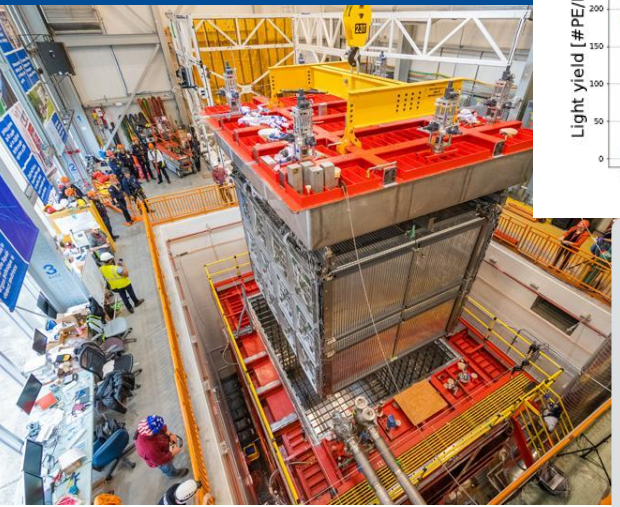
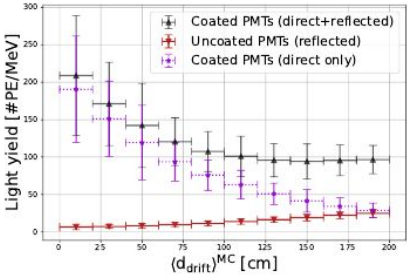
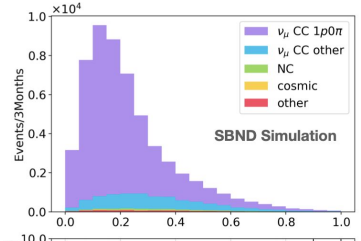
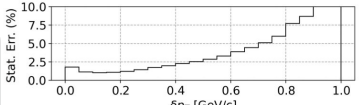
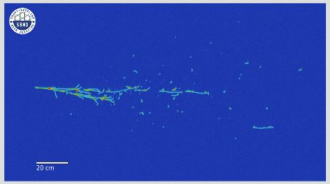




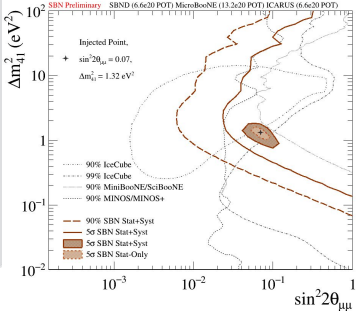




Heavy Neutral Leptons



e^+e^-, $\mu^+\mu^-$, $\mu\pi$



SBND Run Plan and Analysis Outlook

Anne Schukraft, Andrzej Szelc

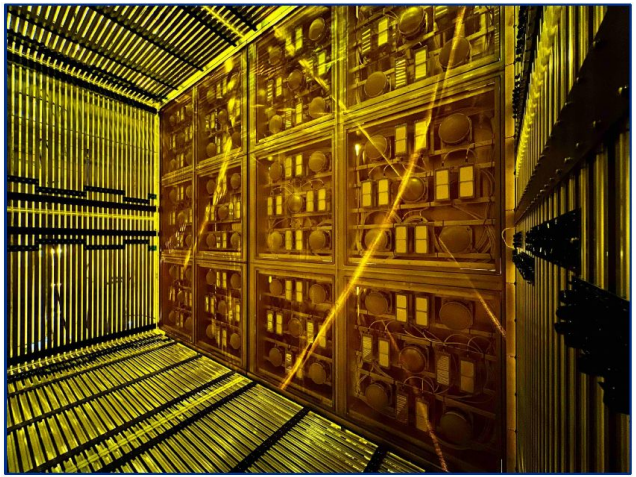
SBND Operations Readiness Review

February 21-22, 2024

Introduction and Outline

- This talk focuses on the Science Goals and Plans of SBND and SBN, i.e. : Why Operate?

- Will focus on tools and readiness for physics analyses, doable after detector is commissioned (Lauren's talk) and calibrated (Mike's talk)
- Outline:
  - SBN(D) main physics goals
  - Who we are (Physics Org Chart)
  - Timelines
  - Status of tools/reconstruction for subsystems/Analyses
  - Plans for near and further future



Science Goals of SBND and SBN

SBND's large detector mass, proximity to the source, and high-performance detector design enables a broad, exciting physics program:

Precision neutrino-nucleus interaction measurements:

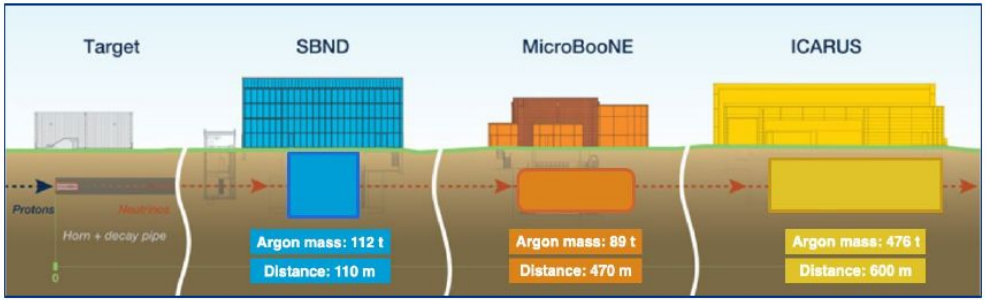
- Differential measurements of high-rate channels (inclusive, single and multi-proton, charged/neutral mesons, etc.) with more than an order of magnitude more ν-Ar data than is currently available.
- High rates of both muon AND electron neutrinos.
- Exploration of low-rate interaction channels not easily studied in smaller data sets (hyperon production, ν-e scattering, etc.)

Tests of Beyond Standard Model scenarios:

- Tests of various models (heavy neutral leptons, Higgs portal scalar models, etc.) in multiple final-states.
- Strong collaboration with theory community and many on-going sensitivity studies.

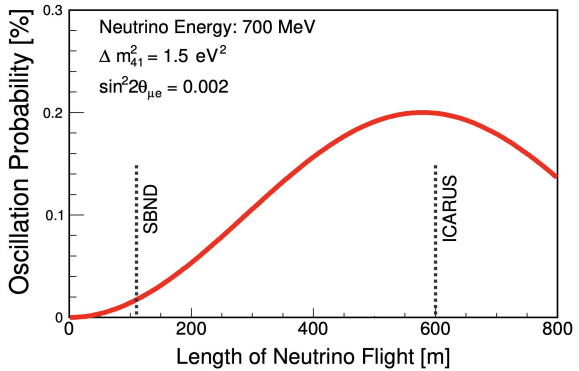
Sensitive searches for sterile neutrino oscillations:

- As the Near Detector in the SBN Program, SBND is the key to mitigating large neutrino flux and cross-section uncertainties.
- Multiple detectors also enables searches in BOTH appearance and disappearance.



Relative Neutrino Interaction Rates (BNB)	23	1	3.3
ν_μ-CC interactions per 1x10^{20} POT (BNB)	625k	27k	90k
ν_e-CC interactions per 1x10^{20} POT (BNB)	4k	0.2k	0.6k

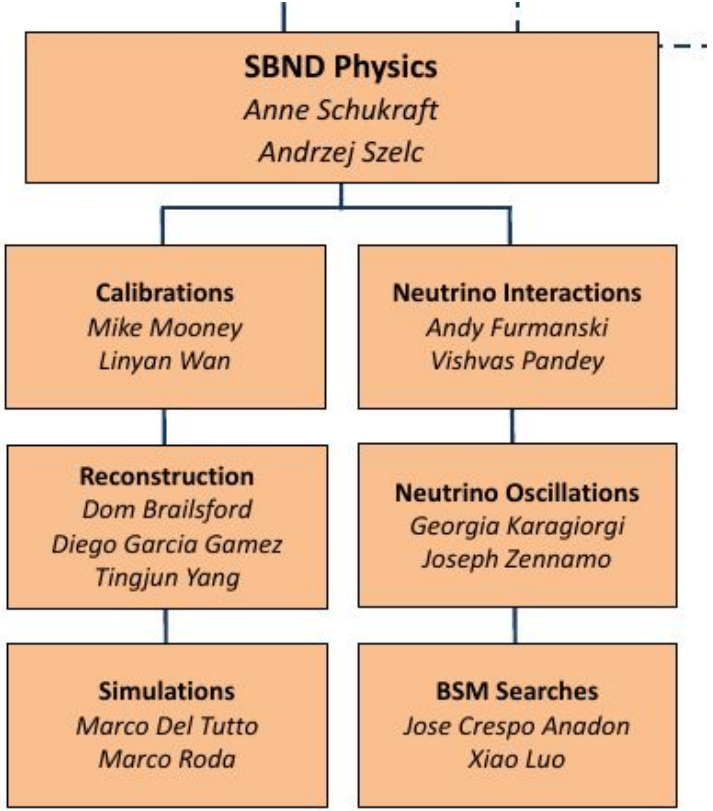
Rates shown for full active TPC masses and integrated over all energies.



