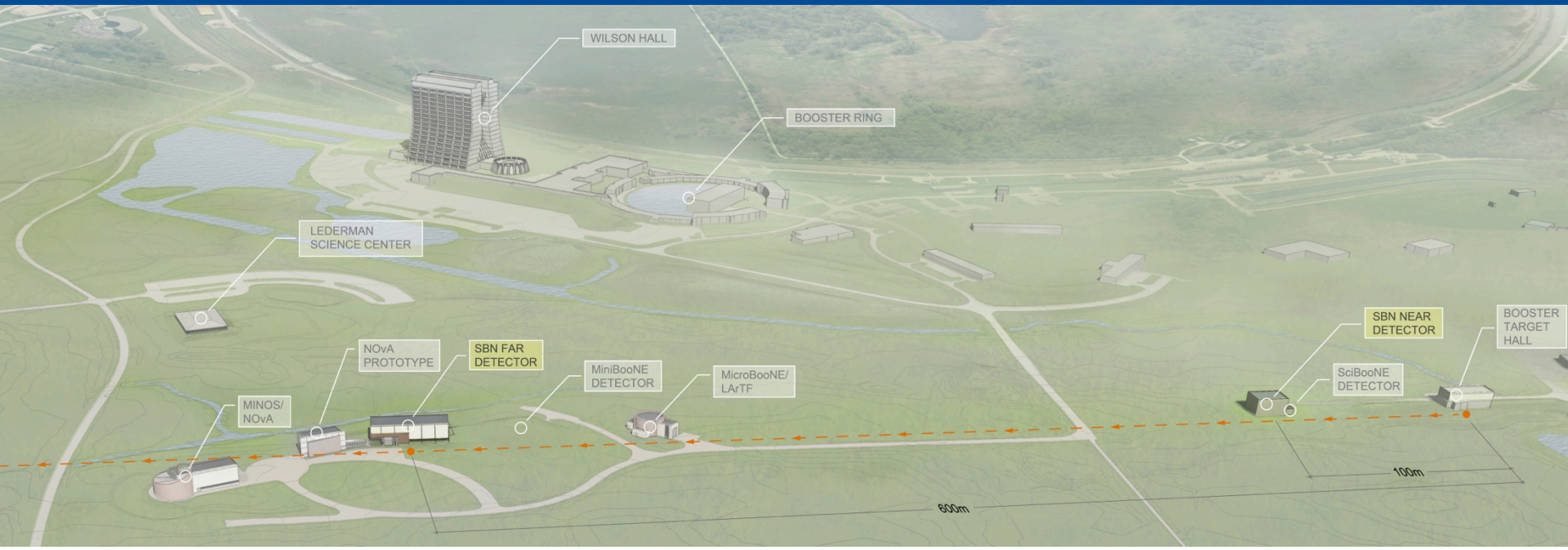



# **SBN:** Unified mixing analysis plans and management structure for operations

*PAC Meeting*

*SURF, South Dakota*

*July 6th 2017*

Ornella Palamara

# SBN – Joint Efforts across the SBN program

- 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-nucleus interactions on argon with unprecedented precision and detail (precision era of neutrino physics!)

- Joint Efforts (from common detector operation to final oscillation analysis) across the SBN program are key to the success of the program.
  - Exploiting synergies
  - Sharing of expertise from different groups
  - Reduce the effort of the single Collaborations
  - Minimize systematics that impact the final analysis

# SBN – Joint Efforts

- Existing joint efforts
  - SBN **Online System Working Group**.
  - SBN **Analysis group**. Current status and plans.

- Planning for SBN **joint Operation**
  - Next is to plan for common operation.
  - Initial discussion with ICARUS on joint operation of the SBN detectors recently at ICARUS PI meeting on June 23, where we were invited to attend for discussion.

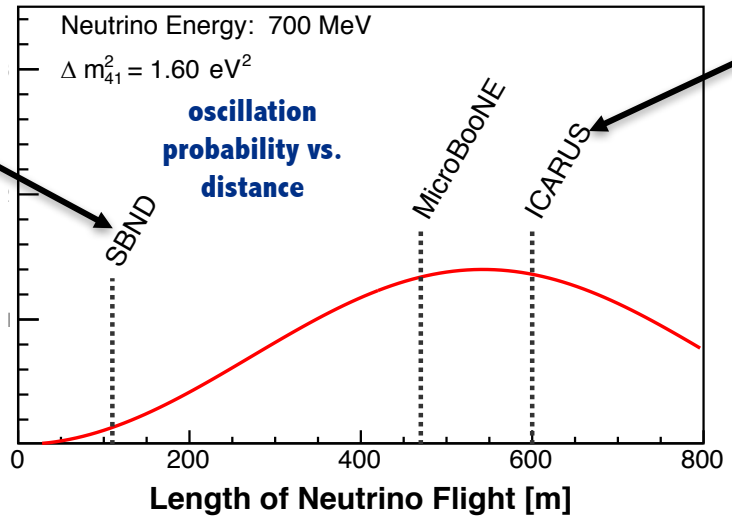
# SBN - Online System Working Group

- A Joint Online System Working Group across the three SBN experiments has been formed in February 2016.
- The group is actively working, with the goal to define common DAQ software solutions, data formats, etc
  - Data acquisition software (artDAQ)
  - Timing distribution (White Rabbit)
  - Slow control
  - Joint building of tools for the implementation of online/quasi-online monitor of detector performance (e.g. electron lifetime, space charge effect)

