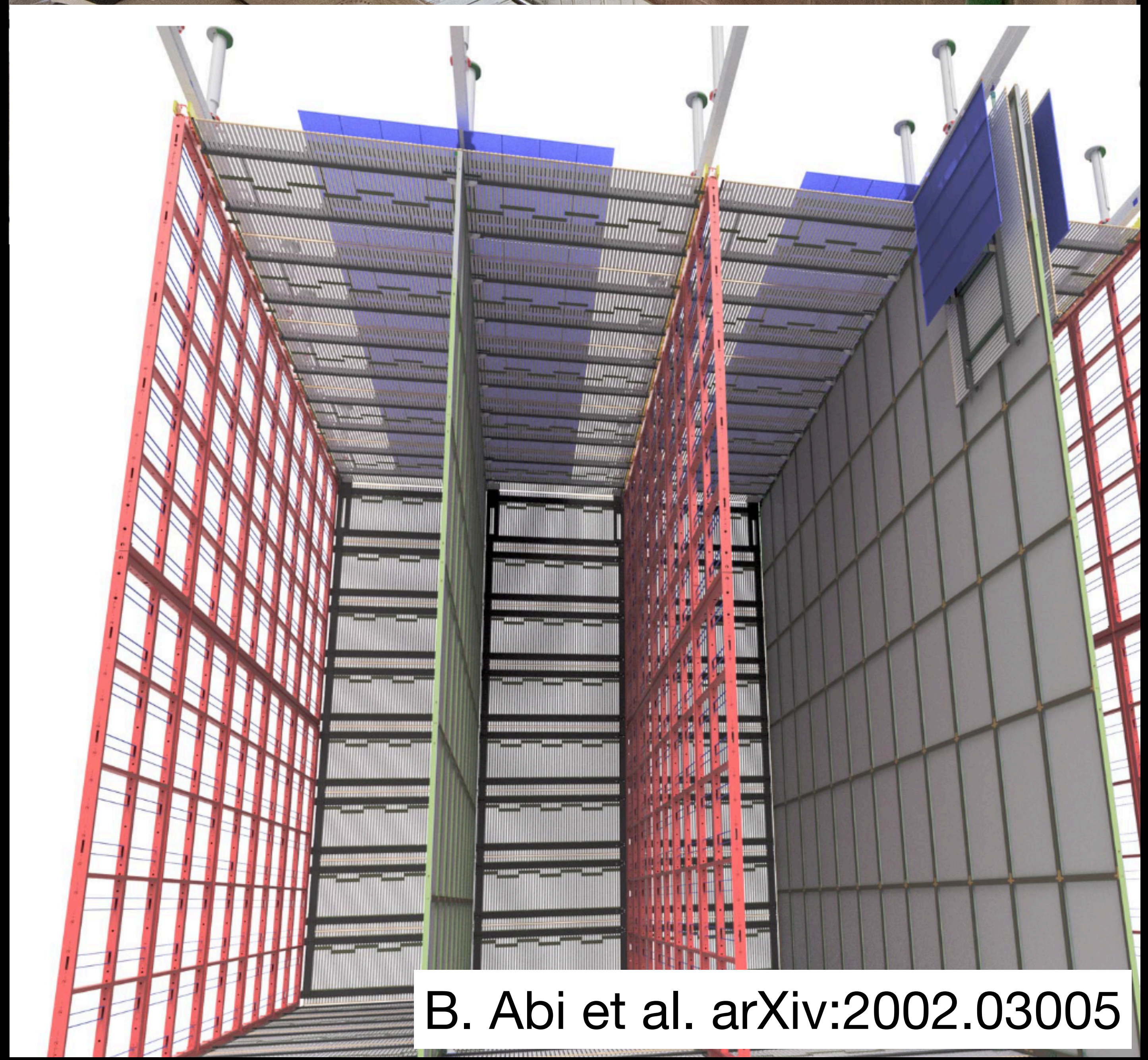
FNAL VMS



B. Abi et al. arXiv:2002.03005

FERMILAB-SLIDES-23-370-ND

Neutrino Hunting with Liquid Argon Neutrino Detectors at Fermilab

Fermilab

DEEP UNDERGROUND NEUTRINO EXPERIMENT

SHORT-BASELINE NEAR DETECTOR

Bruce Howard
7 November 2023

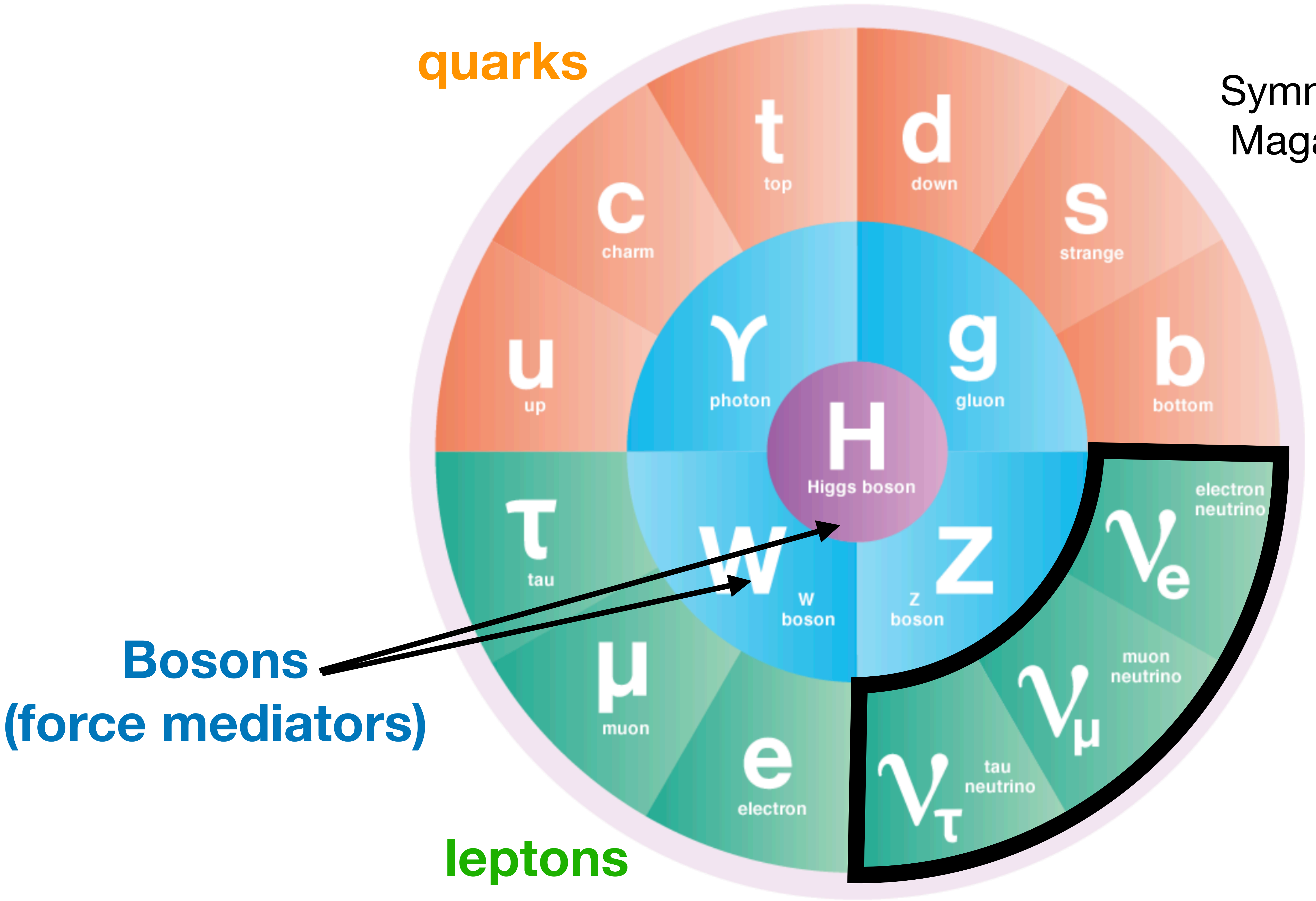
U Mississippi Colloquium

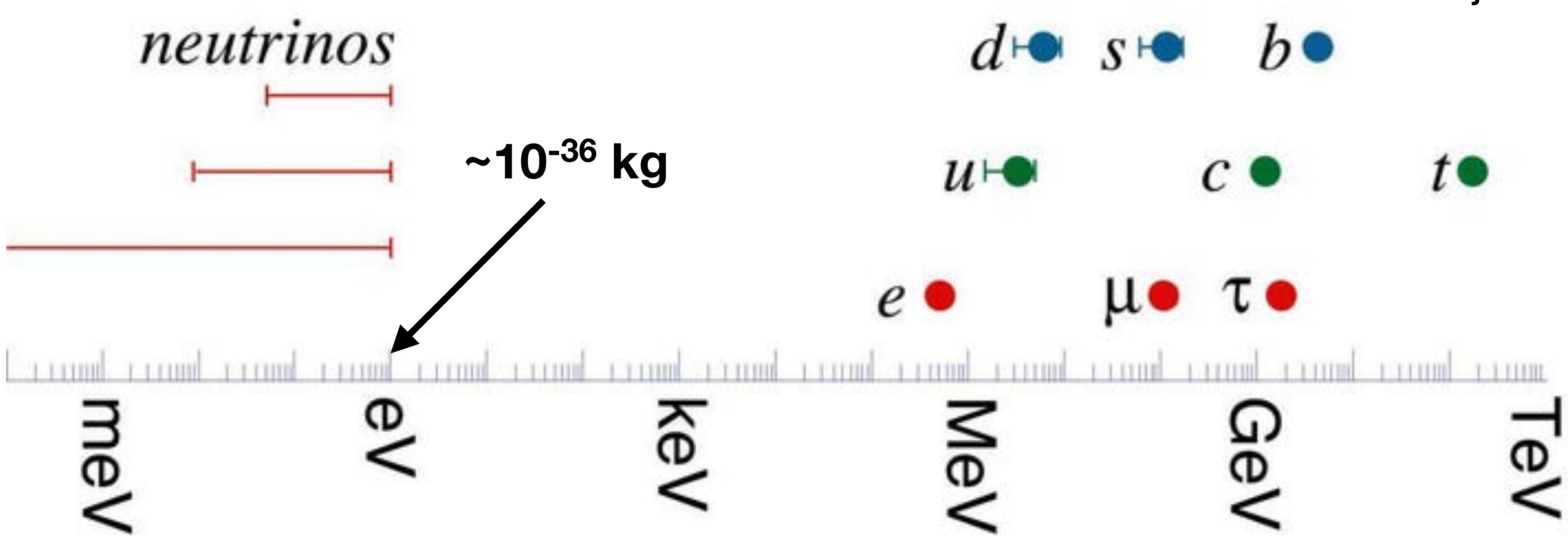
This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

The "particle zoo"

- Nature has presented a set of subatomic particles that constitute the known makeup of Universe and/or can be exchanged during interactions of particles
  - Quarks, Leptons, Bosons

