Inclusive searches for eV-scale sterile neutrinos at SBN

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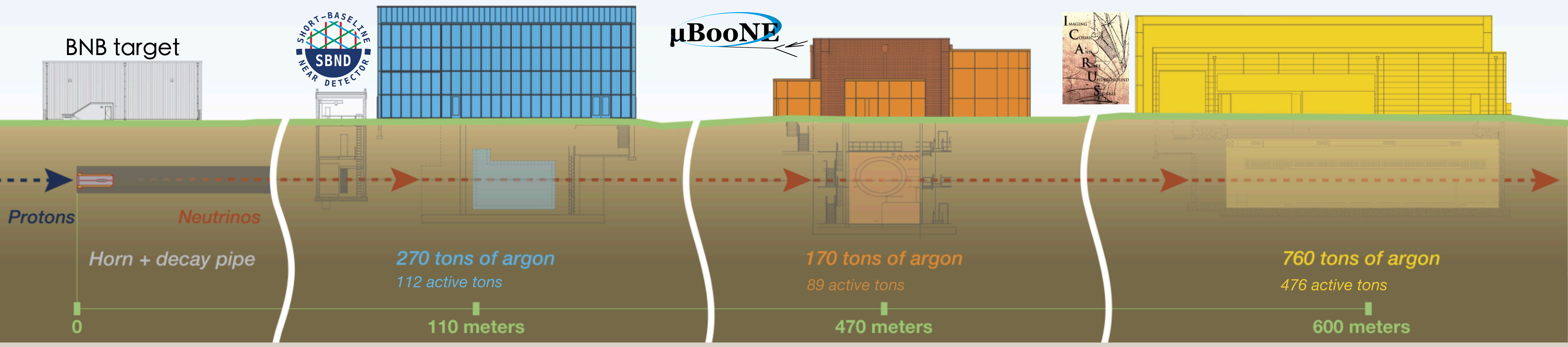
This work was supported by the National Science Foundation under Grant No PHY-2310080

The Short Baseline Neutrino (SBN) Program at Fermilab.



Opportunities

- **Largest neutrino-argon dataset to date:** 2M ν_μ CC events/yr from BNB at SBND and 400k ν_μ events/yr at ICARUS. NuMI off-axis expect 10^5 events/yr above 1 GeV energy.
- **Shared detector technology, nuclear target, and beam**. Access to two beams (BNB and NuMI) with different peak energies and ν_μ/ν_e ratio. LArTPC's allow for simultaneous ν_e and ν_μ searches, a unique strength of the SBN Program.
- Global fits favor **more complicated oscillation scenarios [1]**, or a **combination of oscillation effects and other new physics**.

Challenges

- Fitting frameworks need to be flexible to explore a wide variety of oscillation and BSM models, as well as handle the high neutrino rates, multiple detectors, oscillation channels, beams, and systematic parameters.
- Large correlations will reduce flux and cross-section uncertainties to O(1%). **Detector systematics need to be similarly constrained[2]**.

Oscillations

- The SBN program will provide a powerful probe of eV-scale sterile neutrinos in the 3+1 paradigm.
- Will also have significant sensitivity to more complex oscillation scenarios (3+N, 3+1+decay)

$$\sin^2 2\theta_{ee} = 4\left|U_{e4}\right|^2\left(1-\left|U_{e4}\right|^2\right) \quad (1)$$

$$\sin^2 2\theta_{\mu\mu} = 4\left|U_{\mu4}\right|^2\left(1-\left|U_{\mu4}\right|^2\right) \quad (2)$$

$$\sin^2 2\theta_{\mu e} = 4\left|U_{\mu4}\right|^2\left|U_{e4}\right|^2 \quad (3)$$

