Recent MicroBooNE Cross-section Results: Neutrino-Induced Baryon Production

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On behalf of the NuFACT 2022 collaboration

NuFACT 2022
Need for Accurate Understanding of Neutrino Interactions

• Broad neutrino spectra
• Various complex interaction mechanisms
• Mismodeling can limit experimental sensitivity

Rev. Mod. Phys. 84, 1307 (2012)
- Liquid argon time projection chamber (LArTPC) like SBN & DUNE
- Low detection thresholds
- Precise calorimetric information

Also see talks by S.Gollapinni & M.Ross-Lonergan
- Largest available neutrino-argon data set with ~500k recorded neutrino interactions

Also see talks by X.Ji, E.Gramellini & K.Sutton

- ~35 active MicroBooNE cross-section analyses

- Many focus on topologies with detected hadrons
Hadronic Energy Modeling Is Crucial for Neutrino Calorimetry

• Oscillation measurements require understanding of energy-dependent event rates

  “Easy”       “Hard”

\[ E_\nu = E_\ell + \omega \]

• \( E_{\text{Cal}} \approx E_\nu \): add up everything & correct for missing energy

\[ \omega = E_{\text{had}} + E_{\text{miss}} \]

• \( E_{\text{miss}} \) can be a large fraction of the total
Hadronic Energy Modeling Is Crucial for Neutrino Calorimetry

- Oscillation measurements require understanding of energy-dependent event rates
  - “Easy”  “Hard”
  \[ E_\nu = E_\ell + \omega \]

- \( E_{\text{Cal}} \approx E_\nu \): add up everything & correct for missing energy

- Current simulations do not describe the bias well
- Benchmarked with electron beam data (monoenergetic, high-statistics)

Also see talks by N.Rocco, S.Gardiner, V.Pandey, W.Ketchum & A.Papadopoulou
Four examples with baryons in this talk

• Transverse kinematic imbalance
• Two-proton final states
• Lambda-baryon production
• Exclusive electron neutrino measurement
Transverse Kinematic Imbalance (TKI)
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\[ \delta p_T = |p_T^\mu + p_T^p| = 0 \]

Transverse projections equal and opposite due to momentum conservation

Adapted from S. Dolan, “Exploring nuclear effects with transverse imbalances”
Transverse Kinematic Imbalance (TKI)

\[ \delta p_T = |p_T^\mu + p_T^p| > 0 \]

Imbalance due to initial nucleon motion and other nuclear effects

Adapted from S. Dolan, “Exploring nuclear effects with transverse imbalances”
Transverse Kinematic Imbalance (TKI)

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Orientation of the imbalance ($\delta\alpha_T$) also meaningful

Adapted from S. Dolan, “Exploring nuclear effects with transverse imbalances”
Transverse Kinematic Imbalance (TKI)

Adapted from S. Dolan, “Exploring nuclear effects with transverse imbalances”
\( \nu_\mu \) CC1p0\( \pi \) TKI

- First neutrino-argon differential cross section in TKI variables
- Sensitive to initial nucleon motion & proton FSI modeling

Also see poster by J. Book (award winner)
\( \gamma_\mu \text{ CC1p0}\pi \text{ TKI} \)

- Extension to 2D for the first time on any neutrino target
- Probe regions with greater model discrimination power

MICROBOONE-NOTE-1108-PUB  Also see poster by J. Book (award winner)
$\nu_\mu$ CC2p0$\pi$

- First neutrino-argon cross sections for an exclusive 2p final state
  - Various observables studied
- $\gamma_{\text{Lab}}$: angle between the two protons
  - Sensitive to modeling choices for MEC and QE
\( \nu_\mu \) \text{CC2p0\pi} 

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\[ \nu_\mu \text{ CC}2p0\pi \]

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- Data-MC shape & normalization differences identified

MICROBOONE-NOTE-1117-PUB
$\bar{\nu}_\mu \Lambda$ Production

- Cabibbo suppressed reaction
- Sensitivity to cross section modeling and final state interaction parameters
- Very distinct “track + V shape” topology
- Challenging analysis!
- Expect ~40 interactions in ~2M triggers before any selection

