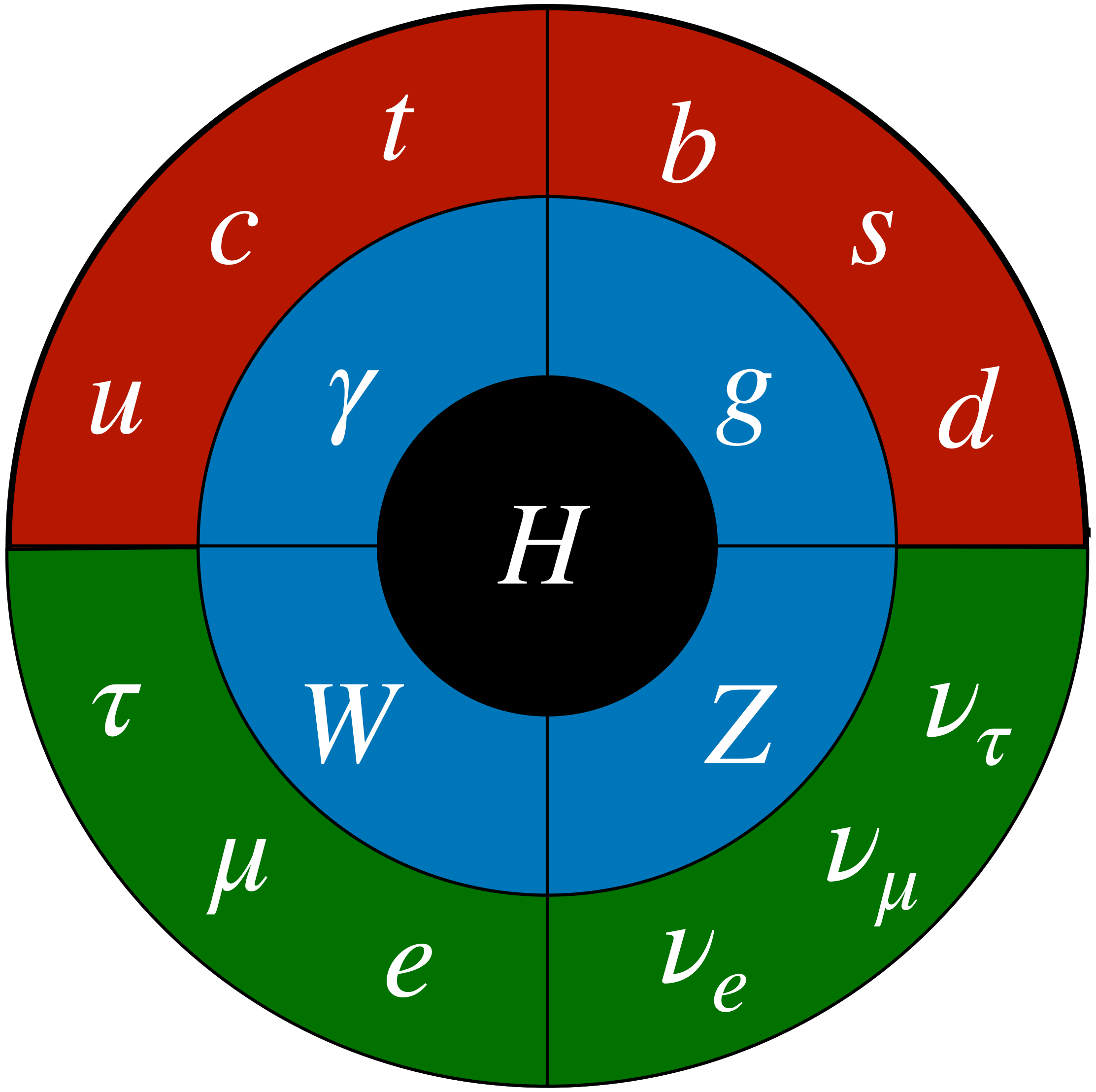
Current Status and Prospects of the ICARUS Experiment

Jacob Zettlemoyer, Fermilab, for the ICARUS Collaboration

56th Fermilab Users Meeting

June 30, 2023

Is the Standard Model Complete?

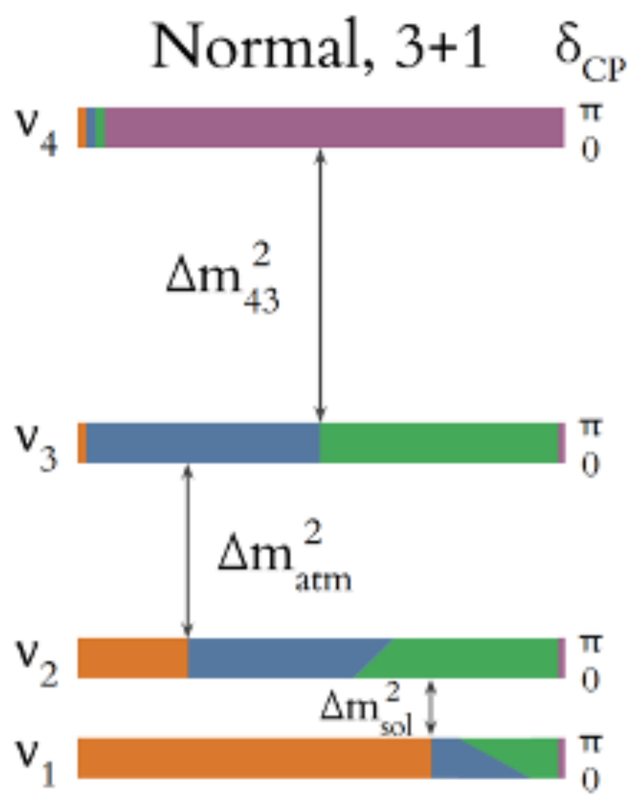


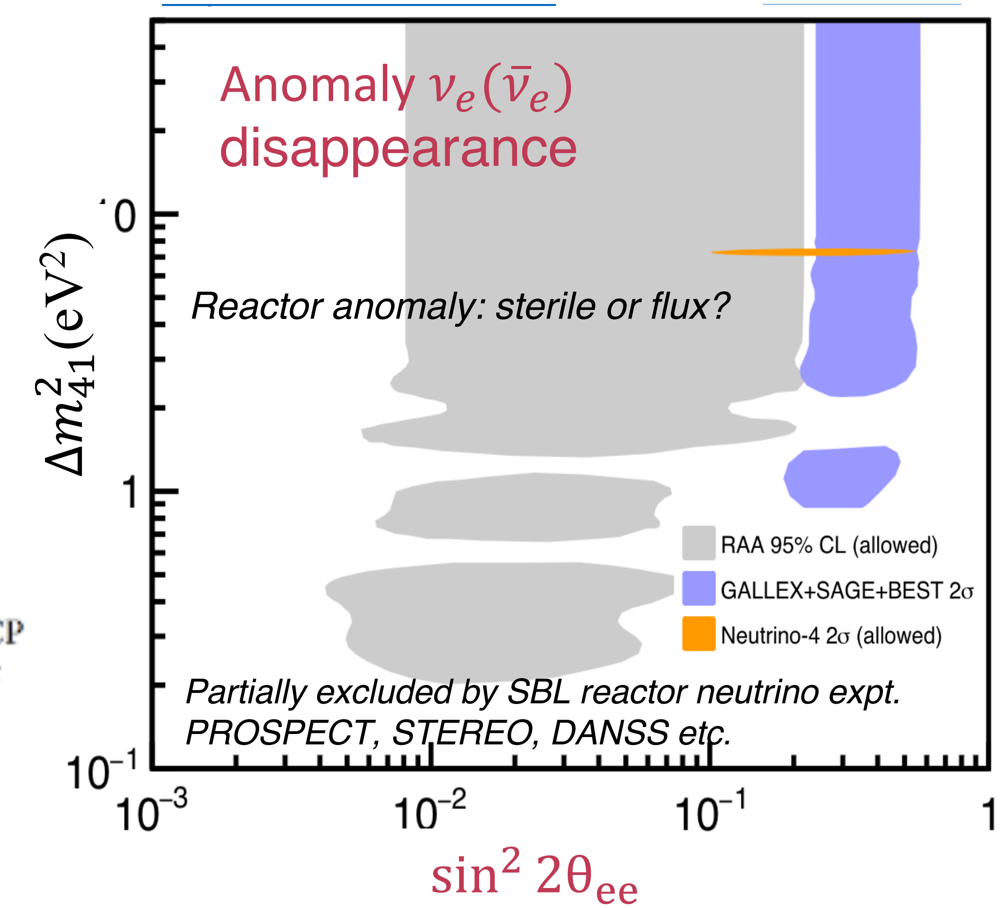
No! We have evidence that it is incomplete!

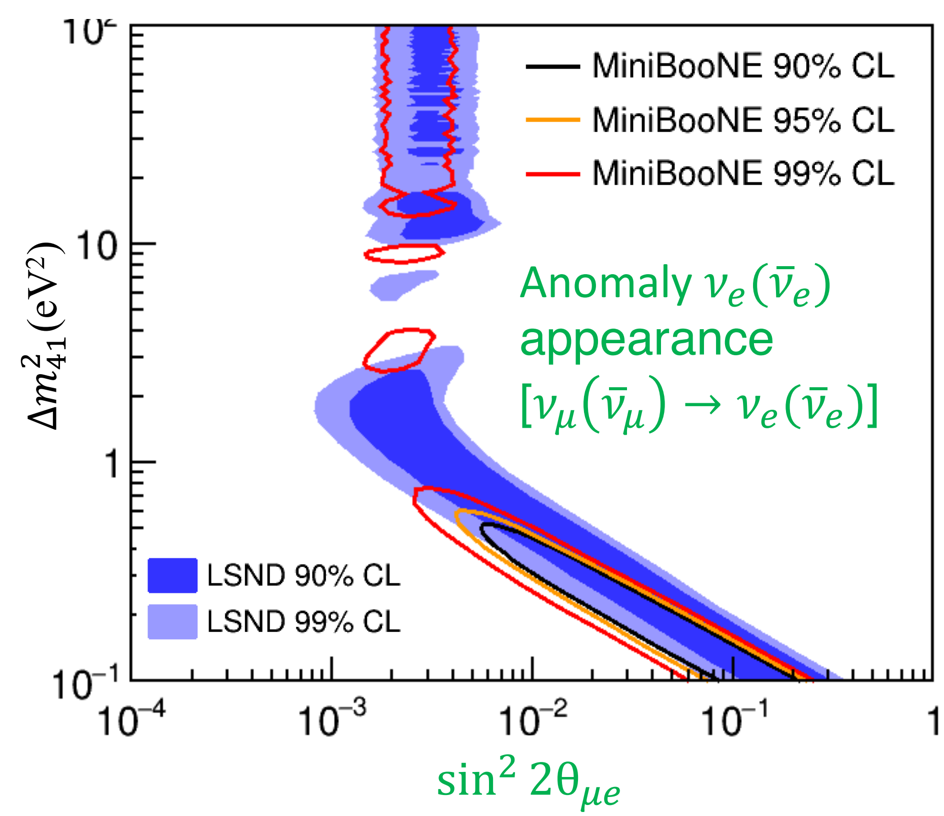
Neutrino oscillations are one prominent example of BSM physics!

Neutrino Anomalies - Additional neutrino states?

- Majority of experimental results consistent with 3-flavor neutrino oscillation paradigm
- Anomalies in short-baseline neutrino experiments
  - The "reactor anomaly" in the ν_e disappearance channel
  - LSND and MiniBooNE in the ν_e appearance channels
- One hypothesis is an eV-scale "sterile neutrino"



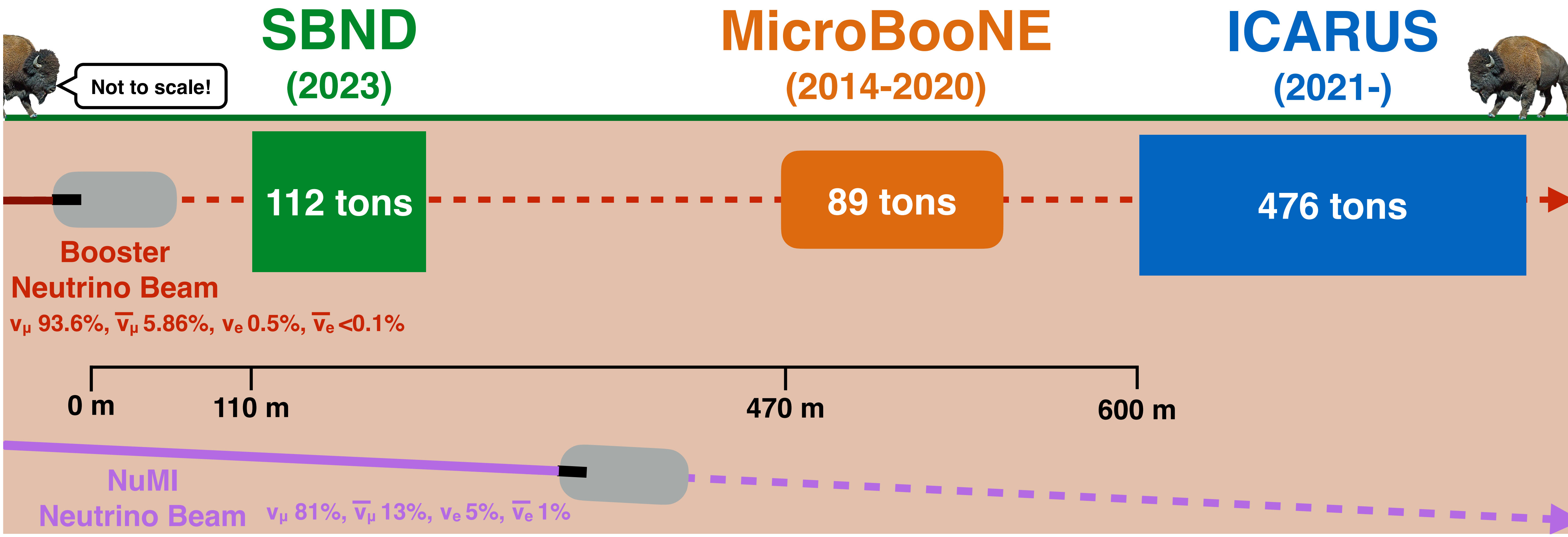




Phys. Rev. D 103, 052002
Phys.Rev. D 64, 112007

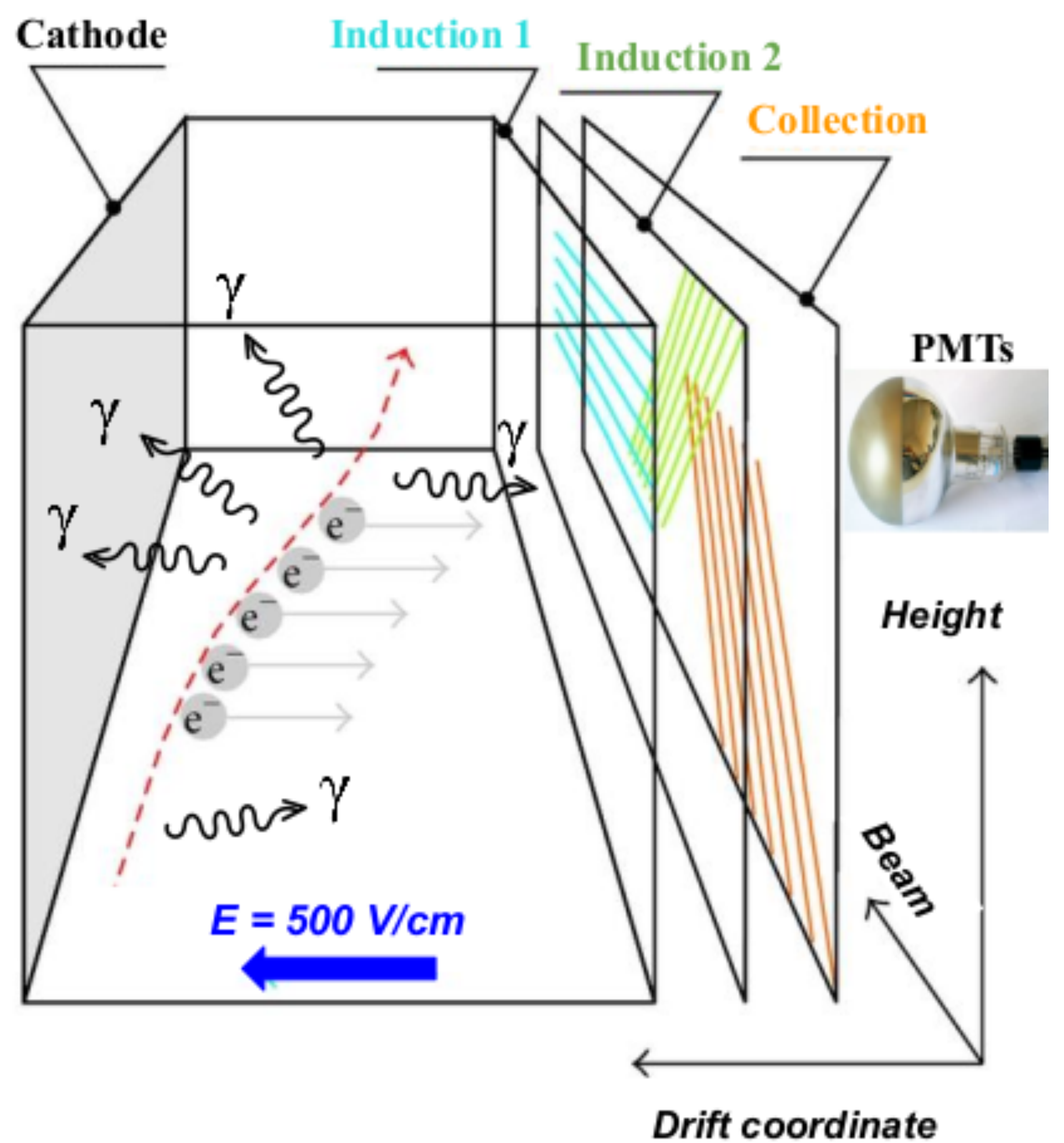
The Fermilab Short Baseline Neutrino (SBN) Program

- Program based at Fermilab designed to definitively probe the sterile neutrino hypothesis of the MiniBooNE anomaly
- The detectors all use the common liquid argon TPC (LArTPC) technology as well as the Booster Neutrino Beam (BNB) as a common beamline
- Ability to also measure neutrino-argon interaction cross sections and also Beyond the Standard Model (BSM) signatures
  - ICARUS is also exposed to the Neutrinos from Main Injector (NuMI) beam at 6 degrees off axis!



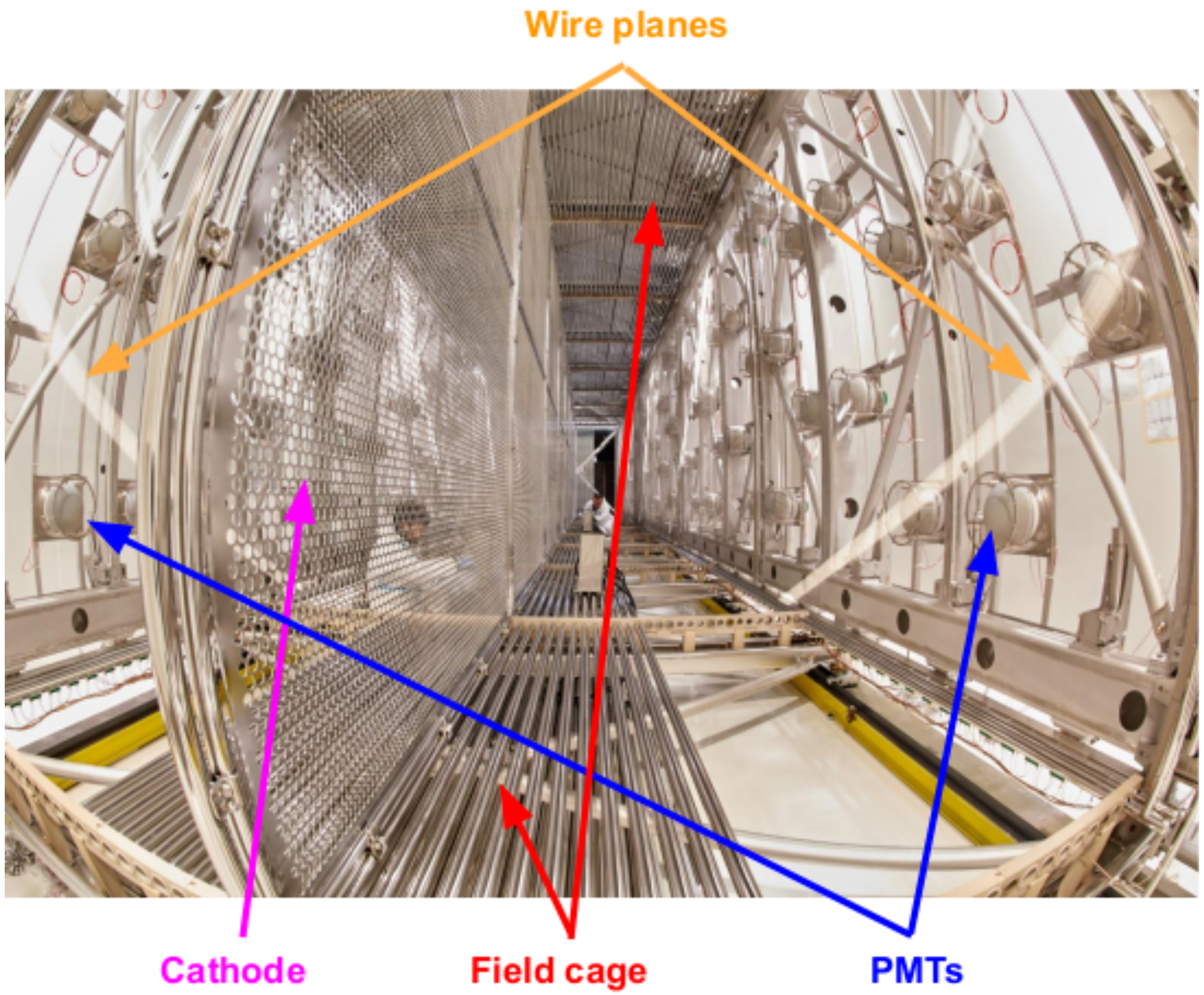
Liquid Argon TPCs as a Medium for Discovery

- Particles traveling through the argon medium ionize the argon nuclei
- Electrons drift to wire planes with presence of electric field in the detector
- LArTPCs are capable calorimeters and also 3D-tracking capable detectors for particle ID at the same time
  - Scintillation light collected by photomultiplier tubes for precise event timing and event calorimetry!



