First Measurement of Neutrino Interactions in MicroBooNE

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on behalf of the MicroBooNE collaboration
Overview

- \(\nu\)-Ar cross-sections in MicroBooNE
  - Introduction to MicroBooNE
  - Motivation
  - Cross-section programme
- The MicroBooNE experiment
  - The MicroBooNE detector
  - The Booster Neutrino Beam
- Charged-current selection(s)
- First \(\nu_\mu\) CC distributions from MicroBooNE data
- Future prospects
ν-Ar Cross-Sections in MicroBooNE
An Introduction to MicroBooNE
Part of the Fermilab short-baseline programme.

Physics goals:
- **Study $\nu$-Ar cross-sections in the 1 GeV range.**
- **Address the MiniBooNE excess of electron-like events.**
- **LAr R&D.**
- **Exotics and non-beam physics (e.g. proton decay background studies for future detectors).**
Why Study $\nu$-Ar Cross-Sections?

The thorny problem of neutrino experiments: what was the **true energy** of the incident neutrino?

- What was the momentum of the target nucleon?
- Nucleon-nucleon correlations
- How much energy was lost in the nuclear medium?
- Final state interactions
- How much energy escaped unobserved?

“Studying neutrino interactions in Ar is like firing a cannon into a tent, and trying to work out who was inside by the arms and legs that come out”
Why Study $\nu$-Ar Cross-Sections?

- Ar is the target nucleus of the future for $\nu$ experiments.

|                  | He | Ne | Ar | Kr | Xe | Water |
|------------------|----|----|----|----|----|-------|
| Boiling Point [K] @ 1 atm | 4.2 | 27.1 | 87.3 | 120.0 | 165.0 | 373   |
| Density [g/cm$^3$]      | 0.125 | 1.2 | 1.4 | 2.4 | 3.0 | 1     |
| Radiation Length [cm]   | 755.2 | 24.0 | 14.0 | 4.9 | 2.8 | 36.1  |
| dE/dx [MeV/cm]          | 0.24 | 1.4 | 2.1 | 3.0 | 3.8 | 1.9   |
| Scintillation [$\gamma$/MeV] | 19,000 | 30,000 | 40,000 | 25,000 | 42,000 |
| Scintillation $\lambda$ [nm] | 80 | 78 | 128 | 150 | 175 |

Table © Mitch Soderberg

- LArTPC technology offers an unprecedented detail in $\nu$ interaction reconstruction $\Rightarrow$ by measuring $\nu$ cross-sections in LAr we can push the boundaries of our $\nu$ cross-section knowledge.

- Constrain cross-section systematics for oscillation measurements

Dense  
- 40% denser than water

Abundant
- ~$2 per litre

Ionizes easily
- 55,000 electrons / cm

High electron lifetime
- $\alpha \gamma \nu \nu$ - "lazy" or "inactive"

Produces copious scintillation light
- Transparent to light produced

08/22/16    P. Hamilton, NuFact 2016
Why Study $\nu$-Ar Cross-Sections?

- We are at the start of a 15-year programme of LAr-based experiments.
- $\nu$-Ar cross-sections are not well known.
- $\nu$ cross-section data is sparse below 1 GeV.
The MicroBooNE Cross-Section Programme

• First step: **Charged-current (CC) inclusive cross-section.**

![Diagram](image)

- Signal: “muon + anything”
- Best for comparison with other experiments.
- Allows us to develop tools for more specific analyses.

• In future:
  - CC-0\(\pi\)
  - CC-N\(\pi\) (N>0)
  - Coherent pion production
  - CC cross-section as function of charged track multiplicity.
  - Kaon production
  - NC-elastic
  - NC-\(\pi^0\)
  - and more!

All currently ongoing analyses within MicroBooNE.
The MicroBooNE Experiment
The MicroBooNE Detector

First large-scale LAr time projection chamber (TPC) to be operated in the US

- 170 tons of LAr.
- Bigger than a school bus.
Time Projection Chambers: How Do They Work?

- E-field
- Scintillation light
- Scintillation light read out by PMTs gives interaction time.
Time Projection Chambers: How Do They Work?

Ionisation from charged particle tracks drifts in E-field.
Ionisation read out by wire planes to form 2D image.

