The Short Baseline Program at Fermilab

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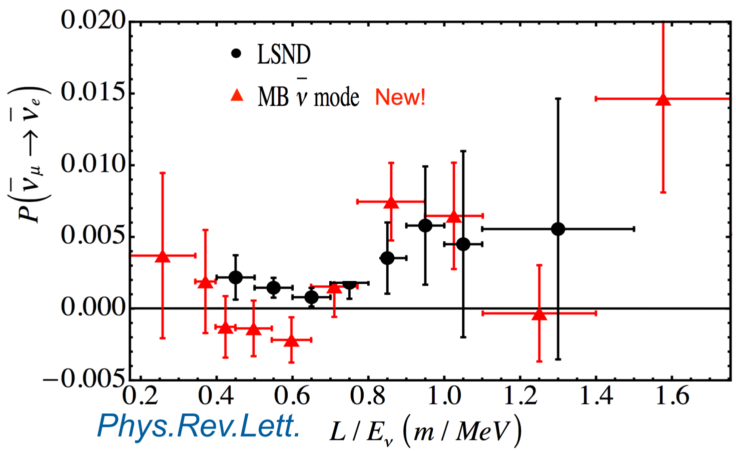
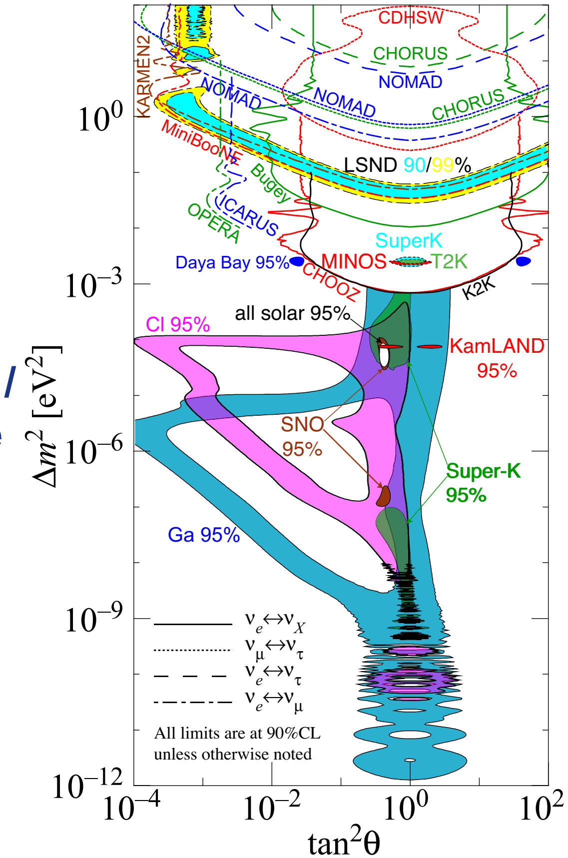
Neutrino Telescopes 2017, Venice Italy
3/16/17

Motivation Behind the Short Baseline Program

- **LSND experiment observes a 3.8σ excess consistent with oscillations at $\Delta m^2 \sim 1\ eV^2$.**
- **Evidence for oscillations at $\Delta m^2 \sim 1\ eV^2$ also found in reactor experiments.**
- **L / E for this oscillation signal order of 1 m / MeV. Neutrinos of energy ~100 MeV require baselines of ~100 m.**



Phys.Rev.Lett. 105 (2010)



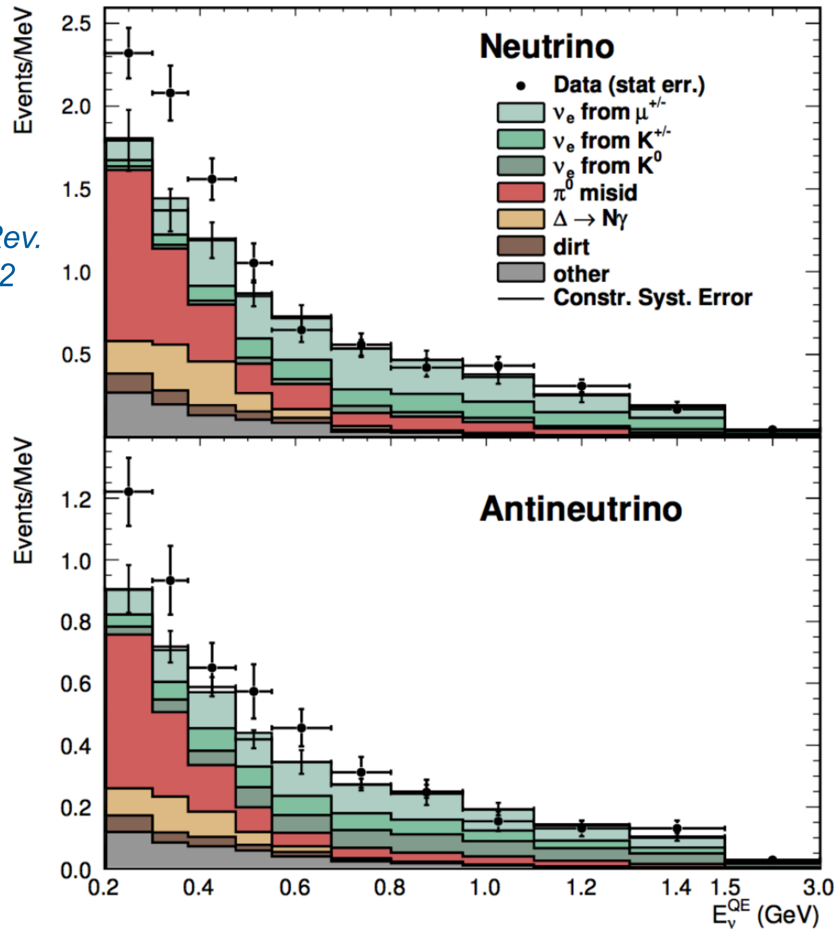
http://hitoshi.berkeley.edu/neutrino

- **MiniBooNE experiment observes 3σ excess at $\Delta m^2 \sim 1\ eV^2$ with a similar L / E as LSND.**

MiniBooNE Low Energy Excess

Phys. Rev. Lett. 102 101802

Phys. Rev. Lett. 105 181801

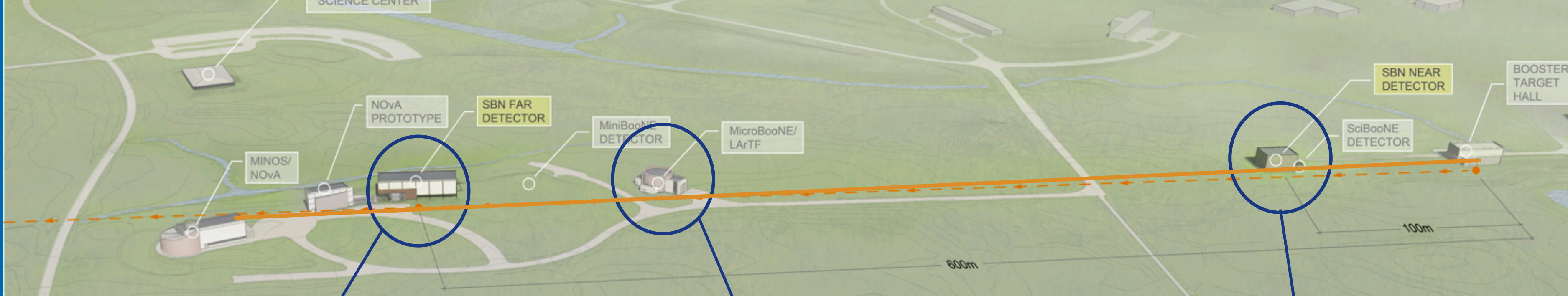


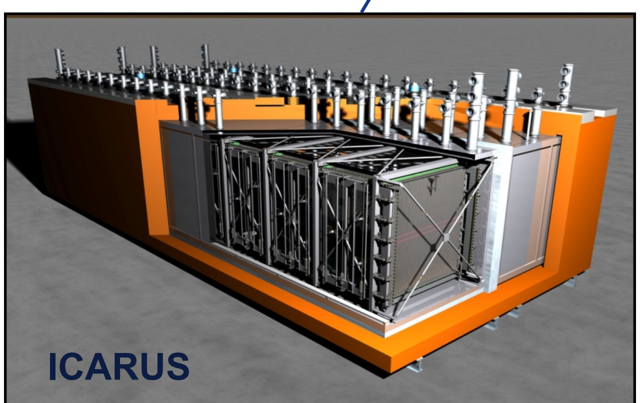
- **MiniBooNE: 600 ton tank of mineral oil, primarily a Cherenkov detector.**
- **Excess of events observed in the energy range of 200-475 MeV.**
- **Seen in both neutrino and anti-neutrino modes.**
- ***Resolution of these effects requires new technology, new measurements and new expertise.***

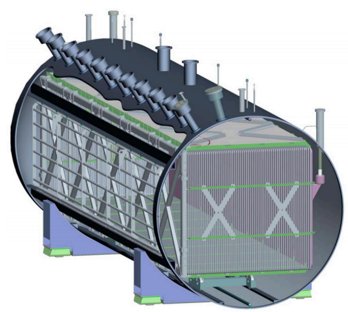
Enter the Short Baseline Program

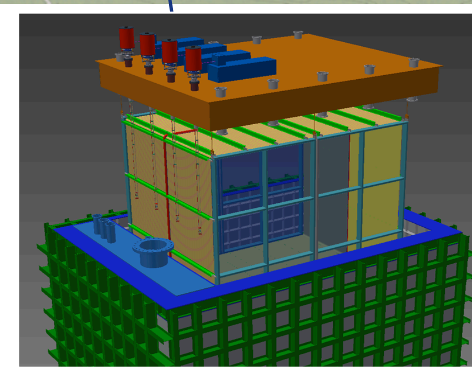
- Three Detectors.
- One neutrino beam.
- Common Technology (LArTPC).

Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton




ICARUS


MicroBooNE


SBND

Enter the Short Baseline Program

- **Three branches of physics to study.**
- ***Every experiment contributes to these fields.***

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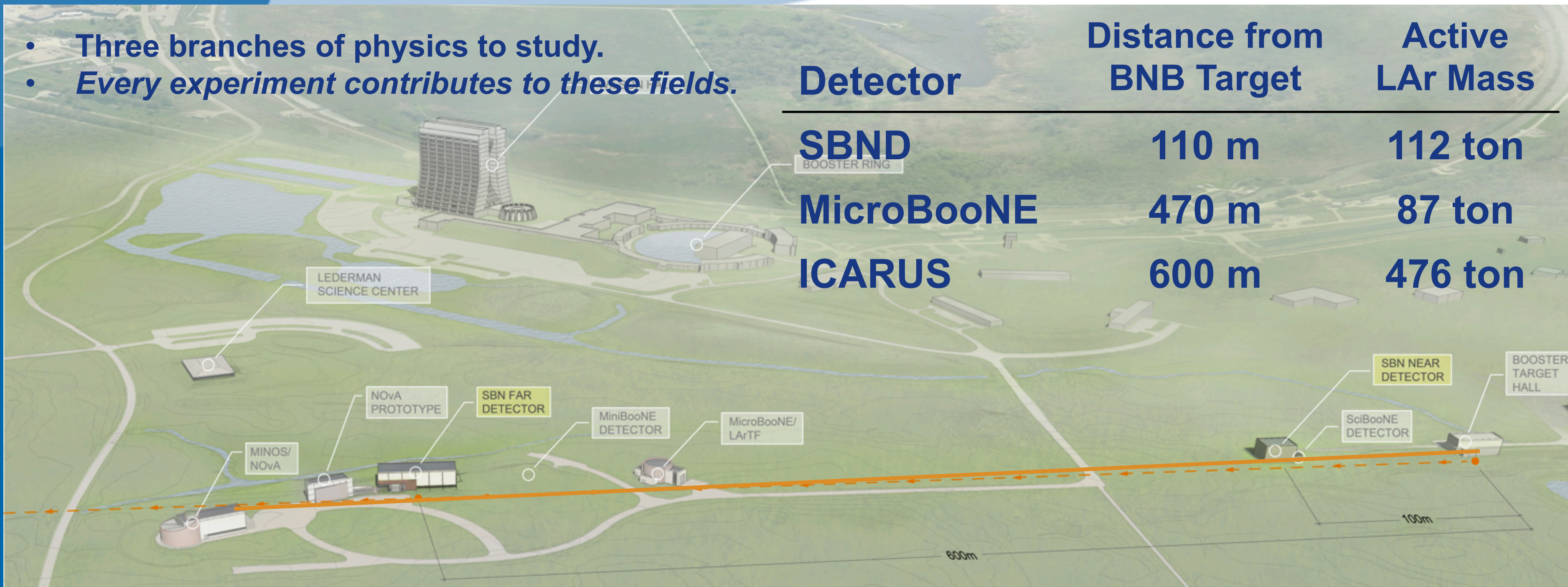
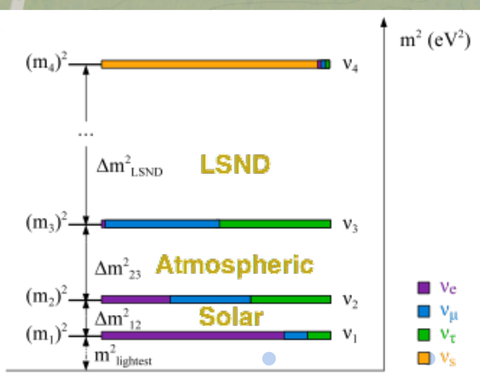
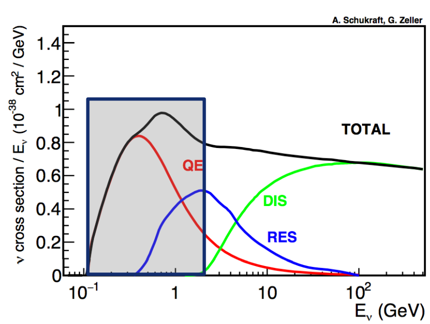
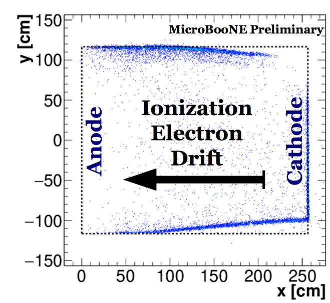




Oscillations



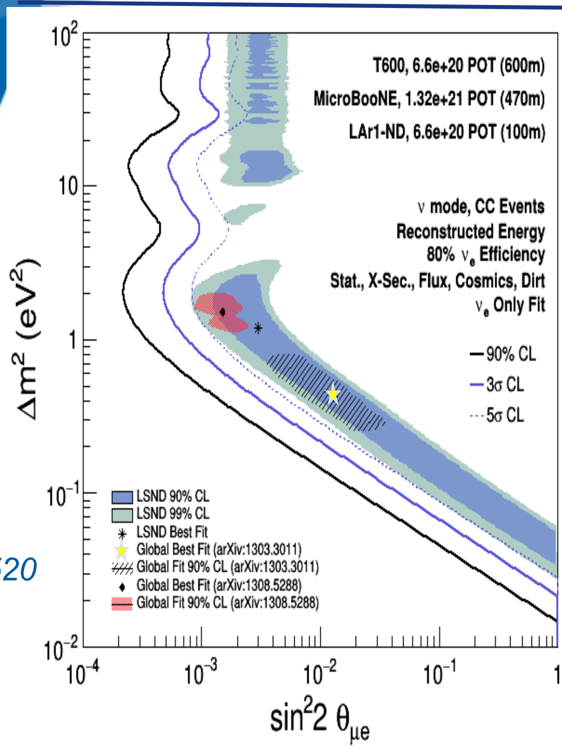
Neutrino Cross-Sections



Detector Physics

Oscillations, Cross-Sections and Detector Physics

Oscillations



arXiv: 1503.01520

- **Expect 5σ coverage of LSND space.**
- **Superior e/γ separation possible with LAr.**

Cross-Sections

- **Large nucleus of Argon (A= 40) makes it ideal to study nuclear effects of neutrino-nucleus scattering.**
- **Further study of multinucleon events observed in MiniBooNE, ArgoNeuT, T2K, MINERvA.**

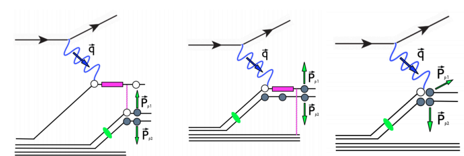
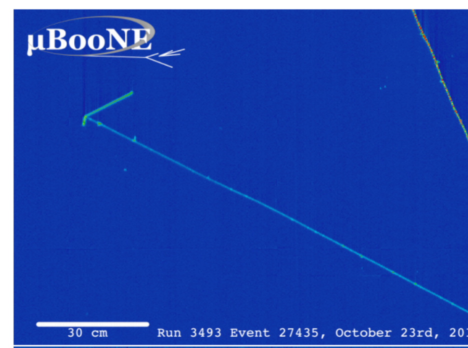


FIG. 5. Pictorial diagrams of examples of two-proton knock-out CC reactions involving *np* SRC pairs. Short range correlated (green symbol) nucleons in the target nucleus are denoted by open-full dots (*n*-*p*), wide solid lines (purple) represent RES nucleonic states, (purple) lines indicate pions.

Phys. Rev. D 90 012008

ν-Detection

- **Fully automated neutrino selection.**
- **All three experiments using common reconstruction (LArSoft) and simulation (GENIE, GEANT).**



MicroBooNE Public Note 1002

ICARUS

- Three Detectors
- One neutrino beam
- Common Technology (Lar TPC)

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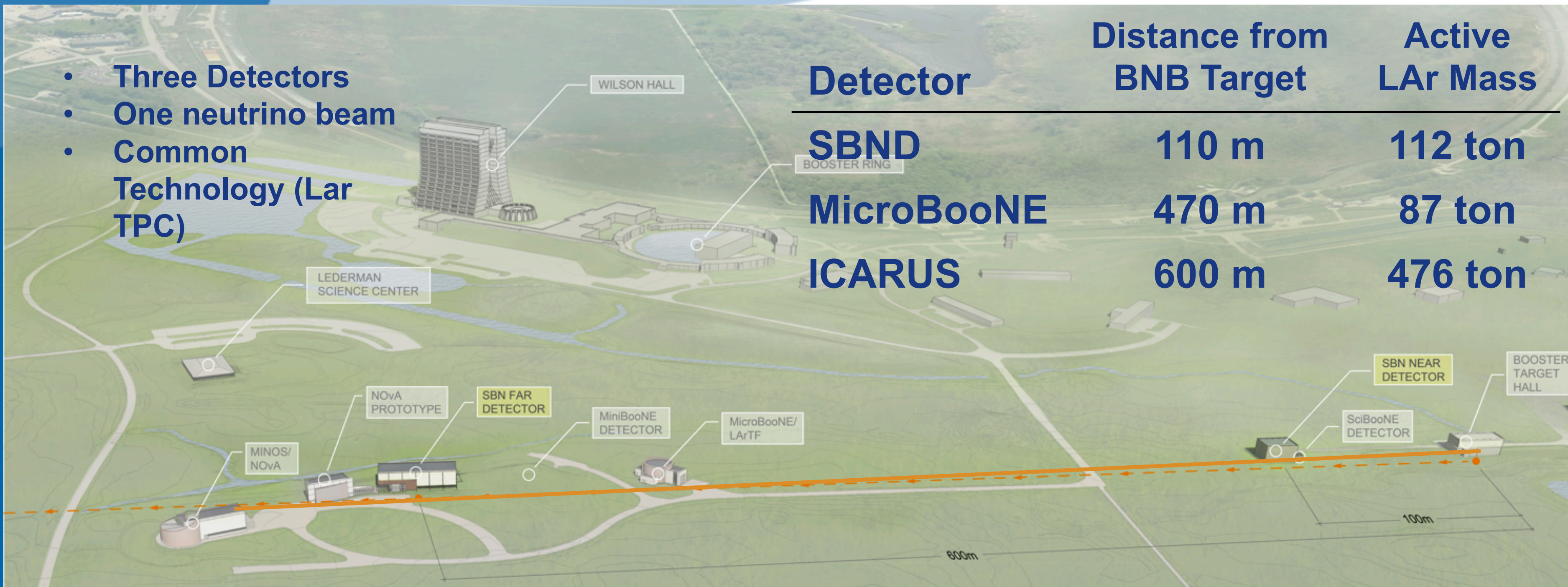
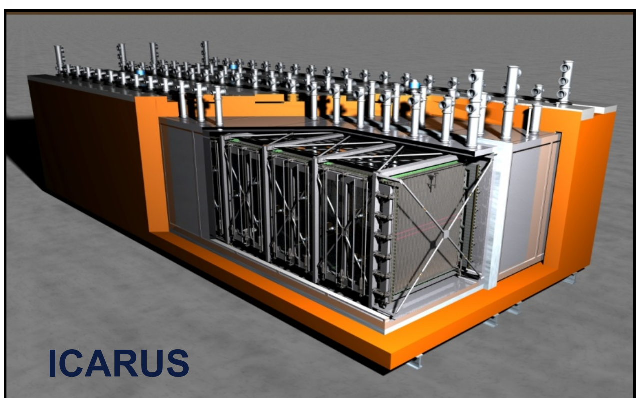
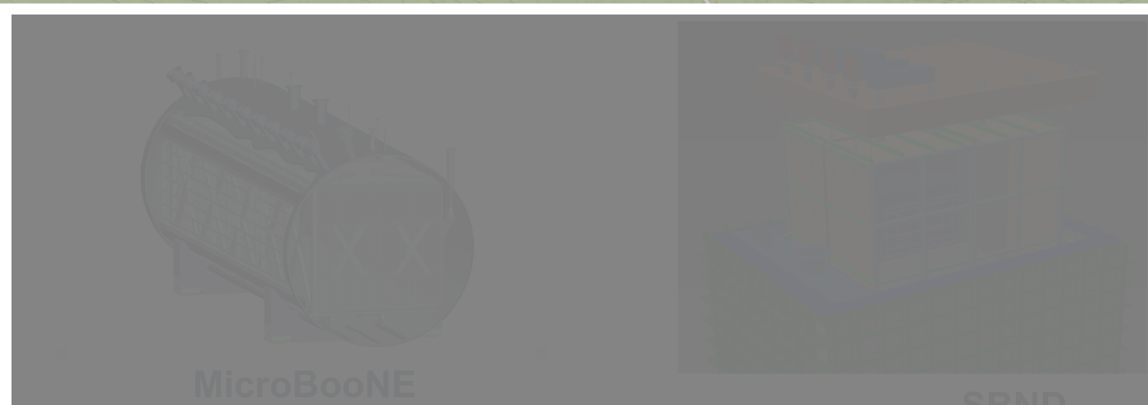
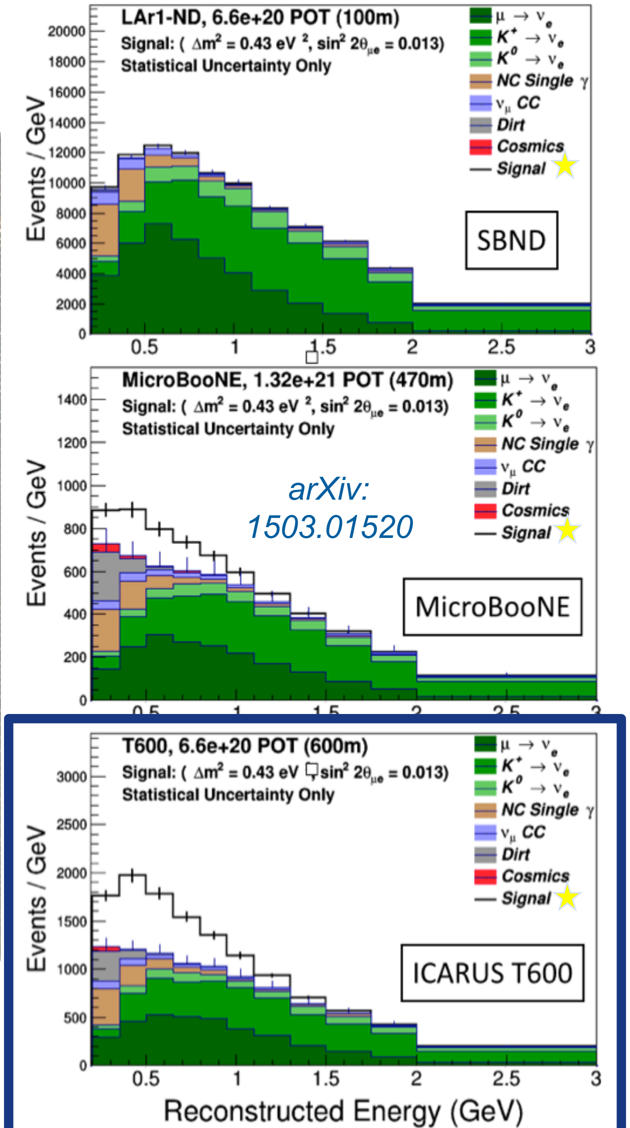






