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

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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 GeV^2) have been determined in electron-neutron scattering

Neutral-Current Elastic νp Scattering

NC elastic νp cross section:

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

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

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

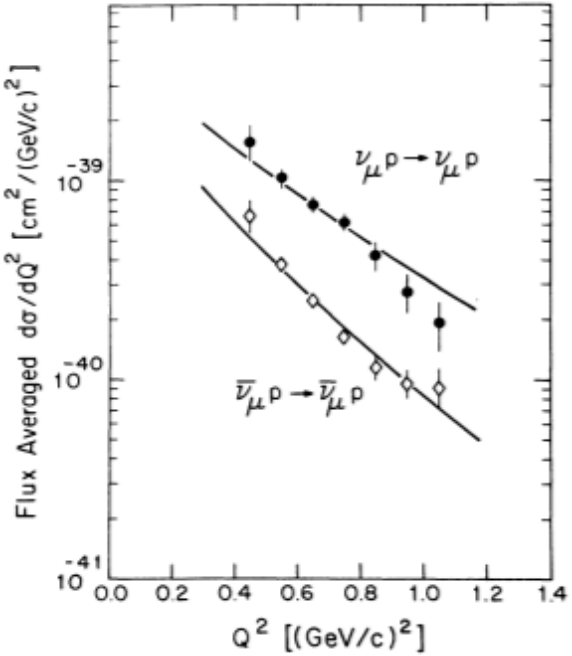
- $\Delta u - \Delta d$ has been determined in neutron decay

Δs 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]

[1] R. L. Jaffe and A. Manohar, Nucl. Phys. B337, 509 (1990).

