MicroBooNE Cross Section Measurements

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August 5th, 54th Annual Users Meeting
MicroBooNE at a glance

MicroBooNE is the longest running Liquid Argon Time Projection Chamber at FNAL. With 85 ton active volume, MicroBooNE collects neutrinos on-axis from the BNB and highly off-axis from NuMI.

Completed 5 years physics runs: 2015-2021. Largest neutrino-argon dataset available to date.

Just started exciting R&D program!
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Inside the MicroBooNE LArTPC: 3 wire planes (8192 gold-coated wires) 73 CRT Modules

Thanks FNAL!!! for all the support during construction, commissioning and data-taking!!!
MicroBooNE has a large body of published work:

**33 papers, 56 public notes**

Sharing findings with LAr community…

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**MicroBooNE Publications**

Search for a Higgs Portal Scalar Decaying to Electron-Positron Pairs in the MicroBooNE Detector

Measurement of the Longitudinal Diffusion of Ionization Electrons in the Detector

Cosmic Ray Background Rejection with Wire-Cell LAr TPC Event Reconstruction in the MicroBooNE Detector

Measurement of the Flux-Averaged Inclusive CC νe and Anti-νe Cross Section on Argon using the NuMI Beam in MicroBooNE

Measurement of the Atmospheric Muon Rate with the MicroBooNE Liquid Argon TPC

Semantic Segmentation with a Sparse Convolutional Neural Network for Event Reconstruction in MicroBooNE

Neutrino Event Selection in the MicroBooNE LAr TPC using Wire-Cell 3D Imaging, Clustering, and Charge-Light Matching

A Convolutional Neural Network for Multiple Particle Identification in the MicroBooNE Liquid Argon Time Projection Chamber

The Continuous Readout Stream of the MicroBooNE Liquid Argon Time Projection Chamber for Detection of Supernova Burst Neutrinos

**2021**

Vertex-Finding and Reconstruction of Contained Two-track Neutrino Events in the MicroBooNE Detector

Measurement of Differential Cross Sections for Muon Neutrino CC Interactions on Argon with Protons and No Pions in the Final State

Measurement of Space Charge Effects in the MicroBooNE LAr TPC Using Cosmic Muons

First Measurement of Differential Charged Current Quasi-Elastic-Like Muon Neutrino Argon Scattering Cross Sections with the MicroBooNE Detector

Search for Heavy Neutral Leptons Decaying into Muon-Pion Pairs in the MicroBooNE Detector

Reconstruction and Measurement of O(100) MeV Electromagnetic Activity from Neutral Pion to Gamma Gamma Decays in the MicroBooNE LArTPC

A Method to Determine the Electric Field of Liquid Argon Time Projection Chambers Using a UV Laser System and its Application in MicroBooNE

Design and Construction of the MicroBooNE Cosmic Ray Tagger System

Rejecting Cosmic Background for Exclusive Neutrino Interaction Studies with Liquid Argon TPCs: A Case Study with the MicroBooNE Detector

First Measurement of Muon Neutrino Charged Current Neutral Pion Production on Argon with the MicroBooNE detector

A Deep Neural Network for Pixel-Level Electromagnetic Particle Identification in the MicroBooNE Liquid Argon Time Projection Chamber

Comparison of Muon-Neutrino-Argon Multiplicity Distributions Observed by MicroBooNE to GENIE Model Predictions

**2020**

Calibration of the Charge and Energy Response of the MicroBooNE Liquid Argon Time Projection Chamber Using Muons and Protons

First Measurement of Inclusive Muon Neutrino Charged Current Differential Cross Sections on Argon at Enu ~0.8 GeV with the MicroBooNE Detector

Design and Construction of the MicroBooNE Cosmic Ray Tagger System

**2019**

Ionization Electron Signal Processing in Single Phase LAr TPCs I: Data/Simulation Comparison and Performance in MicroBooNE

Ionization Electron Signal Processing in Single Phase LAr TPCs II: Data/Simulation Comparison and Performance in MicroBooNE

**2018**

The Pandora Multi-Algorithm Approach to Automated Pattern Recognition of Cosmic Ray Muon and Neutrino Events in the MicroBooNE Detector

Measurement of Cosmic Ray Reconstruction Efficiencies in the MicroBooNE LAr TPC Using a Small External Cosmic Ray Counter