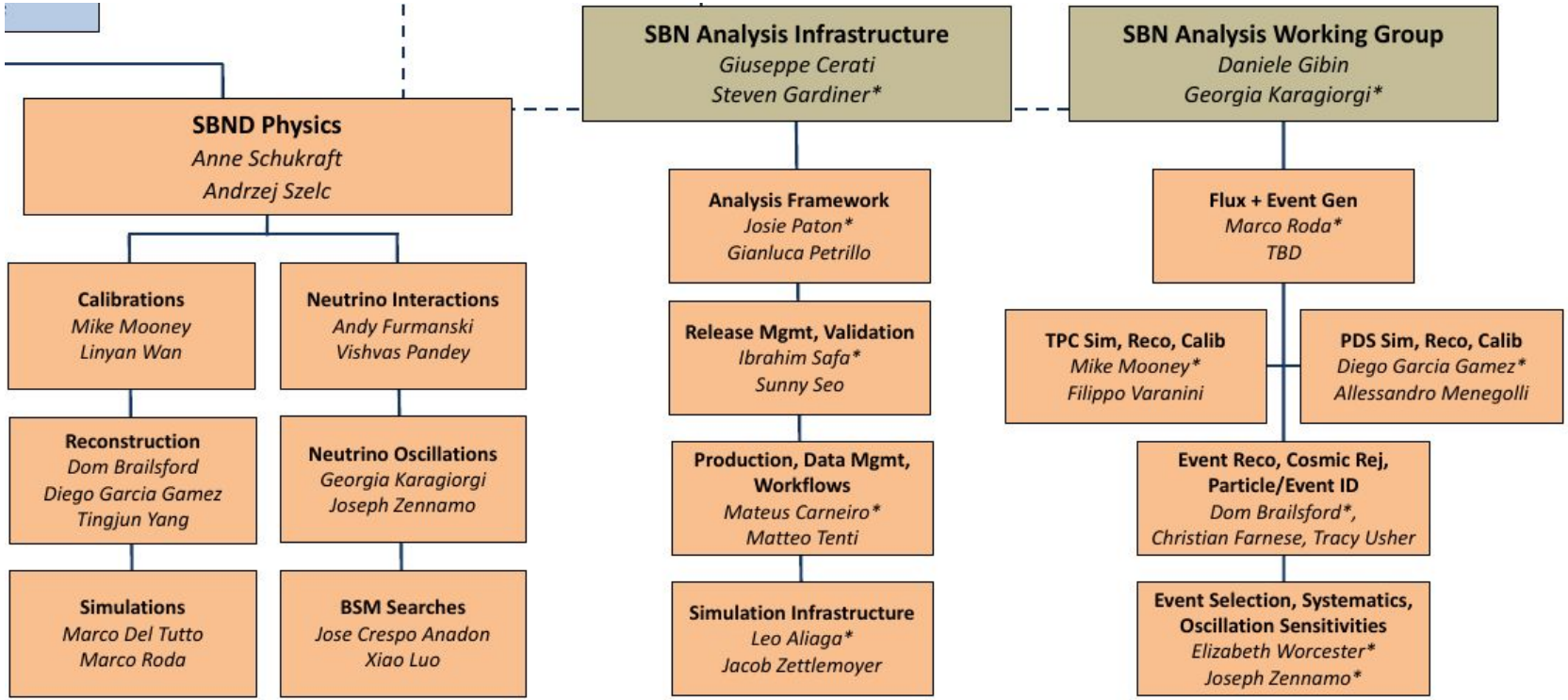
Example sterile neutrino oscillation probability evolution over the SBN baseline

(probability shown near the peak neutrino energy)

Analysis Organization - SBND-physics



Analysis Organization - SBND in SBN

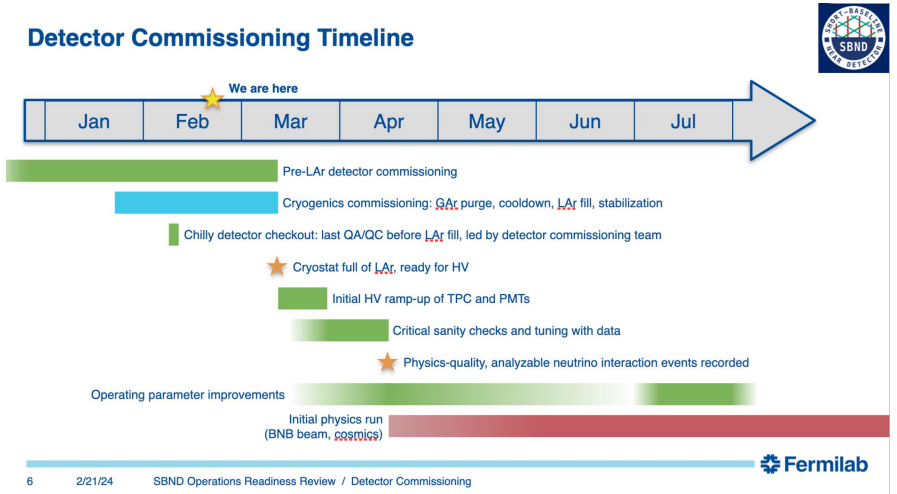


Lots of Activity!

- PhD students and Post-docs driving development of analyses and tools.
- Active participation in the efforts.
- We have held a few dedicated workshops to jump-start/concentrate activity:
  - SBN Analysis (FNAL, Jul 2023)
  - SBND commissioning (FNAL, Aug 2023)
  - SBND Remote Calibrations Workshop (Sheffield, UK, Jan 2024)
- Next ones being planned.

Introduction of Timelines

- Our planning for Physics Results is split into three time periods:
  - **FY24 initial physics run:** Once detector achieves steady/reasonable conditions, plan to take data for detector calibrations, first PhD theses, early publications.
  - **FY25 first full-year Physics run**: During the summer shutdown, the detector will be tuned to optimal conditions for FY25 data taking. This data set will enable many first high-precision measurements.
  - **Until FY27 long shutdown**: The complete data-set will enable full realization of the SBN(D) science program.



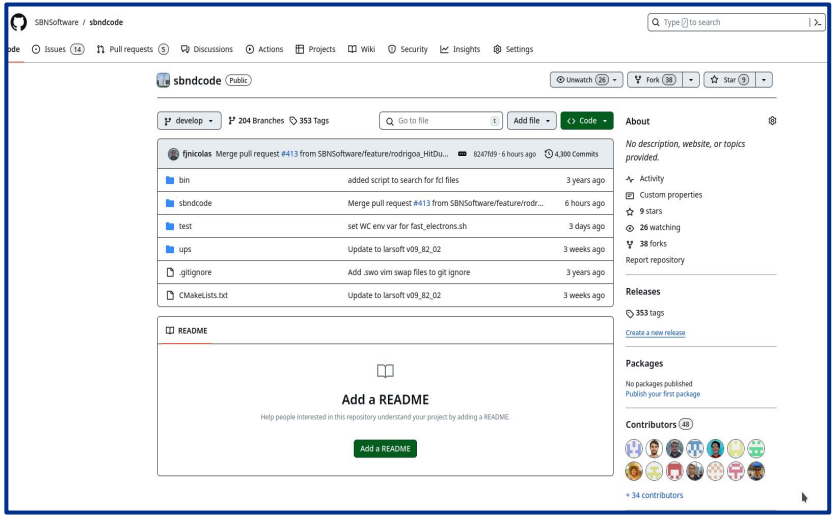
Our tools are already in good shape to analyze the first events.

- ready to write calibration Ntuples and Commissioning trees immediately

Overview of software framework

- LArSoft used to simulate and reconstruct events.
- SBND-specific codes reside in github:sbndcode
  - Inherits from sbncode which is common with ICARUS.
- Simulation chain consists of:
  - generator (e.g. GENIE)
    -> particle tracking (Geant4)
    -> detector simulation
    -> electronics signal convolution.
- Reconstruction chain:
  - deconvolution
    -> “hit” finding
    -> Clustering
    -> 3d object reconstruction
    -> Calorimetry and PID.
- Results stored in CAF (common analysis framework) files for analyzers to use (developed by NOvA, DUNE, used by ICARUS).

more details in S. Gardiner’s talk.