ICARUS

- **476 Ton TPC, successfully used in CNGS beam.**
- **Undergoing a series of refurbishments including upgrades to electronics and DAQ.**
- **Far detector for the short baseline oscillation search.**



SBND

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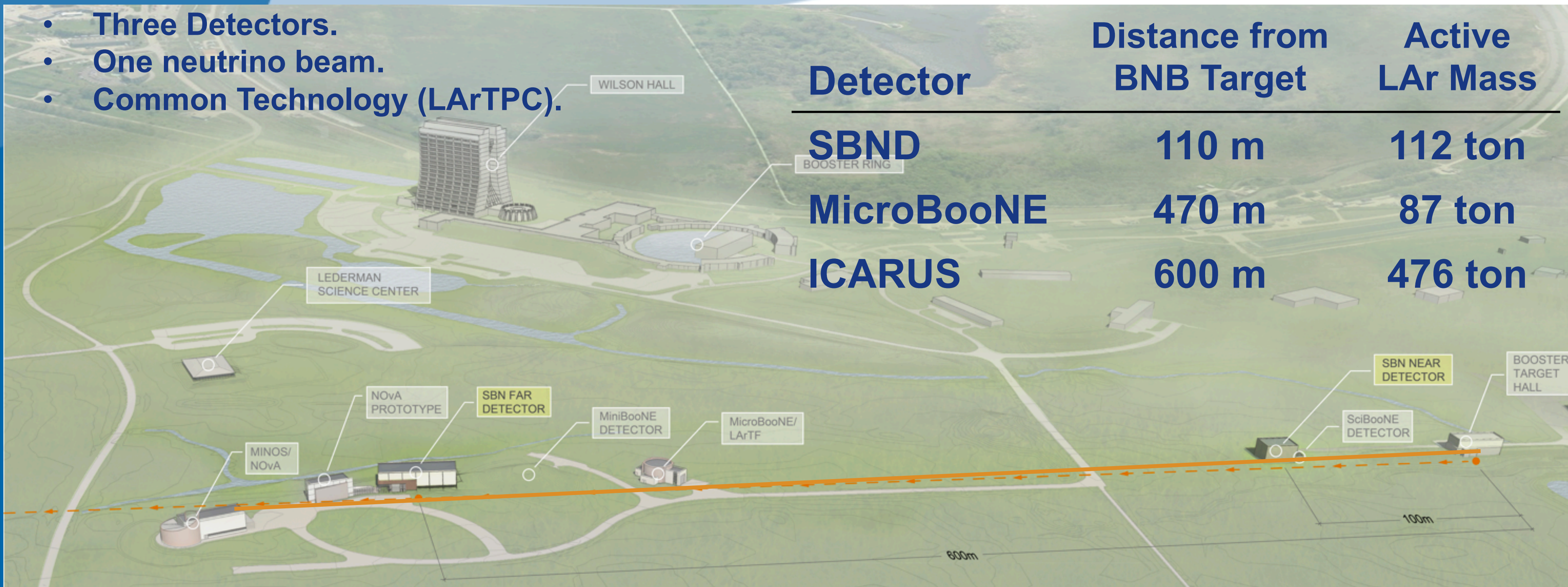
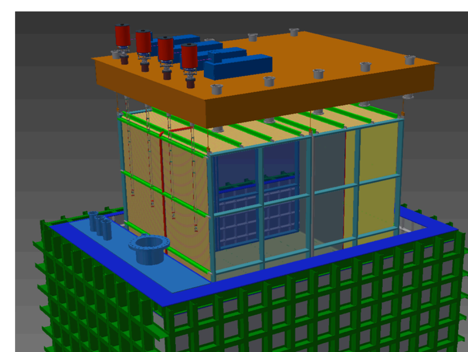
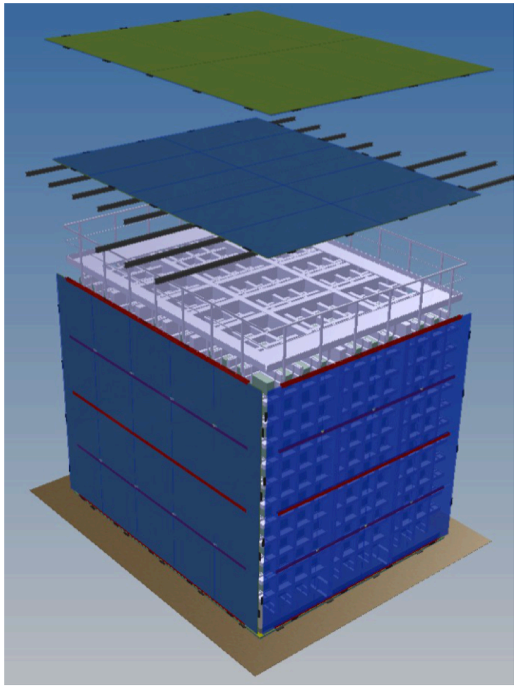
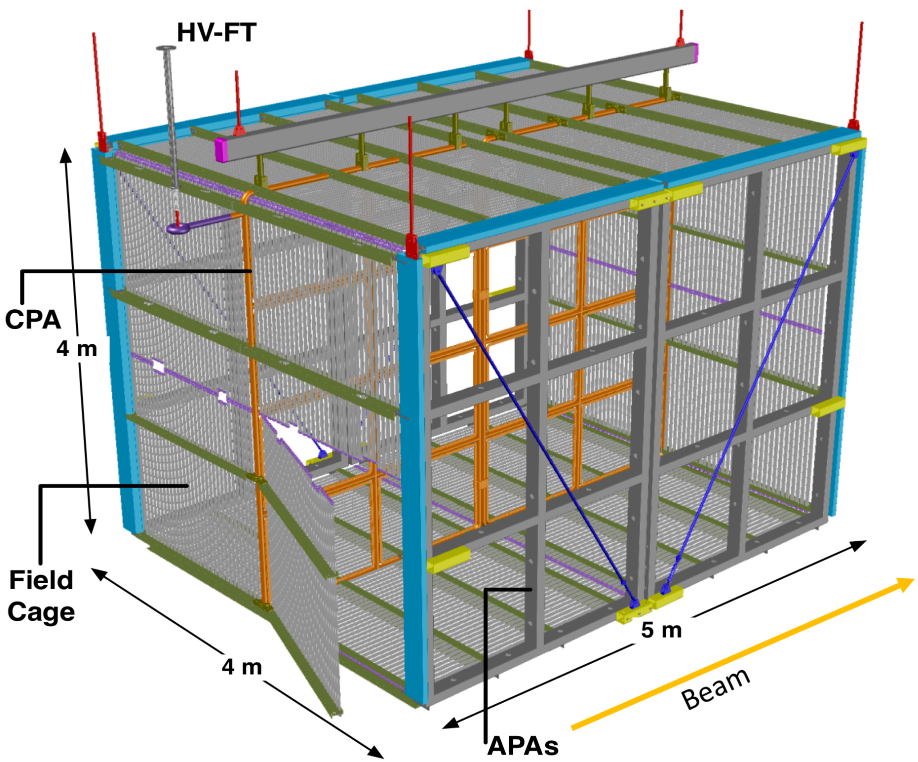




