Status of the MiniBooNE and MicroBooNE experiments

Adrien Hourlier
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August 27 2019
Before MiniBooNE: The LSND Anomaly

- Stopped π beam
  \[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]
  \[ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \]

- appearance of \( \bar{\nu}_e \) in a \( \bar{\nu}_\mu \) beam
- \( \bar{\nu}_e \) signature: Cherenkov light from \( e^+ \) with delayed n-capture
- Excess = 87.9 ± 22.4 ± 6 (3.8σ)

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]

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Before MiniBooNE : The LSND Anomaly

- Stopped $\pi$ beam
  \[
  \pi^+ \rightarrow \mu^+ + \nu_\mu \\
  \rightarrow e^+ + \bar{\nu}_\mu + \nu_e
  \]
- appearance of $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ beam
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- Excess = $87.9 \pm 22.4 \pm 6 (3.8\sigma)$

\[\bar{\nu}_e + p \rightarrow e^+ + n\]
The MiniBooNE Experiment

- Proposed to investigate the LSND anomaly, in search for sterile neutrinos
- Located on the Booster Neutrino Beam at Fermilab
- Single horn focused neutrino beam: Selection of neutrino/antineutrino modes
- Similar L/E as LSND:
  - MiniBooNE ~500 m / ~500 MeV
  - LSND ~30 m / ~30 MeV
- Different systematics due to different fluxes, event signatures and backgrounds
The MiniBooNE Detector

- ∅12.2 m sphere, ∅10m fiducial volume
- 800 tons of mineral oil, 450 tons fiducial mass
- 2 optically isolated volumes
- 1280 inner PMTs, 240 veto PMTs
- Very well understood detector
  - 2% change of the energy scale over 15 years of running
  - Measurements of cross sections for most of the neutrino and anti-neutrino processes
Events in MiniBooNE

- Background reduction using beam timing and hit topology
- Use primarily Cherenkov light
- ID based on ratio of fit likelihoods under different particle hypotheses
- Only sensitive to particles above the Cherenkov threshold
  => no proton detection
- Cannot distinguish single photon from single electron
Energy Reconstruction

- Energy reconstructed using only the lepton kinematics derived from the Cherenkov cone
- Energy is reconstructed under the CCQE assumption
- Assumes CCQE interaction on a nucleon at rest, accounts for nuclear binding energy

$$E_{\nu}^{\text{QE}} = \frac{2(M_n - E_B)E_{\ell} - ((M_n - E_B)^2 + M_{\ell}^2 - M_p^2)}{2((M_n - E_B) - E_{\ell} + p_{\ell} \cos \theta_{\ell})}$$
Data Taking

- 15+ years of data taking with a very stable and robust detector
- New result published in 2018 doubles the statistics in neutrino mode \((\text{PRL 121,221801 (2018)})\)
- Improved data-driven background constraints
Other analyses: DM search in beam dump mode

- First dedicated search for direct detection of accelerator-produced dark matter in a proton beamline
- Beam-dump mode reduced the $\nu$ flux by $\sim 50$
- The goal was to test vector portal model interpretation of $g$-2 (ruled out)
- At time of publication: set world leading limits in the vector portal dark matter model with a dark matter mass between 0.01 and 0.3 GeV

Target | Decay Pipe | Beam Dump | MiniBooNE Detector
---|---|---|---
Be | Air | Steel | Earth

$P = \chi^+ \to \pi^0 \gamma$  

$Y = \frac{2|\alpha_0|}{m_\chi} (m_\chi)^4$

- $K^+ \to \pi^+ + \text{invis.}$
- $\chi^0_{\alpha_0}$ favored
- $J/\psi \to \chi^0_{\alpha_0}$
- $\chi^0_{\alpha_0}$ in $\chi^0_{\alpha_0}$
- $\pi^- \to \chi^{0}_{\alpha_0}$
- $\chi^0_{\alpha_0}$ in $\chi^0_{\alpha_0}$