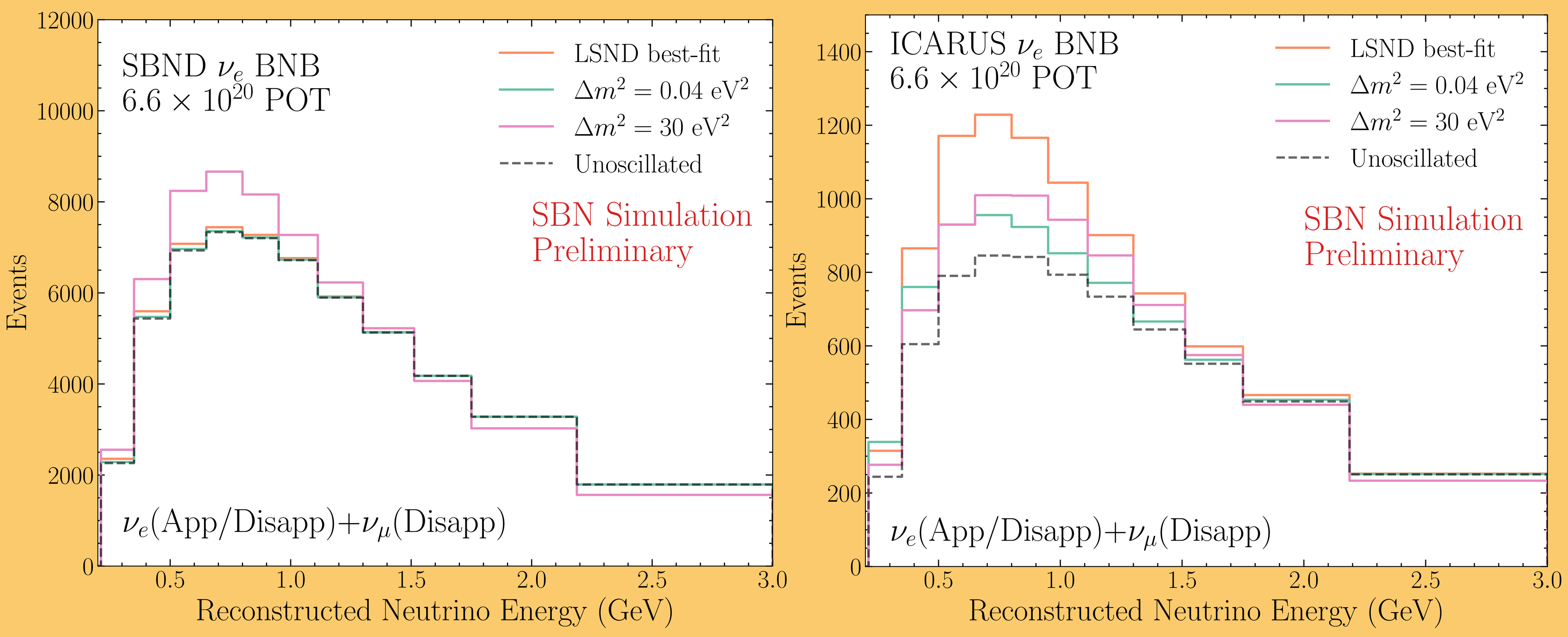


Fig. 1: Predictions for various points in 3+1 space. All relevant oscillation channels are taken into account. Oscillation amplitudes for the green and pink lines are: $\sin^2(2\theta_{\mu e}) = 2.5\times10^{-3}$, $\sin^2(2\theta_{\mu\mu}) = 0.04$, $\sin^2(2\theta_{ee}) = 0.23$.

