NEUTRINO INTERACTION MEASUREMENTS ON ARGON

Kirsty Duffy, Fermi National Accelerator Laboratory
on behalf of the MicroBooNE Collaboration
XXIX International Conference on Neutrino Physics
23rd June 2020
Cross-section measurements on argon are vital to reduce systematic uncertainties for the SBN program and DUNE.

With low thresholds and $4\pi$ acceptance, Liquid Argon Time Projection Chambers (LArTPCs) are powerful detectors to study detailed final state topologies and quantitatively inform theoretical models.

Expanded statistics, better detector understanding since Neutrino 2018.

Are models able to describe $\nu$-Ar data?

**ArgoNeuT**
- pathfinder, low statistics

**MicroBooNE**
- high statistics, but initial measurements had large systematic uncertainties

**Precision MicroBooNE**
- improved detector understanding $\rightarrow$ high statistics, low uncertainties

Future experiments: higher statistics (SBND, ICARUS, DUNE-ND) and lower systematics due to measurements by LArIAT, ProtoDUNEs.
Many measurements of $\nu$-$\text{Ar}$ scattering

- $\nu_\mu$ CC inclusive cross section
  - Single-differential cross section
  - Updated single-differential cross section

- $\nu_\mu$ exclusive channels
  - Charged-particle multiplicity
  - $\nu_\mu$ CCQE-like scattering
  - $\nu_\mu$ and $\overline{\nu}_\mu$ CC2p production
    - Phys. Rev. D 90, 012008 (2014)
  - $\nu_\mu$ CC$\pi^0$ production
  - $\nu_\mu$ and $\overline{\nu}_\mu$ NC$\pi^0$ production

- Other measurements
  - $\nu_e$ and $\overline{\nu}_e$ scattering (inclusive)
  - MeV-scale physics
  - MeV-scale physics
    - MICROBOONE-NOTE-1071-PUB
  - Limits on millicharged particles
    - MICROBOONE-NOTE-1067-PUB
  - $\nu_\mu$ and $\overline{\nu}_\mu$ CC$\pi^+$ production
  - $\nu_\mu$ and $\overline{\nu}_\mu$ Coherent CC$\pi^+$ production
  - $\nu_\mu$ CC kaon production
    - MICROBOONE-NOTE-1076-PUB
  - $\nu_\mu$ NC 1p production
    - MICROBOONE-NOTE-1069-PUB
Many measurements of $\nu$-Ar scattering

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**ArgoNeuT** is a 40x47x90cm³ LArTPC

- **2 planes** of wires with 4mm spacing collect charge from drifting electrons following secondary particle tracks
- **$1.35 \times 10^{20}$ POT** data in NuMI beamline at Fermilab 2009-2010: $<E_{\nu_e}> = 4.3$ GeV, $<E_{\bar{\nu}_e}> = 10.5$ GeV
- Placed in front of MINOS near detector at Fermilab: use as tracking spectrometer

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Figure from T. Yang, NuINT 2017
MicroBooNE: 170 ton LArTPC

- **3 planes** of wires (vertical, +60°, -60°) with 3mm spacing
- **32 PMTs** collect light from flash at time of interaction
- Sits in **two neutrino beams** at Fermilab: BNB (on-axis, \( <E_{\nu\mu} > = 800 \text{ MeV} \)) and NuMI (off-axis, \( <E_{\nu e} > = 650 \text{ MeV} \))
- Stable detector operation since 2015: **longest-running LArTPC to date**
  - >95% DAQ uptime
  - \( 1.52 \times 10^{21} \) POT collected in total (analyses shown here use subsets, not full POT)
  - From December 2017: data with **Cosmic Ray Tagger (CRT)**

See also: “Searches for New Physics with MicroBooNE” by G. Karagiorgi, 2nd July

Thank you to Fermilab Accelerator Division, Cryogenics team, and Operations team!
GETTING THE MOST OUT OF LArTPCs

- MicroBooNE Collaboration has made **huge improvements** in our understanding of the detector since Neutrino 2018.

- Detailed understanding of detector is **key to our R&D mission** for future LArTPCs.

- **Improved signal processing** (2D deconvolution) accounts for interfering wire signals on all three planes.

