Short-Baseline neutrino oscillation searches with the ICARUS detector

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on behalf of the ICARUS collaboration

Mitchell Conference – College Station, TX

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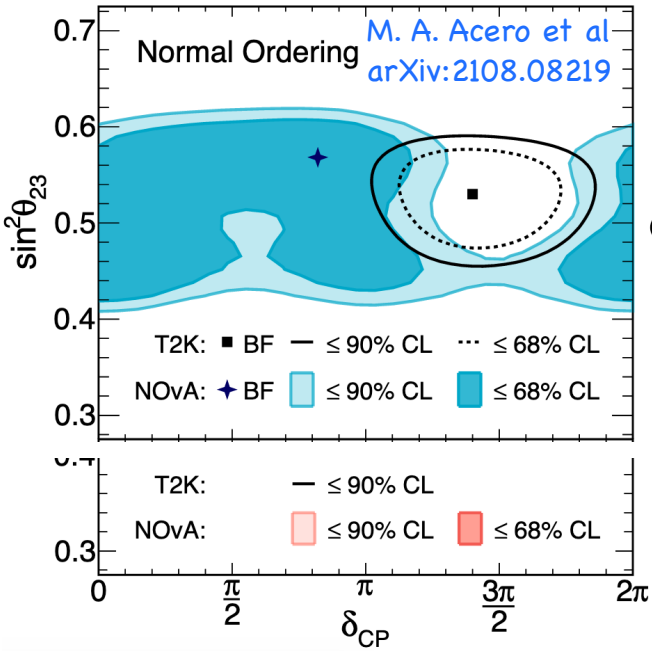
Neutrinos + Oscillation

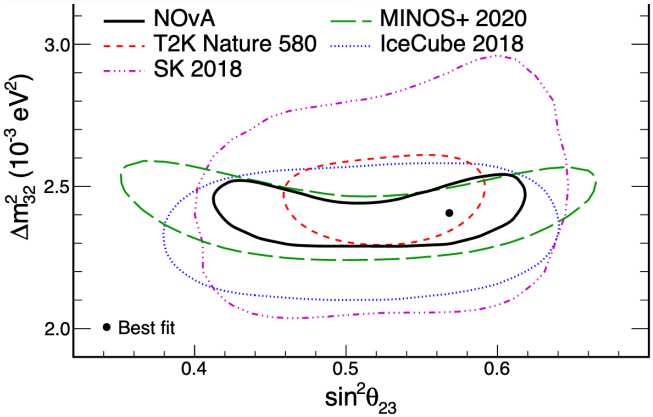
$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2$$
$$+\sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{CP})$$
$$+\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,$$

R. Acciari et al arXiv:1512.06148

$$a = G_F N_e/\sqrt{2} \qquad \Delta_{ij} = \Delta m^2_{ij} L/4E_\nu$$

We have sin & cos of L/E – oscillation is function of baseline (distance) & nu energy

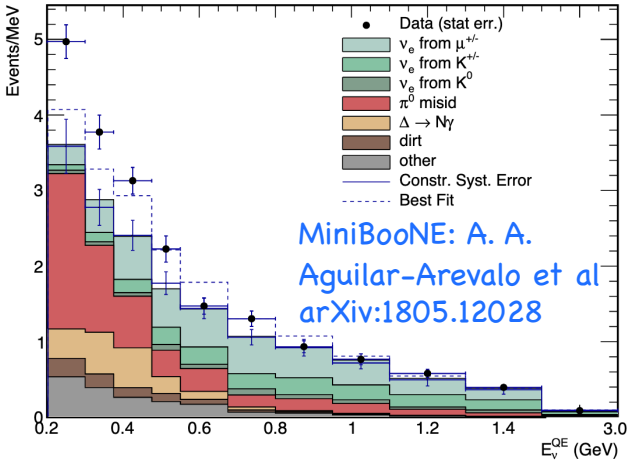


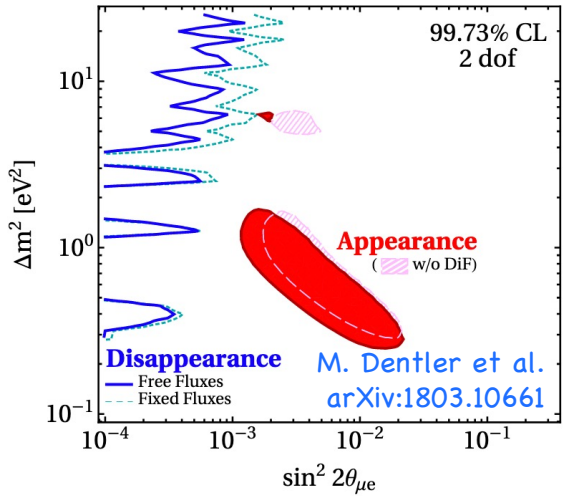


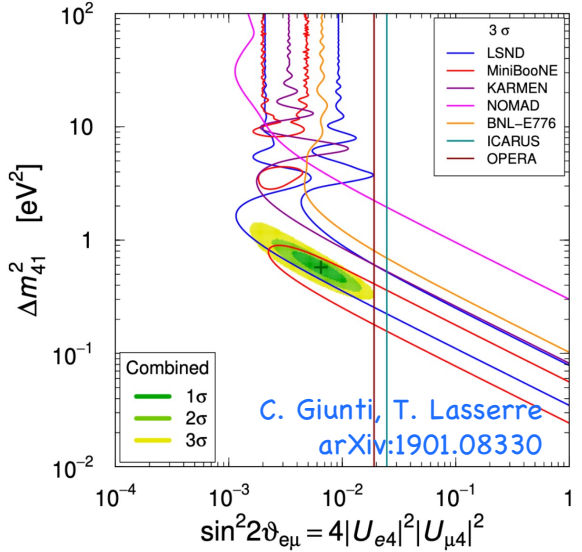
- Neutrinos always interesting place to go searching
  - Answer some questions but raise new ones
  - An area of current study is oscillation (w/ 3 known flavors & looking for possible extra sterile state[s])
- 3-flavor oscillation: current experiments like T2K (Japan) or NOvA (US) working to make best measurements possible but the next generation (e.g. DUNE in the US and HyperK in Japan) will aim to make more definitive measurements

Neutrinos beyond the standard 3?

- LSND & MiniBooNE found anomalous excess of low energy ν_e candidates at short baseline (SBL)
  - Given this L/E and the known 3-flavor oscillation parameters, cannot explain this excess due to standard 3-flavor oscillation
- Look for them indirectly via oscillation signatures (appearance, disappearance, conservation of NC interactions)
- More recently, Neutrino-4 reported possible hint of oscillatory signature. See A. P. Serebrov et al. Phys. Rev. D **104**, 032003 (2021)
- Sterile neutrino is one interpretation of excesses: additional beyond standard model candidates have been proposed as possible answers







Studying sterile neutrinos at FNAL

- To investigate the question of sterile neutrinos and the low energy excess (LEE), we need two things:
  - We need a source of lots of neutrinos with the right energy and distances
  - We need powerful detectors to give us the highest sensitivity possible

- Having these conditions met also enable lots of additional physics, as will be mentioned.

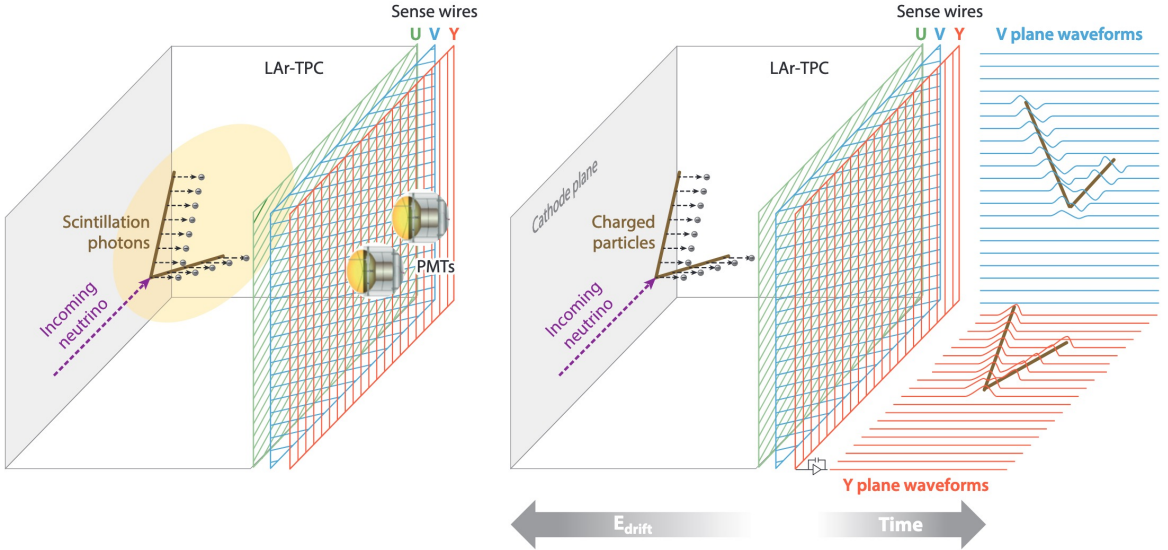
Liquid argon TPCs

- Liquid argon scintillates and ionizes – powerful bulk detector medium
- E-field drifts ionization to wires to measure tracks/showers – wires with mm spacing we have very fine resolution along the beam and vertically
  - Drift speed ~1.6 mm/μs @ 500 V/cm, distance of ~1.5 m → ~1 ms drift
- Light provides prompt signal & ability to match activity in-time with beam (e.g. ν): often use PMTs w/ wavelength shifters (128nm scintillation)

Charge signal read by multiple planes (allows 3D reconstruction) & wire spacing of 3mm allowing O(mm) spatial resolution!

Amount of signal proportional to deposited energy, allows calorimetry.

Light signal is prompt, allows one to determine if the interaction occurred during the expected beam window.

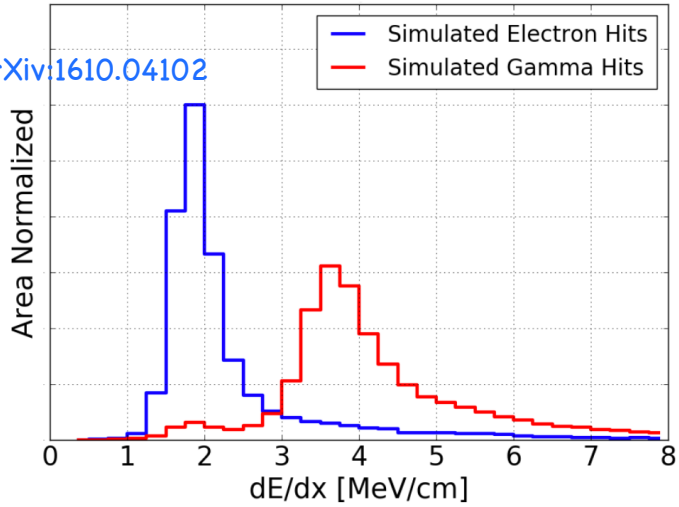


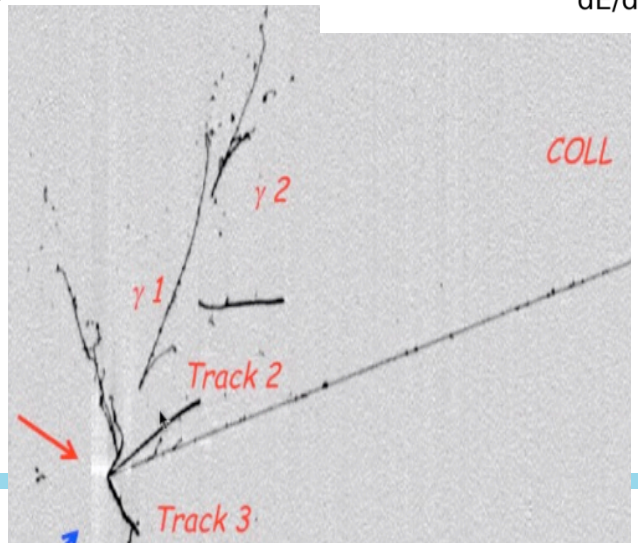
P. Machado, O. Palamara, D. Schmitz. Annu. Rev. Nucl. Part. Sci. (2019). doi: 10.1146

Liquid argon TPCs

- In addition to being an overall sensitive medium, capability w/ **electromagnetic showers** is a key aspect
- Specifically e/γ separation – important to ID electrons from ν_e events and to understand if low energy excess is e or γ related:
  - Spatial resolution allows to look for gaps between vertex, shower start → photons
  - Isolation of initial track-like bit of shower to distinguish e vs pair production (~1 vs 2 minimum ionizing particles)

ArgoNeuT
R. Acciari et al arXiv:1610.04102





A candidate ν_μ CC interaction in **ICARUS** with an apparent π^0 decaying to two photons, with gap from vertex visible.

