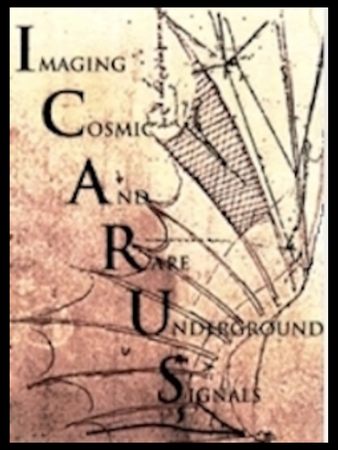
Status and perspective of ICARUS at the Fermilab Short-Baseline Neutrino Program

Bruce Howard *on behalf of the ICARUS Collaboration*

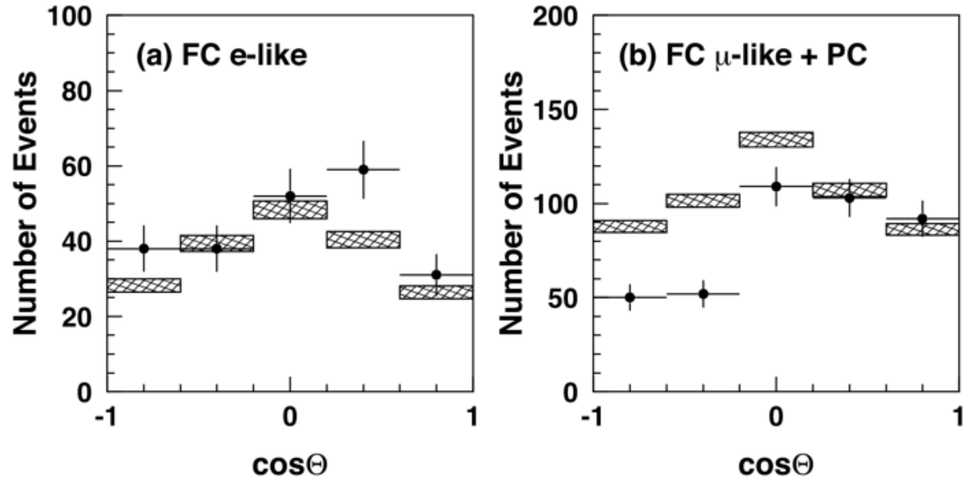
11 October 2023 | NNN2023 | Procida, Italy

Fermilab

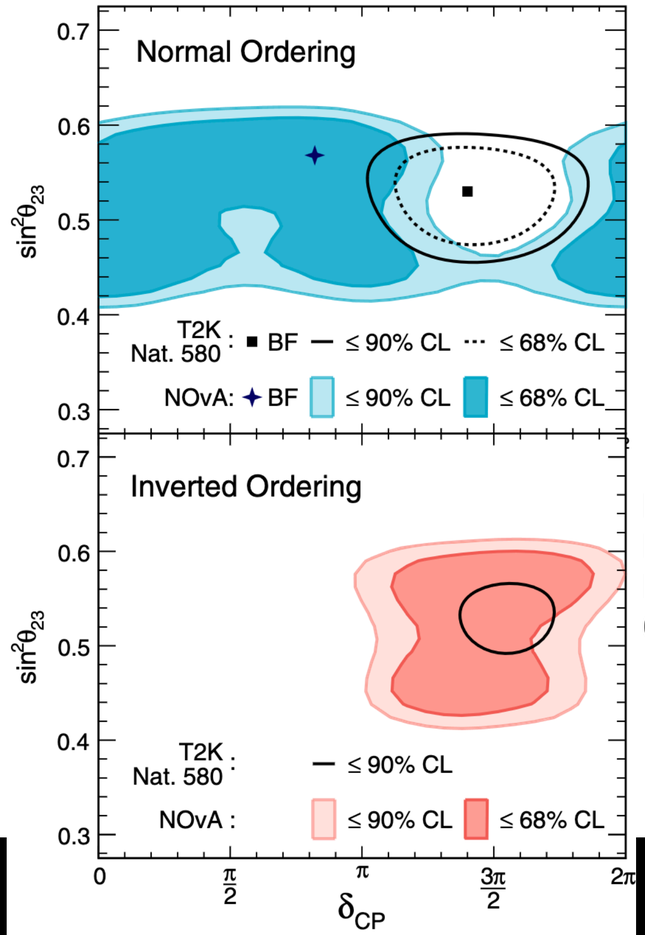


The Neutrino Landscape

- Nature of neutrinos & oscillations comprise key questions facing our community
- A lot of work in developing clearer picture of ν oscillations but still questions, such as:
  - **What precisely are the ν mixing parameters, and: Normal or Inverted mass ordering? Do ν violate CP symmetry? (long-baseline osc)**
  - **Are there more than the 3 known neutrino flavors? (short-baseline osc)**
- Current gen of ν long-baseline experiments (e.g. NOvA, T2K) *might* get significant result on mass ordering, but we need the **next-generation** detectors (*this is NNN!*) to make definitive measurements and to have significant CP violation discovery potential



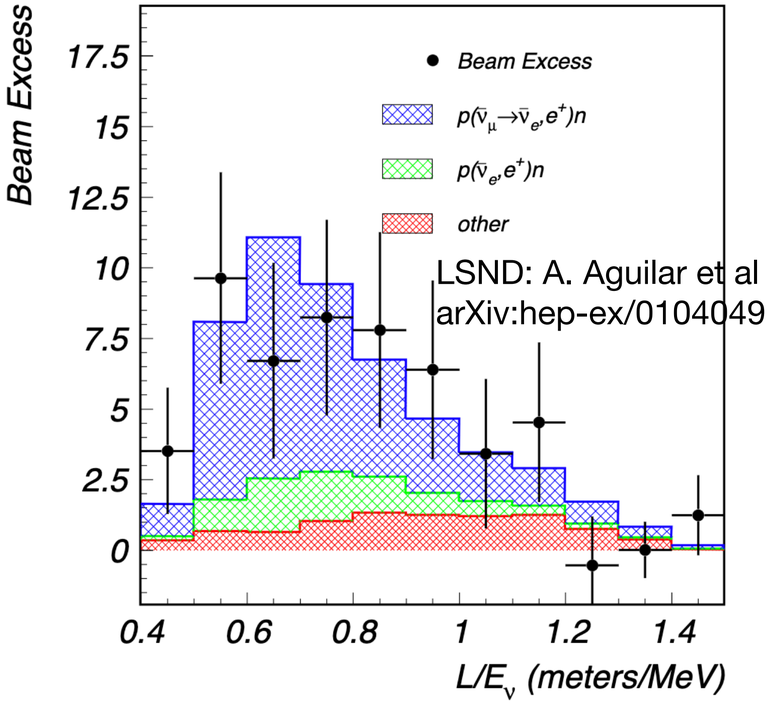
Early Super-K data: T. Kajita, E. Kearns, M. Shiozawa Nuclear Phys B 908 (2016) 14-29

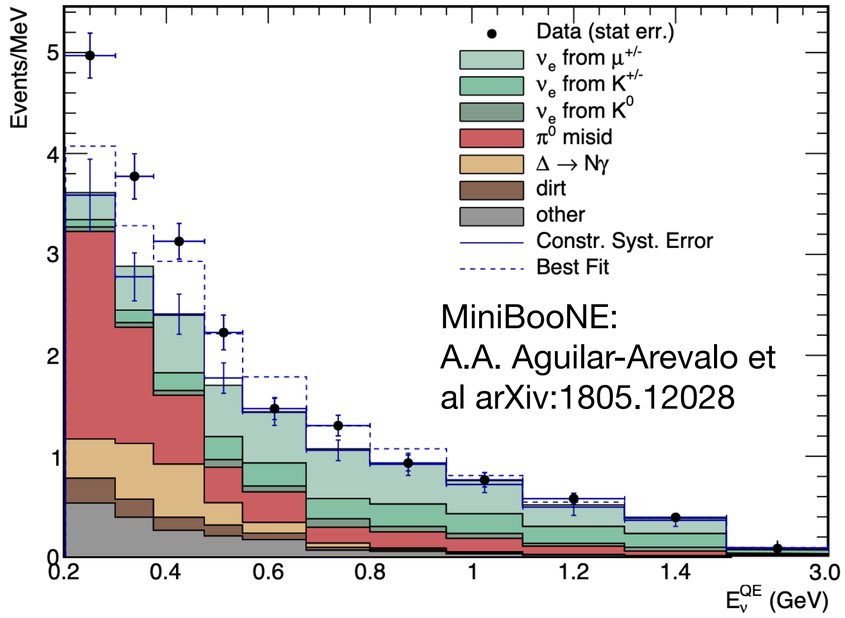


NOvA & T2K: M.A. Acero et al Phys Rev D 106, 032004 (2022)

More than 3 ν?

- LSND, MiniBooNE anomalous excess of low E ν_e candidates at <u>short baseline:</u>
  - Cannot explain via osc among 3 standard flavors. An interpretation of this is oscillation of ν_μ to ν_e due to at least 1 sterile ν state
- **Hard to distinguish e, γ in MiniBooNE** (background constraints important)
- More recently, Neutrino4 collaboration claimed hint of possible oscillatory signature (A. P. Serebrov et al Phys. Rev. D **104**, 032003 (2021))

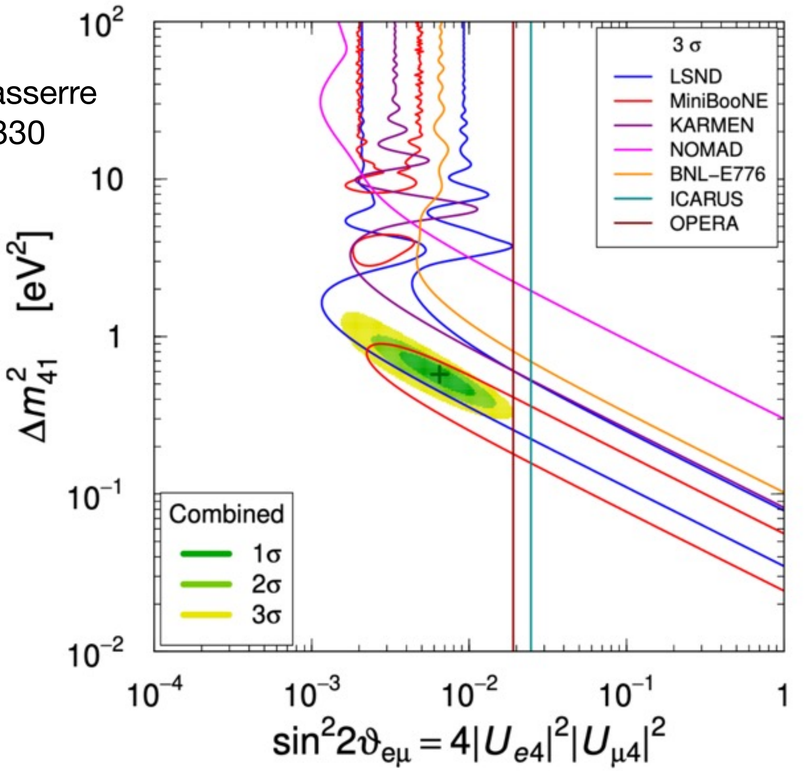




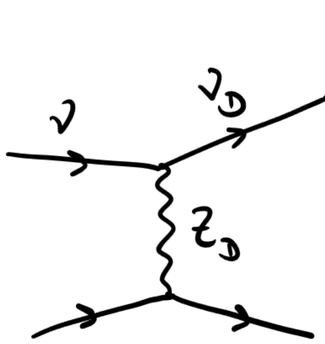
More than 3 ν?

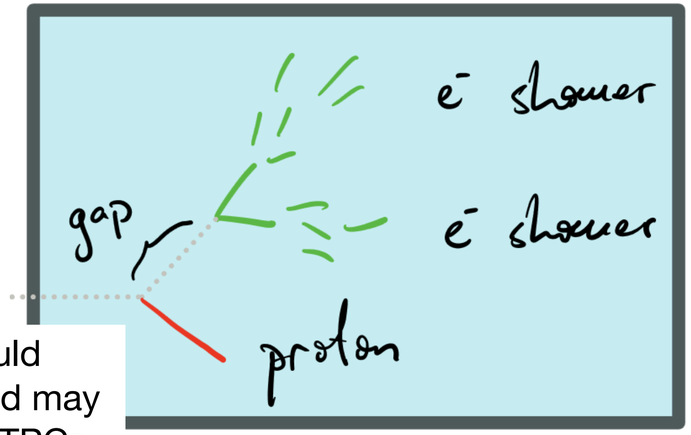
- MicroBooNE results do not show evidence of excess from neutrino candidates, or from poor constraints on Δ decays
- Largely, a global program of experiments searching for further evidence of steriles has set continually more stringent limits, strong tension with ν_μ disappearance searches
  - Additional BSM processes have been proposed as an alternative solution