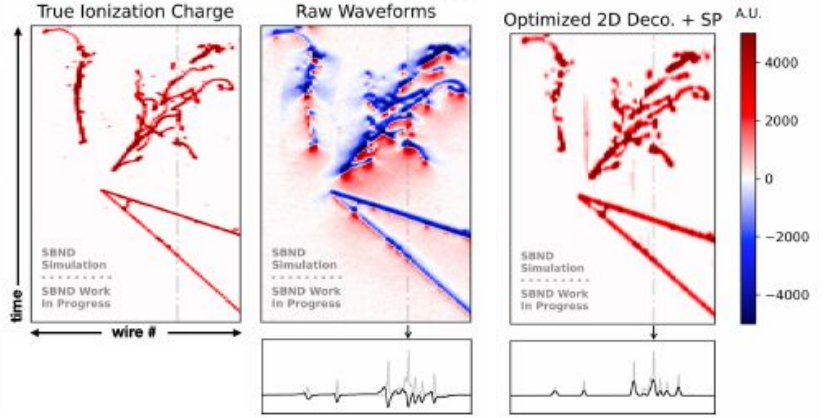


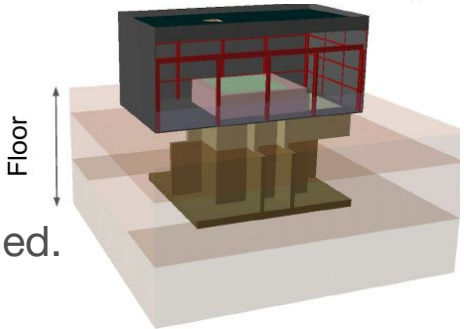
Overview of simulation chain

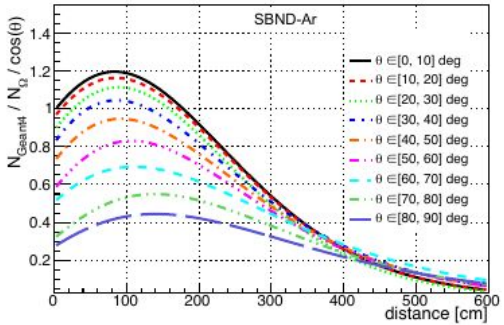
- Flux simulation: BNB simulation is using standard BNB flux files. *Common with ICARUS.*
- Neutrino Interaction simulation: GENIE tune/model in *common with ICARUS.*
- Particle Propagation: One of first experiments to switch to re-factored Geant4.
- Detector Simulation:
  - Infrastructure for 2D induction and deconvolution is in place.
  - Detailed detector geometry model exists.
  - Pioneered use of semi-analytic fast-simulation model for scintillation light.

- Simulation models need data to to be tuned. Hooks are in place to do this (see M. Mooney's talk).

induction view

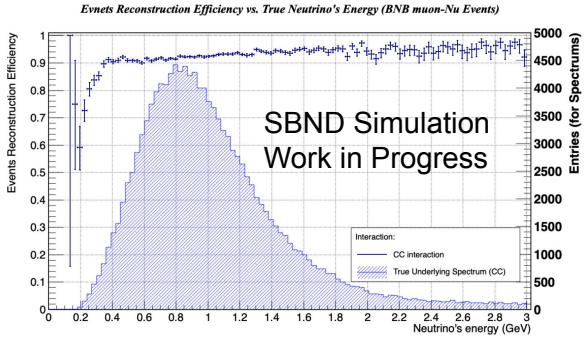


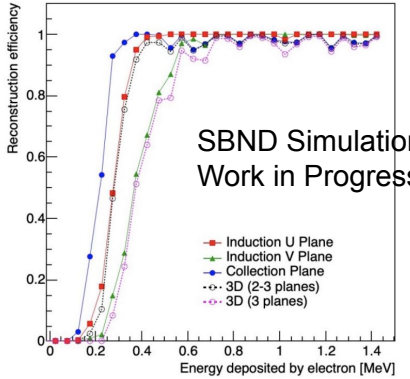


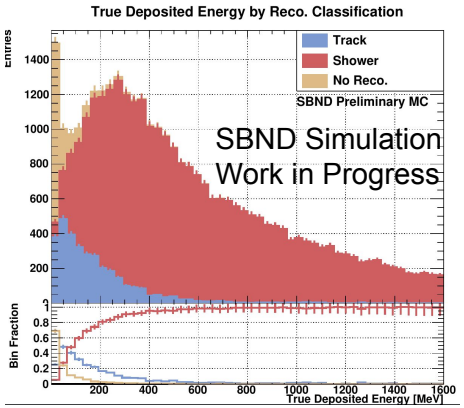


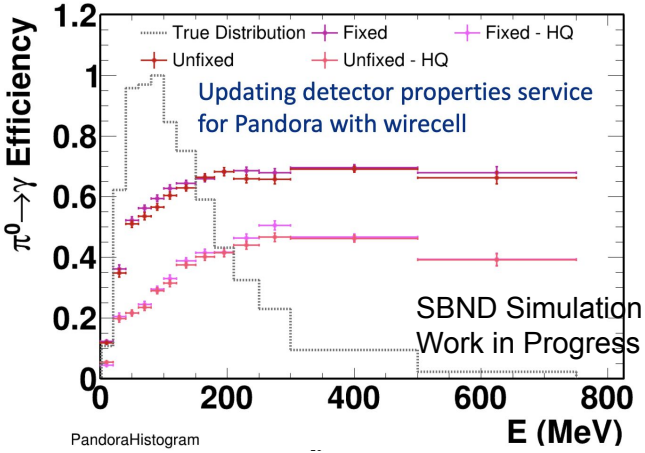
TPC reconstruction

- Pandora is our default reconstruction chain.
- SBND is up-to-date with the “latest and greatest” developments.
- Several developments driven by SBND collaborators.
  - track-shower separation
  - shower reconstruction improvements
- “Blip” reco (ported from uB) down to 200 keV.
- several advanced 3D reco efforts being developed in parallel.





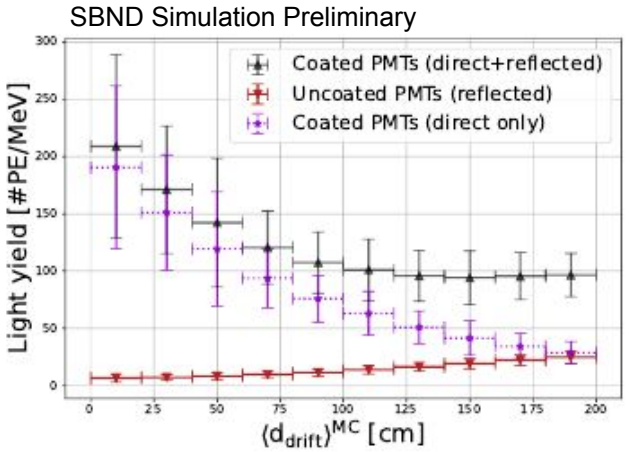




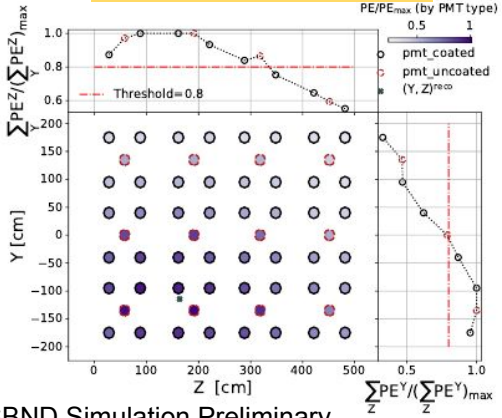
PDS reconstruction

- PMTs are the primary light collection system.
- PDS reconstruction chain is ready for both PMT and X-A:
  - Infrastructure to deconvolve single PE shape is in place.
  - OpHit ad OpFlash finding are ready (may need tuning).
  - Two flash-matching algorithms exist.

