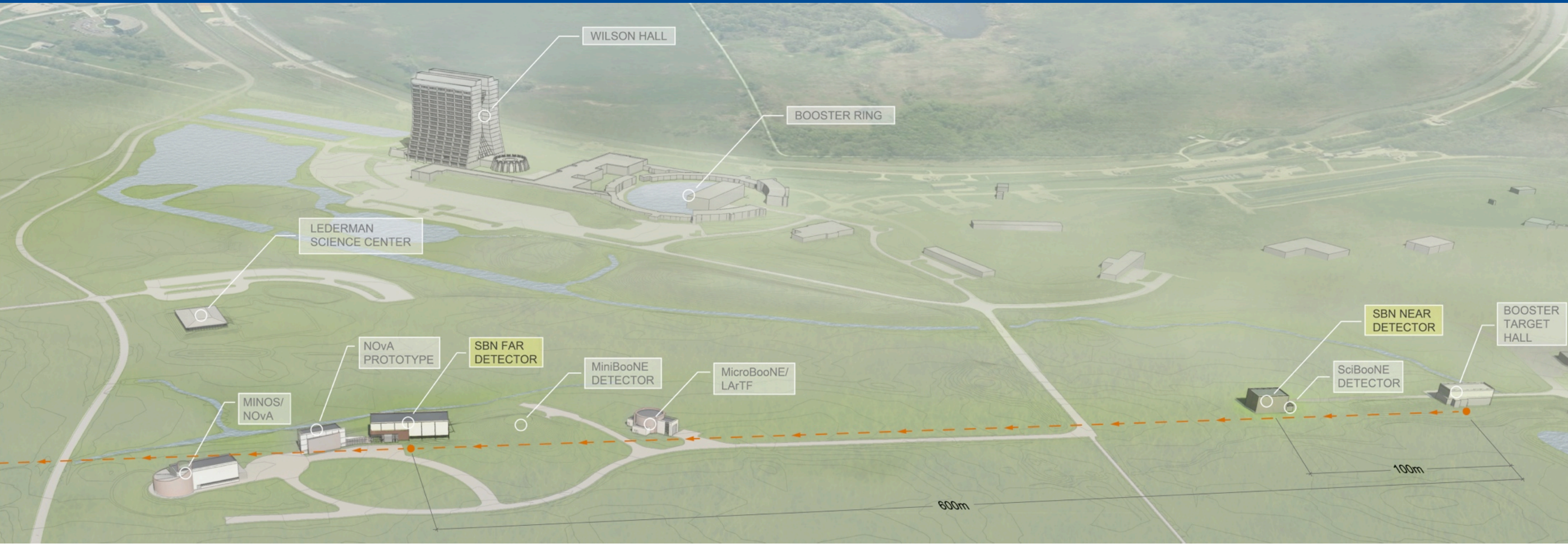


Report on the SBN Analysis Group

PAC Meeting

Fermilab, January 16th 2019

Ornella Palamara, Daniele Gibin

Outline

- SBN joint Efforts
  - Joint Technical Working Groups
  - Analysis Group
    - Goals & Strategy
    - Update since the July 2018 PAC meeting
      - Group Organization & Tasks
      - Oscillation Analysis Strategy & Deliverables
      - Milestones and Timeline to update the SBN sterile neutrino oscillation physics sensitivity
- Summary

Joint Efforts across the SBN program

- Joint Efforts across the SBN program are key to the success of the program
  - Exploit synergies.
  - Share expertise from different groups.
  - Reduce the effort of the single Collaborations.
  - Minimize systematic effects that impact the final oscillation analysis.
- **SBN Joint Working Groups**
  - *Purpose*: co-develop many key aspects of SBN detector operations and physics analysis.
  - *Membership*: the Working Groups are open to all participants to the SBN Program.

SBN Joint Working Groups

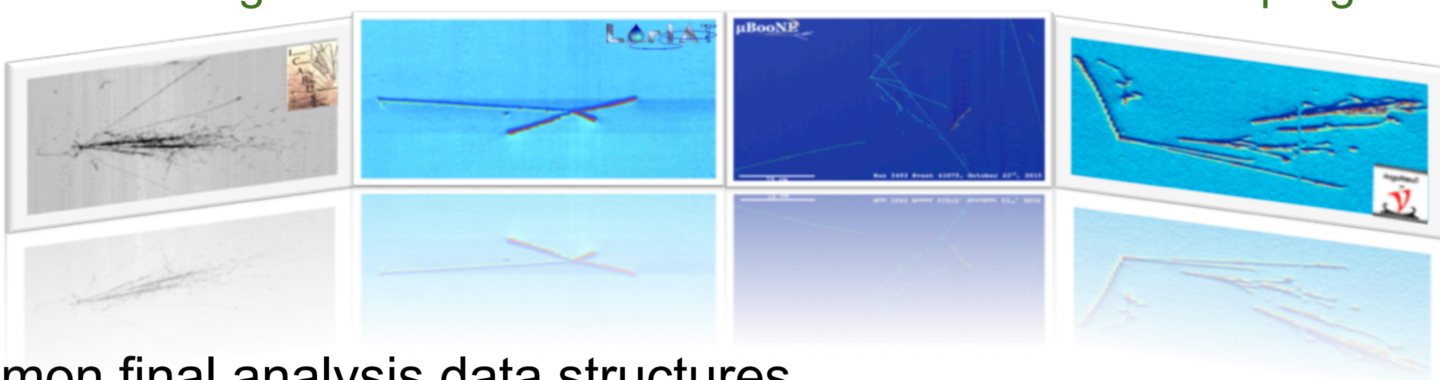
- Existing Working Groups
  - SBN DAQ and Data Pre-Processing *(conveners: B. Badgett, A. Fava, W. Ketchum, S. Ventura)*
    - *Scope*: Identify areas of common effort on **trigger, data acquisition and data pre-processing**, and coordinate activities in those areas.
  - SBN Slow Controls *(conveners: A. Fava, S. Gollapinni)*
    - *Scope*: Develop a **control system** based on hardware and software interfaces as much as possible identical for the two detectors.
  - SBN Cosmic Ray Tagger *(conveners: U. Kose, I. Kreslo, B. Wilson)*
    - *Scope*: Review the **CRT production status and the installation plans for the two detectors**, develop common CRT **DAQ and data output format** (together with the SBN DAQ WG), develop **common CRT monitoring**.
  - SBN Data Management *(*very recently formed, *convener: W. Ketchum)*
    - *Scope:* Review computing resources and needs for SBND and ICARUS, and define a **model for SBN computing**. Collaborate with the Fermilab Scientific Computing Division to develop an **implementation of the SBN computing** strategy.
  - SBN Analysis *(see next slides)*

SBN Analysis Group *(conveners: D. Gibin, O. Palamara)*

- The SBN Analysis Group is responsible for all aspects of the combined, **multi-detector** physics analysis for sterile neutrino oscillation searches at SBN.
- *Scope:* Explore how the combined SBN physics analysis for sterile neutrino oscillation searches can be most effectively performed.
- *Goal*: Develop **simulation/reconstruction/analysis methods** and **tools** to perform the SBN oscillation analyses.
- Work focuses on
  - Implementing a **multi-detector** simulation.
  - Building reconstruction and analysis tools within a common framework (**LArSoft**).
  - Developing an end-to-end common analysis scheme in preparation for real data exploitation.

SBN Analysis Group – Software Strategy

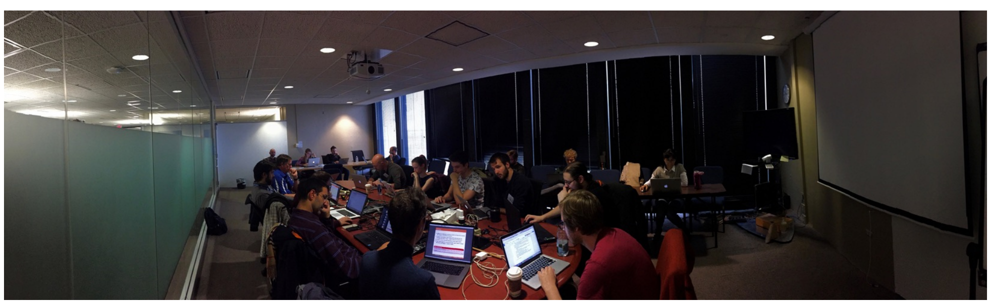
- SBN software tools are all incorporated in **common frameworks** and are based on **common tools**
  - Common reconstruction strategies
    - Application could be detector specific where necessary (e.g. signal processing and noise).
- Capitalize on what has already been developed for LAr TPC signal processing and event reconstruction by previous experiments (ArgoNeuT, LArIAT, ICARUS and MicroBooNE). Shared code in **LArSoft**.
  - Develop reconstruction strategies for SBN detector data, and asses the systematic effects at the few % level.
  - Is the existing/available reconstruction sufficient for the SBN program?

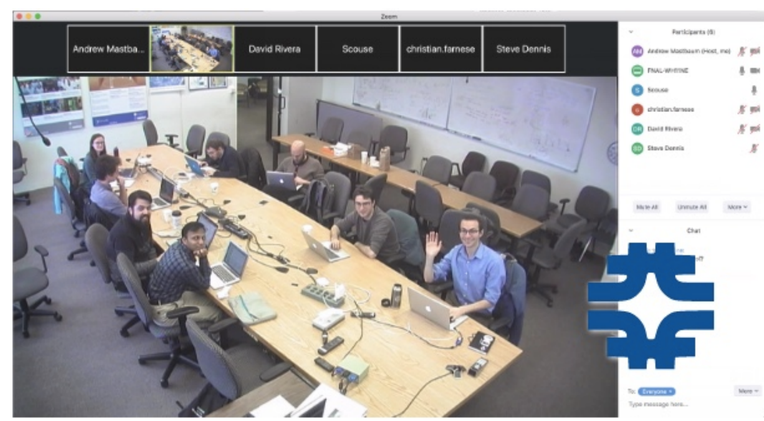


- Common final analysis data structures
  - Controlled in a centralized SBN-wide repository (**sbncode**).

SBN Analysis Group – Meetings

- Meet bi-weekly since September 2016, with typically 30+ participants *(SBN collaborators interested in contributing to the oscillation analysis, and Fermilab computing and beam experts).*
- SBN analysis workshops to facilitate discussion and side-by-side work of SBN Collaborators (*"work-together" scheme*)
  - *Fermilab, October 2017*
  - *Padua, March 2018*
  - *2019: planning to have one workshop in the UK (Spring) and one at Fermilab (Fall).*
- *Fermilab, December 4-5 2018*: SBN Analysis Software Workshop/Hackathon





SBN Analysis Group – Update since the July 2018 PAC

- With the ultimate *goal* of **updating the projections of expected physics capabilities of the SBN program**
  - Generating common MC samples with the current software packages.
  - Including updated reconstruction efficiencies, performances and systematic effects, background rejection from a full MC simulation of the detectors.
  - Combining appearance and disappearance channels.
  - Exploiting different models with multiple sterile states and exclusive topology measurements.
- An **internal organizational structure** with sub-groups working on specific reconstruction and analysis topics has been formed
  - Starting from the informal structure of subgroups already successfully adopted during the past SBN Analysis workshops, and formalizing it by identifying tasks and people involved.
  - **Several analysis sub-groups** are charged with handling important elements of SBN analysis development.
  - Each sub-group has two co-conveners (an ICARUS and a SBND expert).
- **Deliverables, Milestones and timeline** to update the SBN oscillation sensitivity have been defined.