The ICARUS Detector

- LArTPC detector with 760 tons total mass and 476 tons active mass
- Two identical cryostats each divided into 2 TPCs with a central cathode
  - 1.5 m drift distance, 3 wire planes
  - Drift field at 500 V/cm
- Instrumented with 360 PMTs coated with the wavelength shifter TPB
- High coverage cosmic ray tagger (CRT) system to tag and remove cosmic backgrounds
  - **See A. Heggestuen's poster for more information on ICARUS cosmic rejection strategies!**

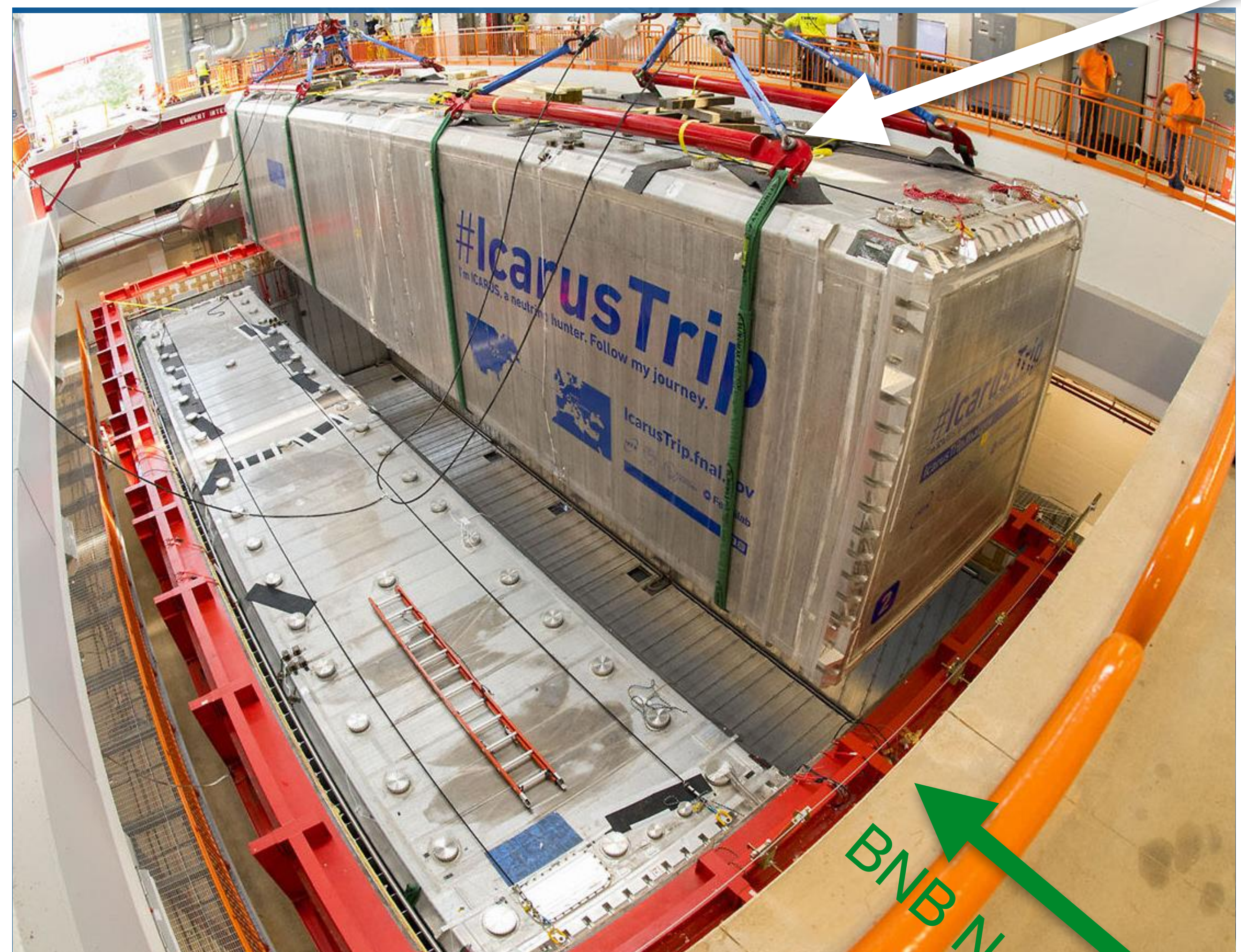


The ICARUS Detector

- Full detector operated at LNGS from 2010-2014
  - **See H. Carranza's talk from New Perspectives on inelastic DM searches using data from this period!**

- Detector upgraded at CERN and moved to Fermilab in 2018 to become the far detector for the SBN program

Neutrinos from NuMI off-axis



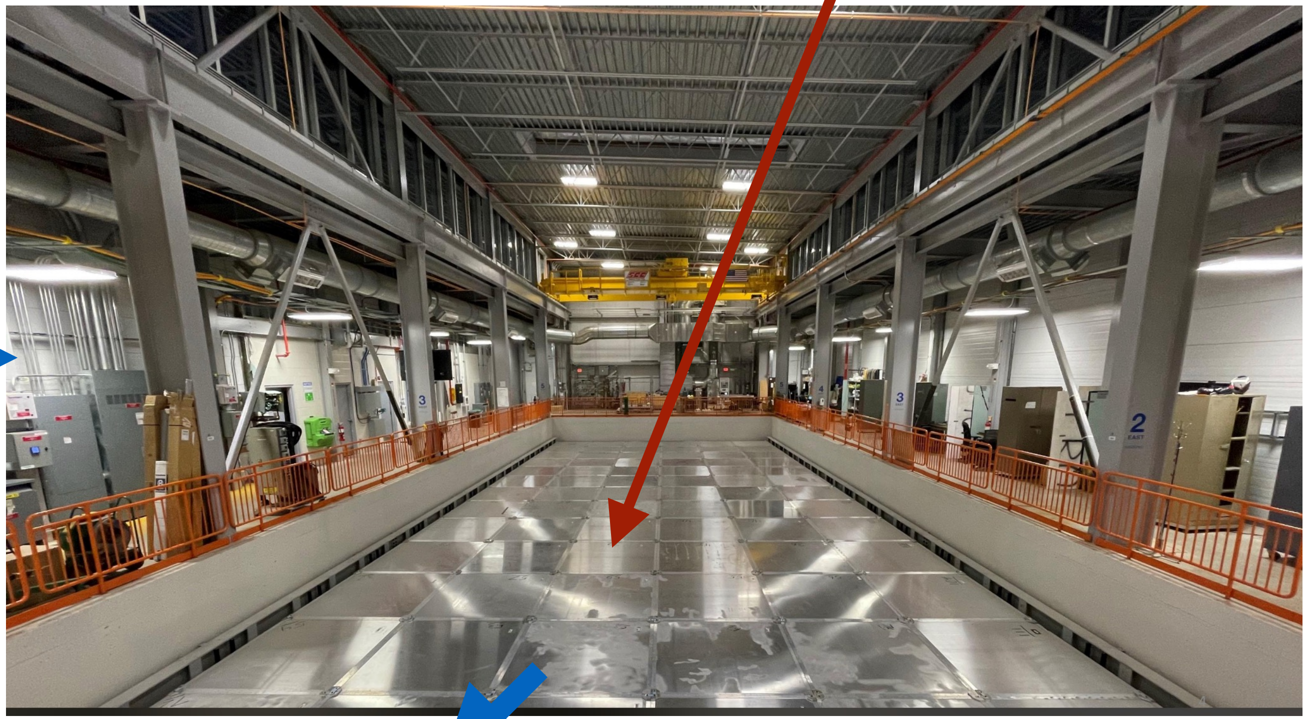
BNB Neutrino beam

ICARUS being installed at FNAL, c. 2018

ICARUS Installation and Current Status

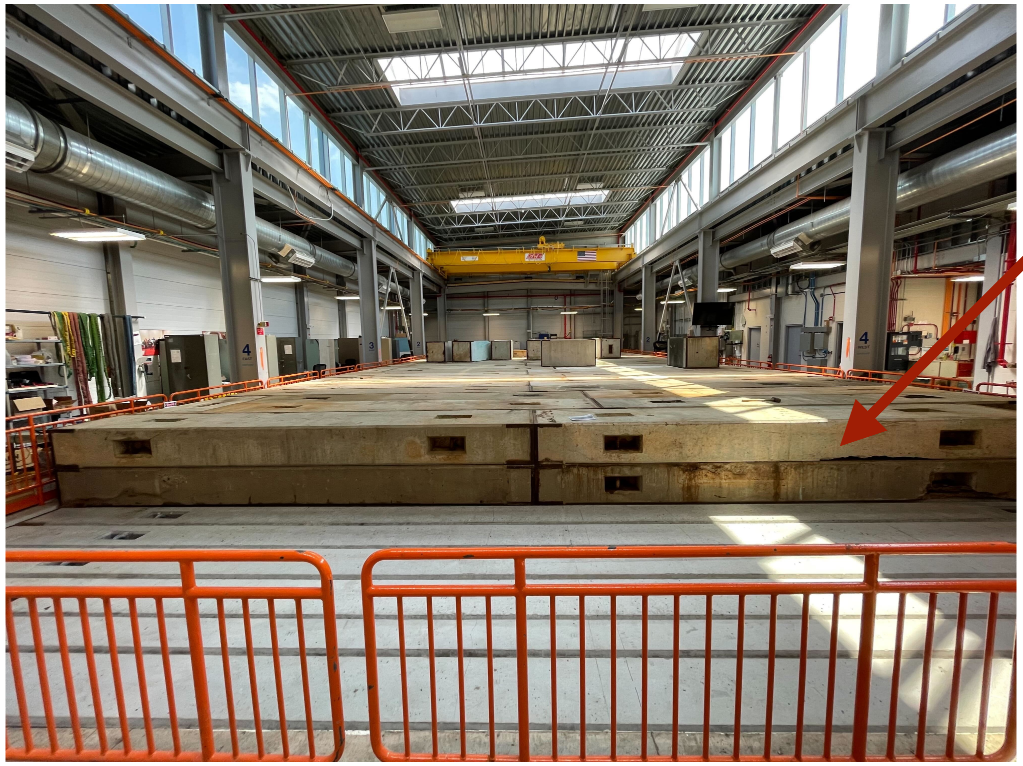
Top CRT panels

September 2020



December 2021

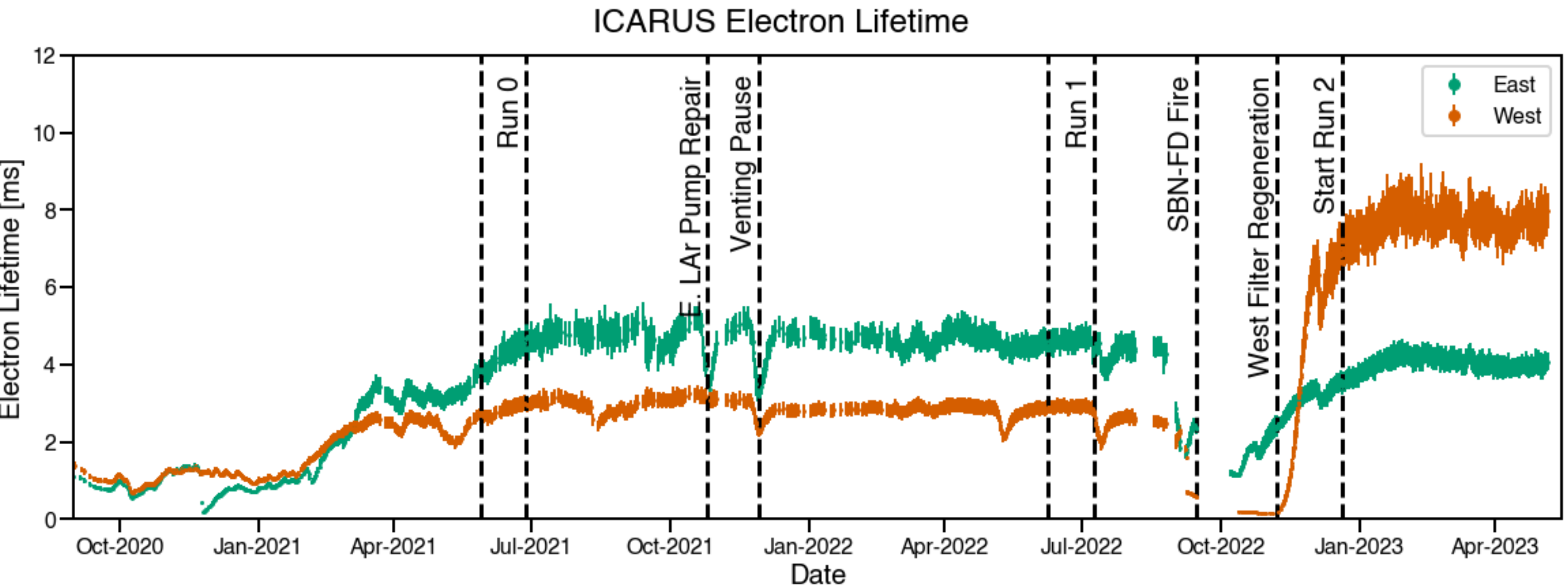
3m concrete overburden



May 2022

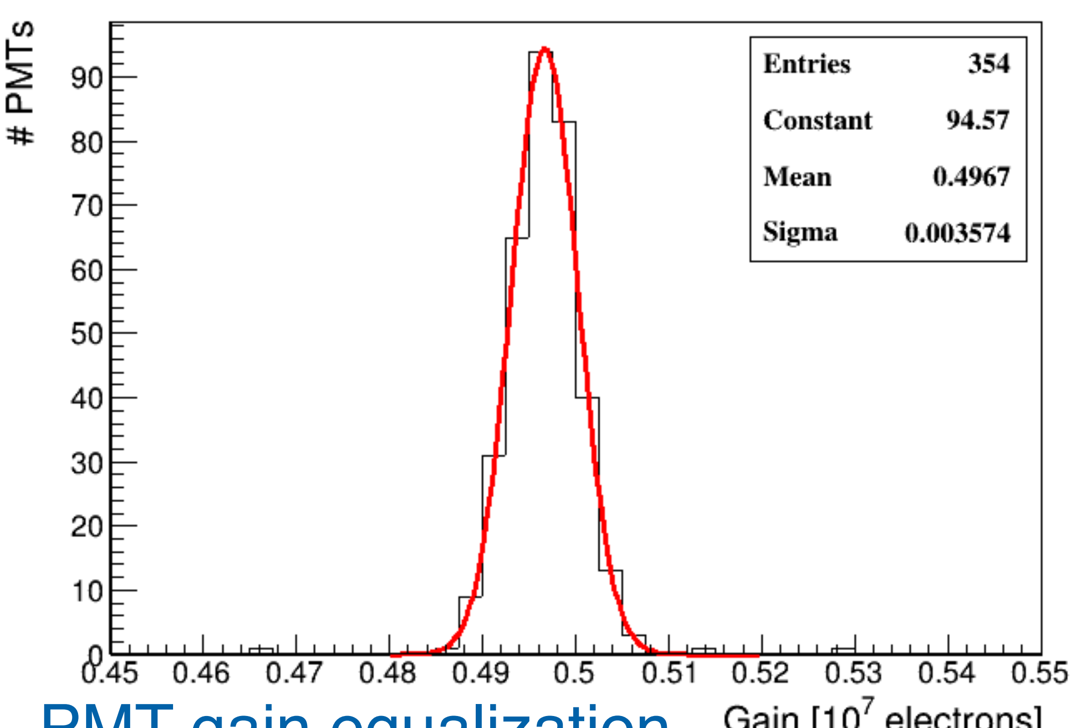
Commissioning the ICARUS Detector at Fermilab

- ICARUS filled with LAr in April 2020 and was fully operational in August 2020

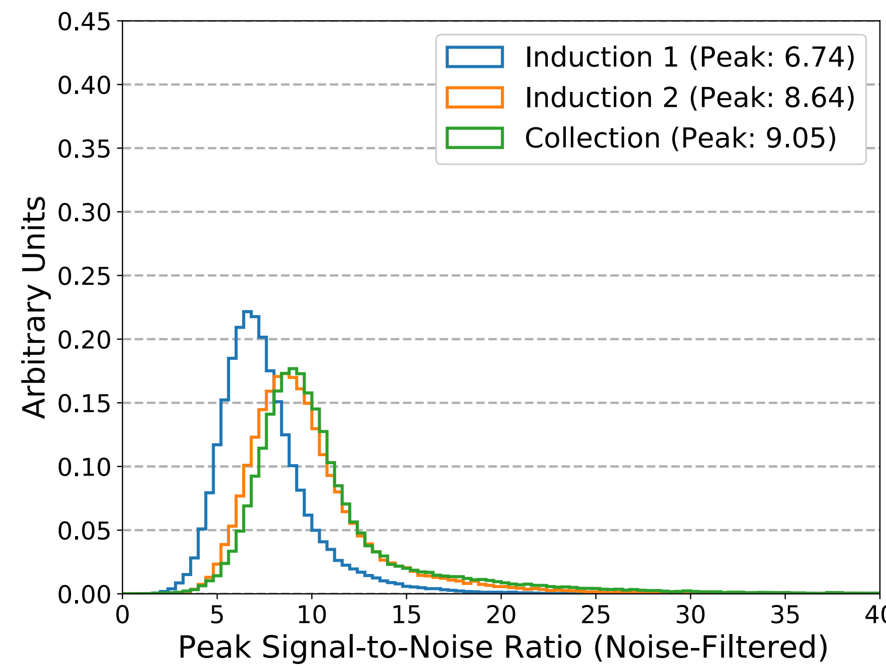


Eur. Phys. J. C 83, 467 (2023)