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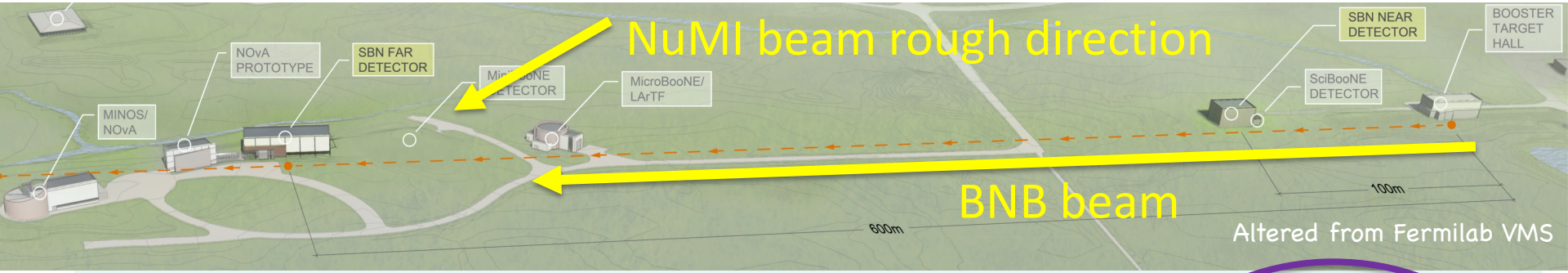
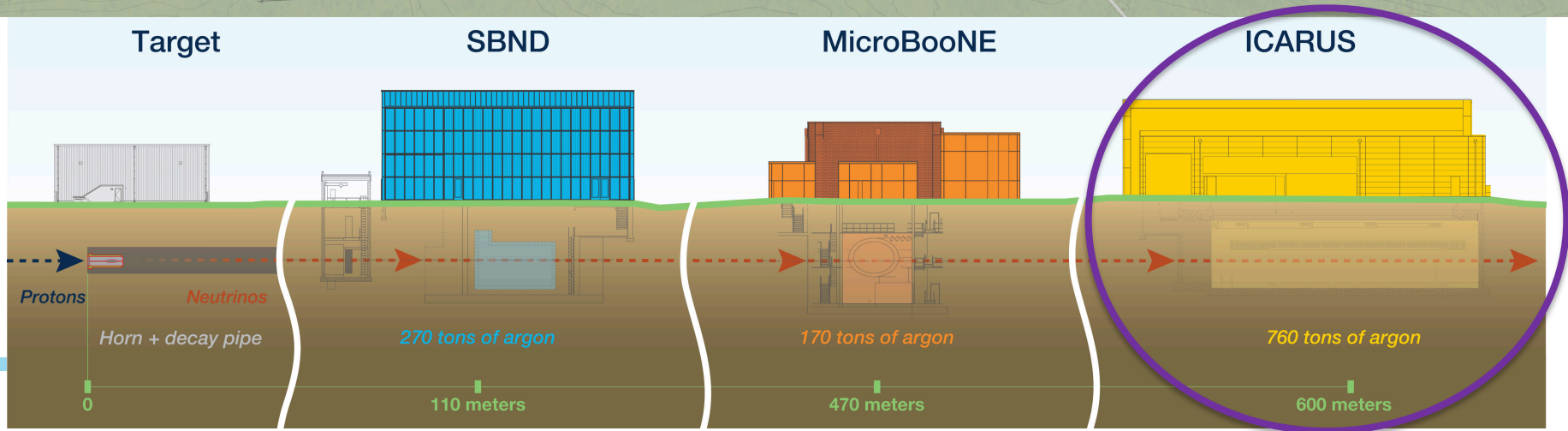
SBN Program at FNAL

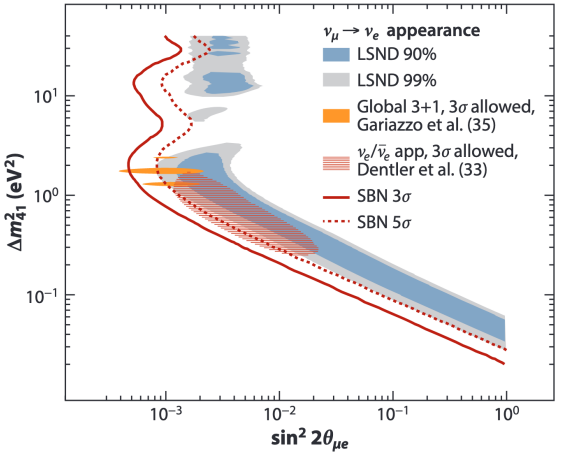
LAr TPCs so, with good e/gamma separation –
(1) is LEE electron-like or photon-like?
(2) Multi-detector oscillation search
Same detector technology, beam, and having multiple detectors reduces systematic uncertainties

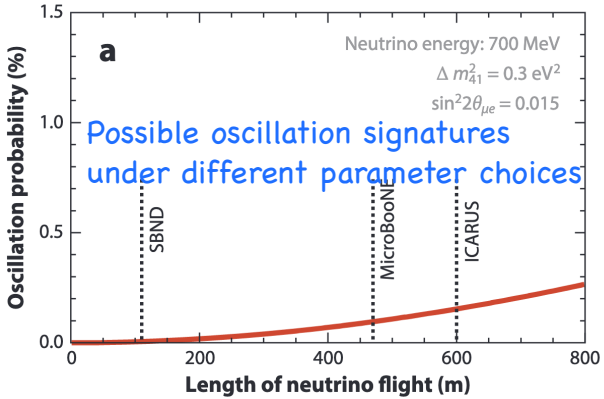


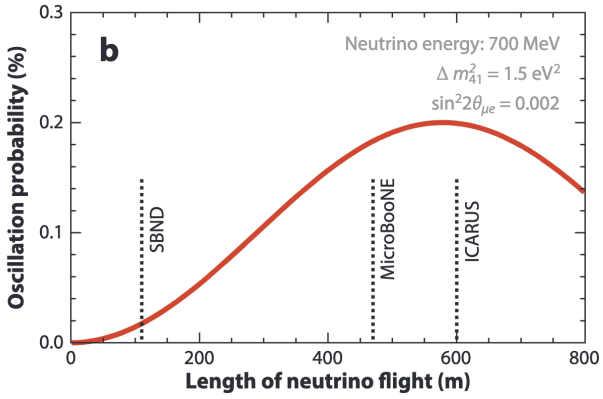


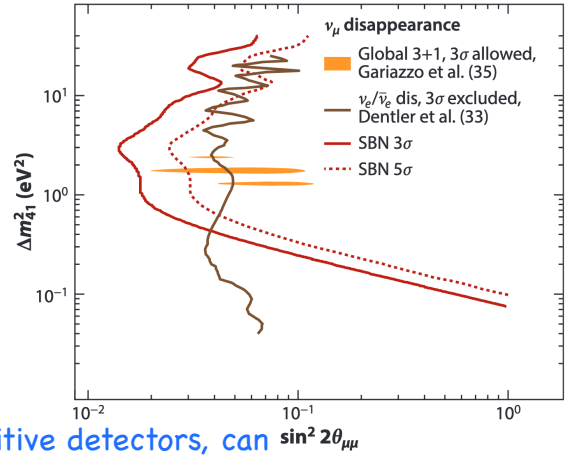
SBN Program at FNAL

- 3 LAr TPC experiments using BNB beamline
- SBND serves as Near detector, ICARUS Far detector
- Studies ν_e appearance and ν_μ disappearance along beam
  - Aim to provide definitive answer on nature of MiniBooNE & LSND excesses and the sterile neutrino interpretation









P. Machado, O. Palamara, D. Schmitz.
Annu. Rev. Nucl. Part. Sci. (2019). doi: 10.1146

With the multi-detector fit and sensitive detectors, can perform both a disappearance and appearance measurement

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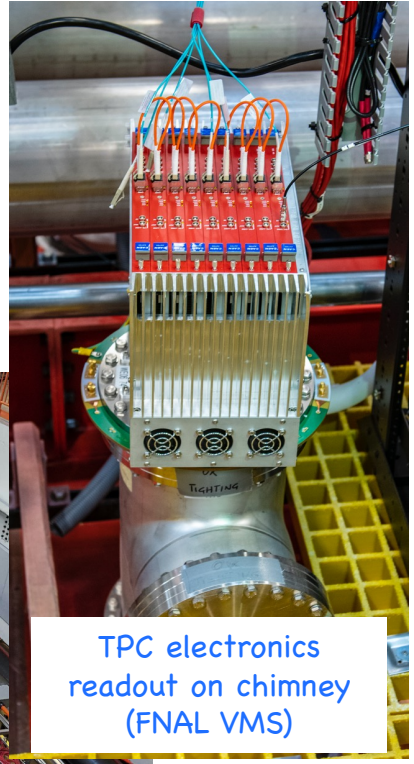
ICARUS at a glance

- First large LAr TPC: still one of the largest in operation
  - 2 modules, each 19.6 x 3.6 x 3.9 m^3
  - Total 760 t LAr, 476 t active.
  - 2 TPCs per module w/ active drift distance ~1.5m
- 90 PMTs per TPC – 360 total, both as a trigger and to match with other systems to ID beam-related activity
- Cosmic ray tagging system to help reject background
  - Operating on surface at FNAL (with overburden)

ICARUS at FNAL

- ICARUS T600 moved from Europe (First LNGS, then CERN for refurbishment) to the US in 2017 & deployed at Fermilab

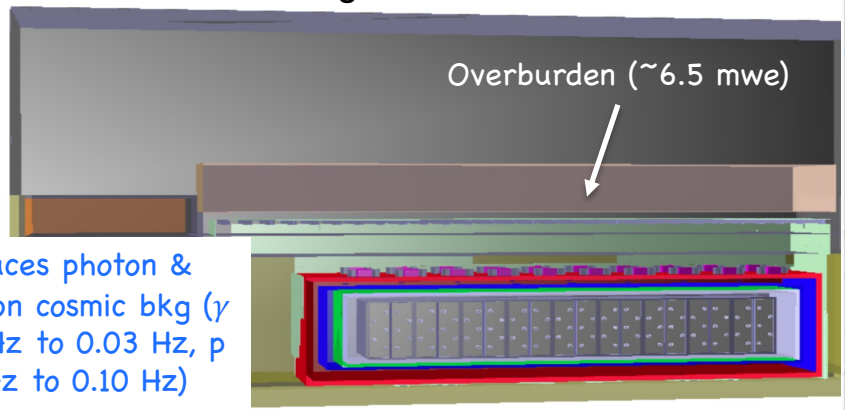


TPC electronics readout on chimney (FNAL VMS)

