UNIVERSITY OF LIVERPOOL

SBN Program

Search for Sterile Neutrinos at the Short Baseline Neutrino Program

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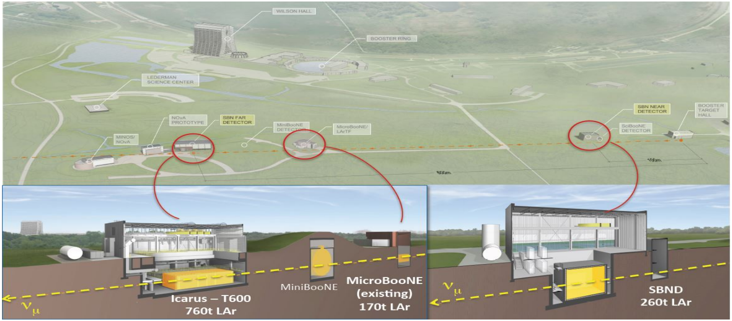
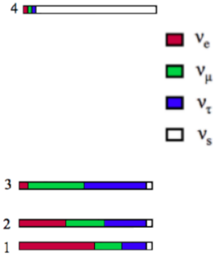
The SBN Program

- 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

$$\begin{pmatrix} e \\ \\ \\ s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\ 1} & U_{\ 2} & U_{\ 3} & U_{\ 4} \\ U_{\ 1} & U_{\ 2} & U_{\ 3} & U_{\ 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} 1 \\ 2 \\ 3 \\ 4 \end{pmatrix}$$

- For the case m^2_{41} m^2_{31}; m^2_{21}, short baseline oscillations are approximated by

$$P_{\ \rightarrow\ } = 1 - 4|U_{\ 4}|^2(1 - |U_{\ 4}|^2) sin^2 (\frac{m^2_{41} L}{4E})$$

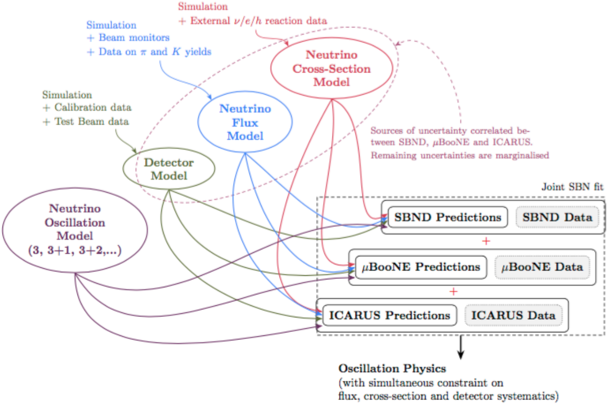
$$P_{\ \rightarrow e} = 4|U_{\ 4}|^2 |U_{e4}|^2 sin^2 (\frac{m^2_{41} L}{4E})$$

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

- $_e$ appearance automatically implies $_e$ and disappearance.

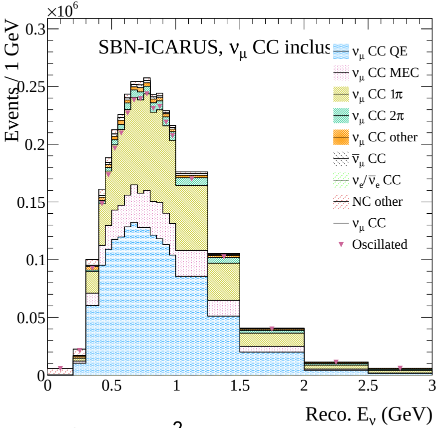
Analysis

- 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 $_e$ appearance, and $_{e/}$ disappearance channels are independent.



