MicroBooNE’s Neutrino Cross-section Campaign

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On behalf of the MicroBooNE Collaboration
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MicroBooNE in a Nutshell

- Liquid Argon Time Projection Chamber at FNAL
  - 85 tonne active volume of Argon
  - 5 years physics runs: 2015-2021
    - Largest v-Ar dataset collected

- Main physics goals
  - Investigate origin of anomalous low energy excess (LEE) of electron-like events seen by MiniBooNE
  - Measure neutrino-Ar cross sections
  - BSM searches
  - Excellent testbed for LArTPC R&D
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  - Measure neutrino-Ar cross sections
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  - Excellent testbed for LArTPC R&D
Neutrinos Towards MicroBooNE
Neutrinos Towards MicroBooNE

Fermilab Accelerator Complex

BNB

MicroBooNE

NuMI

MicroBooNE Simulation Preliminary

\[
\frac{\text{V/POT}}{\text{GeV/cm}^2} = \begin{cases} \frac{1}{10^{-10}} & \text{for } \nu_\mu \\ \frac{1}{10^{-12}} & \text{for } \bar{\nu}_\mu \\ \frac{1}{10^{-15}} & \text{for } \nu_e \\ \frac{1}{10^{-13}} & \text{for } \bar{\nu}_e \end{cases}
\]

Energy (GeV)

0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0

\[
\phi(\nu) / 50 \text{ MeV} / \text{cm}^2 / \text{sr} / 2.4 \times 10^{20} \text{ POT} = \begin{cases} 10^{11} & \text{for } \nu_\mu (56.6\%) \\ 10^{9} & \text{for } \bar{\nu}_\mu (39.4\%) \\ 10^{7} & \text{for } \nu_e (2.5\%) \\ 10^{10} & \text{for } \bar{\nu}_e (1.5\%) \end{cases}
\]

Neutrino Energy [GeV]

0 1 2 3 4 5 6

Off-axis NuMI Flux at MicroBooNE

Forward Horn Current Mode
Neutrinos Towards MicroBooNE

- **On-axis**
  - 95% $\nu_\mu$ and < 1% $\nu_e$

- **8° off-axis**
  - 5% $\nu_e$ composition

Fermilab Accelerator Complex
LArTPC - a sneak peek into the world of neutrinos
A Fully Active Tracking Calorimeter

\( \nu_\mu \) 

e/\gamma\) showers 

proton candidate 

muon candidate 

Improvements with LArTPCs - Low proton threshold

- Measuring proton kinematics provides more information about the interaction

- Low thresholds

MicroBooNE 300 MeV/c
MICROBOONE-NOTE-1099-PUB
Phys. Rev. D 98, 032003

T2K 500 MeV/c

ArgoNeuT 200 MeV/c
Phys. Rev. D 90, 012008

MINERvA 450 MeV/c
PhysRevD.99.012004

Even lower threshold at MicroBooNE 250 MeV/c
MICROBOONE-NOTE-1099-PUB
Neutrino Interactions

Quasi-elastic (QE)

Resonance (RES)

Deep inelastic (DIS)

MicroBooNE

A. Schukraft, G. Zeller

Many open questions need experimental & theoretical input!

Fermilab
Neutrino Interactions

- Experiments need good interaction models
  - Predict final states on a wide range of energies with high precision
- Complex theory
  - Nuclear effects + many interaction processes
- Measurements essential to benchmark and help improve theory
Inclusive Channels:

\[ \nu_\mu \text{ CC Inclusive} \quad \mu \text{ CC Inclusive} \quad \nu_\mu \text{ CC Inclusive} \]

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\[ \nu_e \text{ CC Inclusive} \quad e \text{ CC Inclusive} \quad \nu_e \text{ CC Inclusive} \]

NuMI

Target

Fermilab
Inclusive Muon Neutrino:

Final state $\rightarrow \mu + \text{anything else}$

$\nu_\mu \rightarrow \mu$
Inclusive Muon Neutrino:

- First inclusive cross-section measurement: double-differential in muon kinematics
- Highest stats measurement on argon to-date

Upcoming - higher-statistics, higher-dimensionality measurements
Inclusive Electron Neutrino:

Final state $\rightarrow e + \text{anything else}$

$\nu_e$   $\rightarrow$   $e$

Target
Inclusive Electron Neutrino @ NuMI:

- ~243 selected events - Largest sample of νe -Ar interactions
- Good agreement with various generators
- In future -
  - More exclusive channels
  - Analyses with full dataset

Differential cross section in lepton angle and energy

Signal definition:

Electron + anything else in the final state
Exclusive Electron Neutrino @ BNB:

- Differential cross section in electron and proton kinematic variables ([MICROBOONE-NOTE-1109-PUB](#))

- Shed light on further tuning of generators
  - Improve $\nu_e$ prediction for future new physics searches
Exclusive Muon Neutrino Interactions: Neutral Pion

\[ \text{Target} \rightarrow \nu_\mu, \pi^0, \mu \rightarrow \text{Nucleus} \]

\[ \mu \text{BooNE} \]

Exclusive Muon Neutrino Interactions: Neutral Pion

- First measurement of flux averaged $\nu_\mu$-Ar CC$\pi^0$ cross section

What’s next -
- $\nu_\mu$ CC$\pi^0$ differential
- $\nu_\mu$ NC$\pi^0$ differential
- $\nu_\mu$ CC/NC $\pi^0$
Exclusive Muon Neutrino Interactions: Neutral Pion

- A quick detour - $\nu_\mu$ NC$\pi^0$ total cross section results [arXiv:2205.07943]

Deficits compared to models studied
Exclusive Final States - Protons:

\[ \nu_\mu \text{ CC } 0\pi 2p \]

CCQE-like
Exclusive Final States - Protons:

- First neutrino-argon cross sections for an exclusive 2p final state [MICROBOONE-NOTE-1117-PUB]

- Angle between protons in lab frame
  - Sensitive to modeling choices for MEC and QE
Transverse Kinematic Imbalance (TKI):

\[ \delta p_T = \left| p_T^\mu + p_T^\rho \right| = 0 \]

Transverse projections trivially equal and opposite (momentum conservation)

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

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

*Imbalance* due to initial nucleon motion and other nuclear effects

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

- First neutrino-argon differential cross sections in TKI variables
  ([MICROBOONE-NOTE-1108-PUB])

- Sensitive to details of proton FSI modeling
Energy Dependent Inclusive Muon Neutrino Cross Section:

\[ E_\nu = E_\ell + E_{\text{had,vis}} + E_{\text{had,miss}} \]

- Oscillation measurements require understanding of energy-dependent event rates
- Modeling of the undetected missing hadronic energy
- Overcome the challenge by leveraging LArTPC’s simultaneous measurements of lepton energy and visible hadronic energy
Energy Dependent Inclusive Muon Neutrino Cross Section:

\[ E_\nu = E_\ell + E_{\text{had,vis}} + E_{\text{had,miss}} \]
Energy Dependent Inclusive Muon Neutrino Cross Section:

- Inclusive cross-section looking specifically at hadronic system [Phys. Rev. Lett. 128, 151801]
- Measured $\nu_\mu$ CC differential cross section per nucleon as a function of energy transfer $d\sigma/dv$
Next Gen Measurements at MicroBooNE:

$\nu_\mu$ Inclusive & Exclusive Measurements
- $\nu_\mu$ CC $\pi^0$ differential
- $\nu_\mu$ CC/NC $\pi^0$
- $\nu_\mu$ CC1$\pi^+$
- 2D $\nu_\mu$ CC $0\pi$Np
- 2D $\nu_\mu$ CC $0\pi$1p
- $\nu_\mu$ CC incl. 2D
- $\nu_\mu$ CC incl. 3D