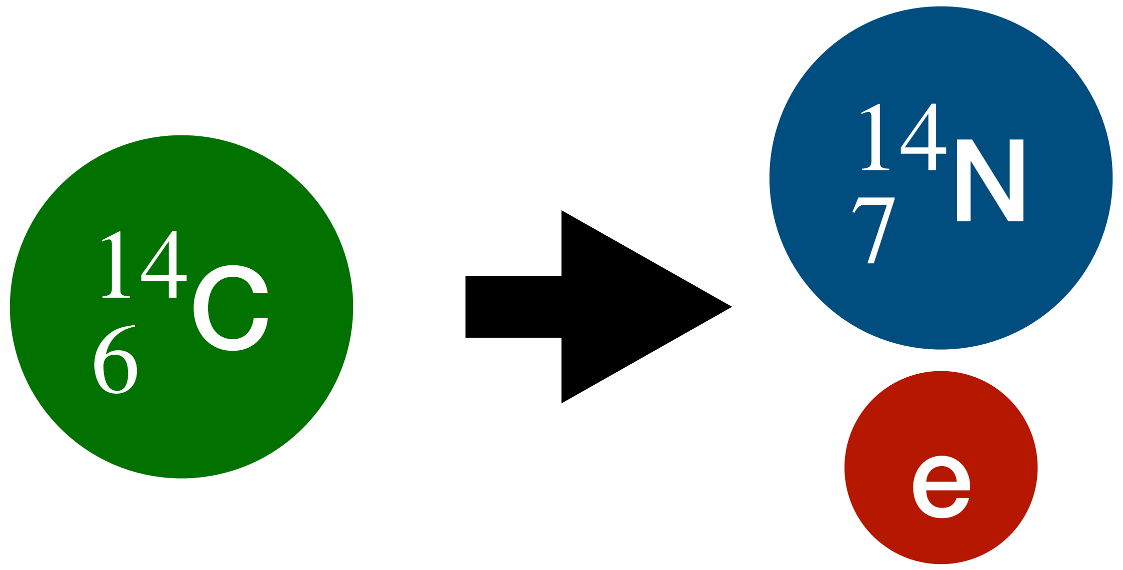
- Neutrinos:
  - Neutral leptons
  - **Very** low mass, < eV
  - Only interact via "weak force" (appropriate name)

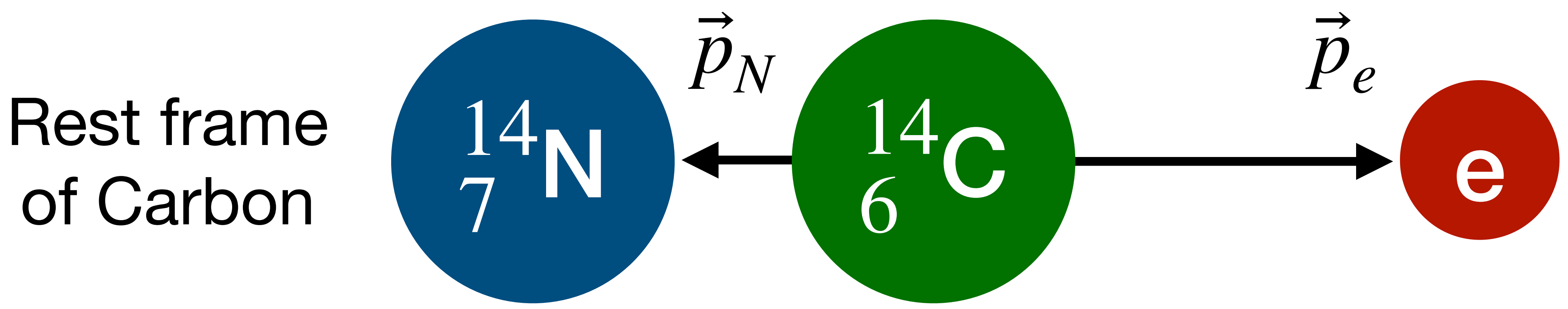




The neutrino

- First proposed in 1930 as a "desperate remedy" by Pauli
- Beta decay is the process by which a neutron in the nucleus decays to (it was thought at the time) a proton and an electron



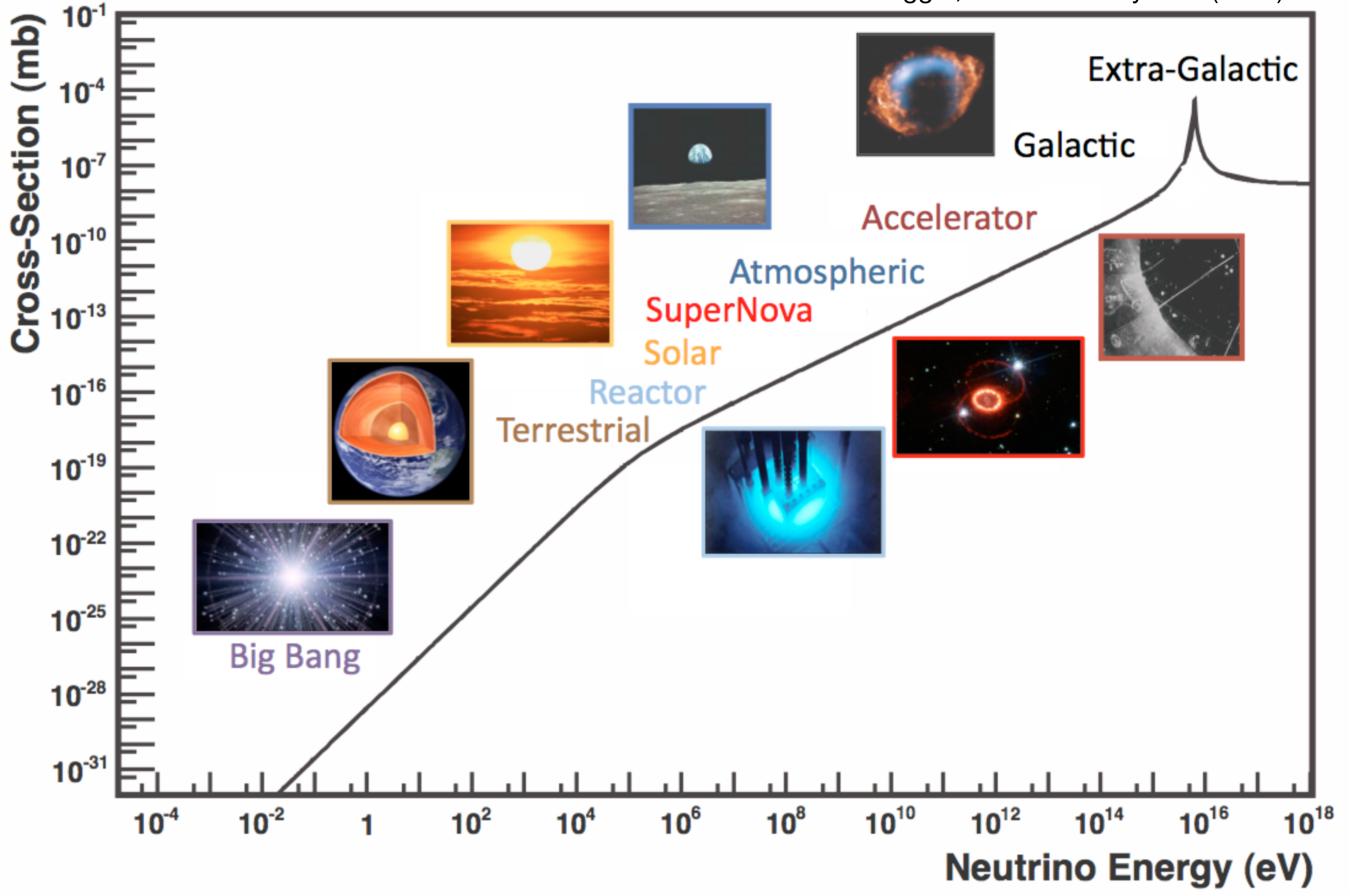


- Available energy: **Mass(C-14) - [Mass(N-14) + Mass(e)]**
  - Apply conservation of energy and momentum
- Instead of a delta function of electron energy, a spectrum is seen
- Pauli proposes that a tiny, neutral particle could be emitted and not seen
  - **Two-body decay vs. three-body decay!**

The neutrino

- Only interact weakly: took decades to find
- 1950s: **e** coupled ν found $\boldsymbol{\nu_e}$ (Reines, Cowan)
- 1960s: $\boldsymbol{\nu_\mu}$ (Brookhaven)
- Early 2000s, $\boldsymbol{\nu_\tau}$ observed for first time (Fermilab)
- Measurements show 3 ν flavors expected
- That ***could*** have been the whole story…

Zeller and Formaggio, Rev. Mod. Phys. 84 (2012)

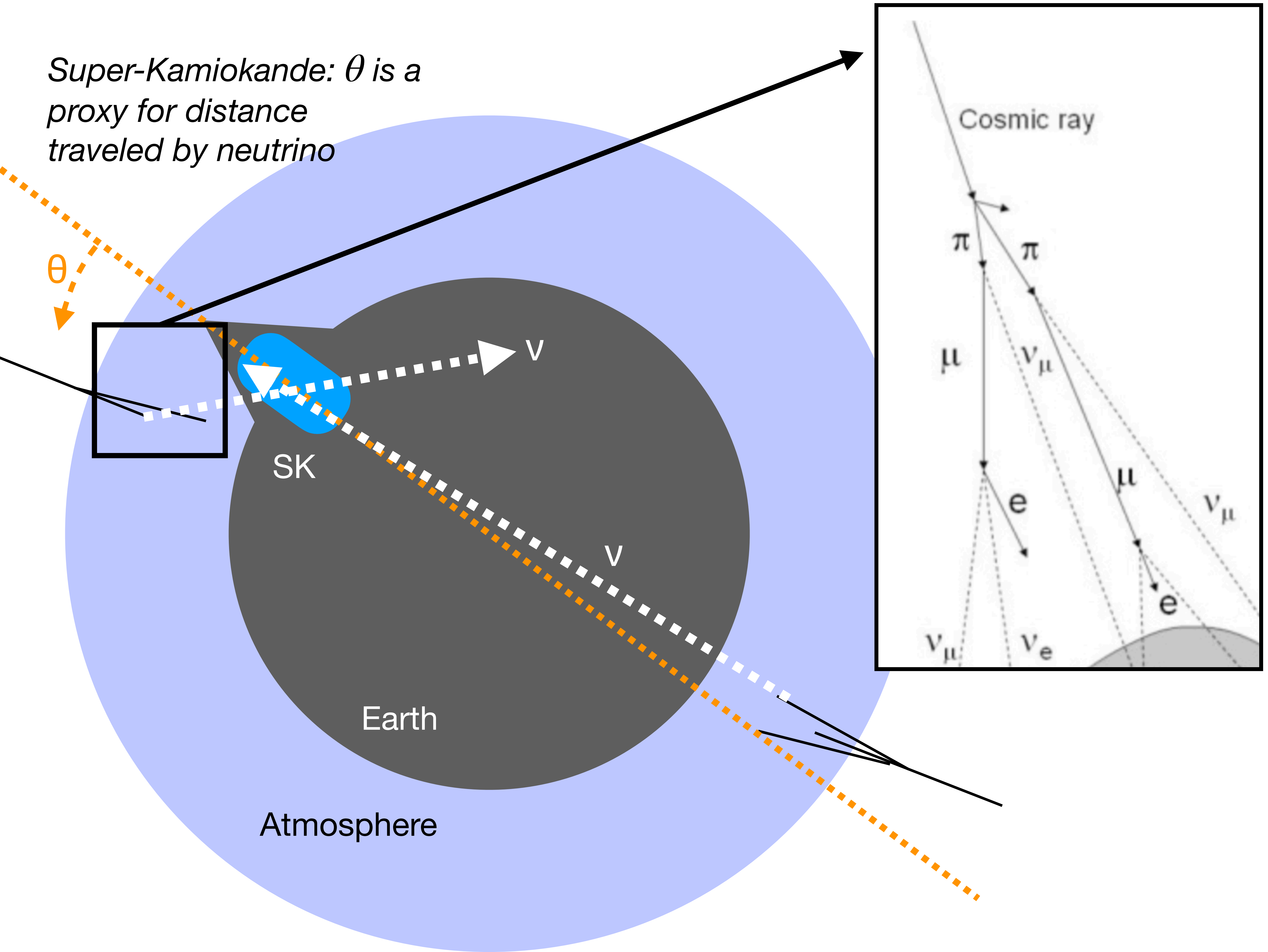


We know now that neutrinos come from many sources!

