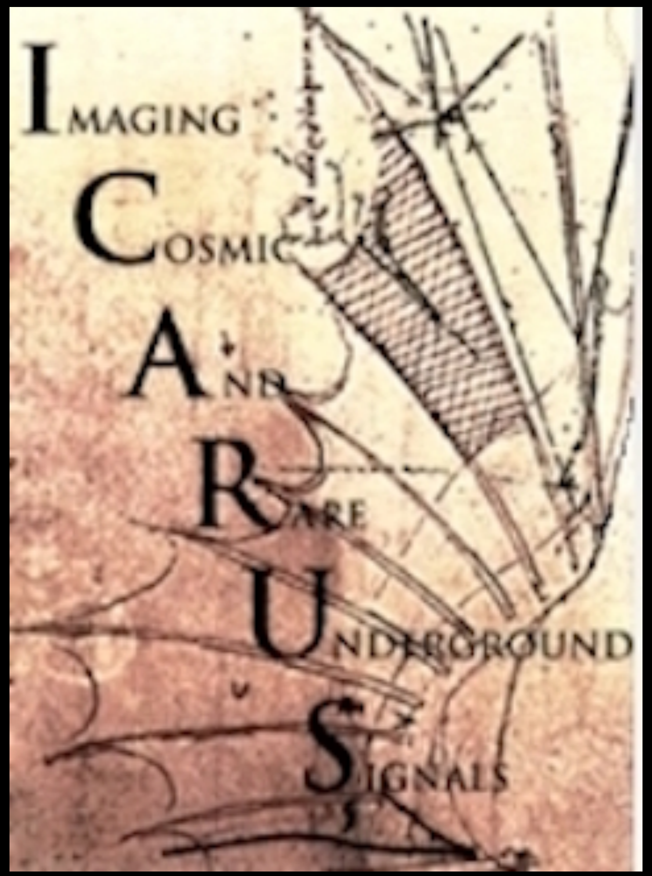
FERMILAB-PUB-0888-PPD

Neutrino Hunting with the Short- and Long-Baseline Neutrino Programs at Fermilab

Fermilab



Bruce Howard

19 Sept 2023

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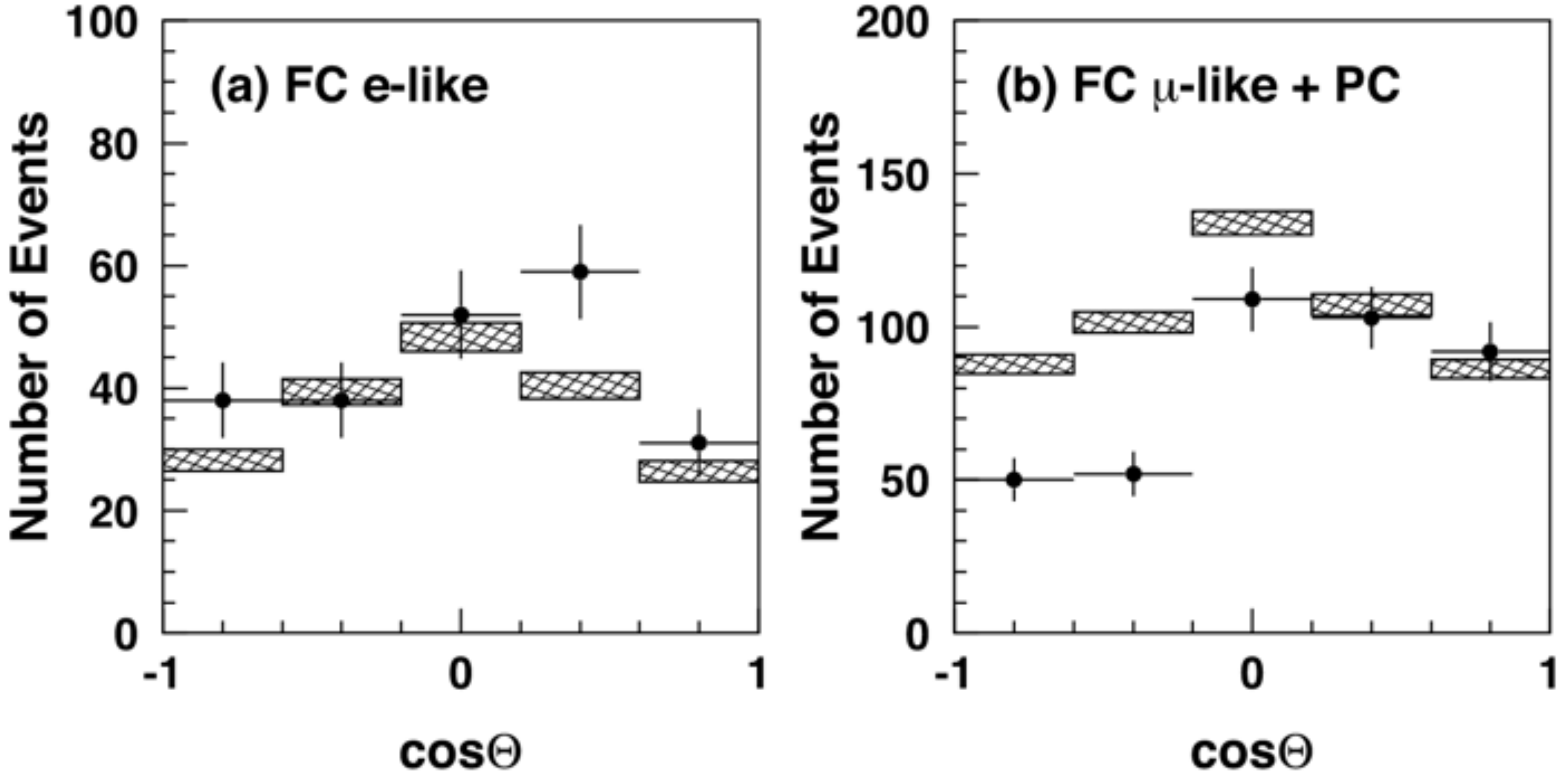
Neutrinos/Neutrino Oscillation

- Standard model neutral leptons
  - 1956: first direct discovery of neutrino (e-type)
  - 1962: ν_μ (BNL), 2000: ν_τ directly observed (FNAL)
- Z decay branching fractions tell us there should be 3 light active neutrinos
- Ray Davis experiment at Homestake measured electron flavor neutrinos from sun: consistently found fewer than predicted
- ν oscillation confirmed by Super-Kamiokande & Sudbury Neutrino Observatory:
  - Confirm neutrinos have >0, but tiny, mass
  - Probabilities to measure different flavor: sinusoidal functions of distance traveled and energy of the ν (L/E) = "oscillation"
  - L referred to as "baseline" so these experiments w/ large L are called "long-baseline" experiments

Anomaly caused by oscillation in early Super-K data
T. Kajita, E. Kearns, M. Shiozawa Nuclear Phys B 908 (2016) 14-29



$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{i\delta_{\mathrm{CP}}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\mathrm{CP}}} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\tan^2\theta_{12} \; : \; \frac{\text{amount of } \nu_e \text{ in } \nu_2}{\text{amount of } \nu_e \text{ in } \nu_1}$$

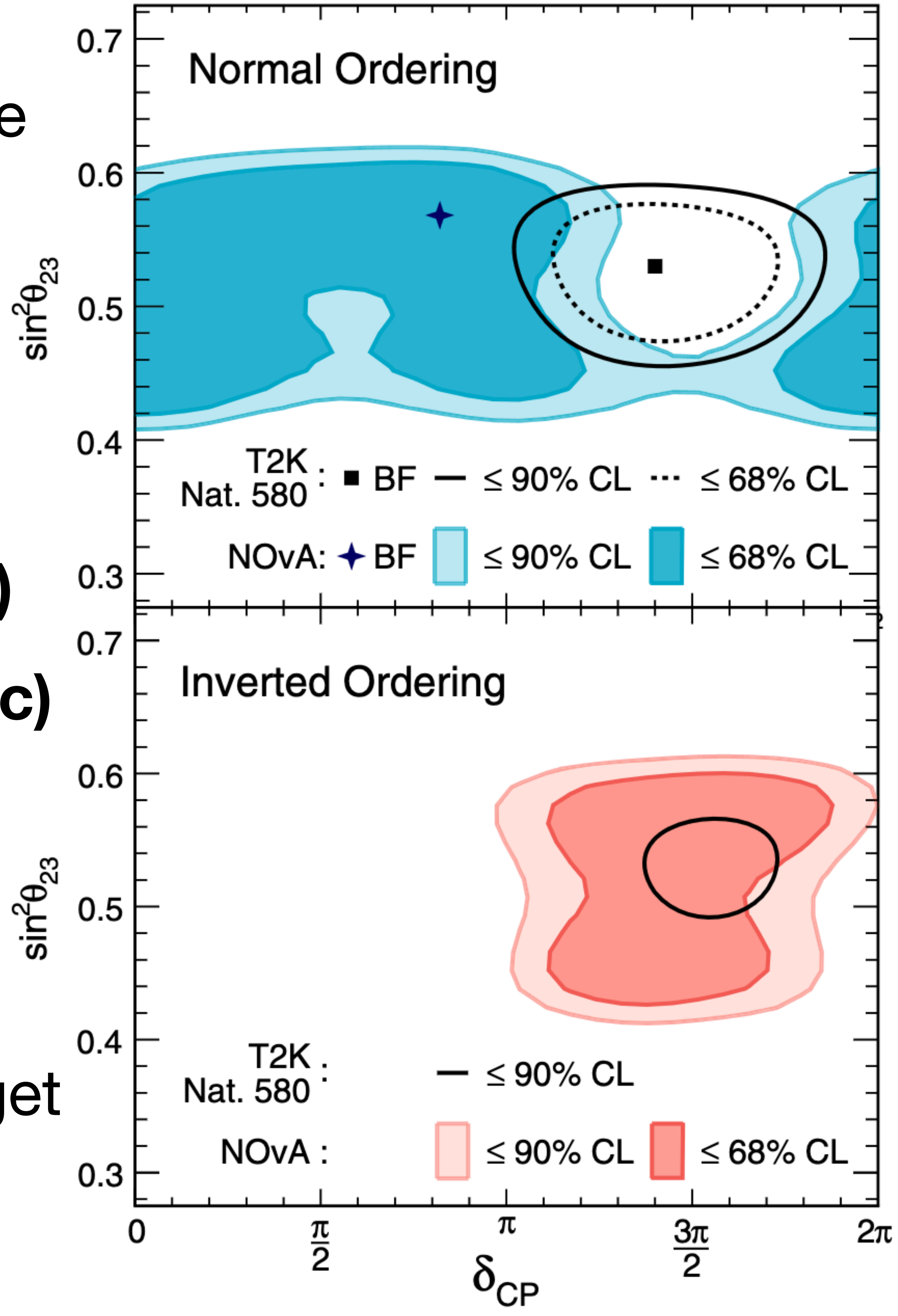
$$\tan^2\theta_{23} \; : \; \text{ratio of } \nu_\mu \text{ to } \nu_\tau \text{ in } \nu_3$$

$$\sin^2\theta_{13} \; : \; \text{amount of } \nu_e \text{ in } \nu_3$$

C. Adams et al
arXiv:1307.7335
(LBNE Science Book)

Neutrinos/Neutrino Oscillation

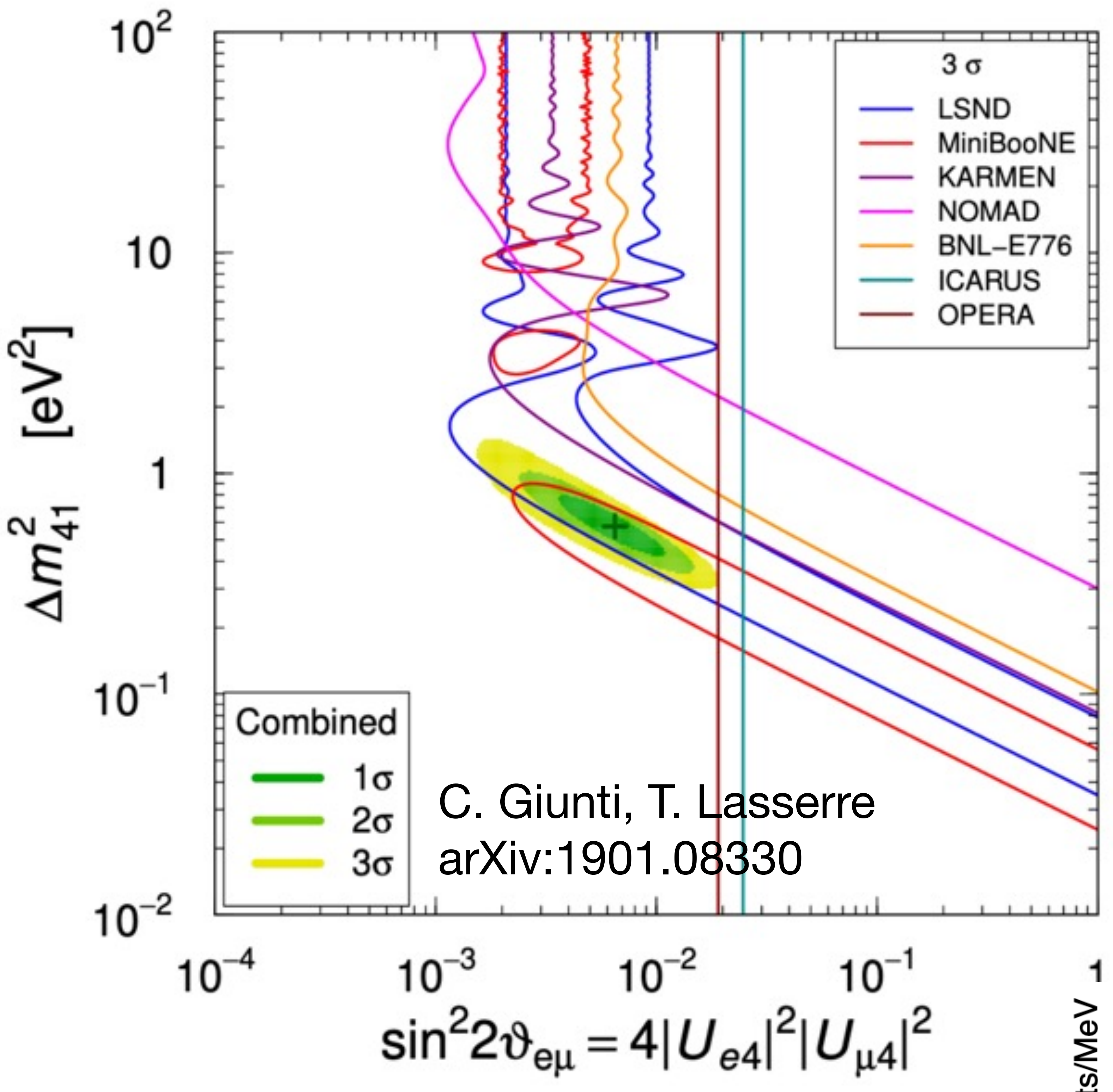
- Nature of neutrinos & oscillations comprise key questions facing particle physics and are being pursued by a broad community, e.g.:
  - What are neutrinos' masses? (bounds from cosmology, KATRIN/ Project8)
  - Are neutrinos their own anti-particles? (0νββ community)
  - **ν mixing, mass ordering? Violate CP? (<u>long-baseline</u> oscillations)**
  - **Just the active neutrino flavors? (sterile ν, e.g. <u>short-baseline</u> osc)**
  - Also some of these projects seek neutrinos from space-based sources, e.g. supernovae (to date only a few supernova ν)
- Experiments have worked to understand the oscillation landscape:
  - Current gen of ν long-baseline experiments (e.g. NOvA, T2K) *might* get significant result on mass ordering
  - Next generation will seek to make definitive measurements on mass ordering and have significant CP violation discovery sensitivity.

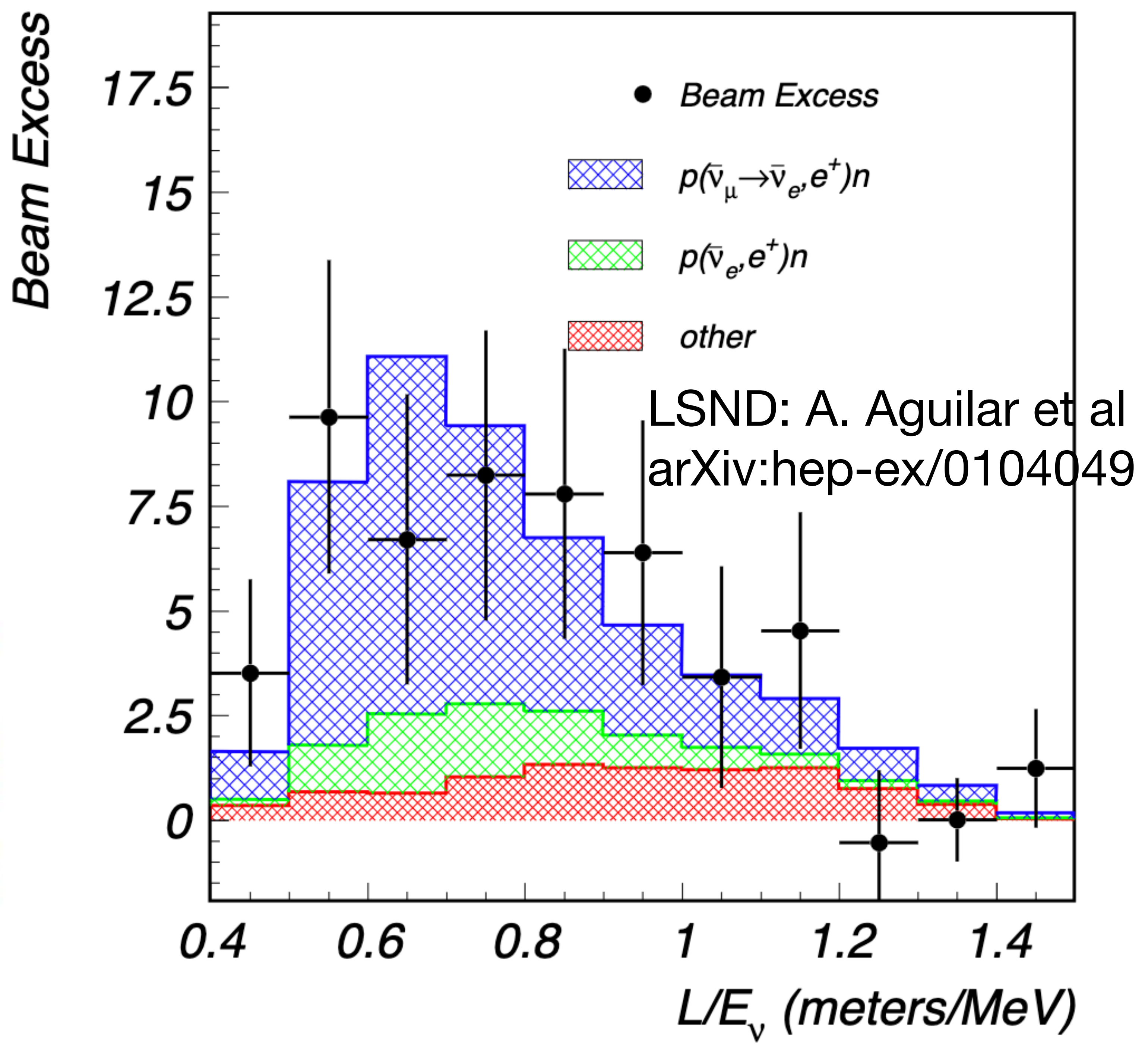


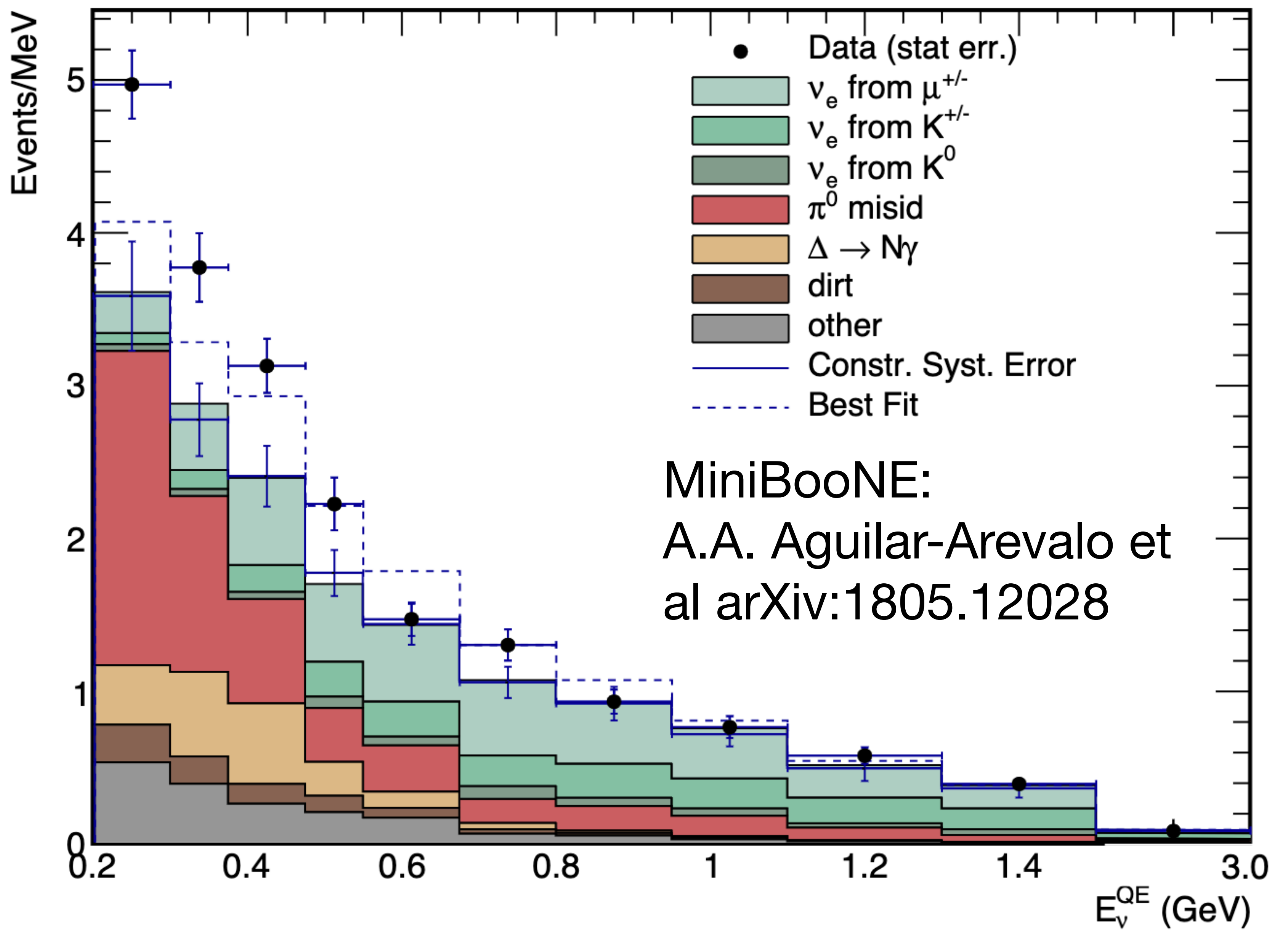
NOvA & more M.A. Acero et al Phys Rev D 106, 032004 (2022)

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))
- Largely, a global program of experiments searching for further evidence of sterile oscillation has set continually more stringent limits, strong tension with ν_μ disappearance searches
    - Additional beyond standard model physics processes have been proposed as an alternative solution

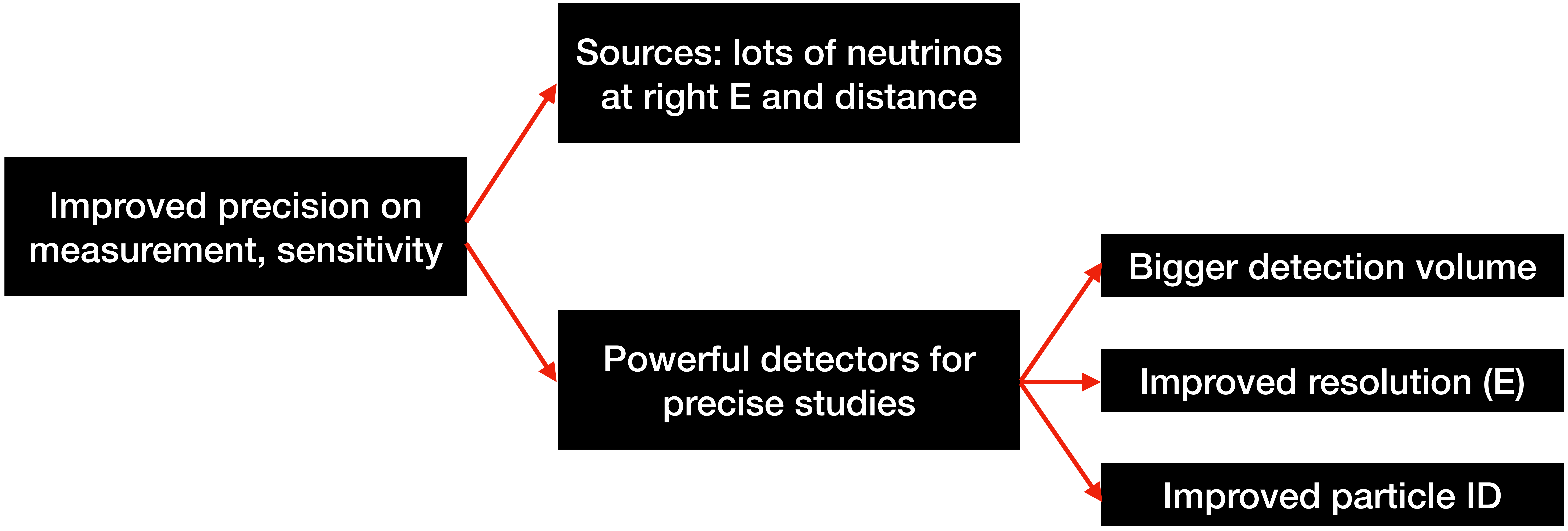


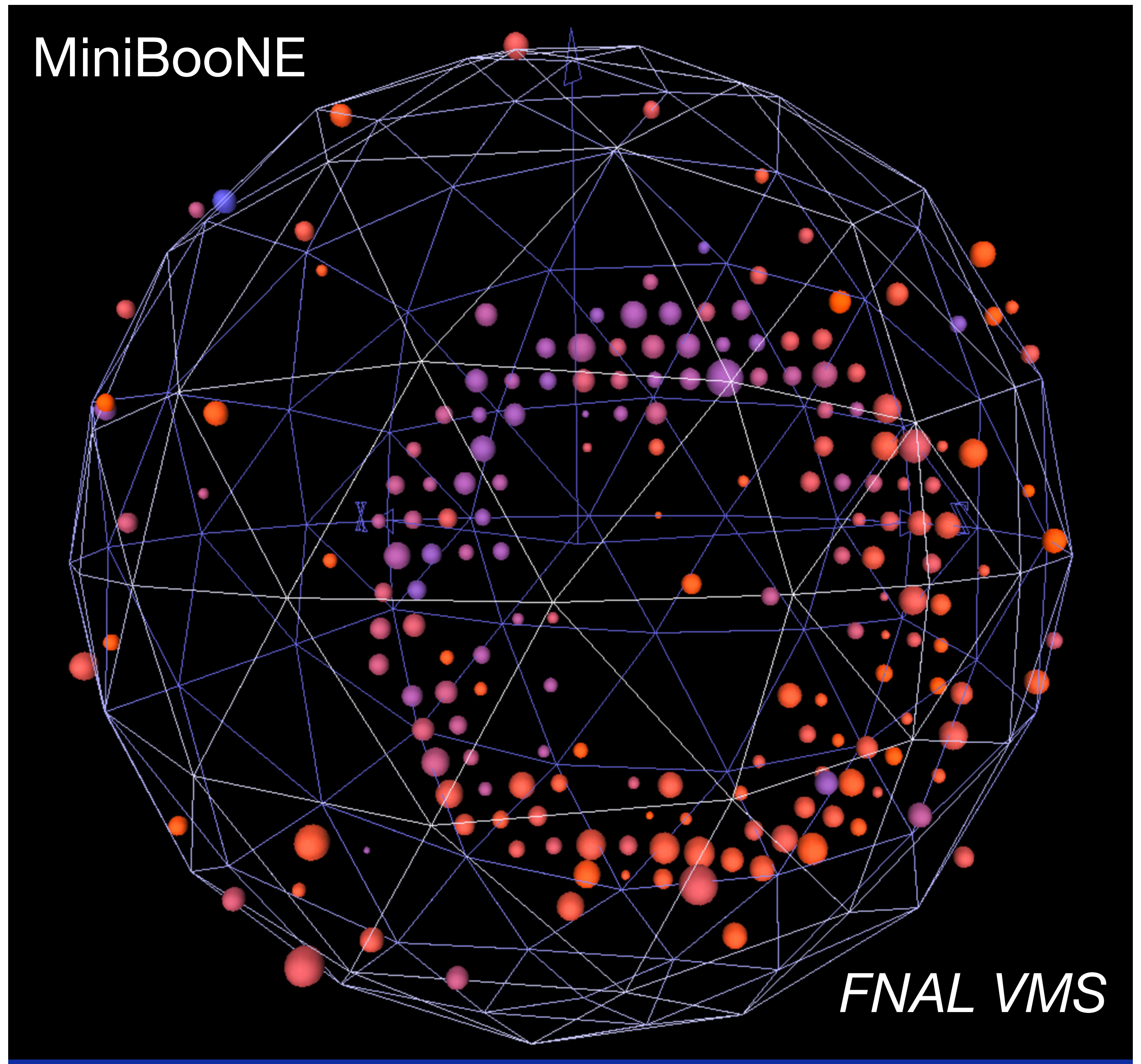


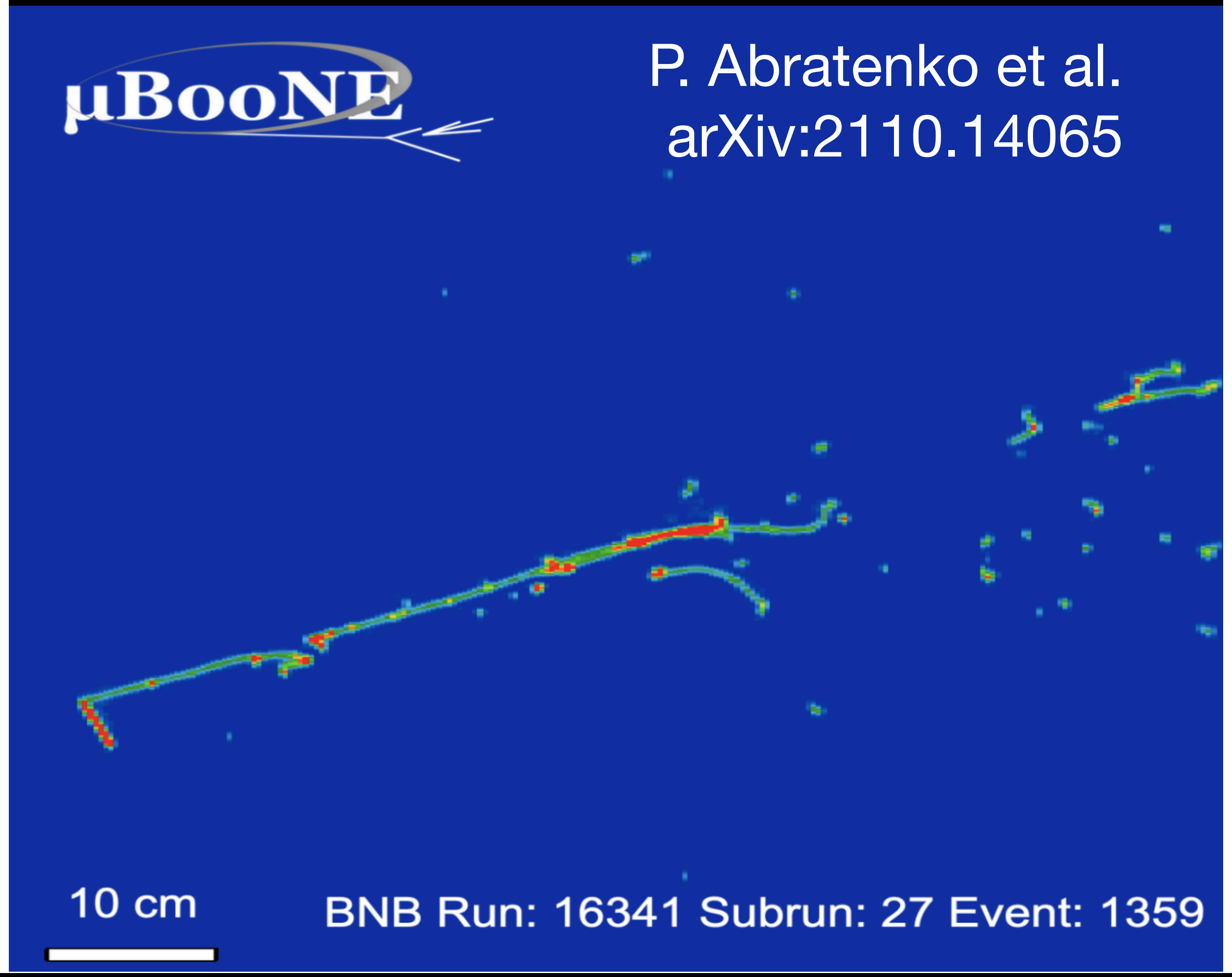


Addressing the Questions of the Last Slides

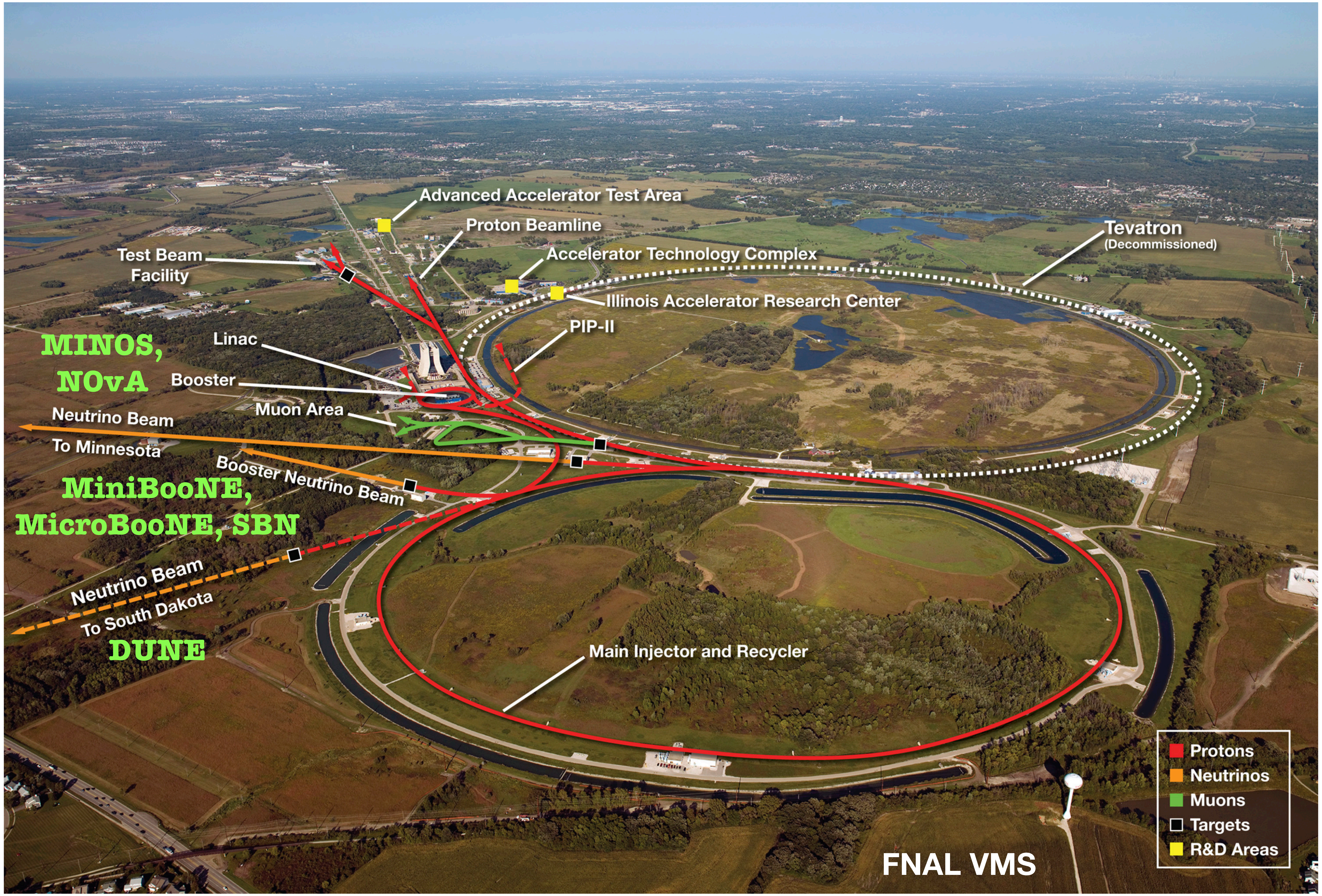
- In order to improve the sensitivity of the next generation of experiments to address these questions, two main categories of things needed: **high yield sources, powerful detectors**
- Having these conditions met can also enable lots of additional physics studies as well







Accelerator-based Neutrino Sources



Fermilab accelerator complex produces neutrinos via 2 beam lines using protons of different energies to service different experiments.

Booster Neutrino Beam (BNB): 8 GeV protons

Neutrinos at the Main Injector (NuMI): 120 GeV protons

Next-generation DUNE experiment will use a new beam [more on DUNE later]

Accelerator-based Neutrino Sources

Depiction from NOvA (A. Himmel talk)

Energetic protons impinge on target material (e.g. C, Be)

Current run across series of metal “horns” produces magnetic field to focus/de-focus particles

Long empty pipe for particles to decay and produce neutrinos

Modern accelerator-based neutrino sources made possible by the experiment which discovered ν_μ (1962)

Danby et al. Phys. Rev. Lett. Vol 9, Number 1

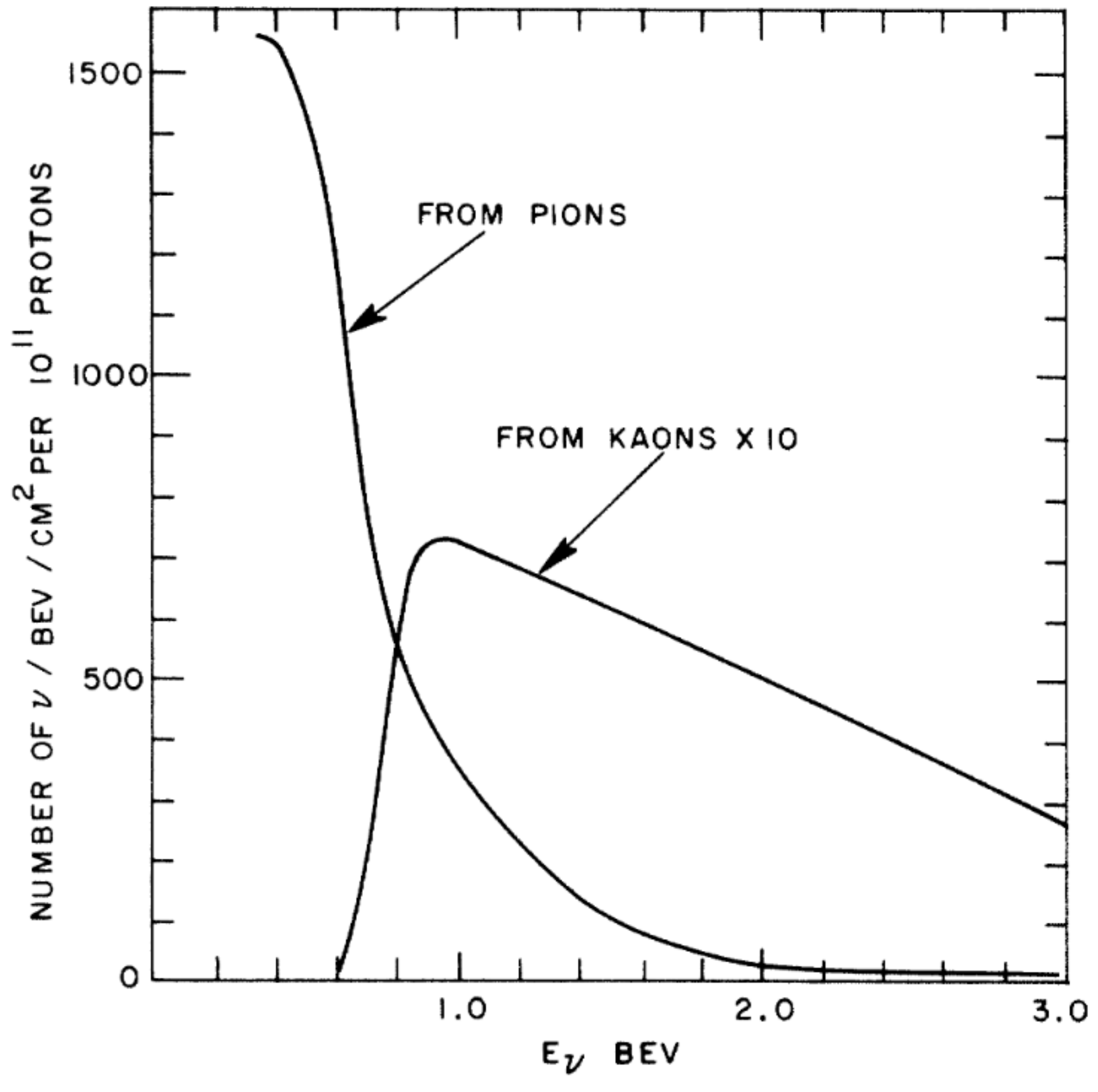
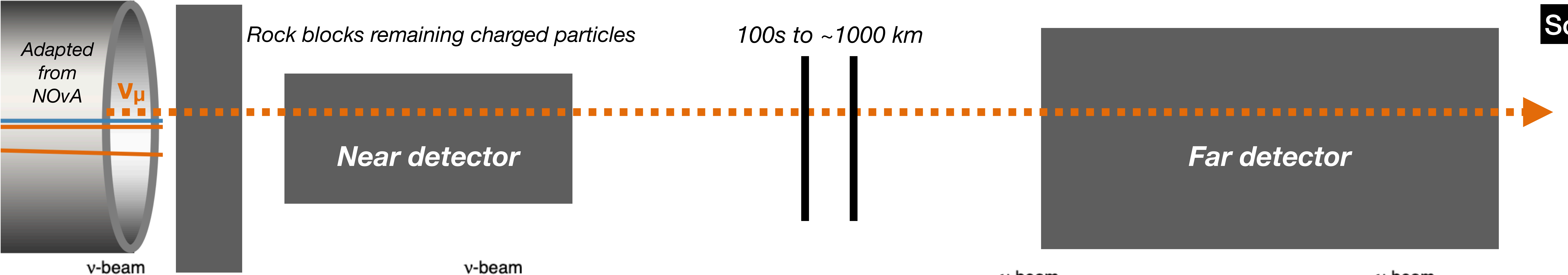
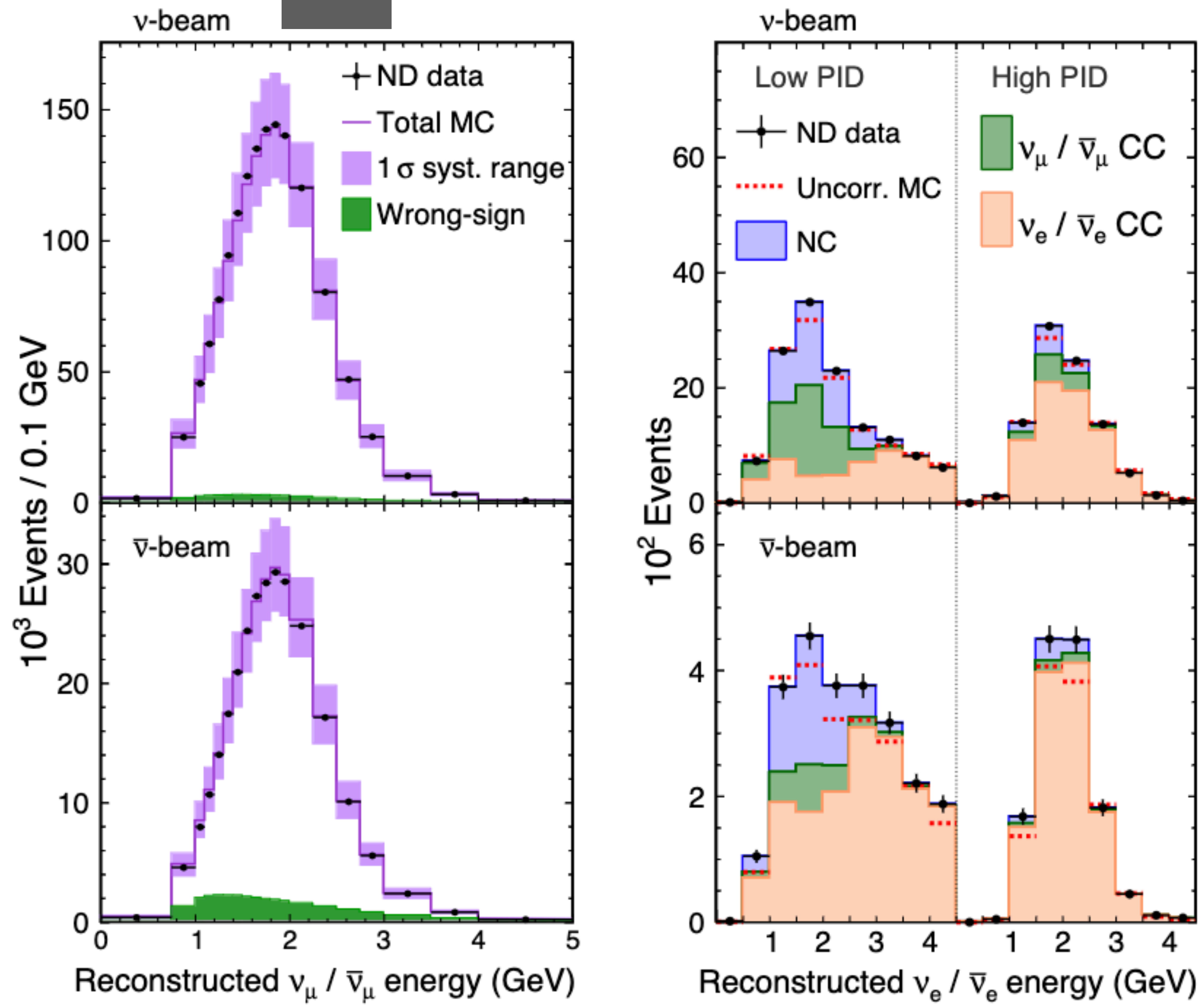


FIG. 2. Energy spectrum of neutrinos expected in the arrangement of Fig. 1 for 15-BeV protons on Be.

Sources

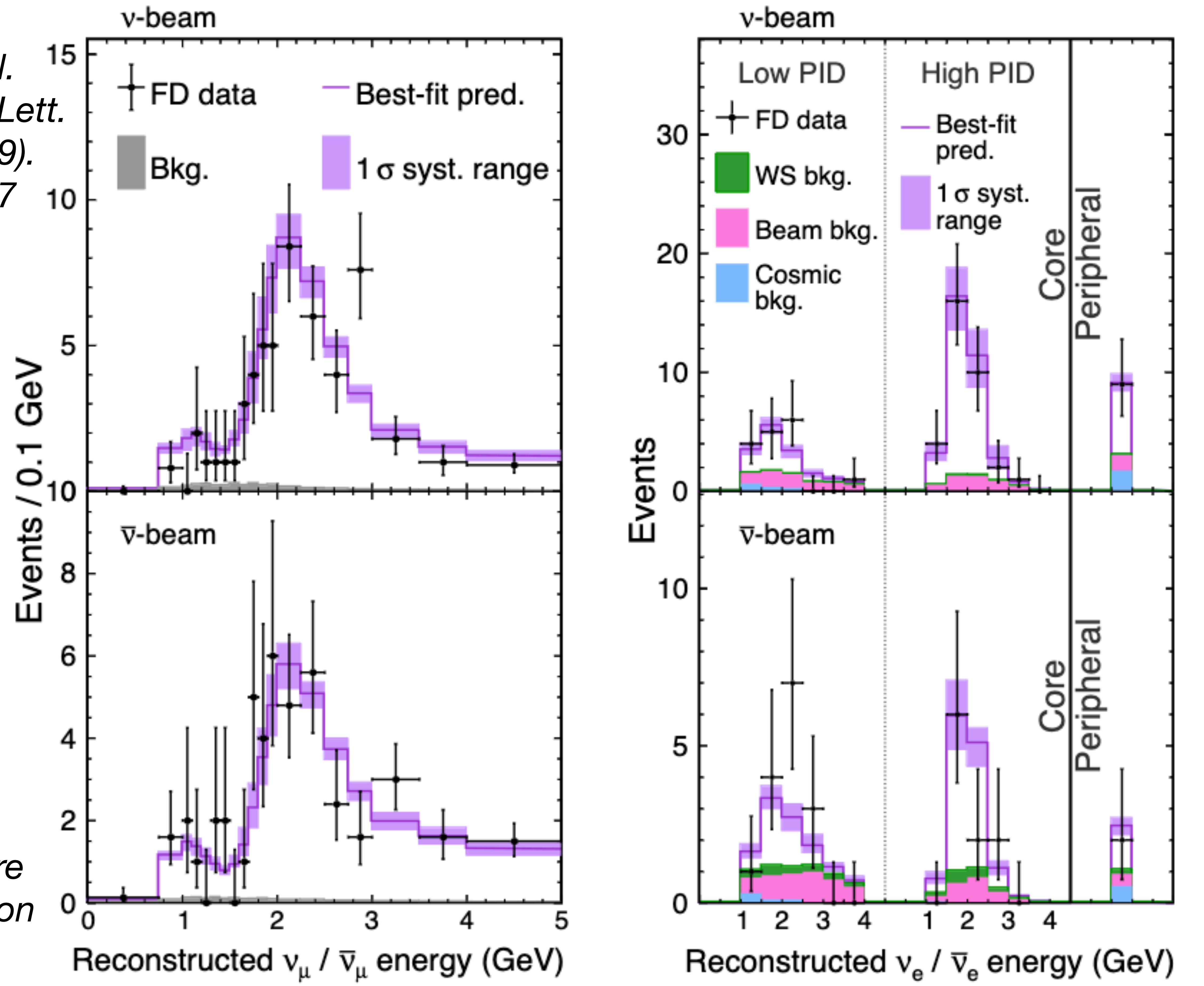




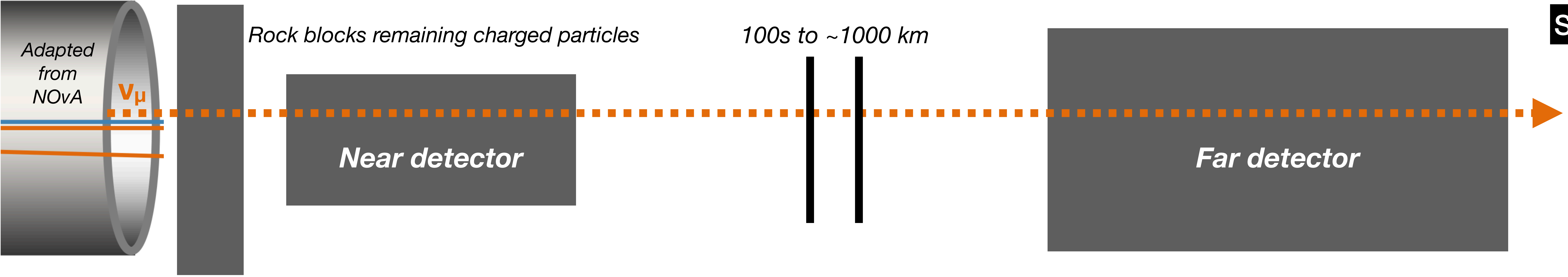
M. A. Acero et al. (NOvA). Phys. Rev. Lett. 123, 151803 (2019). arXiv:1906.04907

Characterize beam

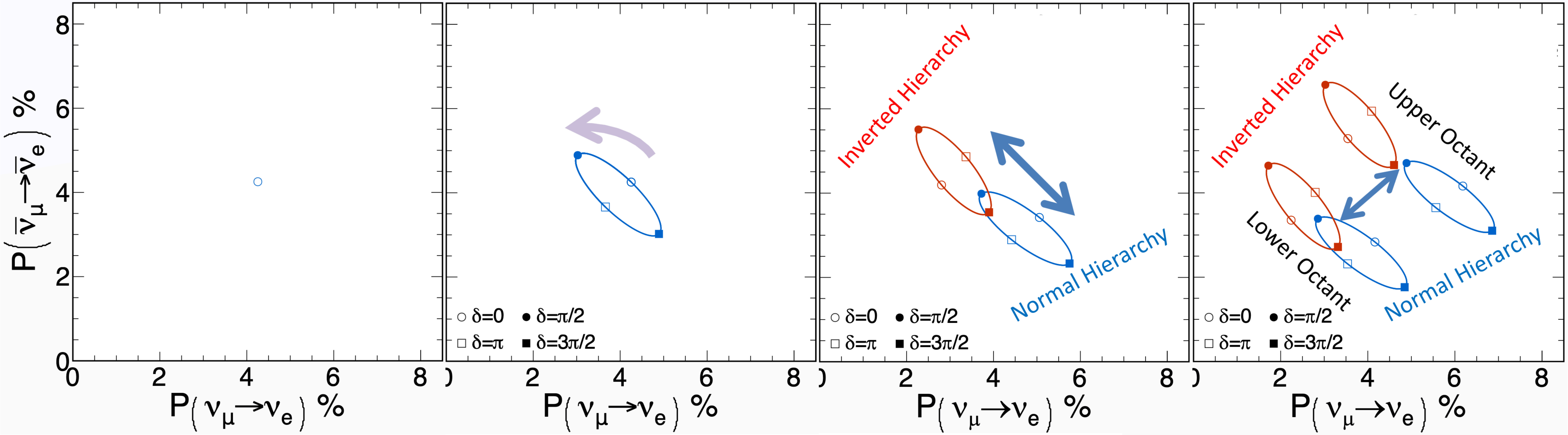
Measure oscillation



Sources



"Bi-probability" plots from NOvA (see A. Himmel talk)



With no CP-violation and in vacuum: oscillation same for nu and anti-nu

CP-violating phase creates a nu-vs-anti-nu difference

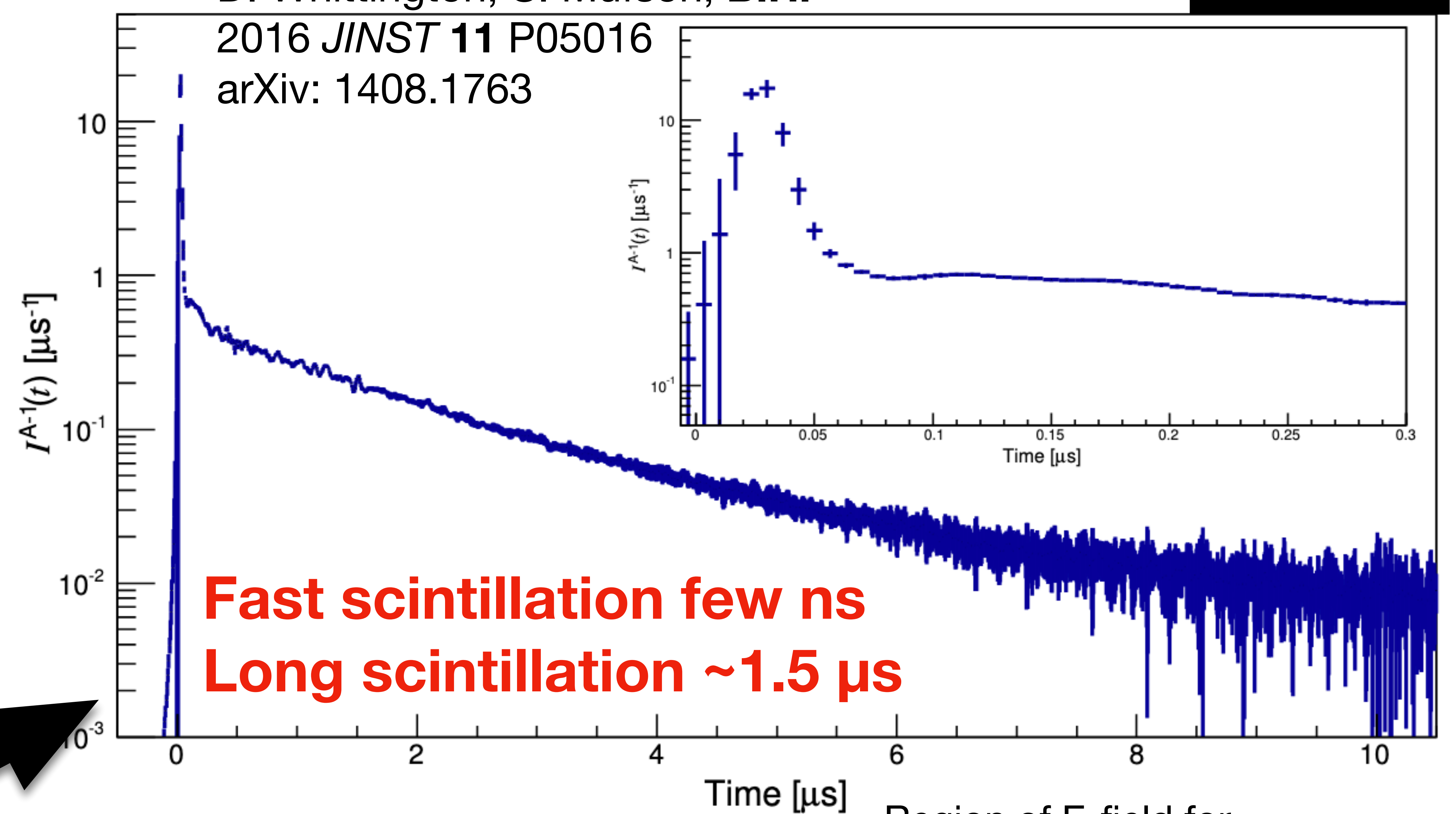
Not vacuum: enhancement of one & depletion of other based on mass ordering

θ_{23} creates overall enhancement or depletion

Liquid Argon as Detector

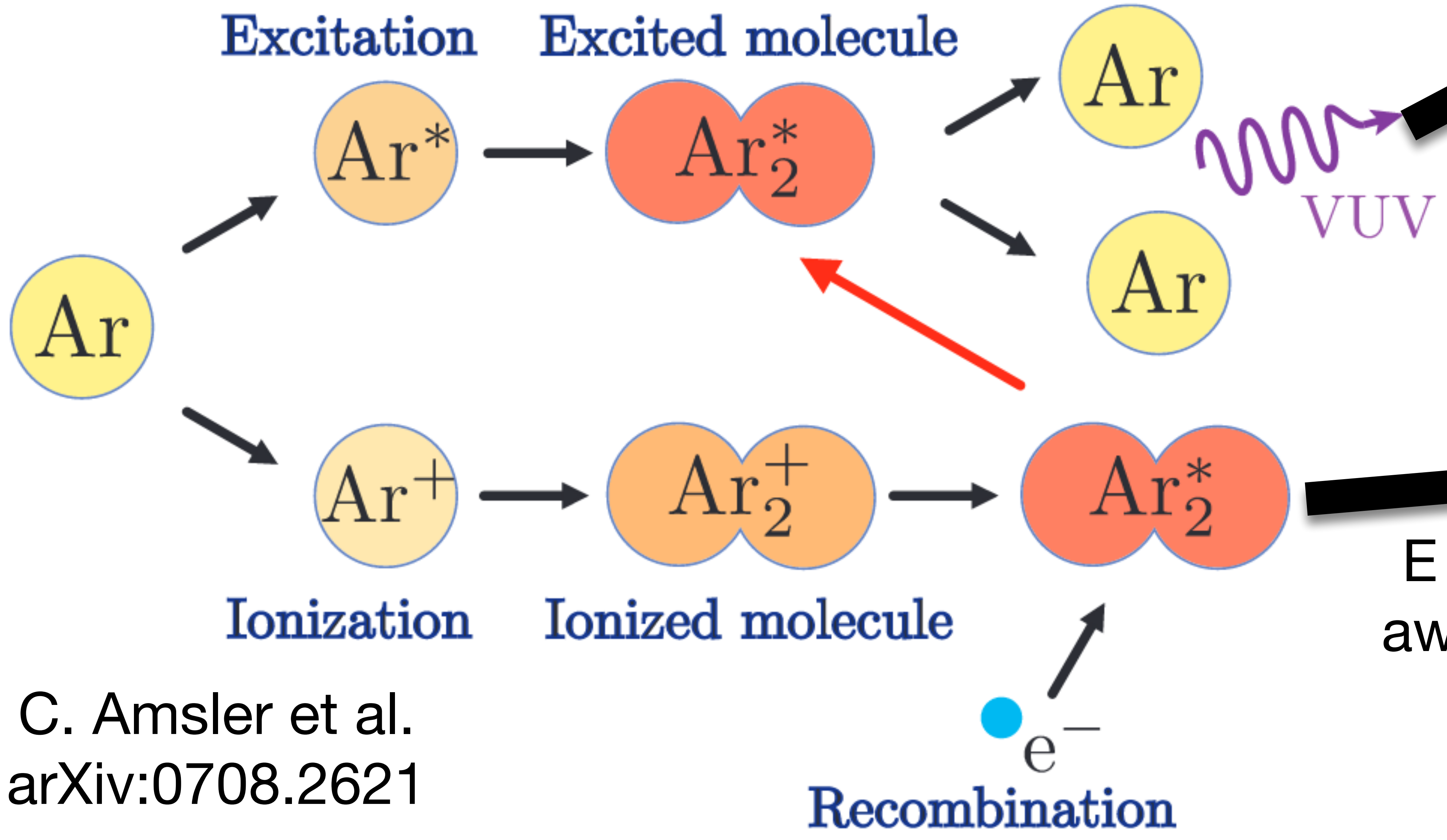
- Liquified nobles: copious signal in passage of charged particles, both in form of light (scintillation) & charge (ionization):
  - LAr common (cheap among viable nobles)
  - A way of sensing ionization is to apply E field

D. Whittington, S. Mufson, **B.H.**
2016 *JINST* **11** P05016
arXiv: 1408.1763



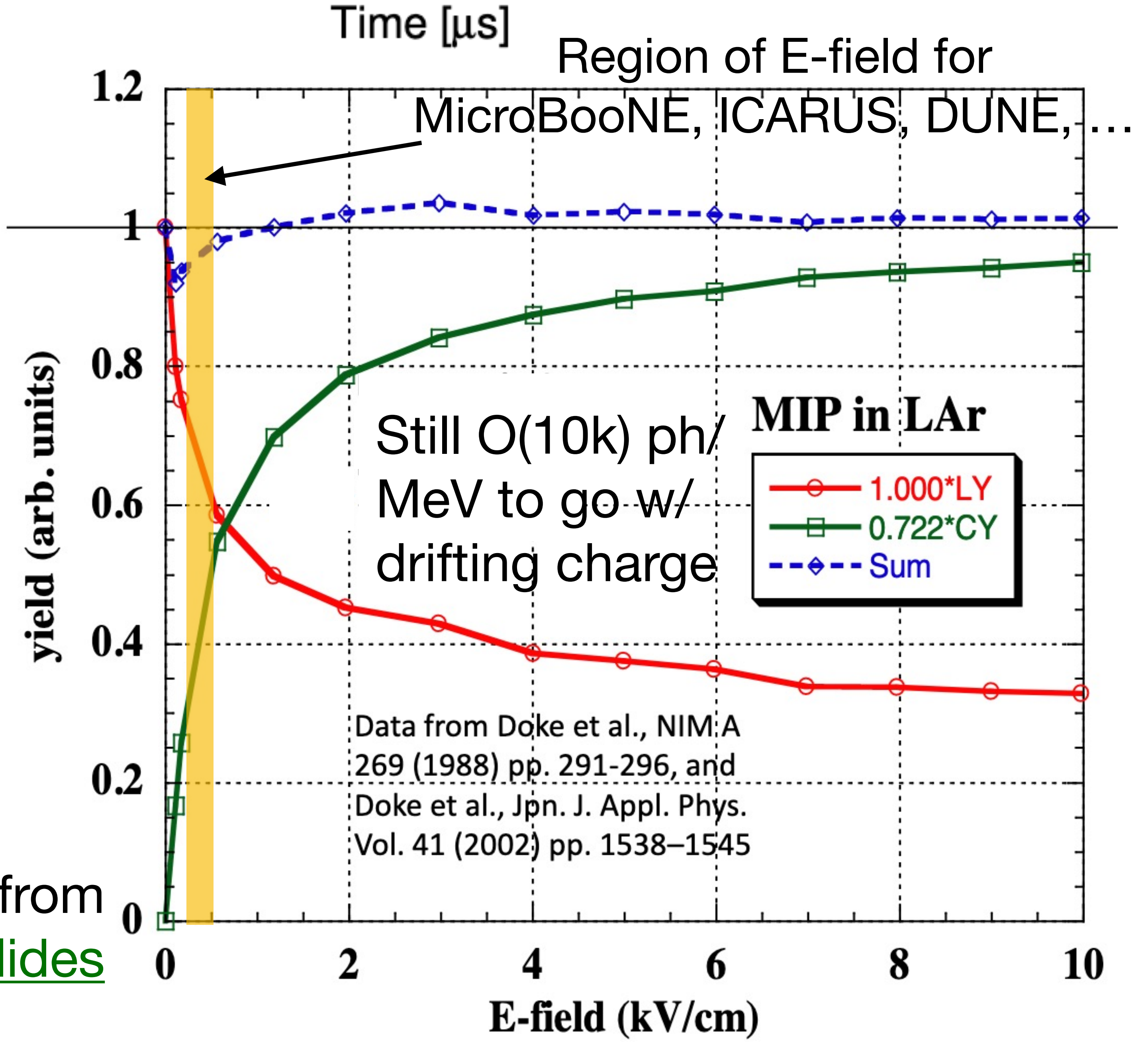
Scintillation production happens on 2 timescales

Few different paths to excite Ar dimers, lead to scintillation



C. Amsler et al.
arXiv:0708.2621

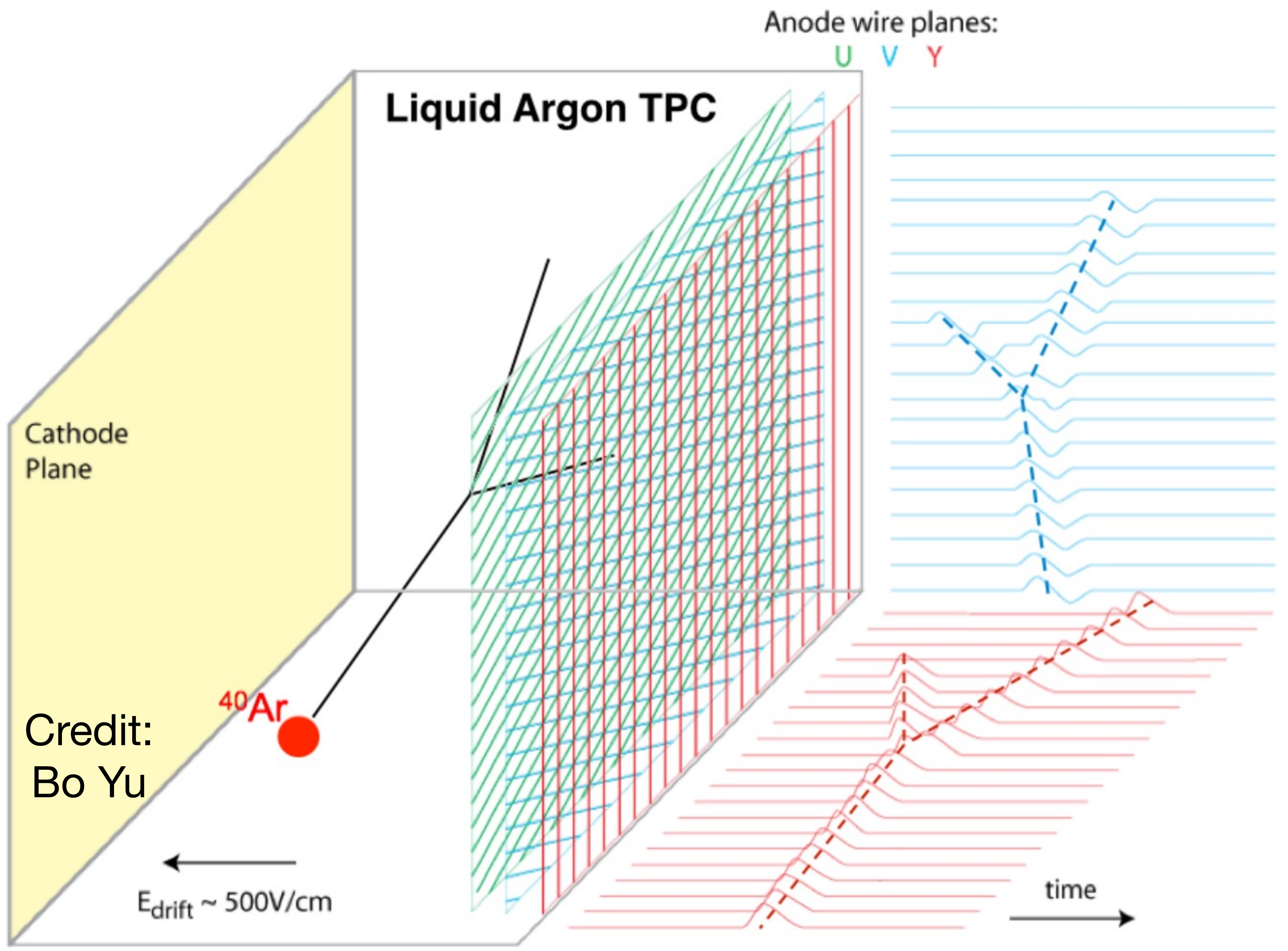
E field pulls ionization away, reducing amount of recombination



