd and Savage (1997) PRD 56.303

Axial form factor z expansion

Using an existing z expansion fit for the charged current axial form factor G_A^{CC}

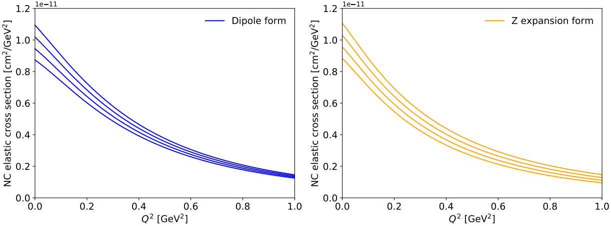
- Fit to deuterium bubble chamber neutrino data
- Meyer, Betancourt, Gran, and Hill. PRD 93.113015 (2016)

No fit has been done to the neutral current axial form factor

- We can do a simple three-parameter fit

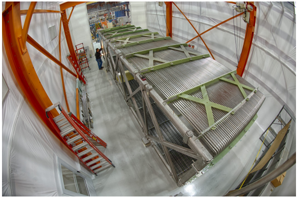
$$G_A^{NC}(Q^2) = \frac{1}{2}G_A^{CC}(Q^2) + \frac{1}{2}G_A^{s}(Q^2)$$
$$G_A^{s}(z(Q^2)) = a_0 + a_1 z + a_2 z^2$$

- The usual physical parameters can still be extracted
  - $\Delta s = a_0$ is the value of G_A^s at $Q^2 = 0$



- Plots show the NC elastic cross section for four different values of $\Delta s \in [-0.15, 0]$
- Left uses dipole form and right uses z expansion form of $G_A^s(Q^2)$

The MicroBooNE detector

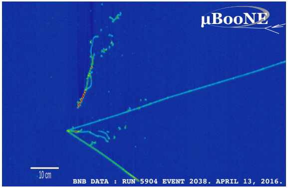


source: FNAL

- Liquid argon TPC
- Dimensions:
  10 m $\times$ 2.5 m $\times$ 2.3 m
- Three anode wire planes with $\sim$3000 wires each
- 3 mm wire spacing

source: FNAL

- 32 PMTs on the anode side
- With wavelength shifting (TPB) plates

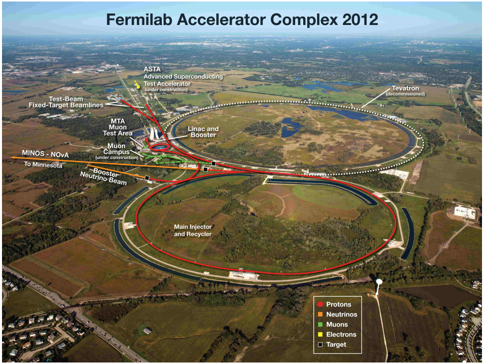


source: FNAL

- Everything is inside a liquid-argon-filled cryostat
- Located at the surface in Fermilab's Booster Neutrino Beam

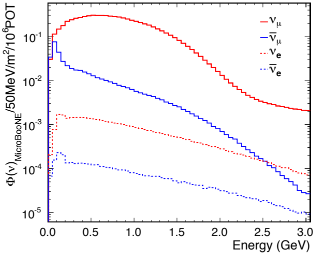
MicroBooNE detector paper: JINST 12, P02017 (2017)

The Booster Neutrino Beam

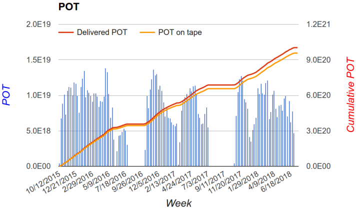


source: FNAL

- The Booster accelerator delivers 8 GeV protons to the Booster Neutrino Beam target



