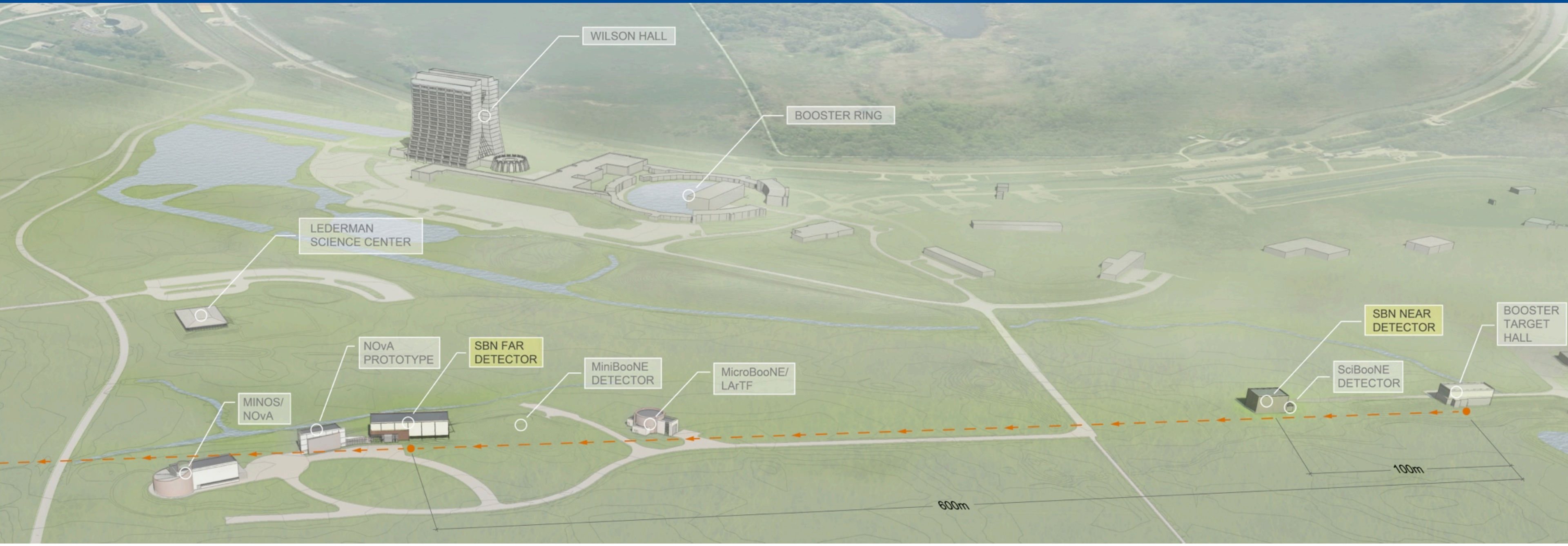


SBN Analysis Working Group Report

PAC Meeting

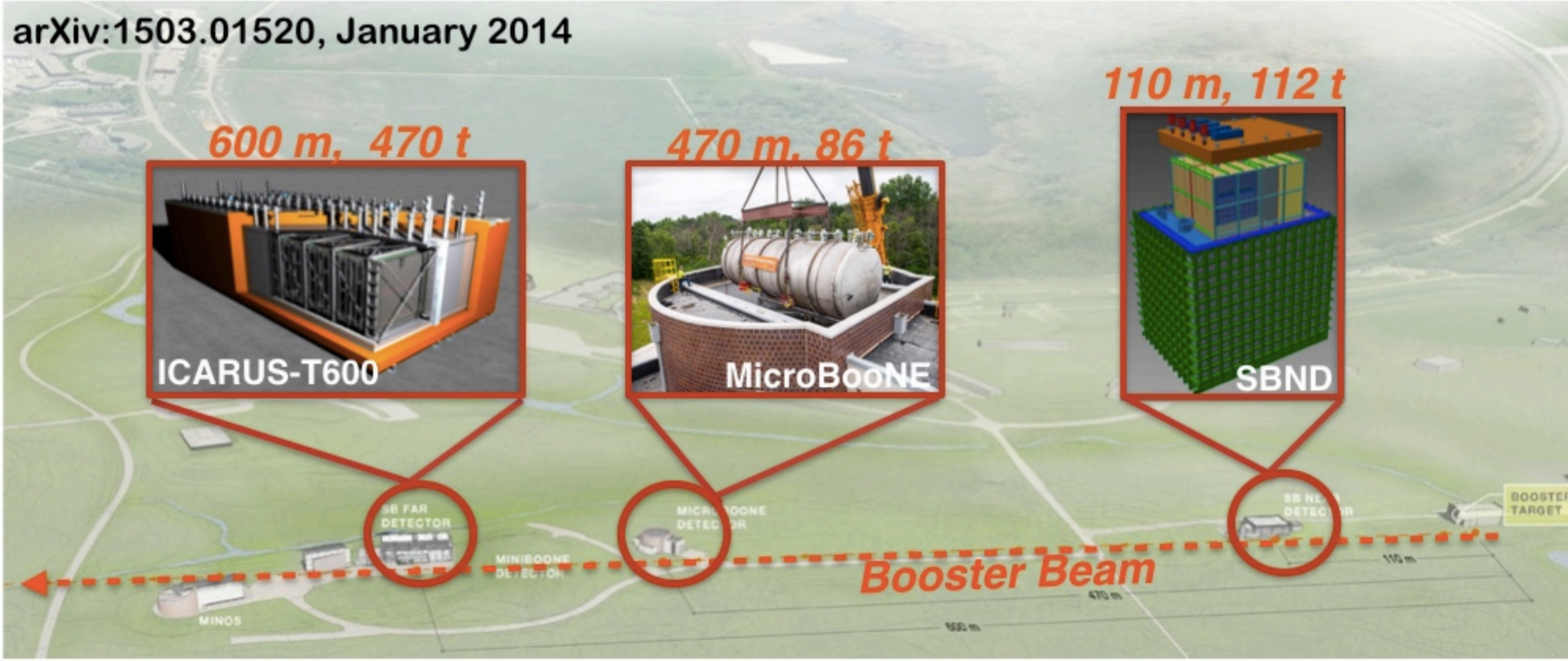
Chicago, July 16th 2018

Ornella Palamara

Outine

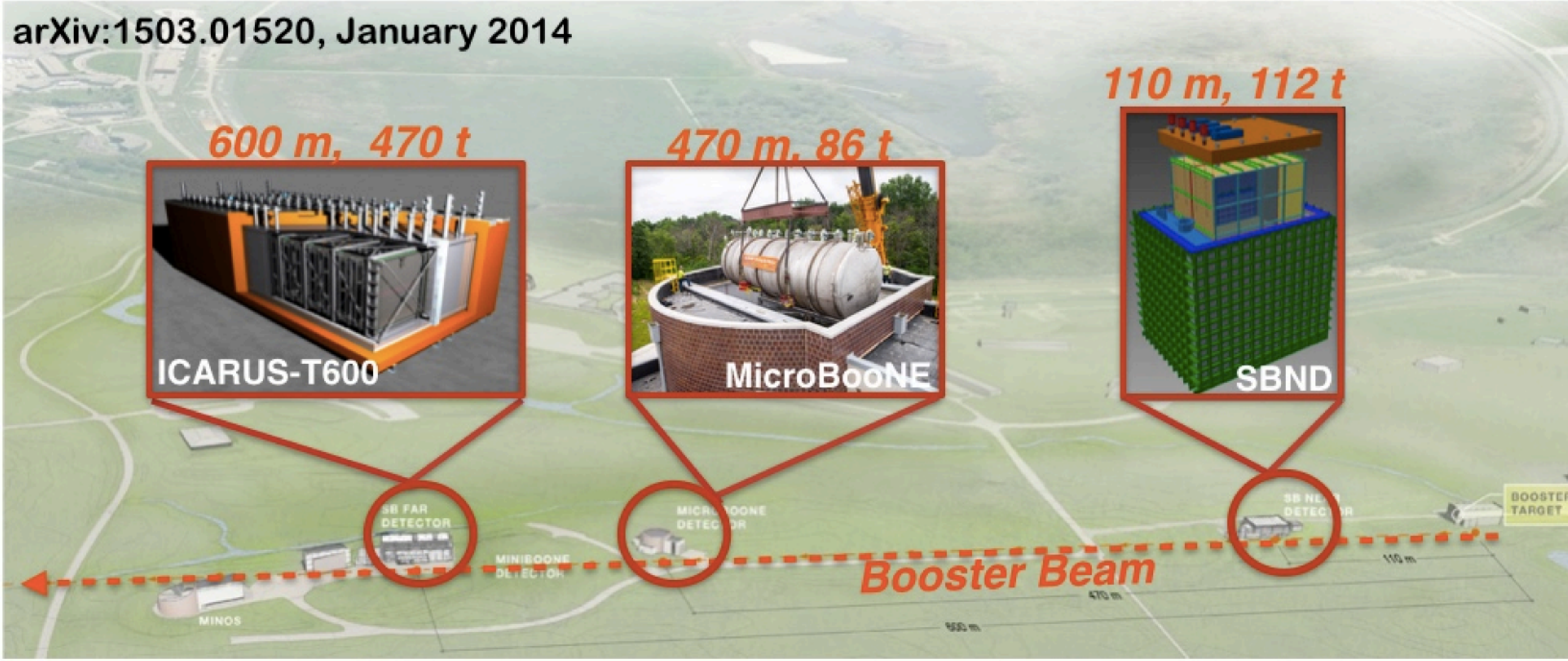
- SBN Analysis Group
  - Goals & Strategy
  - MicroBooNE's role
  - Organization, Status and Milestones
- Neutrino-argon Cross Sections and Beyond Standard Model searches at the SBN