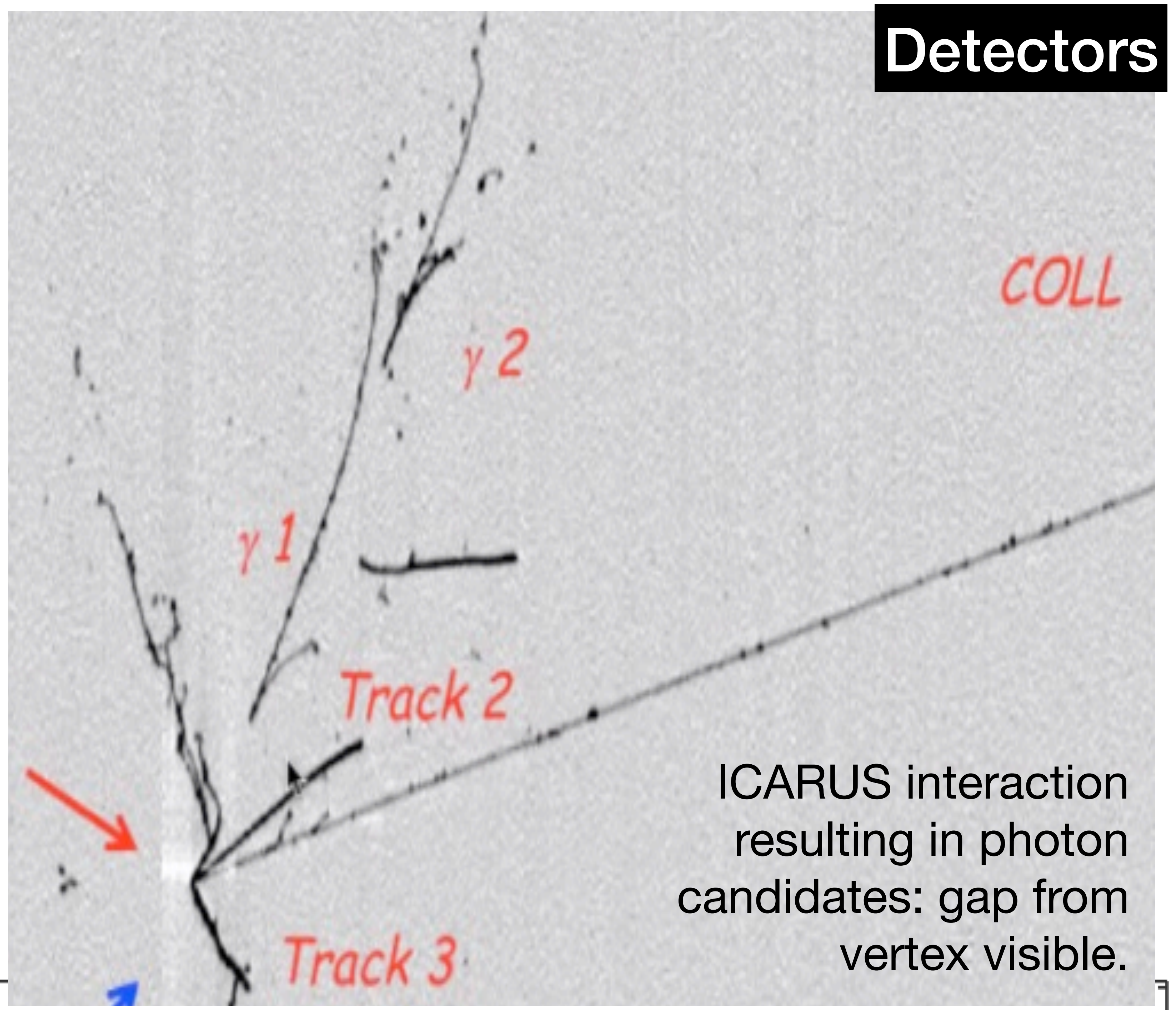
Adapted from
M. Szydagis slides

LAr Time-Projection Chamber

- LAr TPC: mechanism for utilizing powerful signals achievable with LAr
- E-field drifts ionization to wires to measure tracks/showers: wires w/ mm spacing yield fine tracking resolution
- Strength proportional to energy deposition
- **Precision measurements, e-γ separation ability**



Credit: Bo Yu



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

Compare event images from ICARUS (top) to current generation oscillation experiment NOvA

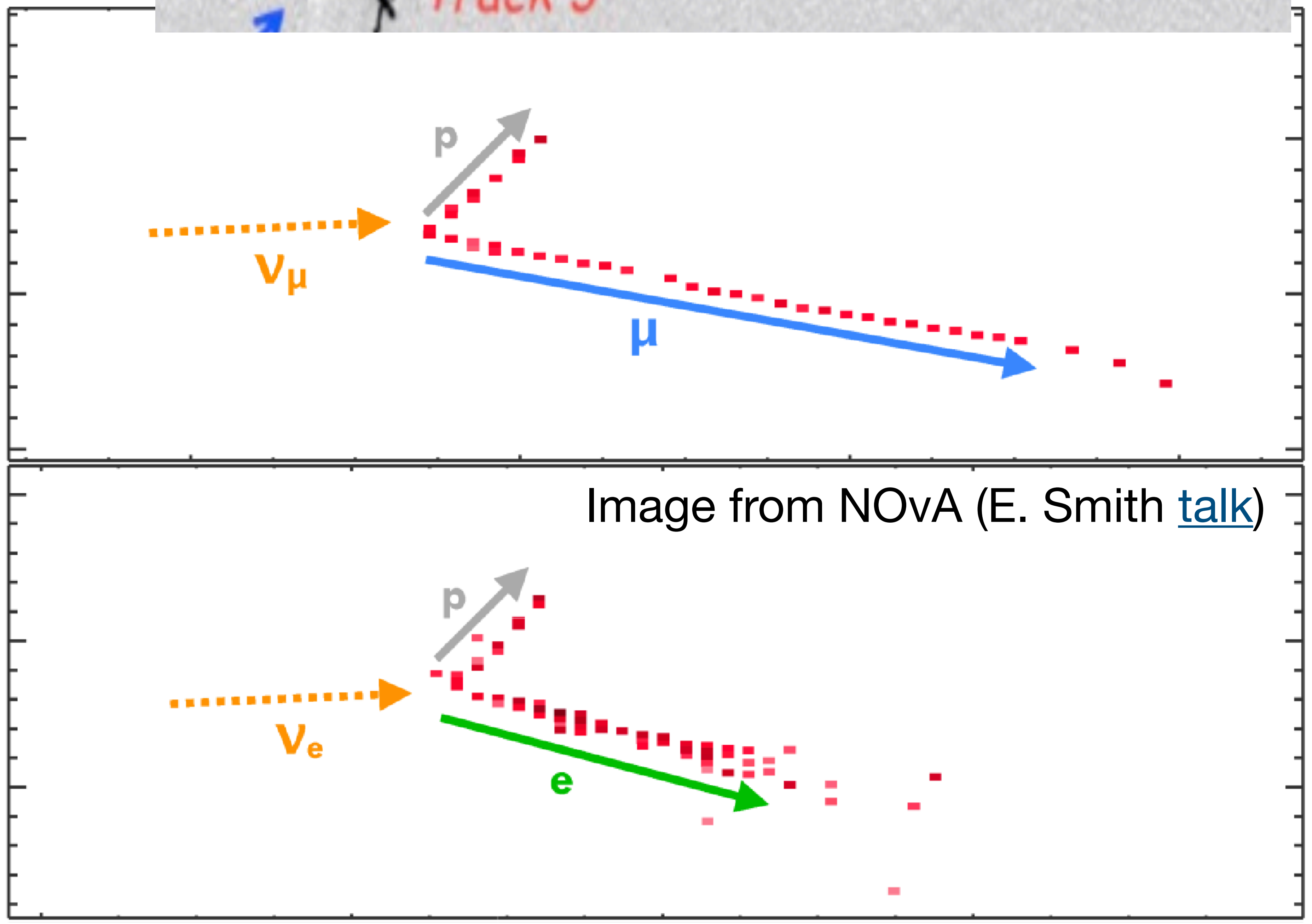


Image from NOvA (E. Smith talk)

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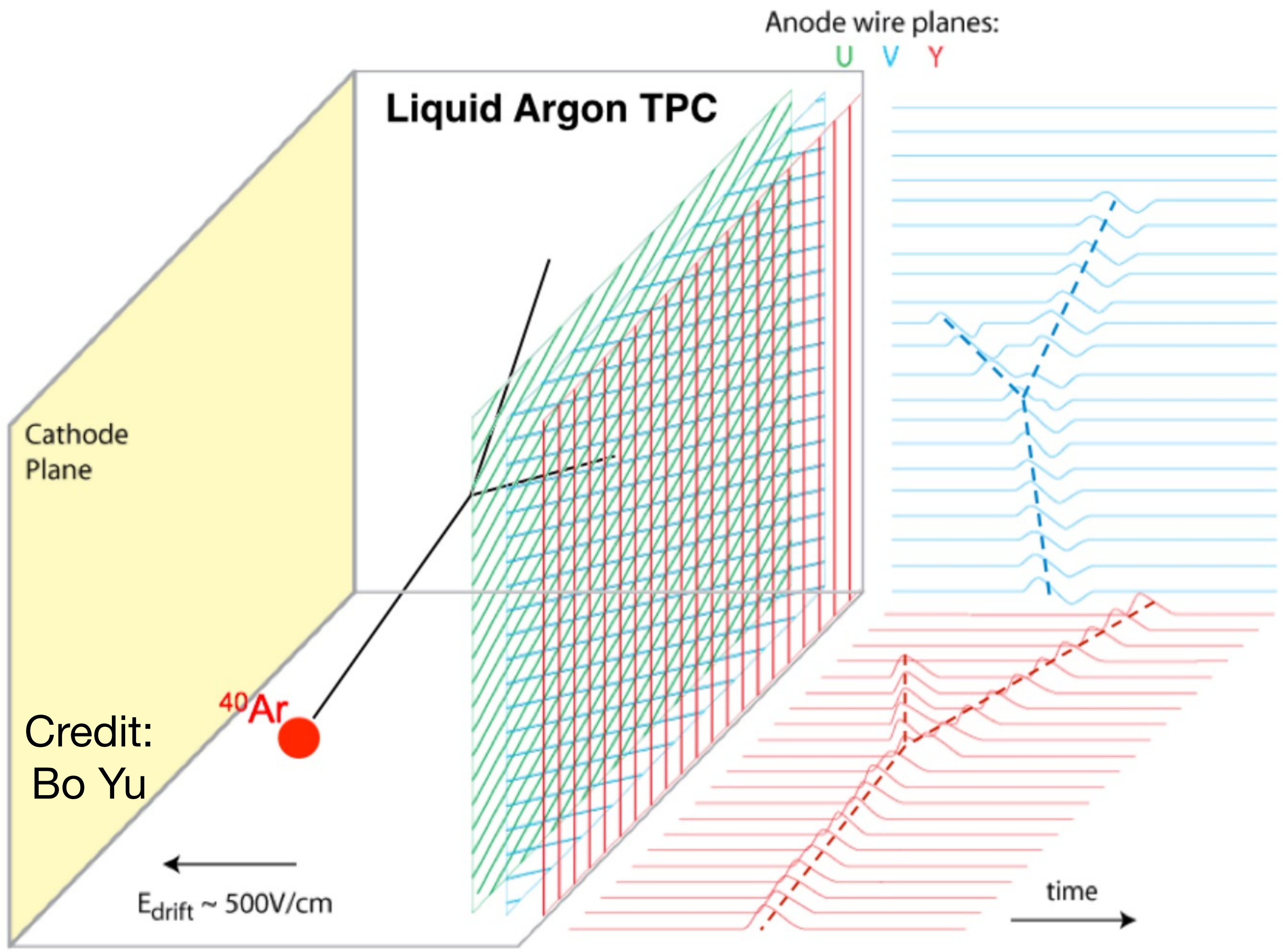
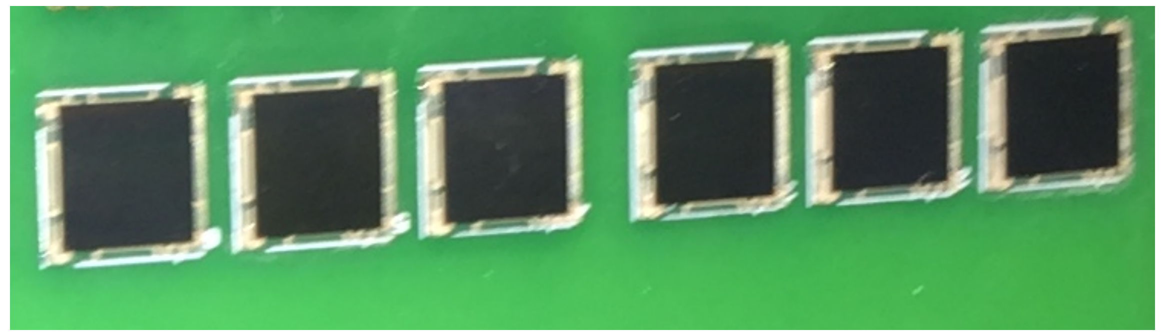
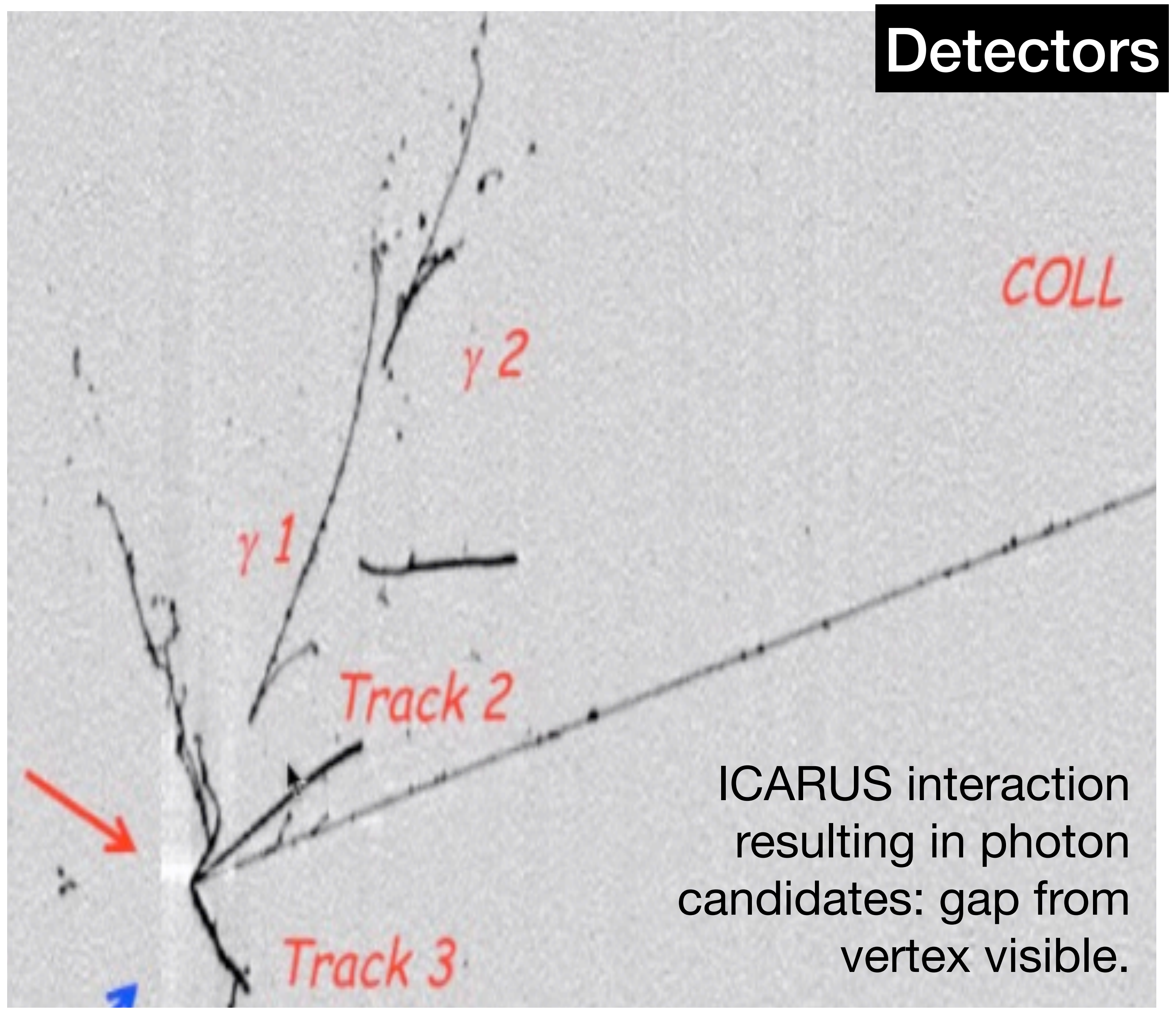


“Traditional” photon detection in LAr TPC: PMT with TPB, from ICARUS image



6x6 mm² silicon photomultipliers (SiPMs) arranged in line. These are optical SiPMs, but (V)UV sensitive SiPM options also now exist.

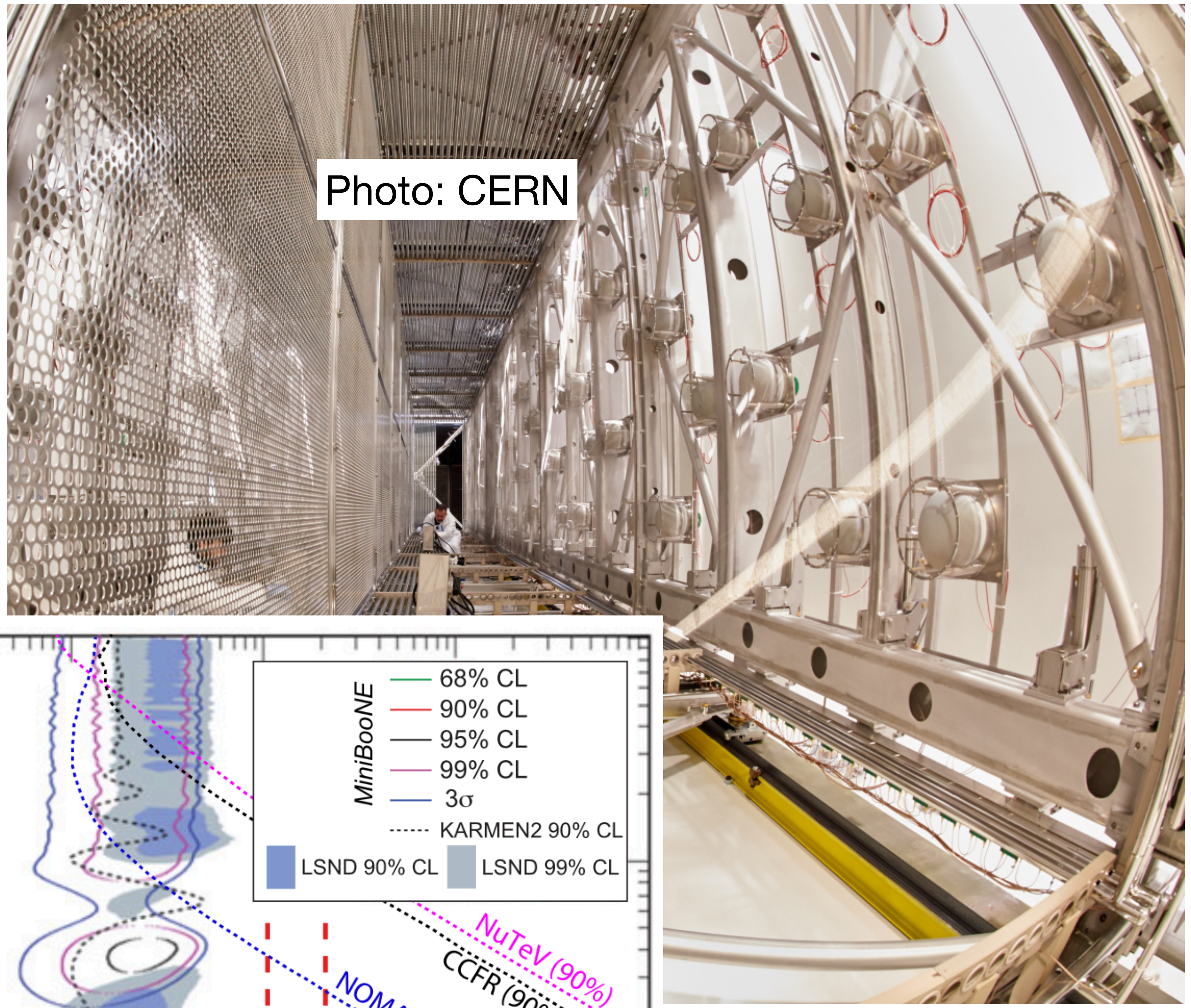


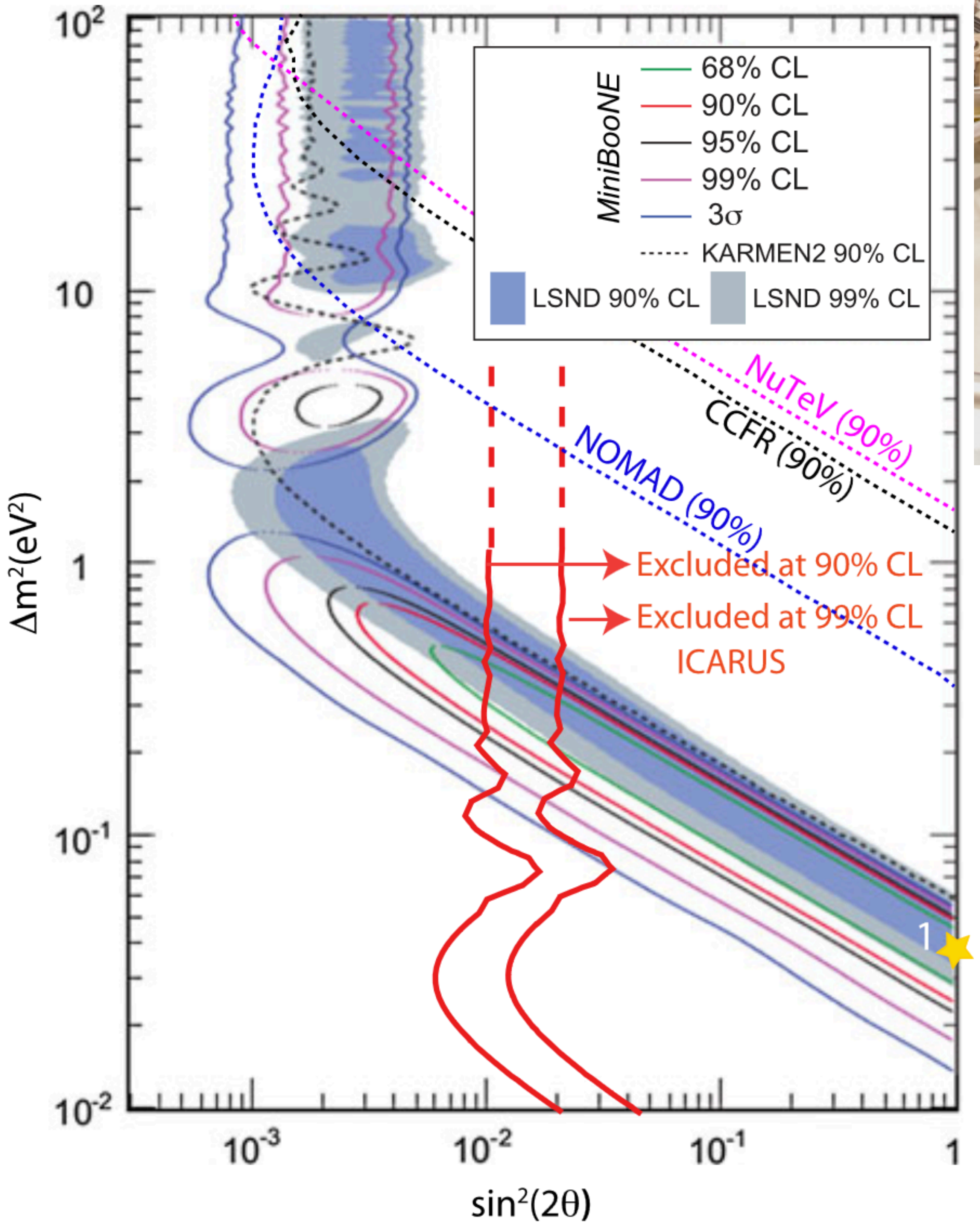
ICARUS interaction resulting in photon candidates: gap from vertex visible.

- Scintillation detection provides prompt signal capable of adding additional info about interaction, provide trigger, cosmic veto, etc.
- Possibility to use both light and charge to do best measurements

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





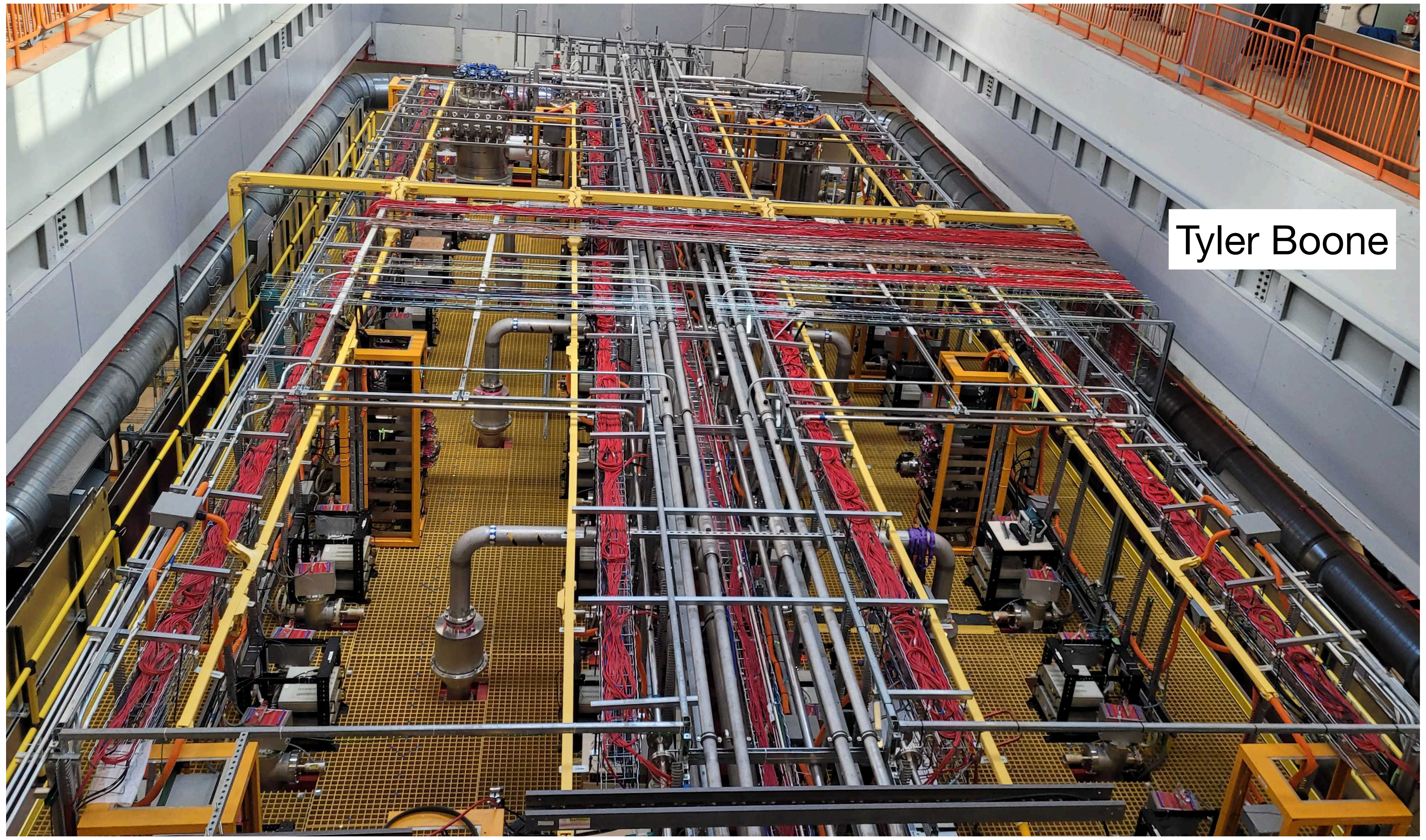
ICARUS at LNGS

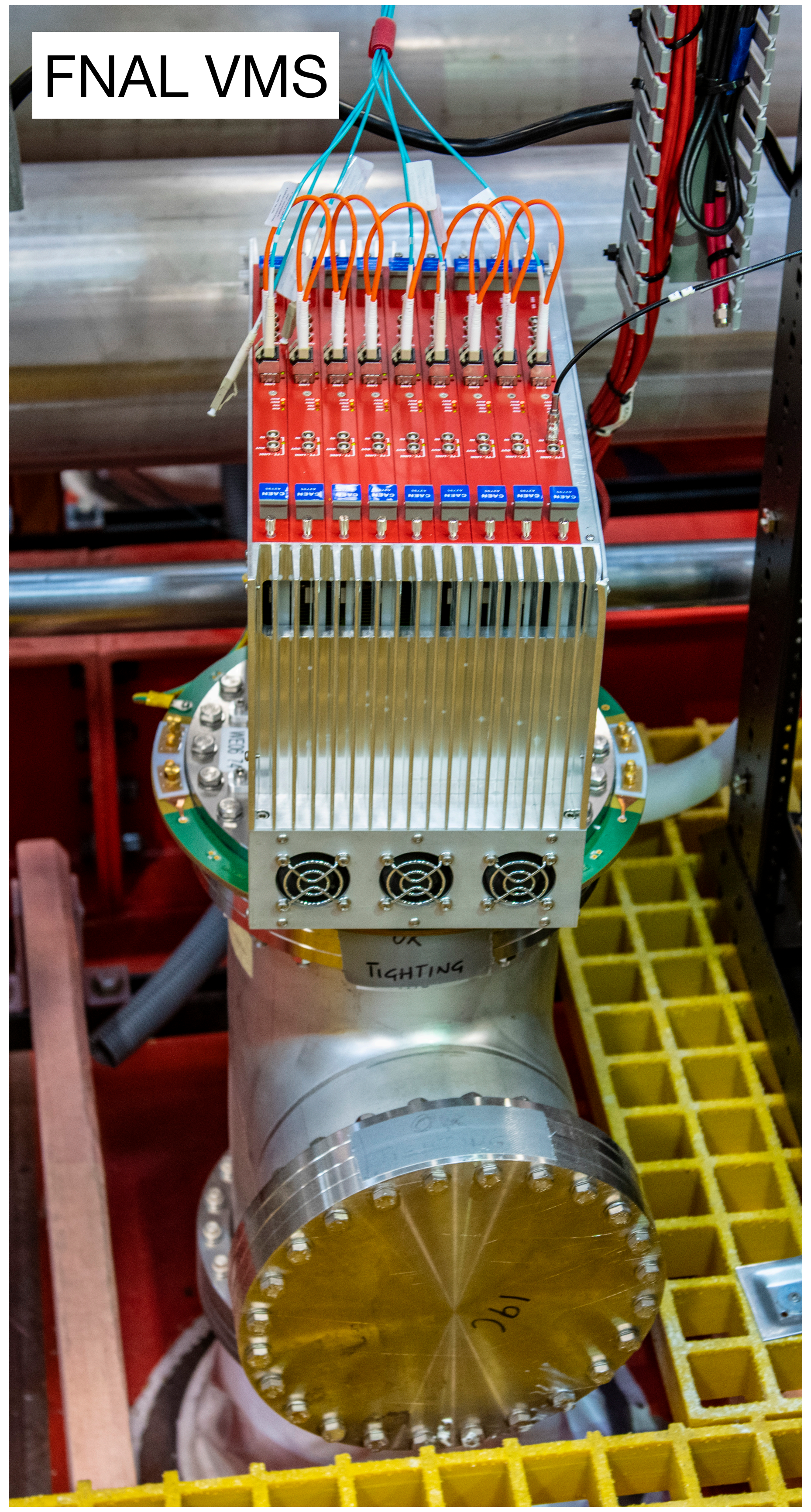
M. Antonello et al. Eur. Phys. Journal C **73**, 2345 (2013)

ICARUS @ FNAL

Right: ICARUS being installed at FNAL after move from CERN.
Left: most components installed (pre-Top CRT/overburden).

- 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 to ID beam activity
- Cosmic ray tagging system: reject cosmics

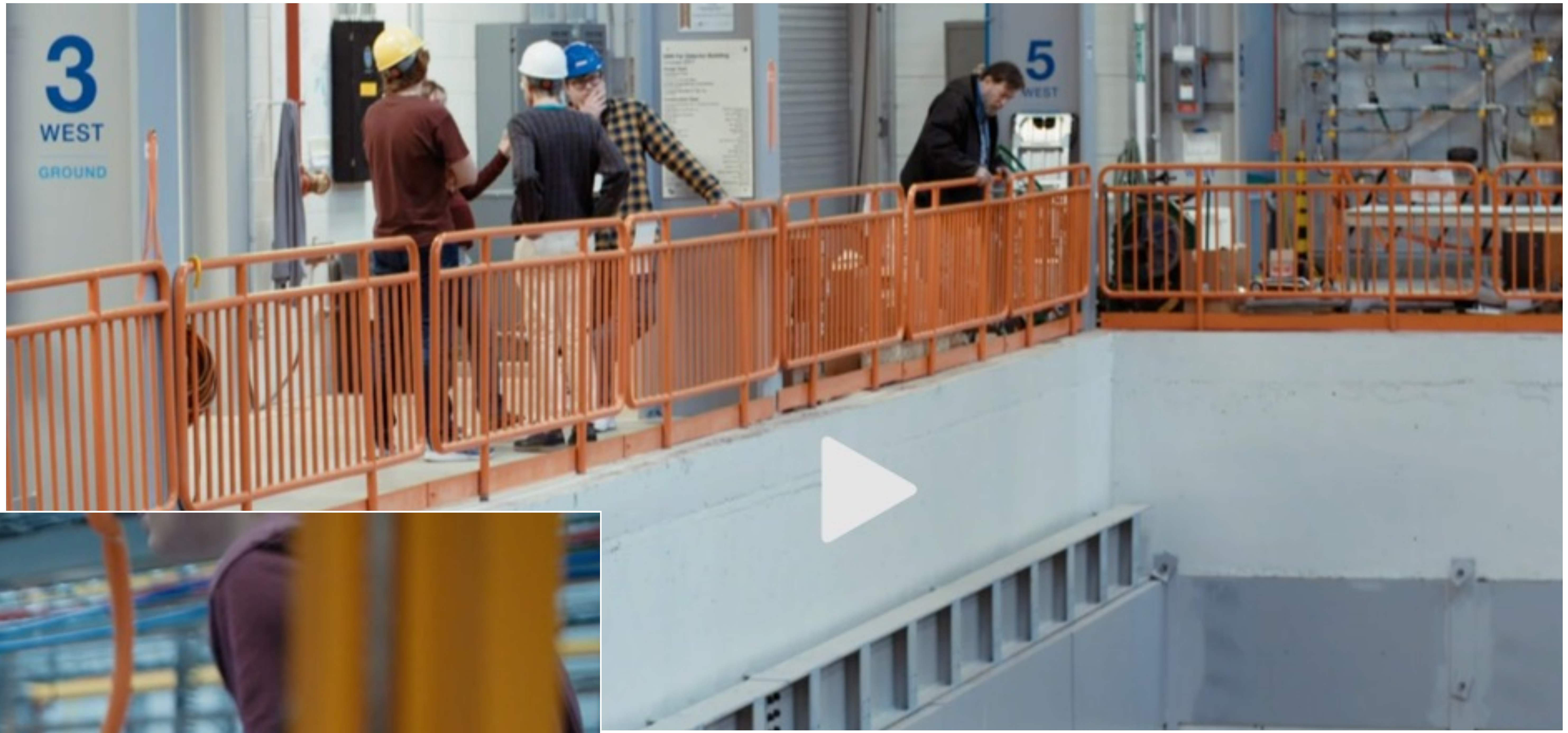

Tyler Boone


FNAL VMS

FNAL VMS

ICARUS @ FNAL

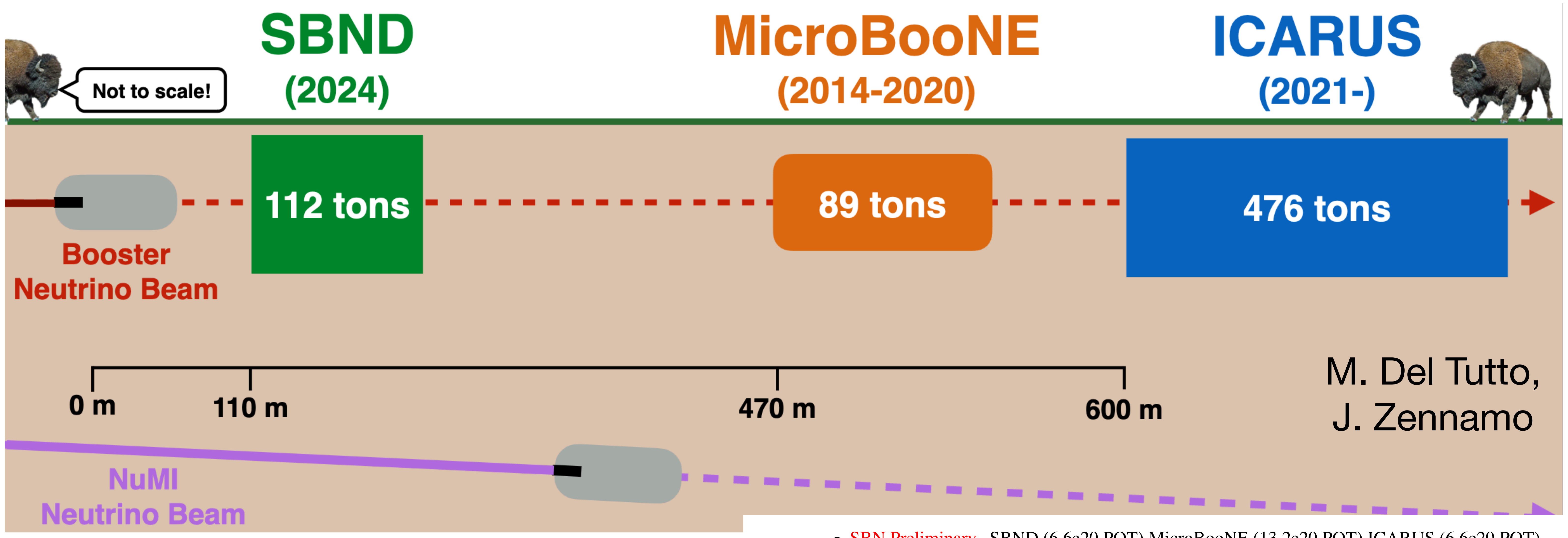
- And it turns out that sometimes when you work on a cool new program and detector area, you might end up in B-roll of a public science documentary… 🎥

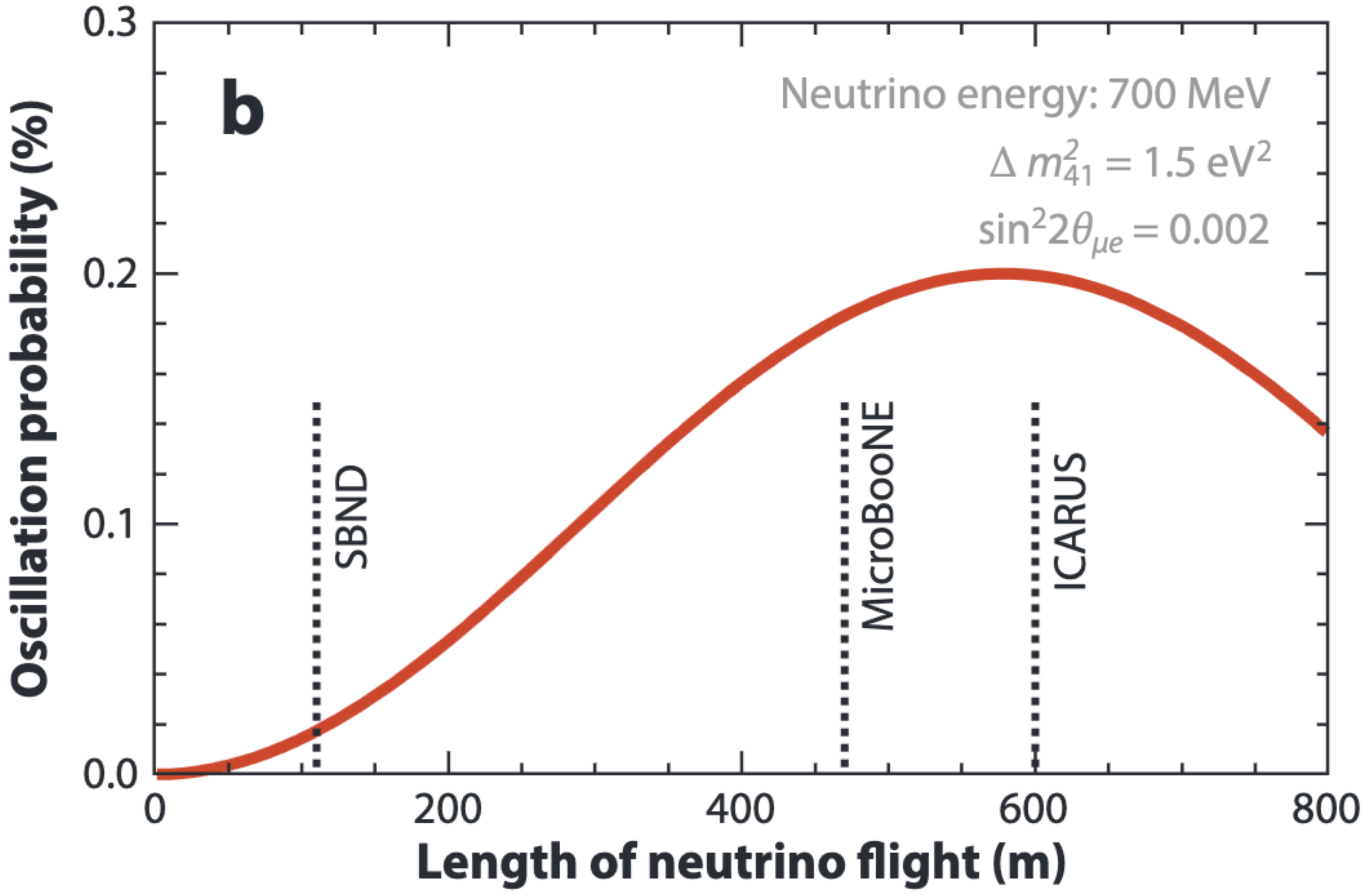


Screenshots from NOvA
Particles Unknown (PBS)

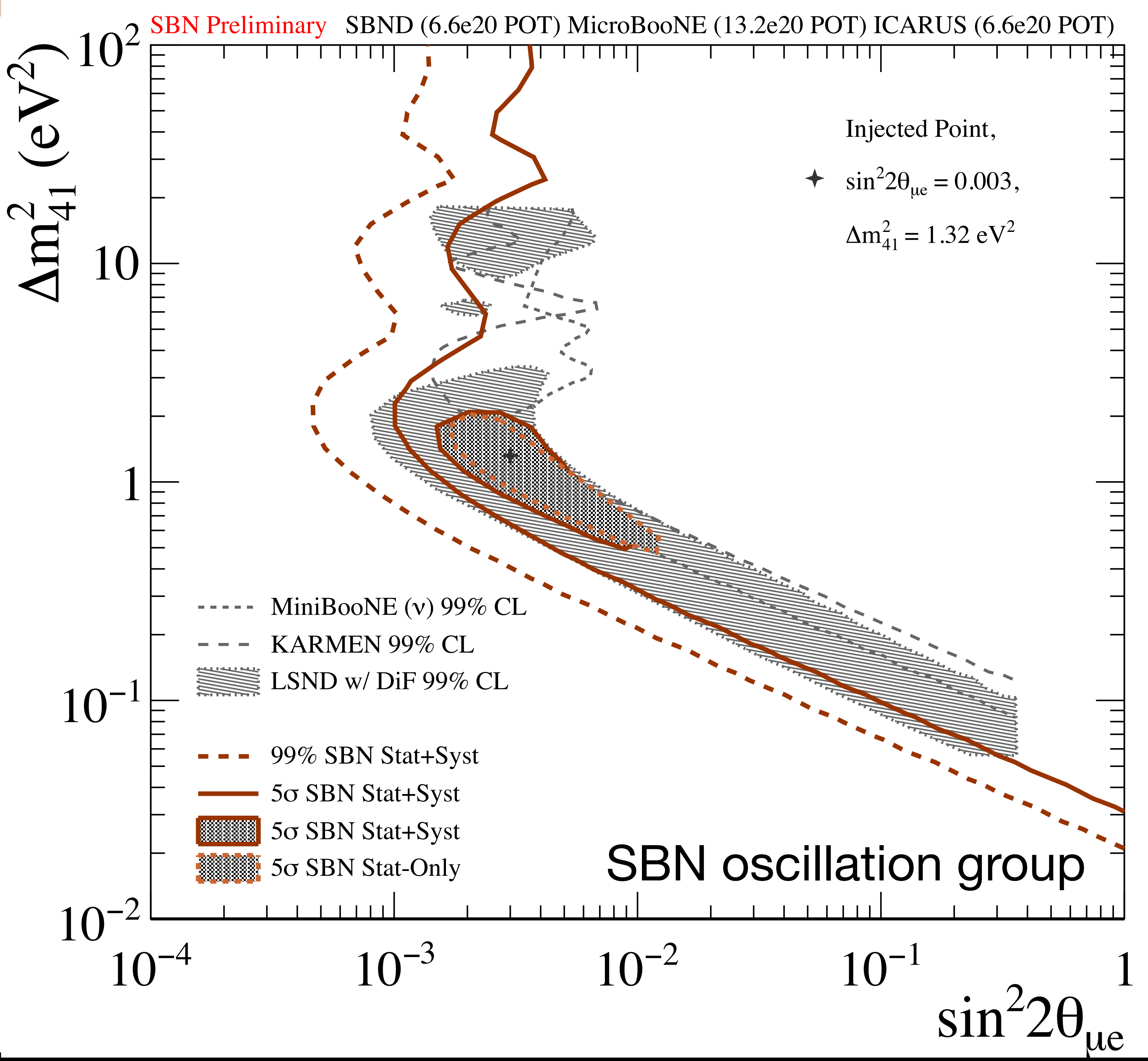
SBN Program

- Short Baseline Neutrino program at FNAL, 3 LAr TPC detectors along BNB beam
- 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 beam component, or NuMI off-axis at ICARUS)





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



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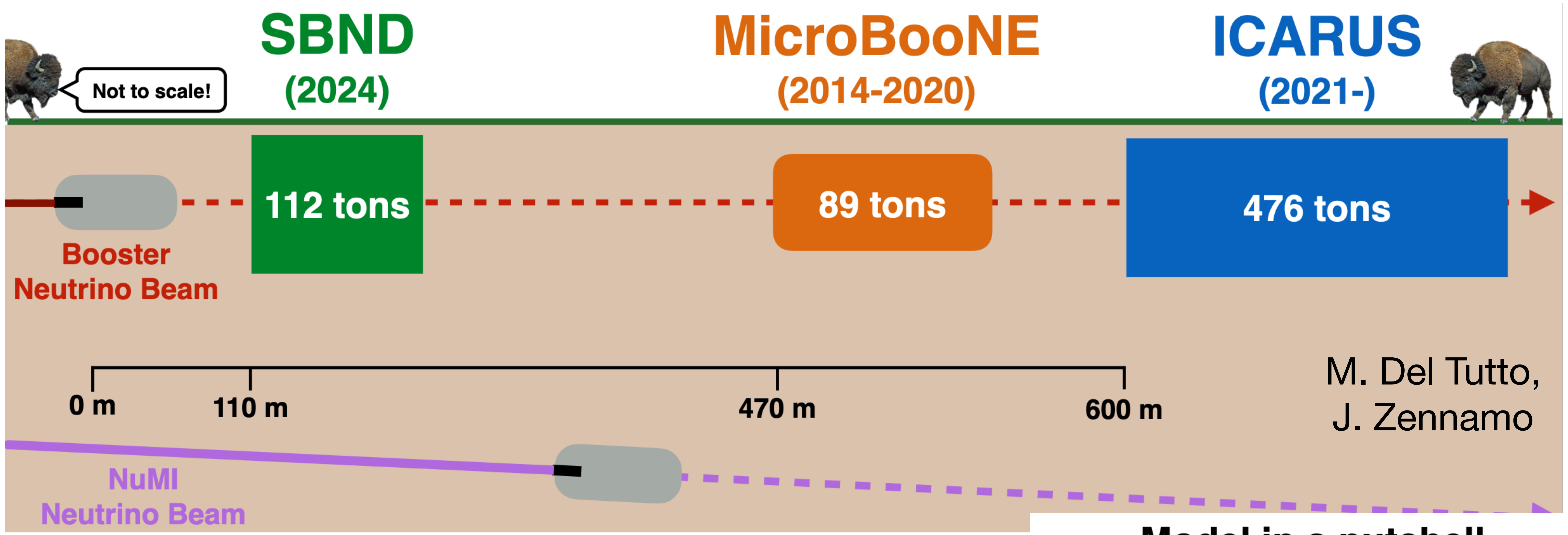
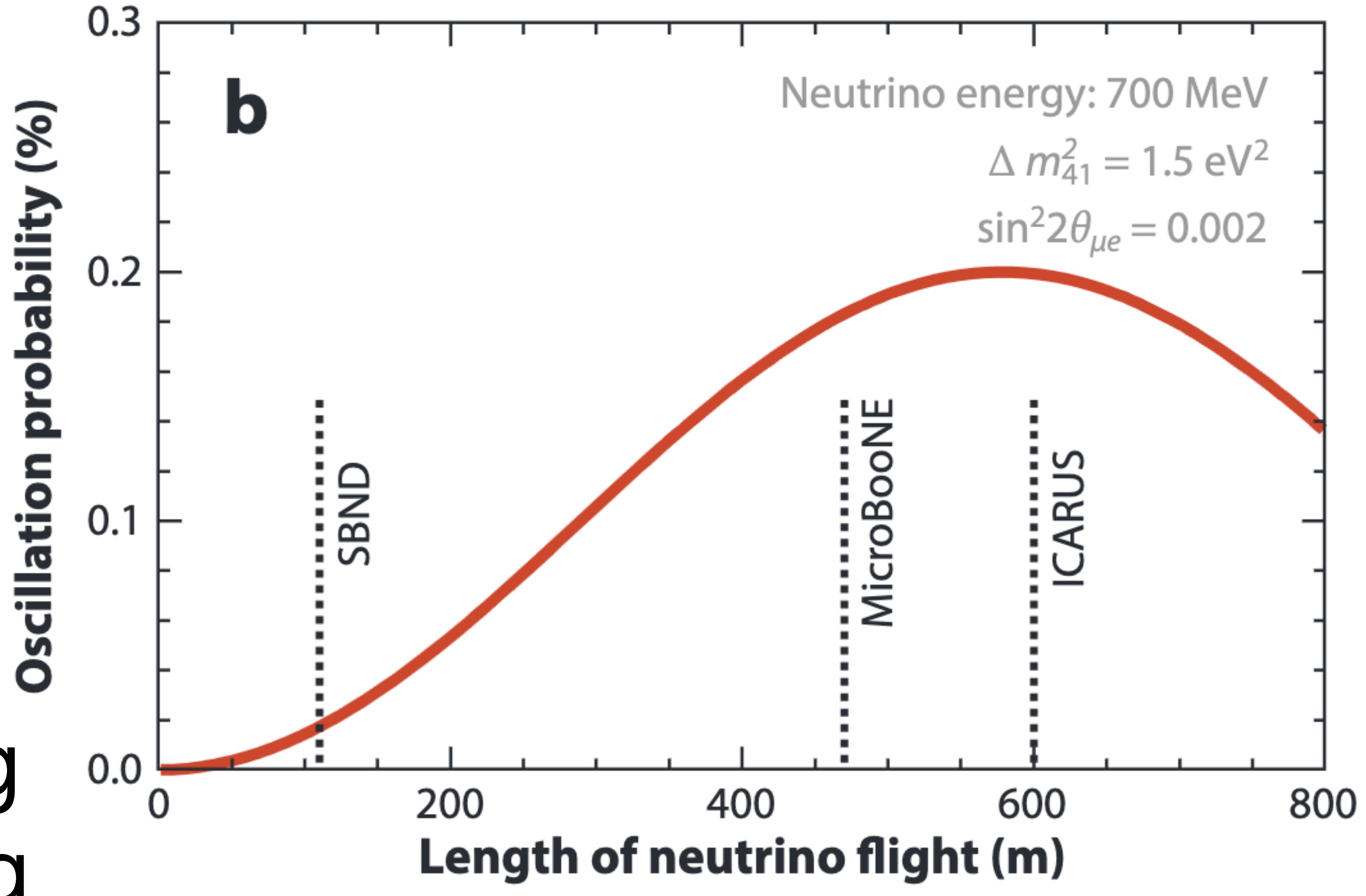
  - SBND=near det, ICARUS=far det
  - Main capability to study both ν_μ disappearance & ν_e appearance
  - Can also probe ν_e disappearance (intrinsic beam component, or NuMI off-axis at ICARUS)
- Utilize LArTPC capability for tracking and particle ID and by virtue of being this sensitive detector, potentially powerful for BSM searches



M. Del Tutto, J. Zennamo

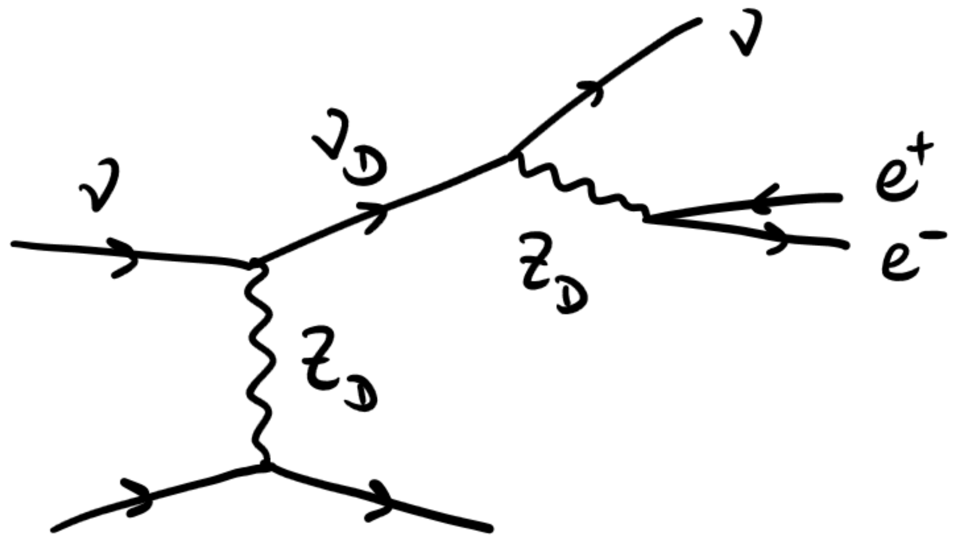


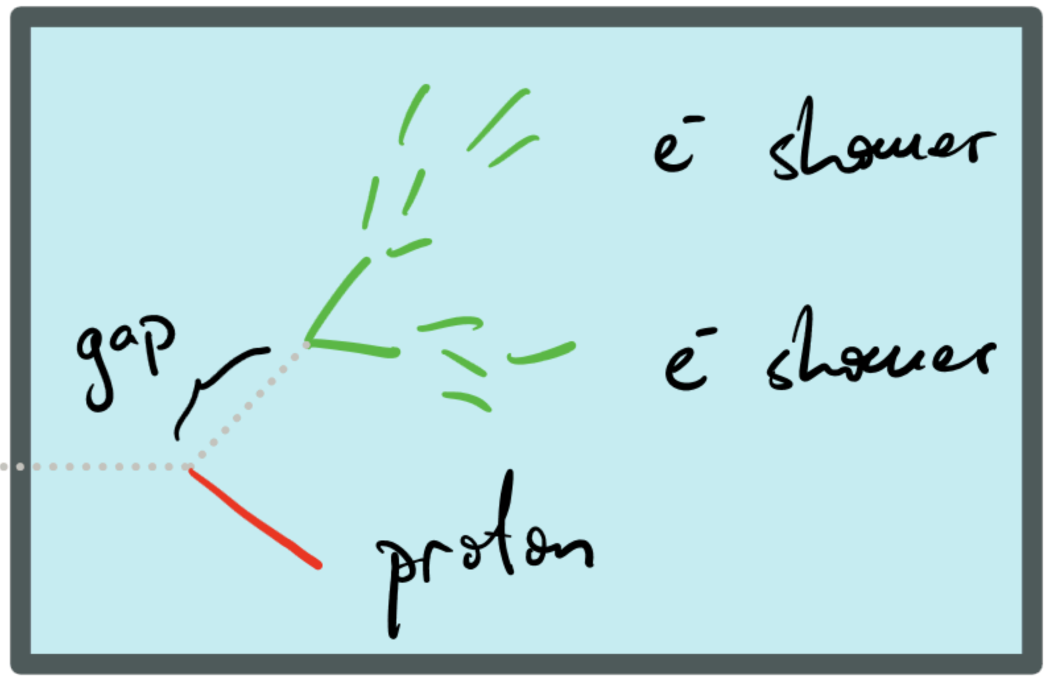
Possible oscillation signature under a set of parameters. P. Machado, O. Palamara, D. Schmitz. Annu. Rev. Nucl. Part. Sci. (2019). doi: 10.1146

Model in a nutshell

Dark neutrinos with heavy Z_D

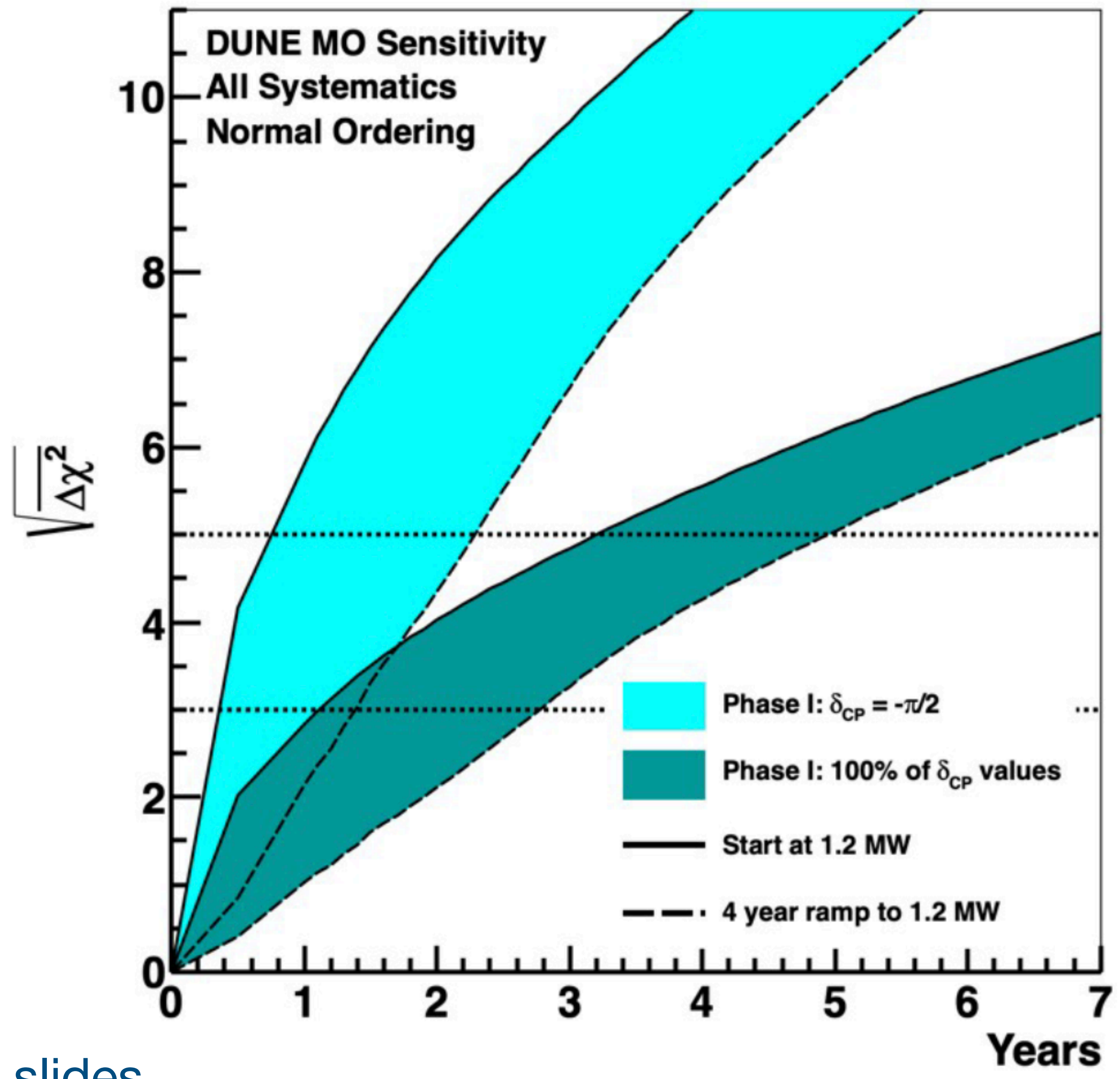
BSM mode which could yield low energy excess and may be explored with LAr TPCs. P. Machado slides



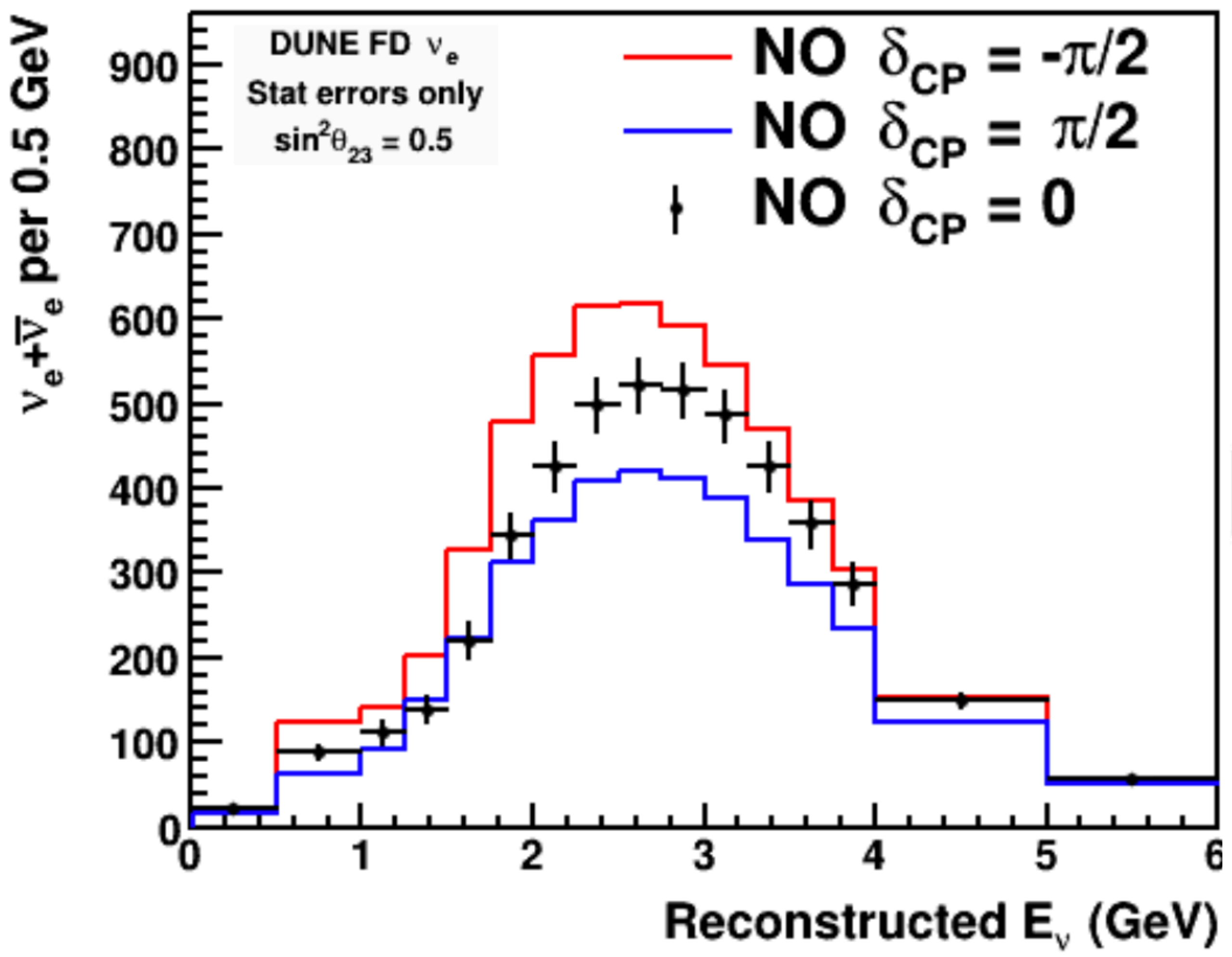


DUNE Program

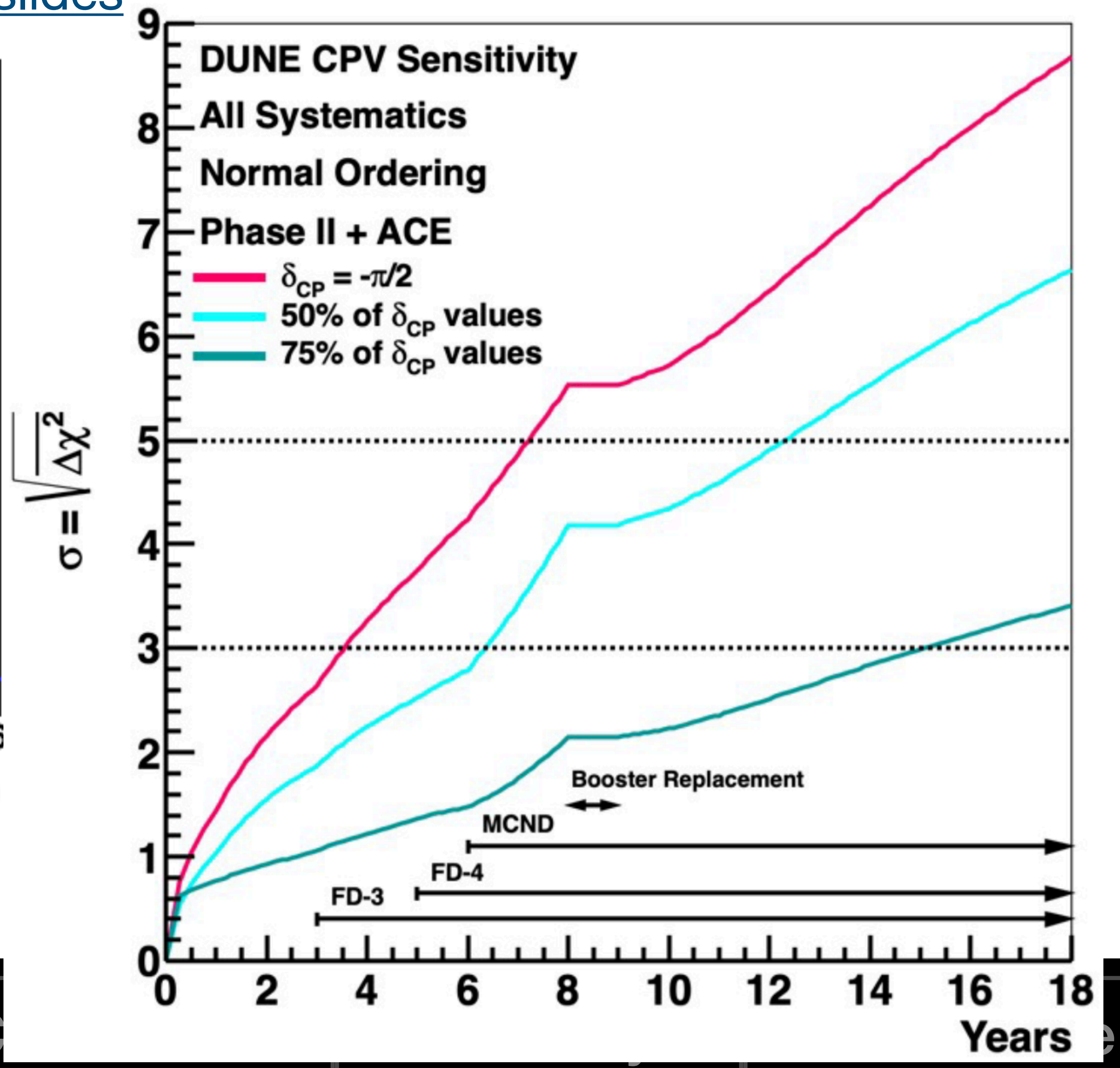
- Placing far detector in Homestake Mine (same as Ray Davis's seminal work with solar ν): next-gen long-baseline project
- DUNE far detector will employ largest ever LAr TPC detectors (at least 20 kilotons active with 2 modules, up to 30 or 40 kT)
  - ICARUS is 0.760 kT LAr, 0.476 kT active
- Will talk more about DUNE towards the end, but for now, important to note that DUNE aims to **vastly improve CP violation sensitivity** and discovery potential compared to current experiments, & should be capable of definitively **resolving the mass ordering**

