Latest Results
From
MicroBooNE
Weak Interactions and Neutrinos 2017

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on behalf of
MicroBooNE Collaboration
Outline

• MicroBooNE: short baseline experiment
• Current status and latest results
• Wrap-up

Latest Results
From
MicroBooNE
Weak Interactions and Neutrinos
2017
MicroBooNE: Introduction

- Short baseline (1m/MeV) $\nu_\mu \Rightarrow \nu_e$ oscillation
- Booster neutrino beam
  - neutrino energy $O$ (1 GeV)
- LArTPC detector
  - 90 tonnes TPC active volume

“Design and Construction of MicroBooNE detector” (JINST 12, P02017)
How LArTPCs Work (I)

1. Charged particles interact in Ar
   - Ionize argon
   - Produce scintillation light
2. Ionization e- drift toward anode
3. Wire planes detect drift e-

Cathode @ 70 kV (plate)  Electric Field ~270 V/cm  Anode (wire plane)

X = 2.5 m  Y = 2.3 m  Z = 10.4 m
How LArTPCs Work (II)

1. Charged particles interact in Ar
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Cathode @ 70 kV (plate)
Electric Field ~270 V/cm
Anode (wire plane)
How LArTPCs Work (III)

1. Charged particles interact in Ar
   - Ionize argon
   - Produce scintillation light
2. Ionization e- drift toward anode
3. Wire planes detect drift e-

Three Wire Planes

- X = 2.5 m
- Y = 2.3 m
- Z = 10.4 m

Cathode @ 70 kV (plate)

Electric Field ~270 V/cm

Anode (wire plane)

Drift Time = X position

Charge collected by wire plane

Scintillation Light detected by PMTs
What Our Data Looks Like

... putting everything together ...

- Digitized bubble Chamber-like images
- Calorimetric measurement + scalability to a large mass
MicroBooNE: Physics Goals

Address the nature of $\nu_e$ like excess seen by MiniBooNE

- Same beam, similar baseline
  - Do we see the excess?
- Different detector: LArTPC
  - Is excess $\gamma$ or $e^-$?

MiniBooNE
$\sim$800 tonnes @ $L = 540\ m$

MicroBooNE
$\sim$90 tonnes @ $L = 470\ m$

Fermilab

$\nu_\mu$ beam (BNB)
MicroBooNE in the SBN Program

**Search for a short baseline oscillation signal (SBN program)**

- **SBND** (near detector)
  - High precision $\nu$-Ar XS
- **ICARUS** (far detector)
  - 6 times larger than UB!

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**Fermilab**

- **ICARUS T600**
  - \(~476~\) tonnes @ $L = 600~m$
- **MicroBooNE**
  - \(~90~\) tonnes @ $L = 470~m$
- **SBND**
  - \(~112~\) tonnes @ $L = 110~m$
MicroBooNE LArTPC R&D

**Detector R&D for future large scale LArTPC experiments**

- Large scale detector
  - Construction & operation
  - Detector calibration
- Data reconstruction/analysis
  - Efficient $\nu_e$ & $\nu_\mu$ search!

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ArgoNeuT
0.3 ton (2008)

MicroBooNE
~170 tonnes (2015)

ProtoDUNE (SP)
~770 tonnes (2017)

DUNE (SP) Module
10 k tonnes (~2024)

≈ 5.5 E20 POT  Physics quality data collected
During stable operation ≈ 97% uptime

**Oct. 2015**
(data taking started)

**June 2017**
(today)
Latest Results From MicroBooNE Weak Interactions and Neutrinos 2017

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Effort Toward Physics Goals

- Particle & event ID
- Energy/momentum reconstruction
- Automated 2D/3D event reconstruction
- Detector response calibration

Our signal: low energy $\nu_e$

Proton, MicroBooNE Simulation, Preliminary
Where We Were (Neutrino 2016)

First CC $\nu_\mu$ kinematic distributions

Automated 2D/3D event reconstruction

Detector response calibration

3D Shower Reconstruction ($CC\pi^0$)

Our signal: low energy $\nu_e$

MicroBooNE Simulation Preliminary

Particle & event ID

Energy/momentum reconstruction

MicroBooNE Preliminary

4.95 x 10^{19} POT

Stat. only error shown

Data: Beam On: Beam Off (2700 ± 62 events)

Simulation:
- selected $\nu_{CC}$+bkgd
- $\nu_e$ bkgd
- $\nu_e + \pi^0$ bkgd
- NC bkgd
- Cosmic bkgd
- $\nu_e$ CC true vertex Out of FV bkgd

Reconstructed Michel Energy Spectrum

Events

$v$ Energy [MeV]

Caution
This is cartoon. No physics here.
Cosmic Ray Background Study/Mitigation

**Cosmic Ray Tracker** (new!)
- Scintillator strips + SiPM
  - designed by University of Bern
- Covers ~85% of cosmic rays
  - **cosmic rejection** (neutrino search)
  - detector response study
  - reconstruction efficiency study

See Roberto S’s talk on Friday!

