Report from the SBN Analysis Working Group

Daniele Gibin[1] and **Georgia Karagiorgi**[2], **SBN Analysis Coordinators**

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Physics Advisory Committee Meeting
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SBN Analysis Working Group “Charge”

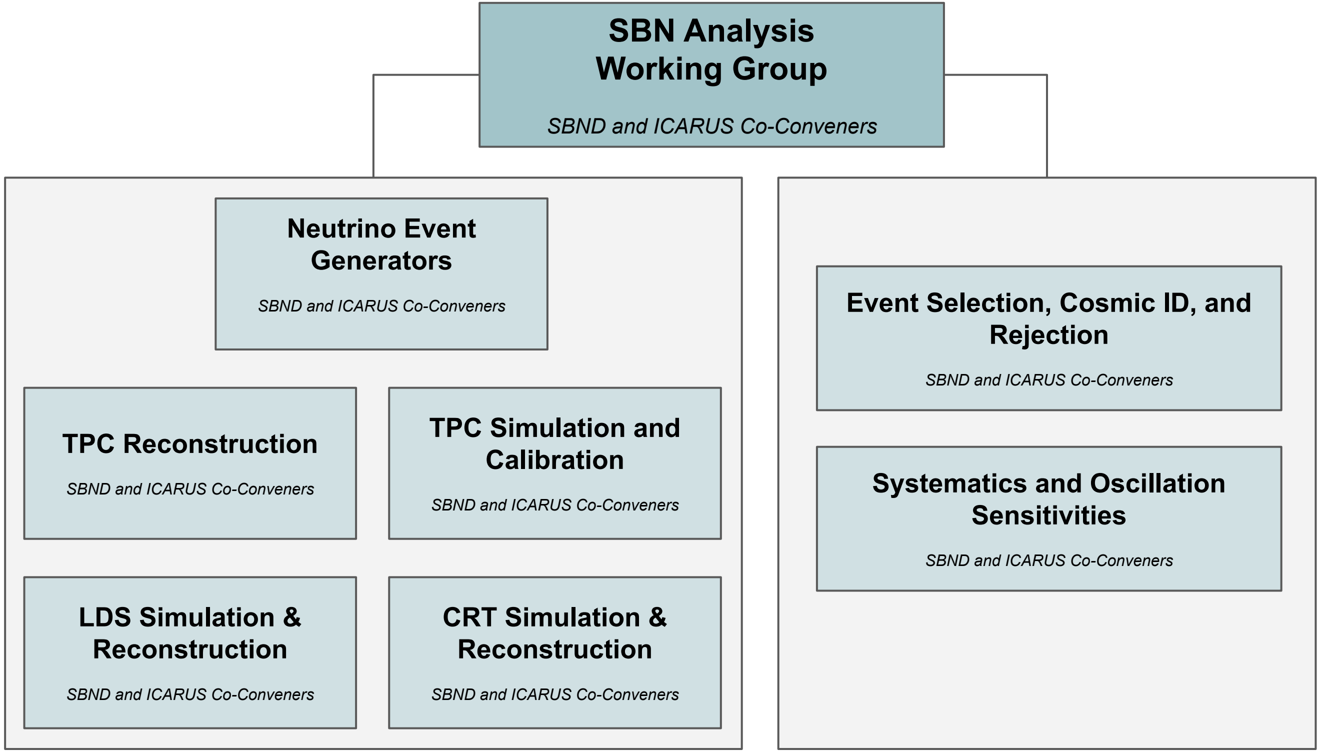
The group was established in 2016 and formally adopted as a SBN Joint Working Group in 2018, in order to:

“Explore how combined SBN physics analysis for sterile neutrino oscillation searches can be most effectively performed. Work focuses on implementing a three detector simulation, building reconstruction and analysis tools within a common framework, and developing an end-to-end common analysis scheme in preparation for real data exploitation.”

Joint analyses, using common methodologies and tools, are not only a unique advantage and key strength of SBN, they are **absolutely imperative** to performing high-sensitivity sterile neutrino oscillation searches, and, therefore, to achieving the goals of the SBN Program.

SBN Analysis Working Group Organization

Present structure*:



*Reorganization in progress; see later slides

SBN Analysis Working Group Organization

Present structure*:

SBN Analysis Working Group

SBND and ICARUS Co-Conveners

- **Neutrino Event Generators**
  Simulation of neutrino interactions and tuning on SBN data
- **TPC Reconstruction**
  Track/shower and vertex reconstruction
- **TPC Simulation and Calibration**
  Simulation/reconstruction of charge, dE/dx, lifetime, space charge, including calibration procedures
- **LDS Simulation & Reconstruction**
  Light detection systems (LDS) signal simulations, timing, LDS-TPC matching
- **CRT Simulation & Reconstruction**
  Cosmic Ray Tracker (CRT) signal simulations, timing, CRT-TPC matching

- **Event Selection, Cosmic ID, and Rejection**
  Exploitation of information from TPC, CRT, LDS, Trigger System, and particle and event identification, including cross-validation on exclusive event selections
- **Systematics and Oscillation Sensitivities**
  Evaluation of flux, cross-section, and detector systematics, development of common tools to search for neutrino oscillations and evaluation of oscillation sensitivities

*Reorganization in progress; see later slides

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SBN Analysis Working Group Scope

As shown in the SBND and ICARUS presentations, the SBN physics program is very broad.

