MiniBooNE Oscillation Results with Complete Dataset

Adrien Hourlier
on behalf of the MiniBooNE Collaboration
2020/07/02

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Comparing MiniBooNE and LSND

**LSND (1993-1998)**

- 0.8 GeV proton beam
- Decay At Rest neutrino flux
- LANSCE proton beam
- **Water target**
- **Beamstop**
- $\pi^+ \rightarrow \mu^+ \nu_\mu$
- $E \sim 30$ MeV
- $L \sim 30$ m

**MiniBooNE (2002-2019)**

- 8 GeV proton beam
- Decay In Flight beam
- **Particle reconstruction**
- **Interaction**
- **Track**
- **Cherenkov**
- **Candidate**

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**Different systematics. Same L/E baseline.**
The MiniBooNE Detector

- Ø12.2 m sphere, Ø10m 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
  - 3% change of the energy scale over 17 years of running
  - Measurements of cross sections for >90% of the neutrino and anti-neutrino processes
• We have added another \(\sim 6 \times 10^{20}\) POT to the neutrino dataset since the previous data release.
• The detector was turned off at the end of summer 2019, mothballed and waiting for future use…
• Almost 17 years of running, or as much as 5 army ants worth of protons!
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graduated from high school!
Dark matter run

- First dedicated search for direct detection of accelerator-produced dark matter in a proton beamline
- Beam aimed off of the target
- \(\nu\) flux reduced by \(~50\)
- Demonstrated the power of neutrino detectors in searching for accelerator-produced dark matter
Exellent long term detector stability over 3 run periods

- We can use two standard candles to calibrate the energy scale over the different data sets
- Scale up the energy response to match the original 2007 data release:
  - 2015-2017 neutrino data => 2% energy scaling
  - 2017-2019 neutrino data => 3% energy scaling
Neutrino energy and 3ν prediction

- Excess of data events with respect to our background prediction
- We report an excess of 560.6 ± 119.6 electron-like events ( neutrino mode)

- Significance : 4.7 σ in neutrino mode only
\( \nu_e \)-like excess stable across 3 runs

- Comparing the data-prediction excess for three data taking periods in neutrino mode
- Comparable statistics between the three data releases
- The observed excess remains well compatible between the three data sets
Constraining the backgrounds

MiniBooNE preliminary
18.75 x 10^{20} POT
Neutrino mode
Constraining the backgrounds

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

\( \Delta \rightarrow \text{N}_\gamma \) resonance  
constrained from \textit{in situ}  
measured NC \( \pi^0 \)  
rate and  
theoretical prediction

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

MiniBooNE preliminary  
18.75 x \( 10^{20} \) POT  
Neutrino mode
New: Dirt constraint with timing

- **Dirt events:**
  - beam-related neutrino interactions in the rocks surrounding the detector
  - time shift due to extra flight path before particles enter the detector
- No cut on the event timing within the beam spill (RF cavity structure of 52.81 MHz)
- Event timing shows no significant excess of off-bunch data
  - **dirt constrained to better than 5σ**
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New: Radial distribution disfavors dirt and $\pi^0$ background

- Improved statistics allow for more distributions to be investigated
- Radial distribution shows that the excess is spread evenly within the volume of the detector
- An excess of $\pi^0$ background would have peaked near the edge (higher probability of missing one of the $\gamma$)
- Similar approach to SNO’s CC/NC constraint
- Second best candidate: NC$\gamma$ background

### Excess shape tests

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>$\chi^2/9\text{df}$</th>
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Adrien Hourlier — The XXIX International Conference on Neutrino Physics and Astrophysics — July 2nd 2020
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Statistics only $\chi^2$
New: Radial distribution disfavors dirt and $\pi^0$ background

- Scaling dirt and $\pi^0$ backgrounds to fit the excess
- The "best fit" corresponds to a 2ν oscillation with a sterile neutrino, and fit the observed excess better than a single background
New: Radial distribution disfavors dirt and $\pi^0$ background

MiniBooNE preliminary 18.75 x 10^{20} POT Neutrino mode

- Investigate if the excess is caused by events spilling in or spilling out of the fiducial volume by varying the fiducial cut
- Excess remains significant when rejecting outer layers of the detector: excess within the detector volume

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<th>Fiducial cut</th>
<th>Excess</th>
<th>Significance</th>
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<td>$R &lt; 500$ cm</td>
<td>$560.6 \pm 119.6$</td>
<td>4.7 $\sigma$</td>
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<td>$R &lt; 400$ cm</td>
<td>$472.6 \pm 81.7$</td>
<td>5.8 $\sigma$</td>
</tr>
<tr>
<td>$R &lt; 300$ cm</td>
<td>$208.8 \pm 40.3$</td>
<td>5.2 $\sigma$</td>
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NC $\Delta \rightarrow N\gamma$ resonance

- The production of $NC \Delta \rightarrow N\gamma$ is highly correlated to the measurement of $NC \pi^0$

- Same probability of a NC interaction, the difference in final state is the relative rate of resonant production.

