DETAILS OF ICARUS & SBN OSCILLATION ANALYSES

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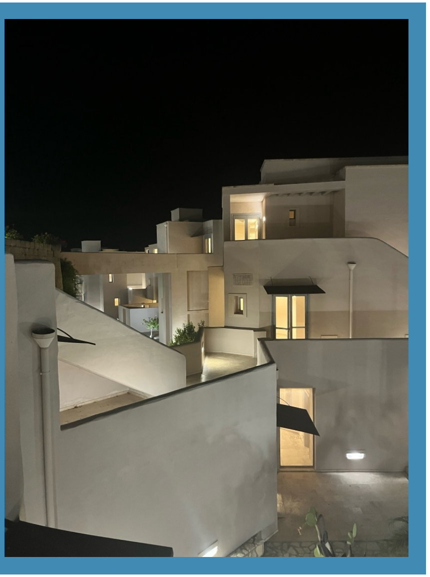
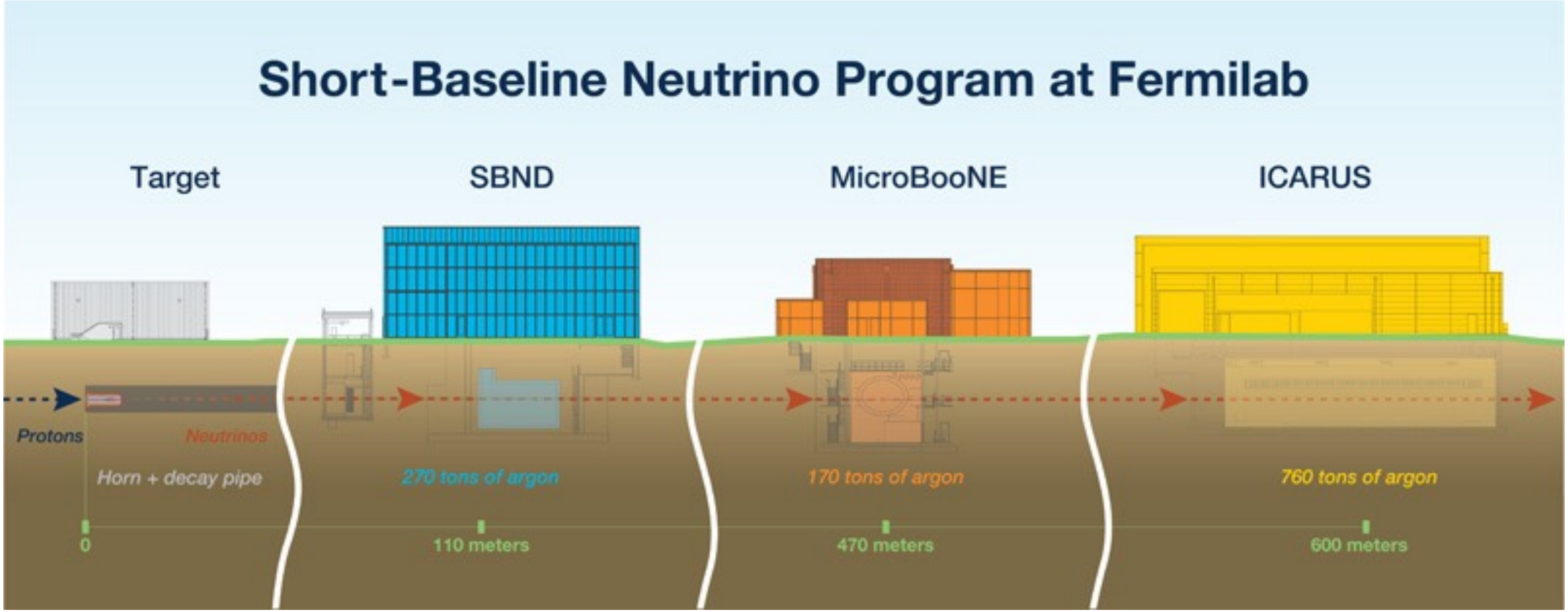
ON BEHALF OF THE ICARUS AND SBND COLLABORATIONS

NEUTRINO OSCILLATION WORKSHOP: OTRANTO, SEPTEMBER 2024



SBN PROGRAM

3 LArTPC detectors in the
Booster Neutrino Beam



Commissioning in progress
First data July 2024!

Taking data 2015-2022

Taking physics data
since June 2022

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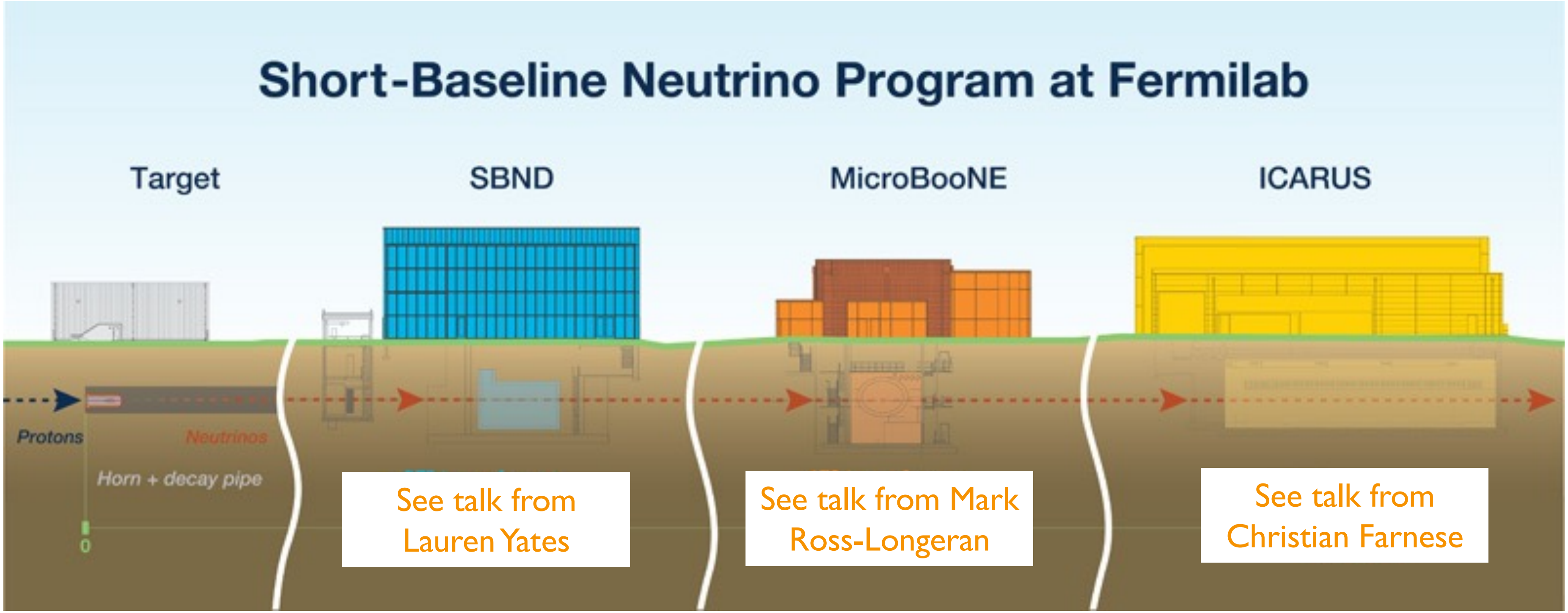

