Automated proton track identification in MicroBooNE using gradient boosted decision trees

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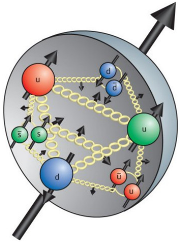
Strange quark contribution to nucleon spin

The net spin of the proton is composed of contributions from its quarks and gluons



$$\frac{1}{2} = \frac{1}{2}\sum_q \Delta q + \Delta G + L_q + L_g$$

- $\sum_q \Delta q$ and ΔG are the contributions from the spin and L_q and L_g are the contributions from the angular momentum of the quarks and gluons
    - $\sum_q \Delta q = \Delta u + \Delta d + \Delta s$

We want to know the total contribution to the nucleon spin that comes from the spin of strange quarks and antiquarks (Δs)

$$\Delta s = (s^{\uparrow} + \bar{s}^{\uparrow}) - (s^{\downarrow} + \bar{s}^{\downarrow})$$

Δs was expected to be zero

- Found to be negative in polarized, charged-lepton, DIS
    - Assumes flavor SU(3) symmetry
    - Analyses give range $\Delta s = -0.08$ to -0.14 [1]
    - Measurements in semi-inclusive DIS gave results consistent with zero

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

Neutral-Current Elastic νp Scattering

Δs can be determined independently in neutral-current (NC) elastic scattering:

- NC elastic νp cross section:

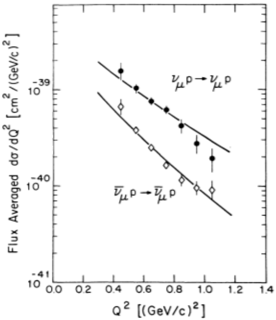
$$\left(\frac{d\sigma}{dQ^2}\right)_\nu^{NC} = \frac{G_F^2}{2\pi}\left[\frac{1}{2}y^2(G_M^{NC})^2 + \left(1 - y - \frac{M}{2E}y\right)\frac{(G_E^{NC})^2 + \frac{E}{2M}y(G_M^{NC})^2}{1 + \frac{E}{2M}y} + \left(\frac{1}{2}y^2 + 1 - y + \frac{M}{2E}y\right)(G_A^{NC})^2 + 2y\left(1 - \frac{1}{2}y\right)G_M^{NC}G_A^{NC}\right]$$

- G_E^{NC}, G_M^{NC}, G_A^{NC} are form factors representing the electric, magnetic, spin and distributions in the nucleon
- 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

Neutrino-Based Experimental Measurements of Δs

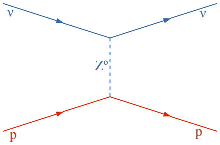


NC elastic measurement from the E734 neutrino scattering experiment at BNL

- 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 shape of form factor
- Much of uncertainty due to lack of data at low momentum transfer (Q^2)

NC elastic νp signal is a single, isolated proton

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

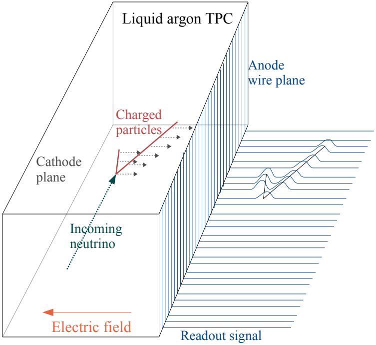


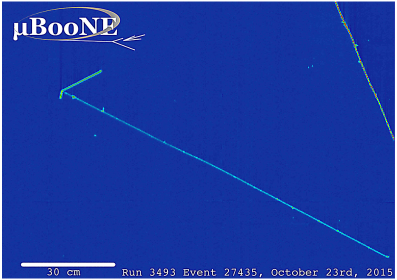
Need a dense, high-resolution detector
$\Rightarrow$ Liquid argon time projection chamber

[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





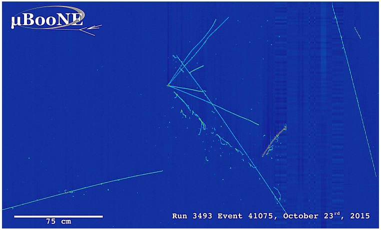
- Signal from electrons on wires is read out
- Reconstruct images of events