FNAL Short Baseline Neutrino program



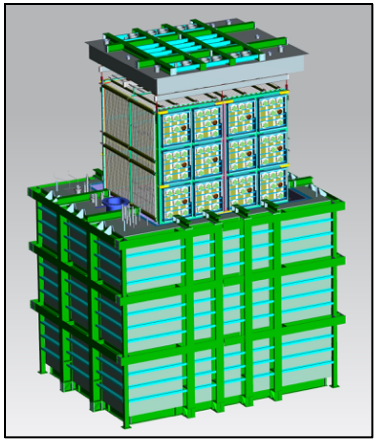
SBN Phase 2 - The MicroBooNE detector will be joined by two additional Liquid Argon TPC detectors at different baselines, the SBND detector and the ICARUS-T600 detector to perform **sterile neutrino oscillation searches.**

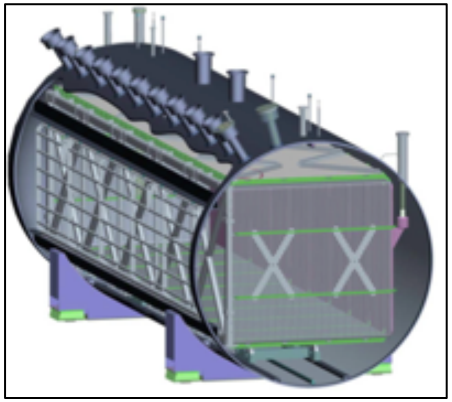
FNAL Short Baseline Neutrino program

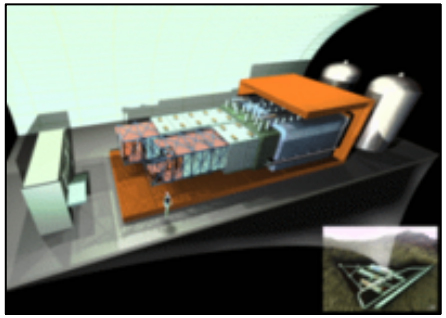


- ❑ Addition of ICARUS and SBND extends science reach from a specific anomaly to the **world-leading neutrino oscillation search experiment** at $\Delta m^2 \sim 1$ eV^2.
- ❑ The MiniBooNE observed excess has strengthened with additional data, and global fits of all experimental data indicate 1-2 eV^2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

SBN Analysis Group - A Unified Effort

- Joint SBN Oscillation Analysis group formed in September 2016

- 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.

- The group has defined the strategy for a **common simulation**, **reconstruction** and **analysis framework**.

- Ongoing **collaborations with theorists**.

SBN Analysis Group - Goals

- Implement a **three detector simulation**, **reconstruction** model within a **common framework** (LArSoft).

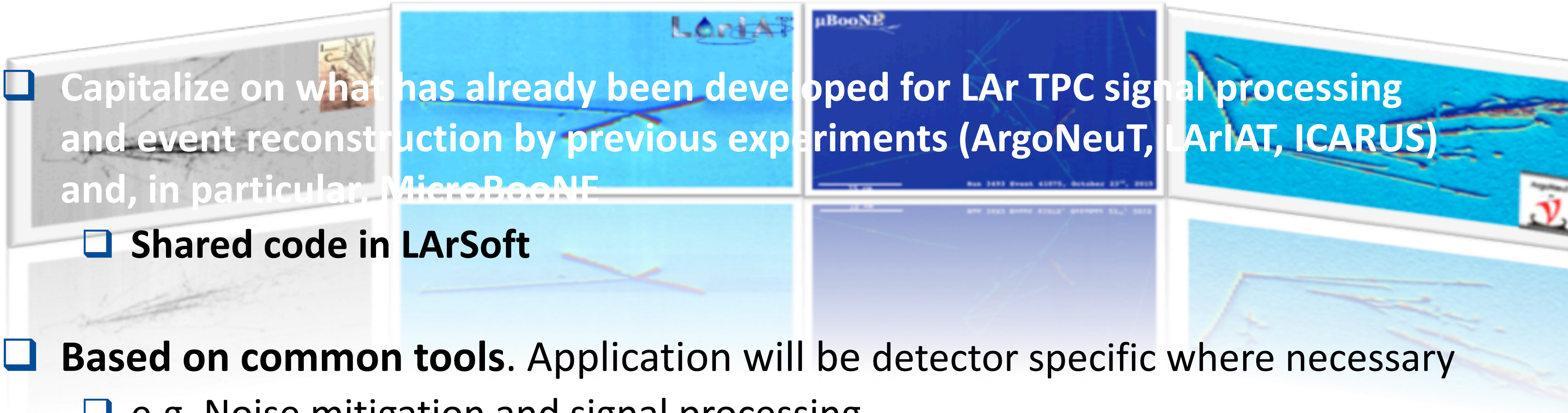
- Implement a **common analysis scheme** in preparation for real data exploitation.

- Update projections of **expected physics capabilities** of the SBN program, including
  - Reconstruction efficiencies
  - Performances and systematic effects
  - Background rejection from a full MC simulation of the three detectors

- Develop **new analysis methods** and **tools** to perform sensitivity analyses
  - Combining appearance and disappearance channels, and
  - Exploiting different models with multiple sterile states and exclusive topology measurements.

SBN Analysis Group - Reconstruction Strategy

- **SBN software tools are all incorporated in common frameworks.**



- **Capitalize on what has already been developed for LAr TPC signal processing and event reconstruction by previous experiments (ArgoNeuT, LArIAT, ICARUS) and, in particular, MicroBooNE**
  - **Shared code in LArSoft**

- **Based on common tools**. Application will be detector specific where necessary
  - e.g. Noise mitigation and signal processing

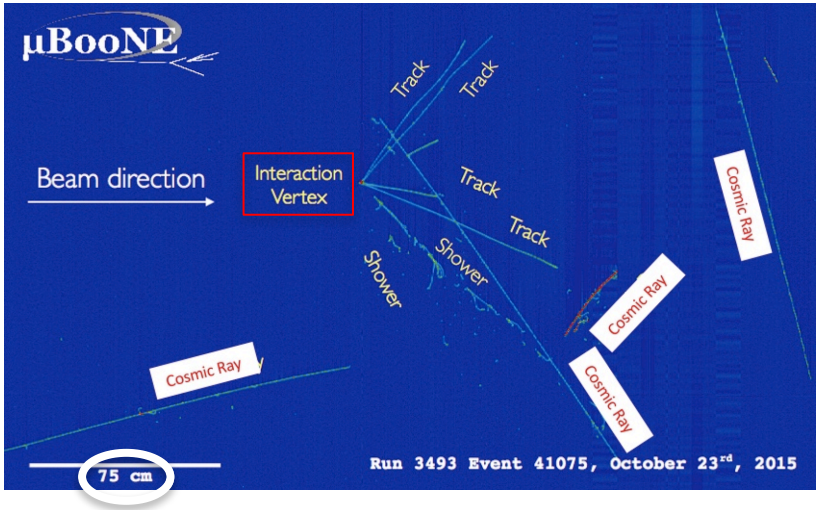
- Strive for **common reconstruction strategies**
  - e.g. once "hits" have been found use common pattern recognition and reconstruction tools available in LArSoft
    - May require some detector specific customizations

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

MicroBooNE's Role

- MicroBooNE is the first large scale LAr TPC running at the surface exposed to a neutrino beam and is laying the foundation for the other SBN experiments.

