Search for Sterile Neutrinos at the Short Baseline Neutrino Program

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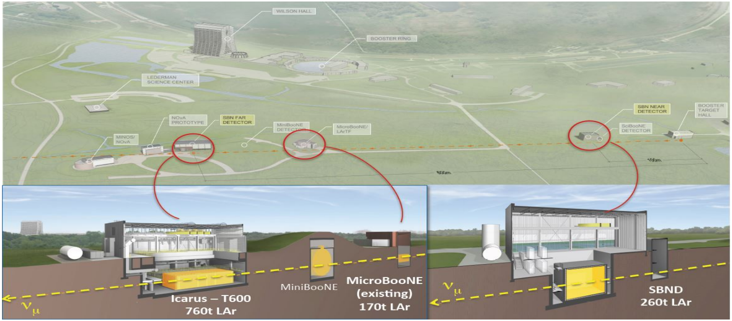
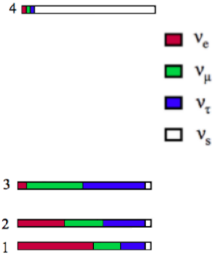
The SBN Program

- 3 LArTPC detectors at baselines ranging from 110 - 600m.
- Located along the Booster neutrino beam at Fermilab.
- Main goal is to search for light sterile neutrinos.
- Motivated by the LSND, MiniBooNE, Gallium & Reactor anomalies.
- Excess or deficit of observed events may be explained by oscillations with an eV scale neutrino.



Oscillation Probability



- PMNS mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

- For the case $\Delta m^2_{41} \gg |\Delta m^2_{31}|, \Delta m^2_{21}$, short baseline oscillations are approximated by

$$P_{\mu\to\mu} = 1 - 4|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2) sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

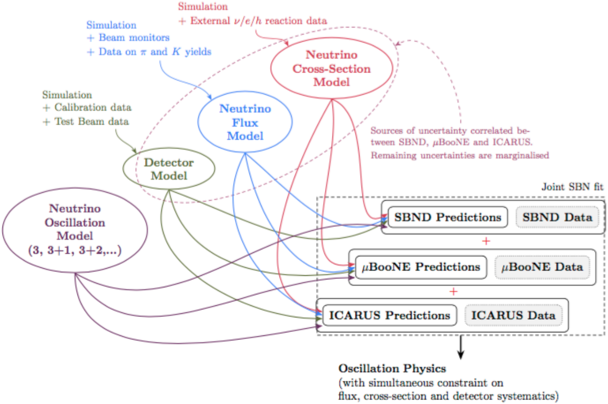
$$P_{\mu\to e} = 4|U_{\mu 4}|^2|U_{e4}|^2 sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$P_{e\to e} = 1 - 4|U_{e4}|^2(1 - |U_{e4}|^2) sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

- ν_e appearance automatically implies ν_e and ν_μ disappearance.

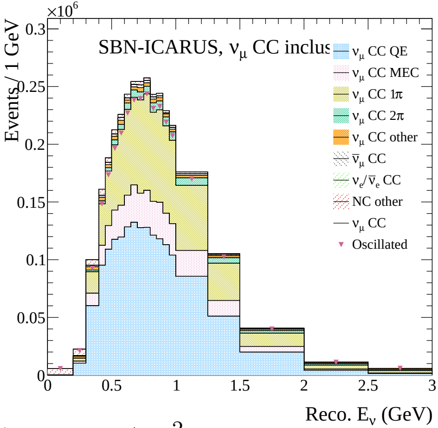
Analysis

- Produce a fit by combining oscillation physics + the cross-section, flux and detector uncertainties.
- Combine data from all three detectors to produce a single SBN fit.
- Currently, the analysis of the ν_e appearance, and $\nu_{e/\mu}$ disappearance channels are independent.