Neutrino-Based Experimental Measurements of Δs

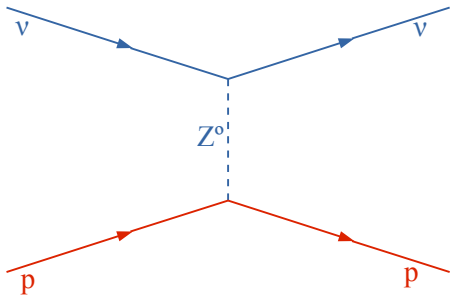


NC elastic measurement from the E734 neutrino scattering experiment at BNL

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

NC elastic νp signal is a single, isolated proton

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

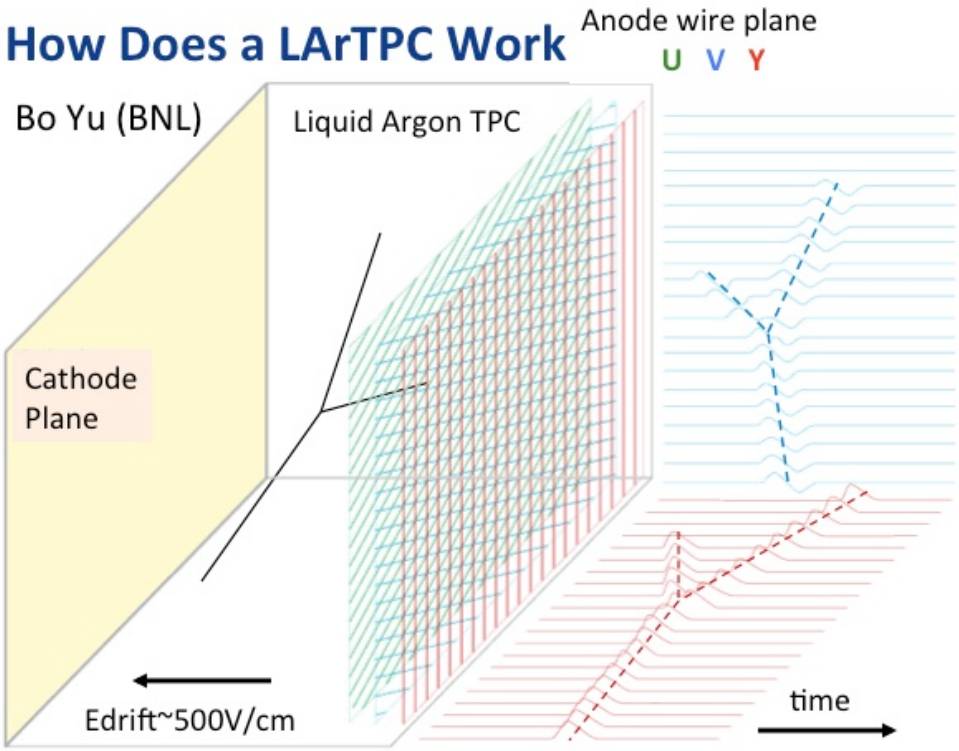


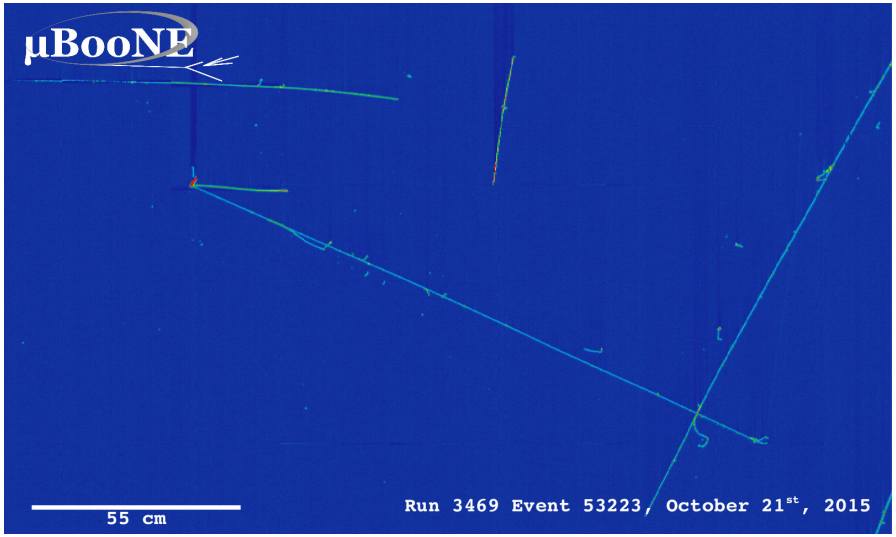
Need a dense, high-resolution detector
$\Rightarrow$ Liquid argon time projection chamber

[2] G.T. Garvey, W.C. Louis and D.H. White, Phys. Rev. C 48 (1993) 761.

Liquid Argon TPCs

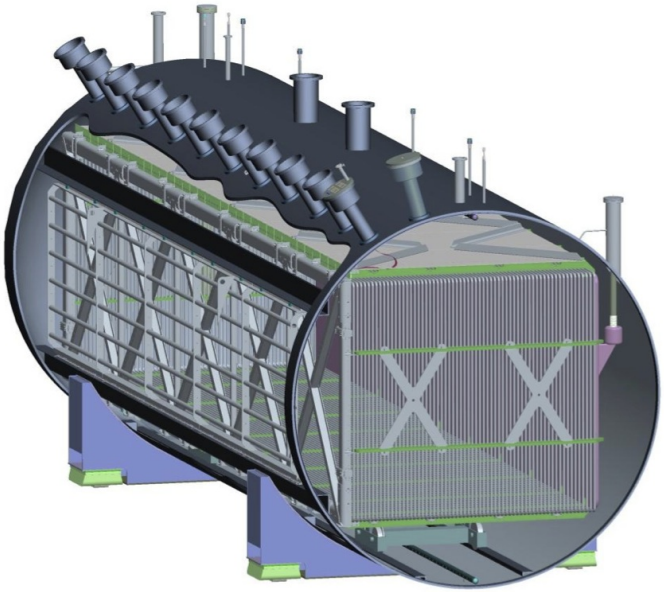
- Large liquid argon target for neutrino interactions
- Charged particles produced in interaction ionize the argon
- Ionization electrons drift to anode wire plane due to electric field





- 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 x 2.5 x 2.3 m^3
- 3 planes of ∼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 3.6e20 protons on target
  - ∼100,000 neutrino events