- MicroBooNE has led critical development in several areas:
  - From **noise filtering** to **signal processing,** to **tracks** and **showers** reconstruction.
  - Because of the Cosmic Ray background, as well the high rate of neutrino events, MicroBooNE is leading the development of **automated** reconstruction tools.

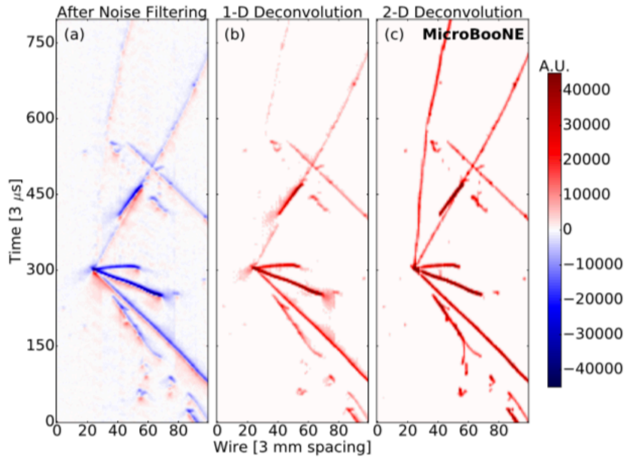


- Both SBND and ICARUS benefit from having a significant number of MicroBooNE collaborators, helping to facilitate the **transfer of lessons learned**, experience and software.
  - In particular both will benefit from the MicroBooNE experience during the initial data taking period.

MicroBooNE's Role*

*See Tracy Usher presentation "SBN coordinated analysis strategy" @ May 24- LBNC meeting for details

- ❑ Some specific examples:
  - ❑ **Noise filtering**: The noise issues encountered early in MicroBooNE running have led to the development of sophisticated software tools to mitigate them.
  - ❑ **Signal processing**: 1D and 2D deconvolution.



"Ionization Electron Signal Processing in Single Phase LAr TPCs I: Algorithm Description and Quantitative Evaluation with MicroBooNE Simulation", arXiv:1804.02583, submitted to JINST

  - ❑ **Space charge effect** (due to cosmics)
    - ❑ Bias on dQ/dx for MicroBooNE is ~10%
    - ❑ Bias of ~3-4% expected for SBND
    - ❑ Bias of ~1-3% expected for ICARUS

MicroBooNE's Role*

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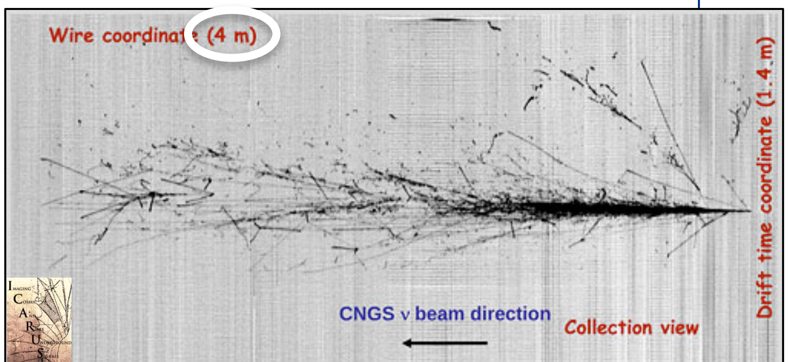
- **Fully automated reconstruction:** First large scale Liquid Argon TPC to attempt fully automated reconstruction
  - Required in order to **find/remove** high background rate from **cosmic rays**
  - Reconstruct **large samples of neutrino events**

ICARUS reconstruction during the run at Gran Sasso was not fully automated. Significant differences in running conditions
  - Underground - low background rate
  - Relatively smaller sample of neutrino events
- Allowed for a semi-automatic reconstruction (pattern recognition was augmented by physicist interaction via the event display)
  - Examples: identification of the primary vertex, adding hits to showers



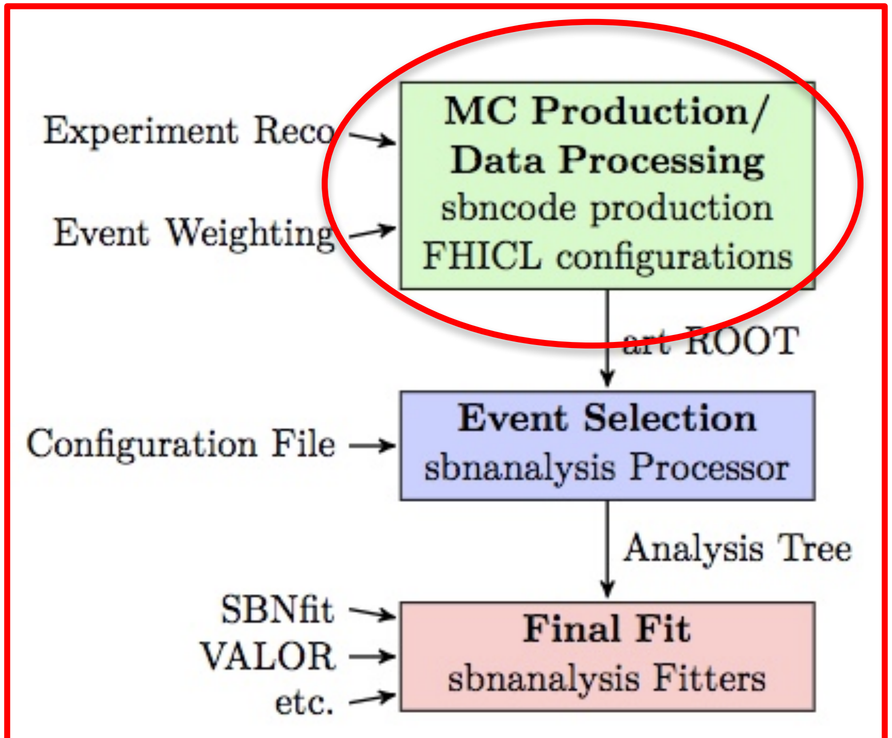
- **Significant improvements in event reconstruction**, development and comparison of different reconstruction algorithms/techniques, implementation of new reconstruction techniques*

*See Bonnie Fleming presentation tomorrow for details about MicroBooNE event reconstruction

SBN common code (**sbncode**)

New 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

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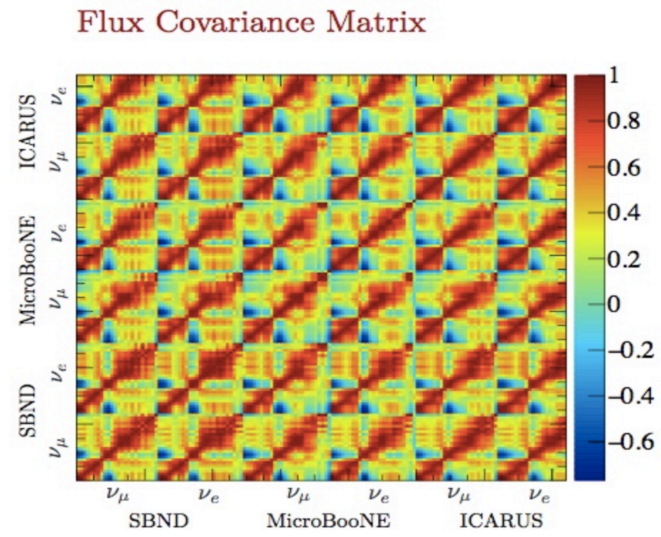
New standard SBN simulation and analysis code