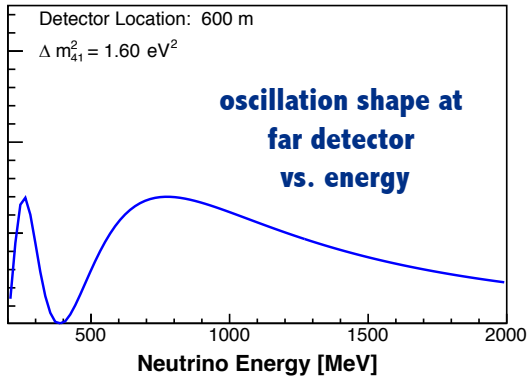
# SBN – Joint Analysis Group

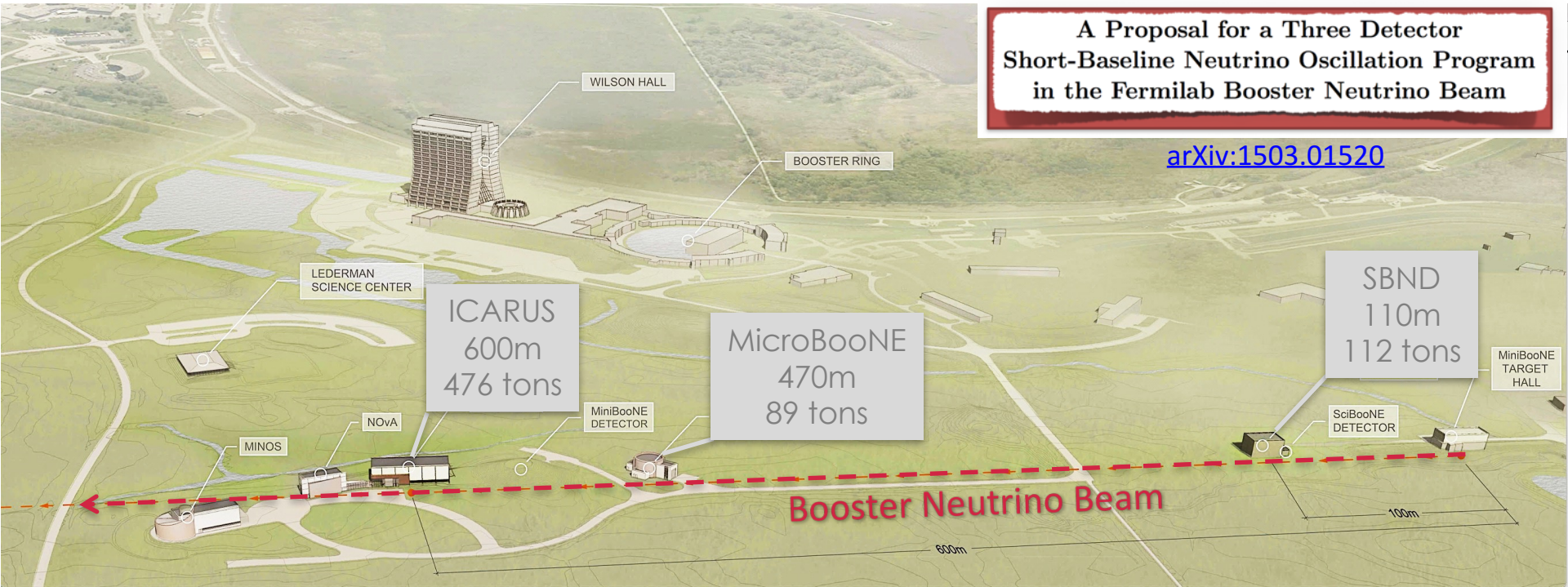
# The Three Detector SBN Program

control **systematics** with near detector before oscillations




increase **statistics** of oscillation signal by adding far detector mass



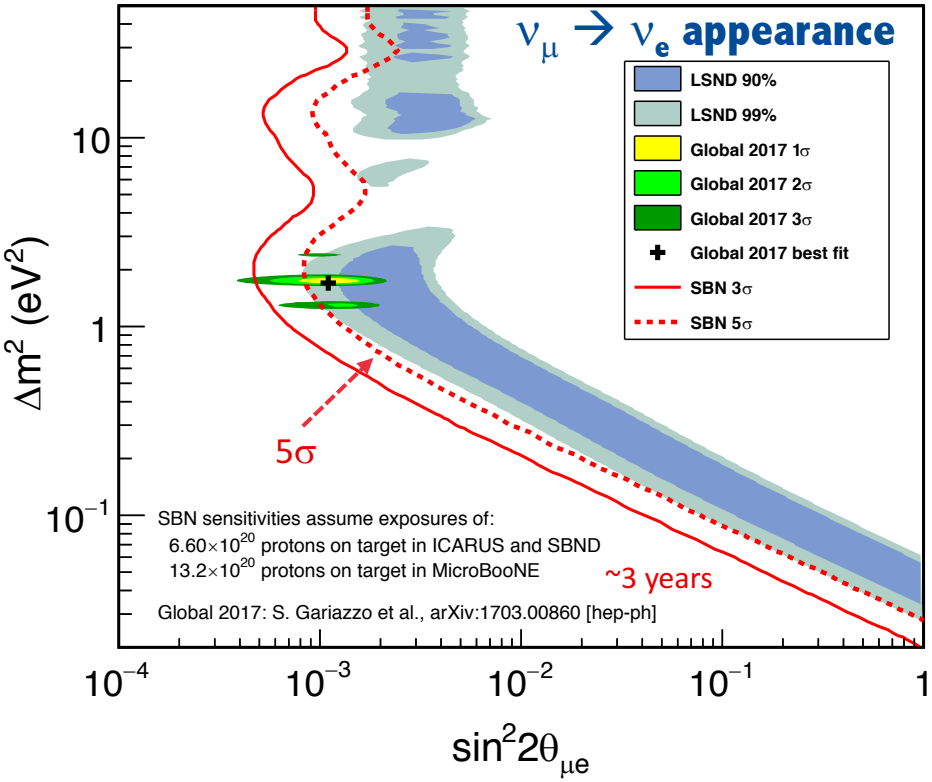



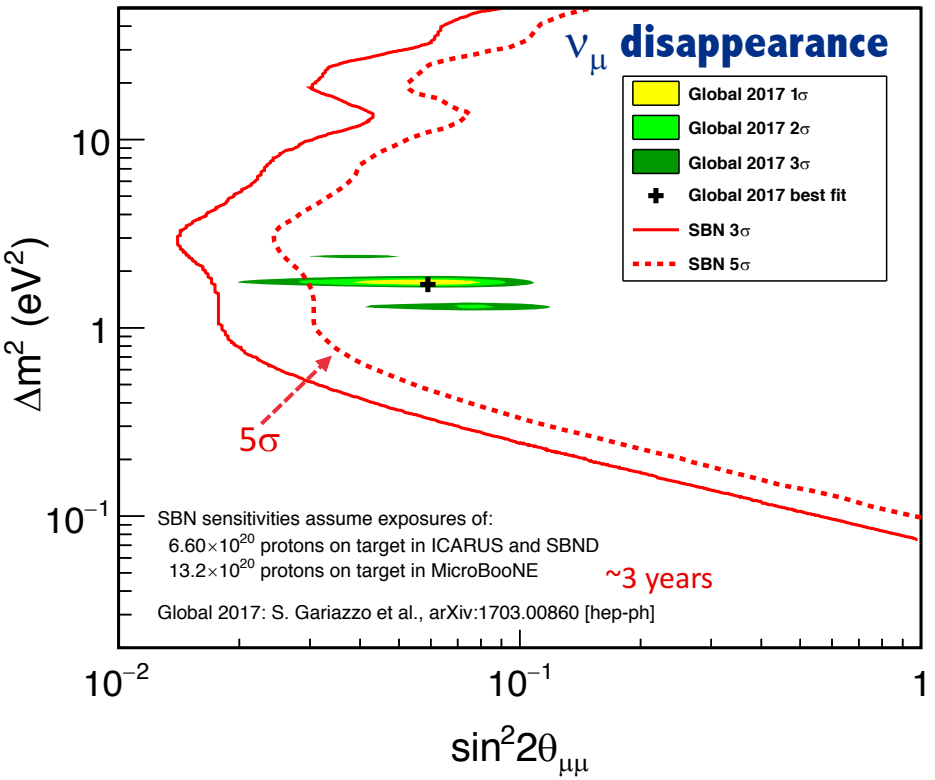

A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam

arXiv:1503.01520

# 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.**

**$\nu_e$ appearance cannot occur without $\nu_\mu$ disappearance.**

**This is a critical aspect of verifying an oscillation hypothesis.**

# SBN Proposal – Physics Sensitivities

- GEANT simulation of GENIE produced neutrino interactions in argon is used
  - Selections are made based on predicted event kinematics.
  - Efficiencies applied to different event types are based on inputs from other simulation results and analysis results from LAr-TPC experiments (e.g. ICARUS, ArgoNeuT).

- Physics sensitivities have been evaluated for $\nu_e$ appearance and $\nu_\mu$ disappearance
  - Under the 3+1 scenario (three active and one sterile neutrino).
  - Assuming the neutrino flux presently delivered from the Booster Neutrino Beam.
  - By computing a $\chi^2$ surface in the ($\Delta m^2_{41}$, $\sin^2 2\theta$) oscillation parameter plane.
  - Including systematics from $\nu$ interaction uncertainties and differences in the neutrino flux at the different detectors.
  - Including beam intrinsic, and $\pi^0$ and $\gamma$ backgrounds.

- After the SBN proposal, *Analysis* and *Software development* has continued across the SBN program, with both short- and long-term aims.

# LAr TPC Software Development

- LArTPC Reconstruction workshop (Fermilab October 2015)
  - Requested by the LBNC Committee
  - Organized and attended by Fermilab and CERN computing experts together with representatives from all SBN (MicroBooNE, ICARUS, and SBND), DUNE, and LArIAT experiments.

  - **Assessment workshop:** to review the current status of LArTPC event reconstruction and analysis - challenges and lessons learned.

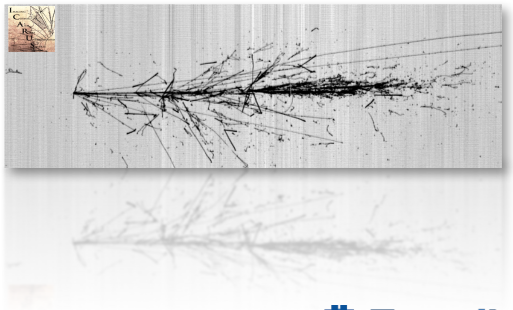
  - **Requirements workshop**: to define the requirements for a LArTPC software platform that will support the analysis needs across multiple LArTPC experiments over the next ~decade.

