Status of MiniBooNE
Anomalous $\nu_e$-like Excess &
Non-Sterile Explanations

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Disclaimers

• I am not a MiniBooNE collaborator! And I don’t play one on TV
  ‣ But some of my friends and colleagues are…

• The views and opinions expressed in this talk are mine and do not necessarily reflect anyone else’s
The LSND Anomaly

• LSND studied $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations, using $\bar{\nu}_\mu$ from $\mu^+$ decay at rest

• Detection mechanism: $\bar{\nu}_e + p \rightarrow e^+ + n$, then $n + p \rightarrow d + \gamma$ (2.2 MeV)
  ‣ Observe Cherenkov and scintillation light from the positron, then delayed light from subsequent neutron capture — coincidence reduces backgrounds

• Observed a $3.8\sigma$ excess of $\bar{\nu}_e$-like events, which corresponds to an oscillation probability of $P_{\text{osc}} \sim 0.26\%$

PRD 64, 112007 (2001)

Signal model not shown
The MiniBooNE Experiment

- The MiniBooNE experiment uses a mineral oil Cherenkov detector located in the Booster Neutrino Beam (BNB) at Fermilab
- Proposed to search for sterile neutrino oscillations suggested by LSND
- Located at a similar $L/E$ as LSND
  - MiniBooNE at ~500m/500MeV
  - LSND at ~30m/30MeV
- Experiments have different systematic uncertainties due to different fluxes, event signatures, and backgrounds

$$P_{\text{osc}} \approx \sin^2(2\theta) \sin^2\left(1.27 \frac{\Delta m^2[eV^2] \cdot L[m]}{E[MeV]}\right)$$
The Booster Neutrino Beam

• Neutrinos from decays of hadrons created by 8 GeV protons on a beryllium target inside a focusing horn

• Horn polarity can be reversed, allowing MiniBooNE to run in both neutrino and antineutrino mode

ν_e flux has significant K component starting at about 600 MeV

“Neutrino Flux Prediction at MiniBooNE”
PRD 79, 072002 (2009)
The MiniBooNE Detector

- 540m from the BNB target
- 12.2m diameter sphere, 10m diameter fiducial vol.
- 800 tons of mineral oil, 450 tons fiducial mass
- Signal region instrumented with 1280 PMTs, which give 10% photocathode coverage
- Veto region instrumented with additional 240 PMTs
MiniBooNE Event Signatures

- MiniBooNE primarily uses Cherenkov light
- Compare fits for different track reconstruction hypotheses for PID
- Cannot distinguish a single photon from a single electron
MiniBooNE Energy Reconstruction

• Energy is reconstructed using the CCQE energy formula

• Assumess initial-state nucleon is at rest and interaction is CCQE, although does account for nuclear binding energy $E_B$

• However, in reality:
  ‣ Initial state nucleon will have some Fermi momentum
  ‣ Not all interactions will be CCQE

\[
E_{\nu}^{\text{QE}} = \frac{2(M_n - E_B)E_\ell - ((M_n - E_B)^2 + M_\ell^2 - M_p^2)}{2((M_n - E_B) - E_\ell + p_\ell \cos \theta_\ell)}
\]
New Dataset: Double the νs!

- In 2018, MiniBooNE released an updated result with double the neutrino-mode data statistics: *PRL 121, 221801 (2018)*
- New data improves signal measurement and data-driven background constraints
- Increases neutrino-mode MiniBooNE excess to 4.5σ and gives a combined significance for the LSND and MiniBooNE excesses of 6σ
Status of the Excess

MiniBooNE $E_{\nu}^{QE}$ distribution for all neutrino mode data, $12.84 \times 10^{20}$ POT

PRL 121, 221801 (2018)
Status of the Excess

Is the new neutrino-mode data consistent with the previous result?

- MiniBooNE has done a many of checks detector stability
- Previous and new excesses are statistically consistent

![Graph showing excess events per MeV versus E_{QE} (GeV)]

Stat. errors only

PRL 121, 221801 (2018)
Status of the Excess

Is the combined neutrino-mode excess consistent with the antineutrino-mode excess? How do these compare to oscillation predictions?

• Excesses in neutrino and antineutrino mode are qualitatively consistent with each other, but not completely consistent with 3+1 model.
Status of the Excess

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Both neutrino- and antineutrino-mode excesses rise above expectation from 3+1 oscillations at low energies.

In neutrino data, 600 MeV bin is \(\sim 2\sigma\) lower than expected.
Status of the Excess

Is the combined neutrino-mode excess consistent with the antineutrino-mode excess? How do these compare to oscillation predictions?

• Excesses in neutrino and antineutrino mode are qualitatively consistent with each other, but not completely consistent with 3+1 model

Linearly rising background below ~600 MeV provides a not-unreasonable fit to the excess

Alternatively, over-subtraction of backgrounds above 600 MeV, e.g., intrinsics from kaons
Possible Explanations for the Excess

• **Underestimation of systematic uncertainties on backgrounds**
  ‣ Beam intrinsic $\nu_e$ events from either muon or kaon decays
  ‣ Misidentified $\pi^0$ events
  ‣ $\Delta\rightarrow N\gamma$ events
  ‣ Dirt events

• **Nuclear effects, affecting energy reconstruction**

• Sterile neutrino oscillations ($3+N$)
• Resonant neutrino oscillations
• Lorentz violation
• Sterile neutrinos that decay
• Non-standard interactions of sterile neutrinos
• Sterile neutrinos propagating in large extra dimensions
• Dark neutrino portal
• … and more!