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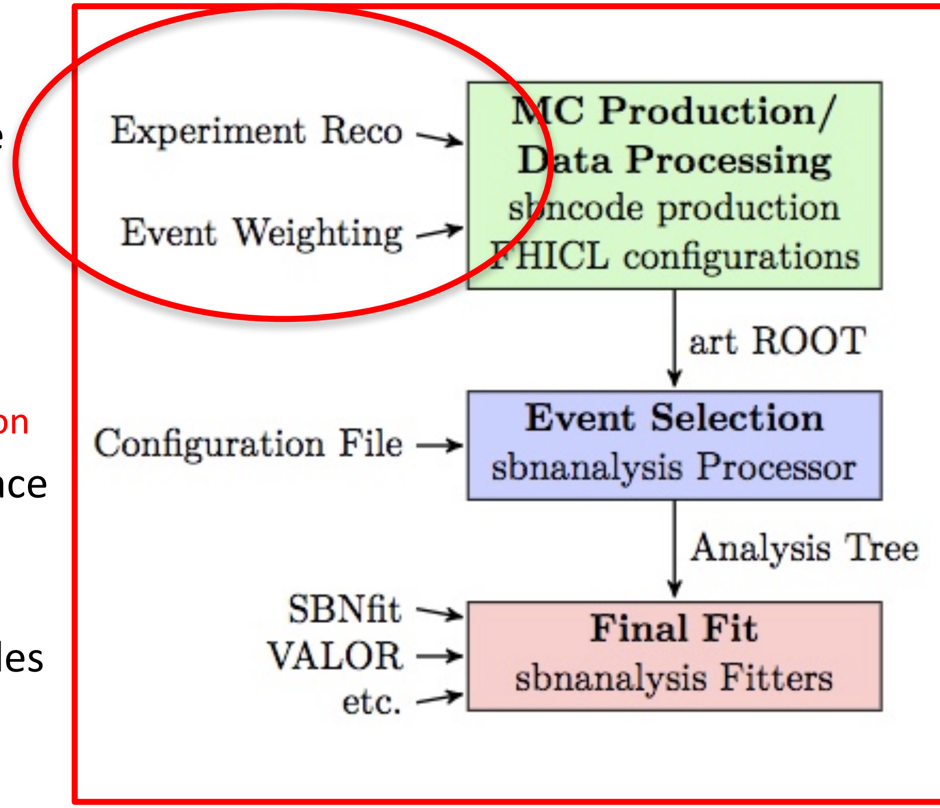

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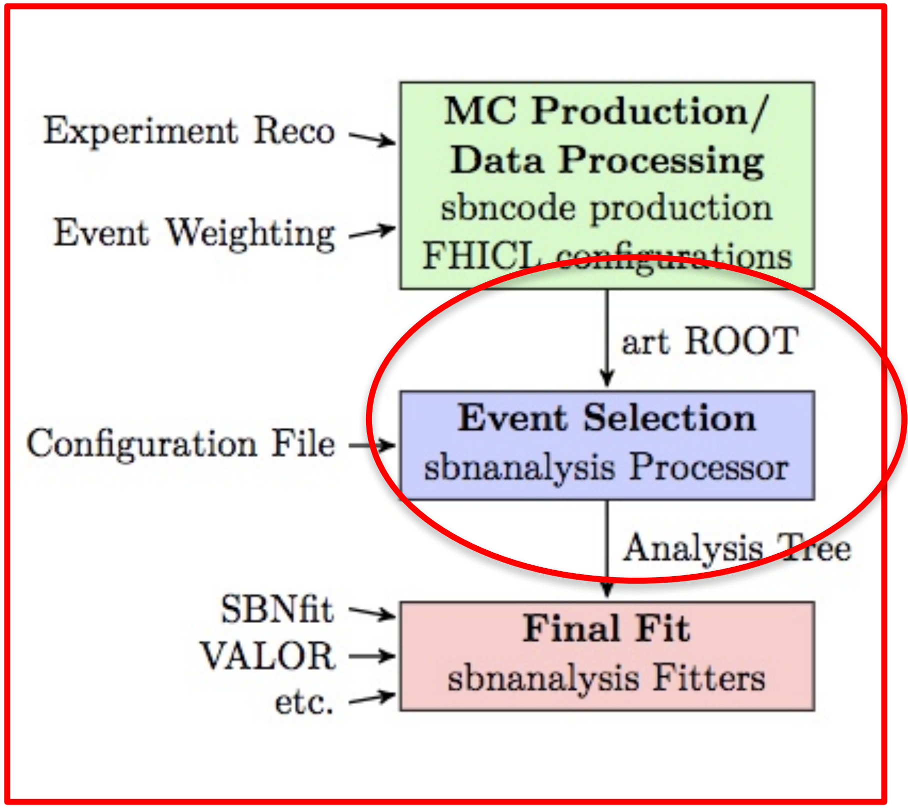

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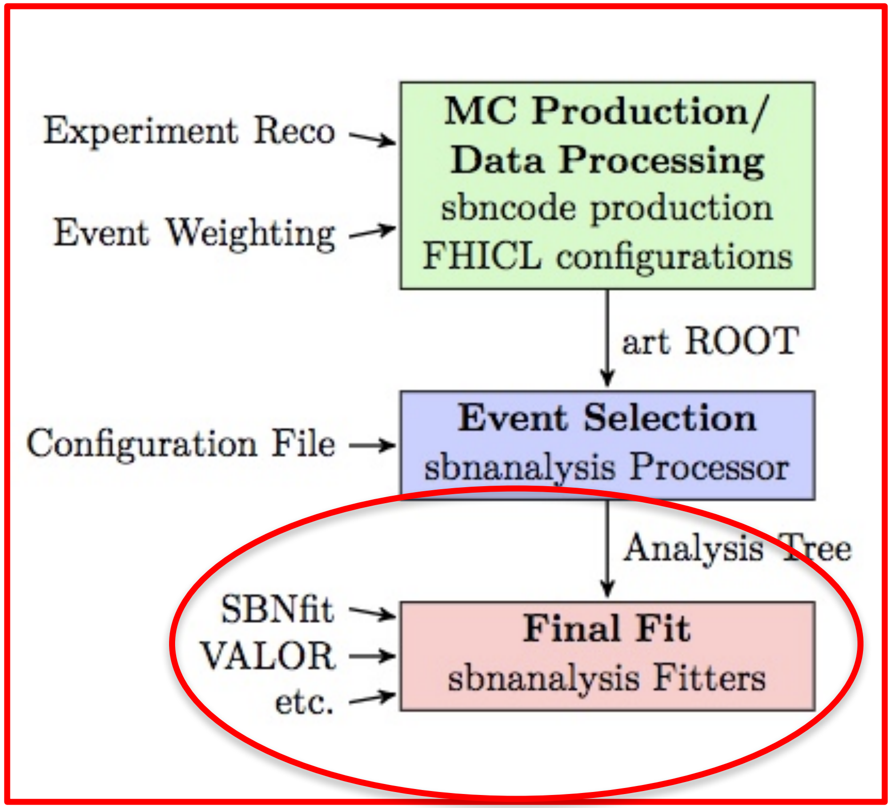
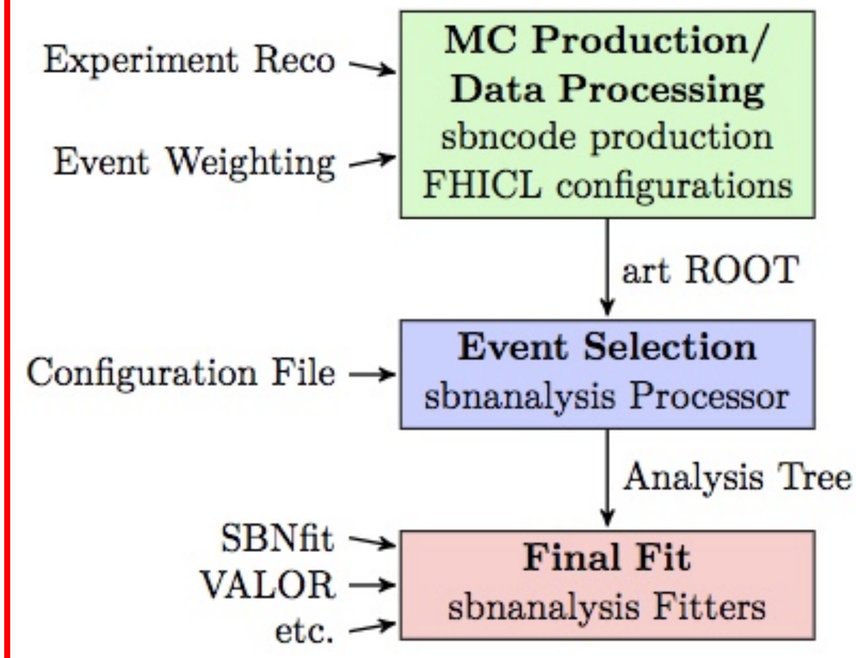


All aimed at a high-quality, readily reproducible oscillation analysis

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 Group – Organization/Status/Milestones

- **Bi-weekly meetings** of the SBN Analysis Working Group

- Activities are organized in subgroups to verify simulation and develop tools for reconstruction for the different subdetectors (TPC, light detection systems, CRT), and analysis tools to be used in any detector.