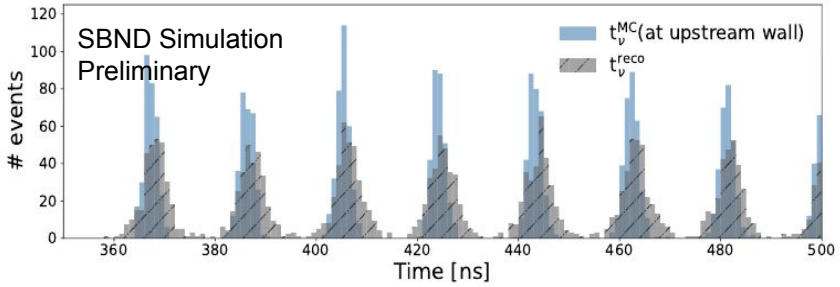
- Full chain exercised on MC:
  - Position reconstruction in all 3 coordinates (10-25cm resolution)
  - Able to reconstruct signal timing to O(2ns)
- Publication in advanced stage (should go to collaboration review imminently).

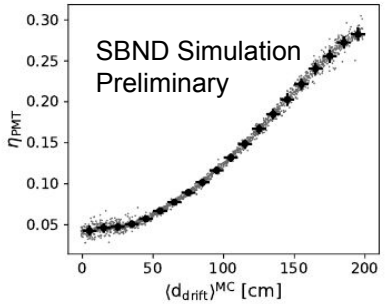


V. High Light Yield



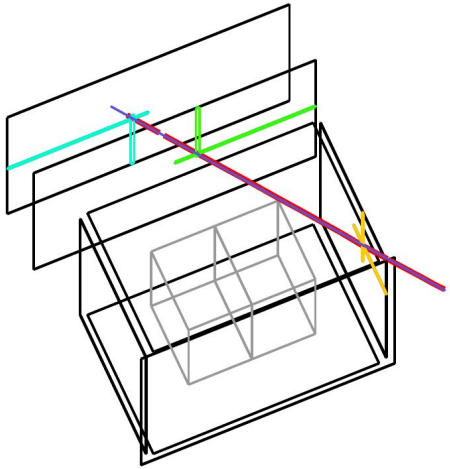
SBND Simulation Preliminary

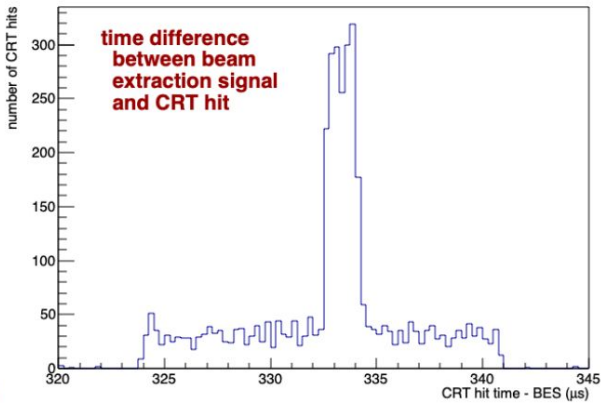


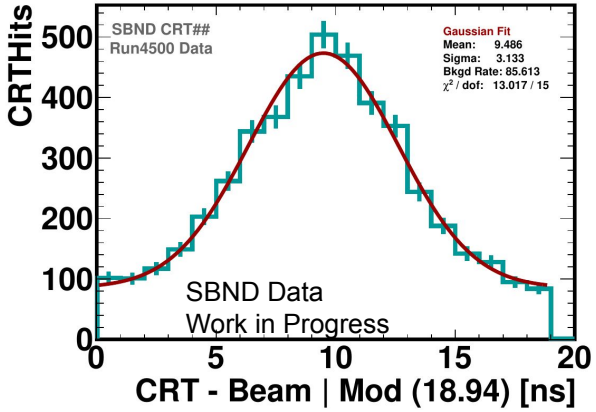


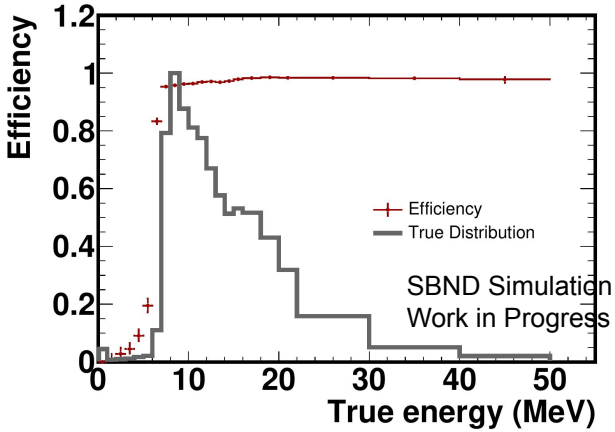
CRT reconstruction

- CRT reconstruction is functional and tested on small CRT test installations (sharp, flat).
- Calibration chain is operational.
- We have already seen neutrinos (and beam buckets).
- Ready to go as soon as it is installed.



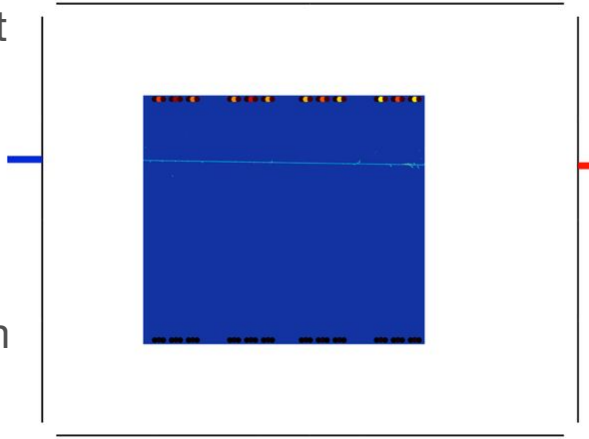


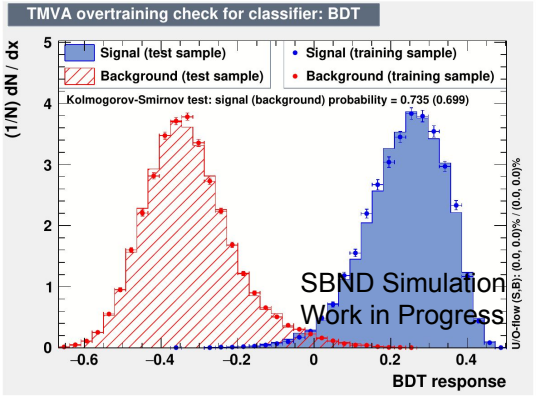


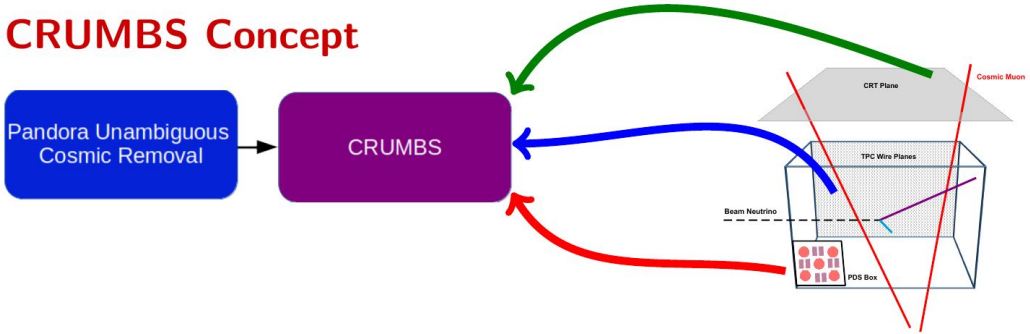


Multi-system event reconstruction

- SBND is the first experiment that will be set up to use the three systems (TPC, PDS and CRT) in analyses from the get go.
- It will change the analysis paradigm and open new possibilities, once the full system is ready.
- We plan to make physics measurements even in the period before the CRT is fully operational:
  - High neutrino/cosmic ratio
  - use light to reject backgrounds
  - focus first on exclusive, contained channels.