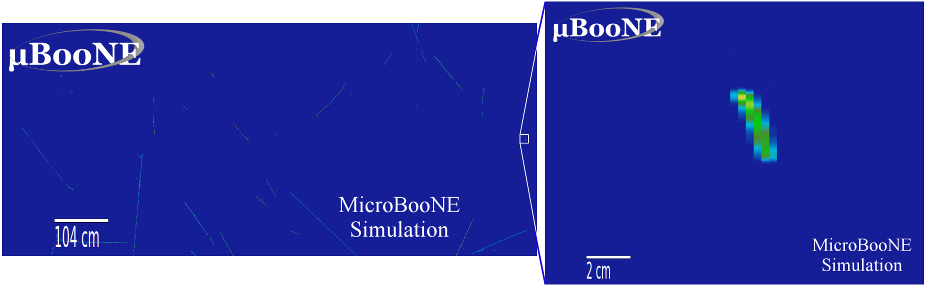
- The resulting neutrino flux peaks ~800 MeV
- We have collected over 9e20 POT (out of approved 1.3e21)



Neutral-Current Elastic νp events in MicroBooNE

We are able to reconstruct protons that traverse as few as eight wires (2.4 cm)

- Corresponds to a proton kinetic energy of at least 50 MeV
- Assuming elastic scattering this gives $Q^2 = 0.1$ GeV^2
  - $Q^2 = 2T_pM_p$



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

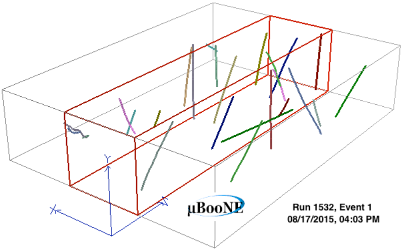
- Makes up 7% of neutrino interactions in MicroBooNE
- ~90% of all triggered events don't contain any neutrino interaction (only cosmics)
- We need accurate particle identification and event selection!

Reconstructed MicroBooNE events

Raw MicroBooNE event data goes through a series of reconstruction stages including:

- TPC noise deconvolution and hit finding
- 2D hit clustering and 3D track finding
- Optical hit and flash reconstruction

The final product is ∼20 reconstructed track objects and ∼1 reconstructed flash object in the beam timing window



The reconstructed track objects contain information about each track that can be used to classify track type

- There are two main classification goals:
  1. Separate neutrino-induced tracks from cosmic-induced tracks
     - Position — is it entering or near the top of the detector?
     - Angle — how forward or downward going is the trajectory?
  2. Identify neutrino-induced particle type (proton, muon, etc.)
     - Shape — how long, dense, or curvy is the track?
     - Charge — charge deposited, how steep is the dE/dx curve?

None of these tell the whole story — we can use a machine learning algorithm to optimize selections in multiple dimensions at once

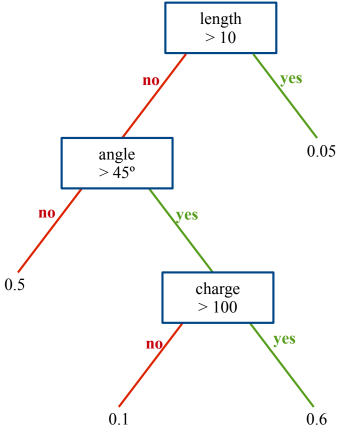
Boosted decision trees

Why trees?

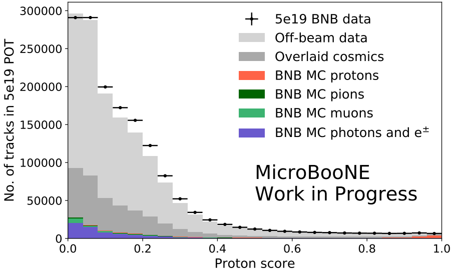
- Conceptually similar to traditional physics cuts
    - The feature space is easily interpretable/understandable
- Works with large datasets

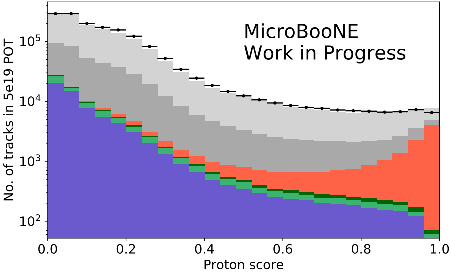
Boosted trees:

- Ensemble method (many weak learners combined)
- Trees are created iteratively
- Each new tree trains based on the mis-classification of the previous trees

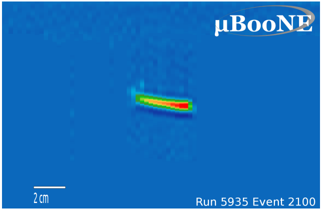


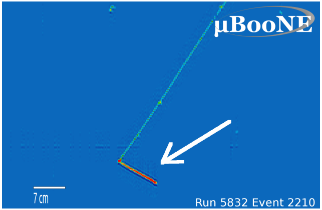
Decision tree proton ID output





- The plots show the decision tree proton ID output on a subset of MicroBooNE data (5e19 POT) and simulated data
  - The left plot is linear scale and the right plot is log scale
- Below are two examples of proton candidate tracks found in the data subset



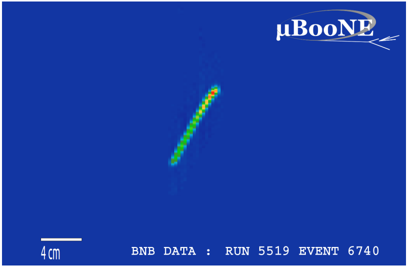


NC single proton selection

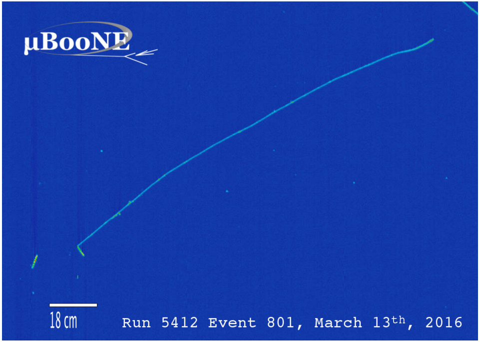
To select NC single protons we use the following information:

1. The proton score from the decision trees
2. The distance between the candidate track and the next closest track
3. The distance between the candidate track and the beam flash
4. The distance between any tracks identified as muons or pions by the decision trees and the beam flash
5. Whether or not the track is forward going

Example signal event:



Example background event:



NC single proton selection

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5. Whether or not the track is forward going

We use these variables as input to a logistic regression model and get a score, S, to cut on

$$S(g(\mathbf{x})) = \frac{e^{g(\mathbf{x})}}{1 + e^{g(\mathbf{x})}}$$

- $g(\mathbf{x})$ is a linear combination of the input values for a given event

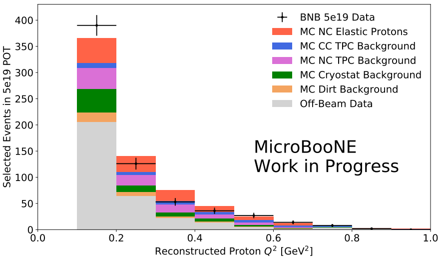
$$g(\mathbf{x}) = w_0 + w_1 x_1 + ... + w_N x_N$$

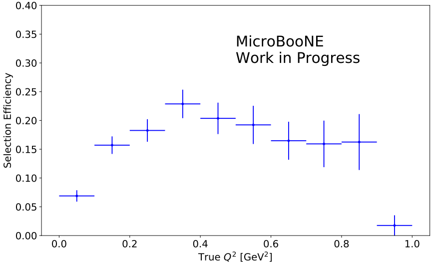
- $\mathbf{w}$ is a set of weights that is determined by fitting to the Monte Carlo
- $\mathbf{x}$ is the set of N input variables for a given event

Agreement between data subset and simulation

Selected all events with a logistic regression score of at least 0.8 in subset of data (5e19 POT):

- According to simulation, ~20% of these are from NC elastic interactions
- The backgrounds are mostly single protons from other types of interactions
- The simulation is based on GENIE v.2.12