- **SBN Analysis Workshops** to facilitate discussion and side-by-side practical work of SBN collaborators
  - **I Workshop – Fermilab Oct. 23-27 2017** (21 participants)
    - Successfully **generated BNB neutrino events** in SBND and ICARUS detectors.
    - Focus on **TPC charge reconstruction** for **tracks**: hit, clusters and track reconstruction, neutrino interaction vertex reconstruction and track calorimetric reconstruction. Use and compare different **track reconstruction** algorithms.
    - Comparison of **track reconstruction performances** in the two detectors.

SBN Analysis Group – Organization and Status

- **II Workshop – Padua (Italy) March 19-23 2018** (32 participants)
  - Further develop **neutrino interaction vertex reconstruction** in the TPC.
  - Reconstruction of **e.m. showers** in the TPC. Use and compare different **e.m. shower reconstruction** algorithms.
  - Develop **exclusive neutrino event selections** tools based on TPC information.
  - Verify geometry and simulation of **Cosmic Ray Tagger**. Develop tools for the reconstruction of CRT signals.
  - Develop tools for the reconstruction of **Photon Detection Systems** signals.
  - Exploit **Cosmic Ray Tagger** and **Photon Detection Systems** for triggering and cosmic ray rejection.
  - First time use of **sbncode** for SBND and ICARUS event simulation, reconstruction and analysis.

- The "work-together" scheme of the workshops is very effective to discuss and progress in the preparation of the necessary tools, share ideas and find common solutions.
- **Next milestones**: reproduce SBN proposal sensitivities through the **sbncode** framework, calculate sensitivities including event selections and reconstructions.

Not only oscillation physics: Cross Sections and BSM searches at the SBN

Neutrino-argon Cross Sections

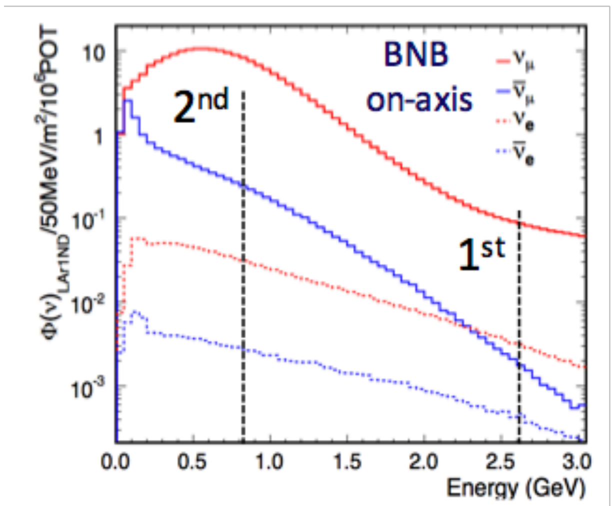
- A correct interpretation of the outcome of ν oscillation experiments requires **precise understanding of ν interaction cross sections**. Argon measurements are relevant for the SBN and DUNE oscillation programs.
- The LArTPC technique opens new perspectives for the study of **nuclear effects** from the detailed reconstruction of **final state event topologies** in ν-nucleus interactions.
- First measurements on argon from a relatively small data set from ArgoNeuT (hundred- to-a-few-thousand events) provide new information about neutrino argon scattering.
- **SBN will have by far the largest data set of neutrino-argon interactions in the world for the foreseeable future.**

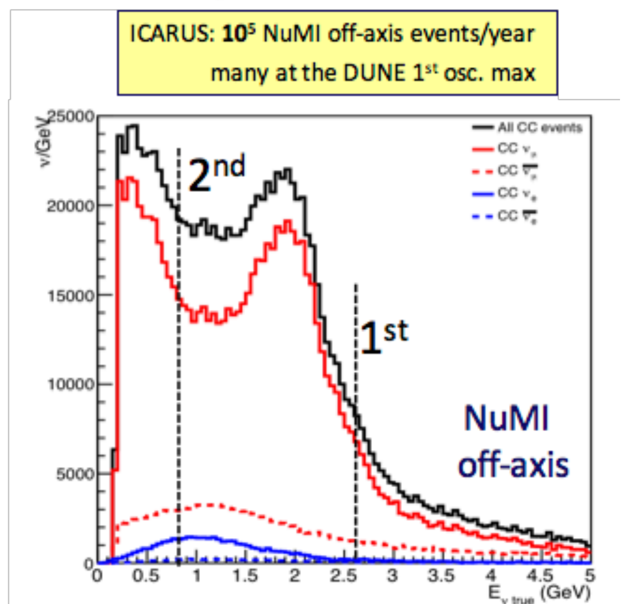
BSM searches

- The proximity to the beam target, large detector mass and relative detection isotropy makes the LAr TPC **SBN detectors well suited for beyond the standard model searches.**

Cross Sections at the SBN

- **SBN detectors will provide huge data sets of ν-Ar interactions from the BNB on-axis and the NuMI off-axis fluxes.**
  - Large samples collected by MicroBooNE (~50,000 ν_μ CC events per year). Many analyses in progress.
  - SBND will record ~**1.5 million ν_μ CC** and ~**12,000 ν_e CC** events per year
  - ~**100,000** NuMI off-axis events in ICARUS-T600 year





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MicroBooNE has reached ArgoNeuT statistics in **1 month of beam**

µBooNE

SBND (closer to the target, ~25 higher rate) will reach ArgoNeuT statistics in **1 day of beam**

SBND will surpass the MicroBooNE 5 year run in about 3 months

SHORT-BASELINE SBND NEAR DETECTOR

Cross Sections at the SBN

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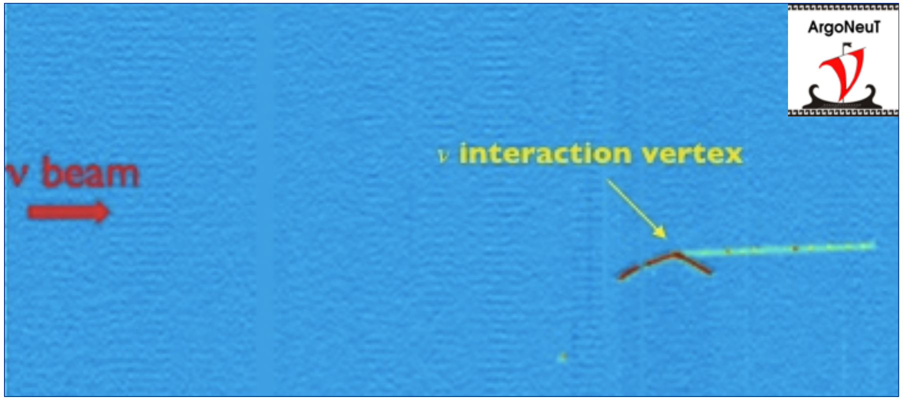
- At the BNB the **CC pion-less ("CC 0 pion")** is the dominant channel
  - High statistics measurement of ν_μ and ν_e CC 0 pion events will allow to quantify **nuclear effects in neutrino-Ar scattering**

μ+2p events



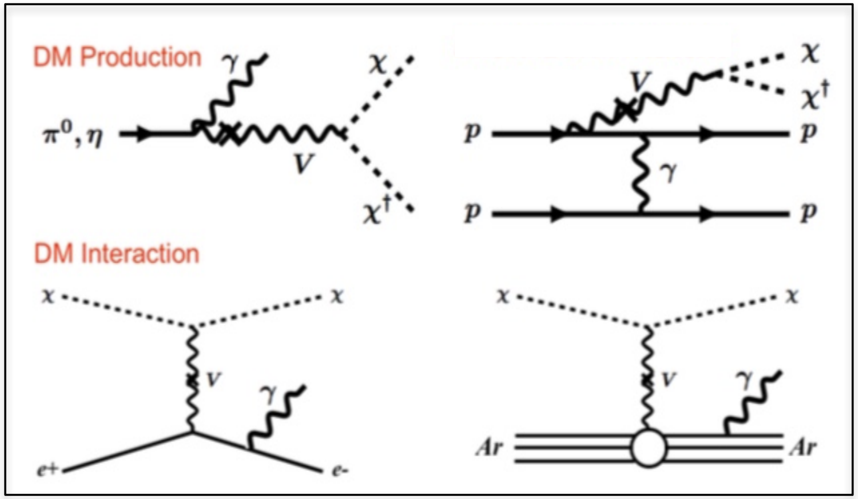
SBND in one year: ~300,00 μ+2p events

Look beyond: BSM searches

- There is a rising interest in potential detection of **unconventional neutrino-sector and dark-sector physics signals** in large-volume neutrino experiments.