- A **common reconstruction and analysis framework** is the first step for interconnections/synergies and effective use of resources between different collaborations.

# LAr TPC Software Development

- Software development efforts - LAr TPC Analysis/Tool development
  - LArSoft provides a **common software infrastructure** for the sharing of reconstruction and simulation codes used by different liquid argon TPC experiments
    - *ArgoNeuT, MicroBooNE, LArIAT, SBND, DUNE, etc. use the **LArSoft** framework*

- ICARUS developed **their own analysis software** for the Gran Sasso physics run before the start of the LArSoft project



# SBN Oscillation Analysis Group

- Close communication on developing **longer-term strategies** for analysis across the three SBN experiments
  - A valuable ingredient in preparing for common data analysis in the future
  - *Critical to the success of the SBN program!*

Joint **SBN Analysis group** formed in September 2016

# SBN Analysis Group - A Joint Effort

Group coordinators: D. Gibin, O. P.

- Aim: Explore how the combined (SBND, MicroBooNE, ICARUS) physics analysis for **sterile neutrino oscillation searches** can be most effectively performed.

- The group includes collaborators from the three experiments interested in contributing to the oscillation analysis, and Fermilab computing and beam experts.

  - Kick-off meeting: Sept. 2016
  - Bi-weekly meetings – 30-40 people in attendance, 67 people on the SBN Analysis mailing list
    - Coordinate development on detector simulation and event reconstruction
    - Prioritize work
    - Share results of development progress on a continuous basis

# SBN Analysis Group - Goals

- Implement a three detector **simulation**, **reconstruction** and **analysis** model within a **common framework**.

- Implement an end-to-end **common analysis scheme**, in preparation for real data exploitation.

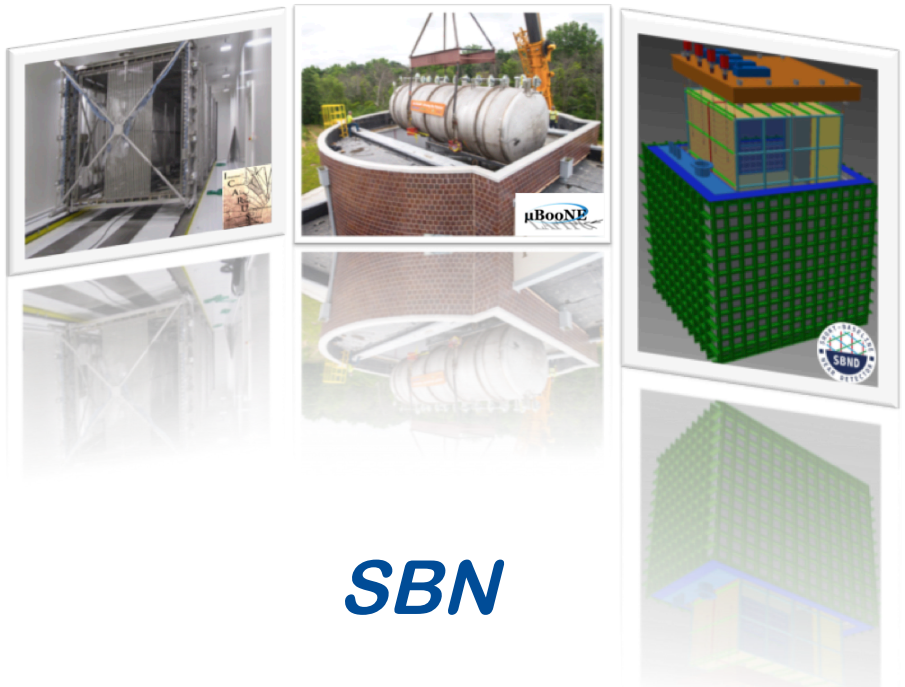
- Update projections of **expected physics capabilities** of the SBN program, including reconstruction efficiencies and performances, and background rejection from a full MC simulation/reconstruction of events in the three detectors.

- Develop **new analysis methods** and **tools** to perform sensitivity analyses.

# SBN Analysis Group – Common Framework

- Adoption of **common simulation**, **reconstruction** and **analysis framework** is crucial for the joint analysis of the three SBN experiments.
  - Different strategies and time/effort needed have been analyzed.

- LArSoft has been identified as the *official* **software framework** for the SBN program.




***SBN***

LArSoft

# SBN – Common Analysis Scheme in the LArSoft Framework

- Description of the detectors
  - Geometry (building, cryostat, TPC [wires…], Light Collection system, CRT)
  - Detector response (charge, light, CRT)

- Production of MC events samples (with different generators) in the three detectors
  - Cosmics
  - Neutrino events
  - External neutrino interactions, “dirt” event
  - Neutrino events + cosmics + “dirt” events

- Event reconstruction in the three detectors
  - Assessment of the performances of the presently working reconstruction algorithms from the LArSoft platform (currently in use by ArgoNeuT, MicroBooNE, LArIAT, DUNE) on events in the three detectors
  - Test/compare with reconstruction algorithms/tools ported from ICARUS software in LArSoft
  - Improve reconstruction software for SBN-specific needs

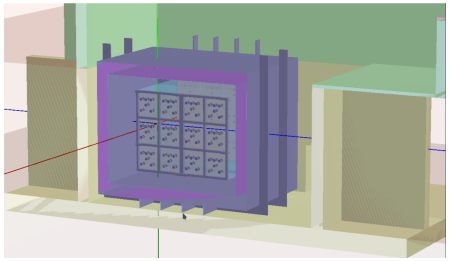
# SBN – Common Analysis Scheme in the LArSoft Framework

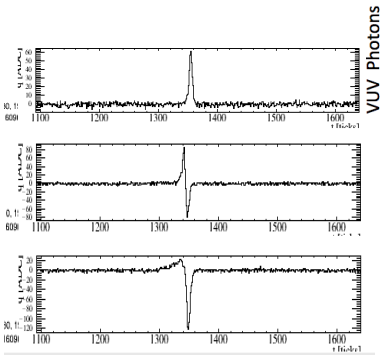
- Exploit analysis strategies on MC events
  - Select neutrino events
  - Reconstruct physical quantities in each detector starting from raw data
  - Implement a common analysis scheme
    - Data from the different detectors must be analyzed side-by-side together with knowing all systematic effects.
    - Identify the most effective way to share data between different detectors (different data sharing scenarios), in order to minimize systematics,… is a critical step.

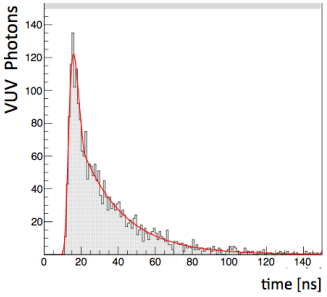
- Update expected physics capabilities of the SBN program, including reconstruction efficiencies and performances, and background rejection.