LAr purity over commissioning period



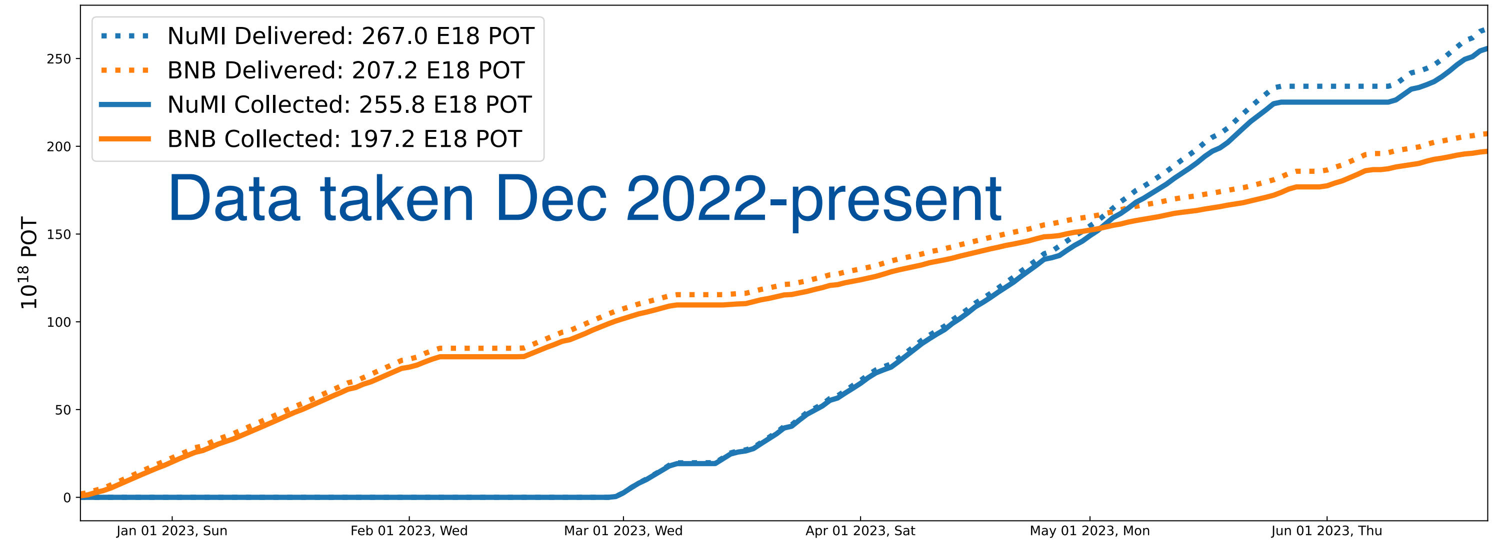
PMT gain equalization



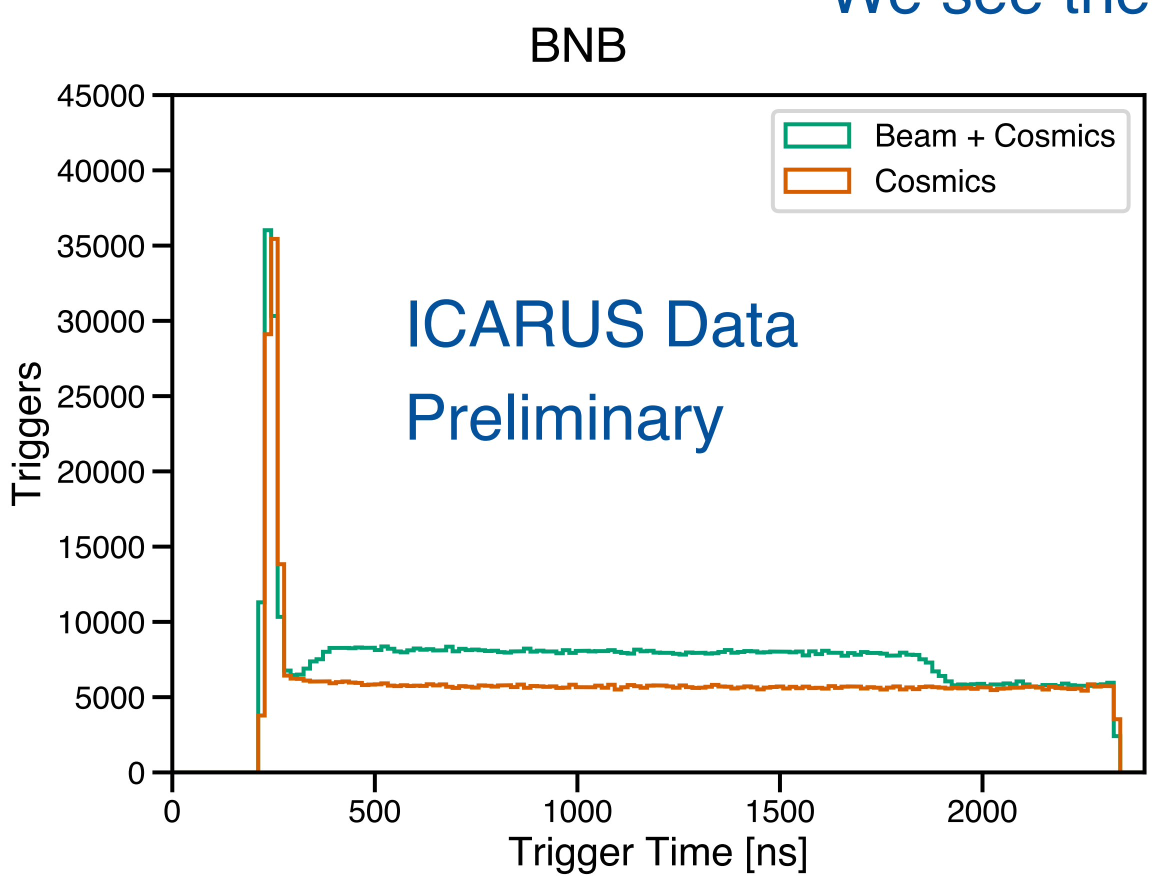
TPC noise measurements on the three wire-planes ~ 550 e-/ADC, SNR = 9

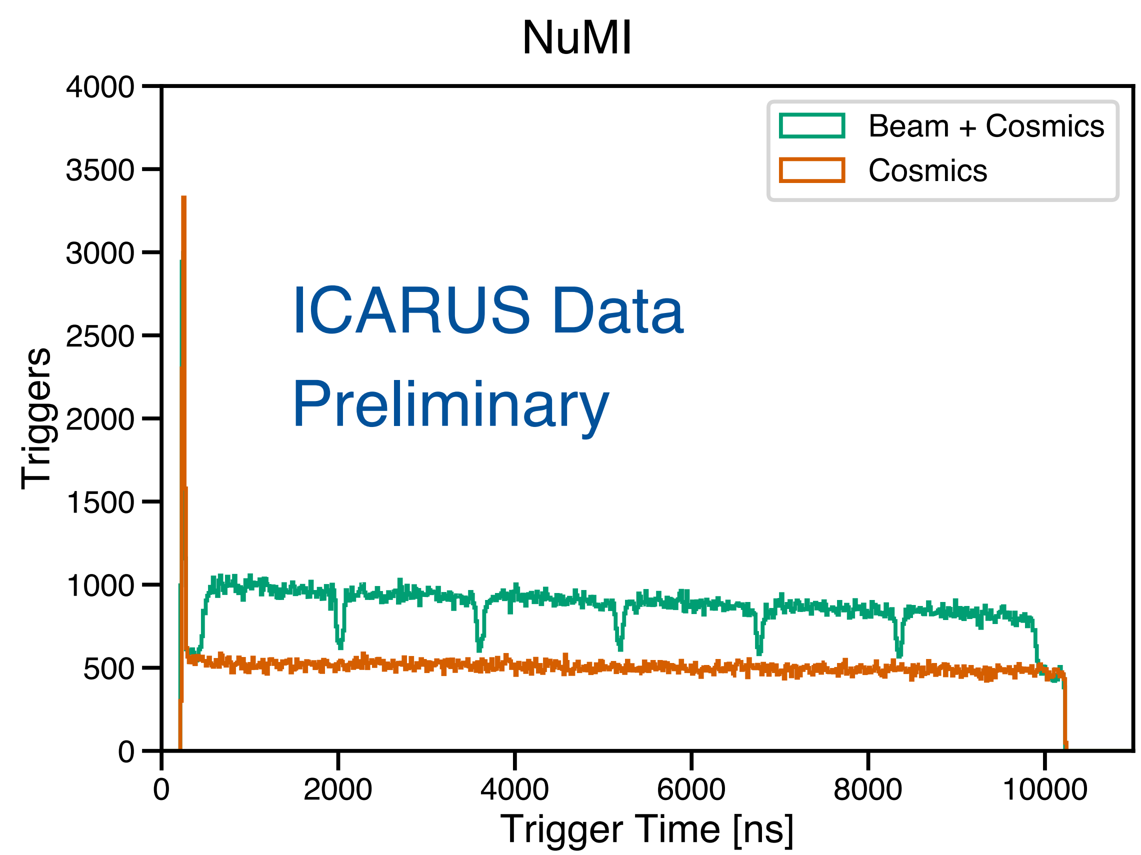
ICARUS is Taking Physics Data!

- ICARUS completed commissioning in June 2022 and is now taking data with both the BNB and NuMI neutrino beams collecting protons on target (POT) at >=95% efficiency
- We are using these data taken during this period to understand the detector performance and inform the first physics analyses from ICARUS



We see the expected beam related excess!

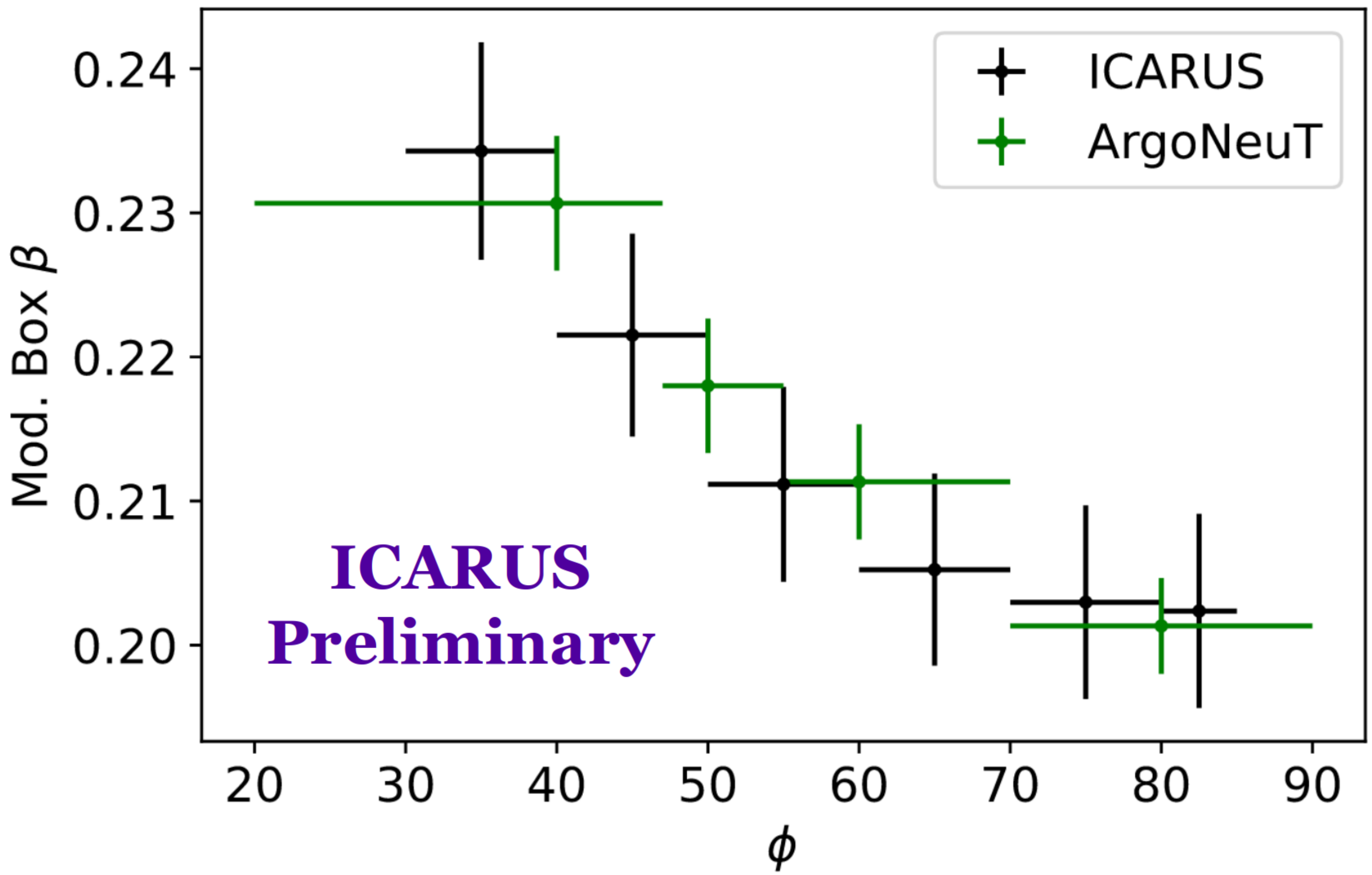




Understanding the ICARUS Detector

- ICARUS is making a number of detector physics measurements that advance the global understanding of LArTPC detectors
  - Angular dependence of the liquid argon recombination model

$$dE/dx = (exp(\beta W_{ion} \cdot (dQ/dx)) - \alpha)/\beta.$$



ArgoNeuT measurement: JINST 8 P08005 (2013)

Understanding the ICARUS Detector

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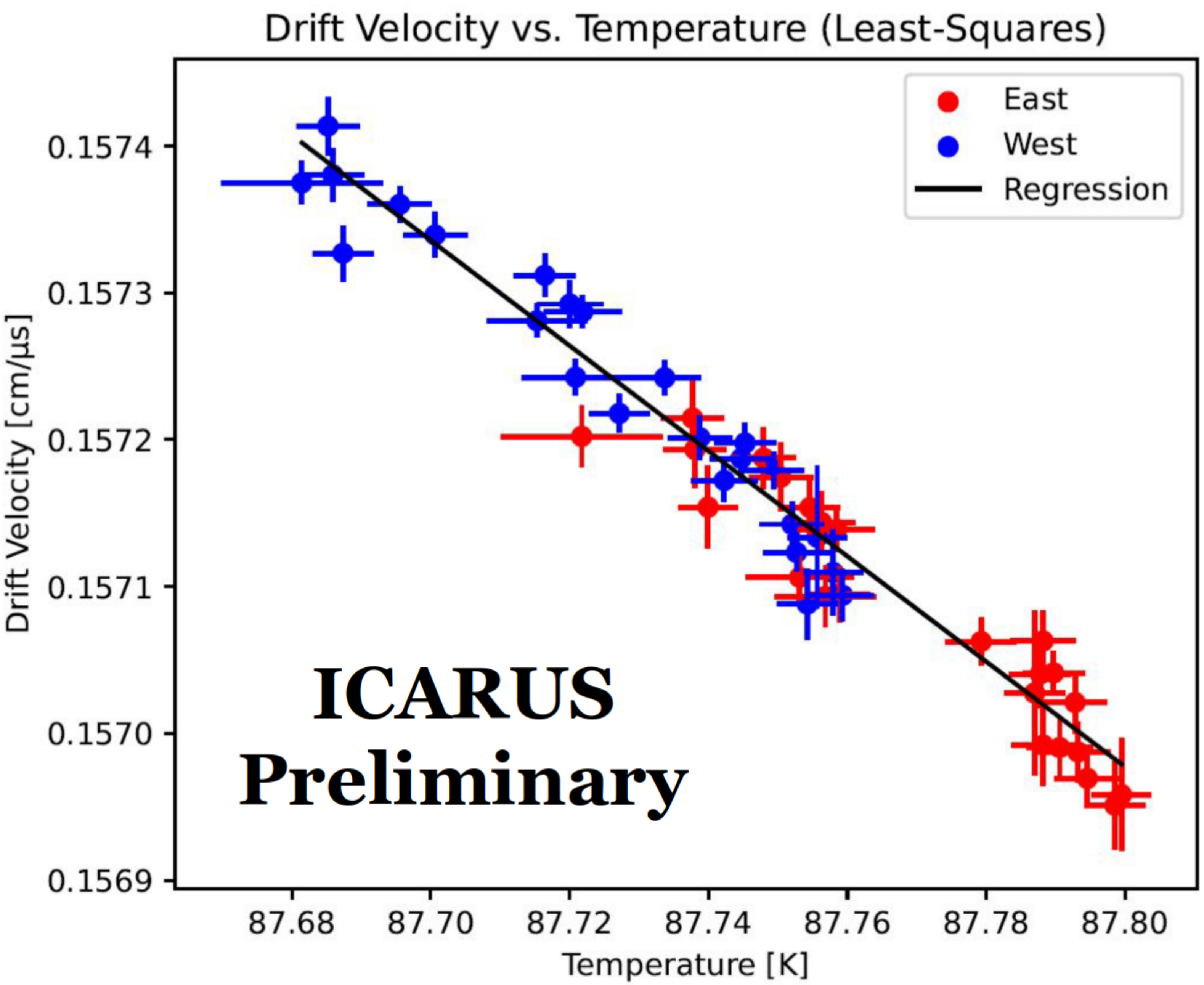
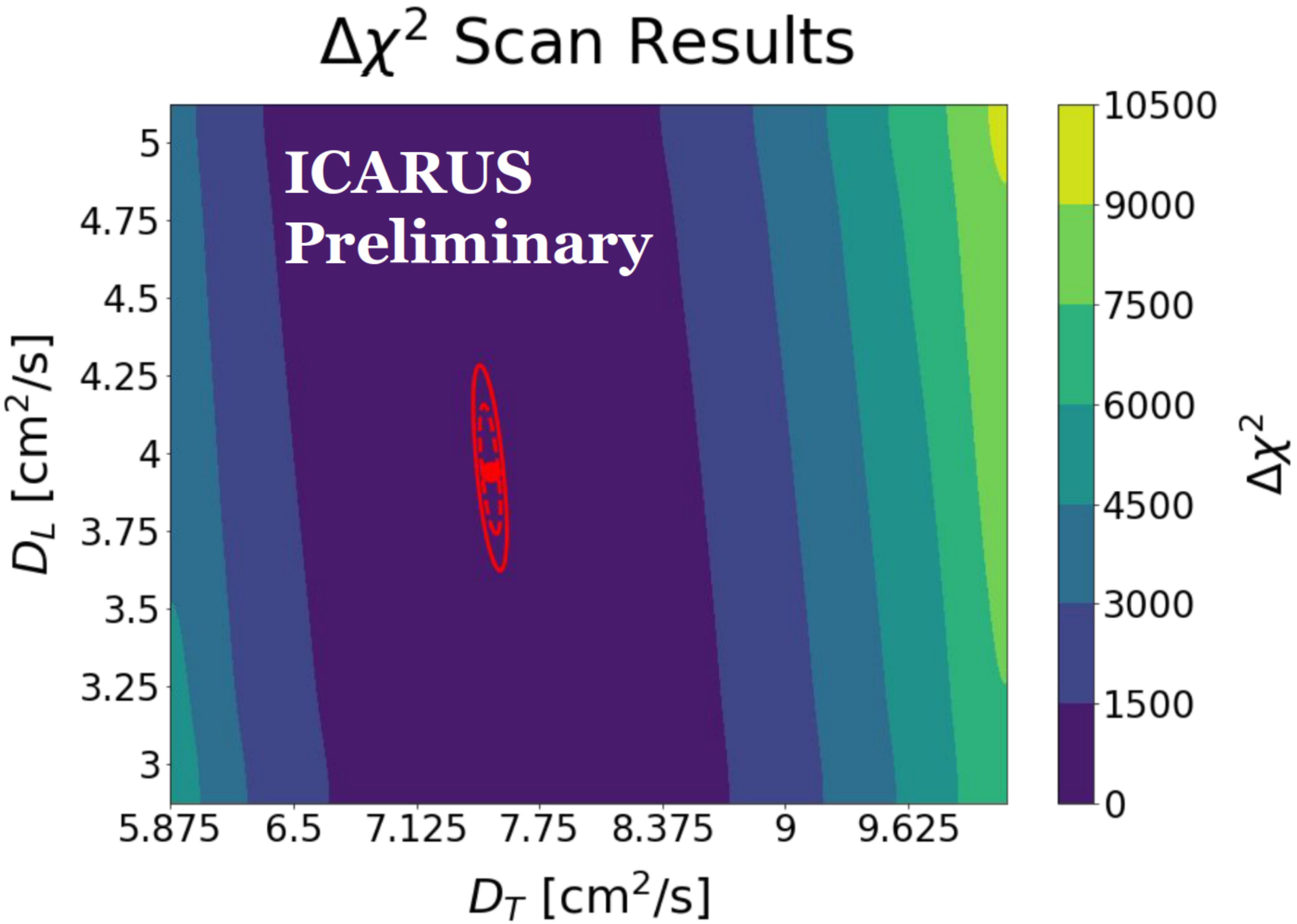
  - Liquid argon drift velocity as a function of the cryogen temperature



Understanding the ICARUS Detector

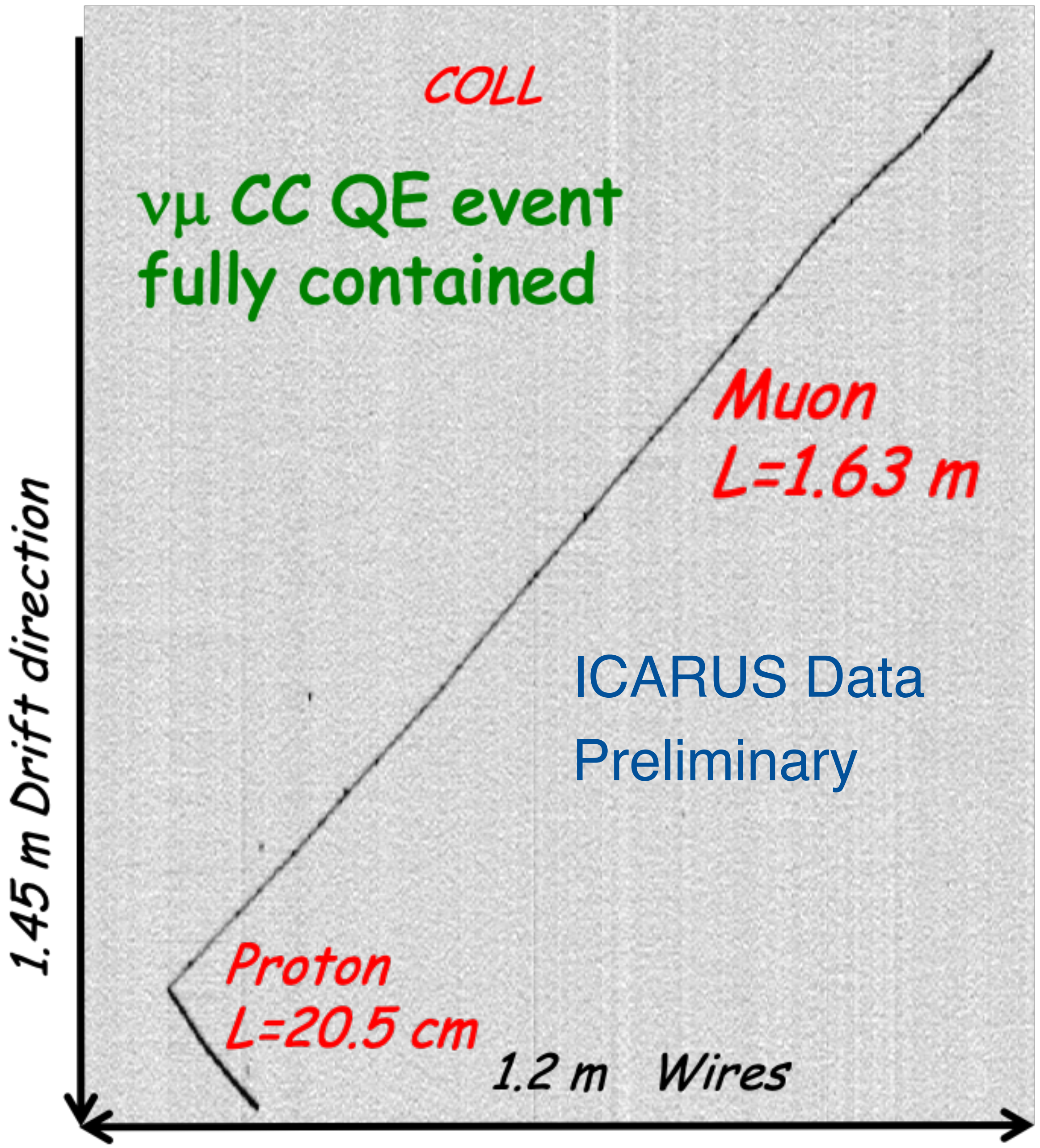
- ICARUS is making a number of detector physics measurements that advance the global understanding of LArTPC detectors
  - Liquid argon electron diffusion measurement
    - First measurement of transverse diffusion in this electric field range!

