Sterile Neutrino Oscillation Searches using VALOR at SBN

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New Perspectives

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Overview

- Sterile Neutrinos
- The SBN Programme
- What is VALOR
- Current Sensitivities
- SBND-PRISM

Sterile Neutrinos

- Limit of 3 active flavours from the Z-boson resonance width and cosmological data
  - 4th active flavour ruled out at a 98% confidence level by ALEPH in 1989 [1]
  - Cosmological limits give $N_{eff}=3.32 \pm 0.27$ (68% CL)[2]
- Well motivated, could be a consequence of neutrino mass
- Experimental anomalies may hint at a fourth neutrino
  - Reactor: deficit of anti-ν_e flux at short baseline
  - Gallium: deficit of ν_e flux from Ar-37 and Cr-51 electron capture decays.
  - Accelerator (LSND and MiniBooNE): excess of ν_e flux from $\nu_\mu \rightarrow \nu_e$
- Tensions between these results and disappearance analyses [3]
- 3 active + 1 sterile is benchmark hypothesis (excluded to high significance)
- Test existence via mixing with active flavours

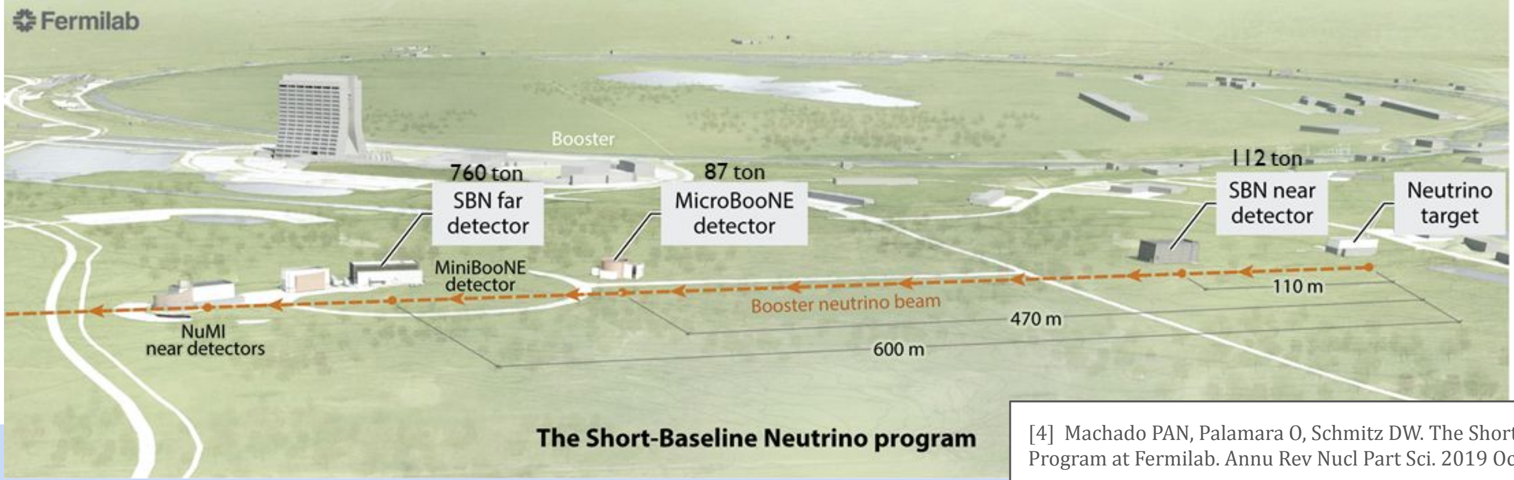
[1] ALEPH, D. Decamp et al., Determination of the Number of Light Neutrino Species, Phys. Lett. B 231, 519 (1989)

[2]On the behalf of the Planck Collaboration. Cosmological constraints on neutrinos with Planck data. In Boston, Massachusetts, USA; 2015 p. 140001.

[3]Dasgupta B, Kopp J. Sterile Neutrinos. Physics Reports. 2021 Sep;928:1–63.