SBN Oscillation Analysis Group Organizational Chart

SBN Analysis Working Group

Convener: Daniele Gibin
Convener: Ornella Palamara

Neutrino Event Generators
(Simulation and tuning on SBN data)
Convener: Jarek Nowak
Convener: Marco Roda

MC Production
(Consistent generation of different type of events)
Convener: Maya Wospakrik
Convener: Dom Brailsford

Track Reconstruction in TPC
(Consistent clustering, vertexing, track reconstruction)
Convener: Tracy Usher
Convener: Jonathan Asaadi

Shower Reconstruction in TPC
(Consistent shower ID, vertexing, and reconstruction)
Convener: Yun-Tse Tsai
Convener: Dom Brailsford

TPC Simulation and Calibration
(Consistent hit/charge reconstruction, dQ/dx->dE/dx, lifetime and space charge measurements and cross-validation)
Convener: Filippo Varanini
Convener: Mike Mooney

Commissioning liaisons: Angela Fava , Michelle Stancari

CRT Simulation & Reconstruction
(CRT signals, timing, CRT-TPC matching)
Convener: Umut Kose
Convener: David Lorca

Light Detection Systems Simulation & Reconstruction
(LDS signals, timing, LDS-TPC matching)
Convener: Alessandro Menegolli
Convener: Diego Garcia Gamez

Analysis Software
(sbncode - General tools for event selection and analysis)
Convener:
Convener: Andy Mastbaum

Event Selection, Cosmic ID and Rejection
(Triggers, PID, consistent combination of TPC, CRT and LDS, cross-validation on exclusive channels)
Convener: Christian Farnese
Convener: Andrzej Szelc

Systematics and Oscillation Sensitivities
(Consistent evaluation of flux, cross-sections and detector systematics, tools to evaluate oscillation sensitivities)
Convener: Daniele Gibin
Convener: Costas Andreopoulos

10 sub-groups

SBN Analysis Group - Sub-groups

- The mission of each subgroup, within its proper domain, includes:
  - Ensure the closest possible **commonality** in simulation, reconstruction and analysis between the two detectors.
  - Develop procedures to **cross-calibrate** and **cross-check** the efficiencies and backgrounds in the near and far detectors.
  - Check that the difference between the detectors and their running condition (**systematics**) are properly understood and handled.
- Sub-groups have defined milestones and timescales relative to their specific domains and have regular meetings.
- Activities progress in parallel within the sub-groups, and there is continuous **sharing of information** through regular presentations of the status of the activities/discussions within the different subgroups at the joint SBN Analysis Group meetings.
- SBN Analysis Group wiki page *(being developed)*
  https://cdcvs.fnal.gov/redmine/projects/sbn-analysis-group/wiki

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Simulation,
Reconstruction
and
Analysis Tools

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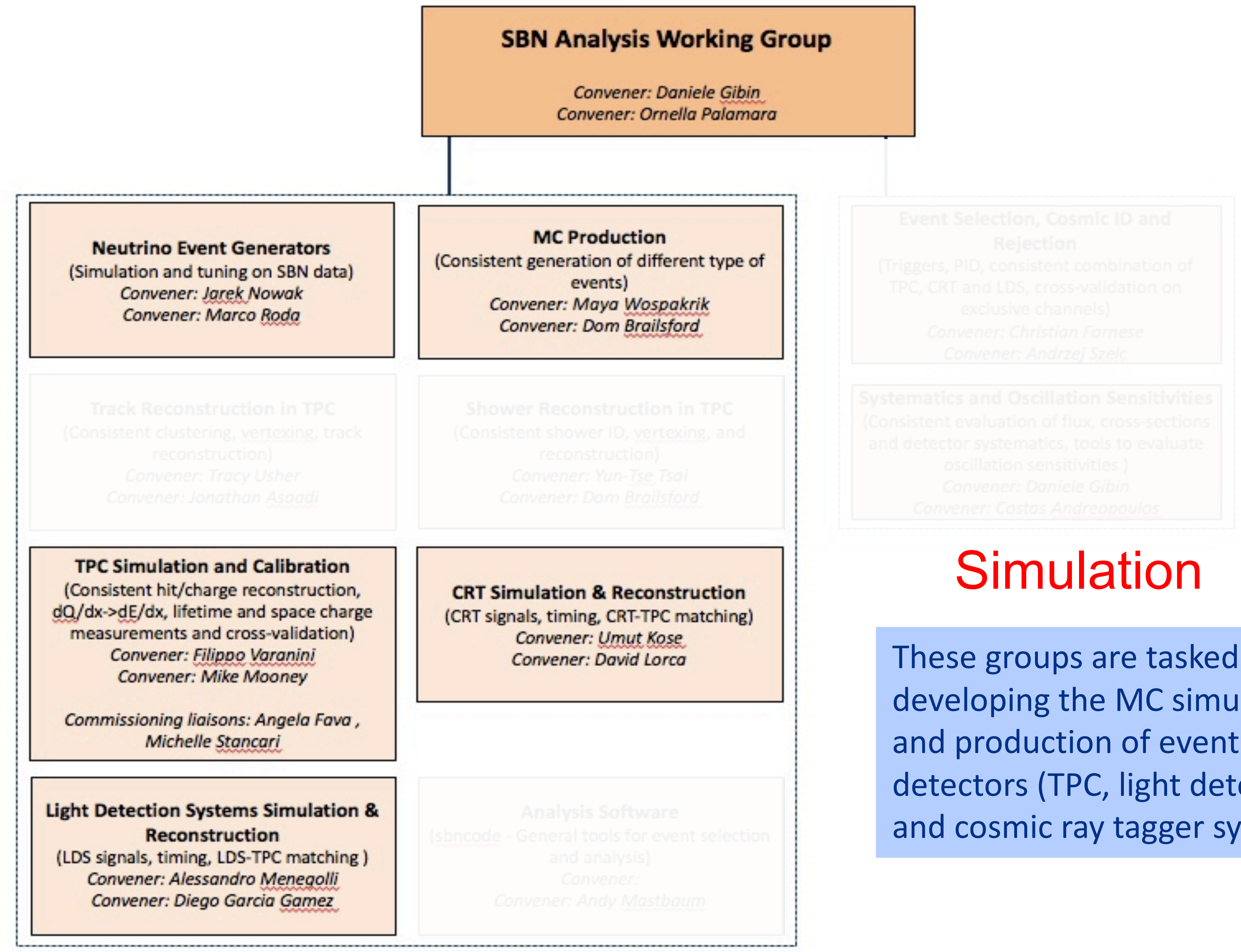
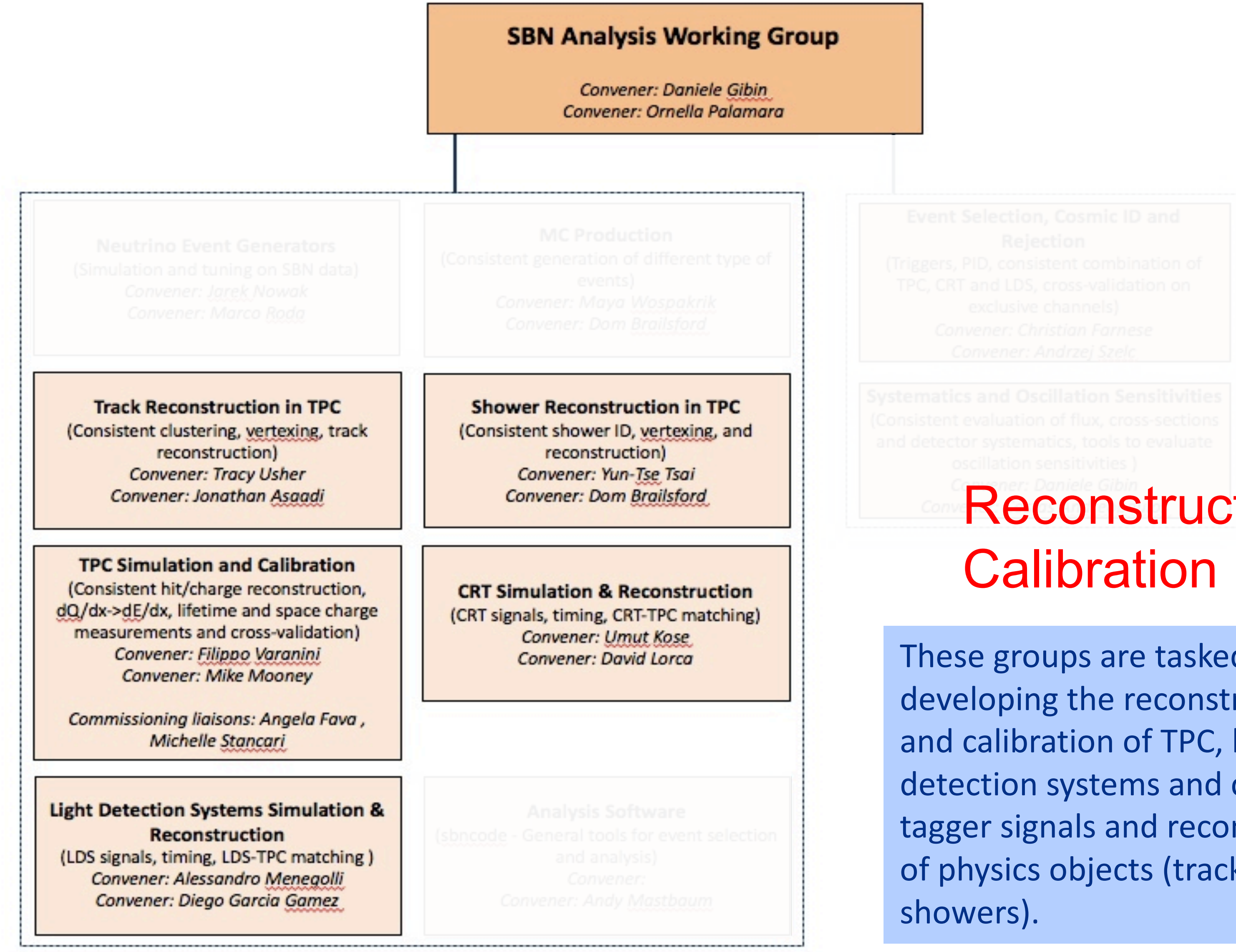


Simulation

These groups are tasked with developing the MC simulation and production of events in the detectors (TPC, light detection and cosmic ray tagger systems).

