Investigating the MiniBooNE excess using MicroBooNE’s data

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The MicroBooNE detector

- Located at Fermilab, close to MiniBooNE
- Longest running large-scale Liquid Argon Time Projection Chamber
- $O(500K)$ $\nu$ interactions collected
MicroBooNE physics reach

Anomaly test

Exotic physics

See Kirsty’s talk for more info!

JINST 15, P03022 (2020)
JINST 13, P07006 (2018)
JINST 13, P07007 (2018)


MicroBooNE physics reach

See Kirsty’s talk for more info!

LArTPC development

ν-Ar cross sections

**Anomaly test**

**Exotic physics**

arXiv:2110.14054, submitted to PRL
arXiv:2110.13978, submitted to PRD
arXiv:2110.14065, accepted by PRD
arXiv:2110.14080, submitted to PRD
arXiv:2110.00409, accepted by PRL


**JINST 15, P03022 (2020)**
**JINST 13, P07006 (2018)**
**JINST 13, P07007 (2018)**

A closer look at MiniBooNE

See Kirsty’s talk for more info!
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A closer look at MiniBooNE

MiniBooNE detector

Signal region

Veto region

Electron, Photon

Muon

Proton

$\pi^0 \rightarrow \gamma + \gamma$

(Cherenkov Detector)

A closer look at MiniBooNE

What is responsible for the excess?
About 200 events, significance of 4.5$\sigma$
Interpreting the MiniBooNE excess

1) Genuine $\nu_e$

2) Single photons

3) Collimated $e^+e^-$ pairs
Interpreting the MiniBooNE excess

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1807.09877, 1808.02915, 2007.11813
General analysis structure

1) From 2D to 3D

2) Identification of neutrino candidate

3) High level variables and event selection

4) Statistical analysis and hypothesis testing
Three reconstruction frameworks

Pandora [Eur. Phys. J. C78, 1, 82 (2018)]
- Algorithmic
- 2D hits
- 2D clusters
- 3D reconstruction

- 2D image is the basic ingredient
- Convolutional networks

- 3D tomography - natively in 3D
Interpreting the MiniBooNE excess

1) Genuine $\nu_e$

2) Single photons

3) Collimated $e^+e^-$ pairs
Single photon signal: $\Delta$ radiative decay

- Standard model process
- $\nu + N \rightarrow \Delta \rightarrow N + \gamma$
- Never measured in neutrino interactions
- $\text{Br}(\Delta(1232) \rightarrow N\gamma) < 1\%$ from theory
- In 3 years of data expected 125 events

MiniBooNE reports that scaling this process by 3.18 reproduces the excess.

Signal = $3.18 \times \Delta^{\text{theory}}(1232)$

- $\Delta(1232) \rightarrow N\gamma$
- Main background = NC$\pi^0$
- $\pi^0 \rightarrow \gamma\gamma$, one $\gamma$ missing

arXiv:2110.00409, accepted by PRL
Single photon analysis

1\gamma 1p

2\gamma 1p

1\gamma 0p

2\gamma 0p
Interpreting the MiniBooNE excess

1) Genuine $\nu_e$

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Electron neutrino signal

Two possible models for a $\nu_e$ signal:
- 3+1 sterile neutrino
- Scaling of the beam

MicroBooNE’s eLEE model:
- Unfold MiniBooNE excess to true energy
- Consider it as an additional component to the beam
- Propagate to MicroBooNE

arXiv:2110.14054, submitted to PRL
Three complementary $\nu_e$ analyses

1e 1p 0$\pi$ - QE-like
- Mostly at low E
- required consistency $E^\text{calo}_\nu$ and $E^\text{inferred}_\nu$ under QE

1e $X_p$ 0$\pi$ - pionless
- Low to medium E
- Two channels: 0p and $N_p>0$

1e $X$ - inclusive
- Benefits from high statistics
- seven channel fit with multiple sidebands

arXiv:2110.13978, submitted to PRD
arXiv:2110.14065, accepted by PRD
arXiv:2110.14065, submitted to PRD
electron/photon separation: $dE/dx$

dE/dx at the start of the shower:
- $e^{-} \sim 2 \text{ MeV/cm}$
- $\gamma \sim 4 \text{ MeV/cm}$

Experimentally:
- Median value in the first 4 cm
electron/photon separation: conversion distance

Theoretically:
- Photon conversion distance ~ 26 cm

Experimentally:
- Vertex-shower start gap

Examples and plot from arXiv:2110.14065, accepted by PRD
LAr TPC allow precise calorimetry and identification of the **Bragg Peak**:
- Deposited charge in a hit -> $\Delta Q$ -> $\Delta E$
- 3D reconstruction -> $\Delta x$
- Reconstruction of local dE/dx along the particle trajectory
Background rejection strategy