Completed panels covering above the detector
(during installation)
Results on Electronics Noise Filtering

Noise Characterization & Filtering

- arXiv: 1705.07341
- The very first step in high quality physics reconstruction
- Crucial experience for future LArTPC with cold electronics
Charged Particle Multiplicity (CPM) Analysis

Extension of **CC $\nu_\mu$ selection**

- Count **number of reconstructed tracks from interaction vertex**
- Using contained $\nu_\mu$ candidate with a reconstructed “long” muon track
- **Further cosmic rejection cuts**
- UB Public Note 1024 ([link](#))

**Directionality check** on $dQ/dX$ (left) and Multiple Coulomb Scattering angle (right) to reject cosmics
Results on Multiple Coulomb Scattering (MCS)

**Muon momentum** reconstruction

- Contained or exiting (crucial)
- Tuned Highland formula for LArTPC, good DATA/MC agreement
- Published: arXiv: 1703.06187
Results on Low Energy e Reconstruction

Michel Electron Analysis

- arXiv: 1704.02927
- Automated 2D reconstruction
- Low energy $e^-$ calibration
- Challenge of clustering energy depositions by radiative photons
Analysis w/ Convolutional Neural Networks (CNNs)

**Machine learning technique**

- **Demonstration for LArTPC**
  - Image classification & object detection
  - Particle ID, neutrino vertex localization, etc.
  - [JINST 12, P03011](http://doi.org/)

- Using for data reconstruction
  - Pixel-level prediction for shower/track separation

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**Real Data Image**

**Network Output**

**Shower/Track Separation via custom CNN**
Automated $\nu_e$ Search

- Established a fully-automated $\nu_e$ reconstruction chain
  - First look: a simple $1e-1p$ topology
  - First time for LArTPC ... tuning for signal/background
- Full chain: cosmic rejection, 3D vertex ID, track/shower separation
  - Using pixel-level shower/track separation by CNN
Effort Toward Physics Goals

- Particle & event ID
- Automated 2D/3D event reconstruction
- Detector response calibration
- Energy/momentum reconstruction

Our signal: low energy $\nu_e$

proton, electron

MicroBooNE Simulation Preliminary

Caution
This is cartoon. No physics here.
Effort Toward Physics Goals (Today)

• **5 papers** (published, [link](#))
• **15 public notes** (toward publication, [link](#))

**Michel Electron** Reconstruction Using Cosmic-Ray Data from the MicroBooNE LArTPC ([arXiv:1704.02927](#))

Determination of **muon momentum** in the MicroBooNE LArTPC using an improved model of **multiple Coulomb scattering** ([arXiv:1703.06187](#))

Measurement of **cosmic-ray reconstruction efficiencies** in MicroBooNE using a small external cosmic-ray counter coming soon

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

**The Pandora** multi-algorithm approach to automated pattern recognition of cosmic-ray muon and neutrino events in the MicroBooNE detector coming soon

**Noise characterization** and filtering in the MicroBooNE Liquid Argon TPC ([arXiv:1705.07341](#))

**Design and Construction of the MicroBooNE Detector**

JINST 12, P02017 (2017)

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proton

MicroBooNE Simulation Preliminary

electron

**Our signal: low energy νₑ**

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22 slide design, courtesy of A. Schukraft
Outline

• MicroBooNE: short baseline experiment
• Current status and latest results
• Wrap-up
MicroBooNE has been stably running
• Since 2015, collected 5.5 E20 POT BNB data

Publications toward final physics results
• Physics
  - Michel electron, MCS, CPM analysis (public note)
• Technical
  - Reconstruction: CNN, Pandora (public note)
  - Detector design, Noise characterization
• Important results not mentioned in this talk
  - NC proton track identification (public note)
  - Space charge effect (public note)

Future prospects
• More toward detector calibration & cosmic rejection
• CC $\nu_\mu$ analysis & $\nu_e$ signal search
Thank you for your attention!

