μBooNE Pushing the Limits for Improved Cross Section Results with LArTPC Technology

New Directions in Neutrino-Nucleus Scattering
NuSTEC workshop 3/15/21

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Introduction

Already now, MicroBooNE offers a series of cross section measurements.

Available cross section on Argon is vital for SBN and DUNE

A LArTPC detector has low detection threshold & $4\pi$ acceptance.

Better understanding of LArTPC, energy reconstruction and improvements of models.
SBN - Short Base Line Neutrino Program
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NuMI Neutrino Beam
120 GeV protons $<E_{\nu}> = 1$ GeV

Booster Neutrino Beam
8 GeV protons $<E_{\nu_\mu}> \sim 1$ GeV
LAr TPC - MicroBooNE

For more see here
Near surface LArTPC detector
Active mass: 85 tons
Fiducial Volume: 2.5 x 2.2 x 10 m
Triggered by 32 PMTs
Anode: 3 wire planes
Stable detector operation since 2015
1.52E21 POT collected
Analysis of the initial subset of the data shown today
Cosmic Ray Tagger (CRT) help rejecting background since 2018
LAr TPC - MicroBooNE

- Low tracking threshold
- Charge collection supply calorimetry
- High statistics
- Latest results with improved detector understanding and reduced systematics uncertainties
<table>
<thead>
<tr>
<th>Improved signal processing</th>
<th>Cosmic Rejection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flash Matching</td>
<td>Data driven based detector uncertainties</td>
</tr>
</tbody>
</table>
LArTPC MicroBooNE’s improvements

Improved signal processing
- Accounting for signals from different wires in all 3 planes
- Better calorimetry in all phase space
- Better efficiency
- Reduced detector systematics

Flash Matching

Data driven based detector uncertainties

For more see: JINST 13 P07006, JINST 13 P07007
LArTPC MicroBooNE’s improvements

Improved signal processing

Cosmic Rejection

Flash Matching

- New methods for TPC/PMT matching
- Predicting light distribution of a cluster and comparing to light measurement.

LArTPC MicroBooNE’s improvements

Improved signal processing

Cosmic Rejection
- Using off beam data as background to simulation
- CRT since 2018 helps exclude crossing penetrating tracks

Flash Matching
LArTPC MicroBooNE’s improvements

- Improved signal processing
- Cosmic Rejection
- Flash Matching
- Data driven detector uncertainties

- Parameterising the hits charge and width with respect to location and orientation
Cross section results

MicroBooNE is shifting gears to precision measurements.

MicroBooNE inclusive results stands in good agreement with many event generator’s prediction. Specifically, GENIE v3.0.6

Exclusive results show differences at specific regions of phase-space
$\nu_e + \nu_e$ CC inclusive with Numi

One of MicroBooNE’s greatest ability: Distinguish between photons and electrons

$dE/dx$ at the beginning of an electron induced shower is of MIP $\sim 2$ MeV/c

$dE/dx$ at the beginning of a photon induced shower, producing $e^+e^-$ pair is twice MIP $\sim 4$ MeV/c

$\pi^0$ background will result with a distance between vertex and beginning of shower
$\nu_e + \bar{\nu}_e$ CC inclusive with Numi

One of MicroBooNE’s greatest achievements: Distinguish between photons and electrons

arXiv:2101.04228v1 [hep-ex]
While searching for $\nu_e$ excess in BNB, measuring the flux averaged cross section in NuMI

First demonstration of electron neutrino reconstruction in a surface LArTPC in the presence of cosmic ray backgrounds. Largest sample to data $> 200$ events

Final selection: purity of 39% and efficiency 9%

Good agreement with models

Stay tuned for the next round of this analysis: differential cross section, with reduced cosmic background and uncertainties

arXiv:2101.04228v1 [hep-ex]
$\nu_\mu$CC inclusive with BNB

First ever double differential cross section measurement on Argon
Overall good agreement with prediction. GENIE v3 best describe data
Disagreement observed in forward scattering angle at high momentum

νμCC inclusive - Looking to the Future

Improved detector understanding and cosmic rejection, improves the results

The purity: From 50% to 71.9%

Detector uncertainties: From 16.2% to 3.3%

Previous published measurement

Current measurement
MICROBOONE-NOTE-1069-PUB
Protons in LArTPC

LArTPC supply the lowest threshold particle detection
MicroBooNE’s proton detection threshold 300 MeV/c
Identified using dE/dx and the Bragg peak at end of track

For more see: *JINST 15, P03022 (2020)*
**CC0πNP N ≥ 1**

Event selection: \(1\mu\) (\(P_\mu > 100\text{ MeV/c}\)) \(1p\) (\(300\text{ MeV/C} < P_p < 1200\text{ MeV/c}\)), \(0\pi\)

71% purity, 29% efficiency

Overall agreement in proton kinematic

Notice low bin allowed by detection threshold, also most sensitive to differences between models