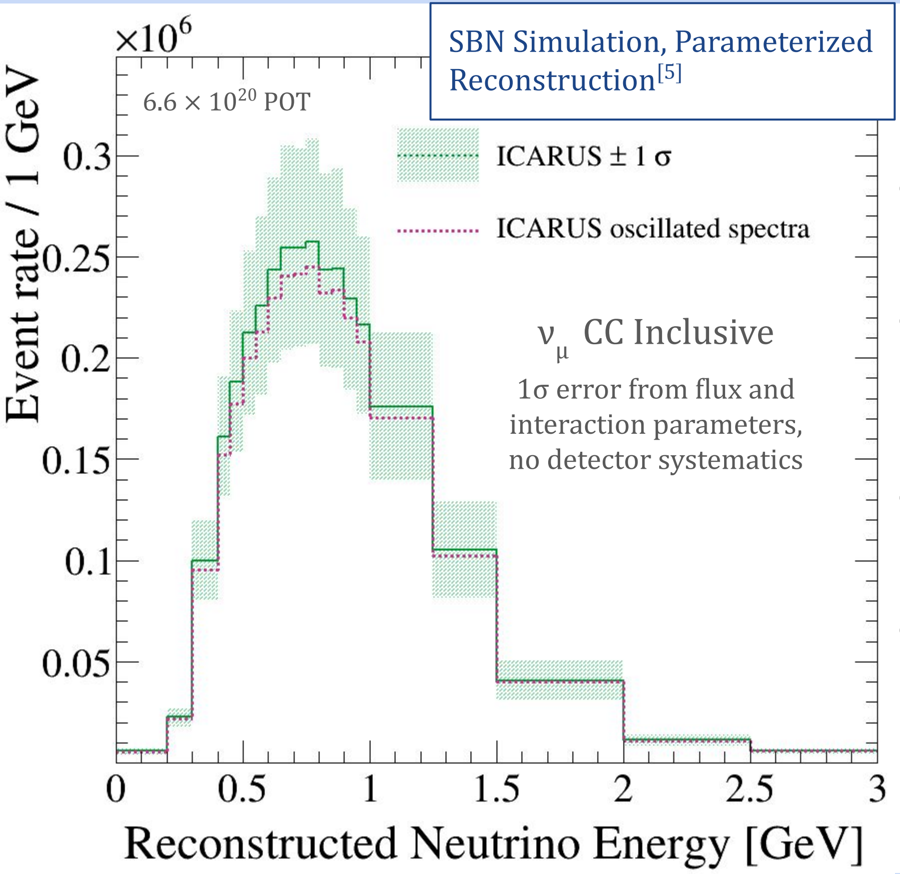
Short Baseline Neutrino (SBN) Programme

- 3 liquid argon TPC detectors along the Booster neutrino beam
  - Similar technology and same beam allows for systematic constraints
- Physics aims:
  - Simultaneous measurements of ν_μ disappearance and ν_e (dis)appearance to search for sterile neutrino oscillations: $\Delta m^2_{41} \sim 1 eV^2$
  - Studying neutrino-argon interactions
  - BSM searches [4]



[4] Machado PAN, Palamara O, Schmitz DW. The Short-Baseline Neutrino Program at Fermilab. Annu Rev Nucl Part Sci. 2019 Oct 19;69(1):363–87.

Role of SBND in the SBN Programme



- SBN will definitively test the parameter space favoured by previous measurements
- Our predictions have uncertainties ~30%
  - Too large to search for new physics
  - Need to reduce to ~1%
- The role of SBND reduces uncertainty to enable new physics searches
- Will need powerful analysis framework to fully exploit the power of SBND samples

