Cross Section Results from the MicroBooNE Neutrino Experiment
And An Outlook For Future Measurements

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Motivation - Potential New Physics

• Both the LSND and MiniBooNE experiments saw an excess of electron-like events.

• These measurements were performed at short-baselines (few hundred metres).

• They may indicate new physics, but some backgrounds are difficult to reduce.

• This anomaly is still unresolved.

*2. FERMILAB-PUB-18-219 LA-UR-18-24586
Many next-generation neutrino detectors plan to use argon as their target material.

Experiments such as DUNE and the SBN Programme need support from operating liquid argon detectors.

This includes not only cross section results, but also reconstruction techniques.
The MicroBooNE Detector

- The MicroBooNE liquid argon time projection chamber (LArTPC) was constructed and began data-taking in 2015.

- It uses 170 tons of argon, making it the largest operating LArTPC in the world.

- MicroBooNE fulfils two primary points:
  - Can provide critical neutrino data results for argon as a target material.
  - Can probe the electron-like short-baseline anomaly with the ability to better differentiate signal and background events.
MicroBooNE is Here!

Booster
MicroBooNE is Here!

Booster Neutrino Beam (BNB) 8 GeV protons
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Main Injector

Neutrino Main Injector (NuMI) Off-Axis 120 GeV protons

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Main Injector

Off-axis NuMI Flux at MicroBooNE Neutrino Mode

Neutrino Energy [GeV]

$\phi(\nu) / 50 \text{ MeV/cm}^2 / 6 \times 10^{20} \text{ POT}$
How does a LArTPC work?
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Detector volume, composed of argon atoms is held at high voltage.
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• Charged particles passing through volume ionise the atoms.
• Groups of electrons and Ar ions drift to edges of the field cage.
• Electrons are read-out by the 3 wire-planes (8256 total wires).
Colton Hill - University of Manchester

75 cm Run 3493 Event 41075, October 23rd, 2015

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16 cm Run 3472 Event 3172, October 22nd, 2015

16 cm Run 1148 Event 778. August 6th, 2015 17:16

NuMI DATA: RUN 10811, EVENT 2549. APRIL 9, 2017.

μBooNE

Run 3493 Event 41075, October 23rd, 2015

Run 3472 Event 3172, October 22nd, 2015

Run 1148 Event 778. August 6th, 2015 17:16
MicroBooNE Cross Section Results

- $\nu_{\mu}$ CC inclusive cross section.
- $\nu_{\mu}$ CC $\pi^0$ cross section.
- $\nu_{\mu}$ CC multi-proton selection.
- $\nu_e + \bar{\nu}_e$ CC inclusive cross section.
- NC elastic selection.
\( \nu_\mu \) CC Inclusive Cross Section

- Signal: \( \nu_\mu + Ar \rightarrow \mu + X \).

- Inclusive \( \nu_\mu \) CC measurement is a standard candle for the detector and selection performance.

- Analysis includes full direction and energy reconstruction of the out-going muon, up to 2.5 GeV.
$\nu_\mu$ CC Inclusive Cross Section

- First double differential $\nu_\mu$ cross section on argon.
- Enables critical comparison of neutrino-argon data versus various models over wide kinematic range.

$\sigma = 0.693 \pm 0.010 \text{ (stat.)} \pm 0.165 \text{ (syst.)} \times 10^{-38} \text{ cm}^2$

Phys. Rev. Lett. 123, 131801
ν\(_μ\) CC Inclusive Cross Section

- First double differential ν\(_μ\) cross section on argon.
- Enables critical comparison of neutrino-argon data versus various models over wide kinematic range.
- Specifically, comparison to older models lacking nuclear effects do not follow the suppression observed in the forward-going phase space.

\[ \sigma = 0.693 \pm 0.010 \text{ (stat.)} \pm 0.165 \text{ (syst.)} \times 10^{-38} \text{ cm}^2 \]

Phys. Rev. Lett. 123, 131801
$\nu_\mu$ CC $\pi^0$ Cross Section

- Signal: $\nu_\mu + \text{Ar} \rightarrow \mu + \pi^0 + X$.

- $\pi^0$ have traditionally been background to selections looking for $\nu_e$.

- DUNE is expected to have a large contribution of $\pi^0$ events.

