Sterile Neutrino Oscillation Searches using VALOR at SBND

Beth Slater

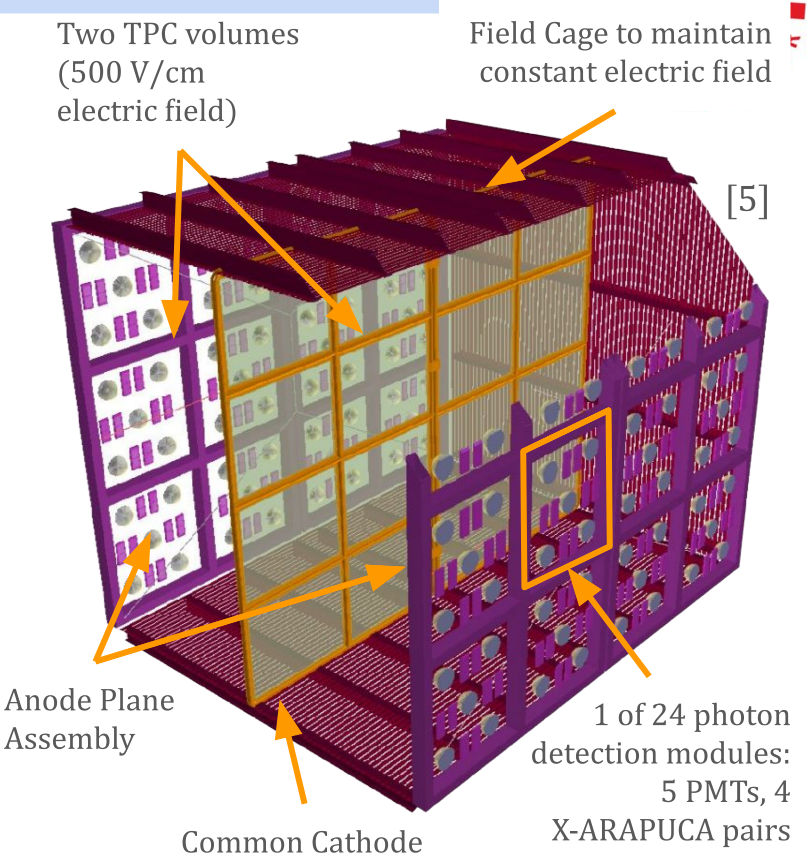
Liverpool HEP Annual Christmas Meeting 2024

Sterile Neutrinos

- Experimental anomalies may hint at a fourth neutrino
  - Gallium: deficit of ν_e flux from Ar-37 and Cr-51 electron capture decays.
  - Accelerator (LSND and MiniBooNE): excess of (anti-)ν_e flux from $\nu_\mu \rightarrow \nu_e$
- 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]
- Tensions between anomalous results and disappearance analyses [3]
- 3 active + 1 sterile is benchmark hypothesis
- Test existence via mixing with active flavours

Short Baseline Near Detector

- First of 3 LAr TPC detectors along the BNB
  - Short Baseline Neutrino (SBN) program
- Physics aims:
  - Search for sterile neutrino oscillations
  - Studying neutrino-argon interactions
  - Searching for new (neutrino) physics [4]
- SBND will measure about 2 million neutrino-argon interactions each year
  - Largest ever ν-Ar dataset
- SBND has recently completed the filling with LAr stage and is currently in the commissioning/calibrations stage.