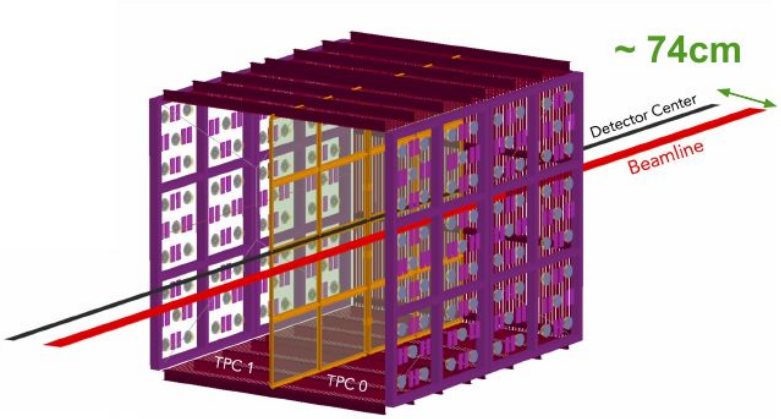


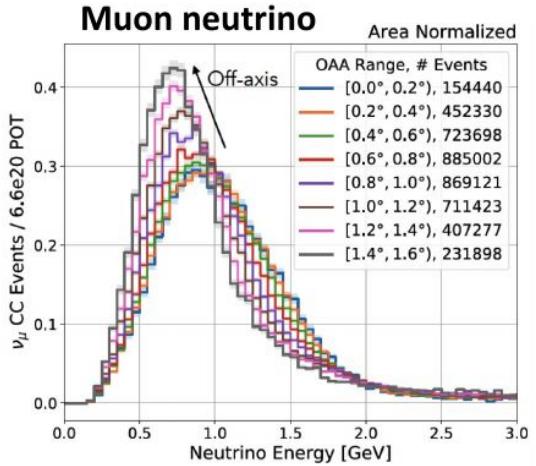


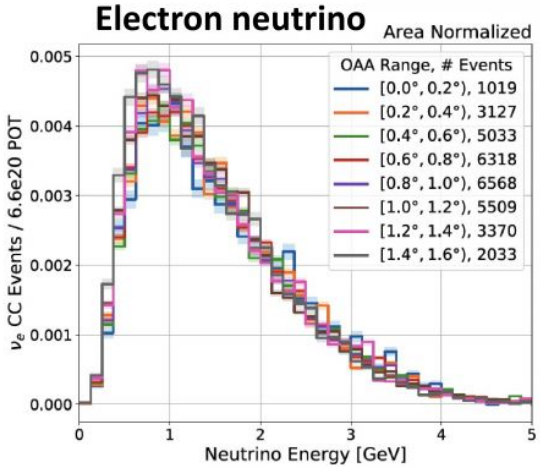
SBND PRISM

With SBND being located very close to the beam target (110m) and slightly off-axis (~74cm), the detector sees a different flux based on position within the detector

- Similar to the DUNE-PRISM concept, but with a fixed detector







SBND-PRISM technique can help with background rejection and systematic constraints in

- oscillation analyses
- BSM searches
- Cross section measurements

Muon and electron neutrino energy distributions are affected differently by the off-axis position

SBND Physics Areas

SBND cross section measurements

SBN Oscillation measurements

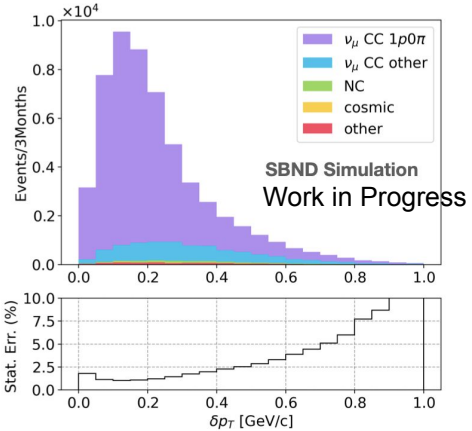
SBND BSM searches

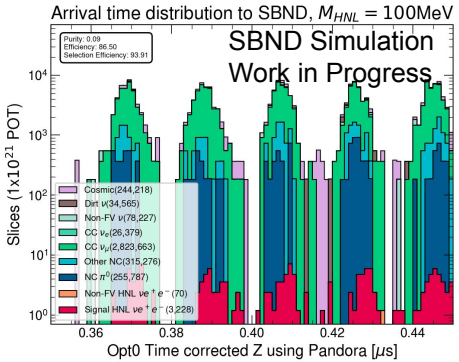
LAr Physics and Technology R&D

SBN(D) Analyses: Status

- First cross-section analysis chains are very mature (culmination of work of multiple generations of graduate students) - first measurements possible in FY24.
- BSM, first focus on HNLs: driving low-energy reconstruction developments, exploit PDS timing precision
- BSM sensitivity paper being prepared (target this summer).
- SBND oscillation analyses share tools with ICARUS. The end-to-end analysis and analysis framework are mature.
- Flux and cross-section uncertainty predictions are well-understood and working smoothly

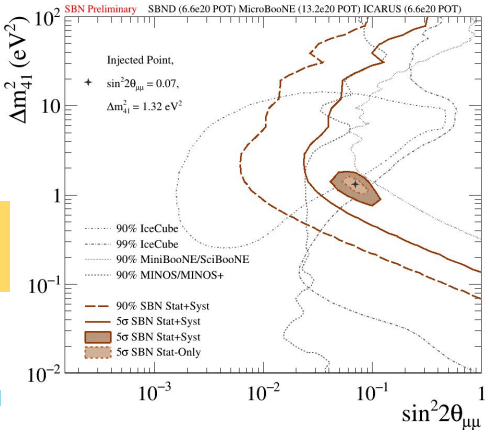
ν_μ CC1p0π





HNL arrival times

ν_μ disappearance



Planning

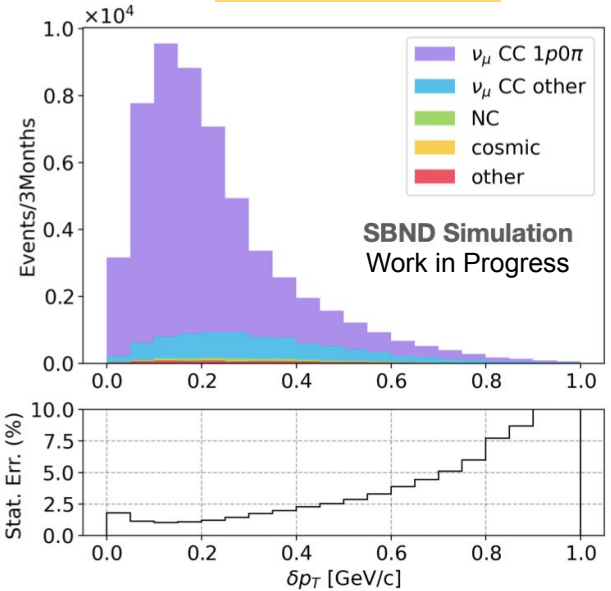
First data & initial run plan

We expect to arrive at a stable detector configuration that will enable us to first physics data this spring.

Even a relatively short run will provide a large number of events. BNB can deliver between 3.5e19 - 5.2e19 POT/month = ~300k ν_μ and 2k ν_e CC events in SBND.

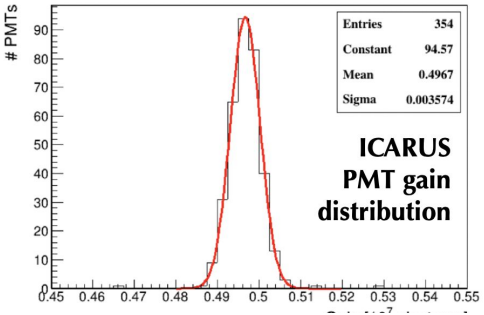
Plan to show first plots at summer conferences. First publications could follow in the early 25 timeframe. These data will be the basis of several PhD theses.