The neutrino

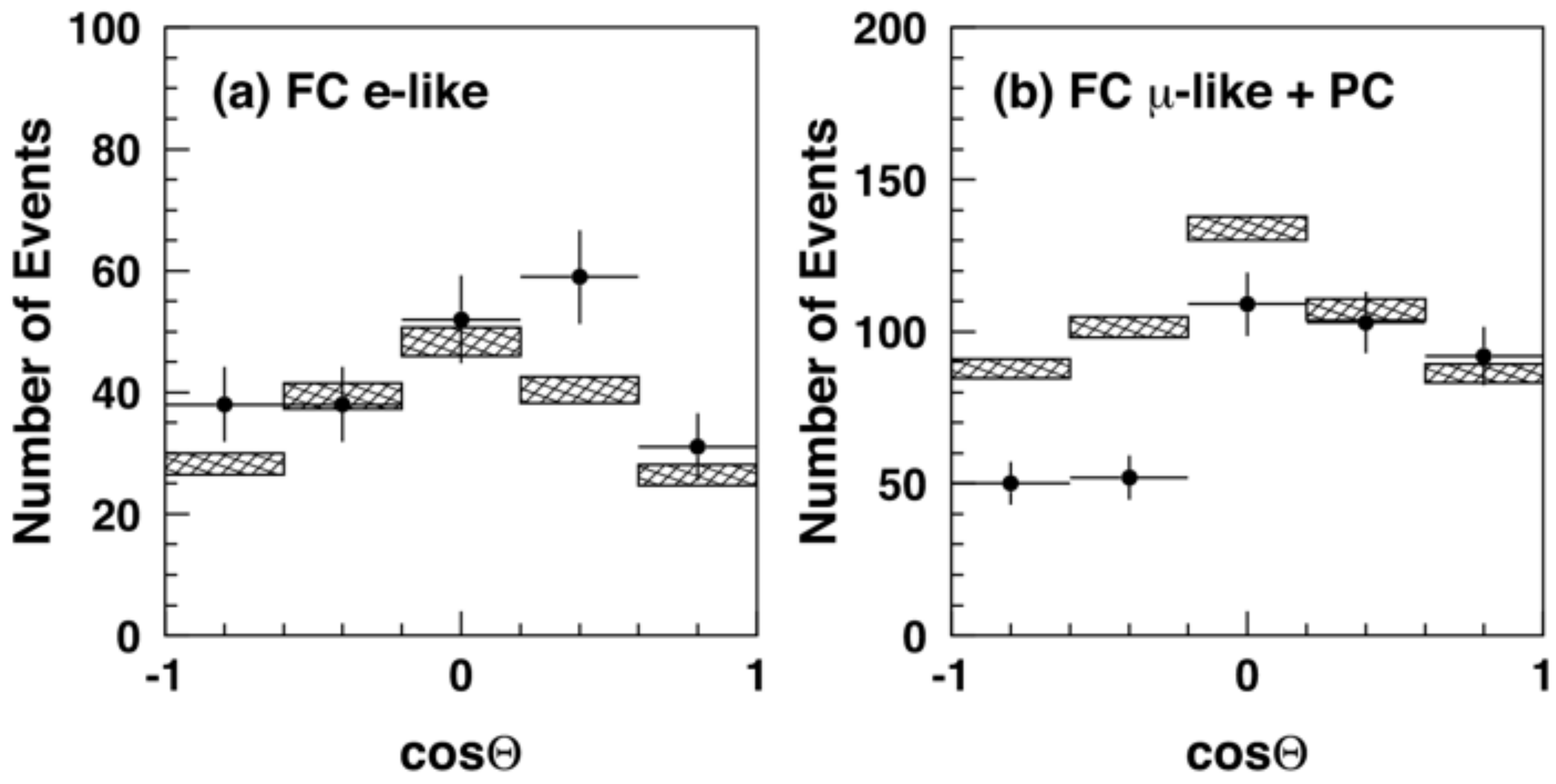
- Seminal work by Ray Davis to measure solar ν yields continually came up short of expectation
- Followed by other experiments studying yields of different flavors: e.g. Super Kamiokande & SNO

Super-Kamiokande: θ is a proxy for distance traveled by neutrino



T. Kajita. Proc Jpn Acad Ser B Phys Biol Sci. 2010 86 (4) 303–321

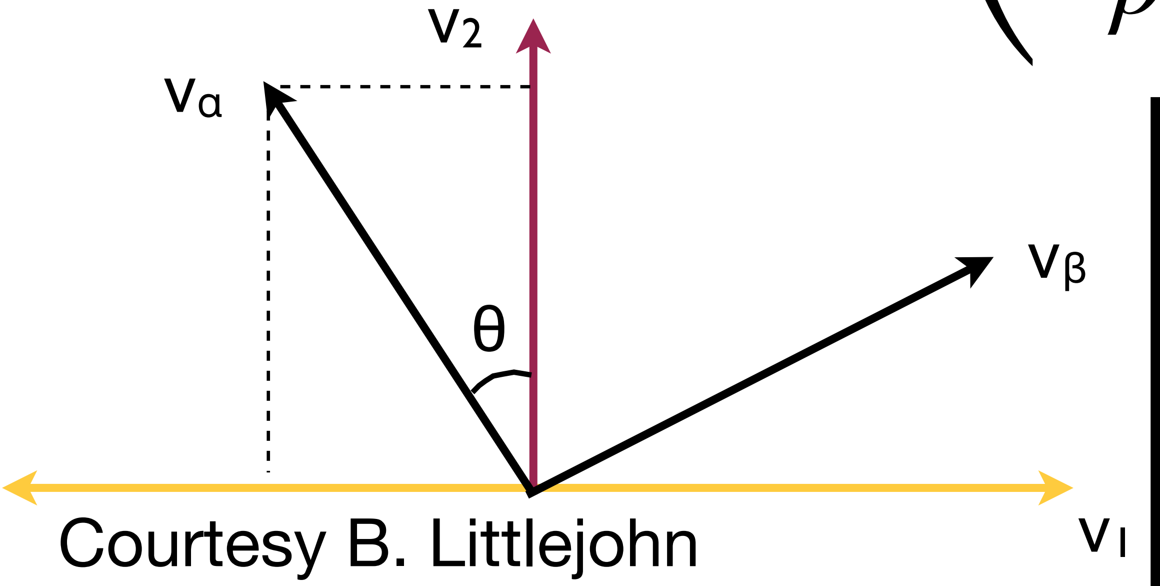
Anomaly caused by oscillation in early Super-K data:
T. Kajita, E. Kearns, M. Shiozawa Nuclear Phys B 908 (2016) 14-29



Neutrino oscillation

- From these we know that the deficit is both flavor (ν_e, ν_μ, ν_τ) dependent and distance (L) dependent, and it turns out to be energy dependent as well
- These are signatures of what's called "neutrino oscillation"
  - Quantum mechanical interference between flavors and mass states (eigenstates)
  - Neutrinos created/detected via coupling to flavors, but propagate as the mass states
- Mass difference 10^{-3} eV^2 and GeV ν, this takes ~100s to ~1000s of km to be maximal → "long baseline"

Neutrino oscillations with 2 flavors:



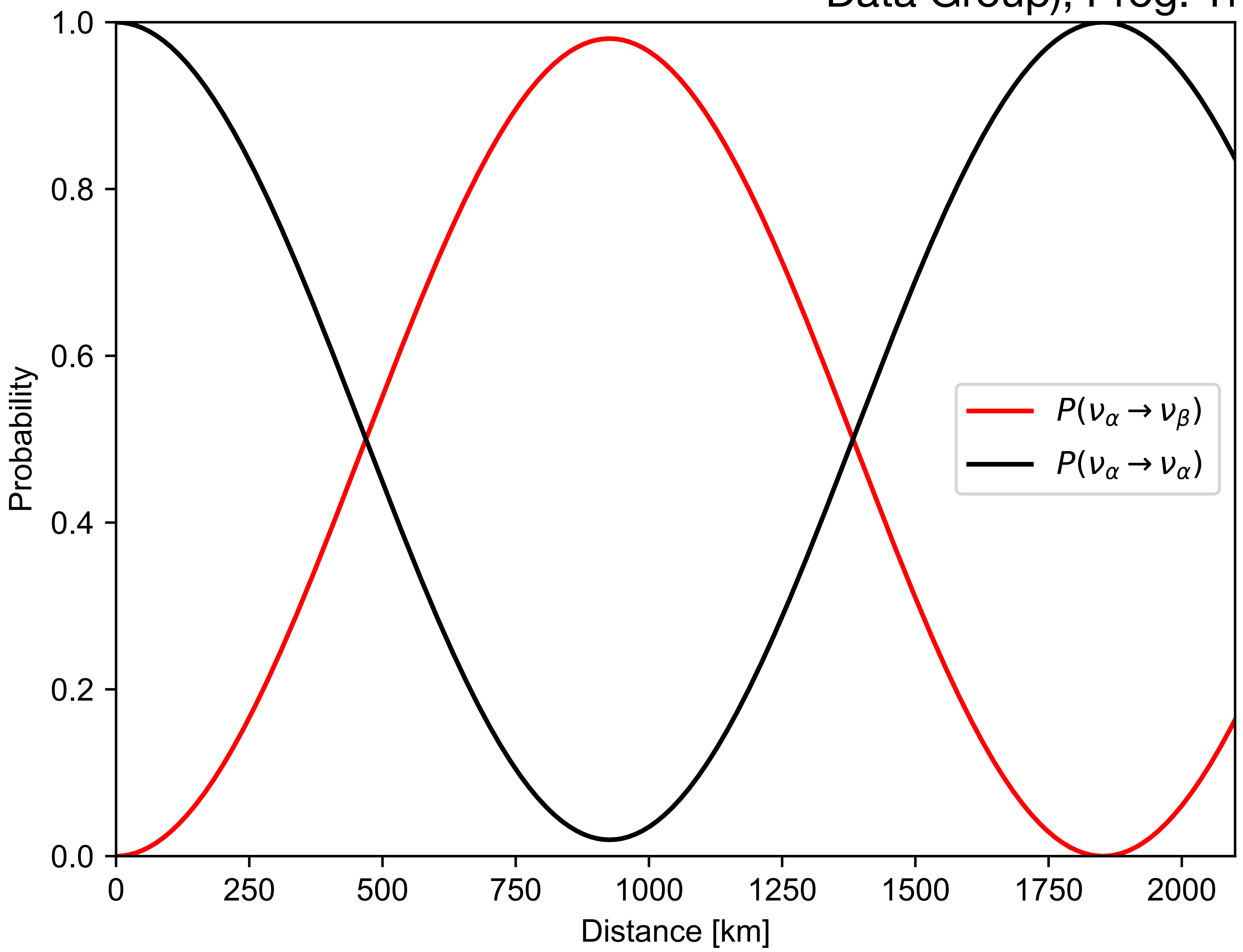
Courtesy B. Littlejohn

Flavors **U** **Mass states**

$$\begin{pmatrix}\nu_\alpha \\ \nu_\beta\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta \\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1 \\ \nu_2\end{pmatrix}$$

$$P_{\alpha\beta} = \sin^2 2\theta \sin^2\left(1.267\frac{\Delta m^2_{21} L}{E}\right) \qquad m : [eV^2] \quad L : [m] \quad E : [MeV]$$

For more details: See chapter 14 of R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022 083C01 (2022)



Drawing out $P_{\alpha\beta}$

& $P_{\alpha\alpha} = 1 - P_{\alpha\beta}$

E=1.8 GeV, L in (0 - 2.1 km), $\theta \cong 49^0$, $\Delta m^2 = 2.41 \times 10^{-3}$ eV^2

NOTE oscillatory nature!