The physics scope of the SBN Analysis Joint Working Group is explicitly **targeted at joint detector analyses, and for now focuses sharply on light (eV-scale) sterile neutrino oscillations.**

Given Booster Neutrino Beam (BNB) beam content, we probe primarily:

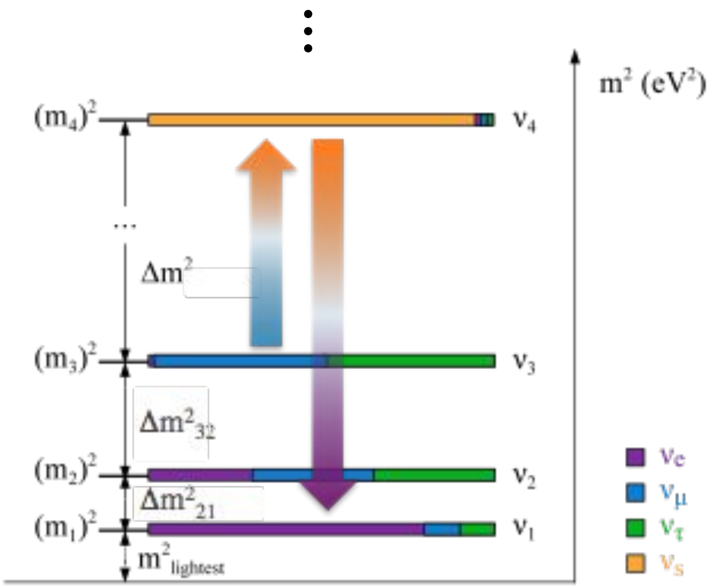
$\nu_\mu \to \nu_e$, $\nu_\mu \to \nu_\mu$, and $\nu_e \to \nu_e$

through charged current (CC) measurements

$\nu_{\mu,e} \to \nu_s$

through neutral current (NC) measurements

(possibly additional, mostly-sterile mass states)



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Overview of Oscillation Analysis Efforts

Over the past two years, efforts have targeted the following three milestones:

1. **Check:** Reproduce the SBN proposal-era oscillation sensitivities with (three) new oscillation fitting frameworks, using truth-level information ("fake reconstruction") and the same inputs for beam, reconstruction efficiencies, backgrounds, and systematic uncertainties, and check for consistency.
2. **Update:** Update the oscillation sensitivities, still using truth-level information ("fake reconstruction"), and exploiting updated inputs for efficiencies, backgrounds, and systematic effects (accounting for the available/developed SBN event reconstruction and recent results from other LArTPC experiments).
3. **Improve:** Repeat oscillation sensitivity evaluation, this time with full event simulation and reconstruction and detector systematics.

Additionally, we have expanded efforts toward improvements to the oscillation physics assumptions, such as the simultaneous inclusion of appearance and disappearance effects in the fits (multi-channel searches).

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Major effort since last PAC meeting, culminating into ~100-page internal technical note [SBN DocID 27037] documenting reproduced and updated (relative to SBN proposal) sensitivities using three independent fitters: VALOR, SBNfit, and CAFAna

Sterile Neutrino Oscillation Sensitivity Simulation in SBN

Costas Andreopoulos, Dominic Barker, Chris Backhouse, Steve Dennis, Guanqun Ge, Daniele Gibin, Thomas Ham, Rhiannon Jones, Georgia Karagiorgi, Tereza Kroupova, Jacob Larkin, Andy Mastbaum, Ornella Palamara, Gray Putnam, Marco Roda, Mark Ross-Lonergan, Glória de Sá Pereira, Elizabeth Worcester, Bruno Zamorano, Joseph Zennamo