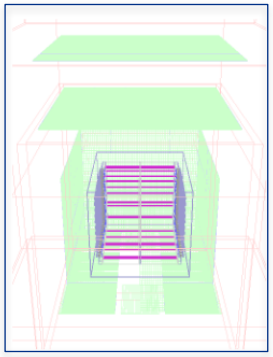
# SBND - Simulation and Reconstruction in LArSoft

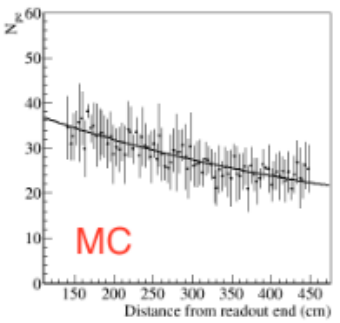
- Simulation of the SBND detector (TPC, Light Detection system and CRT) + experimental hall and surrounding environment is in place



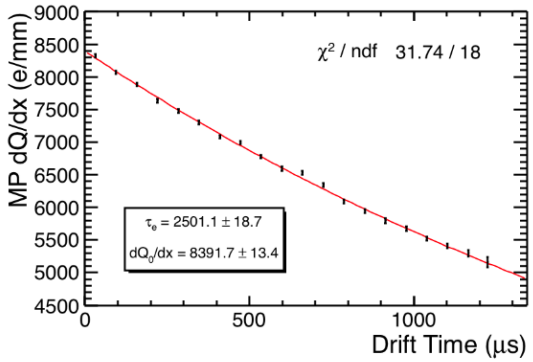


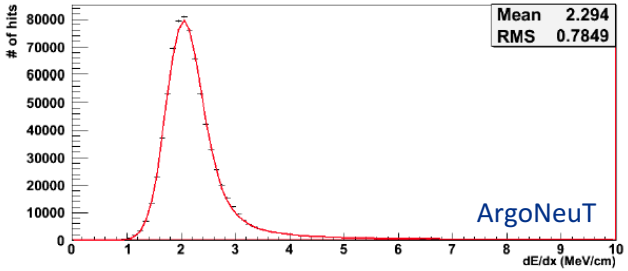





- Tools to make detector measurements (calibrations, detector performance measurements. etc…) are under development

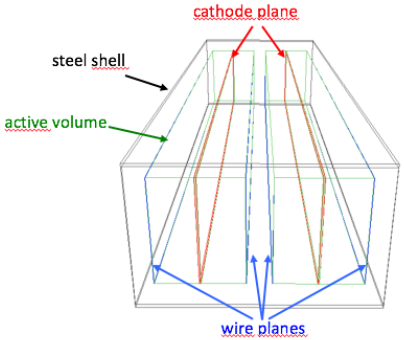


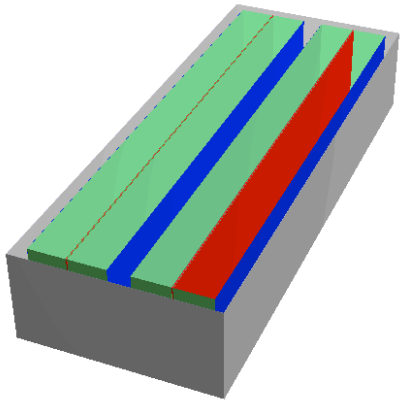

- First large Monte Carlo data production (*different data samples*) is in progress

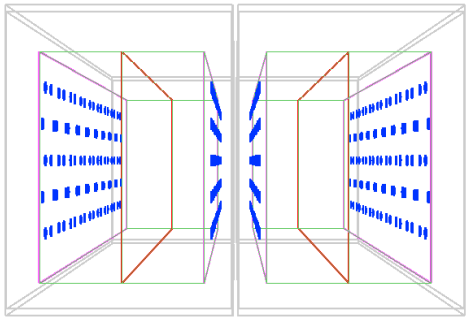
# ICARUS - Simulation and Reconstruction in LArSoft

- First description of the ICARUS T600 geometry is in place. Working on a more detailed description and on the inclusion of details and ancillary instrumentation and surrounding environment.



TPCs schematic views





- Simulation of the TPC and PMT electronics response and CRT geometry and response is in progress (modeled on MicroBooNE and SBND simulations).

- Thanks to the structure of LArSoft, intended to facilitate the creation and maintenance of a common software, and **profiting of the experience of** MicroBooNE and SBND collaborators, a first simulation of the ICARUS T600 in LArSoft has been developed by a dedicated team in a relatively brief amount of time.

# SBN – Planning for an End-to-End Analysis

- Short term goal: one week long **SBN Analysis workshop** in the Fall, with the goal of prototyping strategies for combining data from the different detectors in the LArSoft framework.
  - Generate MC data samples in the three detectors, accounting for the details of the different detectors
  - Exploit similar reconstruction strategies for the three detectors (analyzing detector's data side-by-side).
    - Teams of experts from each detector. The teams work very closely in working groups organized by topics (signal processing, noise characterization, calibration, reconstruction…)
    - Maximize synergies and mutual cross checks
  - Exploit how to share the relevant physical information

- Longer term goal: Test of an end-to-end analysis scheme, start including quantification of systematic effects to re-evaluate physics sensitivities with the same technique used in the proposal.

# SBN Analysis – New Analyses/Tools

- Studies going beyond what has already been explored in the SBN proposal in evaluating SBN sterile neutrino discovery potential are underway
  - Studies of the physics reach achievable with possible **upgrades of the BNB beamline**.
  - Studies of **detector systematics** and **correlations**
    - Single detector systematics.
    - Detector-to-detector correlations, that can be generated by differences between the near and the far detectors, need to be carefully studied in order to minimize the systematic contributions.
    - Measurements/monitoring needed to reduce their impact.

# SBN Analysis – New Analyses/Tools

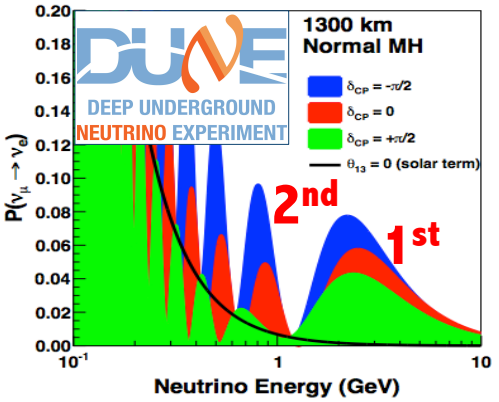
- Considering **new approaches for SBN oscillation sensitivity analyses**, combining appearance and disappearance channels, and exploiting different models with multiple sterile states and exclusive topology measurements.

  - SBN Joint Oscillation and Systematic Constraint Fit [The VALOR Neutrino Fit Group, C. Andreopoulos et al., https://valor.pp.rl.ac.uk]

  - **3+N** sterile neutrino oscillation and CP violation searches at SBN [D. Cianci et al. https://arxiv.org/abs/1702.01758]. *A multi-baseline, multi-channel simultaneous fit is a powerful method of over-constraining 3+N parameter space.*

# Not only oscillation physics: $\nu$-argon interactions at SBN

**SBN will have by far the largest data set of neutrino-argon interactions in the world for the foreseeable future.**




- A broad program of $\nu$-argon cross-section measurements at SBN will have direct impact for controlling the largest systematic uncertainties in oscillation measurements at SBN and at DUNE
  - Large statistics at both the 1st and 2nd DUNE oscillation peaks
  - MicroBooNE is blazing this trail, **but SBND will record the full 3 years of MicroBooNE stats every 2 months of running!**

**Some SBND stats (BNB):**

**1.5M** $\nu_\mu$ CC/year

**12k** $\nu_e$ CC/year

also rare channels, like:

coherent ($10^4$/yr)

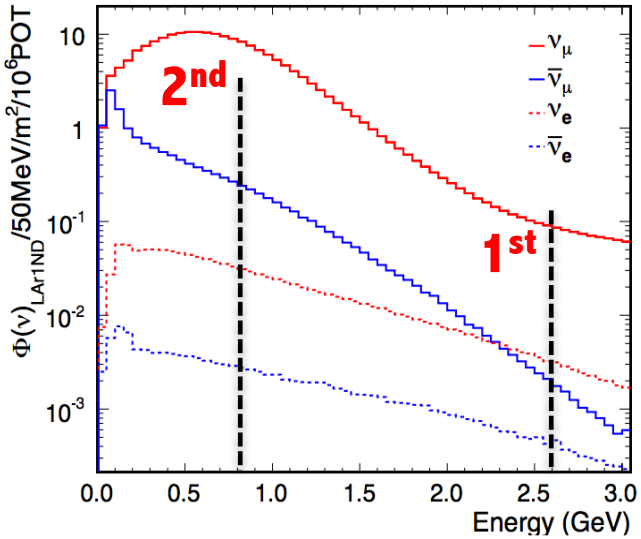
strange prod ($10^3$/yr)

neutrino-electron ($10^2$/yr)

**+ 100K** events per year (**NUMI off-axis)** in **ICARUS,** many at the DUNE 1st osc. max

Dozens of potential scientific results and PhDs!