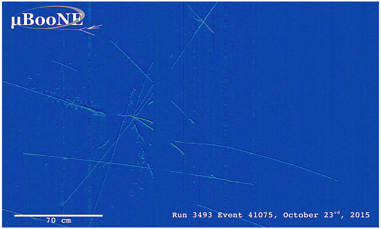
MicroBooNE LArTPC

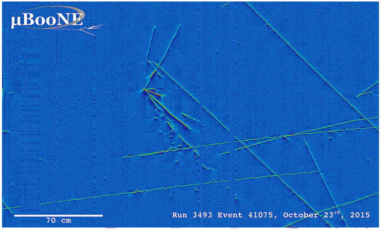
Photo: Fermilab

MicroBooNE detector:

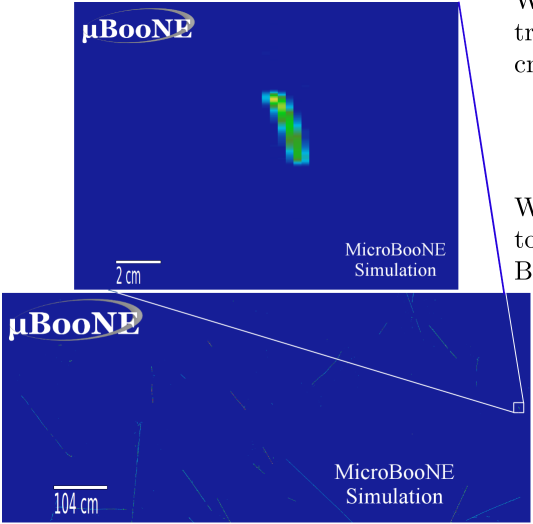
- 3 planes of ∼3000 wires each with 3mm spacing
- 10 x 2.5 x 2.3 m^3
- Each event is ∼30 MB file size
- Installed in detector hall summer 2015
- Two years of running:
  have collected 5.6e20 protons on target
  - ∼200,000 neutrino events







Neutral-Current Elastic νp events in MicroBooNE



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

We are able to detect protons that traverse as few as five wires (1.5 cm)

- Corresponds to a NC elastic interaction with $Q^2 = 0.08$ GeV^2

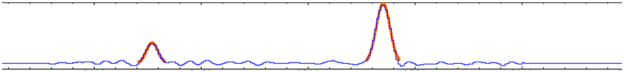
We expect 10,000 NC elastic proton events above during MicroBooNE's three year run

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

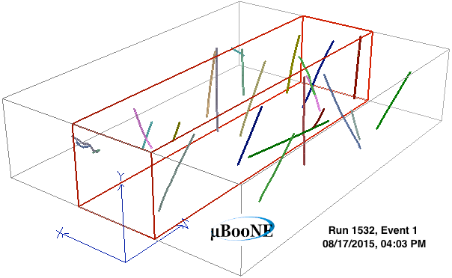
LArSoft Reconstructed Tracks

Reduce the problem by reconstructing track objects before identifying the particle and interaction type

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



2. Track finding:
   - Combine hits from step (1) into tracks
   - Return set of reconstructed three-dimensional tracks



Have gone from 3 × 20 million pixels to ∼20 track objects without losing much information

- Big reduction in dimensionality!

Reconstructed track features

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
  2. Identify neutrino-induced particle type (proton, muon, etc.)

Example goal (1) features:

- Position — is it entering or near the top of the detector?
- Angle — how forward or downward going is the trajectory?

Example goal (2) features:

- 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?