See talk from
Lauren Yates

See talk from Mark
Ross-Longeran

See talk from
Christian Farnese

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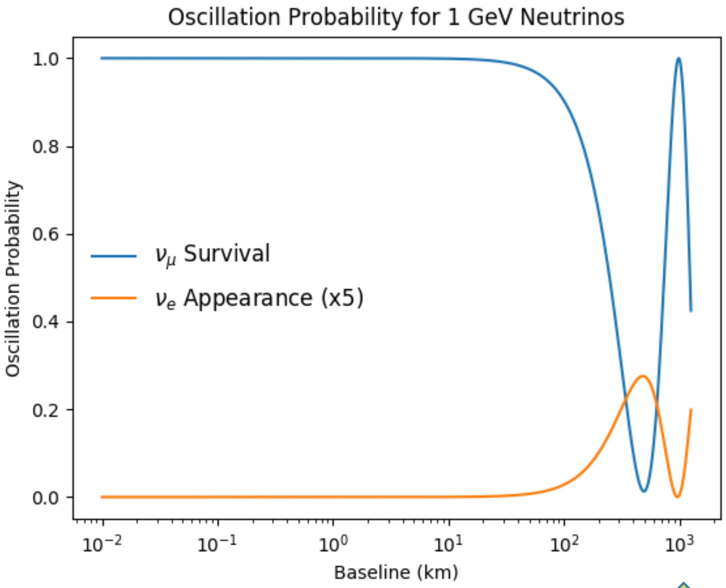
WHY SHORT-BASELINE?



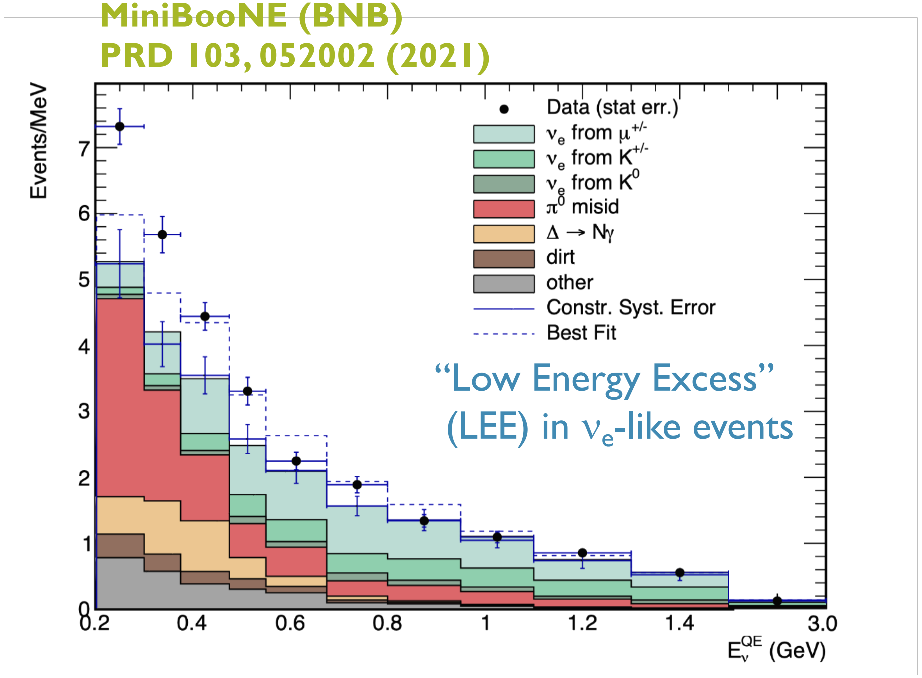
SBL
Experiments

LBL
Experiments

- Based on the already-measured oscillation parameters, we do not expect to see muon neutrino oscillation at small values of L/E
  - i.e.: ν_μ survival probability should be ~1 and ν_e appearance probability should be ~0 for order 1 GeV neutrinos with baselines < 10 km
- **Any ν_μ disappearance or ν_e appearance at these L/E values would require a larger mass splitting, which would require at least 1 additional neutrino mass state → new physics!**

SHORT-BASELINE OSCILLATION?