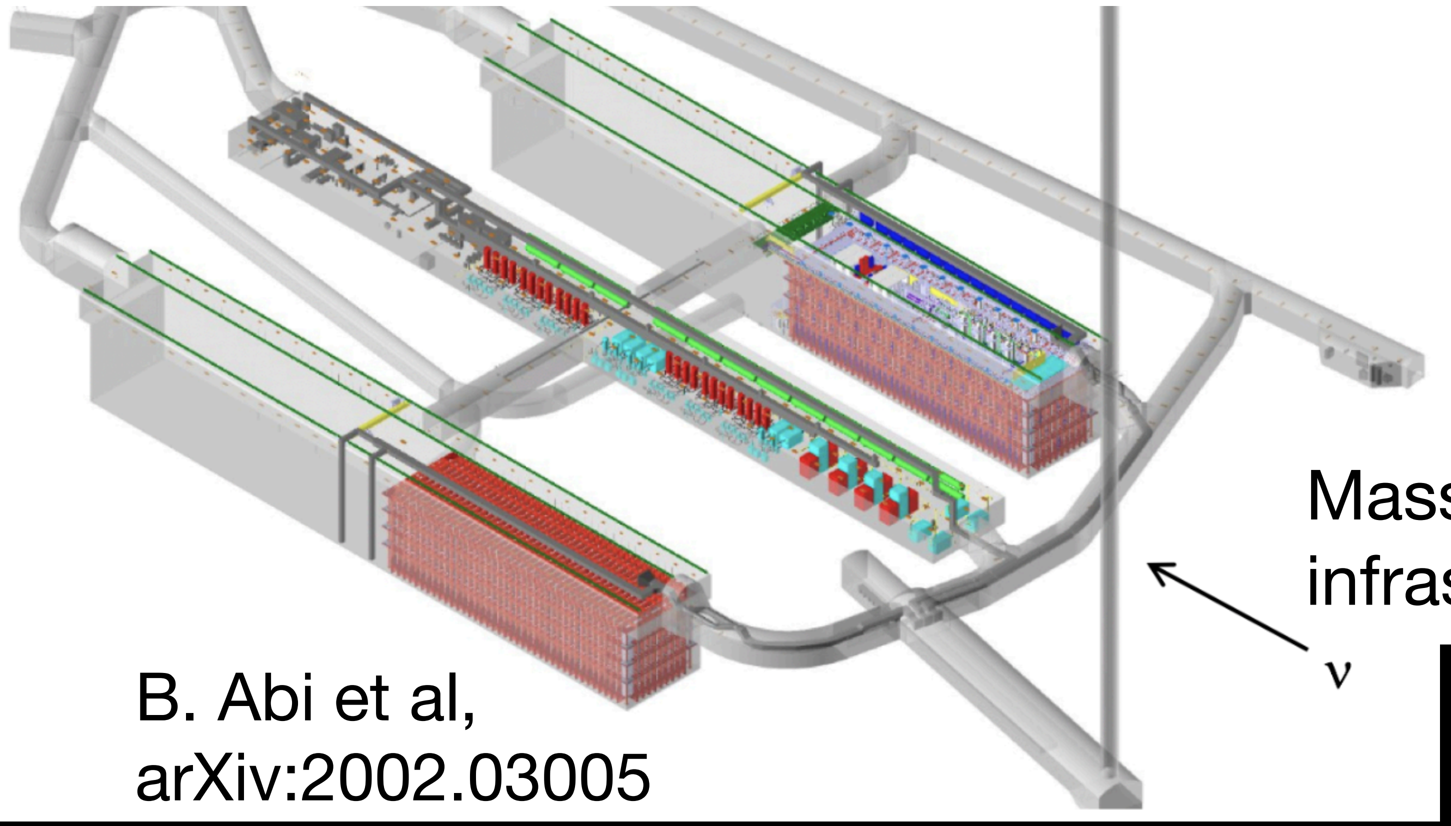


C. Marshall slides



Example event spectrum in DUNE Phase II (after upgrades)

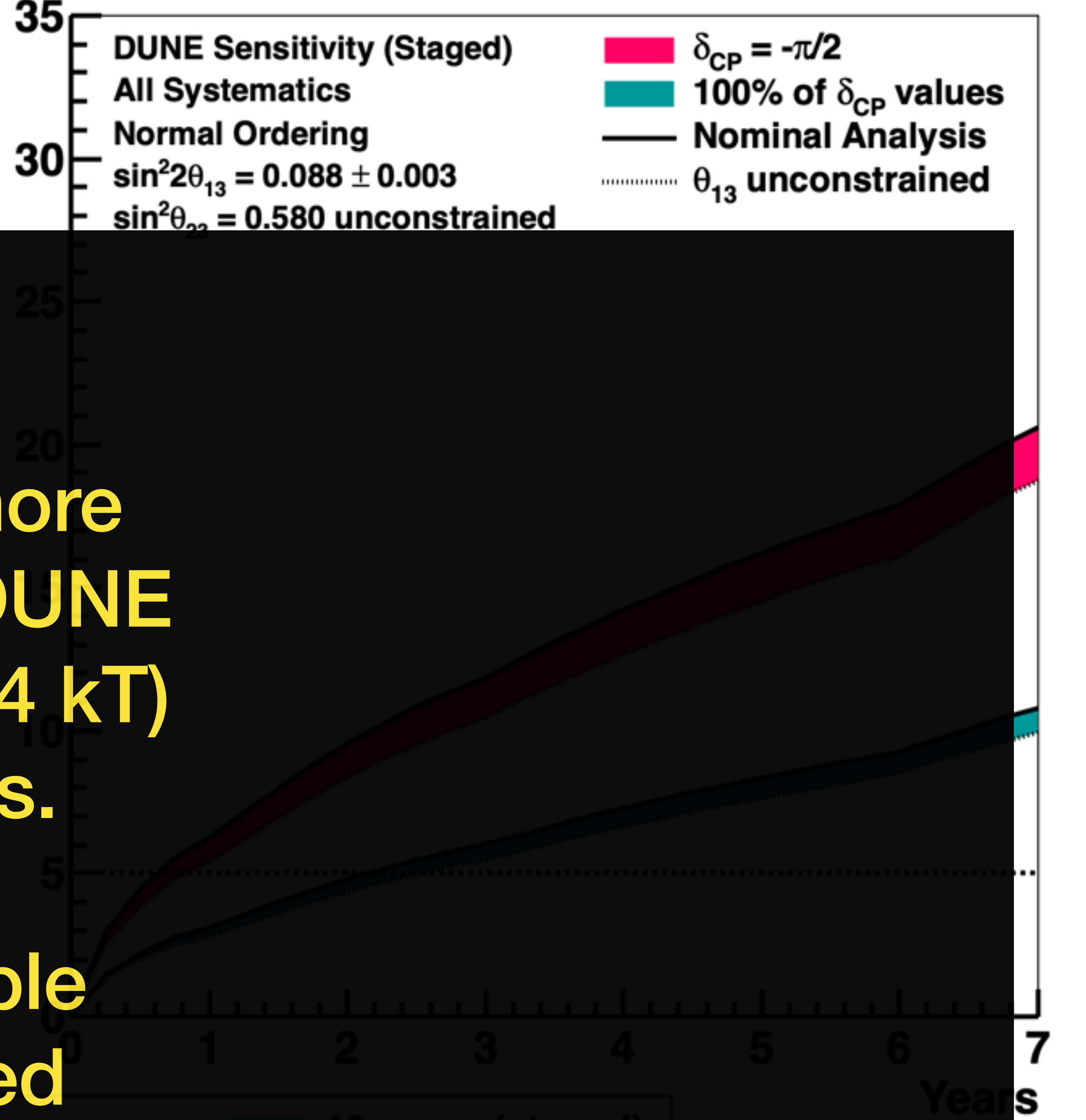




Massive caverns and infrastructure at SURF

B. Abi et al, arXiv:2002.03005

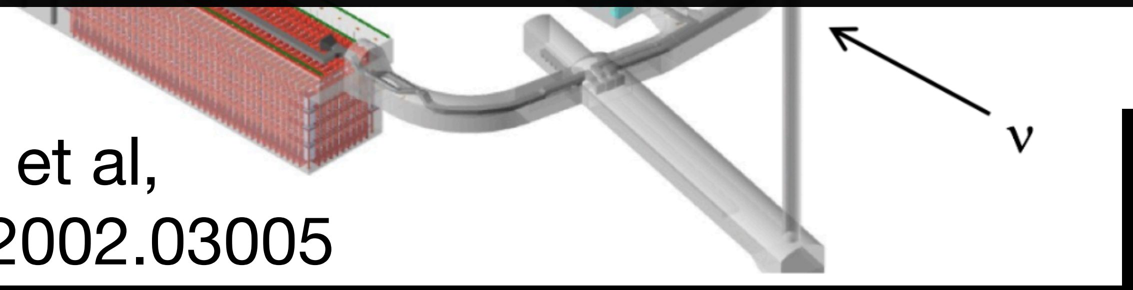
DUNE Program



The improved, more powerful beam combined with more sensitive detector/medium (LArTPC) and bigger size (DUNE will be up to 40 kT Fiducial Volume, NOvA is in total ~14 kT) enable these most precise oscillation measurements.

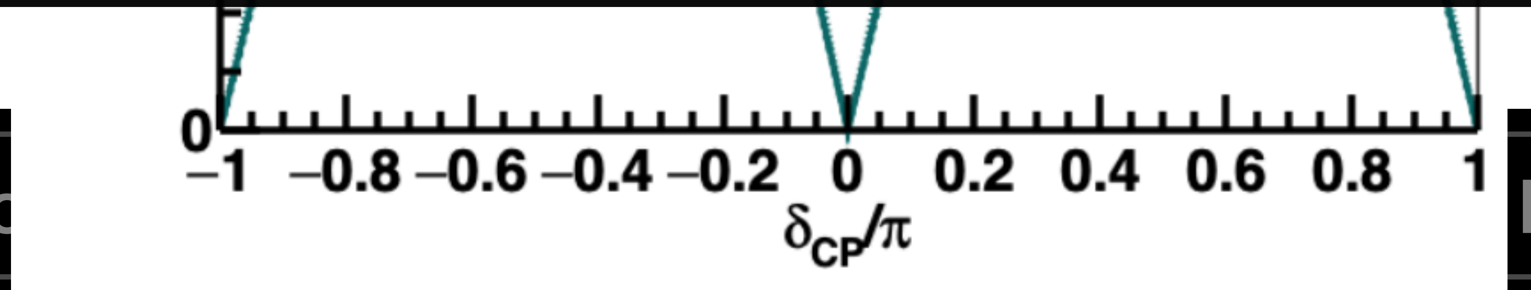
BUT, they are not enough. With this increased possible precision, also need well understood and constrained systematic uncertainties.

For one, the current suite of LArTPCs that have been operating (ICARUS, MicroBooNE, ProtoDUNE) and will soon operate (e.g. SBND) are helping us gain experience with these complicated detectors and performing analysis and systematic studies.



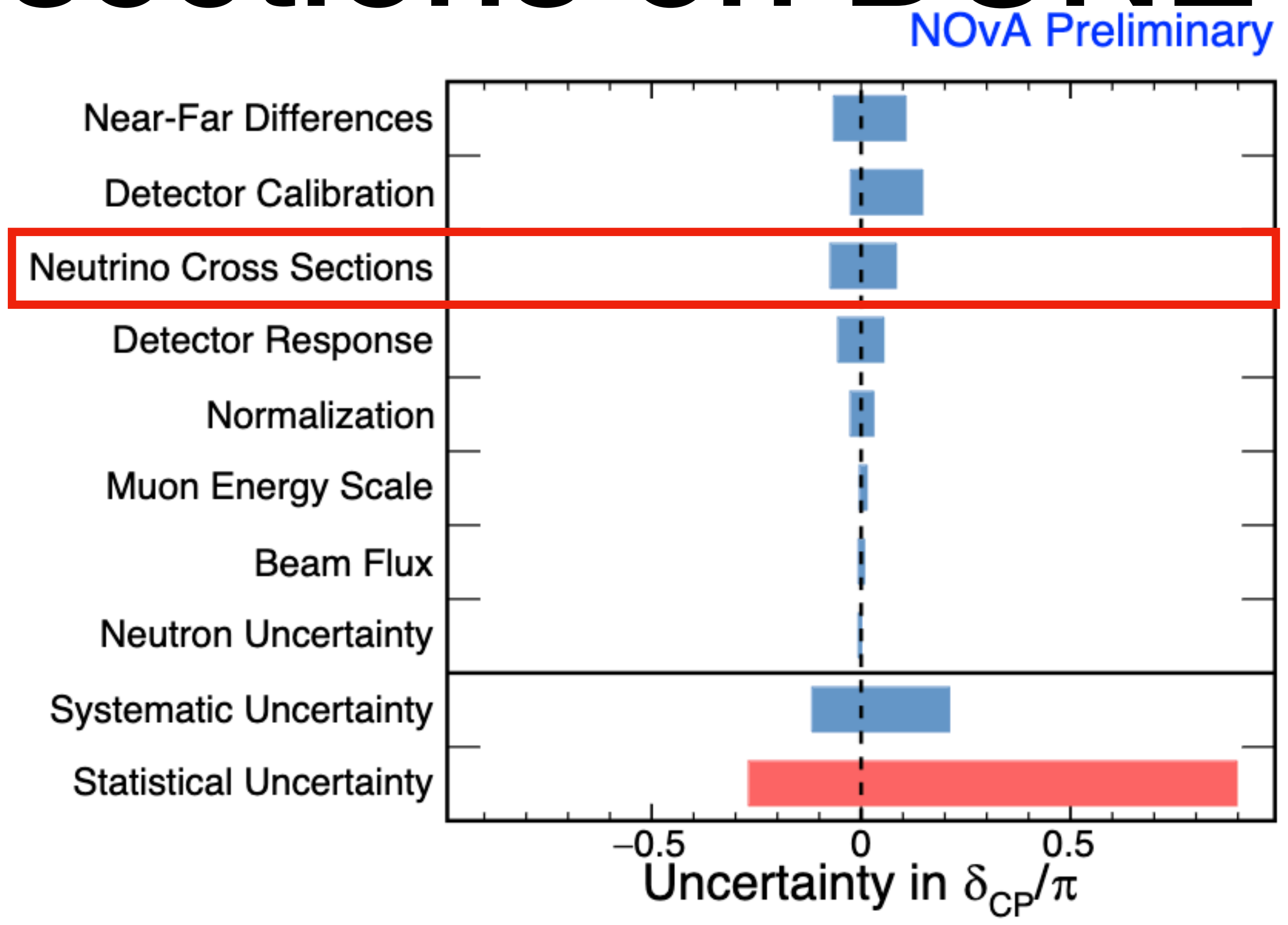
infrastructure at SURF

B. Abi et al, arXiv:2002.03005

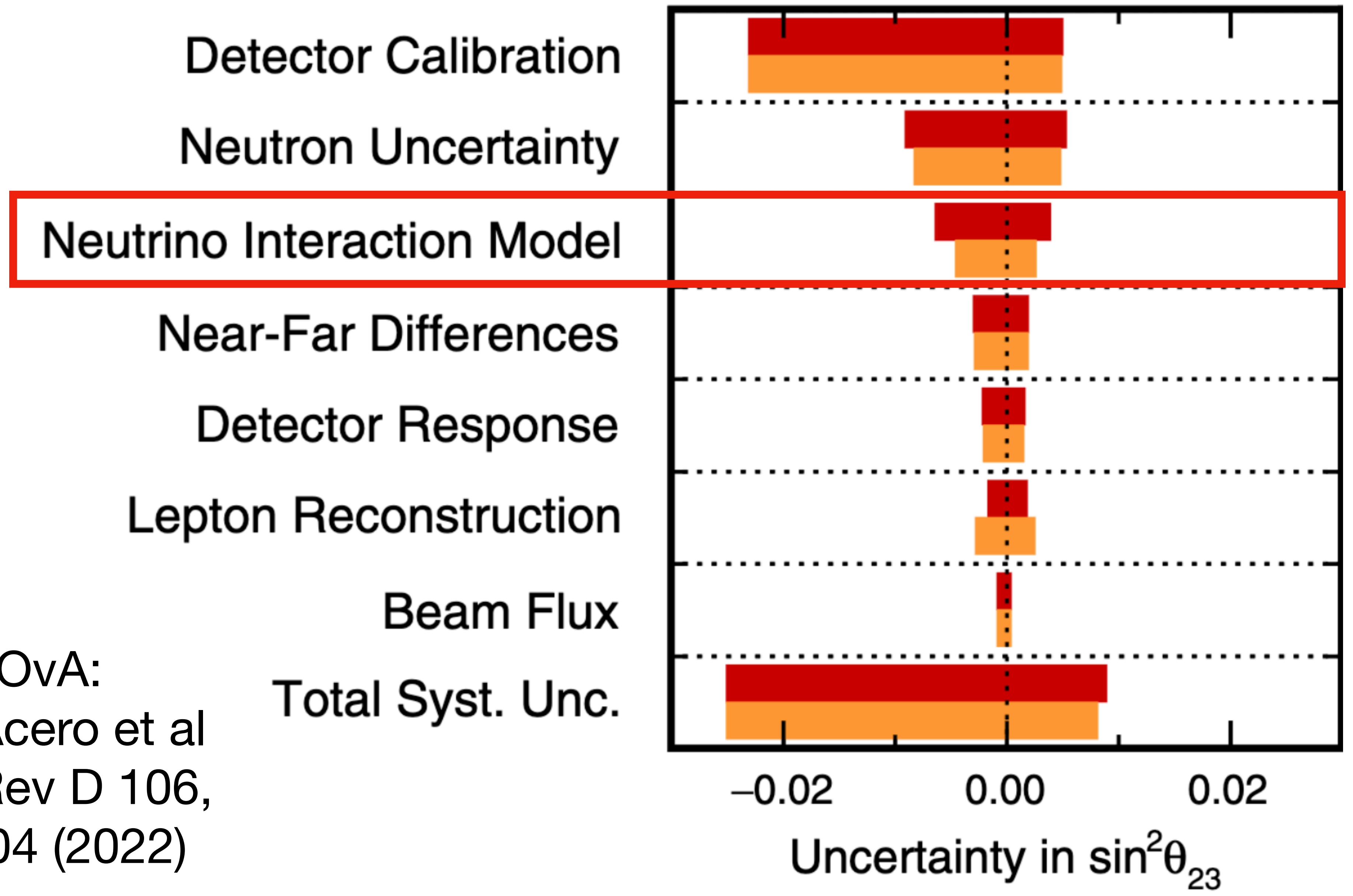


Impact of neutrino interactions/cross-sections on DUNE

- Another critical aspect to make the sorts of precision measurements DUNE will make is in the neutrino cross-section and interaction physics
- The use of a near detector in oscillation experiments greatly confines the overall rate (flux) systematics that would otherwise be a large contributor
  - Also reduces the cross-section uncertainties in a similar manner
  - But does not make them negligible: still important contributor to systematics budget
- This is reflected in recent NOvA results and expected to be similar story for DUNE, especially if we don't do our best to constrain them further



Previous NOvA results (slides from A. Himmel)



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

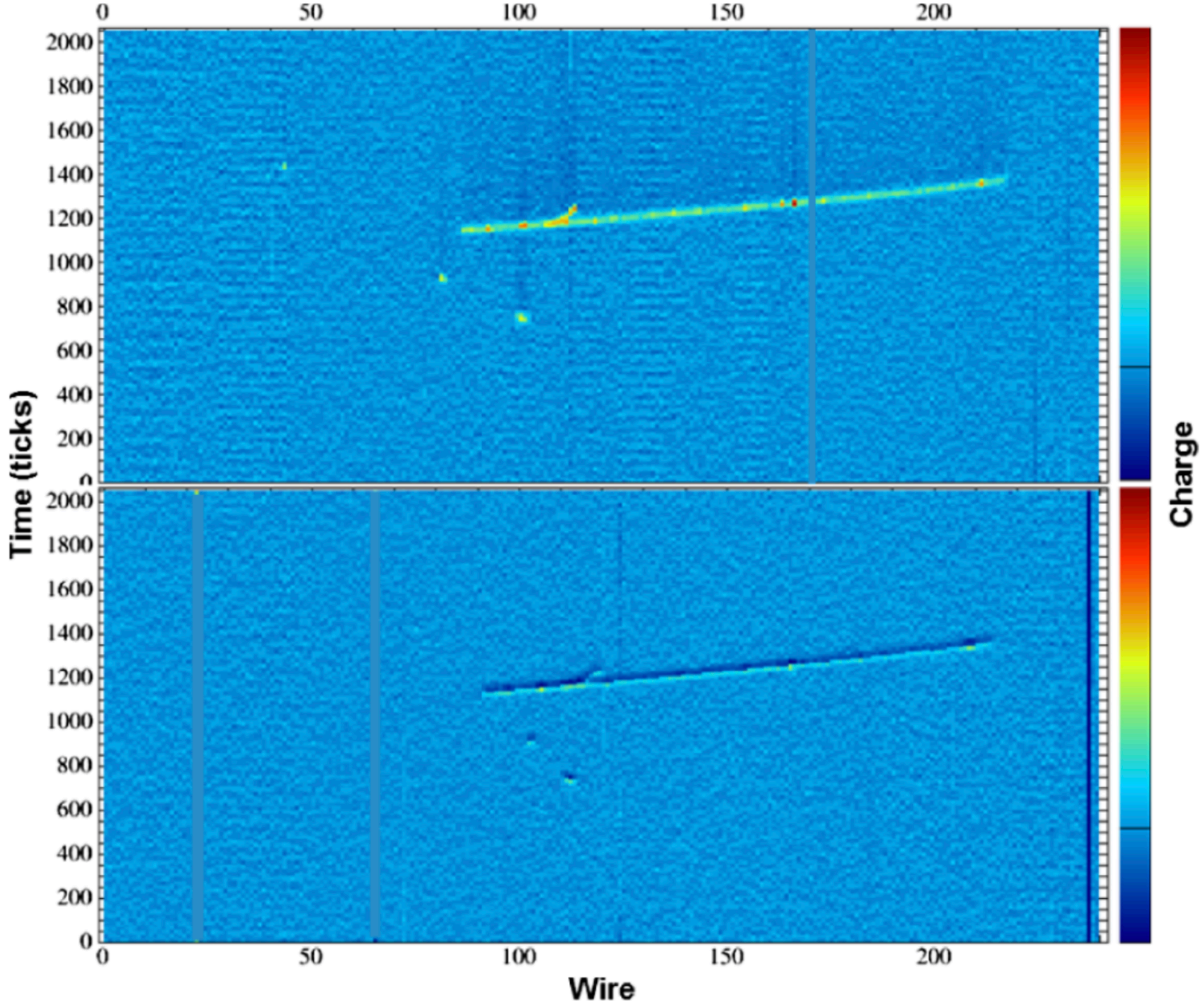
Impact of neutrino interactions/cross-sections on DUNE

- 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 the neutrino energy based on the energy of all the products**
  - What we see in the detector can be a complicated "mess" of the neutrino interaction on a nuclear target (Argon)

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

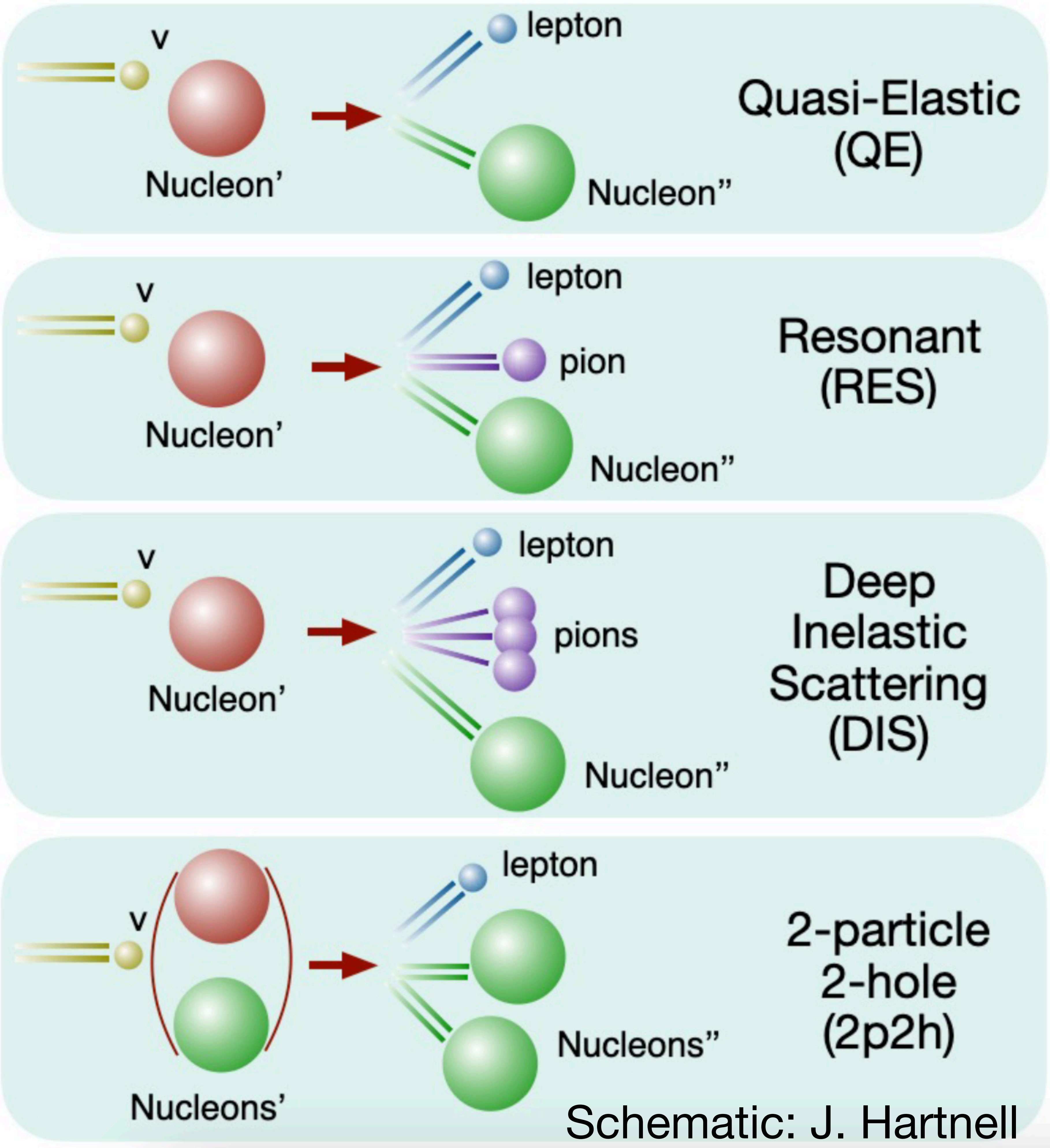
ArgoNeuT data

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

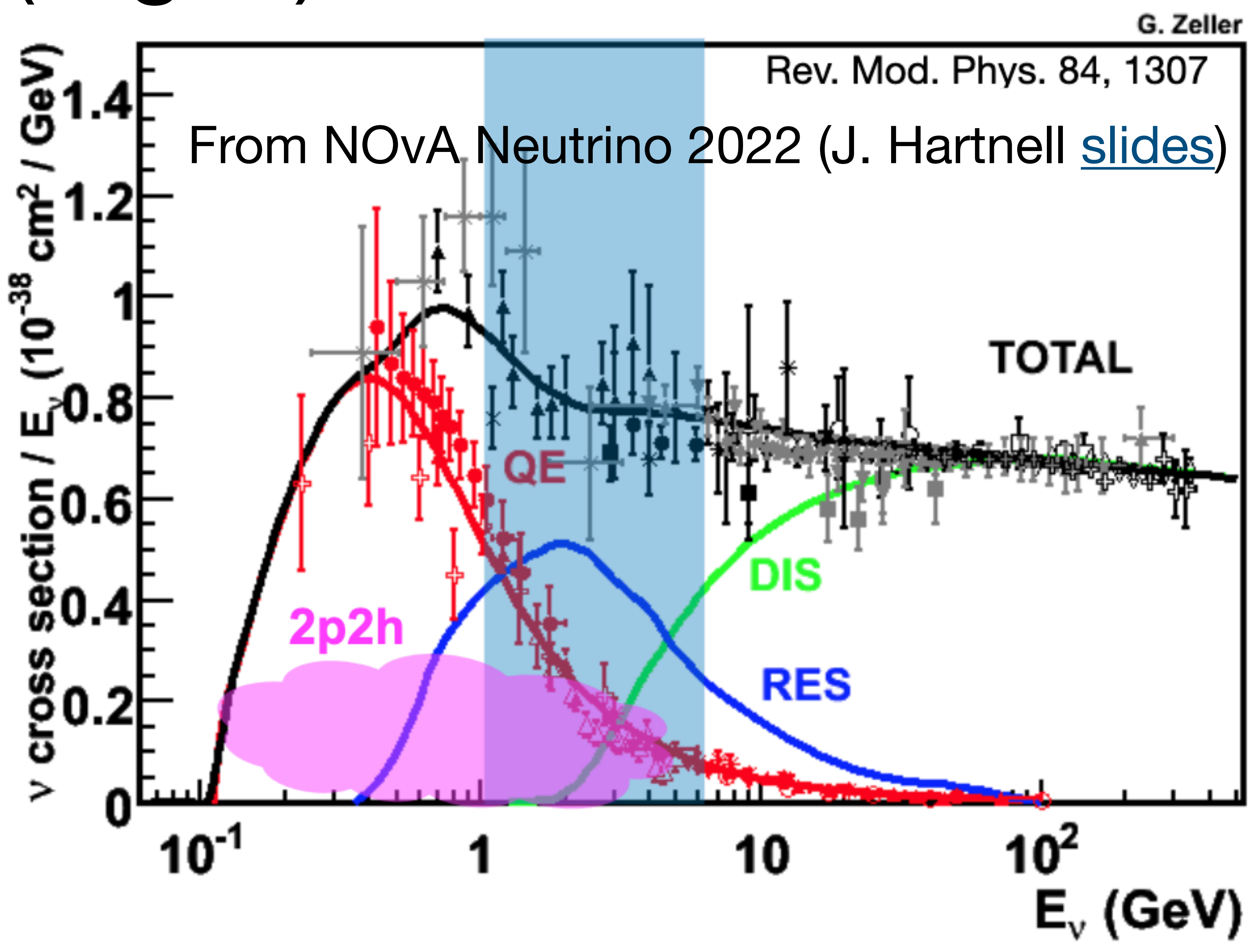


Impact of neutrino interactions/cross-sections on DUNE

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



Schematic: J. Hartnell

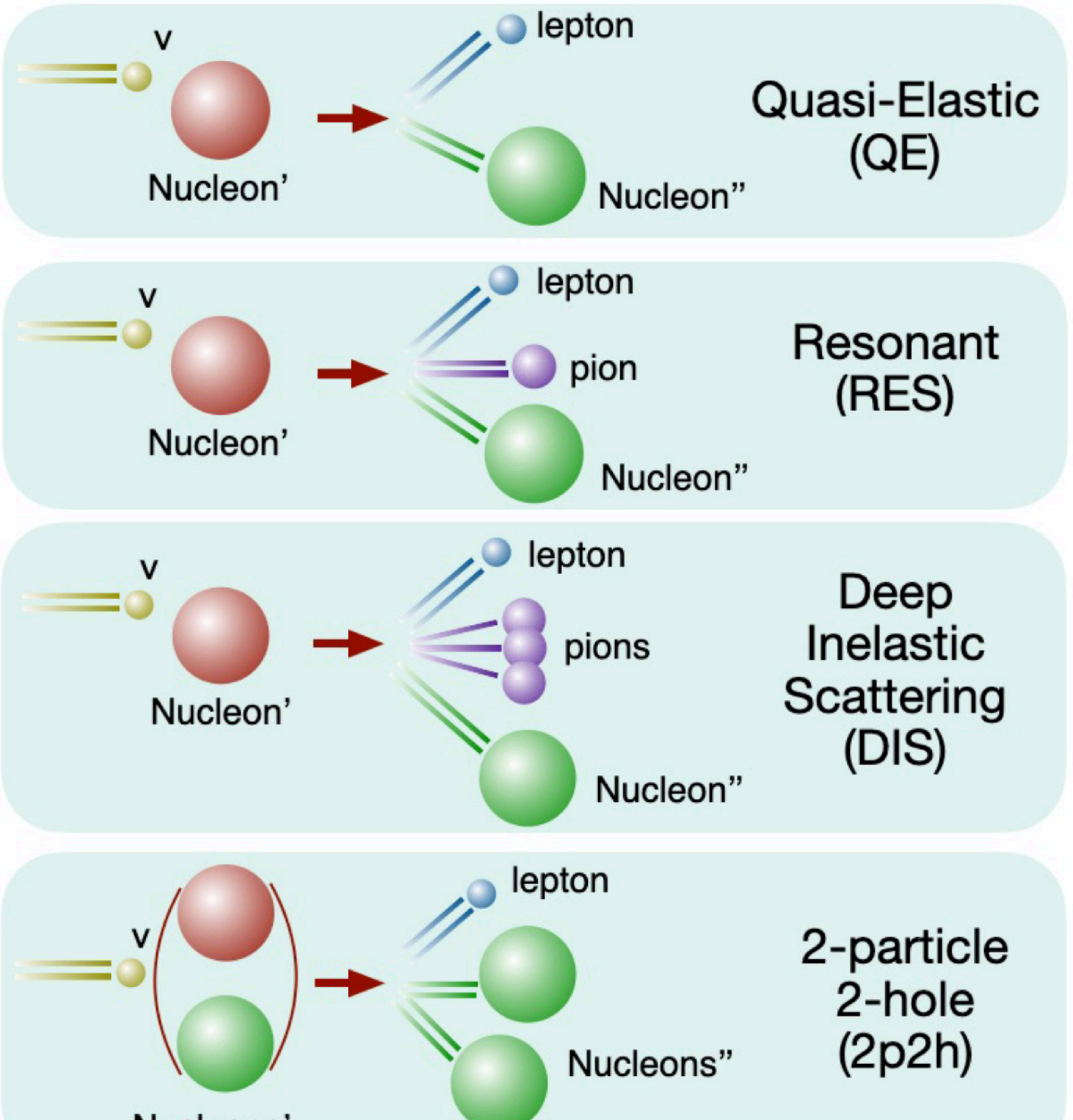


Particles/yields expected depend on mode, therefore so does the energy resolution.

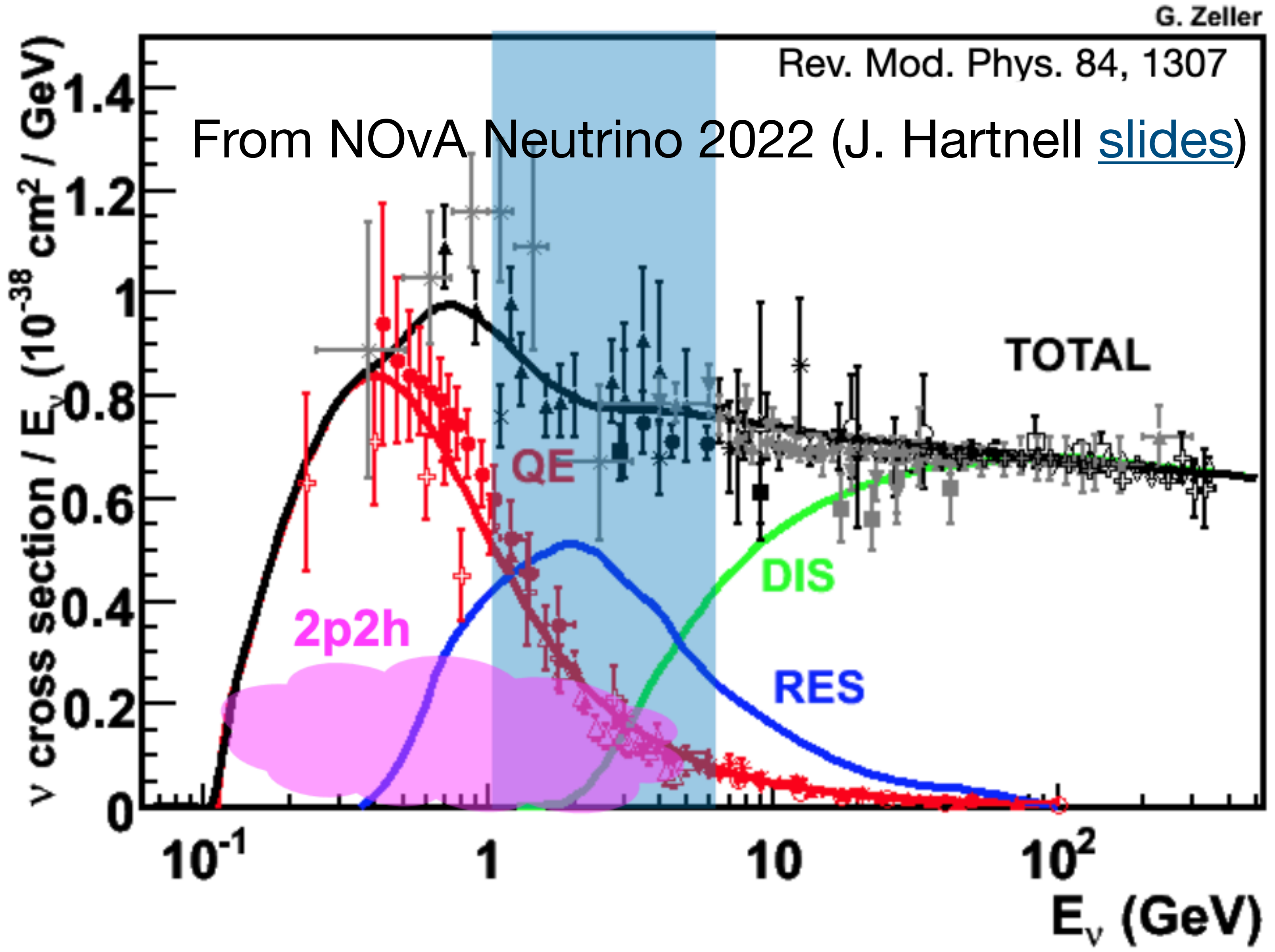
Especially modes w/ neutral particles like (e.g. anti-nu interactions and 2p2h).

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)

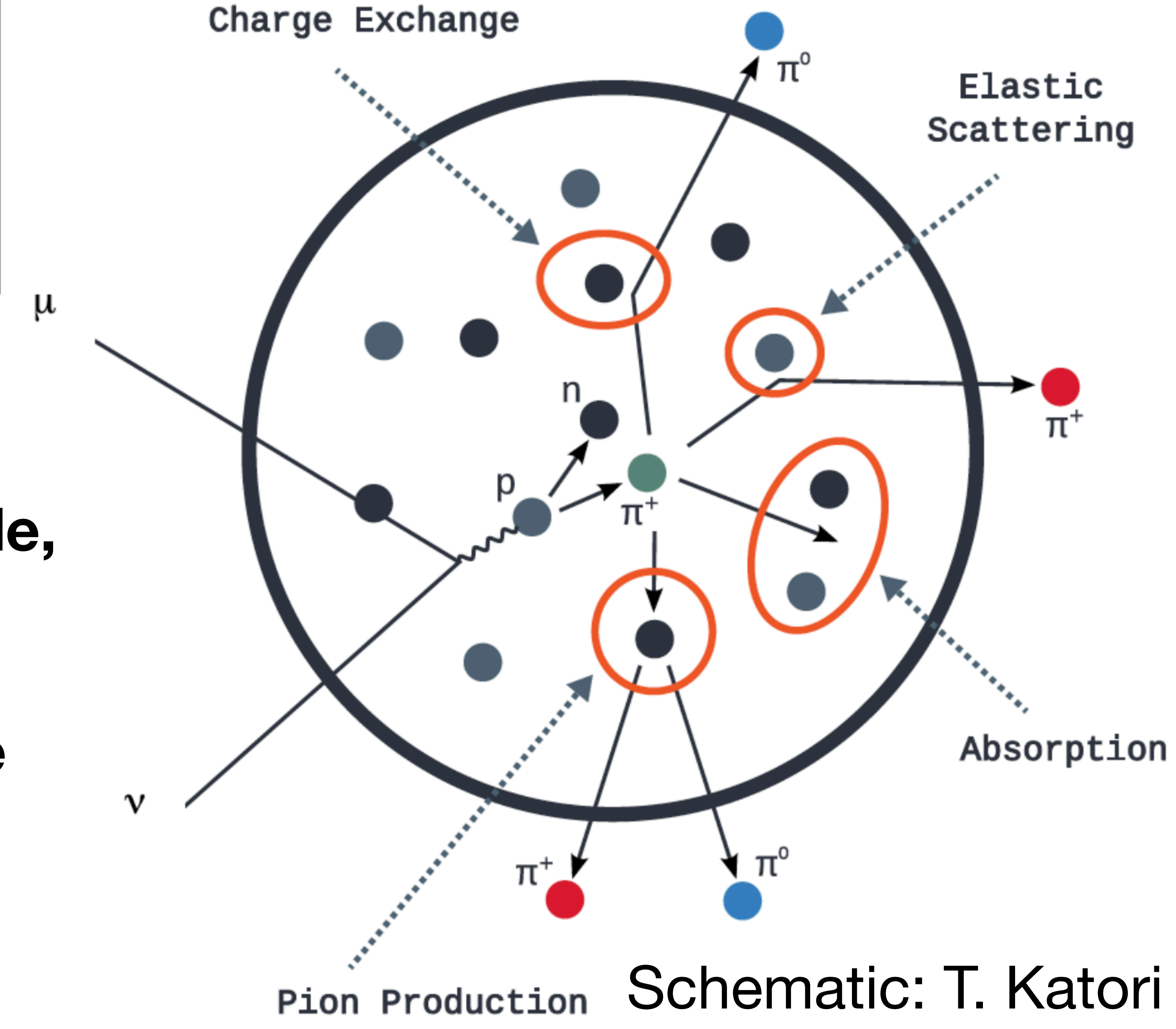


Schematic: J. Hartnell



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)



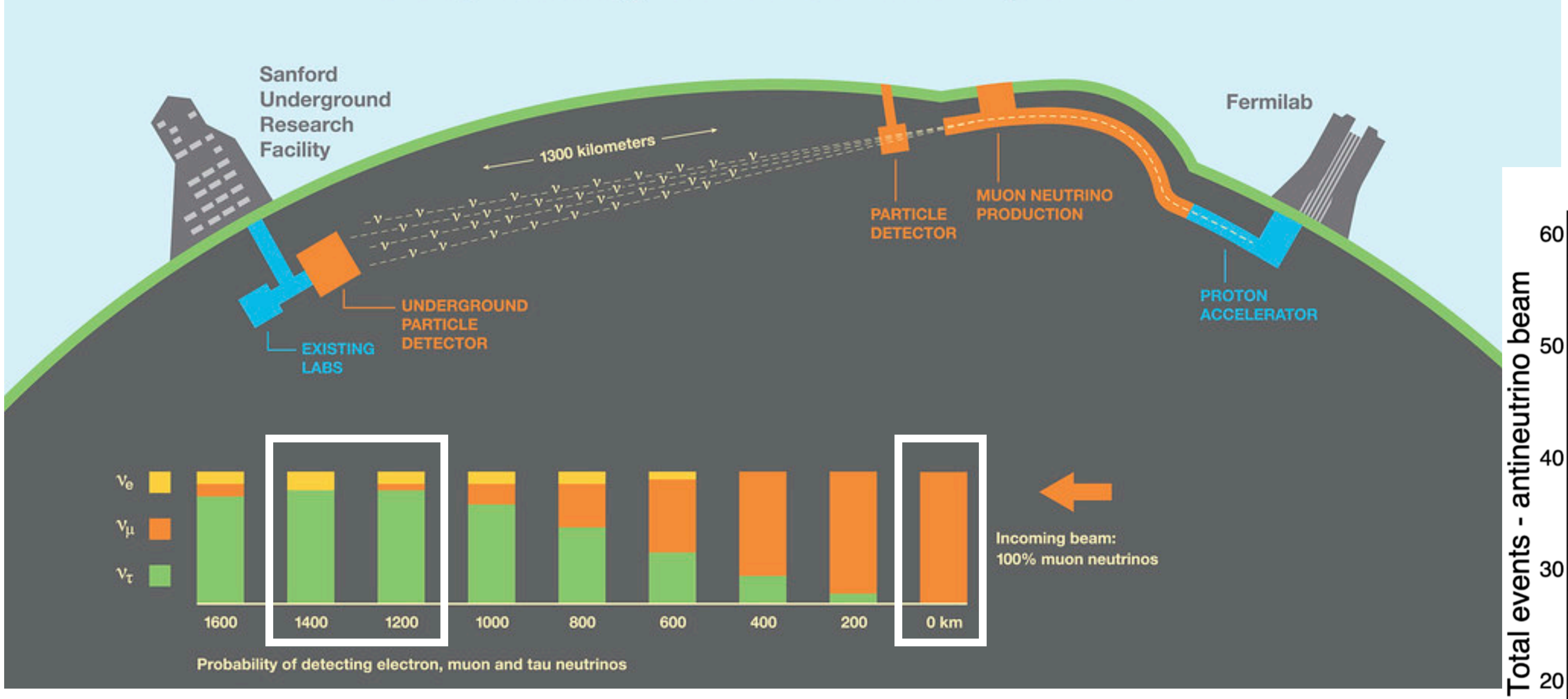
Schematic: T. Katori

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).

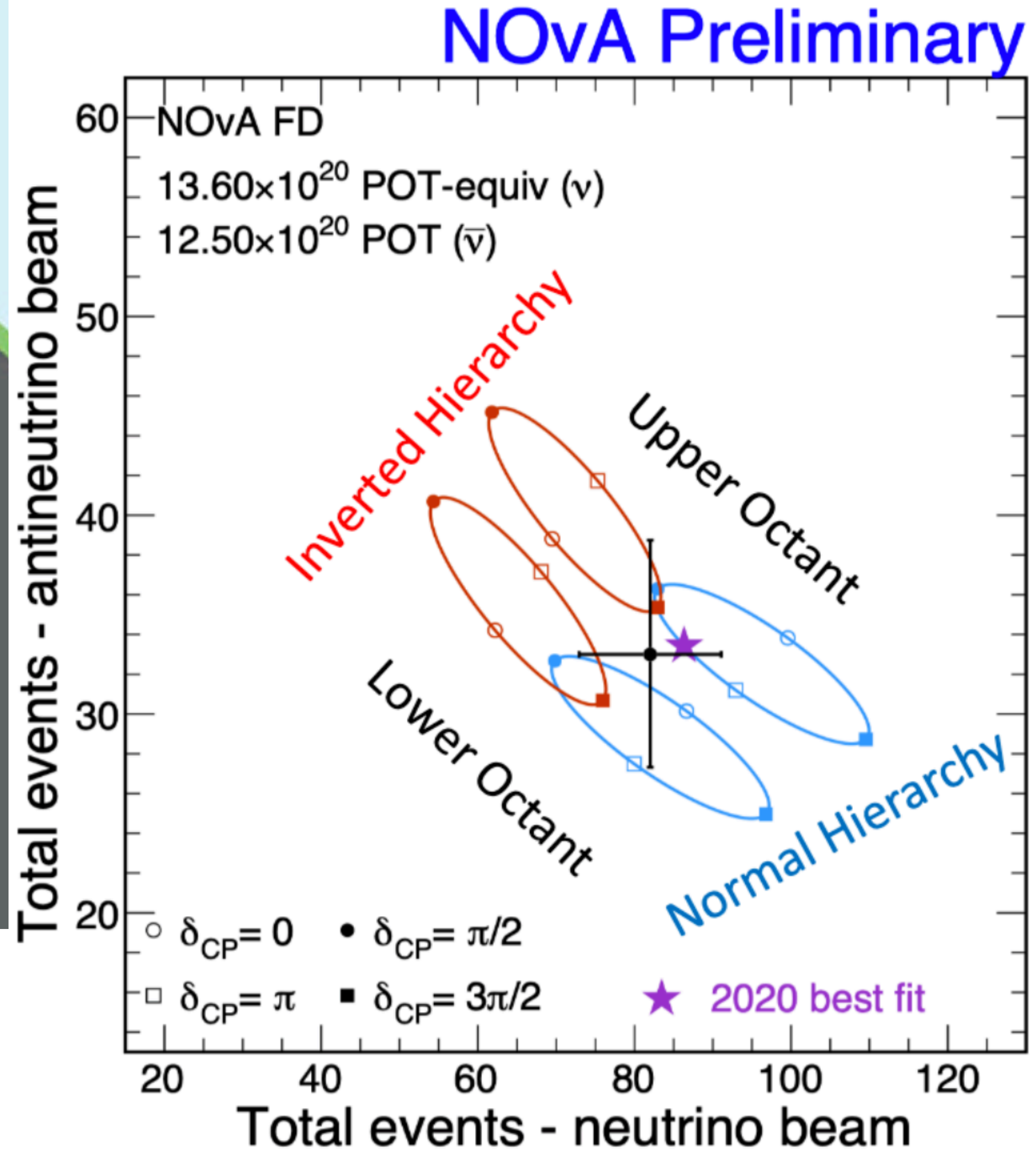
Impact of neutrino interactions/cross-sections on DUNE

- Also, flux is **different** at Far Detector (oscillation): degeneracy in differences seen at FD between **oscillatory effect** or **difference in ν_μ vs ν_e cross-section** relative to expectation



DUNE PR image

NOvA Neutrino 2022 (J. Hartnell slides)



- ν vs $\bar{\nu}$ cross-section: by similar arguments when trying to study both signs for oscillation and measure CP violating phase e.g.

Impact of neutrino interactions/cross-sections on DUNE

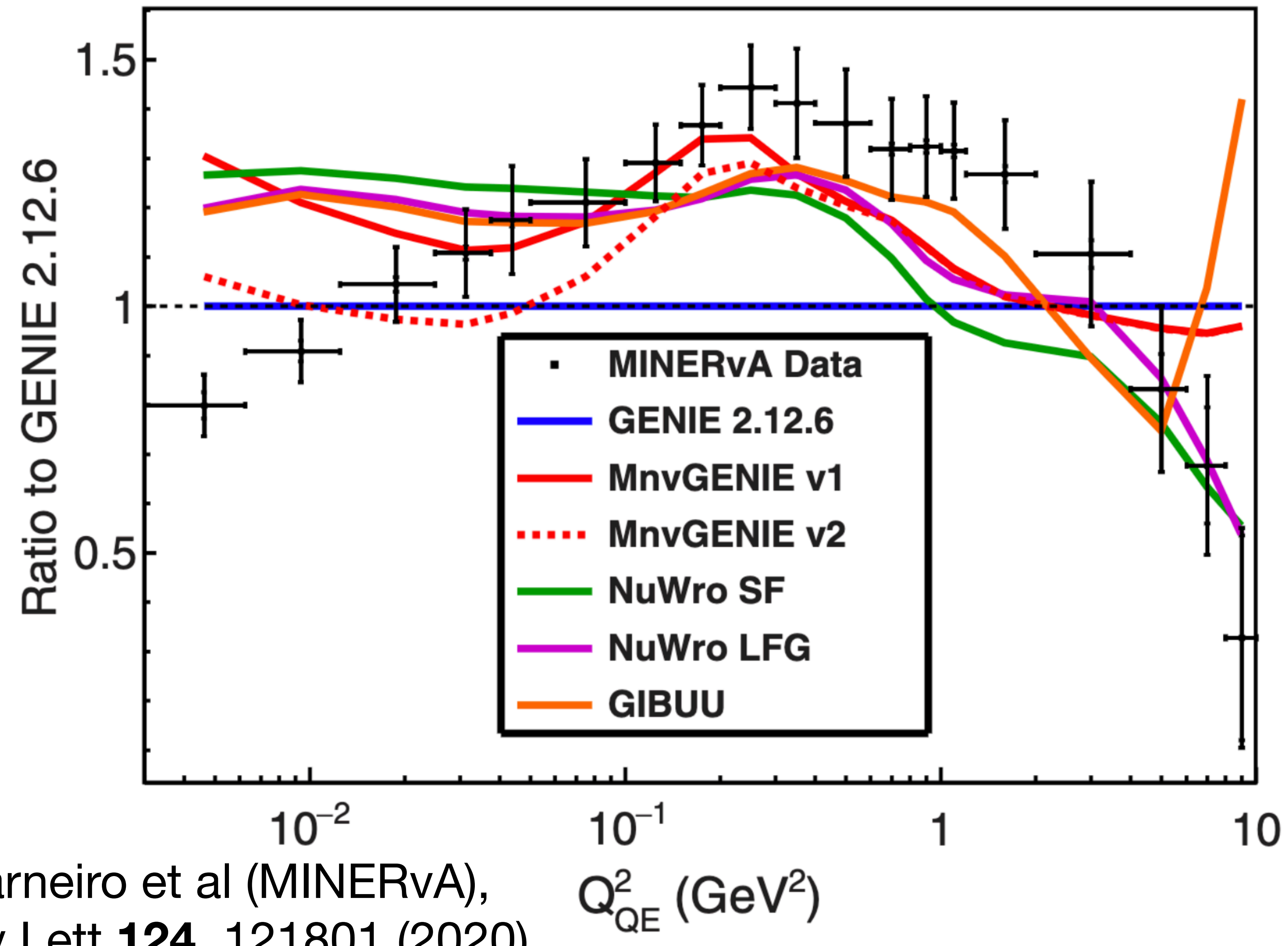
- We rely on event generators giving us predictions of events interacting via different channels with varying kinematics
  - Some are being newly developed as well with various innovations and showing promise with some data
  - Theory community also incredibly important to refine expectations, provide new formulae to better characterize what we expect to see
- Fermilab experiments have a long history with GENIE for the base model: this does come with some out-of-the-box systematic uncertainties as well
- However, 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 the target planned to be used (Ar)

A few different event generators/models

Genie
UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

NuWro
Wroclaw Neutrino Event Generator

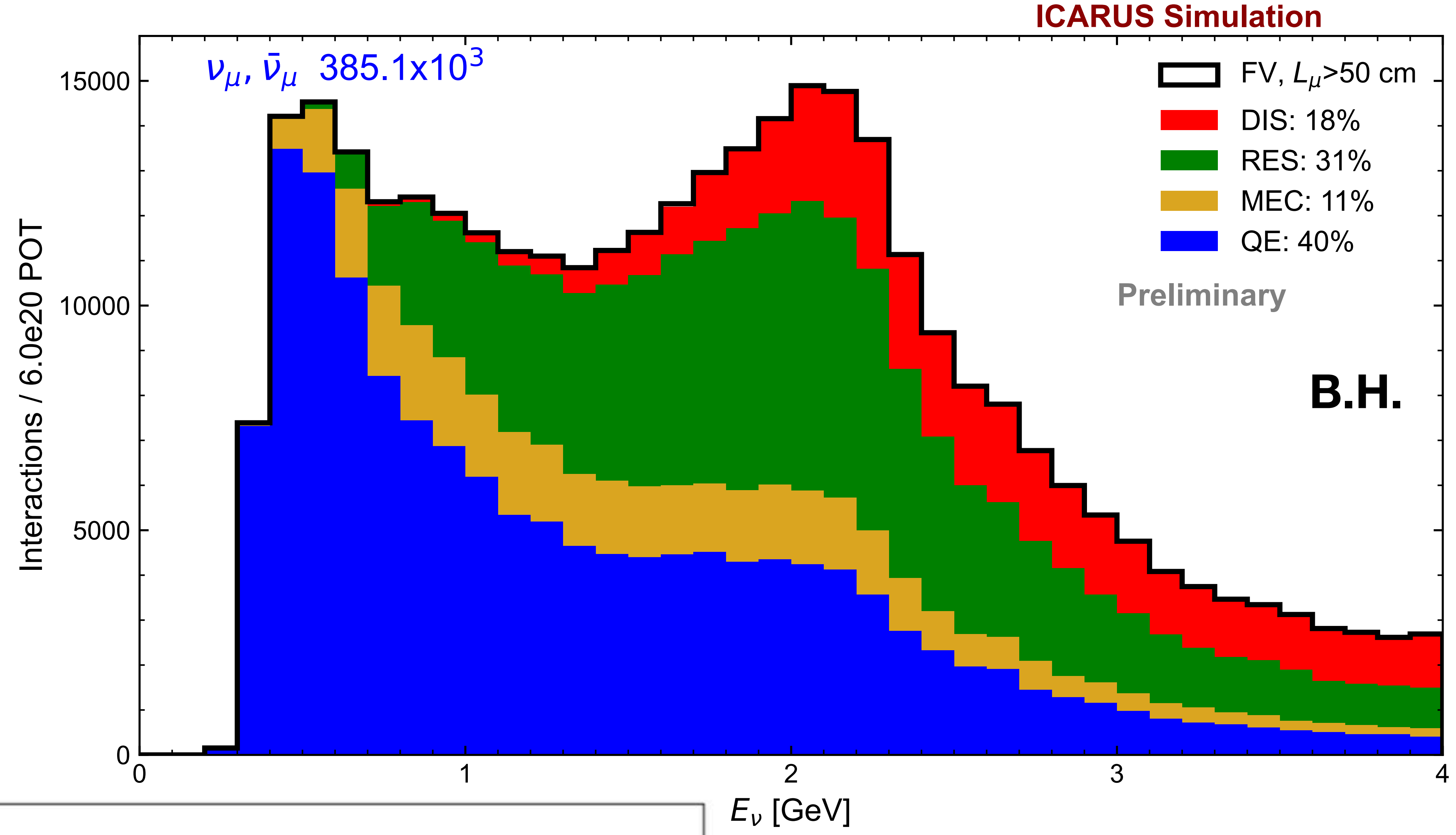
GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

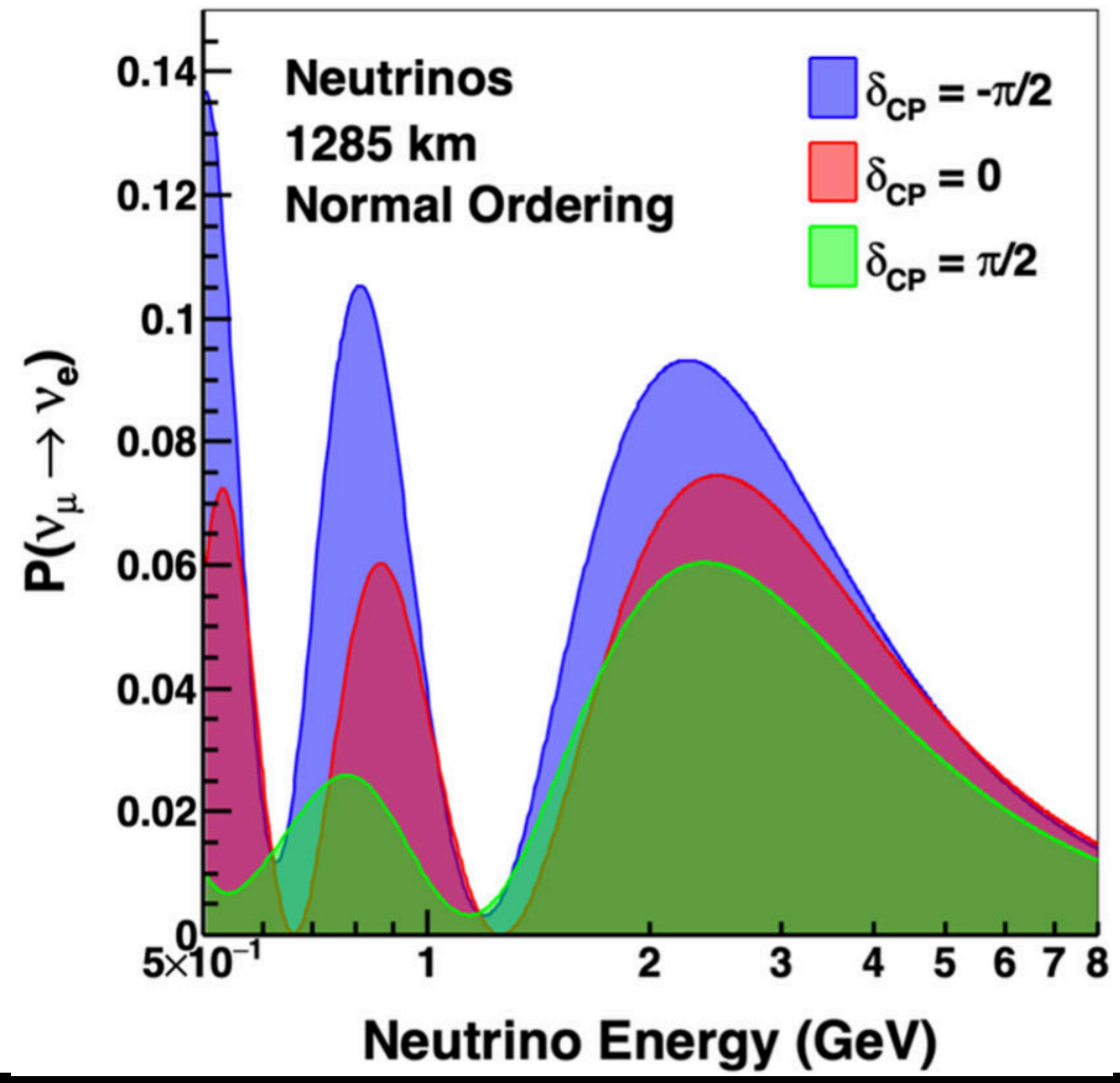


M.F. Carneiro et al (MINERvA), Phys Rev Lett **124**, 121801 (2020)

NuMI ν Interactions in ICARUS

- In addition to oscillations, ICARUS also sees NuMI ν: few deg. off-axis, ~800m from target. Hundreds of MeV to few GeV range: due to kaon parent component, also see significant peak at ~2 GeV
  - Overlaps energy range of SBN program and significant amount of DUNE region of interest (2nd oscillation max and pushing into 1st).
- 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



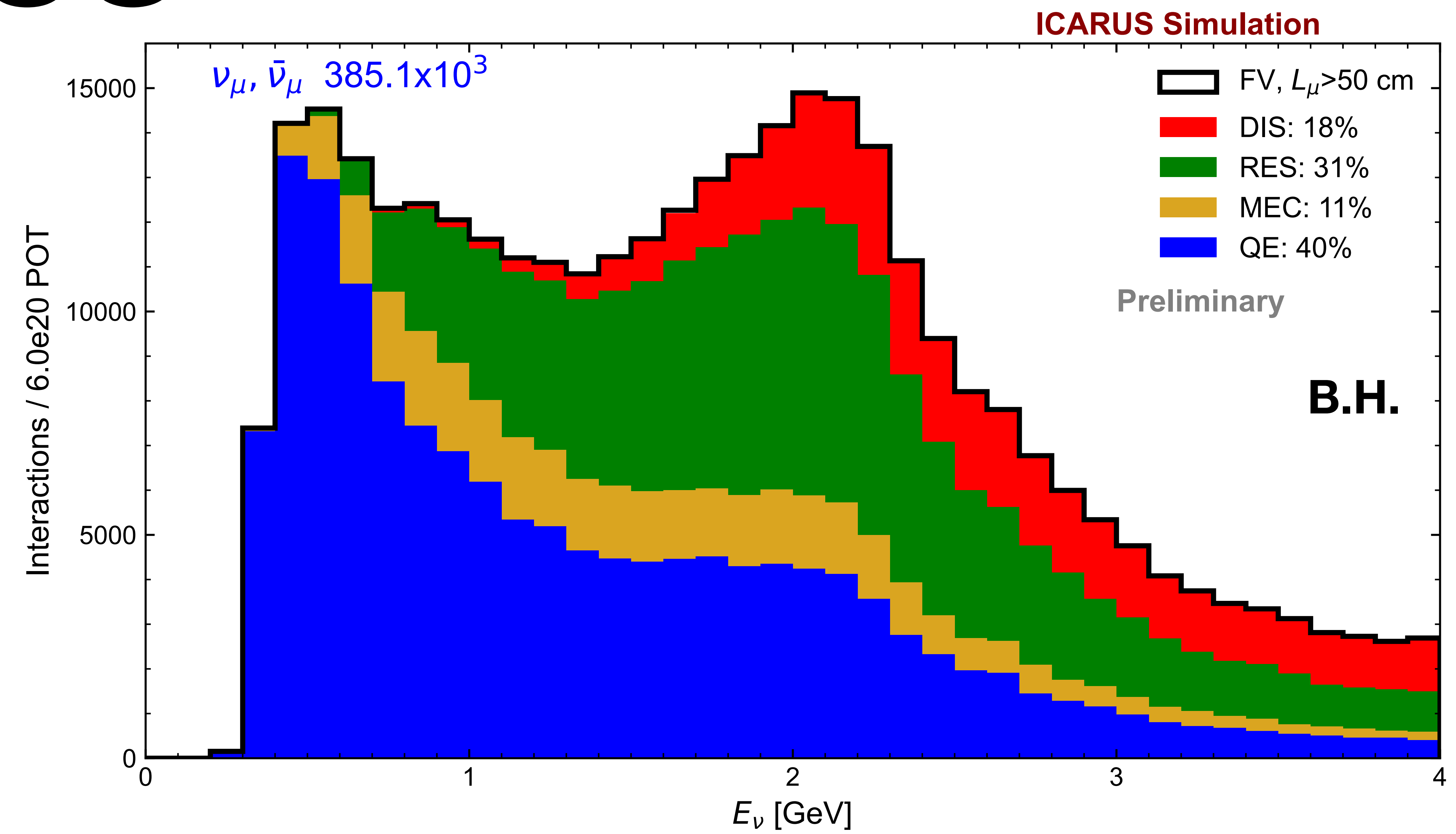


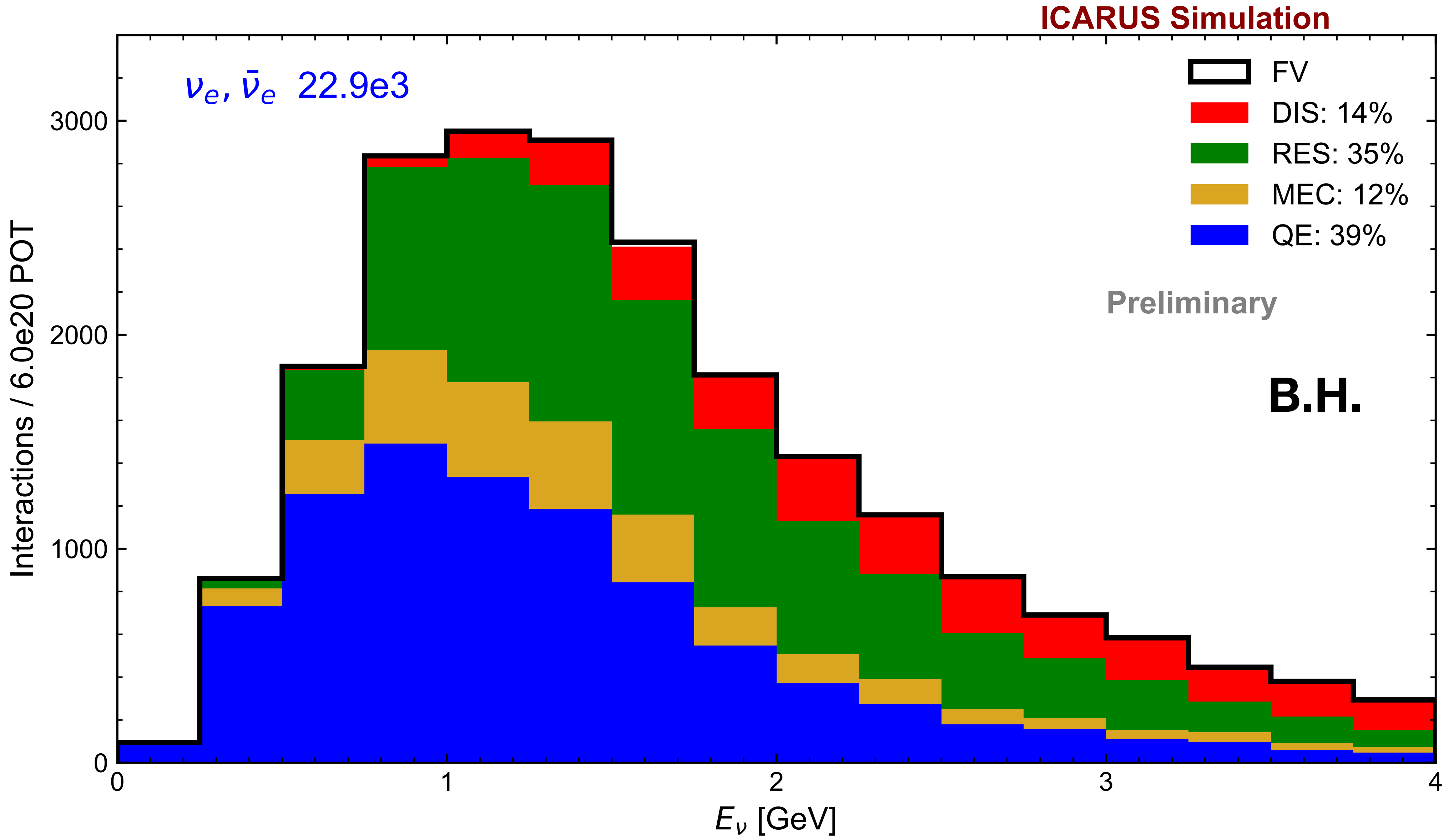
B. Abi et al. Eur. Phys. Journal C **80**, 978 (2020)