Contents

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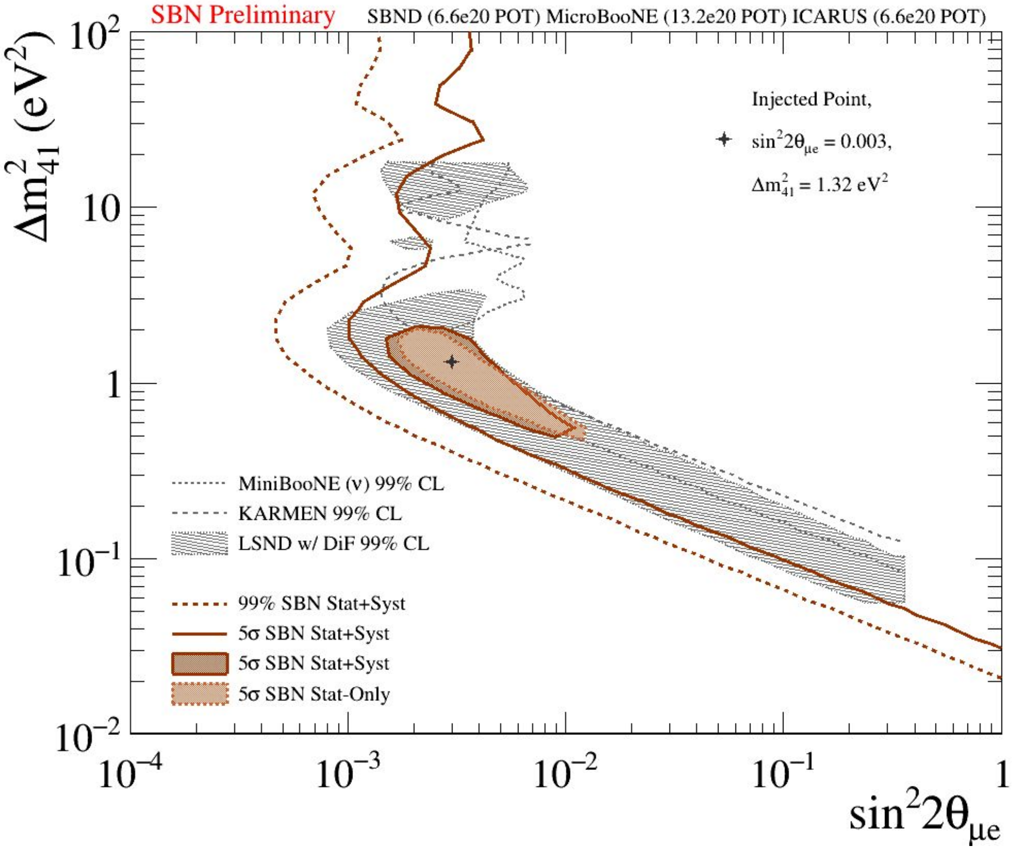
Updated SBN Oscillation Sensitivities

Electron Neutrino Appearance

Assumes no muon or electron neutrino disappearance.

Using truth-level information ("fake reconstruction") and updated neutrino beam flux and neutrino-Ar cross-section systematics.

[SBN DocID 27037]



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Updated SBN Oscillation Sensitivities

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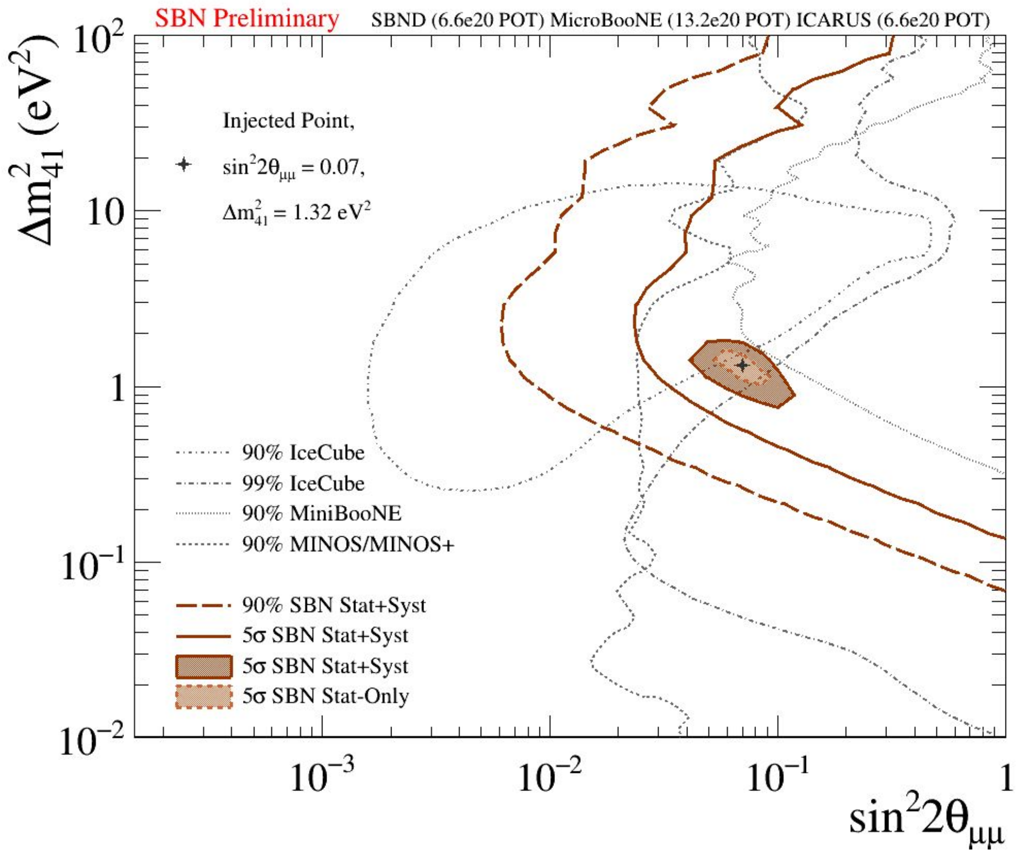