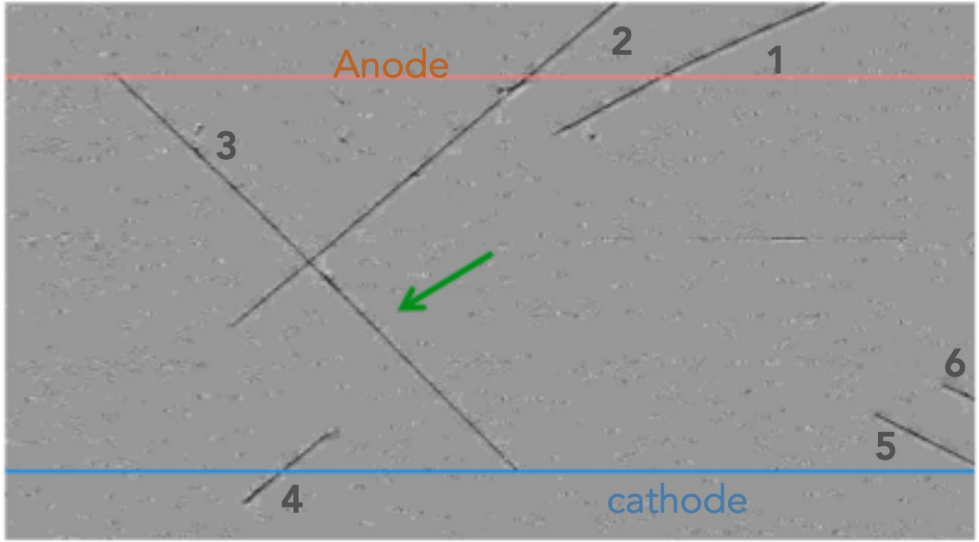
Above: photo of ICARUS being deployed at FNAL (FNAL VMS). Left: Similar position but after first part of installation

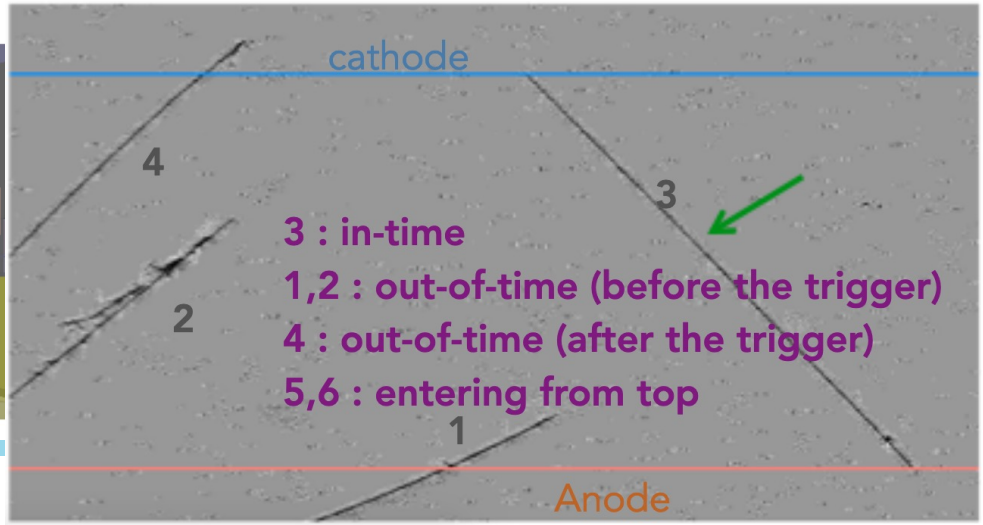
ICARUS at FNAL

- Surface-located & big volume: large cosmic bkg
- Multi-pronged mitigation strategy:
  - Overburden
  - Some cosmics “clear” from just TPC
  - Matching TPC charge to PMT signal
  - Cosmic ray tagger (CRT) – esp. in-time activity. Possibility of CRT-PMT match under investigation



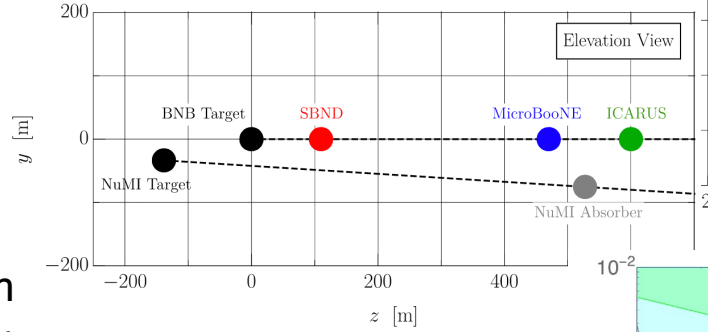
Reduces photon & proton cosmic bkg (γ 116 Hz to 0.03 Hz, p 54 Hz to 0.10 Hz)

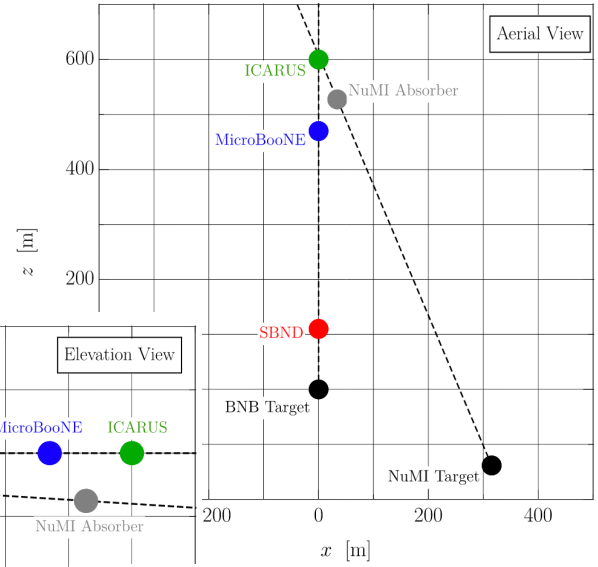




Physics analysis with ICARUS

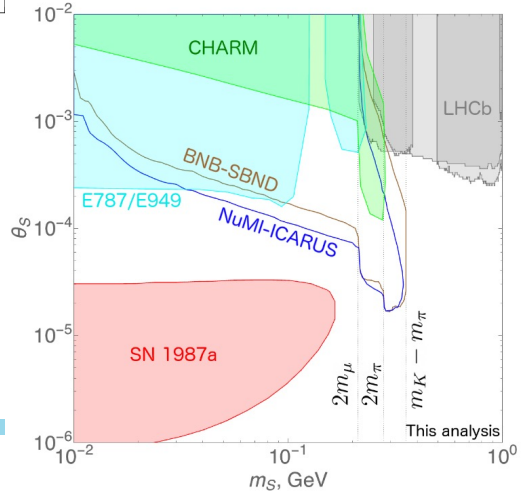
- In addition to multi-detector sterile study, ICARUS has a wealth of planned physics measurements:
  - Can probe sterile hypothesis before SBND comes online w/ study in L/E range consistent with the Neutrino-4 experiment
  - Proximity & angle to NuMI beam make it valuable target for nu-Ar interaction studies, cross-section measurements –*for SBN & DUNE*
  - Can also study beyond standard model physics w/ NuMI





arXiv:1909.11670
B. Batell, J. Berger, A. Ismail

Estimated sensitivity to potential scalar particle mixing with Higgs, phenom. model w/ estimated efficiencies, backgrounds

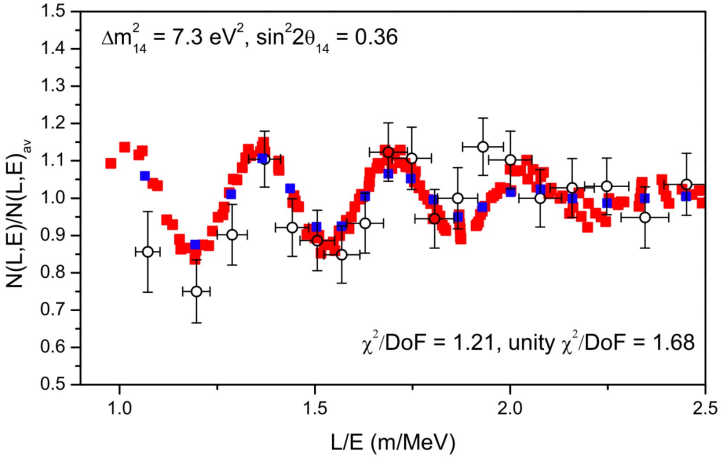


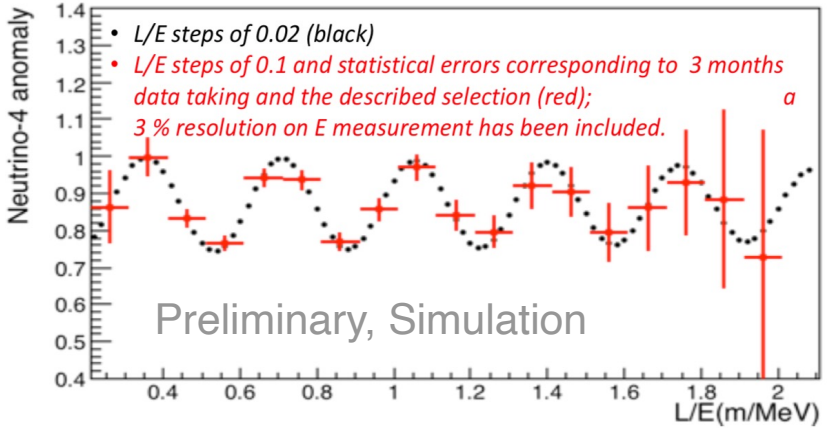
Neutrino-4 study with ICARUS

- Neutrino-4 collaboration reported possible hint of reactor ν disappearance signal in L/E range ~ 1-3
- ICARUS sensitive to similar L/E. Two (separate) samples and beam-off sample can test these findings:
  - ν_μ disappearance in BNB beamline: focus on ν_μ CC QE sample w/ contained μ ≥ 50 cm
  - ν_e disappearance in NuMI beamline: focus on ν_e CC QE sample w/ contained electron shower
- First foreseen measurement is w/ CCQE-like ν_μ
- ICARUS ~600m from BNB:
  L/E ~ 0.5 corresponds to E = 1.2 GeV
  L/E ~ 1.0 corresponds to E = 600 MeV
  L/E ~ 1.5 corresponds to E = 400 MeV

E.g. ν_μ survival probability at Δm^2 ~ 7.25, $\sin^2 2\theta$ ~ 0.26 in ICARUS & corresponding anticipated result assuming 3 months data taking and 3% energy scale resolution.