**Phys Rev. D 102, 112013 (2020)**
This semi-exclusive measurement shows interesting disagreement in muon kinematics at very forward scattering angles.
CC0π1P or CCQE-like events

Vertex of 2 semi-contained tracks
(start within the fiducial volume)
one muon ($P_\mu > 100\text{ MeV/c}$)
one proton ($P_p > 300\text{ MeV/c}$)
no $\pi^0$, no charged $\pi$ ($\geq 70\text{ MeV/c}$)

Additional cuts on:
- To reduce cosmic contamination
  - $|\Delta\theta_{\mu p} - 90^\circ| < 55^\circ$
- To enhance QE contribution
  - $|\Delta\phi_{\mu p} - 180^\circ| < 55^\circ$
  - $p_T = |\vec{p}_{T,\mu} + \vec{p}_{T,p}| < 350\text{ MeV/c}$

$\sim 84\% \text{ CC1p0}\pi \sim 81\% \text{ CCQE}$ purity, 20% efficiency
CC0π1P - CCQE-like events

Overall agreement except for forward muon scattering angle

Phys Rev Lett. 125, 201803 (2020)
$-0.65 < \cos(\theta_{\mu}) < 0.95$

$\chi^2$ Nom

GENIE

6.18

(63.2/28)

$-0.65 < \cos(\theta_{\mu}) < 0.8$

$\chi^2$ Nom

GENIE

4.04

(30.1/27)

Significantly better agreement when excluding events with forward going muon

Phys Rev Lett. 125, 201803 (2020)
Going more exclusive with protons

CC inclusive
Overall agreement small deficit in forward bin

CCNP
Semi exclusive notice turn over in data

CC1P
Exclusive Biggest deficit in data

Stay tuned to new results with better detector understanding and differential cross section from off axis NuMI
NC1P

Challenging signal: 1 proton track (1.2 < L < 200 cm) no additional tracks / showers
Lowest Q² NC1P analysis to date (0.1 GeV²)

Using BDT based on 13 track variables
(exp. dE/dx, length, direction)
Efficiency 29.8% purity 42.1%

Using:
- off beam data background
- Data driven based detector uncertainties
- Comparing to MicroBooNE tune
NC1P

Challenging signal: 1 proton track ($1.2 < L < 200 \text{ cm}$) no additional tracks / showers

Using BDT based on 13 track variables (exp. dE/dx, length, direction)
Efficiency 29.8% purity 42.1%

Using:
- off beam data background
- Data driven based detector uncertainties
- Comparing to MicroBooNE tune
New Directions
This is only the beginning!

MicroBooNE holds 10 times more data than analysed

MicroBooNE is also working on a specific tune GENIE v3.06 based on T2K data.
Initial studies show for the first time a good agreement between data on Argon and a tune based on Carbon!

Given MicroBooNE’s achievements in detector understanding and improvements:

- Improved signal processing
- Cosmic Rejection
- Flash Matching
- Data driven detector uncertainties

We excited for the coming future
New Directions

Improved $\nu_\mu$CC inclusive - see talk by London Cooper-Troendle

Next step with protons:
   - Double differential cross sections with 1p
   - Extracting differential cross section wrt standard transverse variables
   - Studying 2p

Given recalibration of showers, and improved $\pi^0$ resolution:
   - $\pi$, $\mu$ kinematics, and studies for CC/NC ratio

First analyses with charged pions
   - $\pi$, $\mu$ kinematic, proton multiplicity
   - Coherent $\pi^+$
New Directions with Numi

Improved $\nu_e$CC inclusive see talk by Krishan Mistry

$\nu_e$CC0$\pi$Np

$\nu_\mu$ kaon analysis (for better statistics)

and more…
Summary

Presenting a series of $\nu$Ar cross section results from MicroBooNE

Nice data simulation agreement in inclusive results

Hints for disagreement in:
- forward going muons
- low momentum protons

Looking forward to explore new directions
Thank you for your attention
μBooNE Cross section Publications

$\nu_\mu$ CC inclusive

double differential  *Phys. Rev. Lett.* 123, 131801

single differential  MICROBOONE-NOTE-1069-PUB

$\nu_\mu$ exclusive

particle multiplicity  *Eur Physical Journal C volume 79*


CCNp $1\mu Np$  *Phys. Rev. D* 102, 112013

CC$\pi^0$ pion production  *Phys. Rev. D* 99, 091102

kaon production  MICROBOONE-NOTE-1071-PUB

NC MICROBOONE-NOTE-1067-PUB

$\nu_e$ inclusive  *arXiv:2101.04228 [hep-ex]*
MicroBooNE First Results

Charged particle Multiplicity
First detailed measurement testing GENIE models on Argon nuclei
arXiv:1805.06887 (submitted to PRD)

CC inclusive
good cosmic rejection
model dependencies are negligible

CC $\pi^0$
Low statistics, lower cosmic background
Model dependent
## Protons analyses selection