Neutrino oscillation

- With 3 neutrino flavors:
  - Matrix now 3x3
  - Typically separated by which sources/experiments more sensitive to
- 3 mixing angles, 2 mass differences ("splittings") and ordering, δ_{CP} parameter (switches sign for ν vs $\bar{\nu}$)
  - δ_{CP} : enhancement/deficit of one. If effect is large, could help answer why Universe is matter-dominated
- **We need to set out to measure all these parameters precisely and investigate what nature is telling us!**

Atmospheric (/Accelerator) **Reactor** **Solar**

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

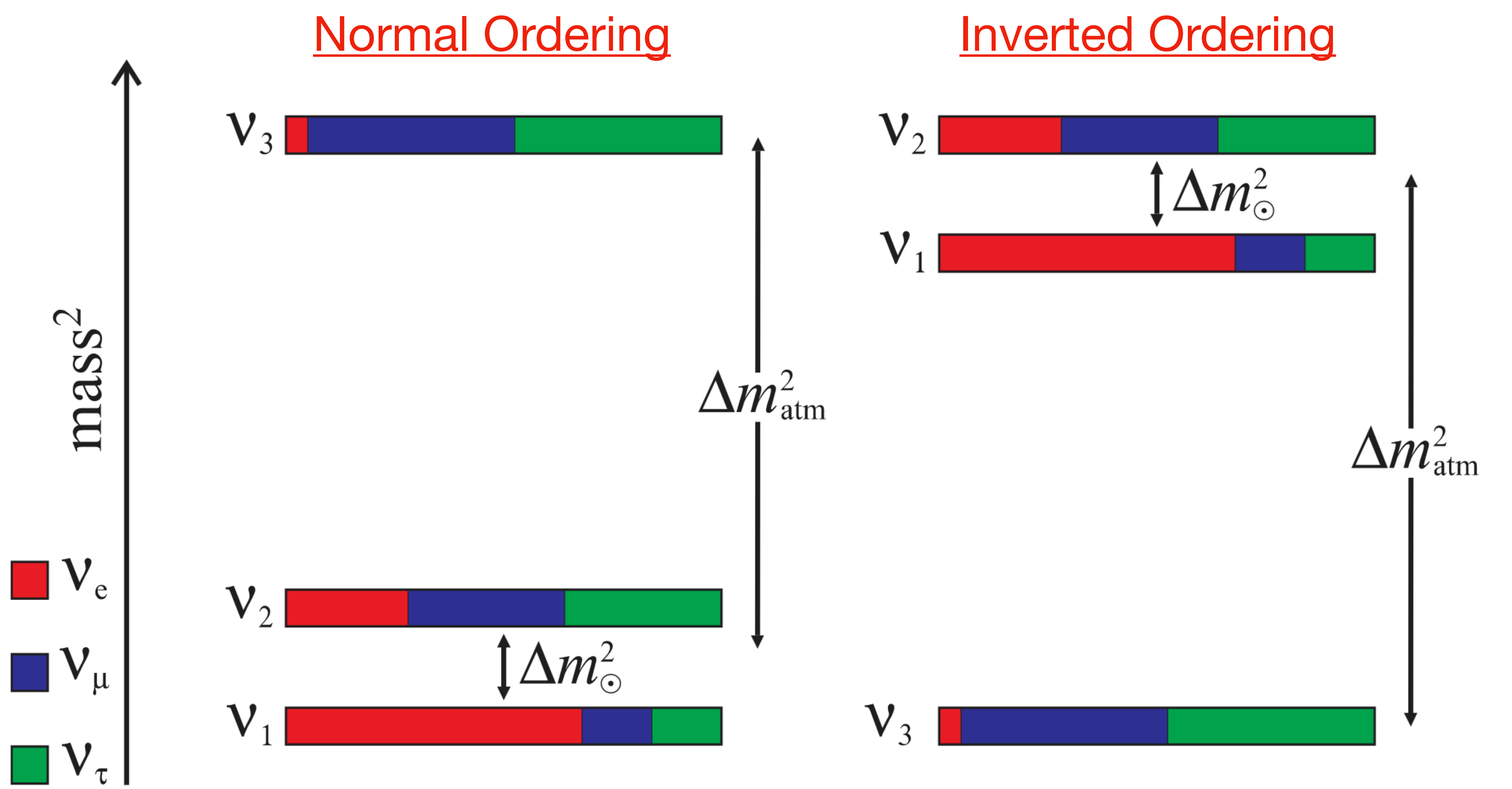
$$\tan^2\theta_{12} \quad : \quad \frac{\text{amount of } \nu_e \text{ in } \nu_2}{\text{amount of } \nu_e \text{ in } \nu_1}$$

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

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

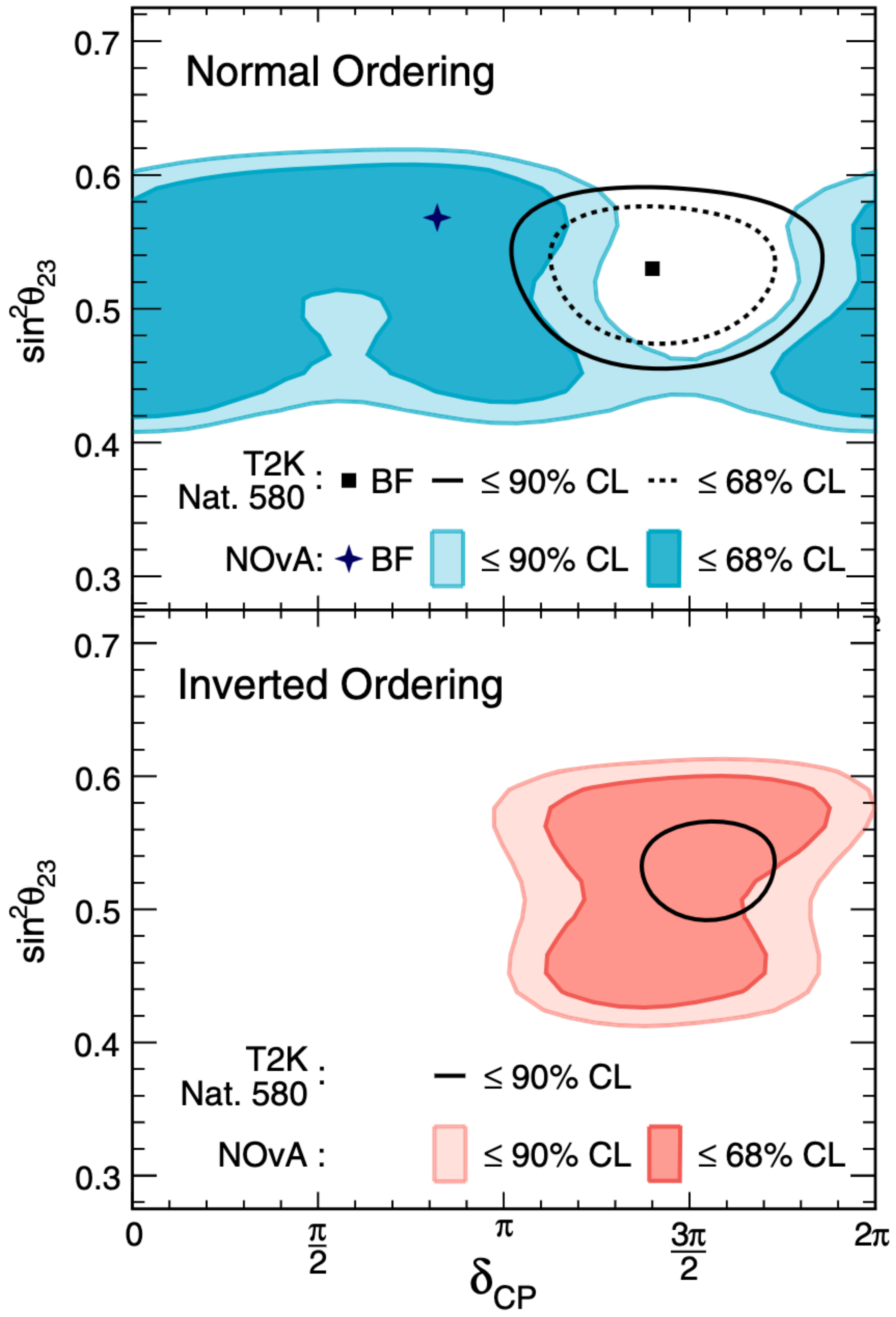
C. Adams et al
arXiv:1307.7335
(LBNE Science Book)

From E. Smith slides



Neutrino oscillation

- Past decades have brought us long way
- Major open questions still, though:
  - **Some values need better study (θ_{23} close to 45^0, on which side?)**
    Fully/precisely measure the mixing parameters!
  - **Sign of Δm_{32}? (We have Δm^2_{32})**
    Is m_3 the lightest or heaviest?
  - **Is δ_{CP} different from 0?**
    Do neutrinos & antineutrinos behave differently?
  - **Do we see same parameters from experiments at very different regimes? (test assumptions)**
    Is the 3 neutrino picture complete?
- Need next generation to answer these definitively…



Portions of parameter space are ruled out, but still large swaths are open

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

Neutrino oscillation

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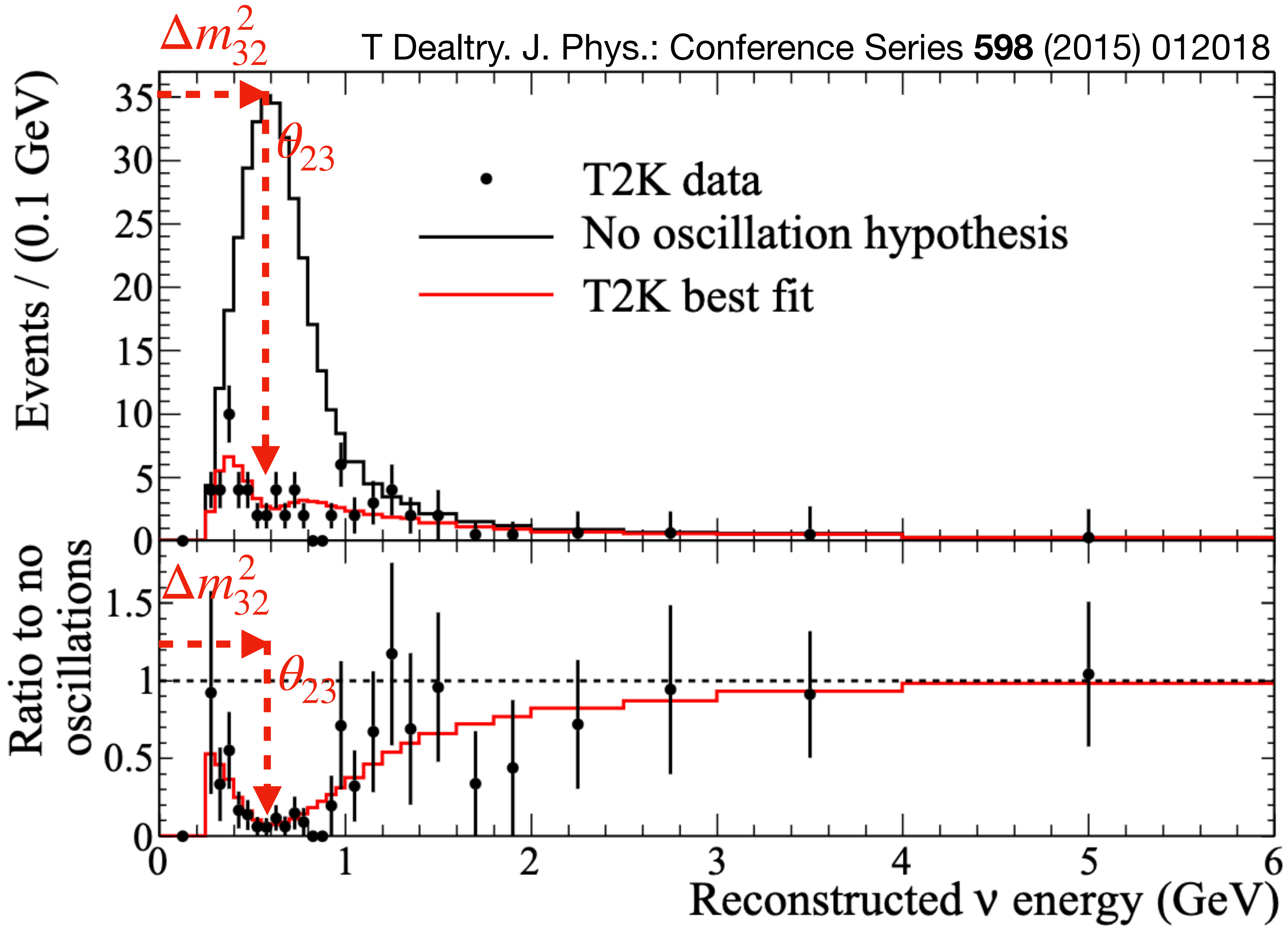
At long baselines, looking for **ν_μ disappearance** approx. reduces to 2ν

$$P_{\mu\mu} \sim \sin^2 2\theta_{23} \sin^2\left(1.267\frac{\Delta m^2_{32} L}{E}\right)$$