- Tracking is hard when particles go parallel to wires. Precise calorimetry on all planes → 3D tracking → **4π particle identification**.
IMPROVED DETECTOR UNDERSTANDING ENABLES BETTER MEASUREMENTS

- Cosmic rejection power (without kinematic requirements) **increased by factor of 8** compared to previous publications
- **High efficiency**: 80.4% for $\nu_\mu$CC (87.6% for $\nu_e$CC)
- **Increased statistics**: 11.3k events, compared to 4.3k events in same data set for 2019 CC inclusive measurement

Wire-Cell 3D imaging and clustering

- Simultaneously match all clusters in event to light → find cluster consistent with neutrino-induced flash

Preliminary

- Events/5x10^19 POT/100 MeV
- Beam-on data, 17305
- Stat. error (beam-off data + MC)
- Cosmic (beam-off data), 1987
- Cosmic (beam-on MC), 589
- $\nu_\mu$ CC in FV, 11379
- $\nu_\mu$ NC in FV, 1629
- $\nu_\mu$ outside FV in cryo, 964
- $\bar{\nu}_e\nu_\mu$ in cryo, 257
- $\nu$ in dirt, 460

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Many measurements of ν-Ar scattering

**ν_μ** CC inclusive cross section

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**ν_μ** exclusive channels

- Charged-particle multiplicity

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- ν_μ and ν̄_μ CC2p production
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- MICROBOONE-NOTE-1071-PUB

**ν_μ** NC 1p production
- MICROBOONE-NOTE-1067-PUB

**Other measurements**

- ν_e and ν̄_e production (inclusive)

- MeV-scale physics

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  - MICROBOONE-NOTE-1076-PUB

- Limits on millicharged particles
CC INCLUSIVE CROSS SECTION MEASUREMENT

- Selection presented at Neutrino 2018 → new since then: **double-differential** cross section measurement

- **First time** double-differential cross section has been measured on argon: compared to worldwide interaction generators

- All models **overpredict in high-momentum, forward going bins**: interesting physics in this region!

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**MicroBooNE** 1.6e20 POT

-1.00 ≤ cos(θ_{μ}^{reco}) < -0.50

<table>
<thead>
<tr>
<th>Model</th>
<th>χ²/N_{bins}</th>
</tr>
</thead>
<tbody>
<tr>
<td>GENIE v2.12.2 + Emp. MEC</td>
<td>245.9/42</td>
</tr>
<tr>
<td>GENIE v3.00.04 G1810a0211a</td>
<td>108.8/42</td>
</tr>
<tr>
<td>GIBUU 2019</td>
<td>172.9/42</td>
</tr>
<tr>
<td>NuWro 19.02.1</td>
<td>126.5/42</td>
</tr>
</tbody>
</table>

Data (Stat. ⊕ Syst. Unc.)

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IMPROVED DETECTOR UNDERSTANDING ENABLES BETTER MEASUREMENTS

Selected Events

- CC (signal), 50%
- $\nu_\mu$, CC, 0.054%
- $\nu_e$, CC, 0.44%
- NC, 1.6%
- OUTFV, 7.6%
- Dirt, 4.3%
- Cosmic, 6.4%
- Data (Beam-off), 29%
- Stat. Unc.

Data (Beam-on, stat. only)

1.6e+20 POT

MicroBooNE

GENIE v2.12.2

Previous Measurement

PRL 123, 131801 (2019)
IMPROVED DETECTOR UNDERSTANDING ENABLES BETTER MEASUREMENTS

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1.6e+20 POT
MicroBooNE

Ratio

\[ \cos(\theta_{\text{reco}}) \]

Previous Measurement
PRL 123, 131801 (2019)

Current Measurement

MicroBooNE Preliminary

Tuned GENIE v3.0.6

Accumulated POT: 7.644e+18

\[ \cos(\theta_{\text{reco}}) \]
Improving detector understanding enables better measurements.