$\chi_{\alpha_0} = 3m_\chi$  

$\alpha_0 = 0.5$

MB 90% CL  

MB 90% Sensitivity  

Relic Density  

$\chi$ (GeV)  

$\sigma_1 \pm \sigma_2 \pm \sigma_3$

$\chi_{\alpha_0}^0 = 0.5$

$\alpha_0^\prime = 0.5$

$\chi_{\alpha_0}^0 = 0.5$

$\alpha_0^\prime = 0.5$

$\chi_{\alpha_0}^0 = 0.5$

$\alpha_0^\prime = 0.5$
Other analyses : KDAR

• Kaon Decay At Rest
• KDAR neutrinos from the NuMI beam line absorber have been identified based on energy reconstruction and timing
• First measurement of $\omega$ (energy transfer to the nucleus) with a known energy, weak interaction-only, nuclear probe
• Results provide a standard candle for understanding $\nu_\mu$ CC events at a known energy (236 MeV)

![Graph showing $T_\mu$ and $\omega$ distributions](image)

![Graph showing event rates vs. PMT hits](image)
**νₑ-Like Excess**

- Old+new dataset in neutrino mode
- Neutrino mode νₑ excess of 4.5σ
- Main backgrounds are related to separating γ and e⁻
Constraining Backgrounds

\( \pi^0 \) MisID
constrained from \textit{in situ} measurement of NC \( \pi^0 \) rate

\( \Delta \to \text{Ny resonance} \)
constrained from \textit{in situ} measured NC\( \pi^0 \) rate and theoretical prediction

\( \text{Dirt} \)
constrained from \textit{in situ} dirt data sample

\( v_e \) from \( \mu \) decay
is constrained by \textit{in situ} \( v_\mu \) CCQE measurement

\( v_e \) from \( K \) decay
constrained from \textit{in situ} high energy events + SciBooNE high energy \( v_\mu \) event rate

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**TABLE I:**

<table>
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<tr>
<th>( \nu_e ) from ( \mu^+ )c</th>
<th>( \nu_e ) from ( K^+ )c</th>
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**Fig. 2:** The MiniBooNE total event excesses as a function of \( E^E \) (MeV) for CCQE data (points with statistical errors) and background.

**Fig. 3:** Comparison of the theoretical prediction with the empirical data for 1250 MeV. The LSND measurement of NC \( \pi^0 \) is constrained in the measured NC \( \pi^0 \) rate and theoretical prediction.
provide better fits to the data. The oscillation parameters are

\[ \sin^2 \theta \]

for the energy interval from 1500 \text{MeV} to 2000 \text{MeV}.

The dashed curves show the two-neutrino oscillation hypothesis as a function of the oscillation parameters, \( \Delta m^2 \) and \( \theta \).

The solid (dashed) curve is the best-fit point and the 90\% (99\%) C.L. limits from the KARMEN2000 reactor antineutrino experiment.

Comparing the data-prediction excess for two data sets in neutrino mode:
- 2009 data release in neutrino mode
- 2018 data release in neutrino mode

The observed excess remains well compatible between the two data sets.

KS-prob : 76\%
**Preferred regions in a (3+1)ν interpretation**

**Neutrino + Anti-Neutrino Mode**

\[(\Delta m^2, \sin^2 2\theta) = (0.041 \text{ eV}^2, 0.918)\]

\[\chi^2/\text{ndf} = 19.4/15.6 \text{ (prob = 21.1\%)}\]

- Neutrino mode excess 4.5σ,
- Neutrino+Anti-neutrino modes excess 4.8σ
- Combined LSND and MiniBooNE significance of 6.1σ
- Similar agreement of neutrino and anti-neutrino data to (3+1)ν fit

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Preferred regions in a (3+1)v interpretation

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MiniBooNE : take away

• MiniBooNE observes a low energy $\nu_e$-like excess with a significance of 4.8$\sigma$, compatible with the LSND excess