T Dealtry. J. Phys.: Conference Series **598** (2015) 012018



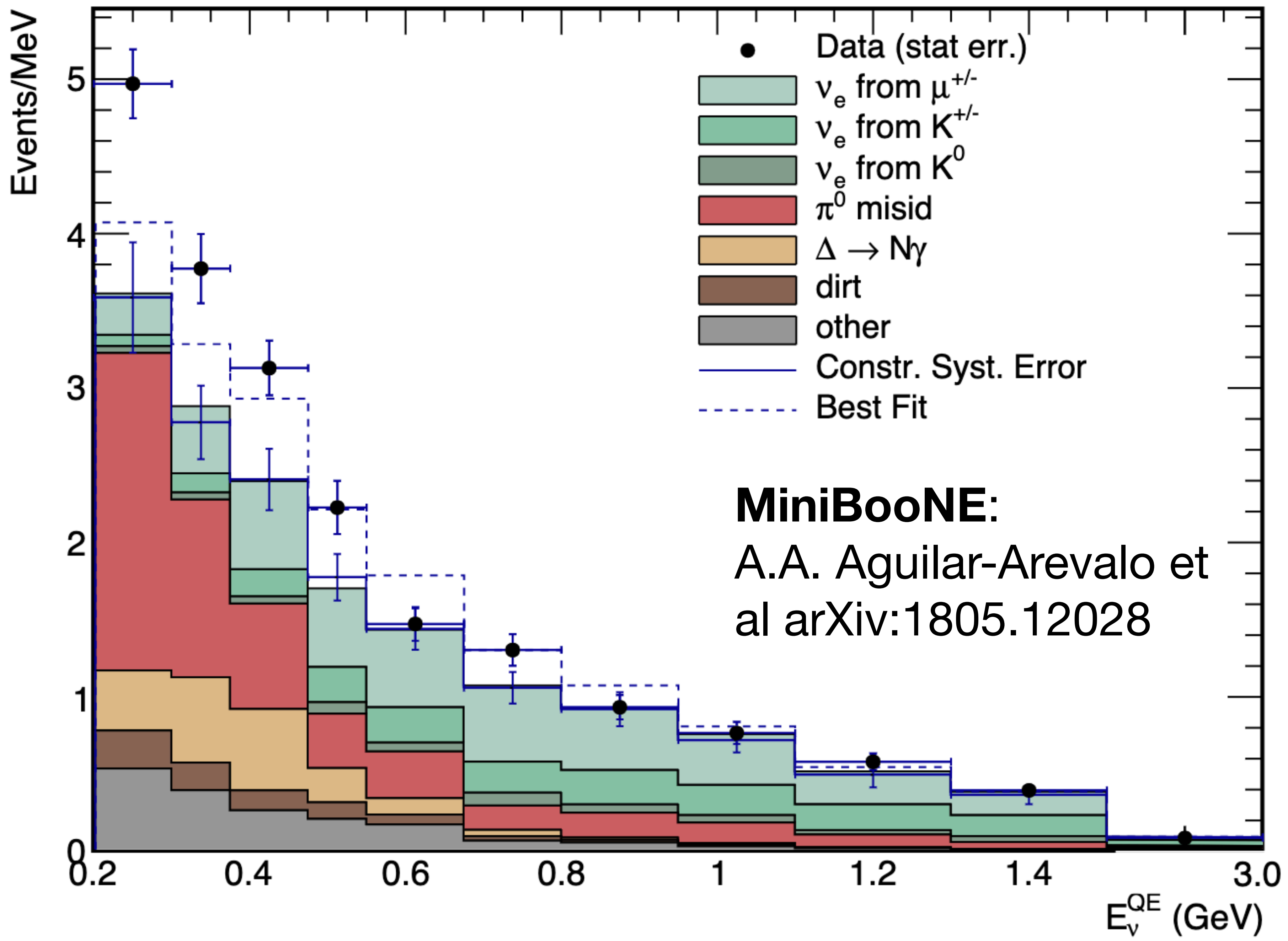
ν_e appearance:

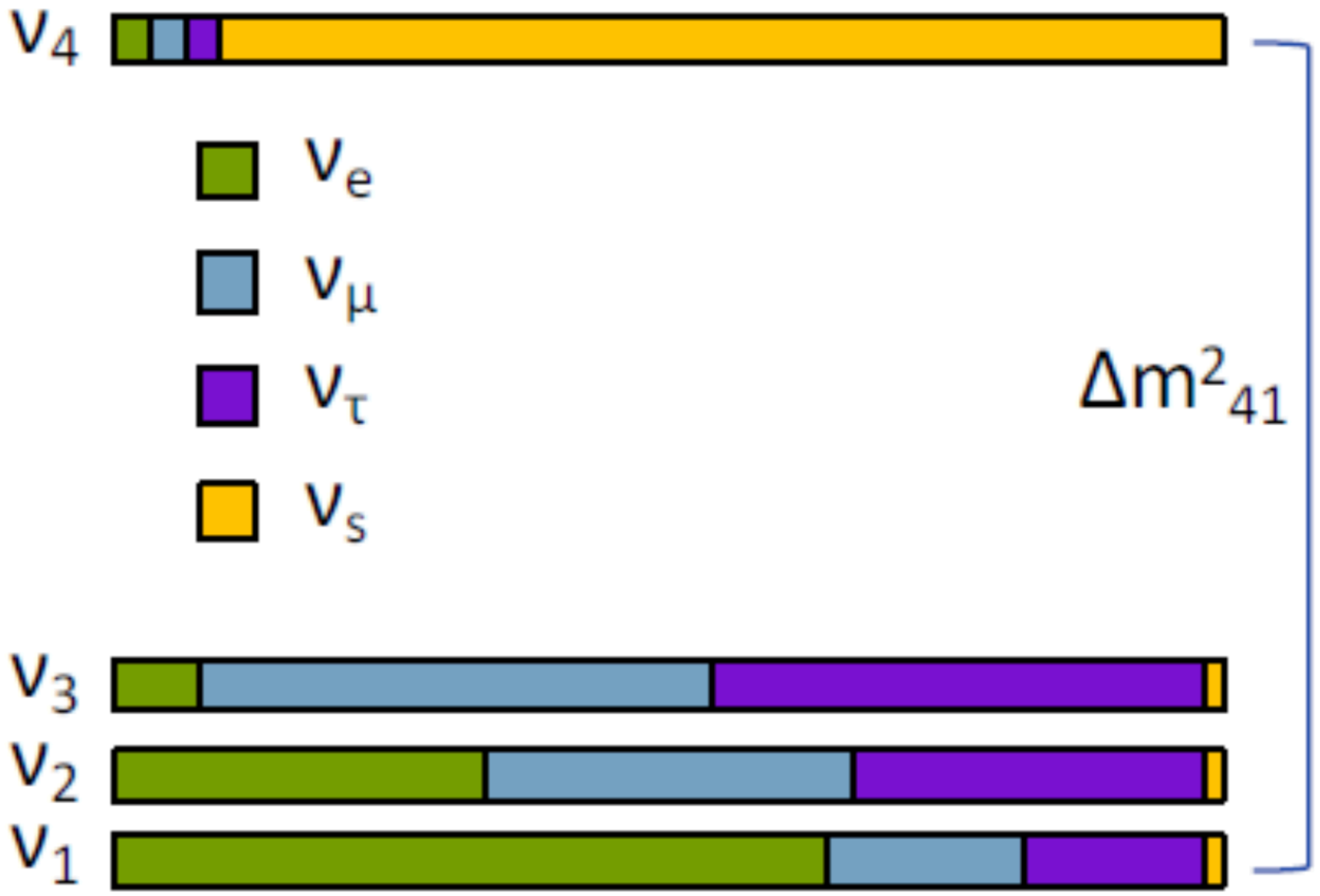
$$P(\nu_\mu \to \nu_e) = P_{\text{atm}} + 2\sqrt{P_{\text{atm}} P_{\text{sol}}}(\cos \Delta_{32} \cos \delta_{\text{CP}} \mp \sin \Delta_{32} \sin \delta_{\text{CP}}) + P_{\text{sol}}$$

M.D. Messier. Nuclear Physics B 908 (2016) 151–160

More than 3 neutrinos?

- Another open Q: **are there more than the 3 known ν?**
    - Think there should only be 3 lepton families, but:
    - Some experiments measured unexpected **excess** of ν_e candidates(events with electron activity identified)
    - Standard oscillation: mass differences 10^{-3} or lower. **~100s MeV ν @ 100s of m = eV scale ν.**
        - Short distance effect = **"short baseline"**
    - So, if it is an "oscillation" like effect, is ν_μ oscillating to **sterile states** and then to ν_e at short distances
    - Global program wishes to clarify picture or understand if it is alternative process
        - **SBN Program at Fermilab (later) aims to control backgrounds and utilizes multiple detectors**





