Exclusive $1 \mu + Np$
Topologies in ArgoNeuT

Particle Signatures
Fermilab 2009

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Yale University
Outline

• LArTPC technique
• Argon Neutrino Test (ArgoNeuT)
• Topological Analysis $1\mu+\text{Np}$
  (rates only, cross-section calculations are in progress)
• Energy Reconstruction
• Conclusions
Liquid Argon Time Projection Chamber (LArTPC) technique
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Liquid Argon Time Projection Chamber (LArTPC) technique
Event Display

- Bubble chamber quality!

- Pixel size of $(4.0 \times 0.3) \text{ mm}^2$

4mm wire pitch
198 ns sampling time
ArgoNeuT Introduction

- NSF/DOE R&D project at Fermilab
- LArTPC (Liquid Argon Time Projection Chamber)
- 175L active volume
- 480 channels - (240 wires/plane)
- ~ Max 50cm drift-distance
- ~ 500 V/cm E field
- two wire planes at $60^\circ$ to each other
- $T_0$ from beam information

ArgoNeuT

- Located underground on NuMI Beamline between MINOS ND and MINERνA
- MINOS helps with reconstruction of muons
ArgoNeuT’s Physics Run

- ArgoNeuT completed its phase I physics run (9/14/2009-2/22/2010)
- Collected events in the 0.1 to 10 GeV range, ArgoNeuT produced the first ever data for low energy neutrino interactions within a LArTPC.
- Stable, shift-free operation
- Goals:
  - Multiple neutrino cross sections
  - Demonstration of dE/dx particle separation capabilities
  - Developing automated reconstruction techniques for all future LArTPCs

POT with MINOS present:
- anti-nu mode 1.20e20
- nu-mode: 8.5e18
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Neutrino channel definitions are largely ill defined given the effects of FSI
We want to report what our detector actually sees!
How is it done?

- **Automatic reconstruction + visual scanning**
  - Particle Identification
  - Proton threshold
  - Matching with MINOS Near Detector
  - final scanned sample includes events with contained protons in fiducial volume

- **Efficiency and Purity for different proton multiplicities** evaluated using a full MC simulation (GENIE/Geant4/Larsoft)
  - take proton containment into account

- **Energy reconstruction with muon kinematics.**
  (Analysis including proton kinematics in progress)

\[
E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos \theta_\mu)}
\]
Topology appearance

\[ \mu + 0p \]

\[ \mu + 1p \]

\[ \mu + 1p \]

\[ \mu + 2p \]

\[ \mu + 3p \]
Example of Low energy proton reconstruction

The short track behaves like proton

Length = 0.5 cm

KE = 22 ± 3 MeV

proton threshold is 21 MeV of Kinetic Energy
Calorimetry Example

- Muon
- proton
Muon Reconstruction

muon kinematics: ArgoNeuT 3D, ArgoNeuT calorimetric reconstruction + MINOS ND measurement (momentum and sign)
Data Analysis still in progress
Preliminary Results!

Note: Flux in anti-neutrino needs to be studied (no uncertainties included)
MC used for comparison with data: GENIE v3665
Analysis has been focused on lower multiplicity proton events!
(No optimization for higher multiplicities at the moment)
More in depth studies of background effects are ongoing and will be finalized soon
### $\nu_\mu$ - neutrino mode run

<table>
<thead>
<tr>
<th>Multiplicity</th>
<th>Genie Expectation</th>
<th>Genie % of Total</th>
<th>DATA**</th>
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</tr>
</thead>
<tbody>
<tr>
<td>0p+1mu</td>
<td>28±4</td>
<td>16%</td>
<td>15±3</td>
<td>14%</td>
</tr>
<tr>
<td>1p+1mu</td>
<td>80±7</td>
<td>47%</td>
<td>51±10</td>
<td>48%</td>
</tr>
<tr>
<td>2p+1mu</td>
<td>23±4</td>
<td>13.4%</td>
<td>28±6</td>
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<tr>
<td>3p+1mu</td>
<td>14±3</td>
<td>8.3%</td>
<td>13±3</td>
<td>12%</td>
</tr>
<tr>
<td>4p+1mu</td>
<td>8±2</td>
<td>4.5%</td>
<td>0</td>
<td>0</td>
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<tr>
<td>TOTAL (including &gt;4p)</td>
<td>172±10</td>
<td>-</td>
<td>107±12</td>
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**No of expected $1\mu+np$ events in FV**