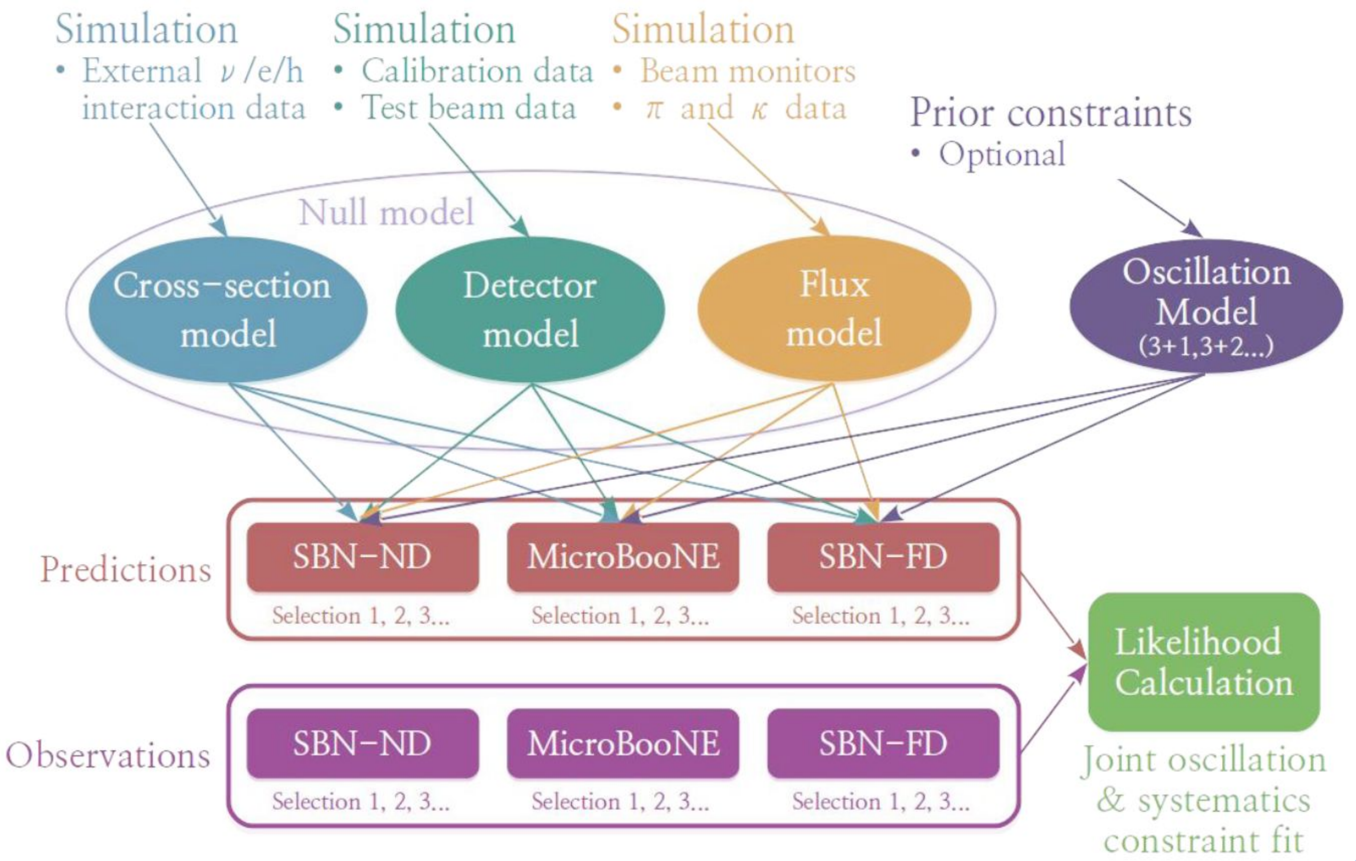
[5] Acciarri R, et al. A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam arXiv; 2015

VALOR

- Well established and tested neutrino fitting framework [6]
- Developed within T2K and used for many published results
- Can perform standalone (single oscillation channel) or joint multi-channel analyses
- VALOR can fit multiple different inclusive or exclusive samples for all detectors
  - Complementary information from different samples helps solve the degeneracies between systematic effects and/or new physics
- VALOR simultaneously fits for oscillation and systematic parameters
  - Provides explicit constraints on systematics

[6] VALOR Neutrino Fit [Internet]. hep.ph.liv.ac.uk. Available from: https://hep.ph.liv.ac.uk/~costasa/valor/

VALOR: Analysis Strategy



- The analysis strategy uses indirect extrapolation
- Event rate model is a convolution of flux, xsec, and detector models
- Explicit systematic constraints