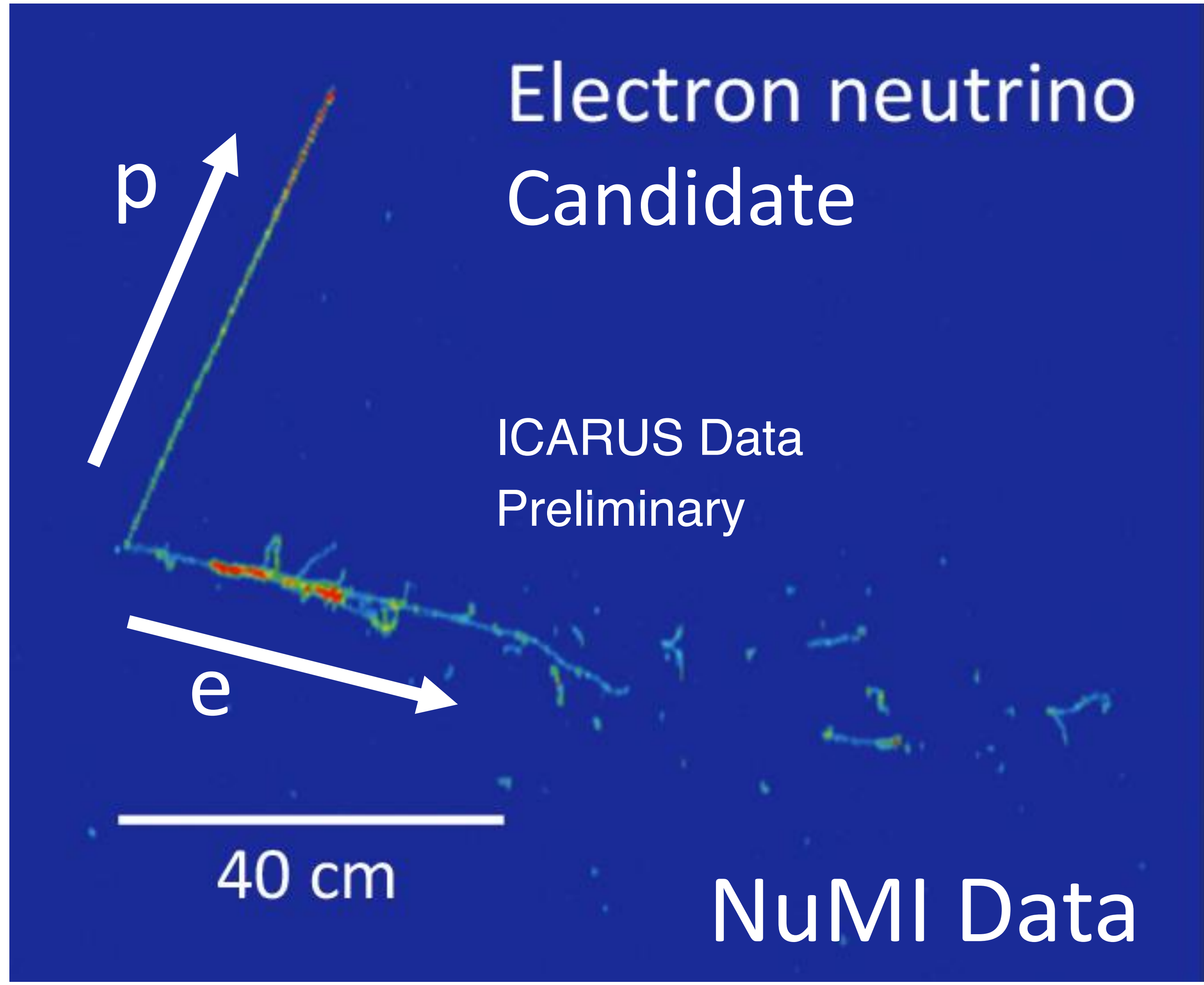


Current Physics Searches Envisioned with ICARUS

- ICARUS is currently pursuing a number of physics studies focusing on contained particle track reconstruction
  - Single-detector oscillation measurements using charged-current quasi-elastic events
    - ICARUS-only BNB ν_μ disappearance analysis sensitive to large mixing angle, large Δm^2 parameter space focusing on a 1 muon, 1 proton final state
    - NuMI ν_e disappearance is also the relevant channel for claimed sterile neutrino observation from the Neutrino-4 experiment (Phys. Rev. D 104, 032003 (2020))
  - Neutrino-Argon cross section analyses with the NuMI off axis focusing on identifying events with 1 muon and at least 1 proton
  - BSM searches initially focusing on muon final state signatures

ICARUS is Identifying Neutrino Interactions!



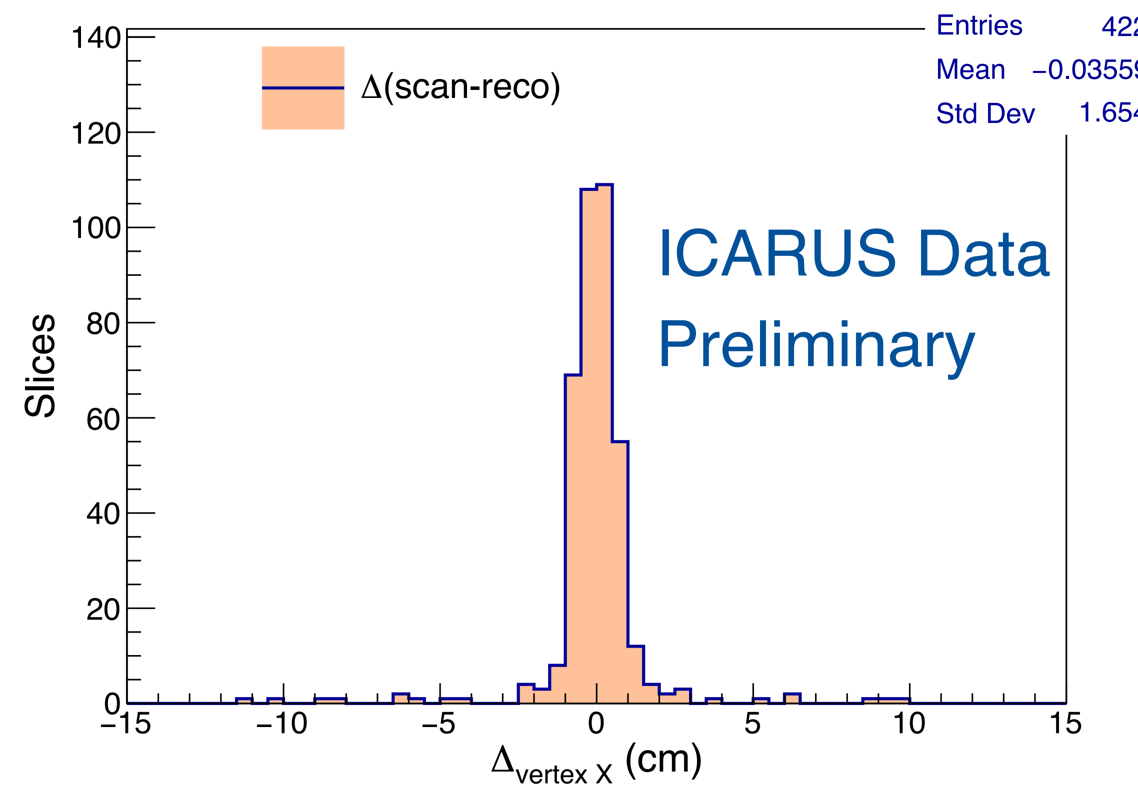


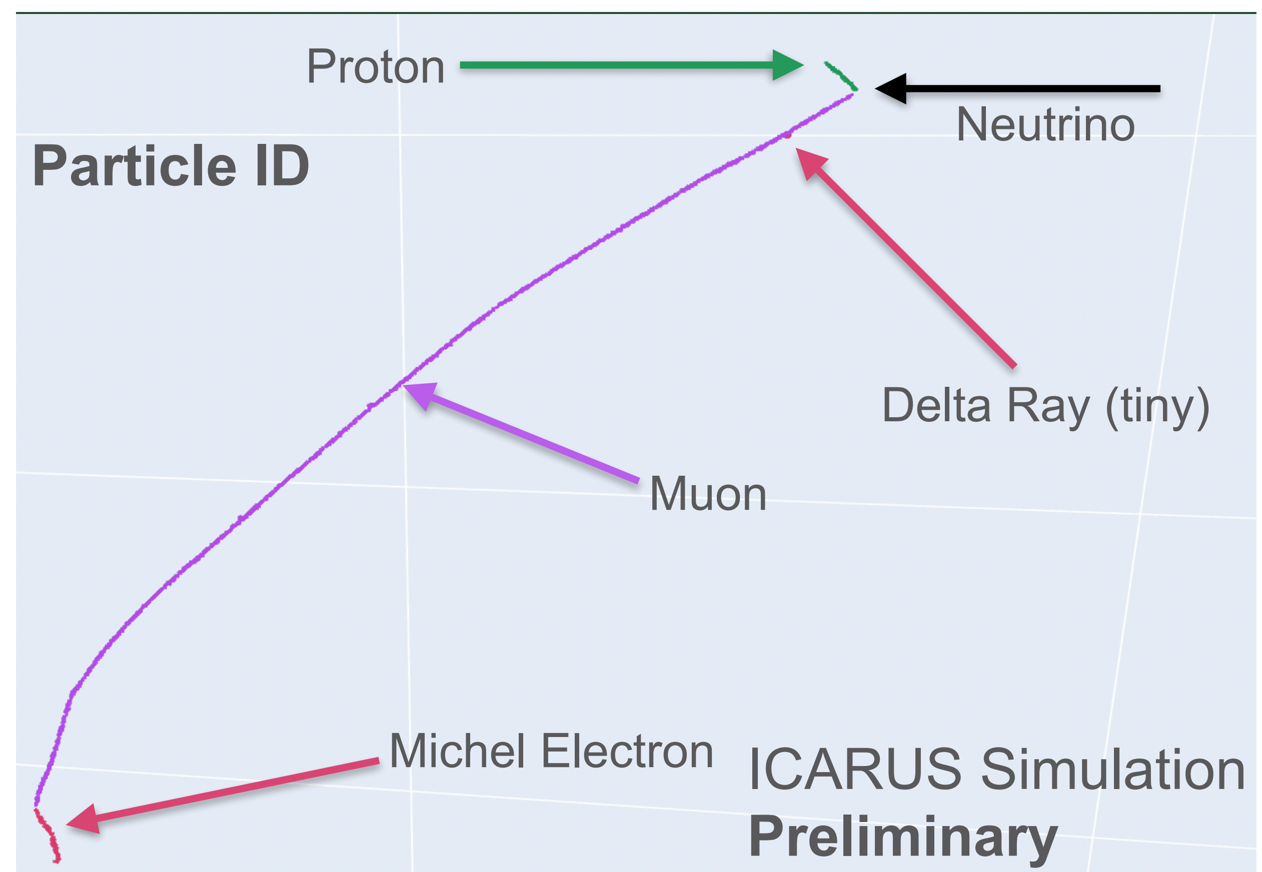
ν_μ charged current
quasi-elastic candidate

ν_e charged current
quasi-elastic candidate

ICARUS Neutrino Event Reconstruction

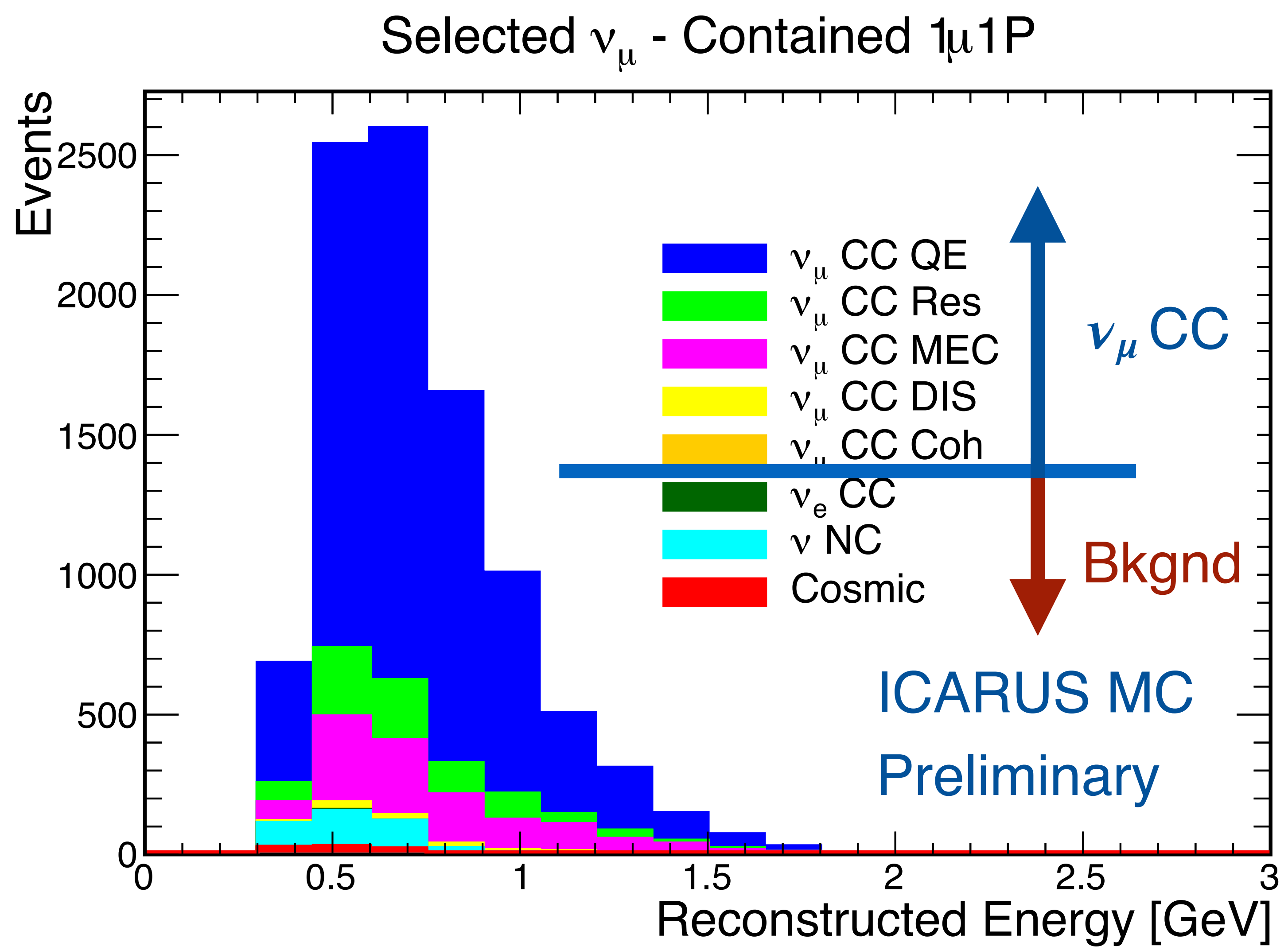
- Once neutrino candidate events are identified, need to understand the particles in the interaction and resolve the final state
- We employ parallel reconstruction pathways
  - One path is the Pandora multi-algorithm pattern recognition based reconstruction
  - An alternative path to reconstruction employing Machine Learning (ML) techniques
  - These two approaches can benefit one another as they are further developed and will allow us a powerful cross-check of our measurements
- Initial comparisons between visually identified ν_μ candidate interactions and the automatic reconstruction of those interactions is promising





ICARUS Event Selections for Oscillation Analyses

- Initial measurements focusing on 1 muon and 1 proton final states in order to make a ν_μ disappearance measurement
  - Simplest place to start as we can identify and reconstruct these events well
  - Focus on high-purity sample of well-reconstructed events without complications of hadronization
  - We can fiducialize these events and can successfully separate the muon and the proton candidate tracks



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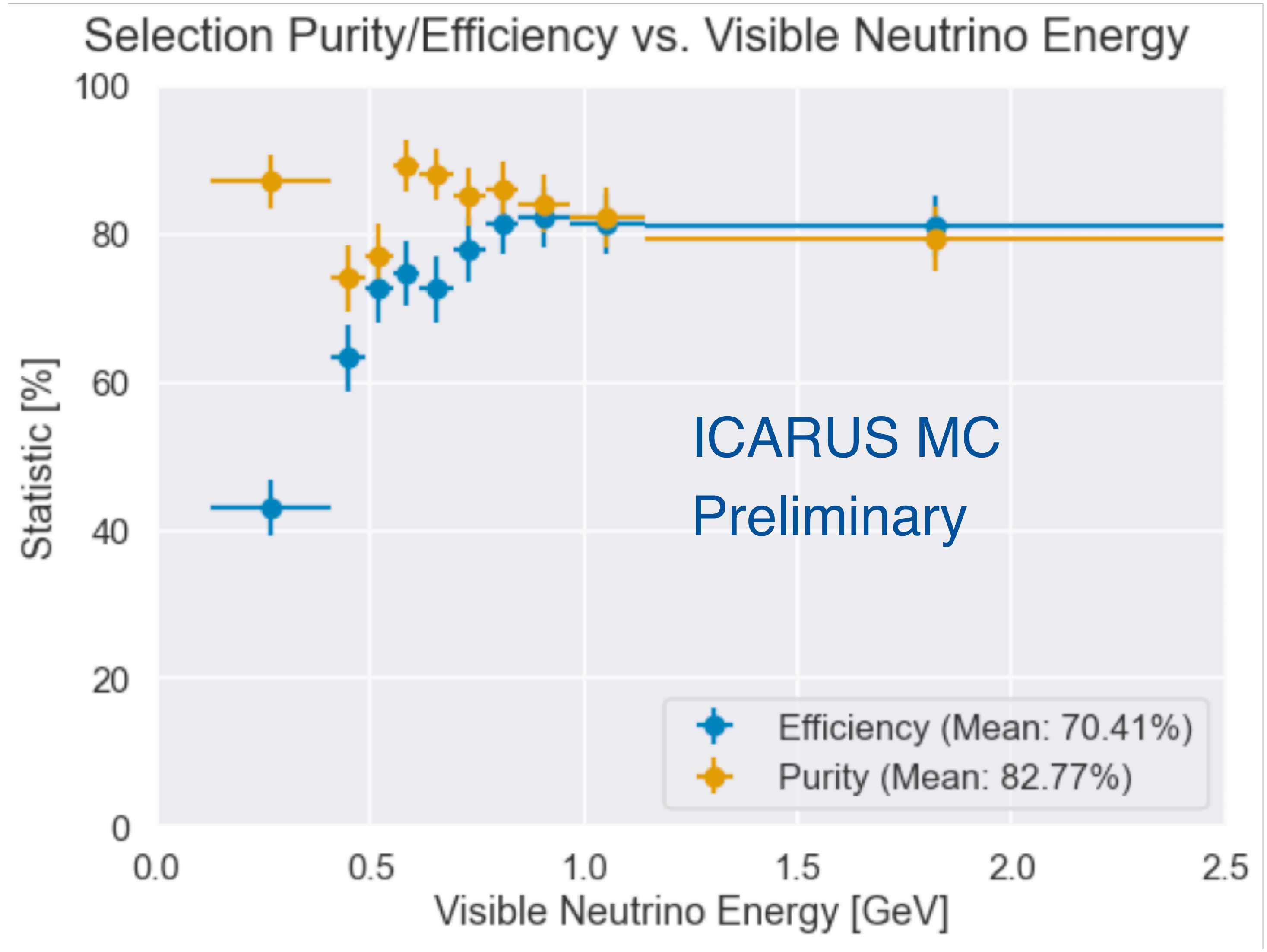


Purity = fraction of selected events that are true 1μ1p

Efficiency = fraction of true 1μ1p selected

Argon Cross Section Program using NuMI off-axis

- ICARUS will have excellent statistics for neutrino-argon cross section measurements in both electron and muon channels
- The expected electron/muon neutrino spectra from NuMI covers a lot of relevant phase space for DUNE

Events Selected

Unfolding

Backgrounds

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\sum_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{A_\alpha(\Phi T)(\Delta x)}$$

