Towards The First Measurement Of Differential $\gamma_\mu$-Argon Charged Current Single Transverse Variable Scattering Cross Sections

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Why Precision Cross Sections Measurements?

Oscillation measurements rely on unprecedented understanding of $\nu$-nucleus scattering. BUT ... many known unknowns:

- Wide $\nu$ energy spectra
- Fermi motion
- Multi-nucleon effects
- Final state interactions (FSI)
- ....
CC1p0\pi Interaction Channel

Simple topology, dominant at energies relevant for MicroBooNE

- Single muon $P_\mu > 100$ MeV/c
- Single proton $P_p > 300$ MeV/c
- No neutral pions
- No charged pions with $P_\pi > 70$ MeV/c
First Analysis Identified Regions Where Improvement Is Required

Current Analysis With Much Higher Statistics & Improved Modeling

• Largest $\nu_{\mu}^{40}$Ar dataset to date

• Latest version of
  GENIE Event Generator
  arXiv:2106.09381,
  MICROBOONE-NOTE-1074-PUB

• Currently finalizing
  central values
  & uncertainties

• Also longitudinal variables

• Today, discussion on
  MC sensitivities
Transverse Components Cancel Out In Absence Of Nuclear Effects

\[ \delta p_T = |p_T^l + p_T^p| = 0 \]

\[ p_T^l = -p_T^p \]
Imbalance In The Presence Of Nuclear Effects

\[ \delta p_T = |p_{T_T}^l + p_{T_T}^p| > 0 \]
proxy for Fermi motion

\[ p_{T_T}^l \neq -p_{T_T}^p \]
$\delta p_T$ Probes Fermi Motion

MC uses Local Fermi Gas for ground state

No FSI

In Progress
Adding FSI Gives Rise To High Momentum Tail

* Used as the nominal MC by the MicroBooNE Collaboration arXiv:2106.09381, MICROBOONE-NOTE-1074-PUB
Nuclear Model Shifts Peak Location

Local FG with FSI

Relativistic FG with FSI
No Preferred $\delta \alpha_T$ Direction Without FSI and $\delta p_T \sim 0$
Adding FSI Causes $\delta \alpha_T$ To Rise

Proton “deceleration” due to FSI

In Progress

Graph showing the change in $\delta \alpha_T$ with and without FSI.

No FSI

With FSI
Alternative MC Doesn’t Show “FSI Deceleration”

Nominal MC = GENIE v3.0.6 with MicroBooNE Tune  \textit{arXiv:2106.09381}

$\delta \phi_T$ is small in the absence of FSI.
Adding FSI Gives Rise To High Angles Tail

In Progress

No FSI

With FSI

\[ \frac{d\sigma}{d\delta\phi_T} \left[ 10^{-38} \right] \]

\[ \text{cm}^2 \text{ deg Ar}^{-1} \]
MC Versions Show Differences At Small Angles

Older MC

Current MC

Older MC = GENIE v2.12.10
arXiv:1510.05494

Current MC = GENIE v3.0.6
with MicroBooNE tune
arXiv:2106.09381
Wrap Up

• Single transverse variable sensitivity to nuclear models, FSI and multi-nucleon effects
• Powerful tools to reduce cross section uncertainties
• Performed the first CC1p0π analysis studying these variables on MicroBooNE

In Progress

No FSI

With FSI
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Connections To Electron Scattering

Khachatryan and Papadopoulou et al.
Nature, in process (2021)
Thank you!
Backup Slides
## Largest $\nu_\mu$-Ar Dataset!

<table>
<thead>
<tr>
<th>Combined Runs</th>
<th>Number of Events</th>
<th>Beam–On Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>BeamOn</td>
<td>10952.00 ± 104.65</td>
<td>10952.00 ± 104.65</td>
</tr>
<tr>
<td>MC</td>
<td>36592.00 ± 191.29</td>
<td>6971.48 ± 83.50</td>
</tr>
<tr>
<td>CC1p0π MC</td>
<td>26953.00 ± 164.17</td>
<td>5135.07 ± 71.66</td>
</tr>
<tr>
<td>ExtBNB</td>
<td>2396.00 ± 48.95</td>
<td>681.35 ± 26.10</td>
</tr>
<tr>
<td>Dirt</td>
<td>184.00 ± 13.56</td>
<td>143.23 ± 11.97</td>
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</table>

<table>
<thead>
<tr>
<th>Run 1</th>
<th>Purity (%)</th>
<th>Overall Efficiency (%)</th>
<th>Contained Part Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC1p0π</td>
<td>69.10 ± 0.48</td>
<td>10.70 ± 0.06</td>
<td>28.62 ± 0.17</td>
</tr>
</tbody>
</table>
Single Transverse Variables

Transverse direction characterized by magnitude & 2 angles

Transverse missing momentum

\[ \delta \vec{p}_T = \vec{p}_T^\ell + \vec{p}_T^p \]

\[ \delta \phi_T = \arccos \frac{-\vec{p}_T^\ell \cdot \vec{p}_T^N}{p_T^\ell p_T^N} \]

\[ \delta \alpha_T = \arccos \frac{-\vec{p}_T^\ell \cdot \delta \vec{p}_T}{p_T^\ell \delta p_T} \]


Phys. Rev. Lett. 121, 022504
Single Transverse Variables

\[ -p^\mu_T, \delta p_T, \delta \alpha_T, \delta \phi_T, p^p_T \]
Nuclear Models In The GENIE Event Generator
Better Data/Simulation Agreement From Improved Modeling

• GENIE v2.12.2 → GENIE v3.0.6

• Tuned CCQE and CCMEC models to T2K $\nu_\mu$ CC0π data

• T2K data is on a carbon target
→ Tuning seems to give good agreement with MicroBooNE’s argon-target data

MICROBOONE-NOTE-1074-PUB

MICROBOONE-NOTE-1069-PUB
GENIE v3.0.6 models used:


• High statistics & fine binning

• Currently finalizing central values & uncertainties

• Excellent handle to study known unknowns

• Today discussion on MC sensitivities