C. Giunti, T. Lasserre
arXiv:1901.08330

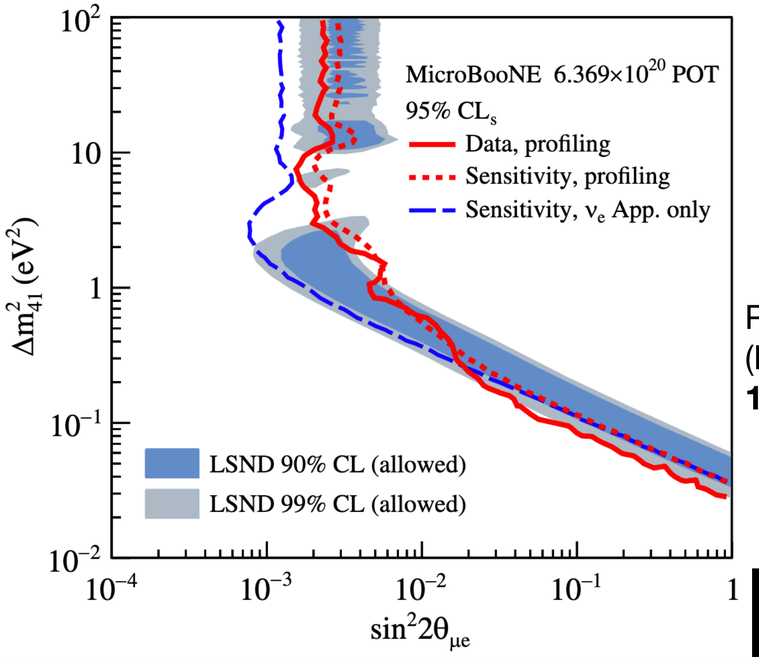


Dark neutrinos with heavy Z_D





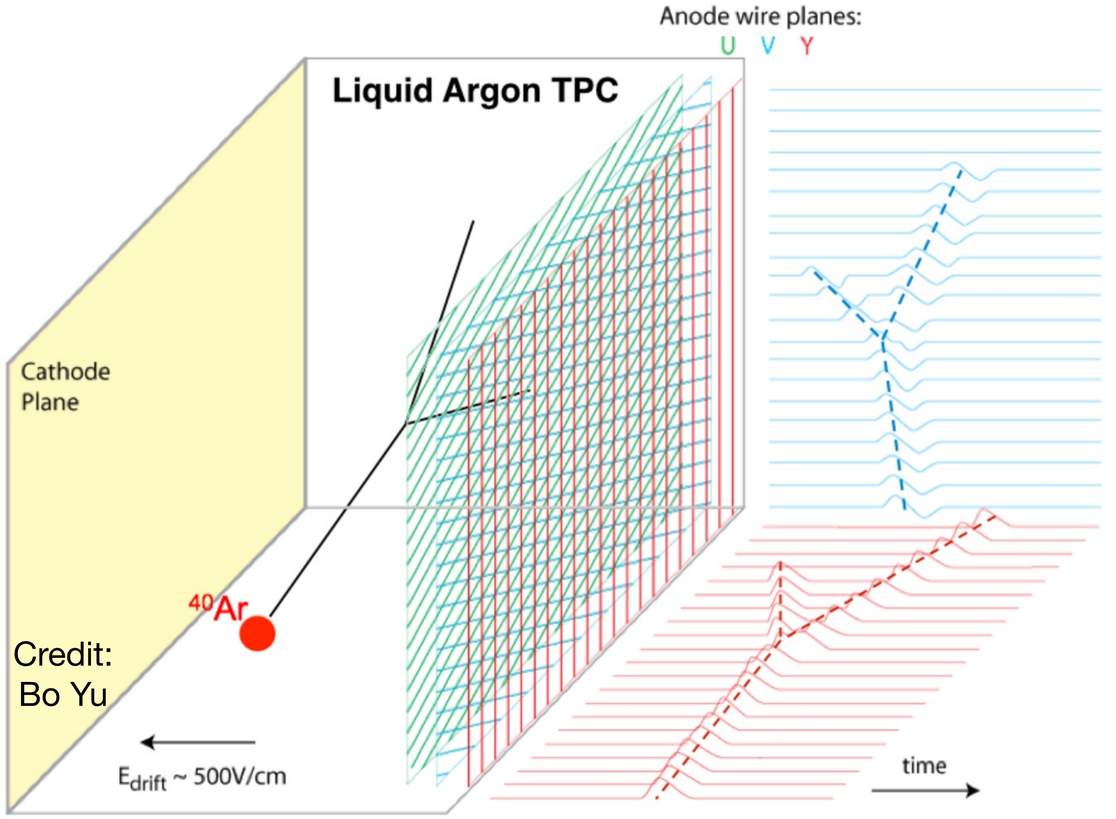
BSM mode which could yield low E excess and may be explored with LAr TPCs e.g. (P. Machado slides)



P. Abratenko et al. (MicroBooNE). PRL **130**, 011801 (2023)

The LAr TPC detector

- Liquid Argon time-projection chamber: mechanism for enabling power tracking and calorimetry
- E-field drifts ionization to wires (~ms) to measure tracks/showers: wires w/ mm spacing yield fine tracking resolution
  - Strength proportional to energy deposition
  - **Precision measurements, e-γ separation ability**
- Scintillation much faster (ns-μs) and can provide (at minimum) triggering and background rejection
- LArTPCs are being used in the current-generation short-baseline studies, and will power the next-generation measurements at DUNE



R. Acciarri et al. arXiv:1503.01520

"Traditional" photon detection in LAr TPC: PMT with TPB, ICARUS

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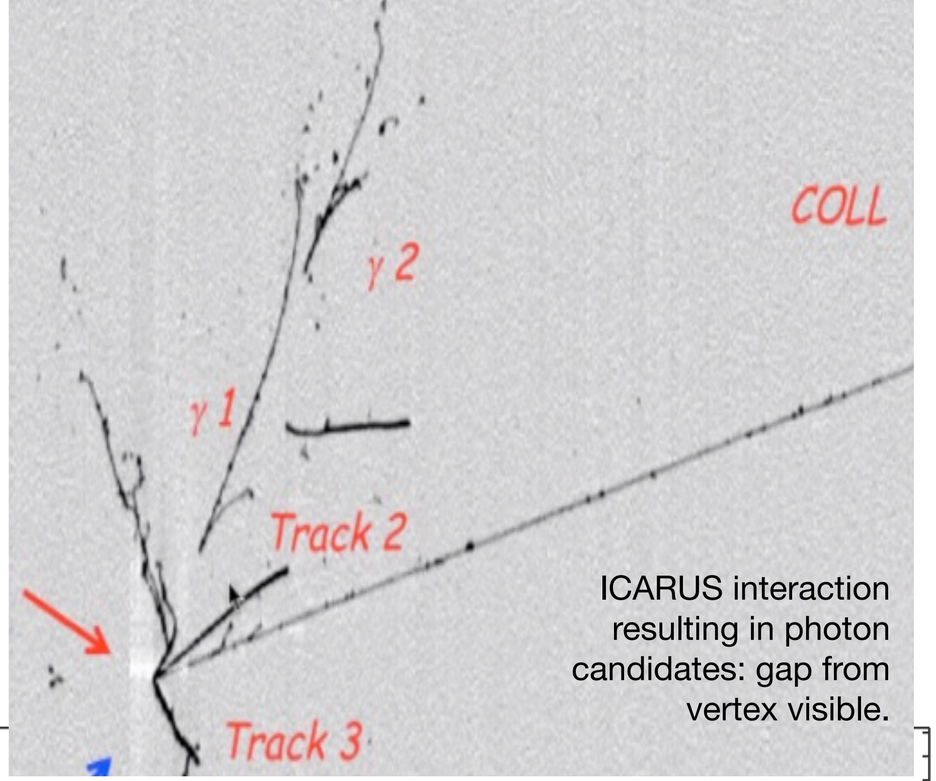


ICARUS interaction resulting in photon candidates: gap from vertex visible.

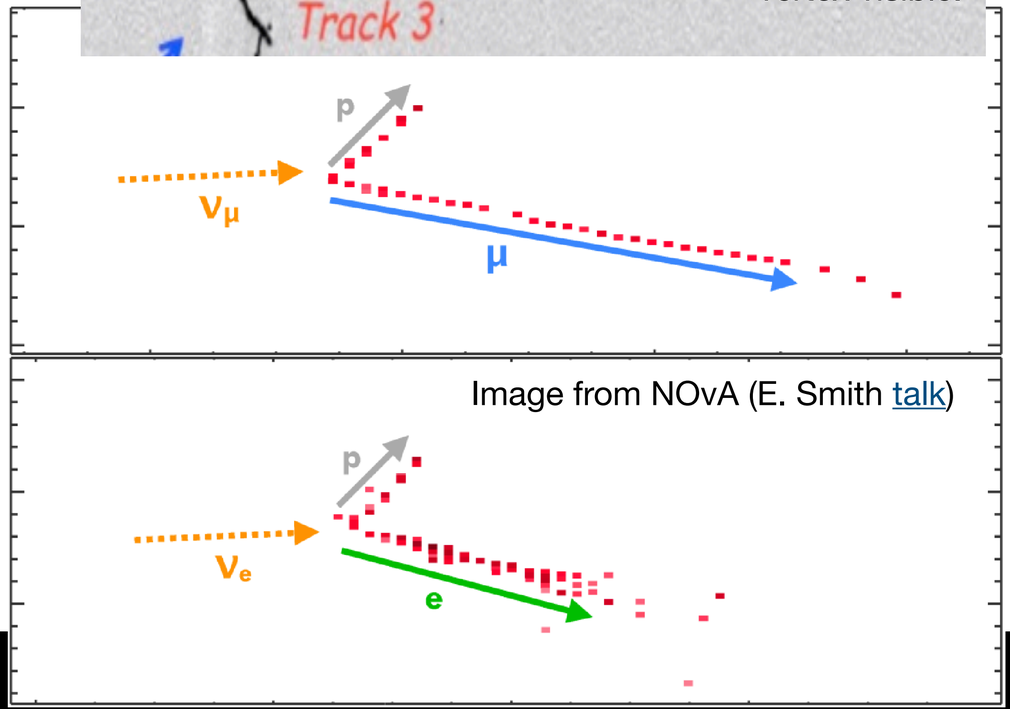


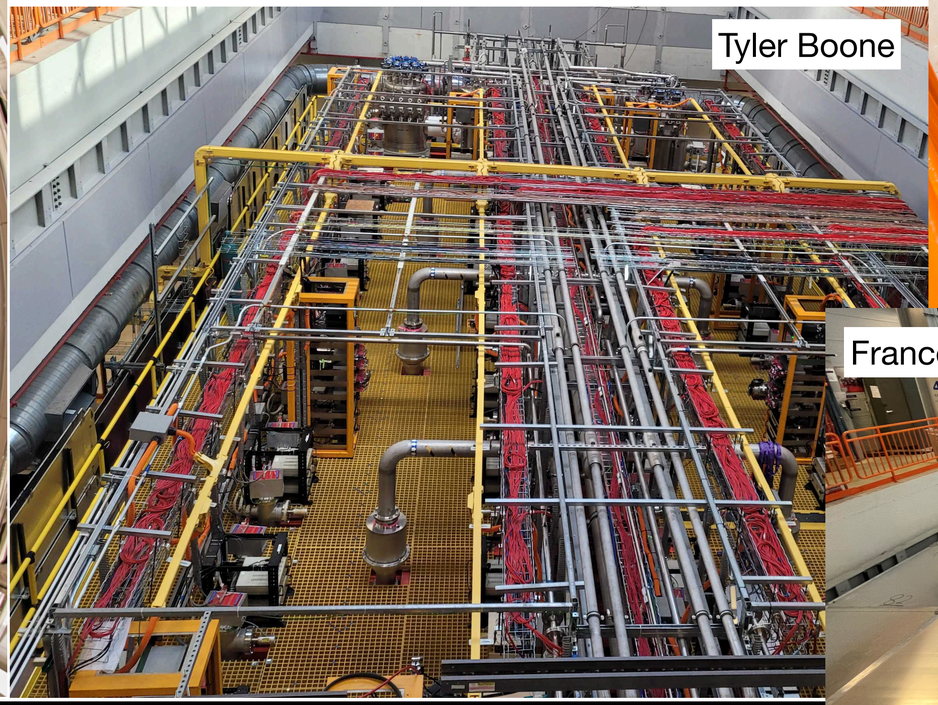
Image from NOvA (E. Smith talk)

ICARUS @ FNAL

- 760 t LAr (476 t active): 2 modules, each 19.6 x 3.6 x 3.9 m^3
  - 2 TPCs per module w/ drift distance ~1.5 m
- 90 PMTs per TPC (tot: 360): trigger, match w/ other systems t
- Cosmic ray tagging system: reject cosmics

FNAL VMS

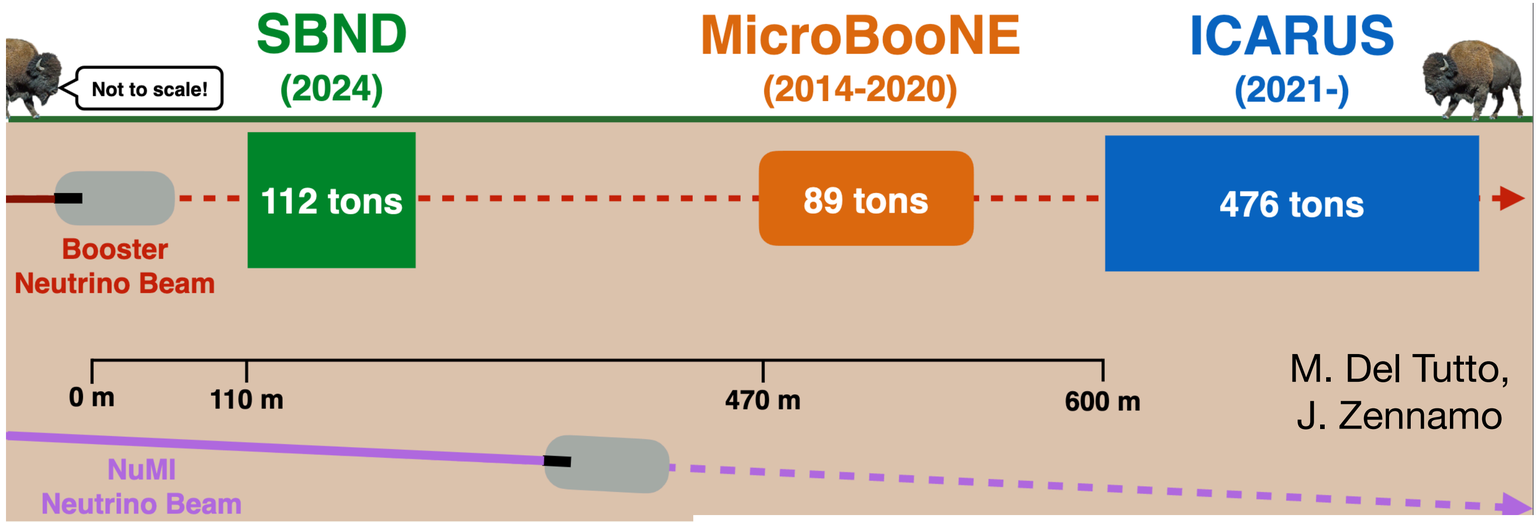

Photo: CERN

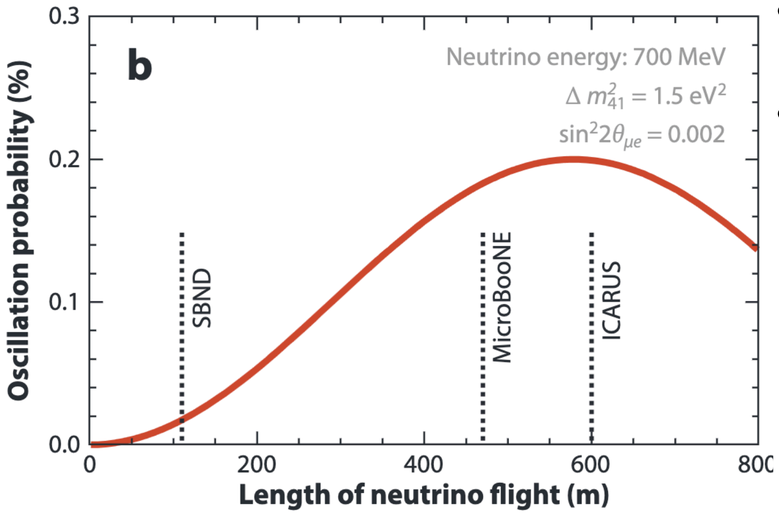

Tyler Boone


Francesco Poppi

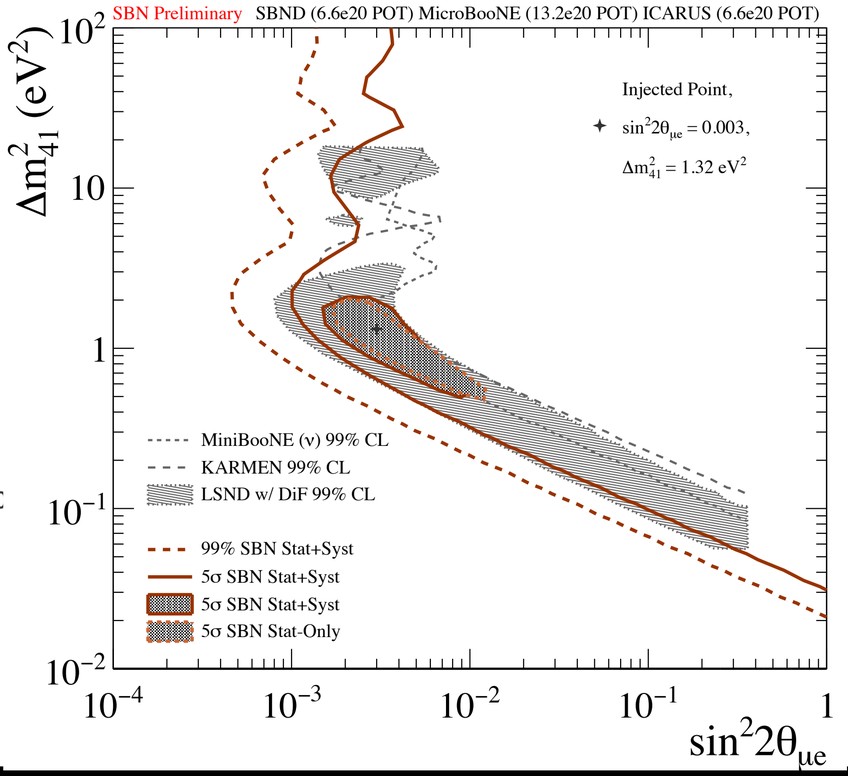
FNAL SBN Program

- 3 **LAr TPC** detectors along BNB beam
- MicroBooNE already took data and made measurements, **SBND and ICARUS will operate simultaneously**
- Allows oscillation measurement like long-baseline, 3-flavor studies
  - SBND=near det, ICARUS=far det
  - **Main capability to study both ν_μ disappearance & ν_e appearance**
  - Can also probe ν_e disappearance (intrinsic component, or NuMI off-axis at ICARUS)
- Utilize LArTPC capability for tracking and particle ID and by virtue of being this sensitive detector, **powerful for BSM searches**