- LAr TPC technology provides excellent particle identification and tracking efficiency, good angular/energy resolution, and relatively low energy thresholds.

- The proximity to the beam target, large detector mass and relative detection isotropy makes the LAr TPC **SBN detectors well suited for beyond the standard model searches**.
  - Sub-GeV dark matter (with proton beam dump)
  - Hidden-sector particles
  - Exotic signatures



Some existing calculations for SBN:
- G. Magill et al.,"Dipole portal to heavy neutral leptons", arXiv:1803.03262 [hep-ph]
- G. Magill et al., "Millicharged particles in neutrino experiments", arXiv:1806.03310v1 [hep-ph]

Experimental-Theory collaboration on BSM physics at short-baseline neutrino experiments

- A productive collaboration between **SBN experimentalist** and the **Fermilab Theory** Group started some months ago
  - Goal: study of the capabilities of detecting dark matter in the SBN detectors.

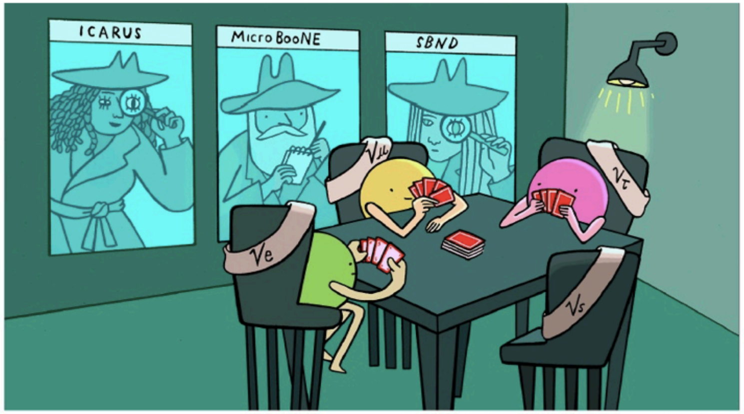
- **SBN-Theory** bi-weekly **meetings*** : bring together (FNAL) theorists and SBN experimentalists and jointly develop new ideas, thereby **further enriching the physics opportunities of the SBN program**.

*Organizer: Pedro Machado, FNAL theory Liaison for SBN

Summary

- The SBN program has a rich physics program (**Sterile neutrino oscillation, neutrino cross sections and BSM searches**)
  - Many PhD students!
  - SBN data also present important physics opportunities valuable to the DUNE program
    - Development and validation of LAr calibration
    - Measurements of neutrino-argon interactions
  - Execution of precision oscillation searches will drive the development of **sophisticated reconstruction and data analysis techniques using TPC data.**

symmetry
dimensions of particle physics



Artwork by Sandbox Studio, Chicago with Corinne Mucha

Sterile neutrino sleuths

01/30/18

| By Tom Barratt and Leah Poffenberger

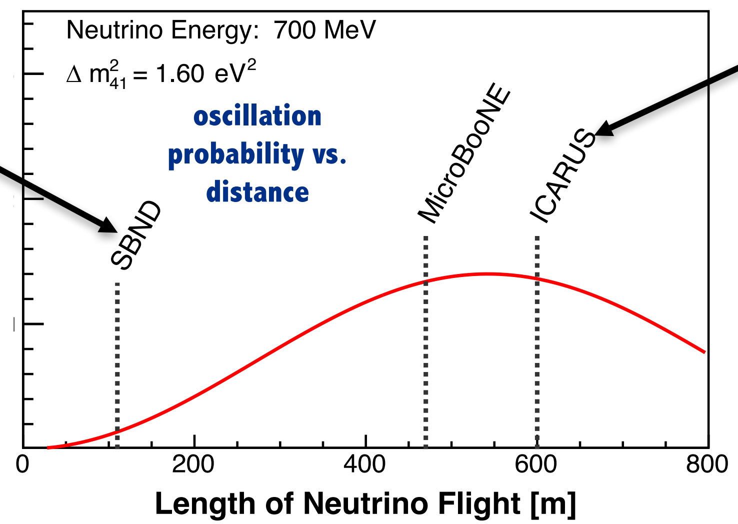
Meet the detectors of Fermilab's Short-Baseline Neutrino Program, hunting for signs of a possible fourth type of neutrino.

- The SBN Analysis Group, acting as a **unique collaborative effort** in preparation for the SBN oscillation analysis, establishes a **long-term continuous, direct connection/collaboration** between SBND, MicroBooNE and ICARUS experiments.