Photo: Fermilab

Measuring Δs in MicroBooNE

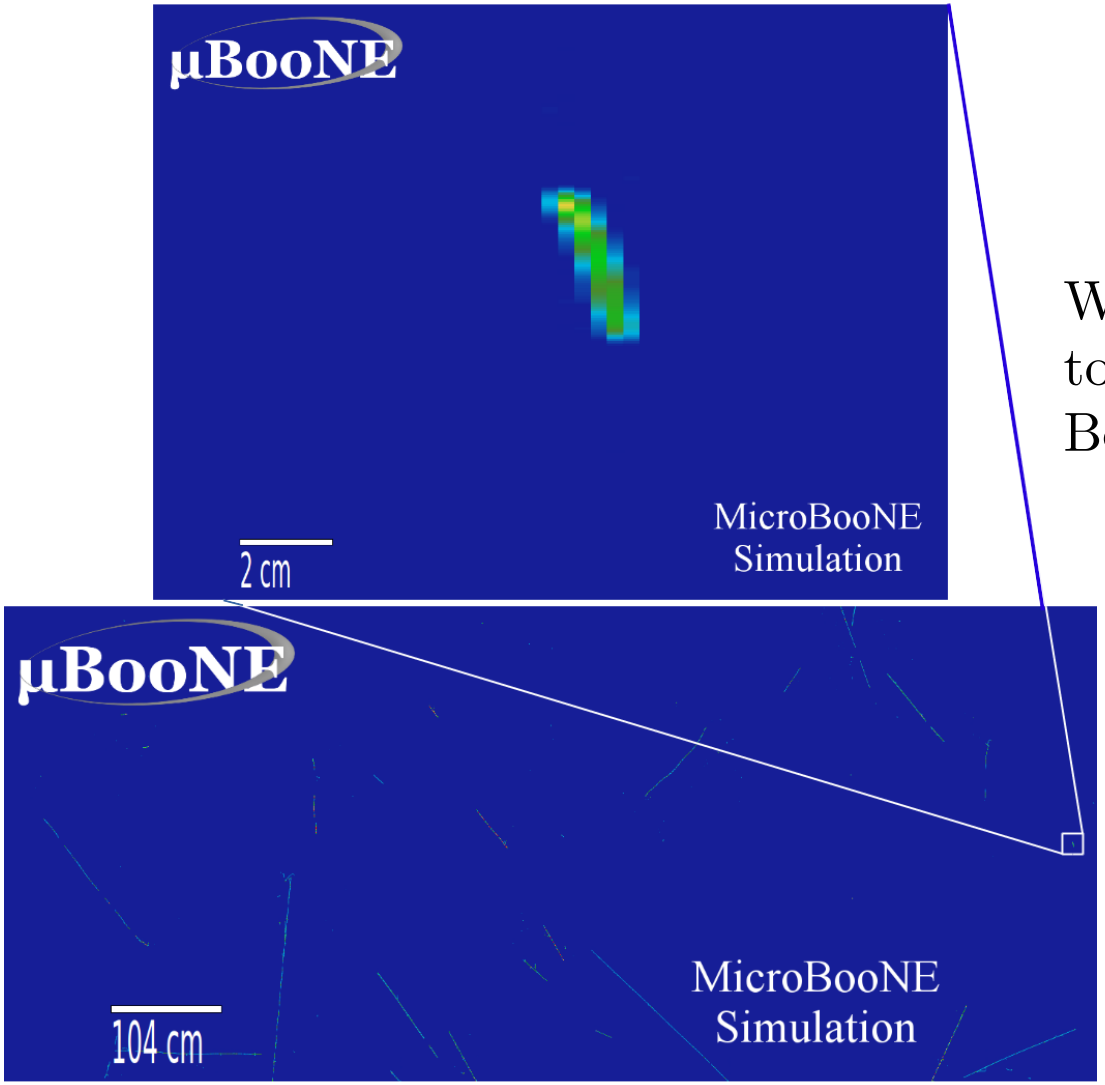
Measuring Δs:

- 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

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

- Will be able to detect protons that traverse as few as five wires (1.5 cm)
  - Corresponds to a NC elastic interaction with $Q^2 = 0.08\ \mathrm{GeV}^2$

Neutral-Current Elastic νp events in MicroBooNE



Simulated 70 MeV proton from NC elastic event (Q^2=0.13 GeV^2)

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

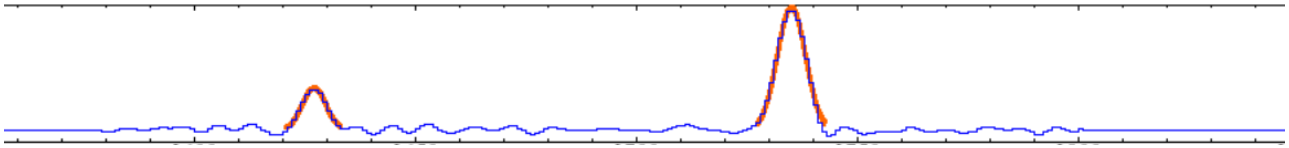
- Makes up ~5% of neutrino interactions in MicroBooNE
- Large cosmic background
- Need automated reconstruction and selection!
  - Hasn't been done before in a LArTPC

