Recent results from MicroBooNE

Pawel Guzowski*
The University of Manchester
Lake Louise Winter Institute
February 14, 2019

Outline:
Latest results, from the past year
• Cross section measurements
• Progress on MiniBooNE anomaly
• Prospects for 2019

* on behalf of the MicroBooNE Collaboration
Goals of the experiment

- Study performance of liquid argon time projection chamber technology
  – See talk by Christopher Barnes
- Measure neutrino interaction cross sections on argon
- Make definitive statement about nature of MiniBooNE low energy excess
- Search for exotic beam-related or astrophysical phenomena

FIG. 2. The hadronic shower produced in the initial interaction must still traverse the dense nuclear matter and is then subject to Final State Interactions (FSI) before appearing in the detector. These FSI include nucleon-nucleon interactions as well as pion-nucleon interactions as illustrated. Figure from Tomasz Golan.

It cannot be stressed enough that the incident neutrino energy is not a priori known. This situation differs dramatically from electron or muon scattering studies where the amounts of energy and momentum that are transferred to the nucleus is known precisely on event-by-event basis. For neutrino nucleus scattering the incoming neutrino energy and initially produced hadronic particles, which have been subject to the above mentioned nuclear effects, can only be estimated from what is observed in the detector.

Since it is the initial neutrino energy spectrum as well as signal and background topologies that have to be used in the extraction of oscillation parameters, the strong dependence of the unbiased extraction of neutrino-oscillation parameters on neutrino-interaction physics can best be summarized by noting that the energy and configuration of interactions observed in experimental detectors are, aside from detector effects, the convolution of the energy-dependent neutrino flux, the energy-dependent neutrino-nucleon cross section, and these significant energy-dependent nuclear effects.

Practically, experimenters combine information about the energy dependence of all exclusive cross sections as well as nuclear effects into a nuclear model. This model along with the best estimate of the spectrum of incoming neutrino energies then enters the Monte Carlo predictions of target nucleus response and topology of final states and is a critical component of oscillation analyses.

To illustrate how oscillation experiments depend on this nuclear model, consider the following illustrative conceptual outline of a two-detector, long-baseline oscillation analysis:

1. Reconstruct the observed event topology and energy (final state particles identification and their momenta) in the near detector (ND).

2. Use the nuclear model to take the reconstructed event topology and energy back through the nucleus to infer the neutrino interaction energy $E_{\text{nd}} \nu_{\text{f}}$.

3. Using information on geometric differences between near and far detector fluxes and perturbed via an oscillation hypothesis, project the resulting initial interaction neutrino energy spectrum ($E_{\text{nd}} \nu_{\text{f}}$), into the predicted spectrum $0(E_{\text{fd}} \nu_{\text{f}})$ at the far detector.

http://nustec.fnal.gov

4.5σ excess

PRL 121, 221801 (2018)
**Booster Neutrino Beam**

12×10^{20} POT delivered since 2015
- approved for 13.2×10^{20} POT

See Christopher’s talk for details on detector, calibration, and detector physics

Surface detector – large cosmic ray background. Cosmic rejection paper: arXiv:1812.05679
Charged particle multiplicity

- LArTPCs have excellent spatial resolution of charged tracks
  - High-multiplicity exclusive cross section measurements
- Charged particle multiplicity agrees with GENIE [1] generator at 2σ level; data favours lower multiplicities

4 proton-candidate real data event

ν_μ - Ar CC-inclusive cross section

- Signal: μ + X
- First year data only (so far)
- **Largest ever sample** of muon neutrinos on argon
- Double differential cross sections will also be produced

σ = 0.76 ± 0.01 (st.) ± 0.19 (sys.) × 10^{-38} cm^2/n

**Single-differential σ w.r.t. muon momentum**

**Single-differential σ w.r.t. muon angle**
CC neutral pion production

- Signal: $\mu + \pi^0 + X$
- MicroBooNE’s first PRL submission
- First $\pi^0$ cross section on argon to use fully automated reconstruction

$$\sigma = 1.94 \pm 0.16 \text{ (st.)} \pm 0.60 \text{ (sys.)} \times 10^{-38} \text{cm}^2/\text{Ar}$$

**Photon conversion length**

**$\pi^0$ mass reconstruction**

Directly informs the DUNE TDR effort

Data: Mean $128 \pm 5 \text{ MeV/c}^2$

- Neutrino Induced $\pi^0$
- Charge Exchange $\pi^0$
- Cosmic (data)
- Other

Simulation Normalized to Data

- Data
- Neutrino Interaction, primary $\gamma$
- Neutrino Interaction, not a primary $\gamma$
- Neutrino Interaction, uncorrelated activity
- Cosmic only (data)
- Fitted Data Conversion Length: 24 ± 1 cm
- Simulation Conversion Length: 25 cm

Simulation: $\pi^0$ mass reconstruction

Fitted Data Conversion Length: 24 ± 1 cm

Simulation Conversion Length: 25 cm

**Vertex to Shower Start Distance [cm]**

**Corrected Diphoton Invariant Mass [MeV/c²]**

- Data: Mean $128 \pm 5 \text{ MeV/c}^2$
- Neutrino Induced $\pi^0$
- Charge Exchange $\pi^0$
- Cosmic (data)
- Other