Spectra (sample)

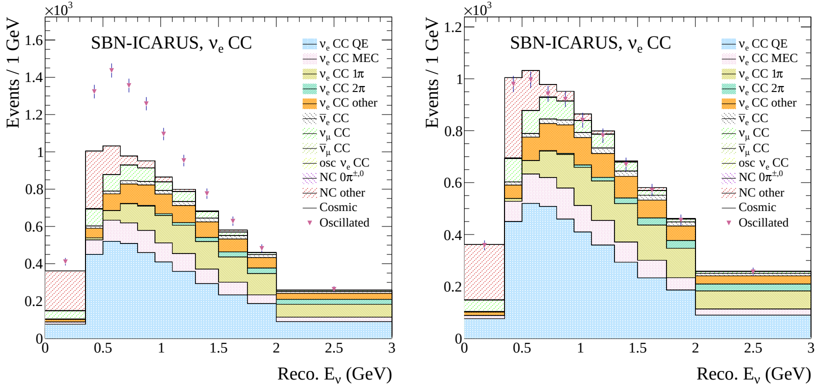
- Nominal spectrum in the far-detector with interaction mode breakdown.
- Overlayed with integrated oscillated spectrum (disappearance).
- Assuming a POT of $6{:}6 \times 10^{20}$ (3 years of detector operation)



Osc params: $sin^2 2$ $= 0{:}1$, $m^2_{41} = 1{:}1eV$

Spectra ($_e$ sample)

- Nominal $_e$ spectrum in the far-detector with interaction mode breakdown overlayed with integrated oscillated spectrum.
- Neutrino beam is predominantly - Event rate for $_e$ <<



Osc params: $sin^2 2\ _{\mu e} = 0{:}003$, $m^2_{41} = 1eV$, $sin^2 2\ _{ee} = 0{:}053$, $m^2_{41} = 1{:}32eV$

Sensitivities

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

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

$\sin^2 2$ 4$U $_4$S^{2}ˆ1 $U $_4$S^2•

$_{e}$ Sensitivities

- Independent $_{e}$ appearance and disappearance analyses.

$_{e}$ Appearance

$_{e}$ Disappearance

$\sin^2 2_{e} \quad 4 S U_{e4} S^2 S U_{4} S^2$

$\sin^2 2_{ee} \quad 4 S U_{e4} S^2 \hat{\ } 1 \quad S U_{e4} S^2 \bullet$

Conclusion

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

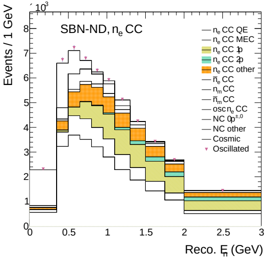
- Previous individual results in favour of sterile neutrinos only at the 3 - 4 level.
- SBN will provide a de nitive test at the 5 level.