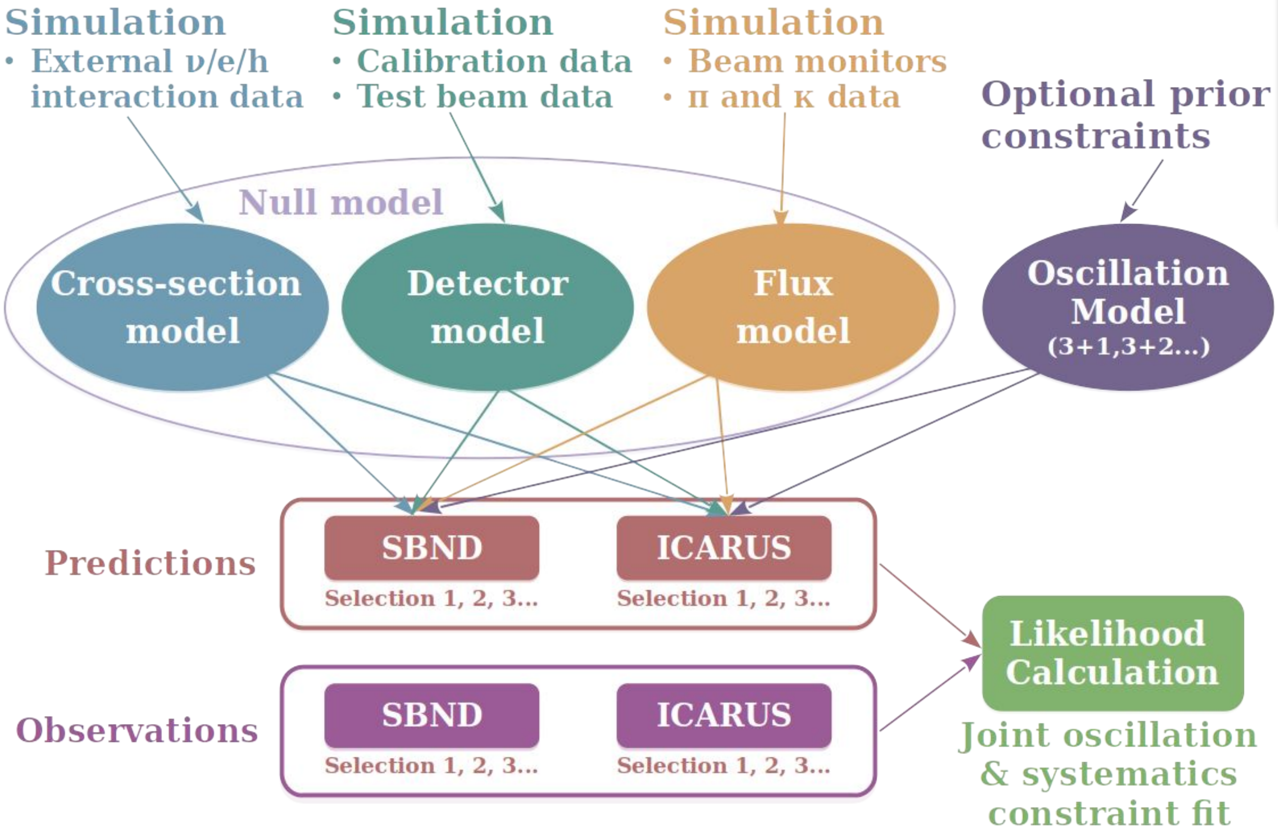
Role of SBND in the SBN Programme

- SBN will definitively test the parameter space favoured by previous measurements
- Our predictions have a-priori uncertainties ~30%
    - Too large to search for new physics
    - Need to reduce to ~1%
- The role of SBND is to reduce uncertainty to enable new physics searches
    - The detector will fully characterise the neutrino flux and neutrino-Argon cross-section
- Will need powerful analysis framework to fully exploit the power of SBND samples

VALOR

- Well established and tested neutrino fitting framework [6]
- Developed within T2K and used for many published results [7]
- Can perform single and multi-oscillation 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

VALOR: Global Analysis Strategy



Joint fits as systematics will impact each sample in a different way, increasing sensitivity to variations of those parameters

- Joint fits matching prediction to data
- Simulation data informs models
- Models used to generate predictions
- Obtain explicit systematic constraints

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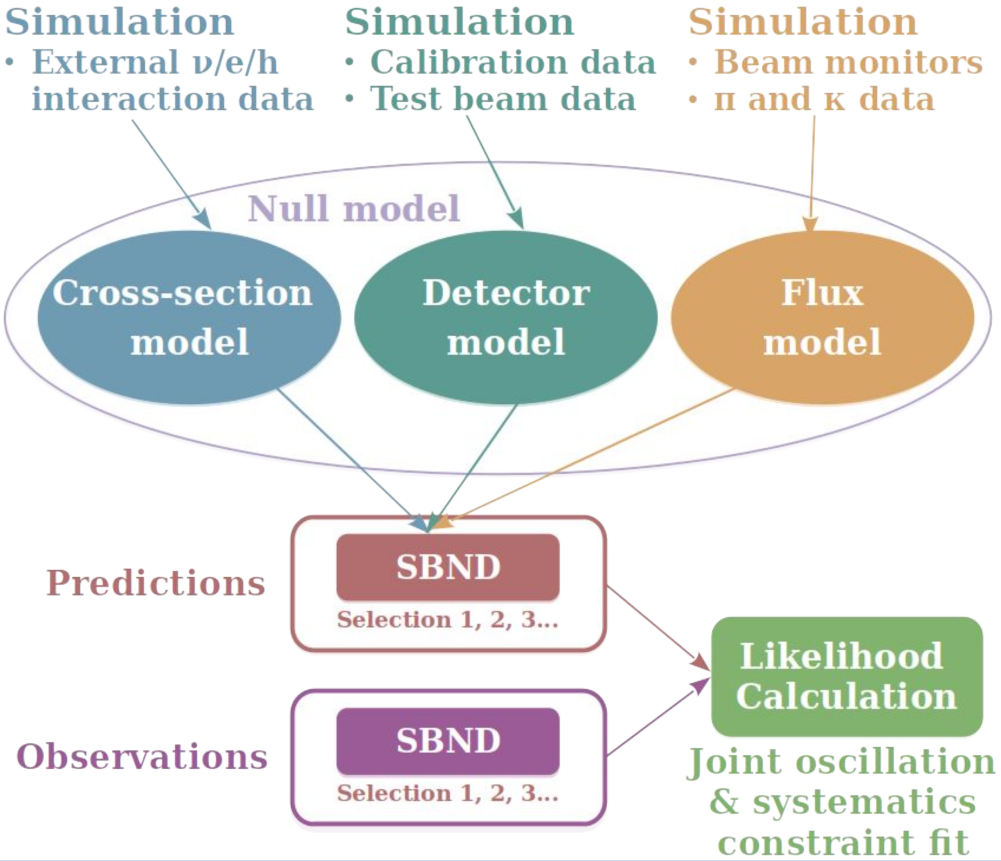
VALOR: Analysis Strategy