Oscillation probabilities expected in DUNE

NuMI ν Interactions in ICARUS

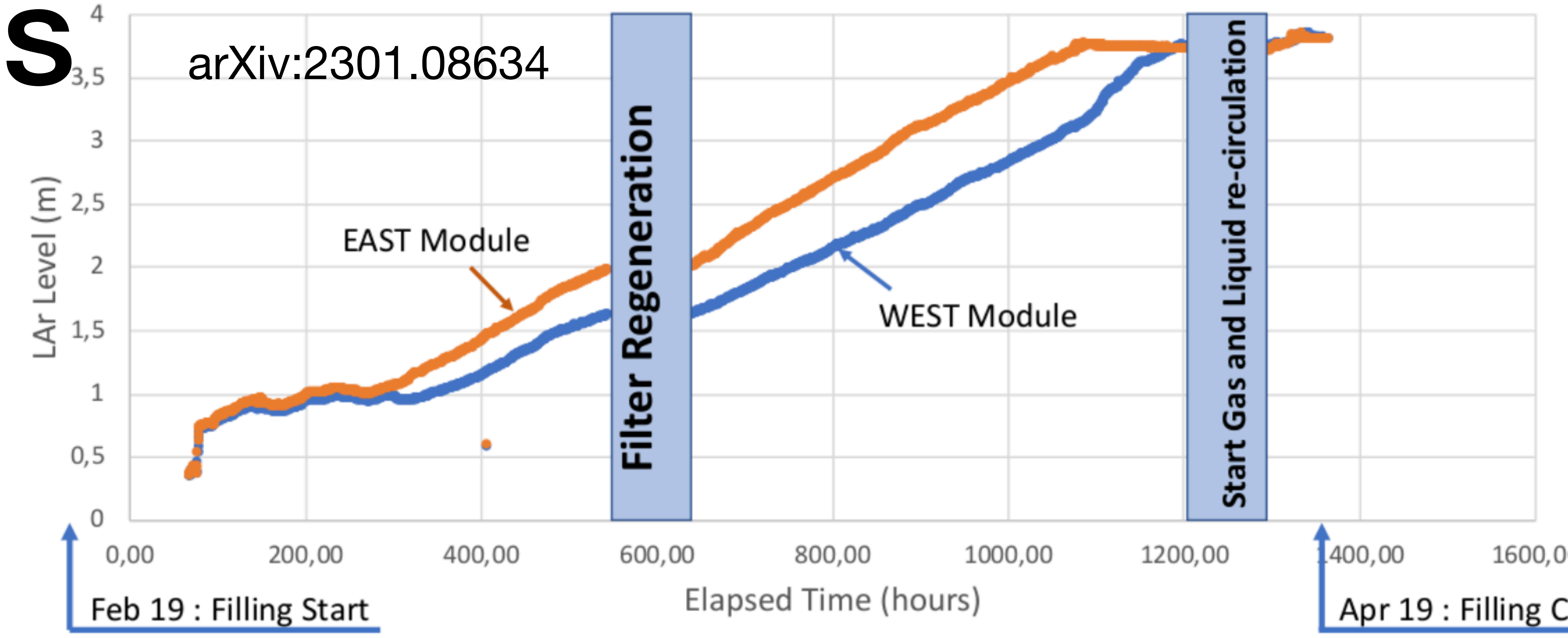
- Due to reasonably large ν_e rate and flux constraints, we will also target ν_e-to-ν_μ cross-section ratio
- Aim study current models and aid advance of them before DUNE turns on, but also to use commonalities to better share:
  - Unified GENIE base model between SBN detectors and DUNE: choice of model 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.
  - Similar software environment and analysis frameworks enable further sharing of developments as we make measurements

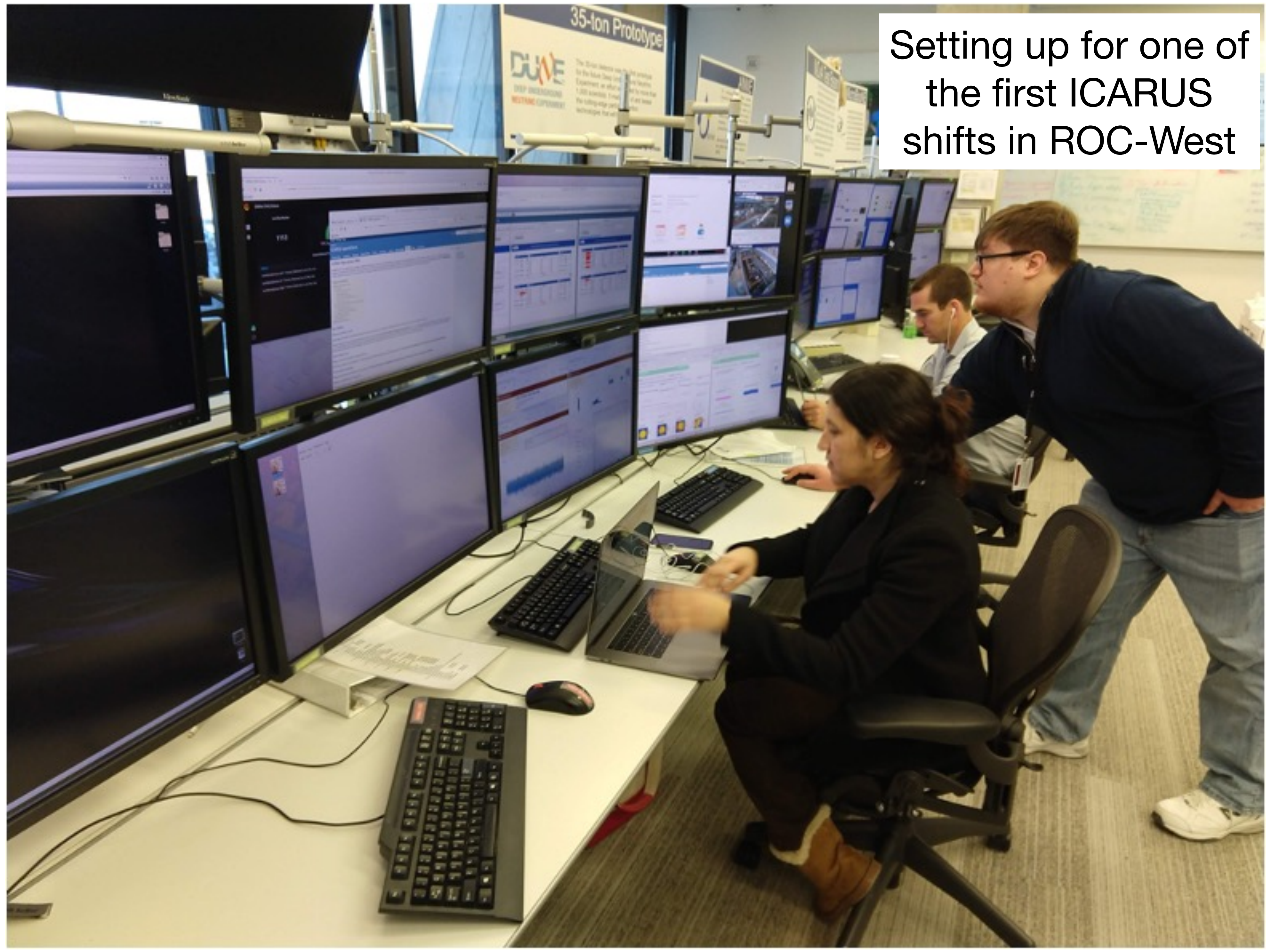




Commissioning/Operations

- Actually making it happen is a process
- After much of the major installation, the cooldown/ filling began in Feb 2020
- Started 24/7 shifts in Feb 2020: after 1 month, we were forced to move remote due to COVID
- By Fall 2020 systems were being activated and commissioning of the systems were underway
- Final installations including important systems as the CRT (esp top CRT) and overburden took place after this period
- During this period the hardware & software groups have been commissioning, validating, improving using cosmic data, hand-scan events, etc.
- Finally at the end of Spring 2022 (June) the overburden and systems (e.g. top CRT) were fully in place and physics data-taking began

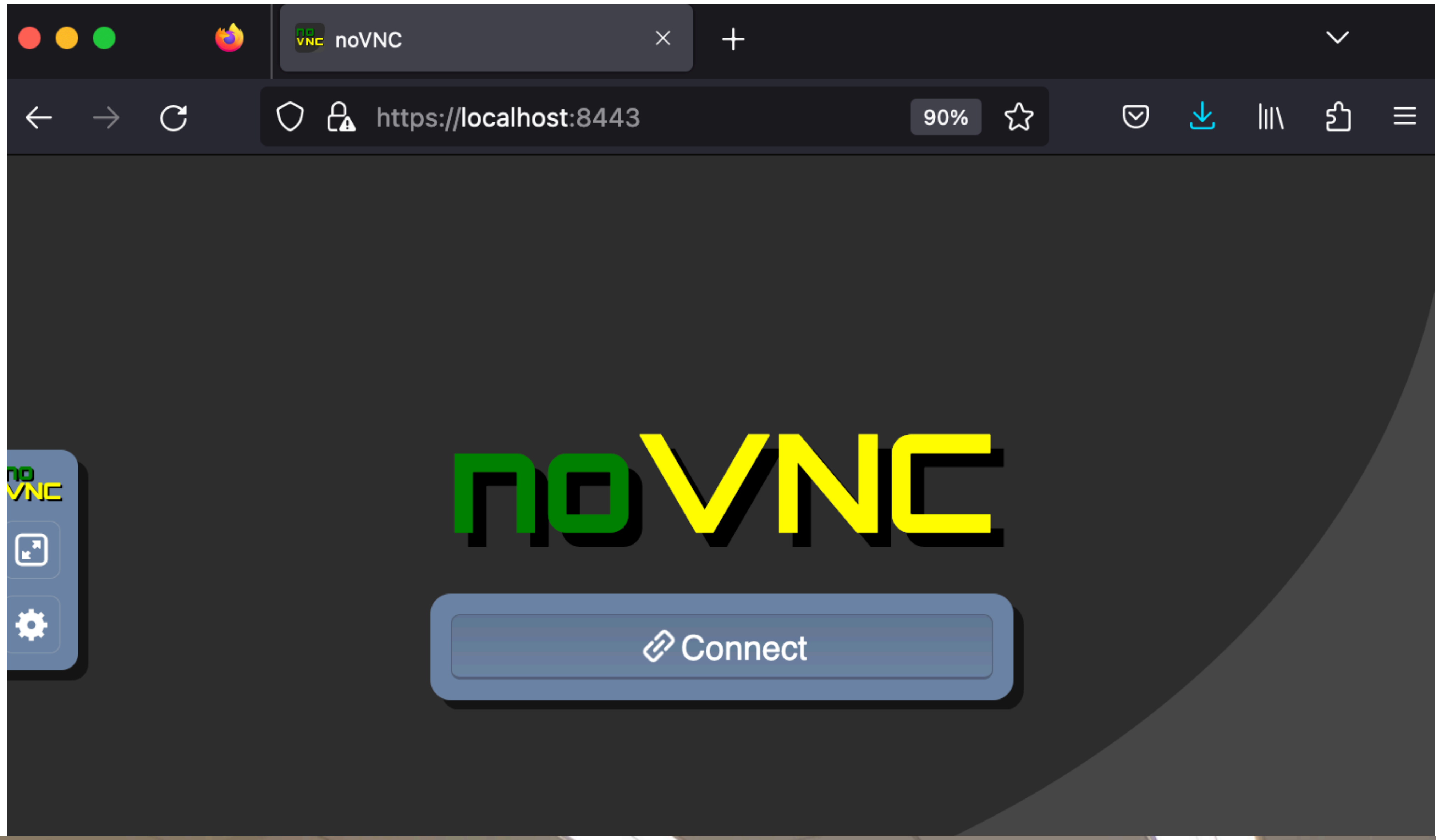


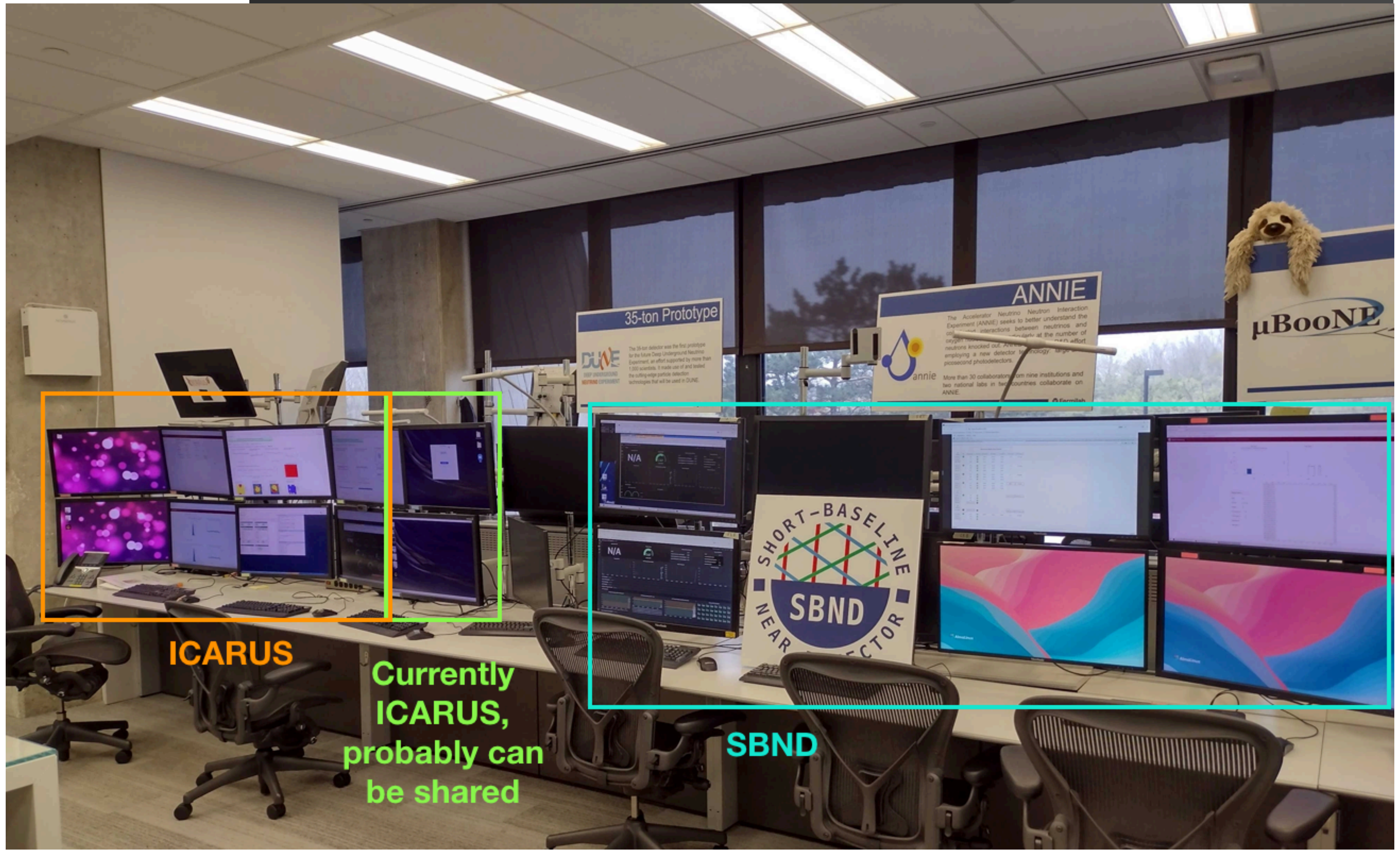


Setting up for one of the first ICARUS shifts in ROC-West

Detector Shift Operations

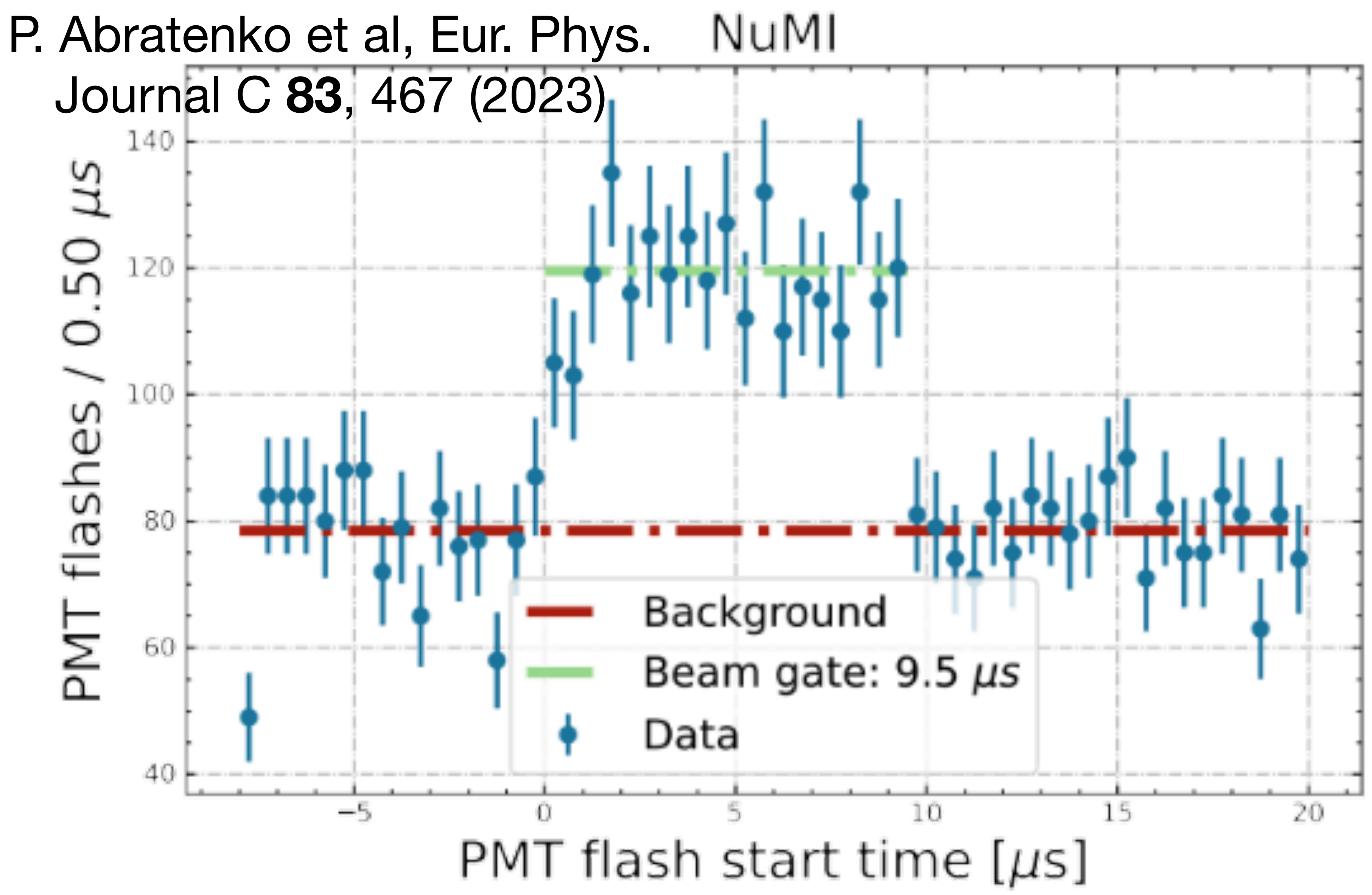
- I played a large role in the control room and ops setup and was Deputy Commissioning Coordinator for much of 2020
- Initially, ops shifts were foreseen to take place from FNAL then probably mixture of FNAL and institutional control rooms:
  - Due to COVID-19, were forced to move to **remote** scheme
  - We were able to quickly adjust and maintain *active* shifts thanks in part to web-based tools for many aspects (Online Monitor is web page for example, use "NoVNC" over a ssh tunnel instead of requiring each shifter to install VNC viewer, etc.)
- Now nearly have the SBND control room set up
  - Basing in several ways on experience w/ ICARUS
  - Finalizing setup and decisions and preparing documentation for operations, review(s)
  - Will be good to try to persist good choices/ experiences with DUNE

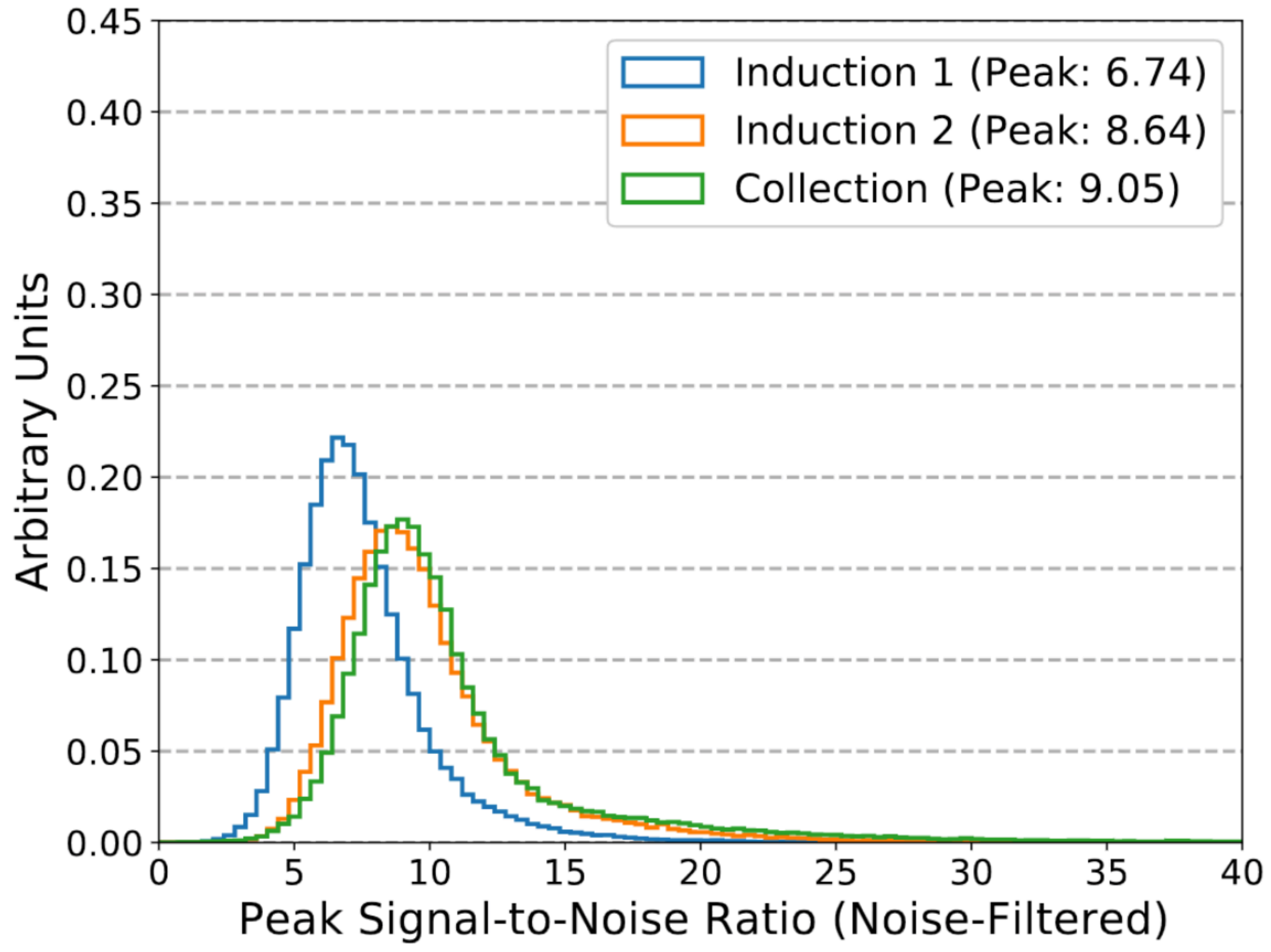


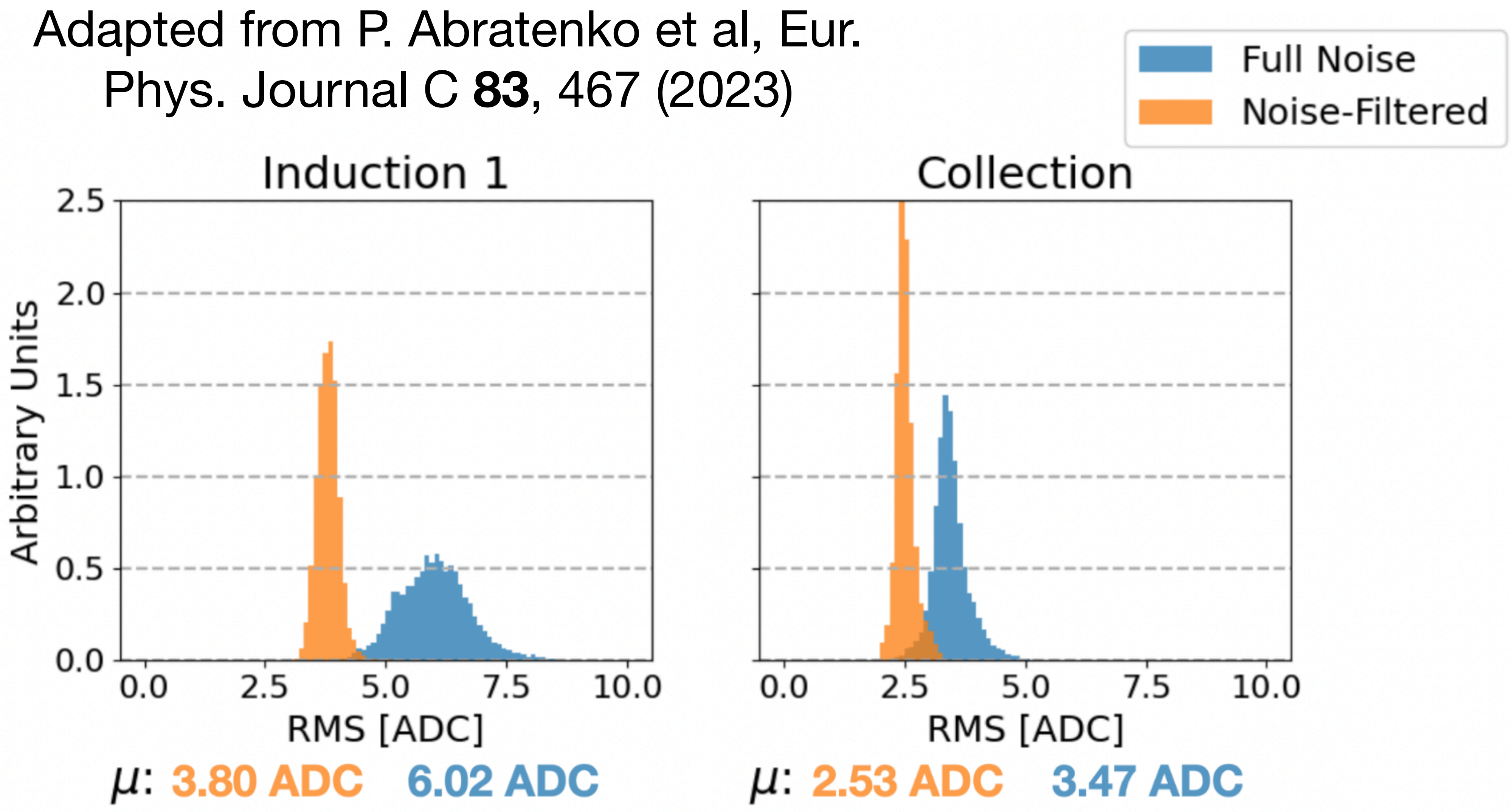


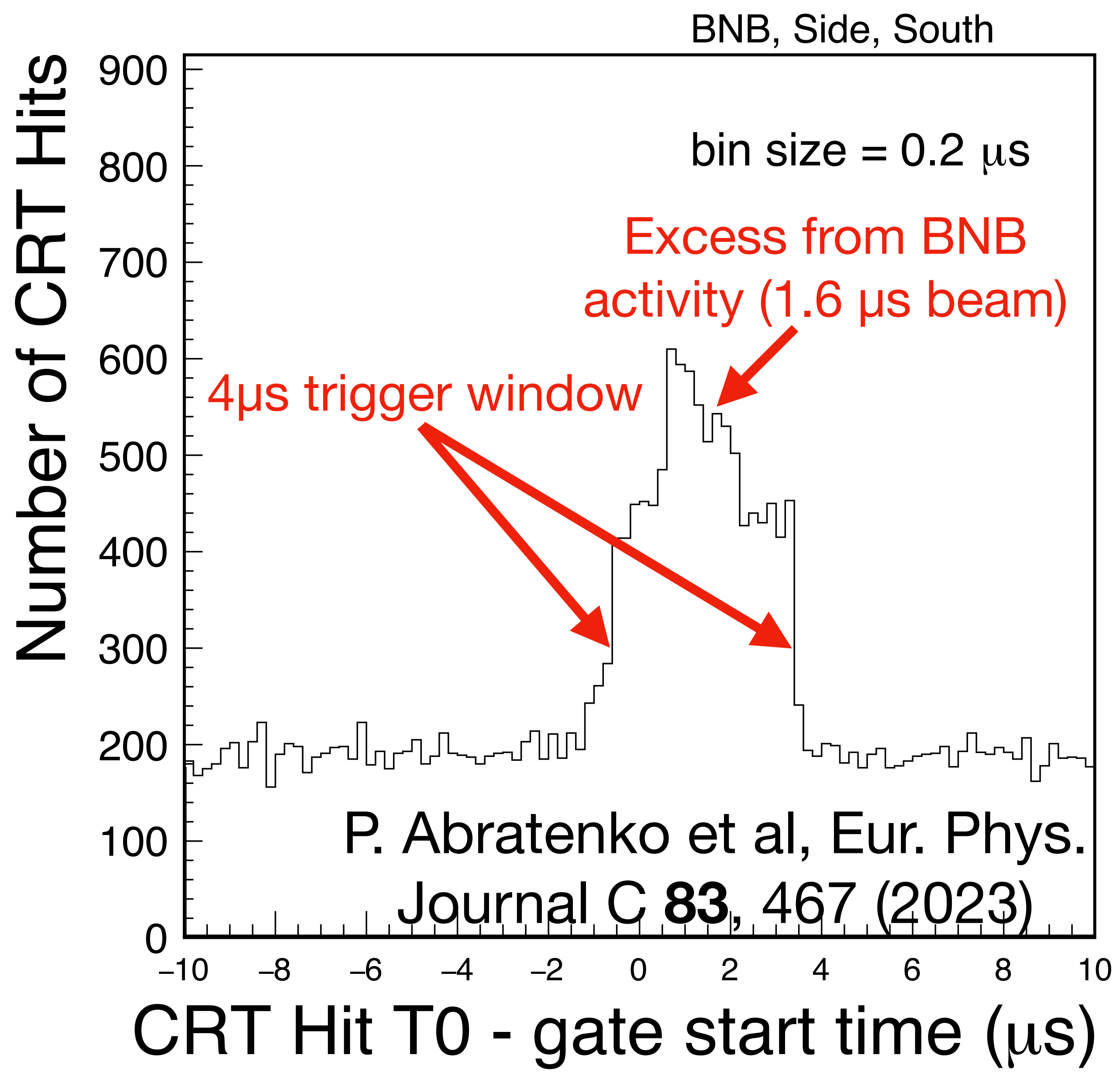
Performance/Initial Studies

- The different subsystems have undergone a set of commissioning & characterization studies to detail their performance: Eur. Phys. Journal C **83**, 467 (2023)
- Few examples here of timing plots from PMT and CRT system, signal and noise from TPC



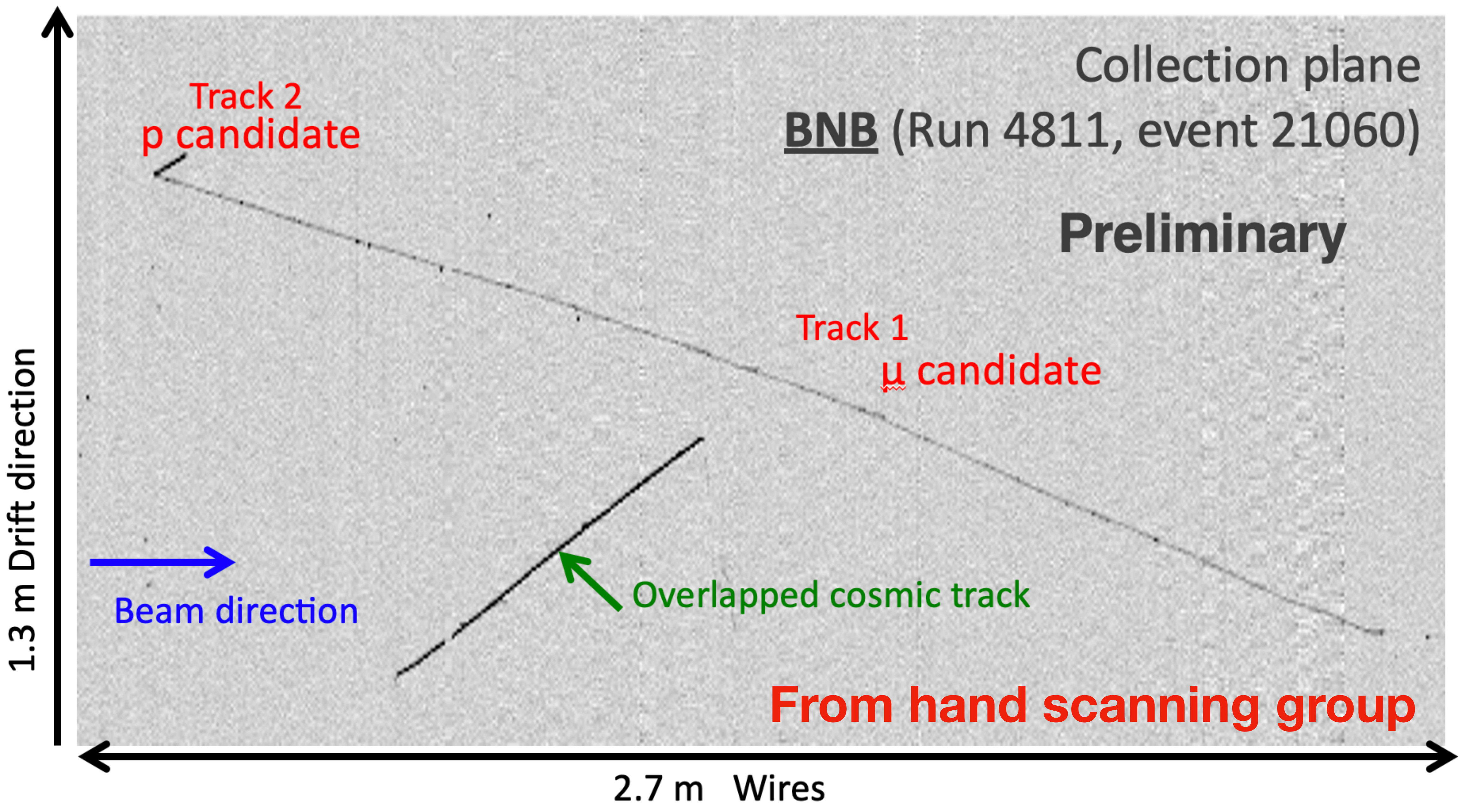


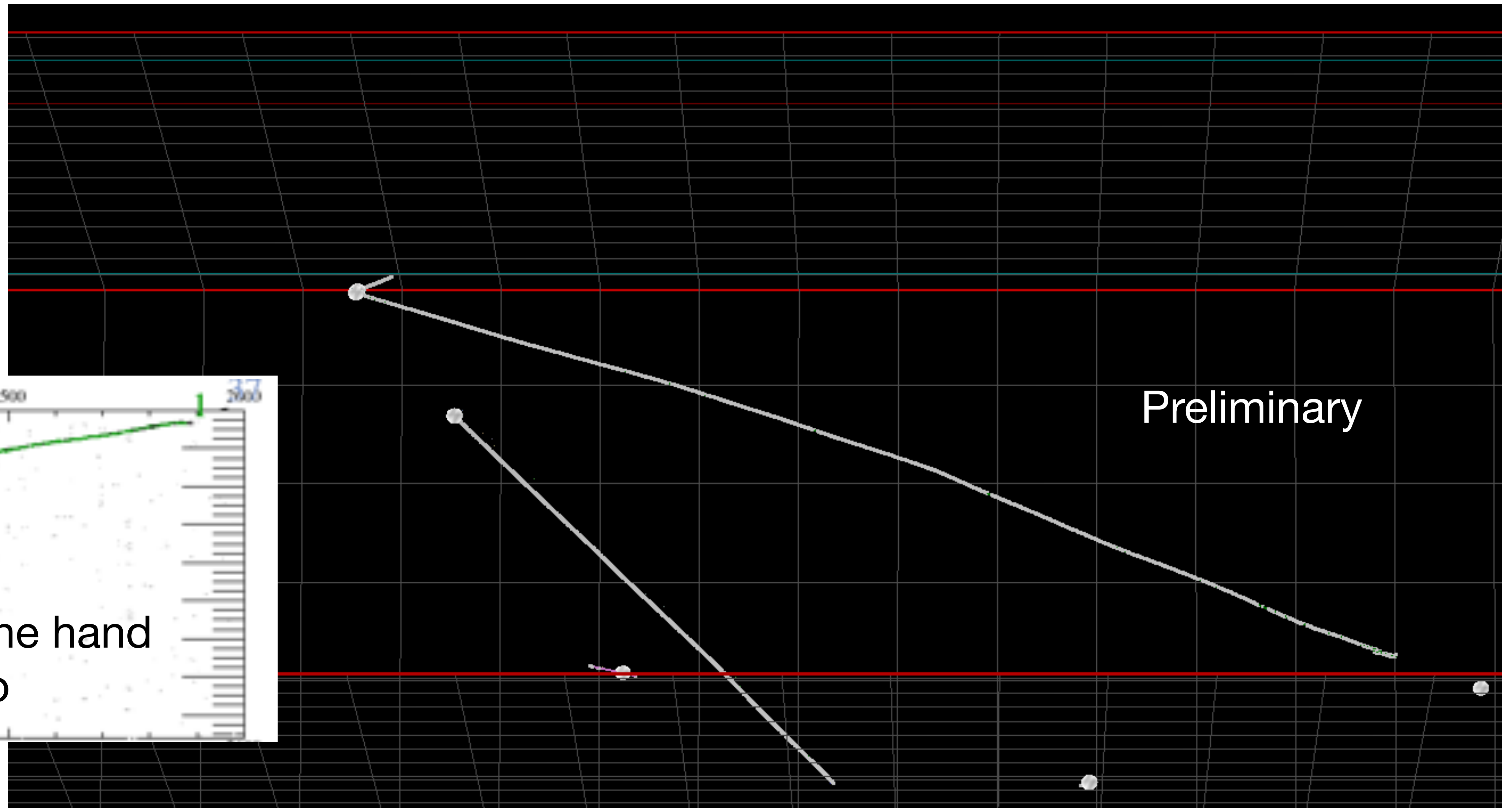


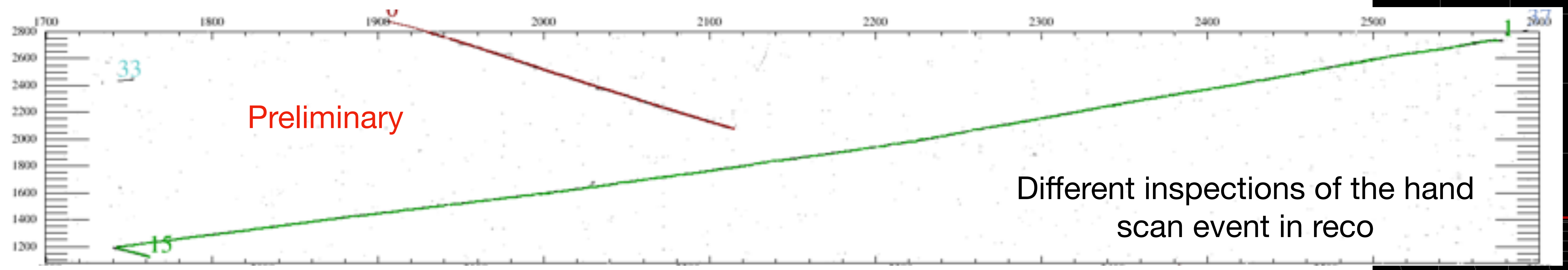


Investigating the Data

- **Beyond ops, also needed to investigate data**: that systems work as intended, we see ν & how software/tools perform, …
  - Hand scanning confirmed candidates in beam window. Trigger/PMT see excess of in beam, CRT also (μ from external ν interactions)
  - Along with cosmics, we used this set of actual neutrino candidates to inspect the software performance and to recognize certain pathologies to address, build up studies and methods of characterization, etc.







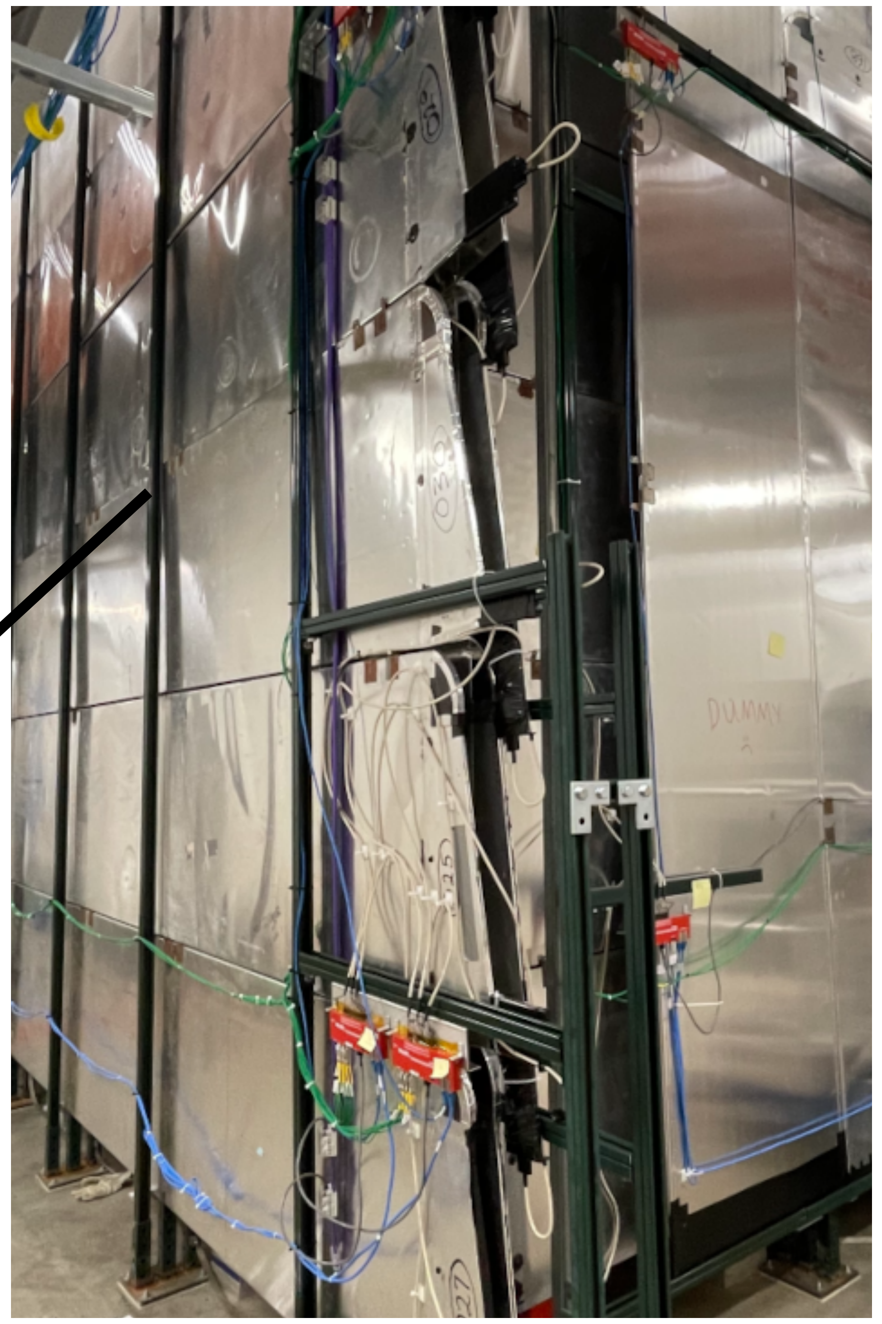
Different inspections of the hand scan event in reco

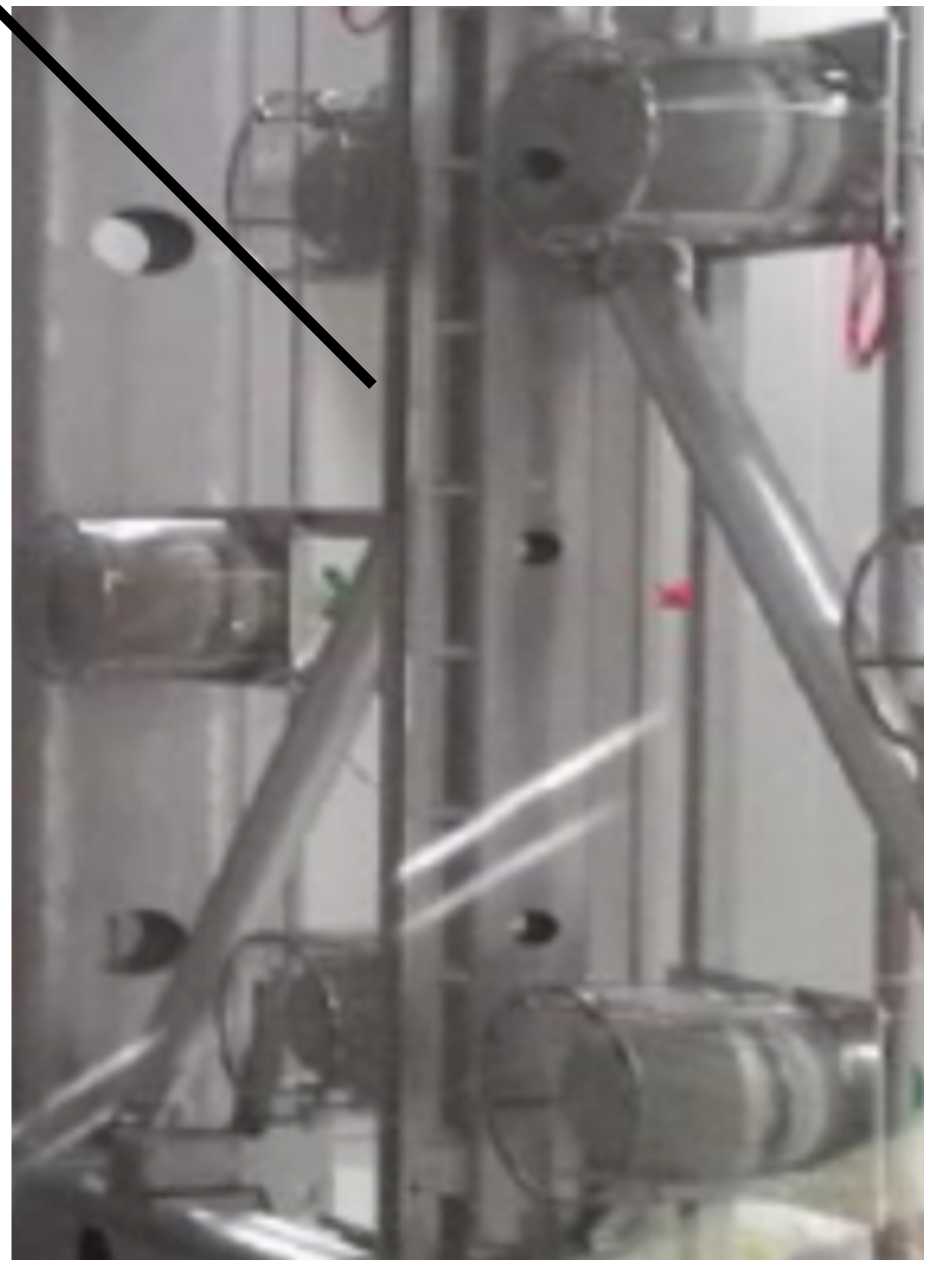
ICARUS Event Reconstruction

- Moving from operating and commissioning the detector to extracting physical observables (reconstruction)
  - TPC signals go from waveforms to reco track and shower particles
  - Photon detector waveforms processed to “hits” which are collected into “flashes”
  - CRT info also collected into “hits”
  - Additionally, tools to match between subsystems or pass info to analysis files for this purpose are important
- Since I have been leading efforts in and am a convener of a group focused on TPC reco, I’ll focus here in next bit

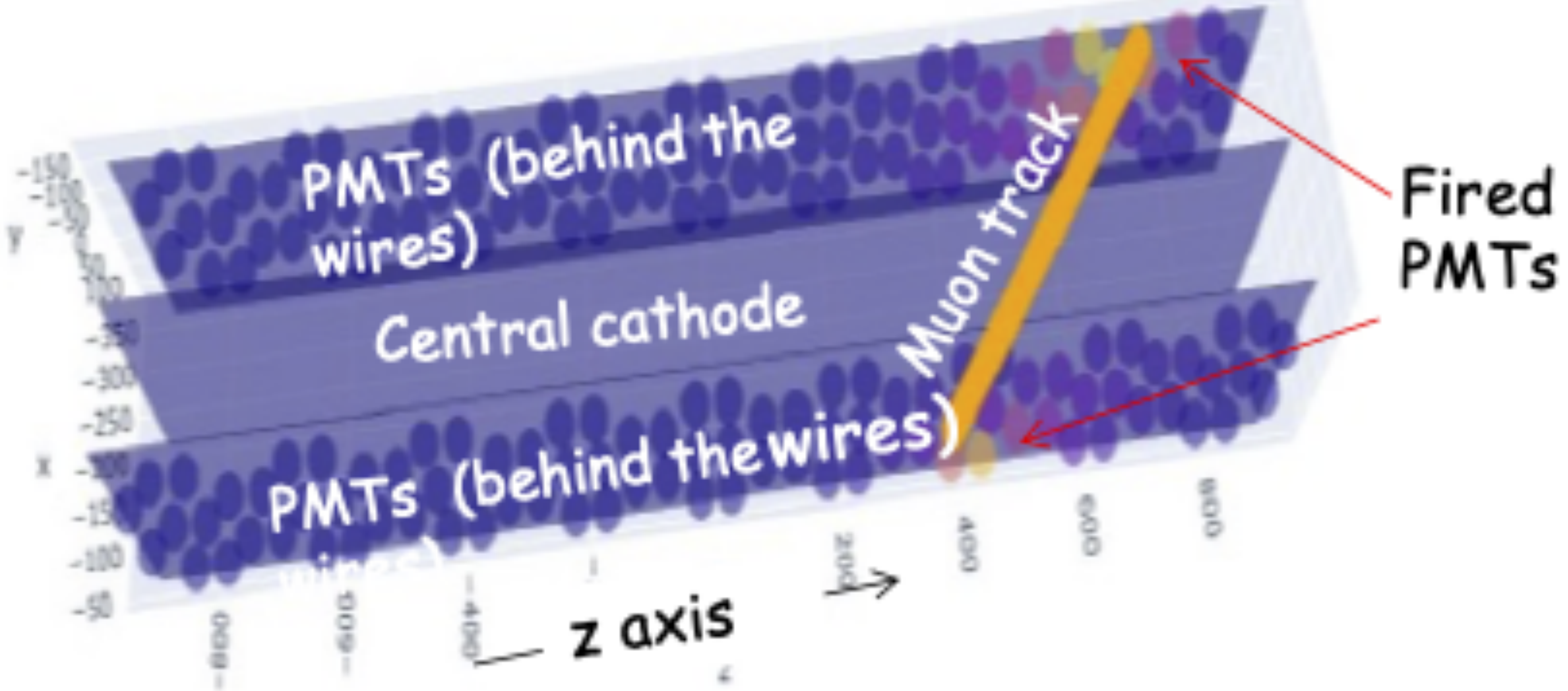
R. Acciarri et al.
arXiv:1503.01520

EVENT RECO



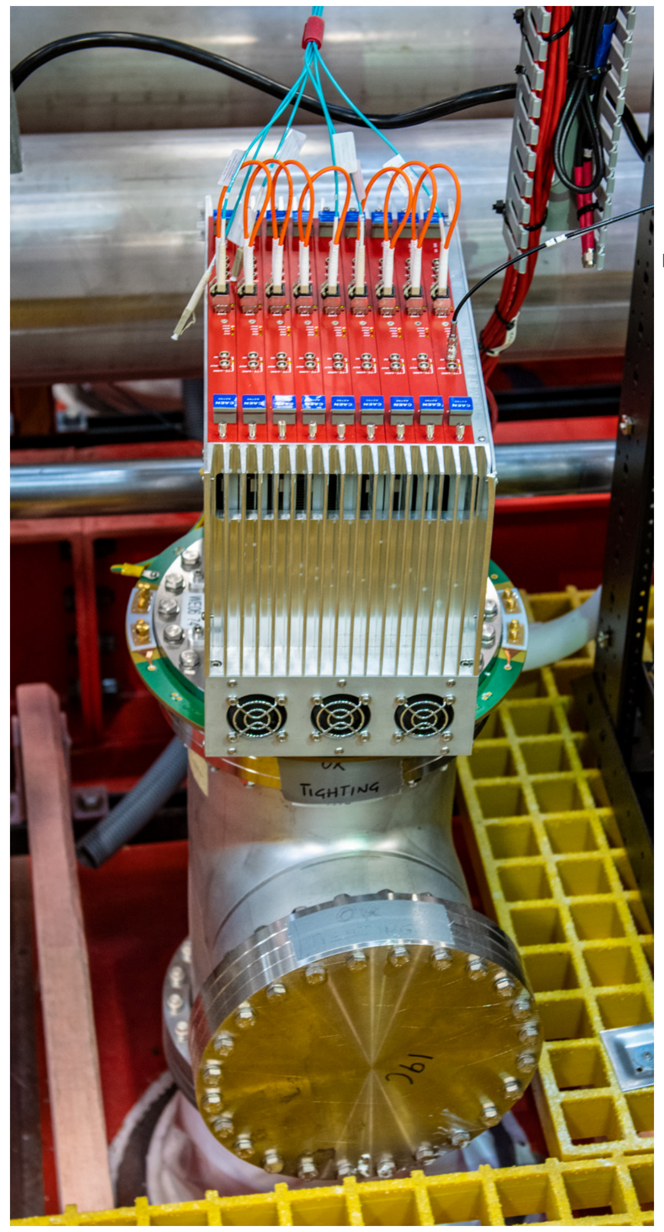


(right and bottom left)
P. Abratenko et al.
Eur. Phys. Journal C
83, 467 (2023)



Schematic from PMTs

ICARUS TPC Reco


FNAL VMS

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

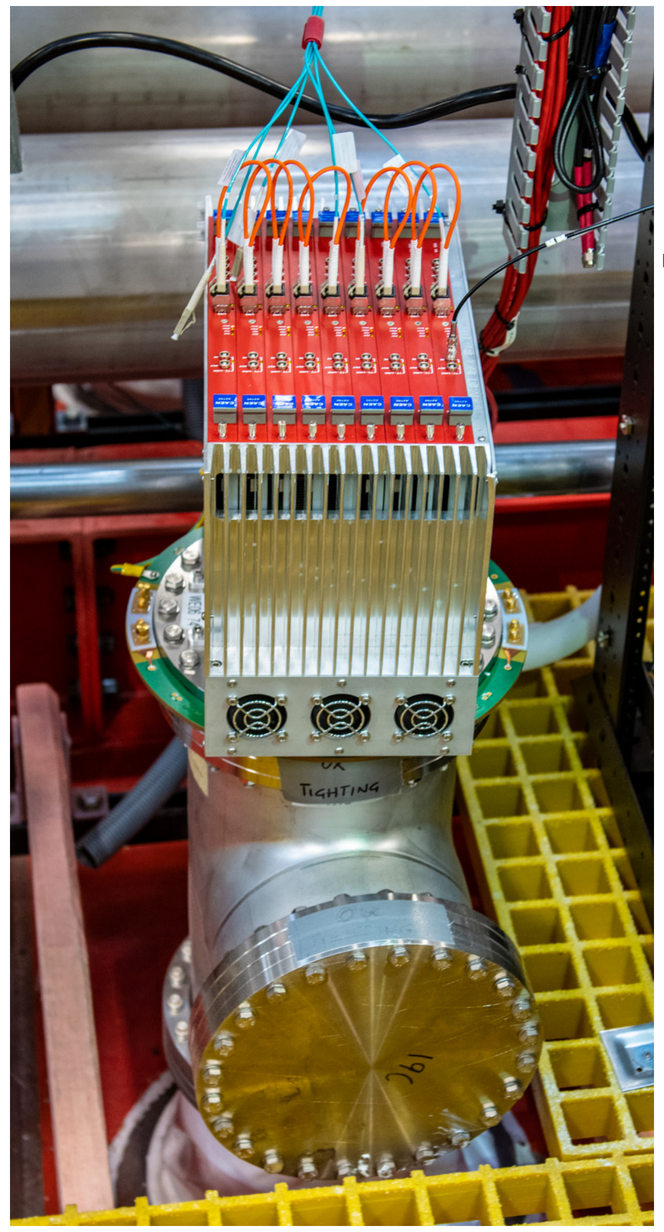
→ **Machine Learning Reco**

Pandora → **Track Reco & downstream reco like calo**

Pandora → **Shower Reco**

Track Reco → **ANALYSIS**

ICARUS TPC Reco



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Pandora
Cluster, Slice, Pattern Recognition

Machine Learning Reco

Track Reco & downstream reco like calo

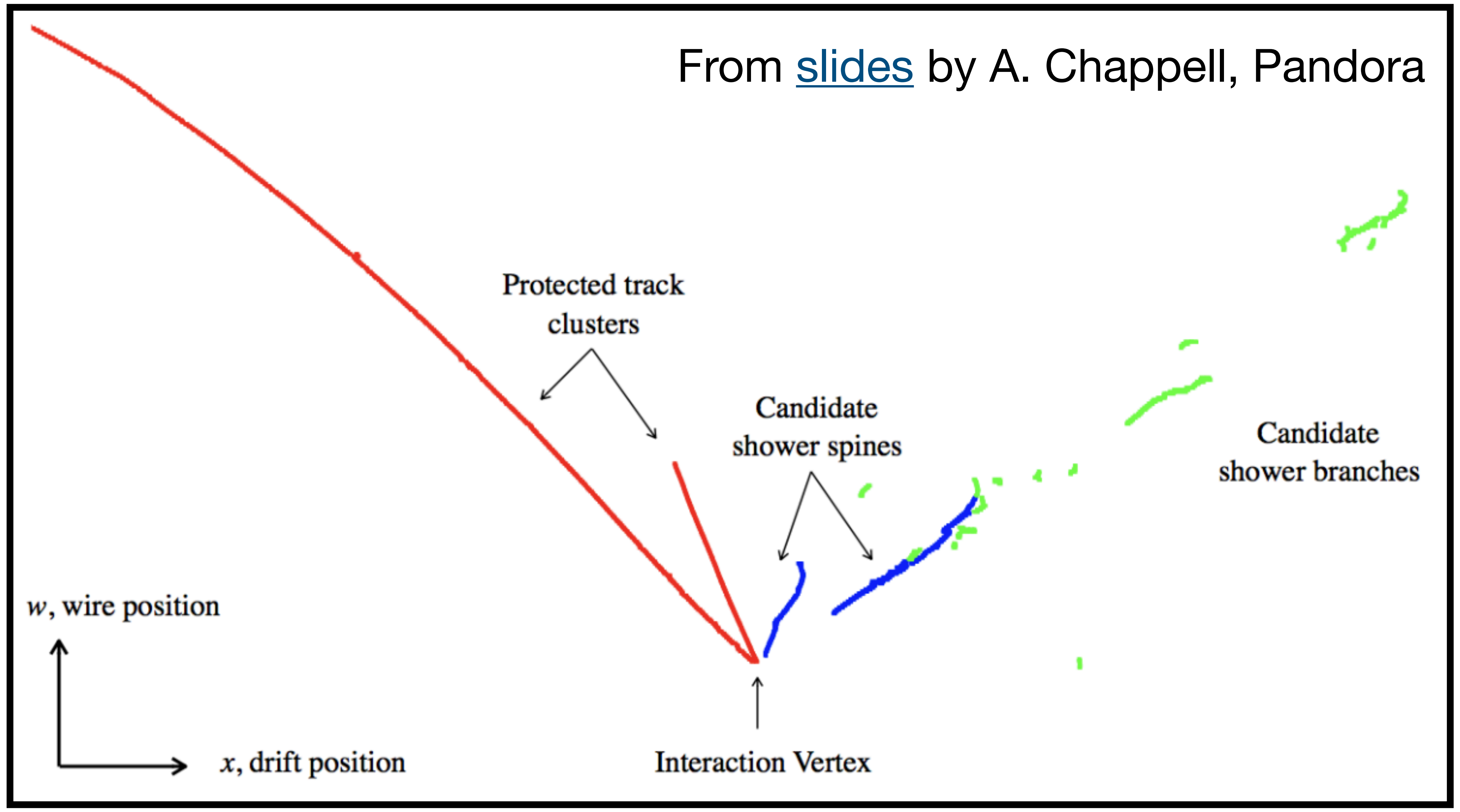
Shower Reco

ANALYSIS

ICARUS TPC Reco

- The default ICARUS/SBN reco pathway has been using Pandora multi-algorithm pattern-recognition kit (https://github.com/PandoraPFA) which has established interface in LArSoft framework (https://larsoft.org/) commonly used in LAr TPCs
  - Clusters objects together into reco particles in 3D, joining together across planes
  - Reconstructs vertex (common point where ν interacted and particles originate)
  - Forms particle hierarchy (parent/child particles)
  - Classifies particles track-like (e.g. μ, p, $\pi^{\pm}$, $K^{\pm}$) or shower-like (e.g. e, photon)
- Series of algorithms that one can alter/extend, change which to use (add, remove, modify), etc.
  - Can thus work to improve output, explore deep learning algorithms (either in Pandora or by deferring decisions downstream), etc.