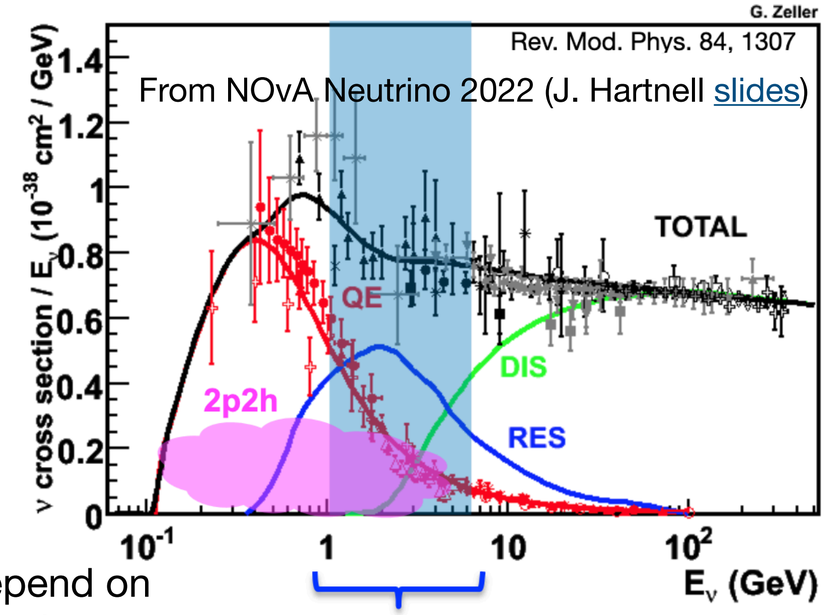


Possible oscillation signature under a set of parameters. P. Machado, O. Palamara, D. Schmitz. Annu. Rev. Nucl. Part. Sci. (2019). doi: 10.1146



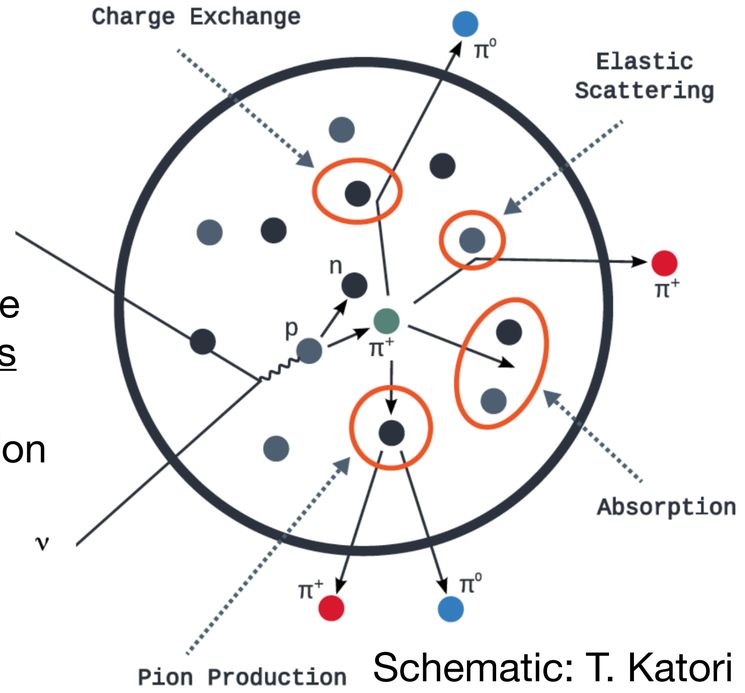
Preparation for next-gen

- SBN detectors will provide other **crucial** pieces for **next-generation measurements with DUNE**:
  - Gain **experience with LAr TPC detectors** and perform **detector physics** studies
  - **Validate and improve neutrino-Ar interaction modeling** before DUNE comes online
- Use of near detector confines overall rate (flux) systematics that would otherwise be large
  - **Interaction related uncertainties still large, especially w/ expected increased statistics**
- Reliance on **generators/models** predicting impact of different interaction-related effects (e.g. Near-Far rate differences and ability to resolve E_ν)
  - More studies to inspect model disagreement & drive further development, especially w/ Ar



Particles/yields depend on mode, therefore so does energy resolution.

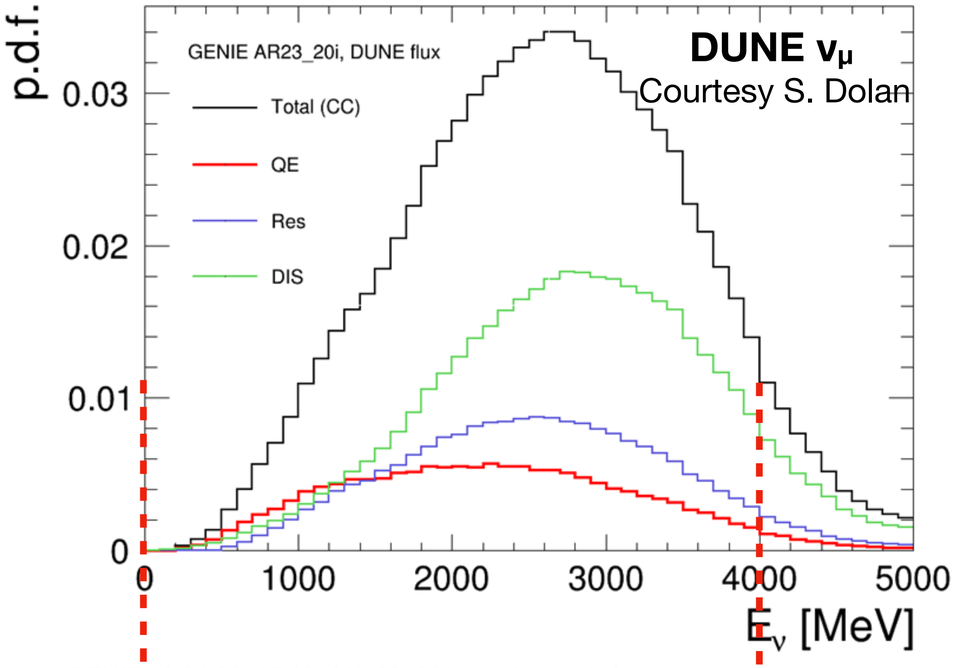
FSI may either alter the energy we see, or <u>miss</u> particles entirely (absorption, or reduction to below thresholds)

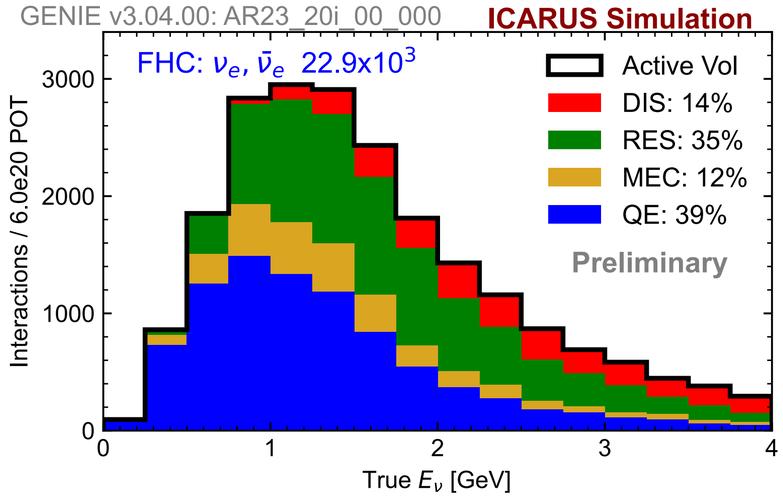


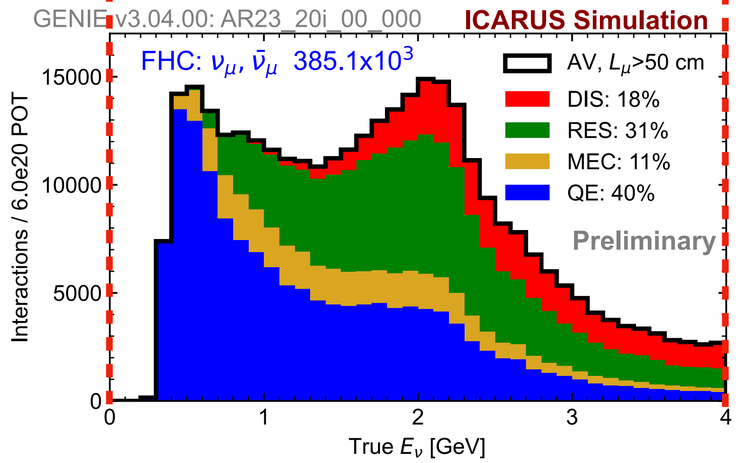
Schematic: T. Katori

NuMI ν Interactions in ICARUS

- ICARUS off-axis of NuMI, ~800m from target: 100s MeV to few GeV range. Due to kaons, also see peak at ~2 GeV
- Will use these neutrinos to perform neutrino interaction studies and cross-section measurements
  - Inclusive and exclusive cross-sections in various kinematic variables for muon (anti-)neutrinos and electron (anti-)neutrinos
  - Due to reasonably large ν_e rate and flux constraints, we will also target ν_e-to-ν_μ cross-section ratio

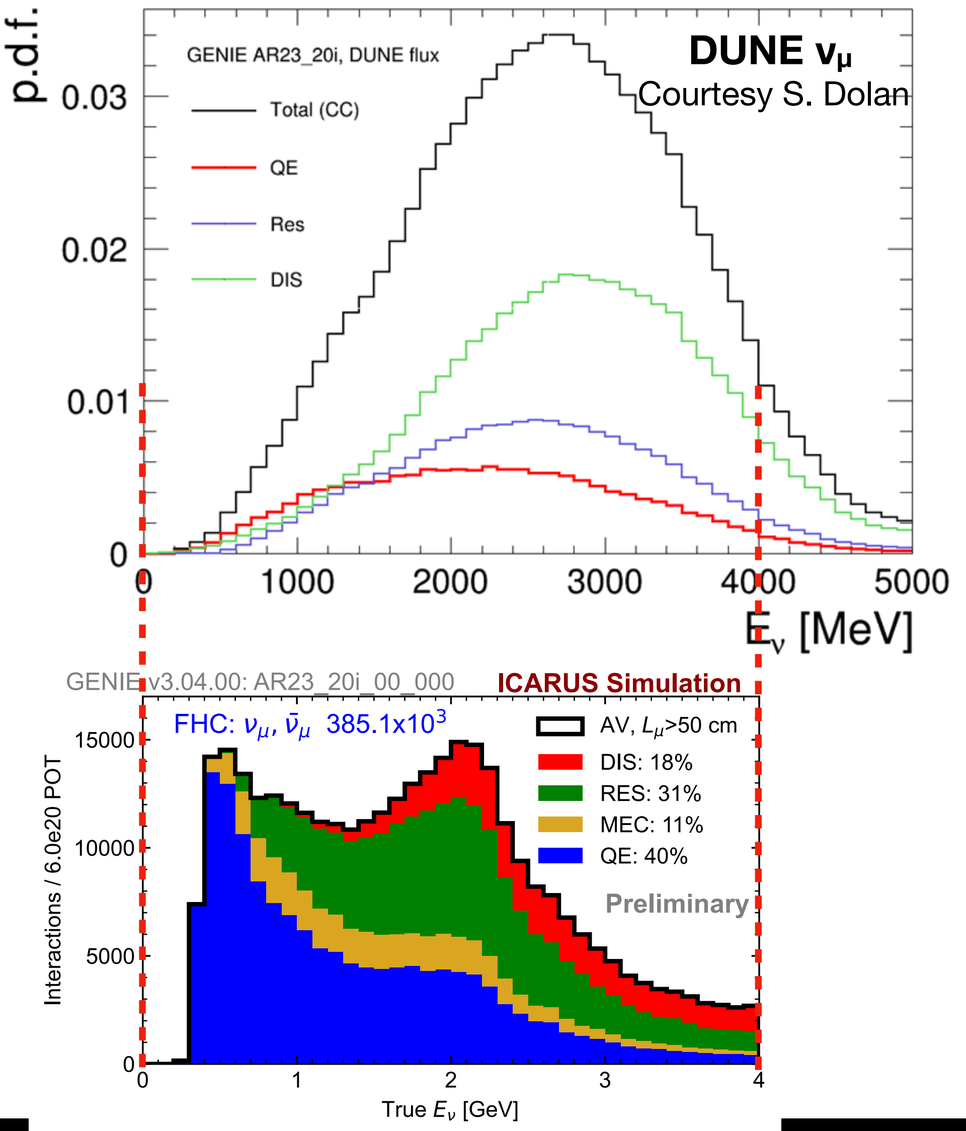






NuMI ν Interactions in ICARUS

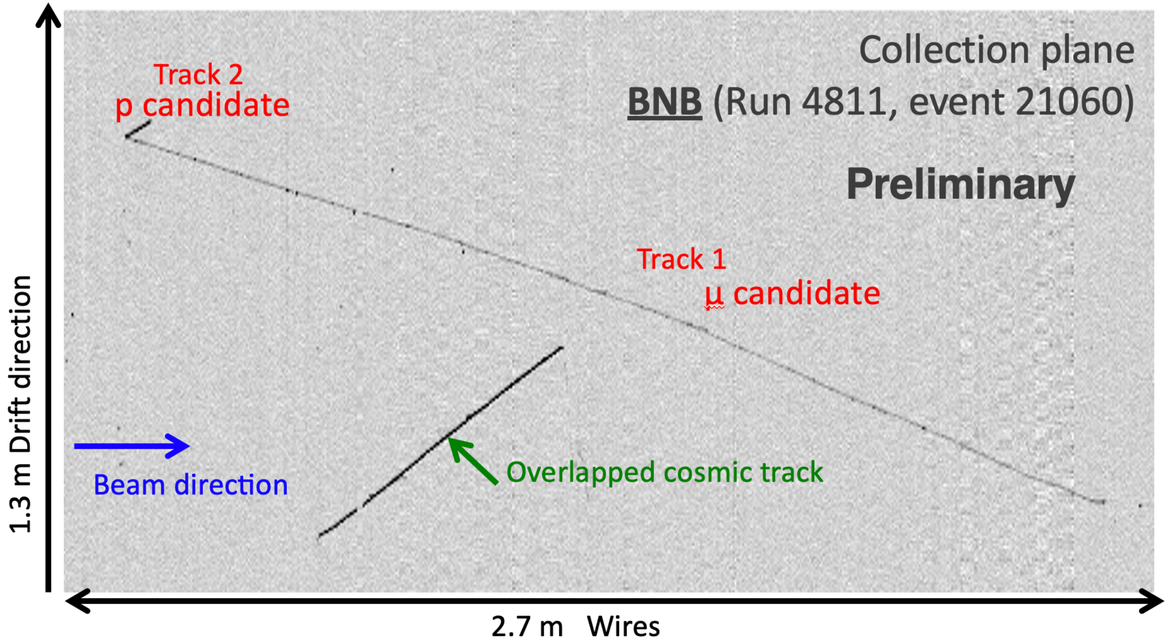
- Aim study current models and aid advance of them before DUNE turns on, but also to use commonalities to better share developments between experiments:
  - Unified **GENIE base model between SBN detectors and DUNE**: choice of model which is also re-weightable to other models
  - Use of **nusystematics** framework for interaction uncertainties initially developed by DUNE. We can feed back to this based on our findings.
  - **PPFX** used to constrain flux expectations, also used by MINERvA and NOvA (other experiments using NuMI)
  - Similar software environment and analysis frameworks enable further sharing of developments as we make measurements