This presentation will focus on fits using only SBND assuming no oscillations

No far detectors are used, unless clearly stated

VALOR: Event Rate Prediction

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

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

Physics parameter set

Systematic parameter set

Oscillation probability,
Effective sterile hypothesis

Event rate template

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

VALOR: Systematic Parameters

$$R_{b;d;s;m}(r, t; \vec{f})$$

Uncorrelated Parameters:

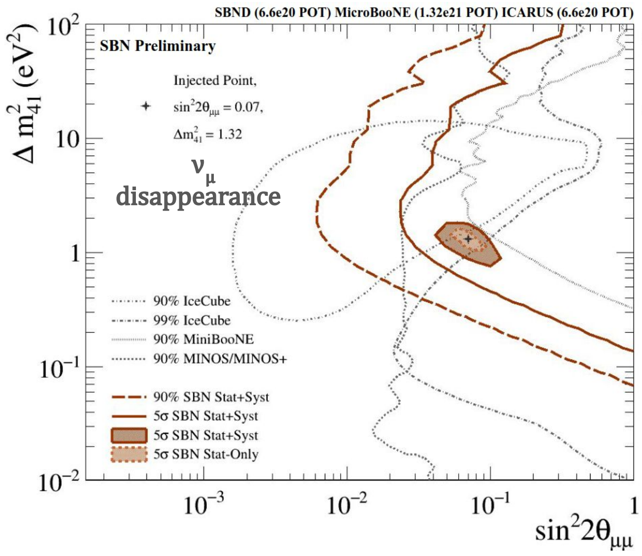
- We construct Response Functions (splines) to encapsulate the impact of nσ variations on every 2D template bin, interaction mode, and beam・detector・sample configuration
- Allows for mode-dependant variations and unique granularity
- Systematic parameters are currently eliminated via profiling
  - Option to use marginalisation

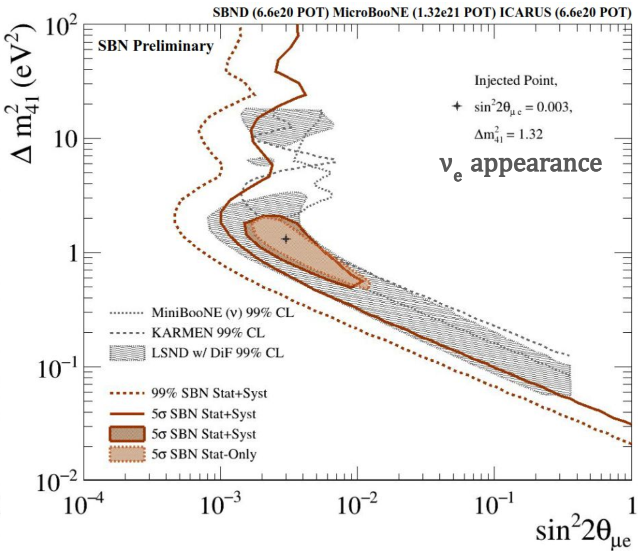
Correlated Parameters:

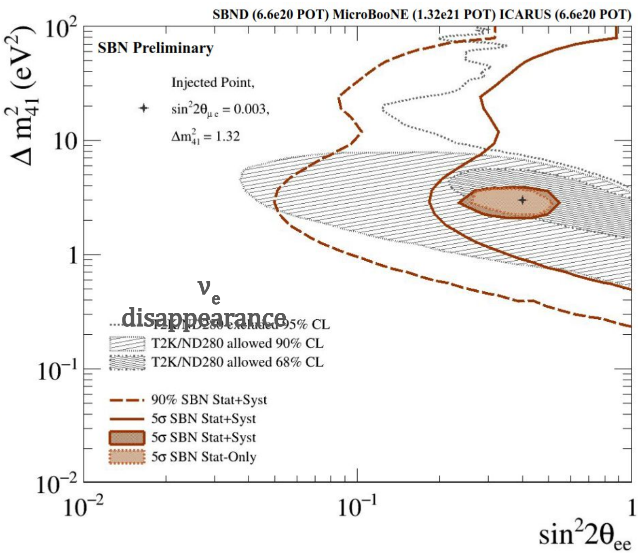
- We construct Covariance Matrices
- There is development to build multidimensional response functions