SBND

SBND: Design

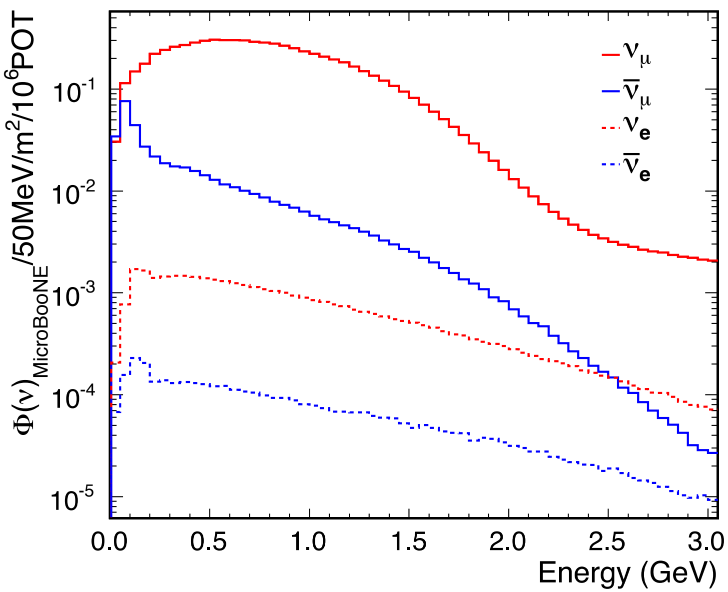


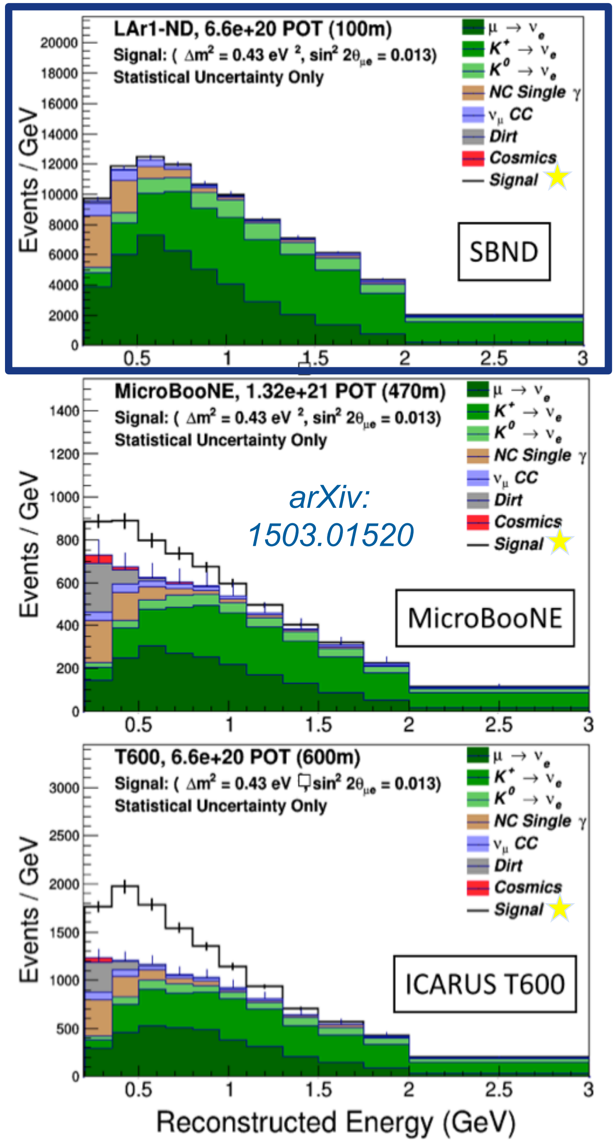


- Left: SBND detector including CRT tagger. Nearly 4π coverage reduces largest background.
- Right: Detailed view of TPC including field cage, cathode plane assembly (CPA) and anode plane assembly (APA).
- Not pictured: light collection system, 120 8" PMTs sit behind APA.

SBND: Oscillations

- Near detector for short baseline program, important for controlling detector and interaction systematics.
- Provides a cross-check of (anti)-ν_μ and ν_e flux shown below.
- Vital for ν_e appearance and ν_μ disappearance.





SBND: Cross-Sections

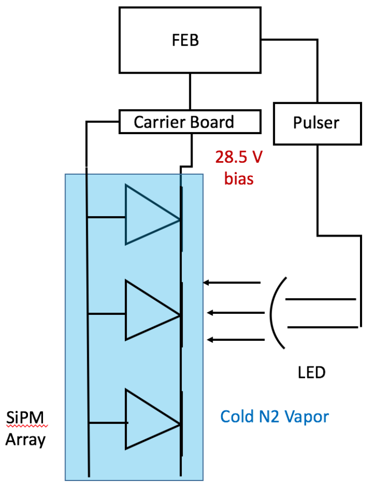
Process		No. Events	Events/ ton	Stat. Uncert.
	ν_μ *Events (By Final State Topology)*			
CC Inclusive		5,212,690	46,542	0.04%
CC 0 π	$\nu_\mu N \to \mu + Np$	3,551,830	31,713	0.05%
	$\cdot\ \nu_\mu N \to \mu + 0p$	793,153	7,082	0.11%
	$\cdot\ \nu_\mu N \to \mu + 1p$	2,027,830	18,106	0.07%
	$\cdot\ \nu_\mu N \to \mu + 2p$	359,496	3,210	0.17%
	$\cdot\ \nu_\mu N \to \mu + \geq 3p$	371,347	3,316	0.16%
CC 1 $\pi^\pm$	$\nu_\mu N \to \mu + \text{nucleons } + 1\pi^\pm$	1,161,610	10,372	0.09%
CC $\geq 2\pi^\pm$	$\nu_\mu N \to \mu + \text{nucleons} + \geq 2\pi^\pm$	97,929	874	0.32%
CC $\geq 1\pi^0$	$\nu_\mu N \to \mu + \text{nucleons} + \geq 1\pi^0$	497,963	4,446	0.14%
NC Inclusive		1,988,110	17,751	0.07%
NC 0 π	$\nu_\mu N \to \text{nucleons}$	1,371,070	12,242	0.09%
NC 1 $\pi^\pm$	$\nu_\mu N \to \text{nucleons} + 1\pi^\pm$	260,924	2,330	0.20%
NC $\geq 2\pi^\pm$	$\nu_\mu N \to \text{nucleons} + \geq 2\pi^\pm$	31,940	285	0.56%
NC $\geq 1\pi^0$	$\nu_\mu N \to \text{nucleons} + \geq 1\pi^0$	358,443	3,200	0.17%
	ν_e *Events*			
CC Inclusive		36798	329	0.52%
NC Inclusive		14351	128	0.83%
Total ν_μ and ν_e Events		7,251,948	64,750	
	ν_μ *Events (By Physical Process)*			
CC QE	$\nu_\mu n \to \mu^- p$	3,122,600	27,880	
CC RES	$\nu_\mu N \to \mu^- \pi N$	1,450,410	12,950	
CC DIS	$\nu_\mu N \to \mu^- X$	542,516	4,844	
CC Coherent	$\nu_\mu Ar \to \mu Ar + \pi$	18,881	169	

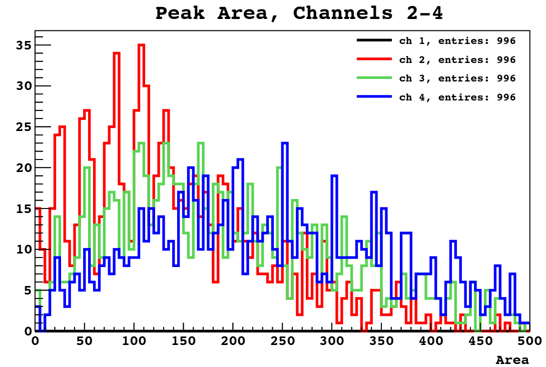
TABLE I: *Estimated event rates using GENIE (v2.8) in the LAr1-ND active volume (112 t) for a* 6.6×10^{20} *exposure. In enumerating proton multiplicity, we assume an energy threshold on proton kinetic energy of 21 MeV. The* 0π *topologies include any number of neutrons in the event.*

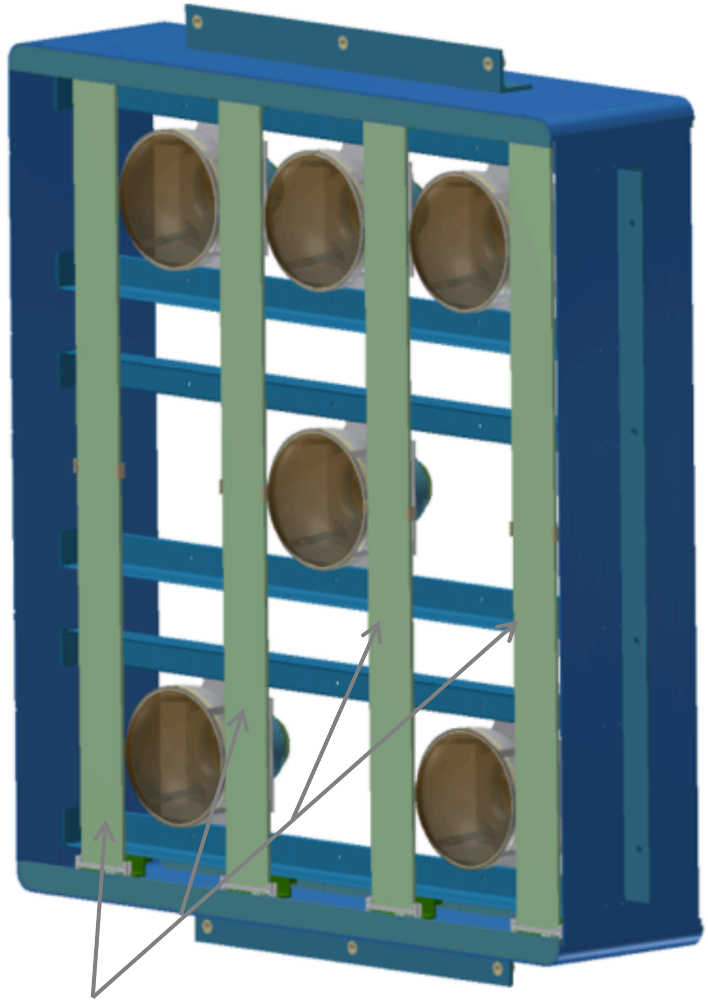
- **Exhaustive list of possible cross-section channels to analyze.**
- **Nearly 5M CC ν_μ events expected over 3 year run, 37k CC ν_e events.**
- **Cross-section uncertainties typically dominate systematics of oscillation analyses. SBND provides invaluable input.**

SBND: Detector R&D

- **Part of SBND's mission is to develop upcoming technologies for liquid argon experiments.**
- **Photon detection necessary to synchronize TPC signals to the beam window.**
- **Testing coated light bars planned for DUNE, connected to low voltage SiPMs.**



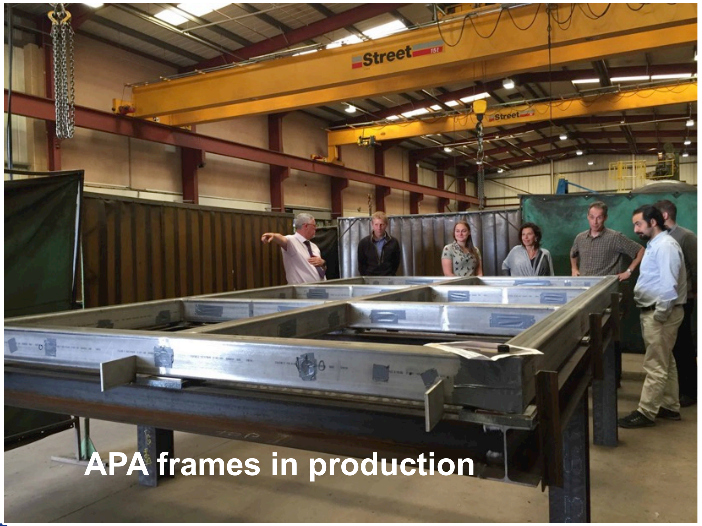




Light Bars installed in APA with PMTS

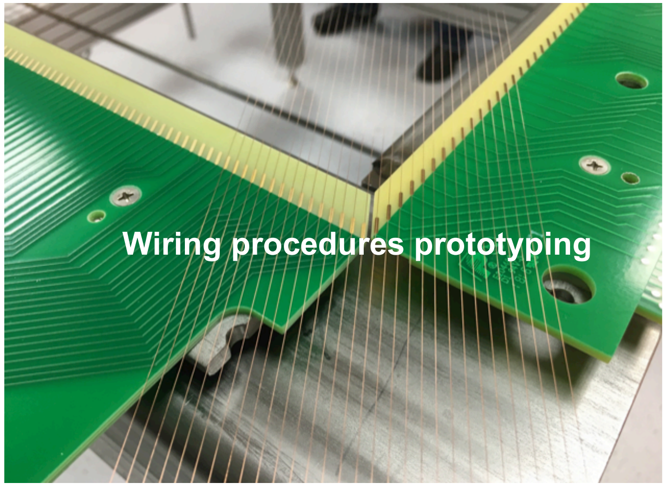
SBND Status

- Construction underway!
- APA and CPA frames in production.
- Wire winding to begin this summer.
- Electronics (including cold ADC) development underway.
- Cryostat installation to take place in 2018.
- Operations and data taking begin in 2019.