MiniBooNE (BNB)
PRD 103, 052002 (2021)



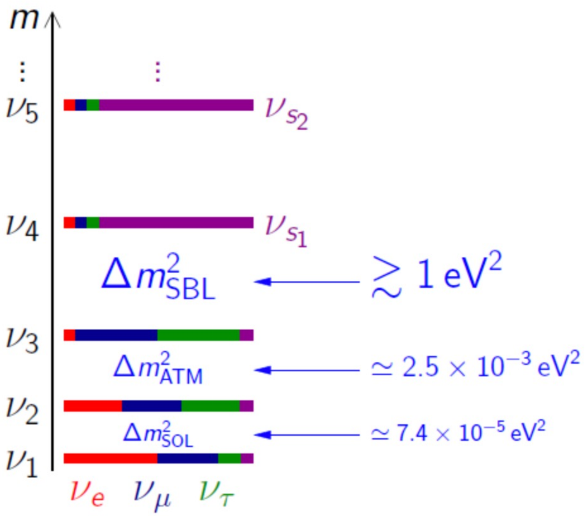
“Low Energy Excess” (LEE) in ν_e-like events

The significance of the excess observed by LSND is 3.8σ and by MiniBooNE is 4.8σ, for a combined significance of 6.1σ

- Several experiments have observations suggesting possible ν_e appearance at L/E ~ 1
    - Possible explanation is eV-scale sterile neutrino
- However, MicroBooNE does not observe evidence for ν_e appearance or disappearance and worldwide there is no evidence for ν_μ disappearance at L/E~1
- SBN will search for ν_e appearance, ν_e disappearance, and ν_μ disappearance in a **single two-detector experiment**, designed to precisely observe final states and minimize systematic uncertainty

STERILE NEUTRINO MODEL

Sensitivity studies and first oscillation search results performed using 3+1 model, but data will be sensitive to other new physics models giving rise to oscillation or other anomalous appearance/disappearance signals



- 3 neutrino model → 3 + x neutrino model, where there are x additional, "sterile" neutrinos
- Sterile neutrinos mix with standard neutrinos (allows for additional oscillation), but do not have weak charge, (consistent with # of neutrinos from LEP/astrophysics)
- "3+1" model is simplest scenario; while this model is nearly excluded by data, we often quote sterile neutrino parameters in a simplified "2 flavor" version of this model
  - $\sin^2 2\theta_{\mu e} = 4|U_{\mu 4}|^2|U_{e4}|^2$ (ν_e appearance)
  - $\sin^2 2\theta_{\mu\mu} = 4|U_{\mu 4}|^2(1-|U_{\mu 4}|^2)$ (ν_μ disappearance)
  - $\sin^2 2\theta_{ee} = 4|U_{e4}|^2(1-|U_{e4}|^2)$ (ν_e disappearance)

2 independent matrix elements

SHORT-BASELINE OSCILLATION?

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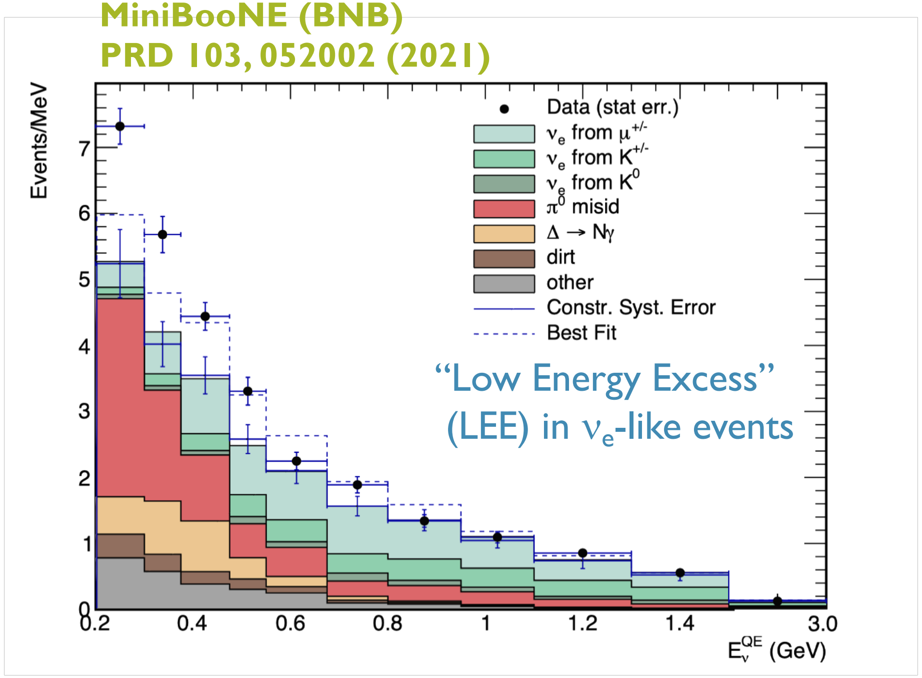

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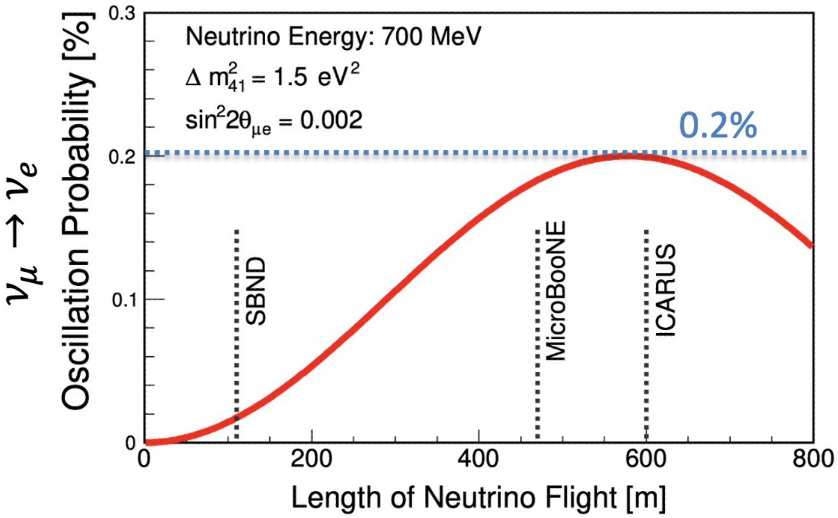
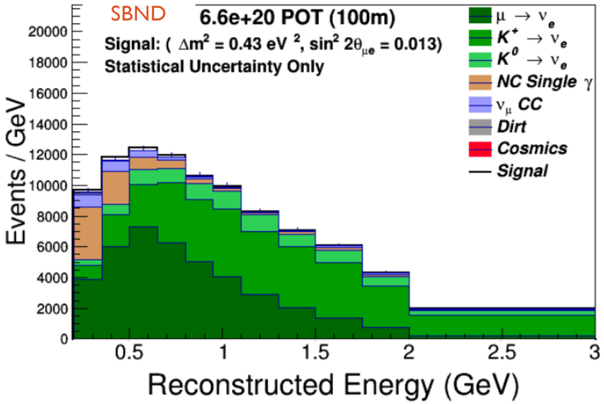
SBN PROGRAM