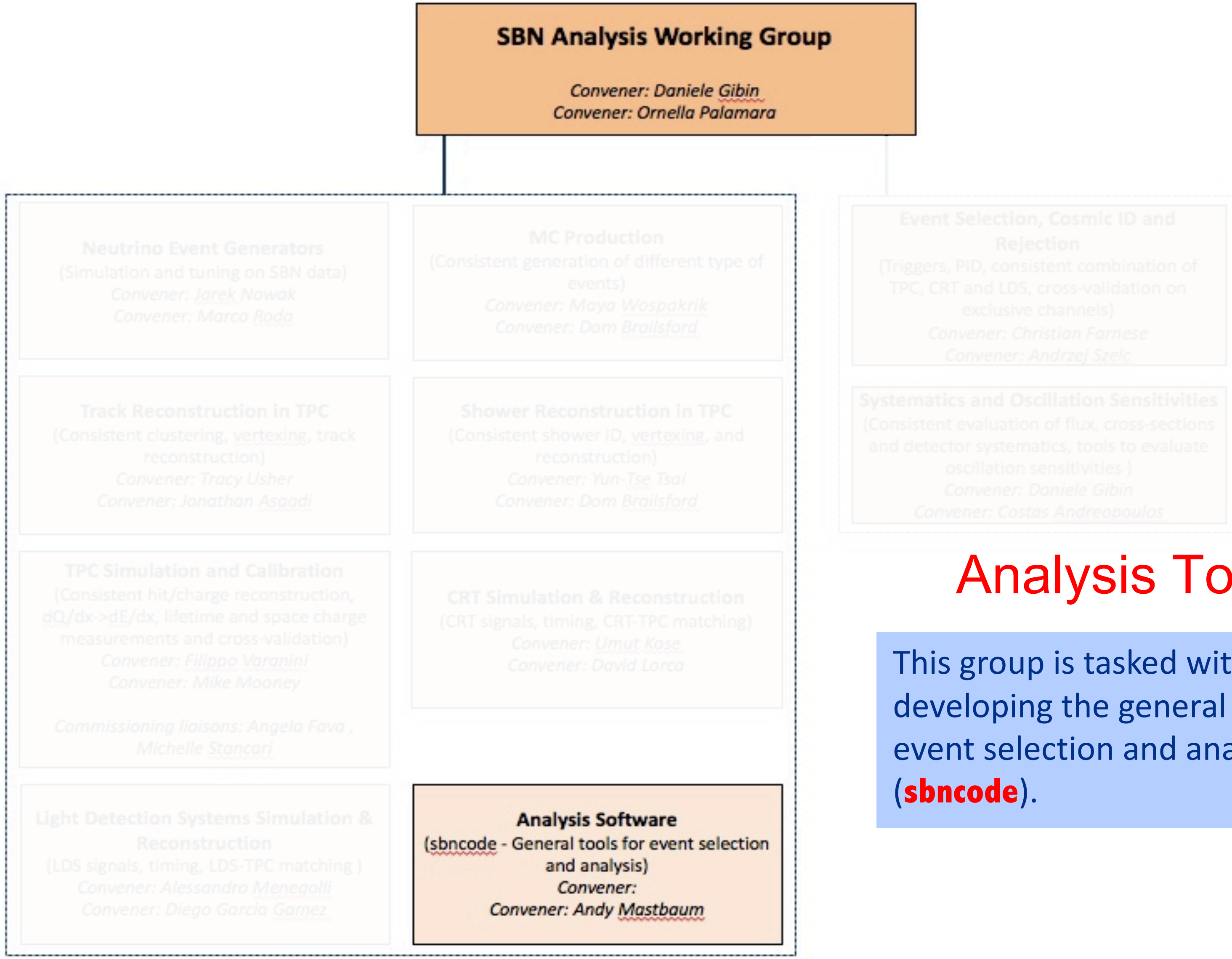
SBN Oscillation Analysis Group Organizational Chart



Reconstruction & Calibration

These groups are tasked with developing the reconstruction and calibration of TPC, light detection systems and cosmic ray tagger signals and reconstruction of physics objects (tracks and showers).

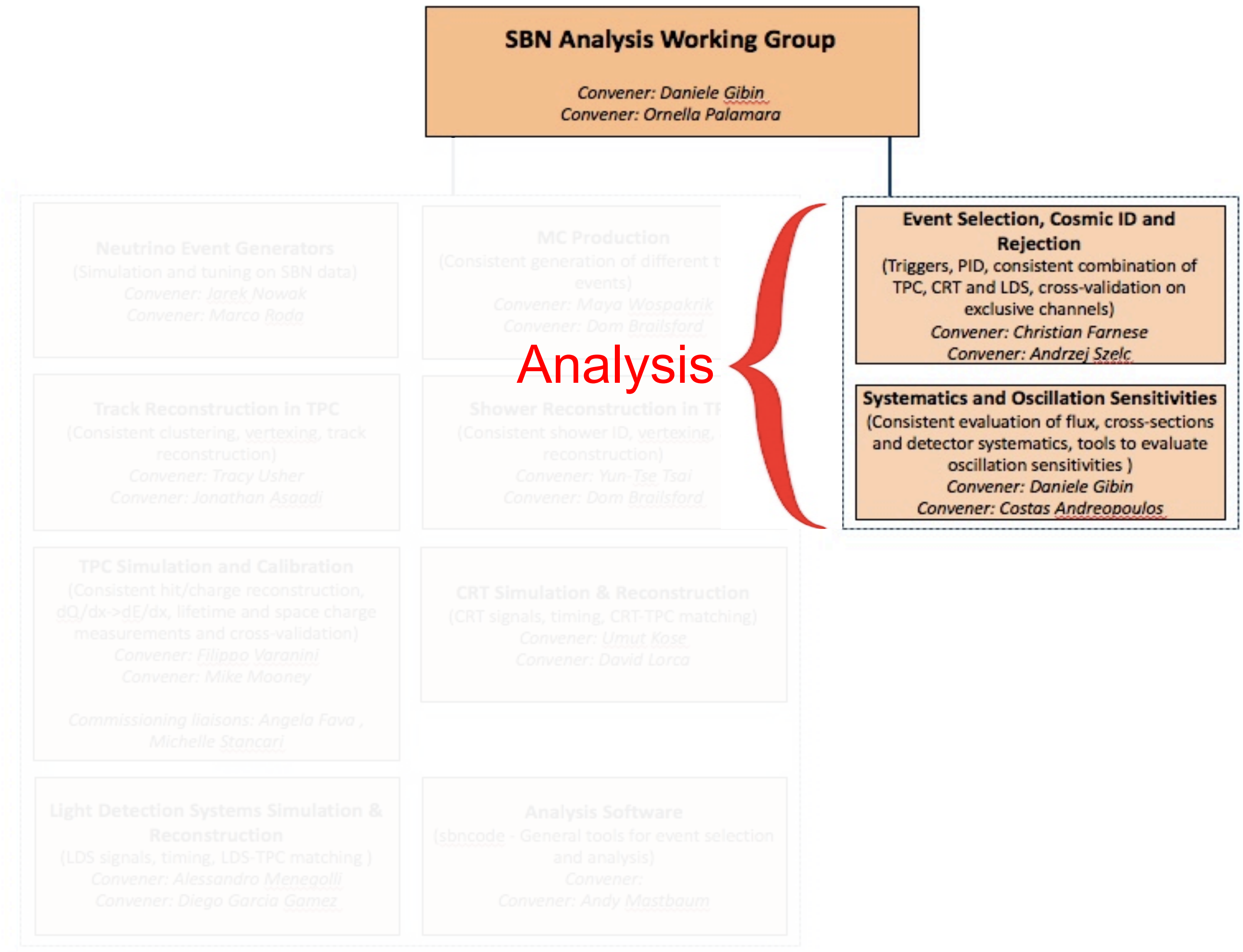
SBN Oscillation Analysis Group Organizational Chart



Analysis Tools

This group is tasked with developing the general tools for event selection and analysis (**sbncode**).