- $\pi^0$ decays can also be used to test energy reconstruction.
$\nu_\mu$ CC $\pi^0$ Cross Section

• First automated selection and measurement of $\nu_\mu$ CC $\pi^0$ interactions in argon.

• Reconstruction of the $\pi^0$ invariant mass informs us how well we're reconstructing the shower energy.

• No cut on the invariant mass of the $\pi^0$. Shower ID and vertex conversion distance allow for tagging.

$$\sigma = 1.9 \pm 0.02 \text{ (stat.)} \pm 0.6 \text{ (syst.)} \times 10^{-38} \text{ cm}^2 / \text{ Ar}$$
$\nu_\mu$ CC $\pi^0$ Cross Section

- First automated selection and measurement of $\nu_\mu$ CC $\pi^0$ interactions in argon.

- Reconstruction of the $\pi^0$ invariant mass informs us how well we're reconstructing the shower energy.

- No cut on the invariant mass of the $\pi^0$. Shower ID and vertex conversion distance allow for tagging.

- Also examined assumed nuclear scaling of event rates with target.
\( \nu_\mu \) CC Multi-proton Selection

- Signal: \( \nu_\mu + Ar \rightarrow \mu + N\ p + X,\ N > 1 \).
- High multiplicity events allow us to test nuclear models.
- The MicroBooNE measurement is also complimentary to the observation in ArgoNeuT.
$\nu_\mu$ CC Multi-proton Selection

- Identification of 300 MeV/c kinetic energy protons possible.

- Automated reconstruction of individual particle energy demonstrated for complex topologies.
νμ CC Multi-proton Selection

- Identification of 300 MeV/c kinetic energy protons possible.
- Automated reconstruction of individual particle energy demonstrated for complex topologies.
- Unique topology also provides a high purity sample.
\( \overline{\nu}_e \) CC Inclusive Cross Section

- Signal: \( \overline{\nu}_e + \text{Ar} \rightarrow e + X \).

- Electron showers are golden channel for oscillation measurements.

- LAr detectors can separate electron-like from photon-like signals, reducing backgrounds.
$\overline{\nu}_e$ CC Inclusive Cross Section

• Signal: $\overline{\nu}_e + \text{Ar} \rightarrow e + X$.

• Electron showers are golden channel for oscillation measurements.

• LAr detectors can separate electron-like from photon-like signals, reducing backgrounds.
\( \bar{\nu}_e \) CC Inclusive Cross Section

- Using dE/dx, historically large \( \pi^0 \) backgrounds for \( \nu_e \) can now be removed.

- First fully-automated selection of \( \bar{\nu}_e \) CC interactions in argon.
$\nu_e$ CC Inclusive Cross Section

- Using dE/dx, historically large $\pi^0$ backgrounds for $\nu_e$ can now be removed.
- First fully-automated selection of $\nu_e$ CC interactions in argon.
- First $\nu_e$ CC cross section in argon.
NC Elastic Selection

• Signal: $\nu + p \rightarrow \nu + p$.

• Probes both proton structure and potential NC disappearance signature for BSM oscillations.

• Resolution of LArTPCs is sufficient to cleanly resolve single proton elastic scatters.
NC Elastic Selection

• Potential to select protons with reconstructed $Q^2$ down to 150 MeV.

• Identification of these protons in the energy range between 0.05 - 0.5 GeV is 80%.

• Monte Carlo appears to model the shape and rate relatively well for both $Q^2$ and direction.
What's Next For the MicroBooNE Cross Section Programme?

• 1) More data: MicroBooNE has collected 4 years of data now, which is being actively analysed and calibrated.

• 2) Recent improvements to detector simulation and reconstruction (updating current analyses).

• 3) Other exclusive channels and unique decays.

• 4) MicroBooNE’s cross section programme will inform all future oscillation measurements on argon.
Conclusion

• This presentation includes some of MicroBooNE's most recent and exciting cross section results.

• These results include the largest dataset of neutrinos ever observed in a liquid argon detector ($\nu_\mu$ and $\nu_e$).

• Iterations of these analyses will make use of further improvements to automation and reconstruction.

• The MicroBooNE cross section results look to inform future oscillation programmes for experiments such as SBND, ICARUS, and DUNE.
• Backup