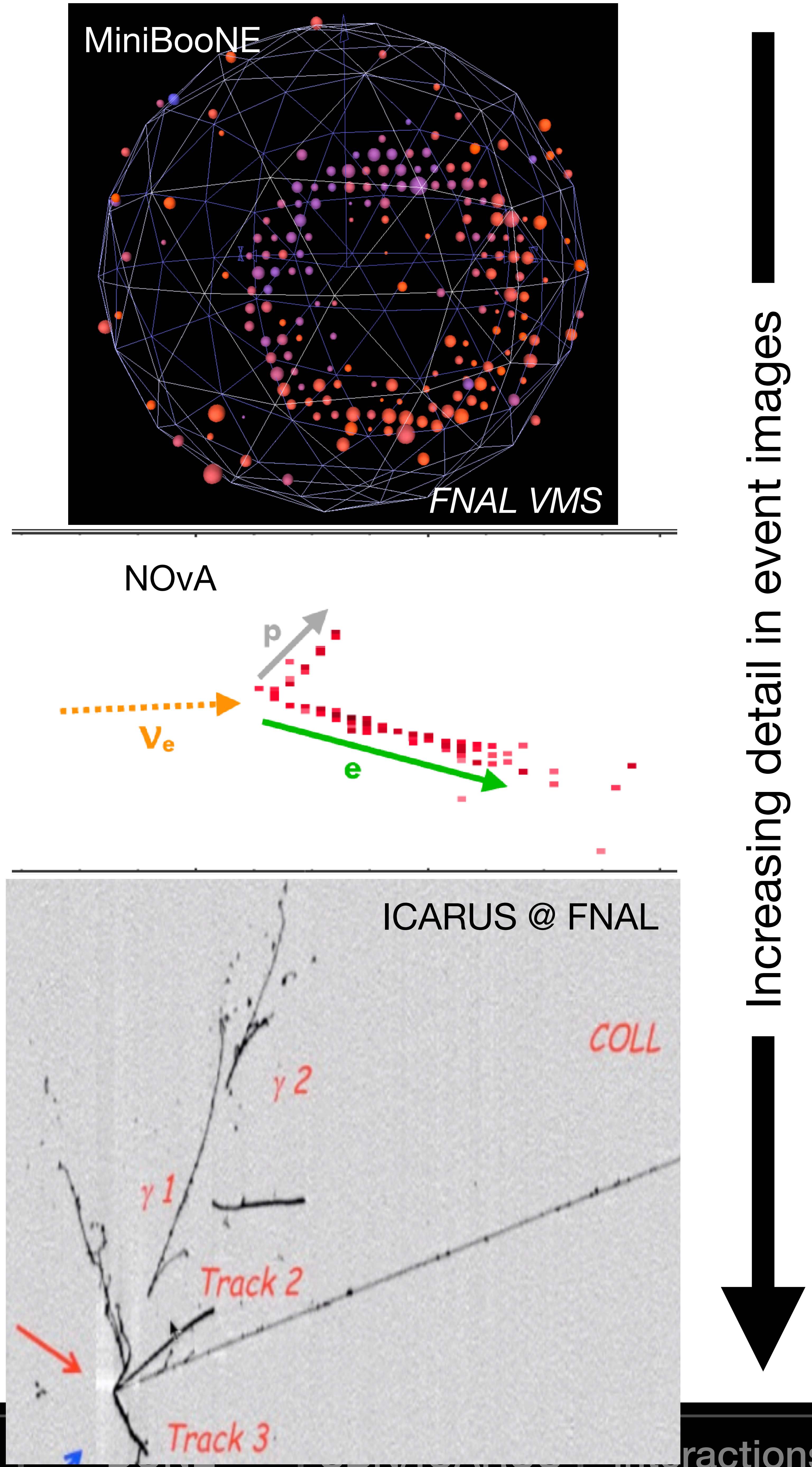
L. Cremonesi NNN2023 sides

Addressing the Questions

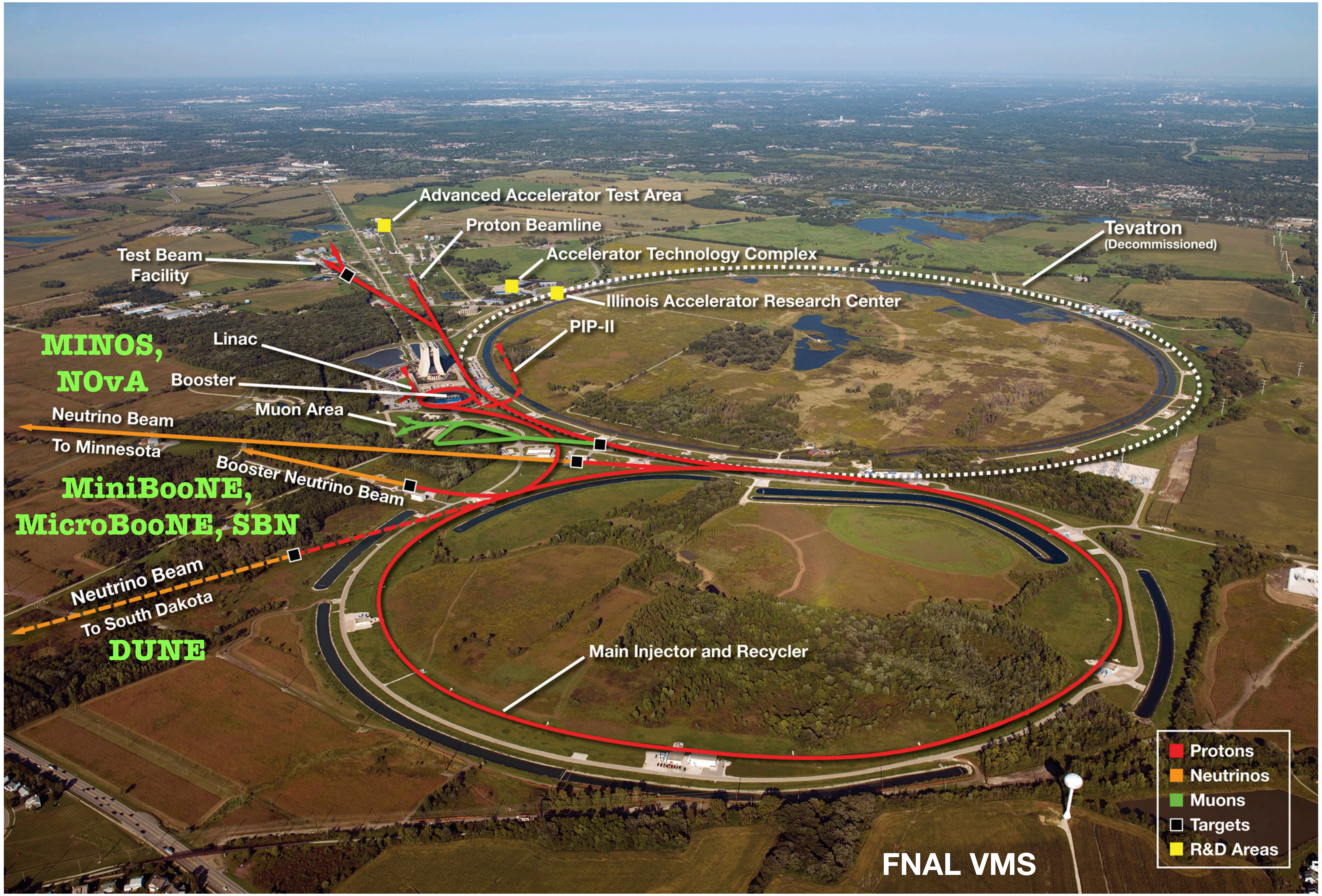
- In order to improve sensitivity of next generation experiments to address these questions, a few main categories of things needed: **high yield sources, powerful detectors, better analysis/models**

Improved precision on measurement, sensitivity →

- Higher statistics → Sources: lots of ν; Bigger detectors
- Better measurements → Tracking, energy, signal/background
- Improved analysis → E.g. better models; smaller error bars



Accelerator-based Neutrino Sources



Fermilab accelerator complex has 2 neutrino beam lines.

Booster Neutrino Beam (BNB): 8 GeV protons, sterile ν searches

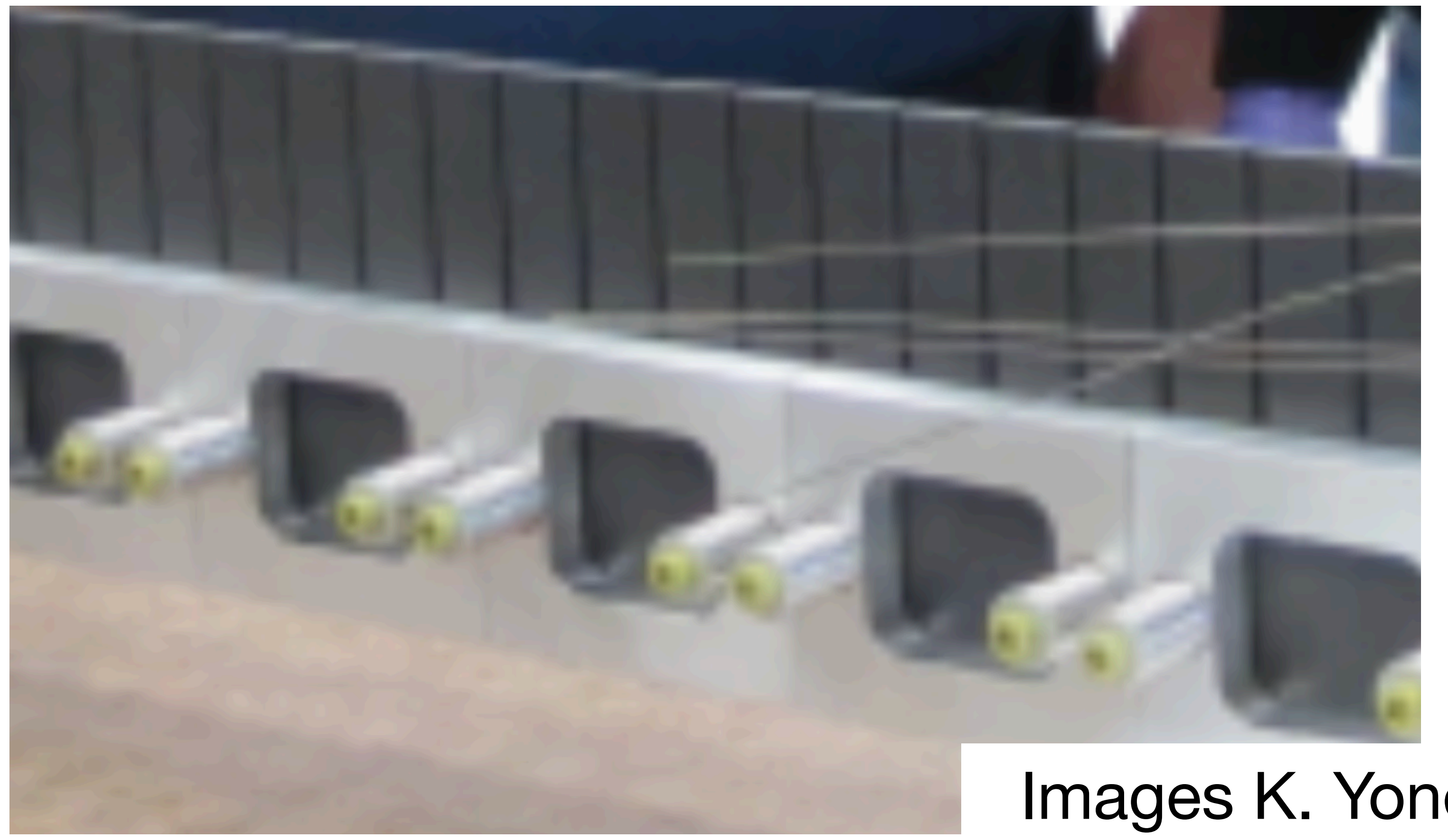
Neutrinos at the Main Injector (NuMI): 120 GeV protons, ν oscillation

DUNE will use a new beamline being constructed. **Will be ~3x more powerful than NuMI (~2.4 MW vs *typically* 700kW)**

Accelerator-based Neutrino Sources

Depiction from NOvA (A. Himmel talk)