**Previous Measurement**

- **ν\(_μ\) CC (signal) purity:** 50% → 71.9%
- **Entering backgrounds:** 33.3% → 13.2%

**Current Measurement**

- Improved detector understanding, reconstruction, CRT → higher purity
- GENIE v2.12.2 vs. Tuned GENIE v3.0.6

**MicroBooNE Preliminary**

Accumulated POT: 7.644e+18

- ν\(_μ\) CC (signal): 71.9%
- ν\(_μ\) CC (not \(\mu\)): 2.6%
- ν\(_ν\) CC: 0.1%
- ν\(_\nu\) CC: 0.6%
- NC: 2.5%
- OUTFV: 3.5%
- Cosmic: 5.6%
- Dirt: 2.4%
- Data (Beam-off): 10.8%
- Data (Beam-on, stat. only)

**MicroBooNE 1.6e+20 POT**

- ν\(_μ\) CC (signal), 50%
- ν\(_\nu\) CC, 0.054%
- ν\(_\nu\) CC, 0.44%
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- Data (Beam-off), 29%
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- Data (Beam-on, stat. only)
**Better data-simulation agreement** from improved neutrino interaction 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

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**Accumulated POT: 7.644e+18**

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Entries per bin</th>
<th>Tuned GENIE v3.0.6</th>
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<tbody>
<tr>
<td>$\nu_\mu$ CC (signal)</td>
<td>71.9%</td>
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**IMPROVED INTERACTION MODELING ENABLES BETTER MEASUREMENTS**

Kirsty Duffy

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**GENIE v3.0.6 models used:**

DRASTICALLY REDUCED SYSTEMATIC UNCERTAINTIES

Flux-integrated cross section consistent with previous measurement

Drastically reduced systematic uncertainties

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<th>Source</th>
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<td>16.2%</td>
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PRL 123, 131801 (2019)
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- Largest reduction in uncertainties comes from improved detector understanding

**Source**

- Uncertainty

**MicroBooNE-NOTE-1075-PUB**

**MicroBooNE-NOTE-1069-PUB**

**PRL 123, 131801 (2019)**
DRASTICALLY REDUCED SYSTEMATIC UNCERTAINTIES

Instead of cosmic ray simulation, now use overlay: simulated neutrino interactions overlaid on real cosmic data → no uncertainty in cosmic ray model

Flux-integrated cross section consistent with previous measurement

Drastically reduced systematic uncertainties

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PRL 123, 131801 (2019)
**IMPROVED CROSS SECTION MEASUREMENT**

**Single-differential cross section** as a function of reconstructed muon momentum and angle → **very good agreement with previous measurement**, but **reduced uncertainties**

Future development towards **double-differential** cross-section measurement
Many measurements of $\nu$-Ar scattering

- $\nu_\mu$ CC inclusive cross section
  - Single-differential cross section
  - Updated single-differential cross section

- $\nu_\mu$ exclusive channels
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  - $\nu_\mu$ and $\bar{\nu}_\mu$ NCC$\pi^0$ production

- Other measurements
  - $\nu_e$ and $\bar{\nu}_e$ scattering (inclusive)
  - MeV-scale physics

- Double-differential cross section

- Single-differential cross section with updated detector and interaction models
  - MICROBOONE-NOTE-1069-PUB

- $\nu_\mu$ and $\bar{\nu}_\mu$ CC$\pi^+$ production

- $\nu_\mu$ and $\bar{\nu}_\mu$ Coherent CC$\pi^+$ production

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- MeV-scale physics
  - MICROBOONE-NOTE-1076-PUB

- Limits on millicharged particles
LArTPC STRENGTH: LOW PROTON THRESHOLDS

- **Low thresholds** → probe 2p2h scattering and nuclear processes
  - **MicroBooNE:** 300 MeV/c
  - **ArgoNeuT:** 200 MeV/c
  - **T2K:** 500 MeV/c
  - **MINERvA:** 450 MeV/c

- Protons identified by Bragg peak in last 30 cm of track

300 MeV/c → 47 MeV KE
First extraction of $\nu_\mu^{-40}\text{Ar}$ CCQE-like cross section using a surface LArTPC

Signal: 1 muon ($p_\mu>100$ MeV/c), 1 proton ($p_p>300$ MeV/c) with extra cuts on coplanarity and transverse imbalance to enhance CCQE contribution

$\rightarrow \sim84\% \text{CC}1p0\pi$ ($\sim81\% \text{CCQE}$) purity, $\sim20\%$ efficiency

Good agreement with models, except at very forward muon scattering angles $\rightarrow$ low momentum transfer (similar effects previously seen in carbon scattering)
Across all kinematic variables, agreement is improved if forward muon angles are excluded.
NC IP CROSS SECTION

- Measure cross section for neutral-current single proton production
- Measurement includes events with $Q^2 \sim 2m_pT_p = 0.1$ GeV$^2$, significantly lower than previous measurements
- Future development towards a measurement of NC elastic scattering cross section → measure strange component of neutral-current axial form factor