Noise Characterization and Filtering in the MicroBooNE Liquid Argon TPC

Michel Electron Reconstruction Using Cosmic Ray Data from the MicroBooNE LAr TPC

Determination of Muon Momentum in the MicroBooNE LAr TPC Using an Improved Model of Multiple Coulomb Scattering

**2017**

Convolutional Neural Networks Applied to Neutrino Events in a Liquid Argon Time Projection Chamber

Design and Construction of the MicroBooNE Detector

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...to boost SBN and DUNE’s success

See Denver Whittington’s talk
Ingredients for a successful on-beam neutrino experiment

1. Know your neutrino flux
Ingredients for a successful on-beam neutrino experiment

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1. Know your neutrino flux → MICROBOONE-NOTE-1031-PUB
2. Know your detector → JINST 15, P03022 (2020) (and many more)
LArTPC in action

Extremely detailed 3D images + calorimetry + PID: unprecedented tool for neutrino interaction & BSM physics
Proton Candidate
automatic reco threshold:
300 MeV/c

Electron Candidate

νₑ

~3 mm resolution

μBooNE

LArTPC in action
Extremely detailed 3D images + calorimetry + PID:
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νₑ

o(100) keV
hit thresholds

NUMI DATA : RUN 5440 EVENT 2577. MARCH 15, 2016
LArTPC in action
Extremely detailed 3D images + calorimetry + PID: unprecedented tool for neutrino interaction & BSM physics

Proton Candidate
automatic reco threshold:
300 MeV/c

Electron Candidate

≈3 mm resolution

ν_e

o(100) keV hit thresholds

e/γ separation

arXiv:2101.04228
To $e^-$ or not to $e^-$? Why is $e/\gamma$ separation a big deal?

**Primary physics goal:**
Investigate the nature of the MiniBooNE excess of low energy electromagnetic events. **Is it electrons? Is it photons?**


![Graph showing MiniBooNE result with data points and error bars for different categories such as $v_\alpha$ from $\mu^{+}$, $v_\alpha$ from $K^+$, $v_\beta$ from $K^0$, $\pi^0$ misid, $\Delta \rightarrow N\gamma$, dirt, other. The plot includes the best fit and constr. syst. error.](Image of graph)

**Electron $dE/dx \sim 2$ MeV/cm**

**Photon $dE/dx \sim 4$ MeV/cm**

**Gap**
Exploring the MiniBooNE LEE

ν_e analyses:
→ MiniBooNE-like final state (Pandora, 1eNp, 1e0p)
→ restricting to quasi-elastic kinematics (Deep Learning, 1e1p)
→ all ν_e final states (Wire-Cell, 1eX)

single photon analysis:
→ targeting Delta radiative decay hypothesis
  (Pandora, 1γ1p, 1γ0p)

3 reconstruction paradigms, 6 complementary channels
Ingredients for a successful on-beam neutrino experiment

1. Know your neutrino flux  →  MICROBOONE-NOTE-1031-PUB
2. Know your detector  →  JINST 15, P03022 (2020) (and many more)
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1. Know your neutrino flux → MICROBOONE-NOTE-1031-PUB
2. Know your detector → JINST 15, P03022 (2020) (and many more)
3. Know how neutrinos interact
Ingredients for a successful on-beam neutrino experiment

1. Know your neutrino flux
2. Know your detector
3. Know how neutrinos interact

Experiments need good interaction modeling: predict final states on a wide range of energies with high precision.

Theory is complex: several interaction processes + nuclear effects (FSI, MEC)

Cross section measurements essential to benchmark theory and help improve it!
$\nu_e + \bar{\nu}_e$ Bar CC Inclusive @ NuMI

Target

$\nu_e$ $e$ $X$

8/05/21

Elena Gramellini | elenag@fnal.gov
$\nu_e + \bar{\nu}_e$ Bar CC Inclusive @ NuMI

Flux averaged total cross section.
Largest ever sample of $\nu_e$-Ar interactions with $> 200$ events
Selection main requirement: at least one shower compatible with electron hypothesis: Purity $\sim 40\%$, Efficiency $\sim 10\%$.
In good agreement with models

arXiv:2101.04228 (PRD accepted)
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In the works from NuMI $\nu_e$:

$\rightarrow \nu_e$ CC inclusive differential in lepton angle and energy, neutrino energy
$\rightarrow \nu_e$ CC 1eNp exclusive
$\rightarrow \nu_e/\nu_\mu$ ratios
$\rightarrow$ Anti $\nu_e$ inclusive
Production of neutral pions

\[ \gamma_e \rightarrow \mu + \pi^0 + X \]

Target

\[ \mu \rightarrow \gamma + p \]

\[ \gamma \rightarrow \mu \]

10 cm

Production of neutral pions

Fundamental background to the LEE search
First measurement of flux averaged $\nu_\mu$-Ar CC$\pi^0$ cross section
Production of neutral pions

Fundamental background to the LEE search
First measurement of flux averaged $\nu_\mu$-Ar CC$\pi^0$ cross section
$\nu_\mu$ CC Inclusive @ BNB
In single detector measurements, muon neutrinos are used to constrain uncertainties on electron neutrinos flux and interaction model. First double differential measurement on Argon → Overall good agreement with theory (Phys. Rev. Lett. 123, 131801 (2019)). More recent models achieve better agreement at forward scattering angles.
$\nu_\mu$ CC Inclusive @ BNB: a Sneak Peek at Next Gen Analyses

Improved detector simulation and tuned nuclear modelling

Previously published measurement

Current measurement
MICROBOONE-NOTE-1069-PUB
$\nu_\mu$ CC Inclusive @ BNB: a Sneak Peek at Next Gen Analyses

Improved detector simulation and tuned nuclear modelling

→ Purity: from 50% to 71.9%
→ 3x Reduction of cosmic contamination
→ Detector uncertainties from 16.2 % to 3.3 %

Better detector understanding: signal processing from all planes & improved calorimetry

Reduced systematic uncertainties via a data driven method
MICROBOONE-NOTE-1075-PUB

Improved neutrino interaction model
MICROBOONE-NOTE-1074-PUB

Cosmic Ray Tagger use, JINST 14, P04004 (2019)

MICROBOONE-NOTE-1069-PUB
$\nu_\mu$ CC Inclusive @ BNB: a Sneak Peek at Next Gen Analyses

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Cosmic Ray Tagger use, JINST 14, P04004 (2019)
$\nu_\mu$ CC exclusive topologies: $\nu_\mu$ CC0$\pi$Np with N $\geq$ 1
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Event selection: $P_\mu > 100$ MeV/c, $300 < P_p < 1200$ MeV/c, $0\pi$
Purity ~70% & efficiency ~30%, overall agreement in proton kinematics
Lowest momentum bin (close to detection threshold) most sensitive to model differences
$\nu_\mu$ CC exclusive topologies: $\nu_\mu$ CC0$\pi$N$p$ with $N \geq 1$

Disagreement in muon kinematics at forward scattering angles

Phys. Rev. D102, 112013 (2020)
$\nu_\mu$ CC exclusive topologies: $\nu_\mu$ CCQE-like
\(\nu_\mu\) CC exclusive topologies: \(\nu_\mu\) CCQE-like

Simple topology dominant at energies relevant for SBN
CCQE-like in restricted phase space boosts CCQE predicted purity: \(~80\%\)
Event selection: \(P_\mu > 100\) MeV/c, single proton \(P_p > 300\) MeV/c

Good agreement with models, except at very forward muon scattering angles.

\(\nu_\mu\) CC exclusive topologies: \(\nu_\mu\) CCQE-like

\[
\begin{align*}
|\Delta \theta_{\mu p} - 90^\circ| &< 55^\circ \\
|\Delta \phi_{\mu p} - 180^\circ| &< 35^\circ \\
P_T &= |P_\mu + P_p|_T < 0.35\text{ GeV/c}
\end{align*}
\]

Consistent Picture for $\nu_\mu$ CC

$\nu_\mu$ CC Inclusive
MC excess in forward bin

$\nu_\mu$ CCNp
Data turnover in forward bin

$\nu_\mu$ CCQE-like
Biggest deficit in forward bin

Forward region is very sensitive to nuclear physics: more modern generators show promise.
Investigation with using exclusive channels will shed light on the matter.
Consistent Picture for $\nu_\mu$ CC

- $\nu_\mu$ CC Inclusive
  - MC excess in forward bin

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Biggest deficit in forward bin