## SBN Fluxes



# SBN VALOR - Joint Oscillation and Systematic Constraint Fit

- A **Multi-detector**, **multi-channel**, *joint oscillation and systematics constraint fit*
- Use **enormous event rate at SBND** to **constrain BNB flux** and **cross-section systematics** for the SBN programme
- Multi-channel approach: exclusive topology measurements. Exploit the **correlations between exclusive samples**

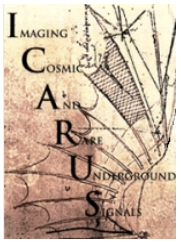
- $\nu_\mu$ **CC**
  1. 1-track $0\pi$ ($\mu^-$ only)
  2. 2-track $0\pi$ ($\mu^-$ + nucleon)
  3. $1\pi^\pm$ ($\mu^-$ + $1\pi^\pm$ + X)
  4. $1\pi^0$ ($\mu^-$ + $1\pi^0$ + X)
  5. Other
- $\nu_e$ **CC**
  6. $0\pi$ ($e^-$ + X)
  7. $1\pi^\pm$ ($e^-$ + $\pi^\pm$ + X)
  8. $1\pi^0$ ($e^-$ + $\pi^0$ + X)
  9. Other
- **NC**
  10. $0\pi$ (nucleon(s))
  11. $1\pi^\pm$ ($\pi^\pm$ + X)
  12. $1\pi^0$ ($\pi^0$ + X)
  13. Other

- Simultaneous fit of several exclusive event samples **maximizes physics sensitivity**

# SBN Analysis Group – Summary

- The SBN Analysis Group establish a **long-term continuous, direct connection/collaboration** on **oscillation analysis topics** between SBND, MicroBooNE and ICARUS experiments.
  - Continuous exchange of information/expertise between analyzers from the three experiments
  - Important contribution from US MicroBooNE collaborators, LArSoft experts, who joined ICARUS
  - Visit to Fermilab of ICARUS collaborators active on simulation/analysis
  - Meetings of sub-groups (including people from the three collaborations) active on specific topics

- Acting as a **unique collaborative effort** in preparation for the SBN oscillation analysis, profiting from the expertise **from three collaborations**!



# SBN: Unified plans

- Major progress has being made on coordinated plans for online and analysis across the SBN program, by exploiting synergies and knowledge-sharing from the three collaborations.
  - Activities in the **SBN Online Working Group** range from Data Acquisition software to Slow Control and joint building of Tools for the implementation of online/quasi-online Monitor of detector performance.
  - Activities in the **SBN Analysis Group** range from implementing detectors in LArSoft to high-level physics sensitivity studies.
  - Experience with BNB neutrino simulation and analysis from MicroBooNE data are a valuable input.

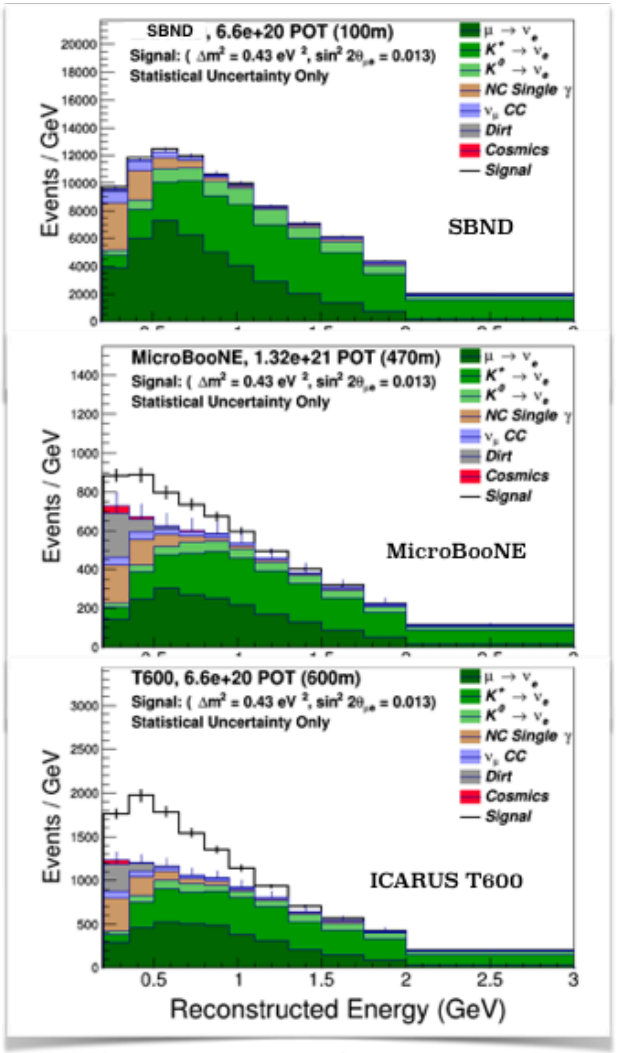
- Planning for **joint Operation**: initial discussion on synergetic operation of the SBN detectors with ICARUS at a recent PI meeting.

# Backup

# Physics reach of the SBN Program

- Oscillation sensitivity of the SBN program has been evaluated in a joint effort by three collaborations.

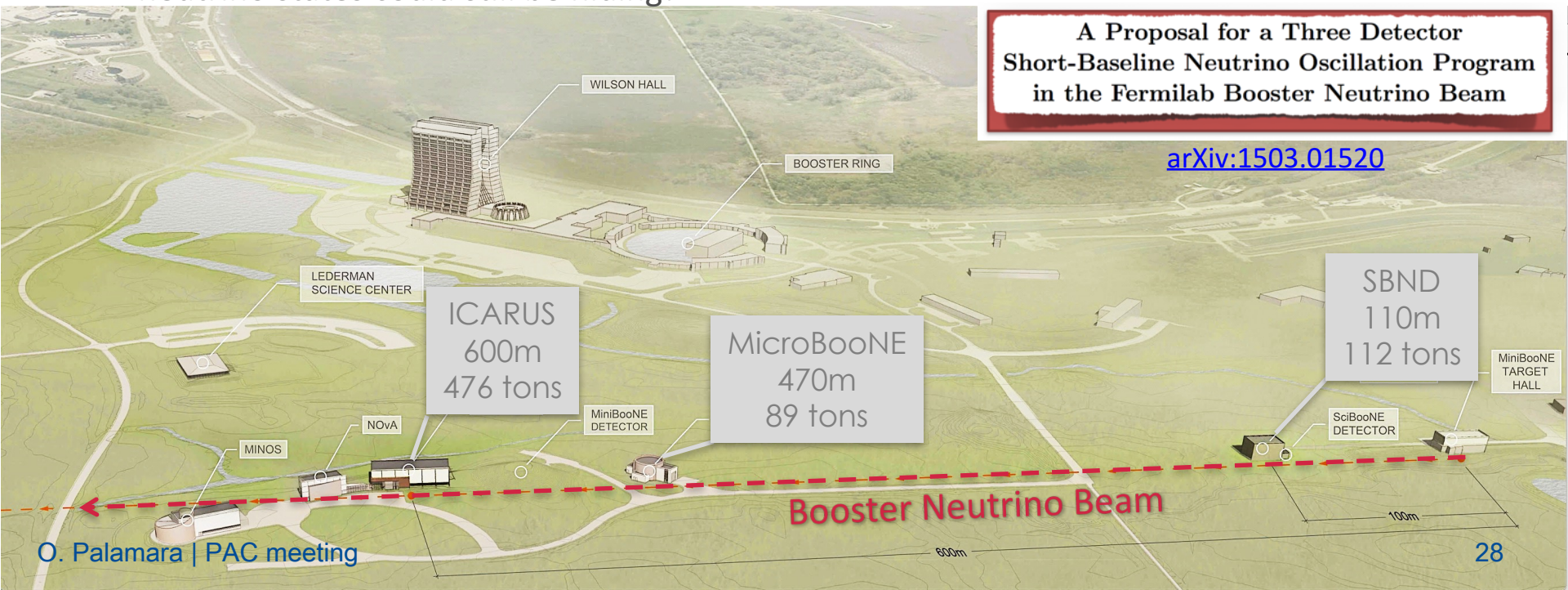
- Sensitivities *(in the context of a 3 active + 1 sterile neutrino model)* are based on full simulations of all known **backgrounds and systematics uncertainties**
  - **intrinsic $\nu_e$** content of the beam
  - **photons** induced by **neutral current** interactions
  - **neutrino interactions** in the **material surrounding the detectors**
  - **cosmogenic photons**
  - **neutrino flux** and **neutrino-argon cross section systematics** and **detector-to-detector systematics** included in the sensitivity analysis