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



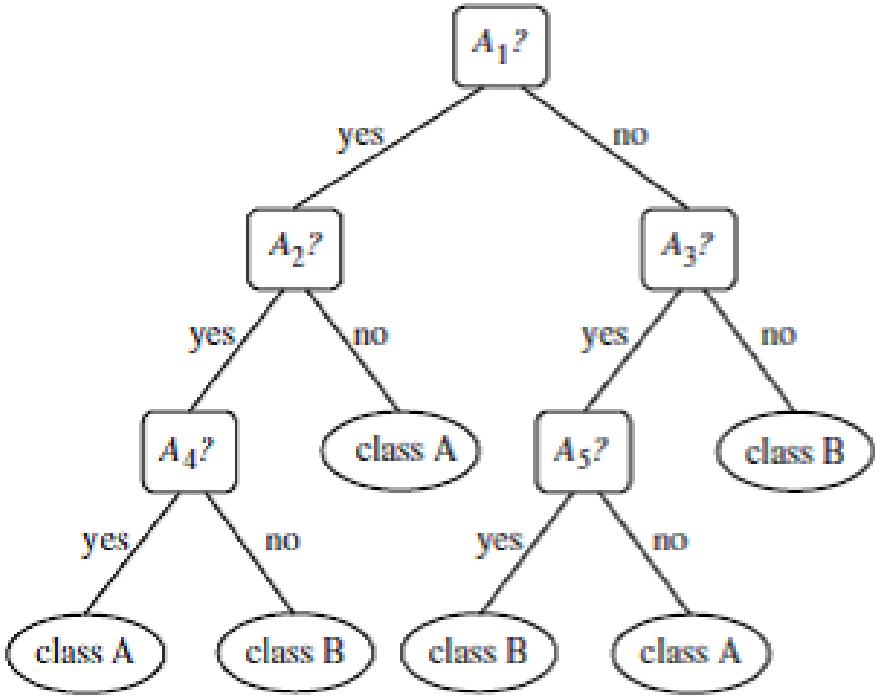
2. Neutrino track finding:
   - Combine hits from step (1) into tracks
   - Return set of neutrino event-like tracks
   - The current neutrino-finding algorithm finds ∼50% of simulated proton tracks — this efficiency is rapidly improving

- 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 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]

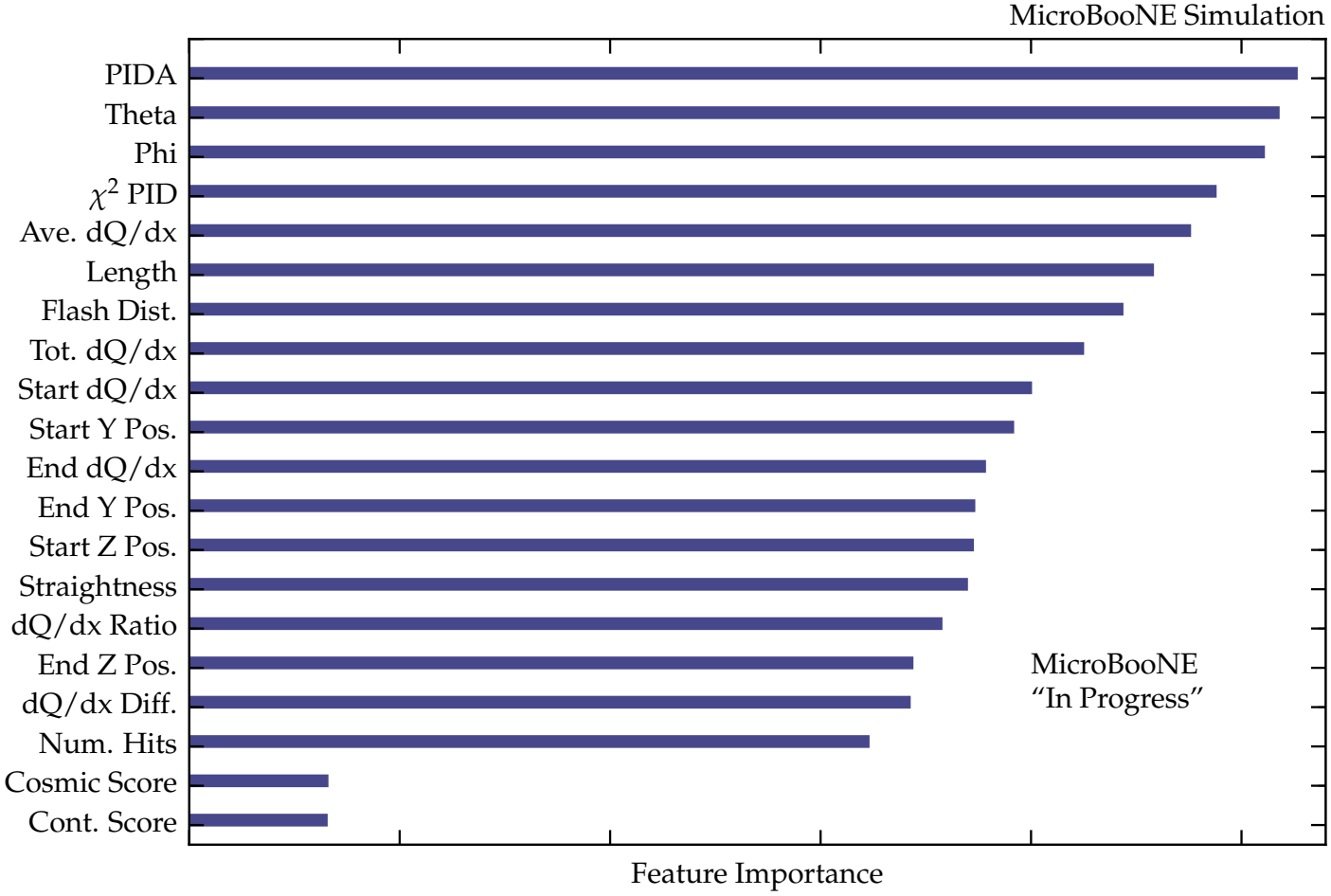
[3] Tianqi Chen and Carlos Guestrin. 22nd SIGKDD Conference on Knowledge Discovery and Data Mining (2016)