SBN Oscillation Analysis Group Organizational Chart



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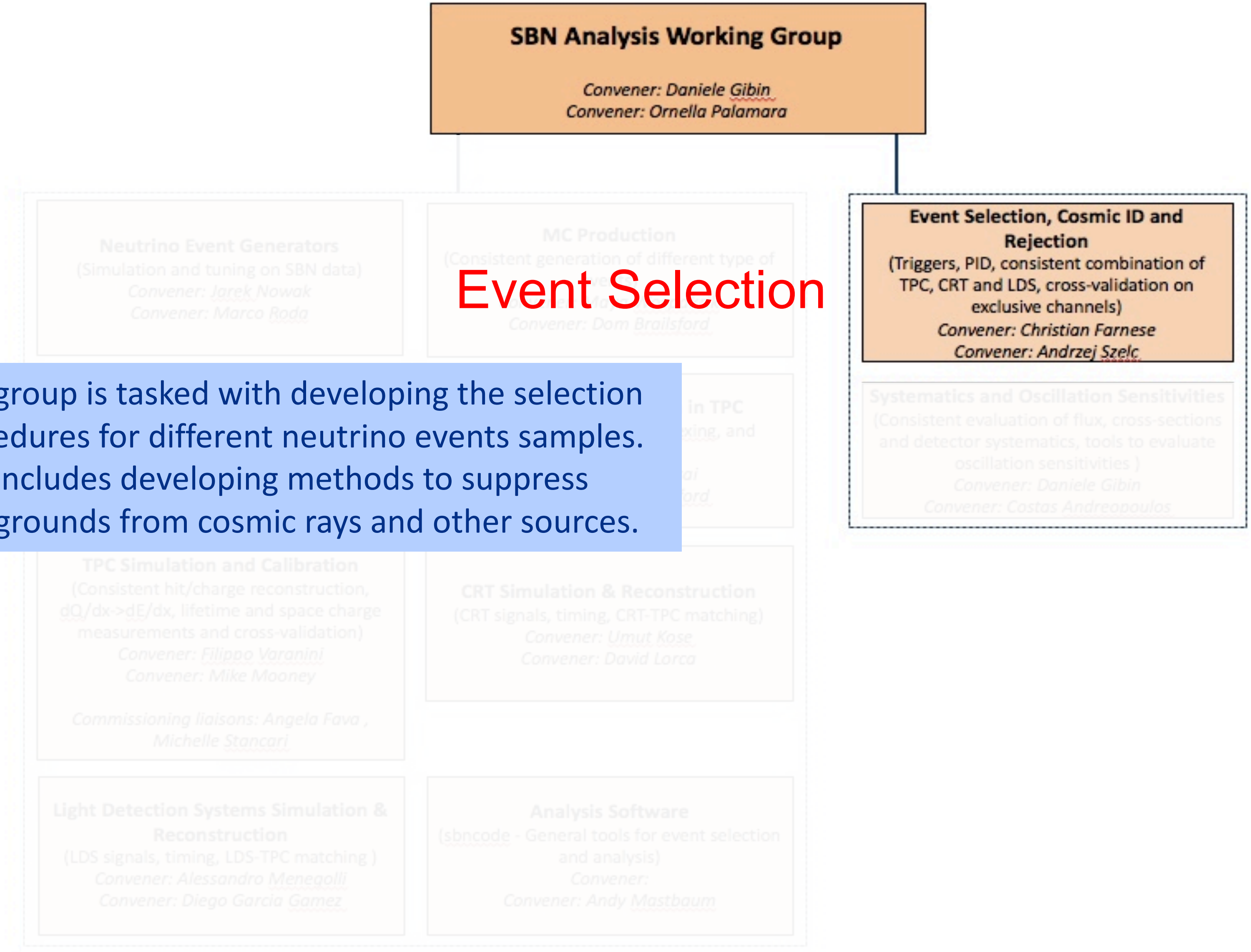
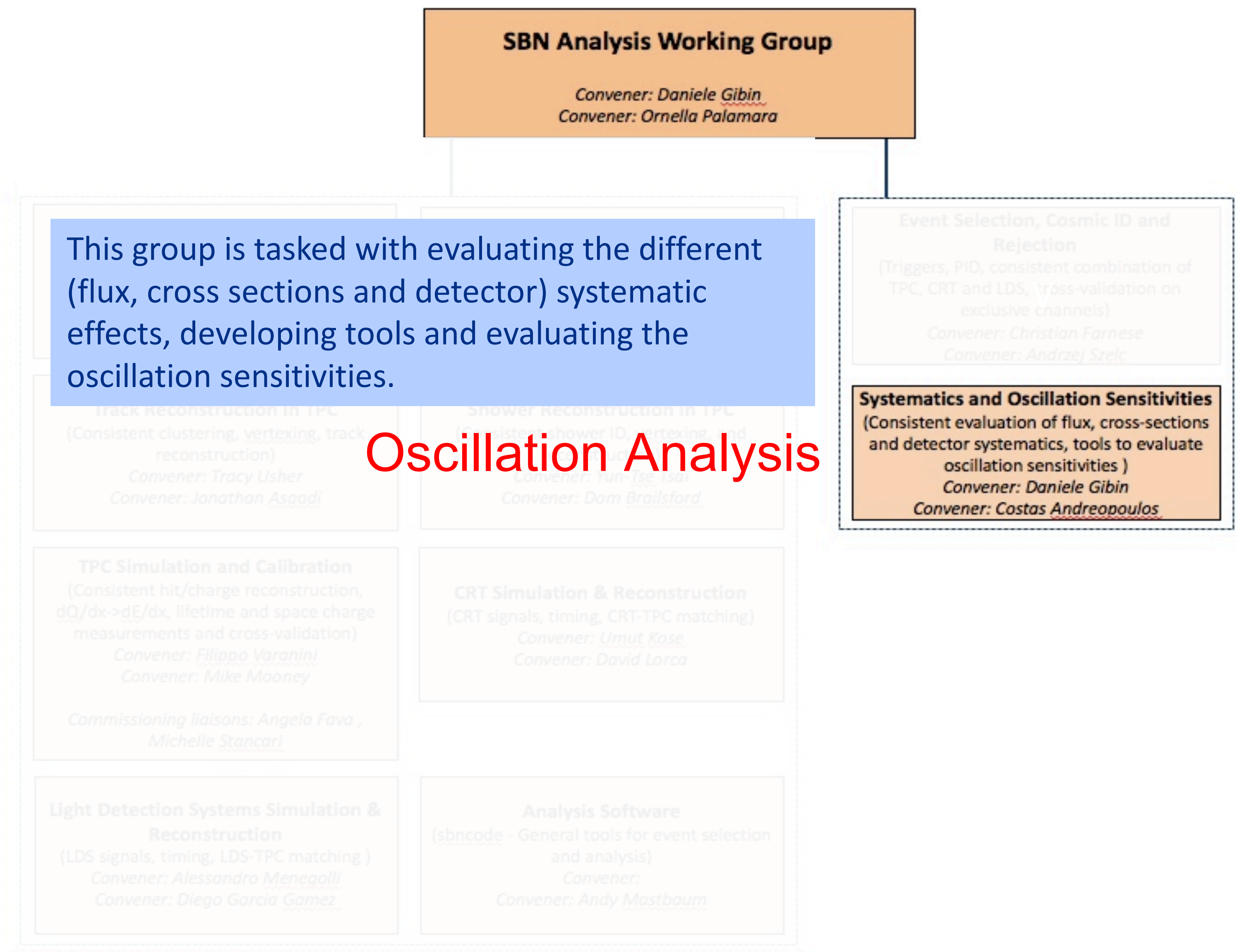


Event Selection

This group is tasked with developing the selection procedures for different neutrino events samples. This includes developing methods to suppress backgrounds from cosmic rays and other sources.

SBN Oscillation Analysis Group Organizational Chart



This group is tasked with evaluating the different (flux, cross sections and detector) systematic effects, developing tools and evaluating the oscillation sensitivities.

Oscillation Analysis

SBN Oscillation Analysis Group Organizational Chart

SBN Analysis Working Group

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Convener: Ornella Palamara

This group is tasked with evaluating the different systematic (flux, cross sections and detector) effects, developing tools and evaluating the oscillation sensitivities.

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Oscillation Analysis

Systematics and Oscillation Sensitivities
(Consistent evaluation of flux, cross-sections and detector systematics, tools to evaluate oscillation sensitivities)
Convener: Daniele Gibin
Convener: Costas Andreopoulos

The Group is responsible for

- The choice of **physics models** and tunes driving the nominal unoscillated predictions.
- The description of prior physics (flux, neutrino interaction) modelling **uncertainties** in the oscillation fit.
- The choices of reconstructed (exclusive or inclusive) **event topologies and kinematical variables** that offers redundancy and mitigation of model dependencies.
- The description in the oscillation fit of the **impact of detector, calibration and reconstruction** effects on reconstructed samples.

The Group **integrates the outputs of several other SBN (event selection, reconstruction, calibration, MC) groups** and **informs the direction of developments** in these groups **through oscillation-driven metrics.**

SBN Oscillation Analysis Group Organizational Chart

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Event Selection +
Reconstruction/Calibration Groups

Systematic and Oscillation group

SBN Analysis Group - Deliverables

- Implement a **multi-detector** <u>simulation</u>, implement <u>reconstruction</u> algorithms/tools and <u>analysis tools</u>.
- <u>Oscillation Analysis</u>: proceed in three (parallel) intermediate steps
    I. Consistency check - **reproduce the SBN proposal-era oscillation sensitivities** with 3 new oscillation fitting frameworks, using truth-level information and the same inputs for beam, reconstruction efficiencies, backgrounds and systematic uncertainties.
    II. Update the oscillation sensitivities - still using truth-level information, and exploiting **updated inputs** for efficiencies/backgrounds and systematic effects (accounting for the available/developed SBN event reconstruction and recent results from other LAr experiments).
    III. Oscillation physics sensitivity results based on full event simulation and full event reconstruction.

Oscillation Analysis - Step I

- We have <u>**3 independently-developed oscillation fitting frameworks**</u> that have implemented a SBN oscillation analysis.

CAFAna: Framework used in various NOvA analyses (including sterile and cross-section) and by the DUNE long-baseline group for the TDR sensitivities.
SBNfit: Framework designed to run multi-channel, multi-detector and multi-running-mode fits (based on MiniBooNE's covariance matrix approach). Now being used in the MicroBooNE low energy excess analysis.
VALOR: Fitting framework used for T2K oscillation analyses and DUNE oscillation sensitivities.

  - Using multiple fitters allows critical and independent cross-checks of all steps in the oscillation analysis chain.
- The aim is that all oscillation fitters implement the same SBN oscillation analysis (**sbncode**), using official inputs (MC data, event selections, physics and detector systematics) provided by the experts of each sub-domain (working within the corresponding SBN WGs).

Oscillation Analysis - Step I

- *Goal:* **Reproduce the proposal-era sensitivities**, using the same inputs and with all 3 new oscillation fitting frameworks.
- While doing so
  1) **Start standardizing the types and formats of deliverables of each WG** (towards the SBN oscillation fit).
  2) **Start defining procedures and developing code to enable detailed comparisons between all SBN fitters**.
- Details on the wiki page *(being developed)*

https://cdcvs.fnal.gov/redmine/projects/sbn-analysisgroup/wiki/Planning_for_fitter_comparisons

Oscillation Analysis - Step II

- ***Goal***: Oscillation sensitivity results **based on full event simulation using updated inputs**
  - Sensitivities (truth-level info) based on updated assumptions for efficiencies, background and systematic effects, based on the outcome of the different sub-group activities (available/developed reconstructions), and on the recent results of other LAr experiments.

1) **Critical review of the assumptions used in the proposal**
2) **Updated efficiency/background/systematic estimates based on new results from simulations/data analyses**

Event generators + MC production + Event Selection + Reconstruction/Calibration Groups

Oscillation group

Oscillation Analysis - Step II

- The use of truth level information in this step
  - Alleviates the required computing and storage, and permits to promptly start the process of updating the sensitivity.
  - Allows parallel improvements within the different sub-groups and the inclusion/modeling of the **most updated reconstruction components** as they become available.
- A **dynamic circular approach** analysis model is envisaged. At each round, the oscillation group identifies the reconstruction issues critical for the sensitivity, and the involved sub-groups work on relative improvements and mitigations.

Oscillation Analysis - Step II

- The baseline is to perform inclusive event analyses.
- Start studying possible improvements from exclusive final state analyses
  - Event selection and reconstruction groups should provide the guidance to select and reconstruct exclusive states.
- Start studying combined appearance and disappearance channels.

Event Selection +
Reconstruction/Calibration Groups

Systematic and Oscillation group

Oscillation Analysis - Step III

- *Goal*: Oscillation physics sensitivity results based on **full event simulation and full event reconstruction**.
- In a first stage concentrate on the ν_μ disappearance channel and afterwards on the more challenging ν_e appearance channel.
- Complete studies of possible improvements from exclusive final state analyses.
- Combine appearance and disappearance channels.

Event Selection +
Reconstruction/Calibration Groups

Systematic and Oscillation group

Oscillation Sensitivities - Milestones and Timeline

M.1: Reproduce the SBN proposal oscillation sensitivity for both ν_e appearance and ν_μ disappearance (**Mid March 2019**).