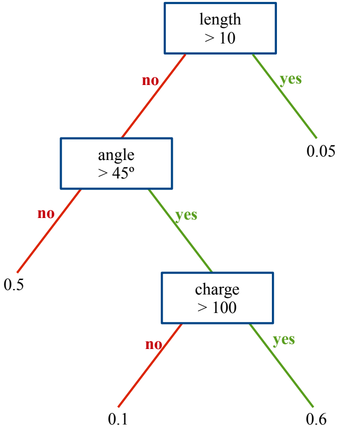
- Conceptually similar to traditional physics cuts
    - The feature space is easily interpretable/understandable
- Works with large datasets

Regression tree:

- A decision tree where each leaf contains a continuous outcome
- Each split made to maximize information gain or minimize loss function

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



Boosting and the XGBoost[3] algorithm

Boosting (continued):

- The prediction is a sum of the output of each tree in the ensemble

$$\hat{y}_i = \sum_{k=1}^{K} f_k(\mathbf{x}_i)$$

- f_k represents the structure and weights of the kth tree

  The goal is to minimize the objective function:

$$\mathcal{L} = \sum_i l(\hat{y}_i, y_i) + \sum_k \Omega(f_k)$$

- The loss function, $l(\hat{y}_i, y_i)$, measures the difference between a prediction ($\hat{y}_i$) the true label (y_i) of the ith sample
- The regularization term, $\sum_k \Omega(f_k)$, penalizes the complexity of the trees

[3] Tianqi Chen and Carlos Guestrin. 22nd SIGKDD Conference on Knowledge Discovery and Data Mining (2016) arXiv:1603.02754 (https://github.com/dmlc/xgboost)

Boosting and the XGBoost[3] algorithm

Gradient-Boosting:

- The loss function, l at tree t is

$$l(y_i, \hat{y}_i^{(t-1)} + f_t(\mathbf{x}_i))$$

- the difference between the true label (y_i) and the prediction of the existing ensemble ($\hat{y}_i^{(t-1)}$) plus the output of the new tree ($f_t(\mathbf{x}_i)$)
- To simplify the computation, use the second-order approximation:

$$l(y_i, \hat{y}_i^{(t-1)} + f_t(\mathbf{x}_i)) \approx l(y_i, \hat{y}_i^{(t-1)}) + \frac{\partial\, l(y_i, \hat{y}_i^{(t-1)})}{\partial\, \hat{y}^{(t-1)}} f_t(\mathbf{x}_i) + \frac{1}{2} \frac{\partial^2\, l(y_i, \hat{y}_i^{(t-1)})}{\partial^2\, \hat{y}^{(t-1)}} f_t^2(\mathbf{x}_i)$$

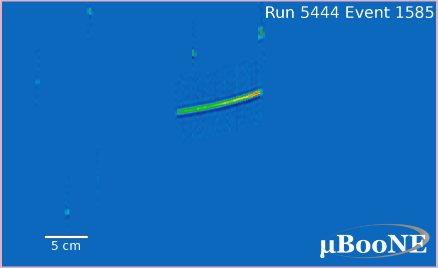
Now only need to compute the loss function and its derivatives once per iteration instead of for each split

[3] Tianqi Chen and Carlos Guestrin. 22nd SIGKDD Conference on Knowledge Discovery and Data Mining (2016) arXiv:1603.02754 (https://github.com/dmlc/xgboost)

MicroBooNE specifics

Using a multi-class classifier

- Classes: proton, muon, pion, electron/photon, and cosmic
  - Protons include both neutrino and cosmic induced simulated tracks
  - Muons, pions, electrons, and photons are neutrino induced like
  - Cosmics are any non-proton cosmic induced tracks
  - Classifies each track independently
  - Returns five probabilities per track

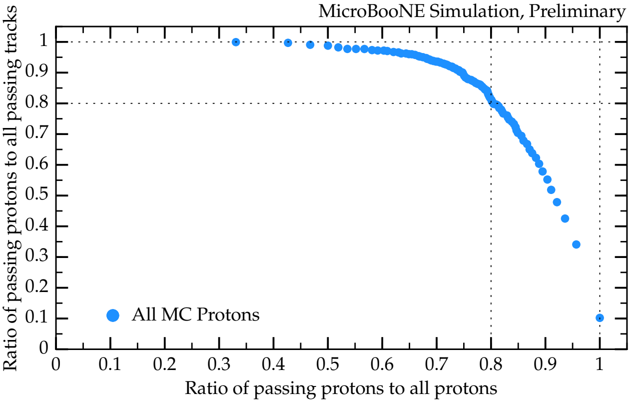


$$
\begin{aligned}
P(\mathrm{p}) &= \mathbf{0.9789} \\
P(\mu^{\pm}) &= 0.0012 \\
P(\pi^{\pm}) &= 0.0067 \\
P(e^{\pm}/\gamma) &= 0.0075 \\
P(\mathrm{cosmic}) &= 0.0058
\end{aligned}
$$

