STERILE NEUTRINO SEARCH AT THE FERMILAB SHORT BASELINE NEUTRINO (SBN) PROGRAMME

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Assembly tent with TPC inside *Cathode and Field Cage* *Membrane Cryostat installation in progress*

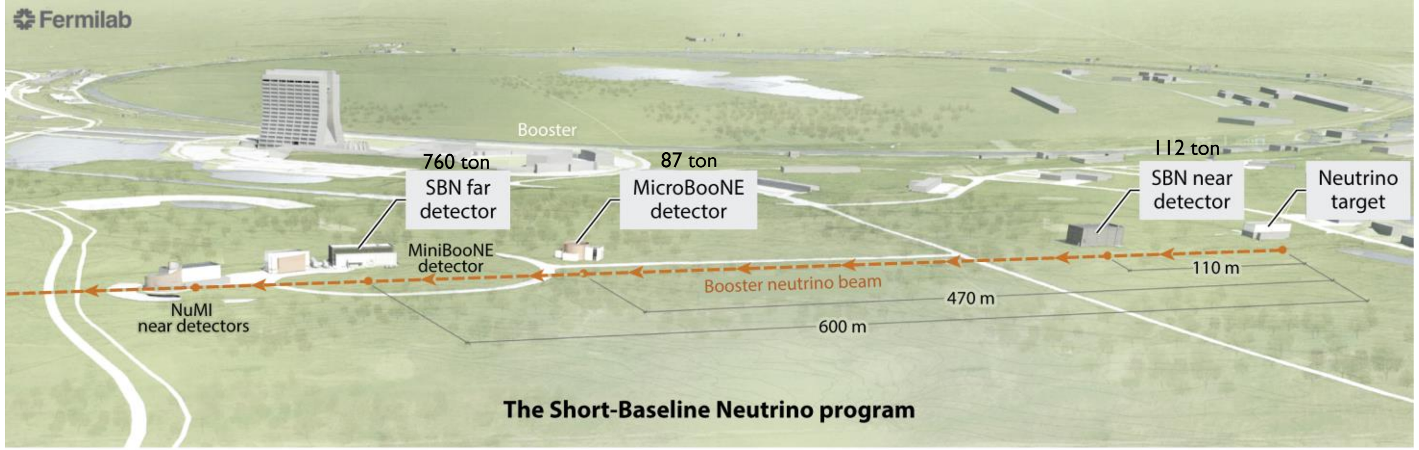
Construction of SBND [1]

STERILE NEUTRINOS

- Limit of 3 active flavours of neutrinos
  - Z boson resonance width
- Experimental anomalies may hint at a fourth neutrino
  - Reactor: deficit of $\bar{\nu}$ 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 $\nu_\mu \rightarrow \nu_e$
  - 3 active + 1 sterile is common hypothesis
- Test existence via mixing with active flavours

SHORT BASELINE NEUTRINO (SBN) PROGRAMME

- 3 LArTPC detectors along the neutrino beam
  - SBND, MicroBooNE, and ICARUS
- Physics aims:
  - Searching for sterile neutrinos
    - Sensitive to oscillations with $\Delta m_{41}^2 \simeq \mathcal{O}(1\ eV^2)$
    - ν_μ disappearance, ν_e appearance and disappearance
  - Studying neutrino-argon interactions
  - Searching for new physics
- SBND
  - Measure about 2 million CC neutrino-Argon interactions each year
  - Greater statistics than have previously been possible
  - Closest so probes higher Δm^2