Updated SBN Oscillation Sensitivities

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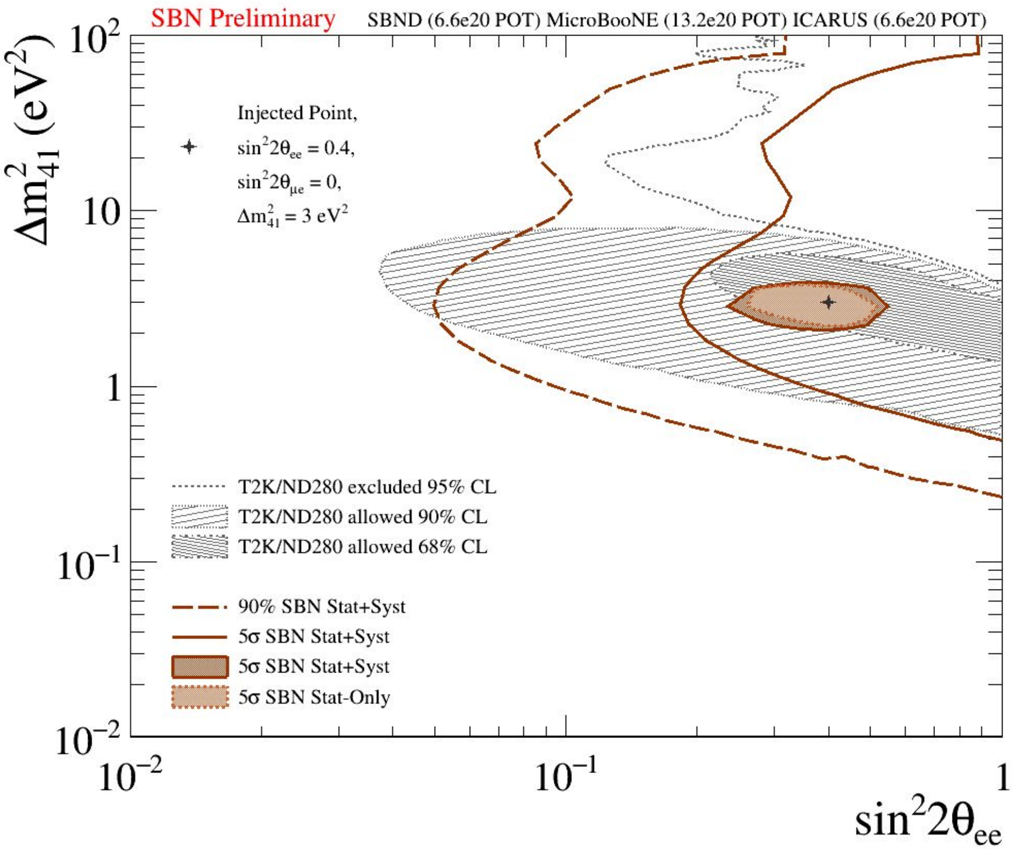
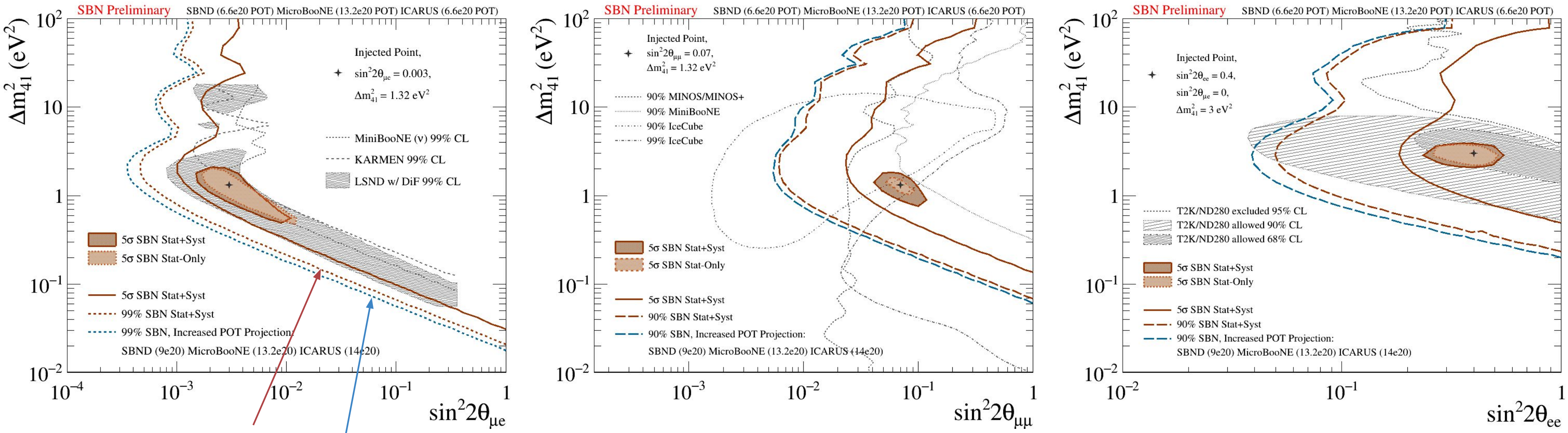