M.2: Revise the proposal assumptions using more realistic estimate of efficiency and backgrounds, implementing a truth-level based sensitivity study for both appearance and disappearance channels (**Summer 2019**).

M.3: Produce an end-to-end analysis of ν_μ disappearance with as complete as possible event selection and reconstruction (**End of 2019**).

M.4: Produce an end-to-end analysis of ν_e appearance with as complete as possible event selection and reconstruction (**Spring 2020**).

M.5: Final, complete, reconstruction & systematics included appearance and disappearance sensitivities (**by end of 2020**)

Summary

- The SBN program presents an opportunity for a **broad science program** and has two primary physics goals:
  - Precise sterile neutrino oscillation searches (multiple LAr TPC detectors at different baselines along the Booster Neutrino Beam at Fermilab)
  - Study of neutrino-argon interactions with unprecedented precision
- The SBN Joint Working Groups, acting as a **unique collaborative effort** in preparation for the SBN oscillation analysis, establish a **long-term continuous, direct connection/collaboration** between the SBN detectors.
- The execution of the SBN precision oscillation searches will drive the development of **sophisticated reconstruction and data analysis techniques using LAr TPC data.**
- With major progress on the detectors and continued **joint efforts** on multiple fronts, we are well on our way for the execution of the **SBN physics program**.

Overflow

SBN DAQ and Data Pre-Processing WG *(conveners: B. Badgett, A. Fava, W. Ketchum, S. Ventura)*

- Scope: Identify areas of common effort on data acquisition and data pre-processing, and coordinate activities in those areas.
- Successful in spreading information on efforts in the common areas, and in coordinating with the experiment specific groups to establish milestones and discuss plans for upcoming work
  - *Match the needs of each experiment*
  - *Need to make more efforts to setup common software platforms to better allow direct and efficient integration of common efforts.*
  - *This will be a priority of the group in the coming month(s), to ensure we are well positioned for ICARUS and SBND to move from test-stand work to full integrated systems and benefit most from each other's work.*
- The group is well-structured, no modifications to the group are considered.
- Meet <u>once every three weeks</u> since July 2016 , alternating with ICARUS- and SBND-specific DAQ working group meetings
  - *Good attendance from both experiments and technical experts at Fermilab*

SBN Slow Controls WG *(conveners: A. Fava, S. Gollapinni)*

- Scope: Develop a system based on hardware and software interfaces as much as possible identical for the two experiments, leading to efficient sharing of resources and effort between both experiments
  - *Both experiments converged on using EPICS as the primary controls system, resulting in a lot of common software and tools development*
- The current model established for this common effort has been very successful and productive!
- <u>Meet bi-weekly</u> since Oct. 2017

Milestones for common activities

Milestone	Date
Cryogenics status into EPICS	Nov. 2018
DAQ server/status monitoring into EPICS	Feb. 2019
Beam Status into EPICS	Feb. 2019
Cameras for monitoring access to the buildings operational	March 2019
Slow Controls Archiver, Alarm Server ready	March 2019
CSS GUI interface & navigation ready	April 2019
Expert/commissioning-level documentation ready	June 2019
Shifter-level documentation ready	Sept. 2019

SBN CRT WG *(conveners: U. Kose, I. Kreslo, B. Wilson)*

- Review the requirements and expected performances of the CRT system for the different detectors.
- Review the CRT production status and the installation plans.
- Develop a common data model for the CRT detector systems.
- Review the DAQ scheme (adjust if needed). Define a common data output format for the CRTs together with the SBN DAQ working group.
- Develop common CRT monitoring for all CRT systems.
- Together with SBN Analysis groups
  - *Identify similarities and differences in the near and far detectors CRT systems that may impact oscillation analysis.*
  - *Identify physics scenarios where CRT detector system will be valuable, such as calibration; rejection of cosmic muon; rejection of electromagnetic activity; beam-based background, "dirt events"; understanding systematics.*
- <u>Meet bi-weekly</u> since September 2018.

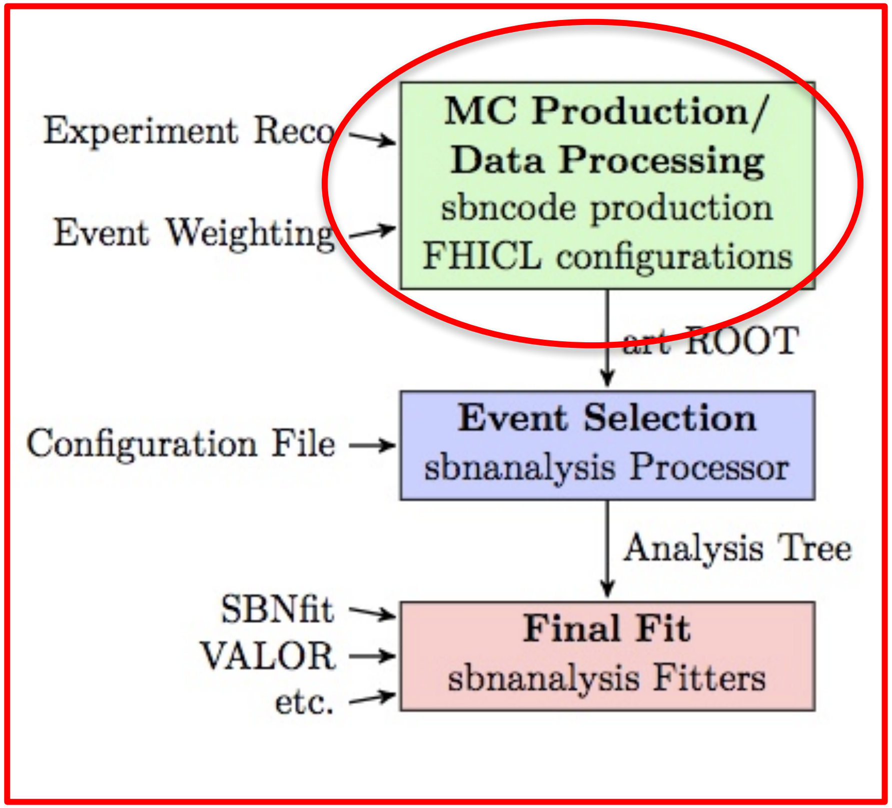
SBN Joint Working Groups

- Working Groups to be formed
  - SBN Cryogenics
    - Scope: Continue exchange of information between different teams in charge of build and support/operate the cryogenics systems
    - *SBN cryogenic activities are a collaborative effort between Fermilab, CERN and INFN*
    - The formation of this group has been approved at the 1st meeting of the SBN Oversight Board in May
    - It has been difficult getting the group started because of the intense activity at CERN associated with filling and starting protoDUNE. Hope to start the group now that protoDUNE is in steady-state operations.

SBN common code (**sbncode**)

Standard SBN simulation and analysis code

- Goals for SBN oscillation analysis code:
  - **Common SBN MC production**: Generate consistent three-detector MC
    - Same fluxes, cross section models and systematics
  - **Centralize SBN-wide shared tools**
    - e.g. event weighting, event reconstruction
  - **Common SBN analysis code:** Central space for analysis code
  - **Common SBN oscillation sensitivity calculations**: integrated with final fit codes



All aimed at a high-quality, readily reproducible oscillation analysis

SBN common code (**sbncode**)

New standard SBN simulation and analysis code

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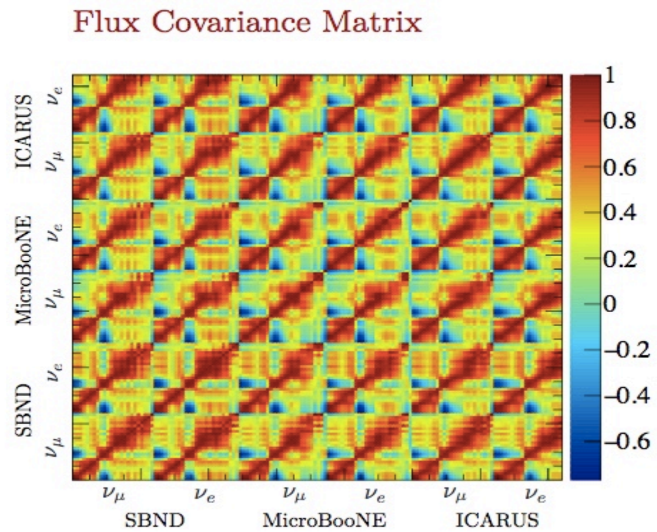

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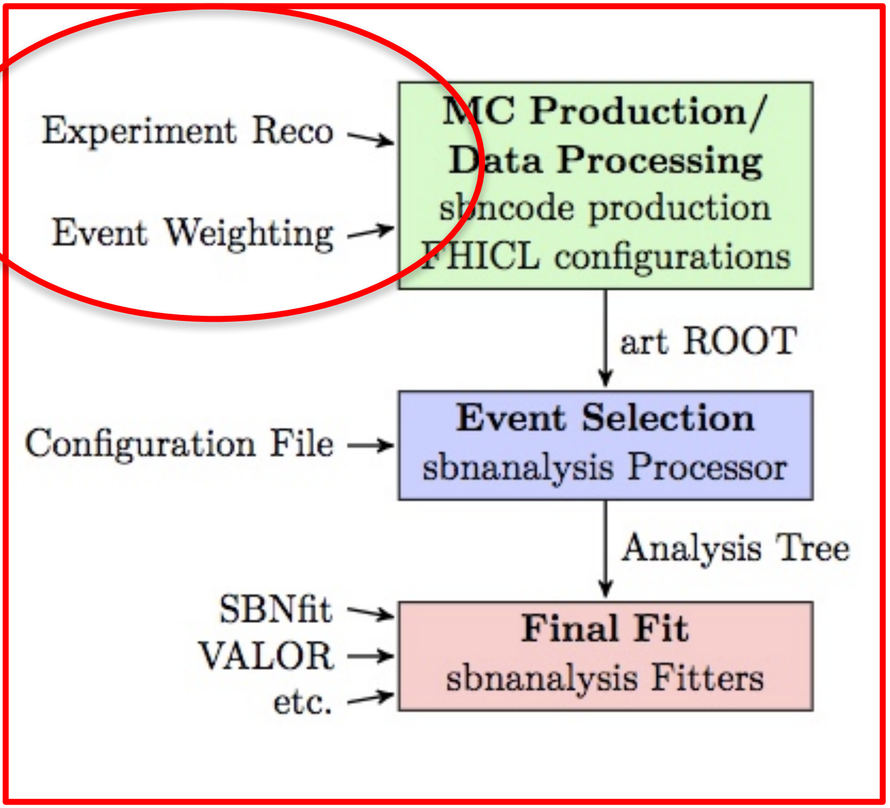