Any Questions

Run 3493 Event 41075, October 23rd, 2015
Back Up Slides
That Hopefully Back Me Up
Misc.
A Probe for EM Showers in MicroBooNE

Two handles for $e^-/\gamma$ separation in LArTPC

1. “Gap” from the vertex to $\gamma$ shower start
2. $dE/dX$ @ shower start
   - $\gamma$ makes twice MIP $dE/dX$

$arXiv:1610.04102$

$dE/dX$ (ArgoNeuT) $e^-$ vs. $\gamma$ discrimination

MicroBooNE Data
**BNB: Neutrino Source**

- 8 GeV protons from Booster hits Beryllium target to produce mesons

- Horn focuses positive (negative) mesons to produce neutrinos (anti-nu)

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**Magnetic Horn** (Meson Focusing)

- Booster (8 GeV Protons)
- Beryllium Target “Thin & Long”

- Horn focuses positive (negative) mesons to produce neutrinos (anti-nu)

- 8 GeV protons from Booster hits Beryllium target to produce mesons

- *New* Horn (replaced in 2015)

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**Detection!**

- MicroBooNE Detector
- Oscillation
- Dirt
- Absorber
- Decay Tunnel
- Magnetic Horn

- Toroidal B field
- Decay Tunnel
- Absorber
- Dirt
- MicroBooNE Detector

- Detection!
**BNB: Providing Neutrinos Over a Decade**

Event Rate Break Down (flux & xs)
- $\nu_\mu \approx 93.6\%$
- $\bar{\nu}_\mu \approx 5.86\%$
- $\nu_e \approx 0.5\%$
- $\bar{\nu}_e \approx 0.05\%$

... high purity $\nu_\mu$ beam ...

Horn: Neutrino Mode

**MiniBooNE**

**MicroBooNE**

**BNB**
On-Axis
d$_{\text{target}} \approx 470$ m

Very well known stable neutrino beam

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**MicroBooNE @ FNAL**

PRD 79, 072002 (2009)
Optical Detector

• What is it? What for?
  - 32 8” PMTs
  - Crucial roles
    ▶ Getting trigger
    ▶ Reconstructing YZ
    ✓ Cosmic background rejection

Crucial for MicroBooNE because of high cosmic ray rate (~5kHz) @ surface!

• LAr optical properties
  - No detail here... but LOTS of physics!
    ▶ Read arxiv 1306.4605 for instance
  - Produced within 6 ns of interaction
  - High light yield = 6000 photons / MeV
  - “Transparent” to its own light
    ▶ No re-scintillation (does Rayleigh scatter)
    ▶ Wavelength shift by TPB
LEE Analysis Chain
Toward Future: $\nu_e$ Search

Automated $\nu_e$ Search

- Collaborative effort, first time full automation!
- First look: a simple $1\text{e}-1\text{p}$ topology
  - Multiple approaches, this is just one type

MicroBooNE Simulation Preliminary
Automated $\nu_e$ Search

- Collaborative effort, first time full automation!
- **First look**: a simple **1e-1p topology**
  - Multiple approaches, this is just one type
- Mitigate a difficulty of identifying shower cluster using convolutional neural networks

*Toward Future: $\nu_e$ Search*
Automated $\nu_e$ Search

- Viewing all 3 planes together
  - RGB ... 1 color per plane
  - 3D particle track shows up on all planes
  - Time on Y-axis, wires (beam) on X-axis

Where is Neutrino?

Toward Future: $\nu_e$ Search

MicroBooNE Simulation Preliminary

$\nu_e$ 1e-1p
K.E.$\nu$ = 563 MeV
K.E.p = 110 MeV
$\Delta R = 0.33$ cm
On-Going Work: $\nu_e$ Search

Automated $\nu_e$ Search

MicroBooNE Simulation Preliminary

A full chain has been exercised
Now tuning toward $\nu_e$ signal search
CPM Analysis
Details
PH Test

Rate of energy loss increases along the track from upstream to downstream end.

MCS Test

Scattering is more pronounced along the downstream end of the track as the momentum decreases.

Sub-samples |
--- | --- | --- | --- |
PH, MCS | On-beam Data | Off-beam Data | BNB + Cosmic Default MC |
| | events | acceptance rates | events | acceptance rates | events | acceptance rates |
pass, pass | 847 | (44%) | 1263 | | 2629 | |
pass, fail | 367 | (19%) | 1087 | | 737 | (18%) |
fail, pass | 321 | (17%) | 1141 | | 440 | (10%) |
fail, fail | 387 | (20%) | 1776 | | 403 | (10%) |

Cosmic rays travel forward and backward with roughly equal prob.
Largest non-statistical uncertainty arise from short tracks where the requirement of minimum # of 2D hits can cause DATA/MC discrepancy in track reconstruction.
Space Charge Effect
Space Charge Effect Calibration