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





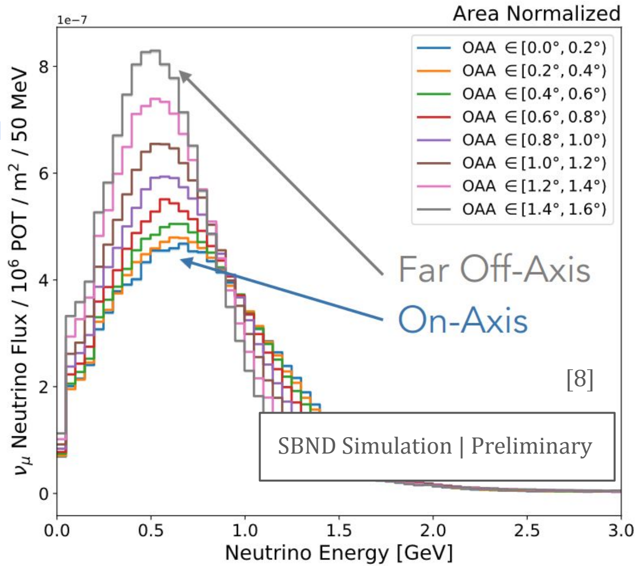


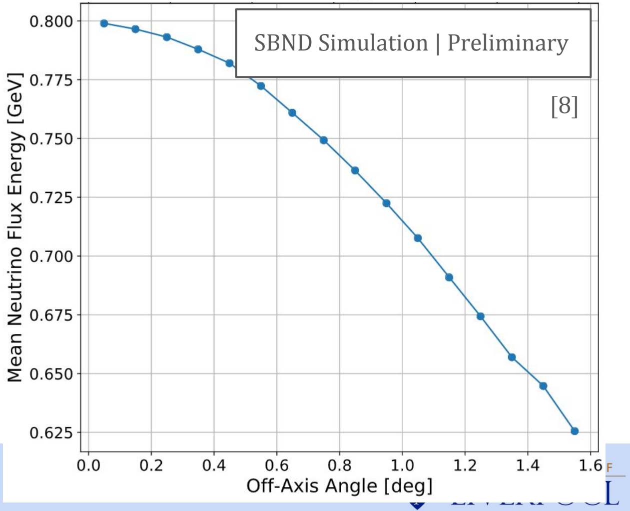
Strengths of using VALOR

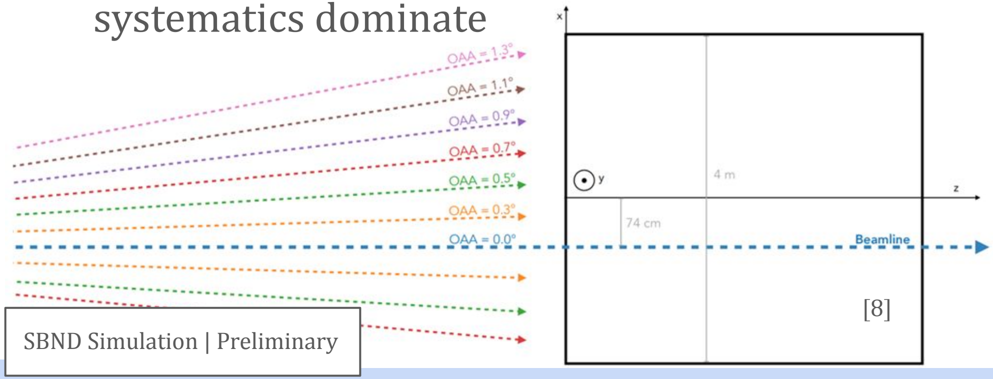
- VALOR oscillation fits obtains explicit post fit parameter pulls for every systematic parameter on every interaction mode
- We can therefore analyse fitting failure modes in great detail and use it to inform targeted modifications to the analysis procedure
    - Improve interaction systematic constraints→ Fit combinations of exclusive and semi-exclusive topologies
    - Improve flux systematic constraints → Fit combinations of off-axis bins (PRISM)

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 angular bins for illustration
  - The statistics in each bin are still large so the systematics dominate