All the high-level variables are combined in a BDT:

➔ Classification of $\nu_e$ from the other background - mostly $\nu$ with $\pi^0$
➔ No weight on energy, no use of kinematics related variables
➔ Cut on BDT score is chosen to provide high purity

Examples and plot from arXiv:2110.14065, accepted by PRD.
\( \nu_e \) and \( \nu_\mu \) share the same systematic uncertainties:
- Flux: same hadronic production
- Cross section: same \( \nu-\text{Ar} \) interaction model

Selection of \( \nu_\mu \) is used as a constraint

One large covariance matrix between \( \nu_e \) and \( \nu_\mu \) selections
- Profile over the \( \nu_\mu \) data
- Obtain updated central value and covariance for the \( \nu_e \) selection

Examples and plot from
arXiv:2110.14065, accepted by PRD
Reconstructed energy spectra

arXiv:2110.14054, submitted to PRL
Overall, no clear evidence for an excess of $\nu_e$ interactions

Ruling out this explanation of MiniBooNE at the $\sim 2\sigma$ level
Conclusions (1)

Short baseline anomalies is a BIG open puzzle in neutrino physics... 

...the more experiments, the more pieces that do not quite fit.
Conclusions (2)

MicroBooNE:

- strongly pushed forward the development of LAr TPCs
- probed the most intuitive explanations for the MiniBooNE excess
- Many other physics results - [publication list](#)

The next steps:

- The SBN program: 3 detectors better than 1!
- Full 3+1 osc analysis
- Searching for a larger set of signatures: $e^+e^-$
Thank you for your attention!
Detector understanding and modelling

- Noise removal
- Deconvolution of signals from induced charge on neighboring wires

- Track distortion induced by non-uniformity of the electric field
Neutrino interaction generator

- Tailored GENIE Tune
- Using external data (T2K ND280) at similar energy and similar processes
- In-situ constraints applied later
Detector systematics

Detector systematics are treated by varying the reconstructed waveforms

➔ Good trade-off between accurate description and computational time
➔ Main effect is on calorimetry, less on topology

This propagates to analysis variables

• Clear effect on the ones more dependent on calorimetric information
• Red is detector systematics, grey is all systematics
Unblinding the data

Blind analysis:
1) Freeze analysis based on small portion of open data
2) Look at the whole datasets in sidebands
3) Progressively closer to the signal box

Reconstruct and measure $\nu_e$ at progressively lower energies

Check the distribution of the backgrounds at progressively larger PID, using BDT scores and box cuts
Single photon results

Fit for $x^\Delta$ - scaling factor for $\Delta$ radiative decay:

- Best-fit = 0
- Confidence interval = [0, 2.3]
- Exclude single photon hypothesis at 94.8% CL
QE-like analysis

QE-like signature:
→ required consistency between $E_{\nu}^{\text{calo}}$ and $E_{\nu}^{\text{inferred}}$ under QE hypothesis

Using Deep-learning based reconstruction:
- **Pixel labelling** using Sparse Networks
- **Multi-particle identification** using **Convolutional** Networks

arXiv:2110.13978, submitted to PRD
Pionless analysis

arXiv:2110.14065, accepted by PRD

Two different sub-channels:

→ X > 0 protons
→ 0 protons

Using Pandora reconstruction framework:

● Selection based on topology
● No use of the event kinematics in the selection to not bias analysis towards low energy
Inclusive analysis benefit from high statistics; - seven channel fit with multiple sidebands

Wire-Cell tomography 3D imaging:
- **Reconstruct directly in 3D space**

*arXiv:2110.13978*, submitted to PRD
Different interaction processes at different energies

**Quasi elastic:**
- $\nu_e + n \rightarrow e^- + p$
- Two particles final state - one track & one shower

**Deep inelastic scattering:**
- Multi-hadron final states

**Resonant and Meson-exchange-current:**
- $\nu_e + N \rightarrow e^- + \pi + N'$ and $\nu_e + n + p \rightarrow e^- + p + p$
- Single pion or 2-proton production
For this analysis:

- **Signal** = $3.18 \times \Delta(1232) \rightarrow N\gamma$
- **Main background** = $\pi^0 \rightarrow \gamma\gamma$, one missing

→ BDT combines high-level information to reject most backgrounds
→ 4 analysis channels: 2 signal and 2 constraining background
Reconstructed energy spectra

1eNp0π

1e1p QE

1e0p0π

1eX