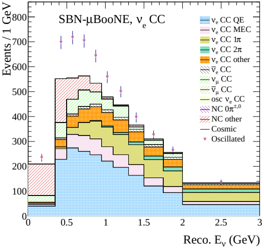
Sterile neutrino motivation

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

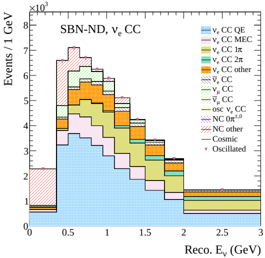
SBND & uB spectra

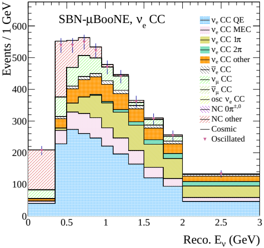
nue appearance





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^-	±11.7%	±1.0%	±10.7%	±0.03%
π^-	Neutrino production mechanism: π^-	±0.0%	±11.6%	±0.0%	±3.0%
K^+	Neutrino production mechanism: K^-	±0.2%	±0.1%	±2.0%	±0.1%
K^-	Neutrino production mechanism: K^-	±0.0%	±0.4%	±0.0%	±3.0%
K^0	Neutrino production mechanism: K^0	±0.0%	±0.3%	±2.3%	±21.4%
Other*	Neutrino produced by another source	±3.9%	±6.6%	±3.2%	±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	±20%
$f_{M_A^{NCRES}}$	Axial mass for NC resonance neutrino production	±20%
f_{NC}	Additional error on NC/CC ratio	±?%
$f_{nR_{\nu n}}^{CC1\pi}$	Non-resonance bkg normalisation in νn CC1π reactions	±50%
$f_{nR_{\nu p}}^{CC1\pi}$	Non-resonance bkg normalisation in νp CC1π reactions	±50%
$f_{nR_{\nu n}}^{CC2\pi}$	Non-resonance bkg normalisation in νn CC2π reactions	±50%
$f_{nR_{\nu p}}^{CC2\pi}$	Non-resonance bkg normalisation in νp CC2π reactions	±50%
$f_{nR_{\bar{\nu} n}}^{CC1\pi}$	Non-resonance bkg normalisation in $\bar{\nu} n$ CC1π reactions	±50%
$f_{nR_{\bar{\nu} p}}^{CC1\pi}$	Non-resonance bkg normalisation in $\bar{\nu} p$ CC1π reactions	±50%
$f_{nR_{\bar{\nu} n}}^{CC2\pi}$	Non-resonance bkg normalisation in $\bar{\nu} n$ CC2π reactions	±50%
$f_{nR_{\bar{\nu} p}}^{CC2\pi}$	Non-resonance bkg normalisation in $\bar{\nu} p$ CC2π reactions	±50%
$f_{nR_{\nu n}}^{NC1\pi}$	Non-resonance bkg normalisation in νn NC1π reactions	±50%
$f_{nR_{\nu p}}^{NC1\pi}$	Non-resonance bkg normalisation in νp NC1π reactions	±50%
$f_{nR_{\nu n}}^{NC2\pi}$	Non-resonance bkg normalisation in νn NC2π reactions	±50%
$f_{nR_{\nu p}}^{NC2\pi}$	Non-resonance bkg normalisation in νp NC2π reactions	±50%
$f_{nR_{\bar{\nu} n}}^{NC1\pi}$	Non-resonance bkg normalisation in $\bar{\nu} n$ NC1π reactions	±50%
$f_{nR_{\bar{\nu} p}}^{NC1\pi}$	Non-resonance bkg normalisation in $\bar{\nu} p$ NC1π reactions	±50%
$f_{nR_{\bar{\nu} n}}^{NC2\pi}$	Non-resonance bkg normalisation in $\bar{\nu} n$ NC2π reactions	±50%
$f_{nR_{\bar{\nu} p}}^{NC2\pi}$	Non-resonance bkg normalisation in $\bar{\nu} p$ NC2π reactions	±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	$\pm 20\%$
$f_{R_\pi^{CEx}}$	Intranuclear charge exchange rescattering fraction for pions	$\pm 50\%$
$f_{R_\pi^{Inel}}$	Intranuclear inelastic rescattering fraction for pions	$\pm 40\%$
$f_{R_\pi^\pi}$	Intranuclear pion-production rescattering fraction for pions	$\pm 20\%$
$f_{R_\pi^{Abs}}$	Intranuclear absorption fraction for pions	$\pm 20\%$
f_{λ_N}	Intranuclear mean free path for nucleons	$\pm 20\%$
$f_{R_N^{CEx}}$	Intranuclear charge exchange rescattering fraction for nucleons	$\pm 50\%$
$f_{R_N^{Inel}}$	Intranuclear inelastic rescattering fraction for nucleons	$\pm 40\%$
$f_{R_N^\pi}$	Intranuclear pion-production rescattering fraction for nucleons	$\pm 20\%$
$f_{R_N^{Abs}}$	Intranuclear absorption fraction for nucleons	$\pm 20\%$

Detector Systematics

Systematic	Beam	Detector	Sample	Mode	Reco. energy bin edges
	Applies to				
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				