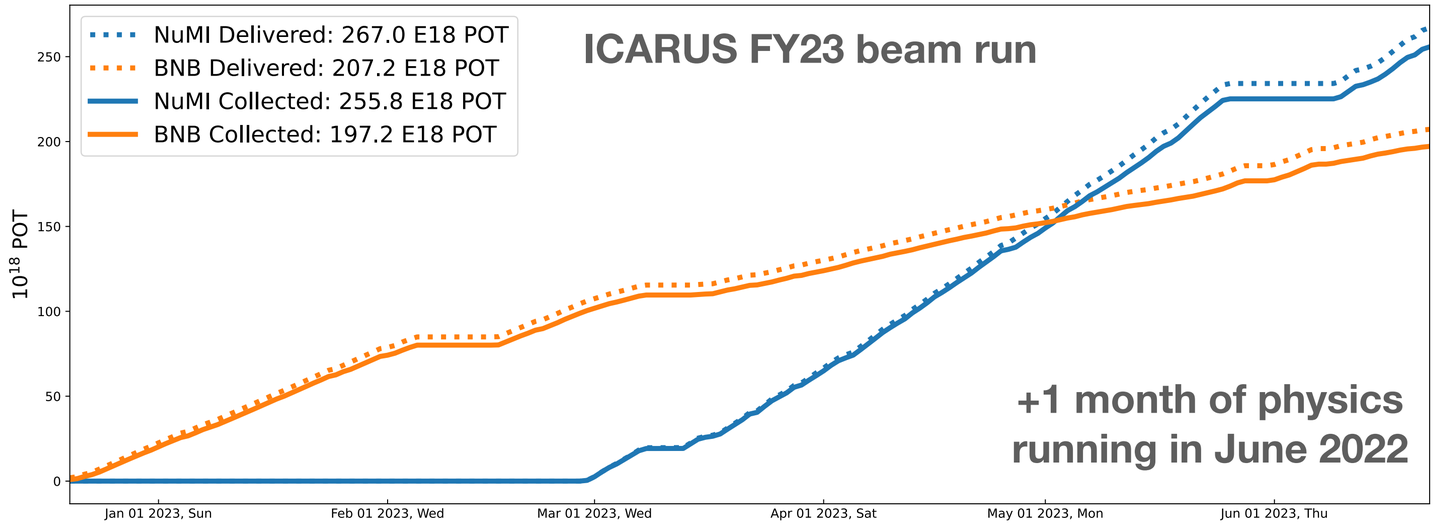


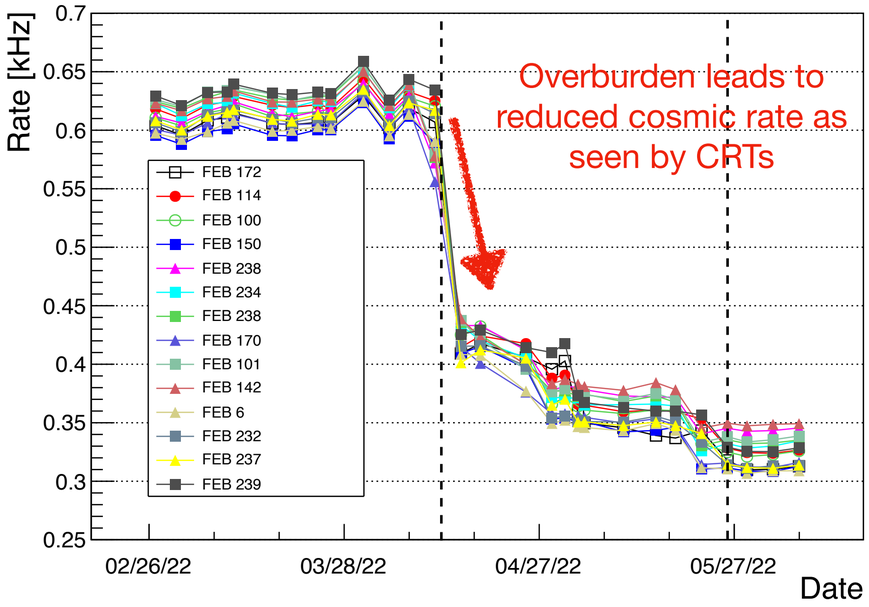
Now to make all that happen…

ICARUS Operations

- ICARUS first filled & activated during pandemic in 2020 and commissioning commenced
- Simultaneously, remaining installations (namely CRT & overburden) were taking place
- Physics quality data began upon completion of these activities in June 2022:
  - Now completed one year of physics data

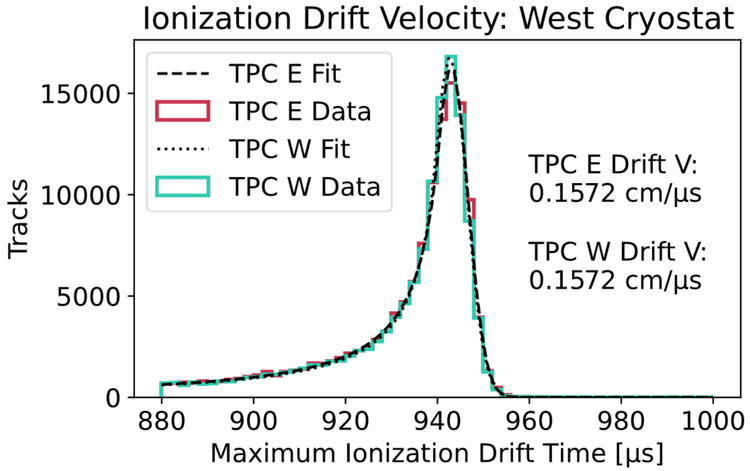


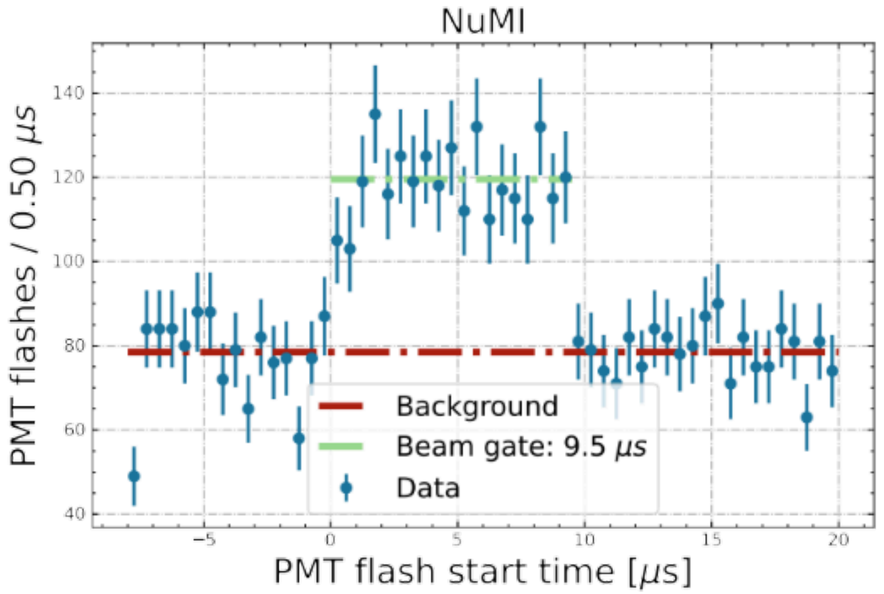


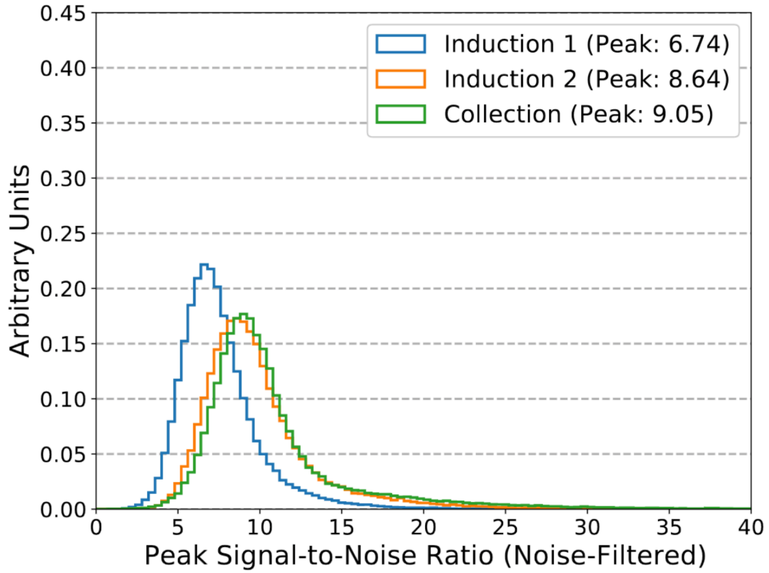


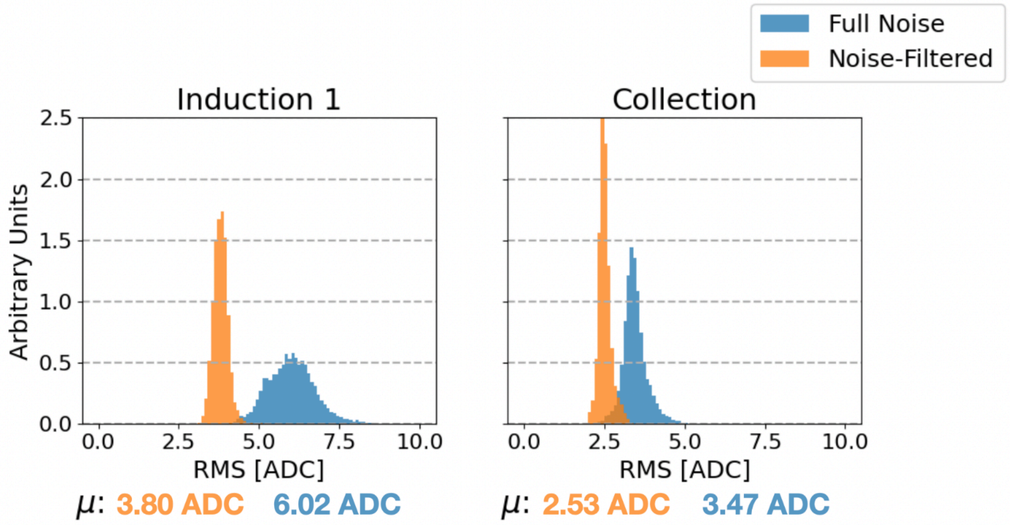
Performance/Initial Studies

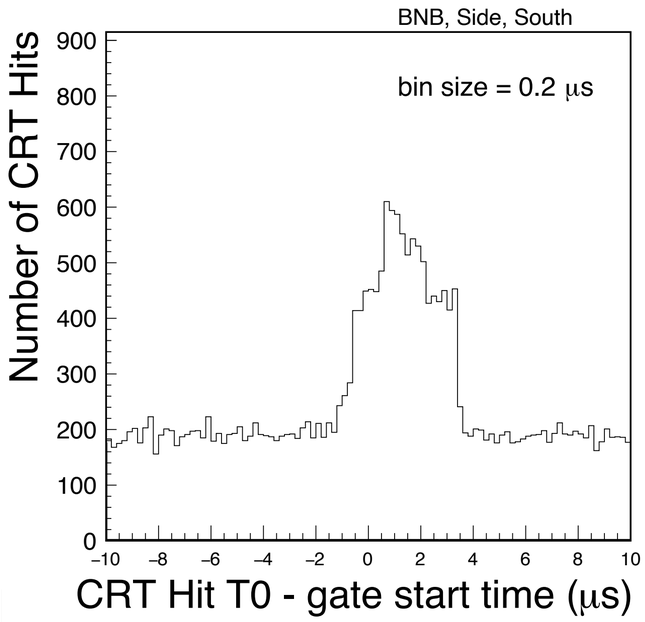
- The different subsystems have undergone a set of commissioning & characterization studies to detail their performance
- Eur. Phys. Journal C **83**, 467 (2023)











TPC Reconstruction

Decoding
Unpack data and turn it into a raw form that can be used in later steps

Deconvolution
Remove effects of field & electronics responses

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

Gauss Hits
Hits formed from the deconvolution chain

Cluster3D
Keep hits consistent with 3d points (SpacePoints)