Machado PAN, et al. 2019.
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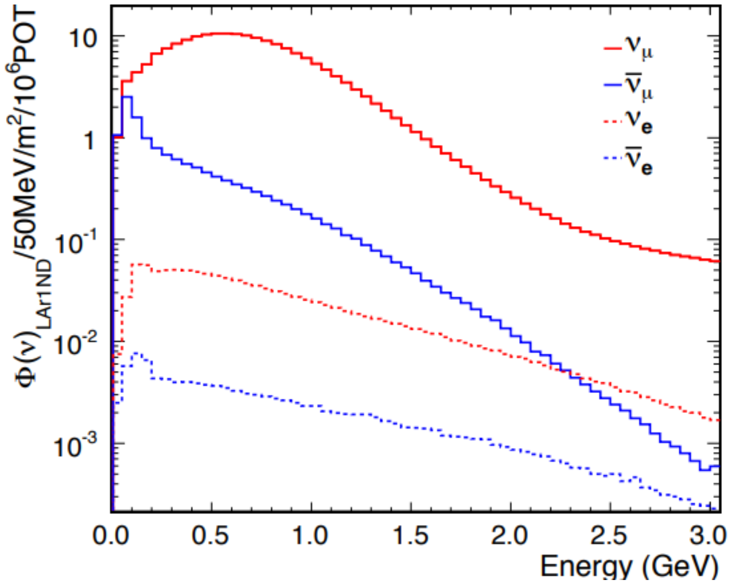
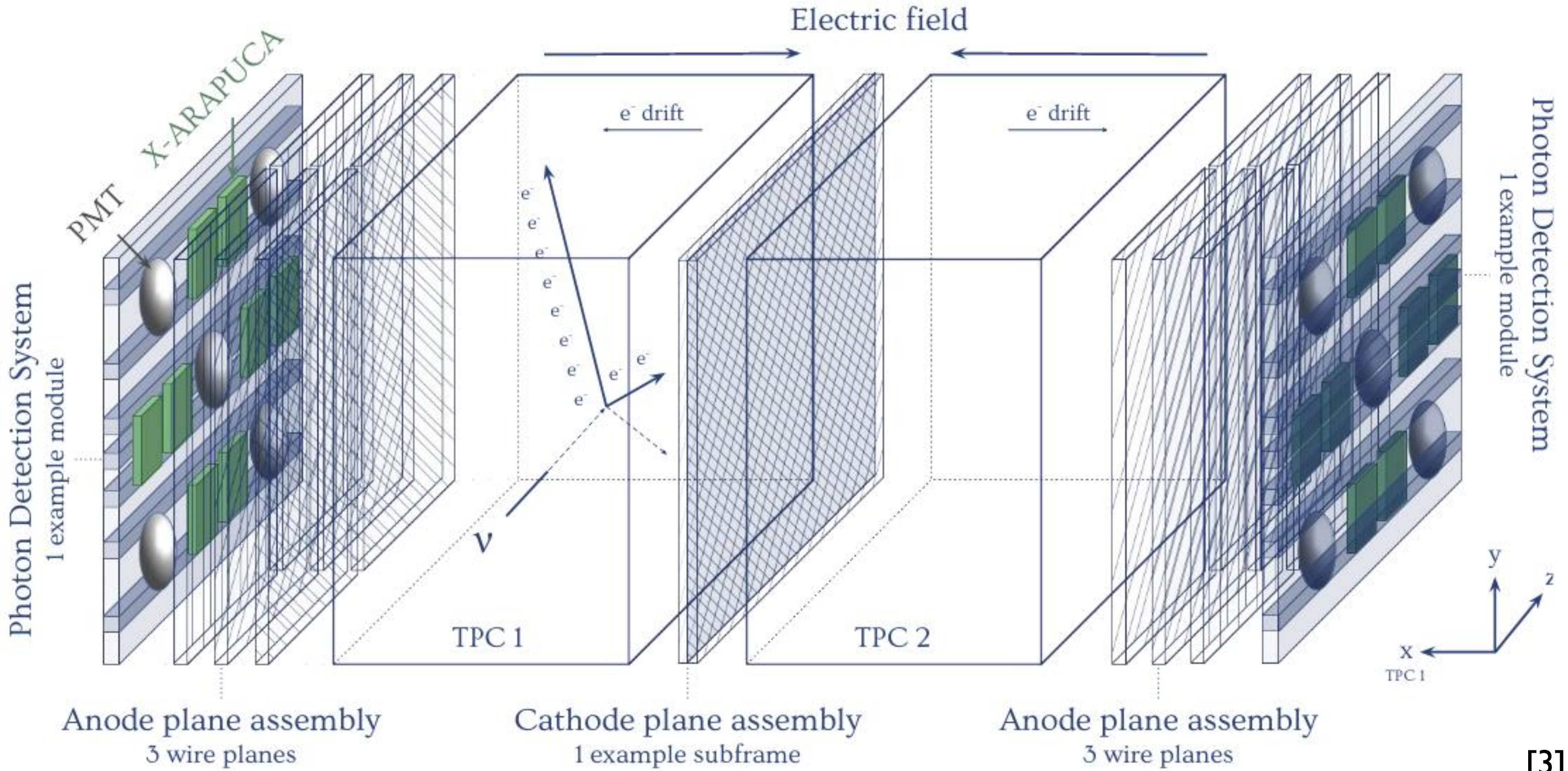