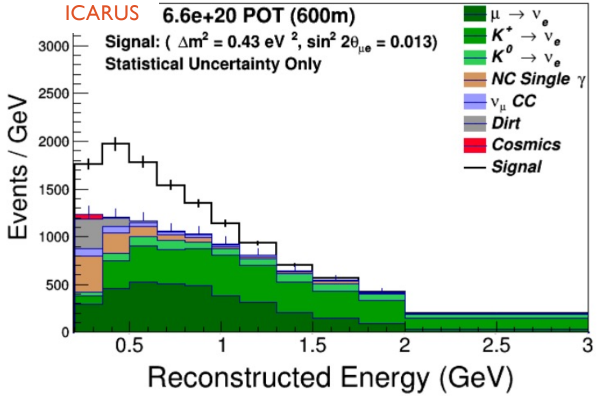
Multiple detectors, at different baselines, using the same detector technology

Example oscillation at BNB peak energy





For these oscillation parameters, very little ν_e appearance at SBND

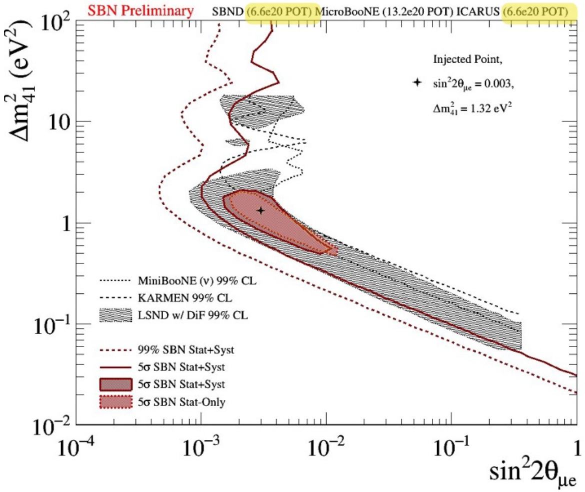


For these oscillation parameters, large ν_e appearance at ICARUS

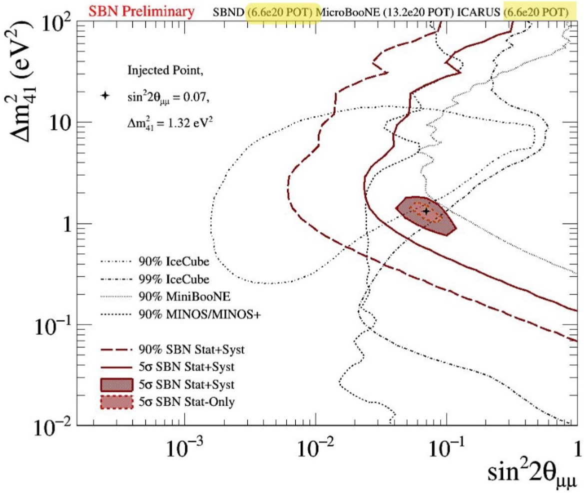
SBN SENSITIVITY

Preliminary assumptions regarding beam delivery, reconstruction, selection, and systematic uncertainties

