Single Photon Emission in 
Neutrino-Nucleon Coherent Scattering

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NEVIS LABS REU 2021
Background

- MiniBooNE observed an excess of events at low energies not accounted for in their simulation.
- Detector was not capable of distinguishing between electron and photon events and so MicroBooNE was designed.
- Both photons and electrons induce electromagnetic showers but photons (electrically neutral) have a gap between the vertex point and the start of the shower.
- Single photon group has been exploring $\Delta$ baryon radiative decay as a potential explanation for the excess.
- My project was to explore coherent neutrino-nucleus scattering as another process contributing to excess of low energy photon emission.
Coherent Scattering

Diagram of neutrino-nucleon coherent scattering

- Using Alvarez-Ruso model for coherent scattering
  - Note: no photon energies < 140 MeV simulated
- In coherent scattering, nucleus is left in its ground state
- Can occur if incoming muon neutrino doesn’t have enough energy to alter structure of nucleus and excite Δ resonance
- We expect its signature to be a low-energy photon that is travelling mostly in forward direction to conserve momentum
- Simulating detector in Monte Carlo simulator and analyzing events to see how these events behave
- Use this information to adjust single photon analysis to look for single photon events caused by coherent scattering in our actual detector
MicroBooNE Detector

- 170 ton liquid-argon time projection chamber (LArTPC)
  - Argon is a good neutrino target because it’s dense, boosts event rate
- Charged particles traverse liquid argon and leave a trail of ionization electrons and scintillation photons
  - Ionization trail moves through Argon at drift velocity kept approximately constant by a large electric field maintained throughout the volume
- Consists of a cathode plane on one side and three planes of wires on the opposite end to record the signals from the drifting ionization electrons
  - Wire planes 0 & 1 are induction planes, plane 2 is the collection plane
  - Some of these wires are dead and so charges don’t induce voltage on them
Equipment

**LArSoft**
Overarching framework which calls on other pieces of code
a set of detector-independent software tools for the simulation, reconstruction and
analysis of data from liquid argon (LAr) neutrino experiments

<table>
<thead>
<tr>
<th>GENIE</th>
<th>Geant4</th>
<th>DetSim</th>
<th>Pandora</th>
</tr>
</thead>
<tbody>
<tr>
<td>a ROOT-based neutrino Monte Carlo event generator written in C++</td>
<td>&quot;the simulation of the passage of particles through matter&quot;</td>
<td>Simulates detector’s electric field, dead wires, voltage readout on wires, etc.</td>
<td>Takes simulated hits and uses pattern recognition to cluster them into higher level classes (tracks &amp; showers)</td>
</tr>
<tr>
<td>Simulates neutrino interactions but doesn’t have a time component</td>
<td>Monte Carlo simulation which propagates the particles in the interaction</td>
<td>Generates event displays</td>
<td>Reconstruction stage</td>
</tr>
</tbody>
</table>
GENIE Simulations

- Analyzed small set of simulated interactions with a constant energy (= 700 MeV) for incoming neutrino
  - Simple simulation to check for obvious bugs
- Ran simulation with an incoming neutrino energy flux equivalent to that of our actual detector
  - More realistic simulation
- Compared incoherent to coherent simulated events
  - Incoherent events = 1g0p NC delta radiative decay events
    - Emits single photon and at least 1 neutron
    - Also a single shower event
Incoherent vs. Coherent Events:

**Photon Energy & Cos(θ)** - where θ refers to the angle the photon makes with the neutrino beam axis
- \( \cos(θ) = 1 \) → forward, \( \cos(θ) = -1 \) → backward, \( \cos(θ) = 0 \) → perpendicular
Incoherent vs. Coherent Events:

Cos(\(\theta\)) & Neutrino Energy
Pandora Reconstruction

Analyzed events which had been simulated in Geant4 and DetSim and passed through reconstruction stage with Pandora

Pandora’s Overall Efficiency:
Out of 1000 simulated coherent single showers,

390 were reconstructed as 1g0p

Rate = 39%

Some Factors Affecting Efficiency:

Photon Energy:
- Pandora is better at reconstruction at higher energies, for photons greater than 0.45 GeV, reconstruction was correct 64% of the time