Updated SBN Oscillation Sensitivities

Also updated to include latest POT projections: **9e20 POT for SBND** and **14e20 POT for ICARUS**



SBN proposal exposure

increased POT projection

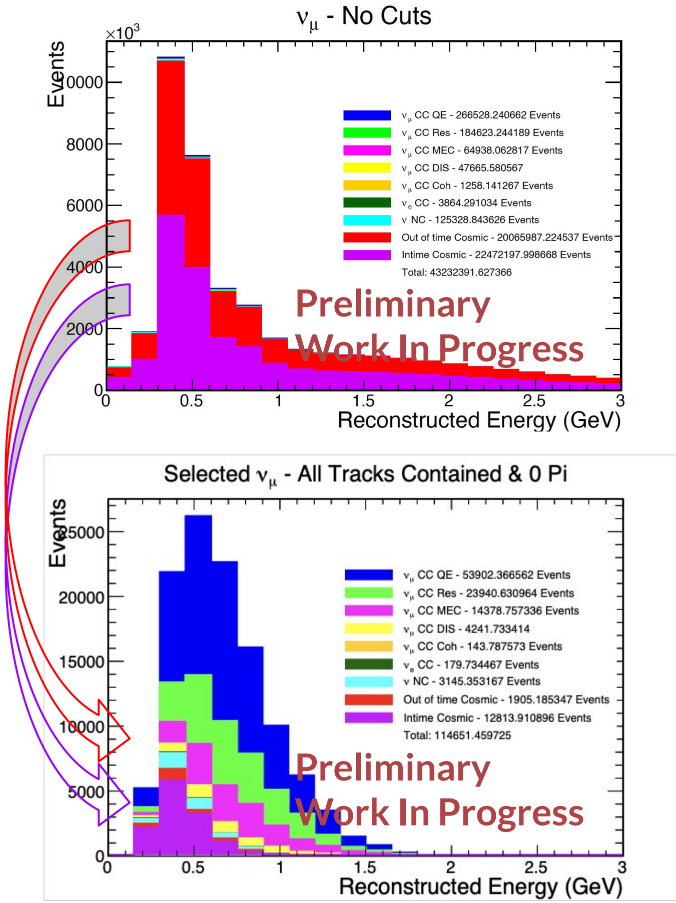
Improved SBN Oscillation Sensitivities

Muon neutrino disappearance sensitivity has been exercised using full reconstruction!

Full reconstruction and selection, including track vertex and momentum reconstruction, has been developed, as well as selection criteria that reduce cosmic background to the <1% level.

Work is ongoing to understand:

- Impact of improved background mitigation and reconstruction quality cuts on the sensitivity
    - Selection efficiency is somewhat lower than the ultimate efficiency anticipated by the truth-based ("fake reconstruction") sensitivities
    - Focus so far on selection purity rather than efficiency
    - Improved cosmic rejection algorithms are being developed that are expected to yield higher signal efficiency