Extra handles

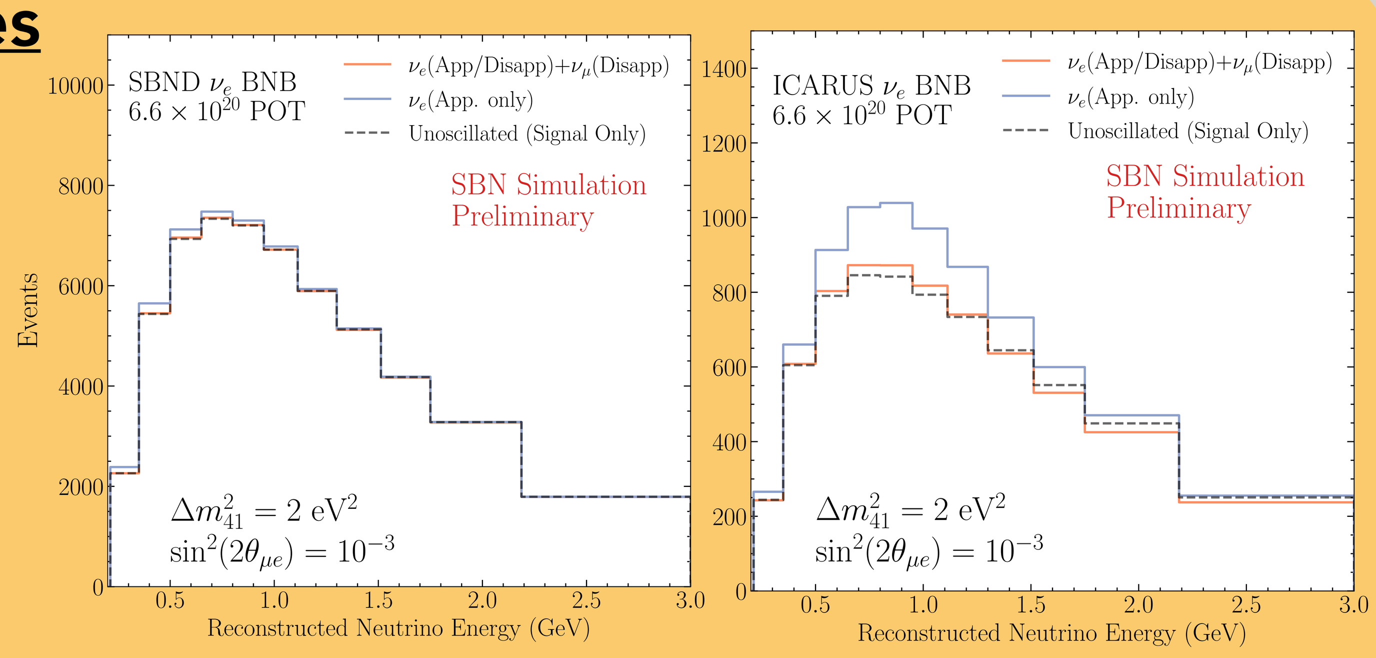


Fig. 2: ν_e appearance and disappearance can interfere when $\sin^2(\theta_{24})$ — the mixing amplitude between ν_2 and ν_4 — is roughly equal to the ν_e to ν_μ ratio in the beam [3,4]. The orange line in this figure includes $\nu_\mu \rightarrow \nu_e$ oscillations. This degeneracy can potentially be broken by including NuMI beam data[4]. The NuMI beam at the ICARUS location is roughly ~5% ν_e flavor, a factor of 10 larger than the fraction of ν_e in BNB. Efforts are ongoing to overhaul NuMI predictions for off-axis detectors at Fermilab[5].

PROfit

- PROfit builds on important features from previous fitters developed for MicroBooNE/ ICARUS[6]. Redesigned to optimize for specific needs of SBN:
  - Ability to compute predictions event-by-event for various oscillation scenarios, detectors, beams, and many systematic parameters efficiently.
  - Fitting infrastructure that natively supports parallel computing and HPC.
  - Flexibility in treatment of systematics to allow both covariance and pull terms.

Combined Pull Term + Covariance Matrix Systematics

$$\chi^2\left(\Delta m^2, \theta : \delta_1 .. \delta_{N_{pull}}\right) = \left(d - p\left(\Delta m^2, \theta, \delta_i\right)\right) M^{-1}\left(d - p\left(\Delta m^2, \theta, \delta_i\right)\right)^T + \sum_{N_{pull}} \left(\delta_i/\sigma_i\right)^2$$

Correlating Detector Systematics

- Detector systematics need to be constrained to few % level for oscillation searches. Total **uncertainty can be reduced if correlated detector uncertainties are constrained.**
- Uncertainties in argon microphysics will be highly correlated between the two detectors.

Test

1) Vary electron recombination model parameters, α and β, by 3σ according to the **modified box model.**

2) Apply a ν_μ**CC inclusive event selection** in ICARUS and SBND.

3) Examine **reconstructed neutrino energy** spectra & study **correlations.**

$$\frac{dE}{dx} = \frac{e^{\beta W_{ion} \times \frac{dQ}{dx}} - \alpha}{\beta}$$

Modified Box Model formula: Equation that describes the relationship between observed charge (dQ/dx) and expected energy deposit (dE/dx). Measured parameters are α and β.