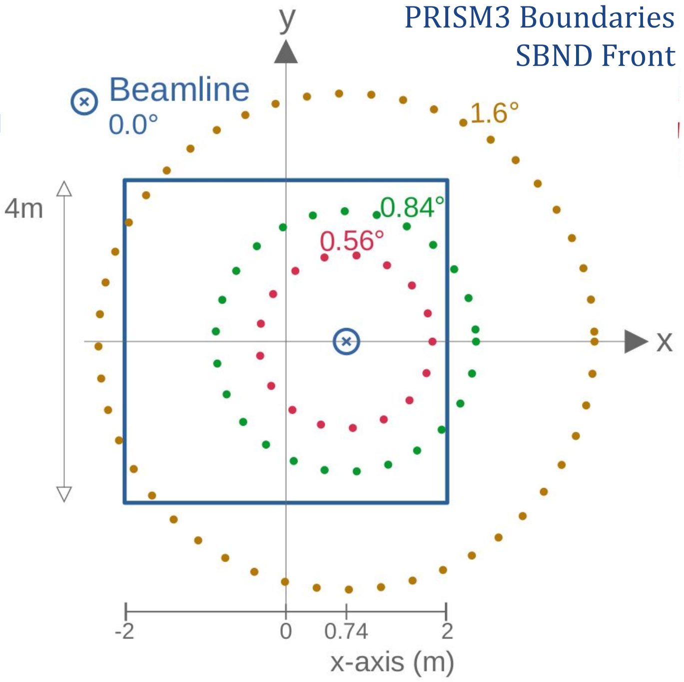






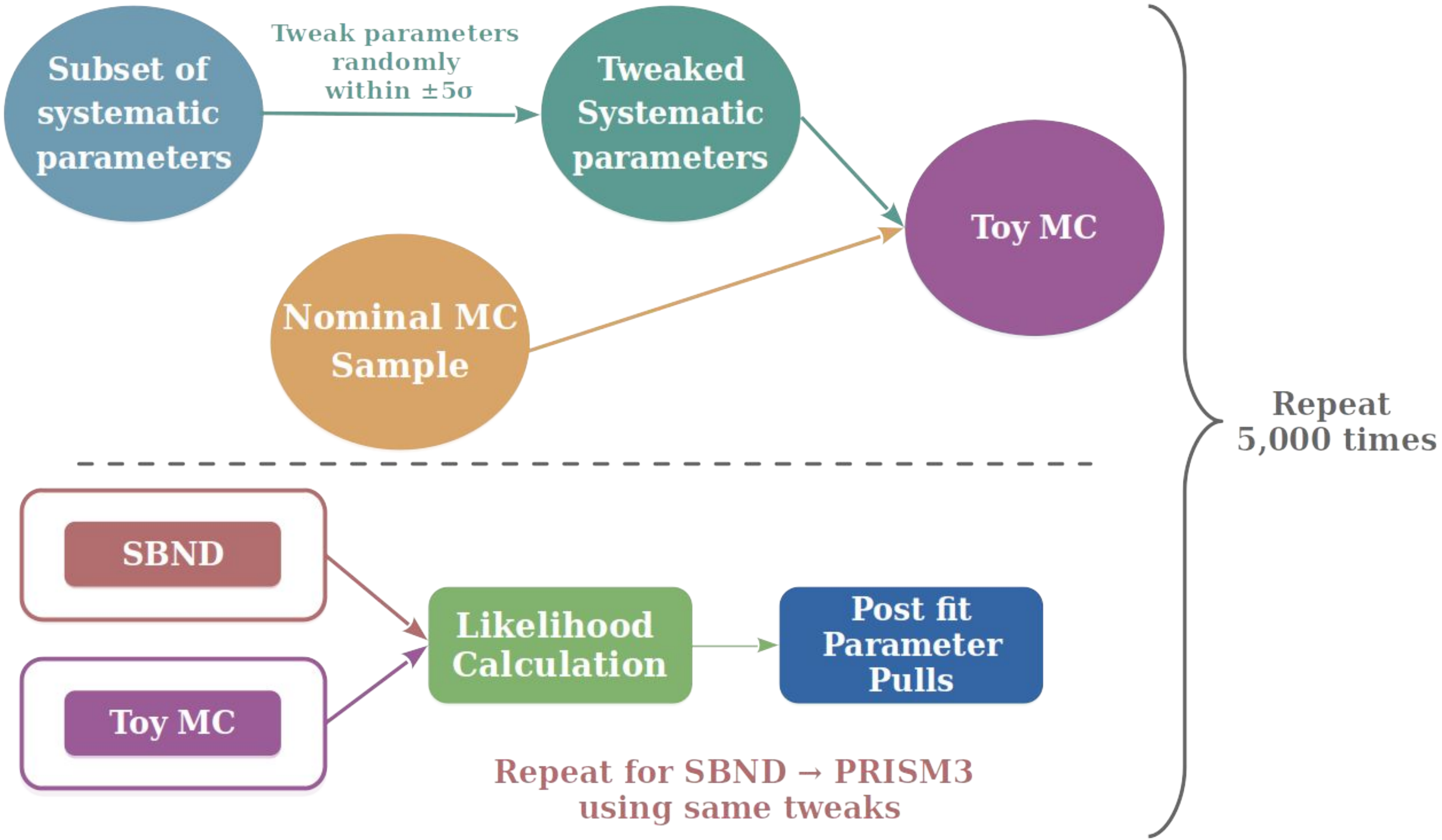
Improvements with PRISM

PRISM3 Boundaries
SBND Front



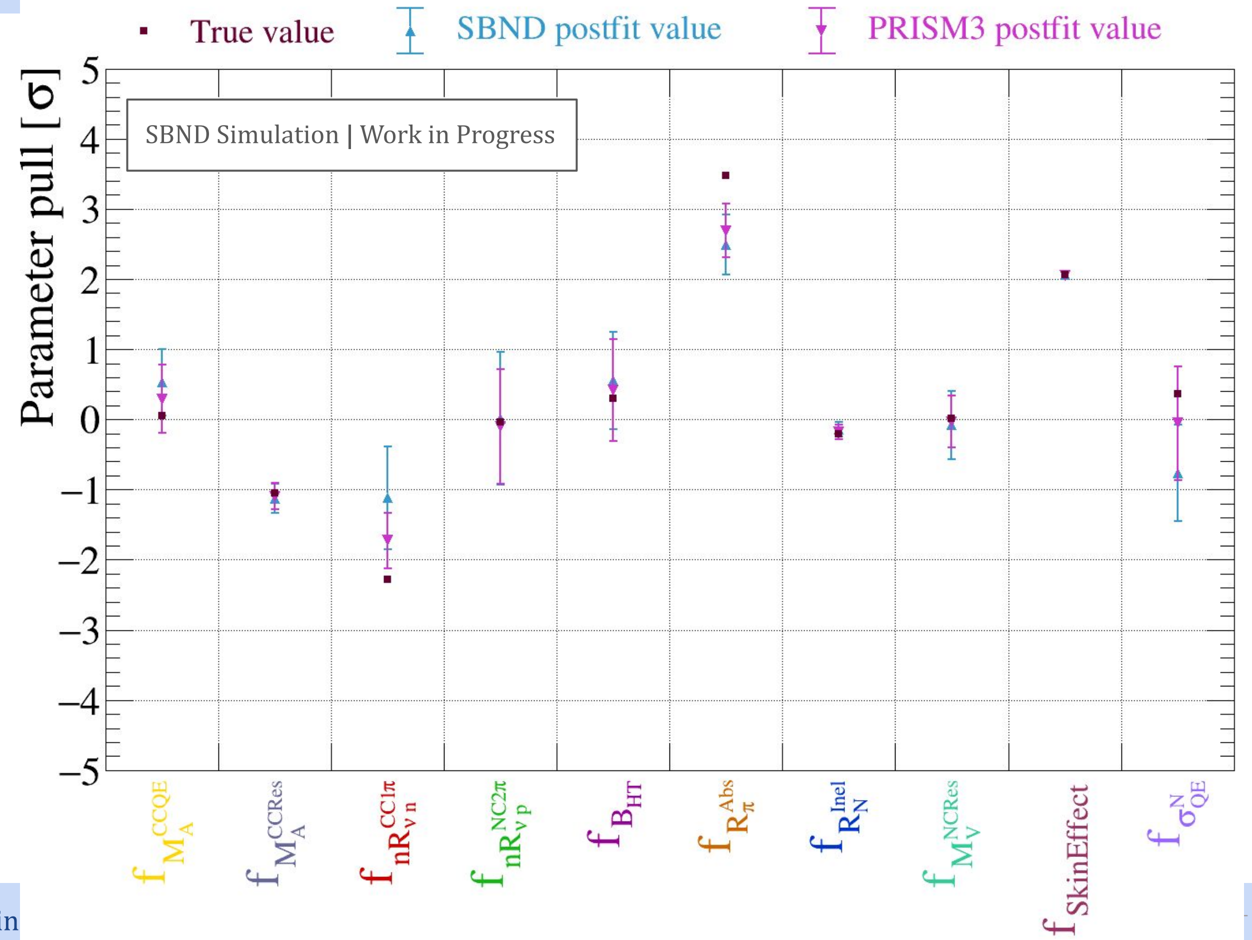
- PRISM3 defined as SBND split into 3 angular bins
  - Split so each has approximately even statistics
- SBND defined as standard whole detector approach
  - Integrated across all off axis angles
- Subset of the full systematic parameter list chosen
  - See backup
- Aim to test:
  - Whether analysis is capable of correctly determining applied tweaks by assigning:
    - Appropriate parameter pulls
    - Sensible corresponding uncertainties
  - Whether the PRISM3 inclusive fits perform better than the standard SBND inclusive fits

Testing Analysis Improvements Procedure



Postfit Parameter Pulls Comparison

- Example postfit parameter pulls from a single set of tweaks
- Parameter pulled to "True Value"
- Test whether the postfit SBND/PRISM3 errors encompass the true value



Results Table

- The number of SBND and PRISM3 fits which correctly found the true parameter pull, within the assigned postfit uncertainty.
  - Ordered from most to least according to the SBND fits.
  - 5,000 fits for each setup
- In all parameters, the number of correct pulls is greater for the PRISM3 setup than SBND