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

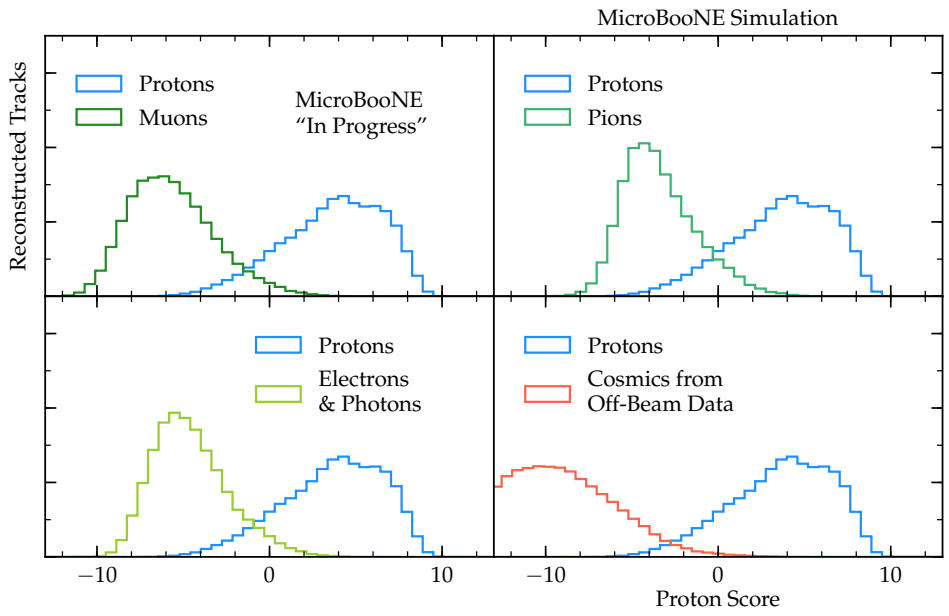
Each input is a collection of reconstructed track features:

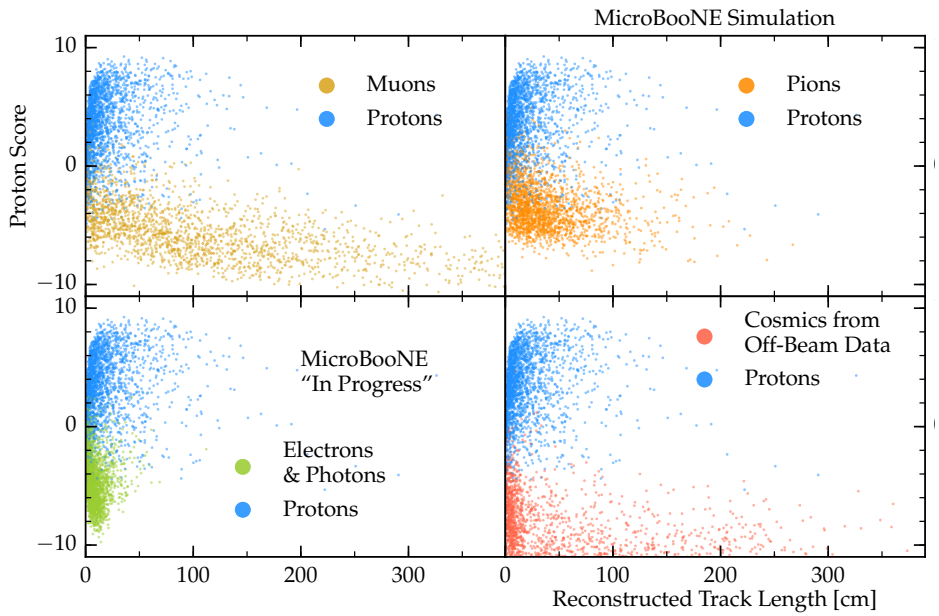


- Geometric: length, angle, ...
- Calorimetric: total charge, ...
- Optical: distance to flash, ...

Performance on Training Set

To train, we used ∼700,000 simulated neutrino events and cosmic data events in MicroBooNE





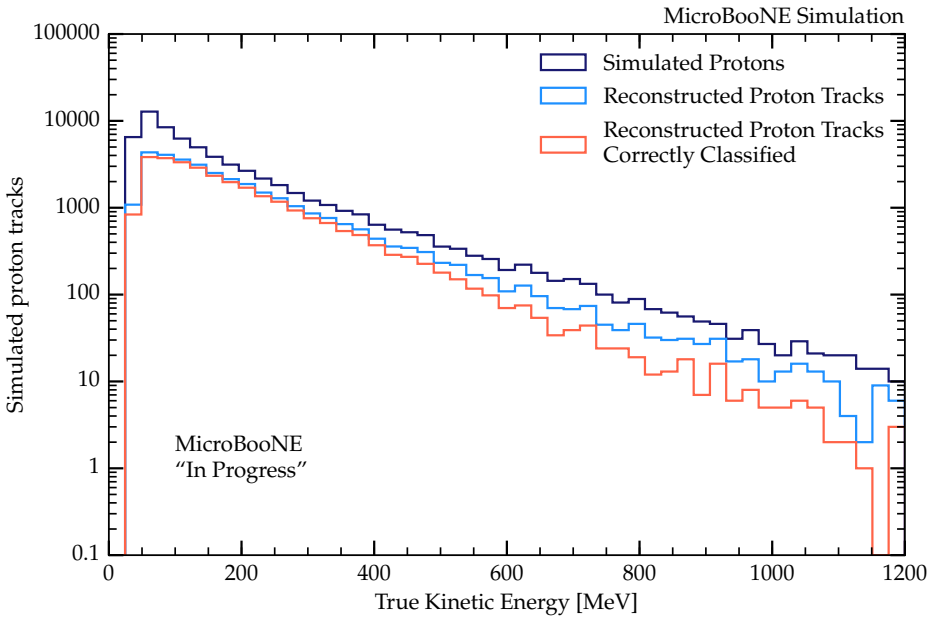
- "Proton Score" is the log-odds of a track being from a proton