**NC IP CROSS SECTION**

$V_\mu$  
$Z^0$  
$P$  
$P$  

L. Ren, poster 292, poster session 4

**MicroBooNE Preliminary**

- Data (Statistical Uncertainty)
- Data (Total Error)
- GENIE v3.0.6 G18_10a_02_11a
CC $\pi^\pm$ PRODUCTION

- **Highly relevant for DUNE**: dominant interaction mode at DUNE energies and less well-understood than CCQE-like scattering

- ArgoNeuT $\nu_\mu$ and $\overline{\nu}_\mu$ CC $\pi^\pm$ measurement:
  - Select **two-track events**: one matched to a track in MINOS (muon candidate)
  - **Select CC $\pi^\pm$ events** using $dE/dx$ of pion candidate, event topology

- MicroBooNE measurement in progress: development work focused on **muon/pion separation** and **pion reinteractions**

**ArgoNeuT $\nu_\mu$**

![Graph showing data from ArgoNeuT, GENIE, NuWro, and NEUT simulations.](image-url)
Electrons and photons produce showers in LArTPCs → important to understand for $\nu_e$ appearance searches in SBN and DUNE

$\pi^0$ interactions are a background (although often can be distinguished by energy deposition) — can also be used to verify shower reconstruction by reconstructing $\pi^0$ mass peak

**MicroBooNE CC$\pi^0$ Measurement:** presented at Neutrino 2018

FIRST MEASUREMENT OF ELECTRON NEUTRINO CROSS SECTION

- Flux-averaged $\nu_e + \bar{\nu}_e$ cross section measured by ArgoNeuT
- Purity 78.9%, efficiency 10.5% → 13 events selected
- First measurement of its kind in an energy regime highly relevant for DUNE, demonstration of fully-automated reconstruction and analysis
- MicroBooNE $\nu_e$ measurements in BNB - see “Searches for New Physics with MicroBooNE”, 2nd July
- $\nu_e + \bar{\nu}_e$ cross-section measurements in progress with NuMI beam: purity 40%, efficiency 9% → ~100 events in $5 \times 10^{19}$ POT

**PUSHING THE LIMITS**

- **CC kaon production**: rare process, few existing measurements, background for proton decay $p \rightarrow K^+\nu$ searches in DUNE
- Selection developed with 68% purity and 7% efficiency → expect 12 candidate interactions in $1.3 \times 10^{21}$ POT

- **Reconstruct sub-MeV particles**: photons from nucleus de-excitation or neutron re-interactions
- Demonstration of low-threshold LArTPC capabilities
- Used in ArgoNeuT to place constraints on BSM physics (millicharged particles)
Many measurements of $\nu$-Ar scattering

- **$\nu_\mu$ CC inclusive cross section**

- **$\nu_\mu$ exclusive channels**
  - $\nu_\mu$ and $\bar{\nu}_\mu$ CC2p production: Phys. Rev. D 90, 012008 (2014)
  - $\nu_\mu$ CC$\pi^0$ production: Phys. Rev. D 99, 091102(R) (2019)
  - $\nu_\mu$ and $\bar{\nu}_\mu$ NC$\pi^0$ production: Phys. Rev. D 96, 012006 (2017)

- **Other measurements**
  - MeV-scale physics: MICROBOONE-NOTE-1076-PUB
FUTURE PROSPECTS

- This talk has focused on current results from MicroBooNE and recent results from ArgoNeuT
FUTURE PROSPECTS

- This talk has focused on current results from **MicroBooNE** and recent results from **ArgoNeuT**

**MicroBooNE** recent improvements in detector understanding directly results in **reduced systematic uncertainties** on CC inclusive measurement

→ will form the basis of new, **more precise** measurements of neutrino interactions on argon in the near future

Additional measurements in progress: $\nu_\mu \text{ CC} \pi^0$, $\nu_\mu \text{ CC} \pi^+$, $\nu_\mu \text{ CC-Coherent } \pi^+$, $\nu_\mu \text{ CC} \pi N p$, $\nu_\mu \text{ CC} \pi 2 p$, $\nu_\mu \text{ CC} \text{ STV}$, $\nu_\mu \text{ KDAR CC} \pi$, $\nu_\mu \text{ CC} \pi 0 p$, $\nu_e \text{ CC inclusive}$, $\nu_e \text{ CC} \pi 1 p$
FUTURE PROSPECTS

- This talk has focused on current results from MicroBooNE and recent results from ArgoNeuT.

