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DPF 2017
MiniBooNE Low-Energy Excess

• MiniBooNE saw a $\sim 3\sigma$ $\nu_e$-like excess between 200 and 600 MeV
• MiniBooNE’s neutrino result is in tension with global 3+1 model fit

• MiniBooNE
  ‣ Significant fraction of background from $\gamma/e^-$ mis-ID
  ‣ Systematic error $\approx$ statistical error

• MicroBooNE
  ‣ Same beam and similar baseline
  ‣ LArTPC gives better $\gamma/e^-$ separation, better background rejection
The MicroBooNE Experiment

- Micro Booster Neutrino Experiment
- 85 ton (active) Liquid Argon Time Projection Chamber
- Located in the Fermilab Booster Neutrino Beam
- $\nu_\mu \rightarrow \nu_e$ appearance experiment
- >95% detector uptime
- $6.1 \times 10^{20}$ POT on tape in the first 18 months of running, of proposed $6.6 \times 10^{20}$ POT in three years
The MicroBooNE Detector

Anode planes: U, V, Y

3 mm spacing

Beam

E_{drift}

Induction

Collection

Time

Wire

“Design and Construction of the MicroBooNE Detector”
JINST 12, P02017 (2017)
A Few Words About Deep Learning

• For us, deep learning $\approx$ convolutional neural networks (CNNs)

• CNNs have been developed primarily for image analysis; we apply them to MicroBooNE event displays
  ‣ For more, see T. Wongjirad’s talk from Tuesday (here)

• I will discuss two uses: classification and semantic segmentation

Example of CNN classification, from “ImageNet Classification with Deep CNNs”, NIPS (2012)

Definition of the Signal

• Define signal to be events with one lepton and one proton (1l-1p) topology
  › Lepton (electron or muon) with kinetic energy >35 MeV
  › One proton with kinetic energy >60 MeV (possibly others below that energy threshold)

• These are “golden events” — low background (~only intrinsic $\nu_e$, constrained by $\nu_\mu$)

$\nu_e$ event: signal

$\nu_\mu$ event: used to constrain the flux and cross-section systematics
Overview of Reconstruction Chain

- PMT Pre-Cuts
- Cosmic Tagging & ROI Finding
- Track vs. Shower Pixel Labeling
- 3D Vertex Reco
- Particle ID
Reconstruction Chain

- PMT Pre-Cuts
  - PMT pre-cuts reject low-energy noise and other backgrounds
  - Keep >96% of neutrinos (based on simulations)
  - Reject >75% of background (based off-beam data)

- Cosmic Tagging & ROI Finding

- Track vs. Shower Pixel Labeling

- 3D Vertex Reco

- Particle ID
Reconstruction Chain

- PMT Pre-Cuts
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An Event Display

These low-energy neutrino events are small, and we have lots of cosmics.

The $\nu_\mu$ event from a few slides ago.

Cosmic Data: Run 6280  Event 6812  May 12th, 2016
Cosmic Pixel Tagging

- Cosmic and other background tracks cross the TPC boundary
- Identify and tag these boundary crossing points
  - Top/bottom: crossings deposit charge on triplets of wires that meet at the boundary
  - Upstream/downstream: crossings deposit charge on the first/last wires on the Y plane
  - Anode/cathode: crossings have specific $\Delta T$ between PMT flash and wire signal
- Build up from end points by following charge using 3D path finding
Region-of-Interest Finding

After tagging cosmic tracks, draw 3D region-of-interest (ROI) box around untagged pixels
Reconstruction Chain

1. PMT Pre-Cuts
2. Cosmic Tagging & ROI Finding
3. Track vs. Shower Pixel Labeling
4. 3D Vertex Reco
5. Particle ID
Track vs. Shower Pixel Labeling

Goal: separate tracks and showers to make the 3D vertex reconstruction and track/shower clustering more efficient.

Semantic segmentation network (SSNet) takes in the wire information and labels each pixel in the image as “track-like” (yellow), “shower-like” (cyan), or “background” (blue).

Wire signal amplitude

K.E.\textsubscript{e} = 341 MeV
K.E.\textsubscript{p} = 161 MeV
SSNet Performance on Data

• To study the performance of SSNet on data, we ran over a sample of selected CC $\pi^0$ events
  ‣ “Study Towards an Event Selection for Neutral Current Inclusive Single $\pi^0$ Production in MicroBooNE”, MicroBooNE Public Note MICROBOONE-NOTE-1006-PUB

• Here, the proton and muon are correctly labeled as track-like

• The two $\gamma$ showers are correctly labeled as shower-like, except the beginning “stub” of one is labeled as track-like

• Overall, SSNet pixel labeling accuracy >90%
Reconstruction Chain

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- Particle ID
If both track-like and shower-like pixels are found (e.g., a $\nu_e$ event):

- For each plane: find endpoint of track where shower is attached
- Correlate these endpoints across planes to identify 3D region
- Scan 3D space around the candidate vertex
- Add a vertex at the 3D point that best matches where the track and shower meet across all three planes
3D Vertex Reconstruction

If there are only track-like pixels (e.g., $\nu_\mu$ normalization sample):

- For each plane: create 2D vertex seeds at any kink points
- Scan space around each seed to find the best vertex point
- Combine information from all three planes
- If the best vertices from each plane are 3D-consistent, add a vertex at that 3D point
Reconstruction Chain