[2]

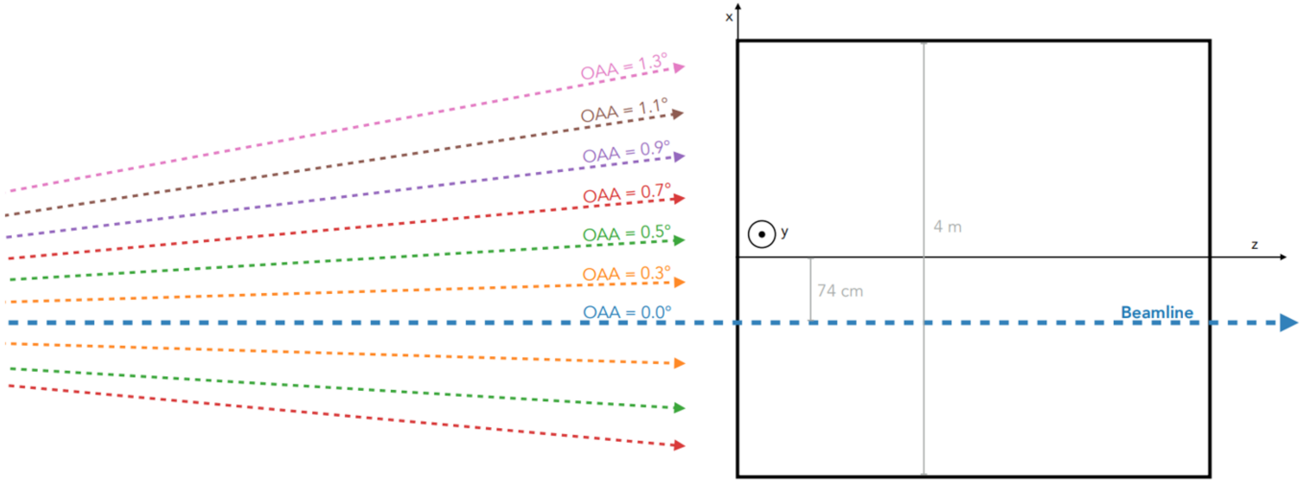
SBND: SET UP

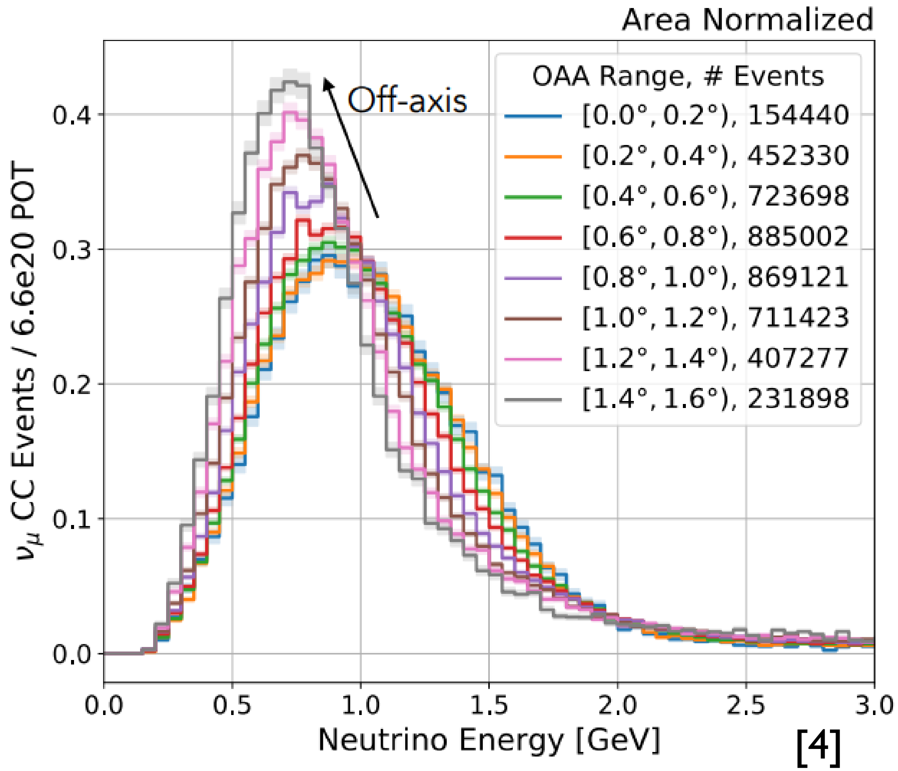

Electric field
e- drift
e- drift
X-ARAPUCA
PMT
Photon Detection System
1 example module
Photon Detection System
1 example module
ν
TPC 1
TPC 2
y
z
x
TPC 1
Anode plane assembly
3 wire planes
Cathode plane assembly
1 example subframe
Anode plane assembly
3 wire planes

[3]

PRISM

- Takes measurements at different locations within the detector