- Exclusive measurements will be informed by test-beam measurements of charged particles in LArTPCs (e.g. interactions of pions, protons) by LArIAT and ProtoDUNE.

- In the future, look out for more measurements from upcoming experiments: SBND, ICARUS, and eventually DUNE-ND.

ICARUS will start taking data very soon.
SBND will collect 7m $\nu$-Ar interactions in 3 years.

See talk: “ICARUS and the Fermilab Short-Baseline Neutrino Program” on 2nd July.
SUMMARY

- Cross-section measurements on argon are **vital** for the success of the SBN program and eventually DUNE

- **Huge progress** over the past two years since Neutrino 2018 → measurements with low-energy protons, \( \pi^0 \)s, \( \nu_e \)s and more are **extremely valuable**

- LArTPC technology has demonstrated \( 4\pi \) acceptance and ability to measure sub-MeV energies — we are already able to make **precise, accurate measurements of exclusive final states**

- First time we can confront **models tuned to carbon** with high-statistics argon data: seem to do well with the data now available

- More (and more precise) measurements expected in the future → **stronger tests** of our models
Cross-section Posters and Supporting Documents

MicroBooNE

- $\nu_\mu$ CCQE-like measurement: A. Papadopoulou, Poster 145, Poster Session 2

- Updated $\nu_\mu$ CC-inclusive measurement: MICROBOOONE-NOTE-1069-PUB

- $\nu_\mu$ NC1p measurement: L. Ren, Poster 292, Poster Session 4 MICROBOOONE-NOTE-1067-PUB

- $\nu_\mu$ CCKaon selection: A. Fiorentini, Poster 369, Poster Session 3 MICROBOOONE-NOTE-1071-PUB

- MeV-scale Physics: A. Bhat, Poster 4, Poster Session 4 MICROBOOONE-NOTE-1076-PUB

- Interaction model and uncertainties: MICROBOOONE-NOTE-1074-PUB

- Detector uncertainties: L. Yates, Poster 176, Poster Session 1 MICROBOOONE-NOTE-1075-PUB

ArgoNeuT

- $\nu_e+\bar{\nu}_e$ CC inclusive measurement: R. Fitzpatrick, Poster 139, Poster Session 4

- Improved limits on millicharged particles: I. Lepetic, Poster 89, Poster Session 2
MicroBooNE Publications

- MicroBooNE collaboration, “Ionization Electron Signal Processing in Single Phase LAr TPCs II: Data/Simulation Comparison and Performance in MicroBooNE”, arXiv:1804.02583, JINST 13, P07007 (2018), Fermilab News article (07/09/18), DOE HEP Science Highlight (05/21/19)
- MicroBooNE collaboration, “Noise Characterization and Filtering in the MicroBooNE Liquid Argon TPC”, arXiv:1705.07341, JINST 12, P08003 (2017), Fermilab News article (07/05/17), DOE HEP Science Highlight (05/16/18)
ARGONEUT PUBLICATIONS


Very **stable detector operation**, smooth and **steady data taking**, efficient data acquisition

Total data collected: $1.56 \times 10^{21}$ POT (protons on target)

Analyses shown today use subsets of data collected between December 2015 and June 2018
COSMIC RAY TAGGER (CRT)

CRT data from December 2017

Delivered POT
POT on tape

Cumulative POT

Week


0.0E00 5.0E18 1.0E19 1.5E19 2.0E19 2.0E21

POT
ELECTRON-PHOTON DISCRIMINATION

MicroBooNE \( \nu_e \) Selection: presented at NuInt 2018

Current: with improved detector understanding

MicroBooNE Preliminary 5.89e+20 POT

Run 123 - 1.05 GeV < Reco energy < 2.05 GeV
1eNp Presel., 1 shower

\[ \frac{dE}{dx} \text{ over first 4cm of shower} \]

\[ \frac{\sum_i^N}{\text{Data} - \text{MC}} \]

Collection Plane \( dE/dx \) [MeV/cm]

MicroBooNE NOTE-1054-PUB

Kirsty Duffy

39
CC INCLUSIVE CROSS SECTION MEASUREMENT

Selection presented at Neutrino 2018

- Topological and optical information → reject background events from cosmic rays
- Energy deposition profile: select candidate muon