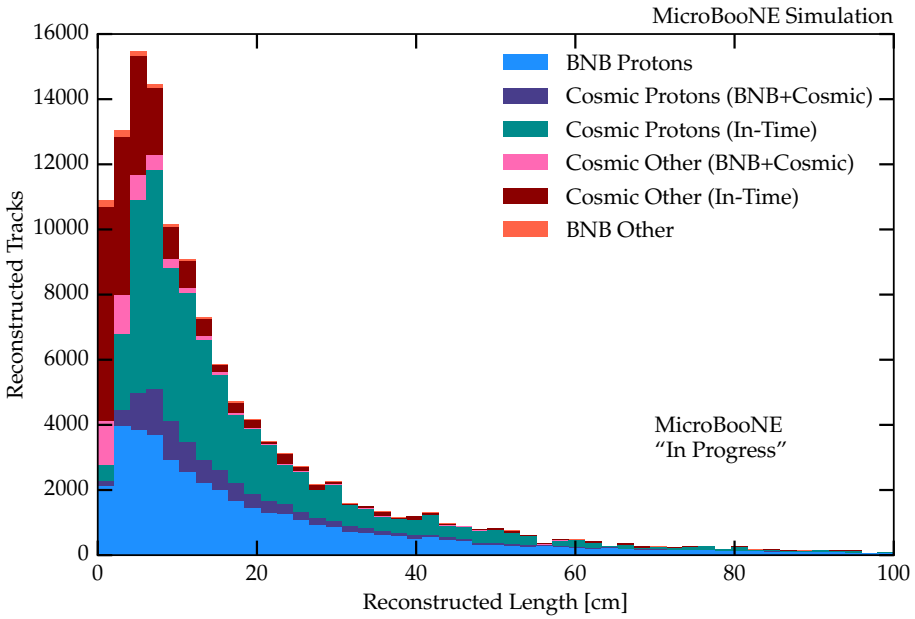
$$S_i = ln\left(\frac{p_i}{1-p_i}\right)$$

- $S = 0$ 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

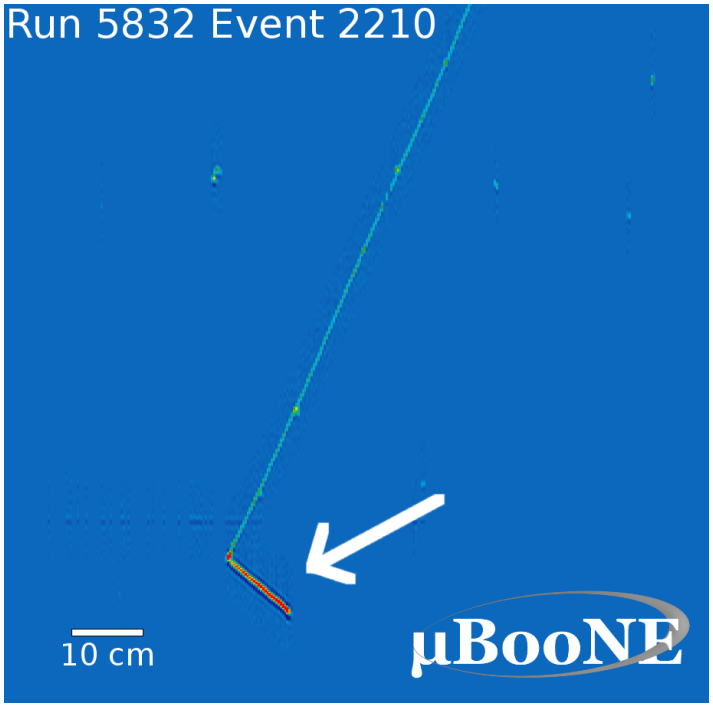




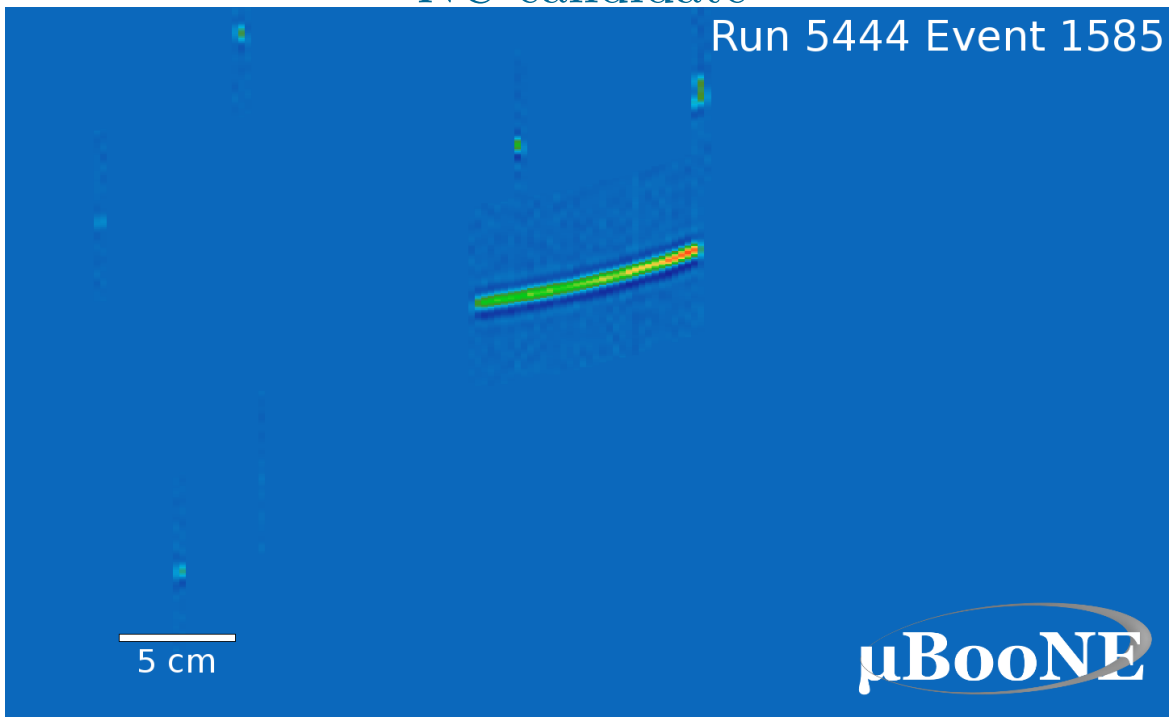
- Greater than 50% proton probability is considered a classification for these plots
- Efficiency is not very dependent on proton kinetic energy
- Most of background tracks are cosmic-induced protons