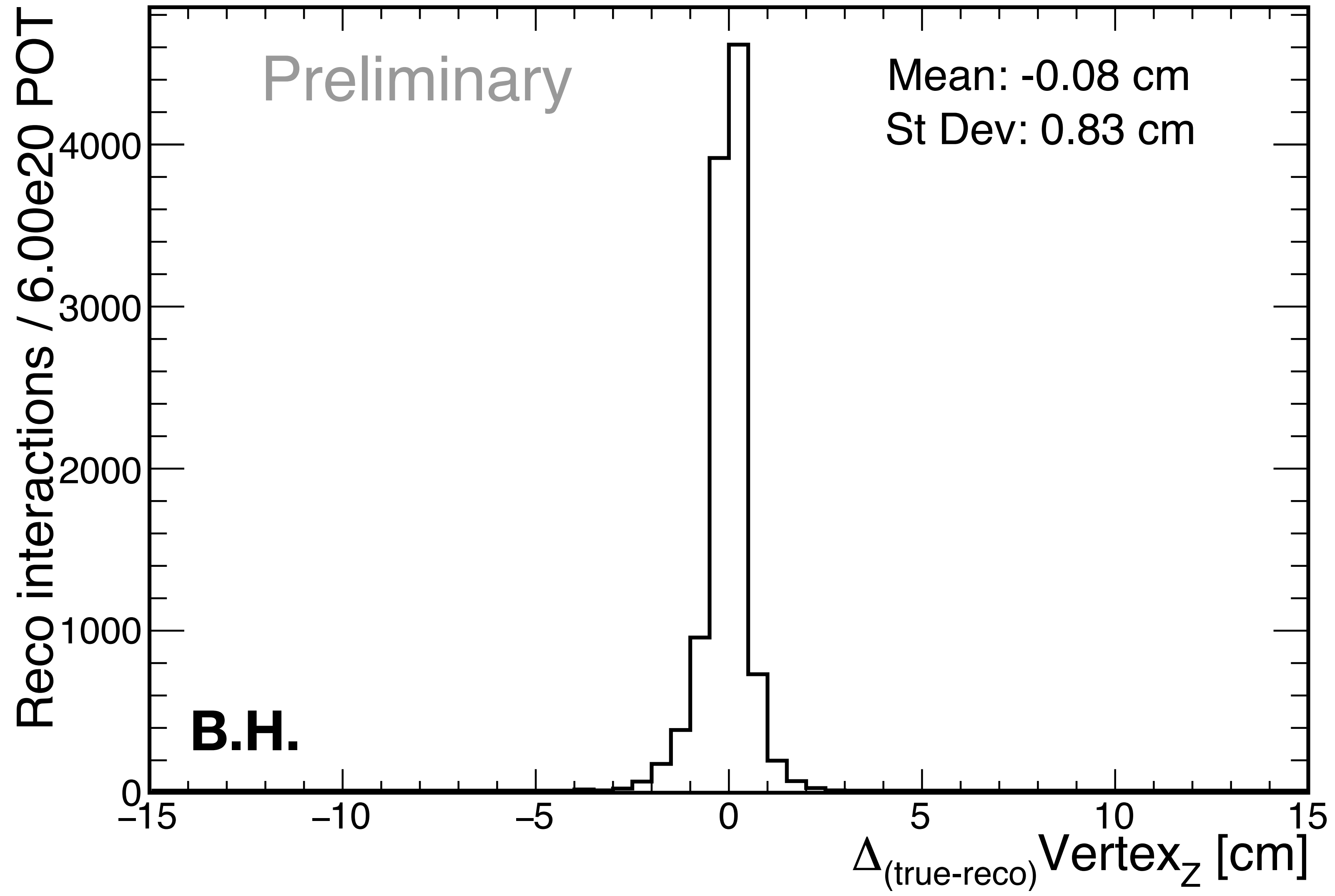
From slides by A. Chappell, Pandora



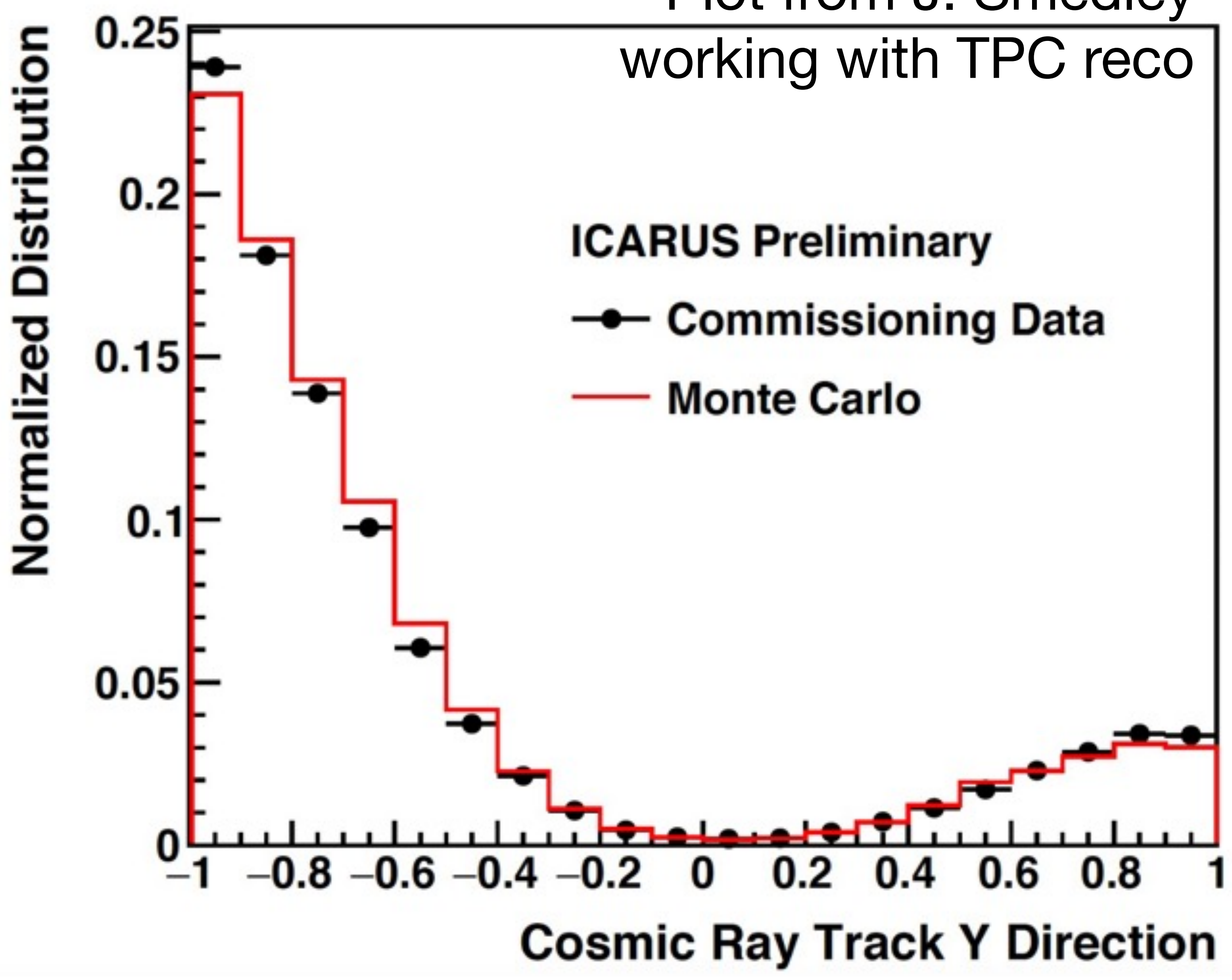
ICARUS TPC Reco

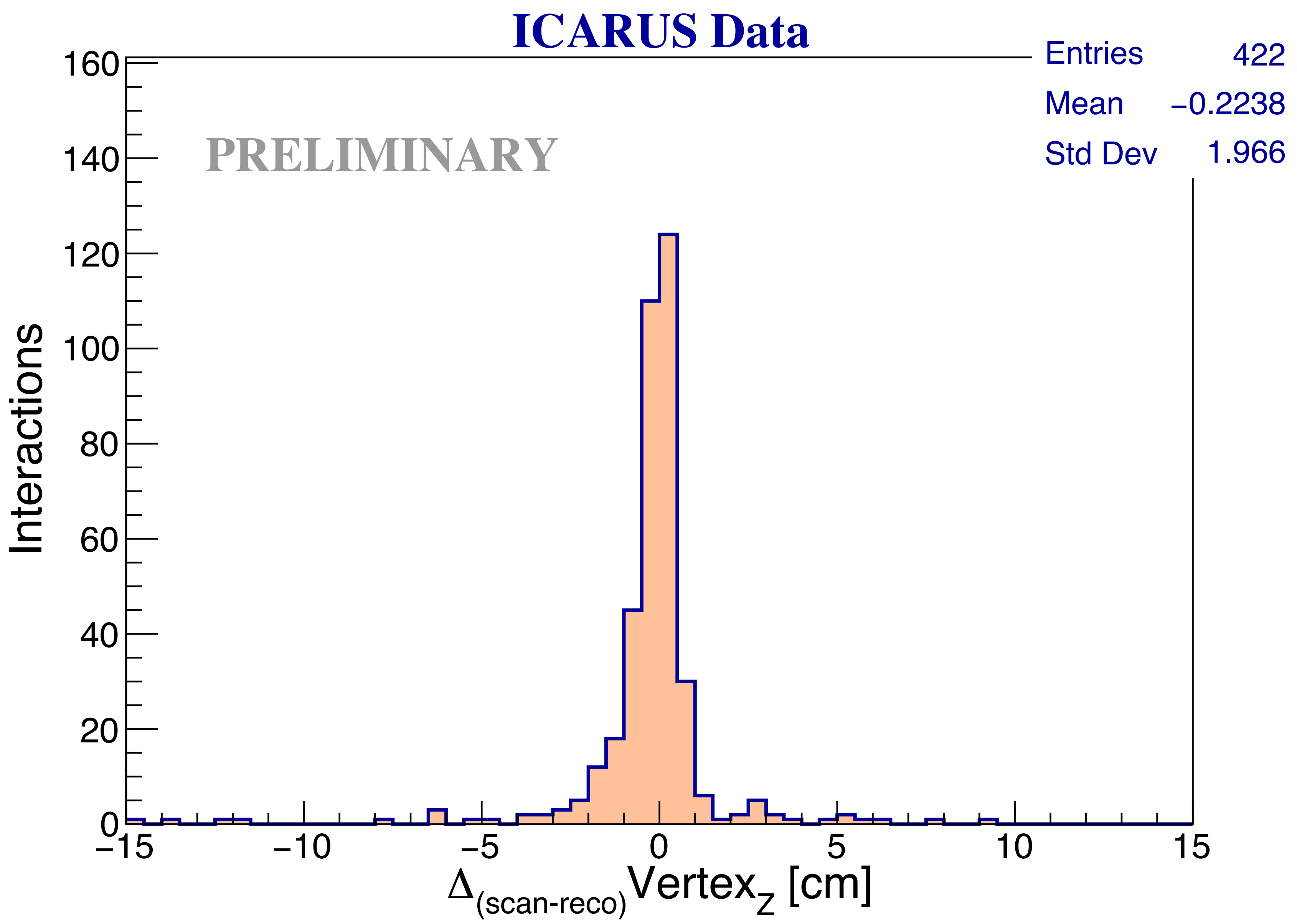
- Use sim & data to understand quality of reco, **identify areas needing improvement, and then work to address them**
- We have had vibrant group of interns, students, postdocs who contribute to the necessary studies and work
- Examples of activity in the group:
  - Evaluating reco w/ events from hand-scan (G. Moreno, M. Artero)
  - data/MC plot (J. Smedley)
  - Improving reco capability/ performance (next slide)

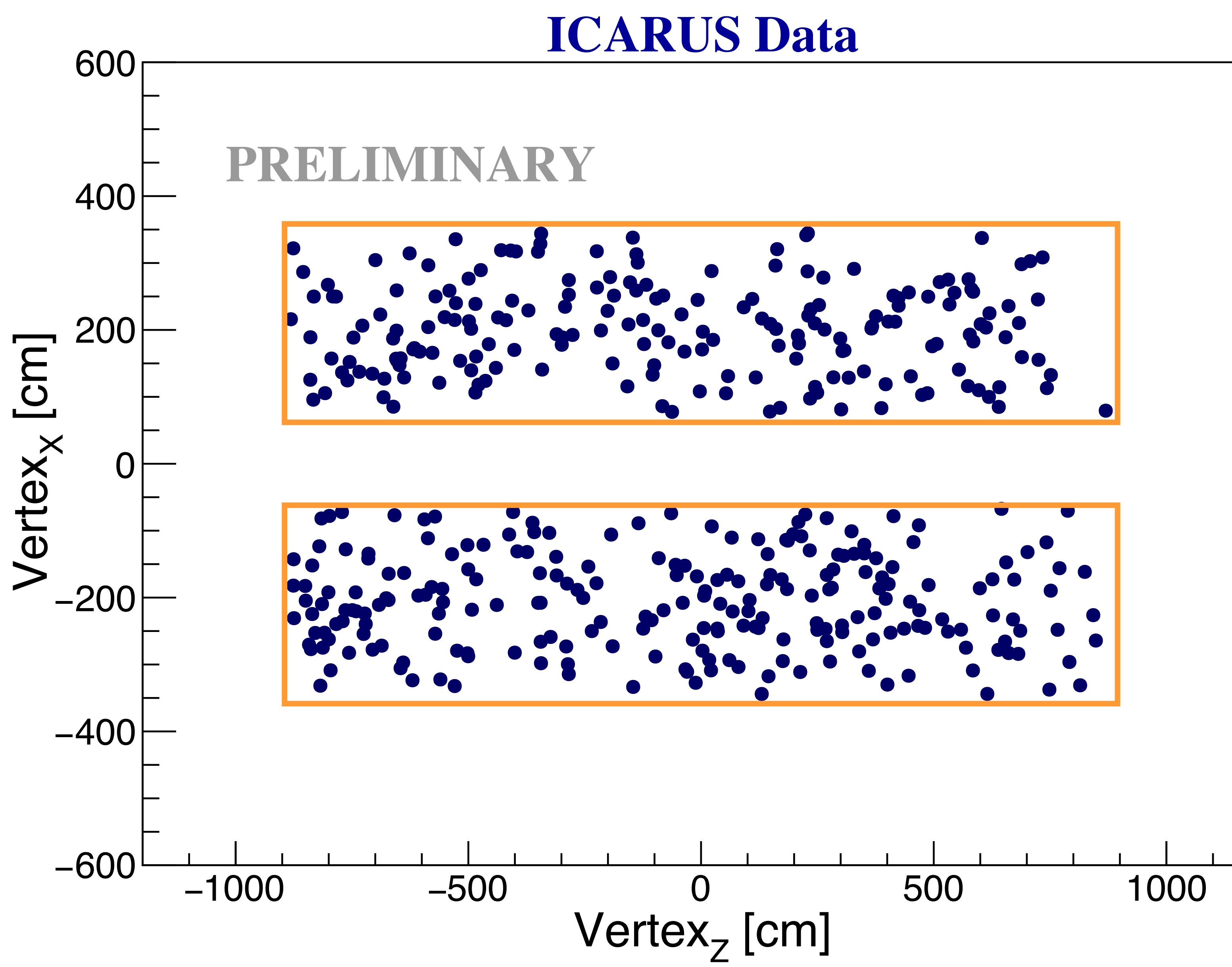
Set of MC events with a muon and proton that pass some cuts on reconstruction.



Plot from J. Smedley working with TPC reco



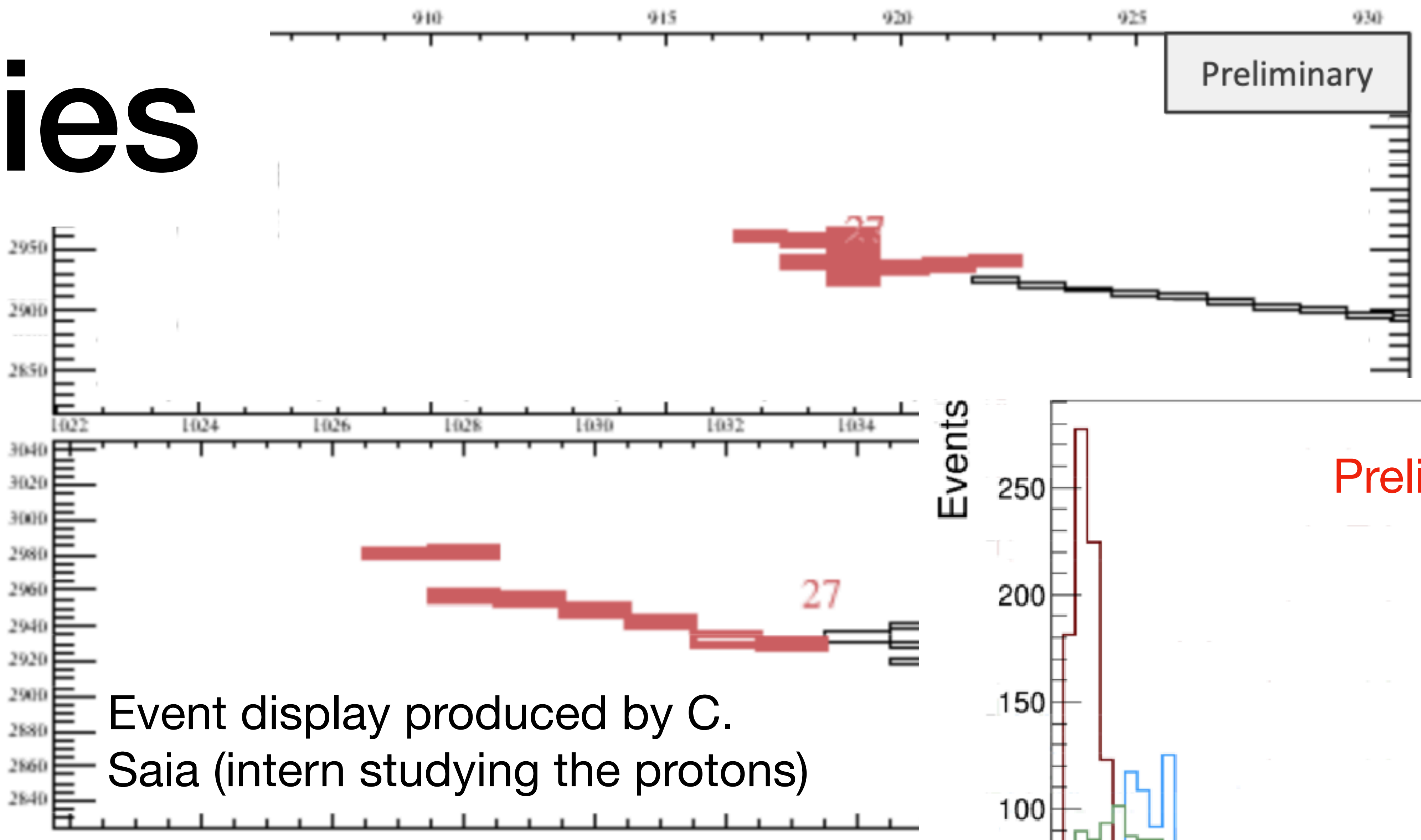


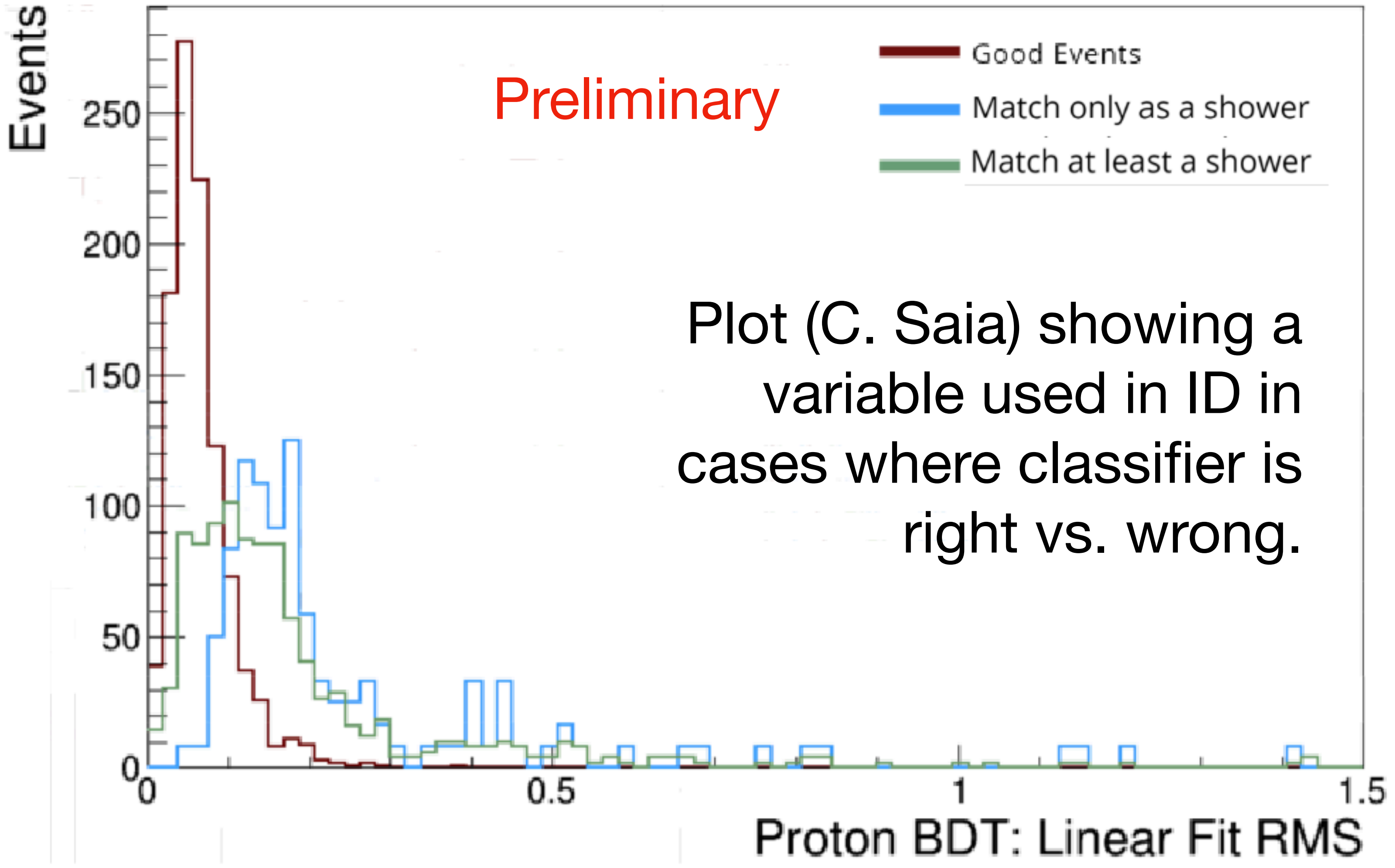


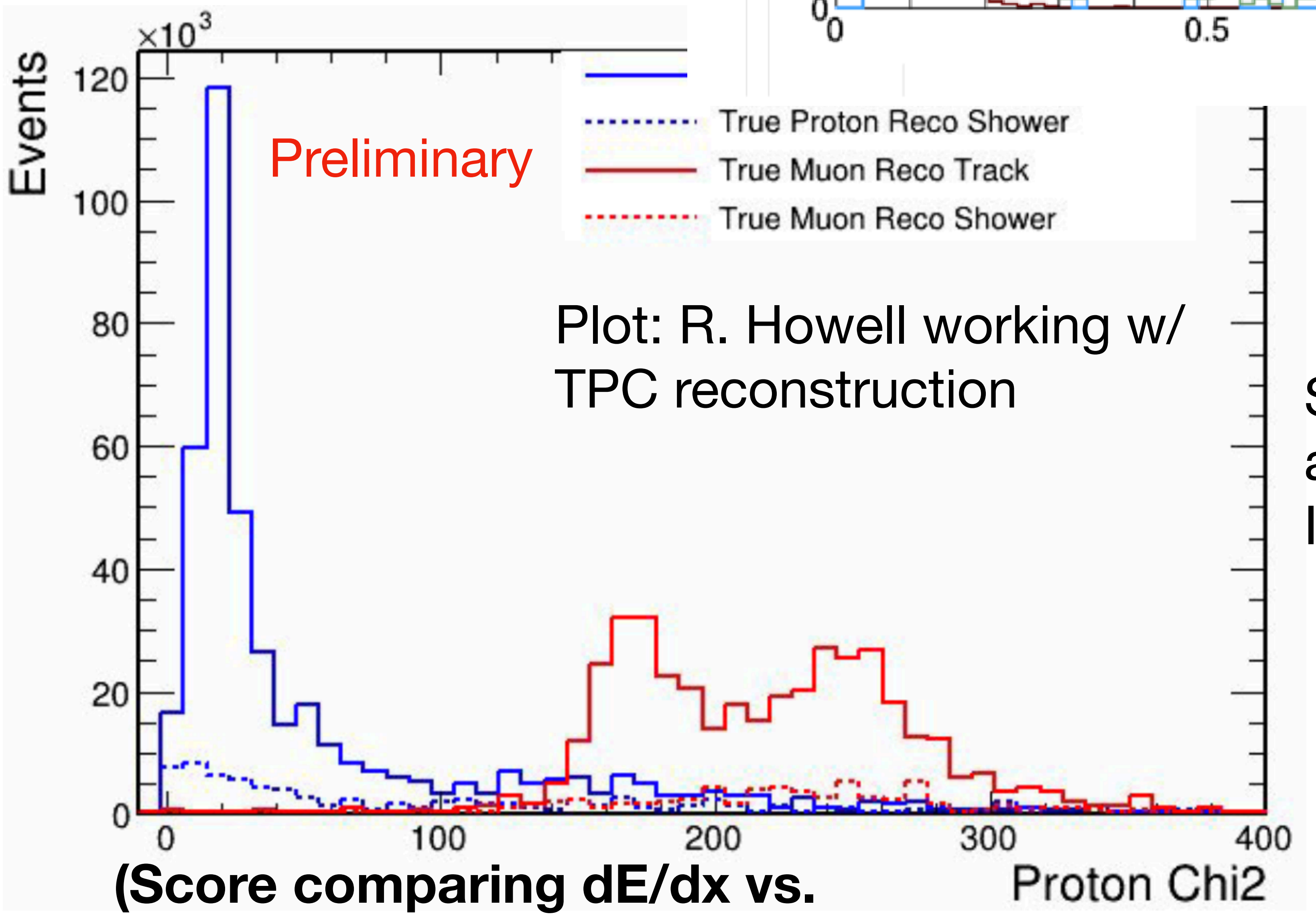
Plots from G. Moreno investigating a set of hand scanned DATA events for similar reconstruction quality checks (Note that some of the same signal and reco quality cuts not made here.)

Addressing Pathologies

- Sometimes reco can get tricked by protons and mis-classify as showers. We worked to address:
  - We added to Pandora & our analysis files to **enable saving feature variables** used in track-shower identification
    - **<u>In</u>** Pandora: available for others!
  - Try **track AND shower fit**, save both (R. Howell)
  - Intern (C. Saia) worked to study mis-classification and look at analysis files with the changes
- **More options at analysis time** to investigate and hopefully recover some misclassified particles
  - Additional tuning of reco, signal processing, etc. will hopefully improve classification as well
  - Also **enables investigating deep-learning based classifiers** (e.g. protoDUNE, Eur. Phys. Journal C **82**, 903 (2022))





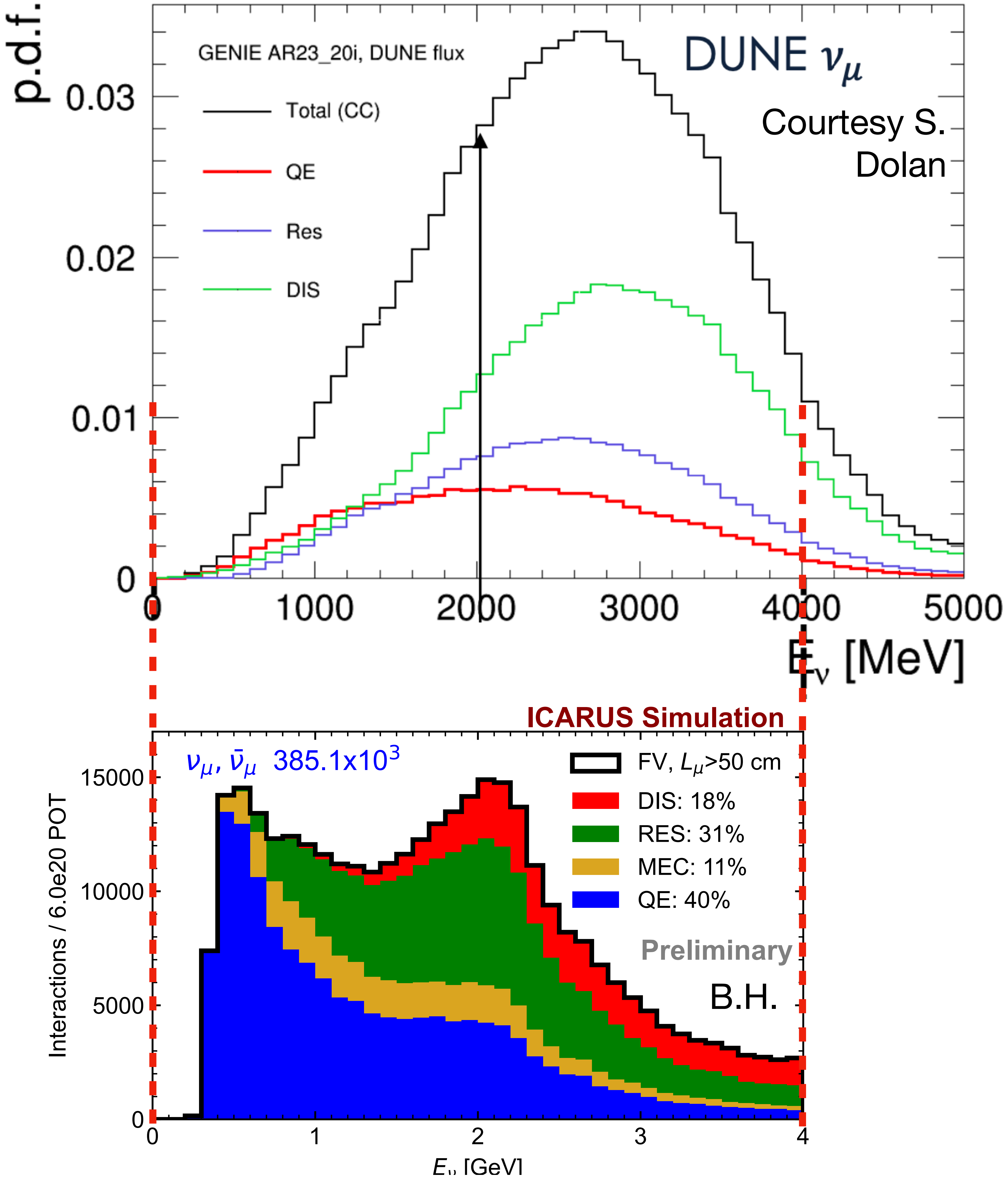


(Score comparing dE/dx vs. residual range to expected curve)

Saving both hypotheses allows one to use particle ID in analysis.

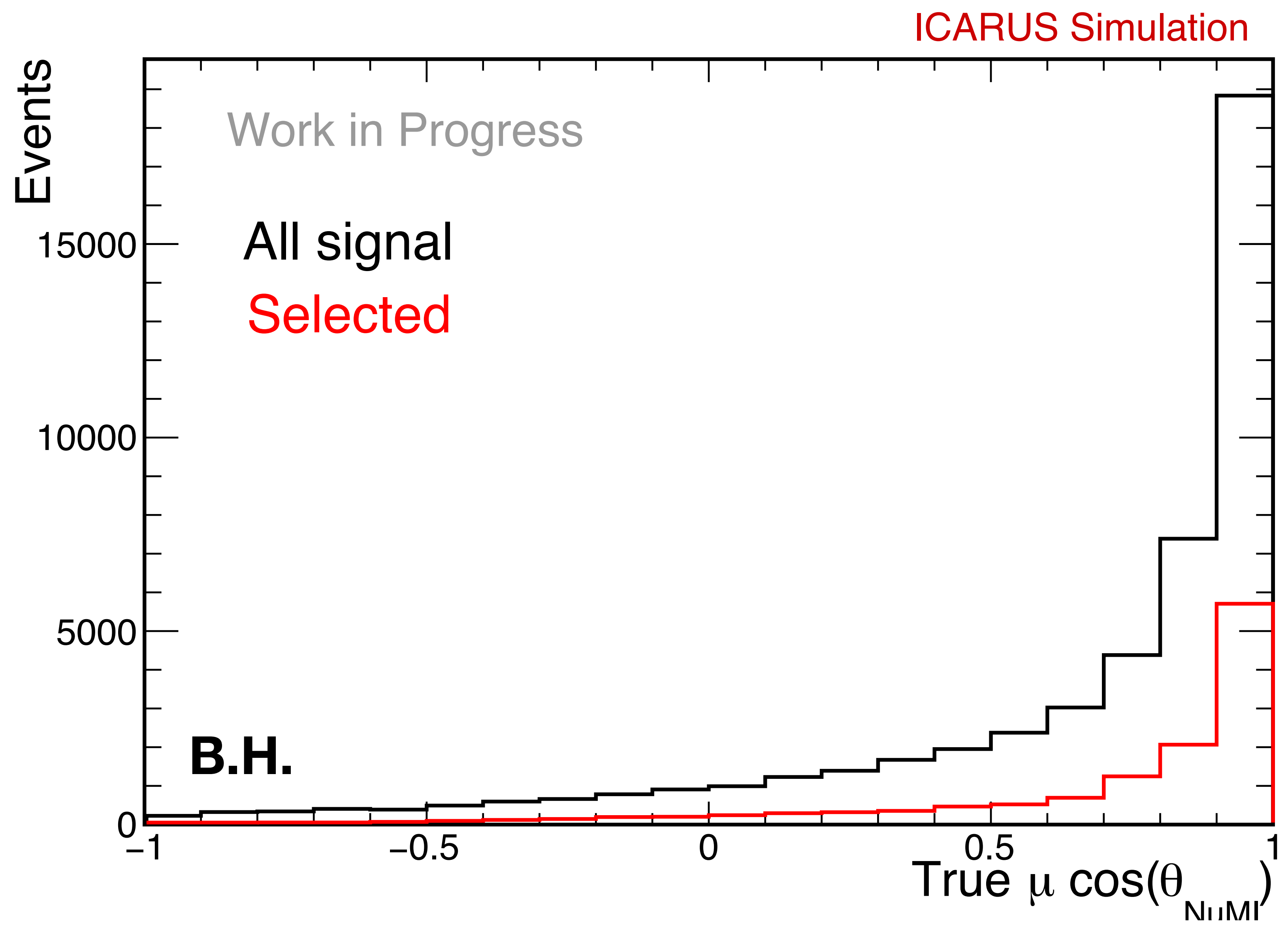
Progressing to cross-section measurements

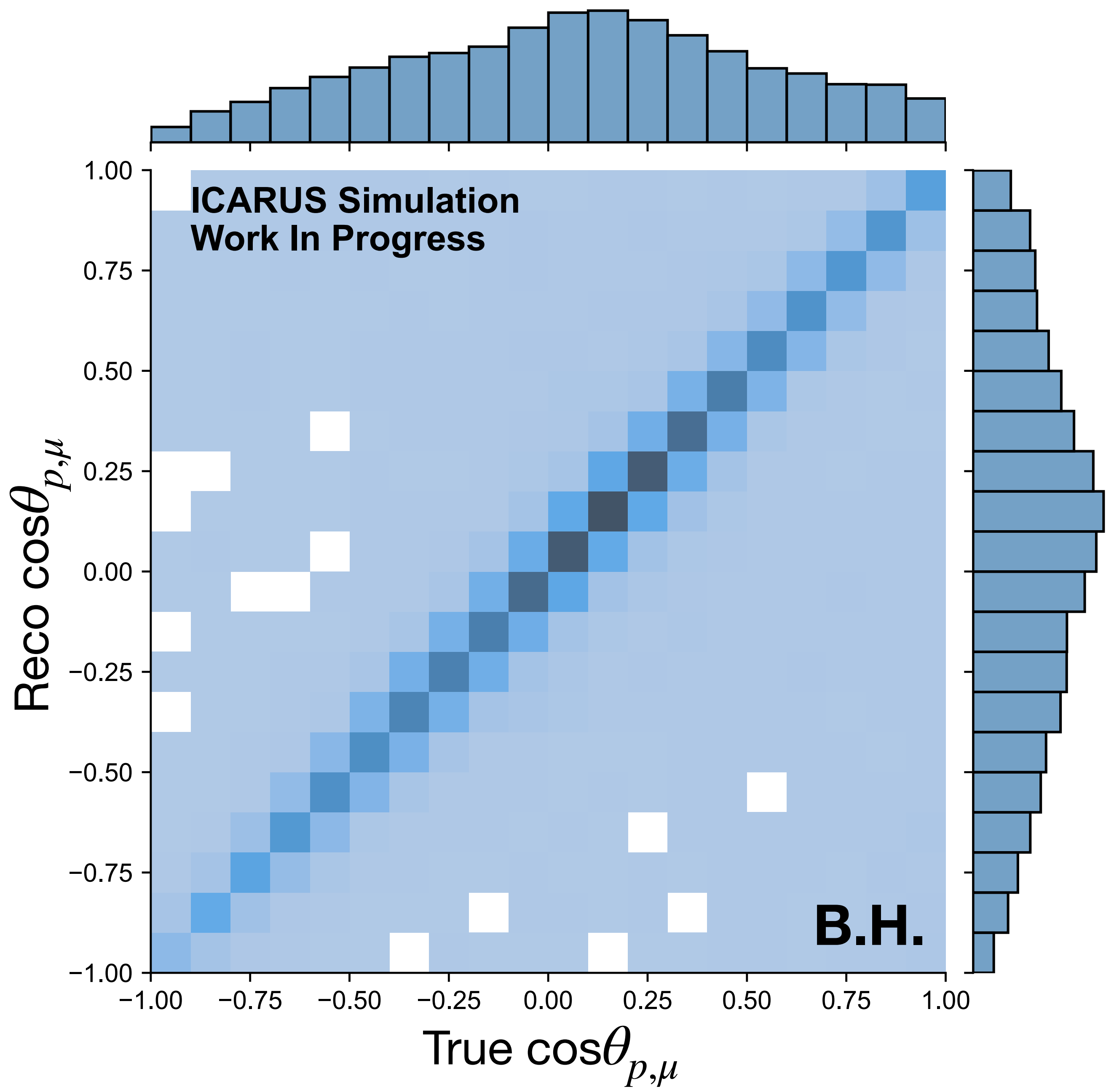
- Building up cross-section analysis, to conduct the model investigations detailed earlier
- First analysis targets 1 (anti-)muon, N proton, 0 pion channel:
  - Because what you analyze is selected based on particles present in the final state, and because things like FSI can *change* what you see, we typically classify events like this
  - 1μ+Np+0pi enhanced in quasi-elastic and 2p2h interactions: DUNE does have significant amount of quasi-elastic events, even if more pion-production dominated
  - These events should be somewhat “cleaner” as a first target in terms of what events look like and ability to reconstruct, but still present an interesting cross-section to measure and investigation of the interaction model behavior
- This is building up the framework and workflow toward end-to-end cross-section analysis, providing basis for future work

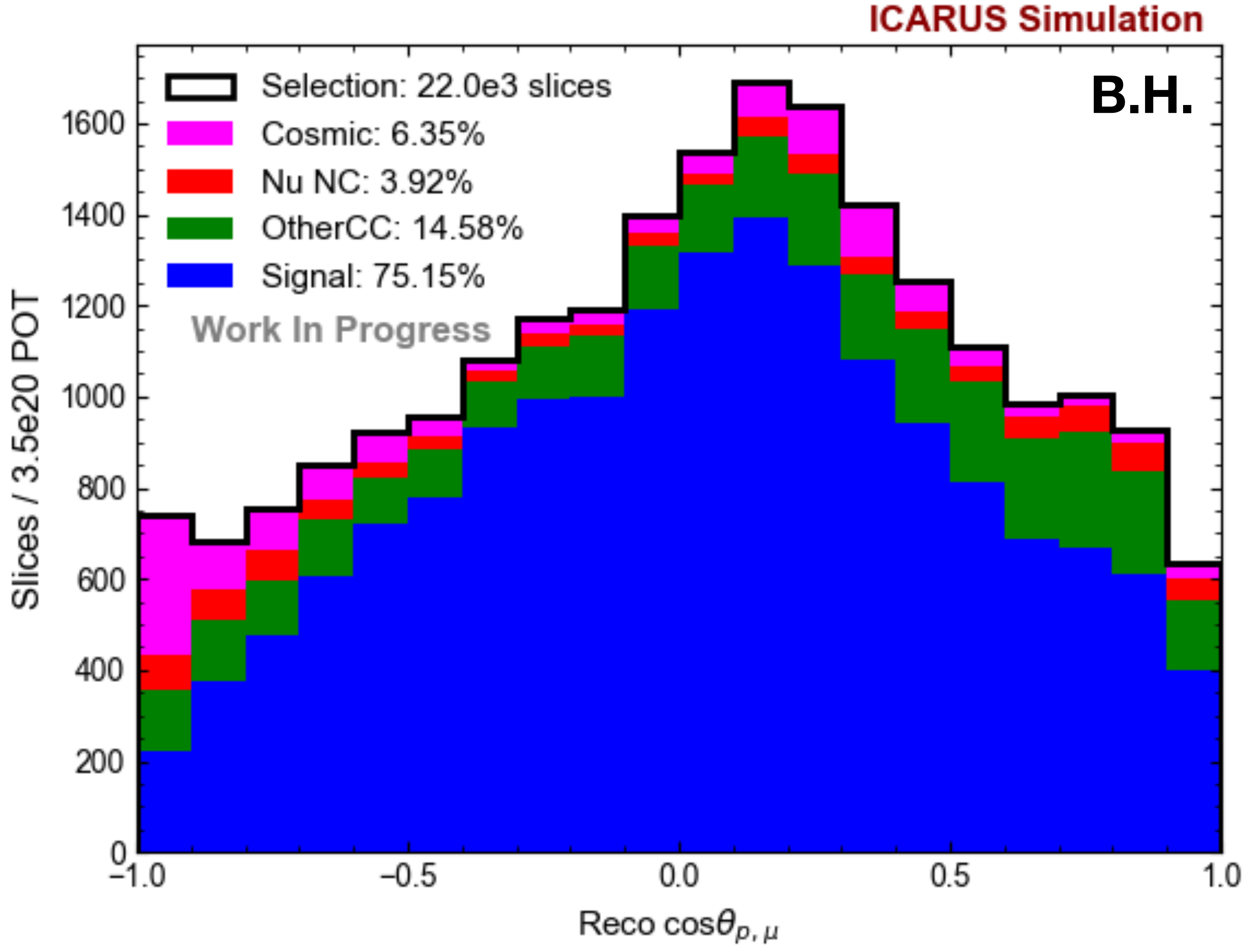


Progressing to cross-section measurements

- I am targeting angular variables for cross-section analysis
  - One choice would be angle of lepton w.r.t. vector pointing from NuMI to ICARUS: most events are in just a few bins
  - Another is angle between the muon candidate and leading proton candidate: populates the phase space more broadly, and is expected to encode more information about FSI
- Selection is aimed to pick out 1μNp0pi events and reject backgrounds (e.g. pions)
- Expect ~20k selected events at current selection & exposure

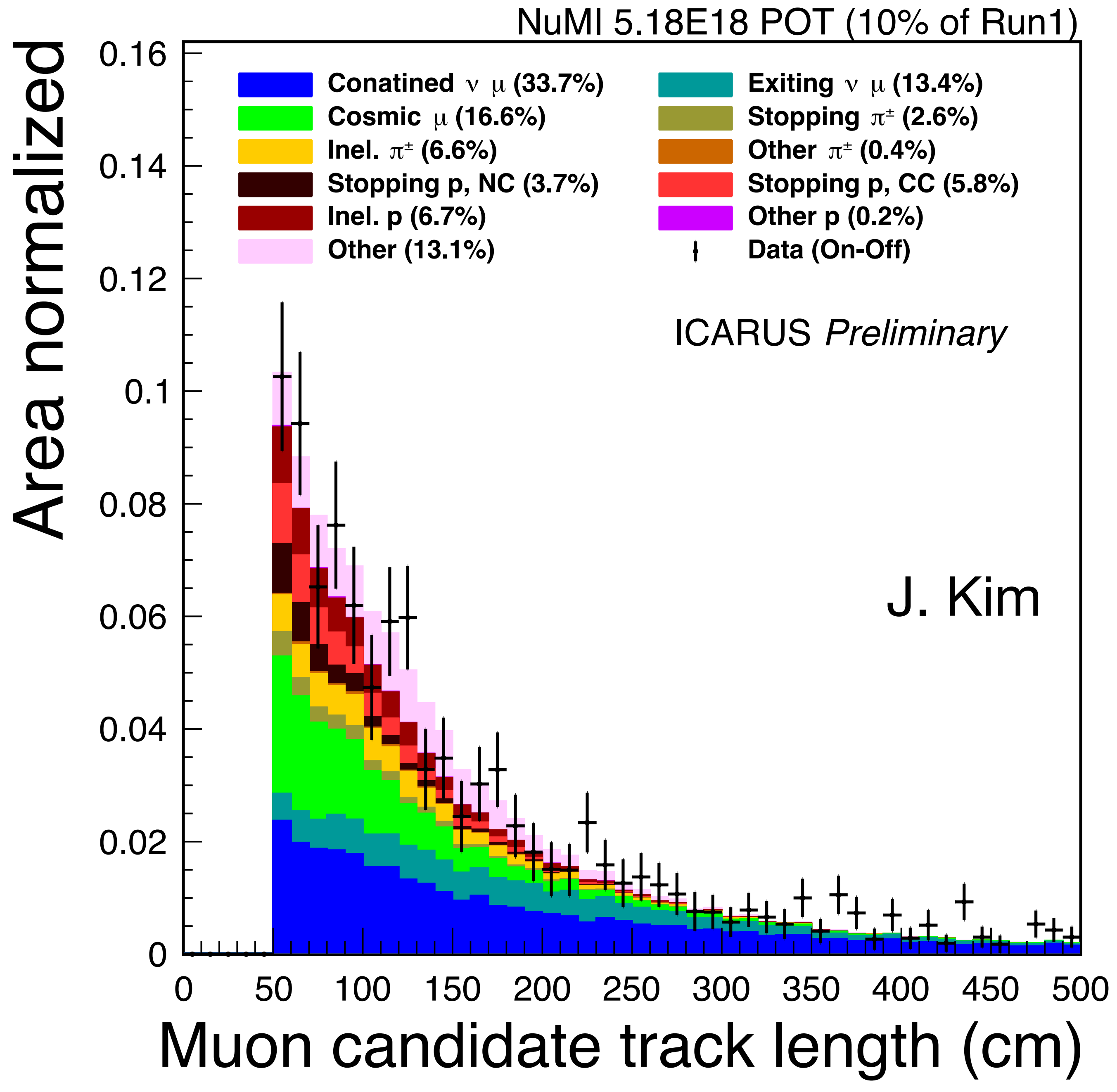


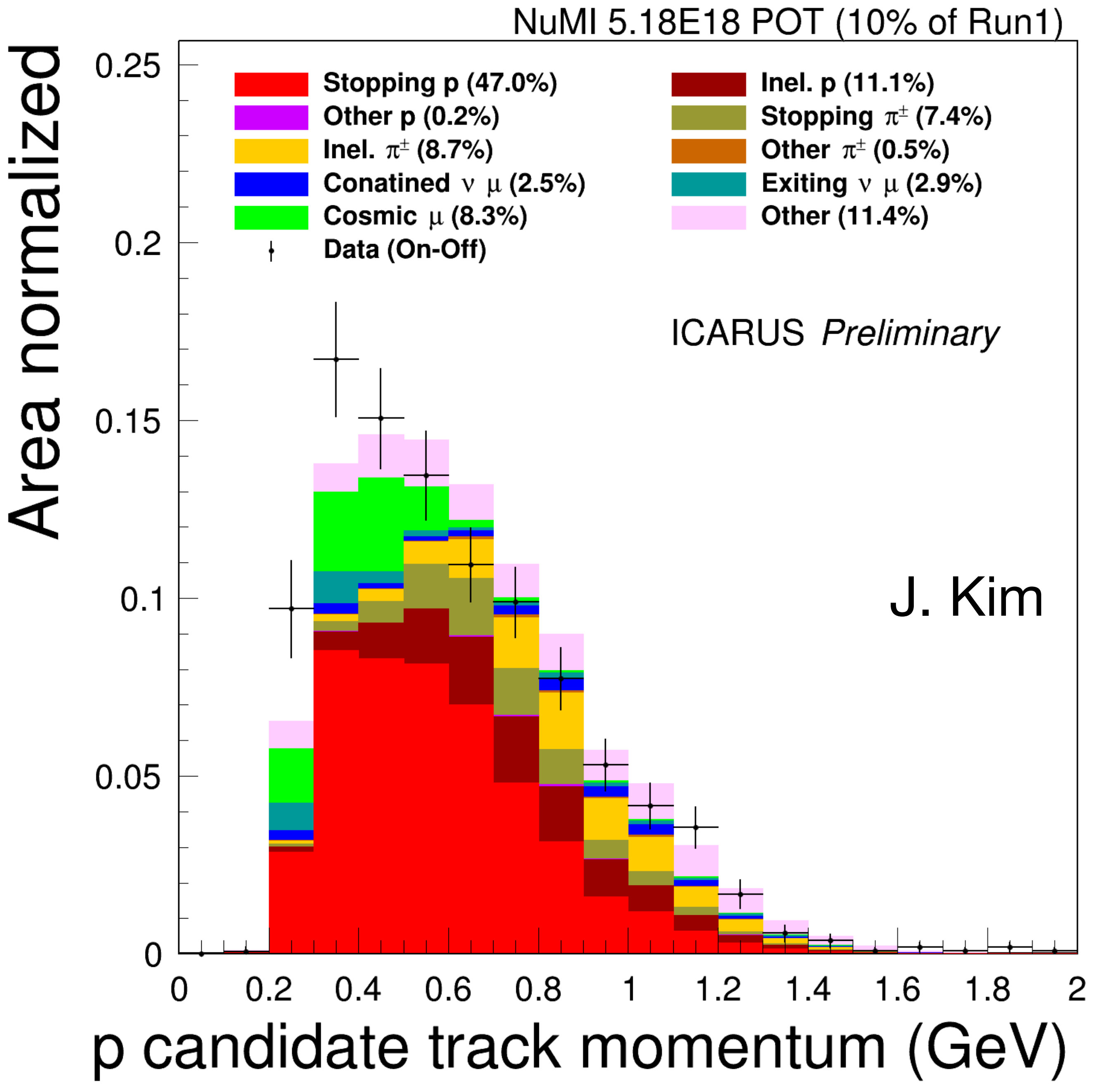




Progressing to cross-section measurements

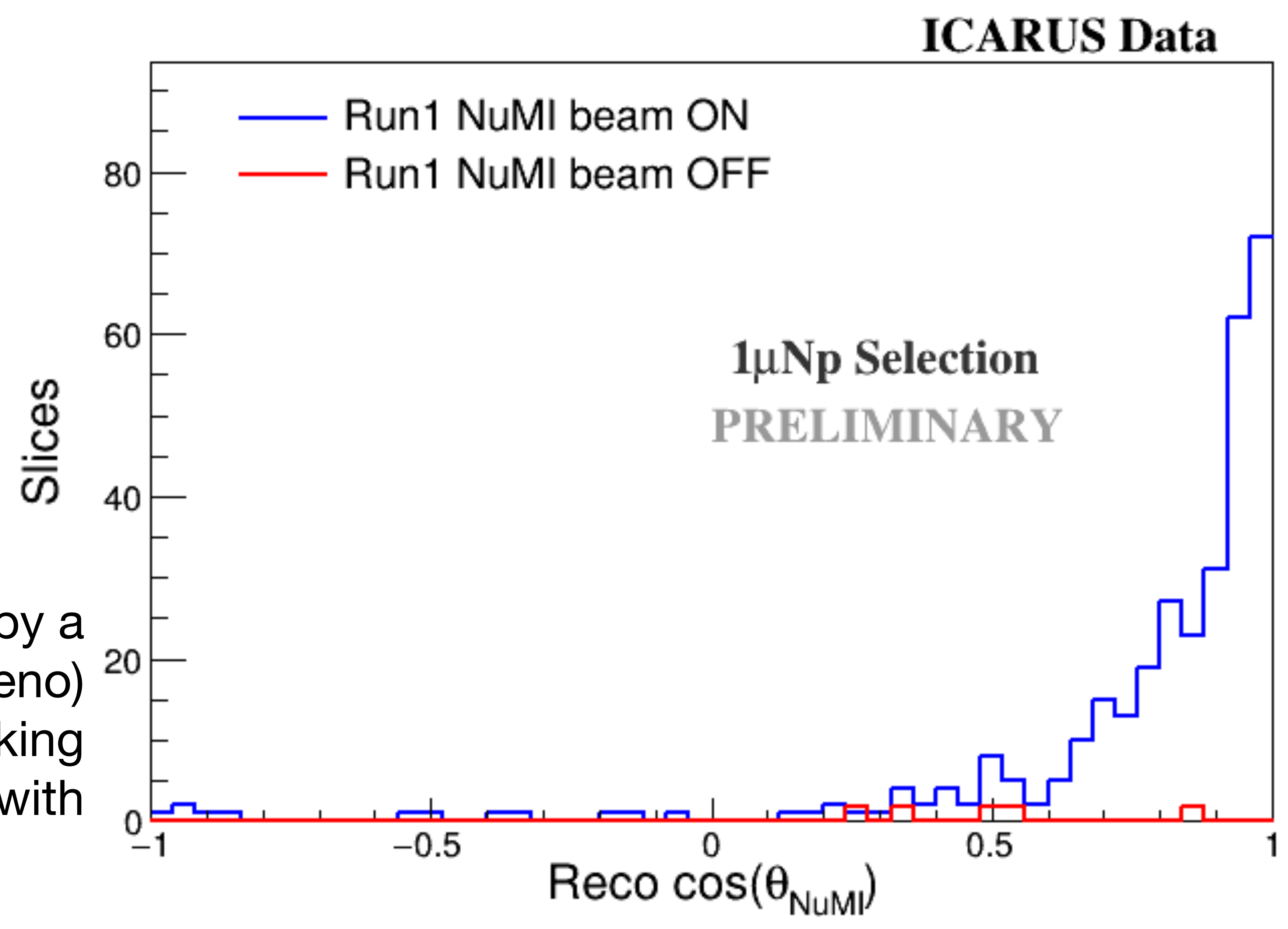
- Have also taken looks at some samples of data:
    - A selection targeting a slightly more inclusive 1μNp+anything were investigated w/ data samples to highlight cosmic rejection power and that selected beam events do peak with muon in forward direction
    - data/MC studies ongoing: shown here some 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)





Data/MC

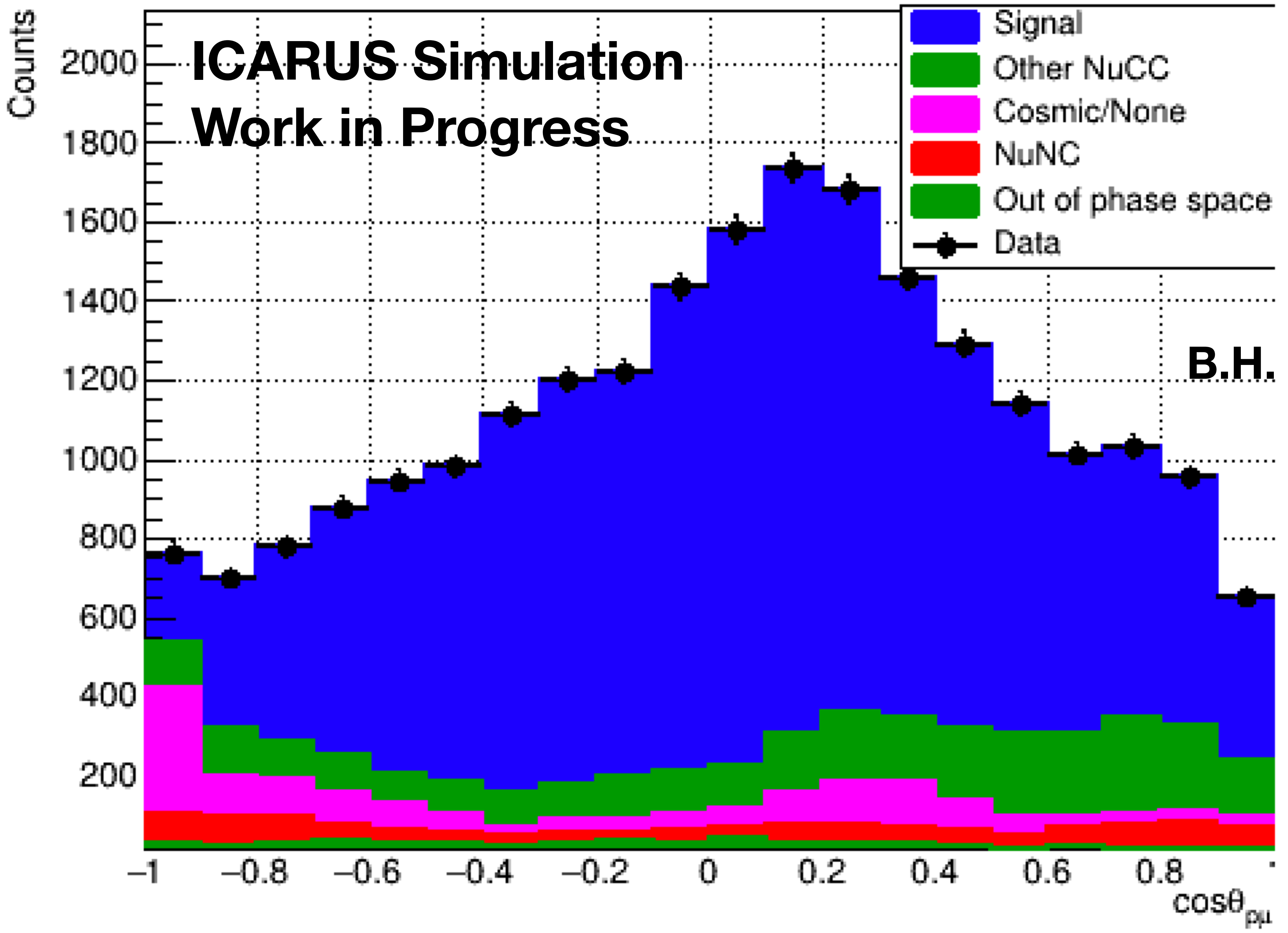
Data looked at by a student (G. Moreno) I've been working closely with



Progressing to cross-section measurements

- 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 it into our workflow and analysis, including upgrades to analysis framework also expected to better enable oscillation fits (or anything with an external fitter)
  - Flux systematics are ready and being used in tests of GUNDAM, cross-section model uncertainties are closely tied with DUNE and nearly ready to go though not yet included in fit, Geant4 systematics are based on DUNE/ MicroBooNE, detector systematics to follow
  - With similar computing environments & software, believe similar workflow can be explored in DUNE

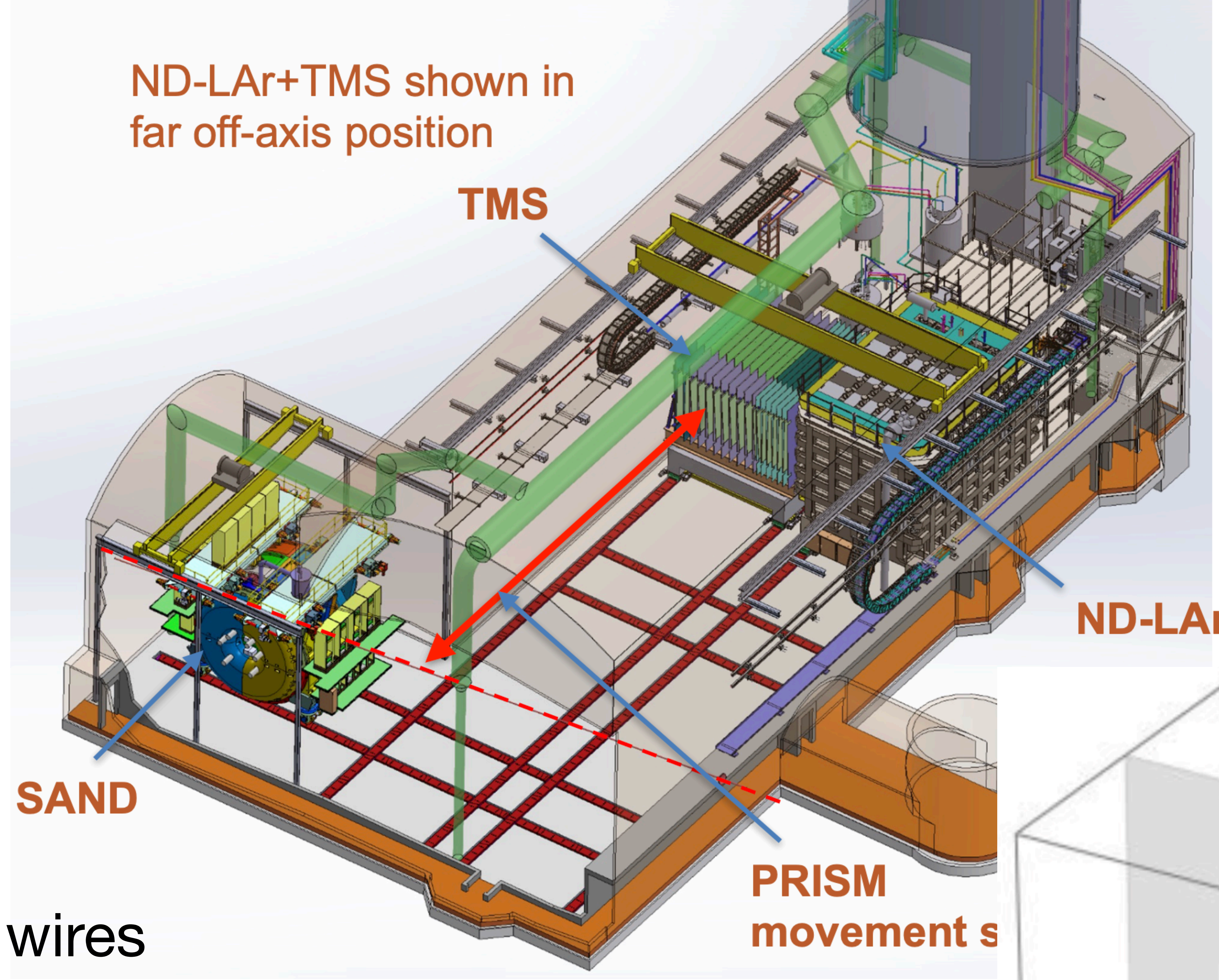
Test fit where data is MC, and w/ beam hadron production uncertainties as systematics



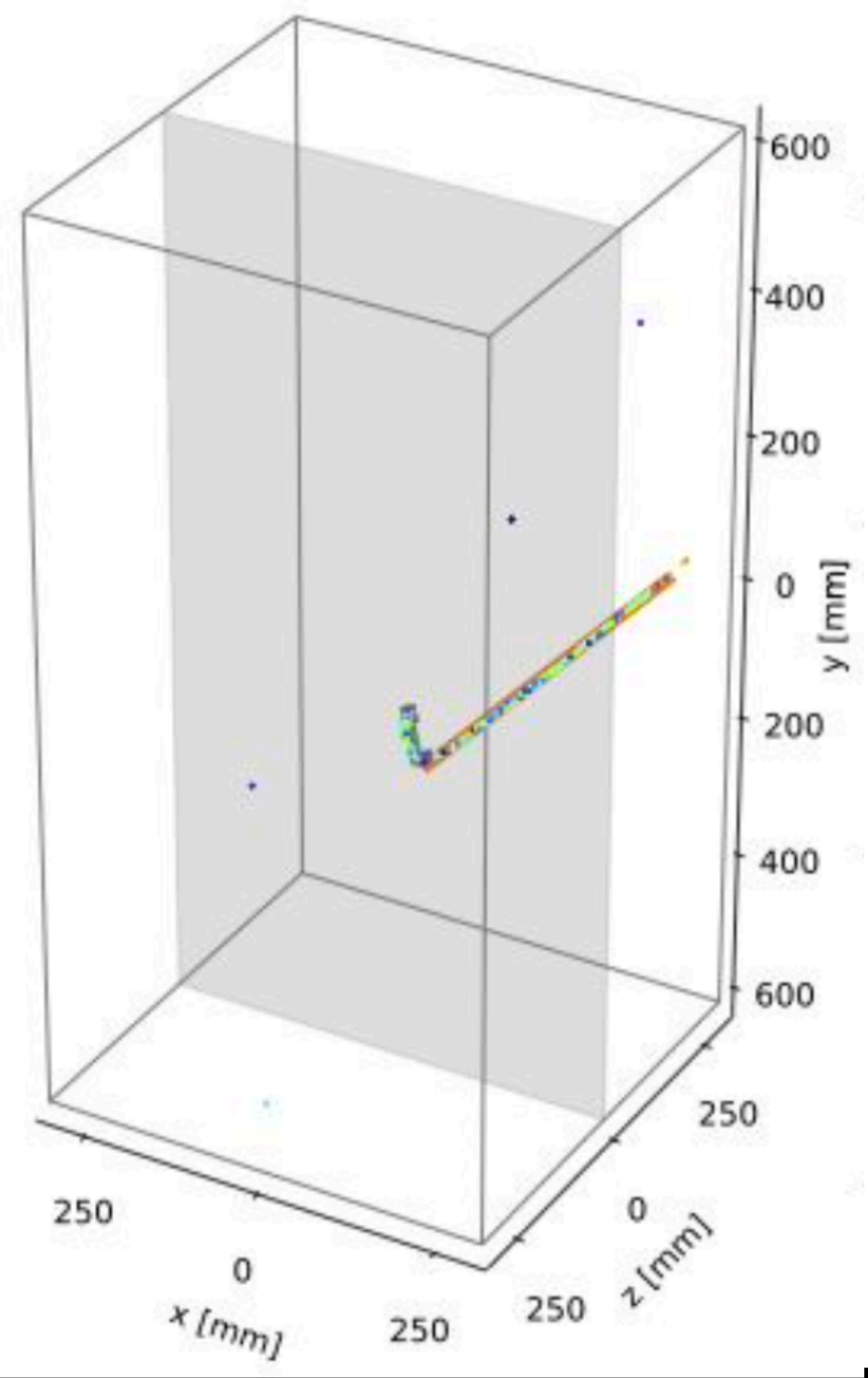
- We are actively working to get this to the finish line and establish the workflow for future ICARUS cross-section measurements. Work on a technical note is in progress.