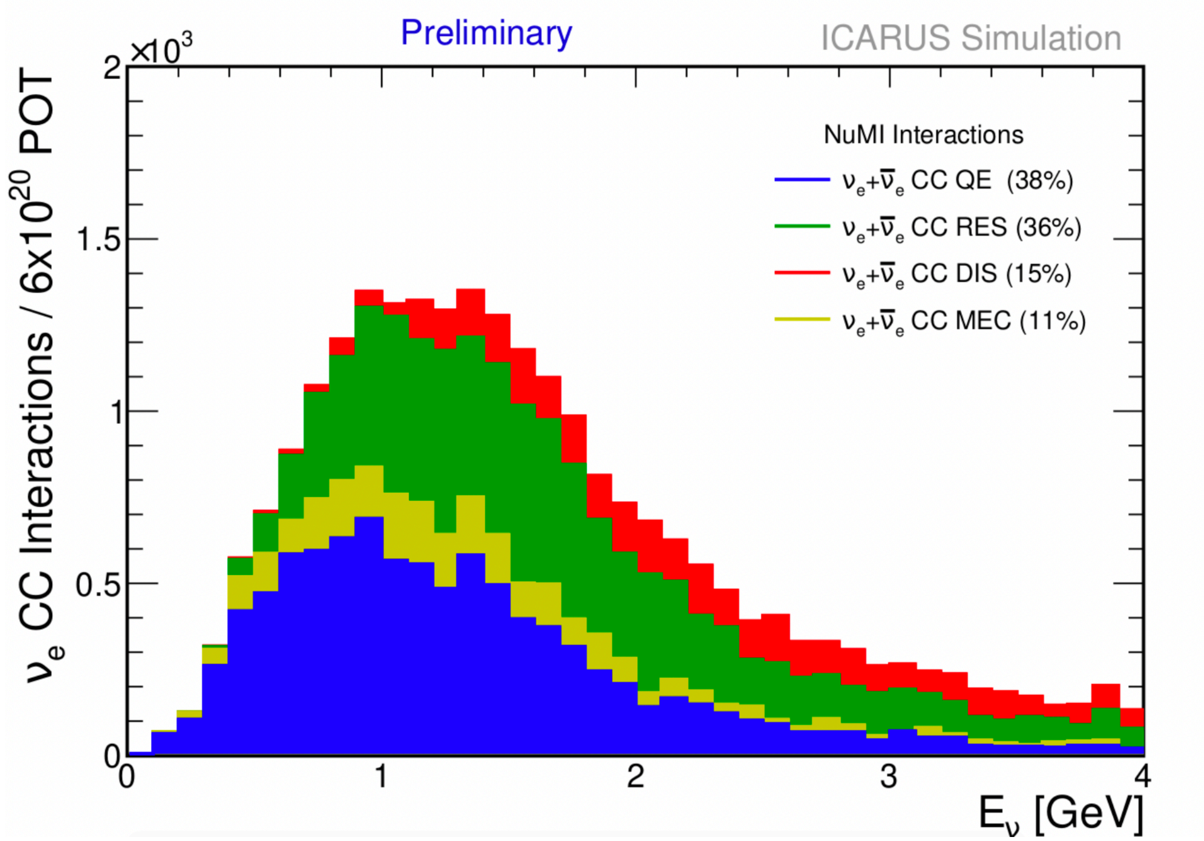
Bin-width

Acceptance

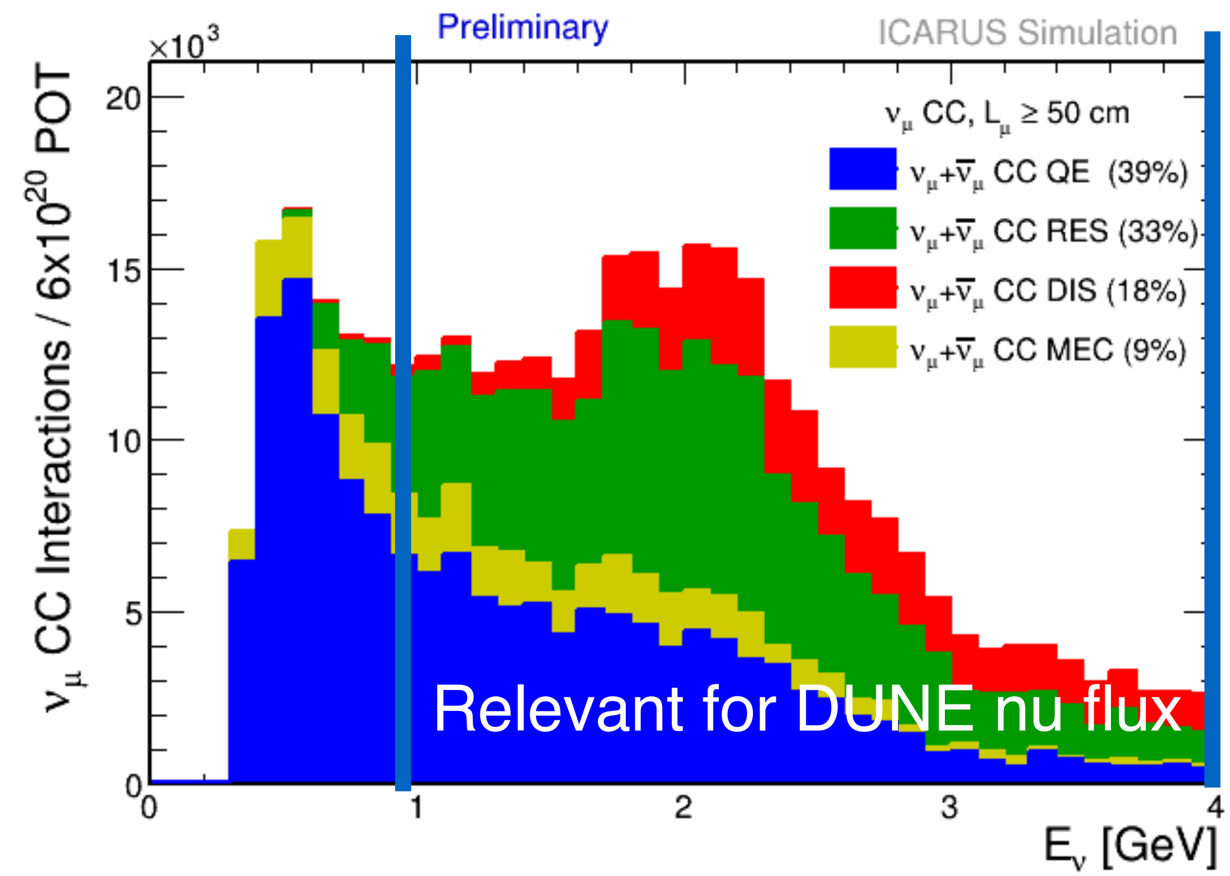
Flux

Targets

Electron Neutrino

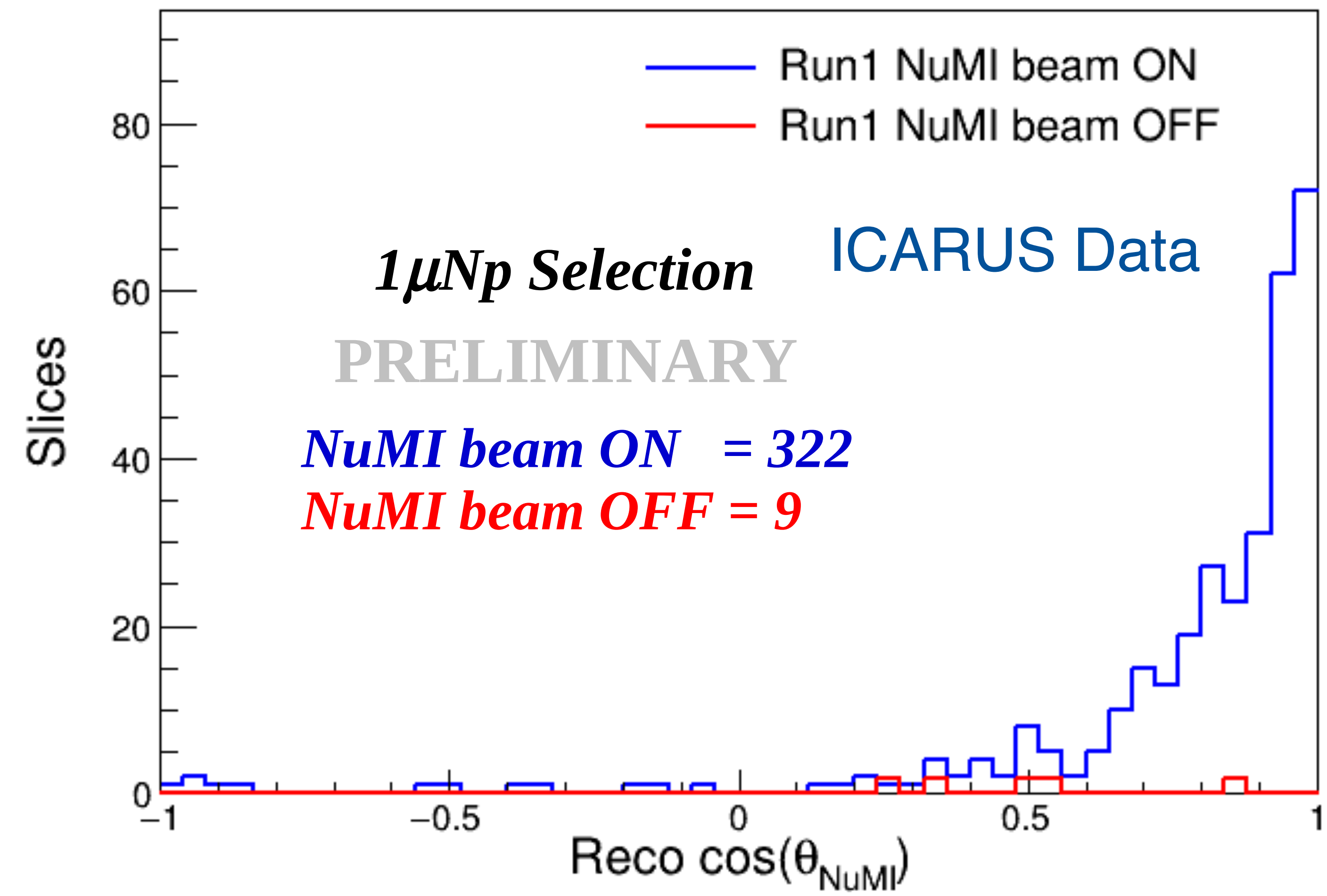


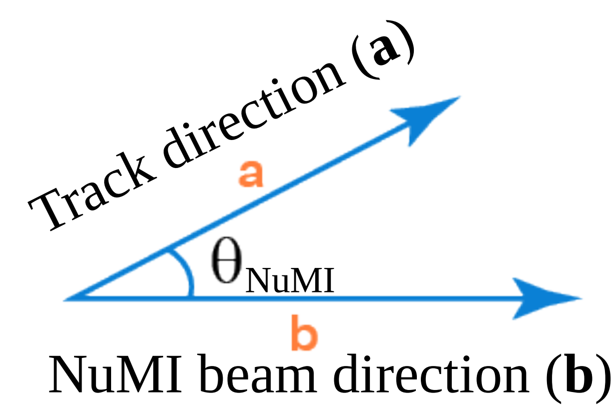
Muon Neutrino



Event selections for Cross Section Analyses

- Initial cross section analyses also focusing on selecting events that we can reconstruct well focusing on inclusive selections with 1 muon in the final state
  - Selection proceeds with same idea as for the oscillation analysis
    - Simple final state where we can correctly identify the particles in the final state
    - Can fiducialize and select a high-purity sample of candidate events using the reconstruction
- **See G. Moreno's talk from New Perspectives and poster here for more!**





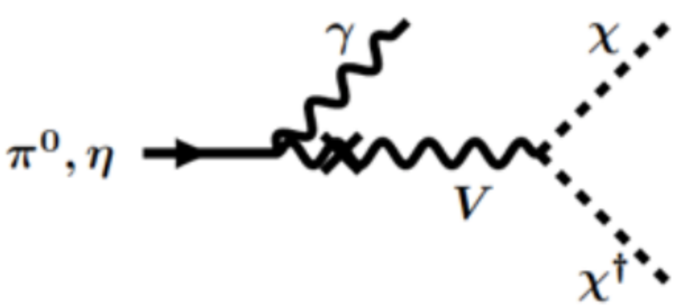
$$cos(\theta_{NuMI}) = \frac{\vec{a}\cdot\vec{b}}{|\vec{a}||\vec{b}|}$$

Searching for Beyond the Standard Model Physics with ICARUS

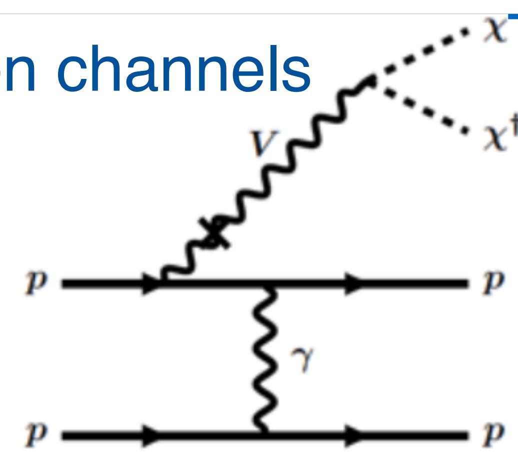
- ICARUS can take advantage of the NuMI beam off axis for powerful BSM physics searches
- Currently focusing on two channels, a Higgs Portal Scalar channel and a vector portal Light Dark Matter channel