- Each track is a set of 20 reconstructed track features
  - Described on slide 9
- Trained on simulated neutrino and cosmic events

Performance on simulated protons

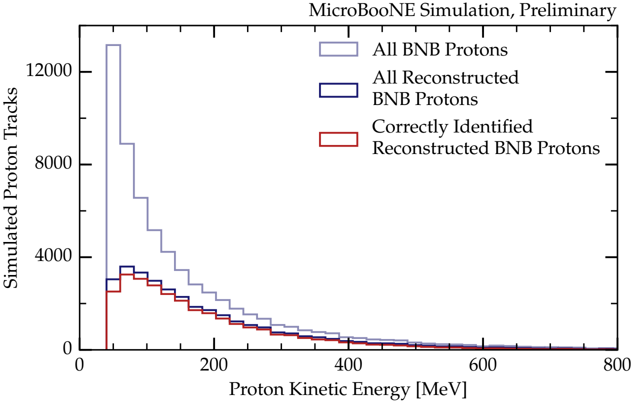
Tested the classifier on Monte Carlo simulated neutrino and cosmic events in MicroBooNE



- Showing the efficiency vs. purity of the selection on all protons in the simulation
- The different points represent cuts on different values of proton probability

Performance on simulated protons

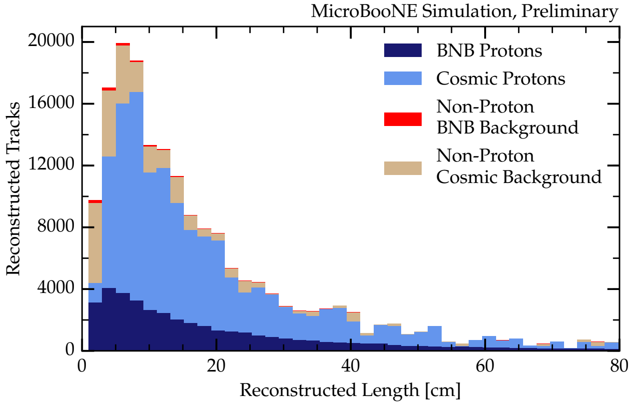
Tested the classifier on Monte Carlo simulated neutrino and cosmic events in MicroBooNE



- Showing the number of simulated neutrino-induced ("BNB") protons **generated**, **reconstructed**, and **classified correctly**
- A proton probability of greater than 50% is considered classified as a proton

Performance on simulated protons

Tested the classifier on Monte Carlo simulated neutrino and cosmic events in MicroBooNE



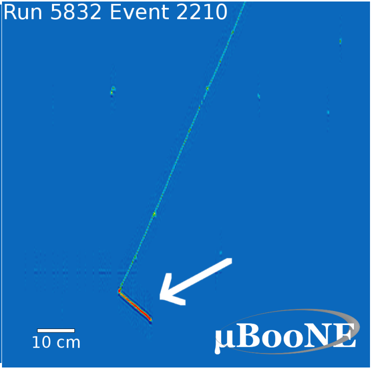
- Showing the different simulated track types classified as protons
- The blues are protons and the others are mis-classified backgrounds
- A proton probability of greater than 50% is considered classified as a proton

Example events from data

- Can select events by requiring that reconstructed tracks are indentified as specific particle types

NC candidate

CC candidate



- Isolated track classified as proton

- Tracks classified as proton and muon

Conclusion

- Can determine the net spin of the strange quarks in the proton through neutral-current elastic νp scattering
- MicroBooNE can measure low Q^2 neutral-current elastic neutrino-proton events
  - The signal is a single short proton track
- Can reconstruct track objects to reduce the dimensionality of the classification problem
  - From 30MB events to tracks with 20 features
- Can accurately classify particle types using gradient-boosted decision trees

Thank you!