  ➡ Our predicted single $\gamma/\pi^0$ ratio is ~0.9%, which takes into account pion absorption in the nucleus, higher mass resonances, coherent scattering, and non-resonant processes

- Apply the same correction and fractional uncertainties to $NC \Delta \rightarrow N\gamma$ as $NC \pi^0$

- Additional uncertainty to account for final state interactions (FSI)

- The single gamma estimate agrees with theory

Single photon events from neutral current interactions at MiniBooNE

En Wang, Luis Alvarez-Ruso *, Juan Nieves

Instituto de Física Corpuscular (IFIC), Centro Mixto CSIC-Universidad de Valencia, Institutos de Investigación de Paterna, Apartado 22085, E-46071 Valencia, Spain

New: Constraints from the beam dump run

- Reduction in neutrino production
- No change to neutral meson production and proton bremsstrahlung to first order
  - Can directly test models that predict the oscillation excess does not scale as neutrino scales (e.g. vector portal, inelastic dark matter, …)

- **Expected**: $35.5 \pm 7.4$ excess events in [200,1250] MeV for a POT-scaling excess
- **Measured**: 6 events, 8.8 backgrounds expected
  - -2.8 excess events
  - Explanation that scale only by POT instead of neutrino production are ruled out at 4.6σ

Excess interpretation in a sterile neutrino hypothesis

- Combined ($\nu + \bar{\nu}$) fit
- LSND and MiniBooNE points follow the same best fit 2ν oscillation interpretation
Preferred regions in sterile neutrino hypothesis

- Neutrino mode excess 4.7σ,
- Neutrino+Anti-neutrino modes excess : 4.8σ

\[
\Delta m^2, \sin^2 2\theta = (0.043 \text{ eV}^2, 0.807) \\
\chi^2/ndf = 21.7/15.5 \text{ (prob = 12.3%)}
\]
New: $\cos(\theta)$ VS $E_{\text{vis}}$ Distributions for $\nu_e$ samples

- Compare data to backgrounds in the ($E_{\text{vis}}, \cos\theta$) space
- We believe that these distributions will guide theorists to explain our data
- These data will soon be provided in a data release with systematic errors
New: $\cos(\theta)$ VS $E_{\text{vis}}$ Distributions for $\nu_e$ samples

Easier to visualize the excess in 1D plots of $\cos\theta$ for slices of $E_{\text{vis}}$
**New**: \( \cos(\theta) \) VS \( E_{\text{vis}} \) Distributions for \( v_e \) samples

Easier to visualize the excess in 1D plots of \( \cos\theta \) for slices of \( E_{\text{vis}} \)
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Easier to visualize the excess in 1D plots of $\cos\theta$ for slices of $E_{\text{vis}}$

Adrien Hourlier — The XXIX International Conference on Neutrino Physics and Astrophysics — July 2\textsuperscript{nd} 2020
New: \( \cos(\theta) \) VS \( E_{\text{vis}} \) Distributions for \( \nu_e \) samples

Easier to visualize the excess in 1D plots of \( \cos \theta \) for slices of \( E_{\text{vis}} \)
New : $\cos(\theta)$ VS $E_{\text{vis}}$ Distributions for $\nu_e$ samples

- The excess at low energy occurs across a wide range of $\cos \theta$
Summary

- MiniBooNE presented a full analysis of 17 years of data taking
- The event excess has remained stable in shape and magnitude over the different data releases
- We now have a $4.7\sigma$ significance in neutrino mode only, and a $4.8\sigma$ significance in a combined ($\nu + \bar{\nu}$) analysis for our nominal cut of $R<500$ cm.
- Several explanations for the excess are disfavored
  - NC $\pi^0$
  - Dirt event
  - Dark matter run ruled out non-neutrino-related beam backgrounds
- In the spirit of responding to requests for more information, we are now in a position to provide additional information on timing, visible energy VS angle of lepton scatter, and radius.
- Further studies under way to better understand the excess, including investigating Meson Exchange Currents, stay tuned!