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**Standard Model**
I have been asked to focus on the SM explanations

**Beyond the Standard Model**
Constraining the Backgrounds

MisID $\pi^0$ is constrained from in-situ measurement of NC $\pi^0$ rate

$\Delta$ resonance is constrained from measured NC $\pi^0$ rate and theoretical prediction

Dirt is rate is measured from in-situ dirt data sample

$\nu_e$ from $\mu$ decay is constrained by $\nu_\mu$ CCQE measurement

$\nu_e$ from $K$ decay is constrained from SciBooNE high energy $\nu_\mu$ event measurement

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Constraining the Intrinsic $\nu_e$ Flux

• The $\nu_e$ rate is small at low energies, so flux would have to be much higher than predicted

• MiniBooNE uses the measured $\nu_\mu$ to constrain intrinsic $\nu_e$ prediction

• Both species of neutrinos come from same population of parent hadrons (mostly $\pi^\pm$)

• Also have constraints on kaons from SciBooNE
Constraining the Intrinsic $\nu_e$ Cross Section

- MiniBooNE tuned cross section model based on their high-statistics $\nu_\mu$ data
  - Fit for a scale factor for CC $1\pi^+$ using a dedicated CC $1\pi^+$ sideband
  - Fit for model parameters $M_A^{\text{QE}}$ and $\kappa$ using their CCQE data
- After tuning, $\nu_\mu$ data shows reasonable agreement with prediction, including in double-differential distribution

PRD 81, 092005 (2010)
Constraining $\pi^0$ Misidentification

• The NC $\pi^0$ background rate is constrained by MiniBooNE’s high-statistics measurement of NC $\pi^0$ production

• Two main sources:
  ▸ One photon exits or is absorbed — well-constrained by the measured rate of two-photon $\pi^0$ events, the interaction length in mineral oil, and knowledge of photo-nuclear absorption
  ▸ Weak second photon — constrained by measurement of kinematics of two-photon $\pi^0$ events, used to tune simulation
Constraining Dirt

• Increased data statistics has allowed better measurement of dirt backgrounds and reduced the associated uncertainty

• Contribution is estimated by isolating events where the vertex is near the boundary and the shower is inward-going — constrained at the ~10% level
  ‣ Better constraint based on using timing information is in progress

• Excess is consistent over the entire radius of the detector
• Current theoretical predictions match well with MiniBooNE’s simulation for NC $\Delta$ radiative decay (NC $\Delta \rightarrow N \gamma$)
  ‣ Other NC processes that produce a single $\gamma$ in the final state are plausible

• MiniBooNE’s simulation is tuned on their measurement of NC $\pi^0$
  ‣ Most NC $\pi^0$ come from NC $\Delta$ events where the $\Delta$ decays via $\Delta \rightarrow N \pi$, so the NC $\pi^0$ events give some information about $\Delta$ production

• However, theoretical uncertainties are large and the process has never yet been measured by a neutrino experiment
  ‣ T2K set a limit; MicroBooNE will measure it on argon
Nuclear Effects & Energy Reconstruction

• The MiniBooNE neutrino interaction generator does not have multi-nucleon effects

• The detector is not sensitive to the final-state protons that might allow one to distinguish multi-nucleon events

• When reconstructing multi-nucleon events with the CCQE energy formula, one tends get an underestimate of the neutrino energy

• This is an un-modeled background in MiniBooNE that would tend to reconstruct at low energies! This could help explain pile up of excess at low energies

PRD 93, 073008 (2016)
Aside: Reconstruction in LArTPCs

- LArTPCs provide additional handles for energy reconstruction, because they allow us to reconstruct the proton.
- In this case, can calculate the neutrino energy in three different ways and check for consistency.

\[
\begin{align*}
E^\text{range}_\nu &= KE_\ell + KE_p + M_\ell + M_p - (M_n - E_B) \\
E^\text{QE, } \ell &= \frac{2(M_n - E_B)E_\ell - ((M_n - E_B)^2 + M_\ell^2 - M_p^2)}{2((M_n - E_B) - E_\ell + p_\ell \cos \theta_\ell)} \\
E^\text{QE, } p &= \frac{2(M_n - E_B)E_p - ((M_n - E_B)^2 + M_p^2 - M_\ell^2)}{2((M_n - E_B) - E_p + p_p \cos \theta_p)}
\end{align*}
\]

- This should allow LArTPC experiments to isolate a purer sample of CCQE events and reduce misconstruction of other interactions.

More on LArTPCs in my other talk!
Summary

• The MiniBooNE anomaly remains puzzling, especially with the release of new data that strengthens the significance of the excess

• Many Standard Model explanations can be ruled out based on MiniBooNE’s own data-driven constraints

• Other explanations remain plausible
  ‣ Unexpected behavior from NC events with a single $\gamma$ in the final state
  ‣ Mis-modeling of nuclear effects that change the energy reconstruction

• 3+1 model for sterile neutrinos is already over-constrained and shows inconsistencies with world data (including MiniBooNE)

• Ideas for BSM explanations beyond just sterile neutrinos would be helpful inputs from the theory community

Thank you!