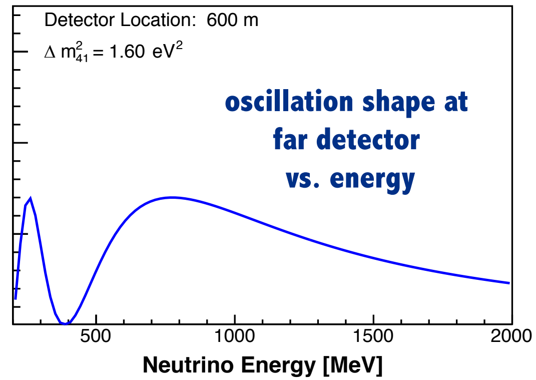
Overflow

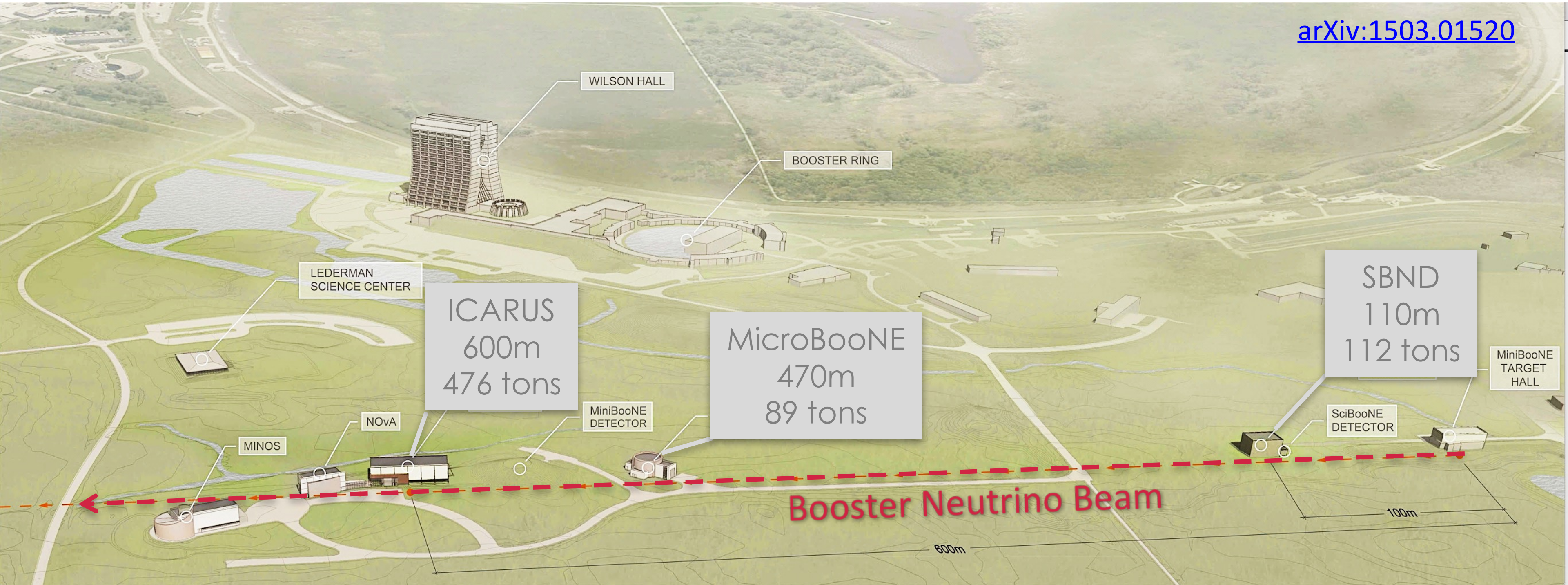
The Three Detector SBN Program

control **systematics** with near detector before oscillations



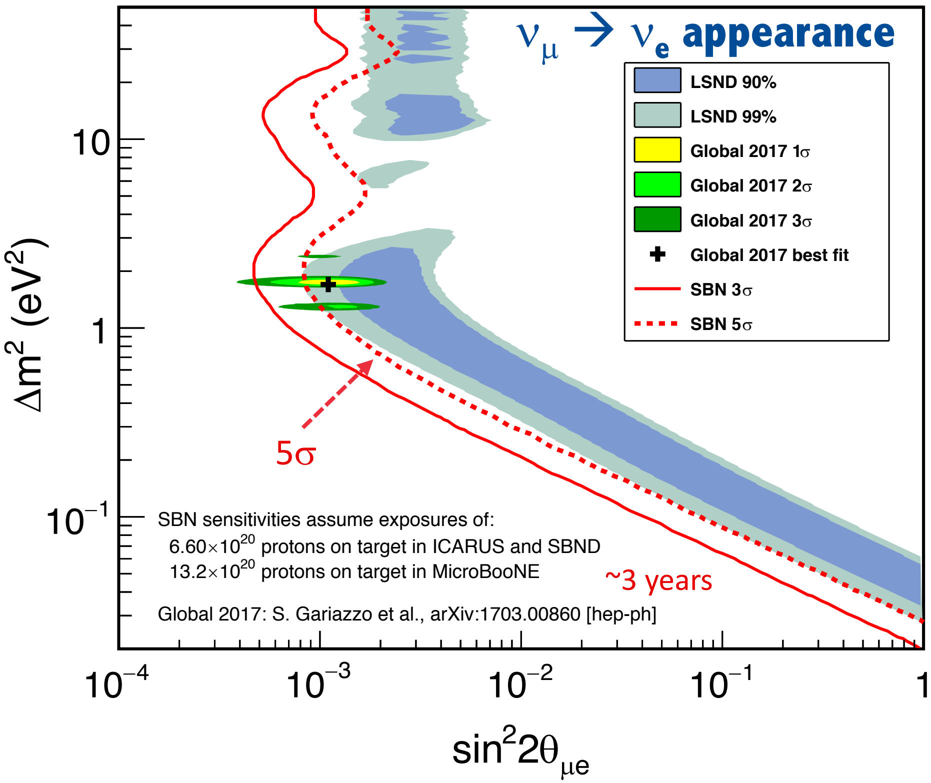
increase **statistics** of oscillation signal by adding far detector mass

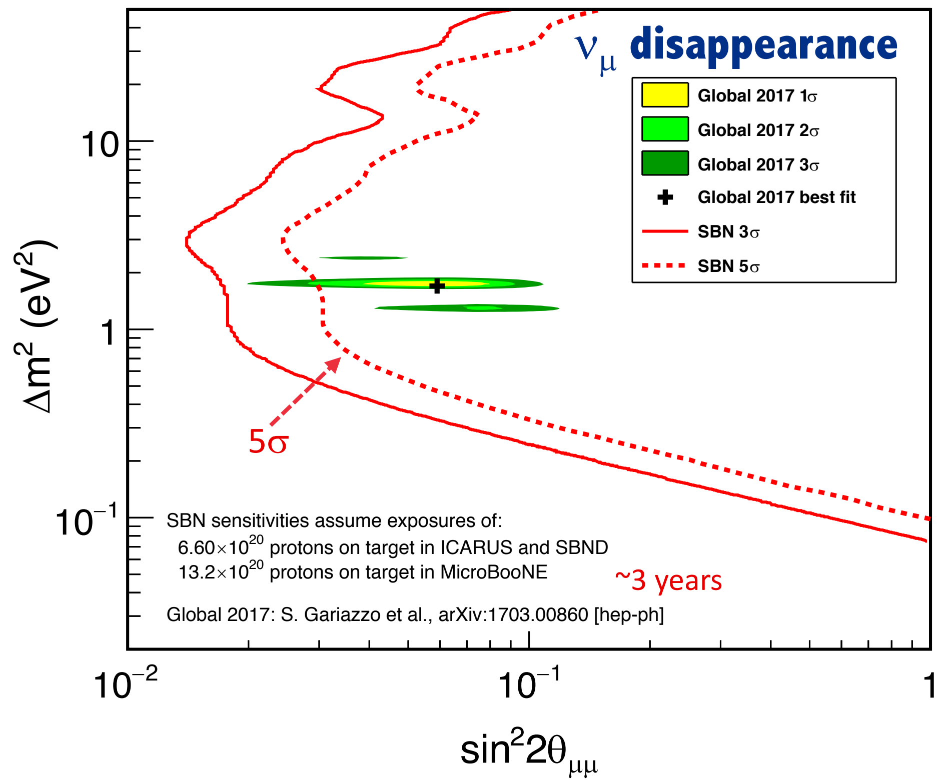




The SBN Oscillation Program

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.

SBND - Cross section measurements

- SBND provide a unique opportunity for the measurement of neutrino-argon scattering.

- SBND will make the **world's highest statistics cross section measurements of ν_μ-Ar and ν_e-Ar**, using well characterized neutrino fluxes, including
  - rarer processes such as ν-e scattering, strange particle production, and coherent scattering with an argon nucleus.
  - expanded differential measurements and studies of nuclear effects ν-Ar interactions.

- Event categorization in terms of exclusive topologies will be used to analyze data and provide precise cross section measurements in different ν_μ and ν_e exclusive channels and careful study of nuclear effects.

Hadronic Final State	GENIE (G17_01b) prediction for 6.6×10^{20} POT ($\approx$ 3 years)
Charged Current	
ν_μ Inclusive	5,389,168
$\rightarrow 0\pi$	3,814,198
$\longrightarrow 0p$	27,269
$\longrightarrow 1p$	1,261,730
$\longrightarrow 2p$	1,075,803
$\longrightarrow \geq 3p$	1,449,394
$\rightarrow 1\pi^+ + X$	942,555
$\rightarrow 1\pi^- + X$	38,012
$\rightarrow 1\pi^0 + X$	406,555
$\rightarrow 2\pi + X$	145,336
$\rightarrow \geq 3\pi + X$	42,510
$\rightarrow K^+K^- + X$	521
$\rightarrow K^0\bar{K}^0 + X$	582
$\rightarrow \Sigma_c^{++} + X$	294
$\rightarrow \Sigma_c^{+} + X$	98
$\rightarrow \Lambda_c^{+} + X$	672
ν_e Inclusive	**$\approx$ 36,000**
Neutral Current	
ν_μ Inclusive	2,170,990
$\rightarrow 0\pi$	1,595,488
$\rightarrow 1\pi^\pm + X$	231,741
$\rightarrow \geq 2\pi^\pm + X$	343,760
$\rightarrow e(^-)$	374

Signal Processing: 1D Deconvolution

Tracy Usher "SBN coordinated analysis strategy" May 24- LBNC meeting

- Technique: Deconvolution

$$s(t) = \int_{-\infty}^{\infty} r(t-\tau)u(\tau)d\tau + n(t)$$

With u the original signal, r the response function, n the noise and s the signal we measure

  - Since the response is time invariant, can Fourier Transform:

$$S(\omega) = R(\omega)U(\omega) + N(\omega)$$

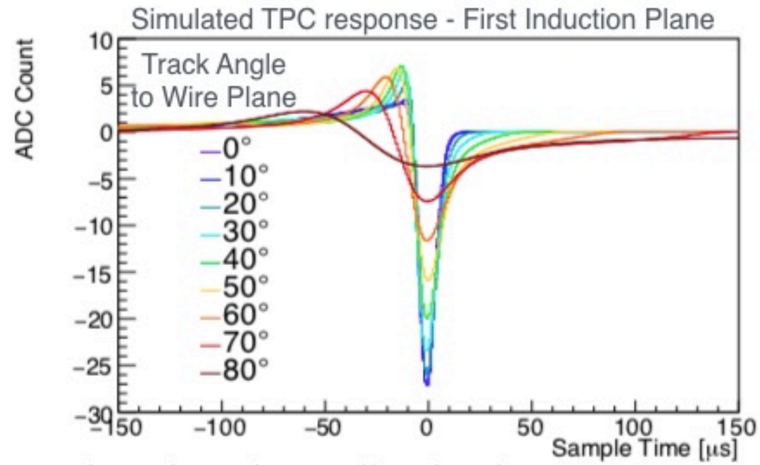
  - Then invert to recover an estimate of the original signal

- Standard signal processing method already employed by several LAr TPC's (e.g. ArgoNeut)
  - Good for extracting signal in the presence of noise
  - Robust and fast technique - good for large number of waveforms!