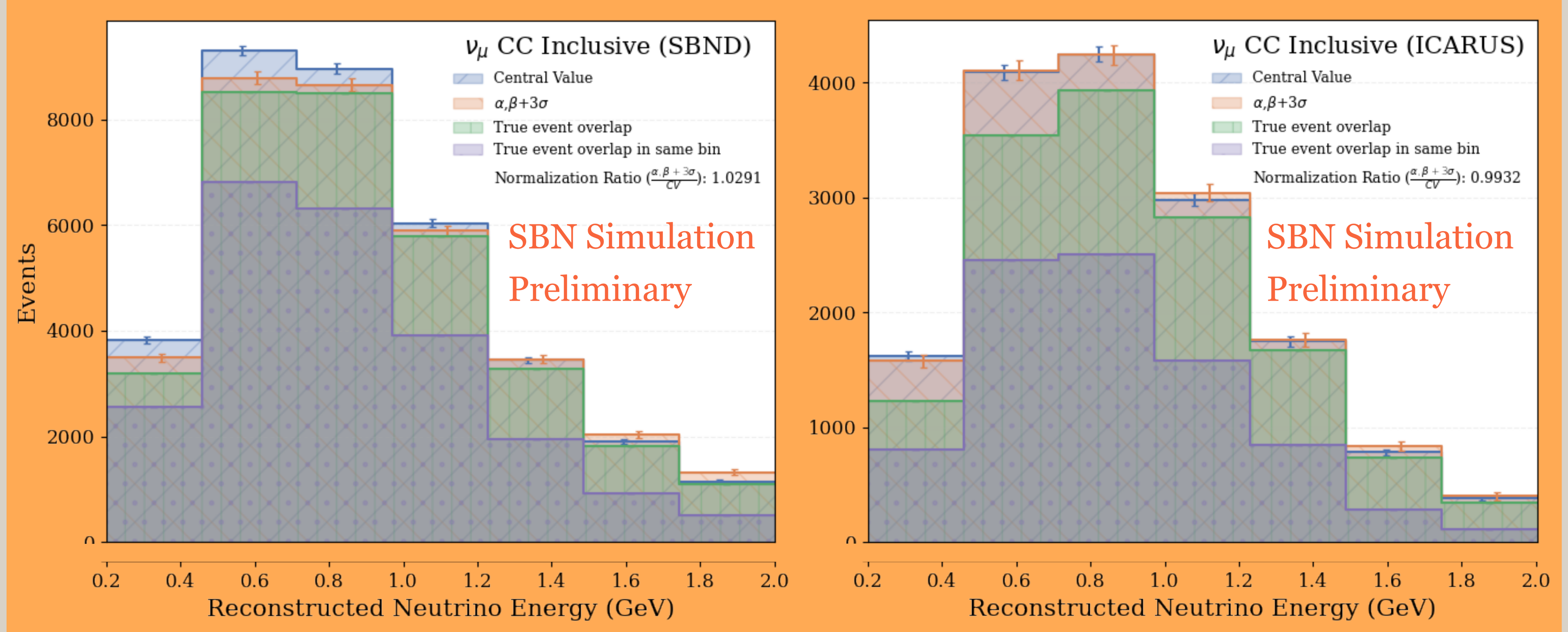


Fig 3: Neutrino energy distributions for SBND (left) and ICARUS (right) for the central value (CV) and α,β +3σ recombination parameters in blue and orange, respectively. The green bars represent the identical truth events that passed the selection in both cases and the purple bars are the identical events that fall in the same bin.