• Combines MiniBooNE+LSND significance of 6.1$\sigma$
• Not a perfect fit to a (3+1)$\nu$ model (large best fit value of $\sin^22\theta$ seems unphysical)
• Very stable detector over 15 years, well constrained backgrounds, from \textit{in situ} measurements

• Excess seems real, needs a satisfactory explanation
MiniBooNE in the global picture

\( \nu_e \) appearance, \( \nu_e \) disappearance, and \( \nu_\mu \) disappearance are interlinked by these three probabilities:

\[
P_{\nu_e \rightarrow \nu_e} = 1 - 4(1 - |U_{e4}|^2)|U_{e4}|^2 \sin^2 (1.27\Delta m_{41}^2 \frac{L}{E})
\]

\[
P_{\nu_\mu \rightarrow \nu_e} = 4|U_{\mu4}|^2|U_{e4}|^2 \sin^2 (1.27\Delta m_{41}^2 \frac{L}{E})
\]

\[
P_{\nu_\mu \rightarrow \nu_\mu} = 1 - 4(1 - |U_{\mu4}|^2)|U_{\mu4}|^2 \sin^2 (1.27\Delta m_{41}^2 \frac{L}{E})
\]

- We see signals in the \( \nu_e \) appearance and disappearance, somewhat compatible, but not in the \( \nu_\mu \) disappearance
- The (3+1) model implies that we also see a signal in the \( \nu_\mu \) disappearance mode
- The (3+1) model alone seems insufficient
- Does MiniBooNE have a sterile signal + a systematics that could lead to a mis-estimation of the appearance excess?
- Are all appearance signals from backgrounds?

see arXiv:1906.00045 [hep-ex] for more details
SBN program

- Same beam line as MiniBooNE
- Three detectors on axis
- Same technology: Liquid Argon Time Projection Chamber (LArTPC)
  => Flux and cross-section systematics constraint, some detector systematics.
- High precision flux measurement
- High precision oscillation measurement
- Production of TPC components in UK and US complete
- Successful alignment, coupling, and QC of first two anode planes
- TPC assembly transport plane under construction at FNAL
- Cryogenics platform, valve box, and proximity cryogenics installation completing this month
- Warm cryostat construction at CERN underway

See the talk from Stephen Robert Dennis on Friday
• Previously at Gran Sasso, shown feasibility of large scale LArTPC
• Significant upgrades and refurbishment at CERN in 2015-2017
• New Cosmic Ray Tagger
• Transported to FNAL, arrived in August 2017, installation ongoing
• Commissioning will start this fall and expect first neutrino data within a year
• Designed to investigate the e-like excess of MiniBooNE and LSND
• LArTPC technology:
  • γ/e- separation
  • Position and topology
  • low detection threshold
• Data taking since October 2015 : longest running LArTPC
• Smooth operation with 96% detector & DAQ uptime
• $13.4 \times 10^{20}$ POT on tape to date
• Surface operation : Cosmic Ray Tagger used to understand/reduce cosmic background (1/2 of data-taking period)
LArTPC Working Principle
LArTPC Working Principle
LArTPC Working Principle
LArTPC Working Principle

10.4 m

2.5 m

2.3 m

32 PMT

Sense wire planes
LArTPC Working Principle

- Developed novel techniques for noise filtering and signal processing.
- Full implementation of 2D deconvolution should improve reconstruction performance and reduce detector-related systematic uncertainties.

"Ionization Electron Signal Processing in Single Phase LArTPCs",

"Noise Characterization and Filtering in the MicroBooNE Liquid Argon TPC",
*JINST* 12, P08003 (2017)
LArTPC Working Principle

