First Results from MicroBooNE's Low Energy Excess Search and Constraints on eV-Scale Sterile Neutrino Oscillations

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Wright Laboratory



MiniBooNE anomaly

 MiniBooNE (2002-2019) observed a low energy excess (LEE) of electromagnetic events with 4.8σ significance

It detected v by the electrons produced in charged current (CC) interactions.

However, **photons**, that pair produce extremely collimated electron/positron pairs produced an identical Cherenkov ring



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- MiniBooNE Cherenkov detector unable to distinguish between electrons and photons
- MiniBooNE also unable to detect hadronic final-state particles below Cherenkov threshold





Liquid Argon Time Projection Chamber (LArTPC)

- LArTPC is capable of identifying different species of particles and reconstructing 3D images with finegrained information
 - neutrino vertex
 - particle flow (mother-daughter particle relationship)
 - track vs. shower separation
 - electron vs. photon (e+e- pair production) separation









MicroBooNE @ Fermilab









MicroBooNE @ Fermilab

Cherenkov detector with 820 tonne mineral oil







170 (85) tonne liquid argon in cryostat (TPC)



Photon excess or electron excess?



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- electron-like excess
 - due to mis-modeled/unknown process?
 - oscillation-driven excess?
- photon-like excess
 - due to mis-modeled/unknown process producing photons, such as Neural-Current (NC) Δ resonance radiative decay?



Single-photon low energy excess (gLEE) search

- targeting NC Δ resonance radiative decay $(\Delta \rightarrow N\gamma)$
 - standard model process
 - never been directly observed in neutrino scattering
- an enhancement in NC $\Delta \rightarrow N\gamma$ by a factor of 3.18 would give good agreement with the observed MiniBooNE LEE









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- the analysis selects two NC Δ rich single-photon channels: $1\gamma 1p \& 1\gamma 0p$
- the result disfavors the most suspected single-photon background as a sole source of the MiniBooNE excess at 94.8% C.L.
- bound on the normalization of $\Delta \rightarrow N\gamma$ • was determined to be 2.3 at 90% C.L.









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v_e low energy excess (eLEE) search

- assumption about the excess: an energy-dependent enhancement of intrinsic v_e events in the beam at low energy
- empirical eLEE model is derived from MiniBooNE, by unfolding detector response, acceptance, efficiency





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eLEE results

- three independent eLEE searches, targeting four different final states: 1e1p, 1eNp0 π , 1eOp0 π , 1eX
- observed v_e candidate rates are statistically consistent with the predicted background rates in the LEE region
- with exception of the low v_e purity channel $1e0p0\pi$, the hypothesis that v_e events are *fully responsible* for the median MiniBooNE LEE is rejected at 97% C.L. and $>3\sigma$ in the inclusive channel
 - however, the existence of sterile neutrinos cannot be ruled out by the MicroBooNE eLEE result, which is a generic low-energy v_e excess search













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3+1 neutrino oscillation analysis

- eLEE results are re-interpreted under a sterile neutrino oscillation hypothesis: a combination of short-baseline
 - v_e appearance, v_e disappearance, and v_{μ} disappearance
 - v_e disappearance can cancel the appearance of v_e events:

degeneracy of oscillation parameters

considering full 3+1 oscillation, BNB Run1-3 data was found to be **consistent with the 3v** hypothesis within 1σ following the Feldman-Cousins approach







3+1 oscillation analysis result: v_e disappearance



- v_{e} appearance-disappearance degeneracy mitigation



competitive limit on the eV-scale v_e disappearance, first v-Ar scattering data limit

sensitivity significantly improved when combining both BNB and NuMI, mainly due to





3+1 oscillation analysis result: v_e appearance



- part of the LSND allowed region is excluded by the MicroBooNE 95% C.L.
- $v_{\rm e}$ appearance-disappearance degeneracy mitigation



sensitivity significantly improved when combining both BNB and NuMI, mainly due to





Summary

- MicroBooNE's first searches for low energy excess found no evidence of excessive v_e or NC Δ radiative decay to explain the MiniBooNE excess
- full 3+1 oscillation analyses were carried out to interpret the MicroBooNE eLEE results under a sterile neutrino oscillation hypothesis
 - the data (50% BNB dataset) was found to be consistent with 3-flavor hypothesis
- further investigation on MiniBooNE excess, searches for other BSM particles/processes (e.g. e+e-), and oscillation analysis with BNB & NuMI data are underway









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Thank You!



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Backup













result in fine-grained 3D images, with calorimetry information

incoming v

proton track candidate

14 cm

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RUN 8617 SUBRUN 46 EVENT 2328





MicroBooNE experiment

- LArTPC Detector
 - 85 tons of LAr active volume
 - TPC: 8192 anode sense wires in 3 planes PMT: 32 8-inch PMTs
 - CRT (cosmic ray tagger) is installed around TPC
 - located at BNB beamline in Fermilab, started taking data since Oct. 2015
- physics goal
 - strong understanding of the detector and highly developed event reconstruction, paving the way to future LAr detectors (SBN & DUNE)
 - neutrino interaction measurements
 - towards low-energy excess: definitively address the MiniBooNE anomaly













Cancellation of v_e appearance and v_e disappearance -- degeneracy of oscillation parameters

MicroBooNE Preliminary



Different degeneracy points: degeneracy mitigation utilizing both

 v_e disappearance v_e appearance $N_{\nu_e} = N_{\text{intrinsic } \nu_e} \cdot P_{\nu_e \to \nu_e} + N_{\text{intrinsic } \nu_\mu} \cdot P_{\nu_\mu \to \nu_e}$ $= N_{\text{intrinsic } v_{\text{e}}} \cdot \left[1 + (R_{v_{\mu}/v_{e}} \cdot \sin^2 \theta_{24} - 1) \cdot \sin^2 2\theta_{14} \cdot \sin^2 \Delta_{41} \right]$

- **Degeneracy** when $\sin^2 \theta_{24}$ approaches $R_{\nu_e/\nu_{\mu}}$ which is the ratio of intrinsic v_e and v_μ in the neutrino flux
- Sensitivity/exclusion limits gets much worse around the degeneracy point









This LEE search proceeds with a simultaneous side-by-side fit of four topologically distinct samples



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MicroBooNE's search for an excess of electron neutrino interactions

three independent searches across multiple single electron final states

exclusive two-body charged-current quasi-elastic (CCQE) v_e scattering [1e1p]

• semi-inclusive v_e scattering without final state pions [1eNp0 π (N \geq 1) + 1e0p0 π]

inclusive v_e scattering [1eX]











MB excess and sterile neutrinos

- the MicroBooNE eLEE result disfavors the MB excess originating from a pure $v_{\rm e}$ excess
- the existence of sterile neutrinos cannot be ruled out by the MicroBooNE eLEE result, which is a generic low-energy v_e excess search
- the MicroBooNE eLEE results can be re-interpreted under a sterile neutrino oscillation hypothesis: a combination of short-baseline v_e appearance and v_e disappearance
- 3+1 oscillation searches using the selections in the MicroBooNE eLEE searches are performed