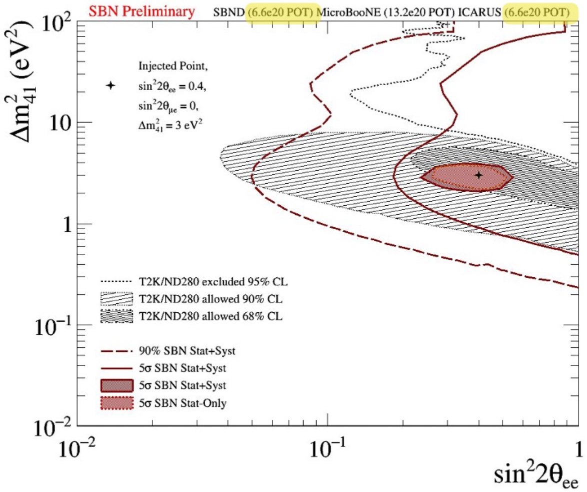
ν_e Appearance



ν_μ Disappearance



ν_e Disappearance

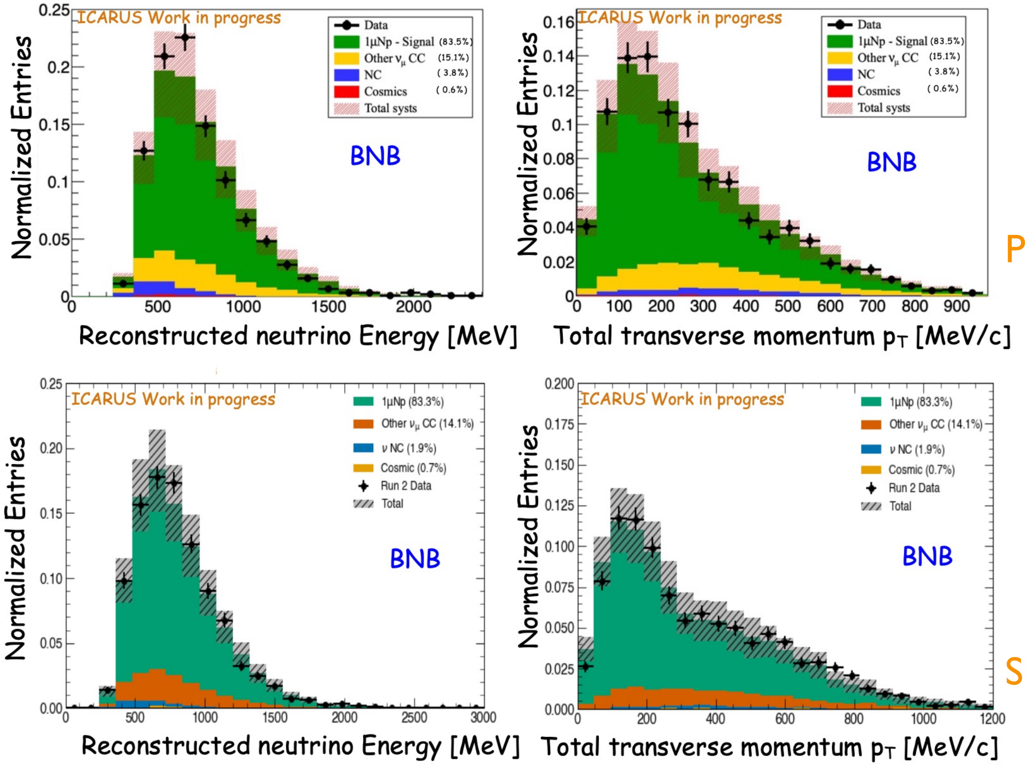


Goal is to rule out remaining 3+1 allowed region – or discover sterile neutrinos – by searching in all three channels with the same detectors! We are also exploring other possible underlying explanations for the short-baseline anomalies -- SBN will also have significant sensitivity to rule in/out these additional models

Sensitivity fits shown here were performed in exclusive channels. Actual analysis will combine channels to properly treat offsetting oscillations.

ICARUS ANALYSIS

- ICARUS has identified a sample of muon neutrino charged-current interactions for a ν_μ disappearance search
  - Two independent event reconstruction paradigms -- Pandora and SPINE -- provide inputs to selection
  - Good selection performance with respect to signal definition:
    - Pandora: ~50% efficiency, ~80% purity
    - SPINE: ~75% efficiency, ~80% purity
    - Less than 1% cosmic background
- These selected events will be input to an ICARUS-only disappearance search (systematics limited) and later to a joint fit with SBND samples
- Reconstruction and selection of ν_e samples in progress



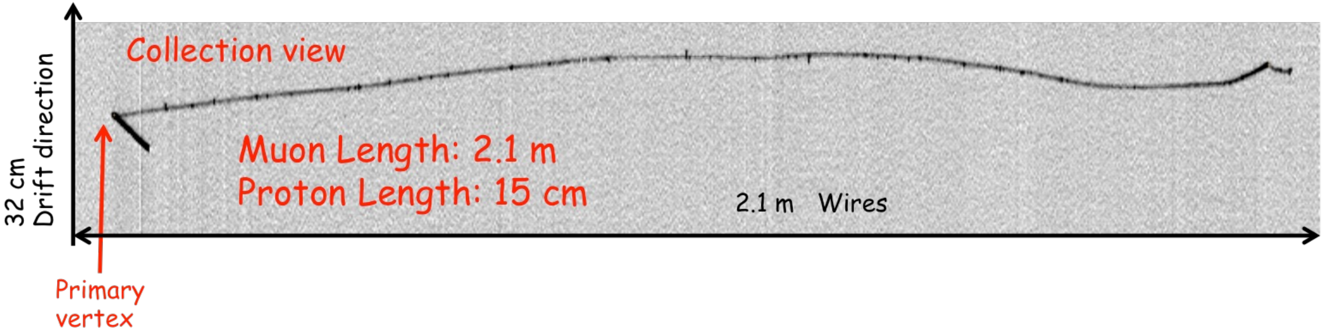
Pandora

SPINE

10% of run 2 data

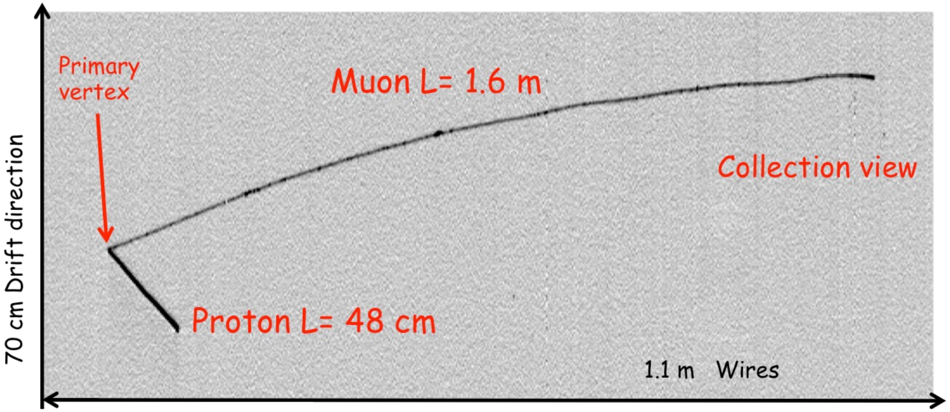
ICARUS SELECTION DETAILS: COMMON TO BOTH SELECTIONS

- Signal definition is fully contained ν_μ **CC** events with **N protons** and **zero pions**, with muon track length greater than 50 cm, and at least one proton with kinetic energy greater than 50 MeV
  - Vertex requirement (at least one proton) significantly reduces cosmic background
  - Additional cosmic rejection from associating tracks with scintillation light and/or CRT signal in the beam window (different algorithms for Pandora and SPINE)
  - Containment and kinematic criteria chosen to focus on regions of best reconstruction performance with lower contamination from NC interactions
  - Containment requirement allows for momentum reconstruction using track range – good neutrino energy resolution
  - Pandora pion reconstruction in progress – strategy was to start with the easiest reconstruction (muons and protons) first