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LArTPC Working Principle

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LArTPC Working Principle


LArTPC Energy Reconstruction

- Calorimetric reconstruction => charge clustered in each track
- Access kinematics of all the particles above O(10 MeV)
- Assumes CCQE interaction on a nucleon at rest, accounts for nuclear binding energy

\[ E_{\nu}^{QE}[l] = \frac{2(M_n - E_B)E_\ell - ((M_n - E_B)^2 + M_\ell^2 - M_p^2)}{2((M_n - E_B) - E_\ell + p_\ell \cos \theta_\ell)} \]
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$$E_{\nu}^{QE}[p] = \frac{2(M_n - E_B)E_p - ((M_n - E_B)^2 + M_p^2 - M_l^2)}{2((M_n - E_B) - E_p + p_p \cos \theta_p)}$$
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\end{align*}
\]

\[E_\nu = KE_l + KE_p + M_l + M_p - M_n + B\]
Studying Detector Physics

- Major calibration campaign completed
- Use through-going muons and stopping muons as standard candles
  - uniformity in position and time
  - ADC to e-/cm calibration
  - E field distortions due to charge accumulation
- Use protons to correct for recombination
  - e-/cm to MeV/cm calibration
- Use UV-laser runs
  - E field distortions due to charge accumulation

arXiv:1907.11736 [physics.ins-det]
Studying Neutrino Interactions

BNB:
- $\nu_\mu$ CC inclusive  
  arXiv:1905.09694 [hep-ex], accepted to PRL
- $\nu_\mu$ CC $\pi^0$  
  PRD 99, 091102(R) (2019)
- Track multiplicity  
- $\nu_\mu$ CCQE  
  arXiv:1812.05679 [physics.ins-det], accepted to EPJC
- NC elastic  
  MICROBOONE-NOTE-1053-PUB
- $\nu_\mu$ CC $N_p$, $2p$  
  MICROBOONE-NOTE-1056-PUB
- CC $1\pi^+$
- CC coherent $\pi$
- CC $K^\pm$
- NC $\pi^0$
- ... and more

NuMI:
- $\nu_e$ CC inclusive  
  MICROBOONE-NOTE-1054-PUB
- $\nu_e$ CC $0\pi$
- Kaon decay at rest (KDAR)

See Pip Hamilton’s talk this afternoon
Studying Neutrino Interactions: $\nu_{\mu}$ CC$\pi^{0}$

- Exclusive measurements like this one allow us to study final state interactions
- Can compare to past measurements on deuterium and carbon
- Can evaluate accuracy of generators assuming different nuclear models
- First implementation of fully automated shower reconstruction to analyze LArTPC data

$$\langle \sigma(\nu_{\mu} + \text{Ar} \rightarrow \mu^{-} + 1 \pi^{0} + X) \rangle_{\Phi} = 1.9 \pm 0.2 \text{ (stat.)} \pm 0.6 \text{ (syst.)} \times 10^{-38} \text{ cm}^{2}/\text{Ar}$$

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Studying Neutrino Interactions: $\nu_\mu$ CC inclusive

- Single and double differential cross sections are measured as a function of $p_\mu$ and $\theta_\mu$
- Use multiple Coulomb scattering for measuring muon momentum => not only contained particles!

```
L. Yates ︱ Rencontres du Vietnam
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\begin{itemize}
  \item Single and double differential cross sections are measured as a function of $p_\mu$ and $\theta_\mu$
  \item Use multiple Coulomb scattering for measuring muon momentum => not only contained particles!
\end{itemize}
```

```
\[ \frac{d\sigma}{dp_{\mu}^\text{reco}} [10^{-38} \text{ cm}^2/\text{GeV}] \]
```

```
\[ \frac{d\sigma}{d\cos(\theta_{\mu}^\text{reco})} [10^{-38} \text{ cm}^2] \]
```

```
arXiv:1905.09694 [hep-ex], accepted to PRL
```

See Pip Hamilton’s talk this afternoon
Low Energy Excess Models for MicroBooNE

- What does a MiniBooNE-like LEE signal look like in MicroBooNE?
- 2 hypotheses:
  - $\nu_e$-like excess
  - $\gamma$-like excess (NC $\Delta$ radiative decay resonance)
- Deconvolve MicroBooNE’s detector effects
- Convolve MicroBooNE’s detector effects
- $\nu_e$-like excess mostly at low energy
  $\Rightarrow$ electron shower topology different at low energy
Low Energy Studies