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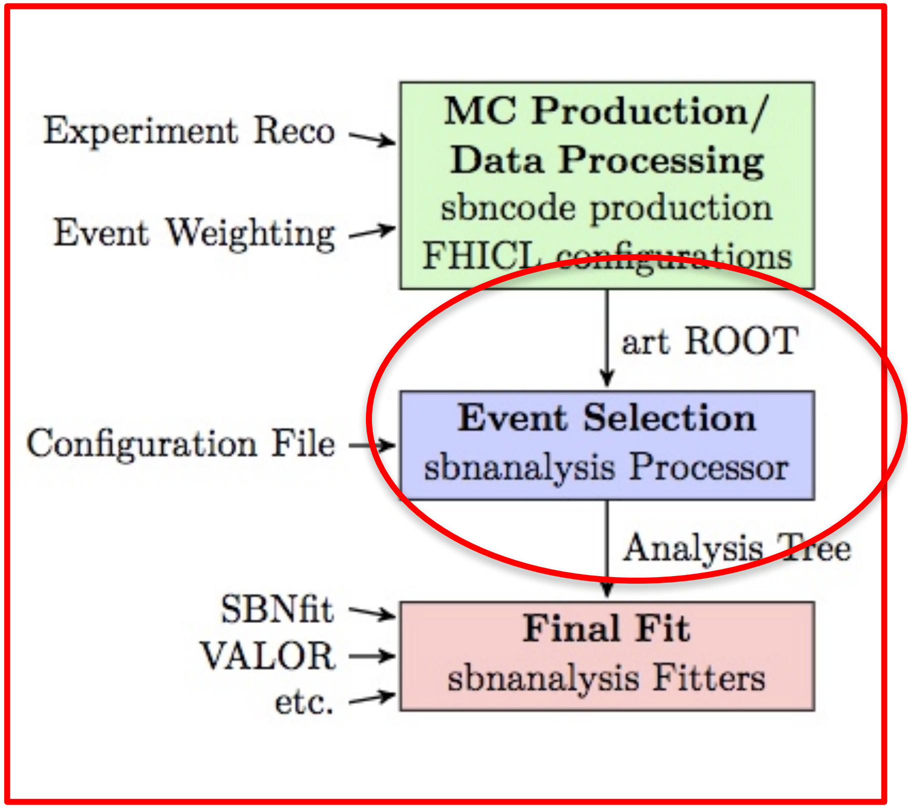

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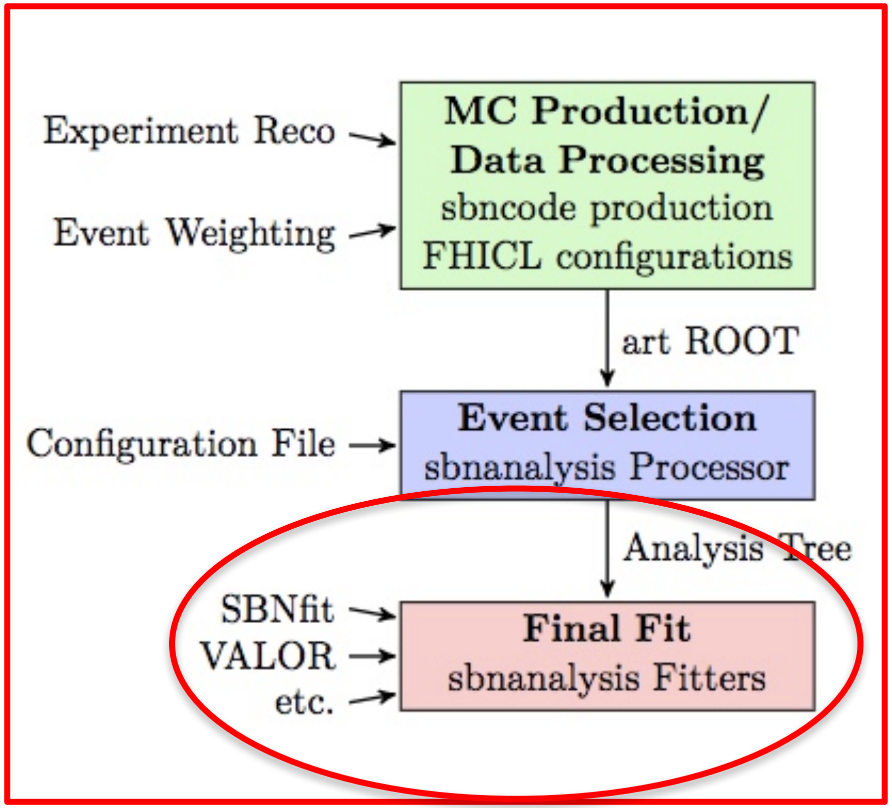
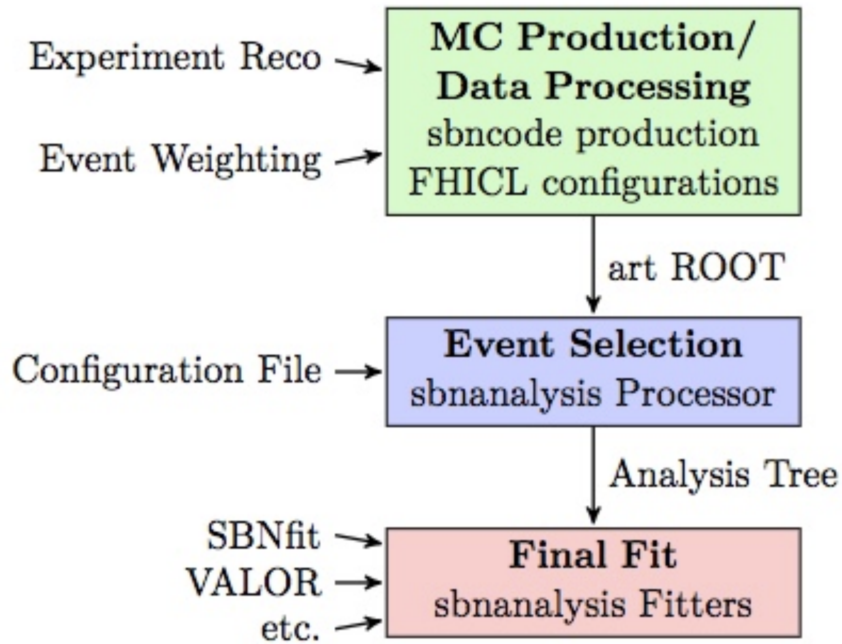


All aimed at a high-quality, readily reproducible oscillation analysis

SBN common code (**sbncode**)

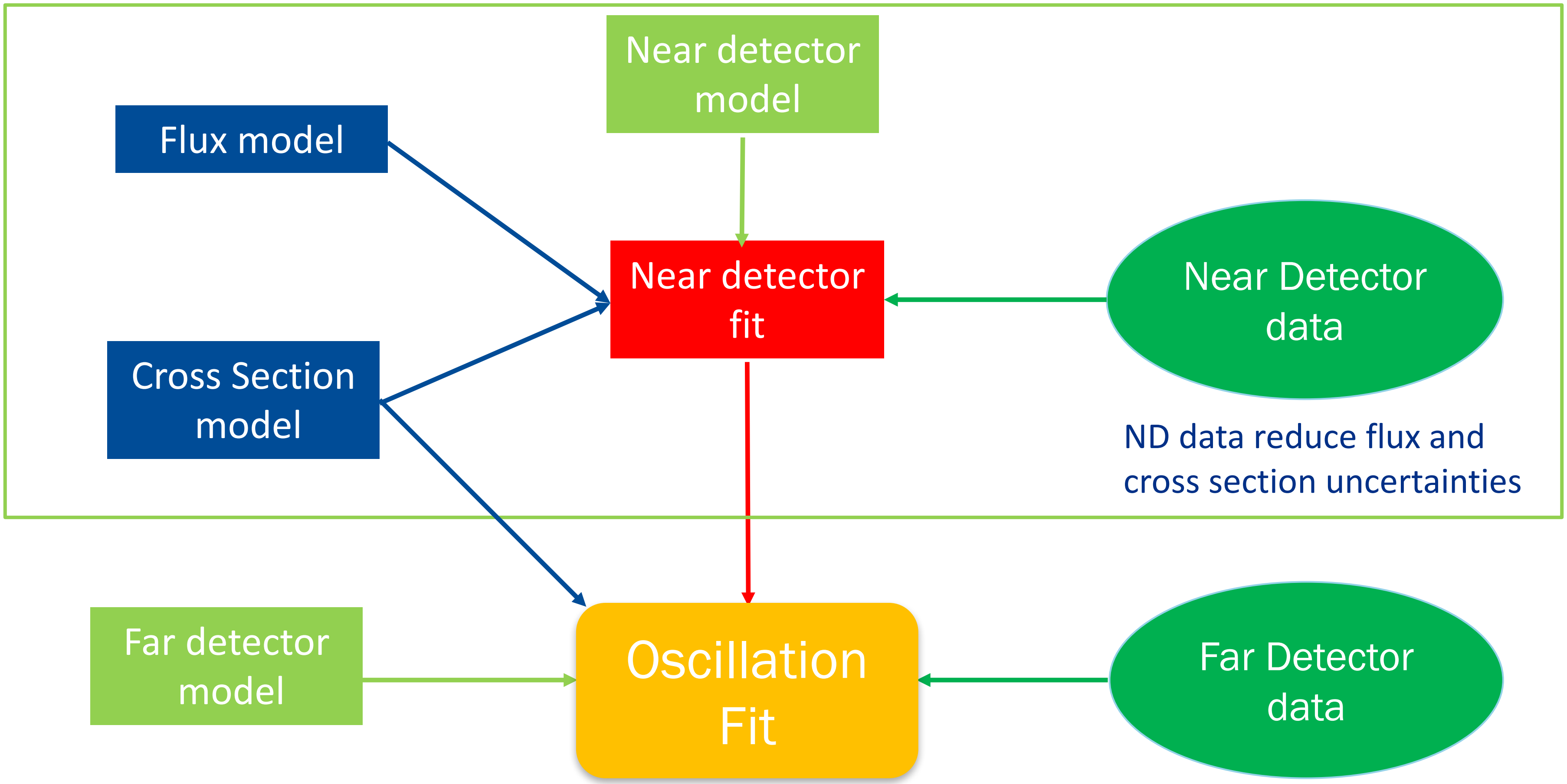
New standard SBN simulation and analysis code

- Lightweight framework for event selection and SBN physics analysis
- Centralized development, provides a **standard analysis tree**
- Can **access any reconstructed object or McTruth information** from any experiment