Also see poster by C.Thorpe
MICROBOONE-NOTE-1097-PUB
Event Selection

• Selection identifies a muon candidate and a proton-pion candidate pair

• Proton-pion “island” activity separated from muon candidate

• Proton-pion kinematics consistency with $\Lambda$ baryon decay

Also see poster by C.Thorpe
MICROBOONE-NOTE-1097-PUB
\[ \bar{\nu}_\mu \Lambda \text{ Production} \]

\( \Lambda \) baryon decay consistency

- Keeping events with
  \[ 1.09 < W < 1.14 \text{ GeV}/c^2 \]
  and angular deviation \( \alpha < 14^\circ \)

- After selection
  Signal = 2.5 events
  Bkg = 2.8 events
  when initially
  Signal = \(~40\) events
  Bkg = \(~2M\) events

Also see poster by C.Thorpe
MICROBOONE-NOTE-1097-PUB
$\nu_e$ CCNp0π

- First differential measurement in lepton and leading proton kinematics
- Data shows best agreement with the generators that predict a lower overall cross section (GENIE v3, NuWro)
$\nu_e CCNp0\pi$

- First measurement to characterize proton production across the visibility threshold on argon

arXiv:2208.02348 (50th paper!)
Summary

- MicroBooNE is paving the path towards high precision modeling with baryons.
Thank you!
Backup Slides
Neutrino Experiments

Goal: Oscillation parameter extraction with few-percent level uncertainties
Need: precise neutrino-nucleus cross-section modeling
Start: Short-Baseline Neutrino Program
Status: ~500k $\nu$ scattering events with MicroBooNE

Completed data collection
Collecting data
Data collection starts in 2023
Data collection starts in ~2030
Time Projection Chambers

- V wire plane waveforms
- Y wire plane waveforms
- PMTs
$\nu_\mu$ CC2p0π

- 65% purity & 13% efficiency
- 3157 selected data events
\[ \nu_\mu \text{ CC}2p0\pi \]

- \( \gamma_{\mu, PL + PR} \): angle between the muon and the vector sum of the two protons
  - Sensitive to modeling choices for MEC and QE
$\nu_\mu$ CC2p0$\pi$

$\cos(\gamma_{\mu,P_L + P_R})$

![Diagram of neutrino interaction](image)

**MicroBooNE Note 1117-PUB**
Transverse Kinematic Imbalance (TKI)

\[ \delta p_T = p_T^\mu - p_T^p \]

Combined
All events
QE = 57.7 %
Cosmics = 7.8 %
MicroBooNE Preliminary

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Transverse Kinematic Imbalance (TKI)
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(a) All events, MicroBooNE Preliminary
(b) $\delta p_T < 0.2$ GeV/c, MicroBooNE Preliminary
(c) $\delta p_T > 0.4$ GeV/c, MicroBooNE Preliminary

\[ \delta p_T \]
Transverse Kinematic Imbalance (TKI)

\[ \delta p = p^\mu_T - p_p^T, \quad \delta \alpha_T = p_T \]

(a) All events

(b) \( \delta p_{T_y} < -0.15 \text{ GeV/c} \)

(c) \(-0.15 < \delta p_{T_y} < 0.15 \text{ GeV/c} \)

[Graphs and data plots showing distributions of \( \delta p_{T,x} \) and \( \delta p_{T,y} \) with axes and data points labeled.

MICROBOONE-NOTE-1108-PUB
\( \nu_\mu \Lambda \) Production

- Uses NuMI flux
- 7% efficiency
- 99.9% background rejection

- Monte Carlo simulation predicts 9.0 ± 0.8 (MC stat.) signal and 3.1 ± 1.4 background events
- Combining \( 1.0 \times 10^{21} \) protons on target of neutrino mode flux and \( 1.3 \times 10^{21} \) protons on target of anti-neutrino mode flux
- Significance of 2.6 \( \sigma \)
$\nu_\mu \Lambda$ Production

$\alpha$ Parameter

- Angle between the direction of the $\Lambda$'s momentum vector and the line connecting the primary vertex to the decay vertex.

Figure: $\alpha$ angle calculation.

Figure: Values for signal and BG.
$\nu_e \text{ CCNp0}\pi$

- First energy and angle measurements for outgoing electron and leading proton on argon