Measurement of Reconstructed Charged Particle Multiplicities of Neutrino Interactions in MicroBooNE

Aleena Rafique for MicroBooNE Collaboration
Kansas State University
DPF 2017
08/01/2017
Physics Motivations

• Very little knowledge of \( \nu \)-Ar interaction measurements exists till date

• Need to understand these interactions for future short and long baseline LArTPCs

• Need to test widely used GENIE for neutrinos interactions on Ar targets
Neutrino Interactions

Charged Current Interactions

- Candidate neutrino CC event
- Gives information about neutrino flavor

Neutral Current Interactions

- Candidate neutrino NC event
- No information of neutrino flavor

Quasi-elastic (QE)

\[ \nu_\mu \rightarrow \mu^- \] (QE)

Resonance (RES)

\[ \nu_\mu \rightarrow \pi^+ \] (RES)

Deep inelastic (DIS)

\[ \nu_\mu \rightarrow \Delta^+ \] (DIS)
Charged Particle Multiplicity

• Number of reconstructed charged particles exiting the target nuclei at the neutrino interaction point.
  • Inclusive study
  • Mainly $\mu^\pm$, $\pi^\pm$, and $p$
  • Track requirement imply kinetic energy thresholds $\sim$82MeV for $p$, 37MeV for $\mu^\pm$ and $\pi^\pm$
  • Primary + secondary interaction particles

\[
\begin{align*}
\nu_\mu & \rightarrow W \\
W & \rightarrow n \Delta^+ \\
\Delta^+ & \rightarrow n n \pi^+ \\
\pi^+ & \rightarrow n \pi^0 \\
\pi^0 & \rightarrow n n
\end{align*}
\]
Why Charged Particle Multiplicity

• Gives knowledge of $\nu$-Ar interactions in form of directly observable quantity
• Provides a stringent test for neutrino event generators inclusively.
• Expand the knowledge of $\nu$-Ar scattering required by the DUNE neutrino CP violation search experiment.
• Early and relatively simple measurement
  • minimal kinematic properties of the final state particles are imposed.
  • does not require complexity associated with particle ID
• First measurement of charged track multiplicity in $\nu_\mu$ CC interactions in argon.
Neutrino Beams at Fermilab

Booster $\nu$ beam
MicroBooNE, SBN program

Booster
proton energy: 8 GeV

NuMI $\nu$ beam
NOvA, MINERvA, MINOS+

Main Injector
proton energy: 120 GeV

DUNE $\nu$ beam
(planned)
Neutrino Beams at Fermilab

Booster $\nu$ beam
MicroBooNE, SBN program

NuMI $\nu$ beam
NOvA, MINERvA, MINOS+

DUNE $\nu$ beam
(planned)

Booster
proton energy: 8 GeV

Main Injector

Beryllium Target

Protons from Booster

$\pi^-$

$K^-$

$\pi^+$

$K^+$

$\mu^+$

$\nu_\mu$

Horn

50 m Decay pipe

Absorber
**MicroBooNE Detector:**
1. 85 ton of liquid argon Time Projection Chamber (LArTPC)
2. Average beam energy = 800 MeV
3. Substantial cosmic ray backgrounds
4. 3 anode wire planes
5. 32 8-inch PMTs

**MicroBooNE Physics Goals:**
1. Knowledge of $\nu$-Ar interactions in $\sim$1 GeV range
2. Search for short baseline neutrino oscillations
3. Detector R&D for future large scale LArTPC detectors (e.g. DUNE)
LArTPCs make 3D reconstruction possible.
• Wire planes give 2D position information
• The third dimension is obtained by combining timing information ($t_0$) with drift velocity ($v_d$) → hence, a “Time projection chamber”
Cosmic rays in MicroBooNE

- Causes of substantial cosmic rays in MicroBooNE:
  - Near to surface operation
  - Long electron drift window (about 2.3 msec maximum drift time)

**Cosmic removal first pass:** Require scintillation light at the beam arrival time (1.6µs)

**Challenge remains:** where cosmics and neutrinos are in same event
Candidate Neutrino Event Displays

**RUN 6101 EVENT 3376**
One prong event
- Candidate interaction vertex
- Candidate muon

**RUN 3631 EVENT 21603**
Two prong event
- Candidate muon

**RUN 3631 EVENT 32212**
Three prong event
- Candidate muon

**RUN 5192 EVENT 1218**
Four prong event
- Candidate muon
- Cosmics

**Candidate**
- Interaction vertex
- Muon
- Cosmic particles
Candidate Neutrino Event Displays

- **One prong event**
- **Two prong event**
- **Four prong event**

- Candidate muon
- Candidate muon
- Candidate muon
- Candidate muon
- Cosmics

**Run 6101 Event 3376**

**Run 3631 Event 21603**

**Run 5192 Event 1218**

**μBooNE**

- 13 cm Run 5192 Event 1218, February 28th, 2016

- 9.67 cm wire (beam direction)