Largest ever sample of neutrino interactions on argon

Signal (CC-inclusive) events: 50.4%

Largest background: cosmic rays (29%) → directly measured with beam-off data

New since Neutrino 2018: double-differential cross section measurement
CC Inclusive double-differential measurement

MicroBooNE 1.6e20 POT

-1.00 ≤ \( \cos(\theta^{\text{reco}}) \) < -0.50

0.00 ≤ \( \cos(\theta^{\text{reco}}) \) < 0.27

0.45 ≤ \( \cos(\theta^{\text{reco}}) \) < 0.62

0.62 ≤ \( \cos(\theta^{\text{reco}}) \) < 0.76

0.76 ≤ \( \cos(\theta^{\text{reco}}) \) < 0.86

0.86 ≤ \( \cos(\theta^{\text{reco}}) \) < 0.94

0.94 ≤ \( \cos(\theta^{\text{reco}}) \) < 1.00

**Tension reduced (smaller $\chi^2$) for GENIE v3, NuWro, and GiBUU compared to GENIE v2**

<table>
<thead>
<tr>
<th>Model</th>
<th>$\chi^2/N_{\text{bins}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GENIE v2+MEC</td>
<td>245.9/42</td>
</tr>
<tr>
<td>GENIE v3</td>
<td>108.8/42</td>
</tr>
<tr>
<td>GiBUU</td>
<td>172.9/42</td>
</tr>
<tr>
<td>NuWro</td>
<td>126.5/42</td>
</tr>
</tbody>
</table>

Large $\chi^2$ driven by high-momentum, forward-going bins

CC Inclusive double-differential measurement

- $-1.00 \leq \cos(\theta_{\text{reco}}) < -0.50$
- $-0.50 \leq \cos(\theta_{\text{reco}}) < 0.00$
- $0.00 \leq \cos(\theta_{\text{reco}}) < 0.27$
- $0.27 \leq \cos(\theta_{\text{reco}}) < 0.45$
- $0.45 \leq \cos(\theta_{\text{reco}}) < 0.62$
- $0.62 \leq \cos(\theta_{\text{reco}}) < 0.76$
- $0.76 \leq \cos(\theta_{\text{reco}}) < 0.86$
- $0.86 \leq \cos(\theta_{\text{reco}}) < 0.94$
- $0.94 \leq \cos(\theta_{\text{reco}}) < 1.00$

**Model**

- GENIE v2+MEC
- GENIE v3
- GiBUU
- NuWro

**Statistical Significance**

- GENIE v2+MEC: $245.9/42$
- GENIE v3: $108.8/42$
- GiBUU: $172.9/42$
- NuWro: $126.5/42$

**Graphs**

- Graphs showing data points and histograms for different ranges of $\cos(\theta_{\text{reco}})$ with error bars.

**References**

CC Inclusive double-differential measurement

MicroBooNE 1.6e20 POT
-1.00 ≤ cos(θ_μ^{reco}) < -0.50
GENIE v2.12.2 + Emp. MEC
GENIE v3.00.04 G1810a0211a
GENIE v3.00.04 G18..., No RPA
Data (Stat. ⊕ Syst. Unc.)

0.50 ≤ cos(θ_μ^{reco}) < 0.00

0.00 ≤ cos(θ_μ^{reco}) < 0.27

CC Inclusive double-differential measurement

Model

GENIE v2+MEC
245.9/42

GENIE v3 (LFG, no RPA)
121.6/42

GENIE v4 (LFG, with RPA)
108.8/42

PREVIOUS CC-INCLUSIVE CROSS SECTION: 1D MEASUREMENT


![Graphs showing single-differential cross section measurement](image-url)
**UPDATED CC-INCLUSIVE SELECTION: SYSTEMATIC UNCERTAINTIES**

Flux-integrated cross section consistent with previous measurement

Drastically reduced systematic uncertainties

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<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><strong>23.8%</strong></td>
<td><strong>12.7%</strong></td>
<td></td>
</tr>
</tbody>
</table>

CRT better able to reject interactions in surrounding material ("dirt") → reduced systematic uncertainty

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Accumulated POT: 7.644e+18

- **σ** [10⁻³² cm²]
  - **σ**, stat. ⊕ sys. error
  - **σ**, stat. error
  - Genie v3, uB prelim tune
  - previous MC