Spectra (ν_μ sample)

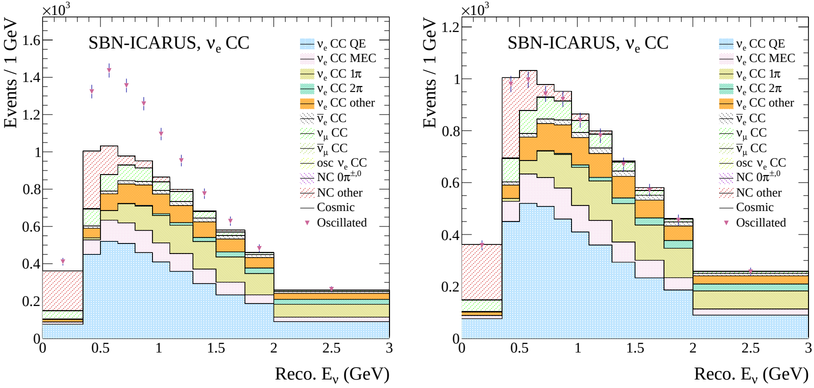
- Nominal ν_μ spectrum in the far-detector with interaction mode breakdown.
- Overlayed with integrated oscillated spectrum (ν_μ disappearance).
- Assuming a POT of 6.6×10^{20} (3 years of detector operation)



Osc params: $sin^2 2\theta_{\mu\mu} = 0.1$, $\Delta m^2_{41} = 1.1eV$

Spectra (ν_e sample)

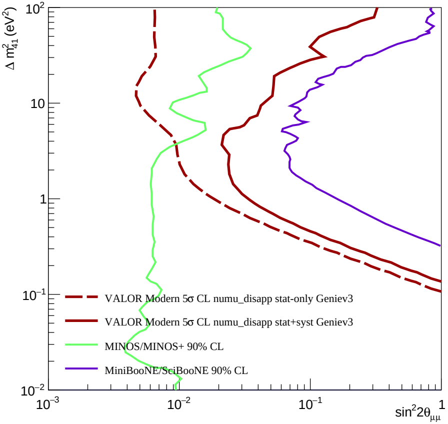
- Nominal ν_e spectrum in the far-detector with interaction mode breakdown overlayed with integrated oscillated spectrum.
- Neutrino beam is predominantly ν_μ - Event rate for $\nu_e << \nu_\mu$



Osc params: $sin^2 2\theta_{\mu e} = 0.003$, $\Delta m^2_{41} = 1eV$, $sin^2 2\theta_{ee} = 0.053$, $\Delta m^2_{41} = 1.32eV$

ν_μ Sensitivities

- Sensitivities produced using the VALOR SBN analysis framework.
- Obtain a sensitivity for the entire SBN program (combine all three detectors).



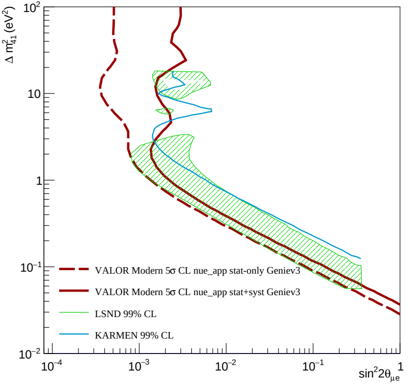
$$sin^2 2\theta_{\mu\mu} = 4|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)$$

- Using a 3+1 framework.
- Independent ν_μ disappearance analysis.
- VALOR exclusion contours: Applying flux + interaction systematics (no detector)

ν_e Sensitivities

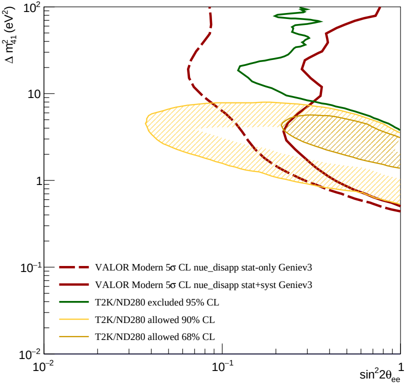
- Independent ν_e appearance and disappearance analyses.

ν_e Appearance



$$sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2$$

ν_e Disappearance



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

Conclusion

- Three LArTPC's investigating multiple oscillation channels.
- Currently have individual analyses of ν_μ disapp, ν_e app and ν_e disapp.
- Eventual goal is to perform a joint analysis of the different oscillation channels.