A. P. Serebrov et al. Phys. Rev. D **104**, 032003 (2021)

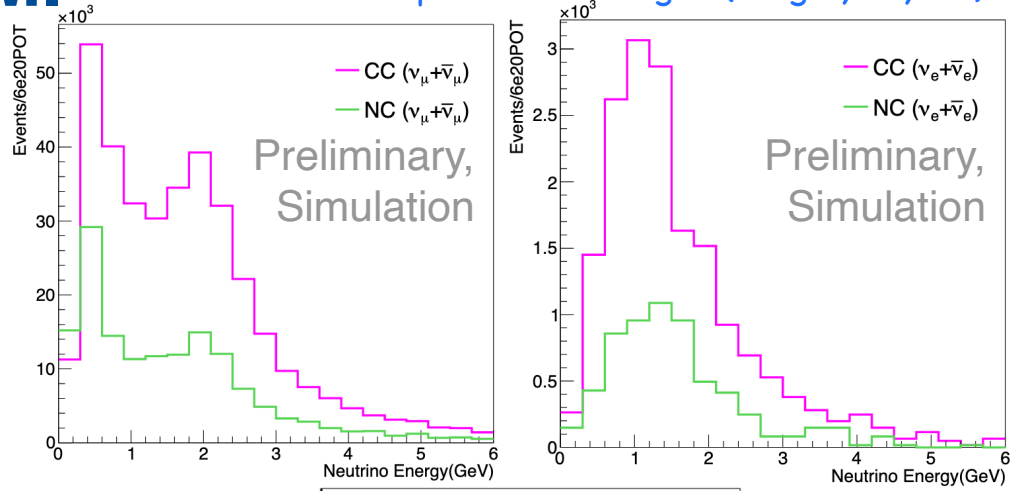


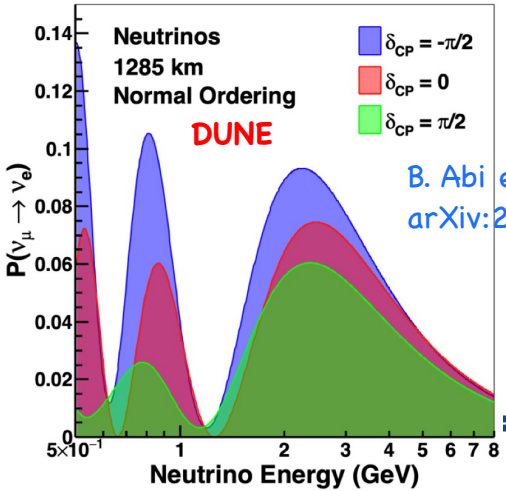


Cross sections with NuMI

- Understanding v-Ar interactions: cross-sections, nuclear effects, final states. **Important to oscillation studies and constraining systematics**
  - Effects e.g. both the rates/signal efficiency understanding and energy resolution
- The NuMI beam provides ICARUS a wealth of ν_μ **and** ν_e interactions, from order of a few hundred MeV to multi-GeV (higher energy ν_e from K decays & are more abundant in NuMI)
- Interesting sample in comparison to BNB oscillation study and also to provide input to DUNE (covers 2nd oscillation max and extends into 1st)

Anticipated NuMI neutrino interactions per 6e20 protons on target (roughly 1 year)





B. Abi et al.
arXiv:2006.16043

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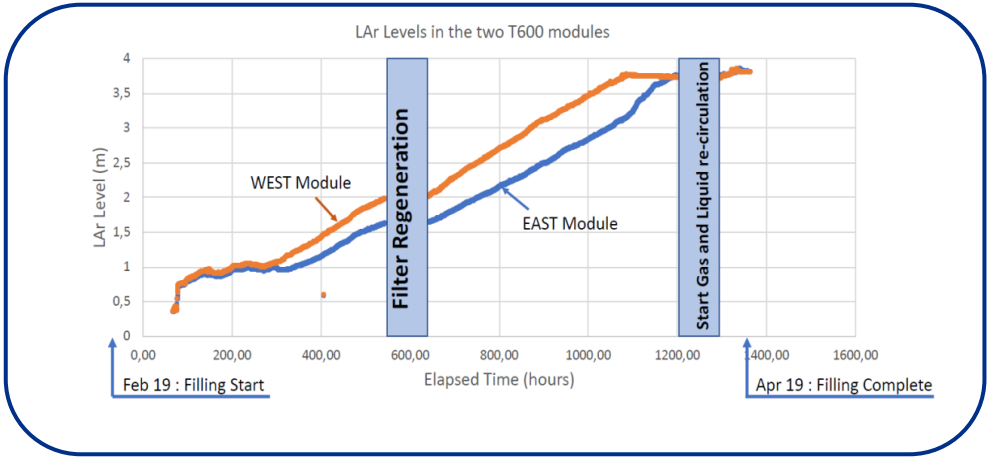
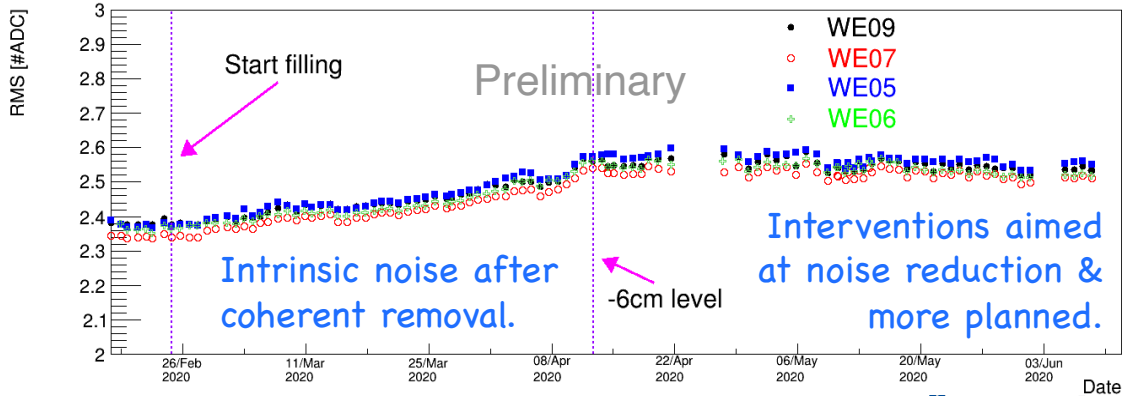
Now, to actually make that happen

- After main installation, ICARUS began cooldown/filling Feb 2020
- Taking detector monitoring shifts since then
- By Fall 2020 detector was activated to the full electric drift field of -75kV (500 V/cm) was reached. PMTs were activated and gain calibration was underway, etc.
- Then comes trigger, commissioning, initial looks at how things are performing
- Also, finalization of installation tasks





Finalizing of installation

- When installation activities paused to allow cool down/ filling, not all subsystems were fully installed
- A good example is the CRT system, where the bottom CRT and part of the sides were installed
- Over pandemic, lot of effort in installing/instrumenting the Side CRT. Then in late 2021, European experts for top CRT were able to visit FNAL and install the system

3rd picture from this level of building looking towards ICARUS, now w/ top CRT. Currently being covered by overburden.

Top CRT

Side CRT

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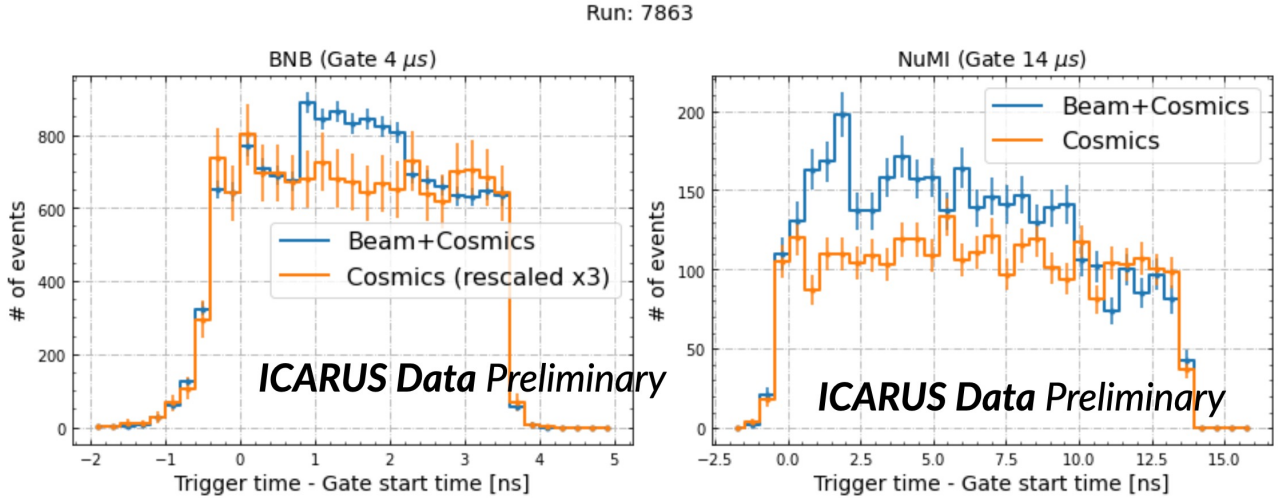
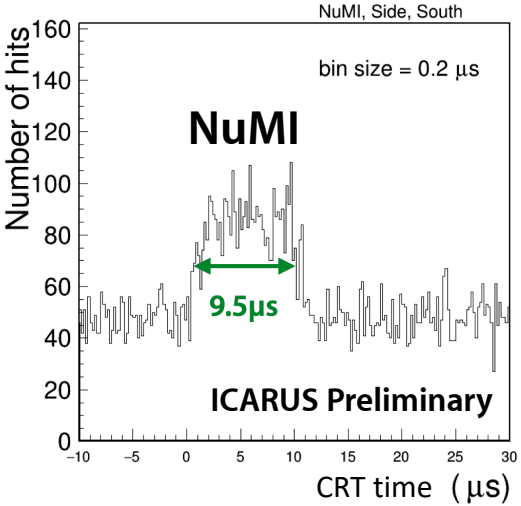
ICARUS at FNAL: Activation & Commissioning

- Trigger commissioning included confirmation of a peak of excess corresponding to beam
- More recently, the CRT system has gone through the exercise of looking for activity from the beam





PMTs – excess of activity in detector corresponding to beam (broader peak related to trigger window and extra excess corresponding to beam)

CRT: excess activity outside detector corresponding to beam as well

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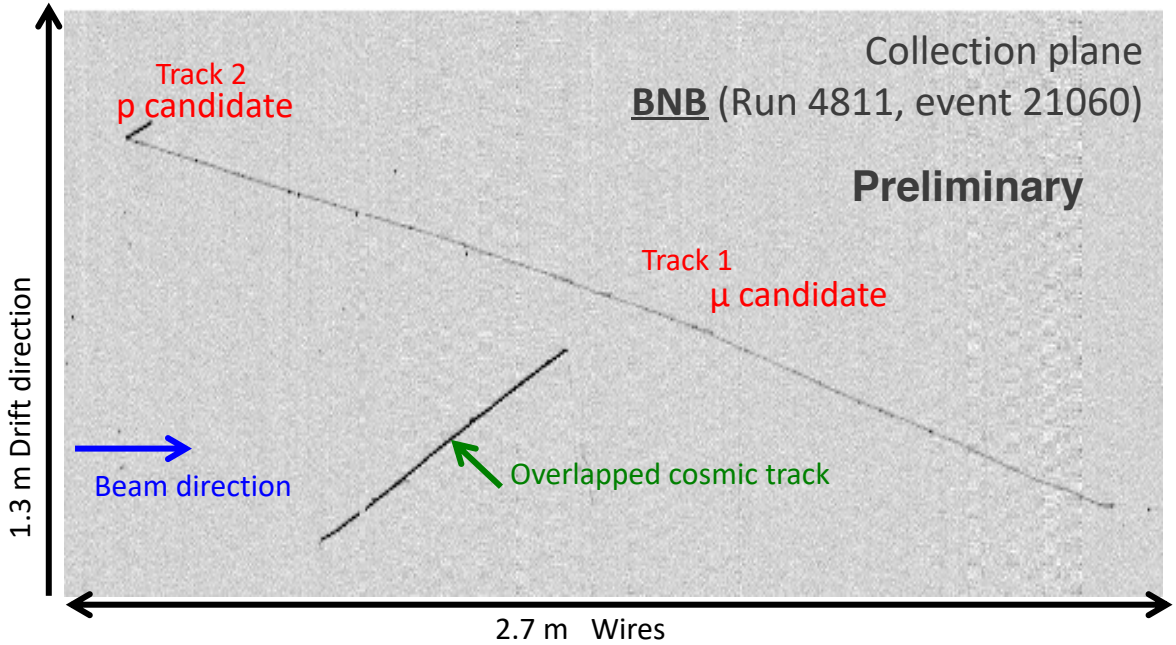
ICARUS at FNAL: Activation & Commissioning

- Visual scanning effort to find neutrino candidates in early collected data



One of the first candidate ν_μ interactions found in BNB.