**Photon conversion length**

- MicroBooNE
- 1.62×10^{20} POT

**$\pi^0$ mass reconstruction**

- MicroBooNE
- 1.62×10^{20} POT

**Vertex to Shower Start Distance [cm]**

- MicroBooNE
- 1.62×10^{20} POT

**Corrected Diphoton Invariant Mass [MeV/c²]**

- MicroBooNE
- 1.62×10^{20} POT

**Vertex to Shower Start Distance [cm]**

- MicroBooNE
- 1.62×10^{20} POT

**Corrected Diphoton Invariant Mass [MeV/c²]**

- MicroBooNE
- 1.62×10^{20} POT

**Vertex to Shower Start Distance [cm]**

- MicroBooNE
- 1.62×10^{20} POT

**Corrected Diphoton Invariant Mass [MeV/c²]**

- MicroBooNE
- 1.62×10^{20} POT

**Vertex to Shower Start Distance [cm]**

- MicroBooNE
- 1.62×10^{20} POT

**Corrected Diphoton Invariant Mass [MeV/c²]**

- MicroBooNE
- 1.62×10^{20} POT
Neutral current elastic scattering

- Signal is isolated single protons
- Can extract the strange axial form factor of nucleus
  - Predicted to be zero
  - 1980's experiments hinted at a non-zero value

\[ d\sigma_{NC}(x) = f_0(d\sigma_{CC}, x) + g_A^s f_1(d\sigma_{CC}, x) + g_A^s f_2(d\sigma_{CC}, x) \]

\[ \text{strange quark contribution to axial form factor} \]
MicroBooNE sits at 8° off-axis to NuMI beam
  - Enhanced $\nu_e:\nu_\mu$ flux ratio compared to BNB
  - Data is unblinded
- Will be first ever measurement of this cross section on argon

$\nu_e$-Ar CC-inclusive cross section

Shower dE/dx

MICROBOONE Preliminary NuMI POT=2.4e20

Shower angle

beam direction

cosmic background

$\nu_e$ signal

$\pi^0$ photons

electron/photon separation

MICROBOONE-NOTE-1054-PUB
Towards a Low Energy Excess search

- Three independent analyses tackling the MiniBooNE LEE $\nu_e$ appearance hypothesis:
  - Deep learning methods [1]
  - Pandora pattern recognition [2]
  - Wire-cell 3D hit reconstruction [3]
    - Inclusive & exclusive (1e1p) channels
- Sensitivities being finalised before unblinding

Photon hypothesis of LEE also being addressed
- Radiative decay of NC-produced $\Delta$: production cross section scaling ($\mu$) by 3 could explain the MiniBooNE excess
- Best experimental limit so far (NOMAD): $\mu < O(10)$

Transitioning towards using a hybrid of Pandora and Deep Learning techniques

**Figure 9:** MicroBooNE sensitivity to the NC-like cross-section, as well as to the MiniBooNE low energy excess, if interpreted as NC-like process. The sensitivity is represented by the CLs parameter, and corresponds to the projected statistical-only sensitivity for the full $6.6 \times 10^{20}$ POT.
LEE prospects for 2019

- Final sensitivities in preparation; exploiting novel signal processing and 2D deconvolution implemented over past year
  - JINST 13 P07006 & P07007 (2018)
- We have only fully unblinded 5% of the full dataset so far
- Results produced so far are only with first-year data
  - Cosmic Ray Tagger (CRT) installed during second year of running, will help to reduce backgrounds

The diagram shows POT delivered over the years 2016 to 2018, with POT per week and cumulative POT. Unblinded neutrino events are indicated for 2016 and 2017.
Astroparticle and Exotics

Rich program of non-beam-neutrino physics, including:

- Neutron-antineutron oscillation & annihilation (baryon number violation)
- Continuous readout stream for supernova neutrino detection
- Heavy Neutral Lepton search (simulated $\mu\pi$ decay) - Publication soon

Dark photons coupled to neutrinos or dark matter

JHEP (2019) 2019:1


Michel $e$ candidate from supernova stream collection plane

Michel $e$ candidate from supernova stream collection plane
Summary

• Large physics output from the experiment in 2018
  – 2 papers on cross sections
  – 5 papers on signal processing, reconstruction & cosmic rejection
  – 15 public notes

• Many more results due in 2019
  – Low Energy Excess analysis
  – At least 3 cross section publications
  – Heavy Neutral Lepton search

• Watch this space!
181 members
34 institutions
5 countries
SUPPLEMENTARY SLIDES
$\nu_\mu$ CC inclusive cross section

**Figure 18:** CC inclusive measurements for $\nu_\mu$ and $\bar{\nu}_\mu$ from different experiments with different nuclear targets in black and grey. The red point represents the result from this analysis. The error bars show the sum in quadrature of the statistical and systematic uncertainties. The error bars on the x-axis come from the width of the neutrino energy spectrum, see Eq. 9. The orange curve shows the GENIE cross section spline as a function of neutrino energy.
CC neutral pion production

MicroBooNE measurement

arXiv:1811.02700
“Dark Tridents” in MicroBooNE


\[ \alpha_D = 0.1, \ M_1/M_A = 0.6 \]
\[ \alpha_D = 0.1, \ M_1/M_A = 2 \]

\[ \alpha_D = 1, \ M_1/M_A = 0.6 \]
\[ \alpha_D = 1, \ M_1/M_A = 2 \]

symmetric DM
asymmetric DM

MicroBooNE sensitivity: Black line