DUNE Near Detector

- Have discussed collecting first ICARUS data, ongoing analysis w/ it, and how we can leverage it to aid DUNE
- DUNE needs own capable Near Detector: characterize flux, perform more measurements/model developments w/ unprecedented statistics, enable BSM searches, etc.
  - Ultimate plan comprises of multiple detectors including LAr TPC and a Gas Argon TPC (lower thresholds for hadrons!)
  - High pileup: pixelated readout for LAr TPC instead of wires
  - Capability to move parts off-axis to fully study flux
- The next years will be critical:
  - Prototype studies such as the 2x2 LArTPC test which will happen at FNAL soon, and ensuring optimal designs will work for DUNE
  - R&D can take place at local labs and Fermilab toward improving technologies: possibility to use prototype detectors for larger scale testing
  - Prepare for analyses and pipeline from current experiments to DUNE, including end-to-end reco, matching detectors



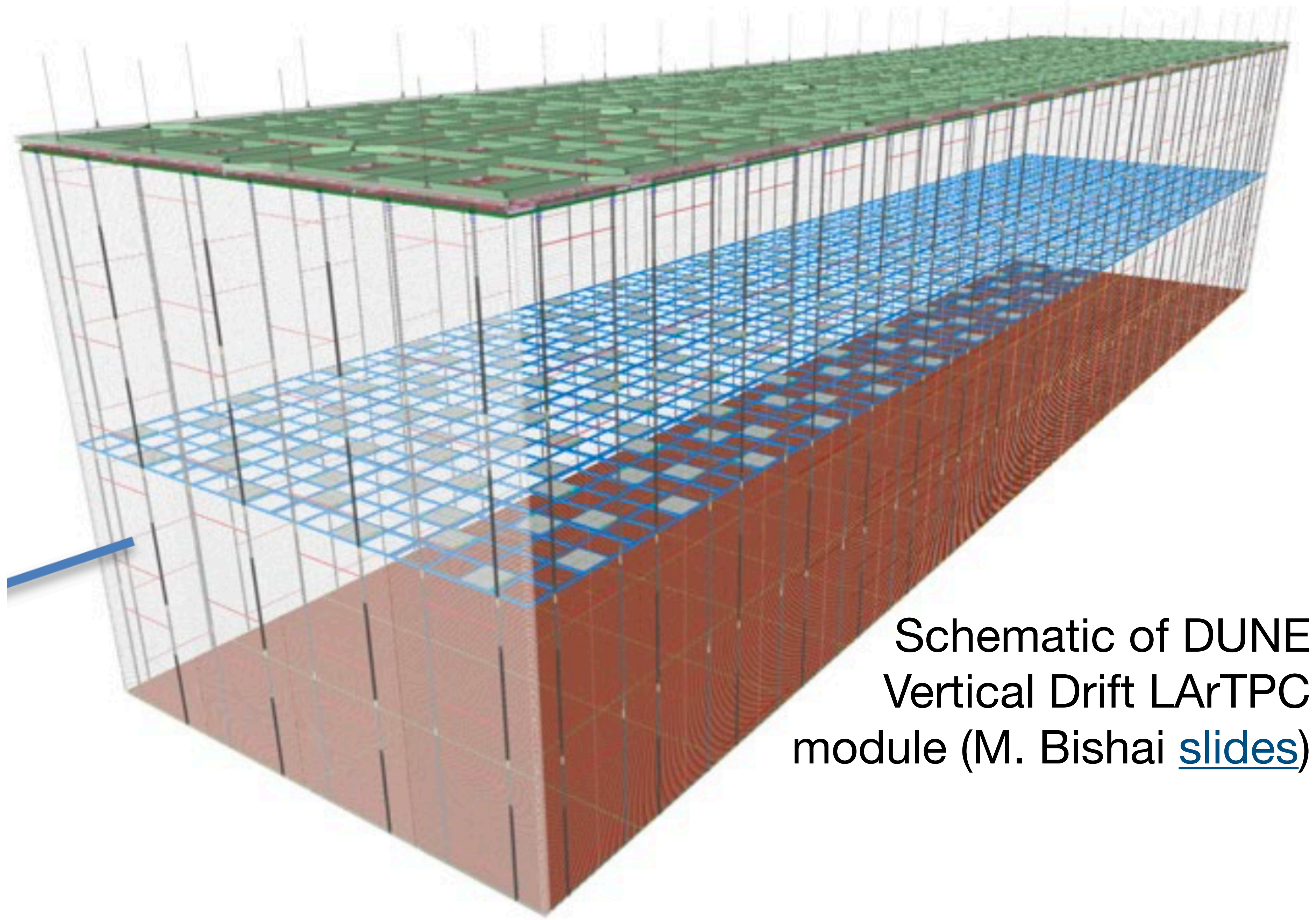
Schematic of DUNE Near Detector (H. Tanaka slides)



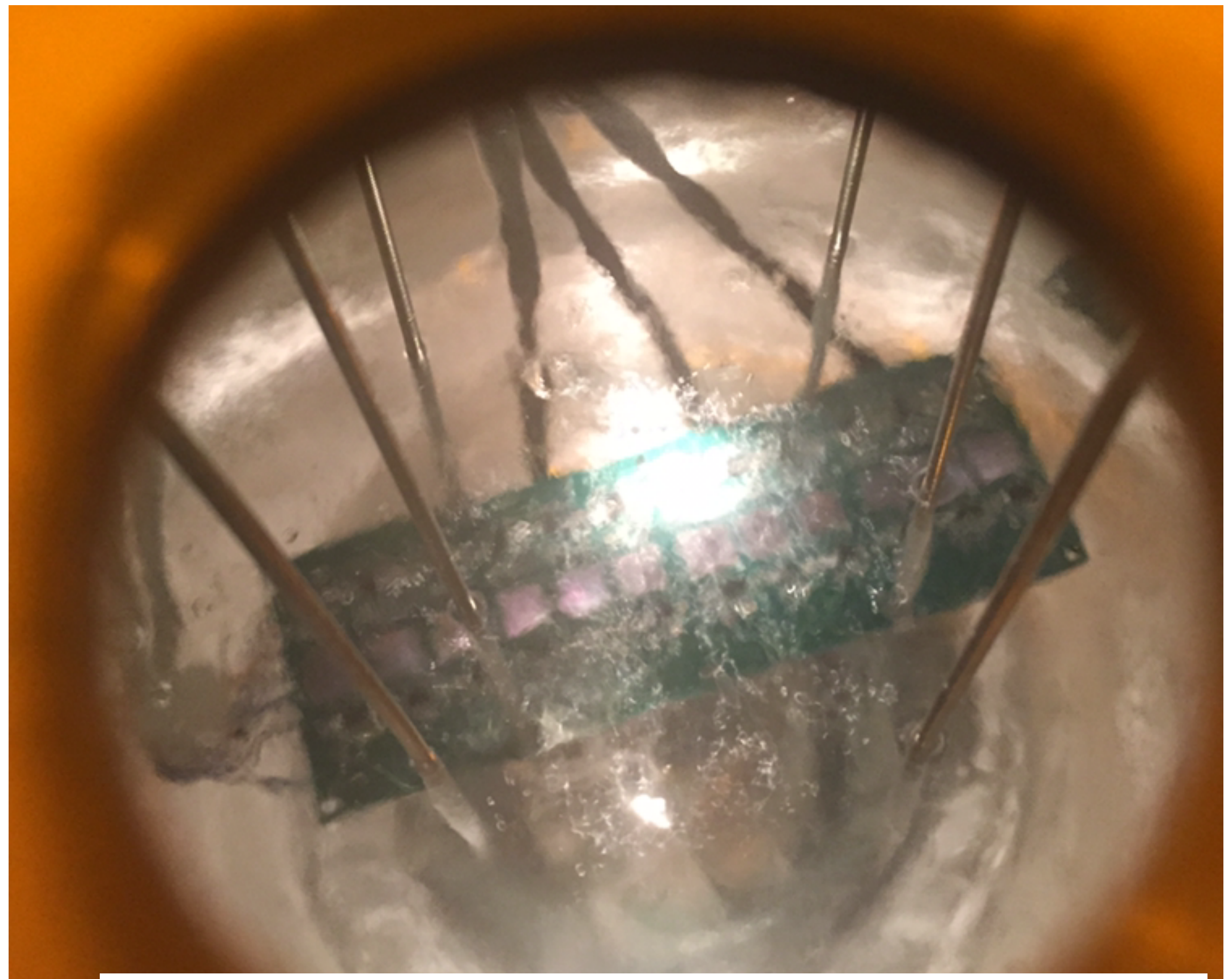
ND-LAr prototype event (Z. Hulcher slides)

Realizing DUNE and R&D

- DUNE will build on the past few decades of work with LAr TPC detectors, but are also **driving forward the medium**: even in a collaboration with >1k people, room for R&D
  - In addition to the technology being driven by making the Near Detector use pixelated readout
  - DUNE also plans to instrument the first large Vertical Drift LAr TPC with different charge readout and photon detectors using power and signals over fiber
  - Even the most "traditional" Horizontal Drift Far Detector module(s) benefitted from R&D, necessitated by the volumes for photon detectors being too thin for traditional PMTs
    - I benefitted from this in graduate studies with R&D for photon detectors using SiPMs, mainly with light guides
  - Last 10kt is "Module of Opportunity:" many ideas from community to complement with additional technology



Schematic of DUNE Vertical Drift LArTPC module (M. Bishai slides)

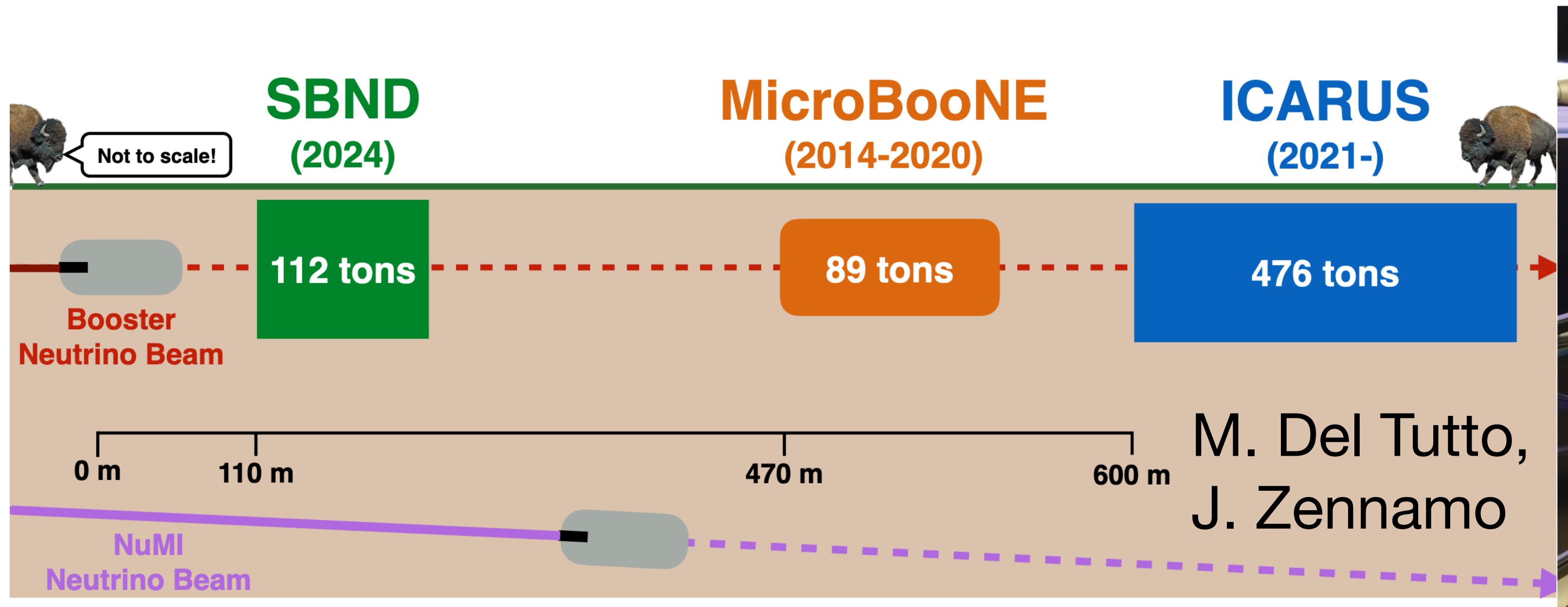


Peering into a tiny test stand a fellow student and I used for detector testing

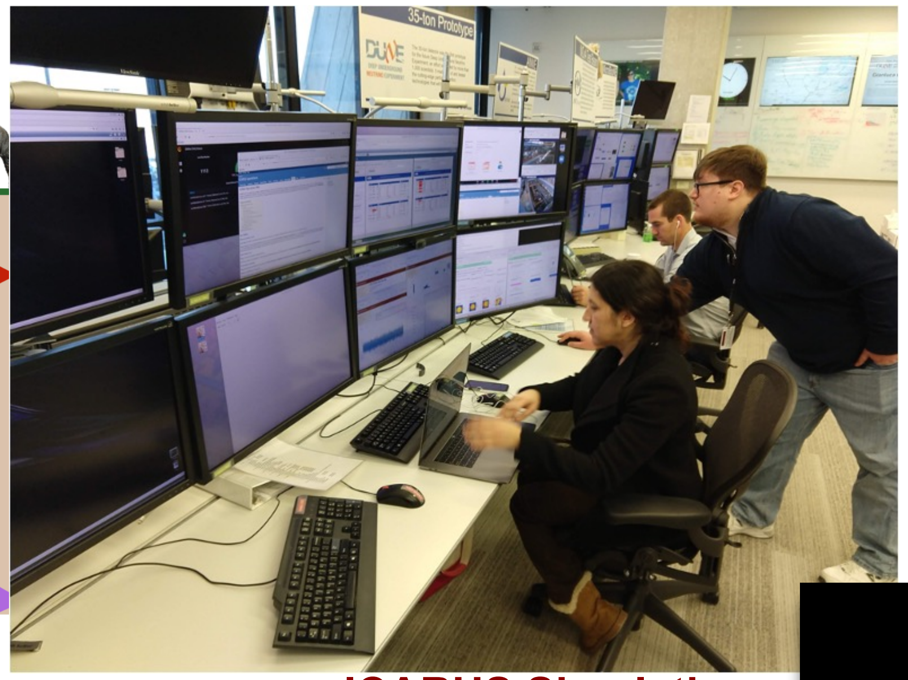
DUNE photon detectors will use modules with SiPMs instead of more "traditional" TPB-coated PMTs

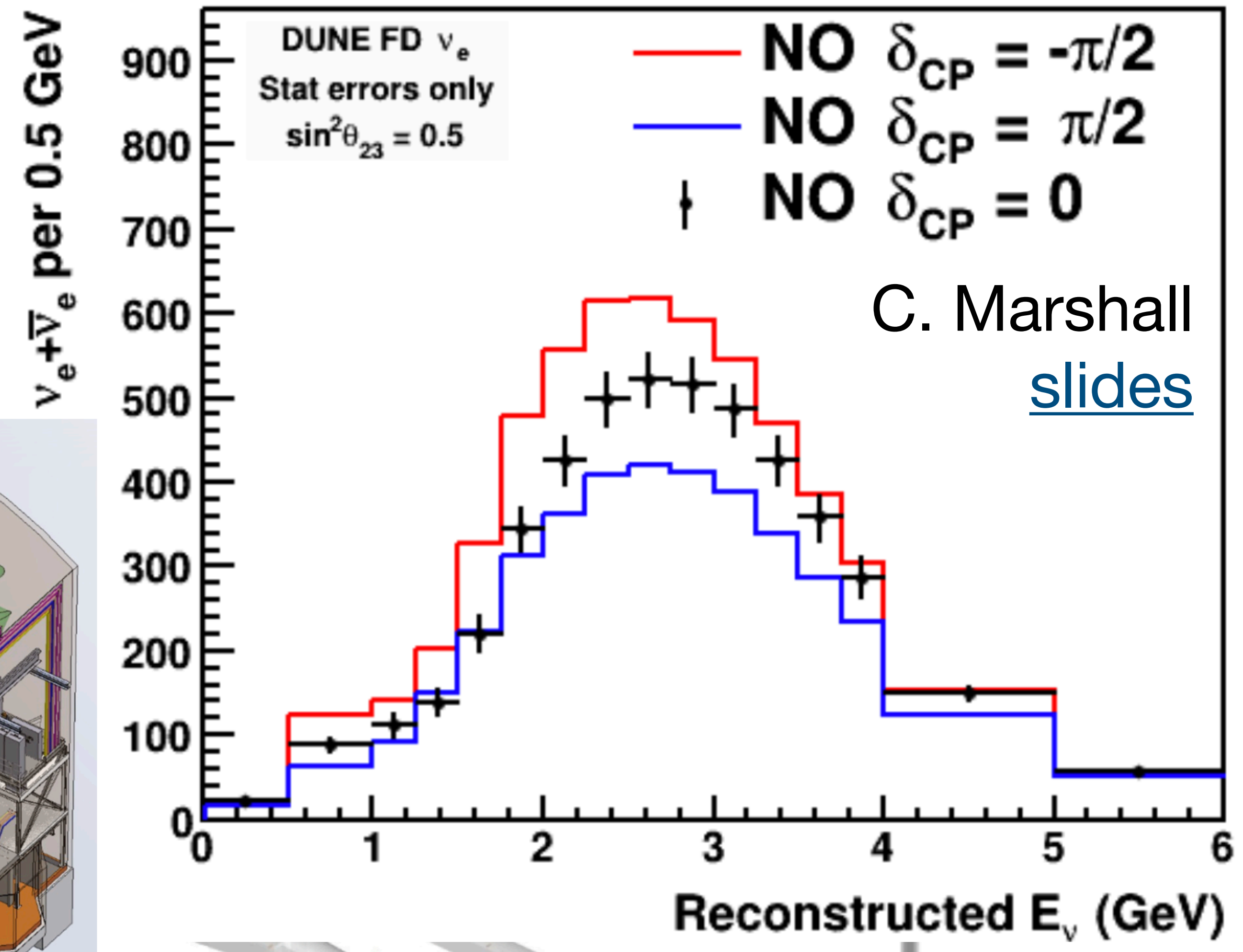
Summary and Conclusions

- LAr TPC detectors with accelerator neutrino beams are probing the nature of excesses seen at LSND/ MiniBooNE and will bring leading results on three-flavor oscillation physics with DUNE
- ICARUS progressed from commissioning to physics operations: in addition to oscillation, analyzing cross-sections w/ NuMI at ICARUS: working towards 1muNp0pi channel & laying groundwork for the many cross-section and interaction studies to be performed over the next years
- Next years crucial to realize DUNE & measurements now also prepare for DUNE

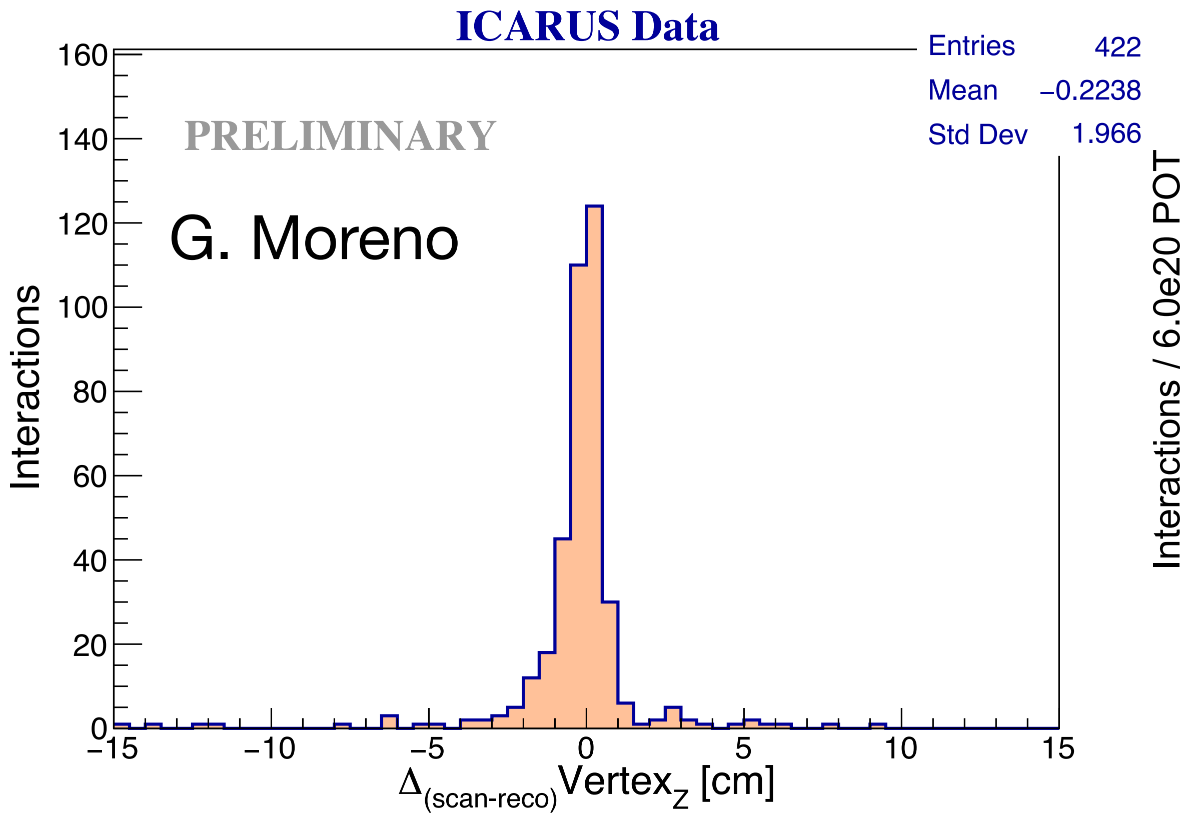


M. Del Tutto, J. Zennamo

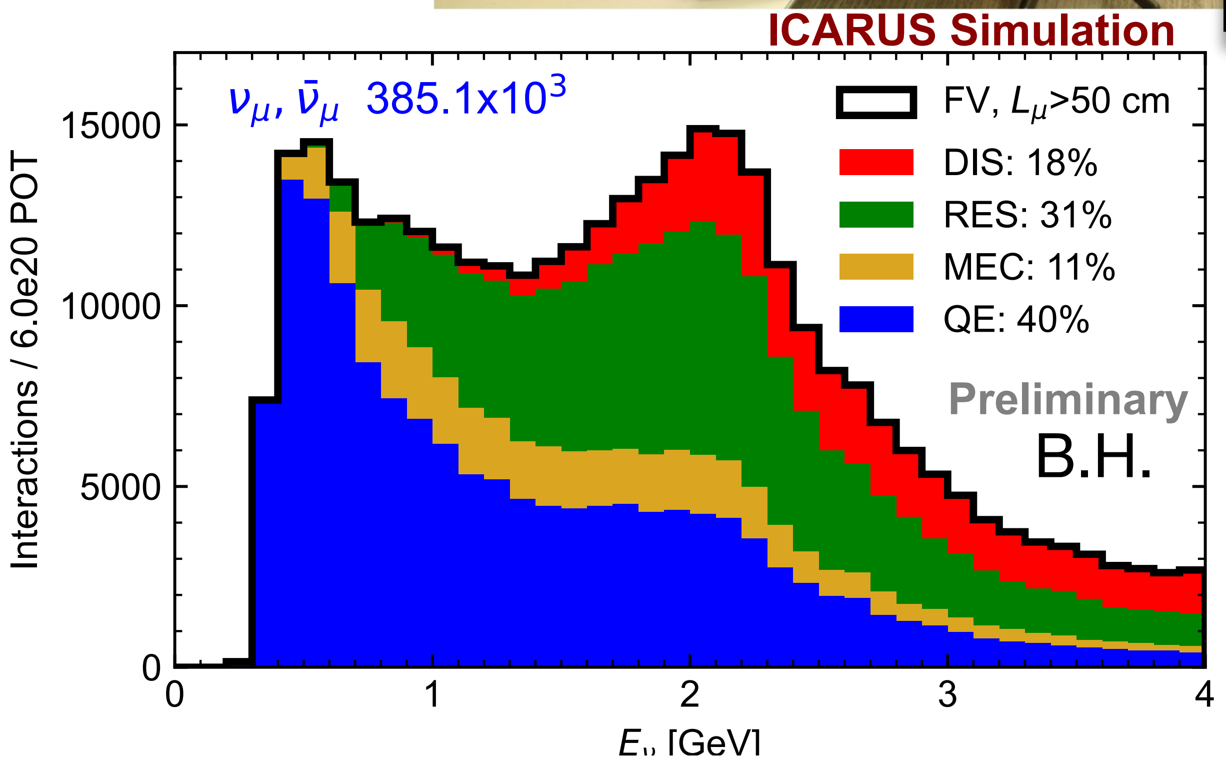




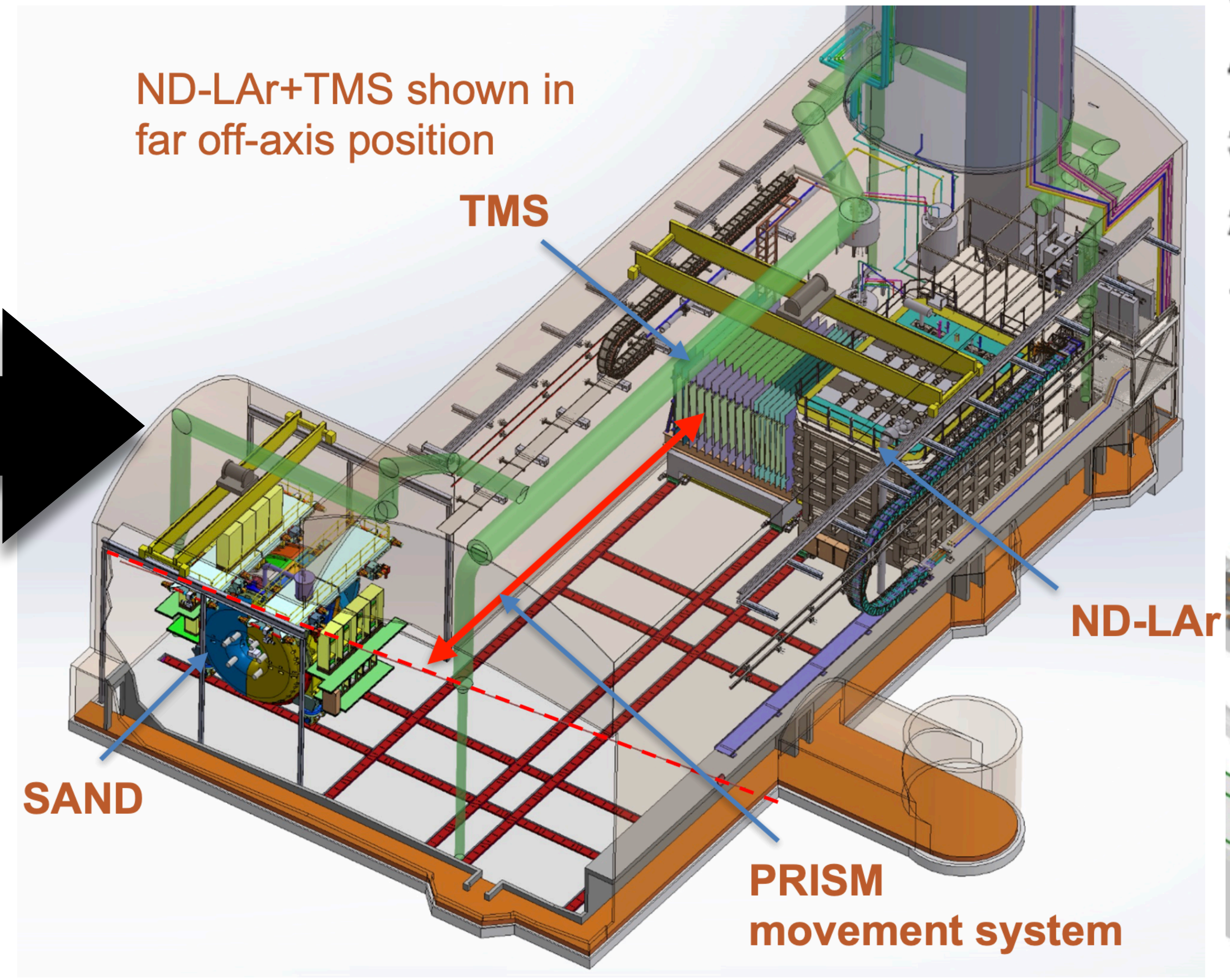
C. Marshall
slides



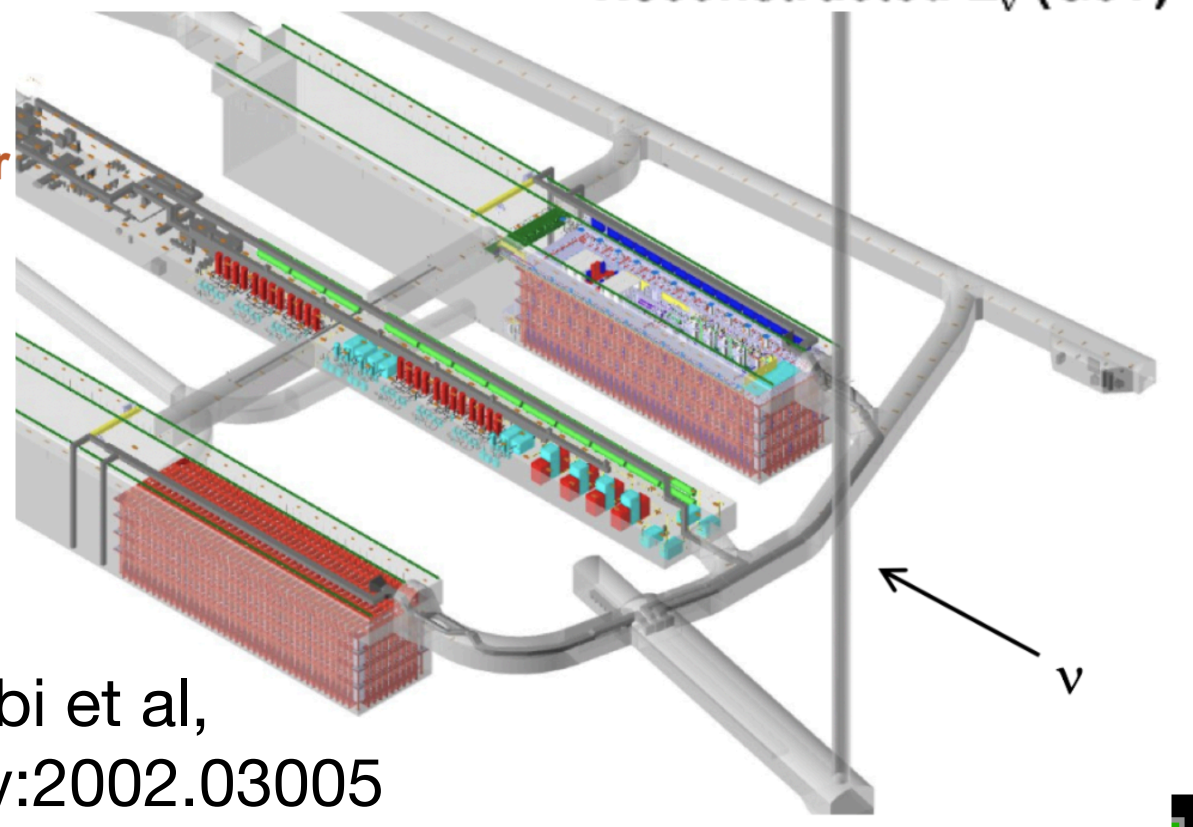
G. Moreno



B.H.



Schematic of DUNE Near Detector (H. Tanaka slides)



B. Abi et al, arXiv:2002.03005

Backup

SBND

Photos: Mônica Nunes

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

Events Selected

Unfolding

Backgrounds

Bin-width

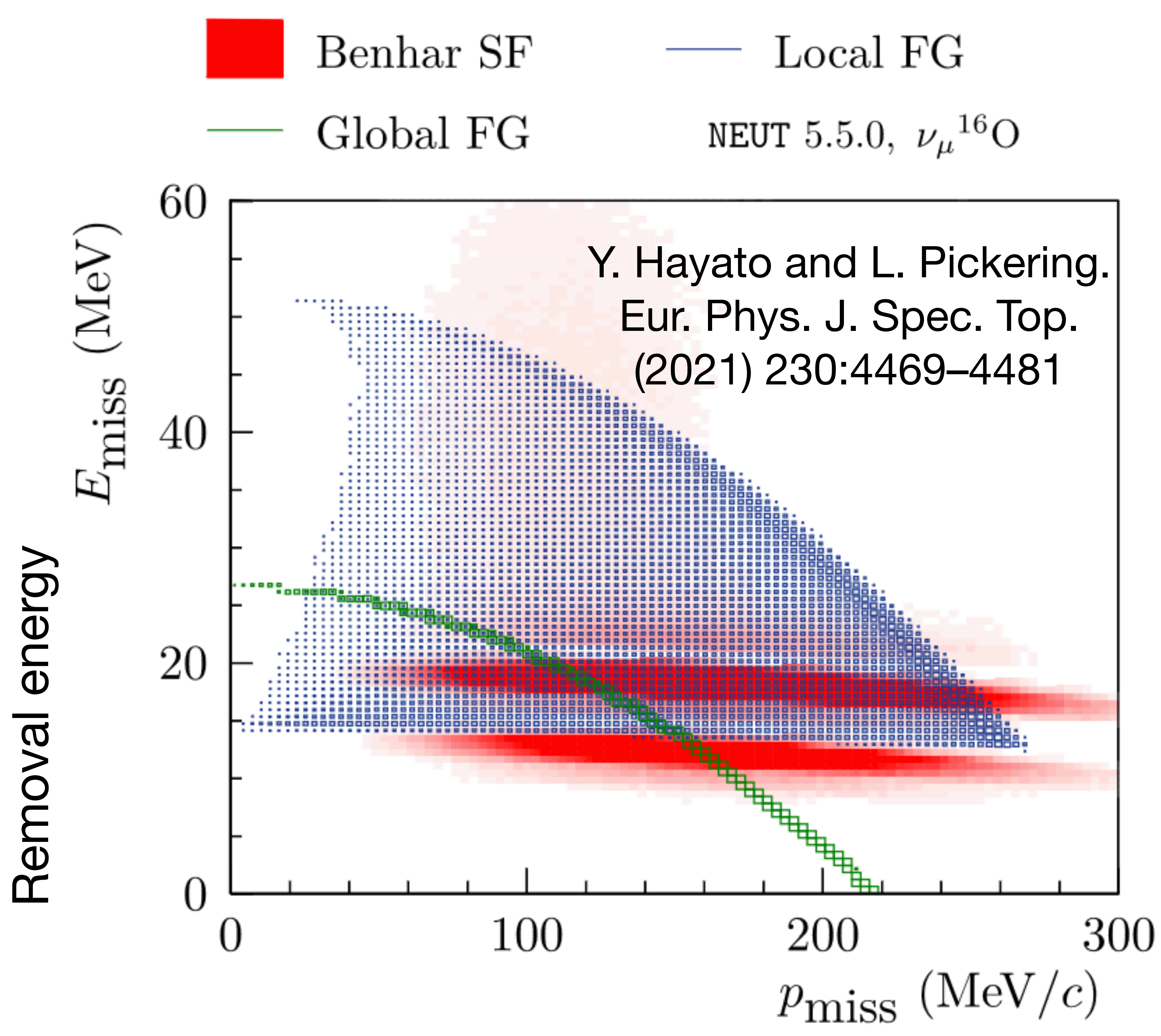
Acceptance

Flux

Targets

From M. Betancourt

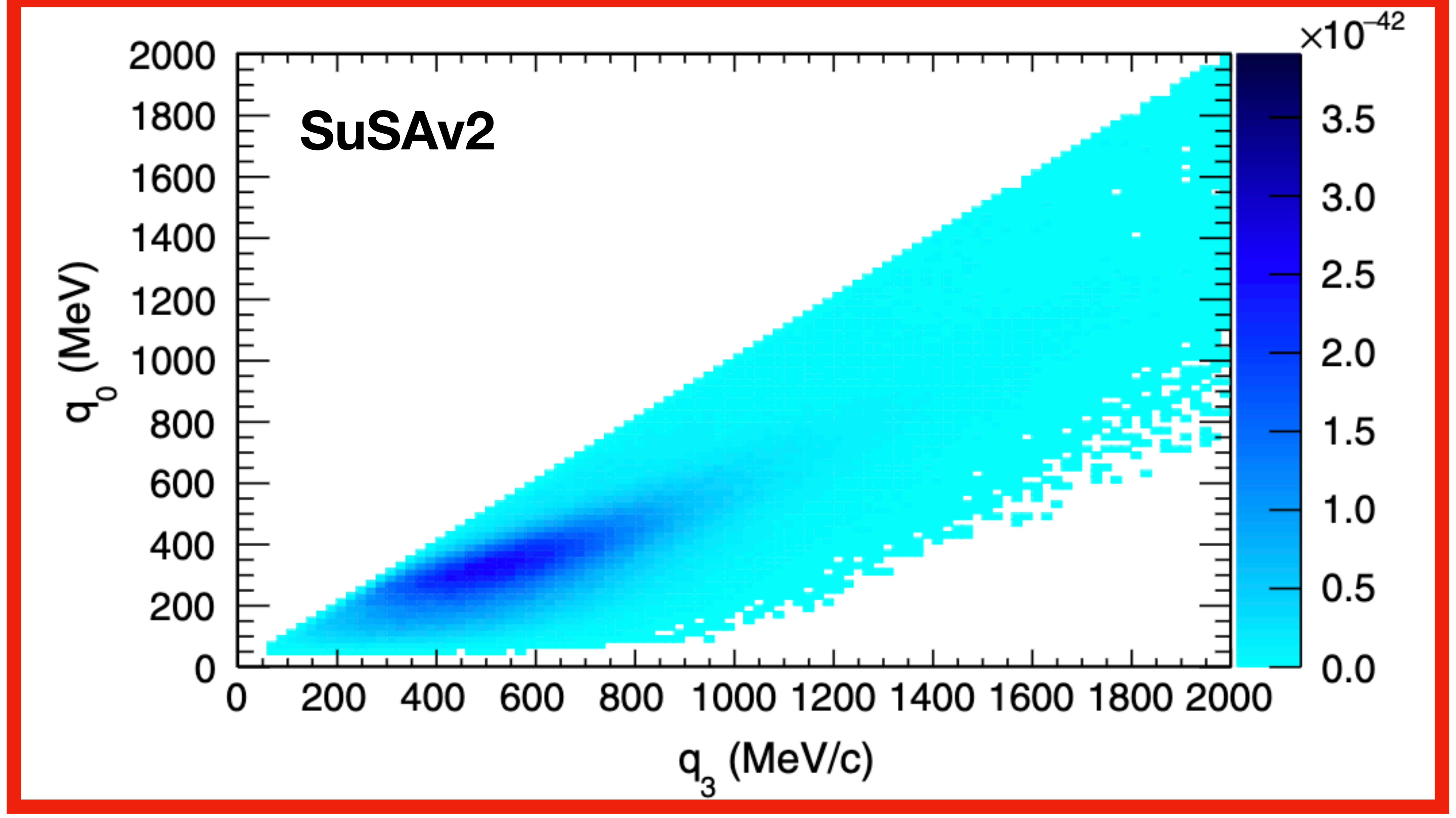
GENIE version



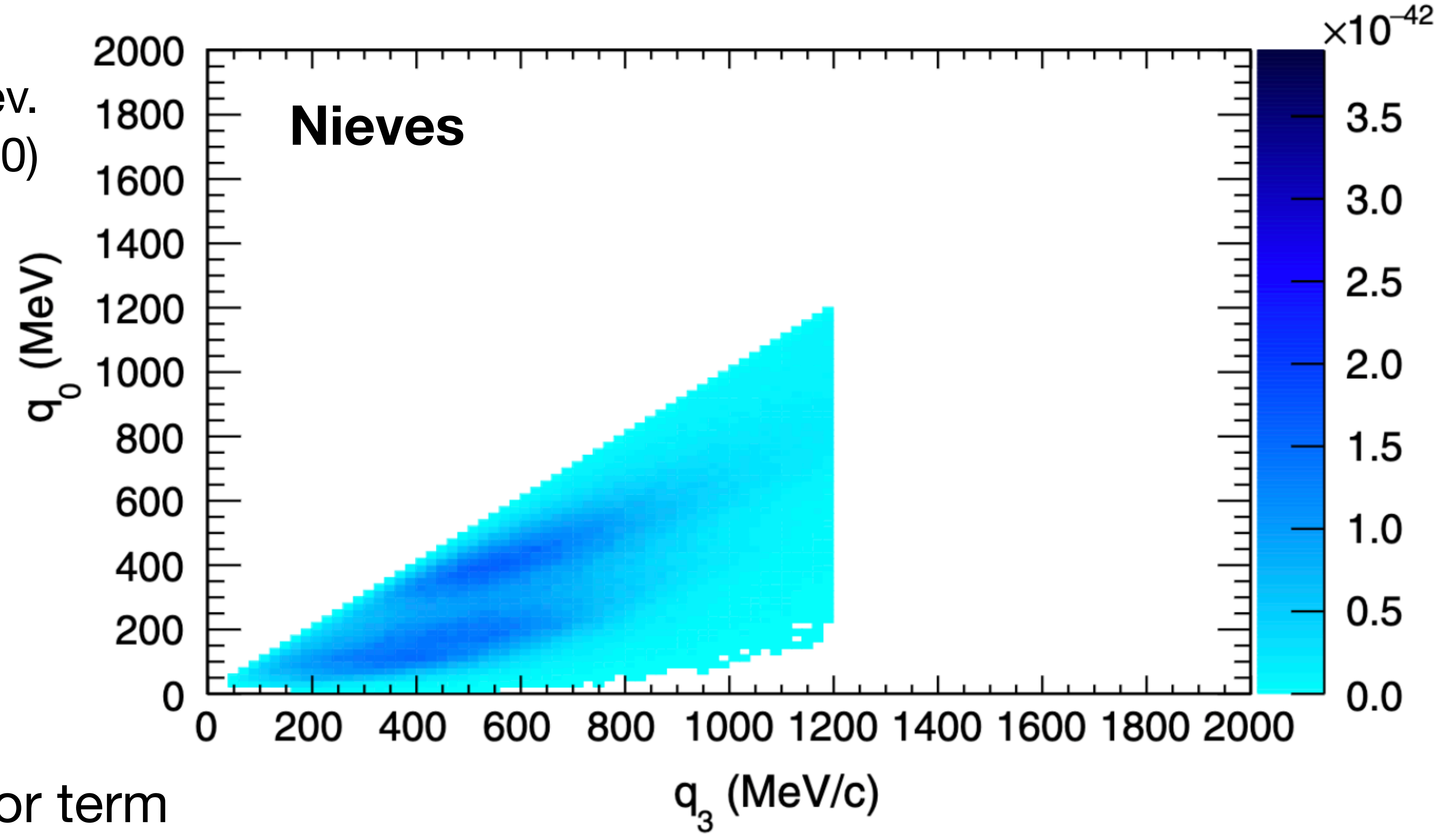
Fermi motion

Our GENIE version is more like the Local Fermi Gas model here but with a short range correlations tail extending below 15 MeV Emiss

2p2h cross-sections



S. Dolan et al. Phys. Rev. D 101, 033003 (2020)



We also have switched to the Z expansion formulation of the CCQE axial form factor term (was a dipole term previously with e.g. an “axial mass” term) — more free parameters.

M.F. Carneiro et al (MINERvA), Phys Rev Lett **124**, 121801 (2020)

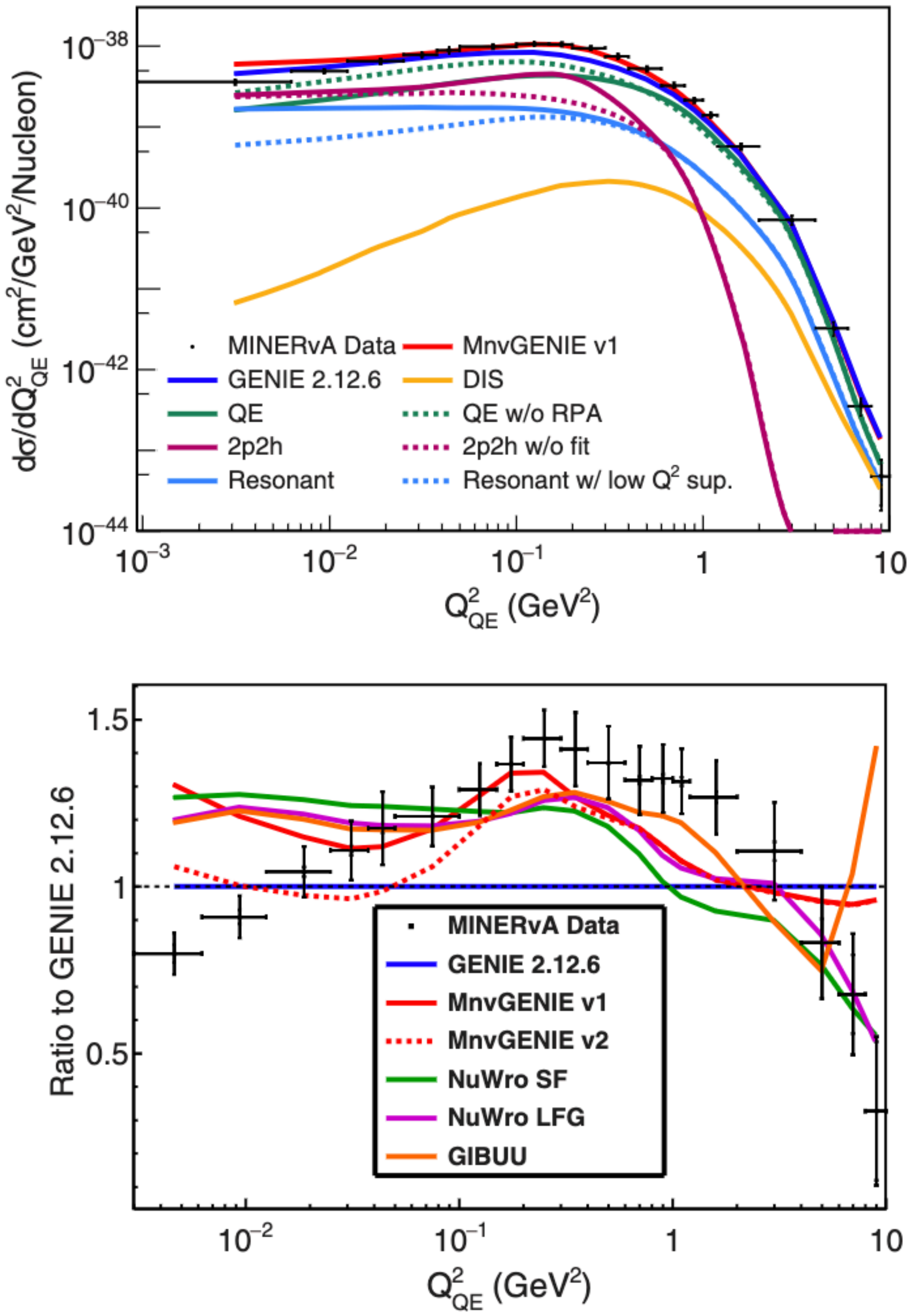


FIG. 5. Top: Differential cross section as a function of Q^2. Bottom: Generator predictions compared to data. All are plotted as ratio to the predictions of unmodified GENIE 2.12.6.

$\nu_\mu \rightarrow \nu_e$

R. Acciari et al arXiv:1512.06148

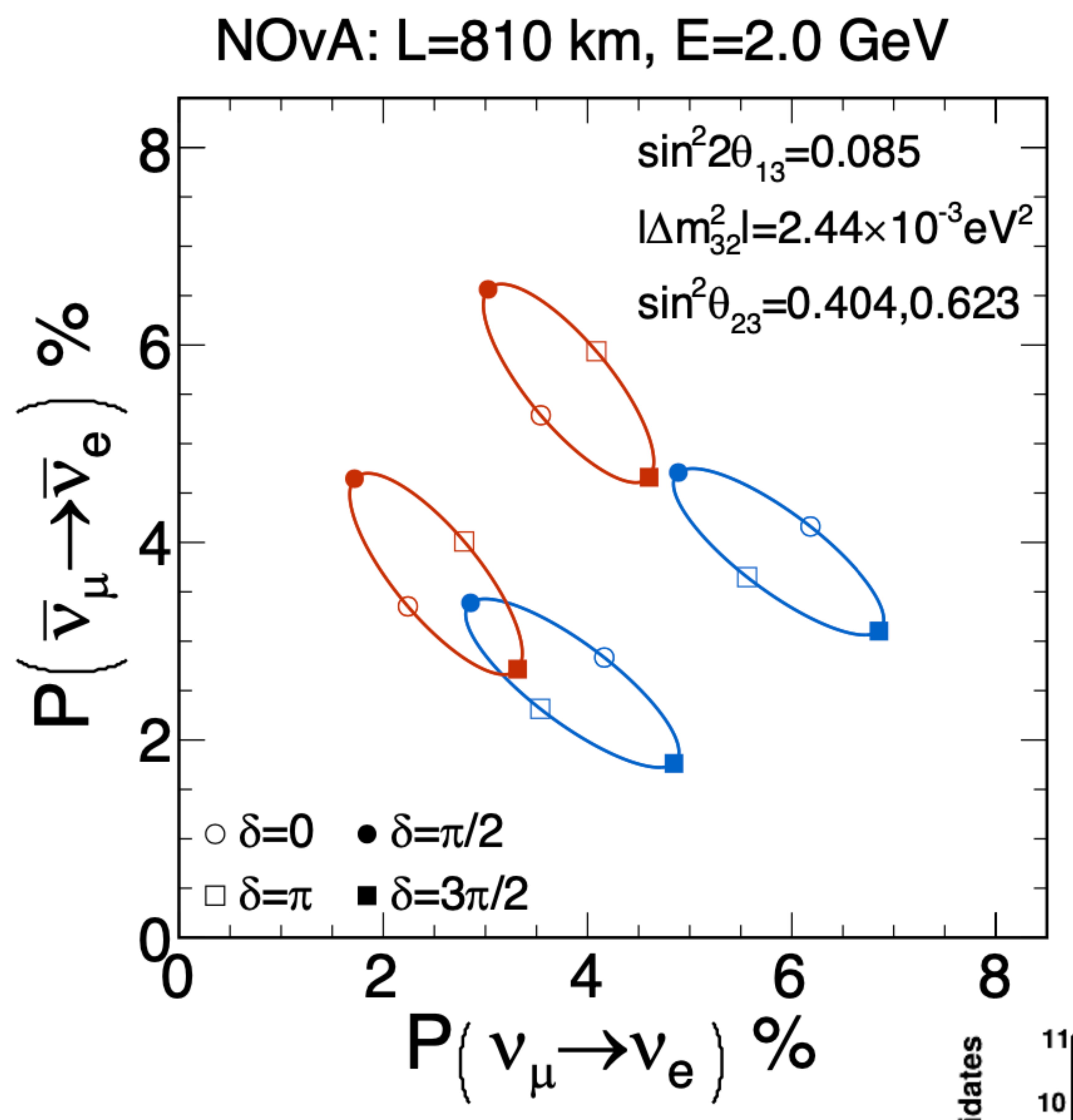
$$P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{CP})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

$$\Delta_{ij} = \Delta m_{ij}^2 L/4E_\nu$$

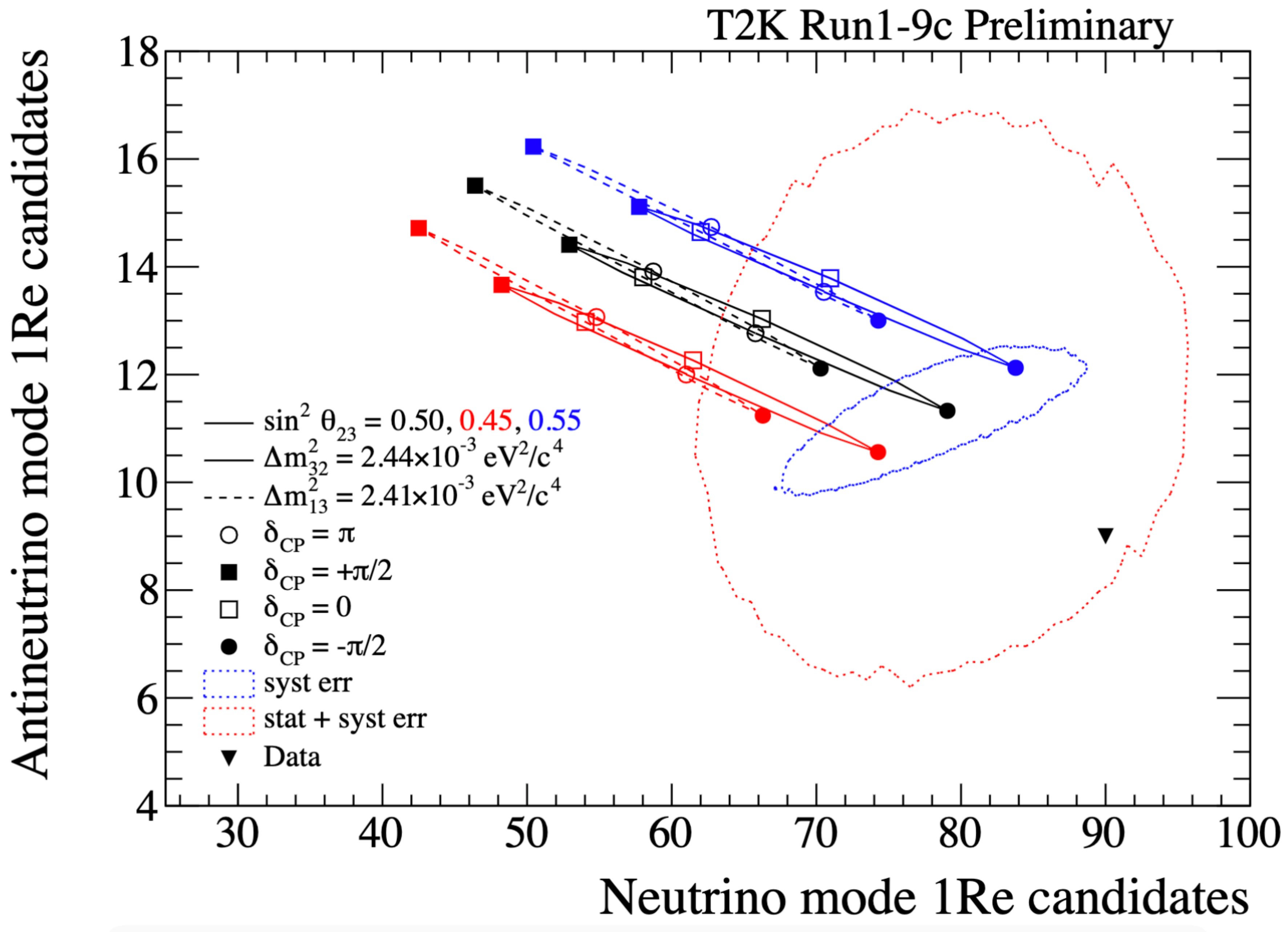
We have sin & cos of L/E - oscillation is function of baseline (distance) & nu energy

$$a = G_F N_e/\sqrt{2}$$

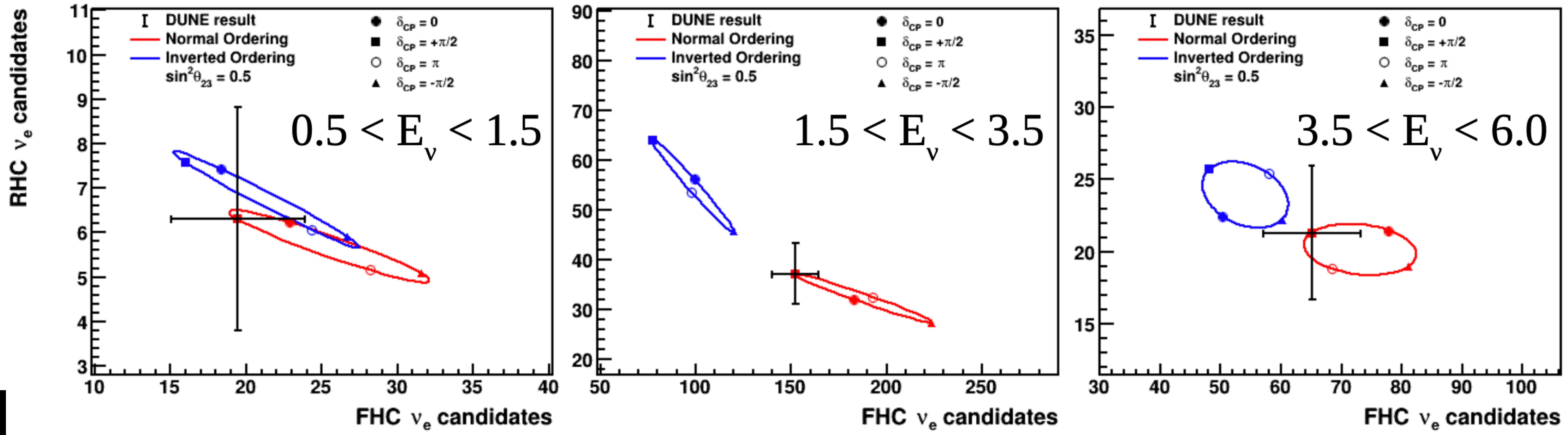
From NOvA



From T2K

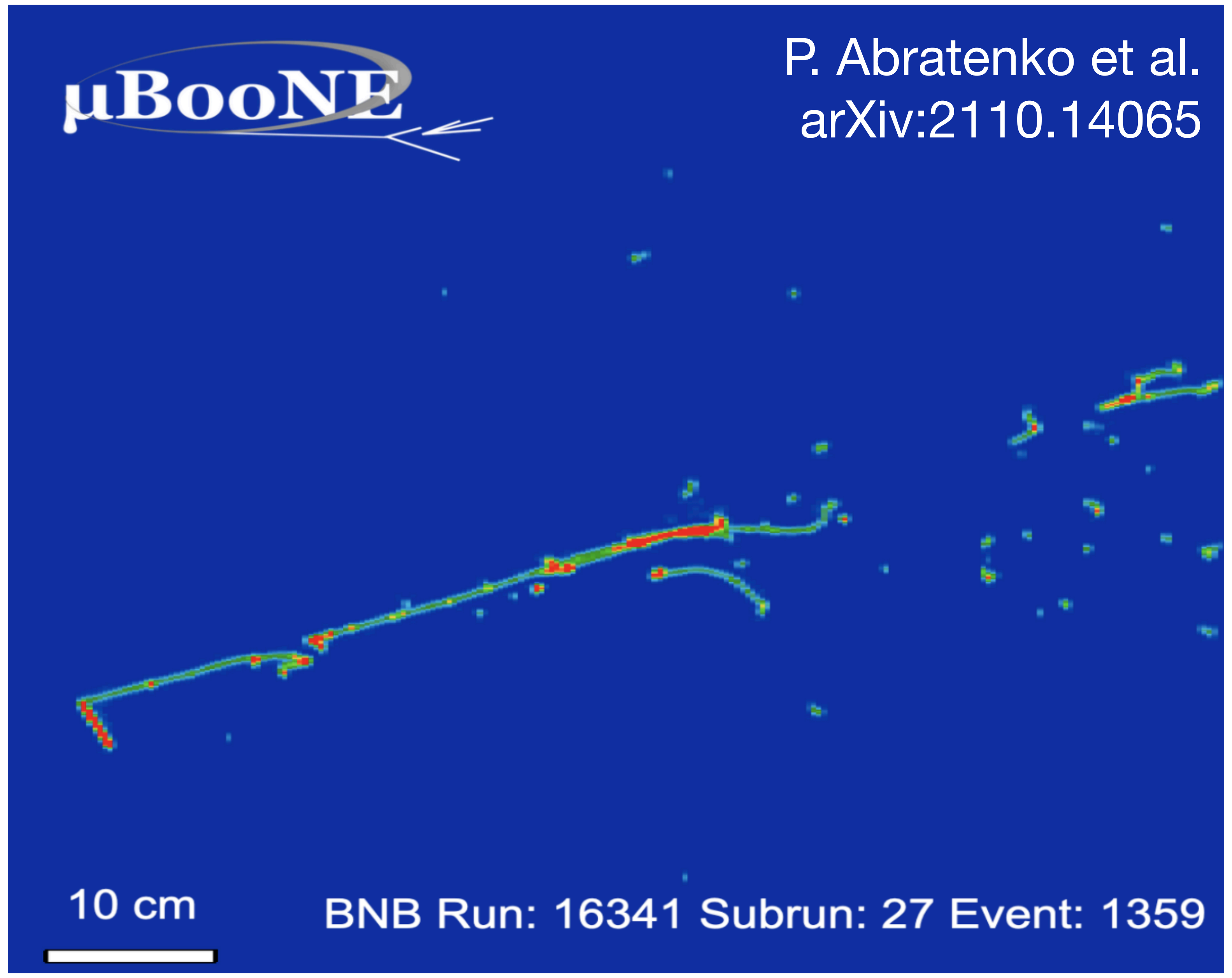


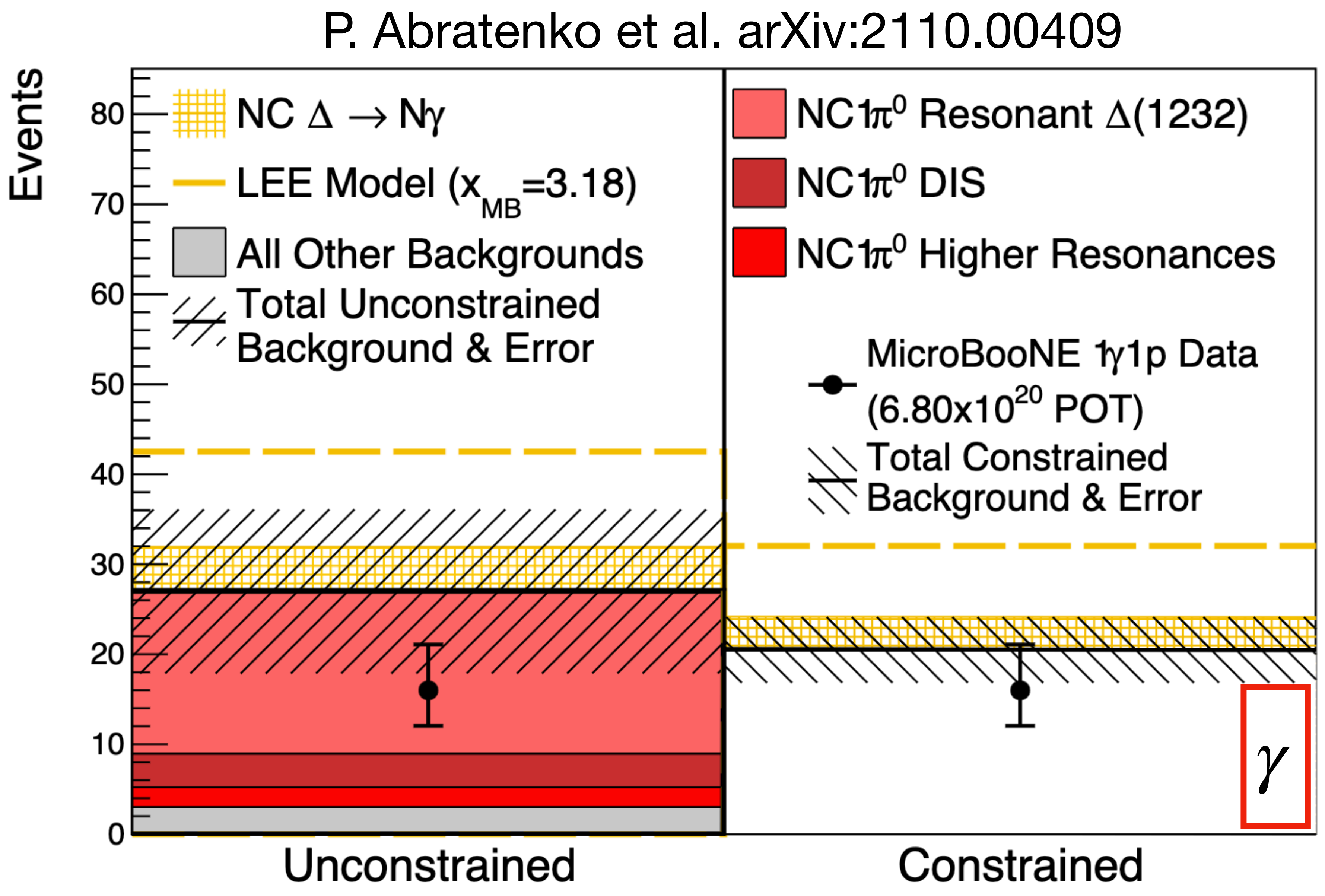
From DUNE, slices of neutrino energy

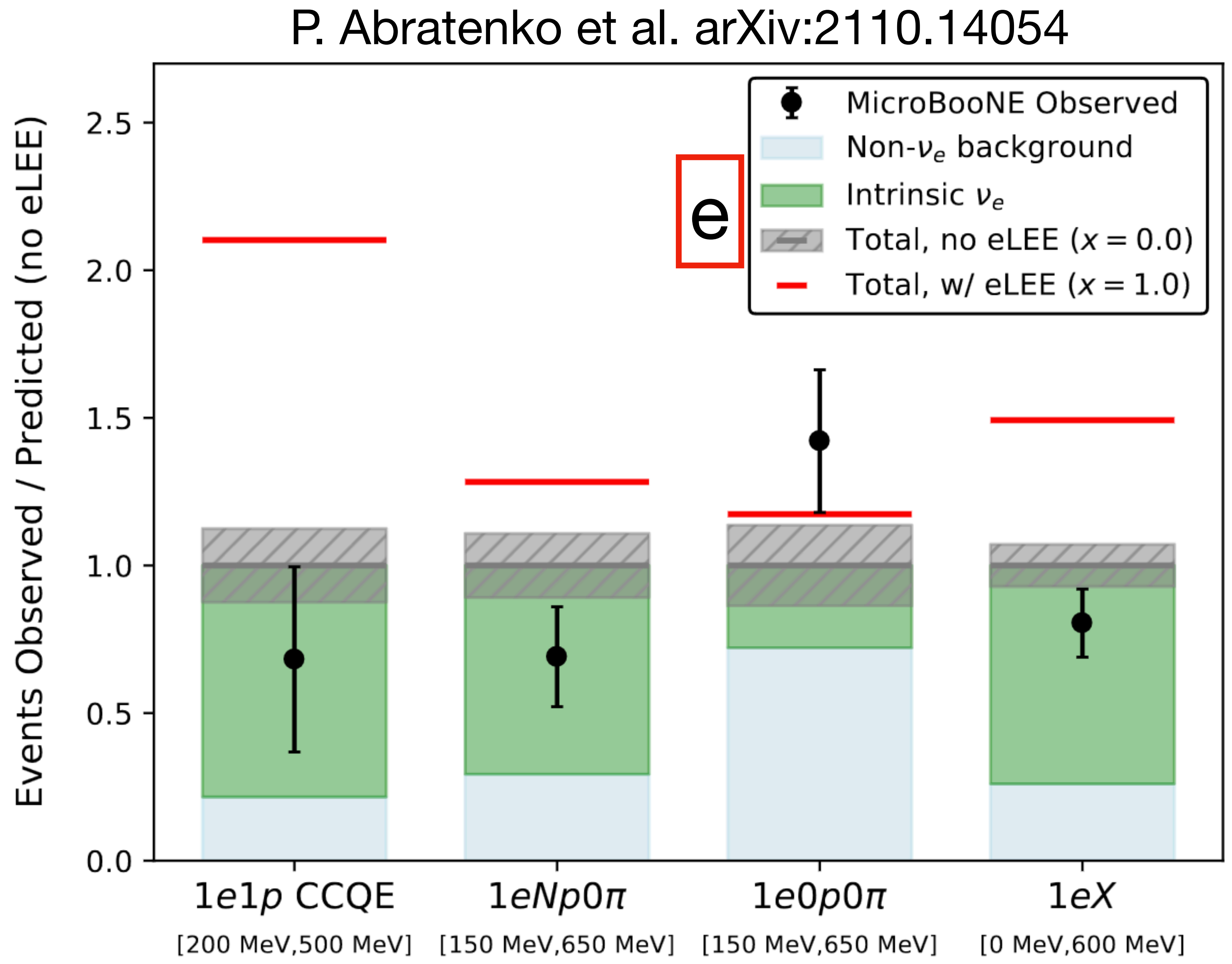


LAr TPCs as Powerful Neutrino Detectors

- A lot of work developing technology & understanding operations, properties, and offline processing/analysis w/ such detectors:
  - Build-up to current/upcoming experiments w/ LAr TPCs
  - But also, already some important sterile neutrino-related results. In addition to ICARUS at LNGS on last slide, MicroBooNE has released a number of results







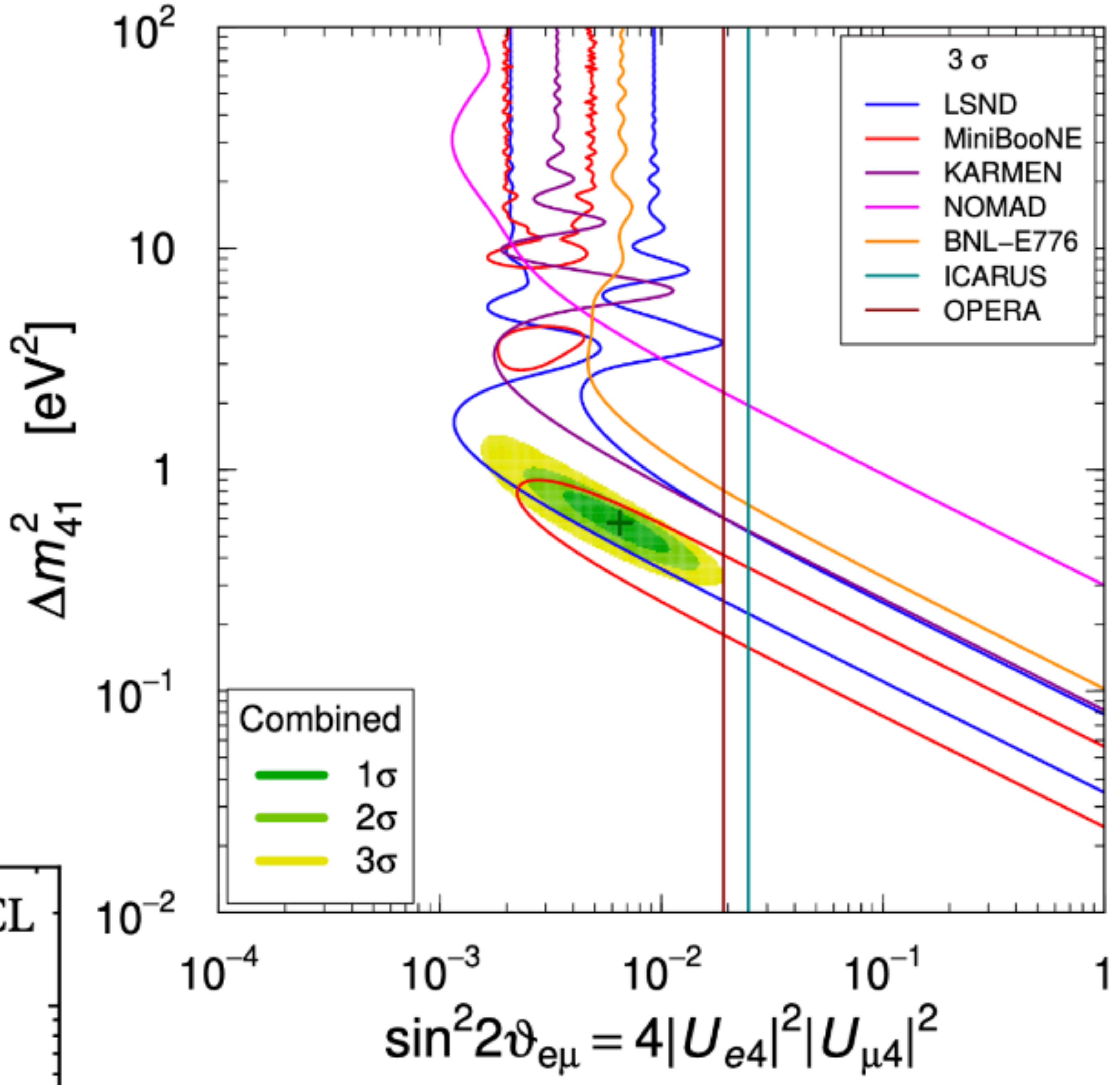
Introduction: Me in a Slide

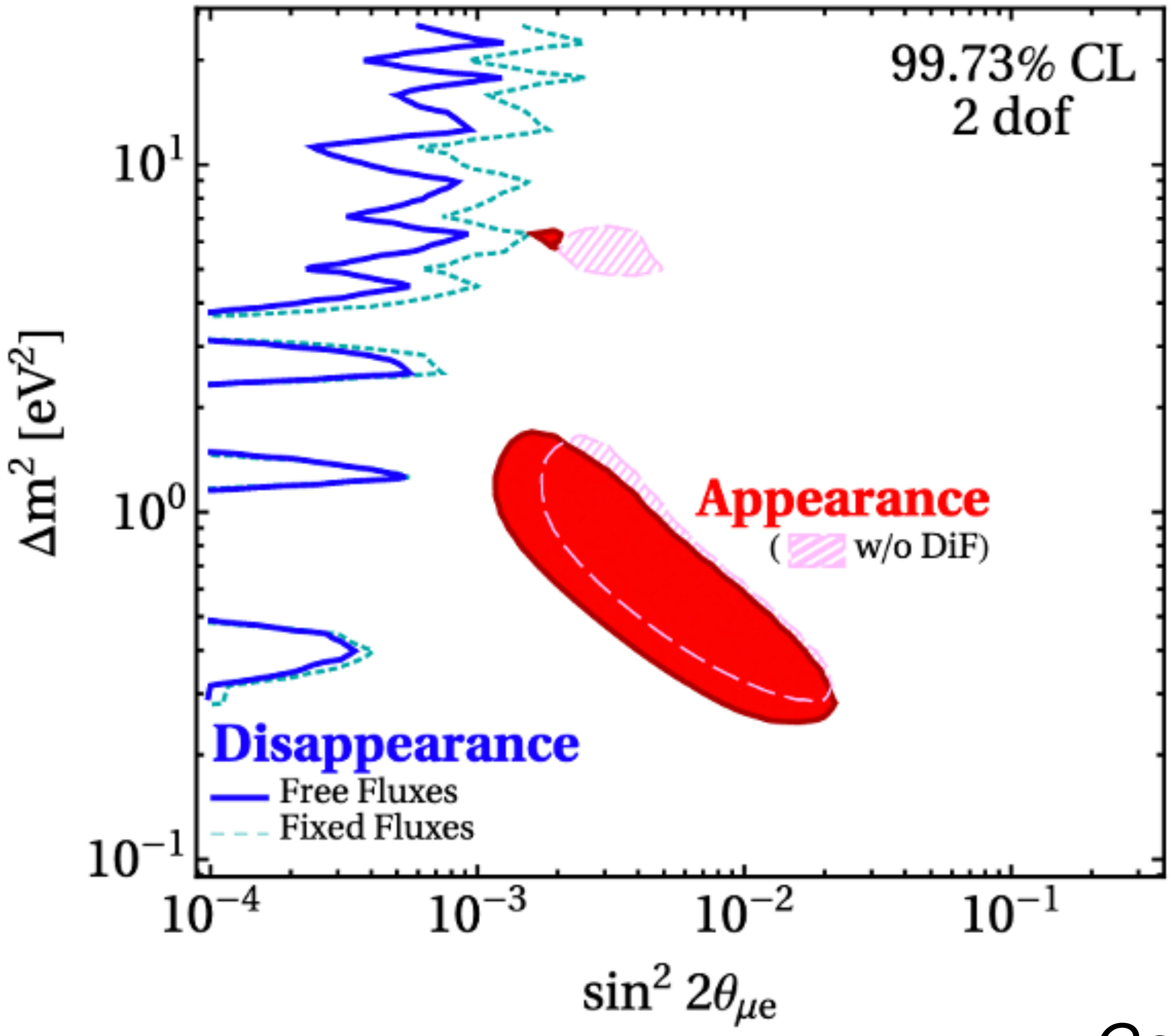
- Undergrad at University of Pittsburgh
- Graduate studies at Indiana University, PhD in late 2019
  - DUNE (LAr TPC detector) & NOvA (segmented scintillator tracking detector)
- Joined FNAL as a research associate at end of Oct 2019
  - Primary focused has been on SBN program (mostly ICARUS)
- A major connecting item of the work I will describe is of course **neutrino physics** and besides NOvA is using **LAr TPC detector technology** so I will spend some time here first
- My research program has enabled me to gain experience and expertise working with the different aspects of LAr TPC detectors (**scintillation and ionization**) and working w/ **smallest aspects of detector R&D up to commissioning and operating fairly large detectors, and using these to analyze** interactions: I will reconstruct this story
- Additionally, I have been able to take on leadership roles in ICARUS as a postdoc: **Deputy Commissioning Coordinator** for much of 2020 and **TPC Reconstruction convener** since early 2022 (with leadership in the activities also before this)
- R&D and prototype tests can lead to realization of the water-based liquid scintillator detector technology with lots of physics use-cases: I will highlight where my experiences lead to a natural fit for leadership in this area. (Matrix above)

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, look for them indirectly via oscillation signatures
- 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
- Additional beyond standard model candidates have been proposed as possible answers

C. Giunti, T. Lasserre
arXiv:1901.08330



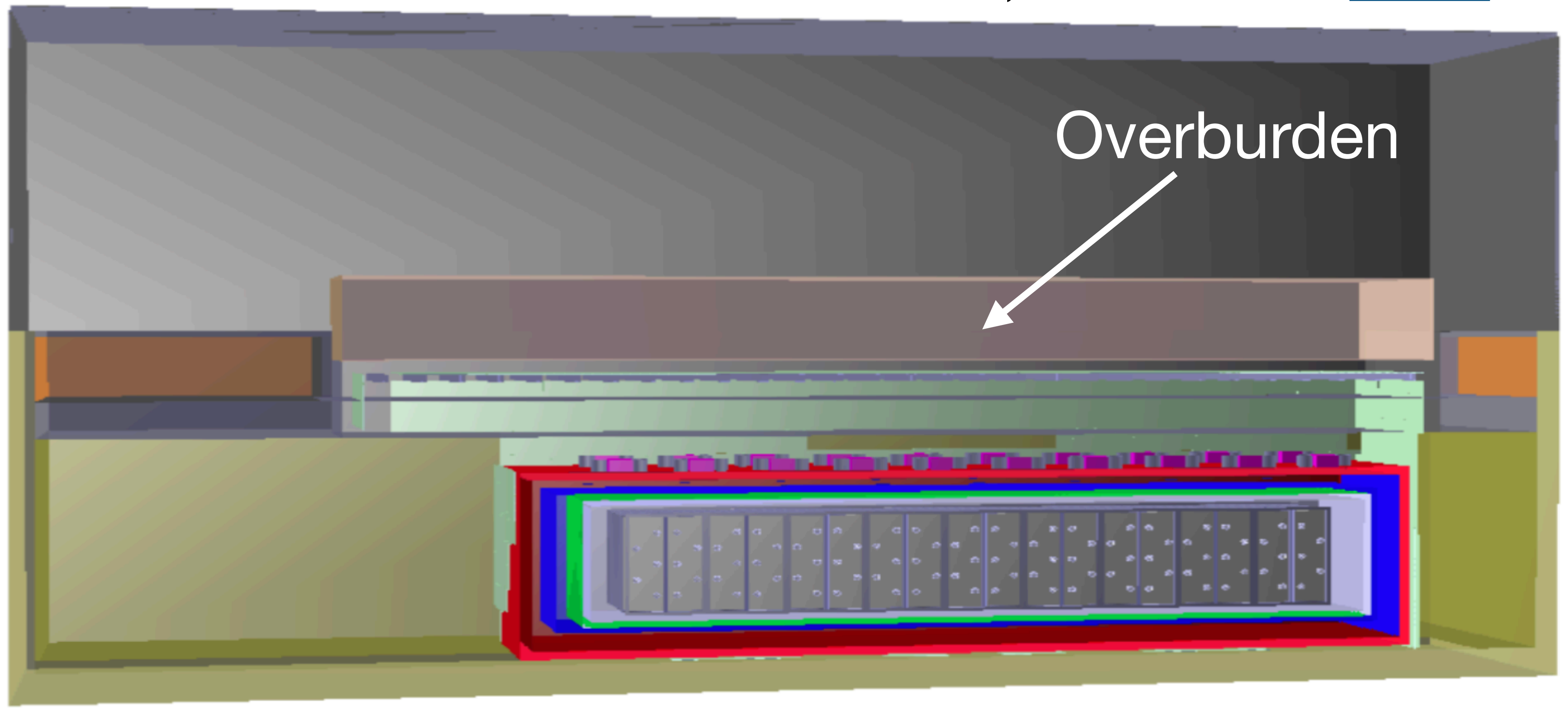


M. Dentler et al.
arXiv:1803.10661

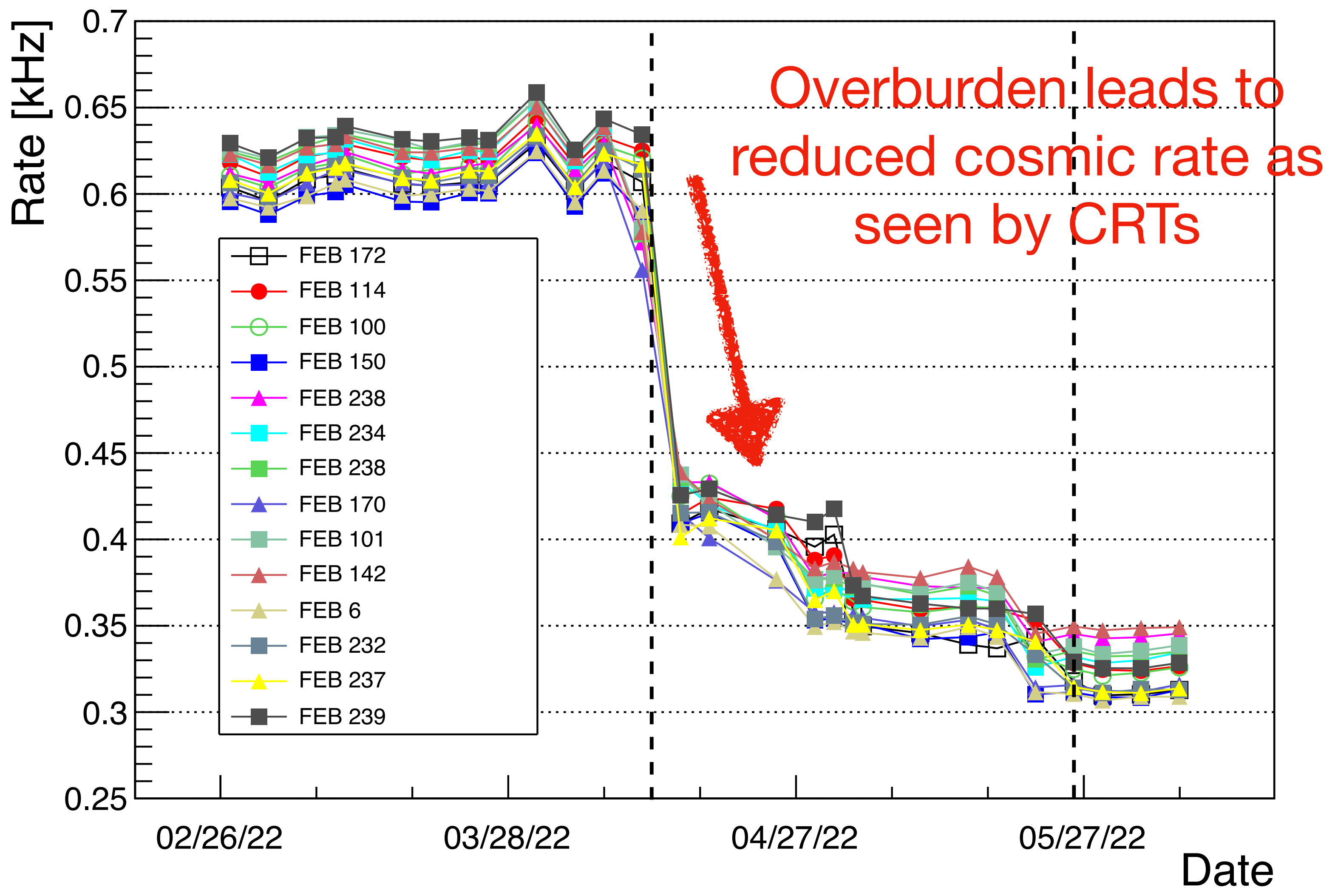
Copied from previous seminar given by B.H.