Data 38% lower

*statistical errors
** stat.+syst. errors- preliminary
# Data-MC comparison

## $\bar{\nu}_\mu$ - anti-neutrino mode

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\[ \mu^-/\mu^+(DATA) = 0.36 \]

\[ \mu^-/\mu^+(MC) = 0.36 \]

- Data 21% lower
- Data 23% lower
**Data-MC comparison**

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$\mu^-/\mu^+(DATA)=0.36$
$\mu^-/\mu^+(MC)=0.36$

- This is closest to MINERvA $\overline{\nu}$ QE selection ($\mu^+$ and no vertex activity)
- This is closest to MiniBooNE selection (muon and any # nucleons)
- This is closest to NOMAD and SciBooNE selection (1+2 track QE)
- This is closest to MiniBooNE selection (muon and any # nucleons)
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For more discussion see O. Palamara’s talk.
Muon Momentum and $Q^2$

All multiplicities

$\bar{\nu}_\mu$ - anti-neutrino mode run

All plots normalized to absolute POT
Neutrino Energy $\bar{\nu}_\mu$ - anti-neutrino mode run

$$E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos \theta_\mu)}$$

All multiplicities

1$\mu$ + 0$p$

1$\mu$ + 1$p$
Proton Multiplicities in Anti-nu mode:

Besides absolute normalization the shape is better reproduced for neutrinos
Neutrino Energy Reconstruction

\[ E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos \theta_\mu)} \]

\[ p_h = \sqrt{(E_\nu - p_\mu \cos \theta_\mu)^2 + p_\mu^2 \sin^2 \theta_\mu} \]

\[ \cos \theta_h = \frac{(E_\nu - p_\mu \cos \theta_\mu)}{p_h} \]

We can compare the two methods!

\[ E_\nu = p_\mu \cos \theta_\mu + p_h \cos \theta_h \]

\( \mu \) kinematics

**automatic reconstruction**

\( \mu + p \) kinematics

**semi-automatic reconstruction**

assumes QE events!
Reconstruction of 1μ1p events

Reconstructed Neutrino Energy = 3.1 GeV

Full neutrino event reconstruction with 3D ArgoNeuT-MINOS ND track matching

μ − escaping ArgoNeuT (and reaching MINOS-ND downstream)

Proton (ArgoNeuT reconstruction):
track length = 10.88 cm,
T = 118 MeV, p = 0.485 GeV/c

μ + p kinematics
Reconstructed Neutrino Energy = 3.1 GeV

μ kinematics
Reconstructed Neutrino Energy = 3.0 GeV
Reconstruction of $\mu p$ events

$p$ track length = 11.4 cm

$\mu+p$ kinematics

Reconstructed Neutrino Energy = 3.3 GeV

$\mu$ kinematics

Reconstructed Neutrino Energy = 3.3 GeV

$p$ track length = 6.2 cm

$\mu+p$ kinematics

Reconstructed Neutrino Energy = 6.5 GeV

$\mu$ kinematics

Reconstructed Neutrino Energy = 6.0 GeV
Conclusions and Next Steps

ArgoNeuT collected first ever data for low energy neutrino interactions with a LArTPC.
Performed preliminary topological analysis of $1\mu+Np$ in terms of rates. Cross section calculations are in progress.
We need to be careful about what we call “QE” and how we compare these samples with other experiments.
Energy reconstruction with the inclusion of proton kinematics is in progress.
ArgoNeuT Collaboration

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