Light Dark Matter production/detection channels

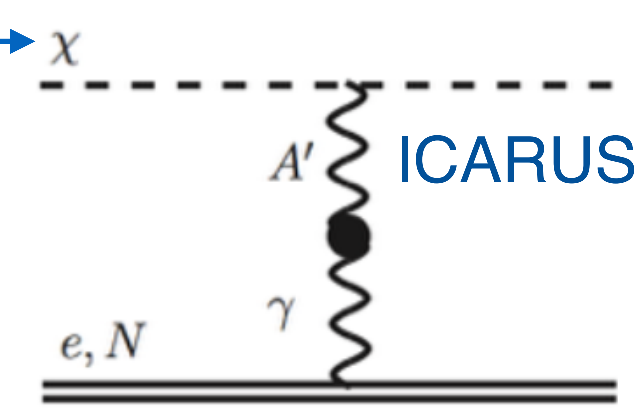
NuMI



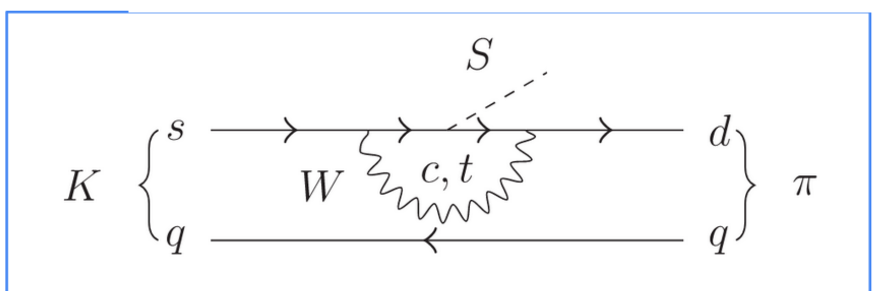
Neutral mesons decays

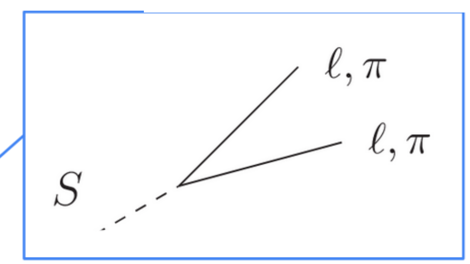


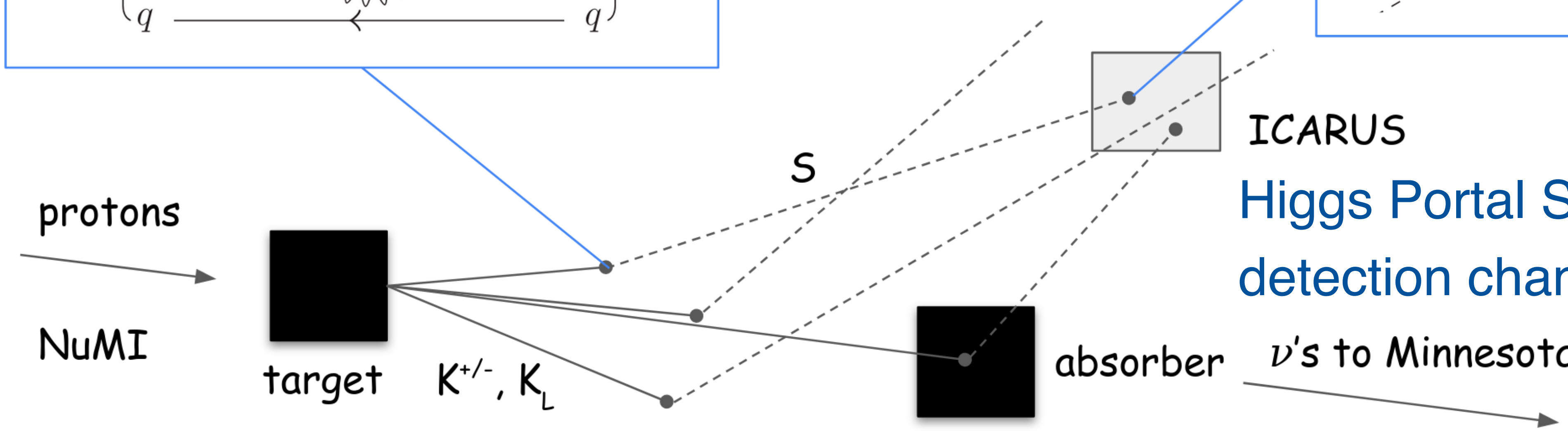
Bremsstrahlung + vector meson mixing



Elastic NC nucleon or electron scattering





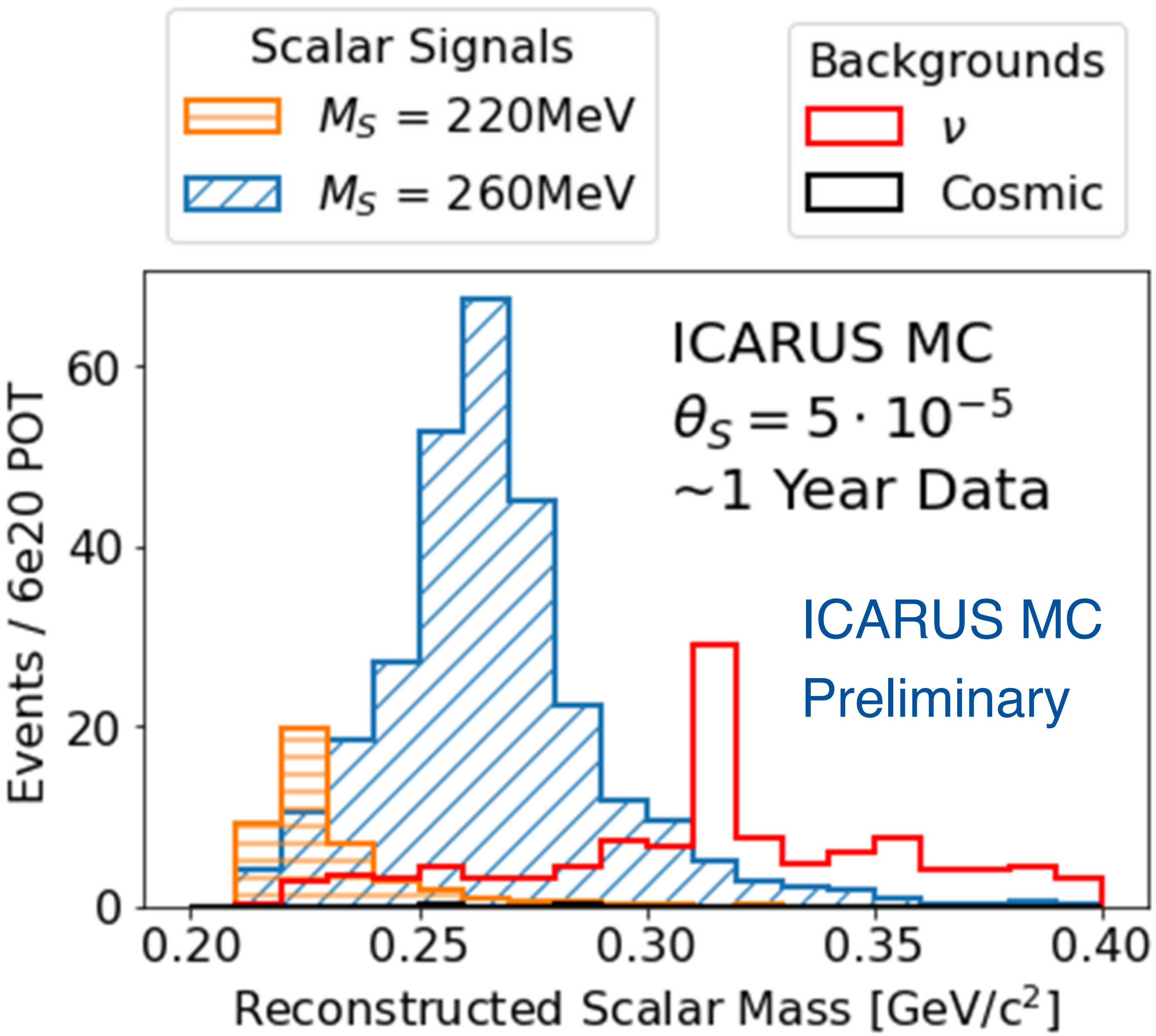


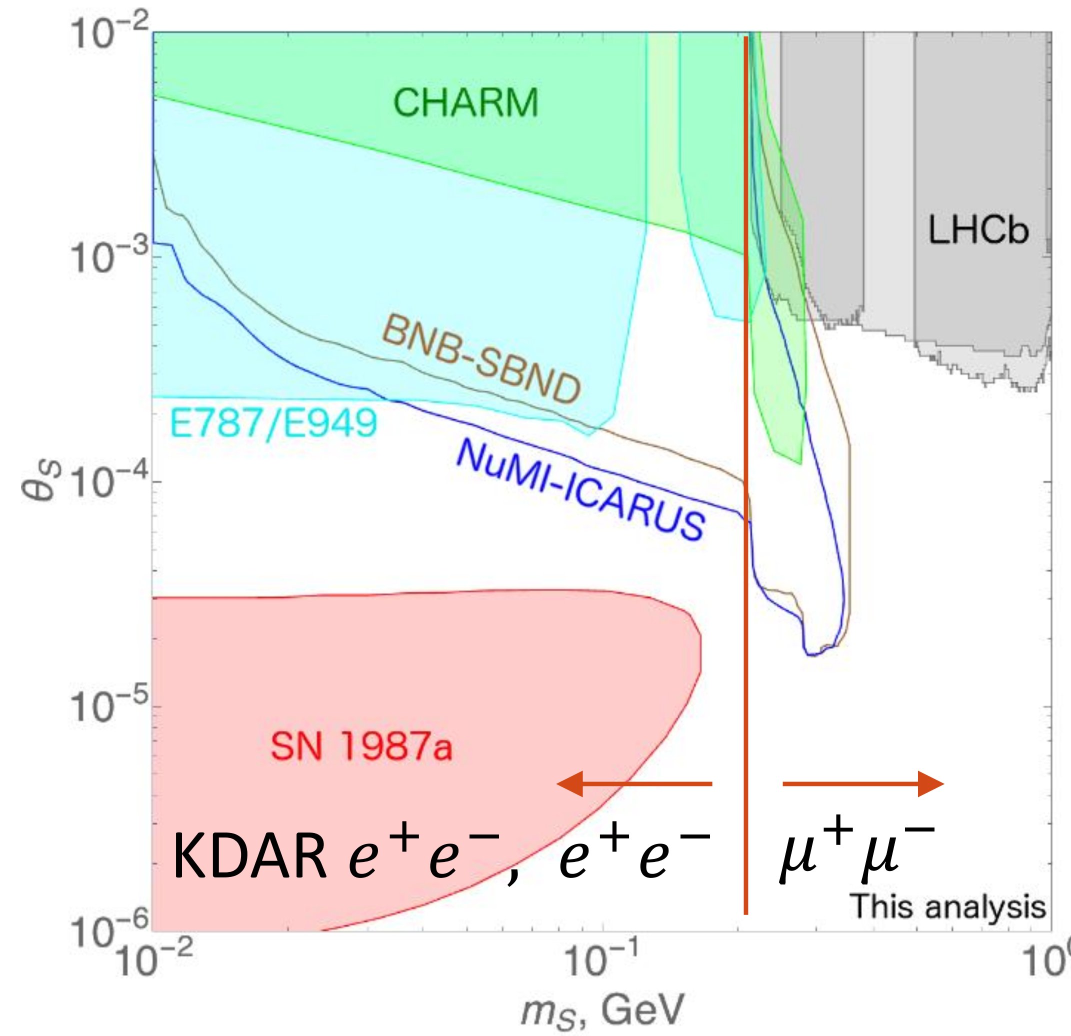
Higgs Portal Scalar production/ detection channels

Fermilab

Higgs Portal Dark Scalar Searches with ICARUS

- Analyses looking at di-muon final states as well as e+/e- final states from kaon decays both in-flight and at-rest

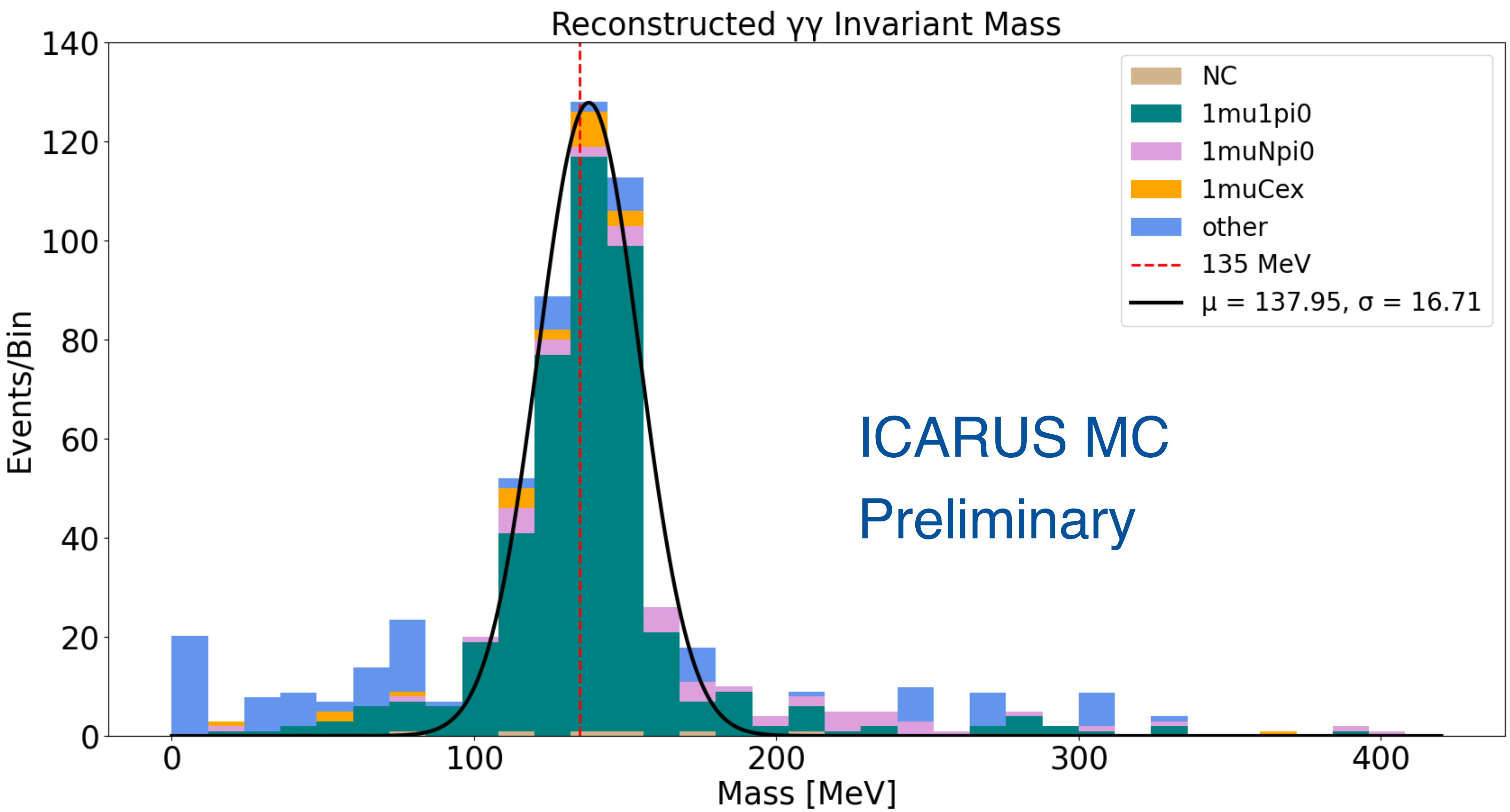




Phys. Rev. D 100,115039 (2019)

(Some) Future Physics Searches Envisioned with ICARUS

- Analyses focusing on EM shower reconstruction
  - Both BSM searches and cross section analyses using electron and photon final states

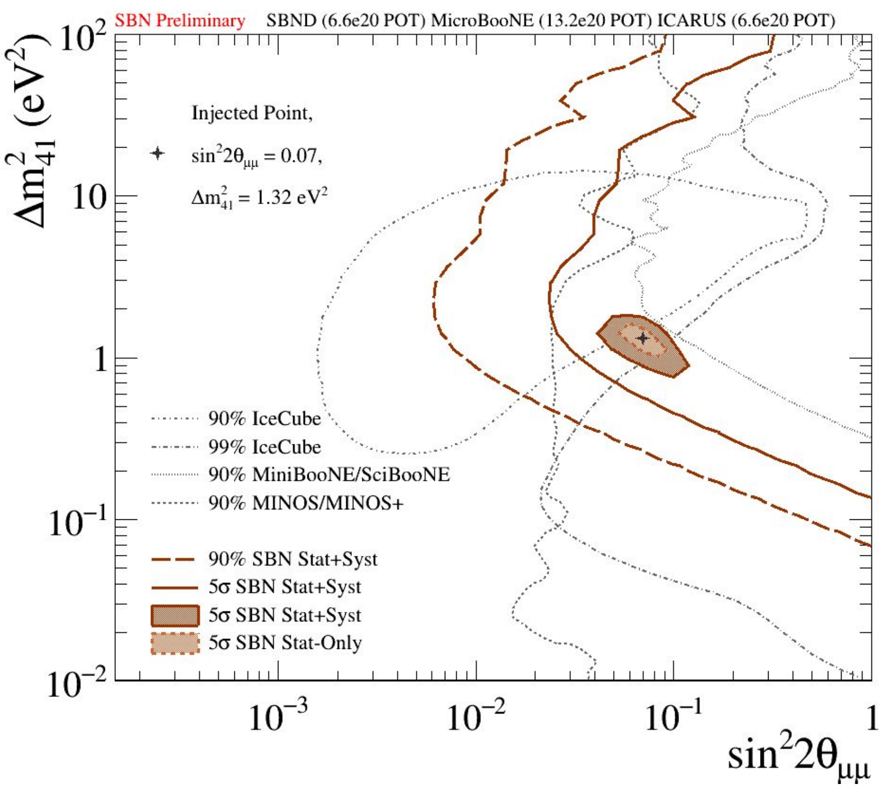


MC study of pi0 invariant mass peak reconstruction using ML reconstruction chain

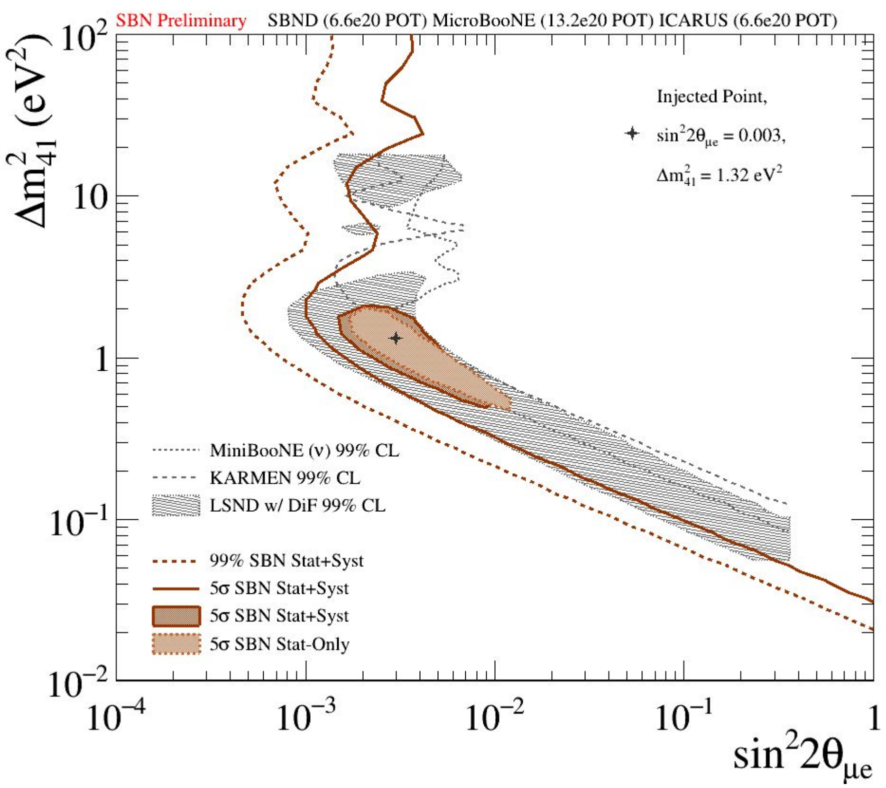
(Some) Future Physics Searches Envisioned with ICARUS

- Analyses focusing on EM shower reconstruction
  - Both BSM searches and cross section analyses using electron and photon final states
- Joint oscillation analysis with SBND in both ν_μ and ν_e channels
  - **See R. Acciarri's talk next for SBND status!**

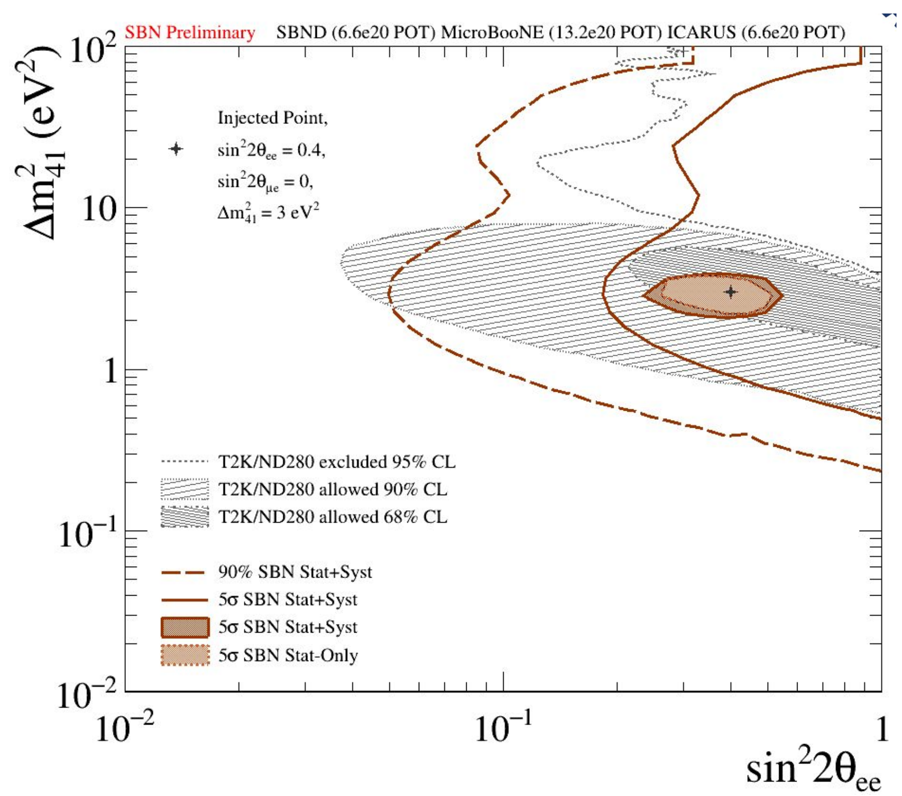
ν_μ disappearance



ν_e appearance

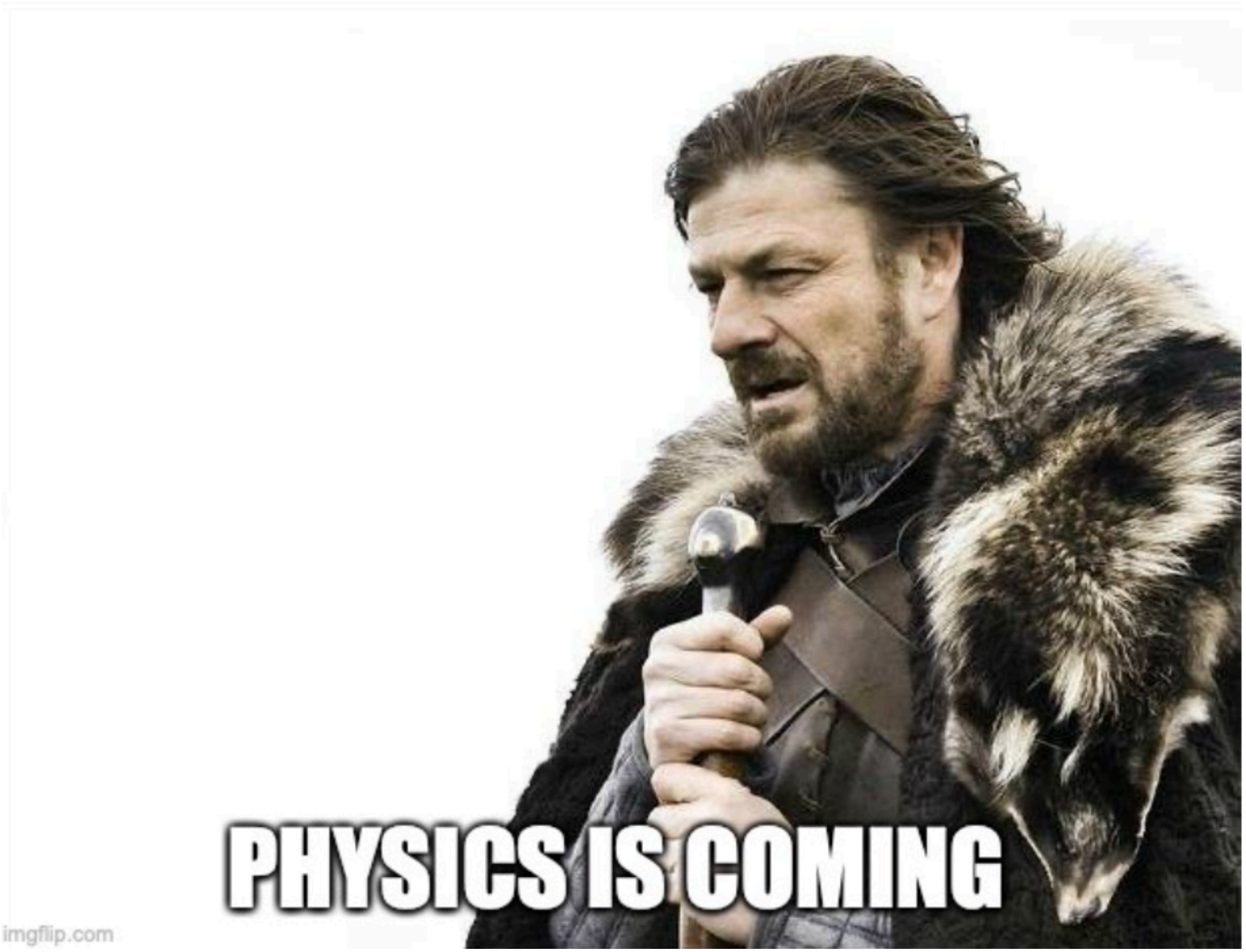


ν_e disappearance



Summary

- Neutrino oscillations are a prominent example of BSM physics and a fourth sterile neutrino state can be postulated to explain recent anomalies
- The ICARUS experiment is currently operating at Fermilab as part of the SBN program and is currently taking physics data after completing its commissioning period in June 2022
- The SBN program is designed to probe the sterile neutrino hypothesis of the MiniBooNE and LSND anomaly with the near detector SBND and the far detector ICARUS
- ICARUS has begun identifying, reconstructing and making selections of candidate neutrino interactions focusing on contained tracks
- ICARUS can search for a variety of physics including single detector oscillation physics in addition to BSM physics
- There are a number of ongoing physics analyses taking advantage of the ICARUS data



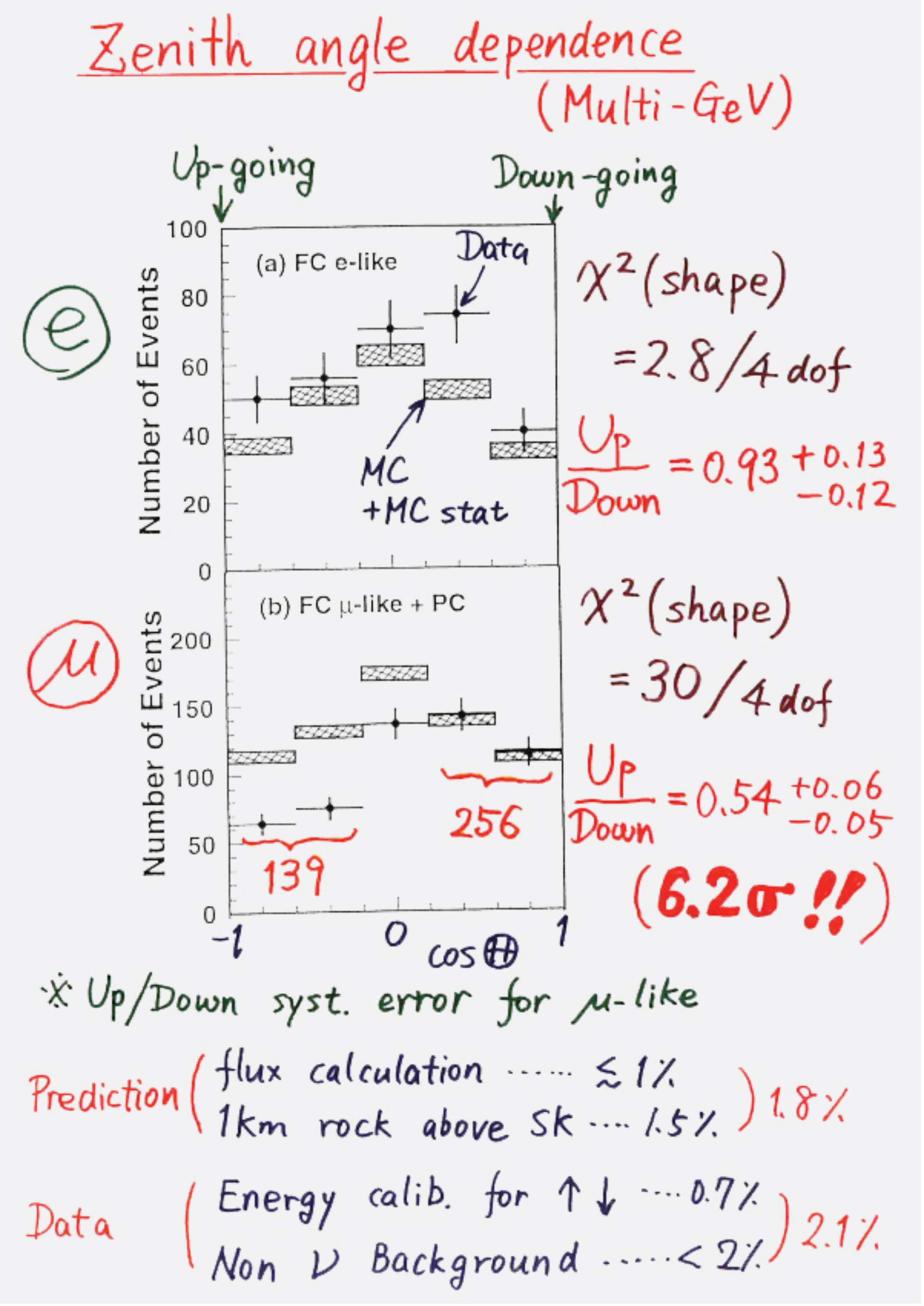
Thank you!