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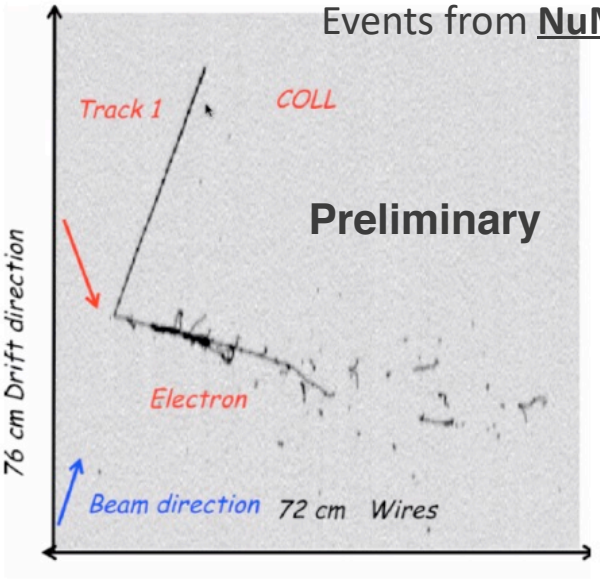
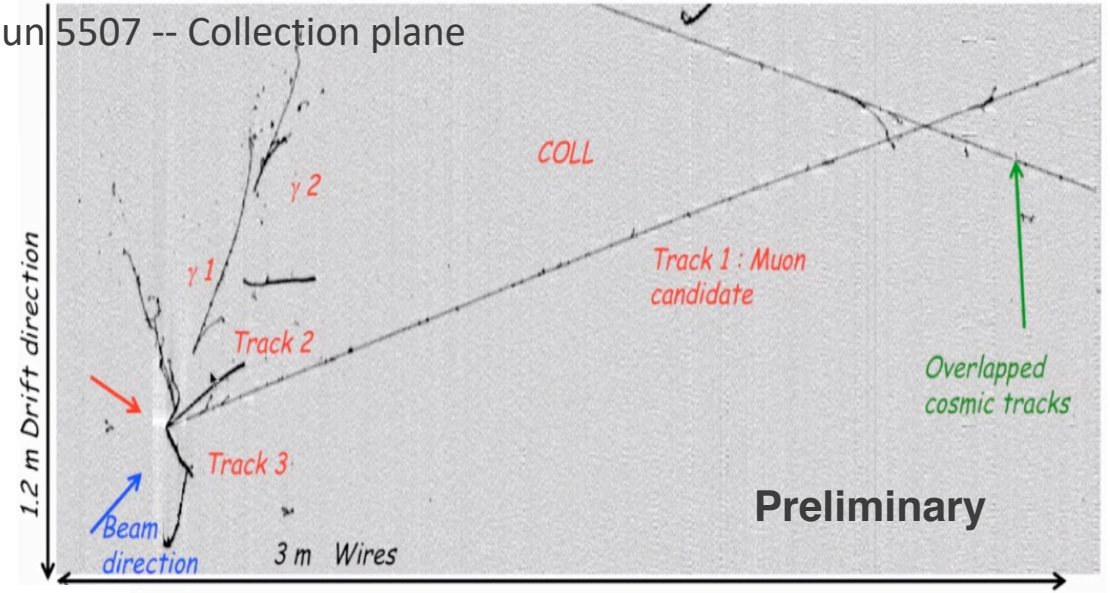
ICARUS at FNAL: Activation & Commissioning

- Visual scanning effort to find neutrino candidates in early collected data



Candidate ν_e interaction from NuMI.

Events from **NuMI** Run 5507 -- Collection plane



Candidate ν_μ interaction from NuMI.

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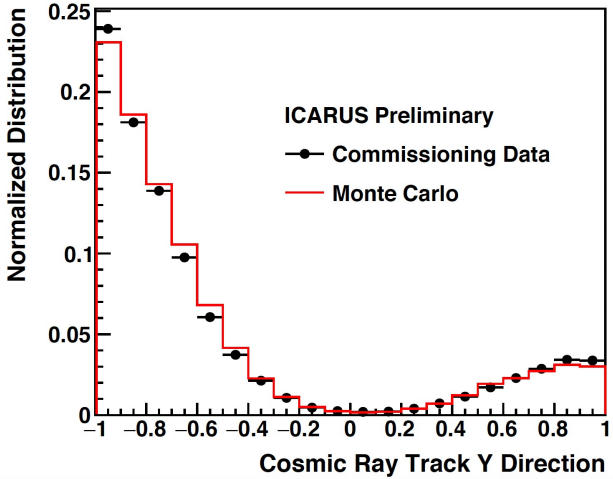
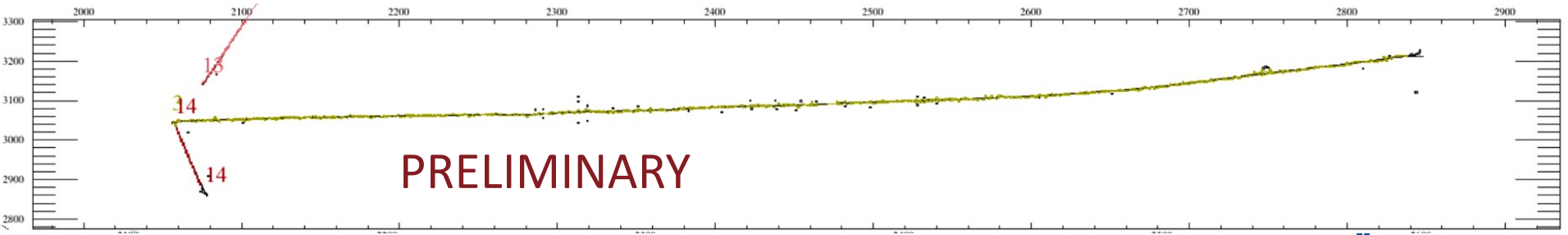
ICARUS at FNAL: Activation & Commissioning

- Neutrino events found from hand scanning useful to investigate and test automated software tools on small set of data & compare performance between MC/data.
- Additionally, we are in process of digging into reco performance & studying things like data/MC agreement with cosmics (beam-off data, cosmic simulation e.g.)
- Below is a sample data event picked by hand scanning with reconstruction overlaid: 2 tracks identified by reco
- Calibration campaign w/ early data to understand detector effects, calorimetry, etc.





Summary

- ICARUS is a liquid argon TPC originally operated at LNGS in Italy
- After a successful refurbishment and upgrade, it was moved to Fermilab in the USA where it sees neutrinos from both the BNB and NuMI neutrino beams at Fermilab
- Question of sterile neutrinos remains open, both related to the previous measurements of LSND and MiniBooNE and the more recent claim of oscillation signature from Neutrino-4
  - Short Baseline Neutrino Program at FNAL will use the BNB beam to probe the LSND and MiniBooNE excess. ICARUS serves as the Far Detector of this study.
- ICARUS is also able to measure cross-sections, search for light dark matter, etc.
  - Cross-section measurements in energy range of interest to SBN but also DUNE
- ICARUS has been commissioning and progressing towards physics data readiness and preparing to perform analyses
  - **Nearly at continuous physics data-taking stage**
- SBND actively being constructed -- excited for the oscillation measurements enabled by a 2 detector fit in addition to the physics ICARUS can perform

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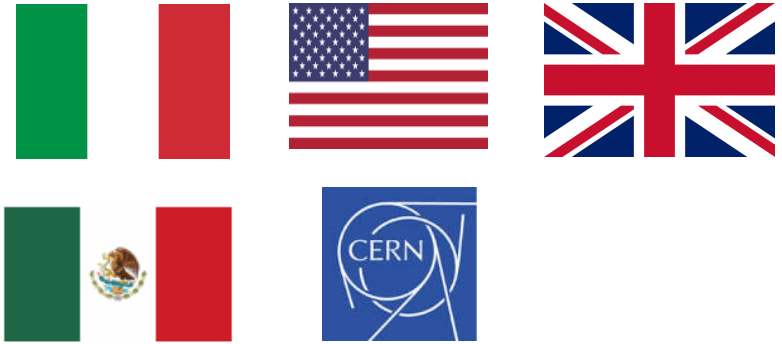
[a] CERN, on leave of absence from Padova
[b] Fermilab, on leave of absence from Pavia

Tufts University, United States
P. Abratenko, T. Wongjirad
University College London, United Kingdom
C. Backhouse

The ICARUS collaboration consists of 160 scientists, engineers, and technical staff from 24 institutions

Spokesperson: Carlo Rubbia
Deputy Spokespersons:
Alberto Guglielmi, Robert J. Wilson
Institutional Board Chair: Mark Convery