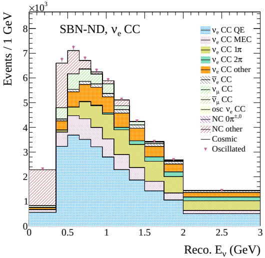
- Previous individual results in favour of sterile neutrinos only at the 3σ - 4σ level.
- SBN will provide a definitive test at the 5σ level.

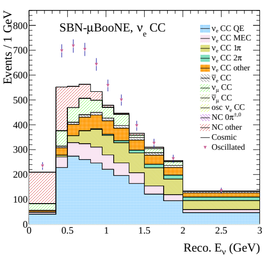
Sterile neutrino motivation

- LSND and MiniBooNE observed and excess of electron (anti) neutrinos from a numu beam.
- Reactor anomaly: Deficit of electron anti-neutrinos observed from β^- decays in fission products.
- Gallium anomaly: Deficit of electron neutrinos observed from radioactive sources decaying via electron capture which were placed in soloar neutrino experiments, SAGE and GALLEX.

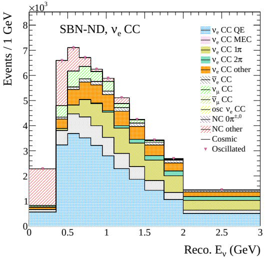
SBND & uB spectra

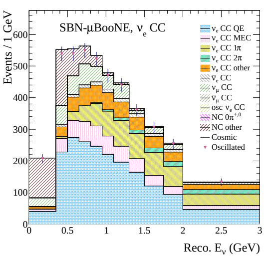
nue appearance





nue disappearance





Flux Systematics

Optical flux parameters

Parameter	Description	Uncertainty
Skin Effect	Depth that the current penetrates the horn conductor	$< 18\%$
Horn Current	Current running in the horn conductor	$\pm 0.6\%$

Hadronic interaction flux parameters (Berillium target, Aluminum horn)

Parameter	Description	Uncertainty	
		Be	Al
Nucleon Inelastic σ	Secondary nucleon interactions in the target (Be) and horn (Al), inelastic cross-section	$\pm 5\%$	$\pm 10\%$
Nucleon QE σ	Secondary nucleon interactions in the target (Be) and horn (Al), quasi-elastic cross-section	$\pm 20\%$	$\pm 45\%$
Nucleon Total σ	Secondary nucleon interactions in the target (Be) and horn (Al), total cross-section	$\pm 15\%$	$\pm 25\%$
Pion Inelastic σ	Secondary pion interactions in the target (Be) and horn (Al), inelastic cross-section	$\pm 10\%$	$\pm 20\%$
Pion QE σ	Secondary pion interactions in the target (Be) and horn (Al), quasi-elastic cross-section	$\pm 11.2\%$	$\pm 25.9\%$
Pion Total σ	Secondary pion interactions in the target (Be) and horn (Al), total cross-section	$\pm 11.9\%$	$\pm 28.7\%$

Flux Systematics cont.

Hadronic production flux parameters

Parameter	Description	Uncertainty			
		ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
π^+	Neutrino production mechanism: π^-	$\pm 11.7\%$	$\pm 1.0\%$	$\pm 10.7\%$	$\pm 0.03\%$
π^-	Neutrino production mechanism: π^-	$\pm 0.0\%$	$\pm 11.6\%$	$\pm 0.0\%$	$\pm 3.0\%$
K^+	Neutrino production mechanism: K^-	$\pm 0.2\%$	$\pm 0.1\%$	$\pm 2.0\%$	$\pm 0.1\%$
K^-	Neutrino production mechanism: K^-	$\pm 0.0\%$	$\pm 0.4\%$	$\pm 0.0\%$	$\pm 3.0\%$
K^0	Neutrino production mechanism: K^0	$\pm 0.0\%$	$\pm 0.3\%$	$\pm 2.3\%$	$\pm 21.4\%$
Other*	Neutrino produced by another source	$\pm 3.9\%$	$\pm 6.6\%$	$\pm 3.2\%$	$\pm 5.3\%$