PANDORA SELECTION DETAILS

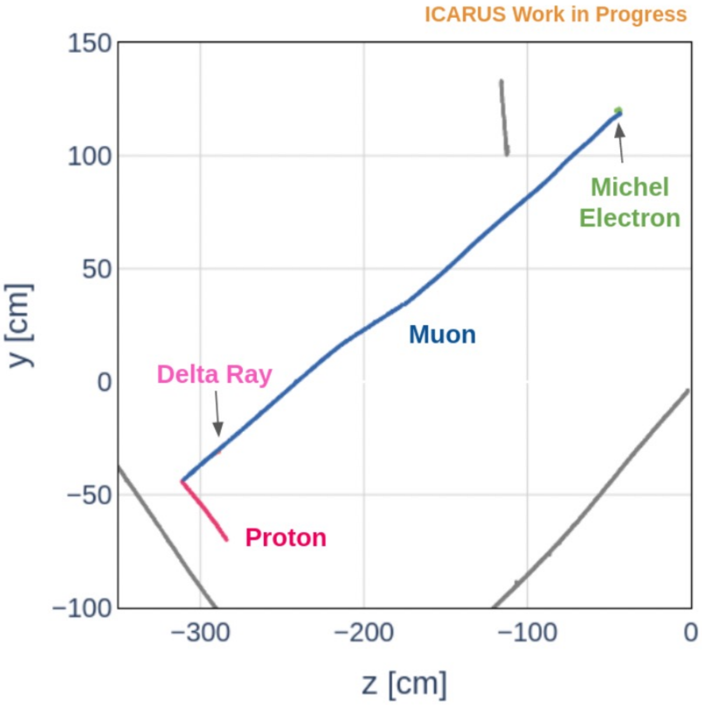
- Track vs shower determination performed using a BDT trained on MC simulation
- Particle identification for tracks is based on track length and/or a PID metric resulting from comparison of track dE/dx to a template derived from MC simulation (χ^2_μ & χ^2_p)
- Cosmic rejection:
  - Scintillation light signals associated with TPC tracks must be inside beam spill time window with no associated CRT activity (algorithm to make the association between scintillation and charge signals based on timing)
  - Charge z-barycenter of interaction in the TPC must be within 100 cm of the light z-barycenter of the triggering flash



- Start point of any particle associated with the event must be <10 cm from the vertex
- Muon track > 50 cm
- At least one proton > 50 MeV KE
- Pions and showers >25 MeV veto event

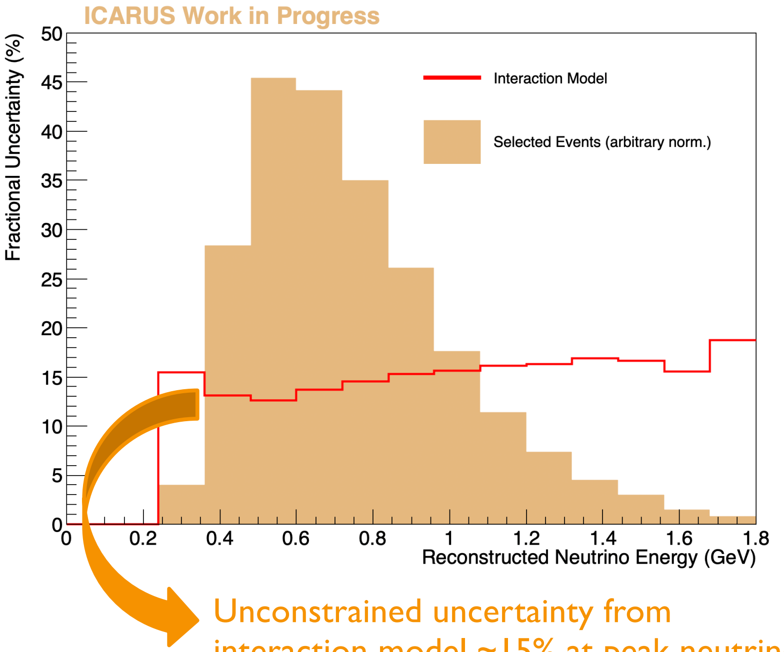
SPINE SELECTION DETAILS

- End-to-end reconstruction chain using machine learning (convolutional neural nets and graph neural nets) to perform particle identification and event classification starting from TPC "hits"
  - See arXiv:2102.01033
- Cosmic rejection: scintillation light signals associated with TPC tracks must be inside beam spill time window (algorithm to make the association between scintillation and charge signals based on expected energy deposit per PMT)



ICARUS SYSTEMATICS

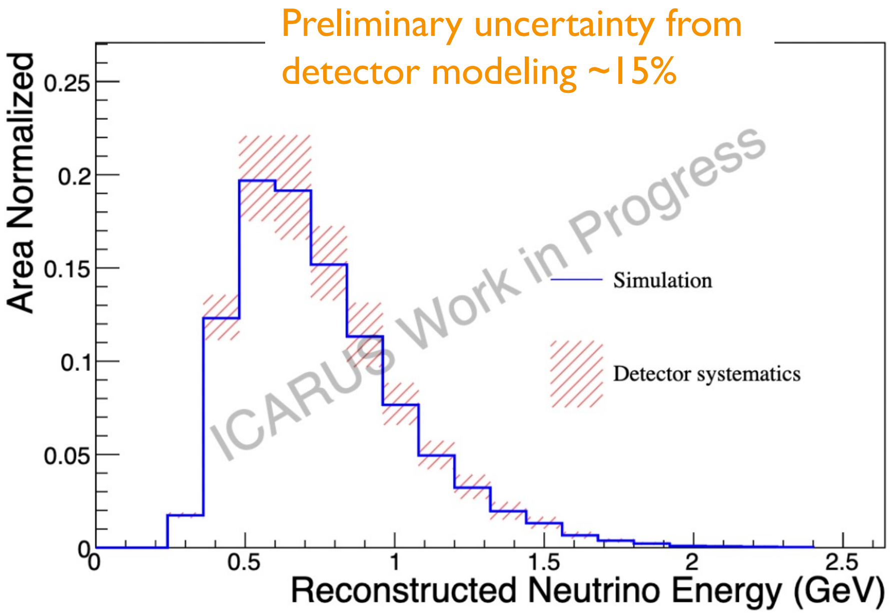
- Neutrino flux:
  - Uncertainty in proton delivery, hadron production & interactions, focusing
  - BNB flux uncertainty has been studied extensively in MiniBooNE and MicroBooNE: Phys. Rev. D**79**, 072002, 2009
- Neutrino interaction model:
  - Preliminary uncertainty based on suite of nominal GENIE weights appropriate for the DUNE/SBN base model: v3.4.0 AR23_20i_00_000
  - Base model does not successfully predict MicroBooNE data: likely need to include a few additional variations (not yet included in uncertainty bands shown here) for full coverage of data-MC discrepancy
- Detector model:
  - Preliminary uncertainty based on MC variations where there are known data-MC discrepancies and/or unmodeled effects