Signal: Kopp et al. Global Best Fit

# The Three Detector SBN Program

- **Three LAr TPC detectors located along the Booster Neutrino Beam (BNB)**
  - Same beam, same neutrino target, same detector technology → **minimize systematics**
- **MicroBooNE has been operational with beam since 2015**
  - MicroBooNE designed very specifically to be sensitive to the MiniBooNE observed anomaly
- **Full SBN Program approved in Feb 2015**
  - Addition of ICARUS and SBND extends science reach from a specific anomaly to the **world-leading neutrino oscillation search experiment** at $\Delta m^2 \sim 1\ eV^2$
  - Up-to-date global analysis of experimental data indicate this as the region where light sterile neutrino states could still be hiding!



# Other Physics Outputs of the SBN Program

- Transferable analysis development, SBN enables/requires:
  - Development and validation of LAr calibration and reconstruction techniques.
  - Precision testing of event reconstruction and identification with large neutrino data sets.
  - Detailed systematics evaluation for sensitive oscillation measurements in appearance and disappearance channels.
- Collaboration, community, and building a knowledge base in LAr
  - SBN provides direct experimental activity with LAr technology for the global neutrino community working toward DUNE.
  - An active SBN program with **International participation** helps to build/maintain the neutrino physics community at Fermilab that will be centered around DUNE in the future.
  - The students, postdocs, faculty and scientists working on SBN are also working on DUNE, and will go on to lead physics analysis on DUNE in the future.
  - In the mean time, people want to confront data, **do physics!** SBN is an ideal opportunity.

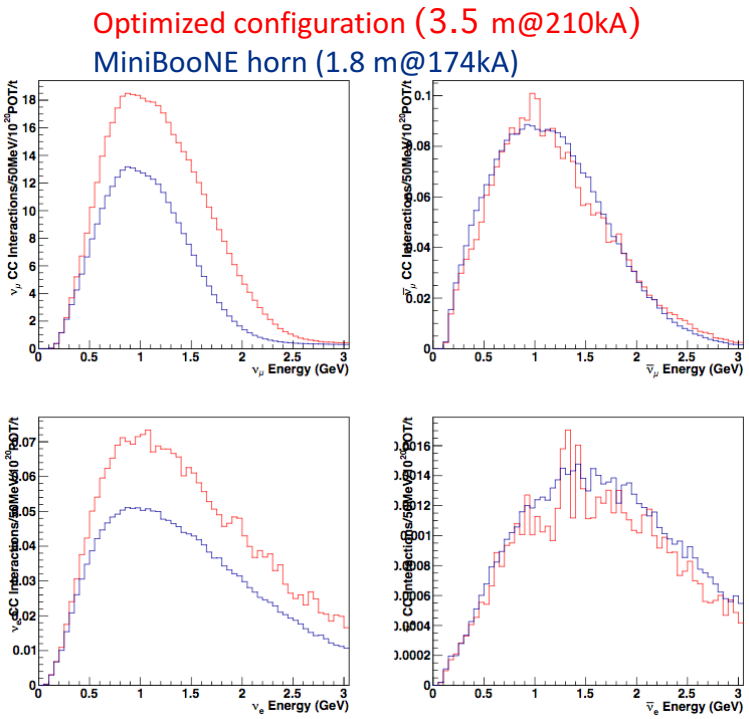
# SBN - Upgrades of the BNB beamline

- Studies have shown that **reconfiguration of the BNB beamline** could provide a significant **improvement in neutrino flux**.

- Specific studies of the BNB upgrade include examining **replacement of the existing target** and **horn** assembly and/or **upgraded power supply** in order to produce increased neutrino fluxes to the SBN experiments.

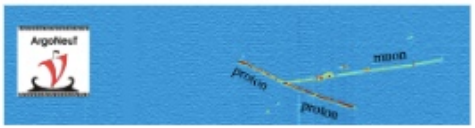
- Oscillation sensitivity with upgraded BNB configuration has been evaluated.

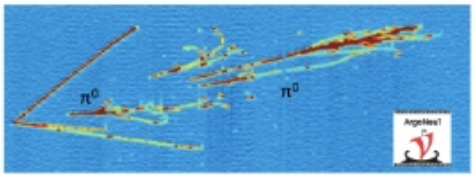
- A Committee has been charged with reviewing the physics reach achievable with the proposed upgrade



# High event rate with excellent imaging capabilities

| $\nu_\mu CC$, BNB/FHC, $6.6\times10^{20}$ POT, 112 tonnes active mass | | |
|---|---|---|
| | GENIE Model Configurations | |
| **Hadronic Final State** | **G17_01b** | **G17_02a** |
| Inclusive | 5,389,168 | 5,329,241 |
| 0 $\pi$ | 3,814,198 | 3,744,108 |
| 0 $\pi$ + 0p | 27,269 | 34,696 |
| 0 $\pi$ + 1p (> 20 MeV) | 1,629,252 | 2,235,338 |
| 0 $\pi$ + 2p (> 20 MeV) | 1,150,368 | 637,535 |
| 0 $\pi$ + 3p (> 20 MeV) | 413,956 | 229,239 |
| 0 $\pi$ + >3p (> 20 MeV) | 396,212 | 263,727 |
| 1 $\pi^+$ + X | 942,555 | 1,021,212 |
| 1 $\pi^-$ + X | 38,012 | 21,242 |
| 1 $\pi^0$ + X | 406,555 | 370,666 |
| 2 $\pi$ + X | 145,336 | 131,308 |
| $\geqslant 3\pi$ + X | 42,510 | 40,702 |
| **Physical Process** | | |
| QE | 1,569,073 | 2,827,928 |
| MEC | 1,398,773 | 513,453 |
| RES | 1,816,570 | 1,539,159 |
| DIS | 581,905 | 441,057 |
| Coherent | 22,846 | 7642 |