Questions?

Backup Slides

Massive Neutrinos and Neutrino Oscillations

- Neutrinos were first predicted as massless in the Standard Model
- Evidence initially from solar and atmospheric neutrino measurements that neutrinos oscillate and must be massive
  - Definitive measurement by Super Kamiokande

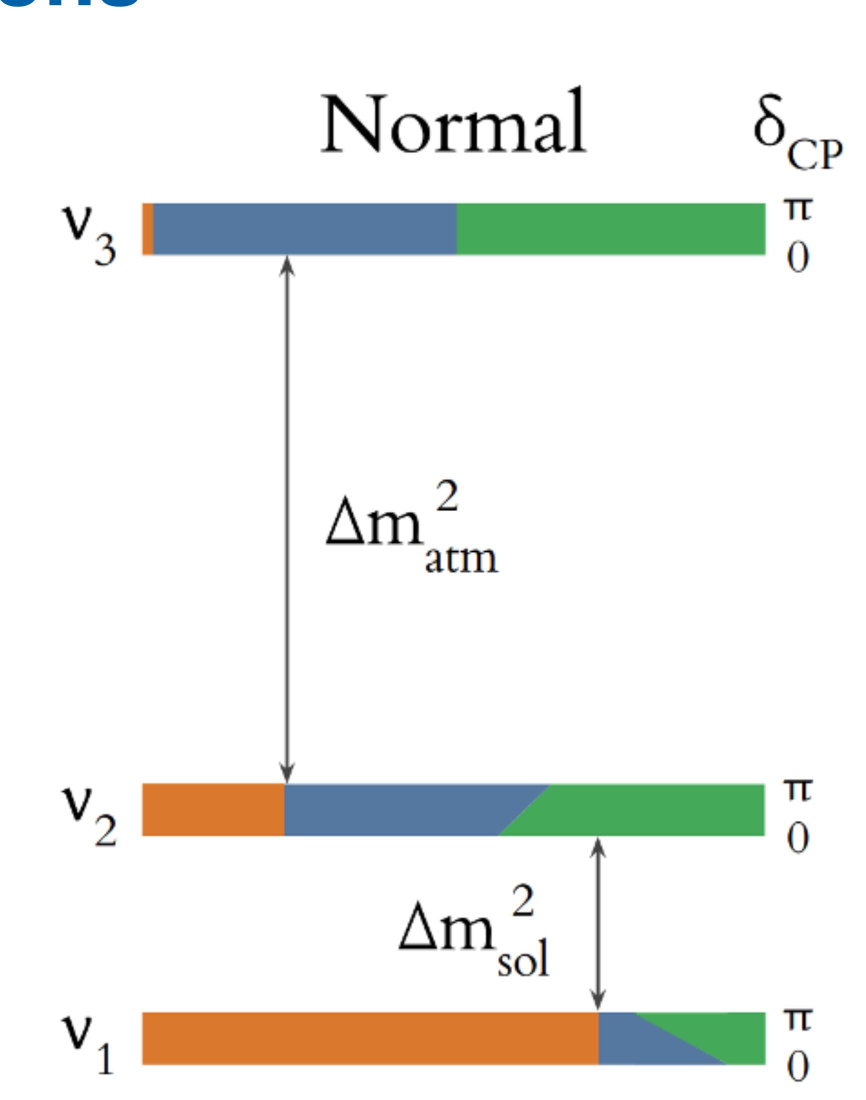


T. Kajita

Massive Neutrinos and Neutrino Oscillations

- Mass states connected to flavor states by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix
- Probability for (two-flavor) oscillations is:

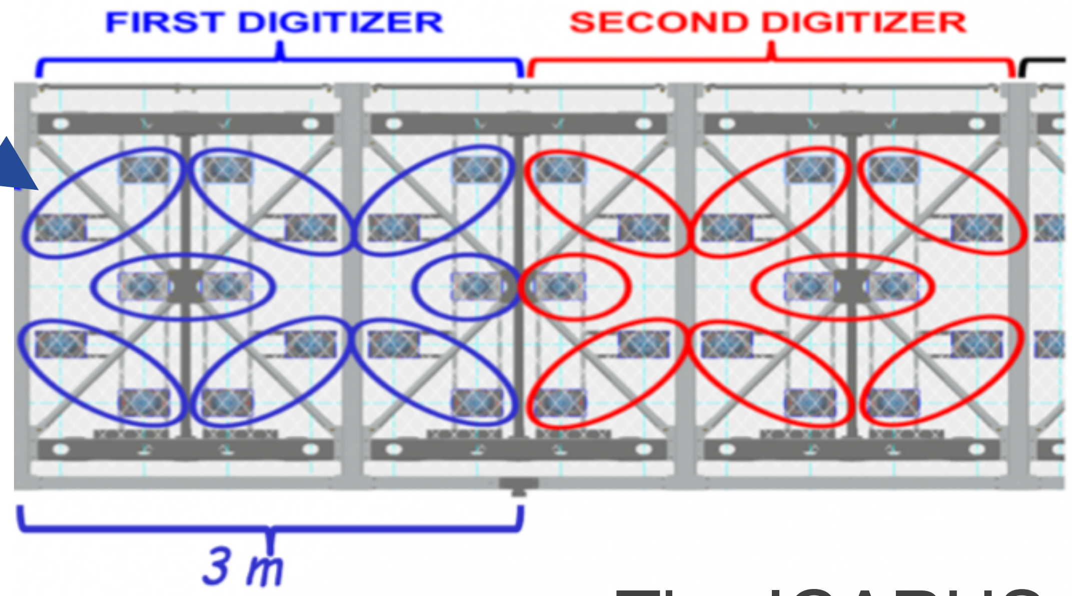
$$P(\nu_\alpha \rightarrow \nu_\beta) \approx \sin^2(2\theta_{\alpha\beta})\sin^2(1.27\Delta m^2_{\alpha\beta}\frac{L}{E_\nu})$$

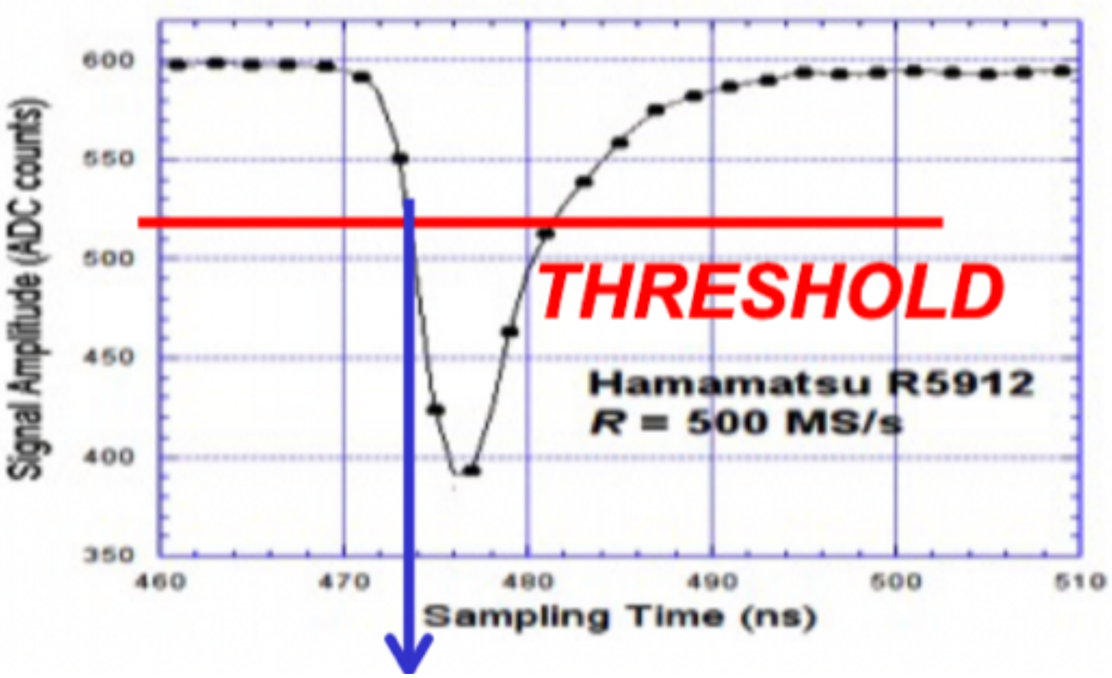


$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \mathbf{U_{PMNS}}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

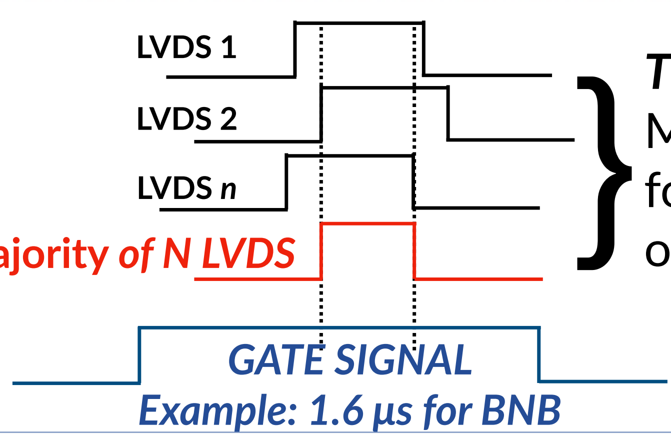
ICARUS Trigger System

PMT PAIRS:
both OR and AND logics are possible





- The ICARUS trigger system operates by generating triggers based either on light seen by the PMTs (“Majority”) in coincidence with the beam spill which comes through a precise timing system
  - Also can generate triggers without need for light activity or equivalent triggers outside the beam spill

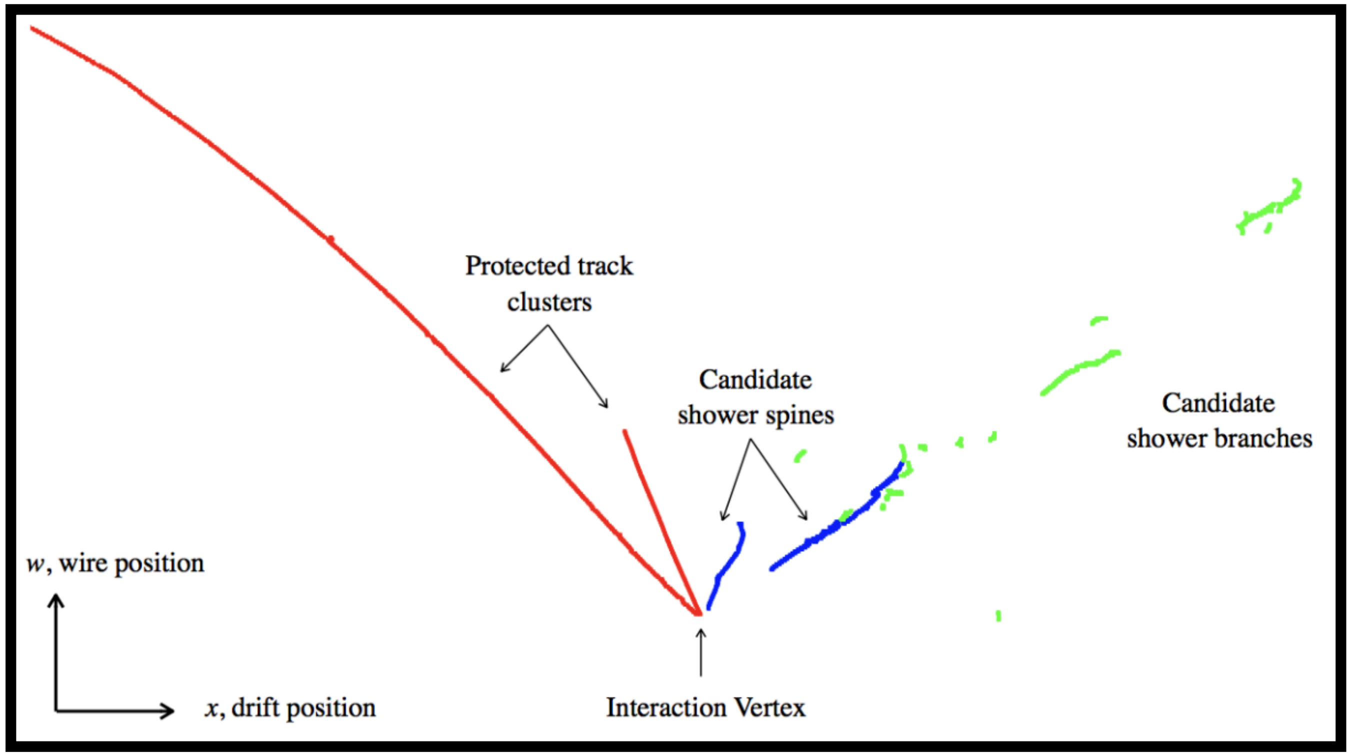


TRIGGER PRIMITIVE:
Majority of N LVDS formed by PMT pairs over a given threshold

IT’S A GLOBAL TRIGGER!
When a trigger primitive is found in coincidence with the beam gate!

Pandora Reconstruction Overview

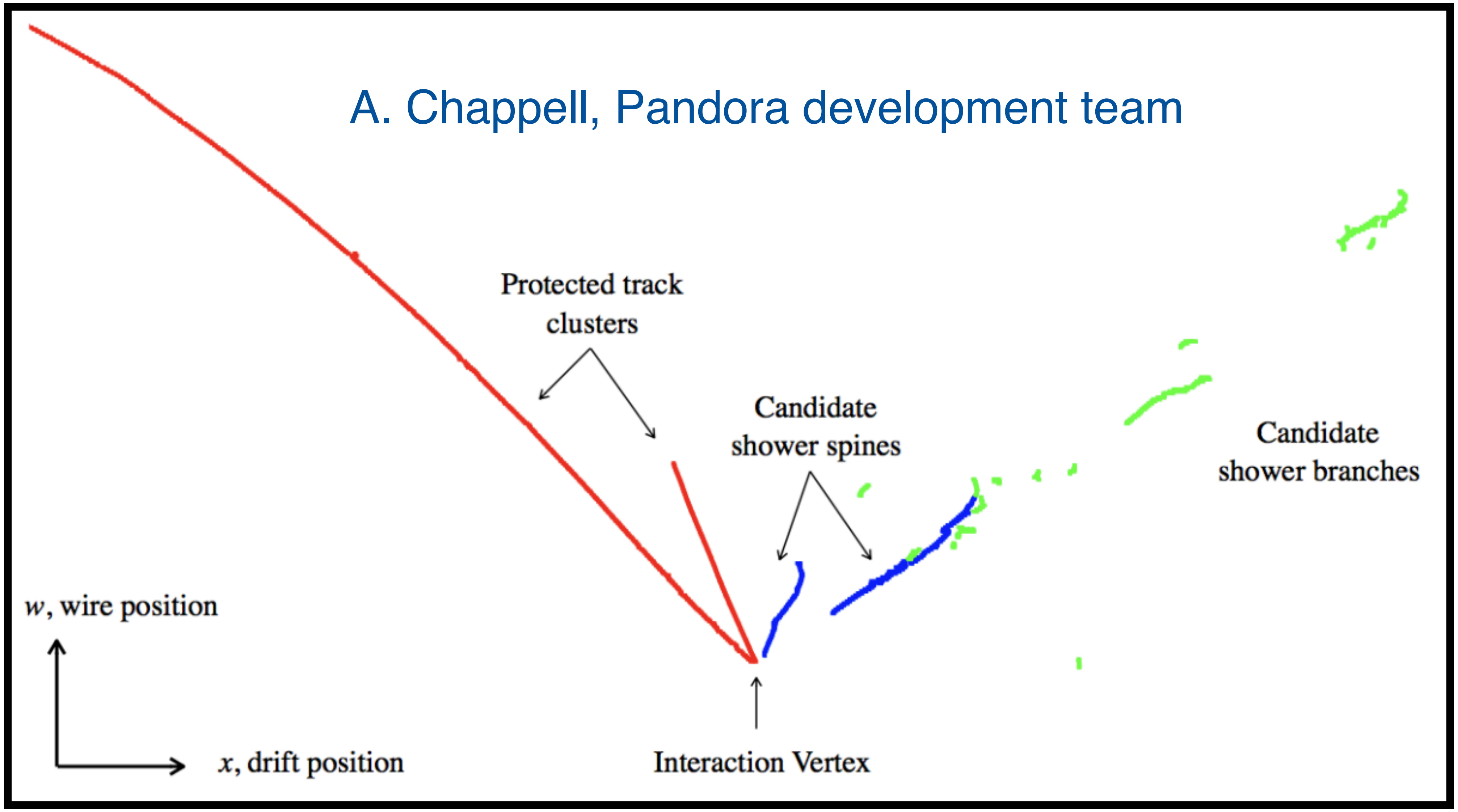
- One of the ICARUS/SBN reconstruction pathways is the Pandora multi-algorithm pattern-recognition kit
- Has an established interface to the common LArSoft software framework commonly used at FNAL LArTPC experiments and proceeds largely as follows:
  - Clusters objects together into reconstructed particles
  - Reconstructs the interaction vertex
  - Forms particle hierarchy (parent/child particles)
  - Classifies particles as track like (e.g. mu, p, pi+/-, K+/-or shower-like (e.g. e-, photon)



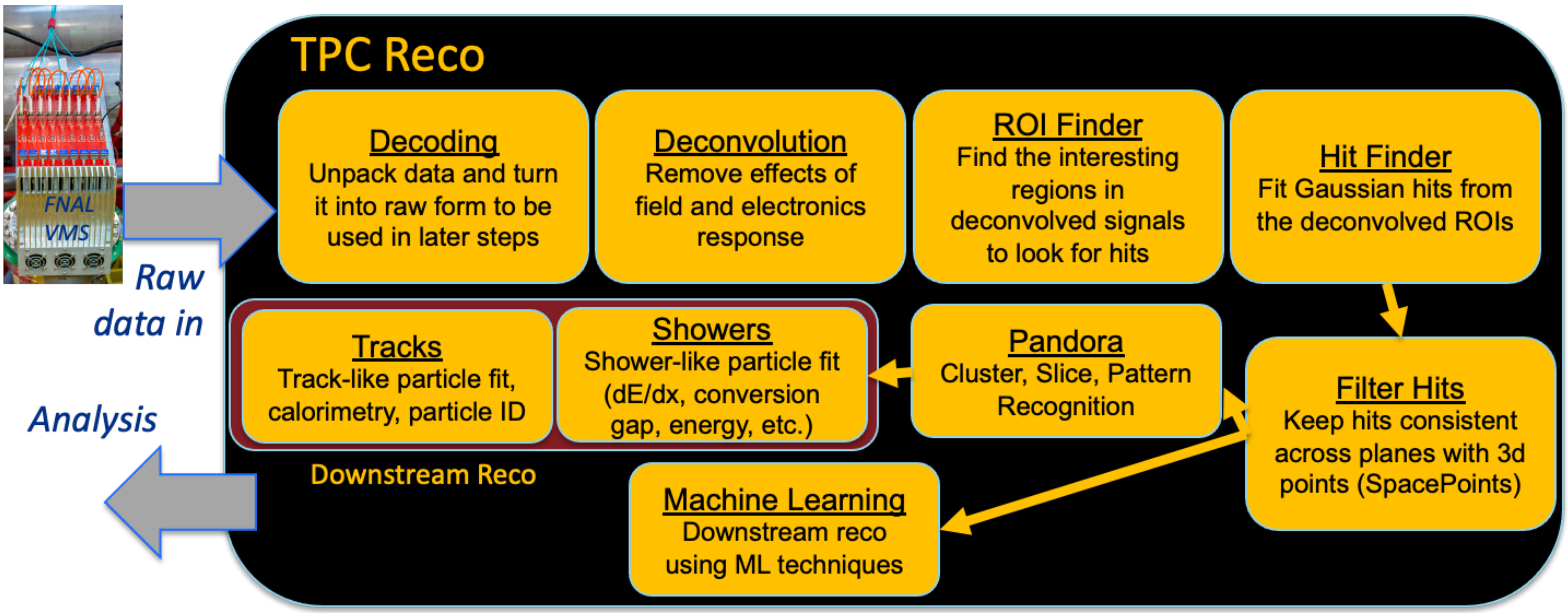
A. Chappell, Pandora development team

Pandora Reconstruction Overview

- Series of algorithms that on can alter and/or extend
- Can also change which algorithms are applied (can add, remove, modify, etc.)
- Can work to improve output, add e.g. deep learning algorithms, either in Pandora or downstream