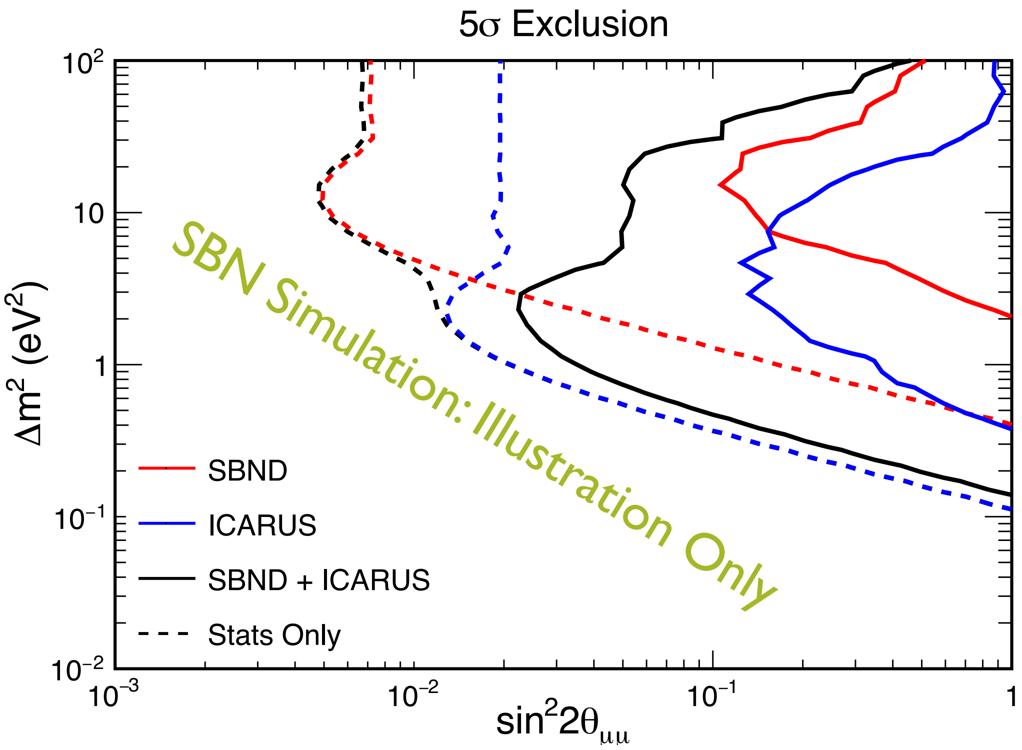
Unconstrained uncertainty from interaction model ~15% at peak neutrino energy: ICARUS-only oscillation search will be systematics dominated

PRELIMINARY ICARUS DETECTOR SYSTEMATICS

- Dominant preliminary detector uncertainty results from comparing simulated samples with tuned vs untuned TPC signal shapes
    - Overestimate of the true uncertainty from TPC signal simulation
- Variations in the TPC noise model, the electron-ion recombination model, and the PMT detector model also included in preliminary uncertainty
- Preliminary detector modeling uncertainties are similar in scale to unconstrained flux and cross-section uncertainties – acceptable for ICARUS-only oscillation analysis
    - Expect significant reduction from work-in-progress improvements to the simulation and more realistic systematic variations



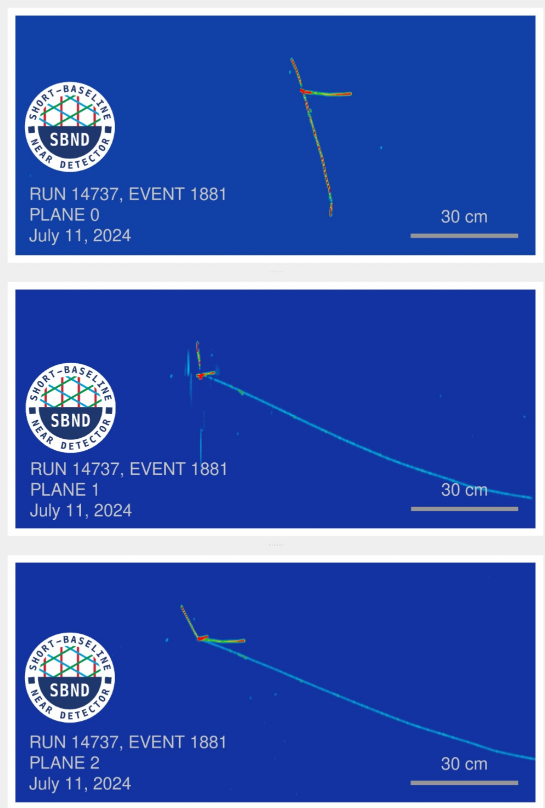
IMPACT OF NEAR DETECTOR



- Example ν_μ disappearance sensitivity in CAFAna, demonstrating the impact of a two-detector analysis in constraining systematic uncertainty: for illustration only – not an actual sensitivity prediction
  - Includes partial list of preliminary flux and interaction model systematics, no detector systematics
- In the combined analysis, significant constraint on flux and cross-section uncertainties (which are highly correlated between SBND & ICARUS) -- uncorrelated (ie detector specific) uncertainties must be reduced to few-percent level with precise simulation and calibration

SBND DATA COMING NOW!