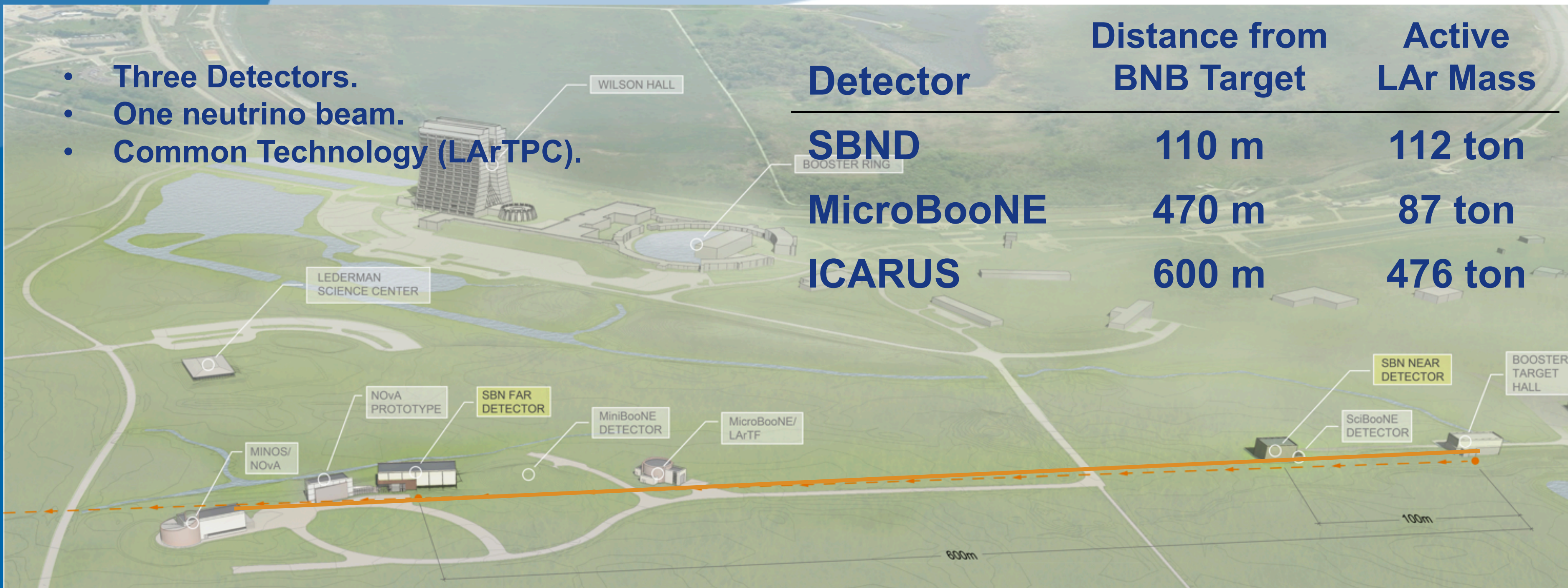


APA frames in production

Construction of SBND building nearly completed


Wiring procedures prototyping

MicroBooNE



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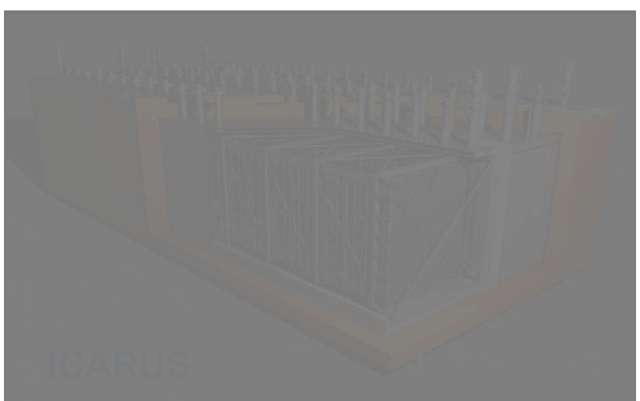
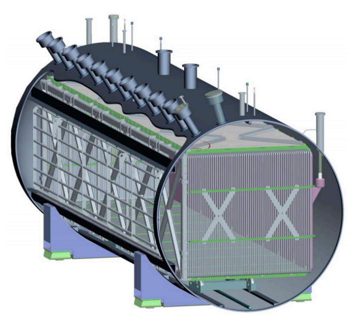
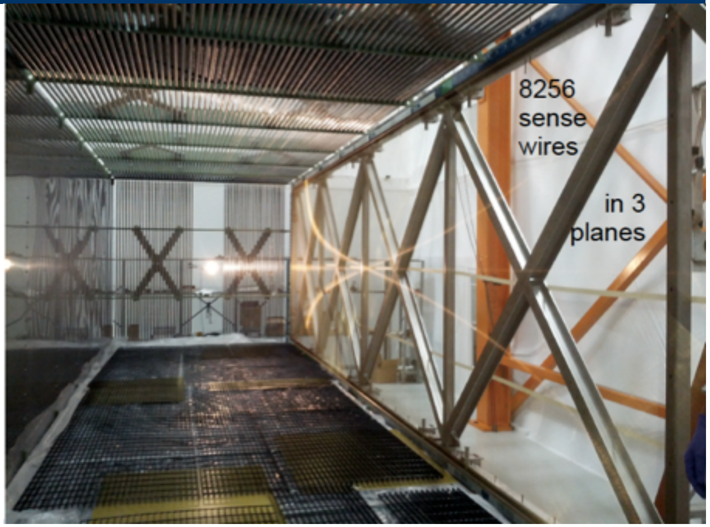




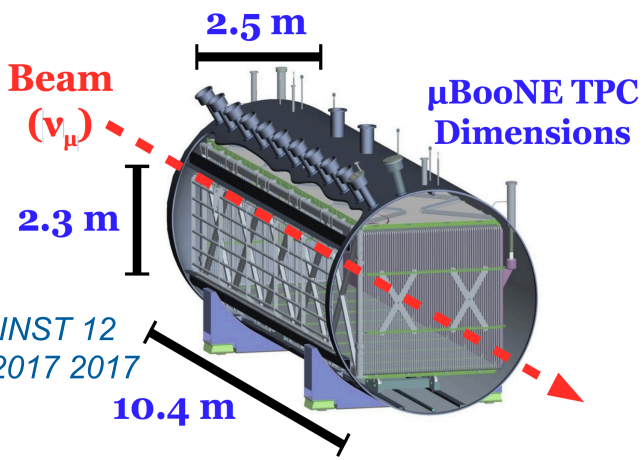
MicroBooNE

MicroBooNE Detector

- 87 ton active LAr mass.
- Single TPC with 2.5m drift distance.
- 32 8” PMTs used to locate events within beam spill.
- Drift time of 2.5 ms, nominal field is 273 V / cm.
- ~8k wires with a 3 mm pitch readout using cold electronics.



Interior of MicroBooNE TPC



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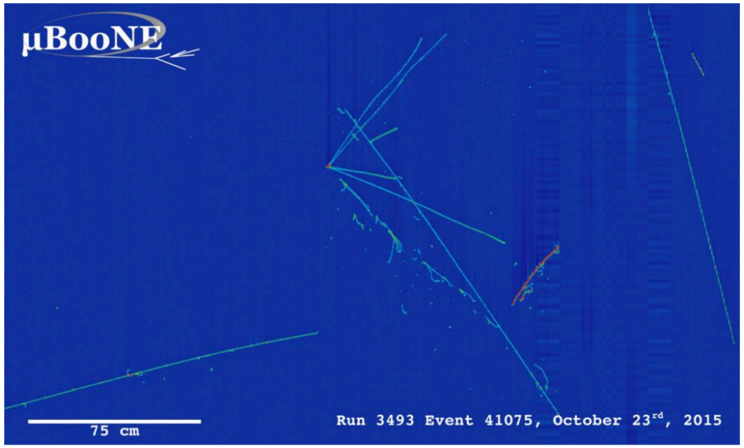
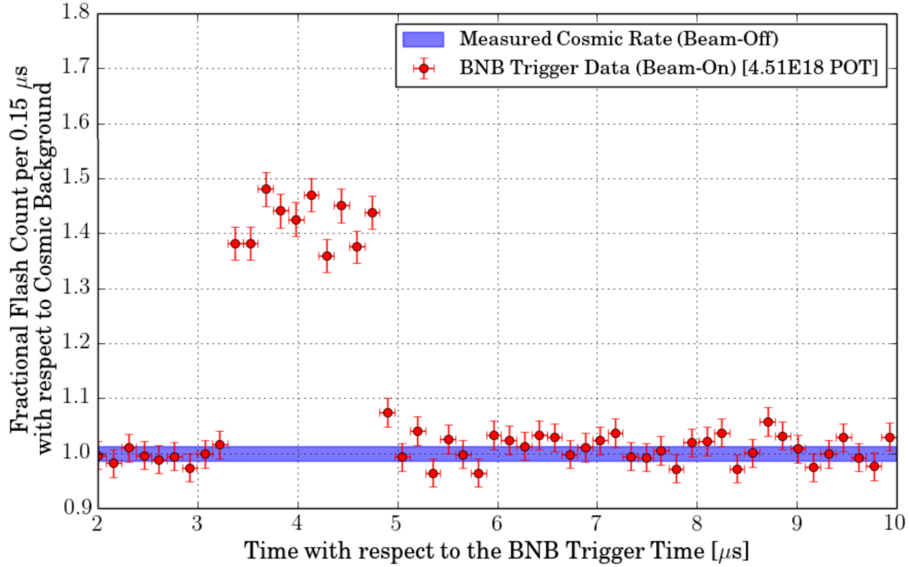
Event display of an automatically selected neutrino event



MicroBooNE Operations

- **Commissioning wrapped up in October 2015, began full data taking shortly after.**
- **Taking neutrino data with BNB and NuMI beam; 95% uptime.**
- **Collected about 70% of our approved neutrino dataset.**

“Flashes” in PMTs used to record neutrino events in beam window



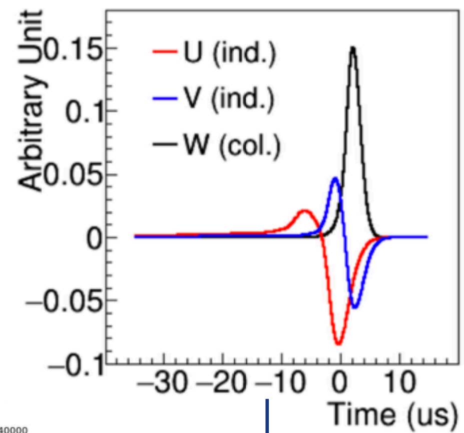
- **Currently commissioning continuous SN data stream, will make MicroBooNE sensitive to SNEWS alerts.**
- **Top panel CRT installation underway.**

MicroBooNE Public Note 1002

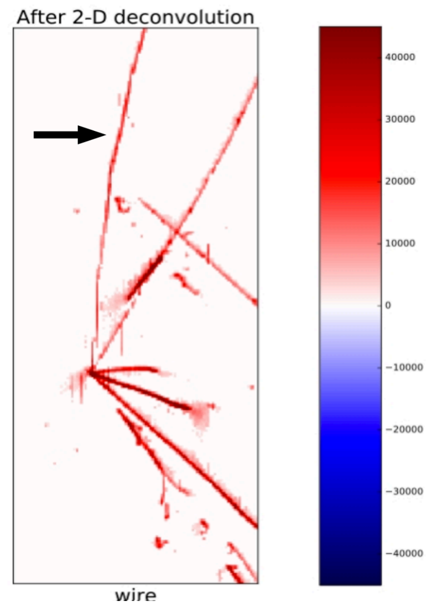
MicroBooNE Reconstruction

- Reconstruction begins with “hit finding:” locating hits from waveforms along the wires, and deconvolving the signal to an (x, u, v, t) coordinate.
- Hits clustered together to form cluster objects, clusters stitched into 3D tracks and showers.
- Numerous algorithms for vertexing, PID.