Event Rate Prediction

Event rate prediction | True integral | Systematic response | POT scale factor

$$n^{pred}_{b;d;s}(r;\vec{\theta};\vec{f}) = \sum_{m}\sum_{t} P_{b;d;m}(t;\vec{\theta}) \cdot R_{b;d;s;m}(r,t;\vec{f}) \cdot T_{b;d;s;m}(r,t) \cdot N^{MC}$$

Oscillation probability, *Effective sterile hypothesis* | Event rate template

Physics parameter set ($\vec{\theta}$)

Systematic parameter set ($\vec{f}$)

b: beam
d: detector
s: sample
m: mode

Systematics within VALOR

- Main power of VALOR is to obtain explicit systematic constraints postfit

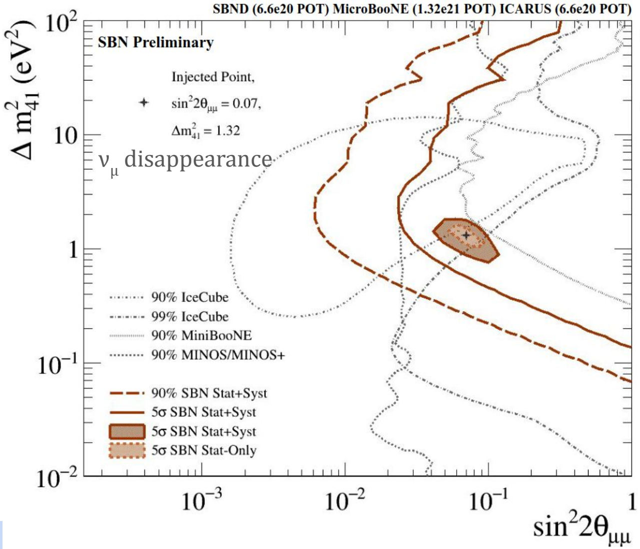
$$n^{pred}_{b;d;s}(r;\vec{\theta};\vec{f}) = \sum_m \sum_t P_{b;d;m}(t;\vec{\theta}) \cdot \boxed{R_{b;d;s;m}(r,t;\vec{f})} \cdot T_{b;d;s;m}(r,t) \cdot N^{MC}$$

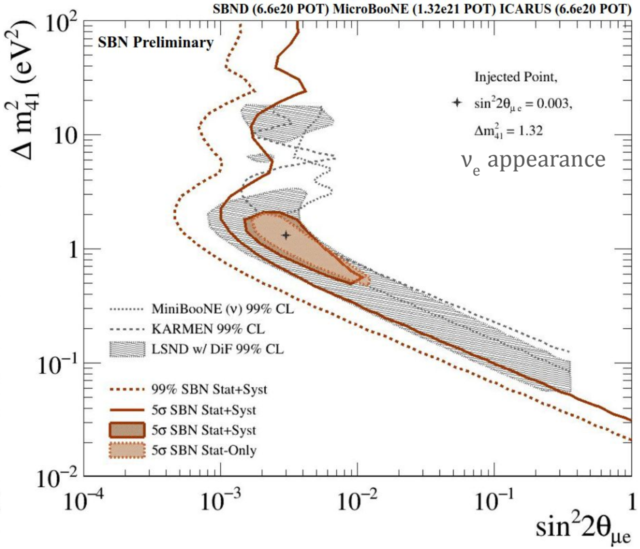
b: beam
d: detector
s: sample
m: mode

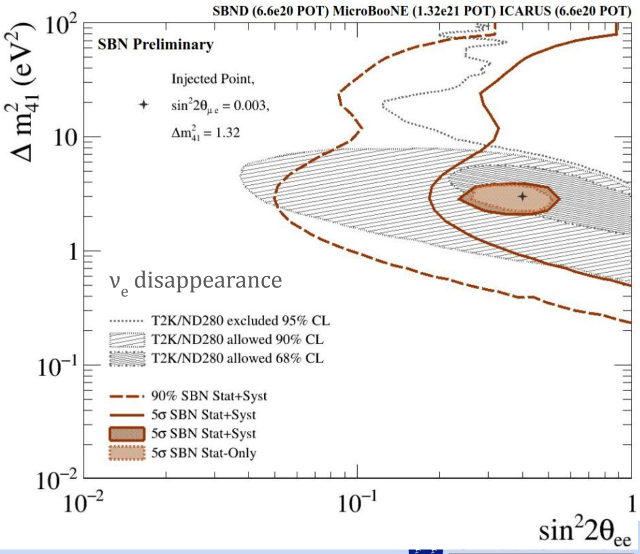
- VALOR has high granularity in parameterising systematic effects
- Systematic parameters are currently eliminated via profiling
  - Option to use marginalisation (used in VALOR-T2K analysis)