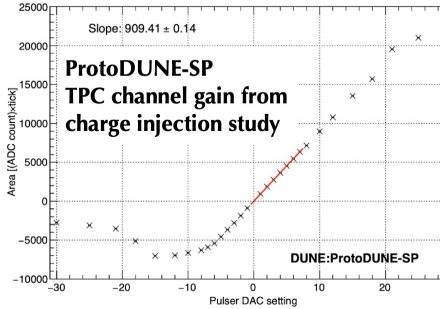
ν_μ CC1p0π

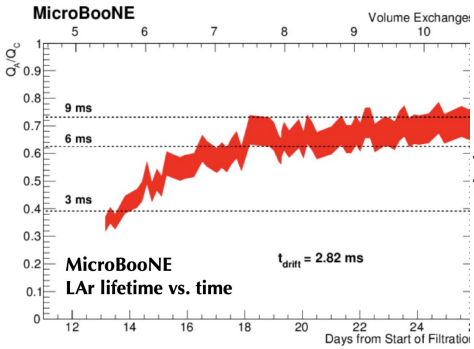


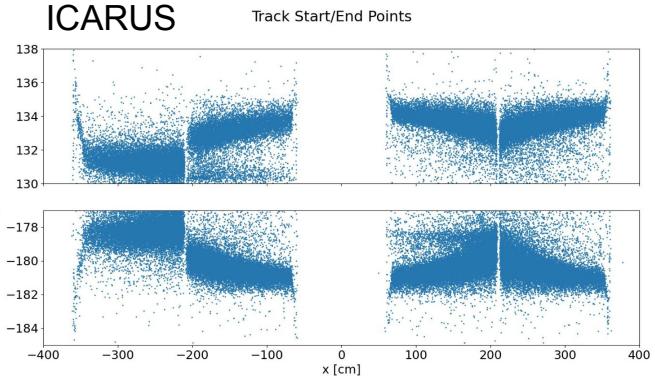
First plots & detector performance paper

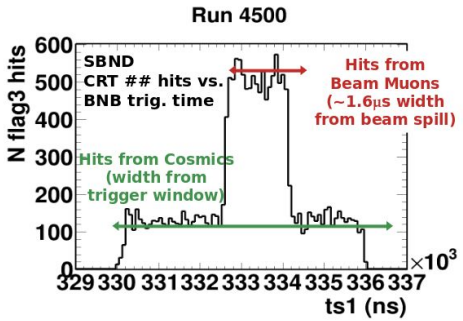
- We plan to publish a detector performance paper, based on the results of the first FY24 data run.
- This will contain many of the results presented in the Commissioning and Calibration talks + overview of first analyses, and e.g. reconstruction performance.
- Inspiration from ICARUS, MicroBooNE and ProtoDUNE papers.











FY25 First Full-Year Physics Run

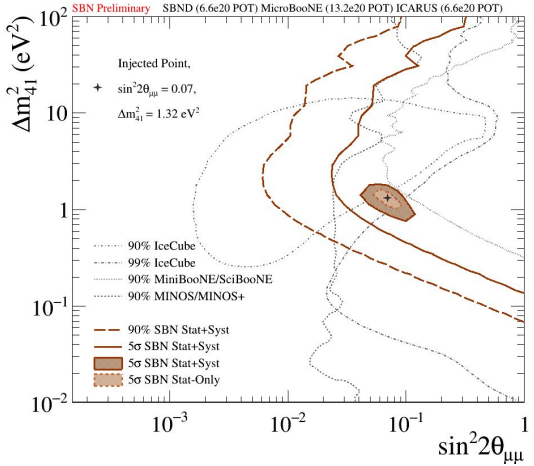
ν_μ disappearance

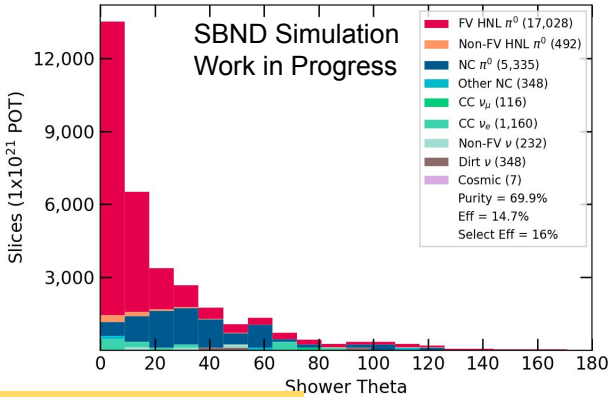
By October, we aim to tune the detector to a level that enables fully optimized physics operations.

First year of running should result in a sample with at least ~2M ν_μ events and ~15k ν_e events. Both largest samples of neutrino interactions on argon to-date.

This data sample will be used for publishing many papers:

- inclusive and exclusive channel differential cross section measurements, including largest sample of nues.
- first BSM searches: e.g. HNLs, Dark Neutrinos
- measurement of the flux constraint for the SBN oscillation





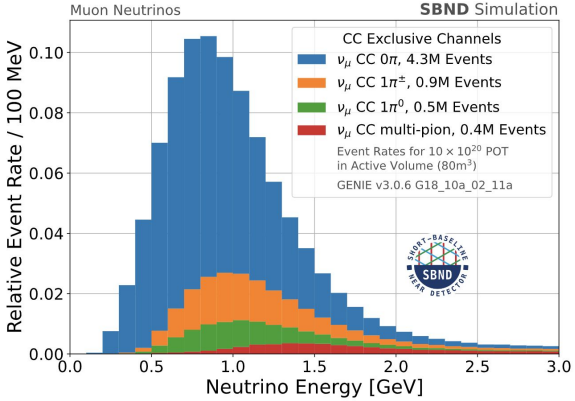
HNL -> π^0 angle

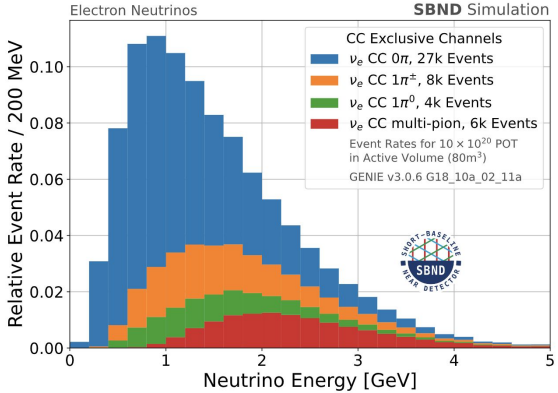
FY25-27 Full Data Set before the Shutdown

A full SBND data set of ~10e20 POT would correspond to ~6.5M ν_μ events and 45k ν_e events.

This will enable precision measurements of many cross-section channels as well as measurements of rare-event channels (e.g. neutrino elastic scattering, hyperon production etc..), pushing the limits of BSM searches, and the full sensitivity SBN oscillation measurements.

We anticipate gradual expansion of the analysis data set, and a steady state of publications.





Conclusions

- Start of SBND operations marks the beginning of the full SBN program at Fermilab!

- Thanks to a tremendous amount of work by our students and post-docs, plus experience from other SBN experiments, the SBND reconstruction and analyses are pretty much ready to go.

- We are the first experiment to switch on with advanced simulation features, reconstruction and event selections. We aim to benefit from this by showing first results by the summer conferences.

- SBND has unique features (PRISM, PDS design, multi-system approach), which combined with an unprecedentedly large neutrino set opens the path to many exciting new physics measurements.

Thank you!

Charge Questions

2. What work remains to prepare the experiment to begin physics data-taking?

a. The installation of the CRT is not expected to be complete at the start of the commissioning period. Is any other work required to complete the assembly of the detector? When will assembly of the full detector be complete? How will this impact the first physics run?

We expect to be able to take physics quality data already in FY24. Despite CRT being only partially installed, we aim to use this data to perform the first set of measurements.

3. Is there a well-understood run plan for the remainder of FY24, consistent with the planned accelerator schedule and performance? Have adequate resources from the laboratory and the collaboration been identified for an efficient and safe running of the experiment and for maintenance of the detector, and have the responsibilities of the collaboration and Fermilab staff been clearly defined?

Once the detector achieves a stable condition, we plan to take beam data opportunistically, while we continue improving detector calibration in preparation for beam in FY25.

4. Are there well-developed plans for data processing and analysis? Have sufficient resources from the laboratory and collaboration been identified to execute these plans?