<table>
<thead>
<tr>
<th>CCQE-like analysis: An event is CC1p0pi “signal” if...</th>
<th>CCNp analysis: An event is CC0pi “signal” if...</th>
</tr>
</thead>
<tbody>
<tr>
<td>True charged-current numu interaction</td>
<td>True charged-current numu interaction</td>
</tr>
<tr>
<td>Exactly one muon, that passes the following requirments</td>
<td>Exactly one muon, that passes the following requirements</td>
</tr>
<tr>
<td>( p_\mu &gt; 0.1 \text{ GeV/c} )</td>
<td></td>
</tr>
<tr>
<td>( p_\mu &lt; 1.5 \text{ GeV/c} )</td>
<td>-</td>
</tr>
<tr>
<td>(-0.65 &lt; \cos\theta_\mu &lt; 0.95)</td>
<td>-</td>
</tr>
<tr>
<td>Exactly one proton, that passes the following requirements</td>
<td>At least one proton, that passes the following requirements</td>
</tr>
<tr>
<td>( p_\pi &gt; 0.3 \text{ GeV/c} )</td>
<td></td>
</tr>
<tr>
<td>( p_\pi &lt; 1.0 \text{ GeV/c} )</td>
<td>( p_\pi &lt; 1.2 \text{ GeV/c} )</td>
</tr>
<tr>
<td>( \cos\theta_\pi &gt; 0.15 )</td>
<td>-</td>
</tr>
<tr>
<td>Non-collinearity: (</td>
<td>\Delta\phi_{\mu\pi} - 90^\circ</td>
</tr>
<tr>
<td>Coplanarity: (</td>
<td>\Delta\phi_{\mu\pi} - 180^\circ</td>
</tr>
<tr>
<td>Small missing transverse momentum: ( p_T =</td>
<td>p_T^{\mu}+p_T^\pi</td>
</tr>
<tr>
<td>Any number of protons with ( p_\pi &lt; 300 \text{ MeV/c} )</td>
<td>Any number of protons</td>
</tr>
<tr>
<td>No charged pions with momentum &gt; 70 MeV/c</td>
<td>No charged pions with any momentum</td>
</tr>
<tr>
<td>Any number of neutrons</td>
<td></td>
</tr>
<tr>
<td>Any number of neutral pions</td>
<td>No neutral pions</td>
</tr>
<tr>
<td>Any number of electrons or photons</td>
<td></td>
</tr>
</tbody>
</table>
## NC models

<table>
<thead>
<tr>
<th>Model</th>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear model</td>
<td>LFG</td>
<td>Local Fermi Gas model</td>
</tr>
<tr>
<td>Final State Interaction Model</td>
<td>hA2018</td>
<td>Hadron-nucleus interaction model</td>
</tr>
<tr>
<td>NC Elastic model</td>
<td>$M_A = 0.96$ GeV</td>
<td>Axial mass in Ahrens model</td>
</tr>
<tr>
<td></td>
<td>$\eta = 0.12$</td>
<td>Strange quark contribution in Ahrens model</td>
</tr>
<tr>
<td>NC Resonance model</td>
<td>$M_A = 1.120$ GeV</td>
<td>Axial mass of Berger-Sehgal model</td>
</tr>
<tr>
<td></td>
<td>$M_V = 0.840$ GeV</td>
<td>Vector mass of Berger-Sehgal model</td>
</tr>
<tr>
<td>NC Meson Exchange Current model</td>
<td>-</td>
<td>Empirical Dytman model</td>
</tr>
</tbody>
</table>
Improved systematics CCνμ Inclusive

![Graph showing improved systematics for CCνμ Inclusive with data from this work compared to previous work.](image)

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
<th>Previous Analysis</th>
<th>This Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector response</td>
<td>16.2%</td>
<td>3.3%</td>
<td></td>
</tr>
<tr>
<td>Cross section</td>
<td>3.9%</td>
<td>2.7%</td>
<td></td>
</tr>
<tr>
<td>Flux</td>
<td>12.4%</td>
<td>10.5%</td>
<td></td>
</tr>
<tr>
<td>Dirt background</td>
<td>10.9%</td>
<td>3.3%</td>
<td></td>
</tr>
<tr>
<td>Cosmic ray background</td>
<td>4.2%</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>POT counting</td>
<td>2.0%</td>
<td>2.0%</td>
<td></td>
</tr>
<tr>
<td>CRT</td>
<td>N/A</td>
<td>1.7%</td>
<td></td>
</tr>
<tr>
<td>Total Sys. Error</td>
<td>23.8%</td>
<td>12.1%</td>
<td></td>
</tr>
<tr>
<td>Statistics</td>
<td>1.4%</td>
<td>3.8%</td>
<td></td>
</tr>
<tr>
<td>Total (Quadratic Sum)</td>
<td>23.8%</td>
<td>12.7%</td>
<td></td>
</tr>
</tbody>
</table>