- Different ν_μ samples have different energy spectra
  - ν_μ produced by pions, if similar angle to beam then they are boosted
  - ν_e produced by kaons, heavier (lower energy) so effect of boost is diminished
- Use different samples to constrain oscillation
- SBND (110m baseline) split into 8 bins (8 samples)
  - The statistics in each bin are large so the systematics dominate

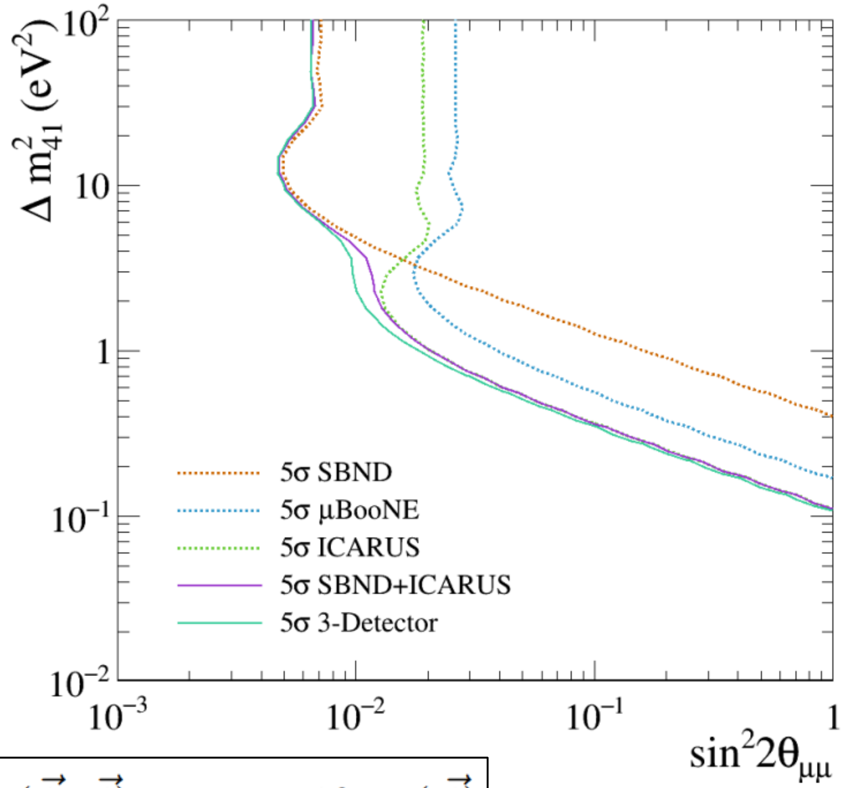




[4]