Pandora
Cluster, Slice, Pattern Recognition

Machine Learning Reco

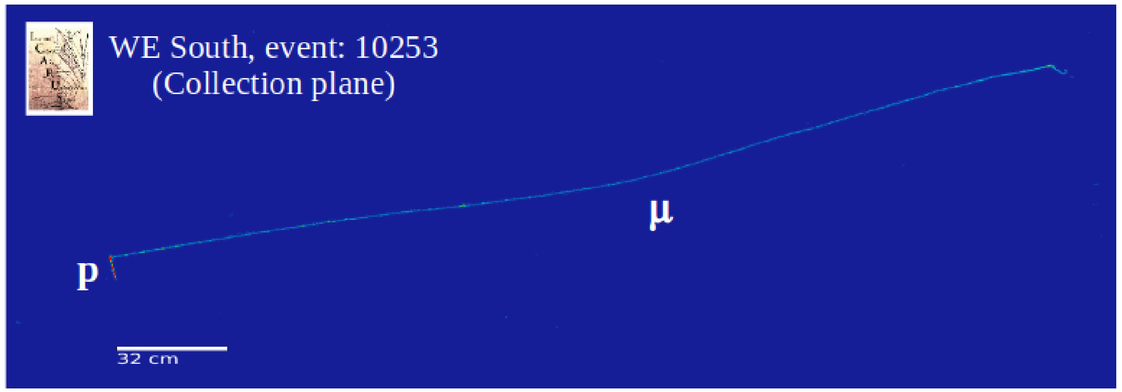
https://github.com/PandoraPFA

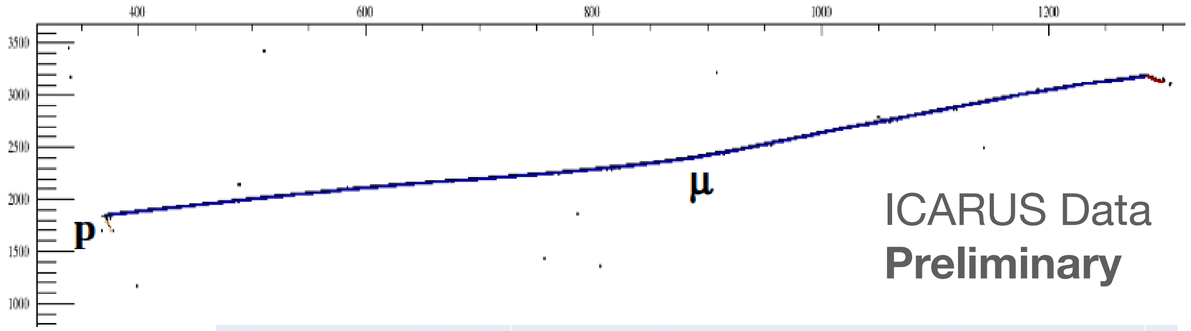
https://github.com/DeepLearnPhysics/lartpc_mlreco3d

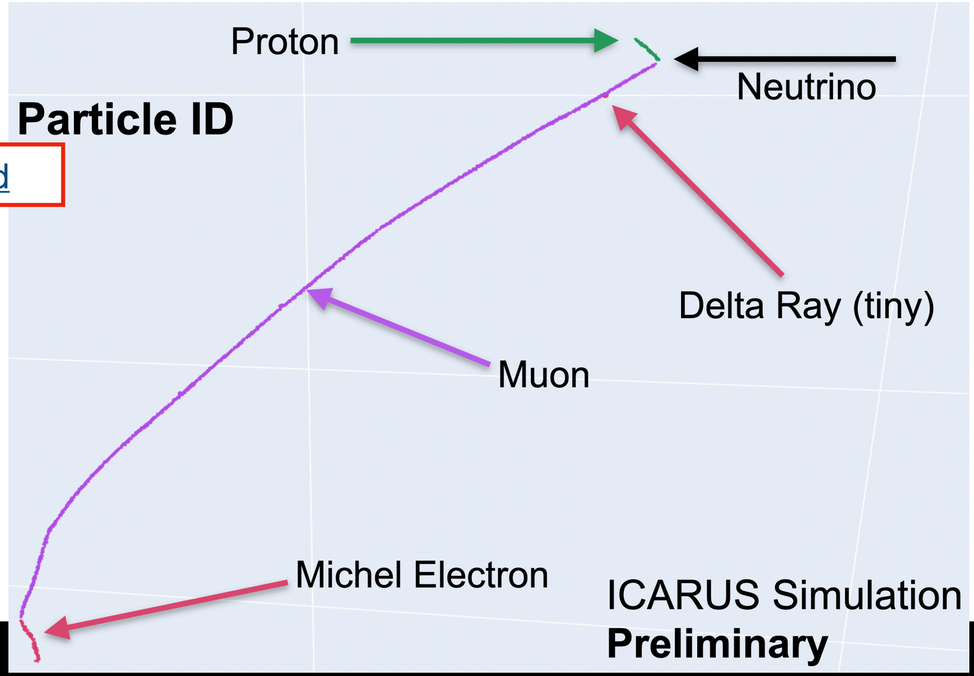
Track Reco & downstream reco like calo

Shower Reco

ANALYSIS



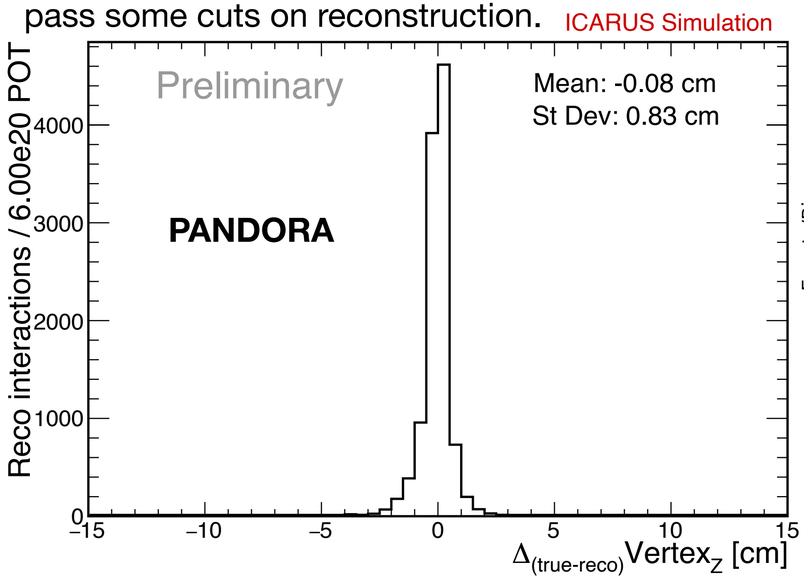


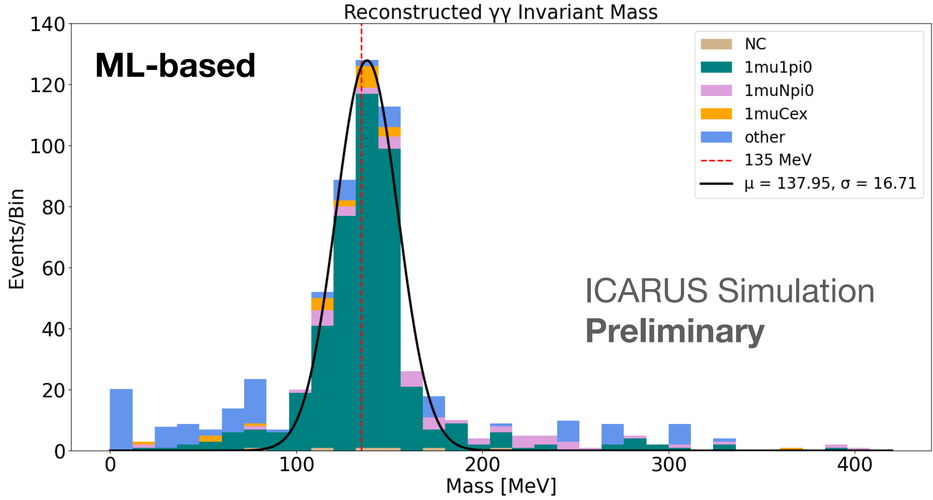


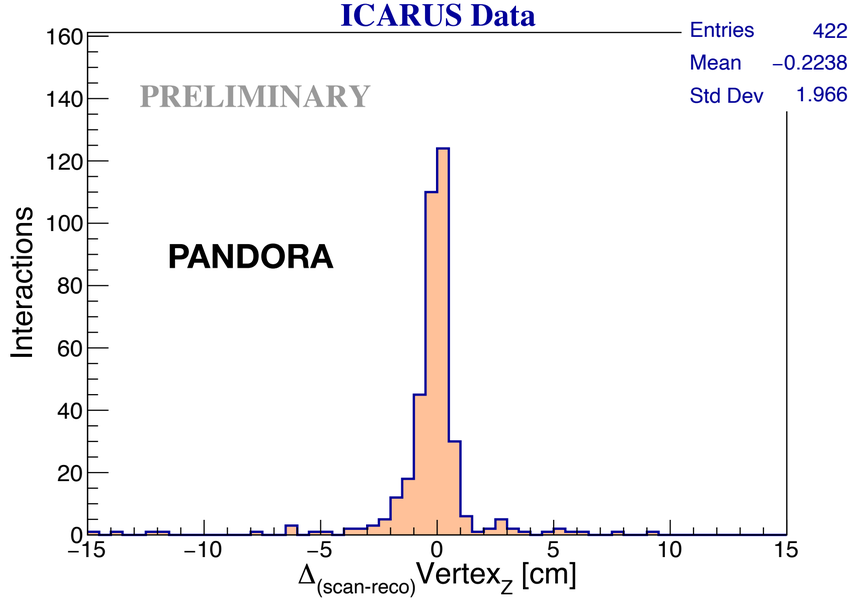
TPC Reco

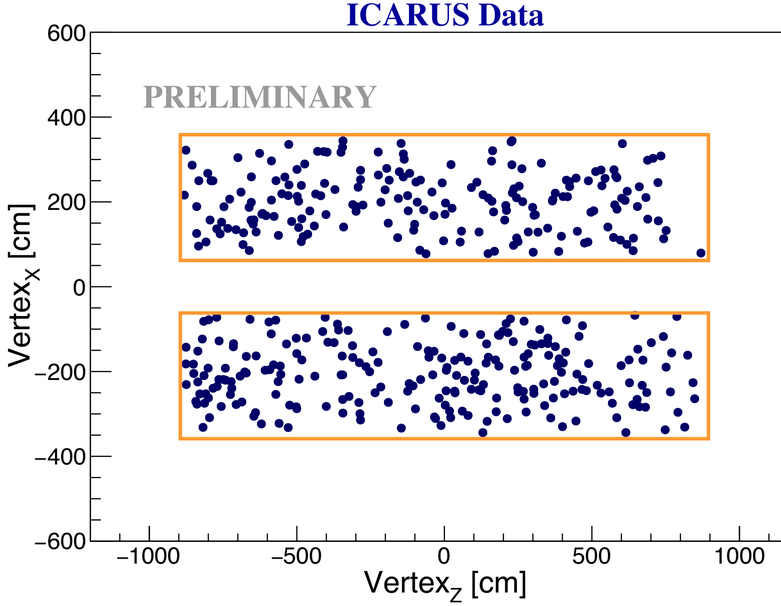
- Use simulated samples of events, cosmic data, etc. to investigate the reco chain
  - Coordination w/ **hand-scanning** effort has provided very useful set of candidates to explore
  - Enabled also to check quality and ID areas needing improvement
- Vibrant groups working with Pandora & ML-based reco

Set of MC events with a muon and proton that pass some cuts on reconstruction.





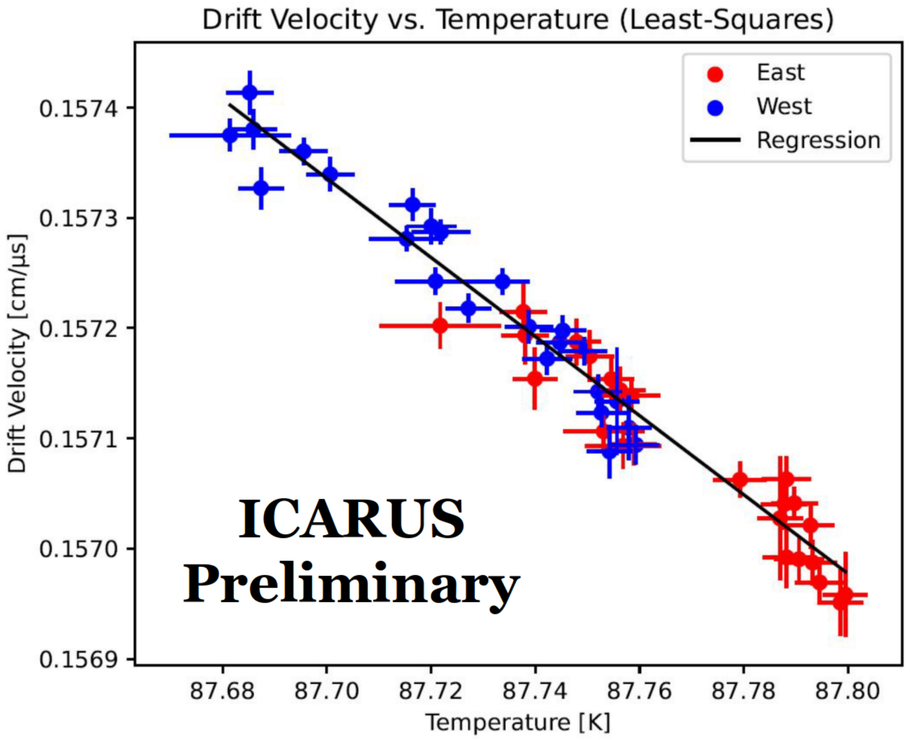


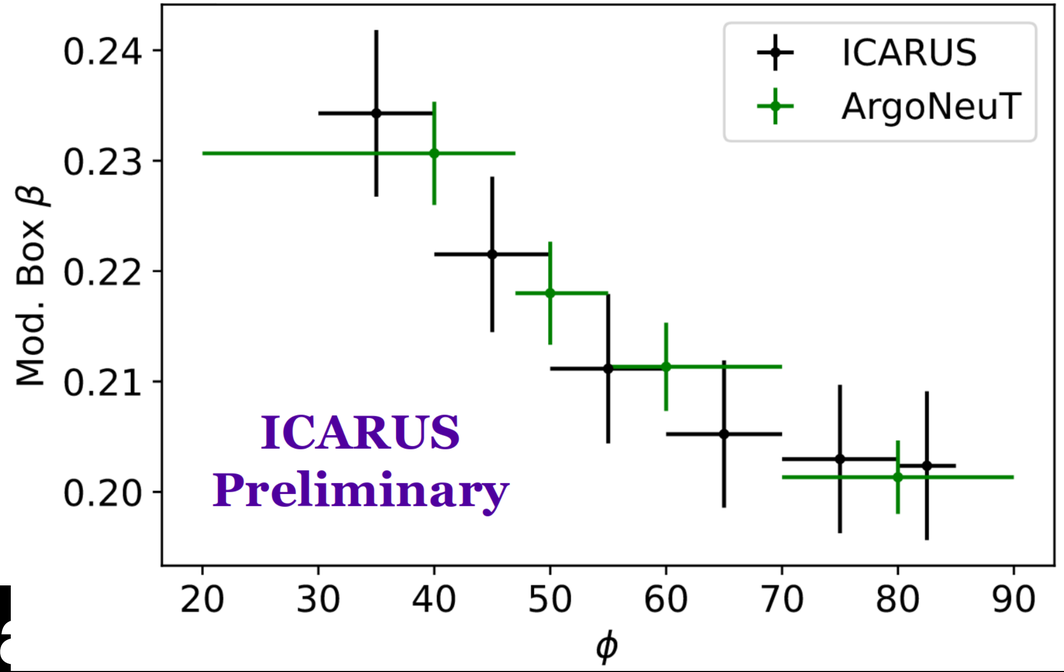


Plots investigating a set of hand scanned DATA events for similar reconstruction quality checks (Note that some of the same signal and reco quality cuts not made here.)