3\textsuperscript{rd} coordinate (x) derived from electron drift time with reference to the initial flash.
The MicroBooNE TPC

- 90 tons active volume of LAr.
- 3 wire planes
  - 1 vertical collection plane
  - 2 induction planes at +/- 60°
  - 3 mm wire spacing
    ⇒ > 8,000 wires!
- 32 8” cryogenic PMTs (+ 4 light guide “paddles”)
Can see even very low-energy particles

Excellent tracking capability

Calorimetric information along length of track

Muon

Cosmic

Vertex

Run 3469 Event 53223, October 21st, 2015
The Booster Neutrino Beam

- 470 m downstream of the Booster Neutrino Beam target.
- Also see the NuMI beam, at an off-axis angle of 135 mrad.
- Results presented here will be from the BNB.
The Booster Neutrino Beam

- Beam and DAQ performance has been excellent.
- Have collected $3.4 \times 10^{20}$ POT (protons on target) to date.
- Results shown in this talk use $5.0 \times 10^{19}$ POT.
- Final target is $6.6 \times 10^{20}$ POT.
Charged-Current Selection(s)
Selecting Neutrinos

MicroBooNE has two CC-inclusive selections, both using **fully automated reconstruction**.

- Contained
- Contained + uncontained

I will be focusing here on the combined contained + uncontained selection.
Cosmic Background

Downside of ground-level detector – tens of cosmic tracks per event.
The Selection

For this analysis we use a cut-based selection

**First cut:** look for a track we can match to a flash of > 50 PE ("flash" = multi-PMT coincident light signal).

Match: start point of track is within 70 cm of centre point of flash in the Z (beam) direction.
The Selection

**Second cut:** check that the track is associated to (i.e. begins within 5 cm of) a vertex that is within the fiducial volume.

**FV limits:**
- 10 cm from wall in X.
- 10 cm from walls in Z.
- 20 cm from walls in Y.
The Selection

After this point we employ branching cuts depending on the event topology.

| Multiplicity = 1 | Multiplicity = 2 | Multiplicity > 2 |
|------------------|------------------|------------------|
| **Signal**       | **Signal**       | **Signal**       |
| **Cosmic**       | **Cosmic**       | **Cosmic**       |

Hard to distinguish from cosmics.
- Require containment.
- Reject highly vertical tracks.
- Look for Bragg peaks.

Can be faked by hard scatters or Michel electrons.
- Make sure end of track with highest dE/dX is pointing **away** from vertex.
- Reject vertices where tracks are too colinear.

Hard for cosmics to fake.
- Go straight to muon PID.

For all multiplicities we identify muons (to recognise CC interactions) by looking at the length of the longest track.
Selection Performance

**Overall efficiency:** 30%

**Overall purity:** 65%

(for results shown here)

This selection improves continuously with our selection tools; these figures currently stand at $E \approx 40\%$ and $P \approx 70\%$.

We parameterise the efficiency in terms of the kinematic variables $p_\mu$, $\cos(\theta)$ and $\phi$. 

\[
\begin{align*}
\mu & \quad \text{(beam direction)} \\
\theta & \\
\end{align*}
\]

\[
\begin{align*}
\mu & \\
\phi & \\
\text{Z (beam direction)} & \\
\end{align*}
\]
Selection Performance

MicroBooNE simulation preliminary

Selection II

- Efficiency of CCQE
- Efficiency of CCRes
- Efficiency of CCDIS

P. Hamilton, NuFact 2016
First $\nu_\mu$ CC distributions from MicroBooNE data
Results – Track Length

Shape-only comparison – simulation normalised to data.
Results - $\cos(\theta)$

NC interactions form dominant background
Results - $\phi$

Suppression of vertical tracks from cosmic background removal
Systematic Uncertainties

Error bars shown here are **statistical only**: systematics not yet fully addressed.

**Key systematics:**

- **Flux** – ~8-10%
- **Detector effects** – under investigation.
  - LAr purity (electron lifetime)
  - Electric field distortions (space charge effects)
- **Model uncertainties** – under investigation.
  - Reweighting model parameters in GENIE
Future Prospects
CC-inclusive – Next Steps

• Turn kinematic distributions into a cross-section!

• Data-driven background constraints.
  – Use cosmic overlays to replace pure Monte Carlo estimation of cosmic background.

• Full treatment of systematics.

• More stats! (6.6×10^{20} POT ⇒ >12× current statistics. >6× current statistics already on tape).
Beyond CC-inclusive

- Exclusive topologies – CC0\(\pi\) etc.
- Neutral-current elastic scattering.
- Kaon production.
- Differential cross-sections in new variables, e.g. track multiplicity.