FITTING PROCEDURE WITHIN SBN USING VALOR

- Fit inclusive ν_μ CC inclusive events
- Template fit using 3+1 hypothesis
- Try to fit prediction with oscillation to data without
- χ_0^2 calculated at every grid point
- Float any included systematics within ±5σ of their limits
  - Flux: 13
  - Interaction: 40
- Apply profiling and minimise the binned-likelihood (χ^2)



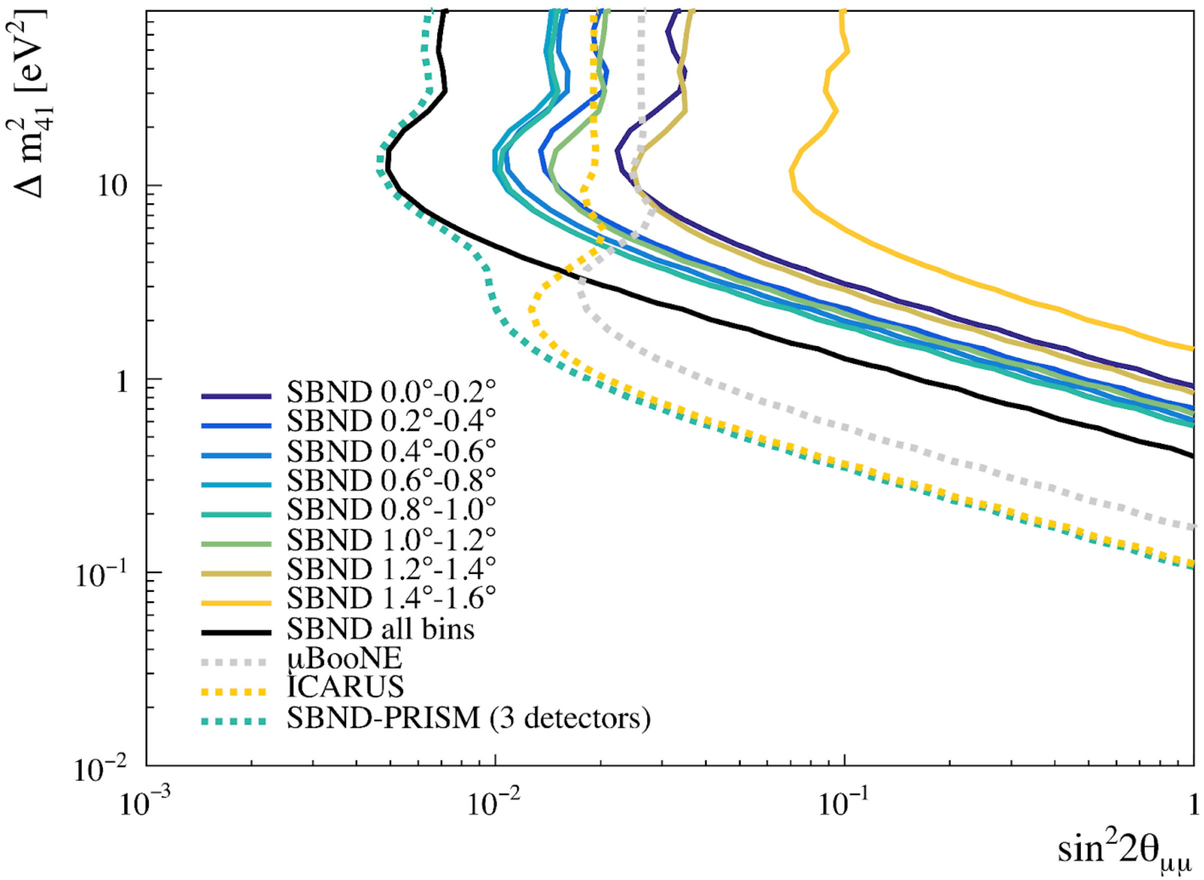
[3]