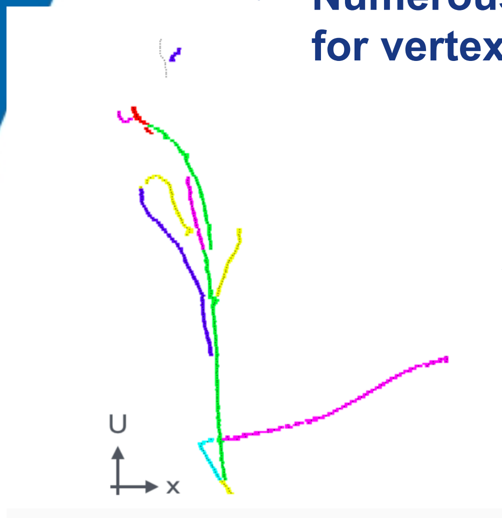
Average Signal Response



Deconvolution



Clustering

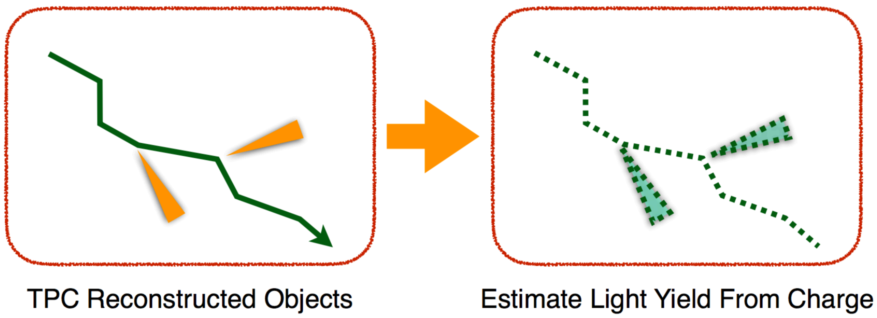


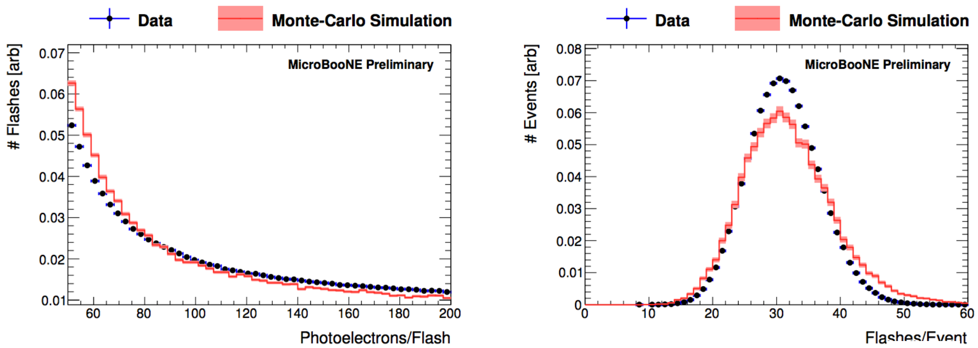
MicroBooNE Public Note 1015

MicroBooNE Reconstruction

- **Match track objects from TPC to light depositions in PMTs.**
- **Estimate light yield from track and shower objects.**
- **Matched objects assigned a *t* value based on PMT flash time, used to align the event with the beam window.**

- **Interesting events typically above 50 PE (bottom).**
- **Improvements to optical model underway.**

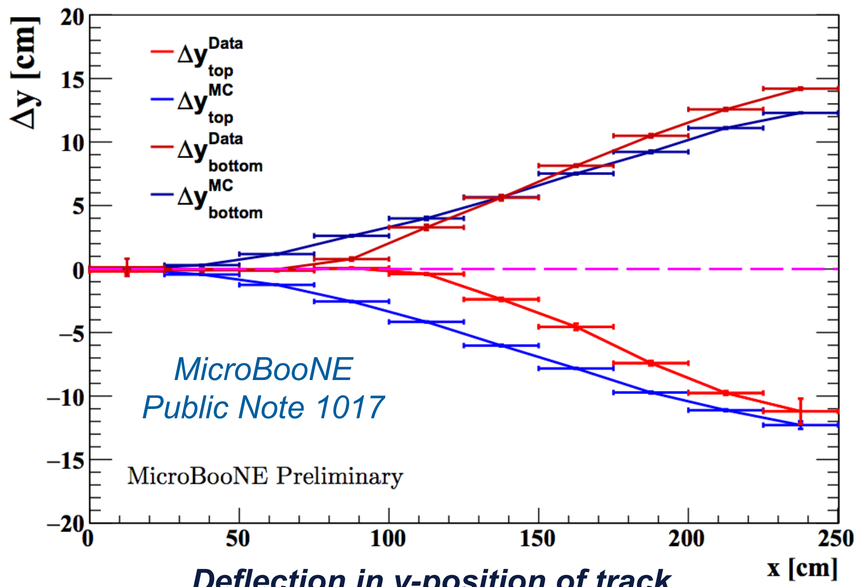




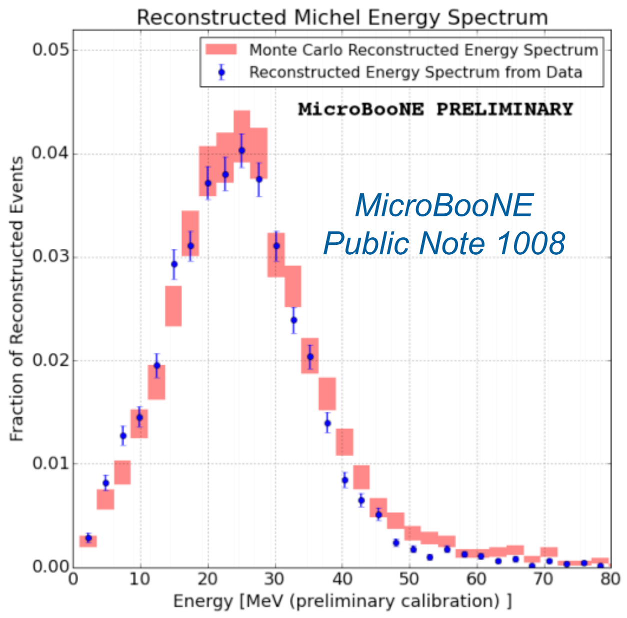
MicroBooNE Public Note 1014

MicroBooNE Analysis

- **Neutrino events may be rare, but cosmic events are *plentiful*.**
- **Allows numerous studies of detector effects including *space charge*.**



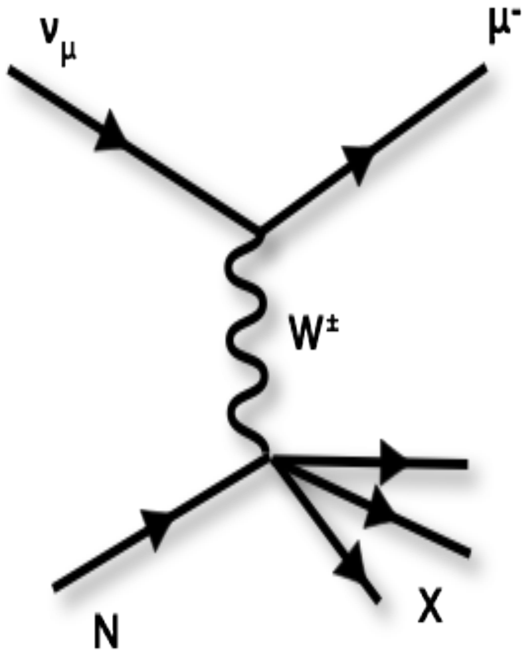
Deflection in y-position of track endpoints due to space-charge effect



- **Michel tagging performed automatically for stopping muon tracks.**
- **Provides valuable cross-check of detector energy response.**
- **Both analyses using well-developed tracking and clustering.**

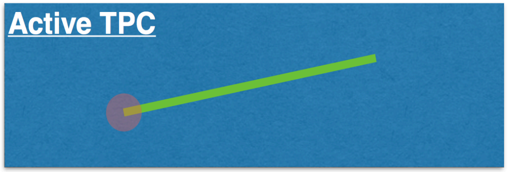
MicroBooNE: Charged Current Analysis

- Look for *Charged Current Inclusive* events initially, events with at least one muon in the final state.
- Flash-matching reduces cosmic background, but there is still a significant contamination after flash cuts.
- Employ two distinct selection criteria:



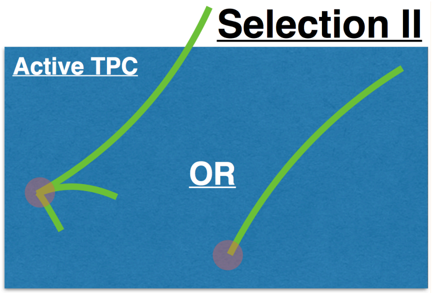
Selection I

- Strict requirements on containment (tracks must be contained)



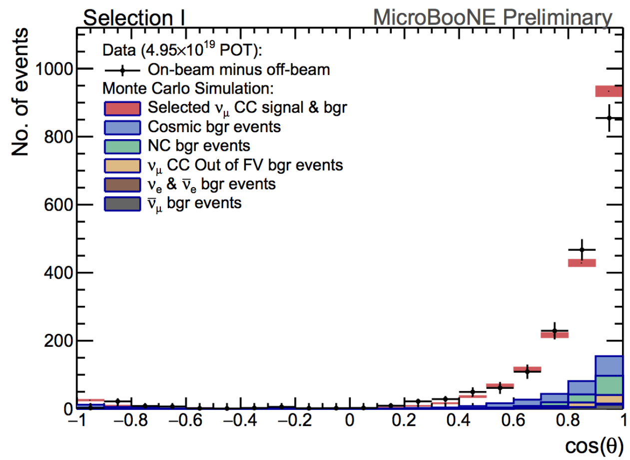
Selection II

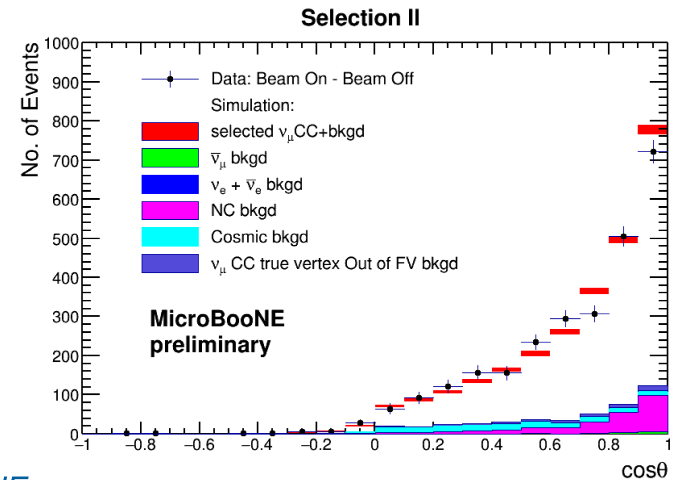
- Looser requirements on containment (for multitrack events).
- Cuts events with a Michel tag, likely a stopping cosmic ray.