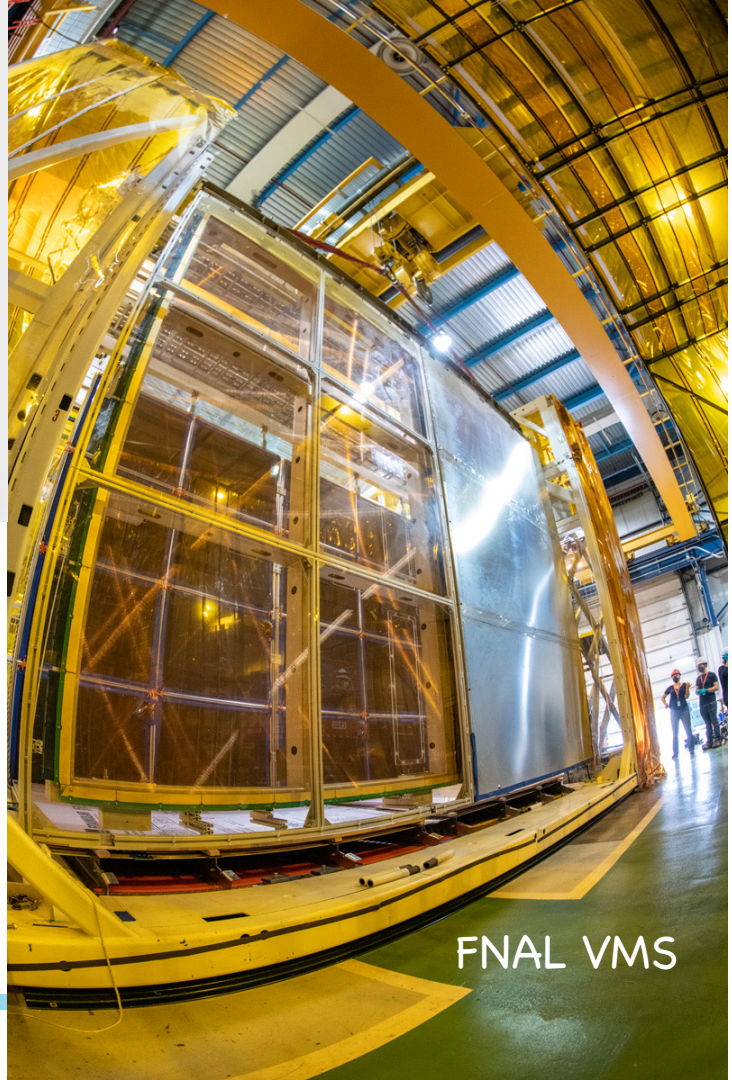


With contributions from INFN Sezione di Lecce and University of Salento

Backup

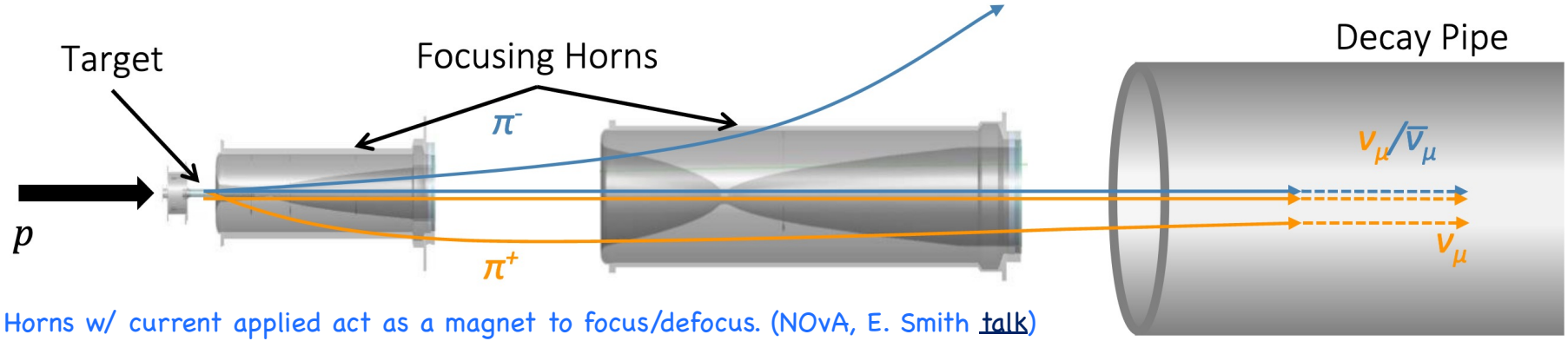
SBND

SBND under active construction



Neutrino Beams @ FNAL

- Depictions of how a neutrino beam works, using the NuMI (Neutrinos at the Main Injector) beam as an example.



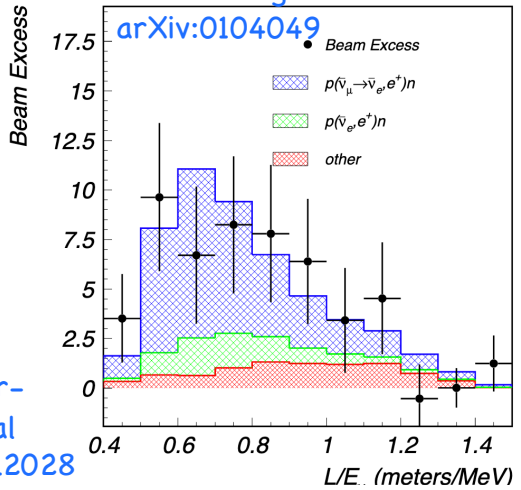
Horns w/ current applied act as a magnet to focus/defocus. (NOvA, E. Smith talk)

Rock/dirt between the end of decay pipe and the experiments range out initial charged particles leaving a "beam" of neutrinos

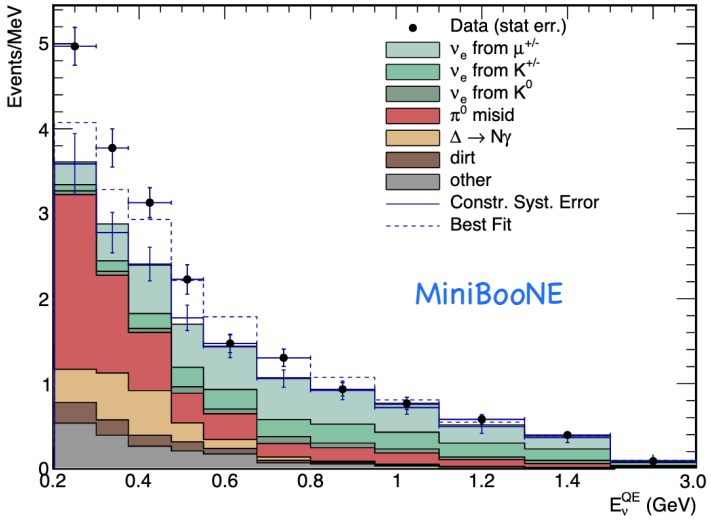
Neutrinos beyond the standard 3?

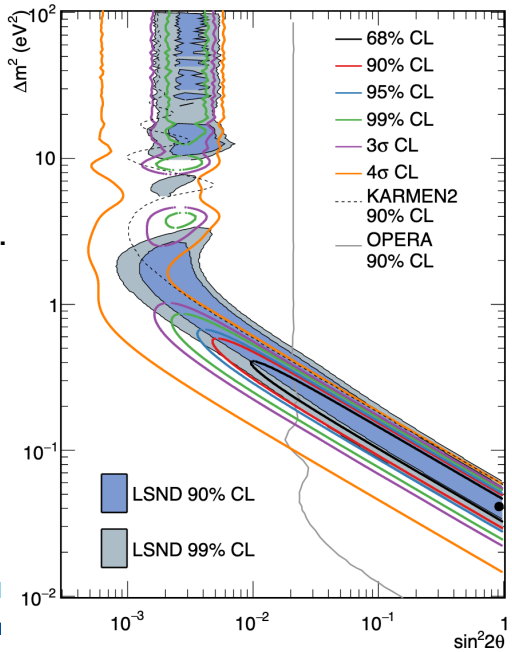
- LSND and MiniBooNE found anomalous excess of low energy ν_e candidates at short baseline (SBL)
  - Given this L/E and the known 3-flavor oscillation parameters, cannot explain this excess due to standard 3-flavor oscillation
  - An interpretation of this signature is oscillation of ν_μ to ν_e via presence of ≥1 sterile ν: can be shown in L/E effects or parameter plots
- Also greater excess at low energy in MiniBooNE (LEE)
  - Is the excess electrons, e.g. from ν, or photons?
- More recently, Neutrino-4 collab. has reported a possible hint of oscillatory signature. See A. P. Serebrov et al. Phys. Rev. D **104**, 032003 (2021)

LSND: A. Aguilar et al arXiv:0104049



A. A. Aguilar-Arevalo et al arXiv:1805.12028

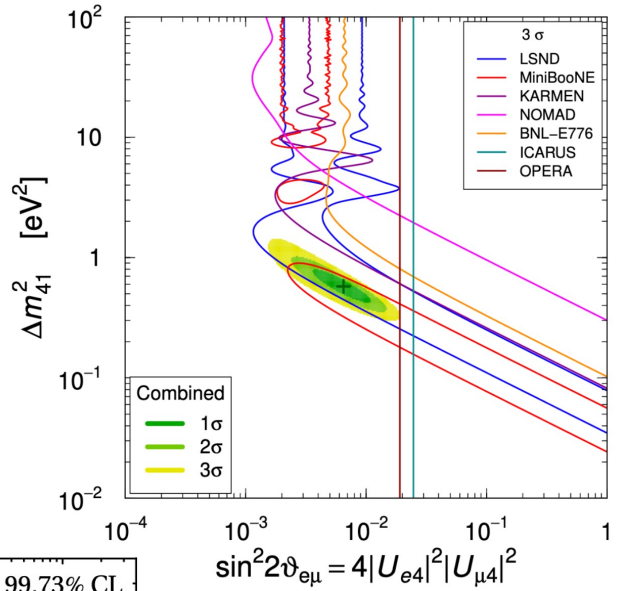


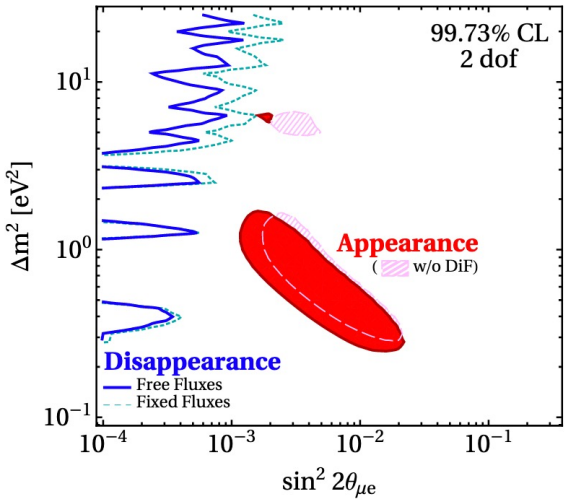


Neutrinos beyond the standard 3?

- Since you don't produce sterile neutrinos and they wouldn't interact even via the weak force in our detectors like a standard ν flavor, we can look for them indirectly via oscillation signatures (appearance, disappearance, conservation of NC interactions)
- Global program of experiments looking to confirm/reject the sterile hypothesis to the LSND and MiniBooNE results
- Other appearance-type experiments have placed limits on allowed sterile oscillation parameters & strong tension w/ ν_μ disappearance
- Sterile neutrino is one interpretation of excesses: additional beyond standard model candidates have been proposed as possible answers

C. Giunti, T. Lasserre
arXiv:1901.08330





M. Dentler et al.
arXiv:1803.10661

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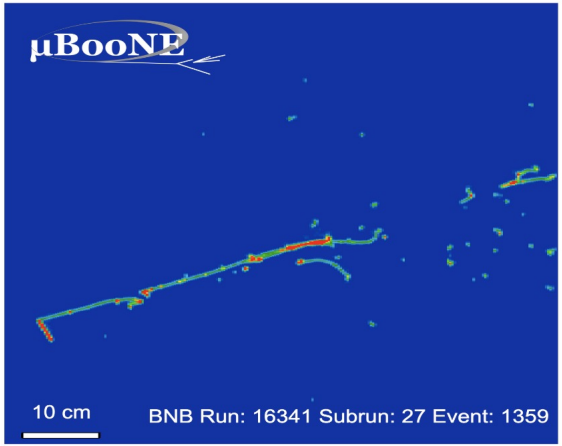
MicroBooNE's 2021 results