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

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

SENSITIVITY STUDY: ν_μ DISAPPEARANCE STATISTICS ONLY CHECK

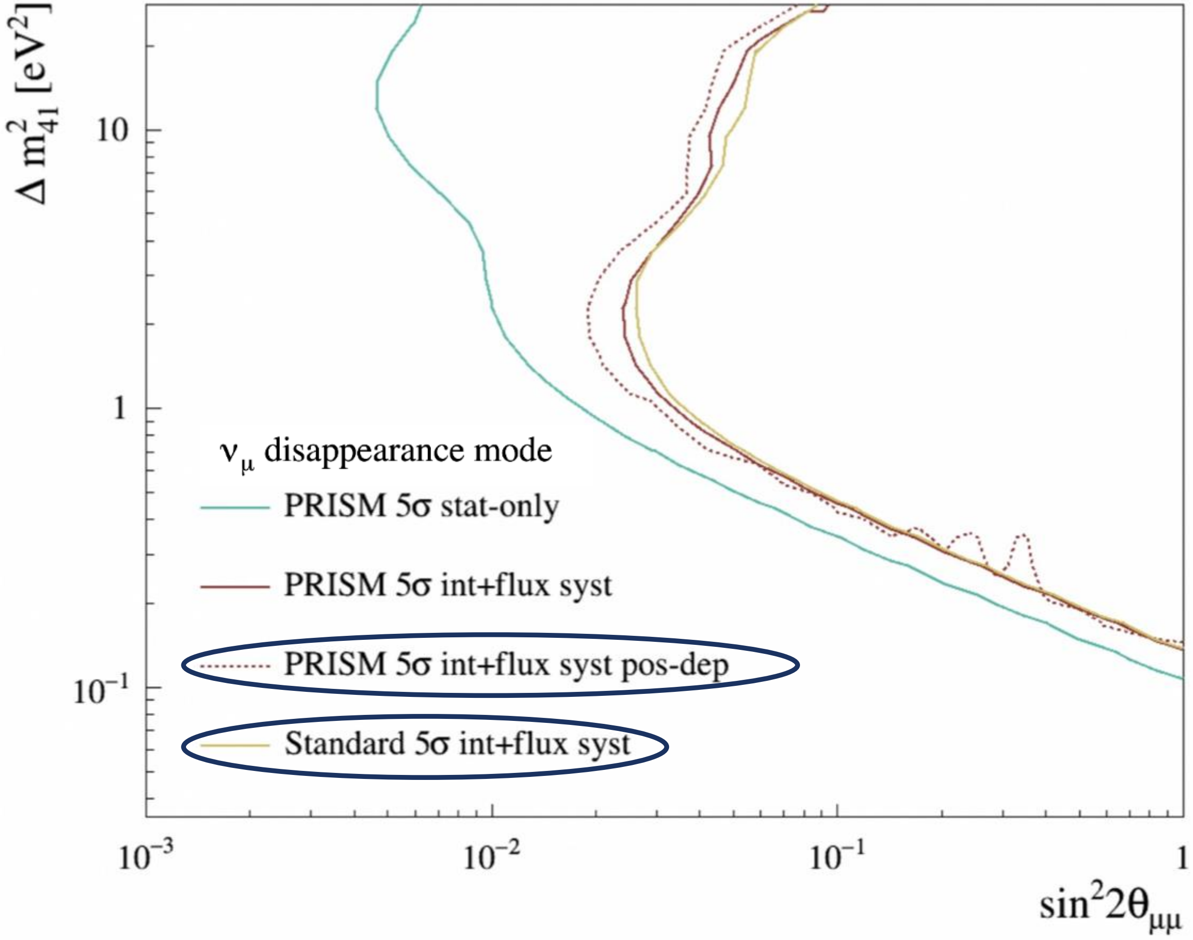
- No systematics included
- Same sensitivity as standard analysis (as expected)
- Can split into contributions from each OA bin
- Shows predicted behaviours
  - Increase in sensitivity when more events
  - Decrease in flux away from beamline
  - Increase in mass results in more events