Cosmic Mitigation in ICARUS

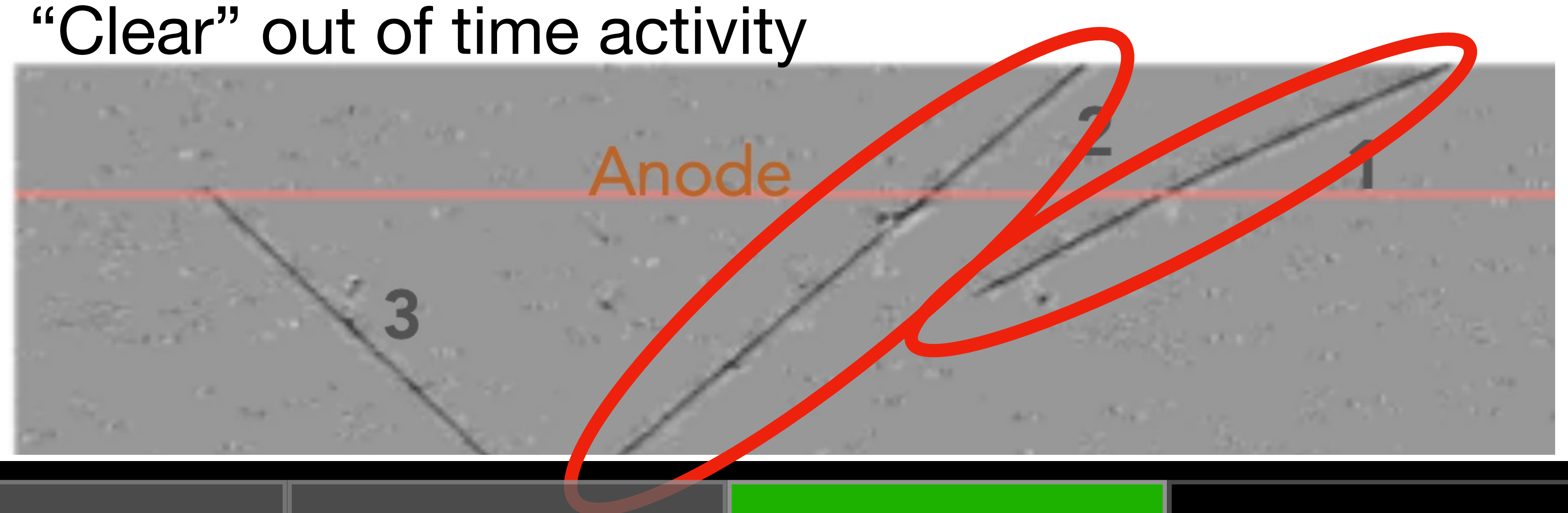
D. Gibin, O. Palamara slides



- One drawback of LArTPC technology: it's slow (drift ~ms)
- ICARUS on the surface: multiple out-of-time cosmic muons in each event and events triggered by in-time cosmic activity (~3 per 1 neutrino event in BNB, little better in NuMI)
- Multi-pronged mitigation strategy, including for example:
  - Overburden (~6 mwe) above the detector will help especially with soft backgrounds (can be important to ν_e measurements)
  - "Porches" of readout from the TPC before/after the drift window shows that some cosmic activity is "clear" even from the TPC (too far outside beam activity drift window)
  - Matching charge from TPC with light in the PMTs can help determine if depositions are in-time with beam
  - CRT-PMT matching enables us to tag entering vs. exiting activity based on which occurs first

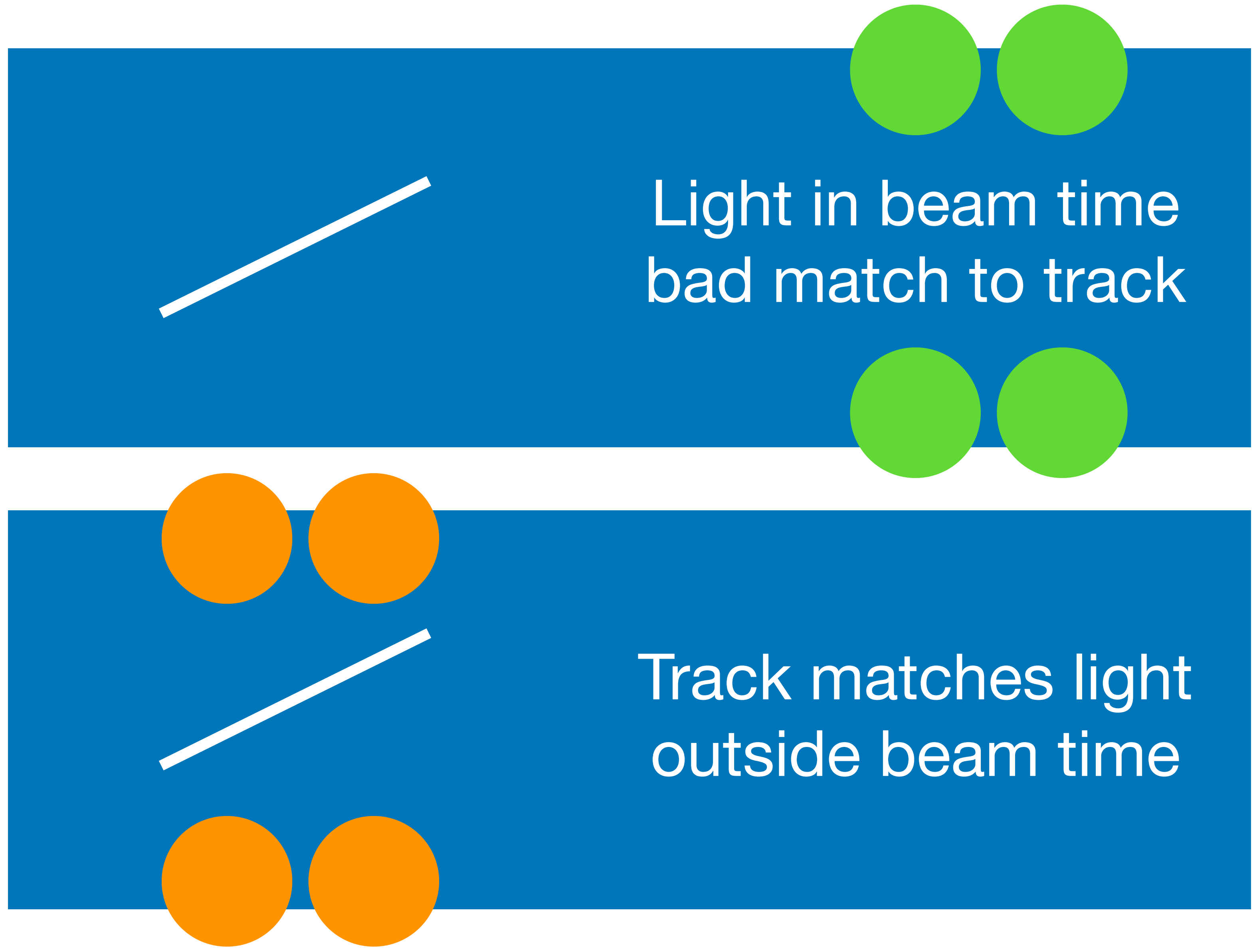


"Clear" out of time activity

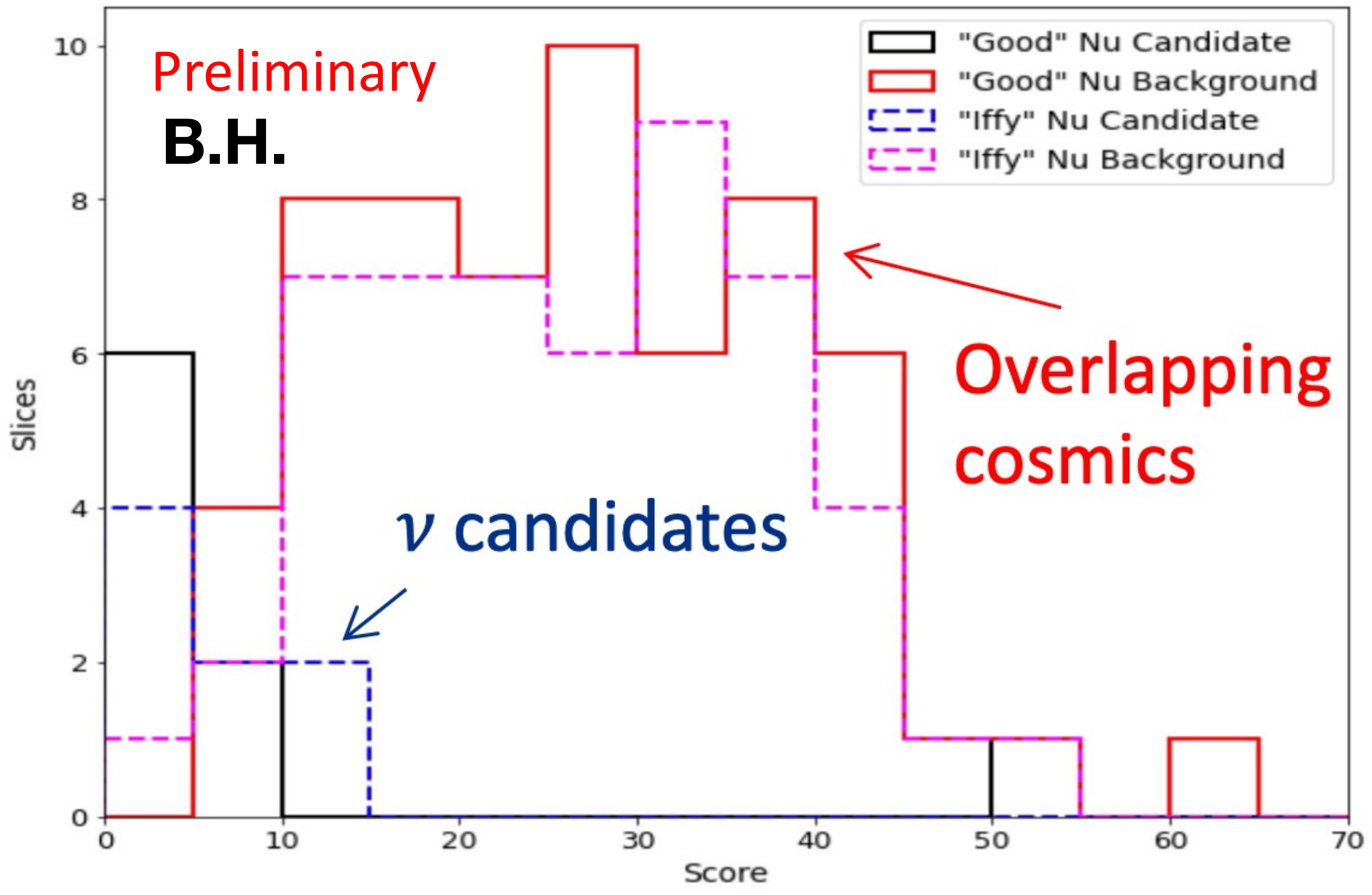


Cosmic Mitigation in ICARUS

- The PMT-TPC matching is often called "flash matching" and is an attempt to either associate given TPC objects with its appropriate flash (or vice-versa) to better understand the interaction, its time relative to the beam window, etc.
- Multiple avenues being explored to do this:
  - One such version utilized in the joint SBN framework returns for each reconstructed TPC object a "score" to the best-matched light cluster (goodness of match to template) and the approximate time of that light
  - In investigating the event reconstruction with commissioning data, was able to make a preliminary look at this tool during commissioning using a few hand-scanned neutrino candidates

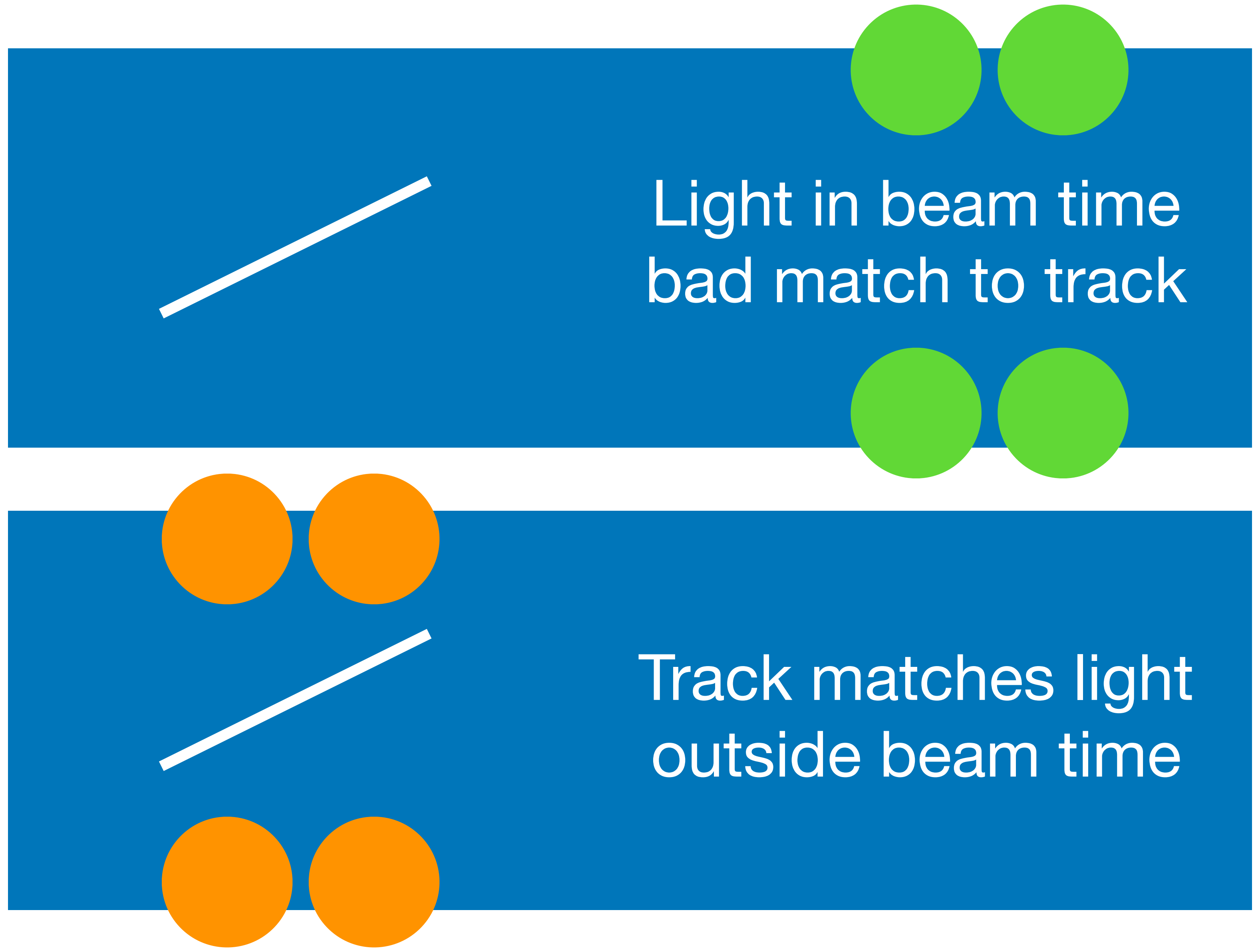


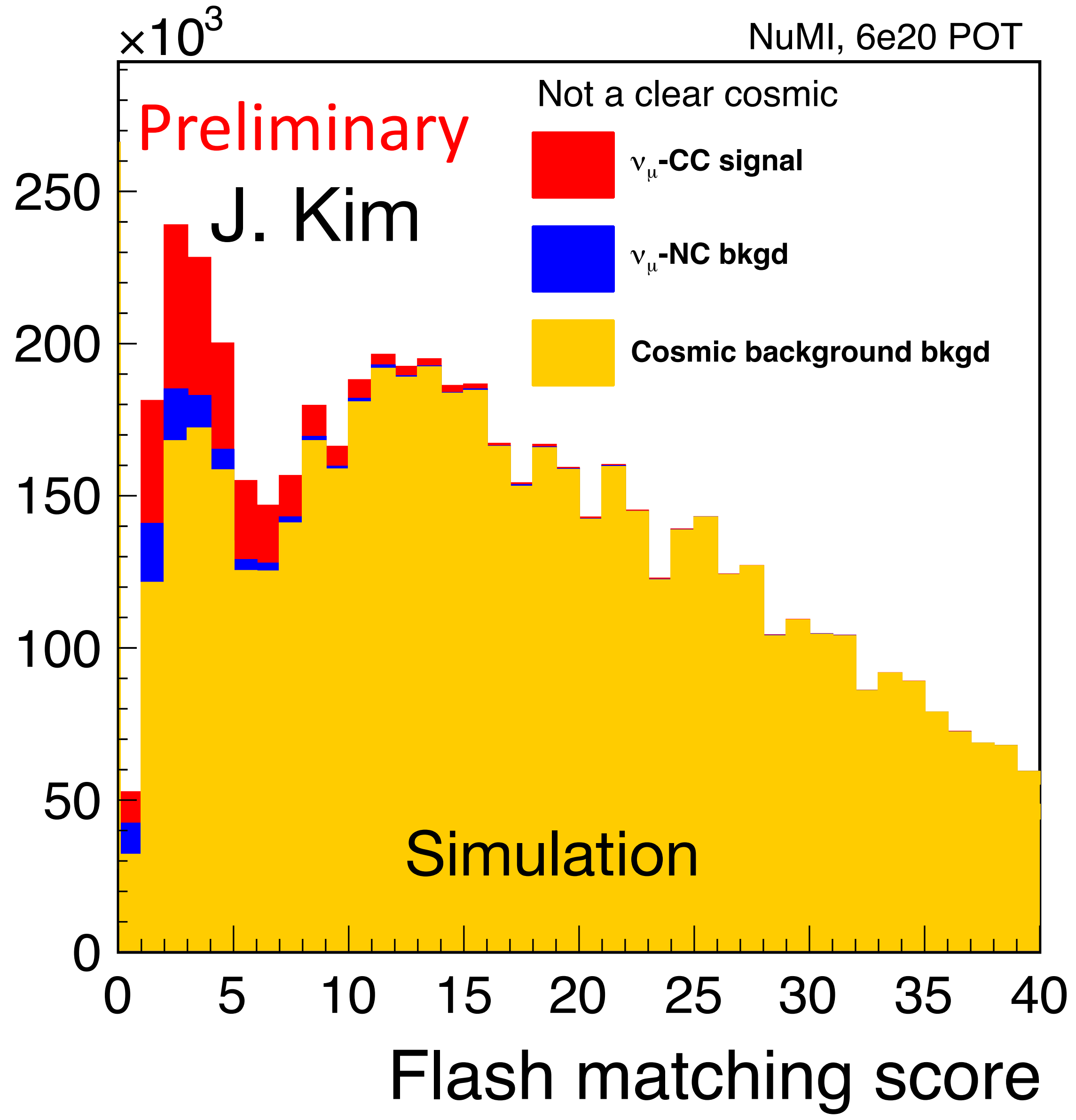
Early look I made with a few hand-scanned events from commissioning: will talk more about commissioning/operating ICARUS shortly



Cosmic mitigation in ICARUS

- The PMT-TPC matching is often called “flash matching” and is an attempt to either associate given TPC objects with its appropriate flash (or vice-versa) to better understand the interaction, its time relative to the beam window, etc.
- Multiple avenues being explored to do this matching:
  - One method being used in the SBN program compares reconstructed interactions in the TPC to light clusters and finds its best match and gives the time of that light cluster and a “score” of the match based on simulated templates
  - Another method under investigation uses many-to-many matching of the charge & light clusters (drawing from the MicroBooNE experience)
  - Also, simpler but not model dependent is doing barycenter based matching





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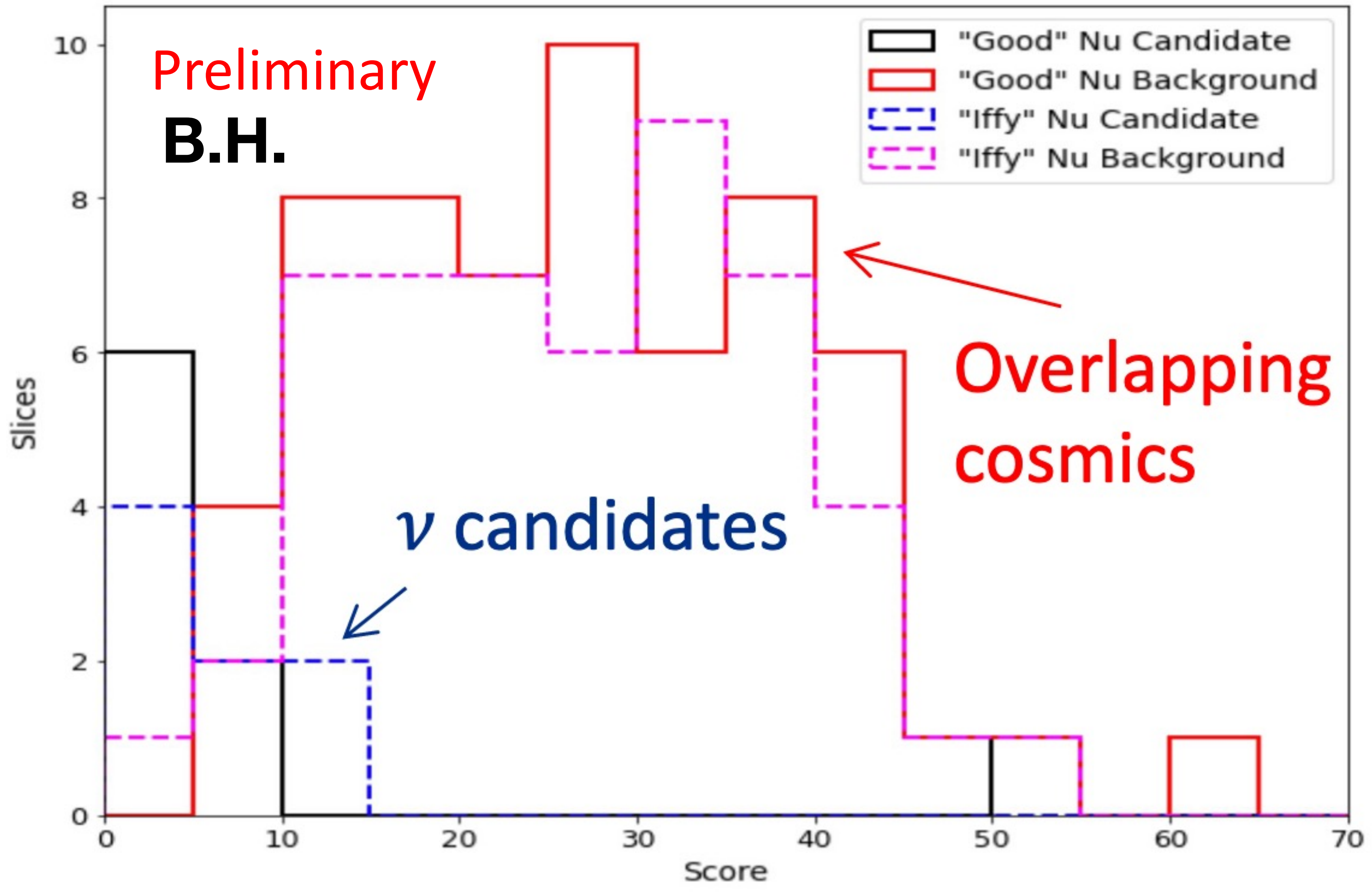
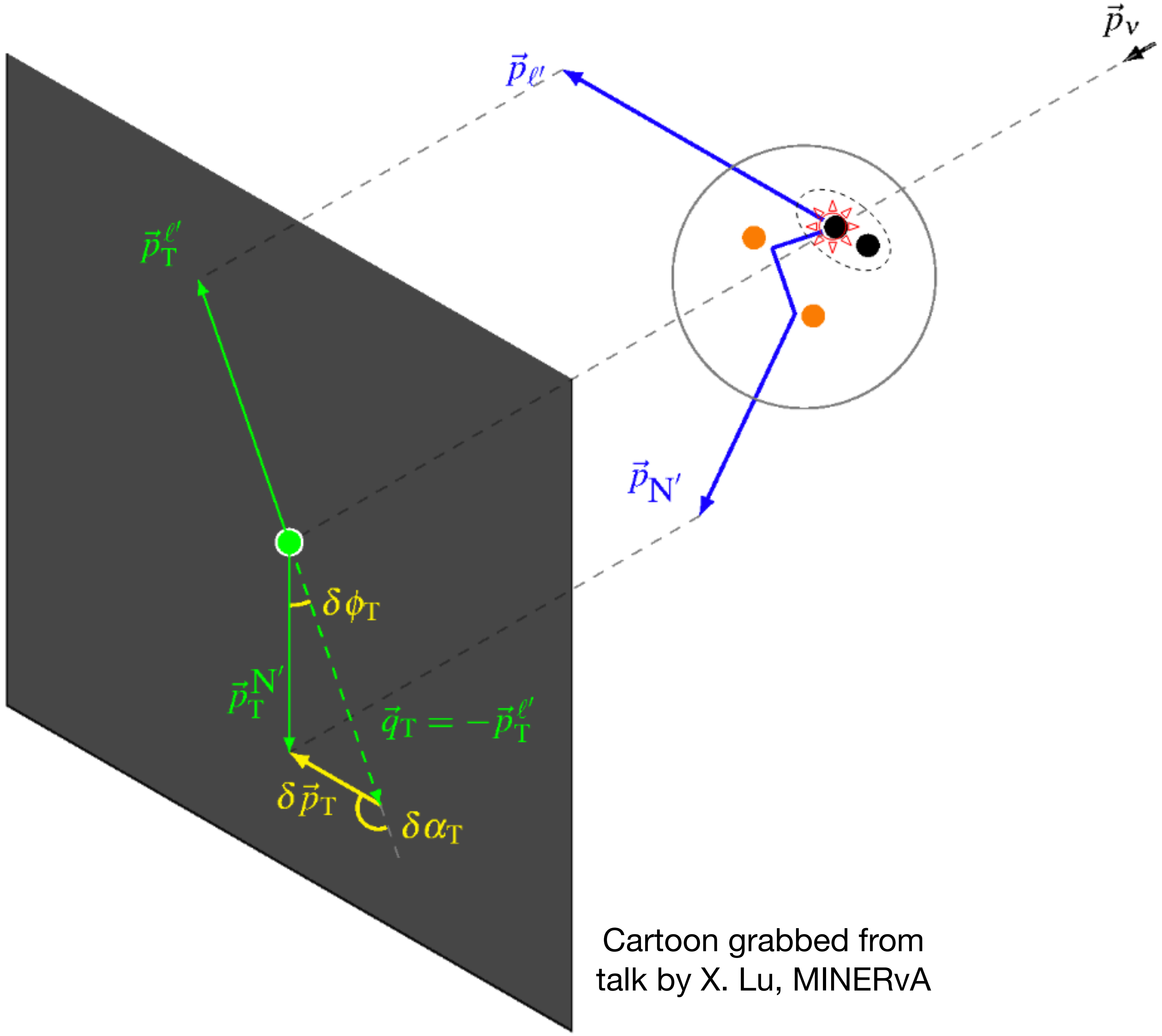


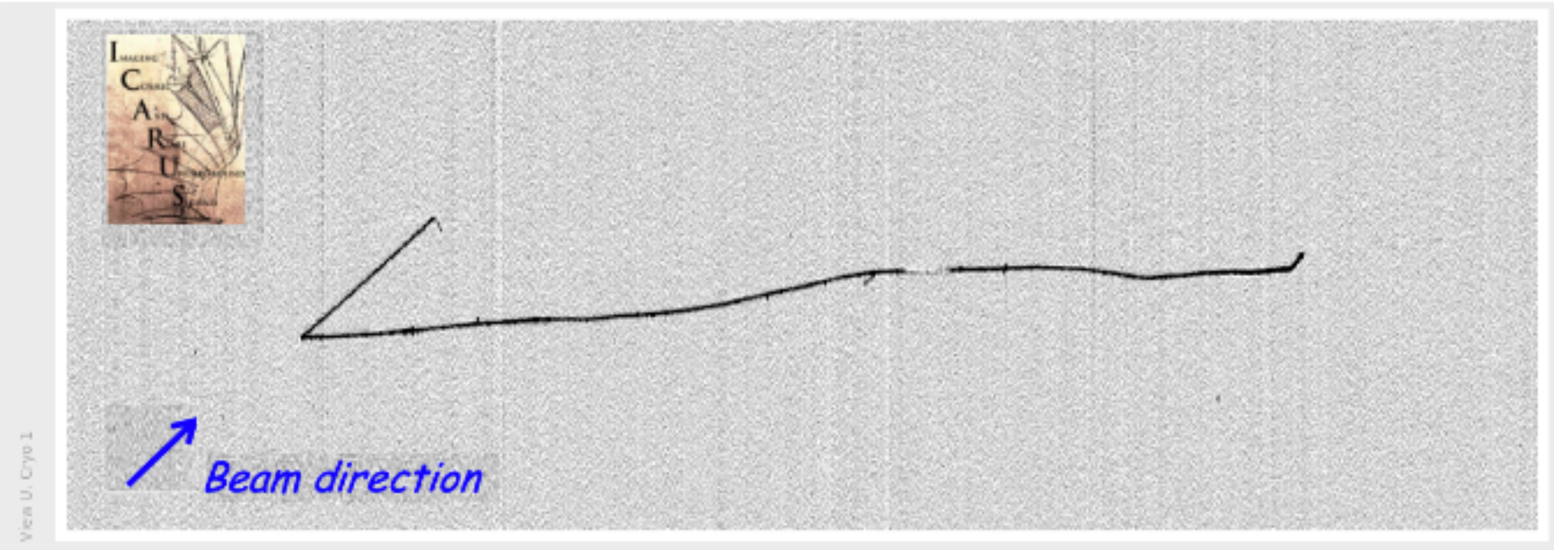
Cartoon of transverse kinematic imbalance

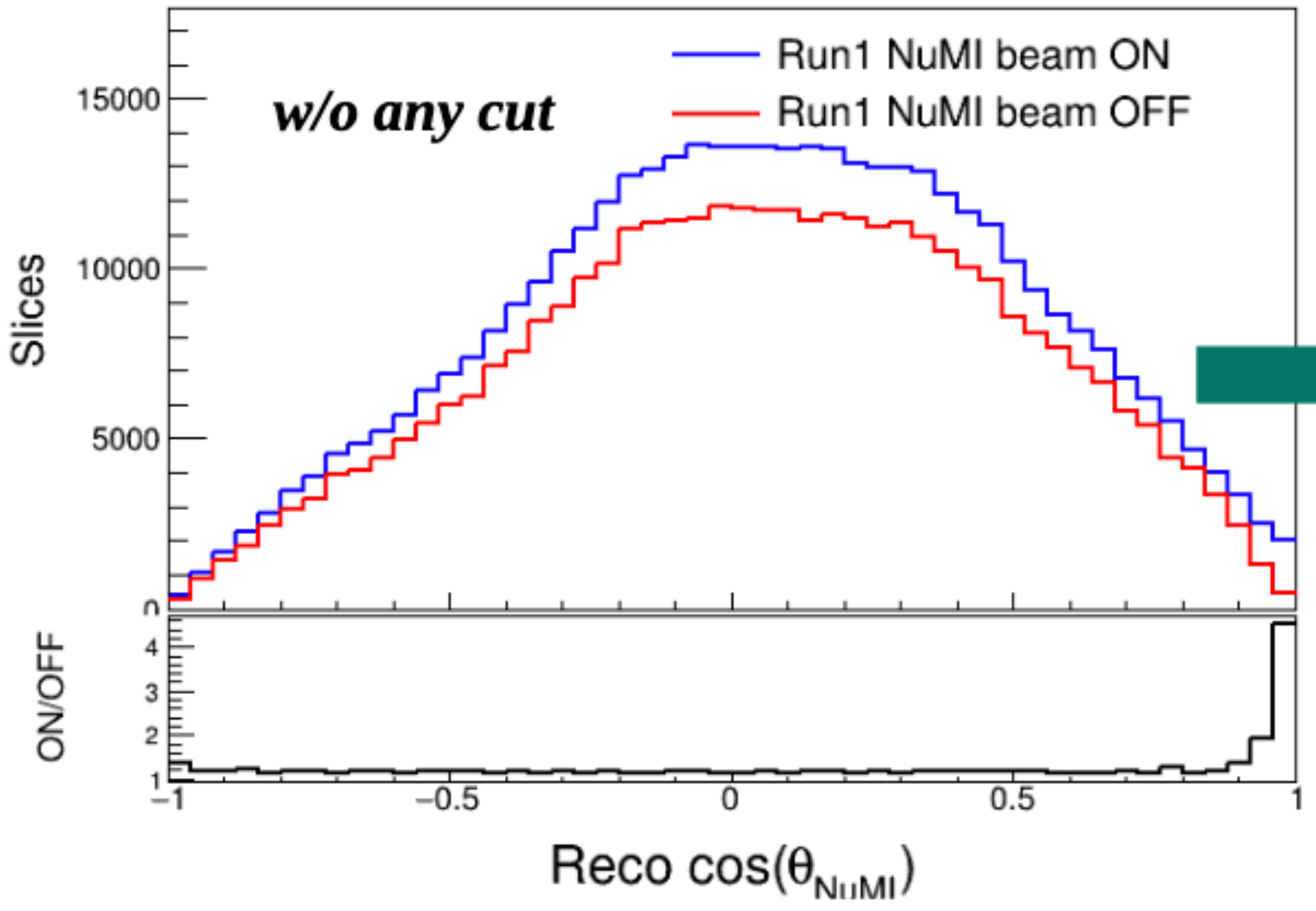


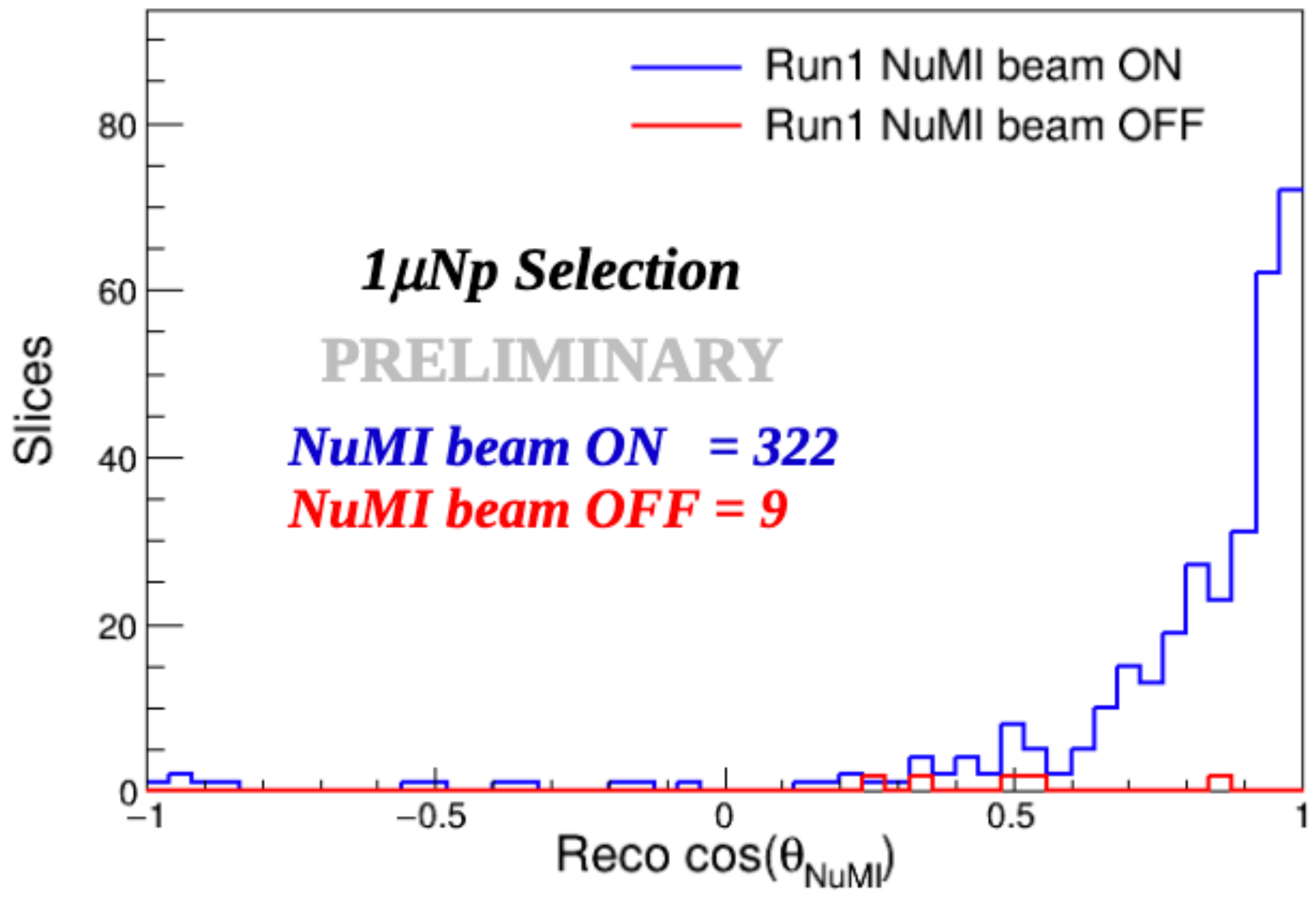
Cartoon grabbed from
talk by X. Lu, MINERvA

Muon Neutrino from NuMI beam at ICARUS

- Starting to study events with one muon and N Protons
- One muon and N $_{proton}$ event selection
  - Vertex in fiducial volume
  - Longest track's Y direction
  - Muon candidate
  - Proton candidate



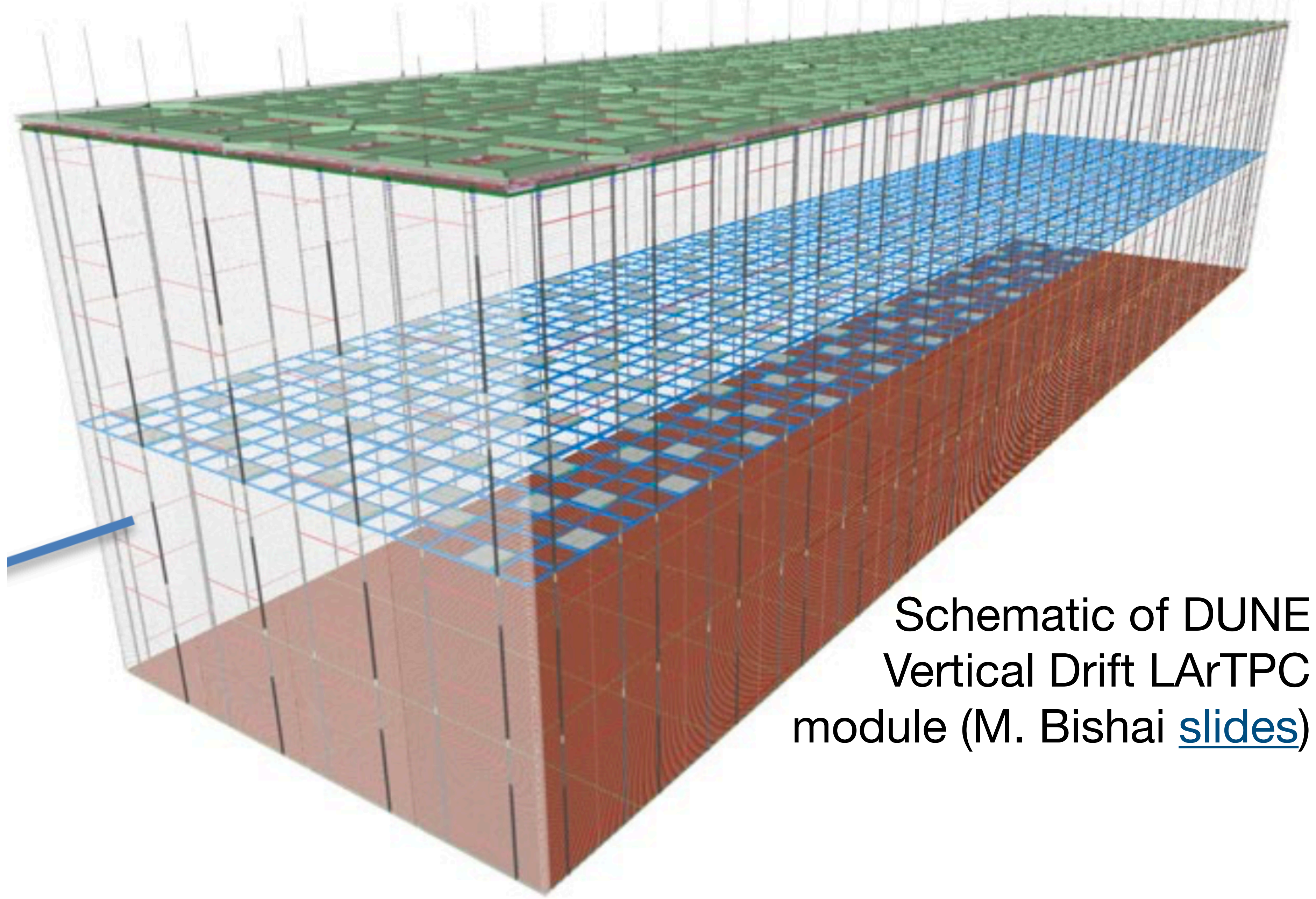




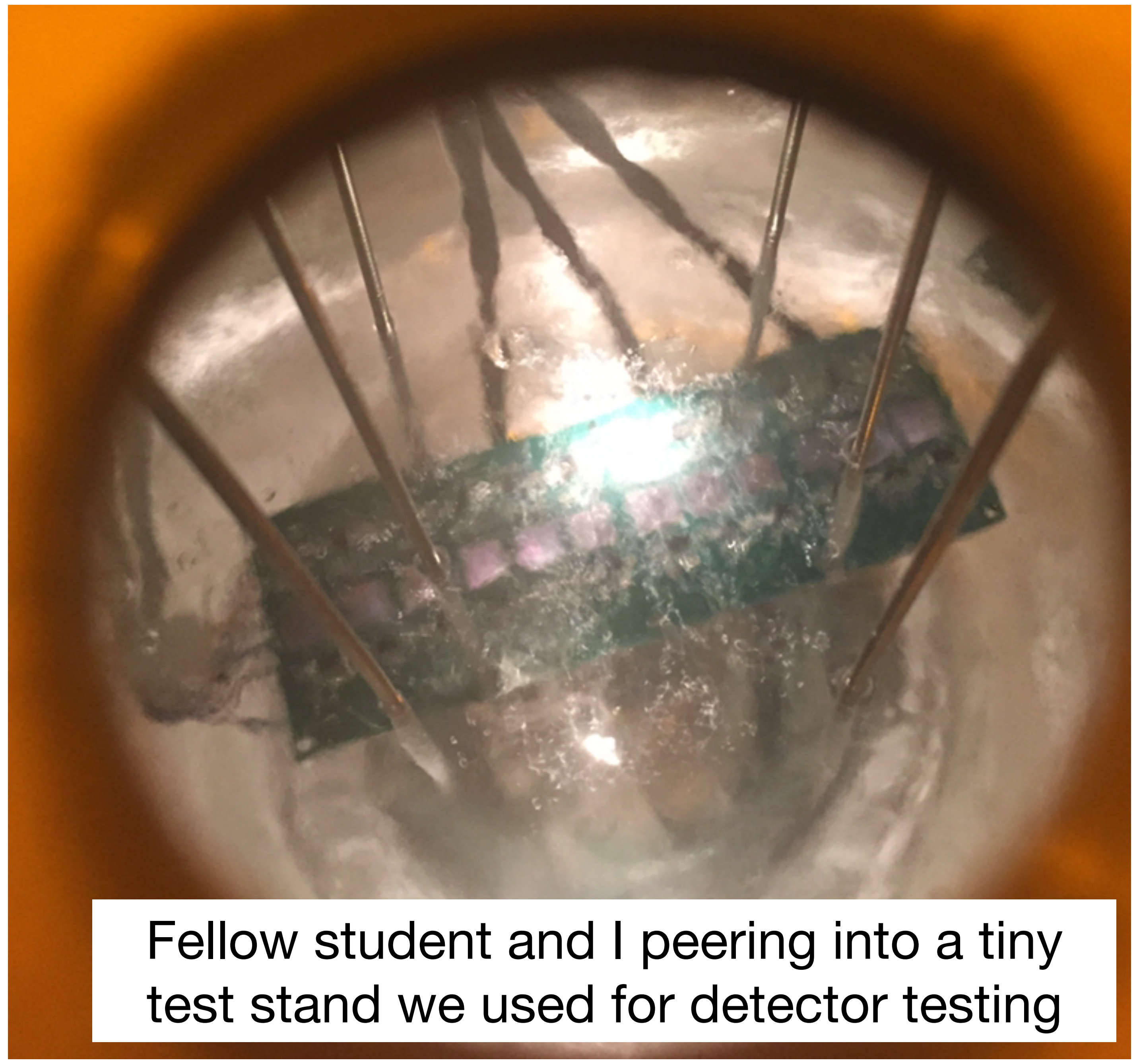
M. Betancourt, APS April 2023

Realizing DUNE

- Have now discussed DUNE, some measurements it will make, and a few ways the current generation of experiments can help DUNE hit the ground running
- DUNE will build on the past few decades of work with LAr TPC detectors, but are also driving forward the medium: even in a collaboration with >1k people, room for R&D
  - This was something I benefitted from in graduate studies researching photon detectors for Horizontal Drift LAr TPC
  - DUNE also plans to instrument the first large Vertical Drift LAr TPC with different charge readout
  - Last 10kt DUNE module is “Module of Opportunity:” many ideas from community to complement with additional technology
- DUNE also needs capable Near Detector to characterize flux (ν,$\bar{\nu}$), perform additional cross-section measurements and model developments, enable BSM searches, etc.



Schematic of DUNE Vertical Drift LArTPC module (M. Bishai slides)

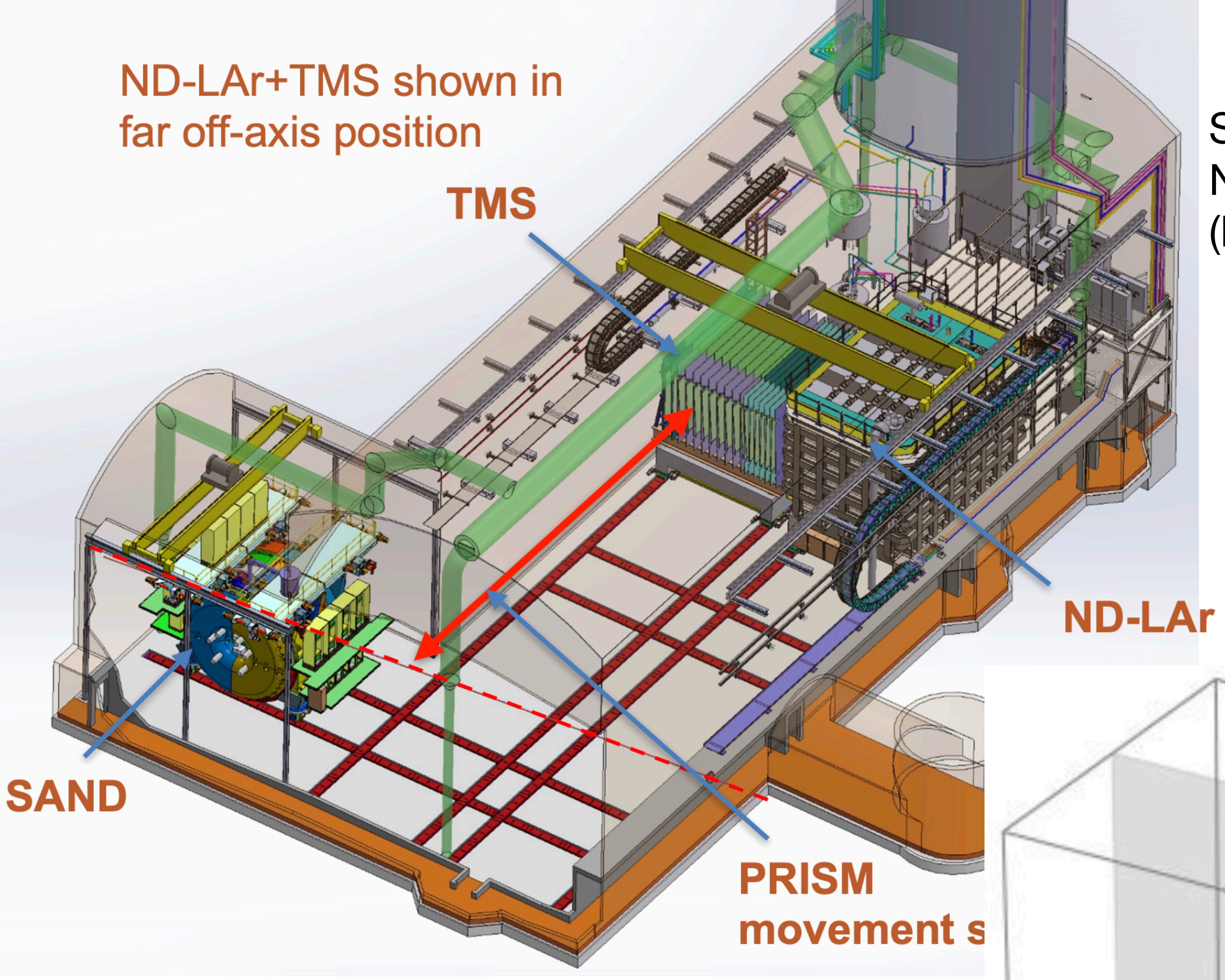


Fellow student and I peering into a tiny test stand we used for detector testing

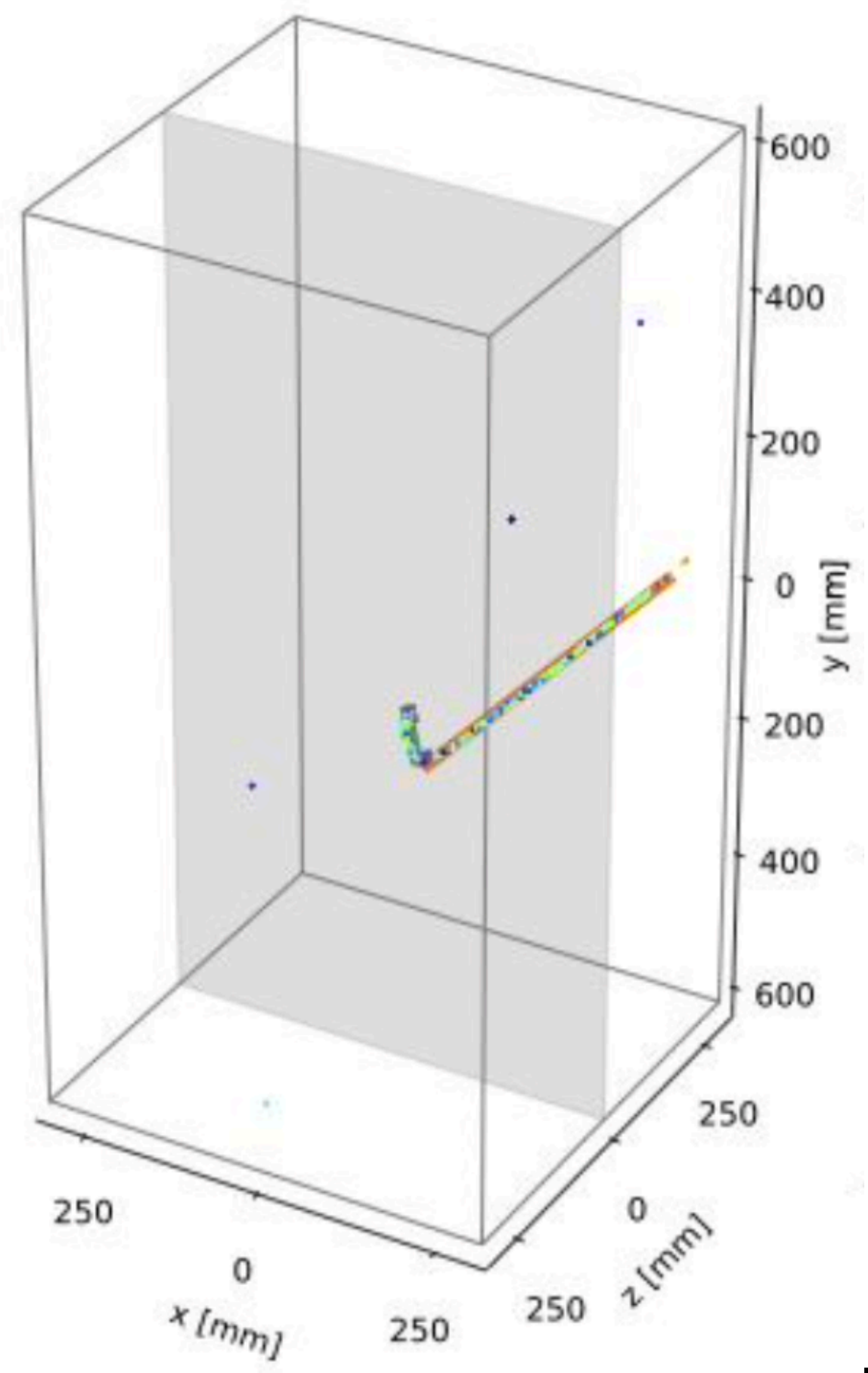
DUNE photon detectors will use modules with SiPMs instead of more “traditional” TPB-coated PMTs

DUNE Near Detector

- Planned Near Detector comprises of multiple detectors including a LAr TPC and ultimately a Gas Argon TPC (even lower thresholds for hadrons!)
    - High pileup environment: use pixelated readout for LAr TPC instead of wires
- Capability to move parts off-axis to enable disambiguation with different expected fluxes
- The next several years will be critical for realizing the DUNE Near Detector:
    - Prototype studies such as the 2x2 test which will happen at FNAL soon
    - Ensuring optimal designs will work for DUNE
    - Prepare for the analyses and pipeline from current experiments to DUNE



Schematic of DUNE Near Detector (H. Tanaka slides)

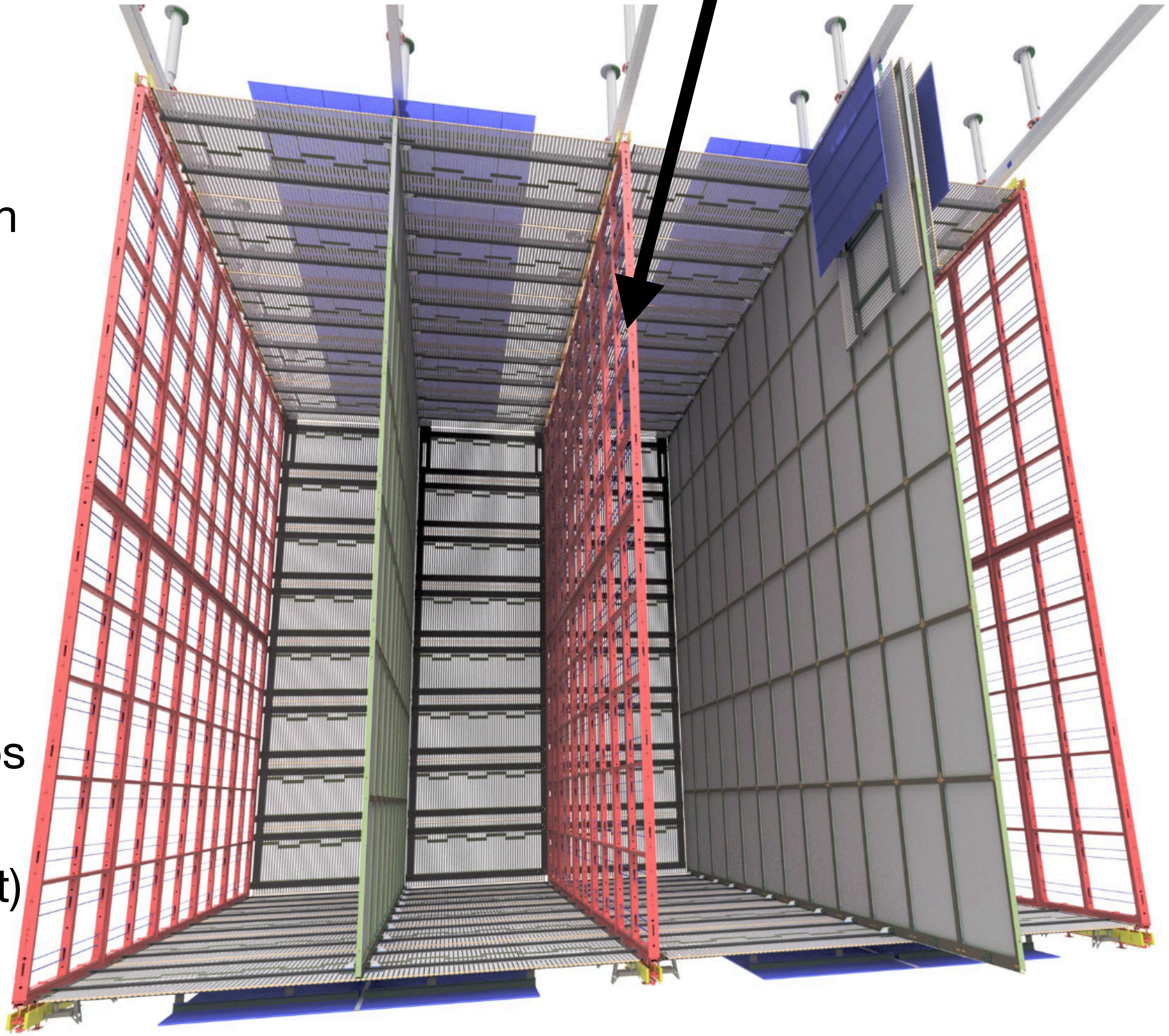


ND-LAr prototype event (Z. Hulcher slides)