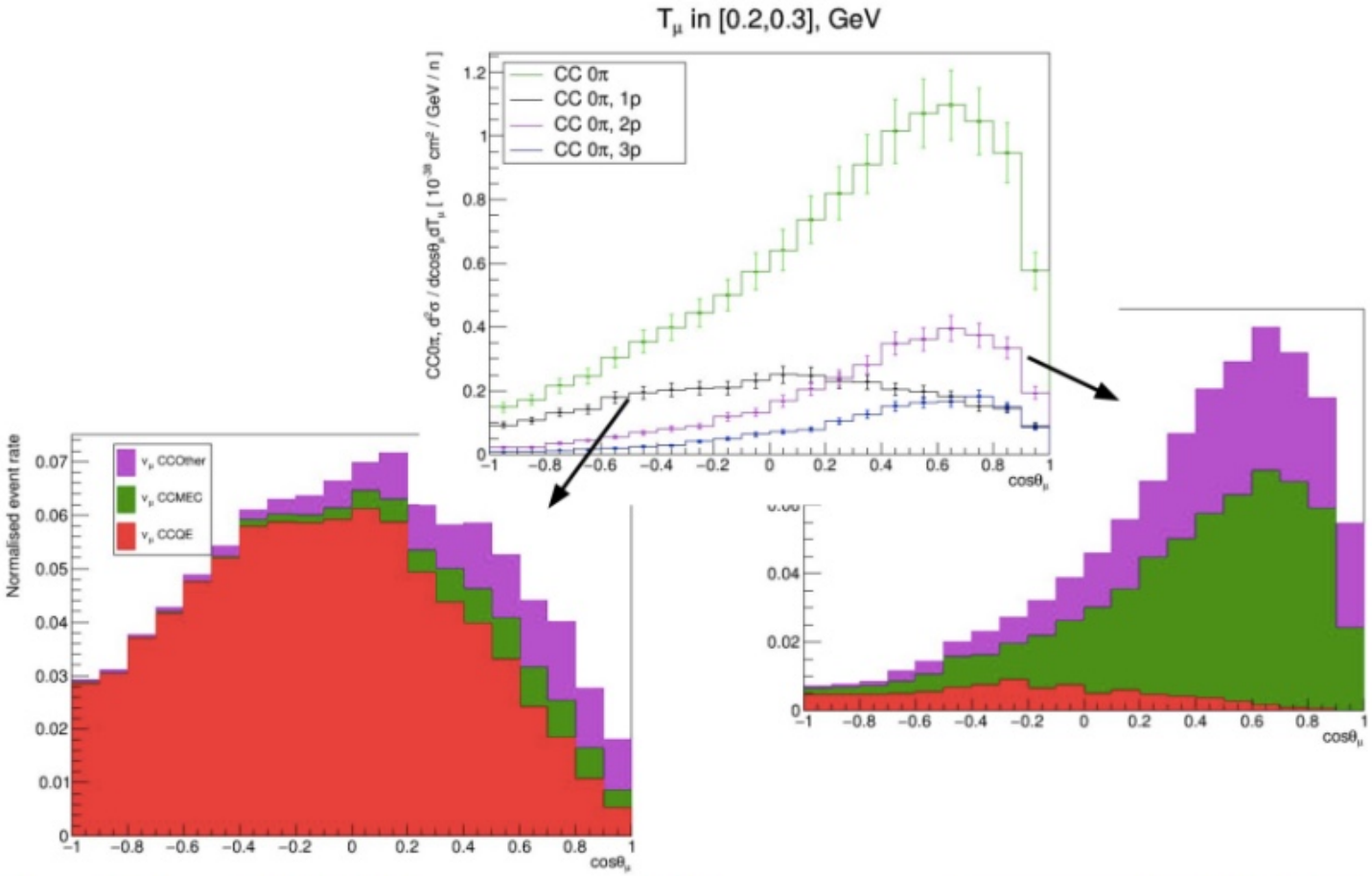

Also:
- ≈ 350k NC$\pi^0$ events
- ≈ 12k $\nu_e$CC events
- ≈ 1k charm (QE) events
- ≈ 400 $\nu + e^-$ events

A generational advance in neutrino-nucleus interaction studies.

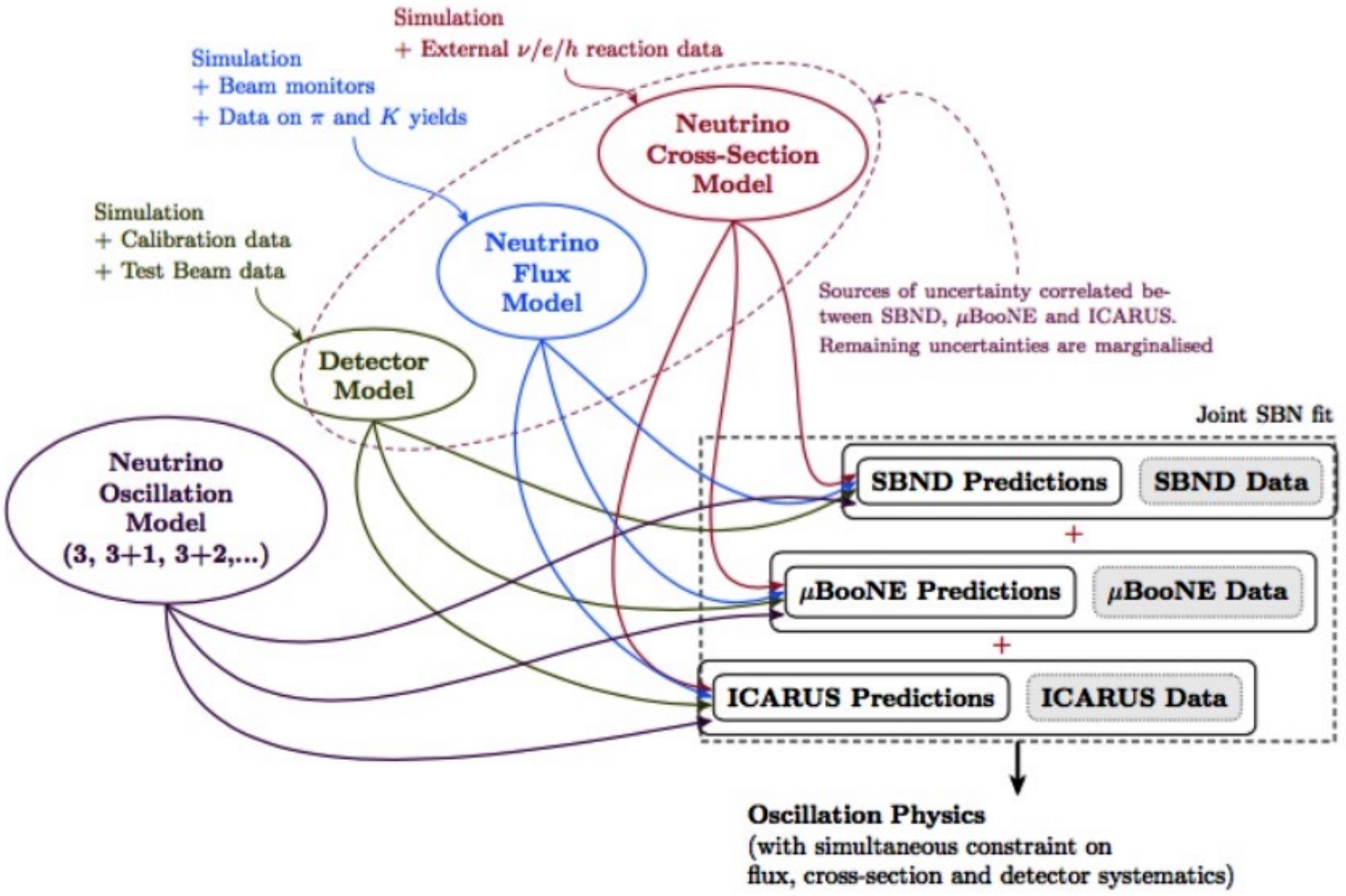
**G17_01b**: Updated empirical model / **G17_02a**: Theory-driven model (See J.Wolcott's GENIE talk)

# Illustration of cross-section measurement capabilities

Study of several exclusive states would allow to disentangle different aspects of neutrino-nucleus interaction phenomenology.