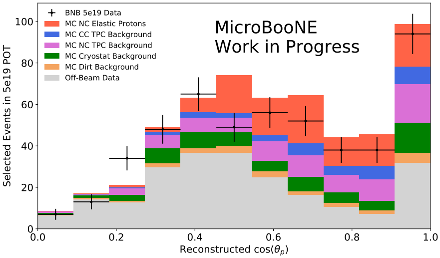


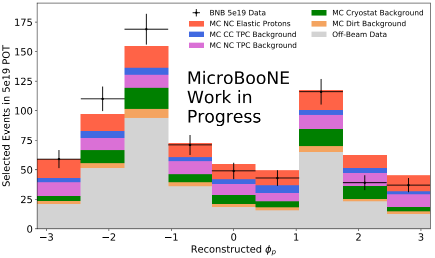


- The left plot shows the selected events in the data subset (black points), the simulation (colored stacked histograms), and the off-beam data (grey histogram) as a function of reconstructed Q^2
- The right plot shows the efficiency of simulated NC elastic proton interactions as a function of reconstructed Q^2
- The uncertainties are statistical only

Agreement between data subset and simulation

Selected all events with a logistic regression score of at least 0.8 in subset of data (5e19 POT):





- The left plot shows the selected events in the data subset (black points), the simulation (colored stacked histograms), and the off-beam data (grey histogram) as a function of reconstructed $\cos(\theta_p)$
- The right plot shows the selected events in the data subset (black points), the simulation (colored stacked histograms), and the off-beam data (grey histogram) as a function of reconstructed ϕ_p
- The uncertainties are statistical only

Event reweighting and G_A^s parameter estimation

To determine the effect of changing the strange axial form factor parameters we can vary them in the Monte Carlo and compare the resulting distributions directly to the distributions in our data

- Instead of rerunning the entire simulation for each possible value of Δs we can calculate the relative probability of an event given the new set of parameters

$$w_{\text{event}} = \frac{\sigma_{\text{mod.}}(E_\nu^{(\text{nucleon frame})}, Q^2, \theta = \Delta s, a_1, a_2)}{\sigma_{\text{simulation}}}$$

- We can estimate the G_A^s parameters by calculating the likelihood

$$P(D|\mathcal{M}(\Delta s, a_1, a_2)) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{1}{2}(D-\mathcal{M}(\Delta s, a_1, a_2))^2/\sigma^2}$$

    - $P(D|\mathcal{M}(\Delta s, a_1, a_2))$ is the probability of the measured data, D, given the model $\mathcal{M}$, which is a function of the parameters Δs, a_1, and a_2

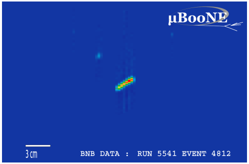
- To calculate the likelihood for each set of parameter values:
    1. Calculate weights for each of the Monte Carlo events for the given G_A^s values
    2. Multiply each MC event by its weight and calculate the new Q^2 distribution, $\mathcal{M}(\Delta s, a_1, a_2)$
    3. Compare the distribution directly to the Q^2 distribution in data, D, using the likelihood equation above

Next Steps:

- Run over the full MicroBooNE data set
    - MicroBooNE will collect 1.3e21 POT of data (20× the subset shown here)
    - Currently the Run I data set (∼2e20 POT) has been fully processed and reconstructed (4× the subset shown here)
- Incorporate systematic uncertainties (including nuclear effects)

Summary:

- The strange axial form factor is one of the largest missing pieces in the neutral current elastic neutrino-nucleon cross section
    - We can measure it down to low Q^2 in MicroBooNE and determine Δs



- The NC elastic signal, a single proton track, has many large backgrounds
    - Highly accurate proton ID is required to find single protons in a large surface detector
    - We are able to identify protons and select NC elastic events with a Q^2 as low as 0.1 GeV^2
- We will be able to extract the strange axial form factor parameters and their likelihood distributions using event reweighting methods

Thank you!