Preliminary Sensitivities

- VALOR has been used within SBN for several years
  - Implemented several oscillation sensitivity analyses
  - Below are the standard sensitivities for the 3 standalone channels
    - Using inclusive samples and pseudo-reconstruction
- Effort is underway to build more sensitive analysis using exclusive samples and exploiting the PRISM effect

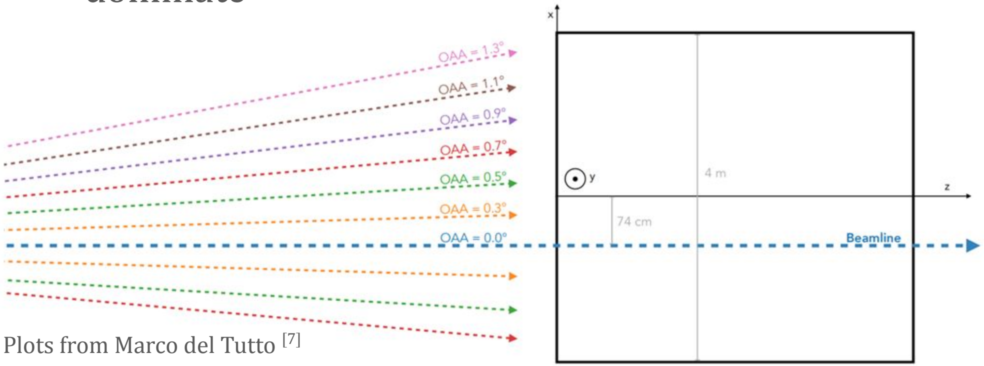




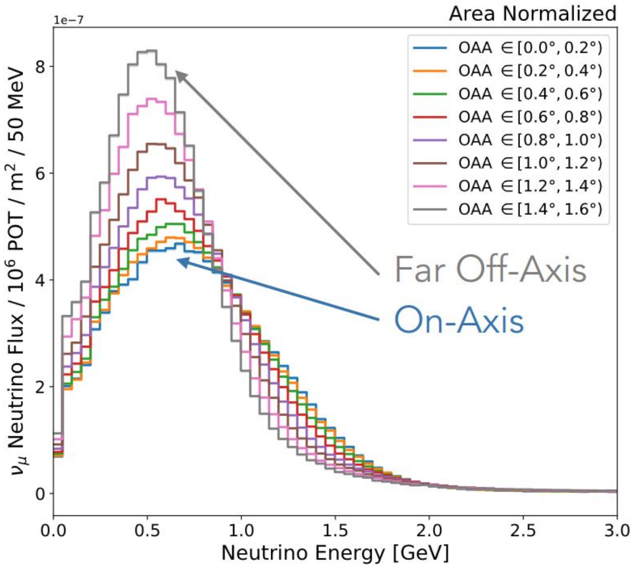


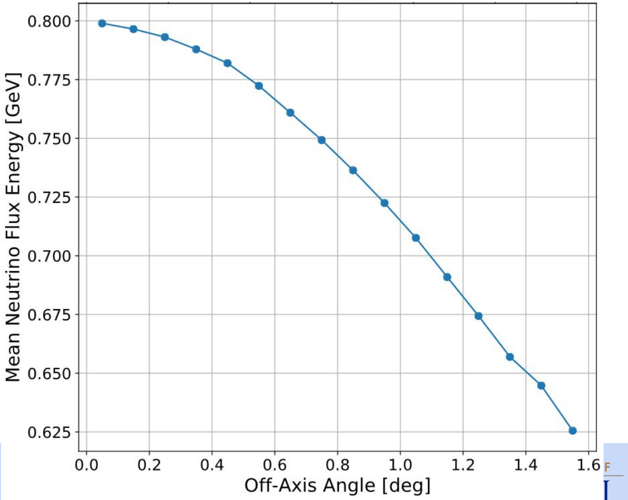
SBND-PRISM

- Takes measurements at different off-axis locations
  - Different energy spectra/composition
- Joint fit of all off-axis samples
  - Improved systematic constraints/degeneracy resolution
  - Enhanced oscillation sensitivity
- SBND split into 8 bins for illustration
  - The statistics in each bin are still large so the systematics dominate