Proposal Interaction Systematics

Proposal neutrino interaction cross-section parameters

Parameter	Description	$\delta P/P$
$f_{M_A^{CCQE}}$	Axial mass for CC quasi-elastic	-15% +25%
$f_{M_A^{CCRES}}$	Axial mass for CC resonance neutrino production	$\pm$20%
$f_{M_A^{NCRES}}$	Axial mass for NC resonance neutrino production	$\pm$20%
f_{NC}	Additional error on NC/CC ratio	$\pm$?%
$f_{nR_{\nu n}}^{CC1\pi}$	Non-resonance bkg normalisation in νn CC1π reactions	$\pm$50%
$f_{nR_{\nu p}}^{CC1\pi}$	Non-resonance bkg normalisation in νp CC1π reactions	$\pm$50%
$f_{nR_{\nu n}}^{CC2\pi}$	Non-resonance bkg normalisation in νn CC2π reactions	$\pm$50%
$f_{nR_{\nu p}}^{CC2\pi}$	Non-resonance bkg normalisation in νp CC2π reactions	$\pm$50%
$f_{nR_{\bar{\nu} n}}^{CC1\pi}$	Non-resonance bkg normalisation in $\bar{\nu} n$ CC1π reactions	$\pm$50%
$f_{nR_{\bar{\nu} p}}^{CC1\pi}$	Non-resonance bkg normalisation in $\bar{\nu} p$ CC1π reactions	$\pm$50%
$f_{nR_{\bar{\nu} n}}^{CC2\pi}$	Non-resonance bkg normalisation in $\bar{\nu} n$ CC2π reactions	$\pm$50%
$f_{nR_{\bar{\nu} p}}^{CC2\pi}$	Non-resonance bkg normalisation in $\bar{\nu} p$ CC2π reactions	$\pm$50%
$f_{nR_{\nu n}}^{NC1\pi}$	Non-resonance bkg normalisation in νn NC1π reactions	$\pm$50%
$f_{nR_{\nu p}}^{NC1\pi}$	Non-resonance bkg normalisation in νp NC1π reactions	$\pm$50%
$f_{nR_{\nu n}}^{NC2\pi}$	Non-resonance bkg normalisation in νn NC2π reactions	$\pm$50%
$f_{nR_{\nu p}}^{NC2\pi}$	Non-resonance bkg normalisation in νp NC2π reactions	$\pm$50%
$f_{nR_{\bar{\nu} n}}^{NC1\pi}$	Non-resonance bkg normalisation in $\bar{\nu} n$ NC1π reactions	$\pm$50%
$f_{nR_{\bar{\nu} p}}^{NC1\pi}$	Non-resonance bkg normalisation in $\bar{\nu} p$ NC1π reactions	$\pm$50%
$f_{nR_{\bar{\nu} n}}^{NC2\pi}$	Non-resonance bkg normalisation in $\bar{\nu} n$ NC2π reactions	$\pm$50%
$f_{nR_{\bar{\nu} p}}^{NC2\pi}$	Non-resonance bkg normalisation in $\bar{\nu} p$ NC2π reactions	$\pm$50%

Modern Interaction Systematics

Modern neutrino interaction cross-section parameters

Parameter	Description	$\delta P/P$
$f_{M_A^{NCEL}}$	Axial mass for NC elastic	$\pm 25\%$
$f_{\eta^{NCEL}}$	Strange axial form factor for NC elastic	$\pm 30\%$
$f_{M_V^{CCRES}}$	Vector mass for CC resonance neutrino production	$\pm 10\%$
$f_{M_V^{NCRES}}$	Vector mass for NC resonance neutrino production	$\pm 10\%$
f_{2p2h}	Normalisation uncertainty for 2p2h interactions	$\pm 100\%$
$f_{A_{HT}}$	Higher-twist parameter A for NC and CC DIS events	$\pm 25\%$
$f_{B_{HT}}$	Higher-twist parameter B for NC and CC DIS events	$\pm 25\%$
$f_{C_{v1u}}$	Valence p.d.f. correction factor C_{v1u} for NC and CC DIS events	$\pm 30\%$
$f_{C_{v2u}}$	Valence p.d.f. correction factor C_{v2u} for NC and CC DIS events	$\pm 40\%$
$f_{M_A^{COH}}$	Axial mass for NC and CC coherent pion production	$\pm 50\%$
$f_{R_0^{COH}}$	Nuclear size parameter controlling π absorption	$\pm 20\%$
$f_{\Delta \to N\gamma}$	Branching ratio for Δ radiative decay	$\pm 50\%$