- Multiple, independent blind analyses
- Multiple reconstruction packages
- Multiple target event topologies

- Electron-like:
  - WireCell reconstruction
  - Deep Learning reconstruction
  - Pandora multi-algorithm reconstruction

- Photon-like:
  - Pandora multi-algorithm reconstruction

See the talk from Mark Ross-Lonergan on Friday
Selecting e-Like Events

**Multiple complimentary searches:**
- High purity, exclusive 1e1p with Deep Learning
- High efficiency, more inclusive 1e0πNp with Pandora
- Fully inclusive with Pandora+WireCell

**Major challenges**
- reconstructing low energy electrons that do not shower
- rejecting non-ν\textsubscript{e} backgrounds

![1e1p Topology](image)

![1e0πNp Topology](image)
Selecting γ-Like Events

- NC Δ radiative search in investigating both $1\gamma 1p$ and $1\gamma 0p$ to maximize signal statistics, and is using Pandora reconstruction.

- Major challenge is understanding and rejecting NC$\pi^0$ backgrounds. Topology for these is $2\gamma 1p$ or $2\gamma 0p$, but second shower can be difficult/impossible to reconstruct.

- First analysis of the NC $\Delta \rightarrow p + \gamma$ interaction by a neutrino experiment!
Constraining Systematics

• Want to constrain systematics on intrinsic $\nu_e$ backgrounds
  • unconstrained flux and cross section uncertainties are 20-30%
  • constraints should significantly improve our sensitivity to an excess
• Also want to constrain other beam-related backgrounds
• Without near detector, we plan to use measurements of $\nu_\mu$ events to constrain our uncertainties
Constraining systematics

- Deep Learning based reconstruction and selection MICROBOONE-NOTE-1039-PUB
- Re-weight events to account for neutrino generator systematic uncertainties (flux & cross section)
- Generate uni-simulations to account for detection and selection systematic uncertainties
Constraining Systematics

1e1p Selected & Reconstructed $E_\nu$. Scaled to 13E20 POT

Uncostrained Systematics

MicroBooNE Preliminary

$\nu_e$-only simulation

Sub-dominant cosmic & $\nu_\mu$ backgrounds not shown

Detector systematics not shown

Reconstructed Neutrino Energy [MeV]
Constraining Systematics

$\nu_e$-only simulation

1e1p Selected & Reconstructed $E_{\nu}$. Scaled to 13E20 POT
Constrained Systematics

MicroBooNE Preliminary

$\nu_e$-only simulation

Sub-dominant cosmic $& \nu_\mu$

Detector systematics not shown

Intrinsic $\nu_e$

Constrained Flux

& GENIE Systematics

M I C R O B O O N E - N O T E - 1 0 3 9 - P U B

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Summary

- **MiniBooNE** has presented an updated measurement of a low energy excess with twice the statistics in neutrino mode in 2018
  - Very stable and well understood detector
  - In Situ measurement of the backgrounds and different $\nu$-C cross sections
  - Combined LSND+MiniBooNE excess has a 6.1$\sigma$ significance

- **MicroBooNE** has made significant progress towards analyses that will test both possible interpretations of the MiniBooNE excess
  - Signal processing, calibration and detector physics
  - $\nu$-Ar cross section measurements
  - Independent analyses, exploring different hypotheses for the excess, different final states and different reconstructions
  - Constraining systematics by using *in situ* measurement of $\nu_\mu$
Thank You!
MiniBooNE KDAR

appearance of a low energy component as a function of time after a NuMI trigger

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Semantic Segmentation Networks

- SSNets identify the content of an image, and work the convolution chain back to the location of the identified objects
- Pixel-level identification
- Trained to recognize tracks to shower
- Track/shower boundaries can be potential vertex!
- How to validate such network?
  - use manual pixel labeling from trained physicist
  - network -human agreement to within 2.5%

JINST 12, P03011 (2017)
PRD 99, 092001 (2019)