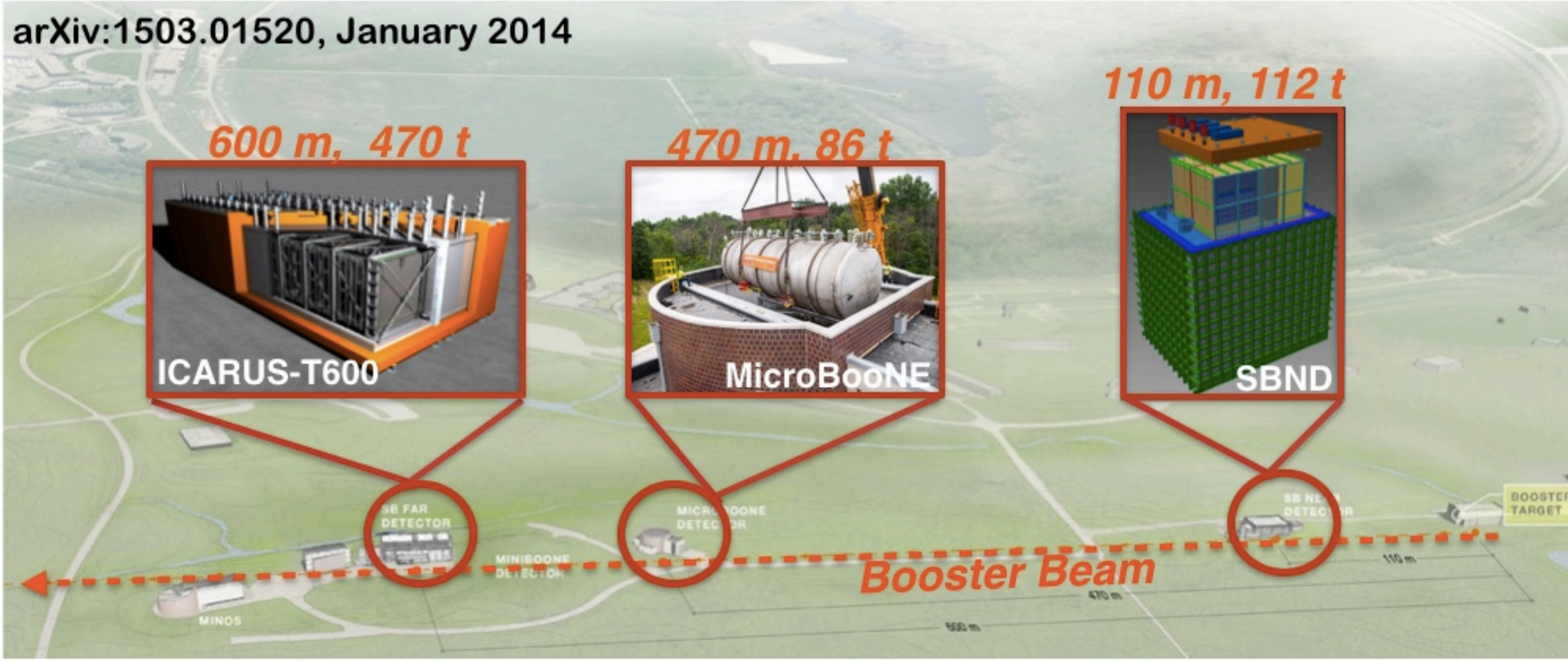


Tool not just for high-level analysis, but also for debugging of the reconstruction algorithms

SBN Analysis Strategy

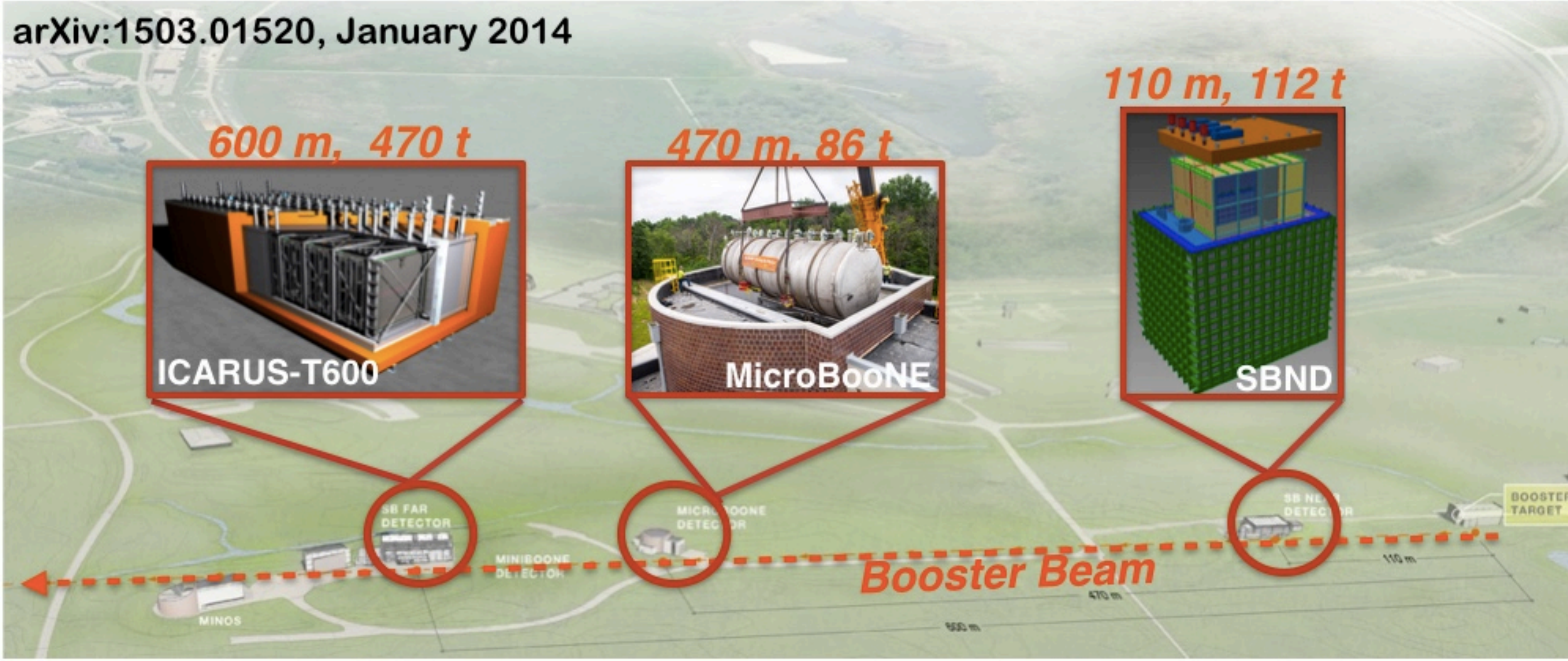


FNAL Short Baseline Neutrino program



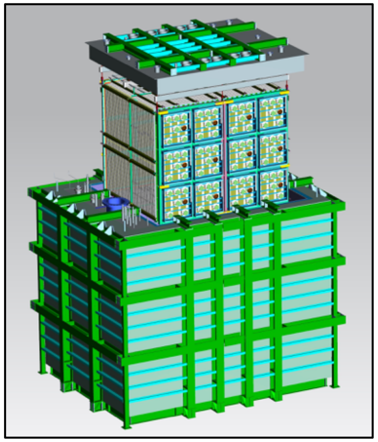
SBN Phase 2 - The MicroBooNE detector will be joined by two additional Liquid Argon TPC detectors at different baselines, the SBND detector and the ICARUS-T600 detector to perform **sterile neutrino oscillation searches.**

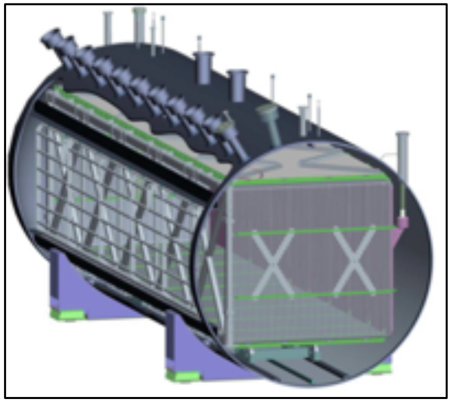
FNAL Short Baseline Neutrino program

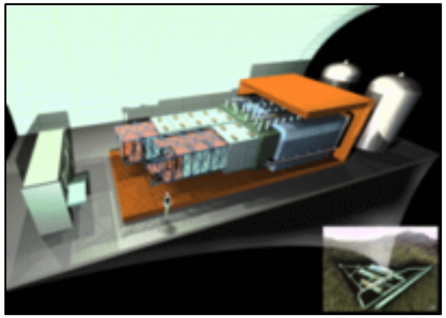


- ❑ Addition of ICARUS and SBND extends science reach from a specific anomaly to the **world-leading neutrino oscillation search experiment** at $\Delta m^2 \sim 1\ eV^2$.
- ❑ The MiniBooNE observed excess has strengthened with additional data, and global fits of all experimental data indicate 1-2 eV^2 as the most likely region where light sterile neutrinos could still be hiding.

SBN Detectors – Quick Overview







SBND

- 220 tons of LAr with **112 ton active volume**, located at 110 m from the BNB source
- 2 TPC's in one cryostat
- **11,264 sense wires** - 3 planes oriented at +60, -60, and 0 degrees, with 3 mm pitch
- Cold electronics, 2 m drift, 500 V/cm
- **60 PMT's, 16 ARAPUCA's and 48 Light Guide Bars** in each TPC located behind the anode plane, and TPB coated reflector foils on the cathode plane
- **Cosmic Ray Tagger** and 3 m of concrete overburden above the detector

MicroBooNE

- 170 tons of LAr with **89 ton active vol**ume, located at 470m from the BNB source
- Single TPC
- **8,256 sense wires** - 3 planes oriented at +60, -60 and 0 degrees, with 3 mm pitch
- Cold FE electronics, 2.5 m drift, 273 V/cm
- **36 PMT's** located behind the anode plane
- **Cosmic Ray Tagger** and 3 m of concrete overburden above the detector

ICARUS-T600

- 760 tons of LAr with **470 ton active volume**, located at 600 m from the BNB source
- 4 TPC's in two cryostats
- **53,248 sense wire**s - 3 planes oriented at +90, +60 and -60 degrees, with 3 mm pitch
- Warm electronics, 1.5 m drift, 500 V/cm
- **90 PMT's** in each TPC located behind the anode plane
- **Cosmic Ray Tagger** and 3 m of concrete overburden above the detector

Inputs for the SBN proposal - ν_e appearance

Assumed 80% efficiency for ν_e identification

Possible sources of background:

- *Intrinsic νe*
- *NC γs*
- *ν_μCC γs*
- *Dirt*
- *Cosmogenic*

Background Mitigation:

- Fiducial cut (30 cm upstream and 25 cm lateral)
- E_{em}>200 MeV
- NC :
  - Detection of second γ (E>100 MeV)
  - Conversion gap Δ>3 cm
  - dE/dx (**rejection at 94%**)
- ν_μCC
  - Muon identification (L_μ>1 m)
  - Same cuts as NC for L_μ<1 m
- Dirt events: Isolated γs produced by neutrino interaction outside the active volume and entering the detector
  - Fiducial cut
  - dE/dx (**rejection at 94%**)