[5]

SENSITIVITY STUDY: ν_μ DISAPPEARANCE WITH SYSTEMATICS

- Perform disappearance analysis 8 times jointly with different energy
- Worsening due to inclusion of systematics
- Worsening lesser when using position dependent systematics
- See improvement compared to standard
- Increase number of observables within the fit
- As the energy is different the observables are not the same in each sample



[5]

FURTHER WORK

- Validation procedures
  - Plotting the post-fit systematic parameters
  - Showing parameters in different OA slices
  - Mock data studies
- Expand to other oscillation channels:
  - ν_e appearance and disappearance
- LTA
  - March-November 2022
  - June-September 2023
- Thesis
  - Near detector treatment of constraints
  - First 3 months of data: ν_μ CC

ANY QUESTIONS?

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References
[1] Schukraft A. ICARUS + SBND Short Baseline Neutrino Program. NEUTRINO2022, Seoul; May 31, 2022.
[2] Acciarri R, Adams C, An R, et al. A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam. arXiv:150301520 [hep-ex, physics:physics]; 2015 Mar.
[3] Jones R. Muon-neutrino disappearance with multiple liquid argon time projection chambers in the Fermilab Booster neutrino beam. University of Liverpool; 2021.
[4] SBND Collaboration, Del Tutto M, et al.. SBND-PRISM: Sampling Multiple Off-Axis Neutrino Fluxes with the Same Detector. Conference Talk at APS April Meeting; 2021.
[5] Kroupova T. SBND PRISM Oscillations. SBND Collaboration Meeting; July 2021.

BACKUP

BACKUP: VALOR

- Uses predicted (MC) neutrino interaction event rates as the main input
- GENIE is used to generate the neutrino interaction events
- Can perform exclusion or allowed sensitivity studies
- Fits performed by comparing MC predictions with oscillations sets of data without oscillation using a binned-likelihood method
- The sensitivity curves in the 2D parameter space are lines of constant $\chi^2_{critical}$

Procedure

- χ^2 is comprised of contribution from the experiment's own data and penalty terms
- Split phase space into a 40 × 40 grid, logarithmically spaced
- Perform fit with oscillation parameters at each grid point
- Float any included systematics within ±5σ of their limits (initially global best-fit)
- Apply profiling and minimise the binned-likelihood
- Extract the χ^2 of the fit at every point in the parameter space