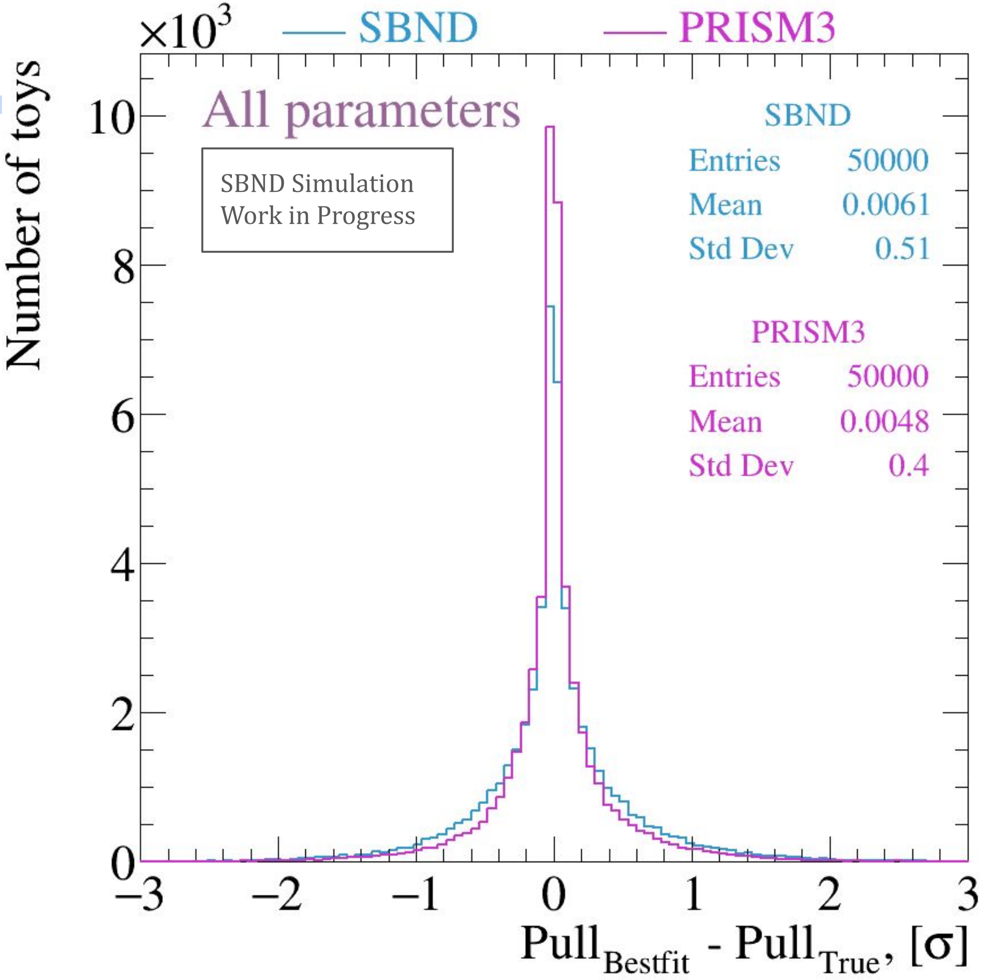
- **SBND: 81% of pulls correct**
- **PRISM3: 88% of pulls correct**

SBND Simulation | Work in Progress

Parameter	SBND	PRISM3
$f_{SkinEffect}$	4742	4915
$f_{M_A^{CCRes}}$	4564	4817
$f_{R_N^{Inel}}$	4535	4941
$f_{nR_{\nu n}^{CC1\pi}}$	4260	4792
$f_{R_\pi^{Abs}}$	4225	4673
$f_{M_V^{NCRes}}$	3928	4286
$f_{M_A^{CCQE}}$	3885	4048
$F_{\sigma_{QE}^N}$	3637	4252
$f_{nR_{\nu p}*NC2\pi}$	3502	3775
$f_{B_{HT}}$	3247	3384
Total	40525	43883

Resolution

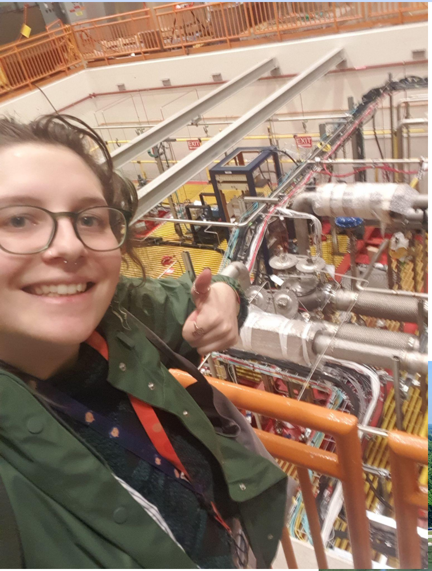
- $Pull_{Bestfit} - Pull_{True}$ in units of the prefit uncertainty, σ_{Prefit}
  - Value of 0 indicates correct pull
  - Does not account for postfit uncertainty on the pull
- Resolution improves when moving from SBND to PRISM3 fits
  - Improvement in Std Dev quantifies this (0.5→0.4)
- There is the same effect when looking at each parameter individually



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 was demonstrated to consistently improve systematic constraints for a variety of dominant parameters
  - PRISM has been implemented in VALOR for all 3 oscillation channels
    - Ongoing work to validate this and 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

Any Questions?