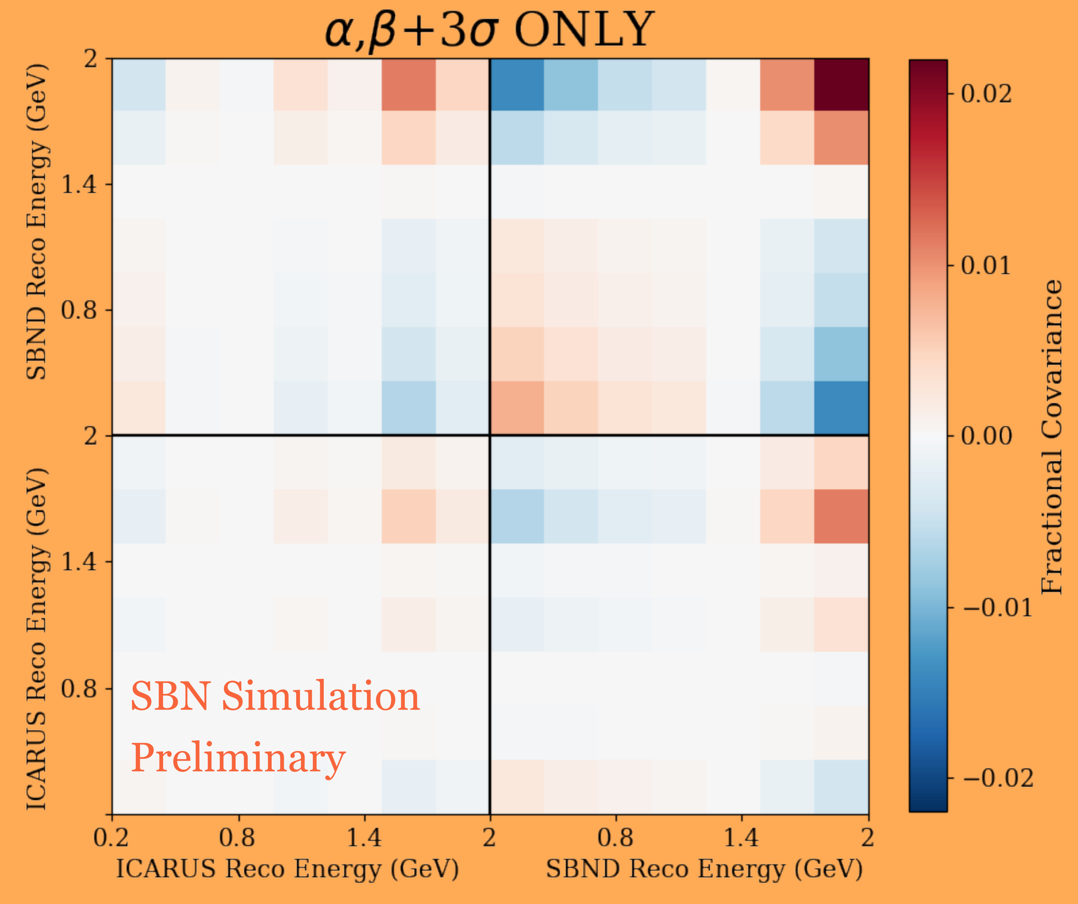


Fig. 4: Fractional covariance matrix for SBND and ICARUS reconstructed neutrino energy.

- The varied distributions skew to higher reconstructed E_ν for both SBND and ICARUS, suggesting some level of systematic correlation. **Correlations can be used to constrain this systematic effect.**
- In SBND, adjusting the recombination higher uncovered a reconstruction pathology, leading to broken tracks being reconstructed as distinct particles, driving reconstructed energy up.
- Results shown here are specific to α,β +3σ recombination variation only. Final correlation studies will explore the entire space of variations.

[1] Diaz, Argúelles, Collin et al. "Where are we with Sterile Neutrinos?" *Phys. Rept. 884 (2020) 1-59* DOI: 10.1016/j.physrep.2020.08.005

[2] MicroBooNE and SBND and ICARUS Collaborations R. Acciarri et al. "A proposal for a three detector short-baseline neutrino oscillation program" e-Print: *1503.01520*

[3] O.L.G. Peres, A.Yu. Smirnov "Testing the solar neutrino conversion with atmospheric neutrinos" Phys.Lett.B 456 (1999) 204-213

[4] MICROBOONE-NOTE-1132-PUB, The MicroBooNE Collaboration, "Search for a Sterile Neutrino in a 3+1 Framework"

[5] MICROBOONE-NOTE-1129-PUB, The MicroBooNE Collaboration, "Updates to the NuMI Flux Simulation"

[6] Cianci, Furmanski, Karagiorgi et al. "Prospects of Light Sterile Neutrino Oscillation and CP Violation Searches at the Fermilab Short Baseline Neutrino Facility" *DOI: 10.1103/PhysRevD.96.055001*