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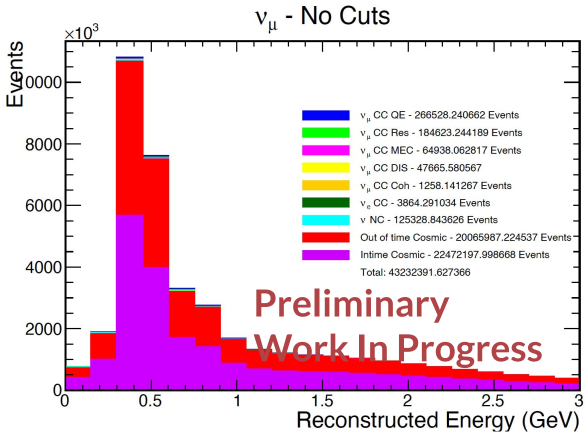
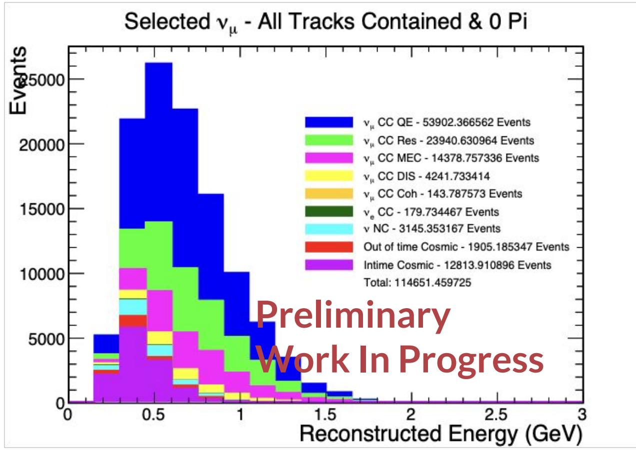
Work is ongoing to understand:

- Impact of improved background mitigation and reconstruction quality cuts on the sensitivity
- Impact of detector systematics evaluation approach and detector systematic uncertainties on the sensitivity

Additionally, we plan to explore what can be gained with more refined analyses (combining multiple sample selections, PRISM concept, off-axis beam samples, etc.)?





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Multi-channel Oscillation Searches

SBN's unprecedented level of precision calls for more robust assumptions in oscillation models, e.g. **simultaneous ν_e appearance, ν_μ disappearance and ν_e disappearance**.

- Work is ongoing to account for these simultaneous effects, e.g. for the 3+1 oscillations search, by fitting ν_e CC, ν_μ CC spectra simultaneously, while varying three independent model parameters: **U_{e4}, $U_{\mu4}$ and Δm^2**

The ability to search for these oscillation channels across three different baselines and in multiple interaction channels (ν_e CC, ν_μ CC spectra) allows SBN to overconstrain appearance and disappearance amplitudes, which is expected to yield a stronger statement on the sterile neutrino oscillation interpretation of the short baseline neutrino anomalies.

This is a unique capability of SBN among other short-baseline experiments!

Multi-channel Oscillation Searches

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- Work is ongoing to account for these simultaneous effects, e.g. for the 3+1 oscillations search, by fitting ν_e CC, ν_μ CC spectra simultaneously, while varying three independent model parameters: U_{e4}, $U_{\mu4}$ and Δm^2
- Work is also ongoing to include **more channels** in the near future (e.g. NC spectra probing $\nu_{\mu,e} \rightarrow \nu_s$ disappearance), probing a total of four independent parameters: U_{e4}, $U_{\mu4}$, U_{s4}, Δm^2, as well as to expand to **3+N models**.

With three (or more) independent oscillation parameters, and additional spectra (bins) included in the fit, a Feldman-Cousins approach to evaluating sensitivity becomes much more computationally intensive.

- **High Performance Computing (HPC) implementation** of fit performed in collaboration with Fermilab SciDAC team allows efficient scan of multi-parameter space, but **will require utilization of dedicated HPC resources.**

Near-term Priorities

- Incorporation of **full reconstruction**
  - Integrate ν_e reconstruction in oscillation sensitivities
  - Re-baseline ν_μ, ν_e reconstruction performance and investigate improvements, including through machine learning developments
- Incorporation of **detector systematics**
  - Investigate different detector systematic schemes: Currently, exploring reconstructed kinematics variations at fitter level. A final set of uncertainties will have to rely on data to MonteCarlo comparisons and/or fully data-driven approaches.
  - Will be partly addressed through an upcoming Calibrations Workshop (see next slides).
- Develop and investigate **SBND PRISM and multi-channel fit concepts**, and impact to SBN analysis
  - E.g., develop and integrate NC reconstruction
- Develop **analysis strategy**
  - Blind analysis? Open/signal-blind samples?
  - Analysis validation scheme
  - Analysis timeline

Other Activities

SBN Calibration Workshop Sep. 27 - Oct. 1, 2021; 60+ registrants

Major goals:

- Further elaborate a full calibration program for SBN, including cross-detector calibration of the ICARUS and SBND detectors
- Prepare common SBN tools for carrying out essential detector calibrations prior to physics measurements at SBND and ICARUS
- Educate new SBND and ICARUS students on detector physics and calibration of LArTPCs, including working examples to study cosmic muon data/MonteCarlo without use of the full LArSoft framework

Successful in:

- Establishing common ntuple formats and developing low-level calibration methods following the scheme developed by ICARUS
- Integrating TPC, LDS and CRT information into calibration efforts
- Identifying and correcting MonteCarlo simulation discrepancies compared to data
- Elucidating questions to be addressed jointly: What is missing in detector model? Data-driven approach to modeling detector response and systematics? What can SBN improve upon compared to previous experiments using “standard candles” for calibration (e.g. p0)? Etc.