LArTPC technology allows the possibility of reconstructing proton tracks down to a kinetic energy of 21 MeV.
Improvements

Improved reconstruction techniques.
- Improved reconstruction of showers and short tracks.
- Improved identification of “broken” tracks.
- More sophisticated flash↔track matching

Improved selection tools.
- Deep learning (public note 1019).

Improved detector
- Installing cosmic ray tagger this summer.
Conclusion

- MicroBooNE has made its first kinematic measurements of $\nu$ interactions in a $\nu_\mu$ beam; a CC-inclusive cross-section will follow soon.
- MicroBooNE demonstrates that a large-scale LArTPC can make excellent measurements of neutrino interactions.
- MicroBooNE still has much, much more to come!
- Progress so far is documented in extensive public notes: http://www-microboone.fnal.gov/publications/publicnotes/index.html (CC-inc selection is note 1010).
Thank you!

Run 3493 Event 41075, October 23rd, 2015
Backups
Electron Lifetime

MicroBooNE

Volume Exchanges

50 ppt $O_2$

Design value

$t_{\text{drift}} = 2.82$ ms
Noise

• We use an online software filter, which improves our peak signal-to-noise ratio by a factor of 2.

• After filtering ratio is
  – > 10:1 for induction planes
  – > 40:1 for collection plane.

• Recent hardware improvements have also made great strides in reducing detector noise.
Reconstruction Performance
Reconstruction Specifics (LArSoft)

• Selection 1:
  – Track reconstruction done with pandoraNu
  – Vertex reconstruction done with pandoraNu

• Selection 2:
  – Track reconstruction done with pandoraNuPMA
  – Vertex reconstruction done with pmtrack
**Contained + Uncontained Selection Cuts**

- **≥ 1 flash of ≥ 50 PE in the beam window (1.6 μs)**
  - Track must be matched to flash (within 70 cm in Z)
  - Vertex must be in fiducial volume (10 cm from walls in Z, 20 in X & Y)

**MULTIPLICITY = 1**

- Track must be contained.
  - Track length must be > 40 cm
  - Vertical projection < 25 cm OR dE/dX (end) ≥ 1.5 dE/dX (start)

**MULTIPLICITY = 2**

- Track is within 5 cm of a reconstructed vertex
  - dE/dX must be greatest at furthest end of track from vertex (Michel removal)
  - Tracks separated by α such that \( \cos(\alpha) < 0.95 \)
  - Longest track > 15 cm

**MULTIPLICITY > 2**

- Selected
Contained Selection Cuts

≥ 1 flash of ≥ 50 PE in the beam window (1.6 μs)

Track is within 5 cm of a reconstructed vertex

Choose vertex with most forward-going tracks

Vertex must be in fiducial volume (10 cm from walls in X & Z, 20 in Y)

Longest track must be matched to flash (within 80 cm in Z)

Track must be contained

Track length must be > 75 cm

SELECTED
Contained Selection Performance

Overall efficiency: 12%
Overall purity: 55%

N.B. efficiency includes acceptance – only ~ 1/3 of signal events are contained.
Contained Selection Results

![Graph 1: Track range vs. No. of events](image1)

- Data (4.95×10^{19} POT):
  - On-beam minus off-beam
- Monte Carlo Simulation:
  - Selected \( \nu_e \) CC signal & bgr
  - Cosmic bgr events
  - NC bgr events
  - \( \nu_e \) CC Out of FV bgr events
  - \( \nu_e \) & \( \bar{\nu}_e \) bgr events
  - \( \bar{\nu}_e \) bgr events

![Graph 2: \cos(\theta) vs. No. of events](image2)

- Data (4.95×10^{19} POT):
  - On-beam minus off-beam
- Monte Carlo Simulation:
  - Selected \( \nu_e \) CC signal & bgr
  - Cosmic bgr events
  - NC bgr events
  - \( \nu_e \) CC Out of FV bgr events
  - \( \nu_e \) & \( \bar{\nu}_e \) bgr events
  - \( \bar{\nu}_e \) bgr events

![Graph 3: \phi angle vs. No. of events](image3)

- Data (4.95×10^{19} POT):
  - On-beam minus off-beam
- Monte Carlo Simulation:
  - Selected \( \nu_e \) CC signal & bgr
  - Cosmic bgr events
  - NC bgr events
  - \( \nu_e \) CC Out of FV bgr events
  - \( \nu_e \) & \( \bar{\nu}_e \) bgr events
  - \( \bar{\nu}_e \) bgr events

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