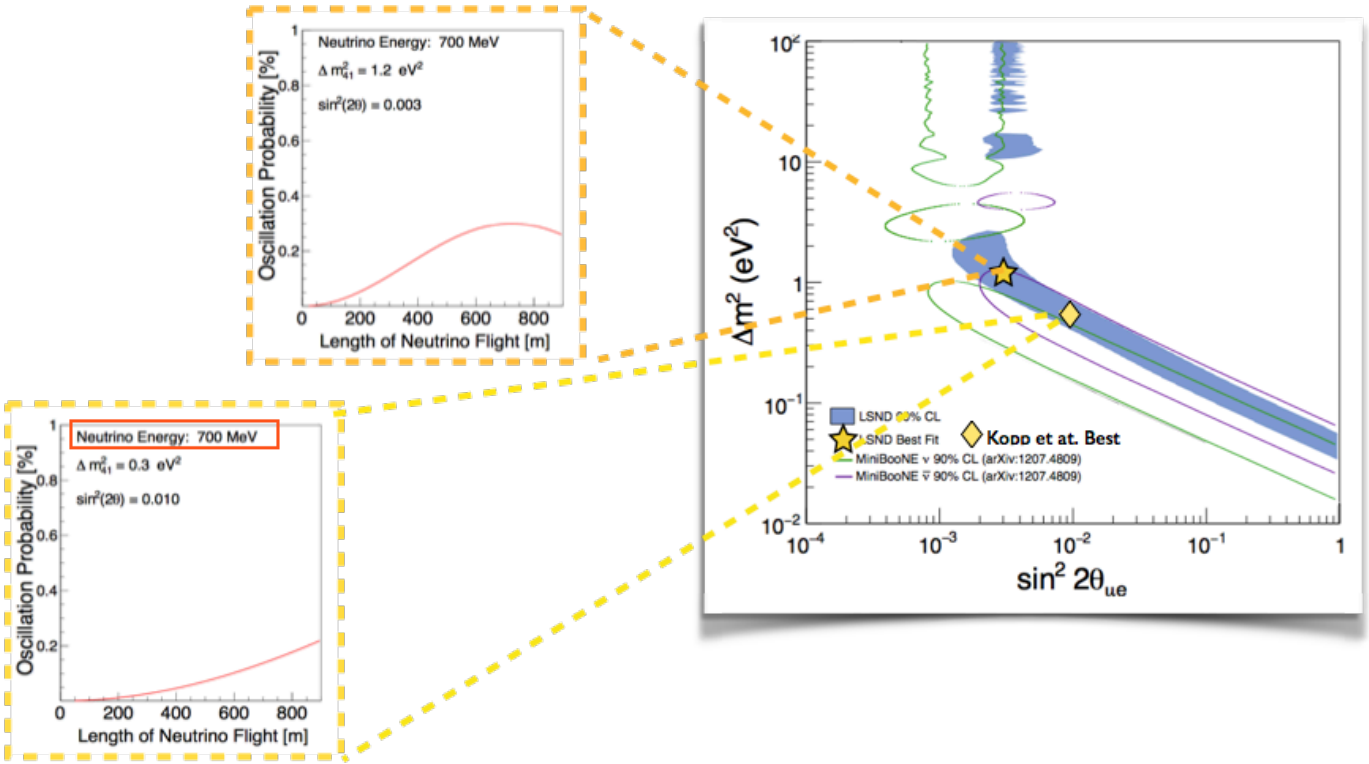


# Towards a joint SBN oscillation analysis



# SBN - Systematics Uncertainties

- The accelerator neutrino anomalies at short-baseline hint at oscillation with very small amplitude
- Resolving small oscillation effects requires good control of systematic uncertainties




- In the SBN proposal it has been estimated that an overall global detector systematic uncertainty in the 2-3% range would preserve the experimental sensitivity. This systematic level is assumed as a **requirement for the detectors.**

# SBN - Systematics Uncertainties

- In a single detector approach, each detector systematic arises from several detector configurations.
- Using control samples and simulations we may be able to measure at each detector the different systematics and their relation wrt detector configuration.

| Detector configurations |
|---|
| Wires orientation |
| TPC readout electronics |
| E-field non-uniformity |
| Drift velocity |
| LAr purity |
| Active volume |
| Light collection & CRT |

| Systematics |
|---|
| Track momentum resolution |
| Track PID |
| Shower PID |
| Shower energy |
| Shower vertex resolution |
| Shower/track mis-ID |
| Track multiplicity efficiency |
| Fiducial volume mass |

$$\text{Det. systematic (k)} = f(\text{wire orientation, TPC readout electronics,etc.})$$
$$\text{Det. systematic (k+1)} = g(\text{wire orientation, TPC readout electronics,etc.})$$

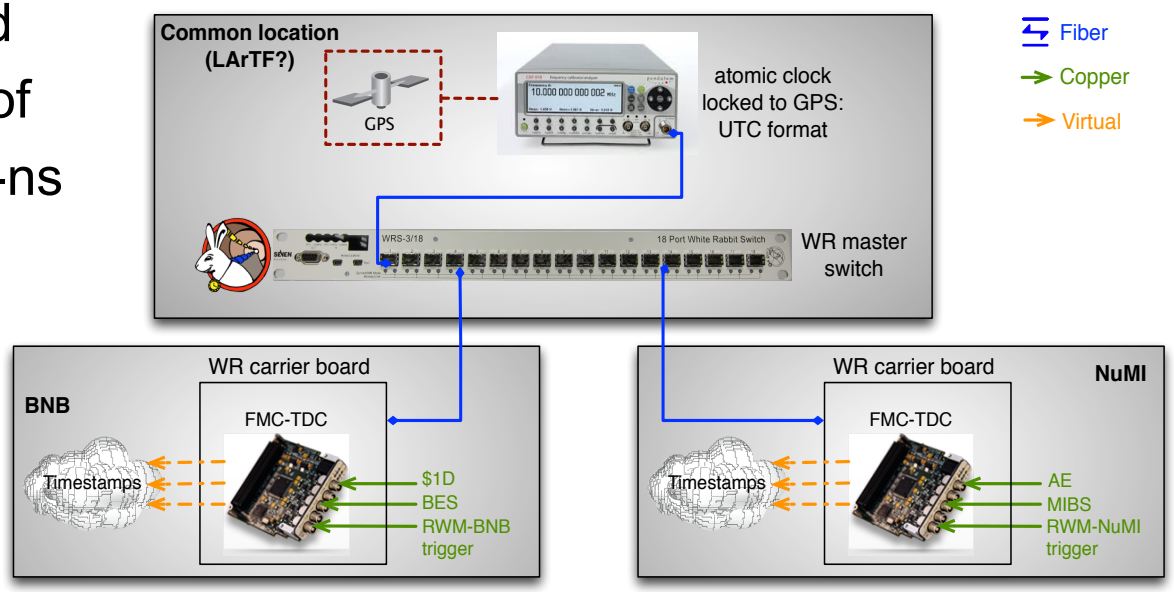
- Detector-to-detector correlations need to be carefully studied in order to minimize the systematic contributions.

# Common SBN DAQ software status

- Core *artdaq* improvements, many from similar requirements for ProtoDUNE-SP
  - Dataflow, run control, and monitoring updates
- CRT DAQ development shared with MicroBooNE
  - Initial DAQ working in MicroBooNE now
  - *artdaq*-based updates expected over summer
  - MicroBooNE initial run already influencing improvements for SBN
- Light system readout works in SBN DAB test stand
  - Focused for SBND, basically “just works” for ICARUS
- Multi-system integration work in test stands at CERN and DAB this summer
  - ICARUS summer student leading the way, direct profit to SBND

# Timing distribution with White Rabbit

- Distribution of an “absolute” pps (pulse per second) GPS timing to the beams extraction locations and the detector halls.
  Used to timestamps several signals related to beam extraction.
- White Rabbit: ethernet based network for synchronization of distributed systems with sub-ns accuracy, < 50 ps precision).
- FNAL set-up in preparation: B. Badgett & D. Torretta in touch with ICARUS/SBND, inputs from CERN experts in Oct. training [https://indico.cern.ch/event/574169/](https://indico.cern.ch/event/574169/).




- Each experiment will independently timestamp its trigger in the same time reference frame. Relevant for exploiting bunched beam structure.

# Other activities

- Investigation of possibility to develop common database tools ongoing;
- Common strategy on slow controls, with ICARUS decision to adopt the Experimental Physics and Industrial Control System (EPICS) software, to be consistent with SBND and MicroBooNE.
  However, resources for common development missing.
- Working group “regularly” meeting to study possible commonalities in online/nearline monitor of LAr purity: SBN-event-441.
  Proposed exploitation of CRT for prompt selection of through-going μ tracks.
- Possible extension to online/nearline monitor of space charge effects.