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



Images K. Yonehara slides

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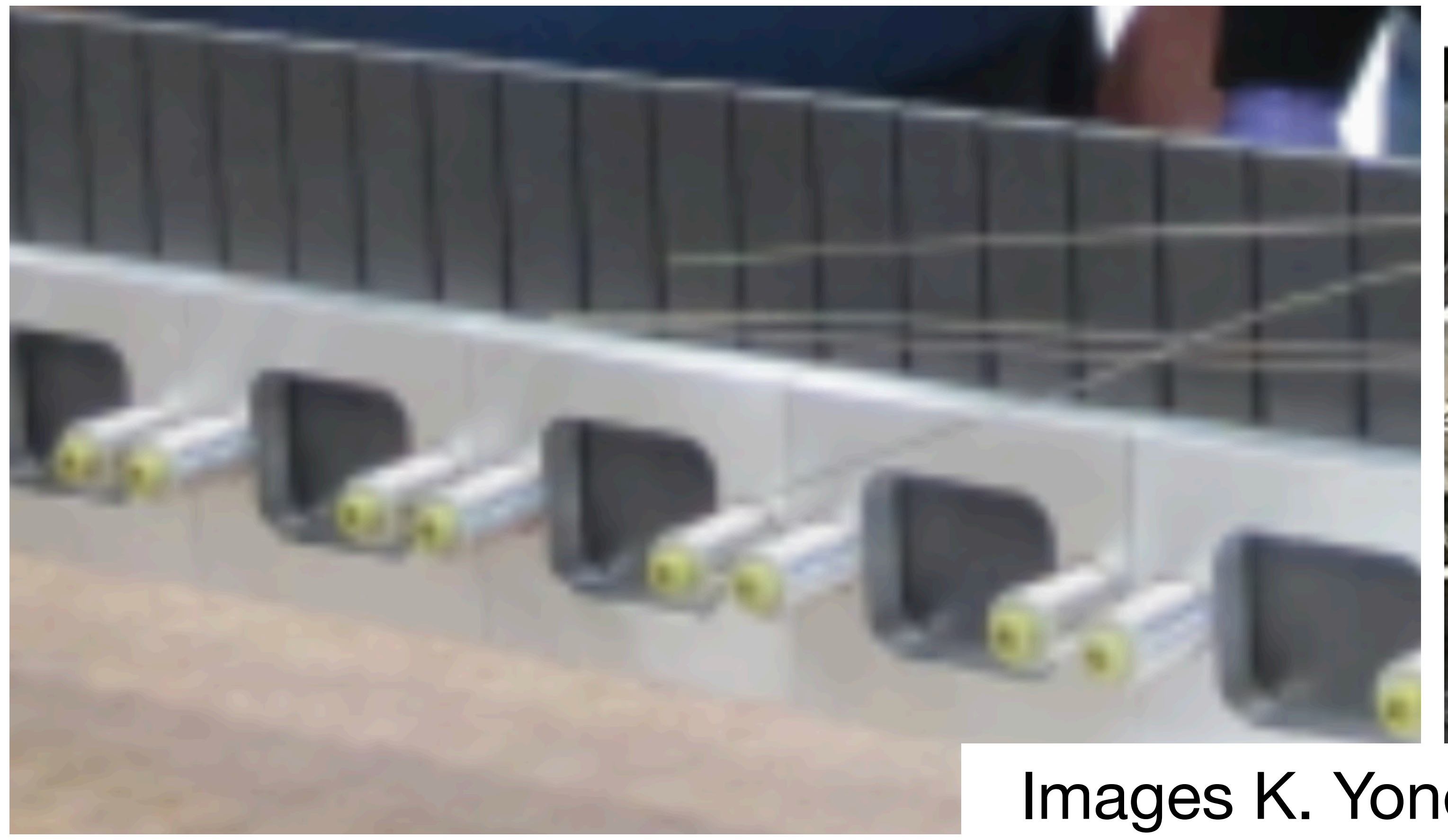
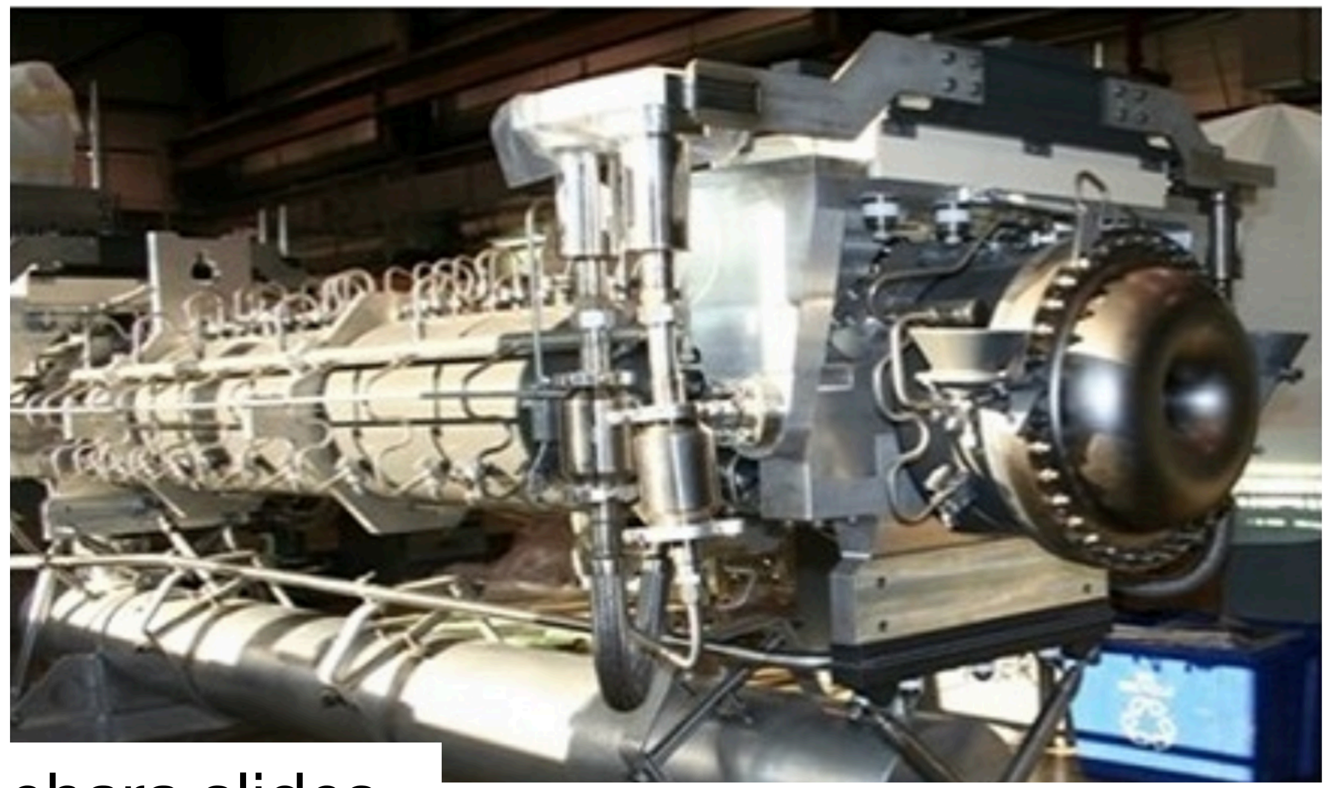
Energetic protons impinge on target material (e.g. C, Be)

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





Images K. Yonehara slides

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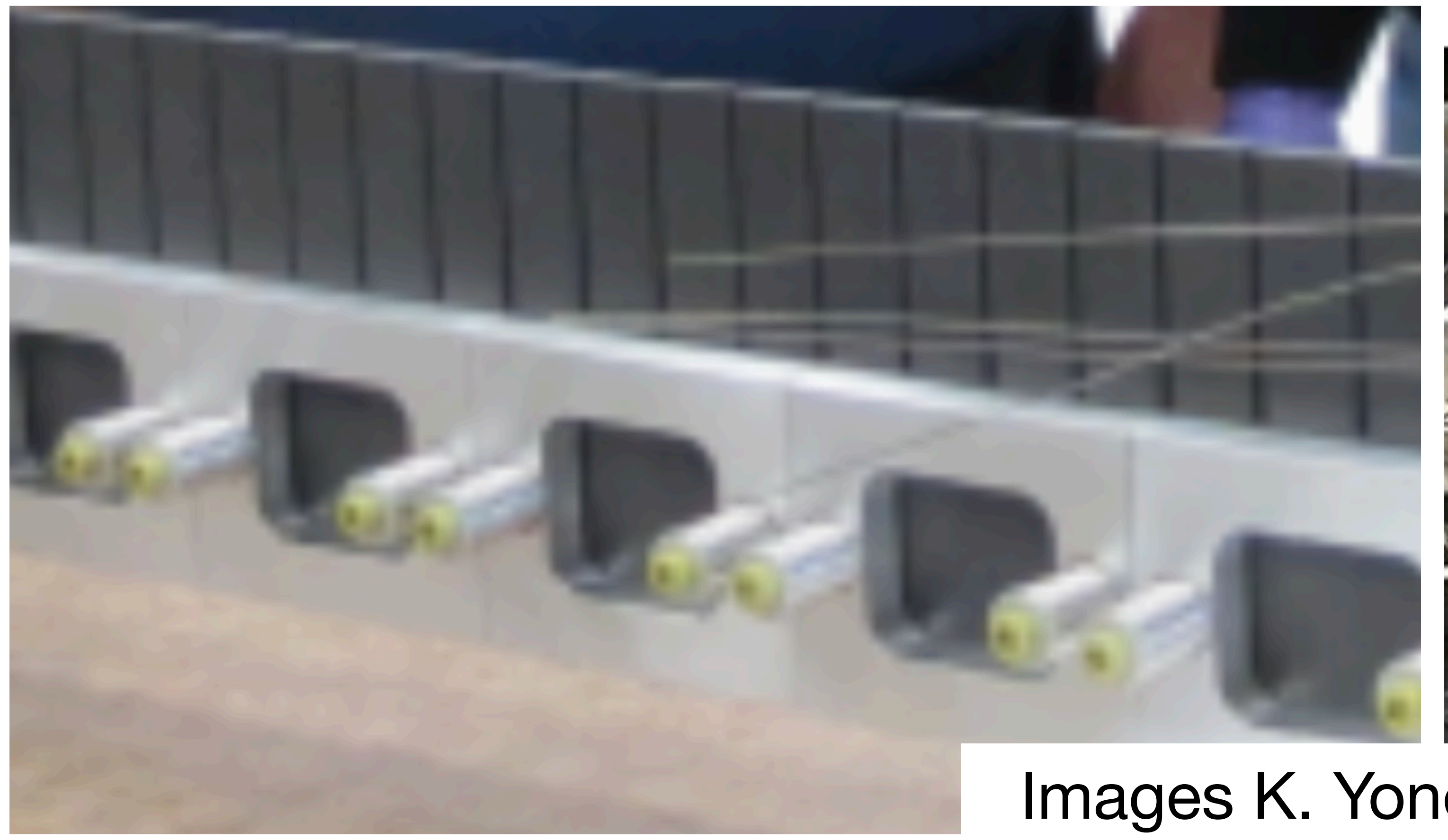
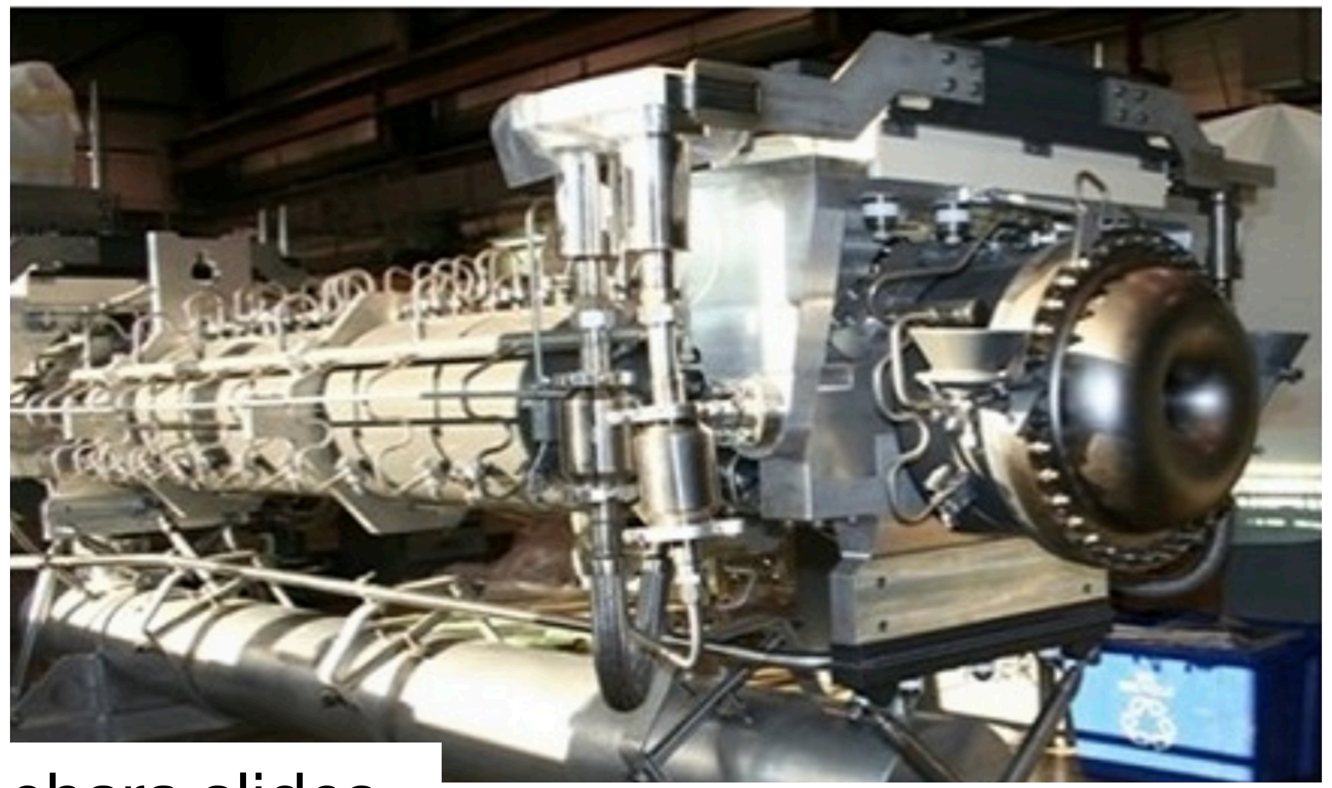
Long empty pipe for particles to decay and produce neutrinos