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Backup

Likelihood Calculation

Contribution to the likelihood ratio from SBN simulation and data

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

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

Penalty term due to prior physics constraints

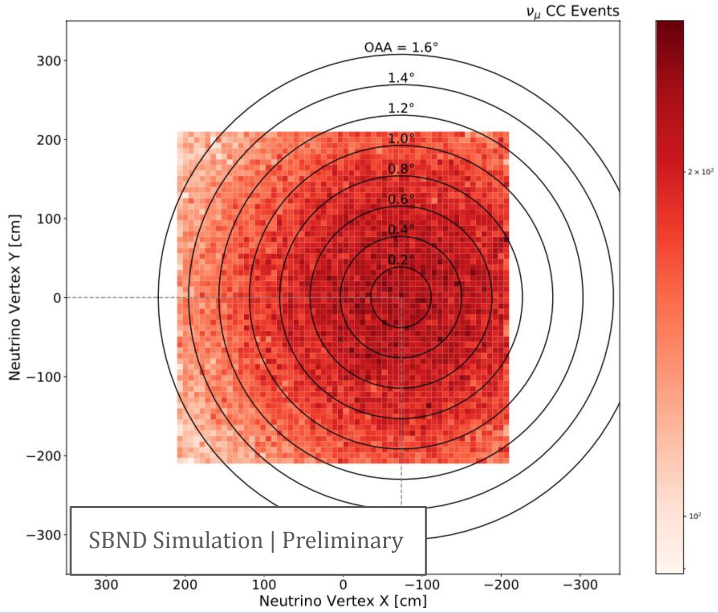
$$\chi_{phys}^2 = -2\ln\mathscr{L}_{phys}(\vec{\theta}) = 0$$

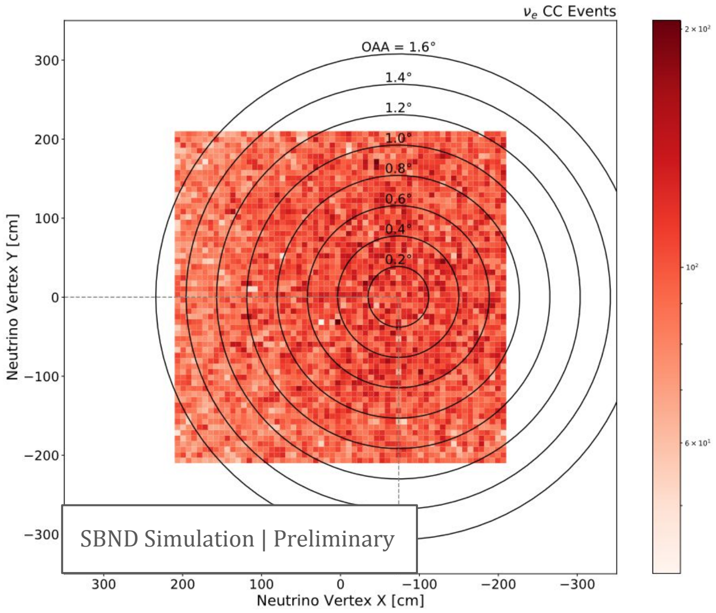
Penalty term due to prior systematic constraints

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

SBND-PRISM: Flux

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





[8]

Subset of Systematic Parameters for Pull Studies

- Subset of systematic parameters chosen for pull study to quantify improvement by using the PRISM technique within SBND.
  - 8 interaction parameters
  - 2 flux parameters

Parameter	Description
	Interaction Parameters
$f_{M_A^{CCQE}}$	Axial mass for CC quasi-elastic
$f_{M_A^{CCRes}}$	Axial mass for CC resonance neutrino production
$f_{nR_{\nu n}^{CC1\pi}}$	Non-resonance bkg normalisation in νn CC 1π reactions
$f_{nR_{\nu p*NC2\pi}}$	Non-resonance bkg normalisation in νp NC 2π reactions
$f_{M_V^{NCRes}}$	Vector mass for NC resonance neutrino production
$f_{B_{HT}}$	Higher twist parameter B for NC and CC DIS events
$f_{R_\pi^{Abs}}$	Intranuclear absorption fraction for pions
$f_{R_N^{Inel}}$	Intranuclear inelastic re-scattering fraction for nucleons
	Flux Parameters
$f_{\sigma_{QE}^N}$	Secondary nucleon interactions in the target (Be) and horn (Al), quasi-elastic cross section
$f_{SkinEffect}$	Depth that the current penetrates the horn current

back

Summary of Results

- How many parameters had their pull assigned correctly X% out of the 5,000 fits
    - Out of the 10 systematic parameters
    - Within postfit uncertainty
- What proportion of all parameters pulls did each analysis assign correctly
    - Out of 50,000 total pulls
    - Within postfit uncertainty

SBND Simulation | Work in Progress

Correct Pulls	<80% of Fits	80-90% of Fits	>90% of Fits	Overall Pulls Correct
SBND	5	2	3	81%
PRISM 3	2	3	5	88%