ICARUS Detector Physics

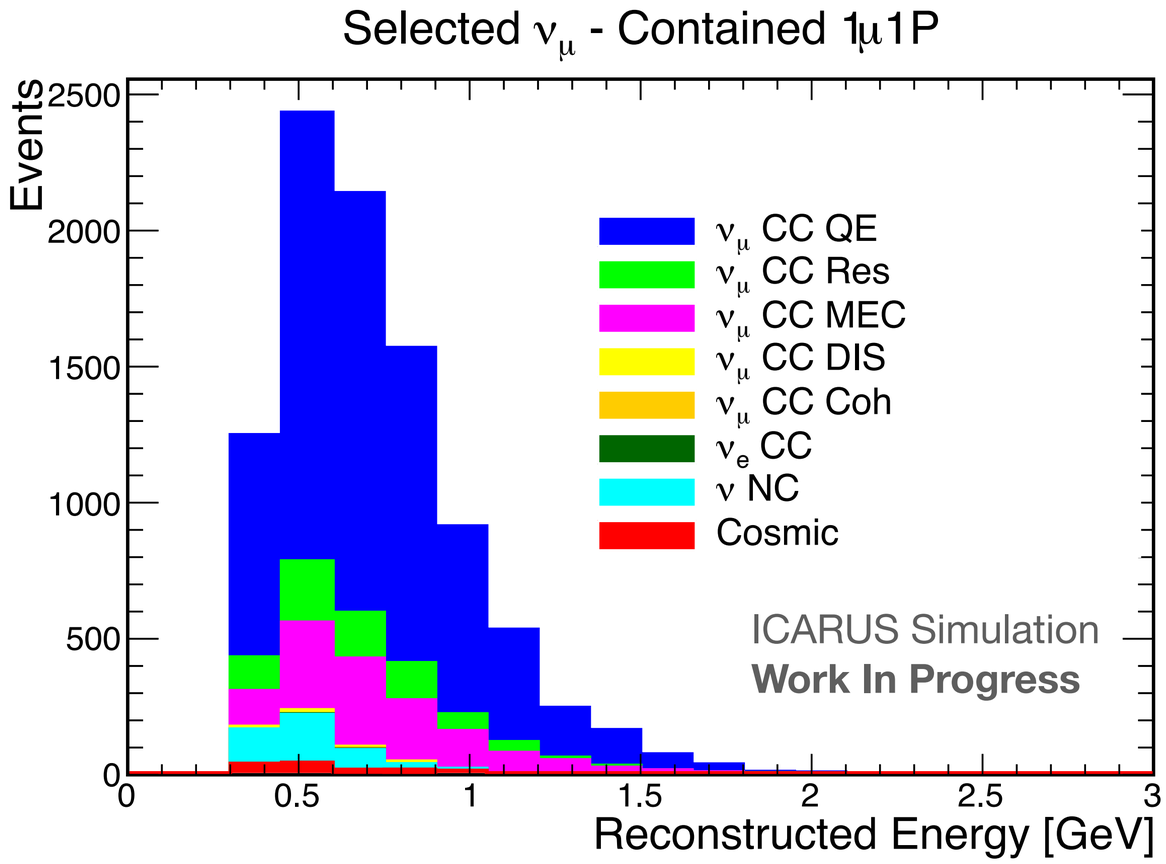
- Calibration group not only making energy scale calibrations but also using data to study and better understand the physics of LAr TPC operation
- Few examples of recent progress:
  - Electron drift velocity in TPC depends on LAr microphysics (T, ρ, etc.): a study was performed
    - Pressure sensors used to give temperature
  - Angular dependence of recombination
    - Impacts charge seen at wires → calorimetry
    - Recombination with (modified) box model: $dE/dx = (\exp(\beta W_{ion}*(dQ/dx))-\alpha) / \beta$
    - Results in agreement with ArgoNeuT study
    - Aids in proton calorimetry and particle ID
  - Also studies of transverse diffusion of e^- & more





Progress Toward Oscillation Analysis

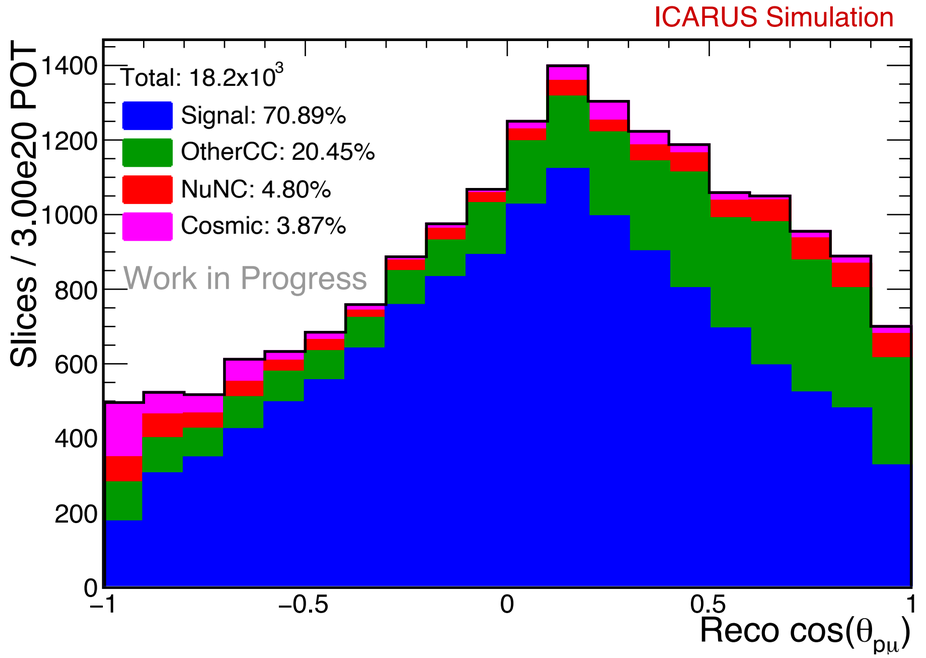
- Actively working toward our first neutrino physics analyses using this data
- First analysis is targeting fully contained 1μ+1p sample for ν_μ disappearance search with short baseline (BNB beam) at ICARUS [~600 m]
  - Expected sensitivity of this early analysis would include the Neutrino-4 reported region of interest
  - Targeting relatively high purity: containment & matching with other subsystems (e.g. PMTs)
  - Contained 1μ+1p should prioritize cleaner events where energy reconstruction would be expected to perform better early on
  - Work ongoing to perform analyses with both Pandora-based & ML Reco-based selections
  - Matching of PMTs to cosmic ray taggers promising to filter exiting ν from entering cosmics (using Δt)

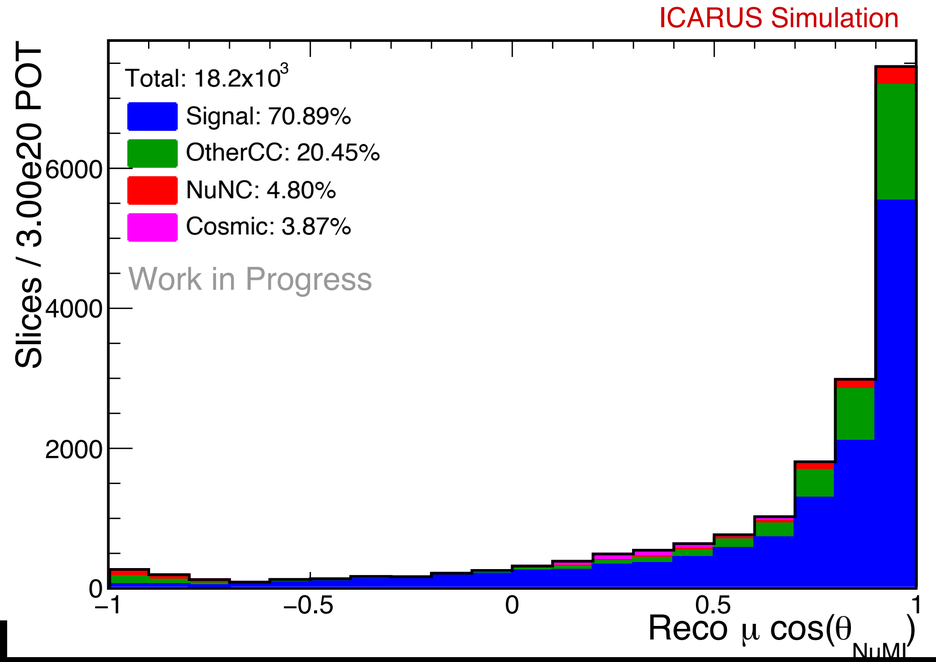


Showing plot from Pandora reco-based selection

NuMI Cross-Sections

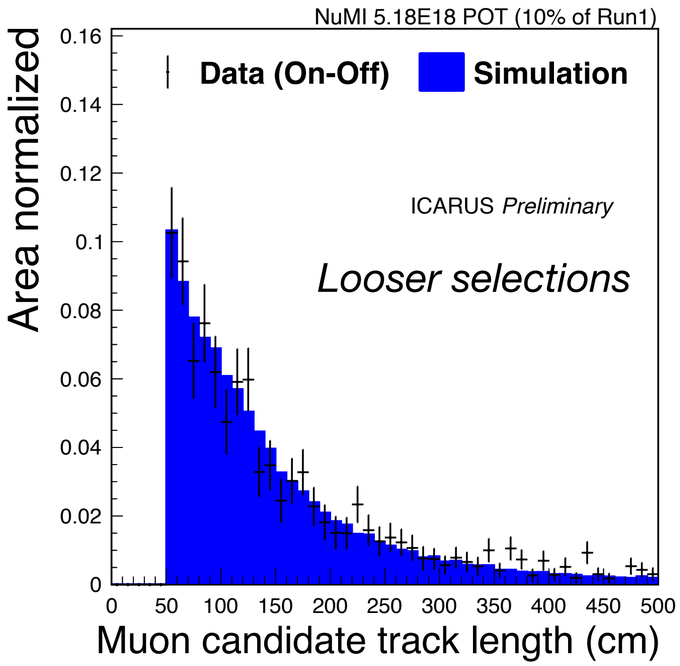
- Building up cross-section analysis to conduct model investigations detailed earlier
- First analysis targets 1(anti-)mu + Np + 0π
  - 1μ+Np+0π enhanced in quasi-elastic and 2p2h interactions, similar to osc should be somewhat “cleaner” as a first target but still provides interesting physics
  - Angle between the muon candidate and leading proton candidate populates the phase space somewhat broadly and would be expected to encode information about FSI
    - Reconstruction shows pretty good reco-true agreement
- Building up framework & workflow for end-to-end cross-section analysis, providing basis for future work
  - Selection is aimed to pick out 1μNp0pi events and reject backgrounds (e.g. pions)
  - Expect ~20k selected events at current selection & exposure

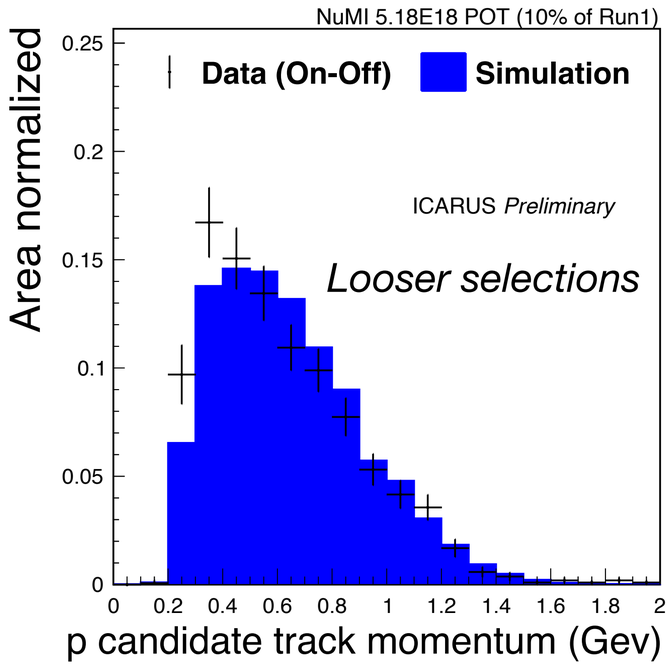


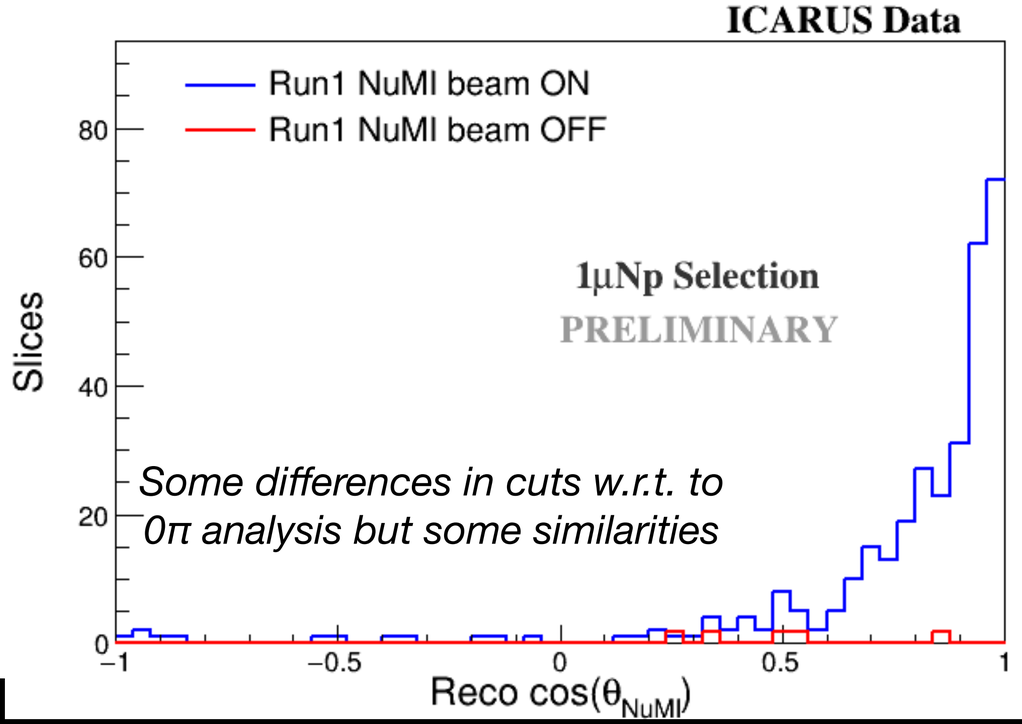


NuMI Cross-Sections

- Have also taken looks at some samples of data:
  - A selection targeting 1μNp+anything with some differences in cuts investigated w/ data samples to highlight cosmic rejection power and that selected beam events do peak with muon in forward direction
  - data/MC studies ongoing: shown here some relaxed cuts area normalized, fairly reasonable comparisons
  - Working towards systematics studies needed to address and adjust detector uncertainties/reco
- Measuring backgrounds/sidebands for analysis (e.g. charged pions, neutral pions by inverting cuts)