Pandora Reconstruction Overview



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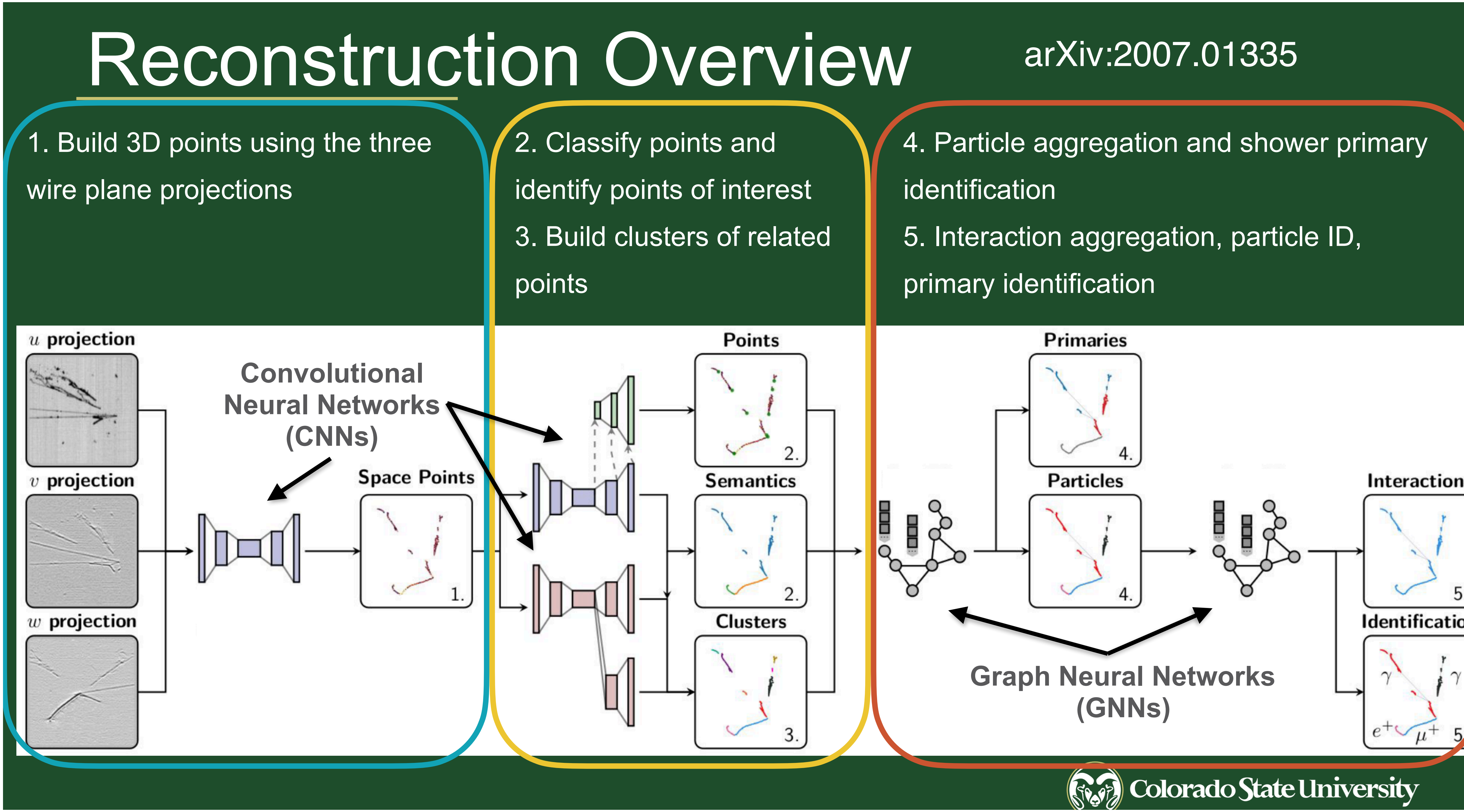
Machine Learning Reconstruction Overview



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Machine Learning Reconstruction Infrastructure

Reconstruction Infrastructure

arXiv:2007.01335

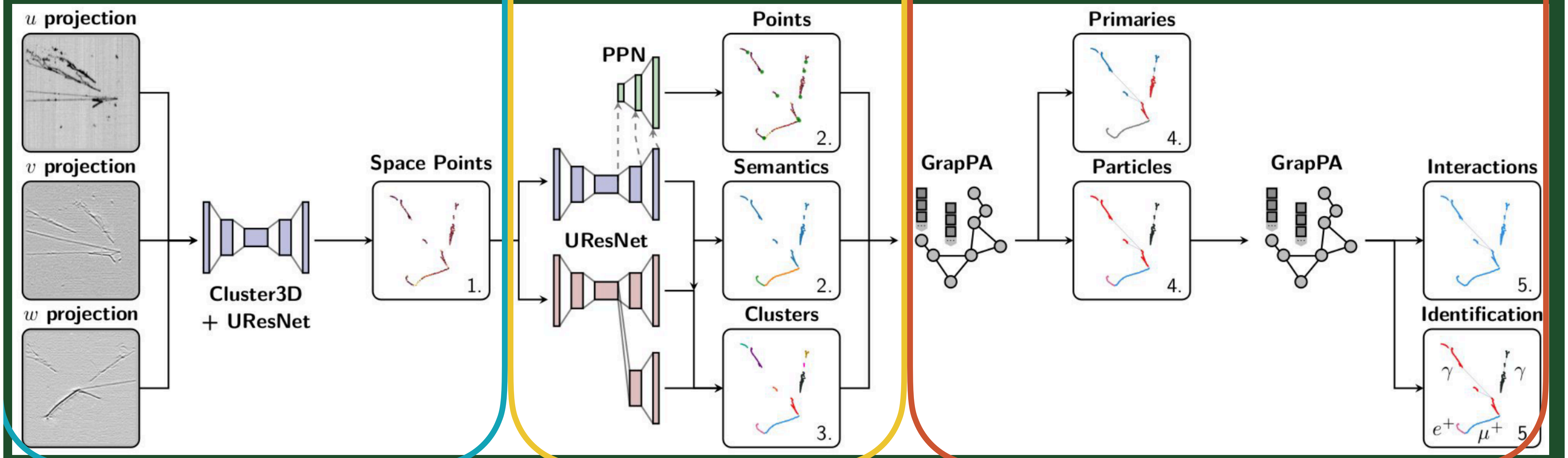
1. Tomographic Reconstruction + **CNN**: **Sparse-UResNet**

2. **CNN**: **UResNet + PPN**

3. DBSCAN + **CNN**: **Graph-SPICE**

4. **GNN**: **GrapPA-Track/Shower**

5. **GNN**: **GrapPA-Interaction**



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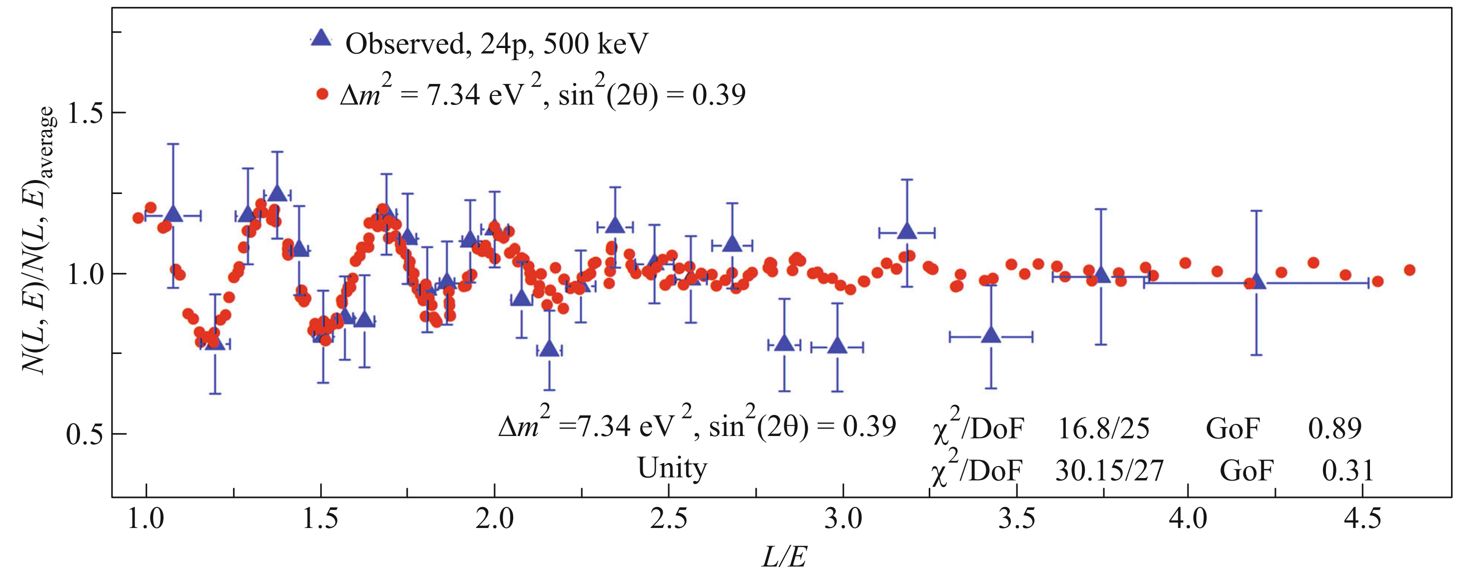
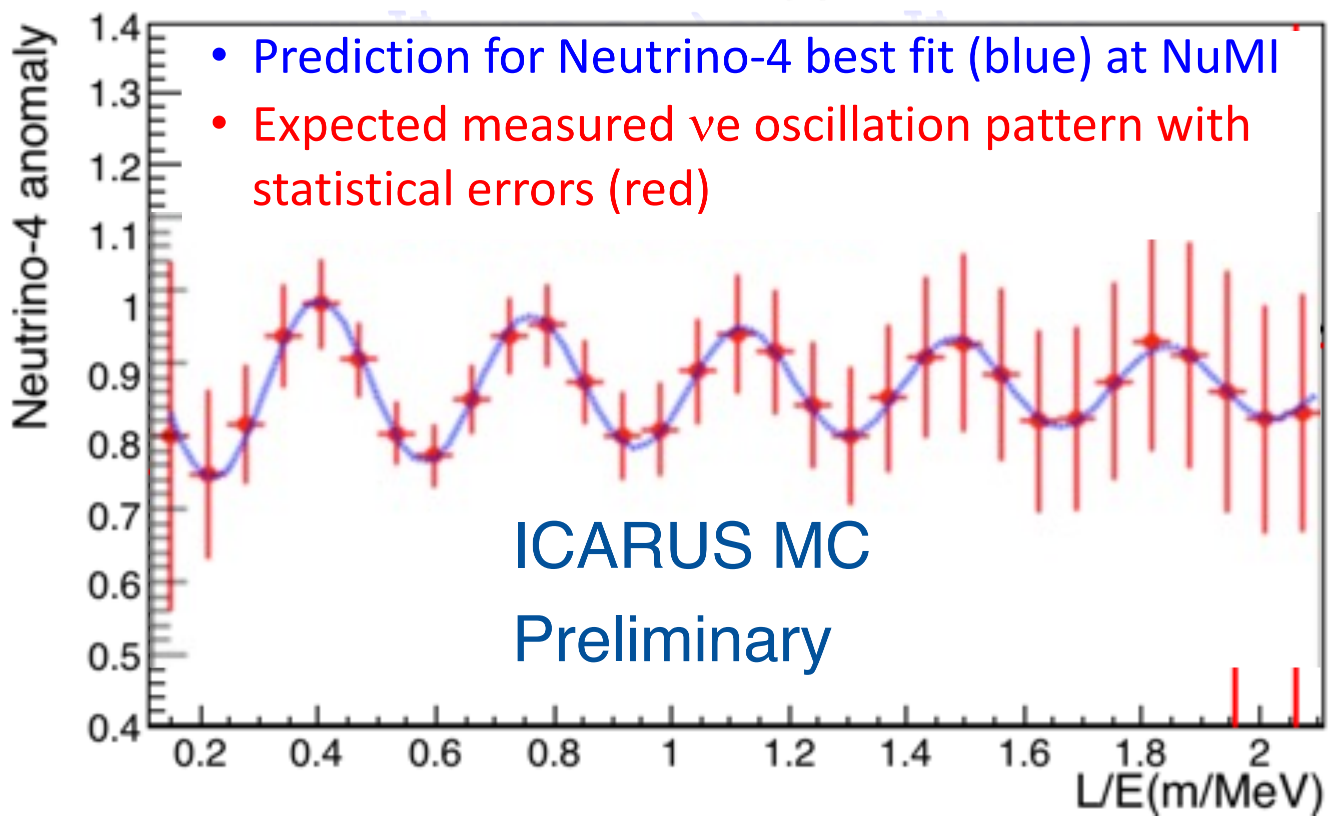
How ICARUS can probe the Neutrino-4 claim

- NuMI ν_e disappearance is also the relevant channel at ICARUS for testing the claimed sterile neutrino observation from the Neutrino-4 experiment
- ICARUS sits at similar values of L/E of 1-3 m/MeV as the Neutrino-4 experiment with the baseline L being largely constant
- Expect around 5000 events with an EM shower contained within the fiducial volume for 1 year of data taking (6E20 POT)
- Statistics-only MC predictions show the possibility to probe the claim with of ICARUS data



JETP Lett. 116, 669-682 (2022)

Δm^2_{14}=7.25 eV^2, $\sin^2 2\theta_{14}$=0.26



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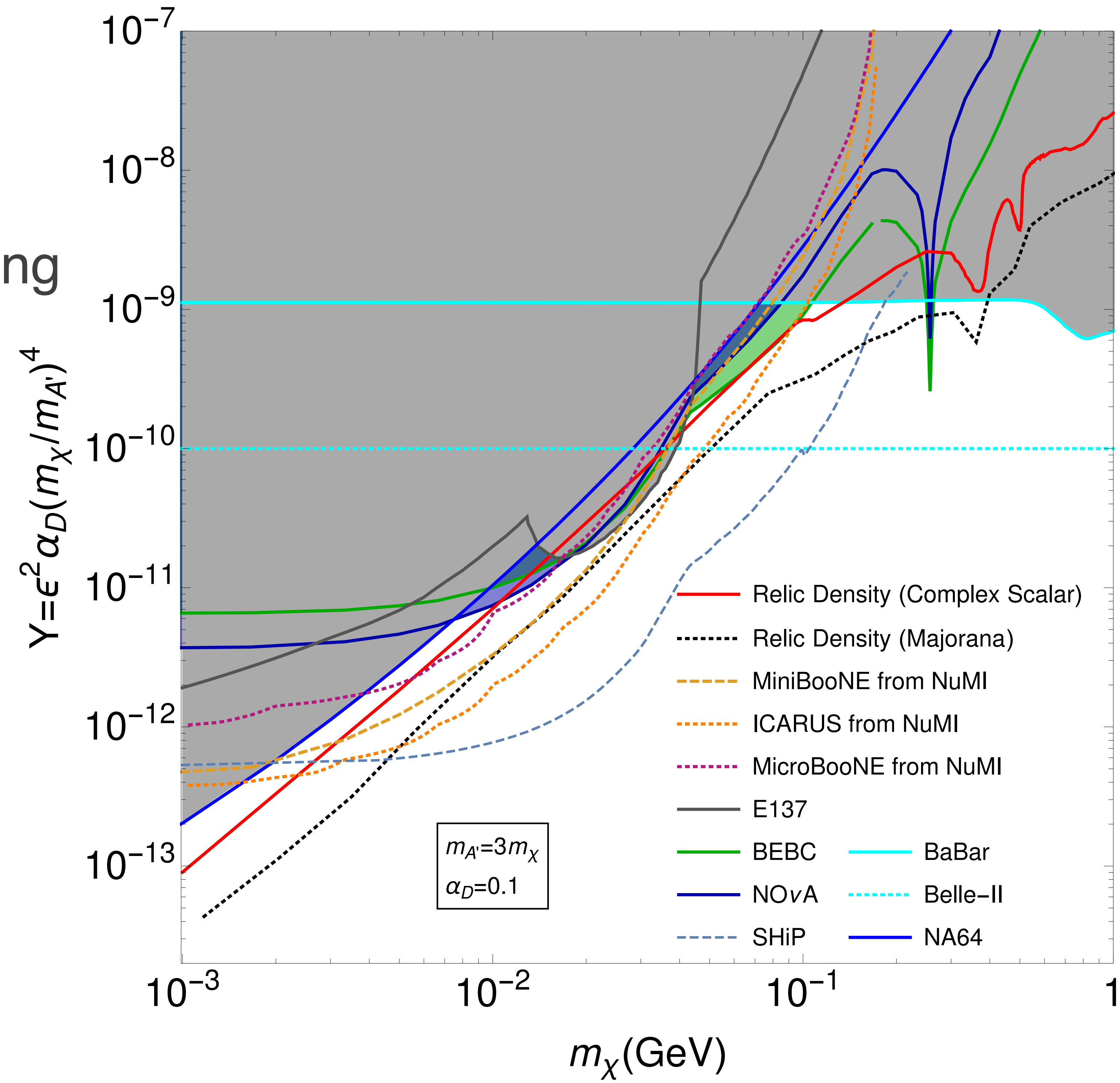
(Some) Future Physics Searches Envisioned with ICARUS

- Analyses focusing on EM shower reconstruction
  - Both BSM searches and cross section analyses using electron final states

Phys. Rev. D 102, 035006 (2020)



ICARUS at NuMI LDM Event Sensitivity

Shower Completeness Correction

- "Completeness" = amount of visible energy/total energy deposited in a shower
- For our ML reconstruction chain, if a shower fragment is too small (10 voxels total or 3 cm), it will not be included in the clustering
  - Therefore the energy within that fragment will not be counted toward the reconstructed energy contained in the shower

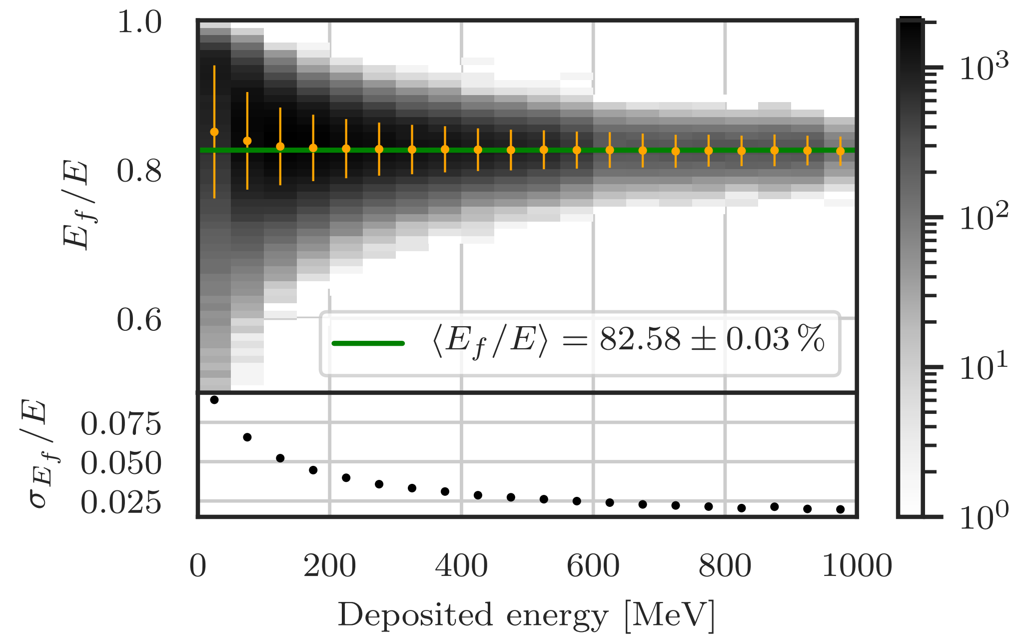


FIG. 5. Fraction of the energy deposited by a shower in fragments of size 10 voxels and above. The orange markers on the top pad represent the mean and their error bars the RMS; the latter is shown on its own in the bottom pad. The green line is a constant fit to the markers above 100 MeV.

ICARUS Data Blinding

- An interim blinding procedure in currently in place for first ICARUS analyses focusing on the oscillation analyses
- 10% of the data is fully available to analyzers
- The remaining 90% is then blinded in the following way
  - The momentum of identified muon candidate tracks is blind to analyzers for tracks with a value of >600 MeV
  - Energy of identified shower candidates is blind to analyzers when the value is >600 MeV
  - The magnitude of the protons-on-target for the data set is adjusted by an unknown offset that may be as large as 30%
  - All other reconstructed quantities are available to the analyzer