preprint available at arxiv:2006.16883
Thank you!
Constraining $\Delta \rightarrow N\gamma$ background from NC$\pi^0$ background

- NC $\pi^0$ produced by:
  - $\Delta$ production in $^{12}$C (52.2%)
  - $\Delta$ production in H$_2$ (15.1%)
  - Coherent scattering on $^{12}$C (12.5%)
  - Coherent scattering H$_2$ (3.1%)
  - higher mass resonance (12.9%)
  - non resonant BG (4.2%)

- 2/3 of $\Delta$ decay in $\pi^0$
- 62.5% $\pi^0$ can escape the nucleus
- $\Delta \rightarrow N\gamma$ BR = 0.60% for $^{12}$C
- $\Delta \rightarrow N\gamma$ BR = 0.68% for H$_2$

\[
\frac{N_{\Delta \rightarrow N\gamma}}{N_{NC\pi^0}} = (0.151 \times 0.0068 \times 1.5) + \frac{(0.522 \times 0.0060 \times 1.5)}{0.625} = 0.0091
\]
Theoretical Estimates for NC-γ production Agree well with MiniBooNE Estimates

Single photon events from neutral current interactions at MiniBooNE

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<td>$E_Y$ (GeV)</td>
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<tr>
<td>[0.1, 0.2]</td>
<td>0.72 (1.5)</td>
</tr>
<tr>
<td>[0.2, 0.3]</td>
<td>3.2 (5.5)</td>
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<tr>
<td>[0.3, 0.4]</td>
<td>3.7 (5.4)</td>
</tr>
<tr>
<td>[0.4, 0.5]</td>
<td>1.0 (1.7)</td>
</tr>
<tr>
<td>[0.5, 0.6]</td>
<td>0.32 (1.0)</td>
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</tr>
<tr>
<td>[0.5, 0.6]</td>
<td>0.10 (0.72)</td>
</tr>
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</table>

Can neutrino-induced photon production explain the low energy excess in MiniBooNE?

Xilin Zhang a,b,*, Brian D. Seror b,1

a Institute of Nuclear and Particle Physics and Department of Physics and Astronomy, Ohio University, Athens, OH 45701, USA
b Department of Physics and Center for Exploration of Energy and Matter, Indiana University, Bloomington, IN 47405, USA

Excess for $\cos \theta$ VS $E_{\text{vis}}$ plot
Neutrino only fit

- Only a small difference with respect to the \( (\nu + \bar{\nu}) \) combined fit
-\( \nu \)-only: \( (\sin^2 2\theta, \Delta m^2) = (0.843, 0.039 \text{ eV}^2) \)
-\( (\nu + \bar{\nu}) \): \( (\sin^2 2\theta, \Delta m^2) = (0.807, 0.043 \text{ eV}^2) \)
Radial distribution in SNO


- NC and CC contributions have difference R-dependencies, one can use the radial distribution to estimate the relative contribution of each process.
- SNO is only one of the many examples of experiment using radial position to constrain components of their data.
FIG. 9: Comparisons between the data and simulation for the electron-muon likelihood distribution after successive cuts are applied: (a) no PID cut, (b) electron-muon likelihood cut, (c) electron-muon plus electron-pion likelihood cuts, and (d) electron-muon plus electron pion likelihood cuts plus a gamma-gamma mass cut. The vertical lines in the figures show the range of energy-dependent cut values.
FIG. 10: Comparisons between the data and simulation for the electron-pion likelihood distribution after successive cuts are applied: (a) no PID cut, (b) electron-muon likelihood cut, (c) electron-muon plus electron-pion likelihood cuts, and (d) electron-muon plus electron pion likelihood cuts plus a gamma-gamma mass cut. The vertical lines in the figures show the range of energy-dependent cut values.
PID variables: $m_{\gamma\gamma}$ distribution

FIG. 11: Comparisons between the data and simulation for the gamma-gamma mass distribution after successive cuts are applied: (a) no PID cut, (b) electron-muon likelihood cut, (c) electron-muon plus electron-pion likelihood cuts, and (d) electron-muon plus electron pion likelihood cuts plus a gamma-gamma mass cut. The vertical lines in the figures show the range of energy-dependent cut values.