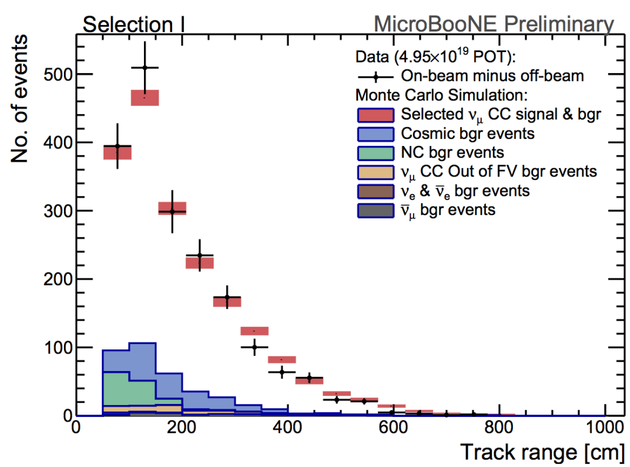
MicroBooNE: Charged Current Analysis

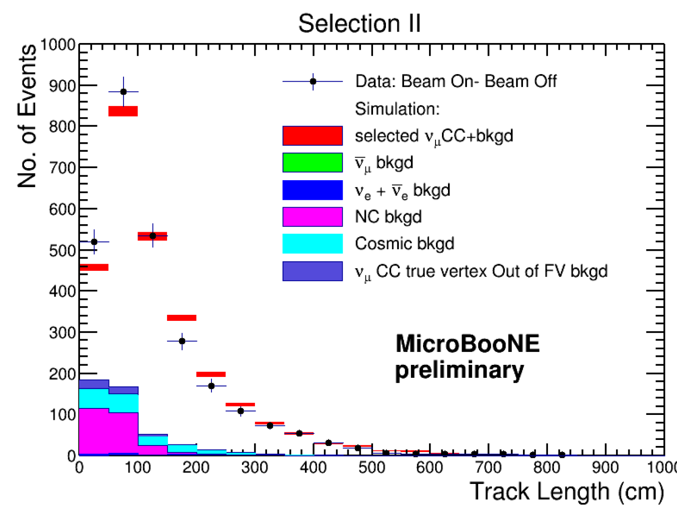
- **Shape-only comparisons show good agreement between data and MC.**
- **Numerous track quantities consistent across two selection methods.**





MicroBooNE Public Note 1010



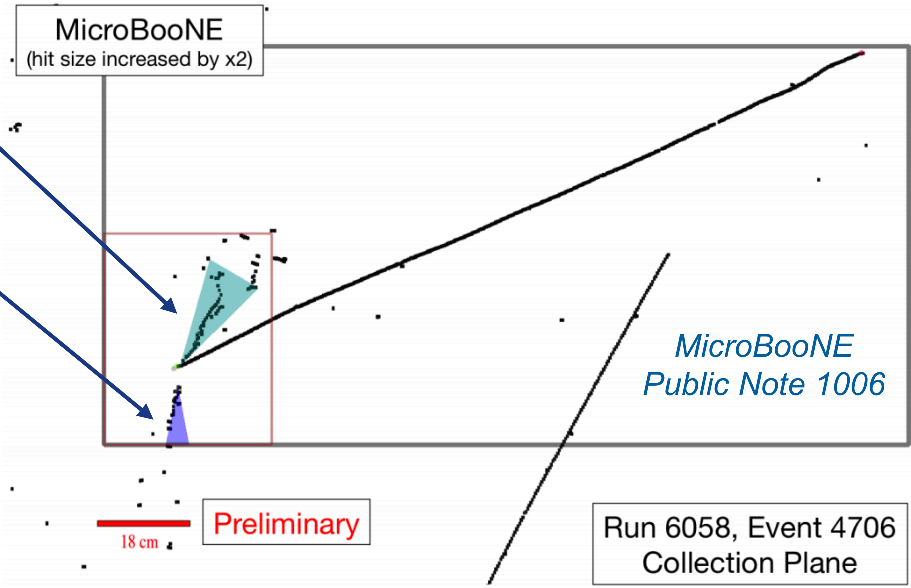


MicroBooNE: π^0 Production

- **Neutral pion production is a perfect channel for tuning shower energy algorithms and energy scales due to the "simple" event topology and distinct mass-peak of π^0.**

$$\nu_\mu + Ar \rightarrow \mu^- + X^+ + \pi^0$$

$$\pi^0 \rightarrow \gamma + \gamma$$



- **Analysis being built on a set of hand-scanned pion events.**

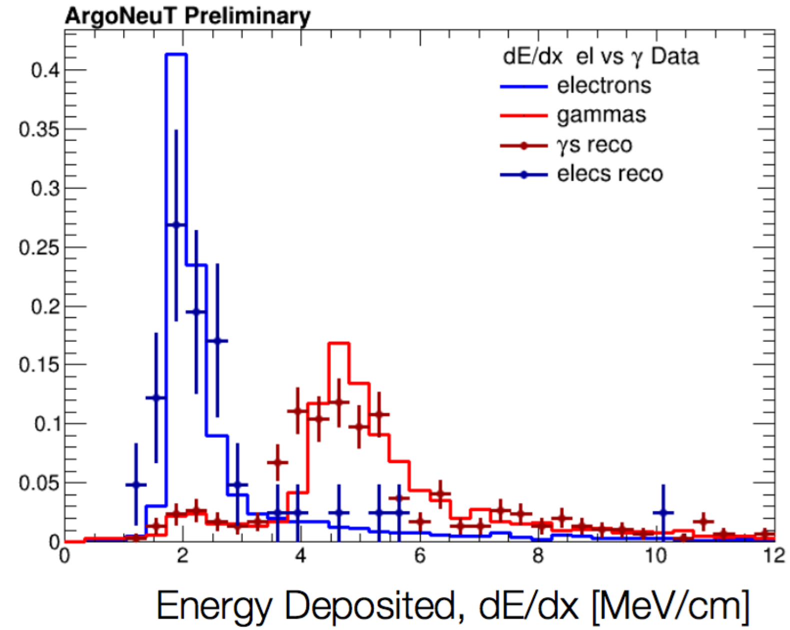
- **Working toward an automated event selection and invariant mass peak.**

MicroBooNE: Low Energy Excess Sensitivity

- **MicroBooNE will, by itself, be sensitive to the MiniBooNE low E excess after 6.6×10^{20} POT.**

- **e/γ separation possible with a large TPC will determine the nature of the excess (electrons or photons).**

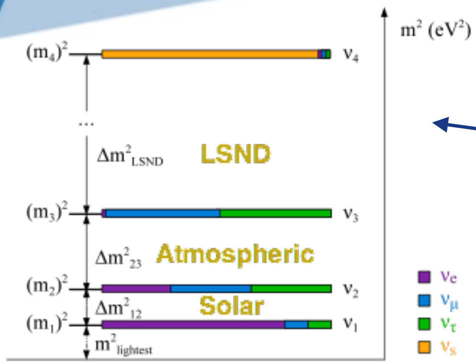
- **First big result of the SBN program will be what MicroBooNE finds in this region.**



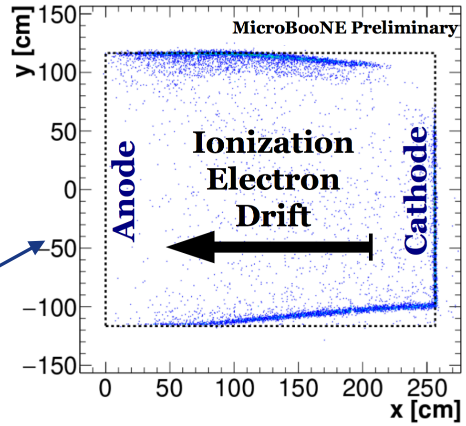
arXiv: 1610.04102

Short Baseline Program: All Together

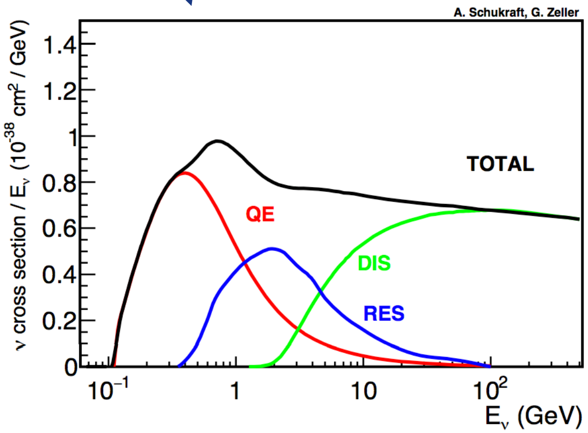
Oscillations



Detector Physics



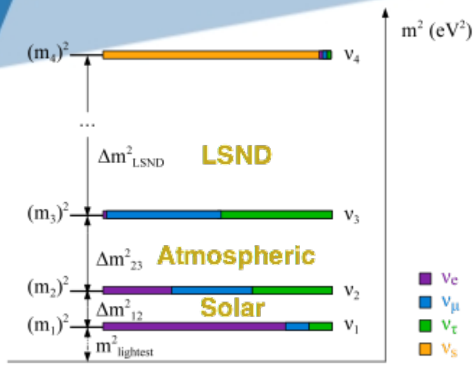
Neutrino Cross-Sections



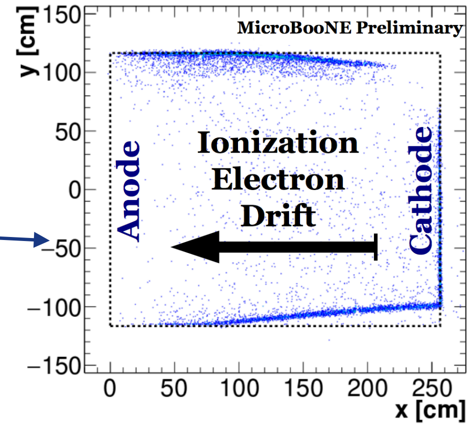
- Three subfields, three detectors, each relying on input from the other.
- Feedback and follow up important in each case.