$\nu_e$ Exclusive Measurements
- $\nu_e$ CC $0\pi$
- $\nu_e$ CC $1\pi$Np
- NuMI $\nu_e$ CC Np
- NuMI $\nu_e / \nu_\mu$
- NuMI $\bar{\nu}_e$-bar

Other Measurements
- NuMI $\Delta$ production
- MeV Scale Physics

+ Many more
Next Gen Cross Section Measurements at MicroBooNE:

- Multi differential cross section measurements to explore phase space for better modeling
- Directly test and improve GENIE by continuing our tuning effort
- Expand new ideas that are more sensitive to mismodelling (TKI, Conditional constraint procedure, etc.)
- Reduce uncertainties through ratio/simultaneous measurements, potentially using both beams
Conclusion

- Largest sample of neutrino-argon interactions available to date
- Rich neutrino interaction physics program at MicroBooNE
  - Crucial for future LArTPC experiments - SBN and DUNE
- Cross section results will help improve $\nu$-Ar interactions modelling for the future
Backup
The Crux of LArTPCs

- Excellent particle imaging detector
- mm scale spatial resolution
- Light signal by PMTs (PDS)
  Current (Future) generation LArTPCs
Improvements with LArTPCs - Electron Photon Separation

- Electron shower: $dE/dx \sim 2 \text{ MeV/cm}$
- Photon shower: $dE/dx \sim 4 \text{ MeV/cm}$

- No gap for electron showers.
- Gap for photon showers.

- $\nu_e$ CC candidate

- $e^-$
- $p$

- Vertex $e^\pm$
- $\gamma$

[Images and diagrams showing the difference between electron and photon showers with and without a gap.]
Systematic Uncertainties:
Comparison of systematic uncertainty budget between similar analyses [CC $1\mu$Np0$\pi$]

Past
Detector simulation / Reconstruction

Current

Phys. Rev. D 102 (2020) 11, 112013

$0.30 \text{ GeV/c} \leq \text{reco } p_\mu < 0.38 \text{ GeV/c}$

MicroBooNE Simulation

Fermilab
Systematic Uncertainties:
Comparison of systematic uncertainty budget between similar analyses [CC $1\nu Np0\pi$]

- Big effort to improve detector modeling to reduce impact of systematic uncertainties ([arXiv:2111.03556](https://arxiv.org/abs/2111.03556))
- As statistics rapidly increase - xsec are still systematic dominated

Past

Detector simulation / Reconstruction

Current


0.30 GeV/c $\leq$ reco $p_\mu$ $<$ 0.38 GeV/c

MicroBooNE Simulation

- Fractional Uncertainty

- $\cos(\theta_{\mu})$

- $p_\mu$

- MICROBOONE-NOTE-1099-PUB
Genie Tune:

- Tuned to T2K CC0π cross-section data
- J-PARC beam used by T2K similar to BNB flux
- 4-parameter fit for CCQE and MEC processes

Examples highlight achieved level of data/MC agreement for νμ CC inclusive, CCQE-like events.
Where are the $\nu_e$ & $\bar{\nu}_e$ coming from in NuMI?

The $\nu_e$ and $\bar{\nu}_e$ flux $> 60$ MeV is dominated by decays from unfocused kaons at the target.
Charged Lepton Angle Reconstruction

1. Assume all electron neutrinos come from the NuMI target.
2. Reconstruct position of interaction vertex.
3. Reconstruct (this) neutrino direction → within 3 degrees from true direction for 95% of selected $\nu_e$
Charged Lepton Angle Reconstruction

1. Assume all electron neutrinos come from the NuMI target.
2. Reconstruct position of interaction vertex.
3. Reconstruct (this) neutrino direction → within 3 degrees from true direction for 95% of selected $\nu_e$
4. Calculate lepton angle $\beta$

$0.01 < \cos \beta$ resolution $< 0.05$
Only 0.2% of showers are mis-reco in the opposite direction.