Works great for tracks propagating parallel to the wire plane!

Signal Processing: 2D Deconvolution

Tracy Usher "SBN coordinated analysis strategy" May 24- LBNC meeting



- Signal seen on a given wire will induce a signal on neighboring wires
  - This effect increases as the track angle to the wire plane increases
  - Effect worse on induction planes where the signal amplitude decreases *and* the width is broadened - can cause signal to nearly "disappear"
- Possible to recover original signal with "2D Deconvolution:"

$$s_i(t) = \int_{-\infty}^{\infty} (... + R_1(t-\tau)u_{i-1}(\tau) + R_0(t-\tau)u_i(\tau) + R_1(t-\tau)u_{i+1}(\tau) + ...)d\tau$$

Where R_0 is average response for the wire of interest

R_1 is the average response for charge drifting past the nearest wire, etc.

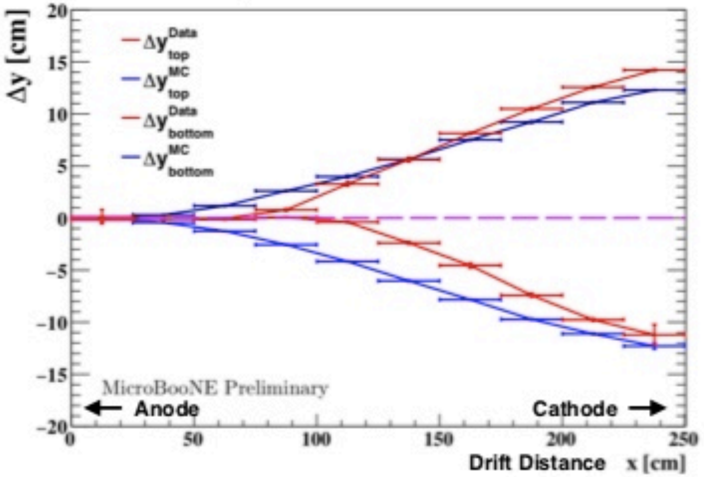
- Requires inversion of a large(ish) matrix - only became available for MicroBooNE after current production processing had begun

Space Charge Effect

Tracy Usher "SBN coordinated analysis strategy" May 24- LBNC meeting

- Space Charge Effect (SCE) - steady state, excess electric charge due to slow moving ions distributed throughout the TPC resulting from the Cosmic Ray background
- Drifting ions act to distort the electric field
  - Impacts the recombination
  - Position dependent drift velocity
  - Scales as (drift distance)^3, (electric field)$^{-1.7}$
- Impacts on reconstruction include
  - Distortion ("bowing") of track trajectories
  - Impacts dE/dx

Predicted/measured SCE distortions at top and bottom of TPC



- MicroBooNE has modeled the effect and sees general agreement with a preliminary cross check with data
  - "Study of Space Charge Effects in MicroBooNE" MicroBooNE-Note-1018-Pub
  - Expect this to be improved soon using both the Laser calibration system as well as matching of tracks to the Cosmic Ray Tagger

Event reconstruction techniques

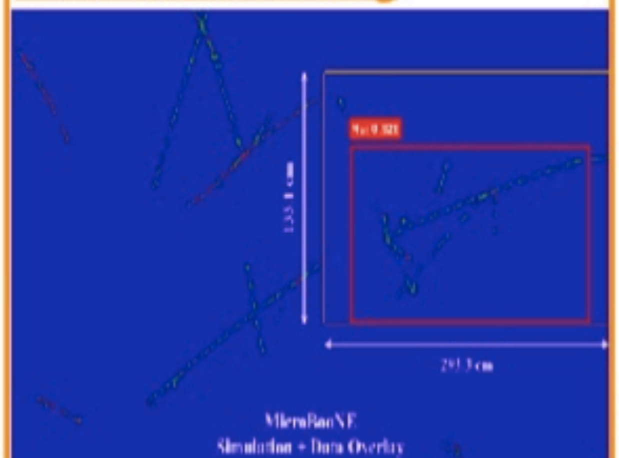
- Different reconstruction techniques have been developed
- Reached high level of sophistication
- Essential for SBN and DUNE (shared software between all experiments!)

Roxanne Guenette "MicroBooNE and the future SBN program" Neutrino 2018 Conference

Pandora

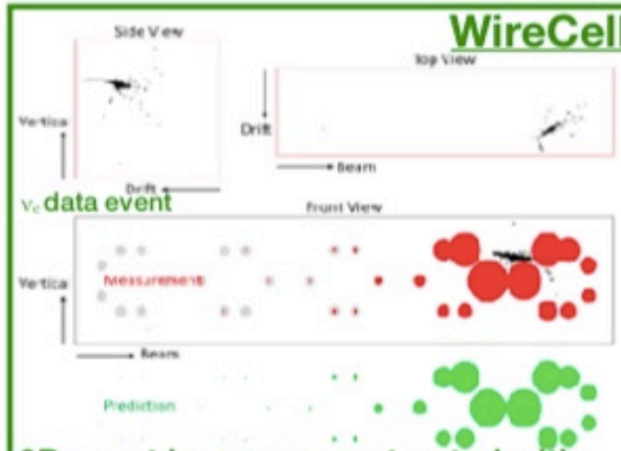
"*The Pandora Multi-Algorithm Approach to Automated Pattern Recognition of Cosmic Ray Muon and Neutrino Events in the MicroBooNE Detector*", Eur. Phys. J. C78, 1, 82 (2018)"

Machine Learning



"*Convolutional Neural Networks Applied to Neutrino Events in a Liquid Argon Time Projection Chamber*", JINST 12, P03011 (2017)

WireCell



3D event image reconstructed with charge matching

New Public Notes and Posters

1. A. Hourlier, "Vertex finding and reconstruction for contained two-track events in the MicroBooNE detector", MICROBOONE-NOTE-1042-PUB, 2018
2. B. Russell, "Towards automated neutrino selection at MicroBooNE using tomorgraphic event reconstruction", MICROBOONE-NOTE-1040-PUB, 2018
3. H. Wei, "Recent progress on wire-cell tomographic event reconstruction for LArTPCs",
4. J. Moon, *Hunting muon neutrinos in microboone with deep learning techniques, MICROBOONE-NOTE-1051-PUB, 2018*
5. L. Domine & K. Terao, Applying deep neural network techniques for LArTPC data reconstruction(Kazu/Laura) **Finalist!**
6. **Reconstruction performance studies with MicroBooNE data, *MICROBOONE-NOTE-1049-PUB, 2018***

Some Thoughts on Data Processing

Tracy Usher "SBN coordinated analysis strategy" May 24- LBNC meeting

- Liquid Argon TPC's generate lots of data
  - 3 high resolution images per event - think of how fast your iPhone fills with pictures!

- MicroBooNE experience:
  - Read 3 "frames" or 9600 ticks for 8256 channels
    - Uncompressed is ~80 MB/event
    - compression level is noise dependent, generally achieving <40 MB/event
  - After reconstruction, including copies of data (provenance), events were running ~100 MB/event
    - Simulation is ~x2 to accommodate truth information
    - At this point without the CRT
  - Data taking rate will be higher than estimated
    - Need calibration/systematics data sets too (e.g. off beam)
    - Raw data rate was originally expected to be 1.6 MB/s, currently > 40 MB/s
  - For current production MicroBooNE forced to "slim down" and reconstructed event sizes for data now less than 60 MB for MC, under 30 MB for data.
  - To date MicroBooNE total data volume *exceeds* 12 PB!

- SBND and ICARUS both larger than MicroBooNE, expect even more data volume. Starting to consider how to handle this