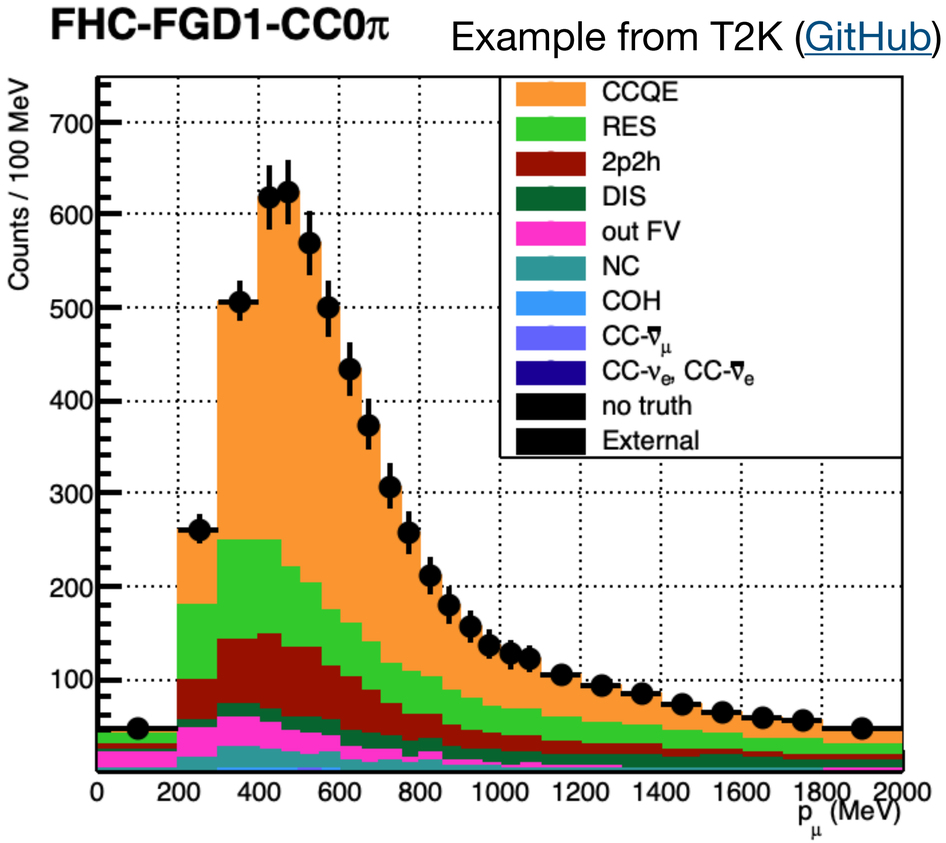






NuMI Cross-Sections

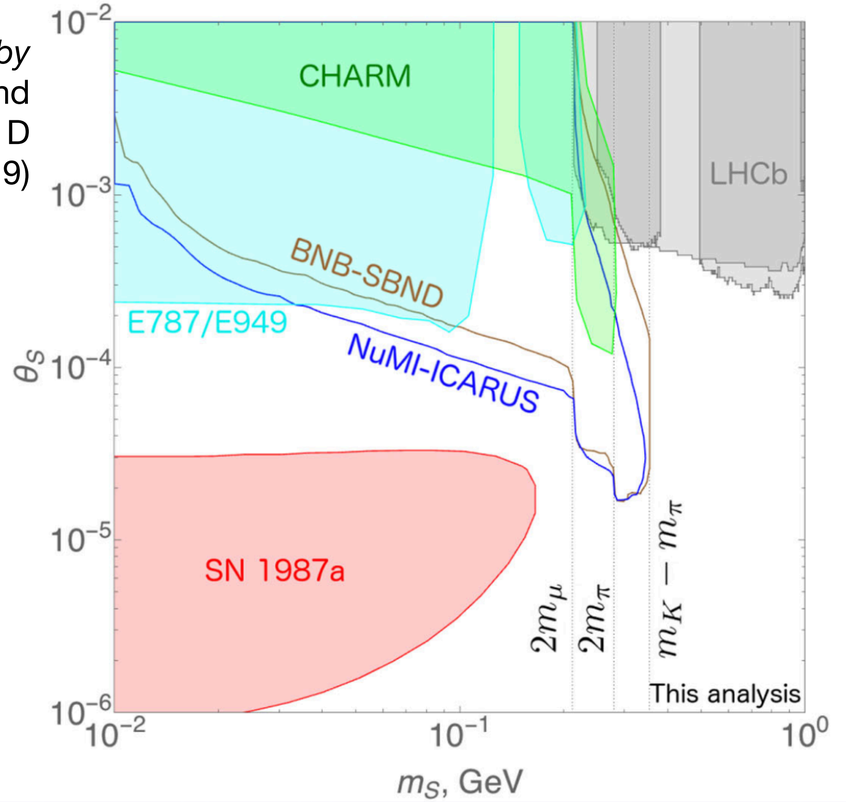
- For the fit and cross-section extrapolation (also relevant to future cross-section analysis), we have decided to use the GUNDAM fitting tool developed by T2K which is now open source
  - Generic fitter for Upgraded Near Detector Analysis Methods
  - Implementing into our workflow and analysis, including upgrades to framework for handling external fitters
  - GUNDAM allows use of uncertainties based on splines and covariance matrices, enables us to feed in systematic uncertainties in different ways
    - Flux systematics based on PPFX, cross-section uncertainties closely tied to DUNE, Geant4 systematics based on DUNE/MicroBooNE
    - Detector systematics will follow
  - With similar computing environments & software, believe similar workflow can be explored in DUNE

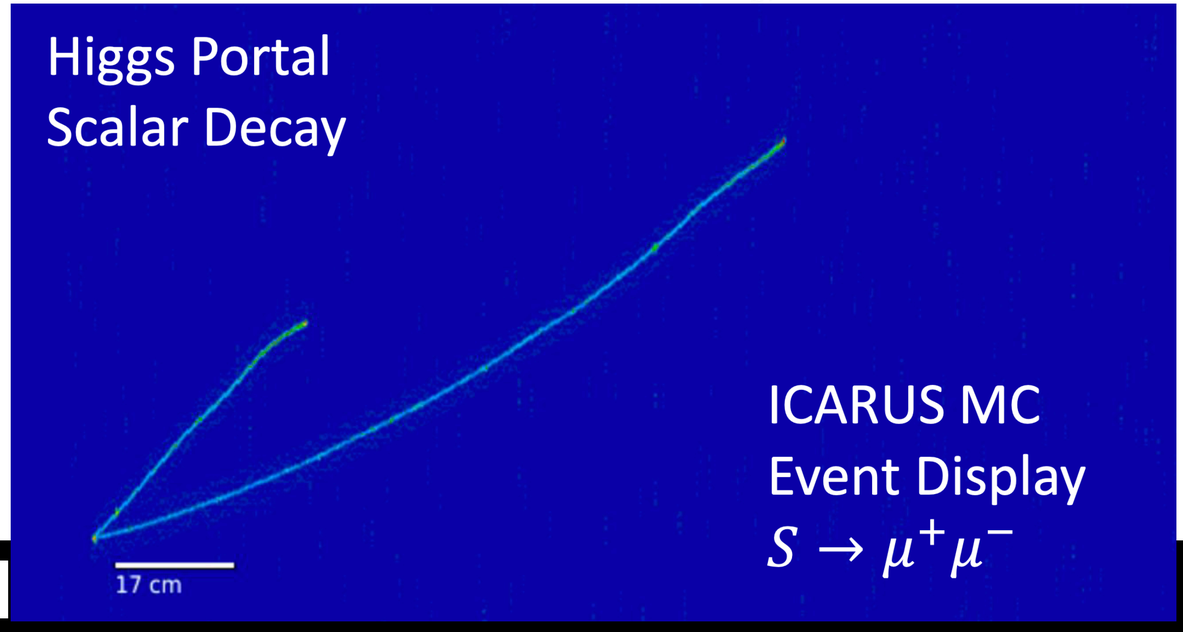


NuMI BSM Searches

- As powerful beam off-axis and using LAr TPC tracking & calorimetry, also searching for Beyond Standard Model processes especially using NuMI beam at ICARUS
  - Enhanced by pointing capability, e.g. pointing back to target or beam dump
  - Looking for light dark matter, Higgs portal scalars and other “long lived particles”
    - Look e.g. via searches to $l, \bar{l}$ pair
- Early analysis on Higgs portal scalar to $\mu, \bar{\mu}$ is well on the way and a number of others are progressing

Phenom. study by Batell, Berger, and Ismail. Phys. Rev. D **100**, 115039 (2019)





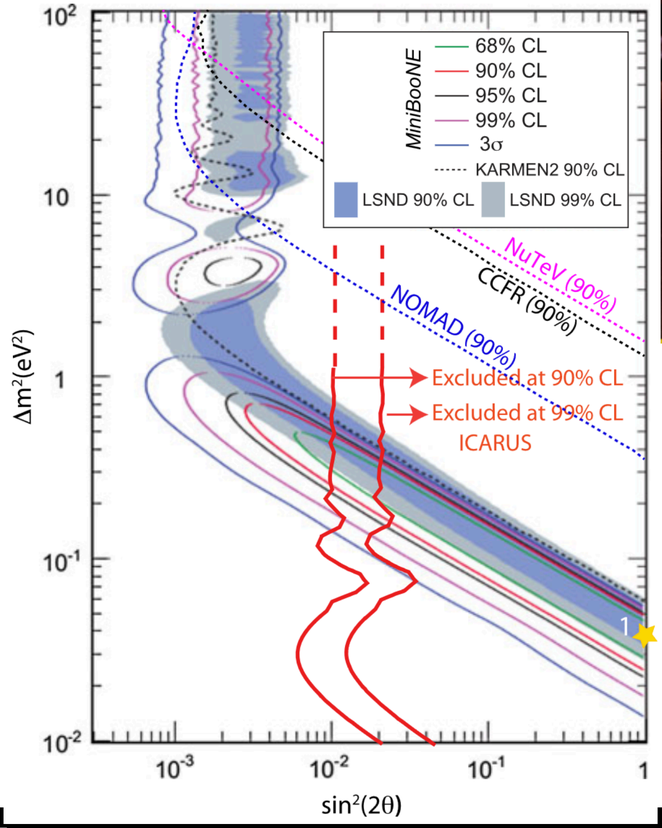
Summary and Conclusions

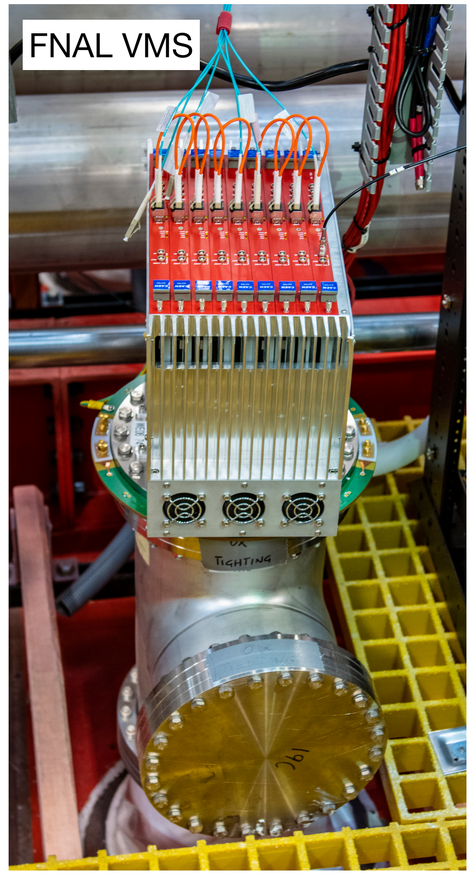
- Neutrino oscillation provides a number of open questions that require investigation and unresolved anomalies from LSND and MiniBooNE could be signs of sterile neutrinos or other BSM physics:
  - ICARUS and the Fermilab Short Baseline Neutrino Program can probe anomalies
- DUNE will be a next-generation oscillation experiment using same detector technology:
  - ICARUS will provide important experiences with operating and conducting analyses with LArTPC detectors, and detector physics measurements will be directly useful for DUNE
  - Conducting neutrino cross-section and interaction measurements using neutrinos from the NuMI beam in a similar kinematic regime as DUNE: important to build better models for use in DUNE
- ICARUS underwent a period of commissioning and first operations as captured in recent paper:
  P. Abratenko et al, Eur. Phys. Journal C ***83****, 467 (2023)*
- Actively pushing forward analyses with the data collected so far and looking forward to collecting more:
  - First results of some detector physics measurements highlighted
  - Remarked on progress towards oscillation measurements
  - Presented status and ongoing work to conduct 1μ+Np+0π ν-Ar cross-section analysis

Backup

ICARUS & History of LArTPC

- 1970s: ideas of TPC (D. Nygren, 1974), LAr as calorimeter (W. Willis & V. Radeka, 1974), & LAr TPC (C. Rubbia, 1977)
- 1985: ICARUS collaboration works to realize LAr TPC
- By mid 1990s: work and tests were being done with progressively larger prototypes
- 2001: technical commissioning run of T600 module conducted in Pavia, Italy
- 2010-2013: T600 module operated in nu beam from CERN: Gran Sasso (LNGS), Italy
- Mid 2010s: T600 module at CERN for upgrades
- 2017: ICARUS moved to FNAL
  - First large LAr TPC, still one of largest in operation
- Late 2020s: next-gen oscillation experiment DUNE will comprise 10s of kilotons of LArTPC detectors