Other Activities

Next Calibration Workshop planned for this winter

> **Goal:** review low-level calibration strategy, develop common higher-level calibration strategy (common selection/samples, event-level calibration methods)

On the horizon (~spring): **Reconstruction** Workshop

Longer term (~summer): **Detector Systematics and Cosmic "Overlays"** Workshop

SBN Analysis Working Group Scope and Challenges

The success of the SBN Analysis Working Group also rests on developments carried out as part of physics analyses outside the scope of the group (e.g. understanding neutrino cross-sections and associated systematics), as well as related efforts in developing state-of-the-art reconstruction and particle identification techniques, etc.

Developing a physics results strategy that is consistent with the SBND and ICARUS physics results strategies and timelines is a high priority going forward, and we will be working closely with SBND and ICARUS leadership to facilitate this.

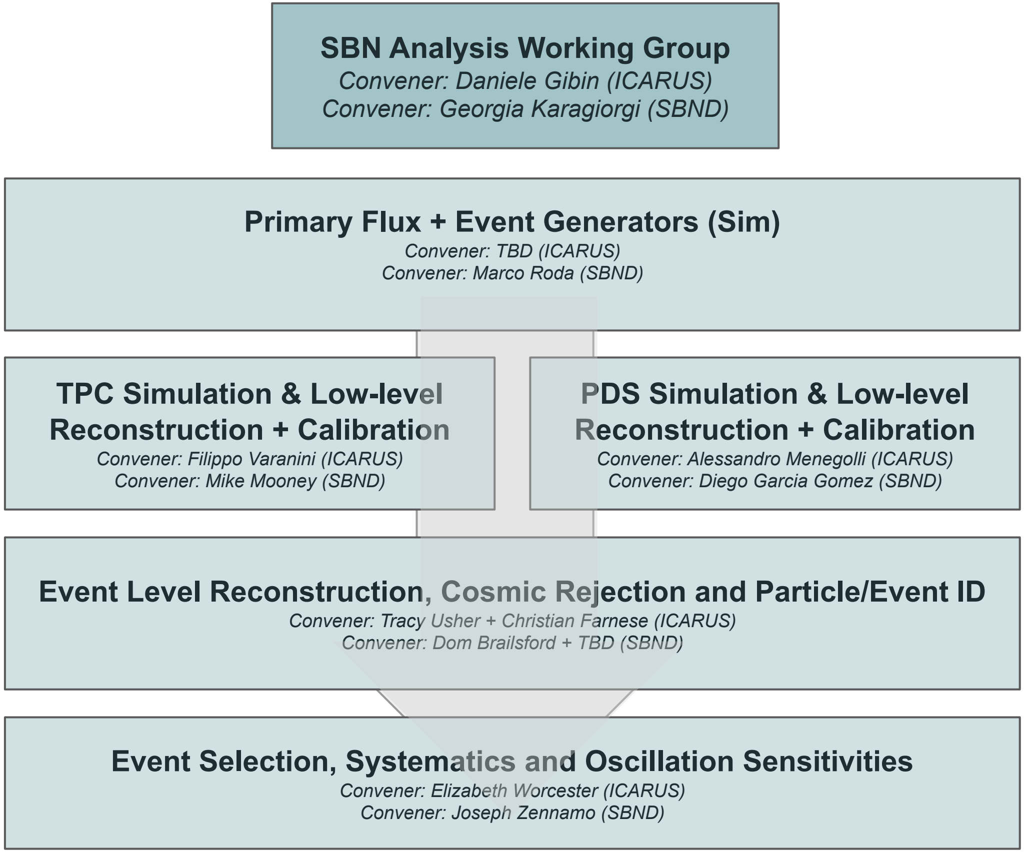
We will continue to make every effort to discuss and help coordinate production of simulation with consistent assumptions (e.g. cross-section "tunes") and common processing (e.g. calibration, reconstruction), working closely with the SBN Analysis Infrastructure Working Group (see subsequent slides).

(Re-)Organization, Going Forward

*Being finalized in communication with SBND and ICARUS leadership and current SBN Analysis Working Group subgroup conveners.

New organizational structure mirrors an "end-to-end" analysis flow and needs.

Consolidates and strengthens overall efforts.



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Continued Coordination with SBN AI Working Group

SBN Analysis Infrastructure Working Group

SBND and ICARUS Co-Conveners

SBN Analysis Working Group
Convener: Daniele Gibin (ICARUS)
Convener: Georgia Karagiorgi (SBND)

The SBN Analysis Working Group also communicates and works closely with the SBN Analysis Infrastructure Working Group in coordinating and addressing data and software infrastructure and computing resource needs across SBN.