BACKUP:VALOR

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

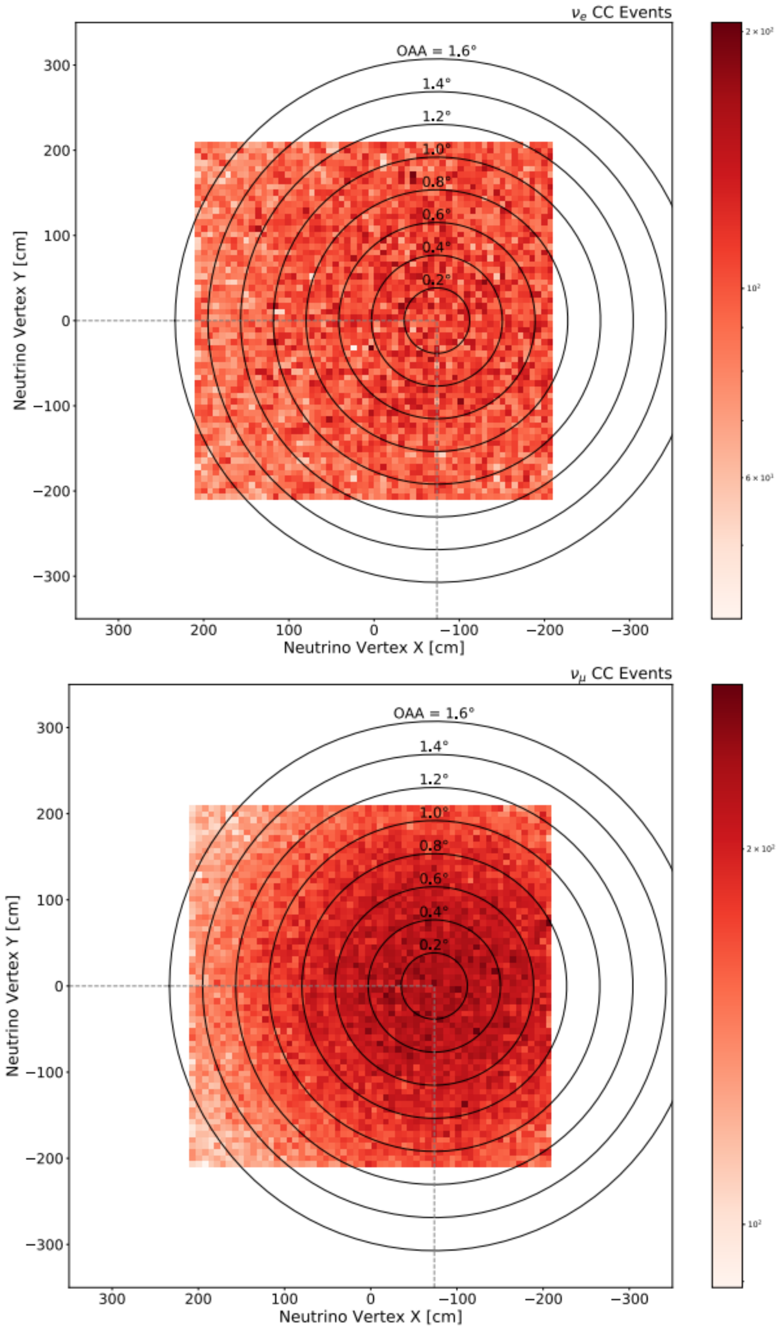
$$\chi_0^2 = -2\ln\mathscr{L}_0(\vec{\theta};\vec{f}) = 2\sum_{b,d,s,r}\left(n_{b;d;s}^{data}(r)\cdot\ln\frac{n_{b;d;s}^{data}(r)}{n_{b;d;s}^{pred}(r;\vec{\theta};\vec{f})} + (n_{b;d;s}^{pred}(r;\vec{\theta};\vec{f}) - n_{b;d;s}^{data}(r))\right)$$

- χ_0^2 is calculated at each point in the oscillation parameter space
- χ_{phys}^2 is the physics penalty based on prior constraints on new physics parameters
- χ_{syst}^2 is the systematic penalty applied to profile out the systematics as they are floated in the fits ($\pm 5\sigma$)

- n^{data} dataset with no oscillations (exclusion sensitivity used best-fit values)
- n^{pred} MC prediction with oscillation parameters ($\vec{f}$) set to grid point values ($\vec{\theta}$)
  - Includes info on oscillation probability, systematic response, event rate template, and POT scale factor

BACKUP: PRISM

- Interaction Model
  - Energy dependence of the cross section
  - Nuclear effects at ~1GeV
  - ν_e/ν_μ cross section
    - Test lepton flavour universality
- Sterile Neutrino Oscillations
  - Improved sensitivity using position-dependant systematics
- BSM searches
  - New particles



BACKUP: PRISM

- Fitting 8 samples jointly, all with different energy
- With a single spectrum it is possible to get the prediction (osc) close to the data (no osc)
- With 8 spectra with different observables, the systematic variation will look different in each so can't get as close to data.
- Hence, it is more difficult for systematic effects to mask the oscillation signal to same degree in all bins