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PRL 123, 131801 (2019)
**Cosmic rejection:**
- Topological and optical information
- Veto events with CRT hits when all tracks are contained
- Cut on CRT hit-reconstructed vertex z position if tracks are uncontained

**Muon selection**
- Longest track > 20 cm is muon candidate
- Topology must be track-like
- Energy deposition must be inconsistent with a proton
Updated CC-Inclusive Selection Efficiency

- Good efficiency to select QuasiElastic, Meson Exchange Current, Resonant pion production, and Deep Inelastic Scattering interaction channels

- \( \rightarrow \) truly inclusive selection

- Efficiency limited at low neutrino energy/muon momentum due to muon candidate track length > 20 cm requirement
Improved detector understanding $\rightarrow$ drastically reduced systematic uncertainties from detector modeling
Efficiency is low for $p_\mu < 150$ MeV due to $>20$ cm track length requirement.

Main result includes all CC interactions in signal definition (no requirement on muon momentum).

As a check: re-extract cross section with signal requirement $p_\mu > 150$ MeV/c (note: statistical uncertainties only).

**Full phase space**

**True $p_\mu > 150$ MeV/c**
Efficiency is low for $p_\mu < 150$ MeV due to $>20$ cm track length requirement.

Main result includes all CC interactions in signal definition (no requirement on muon momentum).

As a check: re-extract cross section with signal requirement $p_\mu > 150$ MeV/c (note: statistical uncertainties only).

Full phase space

True $p_\mu > 150$ MeV/c
CCPI0 SELECTIONS

Low-energy photons appear more track like
→ low reconstruction efficiency
→ requiring that we reconstruct both $\pi^0$ photons limits statistics

Two-shower selection
→ validate $\pi^0$ hypothesis by invariant diphoton mass

Single shower selection
→ validate photon hypothesis
→ maximize statistics for cross section measurement

Select $\pi^0$ events by looking for **one or two** showers in addition to a candidate muon track.

**Two-shower sample:**
- reconstruct $\pi^0$ mass
- validate shower reconstruction

**One-shower sample (higher statistics):**
- total $\pi^0$ cross-section measurement
- agreement with model predictions
CCQE-LIKE CROSS SECTION

First extraction of $\nu_\mu-^{40}\text{Ar}$ CCQE-like cross section using a surface LArTPC

- Important channel for low-energy excess search (and other LArTPC oscillation analyses)
- Signal: 1 muon (>100 MeV/c), 1 proton (300 MeV/c)

**Selection:**
- Two tracks
- Energy deposition consistent with one muon and one proton
- Tracks are not collinear
- Tracks are coplanar
- Low vertex activity
- Low transverse momentum

A. Papadopolou, poster 145, poster session 2

CCQE CROSS SECTION: MODEL COMPARISONS

- **Nominal**: GENIE v2.12.2. Bodek-Ritchie Fermi Gas, Llewellyn-Smith CCQE model, empirical MEC model, Rein-Sehgal resonant and coherent scattering model, “hA” FSI model

- **hA2015**: GENIE v2.12.2 with a more recent “hA2015” FSI model

- **Alternative**: GENIE v2.12.10. Local Fermi Gas, Nieves CCQE model, Nieves MEC model, KLN-BS resonant and BS coherent scattering models, and hA2015 FSI model

- **v3.0.6**: GENIE v3.0.6. Same model configuration as Alternative model, with hA2018 FSI model
**NCIP SELECTION**

- **Single isolated track**
- Must be contained within fiducial volume
- Length 1.2 - 200 cm
- Must be **forward-going** \((\cos\theta > 0\) w.r.t neutrino beam direction)
- **Deposited energy profile** consistent with a proton
- Multi-class gradient-boosted decision tree used to **further reduce background from cosmic interactions**
NCIP CROSS SECTION MEASUREMENT

- Measure cross section for neutral-current single proton production

- Signal: 1 isolated proton

Selection:
42.1% efficiency, 29.8% purity

Largest backgrounds:
- Proton from charged-current interaction (other particles missed by reconstruction)
- Proton from non-1p neutral-current interaction (other particles missed by reconstruction)
CC kaon production: rare process, few existing measurements, background for proton decay $p \rightarrow K^+ \nu$ searches in DUNE

Selection developed on simulation: look for $K^+$ track from neutrino interaction and $\mu^+$ from $K^+$ decay