Primary Flux + Event Generators (Sim)
Convener: TBD (ICARUS)
Convener: Marco Roda (SBND)

TPC Simulation & Low-level Reconstruction + Calibration
Convener: Filippo Varanini (ICARUS)
Convener: Mike Mooney (SBND)

PDS Simulation & Low-level Reconstruction + Calibration
Convener: Alessandro Menegolli (ICARUS)
Convener: Diego Garcia Gomez (SBND)

Event Level Reconstruction, Cosmic Rejection and Particle/Event ID
Convener: Tracy Usher + Christian Farnese (ICARUS)
Convener: Dom Brailsford + TBD (SBND)

Event Selection, Systematics and Oscillation Sensitivities
Convener: Elizabeth Worcester (ICARUS)
Convener: Joseph Zennamo (SBND)

SBN Analysis Infrastructure (AI) Working Group

SBN Analysis Infrastructure Working Group

SBND and ICARUS Co-Conveners

Production and Data Management

SBND and ICARUS Co-Conveners

Workflow Management

SBND and ICARUS Co-Conveners

Release Management

SBND and ICARUS Co-Conveners

Validation Framework

SBND and ICARUS Co-Conveners

Analysis Framework

SBND and ICARUS Co-Conveners

Simulation Infrastructure

SBND and ICARUS Co-Conveners

SBN Joint Working Group responsible for coordinating and addressing **data and software infrastructure** and **computing resource needs** across the SBN Program

SBN AI - Recent Activities

Major activity over last months: Preparation of production release supporting ICARUS early data analysis activities and implementing significant updates in simulation, high-level reconstruction calibration, and analysis framework. Currently developing production plan and what's needed for final simulation release.

Computing plan: Currently preparing a five-year computing plan, including data preservation, in preparation for Fermilab Computing Resource Scrutiny Group (FCRSG), in coordination with SBND and ICARUS Collaborations and SBN Analysis WG.

Tools for cosmics and neutrinos: Significant progress on tools for removal of cosmics (a significant and important background to model correctly for assessment of its impact on neutrino reconstruction and event selection): a) light-track matching utilities in SBN code; b) CRT/PDS timing in ICARUS and development of timing-related filters.

Cosmic ray modeling ("cosmic overlays"): Ongoing, detailed discussions on cosmic modeling, including data-driven models using data collected out-of-time with the beam. Working toward a coherent and effective approach to cosmic modeling, which will be critical for the SBN joint analyses.

Neutrino Event Generators: SBN has encouraged the move of LArSoft to use the updated GENIE v3.2 as a default for neutrino event generation. Need to coordinate base interaction model to use for simulation; discussions are ongoing to converge timely for inclusion in subsequent production campaigns.

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SBN computing needs are vital to the program but challenging on many fronts, as they significantly exceed previous LArTPC detector experiments due to detector sizes and data rates. Primary concerns related to I/O (disk/tape), CPU time for simulation of cosmics, memory requirements.

Tools for cosmics and ... important backgroun ... event selection): a) light-tra ... t of timing-related filters.

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Summary

- Steady progress in SBN oscillation search analyses since last PAC report given by SBN Analysis Coordinators (summer 2021).
    - This has been achieved despite the SBND and ICARUS detectors being at different stages in their lives, which inevitably slowed down joint activities
    - A good level of communication was maintained among the two collaborations, sharing progress on reconstruction, achievements, and hurdles.

- Common infrastructure (production and processing code frame, analysis ntuple format) and back-end of analysis chain is fully established; with both detectors soon to be online, emphasis will shift toward common implementation of common calibration, reconstruction, and event selection, and on understanding and evaluating detector systematics

- Organizational structure of WG will continue to evolve according to evolving SBN analysis needs

- As the SBN oscillation search strategy is refined, we will continue to work with SBND and ICARUS collaborations to ensure well-aligned priorities and compatible results timelines

Backup slides

SBN AI - Resources

- Last year requested and obtained resources to Fermilab computing as SBN:
  - Addressing needs for physics campaigns of ICARUS, commissioning of SBND and updated sensitivity analyses for SBN
  - For FY2023-24 allocated >40M CPU hours, 15-30 PB tape, >3 PB disk
- Currently updating estimates in view of upcoming FCRSG meeting in February 2023:
  - Revisiting model to reduce tape usage in production workflows as much as possible
  - ICARUS data retention model: keeping early stage of reconstructed data from keep-up processing on disk allows for fast turnaround of reprocessing
  - Data overlays (i.e. using data collected off-beam to replace MonteCarlo cosmic simulation) is being explored as a hi-fidelity option to avoid simulation of cosmic rays, but will require reading off-beam data
- Actively using resources from CNAF computing center in Italy, and working to fully integrate them in production workflows with RUCIO
- Planning to use High Power Computing (HPC) resources for Machine Learning workflows; also other ongoing studies for wider and more optimal usage of HPC in other workflows