- Non-uniform E-field distorts reconstructed particle tracks
- Used external muon tracking system to study the effect

2D track can look rotated and/or curved due to SCE

X-Y projection of 3D track start/end points

Simulation vs. Data
- Y distortion along X
- Small time variation (Data)

After correction

External Muon Tracker
MicroBooNE Detector Physics

**Space charge effect**

- Positive ion build-up in the TPC, distorting local electric field
- Distorts the path of ionization electrons (i.e. track gets “bent”)
- Calibration importance for near-surface LArTPCs

**Space Charge Distortion**

Through-going cosmic ray muon tracks’ start and end points in the side-slice of the detector. Distortion is due to space charge affecting the drift electric field.
NC Single Proton Search
Identifying NC Proton Signal

• Challenges
  - Very short proton tracks (~cm!)
  - High cosmic-ray backgrounds

• Boosted Decision Tree (BDT)
  - Use reconstructed track parameters as input variables

- Proton track candidate found by BDT (Real Data)

- BNB + Cosmic (Simulation)

- Output Breakdown

- Efficiency vs. Purity
CC Selection
Fully Contained + Partially Contained Selection

- Purity: 65%
  - Cosmics are still the dominant background
- Acceptance x Efficiency: 30%
  - Containment and minimum length cut are applied to 1-track sample

Before selection:
- 60% QE, 30% RES, 10% DIS

After selection:
- 43% QE, 42% RES, 14% DIS
Oscillation Related
Status of “Anomalies”

Anomalies from appearance/disappearance

- Anomalies ≈ 2σ to 3σ level, each mass state must mix with each flavor state, even sterile
- Sterile neutrino oscillation must be seen in both appearance/disappearance

### Experiment name | Type | Oscillation channel | Significance |
--- | --- | --- | --- |
LSND | Low energy accelerator | muon to electron (antineutrino) | 3.8σ |
MiniBooNE | High(er) energy accelerator | muon to electron (antineutrino) | 2.8σ |
MiniBooNE | High(er) energy accelerator | muon to electron (neutrino) | 3.4σ |
Reactors | Beta decay | electron disappearance (antineutrino) | 1.4-3.0σ (varies) |
GALLEX/SAGE | Source (electron capture) | electron disappearance (neutrino) | 2.8σ |
3+1 Global Fit

Tension in appearance vs. disappearance
• Appearance/disappearance prefer smaller/larger $\Delta m^2$
3+1 Global Fit

Tension in appearance vs. disappearance

- Appearance/disappearance prefer smaller/larger $\Delta m^2$
- MiniBooNE $\nu_e$ appearance favors low $\Delta m^2$, high $\sin^2 2\theta$
3+1 Global Fit

Tension in appearance vs. disappearance

- Appearance/disappearance prefer smaller/larger $\Delta m^2$
- MiniBooNE $\nu_e$ appearance favors low $\Delta m^2$, high $\sin^2 2\theta$
### Score card

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<th>data</th>
<th>theory</th>
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<td>+</td>
<td>-</td>
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<tr>
<td>MiniBooNE</td>
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<tr>
<td>Reactors</td>
<td>++</td>
<td>0</td>
<td>++</td>
</tr>
</tbody>
</table>

++ strong, + adequate, 0 undecided, - likely issue, -- clearly a problem

Discarding the MiniBooNE low-energy excess, a eV-scale sterile neutrino is a simple explanation for all the observations.

**Understanding MiniBooNE is really important since it is standing out from the rest!**
3+1 Global Fit

Possible outcomes from MicroBooNE

**Case A**: no excess
- 3+1 is in a trouble since it predicts signal @ MicroBooNE

**Case B**: some excess but less than MiniBooNE at low energy
- 3+1 is strengthened, MiniBooNE result was likely affected by unaccounted γ background

**Case C**: same excess as MiniBooNE
- Picture is likely much more complicated than 3+1

**Neutrino 2018 will be exciting!**
Expect 1st results from appearance (MicroBooNE) and disappearance (reactor) experiments to meet!
Measuring Oscillation Pattern

From KamLAND experiment with
$L \approx 180$ km observing survival probability of $\nu_e$
from nuclear reactor cores
MicroBooNE Oscillation Signal (I)

**Goal: $\nu_e$ at low energy**

Primarily 200 to 600 MeV neutrino energy
- Most of events have secondary particles contained inside the detector
- This is the region where CCQE interaction dominates

$v_e$ Low Energy Excess Fraction (MiniBooNE)

$v$ Cross Section (A. Schukraft, G. Zeller)
Low Energy Excess
LSND & MiniBooNE