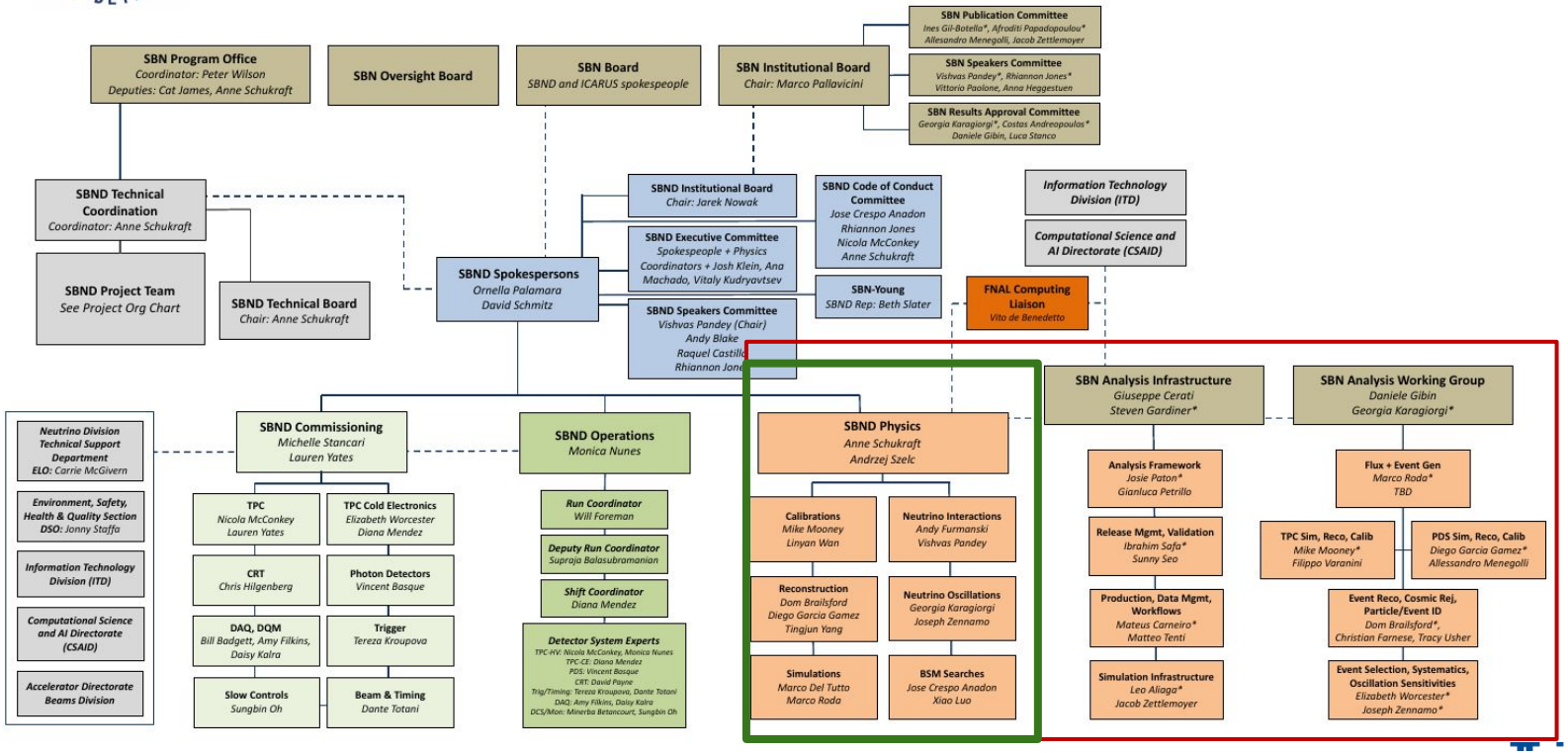
We have a suite of mature cross section, BSM and oscillation selections ready. As well as the simulation, reconstruction and systematic calculation tools to execute them once they are tuned with first data.

5. Are there clear goals set for reporting and publishing the results from the experiment in a timely fashion?

We plan to show first plots at the summer conferences. We anticipate first publications with FY24 data to be ready in the winter. Afterwards we expect to release results as they become mature.

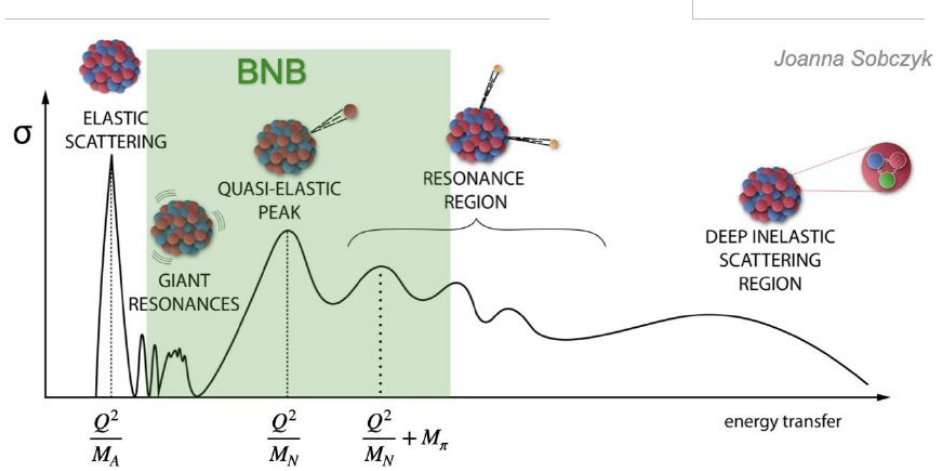
Analysis Organization

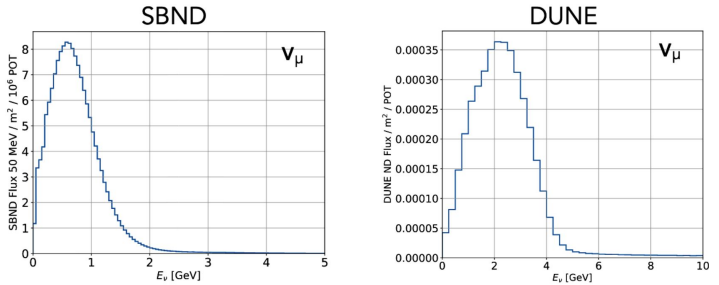
Organizational Chart

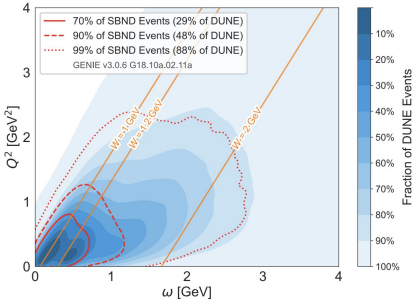


SBN(D) Physics Goals: Cross Sections

- Neutrino-nucleus interactions are complicated! Need to be understood for precision measurements (e.g. oscillations).
- SBND has a unique opportunity to make crucial measurements in this area:
  - extremely high statistics
  - interesting energy range
  - advanced reconstruction.
- In longer term, the proximity to beam will enable previously unavailable rare-event searches.







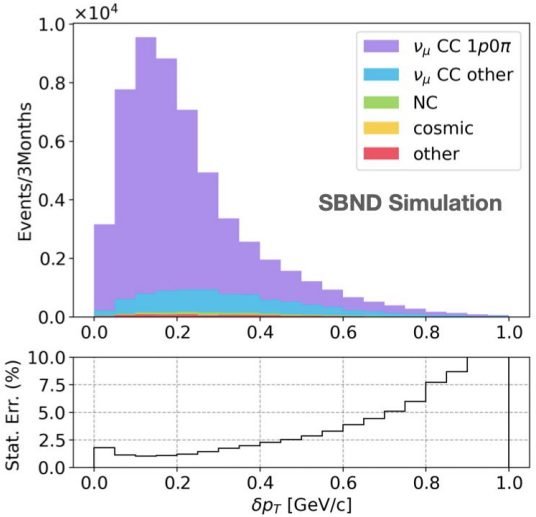
DUNE kinematic coverage is represented with the blue 2D histogram. SBND kinematic coverage is shown with 3 contours, representing 70%, 90%, and 99% of all SBND data.

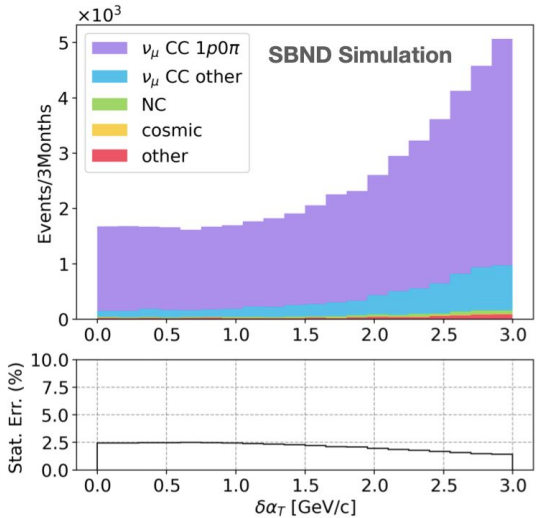
Cross section analysis program

- First analysis chains are very mature (culmination of work of multiple generations of graduate students), examples:

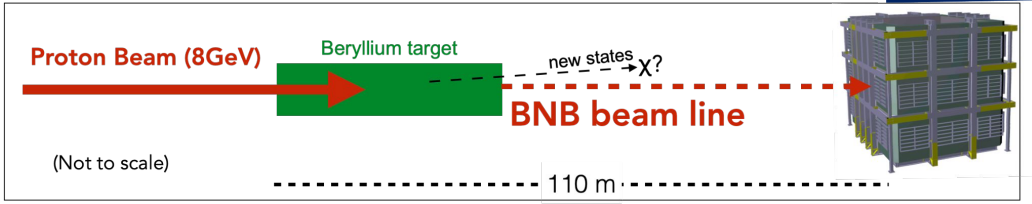
- Numu CC1p0pi Selection:
  - Plot normalised to 3 months of data
  - Shows full event selection (in transverse kinematics) with high-purity

- Nue CC Inclusive and NCπ^0
  - Selections also very mature.