Short Baseline Program: Connecting to DUNE

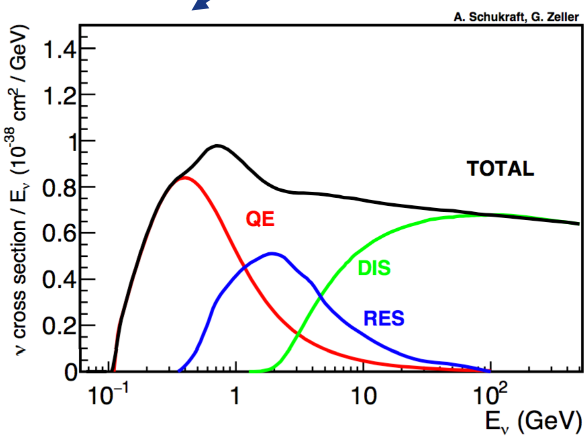
Oscillations



Detector Physics



Neutrino Cross-Sections



- To find CP violation, all aspects are vital for DUNE.
- Good understanding of TPCs, neutrino cross-sections and oscillations are vital.
- SBN program gets us there.

Conclusions

- Short baseline program at Fermilab designed to resolve the LSND signal and reactor anomaly.
- Three detectors built for this purpose:
  - SBND (coming soon).
  - MicroBooNE (running well, taking and analyzing data).
  - ICARUS (coming soon).
- Three fields of study to pursue:
  - Neutrino Oscillations.
  - Neutrino Cross-Sections.
  - Detector science and R&D.
- Building a future of detecting CP violation, one detector (or analysis) at a time.

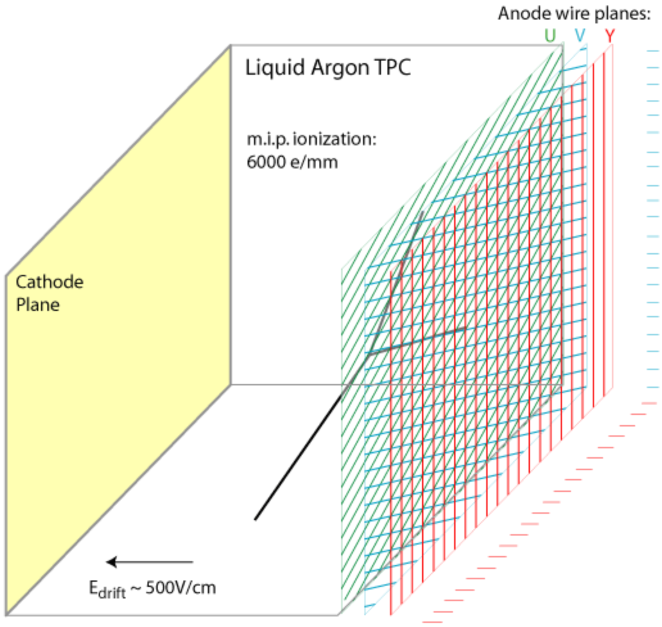
Thank you for Listening!

MicroBooNE Public Notes

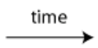
May be found at this URL:

http://wwwmicroboone.fnal.gov/publications/publicnotes/

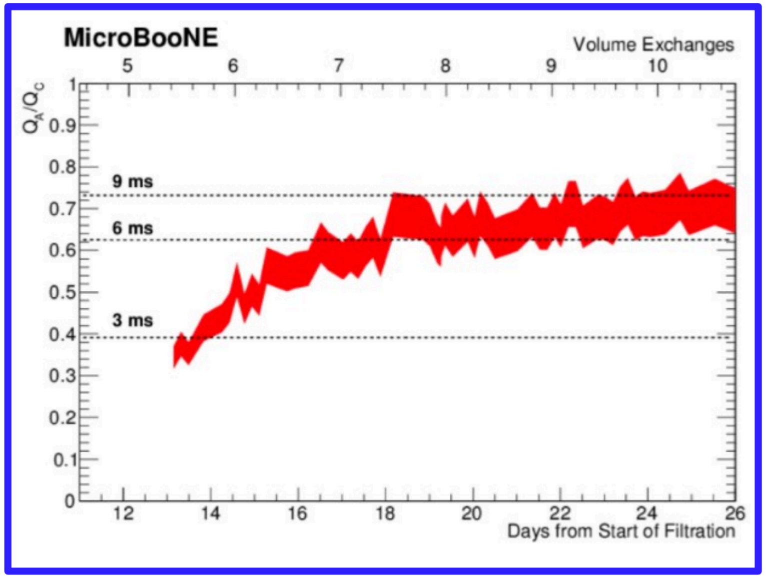
LArTPCs: Operating Principle



- Neutrino+Ar → final state charged particles
- Propagating charged particles ionize the argon
- Electric field drifts free electrons few meters to wire chamber planes (~1.6 mm/ms at 500 V/cm)
- Induction/Collection planes image charge, record dE/dx
- Argon <u>purity</u> of prime importance to avoid signal attenuation



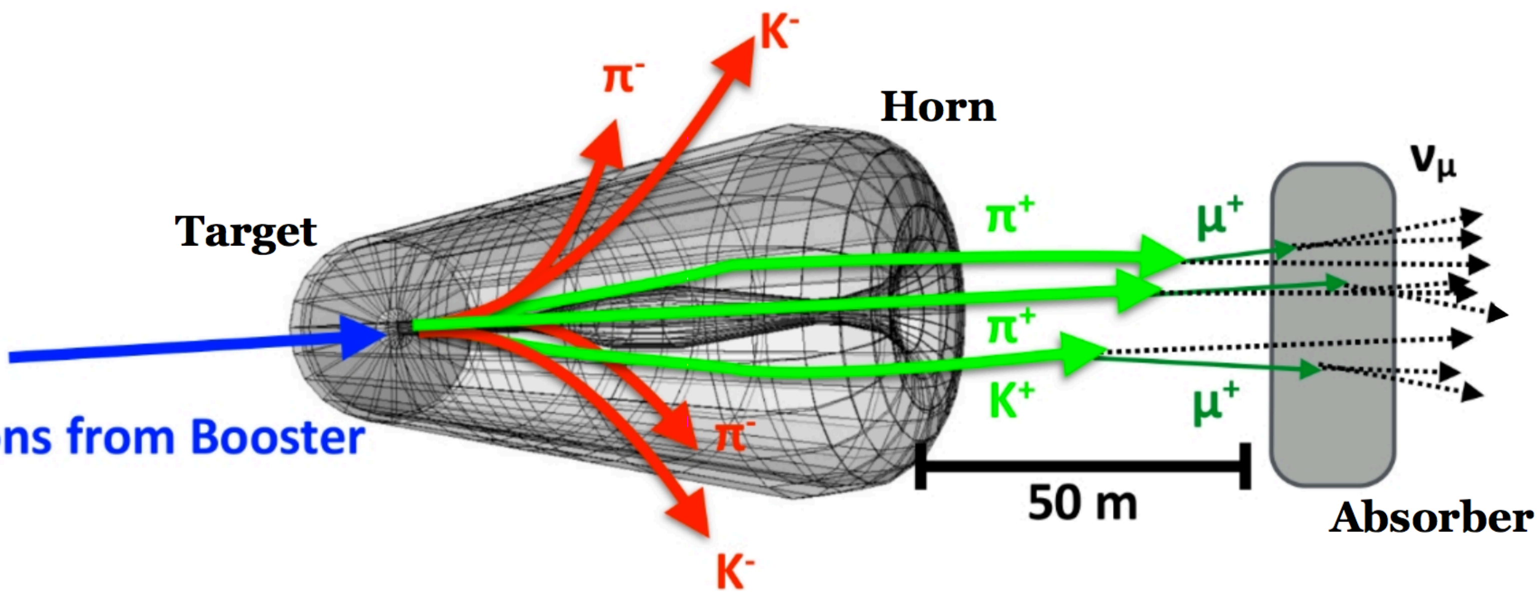
MicroBooNE: More Than Pretty Plots

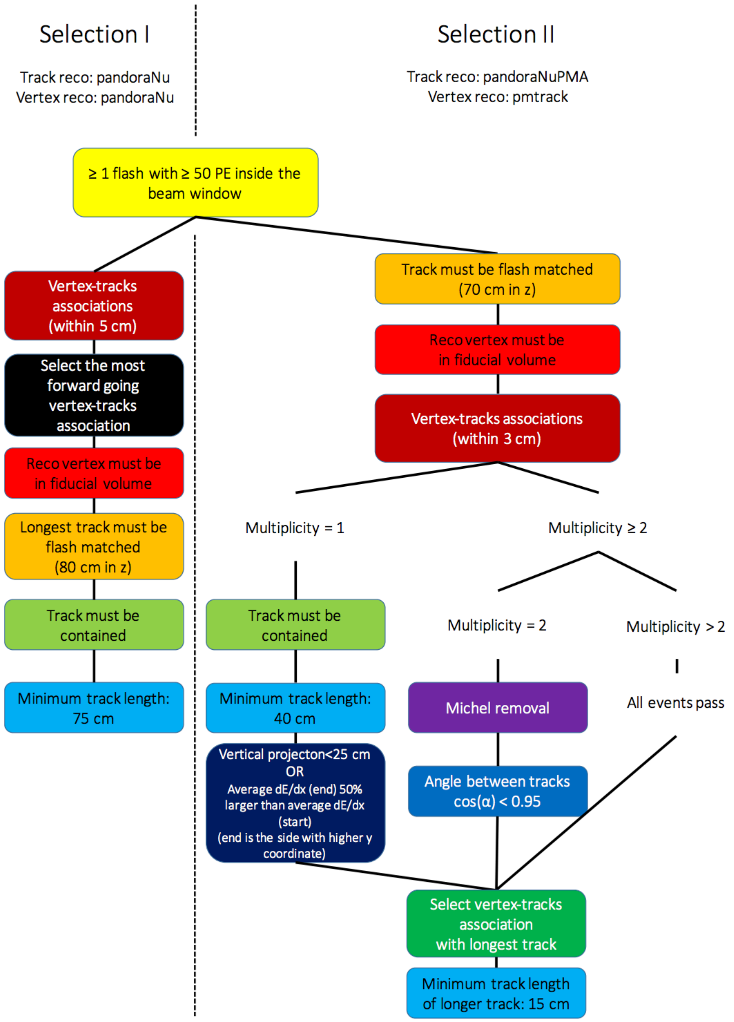


- **Gas purge (vessel not evacuated) and cool-down prior to LAr fill.**
- **Argon purity *above* design specs, filtration working well.**

Building a Neutrino Beam

- 8 GeV protons from FNAL booster collide with a Be target.
- Secondary particles focused (defocused) by magnetic horn.
- Absorbers + earth stop decay products except neutrinos.





Selection I
Track reco: pandoraNu
Vertex reco: pandoraNu
Selection II
Track reco: pandoraNuPMA
Vertex reco: pmtrack
≥ 1 flash with ≥ 50 PE inside the beam window
Vertex-tracks associations (within 5 cm)
Select the most forward going vertex-tracks association
Reco vertex must be in fiducial volume
Longest track must be flash matched (80 cm in z)
Track must be contained
Minimum track length: 75 cm
Track must be flash matched (70 cm in z)
Reco vertex must be in fiducial volume
Vertex-tracks associations (within 3 cm)
Multiplicity = 1
Multiplicity ≥ 2
Track must be contained
Minimum track length: 40 cm
Vertical projecton<25 cm
OR
Average dE/dx (end) 50% larger than average dE/dx (start)
(end is the side with higher y coordinate)
Multiplicity = 2
Multiplicity > 2
Michel removal
All events pass
Angle between tracks cos(α) < 0.95
Select vertex-tracks association with longest track
Minimum track length of longer track: 15 cm