In the works for $\nu_\mu$ CC exclusive:
- Pion production: $\rightarrow \nu_\mu$ CC1$\pi^+$
- $\nu_\mu$ CC-Coherent
- Rare channels $\rightarrow \nu_\mu$ CC Kaon @ BNB & NuMI
- $\eta$ production
- Hyperon ($\Lambda, \Sigma$) production @ NuMI

Forward region is very sensitive to nuclear physics: more modern generators show promise.
Investigation with using exclusive channels will shed light on the matter.
Challenging topologies: NC1p

ν p

ν p

μBooNE

5 cm

BNB DATA : RUN 5122 EVENT 298
Challenging topologies: NC1p

Neutral current interactions w/ single proton:
1 proton track with 1.2 < length < 200 cm
Lowest \( Q^2 \) NC1p analysis to date (0.1 GeV\(^2\))
Purity \( \sim 40\% \) & efficiency \( \sim 30\% \)
Sensitive to strange component of neutral-current axial form factor

No previous data for NCE with \( T < 225 \) MeV

MICROBOONE-NOTE:
1067-PUB
MicroBooNE has collected the largest sample of neutrino-argon interactions available to date and has completed our first era of detector studies and cross section analyses.
→ Stepping stone measurements for many more to come! Much more data to analyze!

Measuring neutrino cross sections on argon with high precision opens a new window in the exploration of the nucleus and it is foundational for BSM work in LArTPCs:
we are setting solid basis for a series of first results on the MiniBooNE low energy excess (coming soon).
Exciting times ahead!!! Stay tuned!

Thanks!!!
Backup
Improved Interaction Model: GENIE Tune

GENIE v2.12.2 → GENIE v3.0.6

Tuned CCQE and CCMEC models to T2K $\nu_\mu$ CC0\pi data

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

MICROBOONE-NOTE-1074-PUB

GENIE v3.0.6 models used:
More on Neutral Pions


MICROBOONE-NOTE-1085-PUB
**MicroBooNE: current R&D**

**Brief R&D parenthesis**

Noise source in MicroBooNE: MicroBooNE noise characterization paper: [JINST 12, P08003 (2017)](https://doi.org/10.1088/1748-0221/12/08/P08003)

Single photo-electron rates as a function of drift HV and with reverse cathode polarity.

HV studies: 70 kV → 128 kV

Impact of UV laser grounding schemes for DUNE?

Real-time triggering solutions that can get physics faster in SBND, DUNE ND

Argon doping
FIG. 3. The position of the MicroBooNE detector relative to the NuMI neutrino beam target with views projected to the side and above. The NuMI beamline is angled $3^\circ$ downwards and the distance of the NuMI target to MicroBooNE is approximately 679 m. The flux of neutrinos at MicroBooNE covers angles ranging from $8^\circ$ to $120^\circ$ relative to the NuMI beamline direction.
**Single Transverse Variables**

Transverse direction characterized by magnitude & 2 angles

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

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

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

**Longitudinal Variables**


\[ R = m_A + p_L^\mu + p_L^p - E^\mu - E^p \]

\[ \delta p_L = \frac{1}{2} R - \frac{m_A^2 - 1 + \delta p_T^2}{2R} \]

\[ p_{n,proxy} = \sqrt{\delta p_L^2 + \delta p_T^2} \]

Struck nucleon momentum

\[ \delta p_{Tx} = (\hat{p}_\nu \times \hat{p}_T^\mu) \cdot \delta p_T \]

\[ \delta p_{Ty} = -\hat{p}_T^\mu \cdot \delta p_T \]

Sensitivity to nuclear effects
MicroBooNE: event reconstruction

3D Event reconstruction is crucial in LArTPC. Multiple avenues:


Cosmic contamination plays a big role on the surface:
Cosmic Ray Tagger installed in 2018 JINST 14, P04004 (2019), Cosmic data as background to simulation (pioneered the “overlay” technique in LAr).
$\nu_\mu$ CC exclusive topologies: protons

Low thresholds probe more detailed interaction channels and nuclear effects

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

→ T2K: 500 MeV/c  
  Phys. Rev. D 98, 032003

→ MINERvA: 450 MeV/c  
  Phys. Rev. D 99, 012004

→ MicroBooNE: 300 MeV/c  
  Phys. Rev. D102, 112013

Protons identified by Bragg peak in last 30 cm of track  
MICROBOONE-NOTE-1056-PUB