Modern Interaction Systematics cont.

Modern neutrino FSI parameters

Parameter	Description	$\delta P/P$
f_{λ_π}	Intranuclear mean free path for pions	$\pm20\%$
$f_{R_\pi^{CEx}}$	Intranuclear charge exchange rescattering fraction for pions	$\pm50\%$
$f_{R_\pi^{Inel}}$	Intranuclear inelastic rescattering fraction for pions	$\pm40\%$
$f_{R_\pi^\pi}$	Intranuclear pion-production rescattering fraction for pions	$\pm20\%$
$f_{R_\pi^{Abs}}$	Intranuclear absorption fraction for pions	$\pm20\%$
f_{λ_N}	Intranuclear mean free path for nucleons	$\pm20\%$
$f_{R_N^{CEx}}$	Intranuclear charge exchange rescattering fraction for nucleons	$\pm50\%$
$f_{R_N^{Inel}}$	Intranuclear inelastic rescattering fraction for nucleons	$\pm40\%$
$f_{R_N^\pi}$	Intranuclear pion-production rescattering fraction for nucleons	$\pm20\%$
$f_{R_N^{Abs}}$	Intranuclear absorption fraction for nucleons	$\pm20\%$

Detector Systematics

	Applies to				
Systematic	**Beam**	**Detector**	**Sample**	**Mode**	**Reco. energy bin edges**
f_0 - f_7	FHC	SBND	ν_μCC-like	signal/ν_μCC	$\{0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.5, 2.0, \infty\}$
f_8 - f_{13}	FHC	SBND	ν_μCC-like	bkg/NC	$\{0, 0.2, 0.4, 0.6, 0.8, 1.0, \infty\}$
f_{14}	FHC	SBND	ν_μCC-like	bkg/Dirt	$\{0, \infty\}$
f_{15}	FHC	SBND	ν_μCC-like	bkg/Cosmics	$\{0, \infty\}$
f_{16} - f_{24}	FHC	SBND	ν_eCC-like	signal/ν_eCC	$\{0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.5, 2.0, 3.0, \infty\}$
f_{25} - f_{33}	FHC	SBND	ν_eCC-like	bkg/ν_μCC	$\{0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.5, 2.0, 3.0, \infty\}$
f_{34} - f_{42}	FHC	SBND	ν_eCC-like	bkg/NC1γ	$\{0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.5, 2.0, 3.0, \infty\}$
f_{43} - f_{51}	FHC	SBND	ν_eCC-like	bkg/NC1π^0	$\{0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.5, 2.0, 3.0, \infty\}$
f_{52} - f_{60}	FHC	SBND	ν_eCC-like	bkg/NCother	$\{0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.5, 2.0, 3.0, \infty\}$
f_{61} - f_{66}	FHC	SBND	ν_eCC-like	bkg/Dirt	$\{0, 0.2, 0.4, 0.6, 0.8, 1.0, \infty\}$
f_{67} - f_{72}	FHC	SBND	ν_eCC-like	bkg/Cosmics	$\{0, 0.2, 0.4, 0.6, 0.8, 1.0, \infty\}$
f_{73} - f_{145}	As above, but for μB				
f_{146} - f_{218}	As above, but for ICARUS				

Sensitivities with Detector Systematics

- Exploring impact of fully correlated error (uncorrelated error at 0%).
- Exploring impact of uncorrelated error (correlated error fixed to 2%).