R&D for DUNE

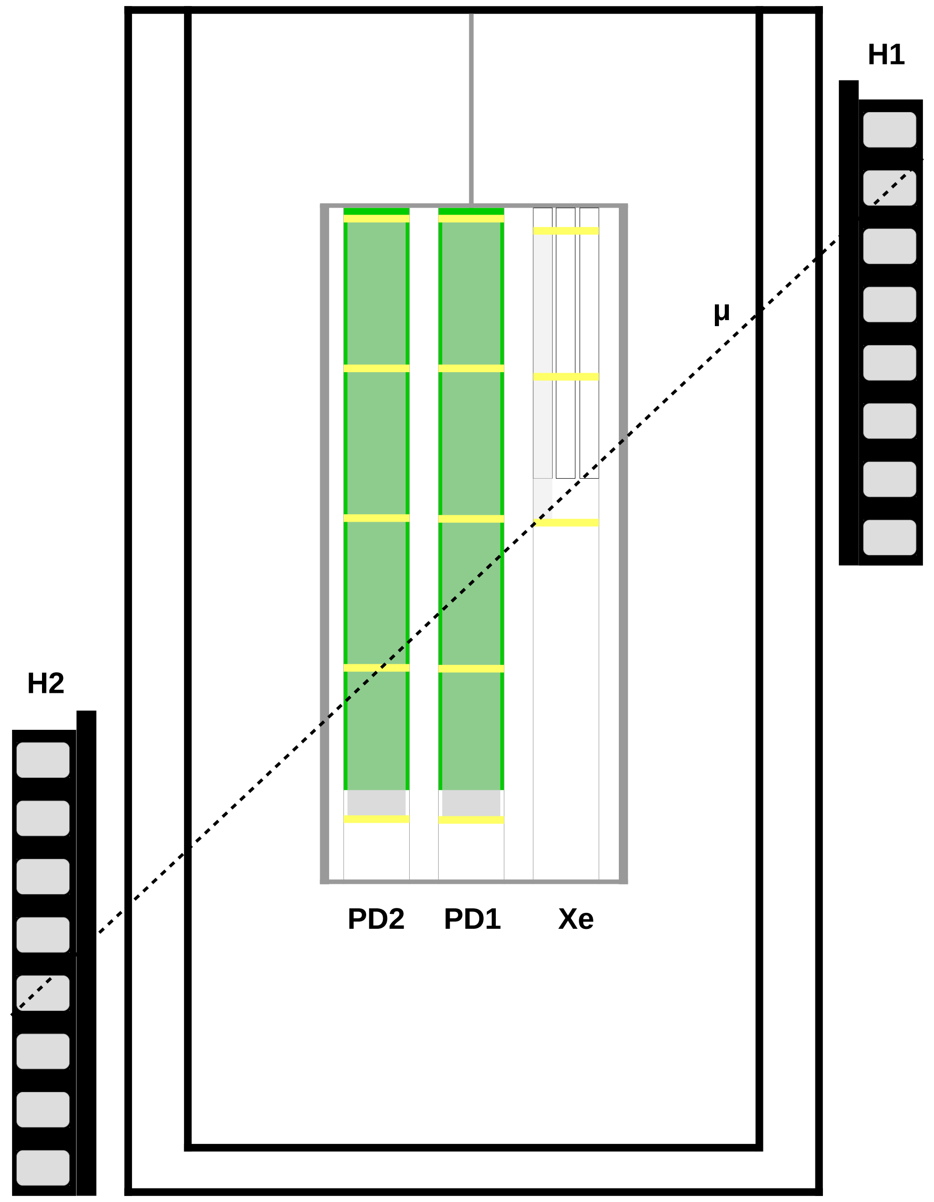
- The R&D driven with DUNE in mind spans many categories: pixelated LArTPCs, vertical drift technology, etc.
- I had chance via graduate studies to be **heavily involved w/ detector R&D for DUNE via scintillation detection system**
- Why can't DUNE just use PMTs behind the anode coated with TPB like other large LAr TPCs?
  - Having multiple drift volumes side-by-side means gives *space considerations*
  - Instead, want to put photon detectors in the anode frame, between the opposite sets of wires
- Also enables lots of creative solutions and there are many more recent advancements in photon detection
  - Thin photon detectors: light guides, ARAPUCAs (light traps w/ dichroic filters, have become baseline for DUNE)
  - SiPM-based readout (VUV sensitive SiPMs even now exist)
  - [biased opinion] Provided area of R&D/experimentation in which a graduate student could be heavily involved

Anode plane in the middle, so common scheme of PMTs behind the anode won't work



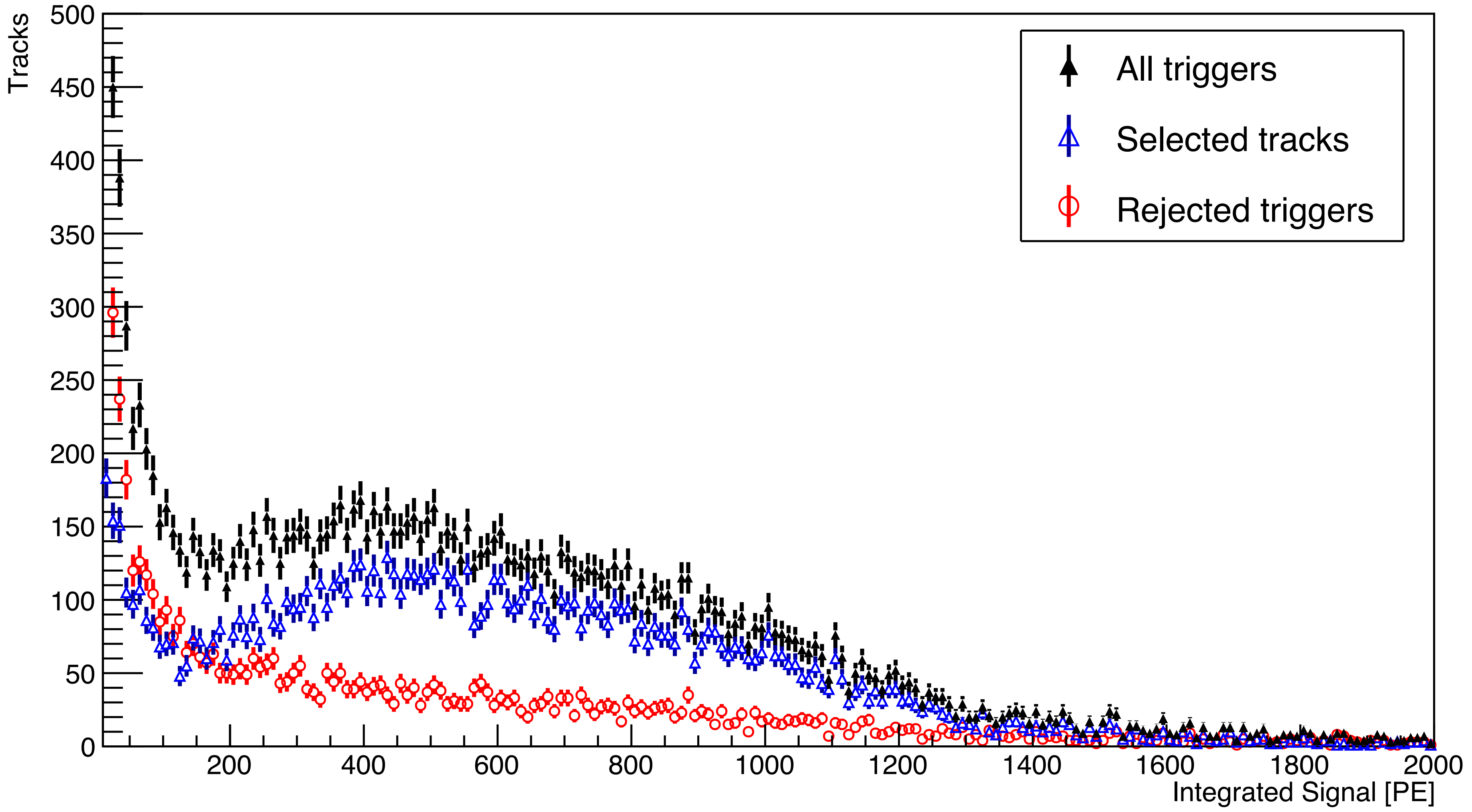
R&D for DUNE

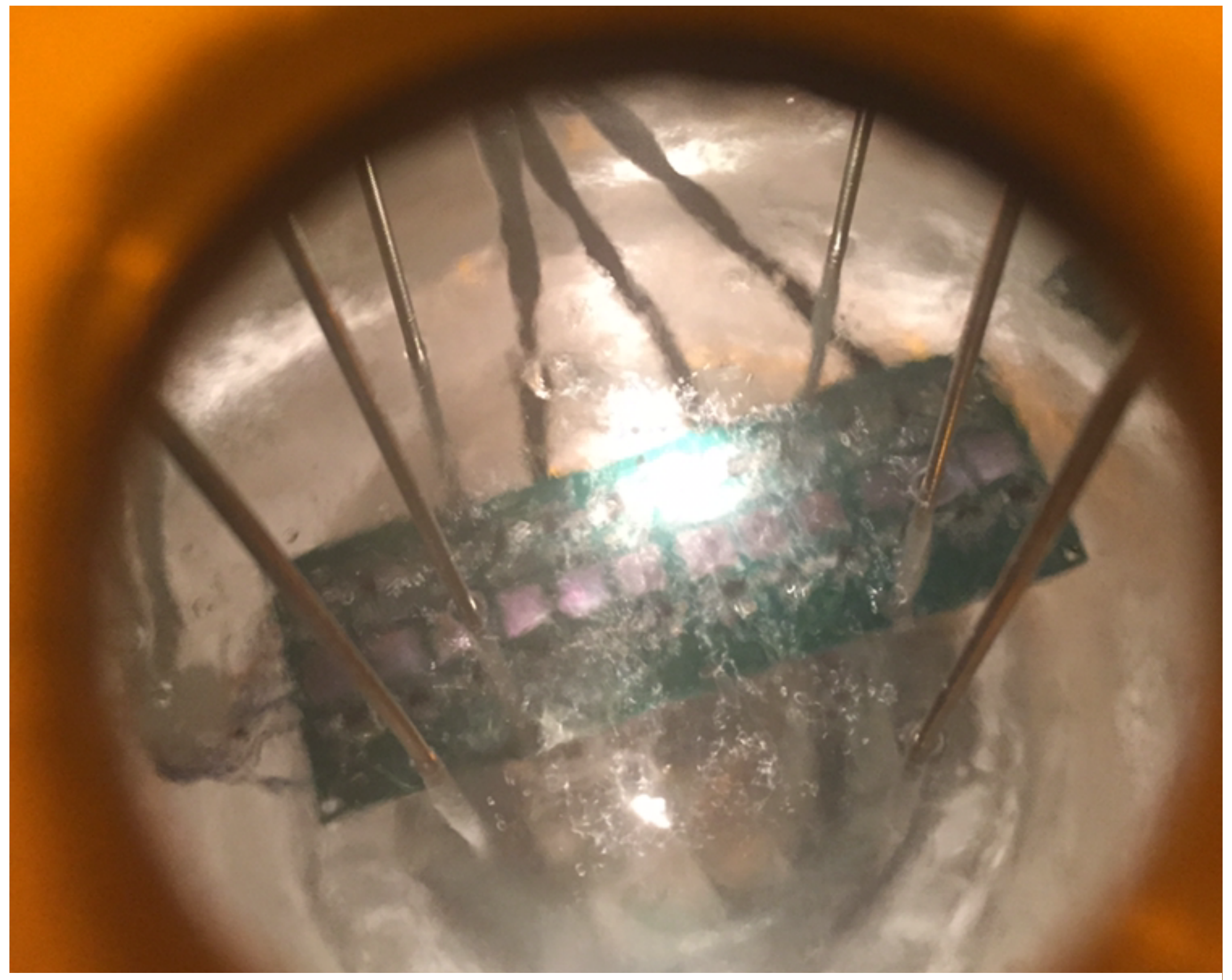
- Specifically worked with a light-guide based prototype
- Used our lab to study individual components, small systems
- Also were able to use LAr test facilities at FNAL (PAB) to test prototypes (still relatively small, no more than ~1m scale)
  - For example expose detector prototype(s) to cosmic rays and test their response
- We published prototype, analysis, & some characterization studies in NIM A



From prototype test at FNAL LAr test facilities

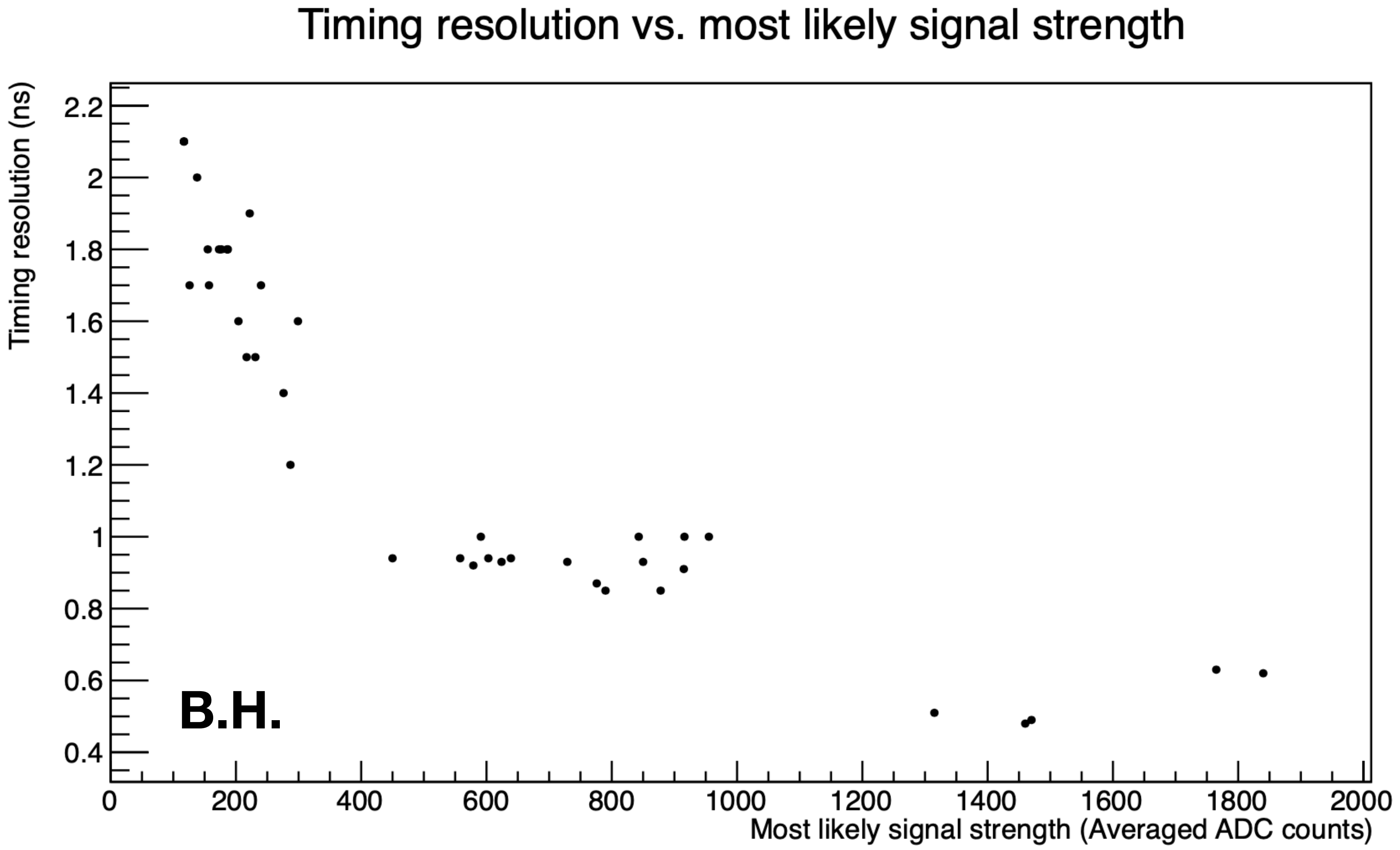
B.H. et al. NIM A 907 (2018) 9-21





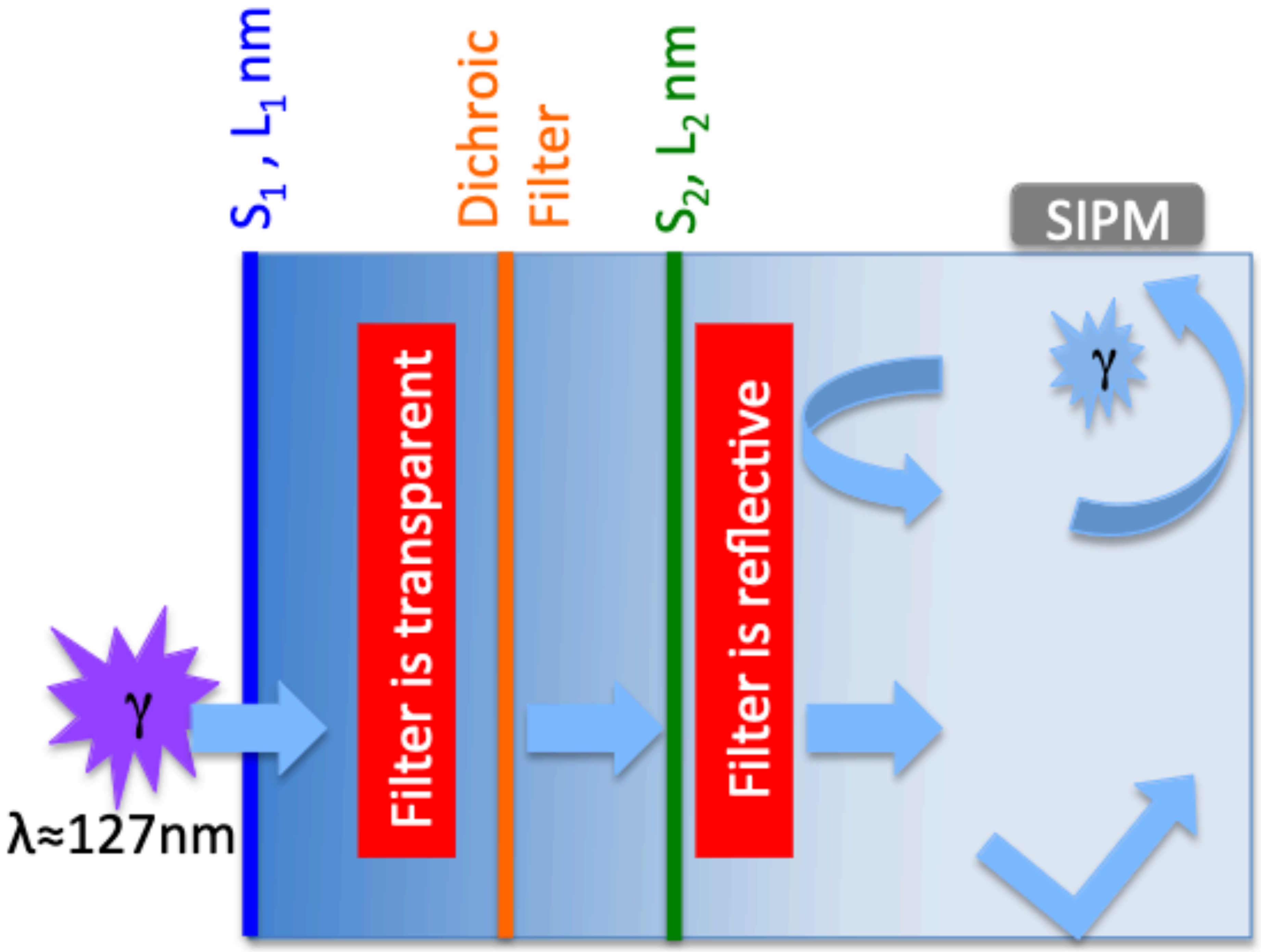
Fellow student and I peering into a tiny test stand we used for detector testing

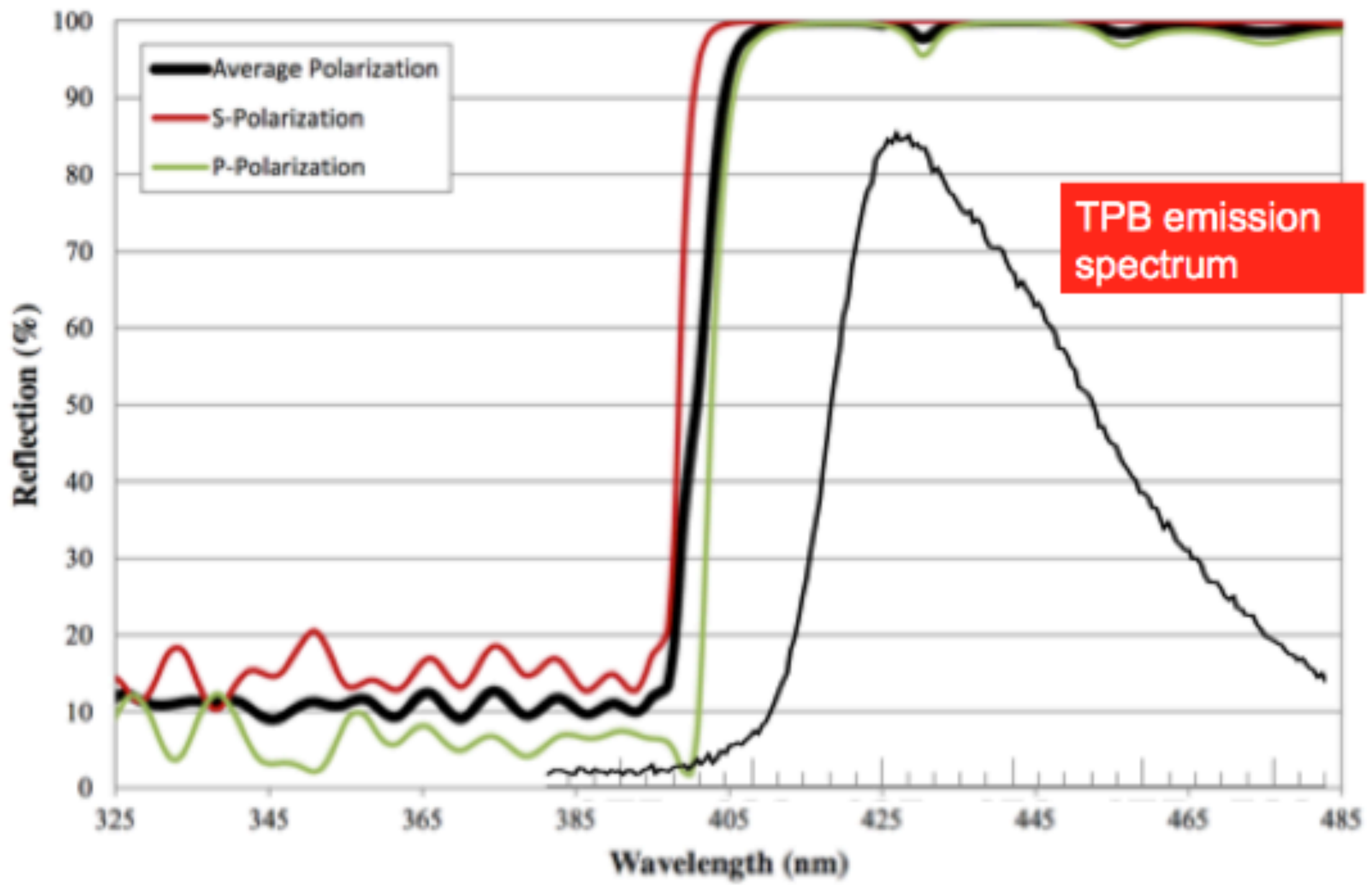
Testing readout electronics with 2 pulses of known time difference combining data from local and prototype testing

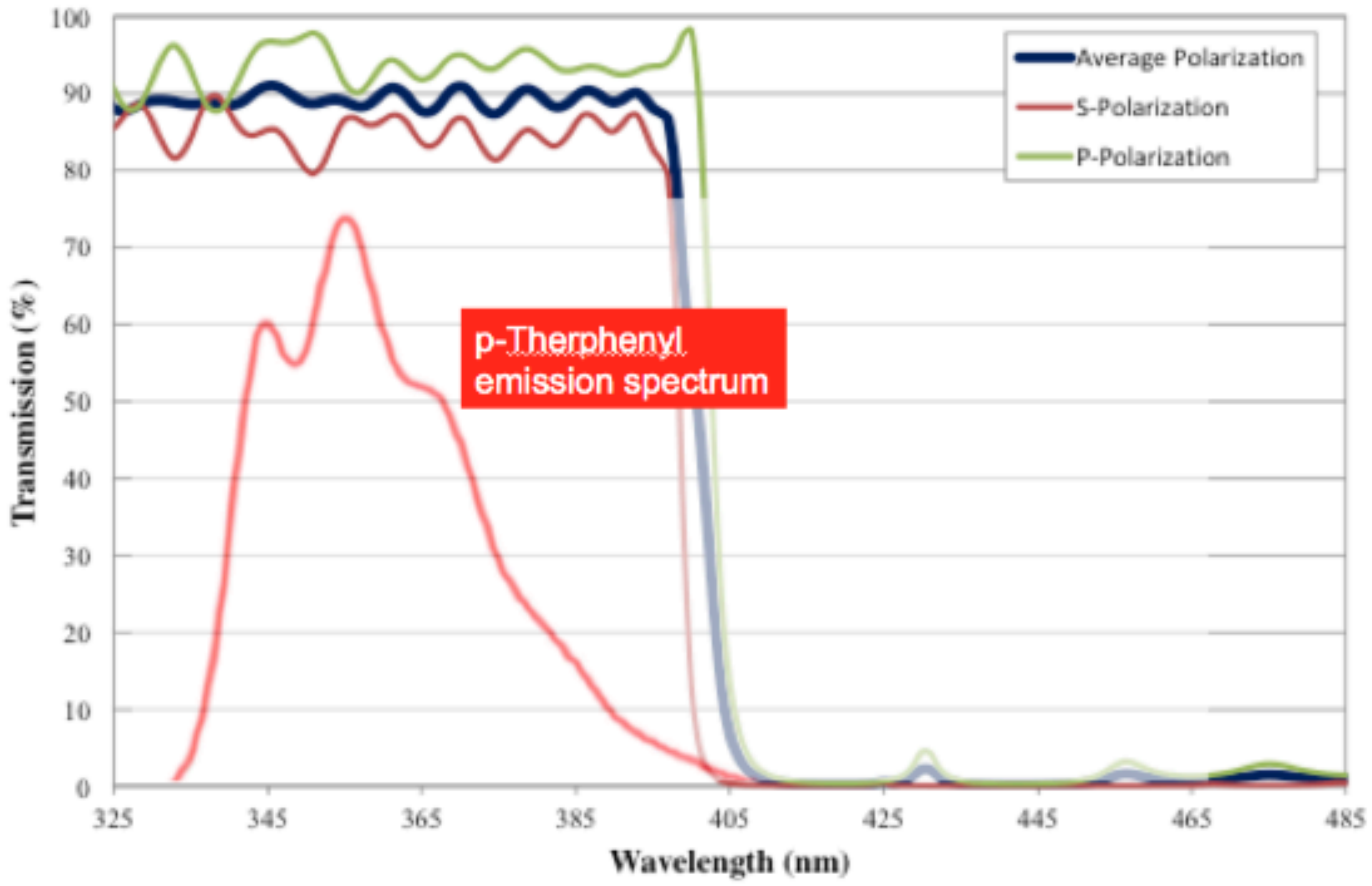


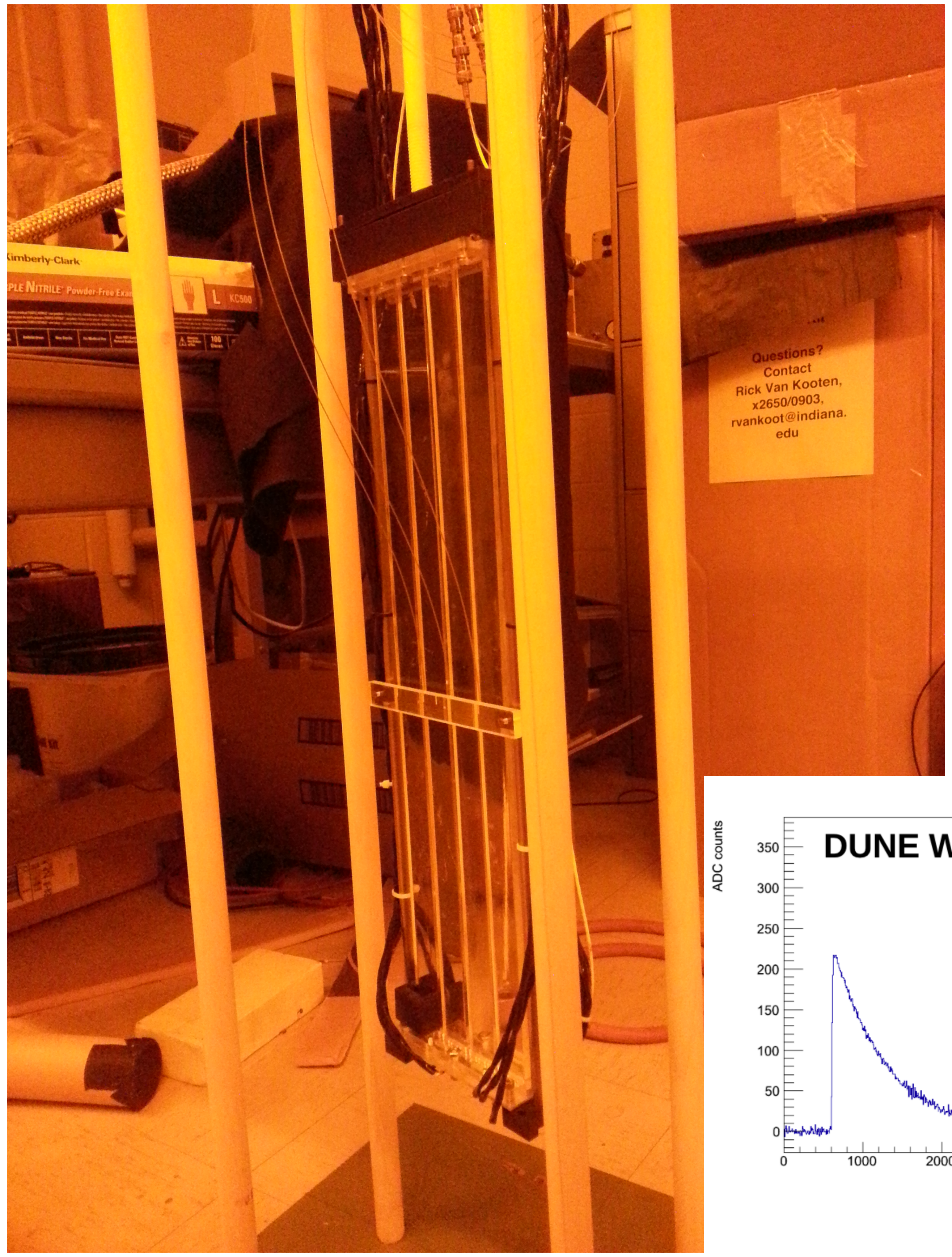
ARAPUCA concept

- Baseline DUNE LAr scintillation photon detector technology
- Figures from A. A. Machado and E. Segreto JINST 11 (2016) C02004

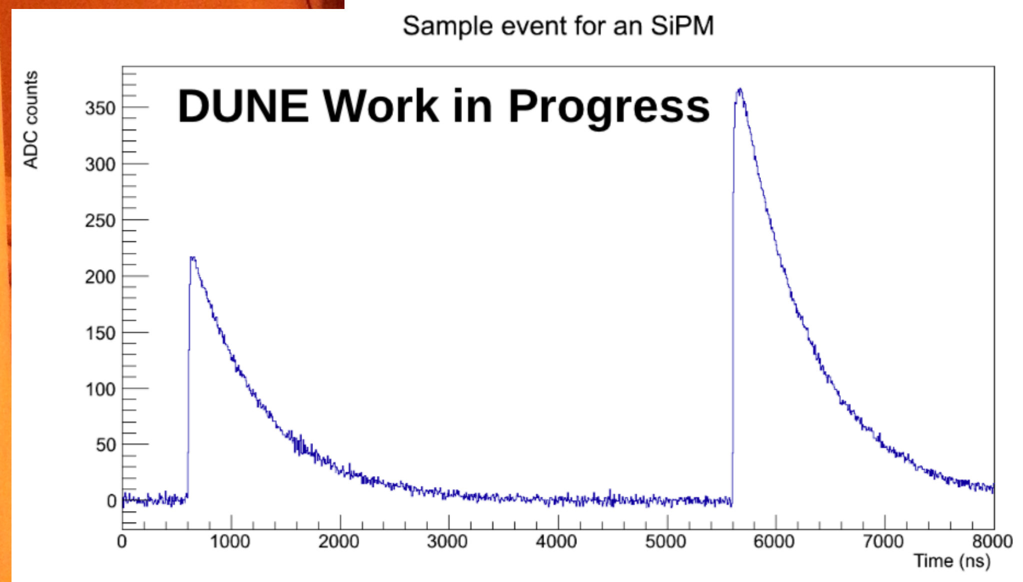






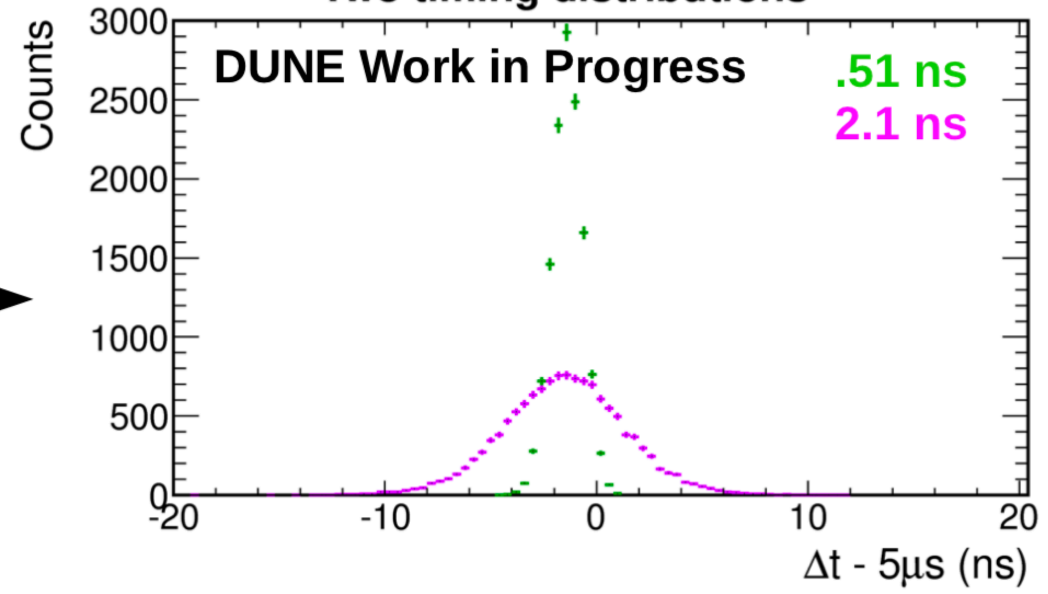


B.H.

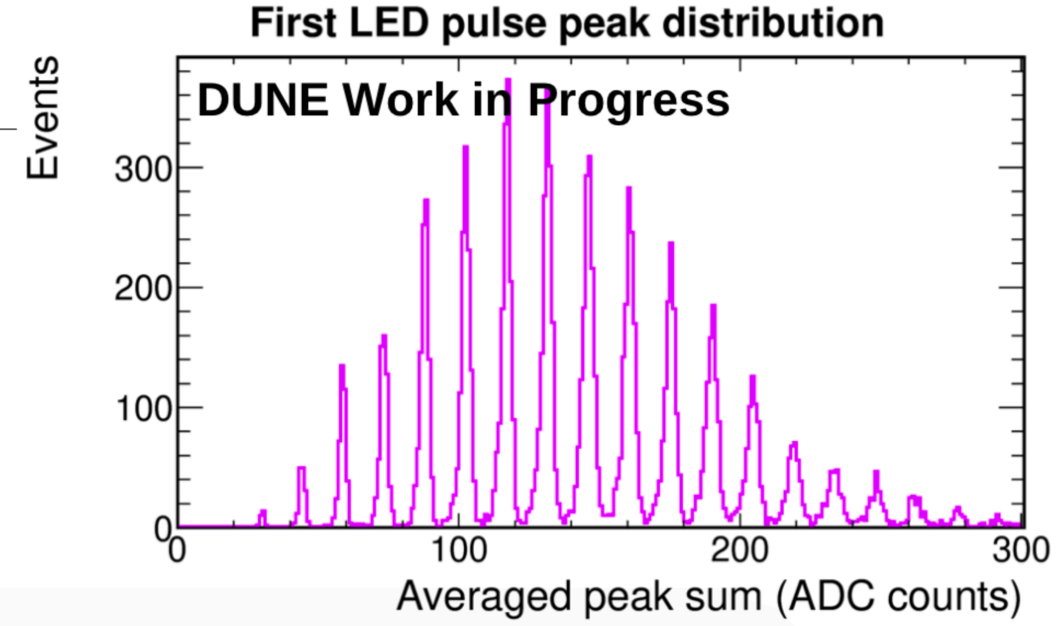


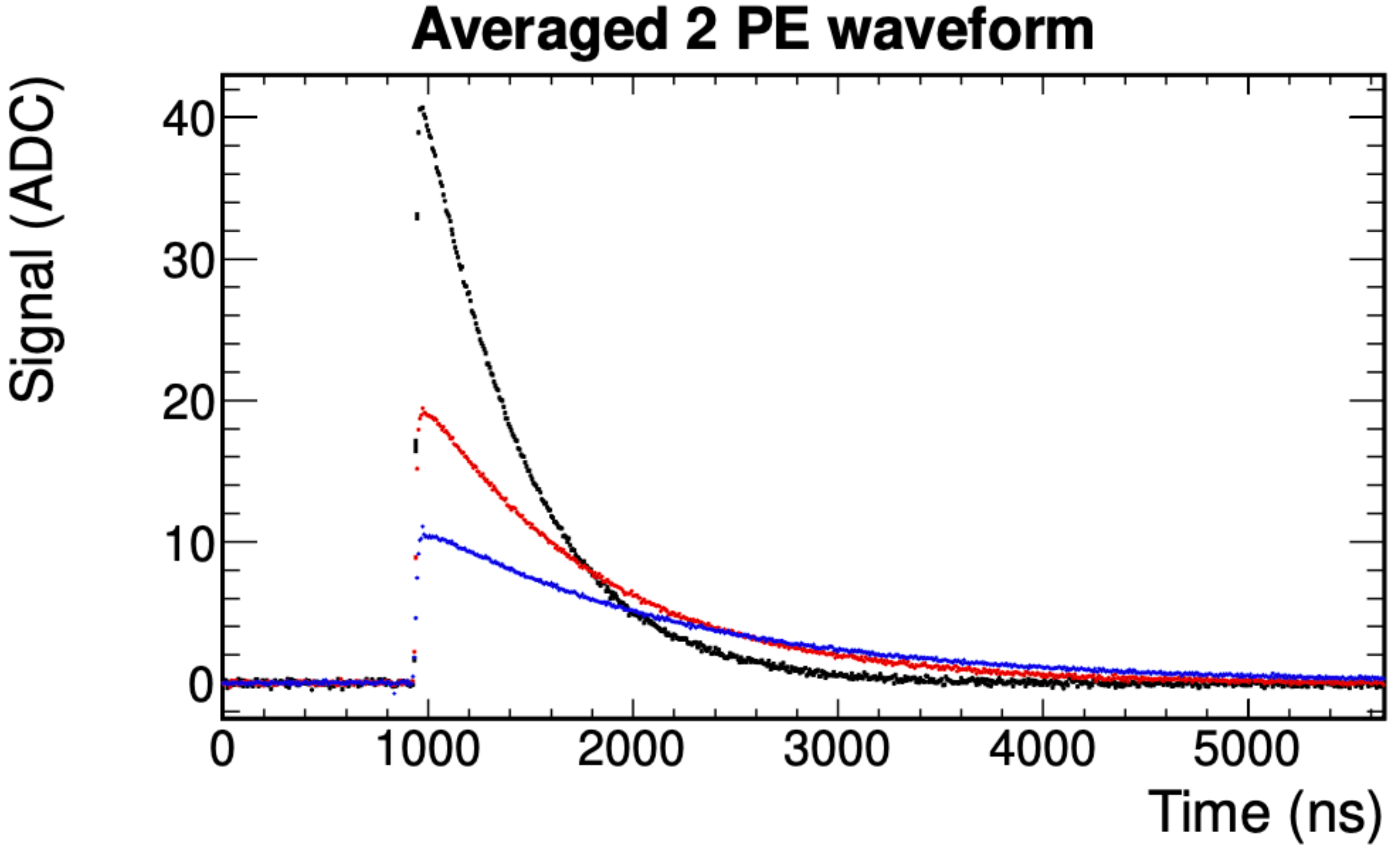
Process collected wavforms to look for spacing of rising edges.

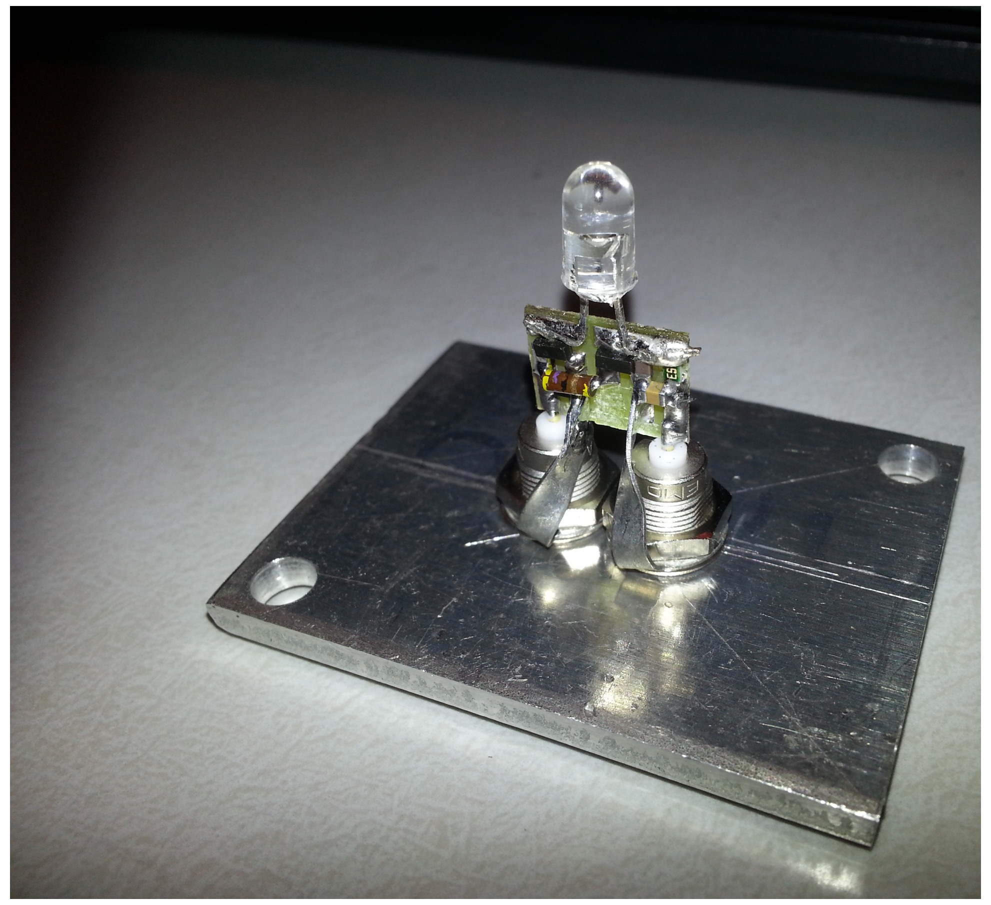
Method based on Bennett et al NIM A622 225 (2010)



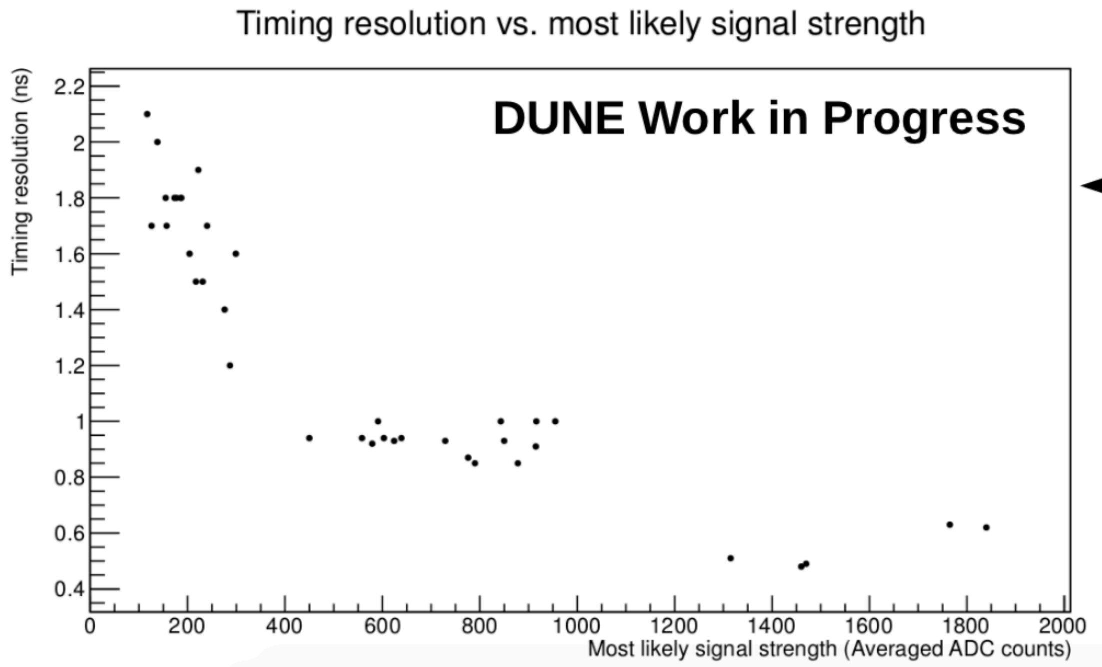
Call the RMS/√2 the time resolution of the channel (b/c 2 pules). Noticed a correlation to most likely pulse height.



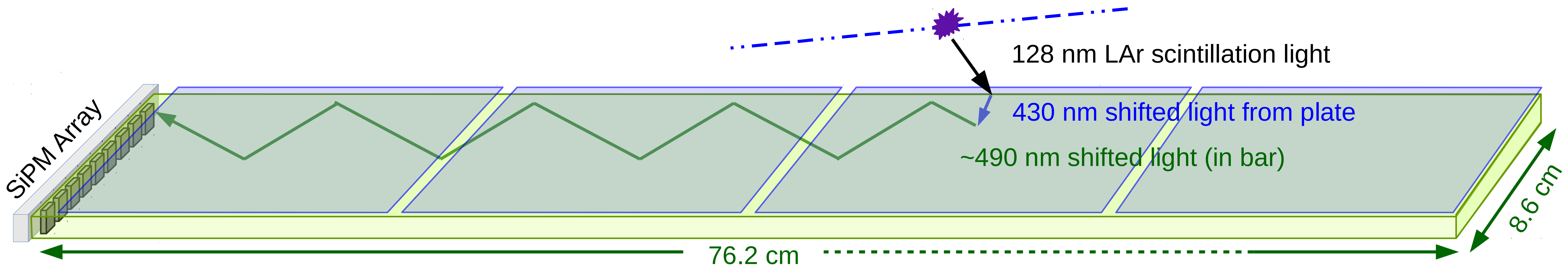


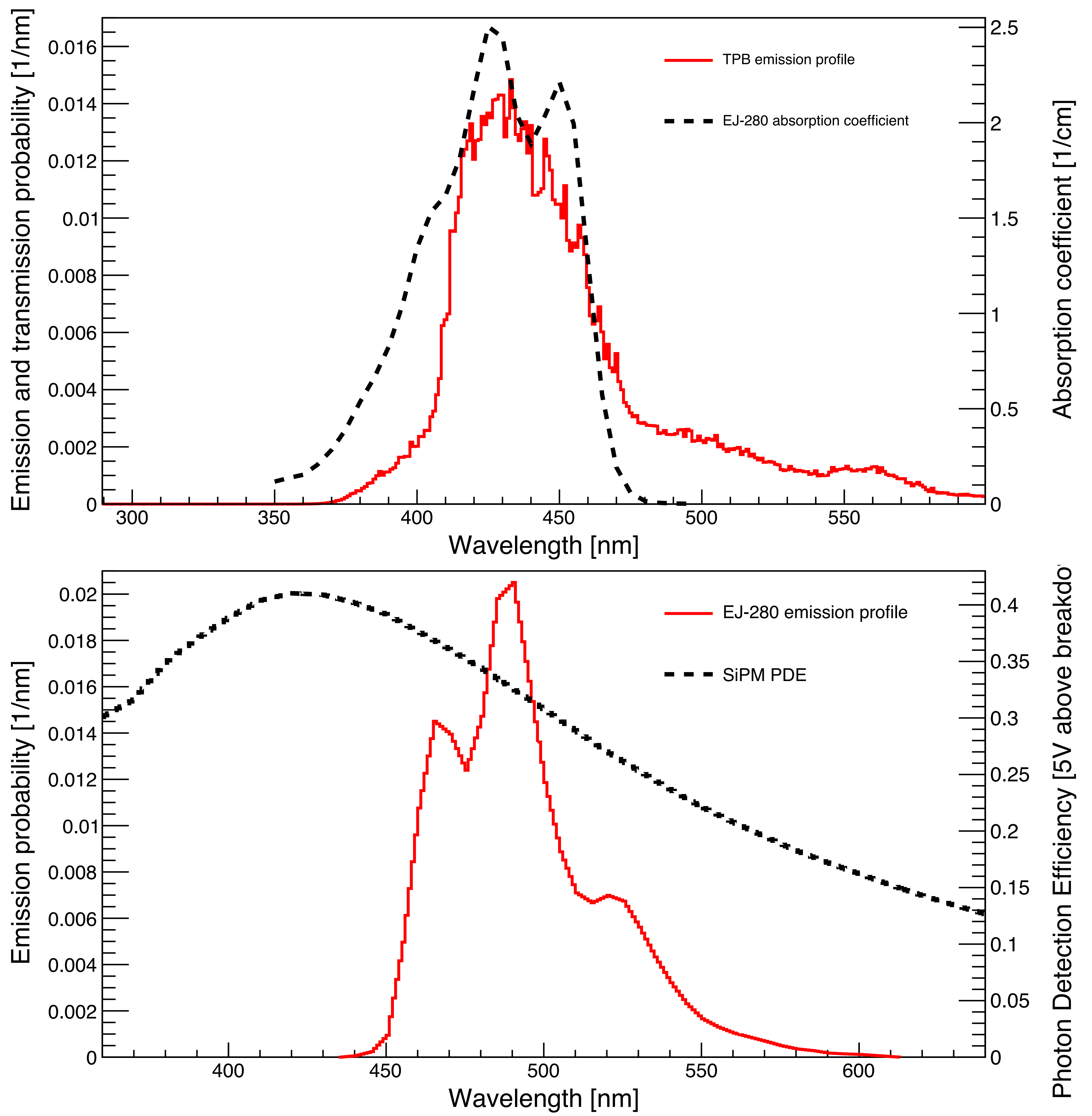


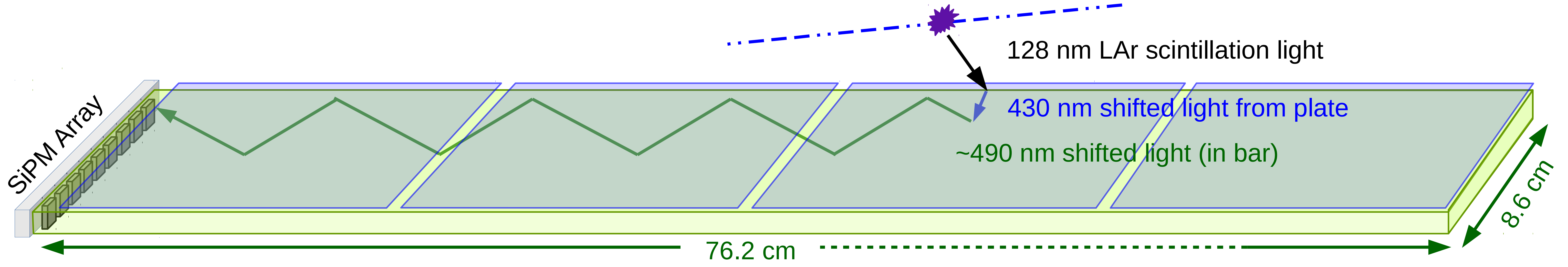
Due to photon statistics, get better timing resolution for brighter signals. Putting together an approx. of the most likely pulse height with the timing resolution

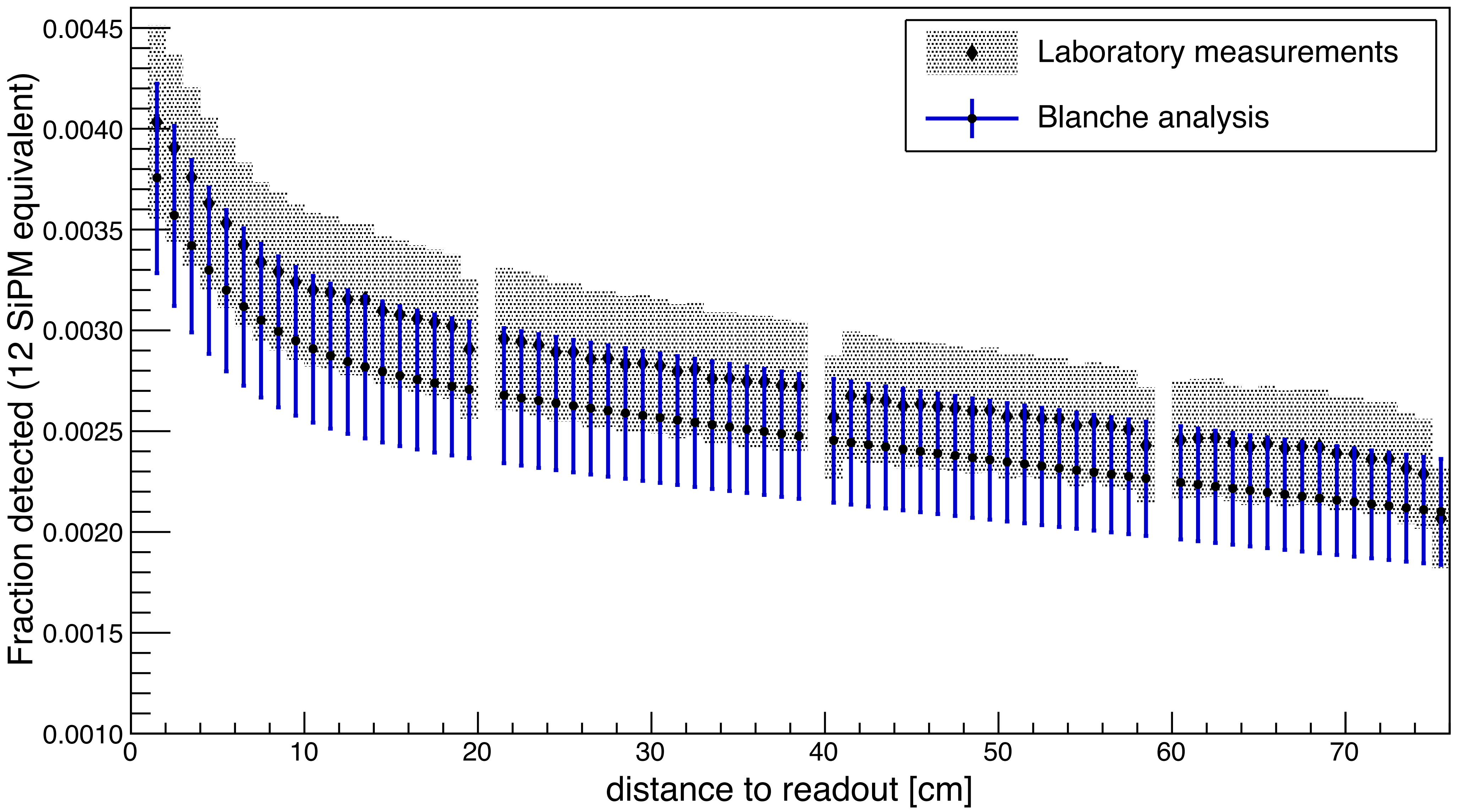


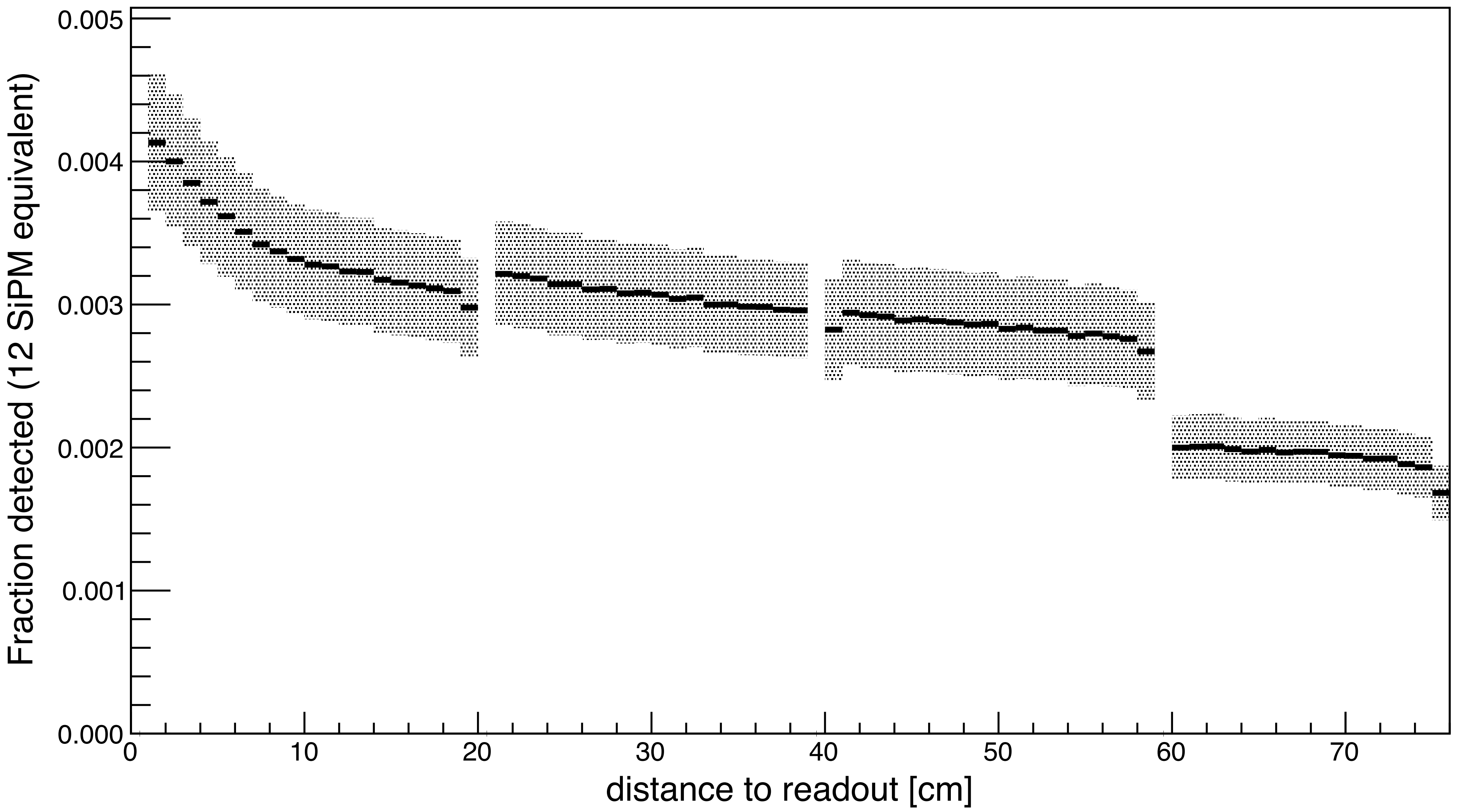
B. Howard, S. Mufson, D. Whittington, et al. NIMA, arXiv:1710.11233





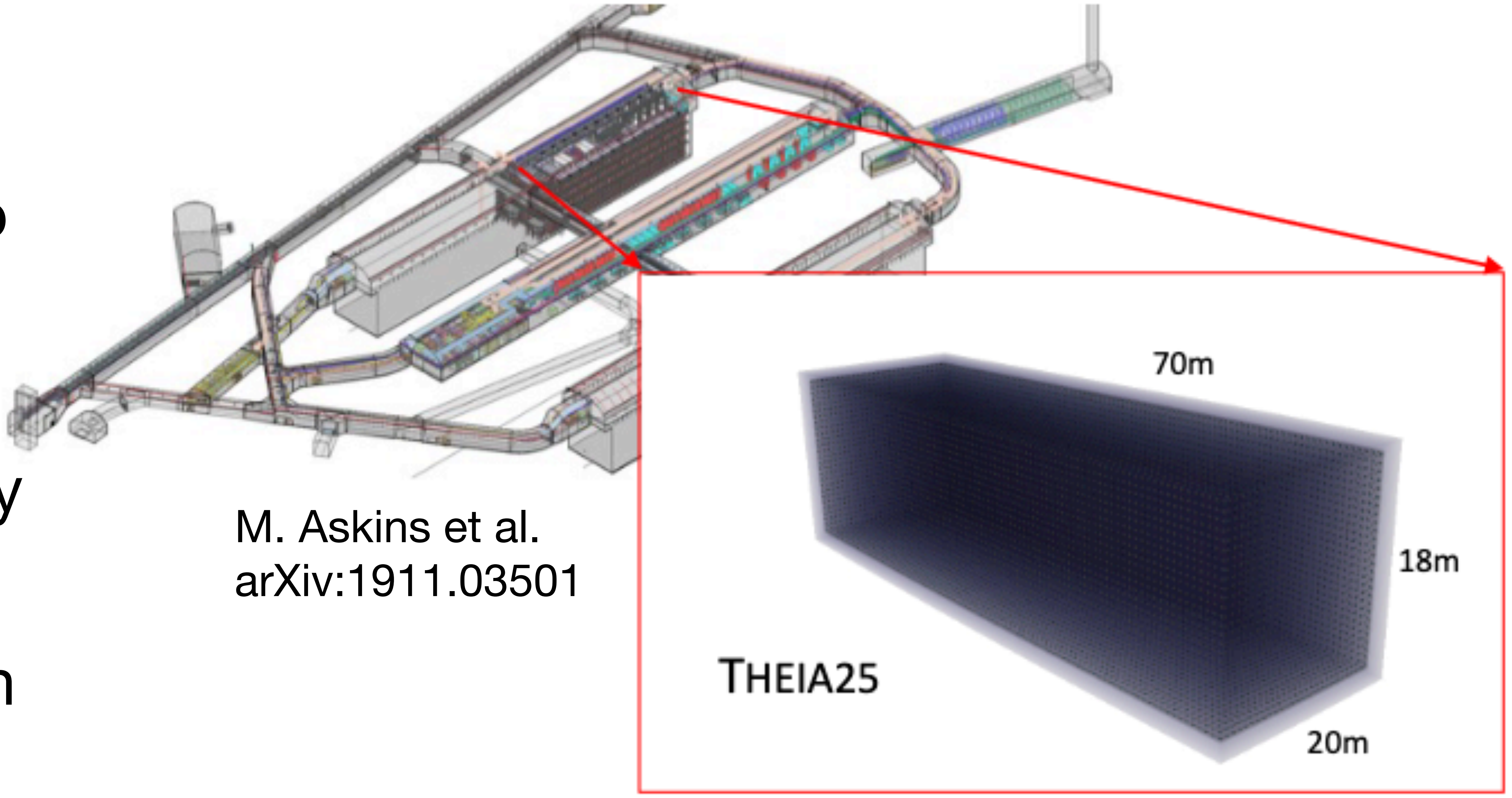

128 nm LAr scintillation light
430 nm shifted light from plate
~490 nm shifted light (in bar)
SiPM Array
76.2 cm
8.6 cm


Laboratory measurements
Blanche analysis
Fraction detected (12 SiPM equivalent)
distance to readout [cm]

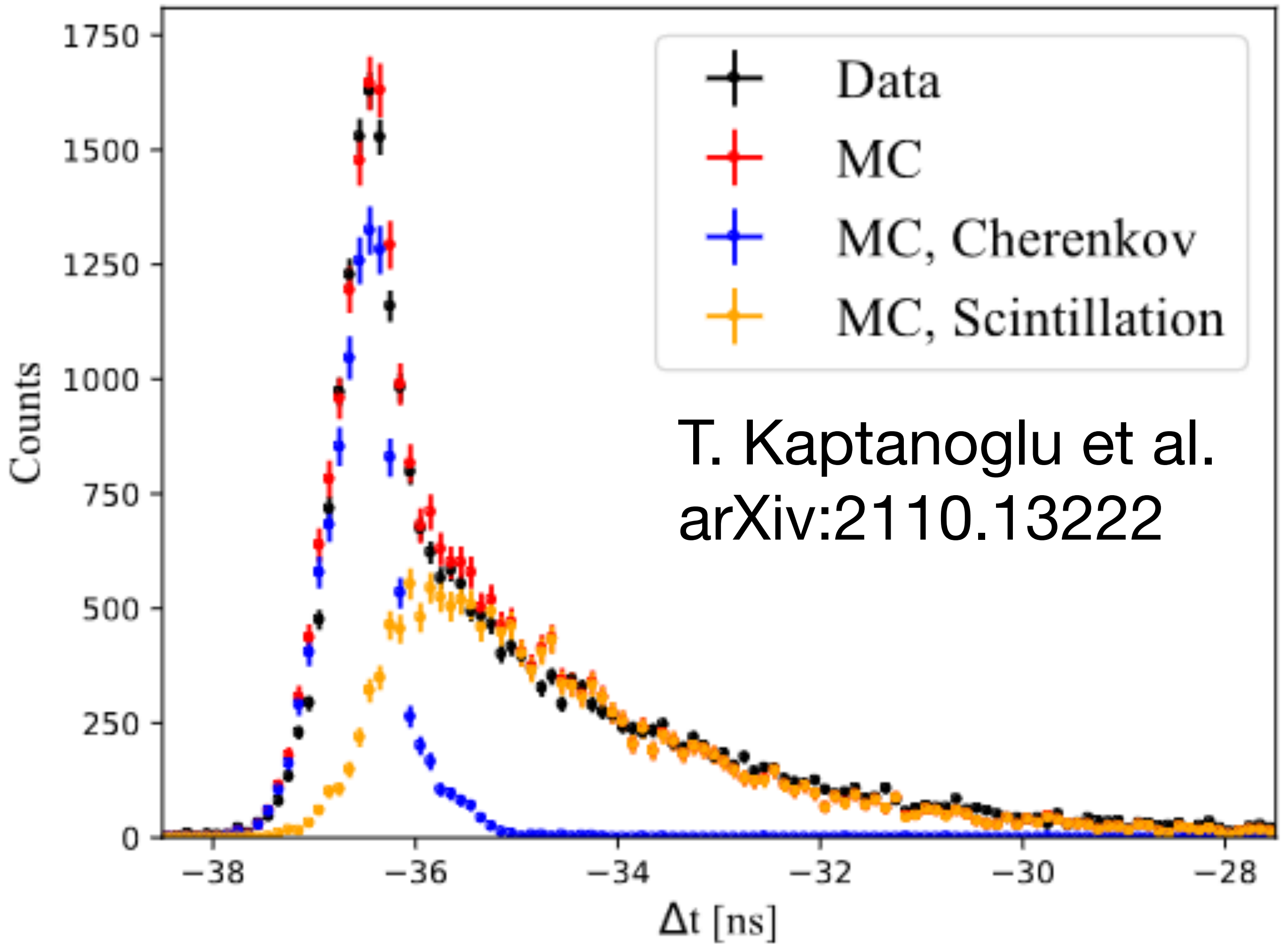

Fraction detected (12 SiPM equivalent)
distance to readout [cm]

Powerful Detectors for the Next Generation

- DUNE has **also encouraged forward-thinking R&D** via the Module of Opportunity:
    - 4th DUNE module can be different technology than LAr to add complementarity (fast, low E, different medium, etc.)
- One such proposal is THEIA, using **Water-based Liquid Scintillator (WbLS)**: a new and powerful detector technology
    - Maintains positives of water Cherenkov: fast detectors, Cherenkov rings for leptons, possibility to naturally or with dopants detect neutrons, etc.
    - Remedies some drawbacks: scintillator gives sensitivity to activity below Cherenkov threshold, better low E capability
    - Ability to use photon detector advances (LAPPD) and/or creative new ideas (dichroicons) to make precise measurements & separate scintons/chertons via time, λ
    - Sensitive detector medium to very wide energy range



M. Askins et al.
arXiv:1911.03501



T. Kaptanoglu et al.
arXiv:2110.13222

Results comparing test-bench data to a best-fit simulation, showing the expected distributions of Chertons and Scintons from the sim.

(1% WbLS solution)

Ability to separate Chertons/Scintons!

WbLS Detector as a DUNE Module

- Capability as ν detector in the long-baseline oscillation studies:
  - Scintillator should enable measurements of the hadronic energy
  - Possibly enhanced utility in the lower E 2nd osc maximum, & depending on ability to tag p & n, could be useful in separating ν, $\bar{\nu}$ statistically (also pointed out in M. Wurm slides)
- Enables many new studies as well as complementarity with LAr. Even just picking supernovae (see arXiv:1911.03501):
  - Enhanced IBD fraction of events in WbLS vs LAr
  - Possibility to use WbLS detector as a trigger for the LAr detector in event of supernova
  - If can push E threshold to O(MeV), can look for pre-supernova neutrinos from late stages of stellar cycle as in KamLAND

CP Violation Sensitivity

M. Askins et al.
arXiv:1911.03501