- 17.52 cm wire (beam direction)
• Picks a long, contained and candidate muon and an associated vertex

• Performs tests for the purpose of cosmic ray removal
  1. Pulse height (PH)
  2. Multiple coulomb scattering (MCS)

- Signal enhanced sample
- Mixed samples
- Background enhanced sample

- Full Sample
- \( \nu_\mu \) CC inclusive filter
- Muon quality Filter
- MICROBOONE-NOTE-1010-PUB

- Minimum collection plane hits cuts for candidate muon
- Candidate muon start/end good detector regions.
Event Classification

Pulse Height Test

MicroBooNE Preliminary

Multiple Coulomb Scattering

MicroBooNE Preliminary

<table>
<thead>
<tr>
<th>Sub samples</th>
<th>On-beam Data</th>
<th>Off-beam Data</th>
<th>BNB+Cosmic Default MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>PH, MCS</td>
<td>events</td>
<td>acceptance rates</td>
<td>events</td>
</tr>
<tr>
<td>pass, pass</td>
<td>847</td>
<td>(44%)</td>
<td>1263</td>
</tr>
<tr>
<td>pass, fail</td>
<td>367</td>
<td>(19%)</td>
<td>1087</td>
</tr>
<tr>
<td>fail, pass</td>
<td>321</td>
<td>(17%)</td>
<td>1141</td>
</tr>
<tr>
<td>fail, fail</td>
<td>387</td>
<td>(20%)</td>
<td>1776</td>
</tr>
</tbody>
</table>
Event Classification

Pulse Height Test
Rate of energy loss increases along the track from upstream to downstream end

Pulse Height Test
Rate of energy loss increases along the track from upstream to downstream end

Multiple Coulomb Scattering

<table>
<thead>
<tr>
<th>Beam Data</th>
<th>BNB+Cosmic Default MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptance rates</td>
<td>events</td>
</tr>
<tr>
<td>(24%)</td>
<td>2629</td>
</tr>
<tr>
<td>(21%)</td>
<td>737</td>
</tr>
<tr>
<td>(22%)</td>
<td>440</td>
</tr>
<tr>
<td>(34%)</td>
<td>403</td>
</tr>
</tbody>
</table>
Event Classification

Pulse Height Test

Multiple Coulomb Scattering
Scattering is more pronounced along the downstream end of the track as the momentum decreases.

MicroBooNE Preliminary
Event Classification

- Muons from neutrinos CC interactions are usually forward-going.
- Cosmic rays travel forward and backward with roughly equal prob.

<table>
<thead>
<tr>
<th>Sub samples PH, MCS</th>
<th>On-beam Data events</th>
<th>On-beam Data acceptance rates</th>
<th>Off-beam Data events</th>
<th>Off-beam Data acceptance rates</th>
<th>BNB+Cosmic Default MC events</th>
<th>BNB+Cosmic Default MC acceptance rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>pass, pass</td>
<td>847</td>
<td>(44%)</td>
<td>1263</td>
<td>(24%)</td>
<td>2629</td>
<td>(62%)</td>
</tr>
<tr>
<td>pass, fail</td>
<td>367</td>
<td>(19%)</td>
<td>1087</td>
<td>(21%)</td>
<td>737</td>
<td>(18%)</td>
</tr>
<tr>
<td>fail, pass</td>
<td>321</td>
<td>(17%)</td>
<td>1141</td>
<td>(22%)</td>
<td>440</td>
<td>(10%)</td>
</tr>
<tr>
<td>fail, fail</td>
<td>387</td>
<td>(20%)</td>
<td>1776</td>
<td>(34%)</td>
<td>403</td>
<td>(10%)</td>
</tr>
</tbody>
</table>
## Signal Extraction Model

Relate number of events in each of 8 subsamples to:

- Number of on-beam neutrinos
- Number of on-beam cosmics
- Number of off-beam cosmics
- Probability that a neutrino or cosmic passes the PH or MCS tests