- SBND started collecting data in July!
- The detector is performing well and we expect to collect a large sample of neutrinos when the beam returns in the fall: expect a million neutrino interactions per year!
- High statistics neutrino interaction samples with precise reconstruction in SBND will allow for sophisticated use of selected samples to more precisely constrain systematic uncertainty
  - Exclusive final states constrain specific portions of the neutrino interaction model
  - Fits binned in multiple kinematic quantities disentangle effects that may be degenerate in neutrino energy
  - Slicing the detector to select different angles with respect to the beam allows exploitation of the PRISM concept



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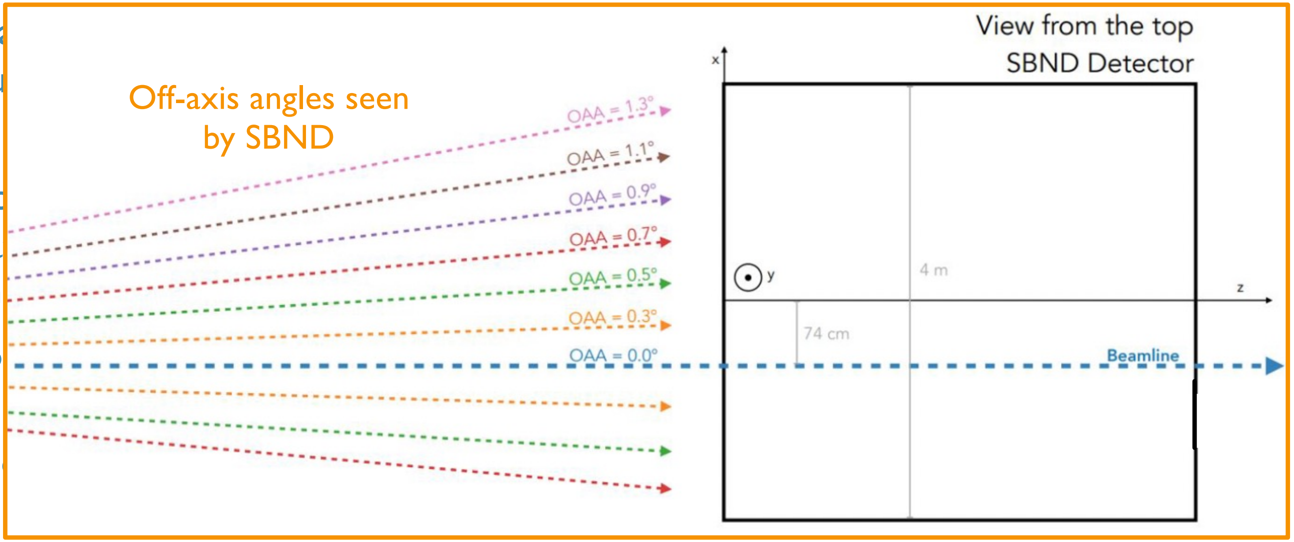
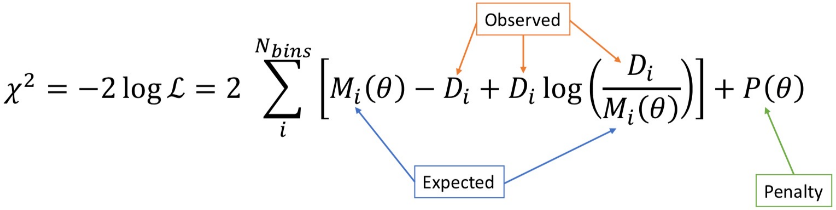
SBND PRISM



OSCILLATION FITTING IN SBN

- All oscillation measurements are made by comparing observed event spectra to the event spectra predicted for different oscillation and systematic parameters, to determine the oscillation parameters most compatible with observation



$$\chi^2 = -2\log\mathcal{L} = 2\sum_{i}^{N_{bins}}\left[M_i(\theta) - D_i + D_i\log\left(\frac{D_i}{M_i(\theta)}\right)\right] + P(\theta)$$

Example of log-likelihood fit function

- Sensitivities in SBN have been studied in a variety of fitting frameworks: CAFAna, SBNFit, VALOR
  - Primary difference is treatment of systematic uncertainties: included in covariance matrix or as pull terms in fit (or combination of these)
  - Extensive cross-validation performed among fitting methods
- Work in progress to develop new framework – PROfit – incorporating features of both SBNFit and CAFAna in standalone, modern fitting framework
  - Systematics treated with a combination of pull terms and covariance matrix
  - Designed to facilitate parallel programming, more complex correlations among systematic parameters, and ease of fitting for additional (beyond 3+1 sterile) models

SUMMARY

- SBN is designed to definitively **rule out or discover eV-scale sterile neutrino oscillation**
- ICARUS ν_μ disappearance search is quite advanced!
  - Two independent reconstruction/selection paradigms are providing **high-purity samples with good efficiency** and a **preliminary suite of systematic uncertainties** has been evaluated
  - First ICARUS-only oscillation result expected in coming year
  - Result will be systematics dominated as expected for a single-detector analysis
- SBND data collection has begun!
  - **Combined fits of SBND and ICARUS will provide significant constraint on uncertainties** from the flux and neutrino interaction models
  - High statistics in SBND allows exploitation of sophisticated methods for constraining systematics
  - Precise simulation and calibration to minimize uncorrelated detector uncertainty will be critical
- **First SBN oscillation results coming soon** – ultimate sensitivity will be achieved with complex multi-channel, multi-detector, multi-beam analyses using precisely calibrated detectors