- PMT Pre-Cuts
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Particle Identification

- After 3D vertex reconstruction, cluster pixels attributed to each single track or shower coming out of the vertex
- Feed individual particle clusters into a CNN trained to do single-particle identification (HighRes GoogLeNet)
- Led to MicroBooNE’s first collaboration publication!
  - “Convolutional Neural Networks Applied to Neutrino Events in a LArTPC”, JINST 12, P03011 (2017)

<table>
<thead>
<tr>
<th>Particle</th>
<th>Correct ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^-$</td>
<td>77.8 ± 0.7%</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>83.4 ± 0.6%</td>
</tr>
<tr>
<td>$\mu^-$</td>
<td>89.7 ± 0.5%</td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>71.0 ± 0.7%</td>
</tr>
<tr>
<td>$p$</td>
<td>91.2 ± 0.5%</td>
</tr>
</tbody>
</table>
Reconstruction Chain

- PMT Pre-Cuts
- Cosmic Tagging & ROI Finding
- Track vs. Shower
  - Pixel Labeling
- 3D Vertex Reco
- Particle ID

Next Steps: Systematic Uncertainties
Topological Sidebands

• In general, a “sideband” study uses events that are outside the “analysis box” but have important similarities to events inside it

• Typically, use events that are similar in their kinematics — instead, we consider events that are similar in topology

• In particular, we want to draw sidebands from data to help us understand CNN performance on simulations vs. detector data

• We plan to use these samples to:
  ‣ Test simulation vs. data agreement
  ‣ Study efficiencies

• Examples of topological sidebands
  ‣ CC $\pi^0$ — has a $1\mu$-$1p$ vertex like $\nu_\mu$ events; already used to test SSNet
  ‣ NC $\pi^0$, where one photon converts near the vertex — has $1e$-$1p$ topology like $\nu_e$
  ‣ Stopping muons — track + EM shower topology, like $\nu_e$
  ‣ “Chimera” events
Chimera Events

• Chimera events are made by “copy-pasting” single-particle components from cosmic ray data that are selected and combined to create neutrino-like events (in terms of topology)
  ‣ Use proton and stopping muon for $\nu_\mu$, proton and electron (or EM shower) for $\nu_e$
  ‣ Allow for but want to minimize spatial translation; do not allow rotation
  ‣ Truncate the entering portion of muon tracks, so they appear contained within the fiducial volume of the detector

• They can provide a sample of data-based events that cover the entire physics parameter space of interest for our signal

• Above: One of the first $\nu_\mu$-like chimeras
Summary

• Fully automated reconstruction chain for low-energy neutrino events, which includes traditional and deep learning algorithms
  ‣ Reject cosmic backgrounds
  ‣ Find the neutrino interaction within the event
  ‣ Separate tracks and showers, cluster
  ‣ Reconstruct 3D vertex
  ‣ Identify individual particles

• Full 3D reconstruction in progress
  ‣ dE/dx, event selection
  ‣ Physics!

• Efficiency and systematics studies in progress

• Important development for upcoming LArTPC programs

Thank you!
Backup Slides
The MicroBooNE Detector

Anode planes: U, V, Y

3 mm spacing

“Design and Construction of the MicroBooNE Detector”
JINST 12, P02017 (2017)
A Few Words About Deep Learning

- Convolutional neural networks have several important properties
  - “Neurons” scan over the image looking at a limited set of pixels at each point
  - They “learn” local, translationally invariant features
  - Each layer of neurons builds on the features found by the previous ones to reach increasing levels of complexity/abstraction

- In the above, the black-and-white boxes show the “activation” of neurons in response to the images; the neuron highlighted on the right responds to faces, while the one on the left responds to text

https://www.youtube.com/watch?v=AgkfIQ4lGaM
More on Deep Learning

- See T. Wongjirad’s talk from Tuesday (here)
PMT Pre-Cuts

- Keep >96% of neutrinos (based on simulations)
- Reject >75% of background (based on rejection of off-beam data)
PMT Pre-Cuts

- Reject: Random, single-photoelectron noise (~200 kHz)
  - No time correlation between these single-photoelectron pulses
  - Require 20 photoelectrons in 93.75 ns — this becomes the definition of a “signal”
- Reject: In-time flash caused by Michel electron, from decay of a cosmic muon
  - Require no signal for 2 µs before the beam window
- Reject: PMT-based noise
  - Limit the total amount of the light collected by a single PMT to <60% of the total light
- Keep >96% of neutrinos (based on simulations)
- Reject >75% of background (based on rejection of off-beam data)
Cosmic Pixel Tagging

- Cosmic and other background tracks cross the TPC boundary
- Identify and tag these boundary crossing points
  - **Top/bottom**: crossings deposit charge on triplets of wires that meet at the boundary
  - Upstream/downstream: crossings deposit charge on the first/last wires on the Y plane
  - Anode/cathode: crossings have specific $\Delta T$ between PMT flash and wire signal
- Connect end points by following the charge using 3D path finding
Cosmic and other background tracks cross the TPC boundary

Identify and tag these boundary crossing points

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• Connect end points by following the charge using 3D path finding
Examples of Topological Sidebands

CC $\pi^0$

NC $\pi^0$, one $\gamma$ converts near vertex

Truncated stopping muon