Plots from Marco del Tutto [7]





Summary

- SBN programme should improve understanding of sterile hypothesis
- SBND will have excellent statistics as the event rate is high
  - Used to constrain systematic uncertainties
- The use of SBND-PRISM should improve systematic constraints for the whole programme
  - This has been implemented for all 3 oscillation channels and is currently being validated
    - Results are encouraging
  - Work ongoing to find optimal number of off-axis bins and understand improvements to sensitivities
- Many other lines of work within VALOR to incorporate exclusive samples and evaluate uncertainties and biases within mock data

Backup

References:

1. ALEPH, D. Decamp et al., Determination of the Number of Light Neutrino Species, Phys. Lett. B 231, 519 (1989)
2. On the behalf of the Planck Collaboration. Cosmological constraints on neutrinos with Planck data. In Boston, Massachusetts, USA; 2015 [cited 2023 Jun 22]. p. 140001. Available from: https://pubs.aip.org/aip/acp/article/907472
3. Dasgupta B, Kopp J. Sterile Neutrinos. Physics Reports. 2021 Sep;928:1–63.
4. Machado PAN, Palamara O, Schmitz DW. The Short-Baseline Neutrino Program at Fermilab. Annu Rev Nucl Part Sci. 2019 Oct 19;69(1):363–87.
5. Acciarri R, Adams C, An R, Andreopoulos C, Ankowski AM, Antonello M, et al. A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam [Internet]. arXiv; 2015 [cited 2023 Jun 23]. Available from: http://arxiv.org/abs/1503.01520
6. VALOR Neutrino Fit [Internet]. hep.ph.liv.ac.uk. [cited 2023 Jun 22]. Available from: https://hep.ph.liv.ac.uk/~costasa/valor/
7. Del Tutto M, Machado P, Kelly K, Harnik R. SBND-PRISM: Sampling Multiple Off-Axis Fluxes with the Same Detector. In: SBND-PRISM: Sampling Multiple Off-Axis Fluxes with the Same Detector [Internet]. US DOE; 2021 [cited 2023 Jun 22]. Available from: https://www.osti.gov/servlets/purl/1827399/

Likelihood Calculation

Contribution to the likelihood ratio from SBN simulation and data

$$\chi_0^2 = -2\ln \mathscr{L}_0(\vec{\theta};\vec{f}) = 2\sum_{b,d,s,r}\left(n^{data}_{b;d;s}(r)\cdot \ln\frac{n^{data}_{b;d;s}(r)}{n^{pred}_{b;d;s}(r;\vec{\theta};\vec{f})} + \left(n^{pred}_{b;d;s}(r;\vec{\theta};\vec{f}) - n^{data}_{b;d;s}(r)\right)\right)$$

$$\chi^2 = -2\ln \mathscr{L}(\vec{\theta};\vec{f}) = -2\ln \mathscr{L}_0(\vec{\theta};\vec{f}) - 2\ln \mathscr{L}_{phys}(\vec{\theta}) - 2\ln \mathscr{L}_{syst}(\vec{f})$$

Penalty term due to prior physics constraints

$$\chi^2_{phys} = -2\ln \mathscr{L}_{phys}(\vec{\theta}) = 0$$

Penalty term due to prior systematic constraints

$$\chi^2_{syst} = -2\ln \mathscr{L}_{syst}(\vec{f}) = (\vec{f}-\vec{f}_0)^T \cdot \mathbf{V}^{-1} \cdot (\vec{f}-\vec{f}_0)$$

SBND-PRISM: Flux

- Muon neutrino flux decreases moving off axis
- Electron neutrino flux remains almost constant