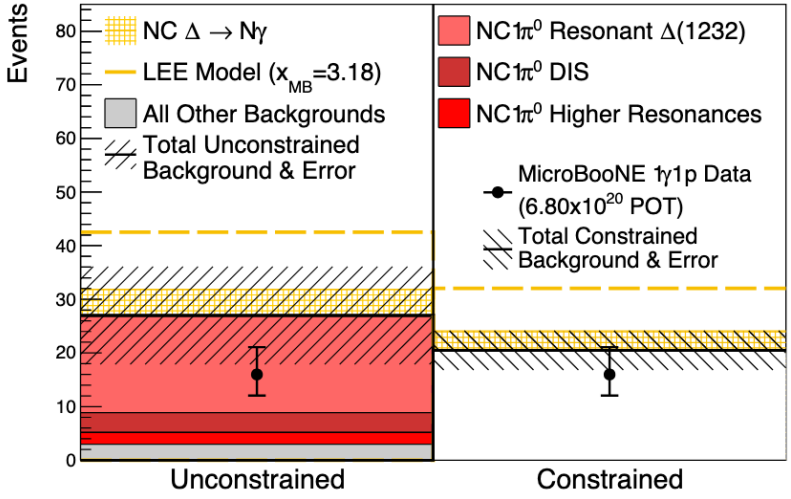
P. Abratenko et al
arXiv:2110.14065

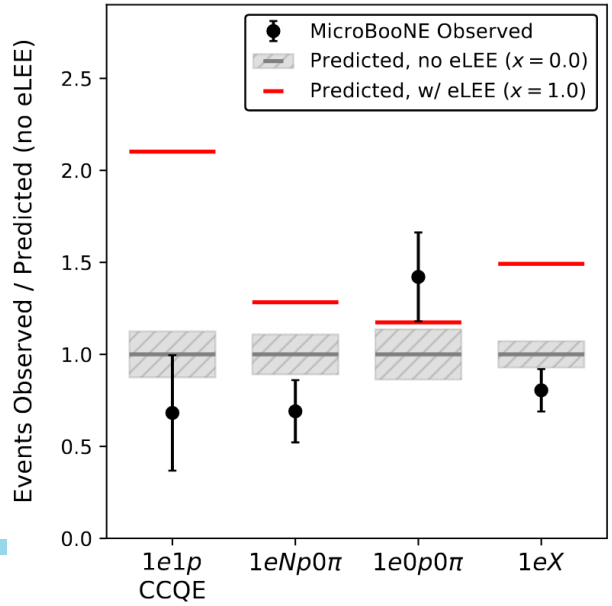
- MicroBooNE released multiple milestone LEE results in 2021, leveraging LAr TPC technology for electron and photon studies:
  - A poorly predicted single photon production (Δ decay) does not seem to make up the difference to explain LEE
  - Also didn't find signature of nu-based electron excess to explain LEE in few topologies via independent methods



(a) $1eNp0\pi$ candidate event

P. Abratenko et al - arXiv:2110.00409





P. Abratenko et al
arXiv:2110.14054

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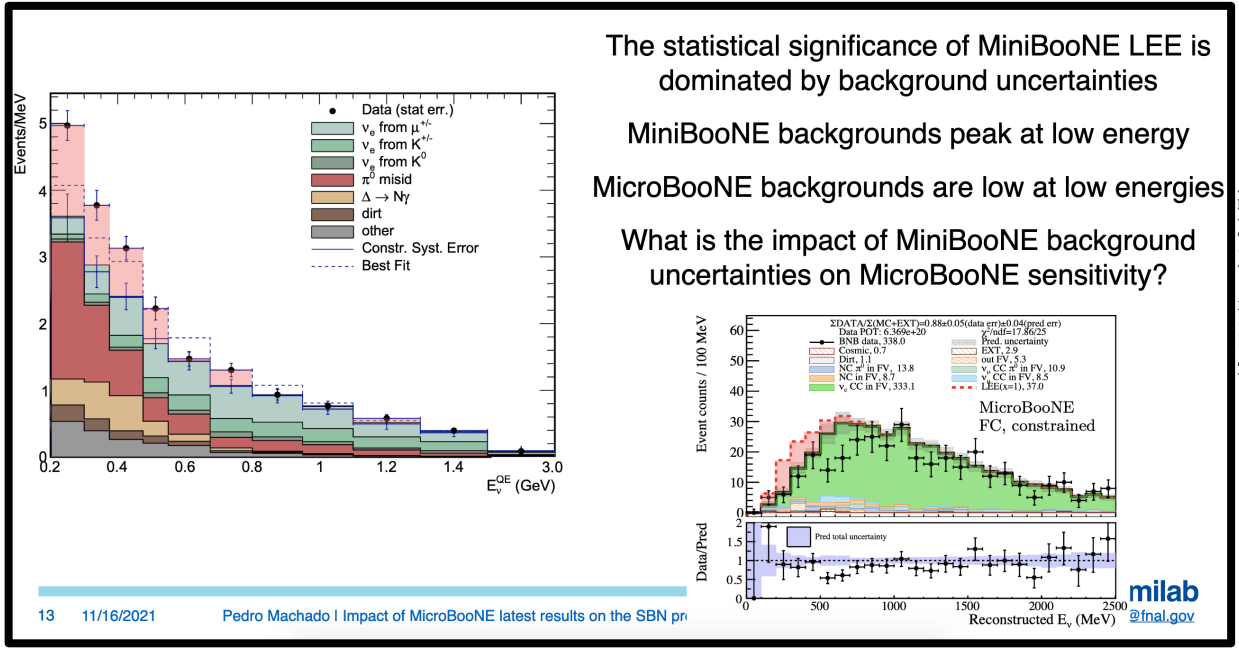
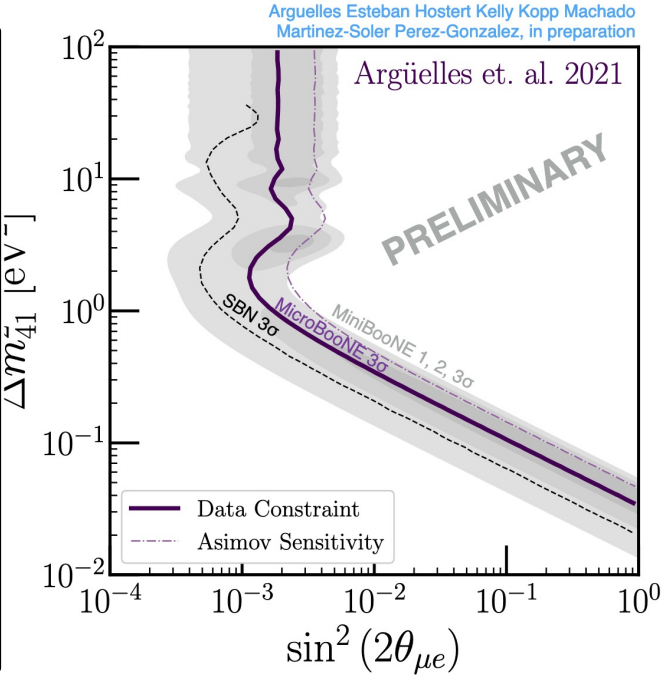
Something beyond the standard?

- Important to keep in mind that this doesn't rule out any oscillation to steriles consistent with LSND+MiniBooNE style anomaly – can provide info on specific model/parameters
- Additionally, LArTPCs can search for other BSM physics that could cause an excess of electron final states in MiniBooNE





Taken from slides by P. Machado

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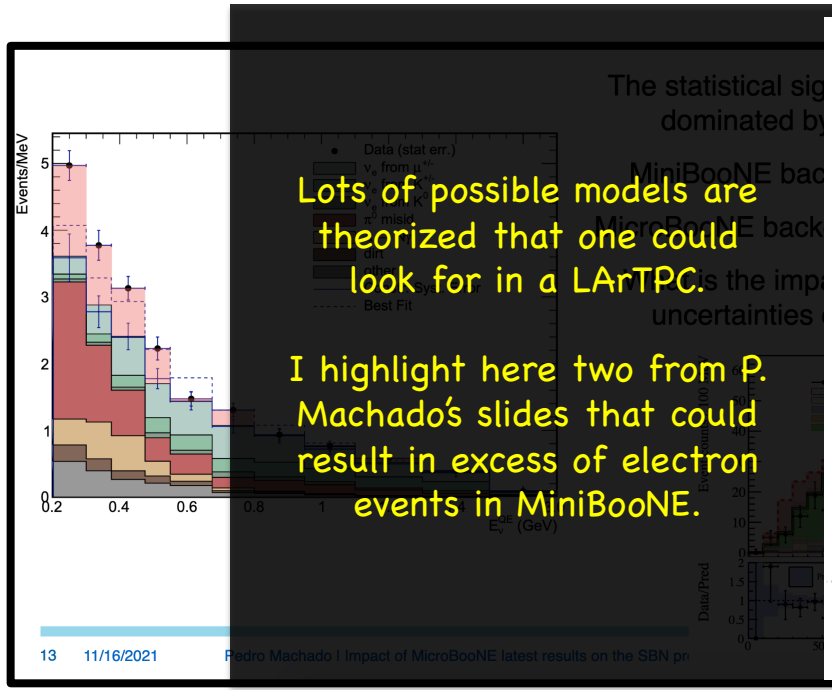
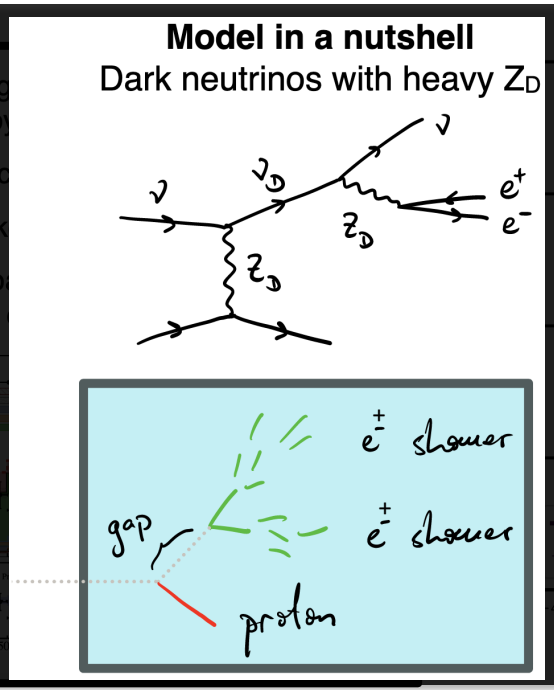
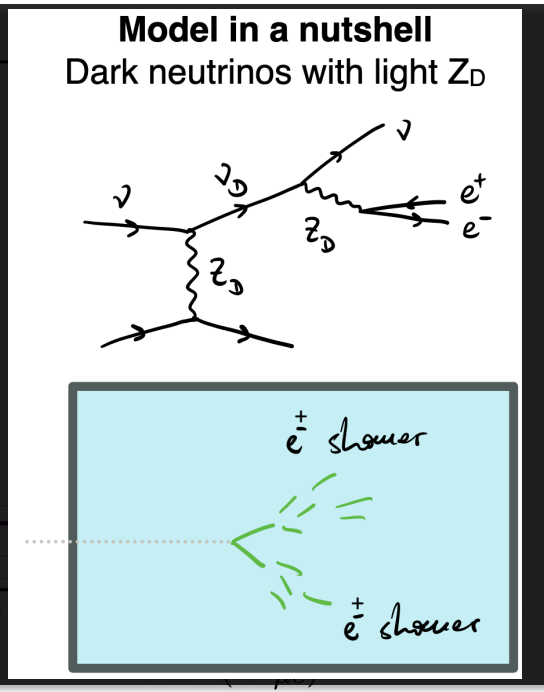


Lots of possible models are theorized that one could look for in a LArTPC.

I highlight here two from P. Machado's slides that could result in excess of electron events in MiniBooNE.