Angle of Shower:
- Pandora is better at reconstructing forward showers, for showers with \( \cos(\theta) \geq 0.85 \), reconstruction was correct 46% of the time
Most Common Reconstructions

1. 1g0p: 39.0%

2. 0g0p: 22.9%
   ~ 26.6% (~ 6.1% of total events) - photon left detector before showering
   - Used reco_slice_num, not completely accurate
   - Removing the photons that left the detector will boost Pandora’s efficiency rate

3. 1g1p: 12.0%
Pandora Accuracy in Reconstructing Angle

Pandora shows excellent reconstruction of angles, important for coherent events

* these are for all correctly reconstructed events (1g0p)
Pandora Accuracy in Reconstructing Energy Of Shower

- Used reconstructed energy of shower on plane 2 (collection plane) and truth value photon energy

Applied to Reconstructed Energy:
- 20% shift - what is standard at MicroBooNE
- 10 MeV - account for the fact this has no overlays

* these are for all correctly reconstructed events (1g0p)
Pandora Accuracy in Reconstructing Shower Starting Point

Large errors can be explained by backwards reconstructions

Note: plots are on a log scale in y
Larger error in z than in x or y can be explained by dead wire regions
Event: 1, Subrun: 16, Run: 1

Plane 2

With reconstruction

No reconstruction
Event: 1, Subrun: 16, Run: 1

Plane 0

With reconstruction  
No reconstruction
MeV Blips

- Neutrons can’t be picked up by the detector since they are not charged
  - When they travel they can interact with Argon atoms, slightly exciting them and these atoms can release a low energy photon when they relax down to ground state
  - These photons are picked up as blips in the detector
- Worked on algorithm to calculate opening angles of a shower in order to define a cone around the shower
- Coordinate conventions:
Min Phi: 1.53737 radians
Max Phi: 2.67562 radians
Opening Angle (Phi): 0.99552 radians
Min Theta: 0.439823 radians
Max Theta: 0.816814 radians
Opening Angle (Theta): 0.376991 radians
**BREAKS**

Min Phi: 0 radians  
Max Phi: $2\pi$ radians  
**Opening Angle (Phi):** $2\pi$ radians  
Min Theta: 0.314159 radians  
Max Theta: 0.816814 radians  
**Opening Angle (Theta):** 0.502655 radians
Min Phi: 5.44656 radians
Max Phi: 0.0681227 radians
Opening Angle (Phi): 0.9240957 radians
Min Theta: 0.314159 radians
Max Theta: 0.816814 radians
Opening Angle (Theta): 0.502655 radians
Opening Angle Distributions for 1000 Coherent Events File:

Cutoff = < 2.5% of total entries

Distribution in Opening Angle $\phi$

<table>
<thead>
<tr>
<th>opening angle</th>
<th>Entries</th>
<th>Mean</th>
<th>Std Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>564</td>
<td>1.494</td>
<td>1.402</td>
</tr>
</tbody>
</table>

Distribution in Opening Angle $\theta$

<table>
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<th>opening angle</th>
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<th>Std Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>564</td>
<td>0.5685</td>
<td>0.5789</td>
</tr>
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</table>
Opening Angle Distributions for 1000 Coherent Events File:

Cutoff = None

Distribution in Opening Angle $\phi$

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<td></td>
<td>564</td>
<td>2.897</td>
<td>1.747</td>
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Distribution in Opening Angle $\theta$

<table>
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<td>564</td>
<td>1.181</td>
<td>0.887</td>
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Opening Angle Distributions for 1000 Coherent Events File:

Cutoff = < 2 cm radius

Distribution in Opening Angle $\phi$

Distribution in Opening Angle $\theta$
Correlation Between Opening Angle and Photon Energy

- Created new TTree with single branch corresponding to my opening angle vector and friended this with original TTree from simulation and reconstruction to use combination of variables

Phi:

![Opening Angle (φ) vs Reconstructed Energy on Plane 2 of Shower](image1)

![Opening Angle (φ) vs Truth Energy of Photon](image2)
No significant correlation, expected lower energy showers to have narrower opening angles
Future Steps

- Analyze coherent events simulated with overlays
  - Run blip-finding algorithm on these interactions
- Use opening angle algorithm to define cone around shower and look at the number of blips found outside of coherent showers compared to incoherent showers
- Refine definition of the cone
Questions?