Inputs for the SBN proposal - Cosmogenic background

Mitigation strategy:

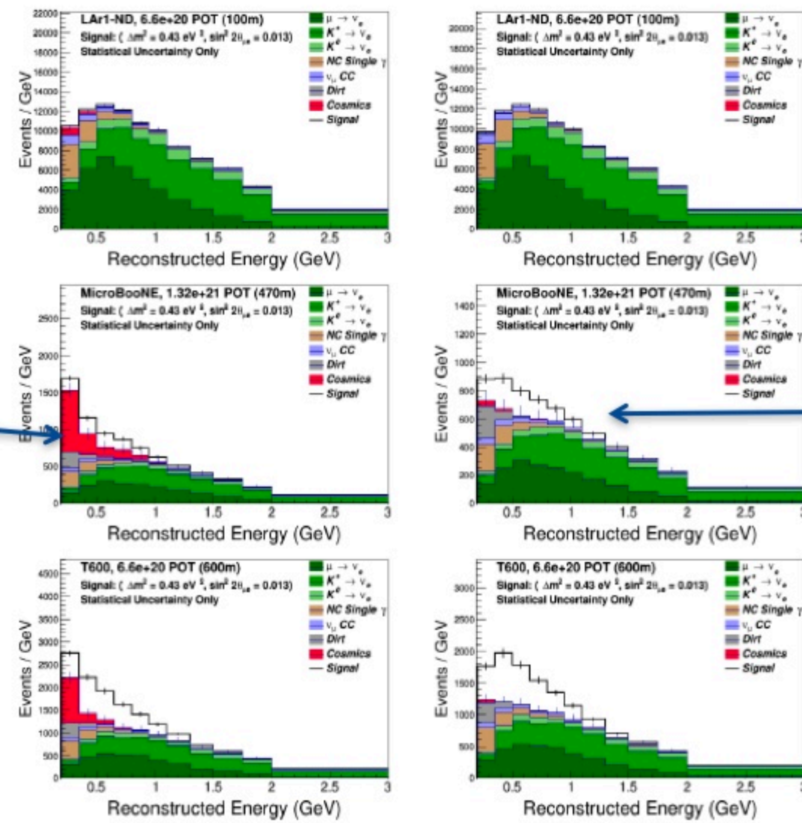
Topological cuts:

- dE/dx cut → 6% γ's survive
- 3D distance from the muon → 1% with D_{μ}>15 cm at the price of ~1% loss in fiducial volume

Additional requests:

- muon tagging (CRT)
- inner scintillation light
- possible exploitation of beam spill structure.

Topological dE/dx and D>15 cm from μ



Additional cuts: 95% reduction From the combination of CRT and light collection → **Assumed 95% cosmogenic rejection**

Inputs for the SBN proposal - ν_μCC disappearance

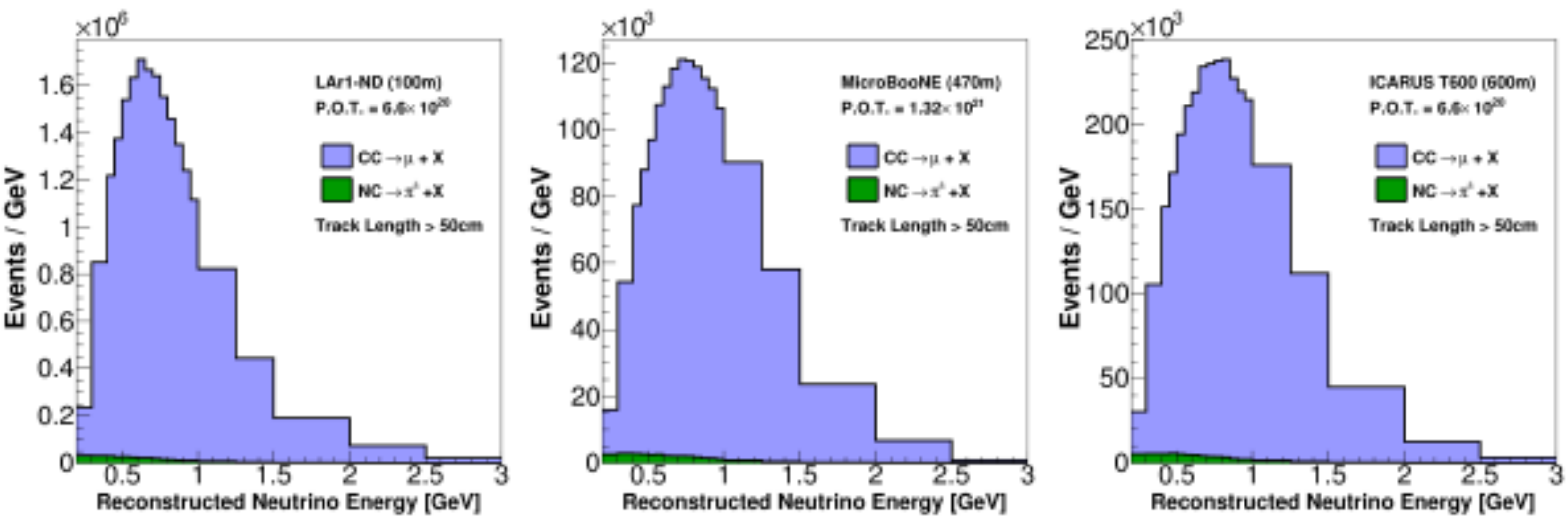
Assumed 80% efficiency for ν_μCC identification

Possible sources of background:

- NC $\pi^\pm$ misidentified ad muon

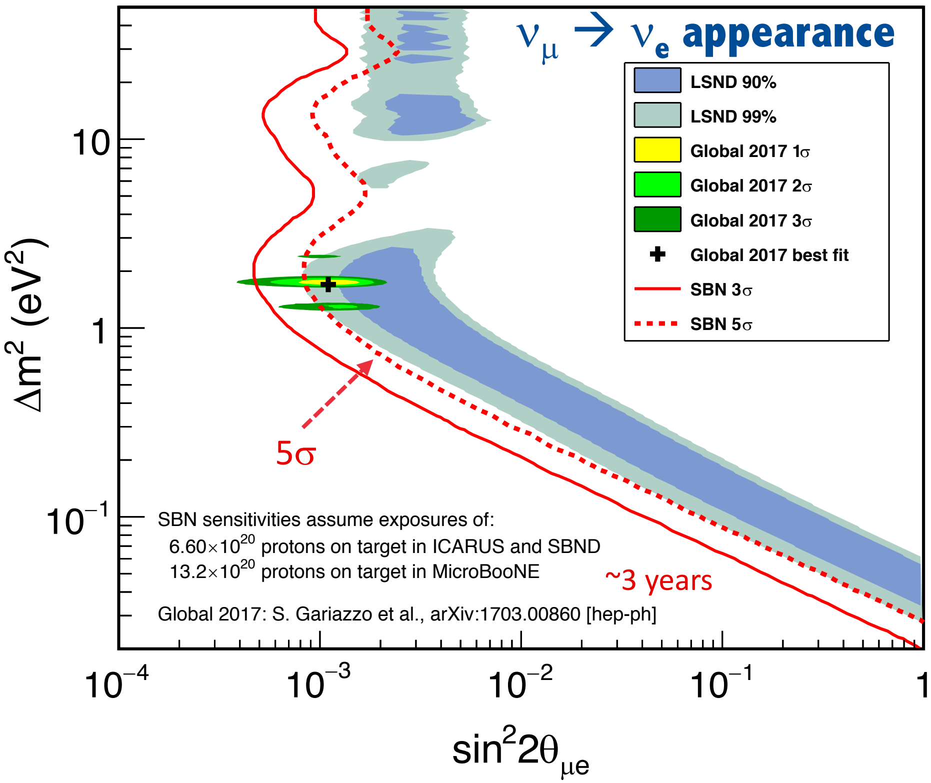
Background Mitigation:

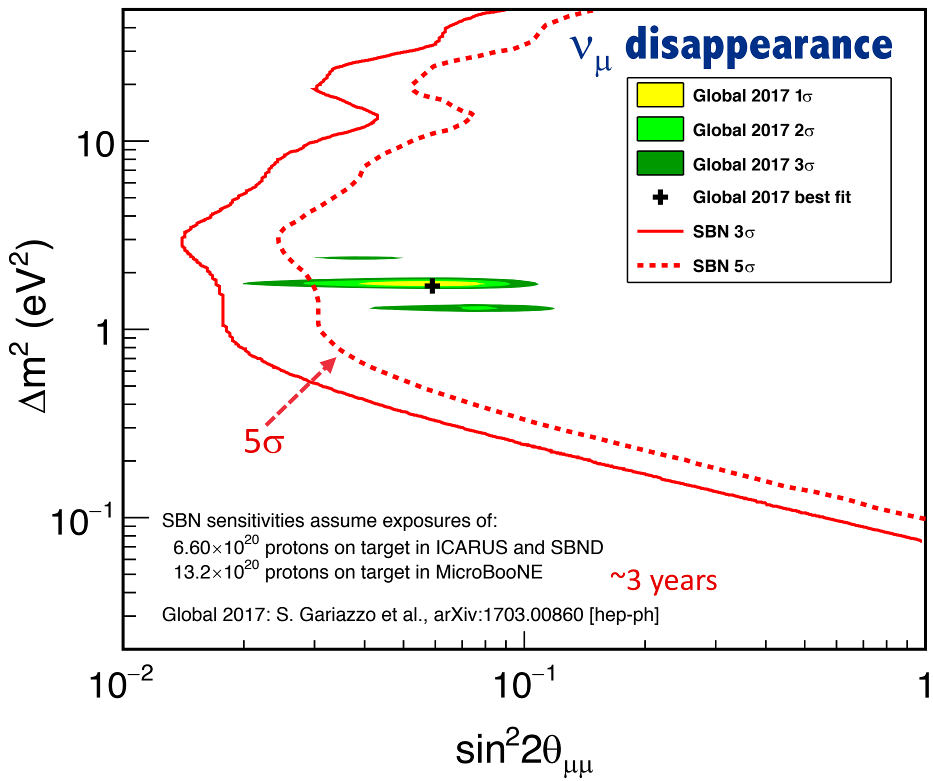
- L>50 cm stopping inside
- L>100 cm if exiting



The SBN Oscillation Program

Sensitivities to oscillations ONLY enabled with near and far detectors





Combination of the SBN detectors enables 5σ coverage of the 99% C.L. allowed region of the original LSND signal and the global best fit values.

ν_e appearance cannot occur without ν_μ disappearance.

This is a critical aspect of verifying an oscillation hypothesis.