Example Protons from Data

CC candidate



NC candidate



Ran classifier on small subset of MicroBooNE data

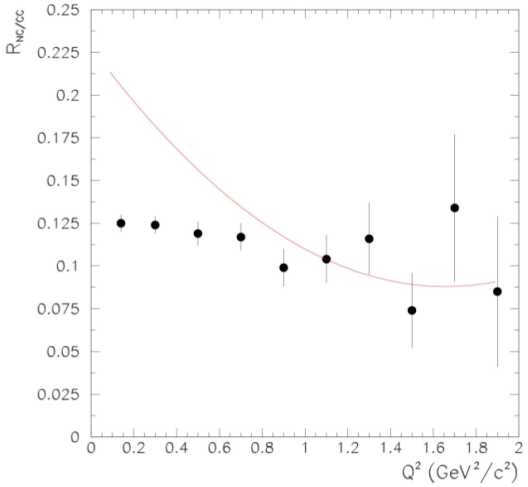
- Found both neutral and charged-current elastic candidate events
- Can select neutral-current by requiring the proton be isolated

Impact on Form Factors and Δs

Predictions based on 2e20 POT and 100% efficiency

- Reduce uncertainty on Δs in global fit by factor of 10

Global Fit from Currently Available Data



Note: Neutrino data stop at ~0.5 GeV
Extrapolation probably meaningless

Vassili Papavassiliou, NMSU
Nuance Simulation for MicroBooNE Detector
January 2010

MicroBooNE: Projected Impact on Nucleon Form Factor Measurements

(3) Repeat fit using simulated MicroBooNE data; see what happens to **uncertainties**.

Q^2	$R_{NC/CC}$	$dR_{NC/CC}$
0.08-0.2	0.206	0.005
0.2-0.4	0.181	0.005
0.4-0.6	0.156	0.007
0.6-0.8	0.136	0.009
0.8-1.0	0.118	0.012
1.0-1.2	0.101	0.015

Parameter	Fit to Existing Data	Including μBooNE
ρ_s	$\pm 0.09 \pm 0.03$	$\pm 0.08 \pm 0.02$
μ_s	$\pm 0.029 \pm 0.022$	$\pm 0.023 \pm 0.017$
ΔS	$\pm 0.42 \pm 0.19$	$\pm 0.036 \pm 0.003$
Λ_A	$\pm 1.0 \pm 1.1$	$\pm 0.42 \pm 0.03$
S_A	$\pm 0.5 \pm 0.2$	$\pm 0.05 \pm 0.02$

Not much effect on vector form factors (no surprise)

BIG effect on axial form factor (expected!)

$$G_E^s = \rho_s \tau \qquad G_M^s = \mu_s \qquad G_A^s = \frac{\Delta S + S_A Q^2}{\left(1 + Q^2/\Lambda_A^2\right)^2}$$

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Stephen Pate, Dennis Trujillo
Strangeness Vector and Axial-Vector Form Factors of the Nucleon.
arXiv:1308.5694v1 [hep-ph]
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 Δs by an order of magnitude

Thank you!