### Table

<table>
<thead>
<tr>
<th>Subsample #</th>
<th>On/off-beam</th>
<th>PH</th>
<th>MCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>On-beam</td>
<td>pass</td>
<td>pass</td>
</tr>
<tr>
<td>2</td>
<td>On-beam</td>
<td>pass</td>
<td>fail</td>
</tr>
<tr>
<td>3</td>
<td>On-beam</td>
<td>fail</td>
<td>pass</td>
</tr>
<tr>
<td>4</td>
<td>On-beam</td>
<td>fail</td>
<td>fail</td>
</tr>
<tr>
<td>5</td>
<td>Off-beam</td>
<td>pass</td>
<td>pass</td>
</tr>
<tr>
<td>6</td>
<td>Off-beam</td>
<td>pass</td>
<td>fail</td>
</tr>
<tr>
<td>7</td>
<td>Off-beam</td>
<td>fail</td>
<td>pass</td>
</tr>
<tr>
<td>8</td>
<td>Off-beam</td>
<td>fail</td>
<td>fail</td>
</tr>
</tbody>
</table>

No dependence on off-beam to on-beam normalization
Nearly model independent
Expectations for Observed Charged Particle Multiplicity Distributions

Common feed-down occurrence is due to efficiency*acceptance effects.
# Uncertainty Estimates

<table>
<thead>
<tr>
<th>Uncertainty Sources</th>
<th>mult=1</th>
<th>mult=2</th>
<th>mult=3</th>
<th>mult=4</th>
<th>mult=5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data statistics</td>
<td>7%</td>
<td>10%</td>
<td>38%</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>MC statistics</td>
<td>3%</td>
<td>4%</td>
<td>7%</td>
<td>21%</td>
<td>50%</td>
</tr>
<tr>
<td>Short track efficiency</td>
<td>7%</td>
<td>11%</td>
<td>25%</td>
<td>33%</td>
<td>44%</td>
</tr>
<tr>
<td>Long track efficiency</td>
<td>1%</td>
<td>2%</td>
<td>4%</td>
<td>7%</td>
<td>9%</td>
</tr>
<tr>
<td>Fixed model parameter systematics</td>
<td>2%</td>
<td>2%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Flux shape systematics</td>
<td>0%</td>
<td>0.4%</td>
<td>0.2%</td>
<td>0.5%</td>
<td>0.8%</td>
</tr>
<tr>
<td>Electron lifetime systematics</td>
<td>0.5%</td>
<td>0.1%</td>
<td>6%</td>
<td>5%</td>
<td>5%</td>
</tr>
</tbody>
</table>
Multipliclity Result Plot

[Graph showing event fractions for different scenarios related to MicroBooNE preliminary results with KE_{\mu,\tau} > 37 MeV and KE_p > 82 MeV.]

Public Note: MICROBOONE-NOTE-1024-PUB
Conclusion & Outlook

• Conclusion:
  • Measured charged particle multiplicity in $\nu_\mu$ CC interactions in Ar for first time
  • Developed and validated data driven method to determine signal and cosmic ray background contributions
  • Compared charged particle multiplicity from data and different generator models
  • Models are consistent within uncertainties with the data
  • Hint for slight discrepancy in data and MC in higher multiplicity bins

• Public Note:

• Outlook:
  • Compare other kinematic properties of particles emerging from interaction vertex with different models.
  • Compare data with wider range of models
  • Working towards a publication (stay tuned)
Thank you
Backup Slides
Short Track Efficiency Uncertainties

- From Pandora public note*, reco efficiency of proton/pion at 20 hit threshold is 0.45±0.05

**Dominant systematic uncertainty**

<table>
<thead>
<tr>
<th>Observed multiplicity</th>
<th>$\frac{\Delta P_n}{P_n}$ Default</th>
<th>$\frac{\Delta P_n}{P_n}$ MEC</th>
<th>$\frac{\Delta P_n}{P_n}$ TEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+7%</td>
<td>+7%</td>
<td>+8%</td>
</tr>
<tr>
<td>2</td>
<td>−11%</td>
<td>−12%</td>
<td>−12%</td>
</tr>
<tr>
<td>3</td>
<td>−25%</td>
<td>−25%</td>
<td>−25%</td>
</tr>
<tr>
<td>4</td>
<td>−33%</td>
<td>−36%</td>
<td>−39%</td>
</tr>
<tr>
<td>5</td>
<td>−44%</td>
<td>−48%</td>
<td>−</td>
</tr>
</tbody>
</table>

**Overall eff. $\propto \epsilon^{\text{(no of short tracks)}}$**

*MICROBOONE-NOTE-1015-PUB*