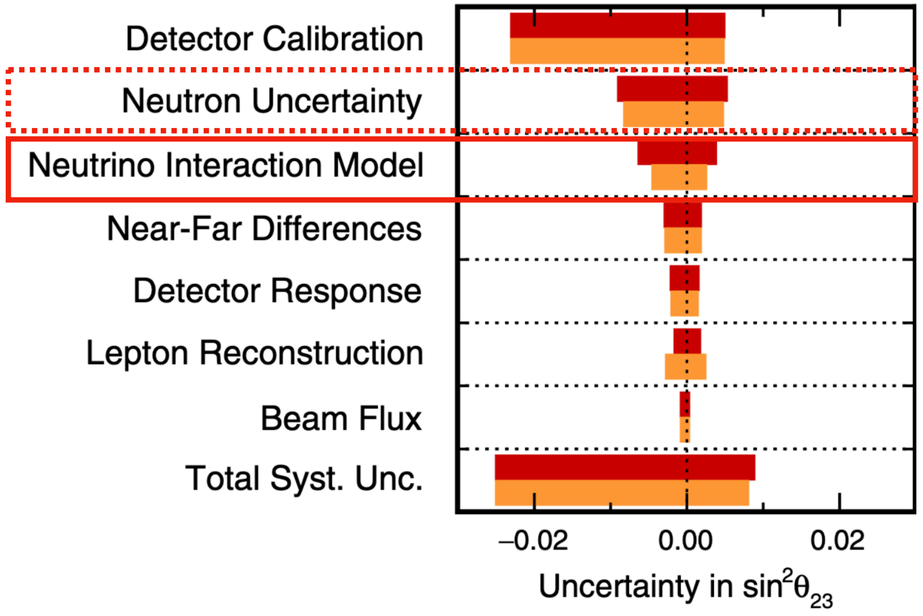
ICARUS at LNGS

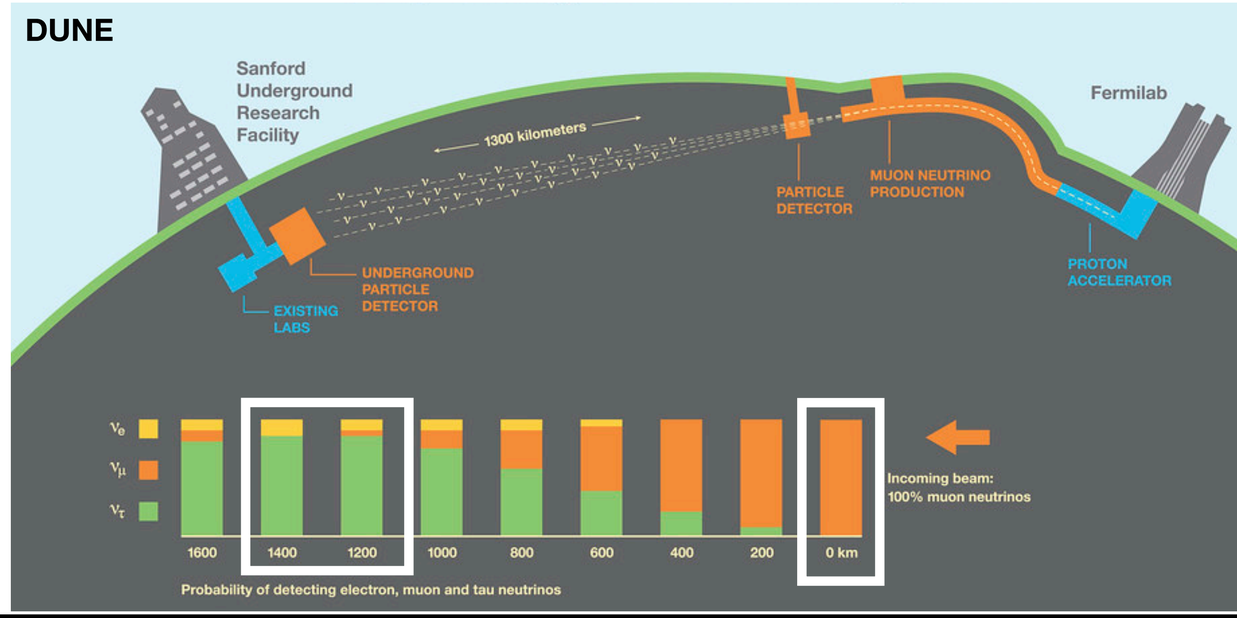
M. Antonello et al. Eur. Phys. Journal C **73**, 2345 (2013)

Preparation for next-gen

- In addition, the SBN program detectors will provide other **crucial** pieces in preparation for the next-generation measurements with DUNE:
  - Gain **experience with LAr TPC detectors** and perform **detector physics** studies
  - **Validate and improve neutrino-Ar interaction modeling** before DUNE comes online
- Use of near detector confines overall rate (flux) systematics that would otherwise be large
  - But does not make cross-section/interaction related uncertainties negligible: still important
- For one: flux is **different** at far detector (oscillation): degeneracy in differences seen at far detector between **oscillatory effect** or **difference in ν_μ vs ν_e cross-section** relative to expectation

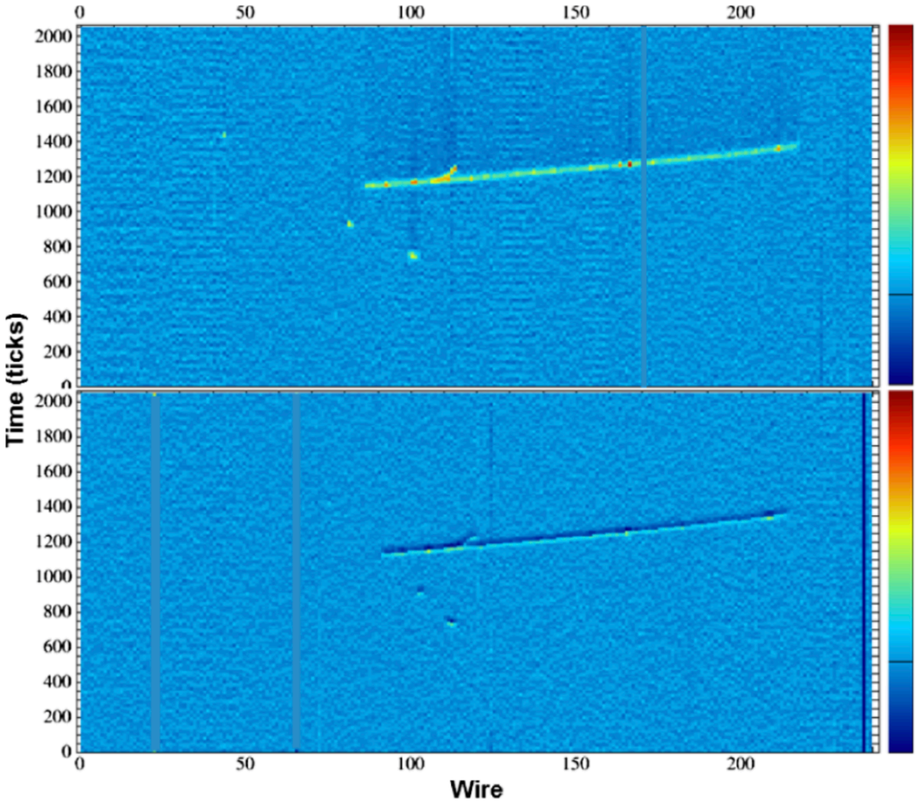
NOvA: M.A. Acero et al Phys Rev D 106, 032004 (2022)





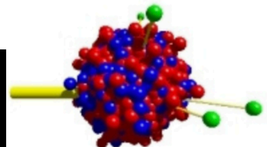
Impact of neutrino interactions/cross-sections on DUNE

- Recall oscillation goes as (Distance / E_ν), so E_ν is critical to measure both as precise as possible and with knowledge of systematic uncertainties. But we don't see the neutrino, only products of its interactions
  - So we estimate E_ν based on the energy of all the products**
- We rely on event generators giving us predictions of events interacting via different channels with varying kinematics
  - Some are being newly developed as well and showing promise
  - Theory community also incredibly important to refine, and provide new formulae to better characterize what we expect to see
- Measurements continue to show differences with model predictions
  - Need more measurements to check/find discrepancies in models and drive further development of them, especially with Ar



ArgoNeuT data
R. Acciarri et al. Phys. Rev. D 99, 012002 (2019)

A few (of several) different event generators/models

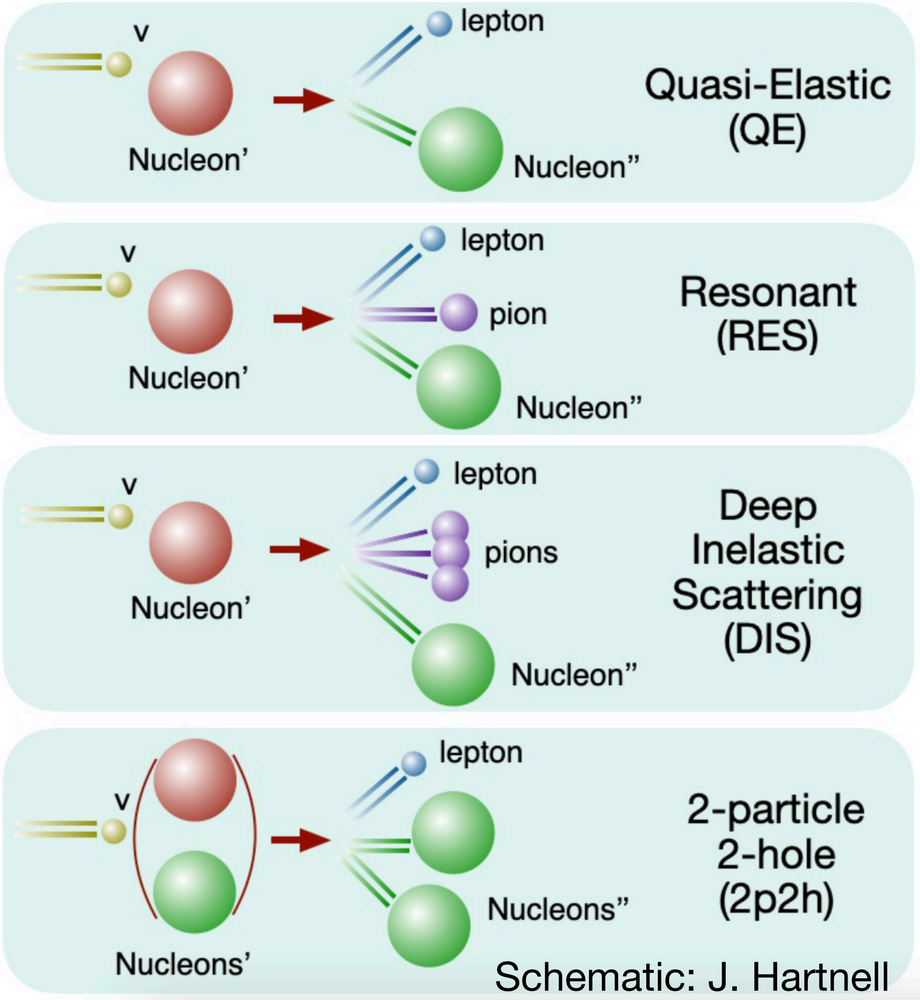


GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

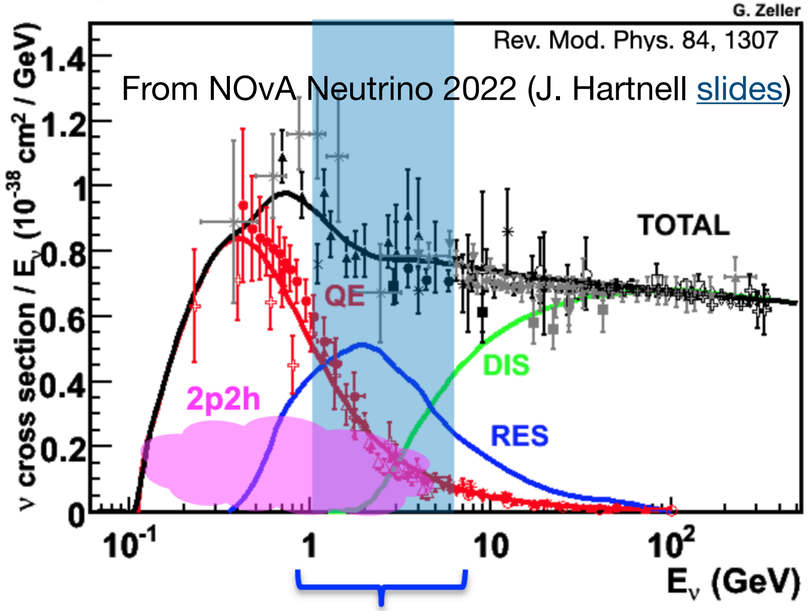
** Except our detectors are sensitive to charged particles. Neutral particles add difficulty in E_ν measurement…

Impact of neutrino interactions/cross-sections on DUNE

- Also what we see in the detector can be a complicated "mess" of the neutrino interaction on a nuclear target (Argon)



Schematic: J. Hartnell

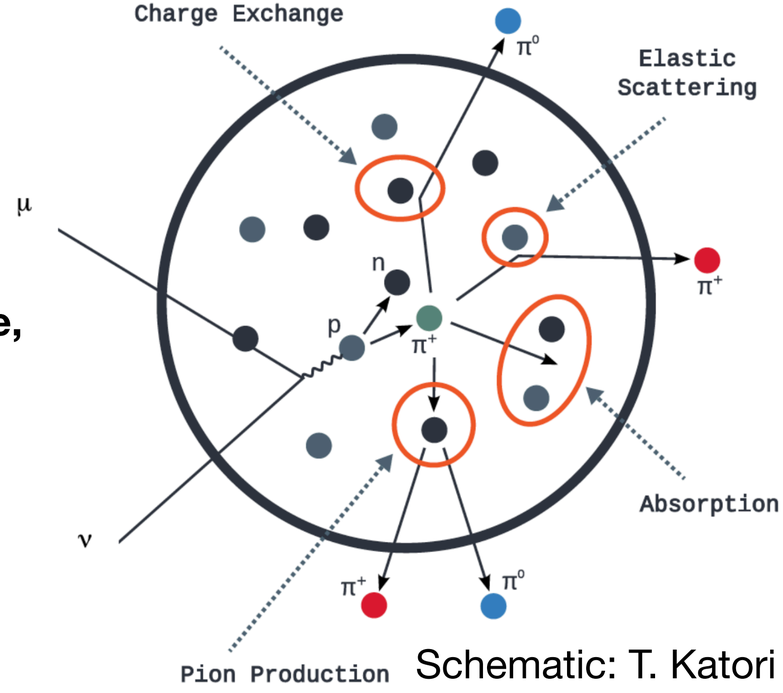


Particles/yields expected depend on mode, therefore so does the energy resolution.

Especially modes w/ neutral particles like (e.g. anti-nu interactions and 2p2h).

Due to nuclear medium, particles may have "Final State Interactions" (FSI).

We may either alter the energy we see, or miss particles entirely (absorption, or reduction to below thresholds)



Schematic: T. Katori

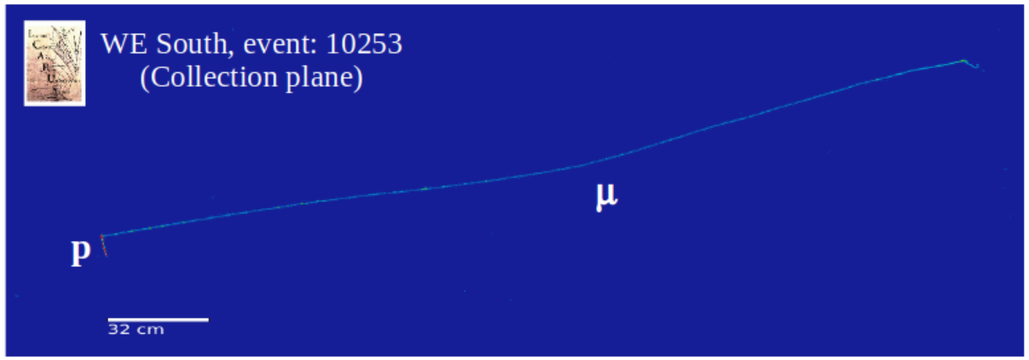
Pandora multi-algorithm pattern-recognition kit (https://github.com/PandoraPFA) which has established interface in LArSoft framework commonly used in LAr TPCs

- Clusters objects together into reco particles in 3D, joining together across planes
- Reconstructs vertex (common point where ν interacted & particles originate)
- Forms particle hierarchy (parent/child)
- Classifies particles track-like (e.g. μ, p) or shower-like (e.g. e, photon)

Machine Learning Reco splits off from other reco path at the point of having hits matched across planes “Cluster3d” and utilizes e.g.:

- Semantic segmentation (e.g. track, shower)
- Graph neural networks build clusters/ interactions
- Classification of particle type/events

Having both pathways is useful to provide alternative views of events to better understand and chances to cross-check/validate



TPC Reconstruction