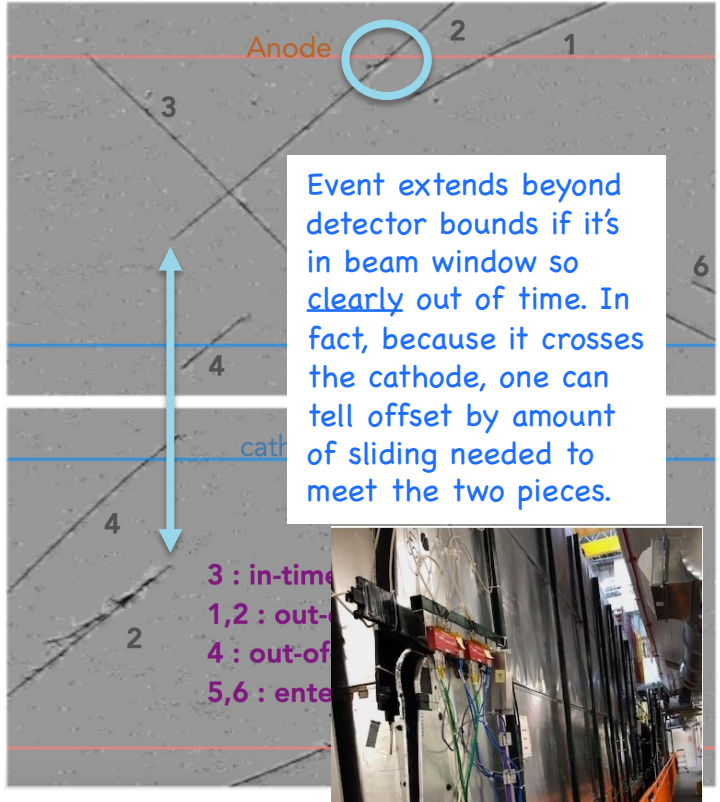


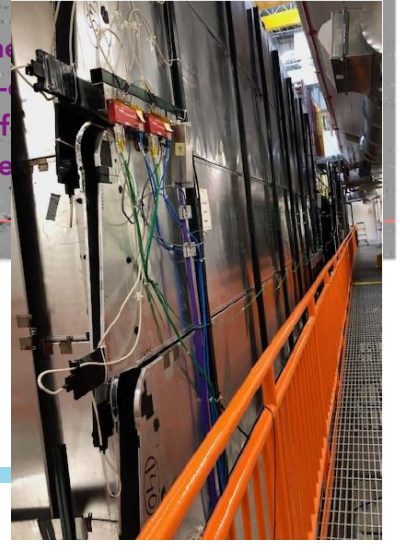


Taken from slides by P. Machado

ICARUS at FNAL

- Because surface-located & big, significant cosmic bkg (~3 cosmic triggered events per 1 from ν in LAr in BNB (1-2 per ν in NuMI))
- Multi-pronged mitigation strategy:
  - Overburden to be placed above detector
  - Some cosmic activity is “clear” (e.g. too far outside expected detector bounds to be from beam time)
  - Matching of charge from TPC with light in the PMTs can help determine if depositions in-time w/ beam
  - In addition to TPC/PMT systems, cosmic ray tagger (CRT) is installed to help identify cosmic tracks entering detector, especially helpful in-time activity
    - Possibility of CRT-PMT match to distinguish entering/exiting tracks under study



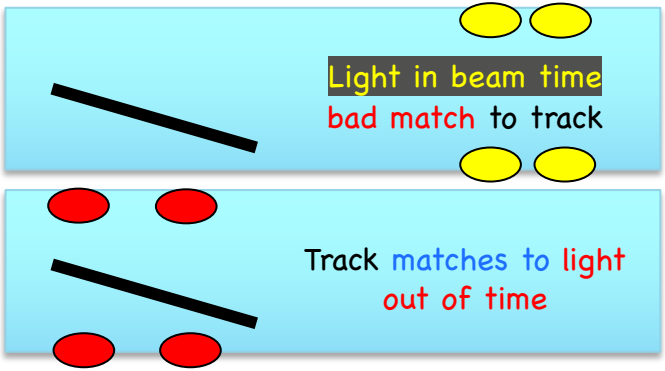


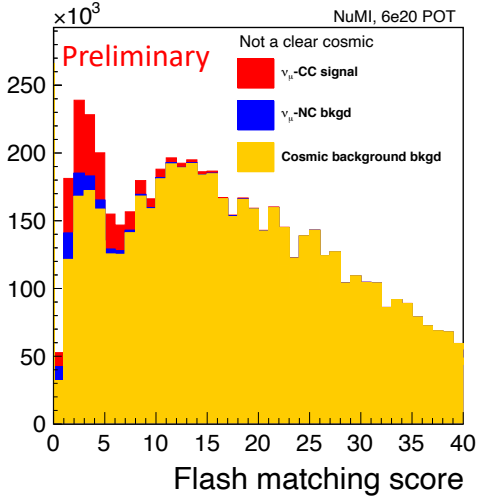
ICARUS Side CRT

Flash Matching to reject out-of-time cosmics

- A way of understanding if the TPC signal is out of time is comparing it to the light signals.
- Light from PMTs give approximate location of event. Can compare how well the info gathered from the PMT matches to the apparent info from the TPC.
- If interaction is out of time, it will look shifted in the TPC with respect to where it really was in detector.
- Flash match score characterizes how well PMT & TPC info match – low score means good match between the TPC and PMT info
  - Version on right developed by SBND collaborators! – multiple detectors working together to do best physics possible.

If light and TPC are far apart or match but out of beam time, can reject! E.g.:





Score is 1 part of flash match: time (i.e. did interaction occur during beam) also matters.

For cosmics actually in time with beam, CRT is very useful.

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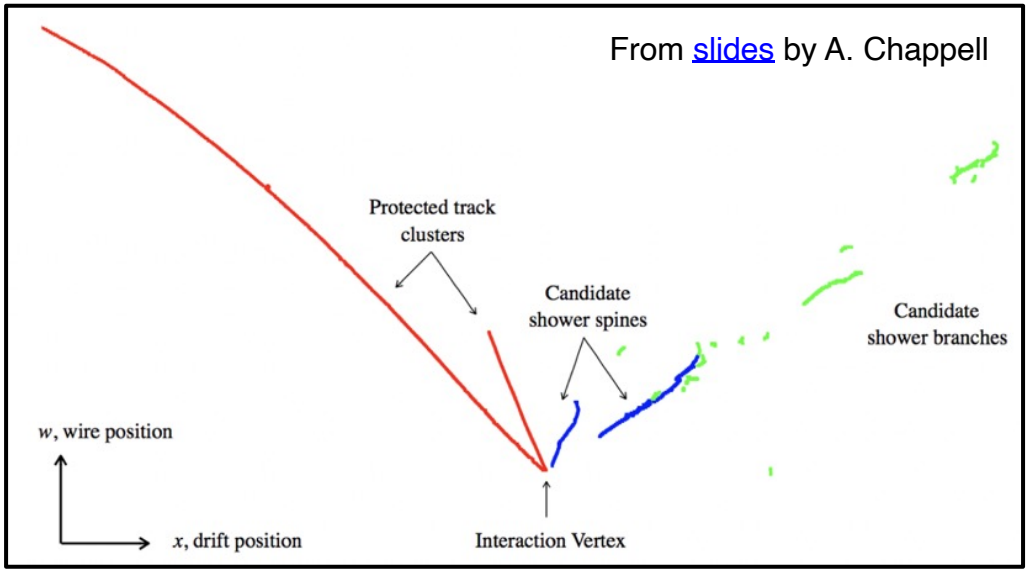
ICARUS TPC Reconstruction

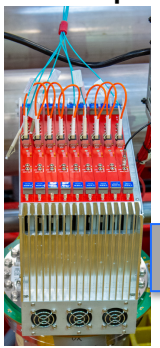
- Default reconstruction uses Pandora (see https://github.com/PandoraPFA) – pattern recognition software suite with well-established LArSoft interface (for more info)
  - Clusters the objects together into reconstructed particles in 3D by joining together info from the planes
  - Reconstructs vertex (common point where particles originate, signifying where nu interacted)
  - Forms reconstructed particle hierarchy (parent/child particles)
  - Classifies particles as track-like (e.g. μ, p, $\pi^{\pm}$, $K^{\pm}$) or shower-like (e.g. electromagnetic: e, photon)

- Because Pandora is series of algs, one can alter/extend them, change which are used and/or add and remove.



ICARUS TPC Reconstruction

- TPC signal reconstruction takes place in several steps, starting from low level signal processing to high level particle-level tracking, calorimetry, identification, …



Raw data in

Analysis

TPC Reco

Decoding
Unpack data and turn it into raw form to be used in later steps

Deconvolution
Remove effects of field and electronics response

ROI Finder
Find the interesting regions in deconvolved signals to look for hits

Hit Finder
Fit Gaussian hits from the deconvolved ROIs

Filter Hits
Keep hits consistent across planes with 3d points (SpacePoints)

Pandora
Cluster, Slice, Pattern Recognition

Tracks
Track-like particle fit, calorimetry, particle ID

Showers
Shower-like particle fit (dE/dx, conversion gap, energy, etc.)

Downstream Reco

Machine Learning
Downstream reco using ML techniques

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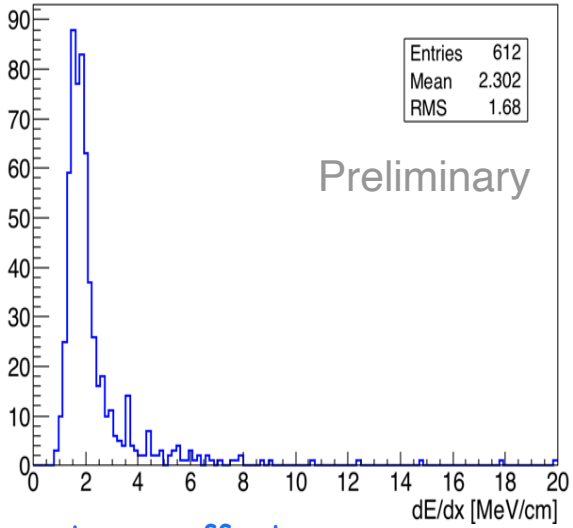
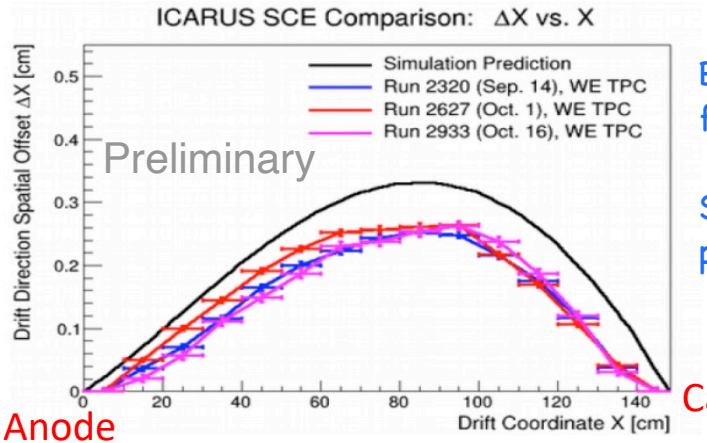
- Calibration campaign with early data to understand detector effects, calorimetry, etc.

From the BNB scan event shown in slides – shows idea behind dE/dx calibration using muon tracks.



~few mm



Anode

Cathode

Early measurement of space charge effect from tracks extending from anode to cathode

Studying these fine details and effects are powerful tools to calibrate detector.

Also drift velocity, calorimetry measurements (i.e. e/ADC), look at recombination, etc.

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