67.7% purity and 7% efficiency $\rightarrow$ expect to select 12 candidate interactions in $1.3 \times 10^{21}$ POT MicroBooNE data set

Aim: cross section measurement and study of $K^+$ in LArTPC
CC KAON SELECTION

- Reject cosmic rays based on topology and optical information
- Must have one track with energy deposition consistent with a muon
- K^+ candidate selected based on energy deposition: consistent with a kaon and inconsistent with a proton
- Must have exactly one μ^+ candidate: must start within 5cm of end of kaon track, track length >30cm, energy deposition inconsistent with a proton
ARGONEUT ELECTRON NEUTRINO SELECTION

- Focus on reconstructing leading shower in neutrino interaction
- Reject events with a muon reconstructed in downstream MINOS detector
- Reject events with through-going muons
- Reconstructed shower must be forward-going: \( \cos(\theta) > 0.05 \) w.r.t. beam direction
- Shower must start within 2cm of reconstructed vertex
- Electron candidate selected based on topology and charge of entire candidate shower using a BDT: BDT score >0.9
ARGONEUT CHARGED PION PRODUCTION MEASUREMENT

- ArgoNEUT: CC1 $\pi^\pm$ production Phys. Rev. D 98, 052002 (2018)

- Select two-track events: one matched to a track in MINOS (muon candidate)

- Select CC1 $\pi^\pm$ events using $dE/dx$ of pion candidate, event topology

- Overall purity 35.8% (ν), 55.7% (ν̅)

- 337 selected ν events (285 ν̅)

Figure from T.Yang, NuINT 2017
ARGONEUT CHARGED PION PRODUCTION MEASUREMENT

$\nu_\mu$ CC $\pi^\pm$ ArgoNeuT measurement

ARGONEUT CHARGED PION PRODUCTION MEASUREMENT

$\bar{\nu}_\mu$ CC $\pi^\pm$ ArgoNeuT measurement

**Resonant pion production model**
- GENIE, NEUT: Rein-Sehgal
- NuWro: $\Delta(1232)$ resonance only

**Nonresonant model**
- NEUT: Rein-Sehgal
- GENIE, NuWro: Bodek-Yang above resonance region, extrapolate smoothly to converge with resonance model at lower W

**FSI**
- NEUT, NuWro: Salcedo-Oset cascade
- GENIE: effective cascade model
- GiBUU: quantum-kinetic transport theory

**Paper conclusions**
- GiBUU: good agreement
- NuWro, NEUT: similar, higher than measured cross section
- GENIE: higher than other generators and measured cross sections (with reanalysis of bubble chamber data in EPJC (2016) 76: 474 points to GENIE's nonresonant background prediction)

All predictions within $2\sigma$ of measurement, except GENIE $\bar{\nu}$ (3.3$\sigma$)
MICROBOONE $\nu_e$ CC INCLUSIVE SELECTION

$\nu_e$ selection efficiency: 9%, purity: 40%
MICROBOONE $\nu_e + \bar{\nu}_e$ MEASUREMENTS

- Select $\nu_e + \bar{\nu}_e$ CC inclusive interactions by looking for single shower

- Purity 40%, efficiency 9% $\rightarrow \sim 100$ events in $5 \times 10^{19}$ POT

- Future plans:
  - $\nu_e + \bar{\nu}_e$ CC inclusive flux integrated cross section measurement
  - $\nu_e + \bar{\nu}_e$ CC inclusive differential cross-section measurement
  - Exclusive $\nu_e + \bar{\nu}_e$ CC inelastic differential cross-section measurement

---

**MICROBOONE Preliminary**

NuMI POT = 2.4e20

dE/dx over first 4cm of shower
Precise resolution of a LArTPC allows us to look in detail at particles produced in a neutrino interaction → measure number and kinematic distributions of charged tracks produced.
Both ArgoNeuT and MicroBooNE have demonstrated ability to reconstruct energy depositions from sub-MeV particles (ArgoNeuT: 300 keV, MicroBooNE: 100 keV)

Demonstration of low-threshold LArTPC capabilities: important for measurements of cross sections, especially solar neutrinos, supernova neutrinos, and neutrinos from µDAR

Measurement of Ar-39 decays in MicroBooNE

BSM physics search for millicharged particles in ArgoNeuT set leading limits (poster by I. Lepetic)