Alternative Explanations for the LEE & beyond

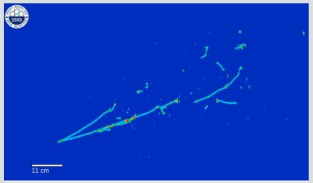


SBND can explore many alternative models that explain the MiniBooNE excess, and other BSM scenarios

We are very actively collaborating with theorists to explore possibilities for searches & capabilities of our detector

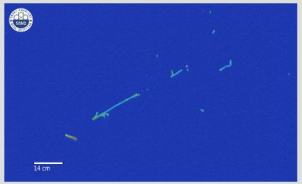
- several models already implemented in our simulation & reco

Dark Neutrinos



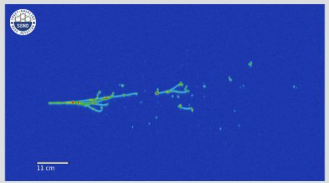
e+e- pair w/ or w/o hadronic activity

Transition Magnetic Moment



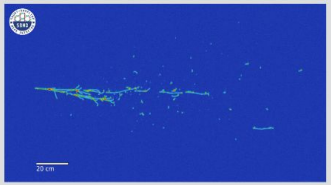
photon shower and hadronic activity

Axion-like Particles



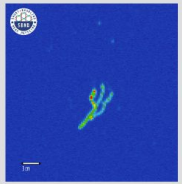
high-energy e^+e^-, $\mu^+\mu^-$

Heavy Neutral Leptons



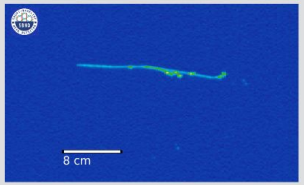
e^+e^-, $\mu^+\mu^-$, $\mu\pi$

Higgs Portal Scalar



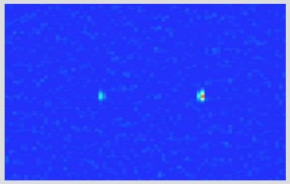
e^+e^-, $\mu^+\mu^-$, no hadronic activity

Light Dark Matter



electron scattering

Millicharged Particles

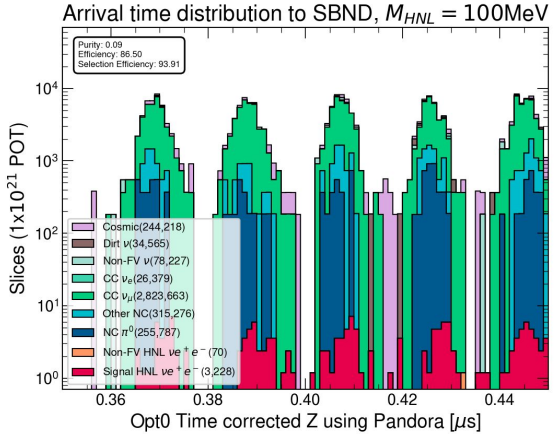


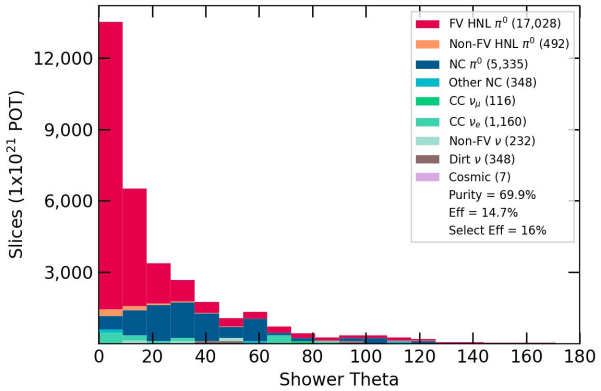
blips/faint tracks

Fermilab

Searches for Physics Beyond the Standard Model

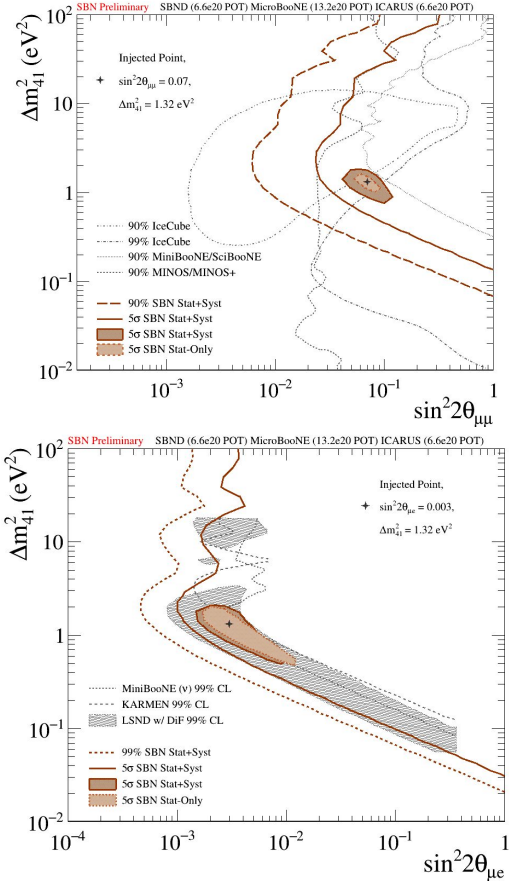
- several analyses under development
  - HNL search in most advanced state
  - Work ongoing on Dark Neutrinos and DM scatters
- BSM searches driving the development of low energy (shower) reconstruction developments, exploit PDS timing precision
- sensitivity paper being prepared by the group (target this summer).
- Most analyses being developed with assumption of first year of data available.





SBN(D) Physics Goals - oscillations

- SBND plays the role of the near detector in the SBN, constraining the flux and reducing the systematic error.
- The SBND Oscillations WG is integrated within the SBN Analysis WG structure, and benefits from close coordination with the SBN Analysis Infrastructure WG.
- SBND oscillation analyses share the tools with ICARUS.
- The end-to-end analysis and analysis framework are mature.
- MC-based selections are continuously optimized
- Flux and cross-section uncertainty predictions are well-understood and working smoothly



Oscillations analysis plan

- The ultimate oscillation analysis would use:
  numu disappearance + nue appearance + nue dissapearance + NC disappearance.
- The intermediate steps to get there go through subsets of channels:
  - st.1 exclusive numu disappearance
  - st.2 inclusive numu disappearance + nue dis/appearance
  - st. 3 and beyond full search, with increasing stats.
- Framework matured and tested on ICARUS data.
- We are capable of propagating selection and systematics through to sensitivity evaluations, and are ready to push forward with detector systematics assessment and incorporation into the sensitivity.
- This rests on detector data, crucially needed to validate our detector model.

Detector conditions over time

Initial Physics Data (FY24)

We expect the data to enable physics analyses out of the box

- Good TPC cold electronics noise level
- PMT gain values roughly aligned with reasonable spread
- Partial X-ARAPUCA system
- Partial CRT installation (bottom and downstream/North wall initially)
- Some Trigger background rejection possible (1 in ~20 events with a neutrino interaction with an “every beam spill” trigger)
- Stable DAQ running
- Exposure accounting capability

Detector conditions over time

Initial Physics Data (FY24)	High-quality Physics Data (Fall 2025 onwards)
• Good TPC cold electronics noise level	• TPC cold electronics noise level: tuned to excellent level
• PMT gain values roughly aligned with reasonable spread	• PMT gain values stable and maintained with a small spread
• Partial X-ARAPUCA system	• X-ARAPUCA system fully installed, commissioned and calibrated
• Partial CRT installation (bottom and downstream/North wall initially)	• Complete CRT installation including both top layers, fully commissioned
• Some Trigger background rejection possible (1 in ~20 events with a neutrino interaction with an “every beam spill” trigger)	• Trigger fully operational and capable to simultaneously run multiple event trigger types
• Stable DAQ running	• DAQ maximum sustainable output rate
• Exposure accounting capability	• Sophisticated Exposure accounting capability