Images K. Yonehara slides

Accelerator-produced neutrino sources used by the experiment which discovered ν_μ (1962)

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

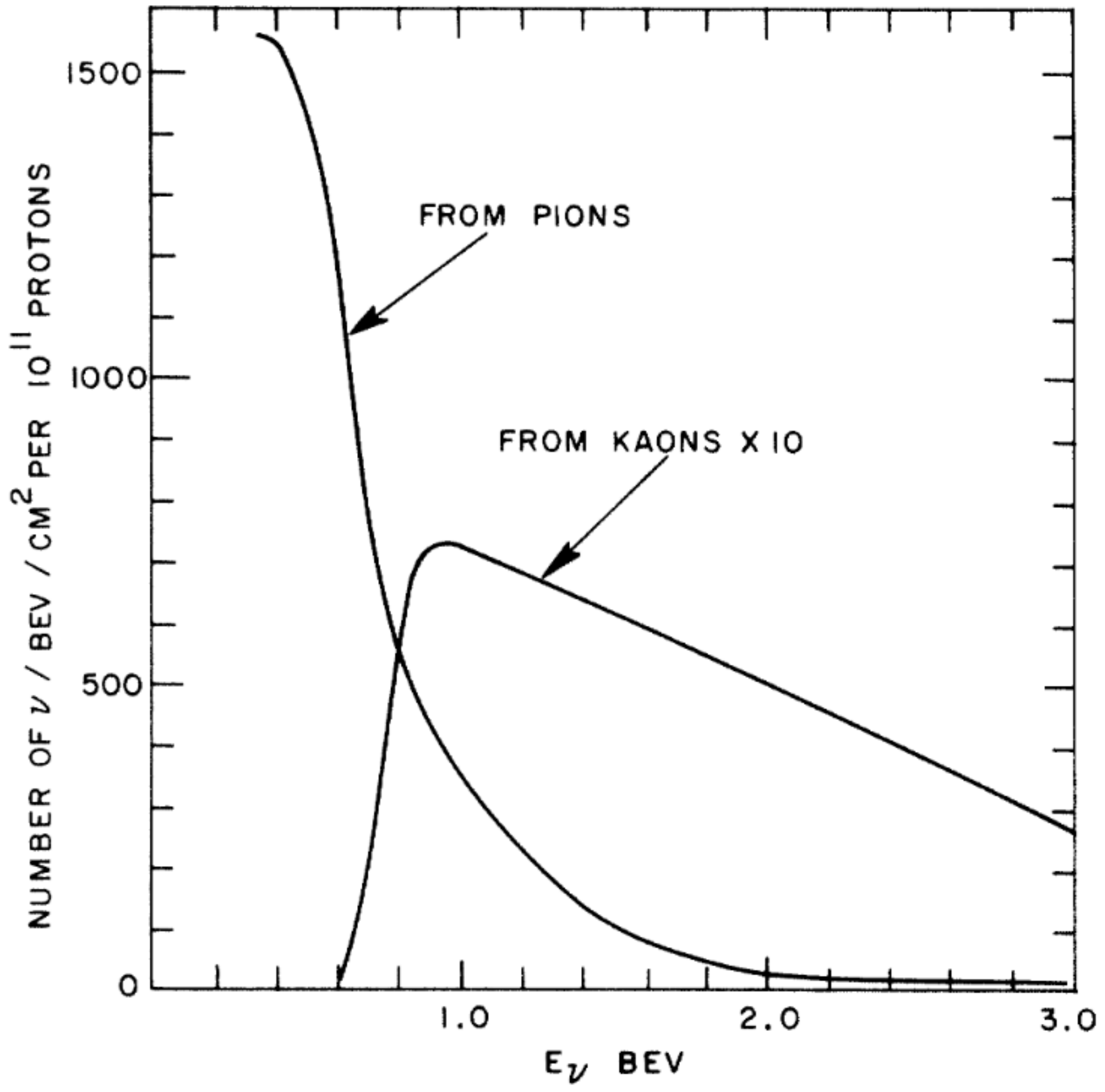
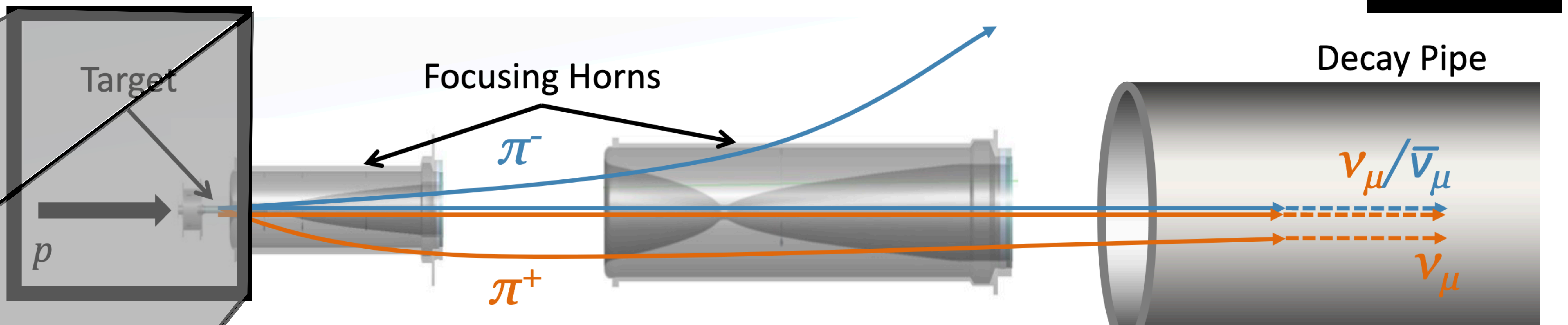


FIG. 2. Energy spectrum of neutrinos expected in the arrangement of Fig. 1 for 15-BeV protons on Be.

What do we mean when we say our beam is 700 kW or 2.4 MW?



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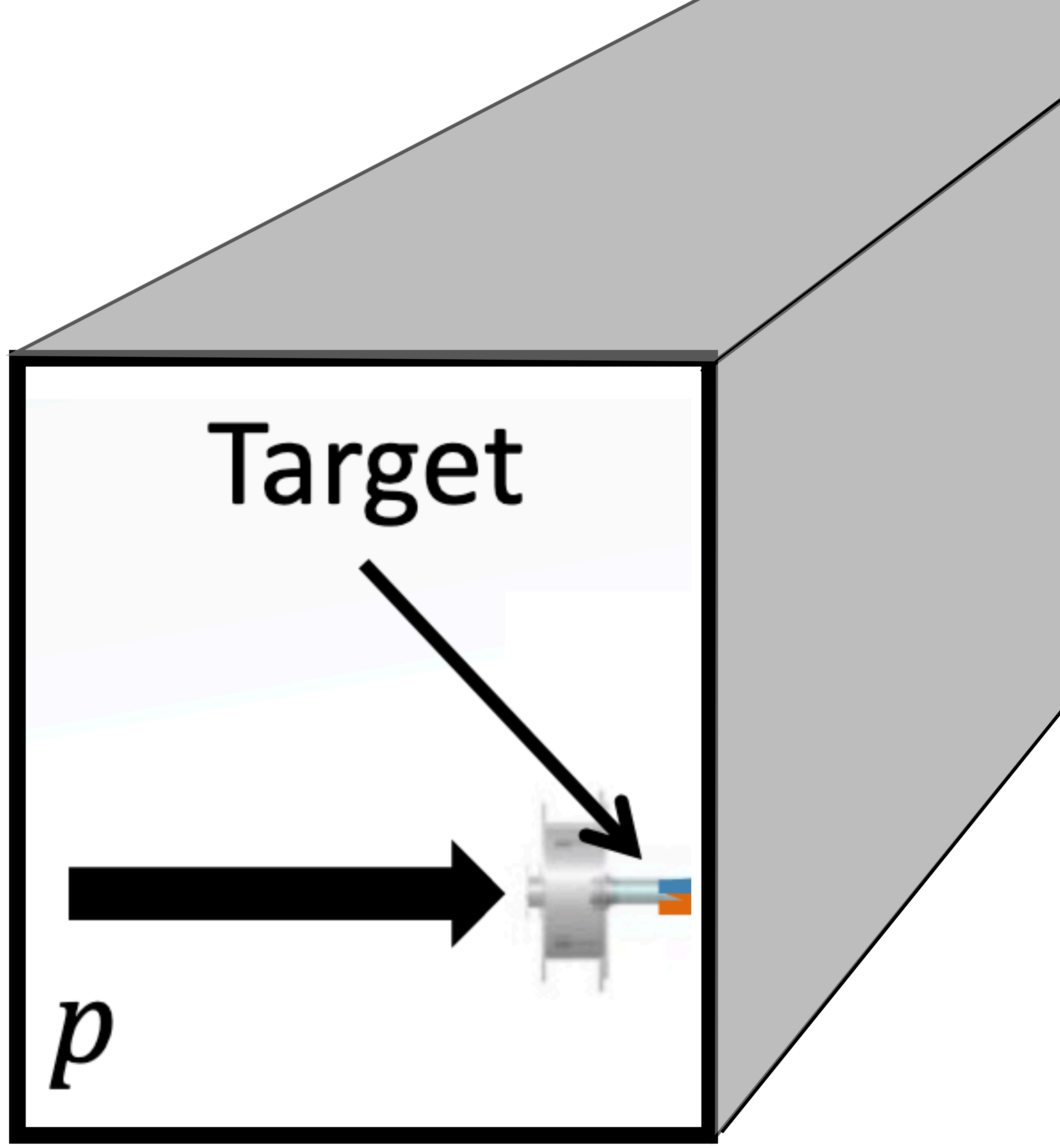
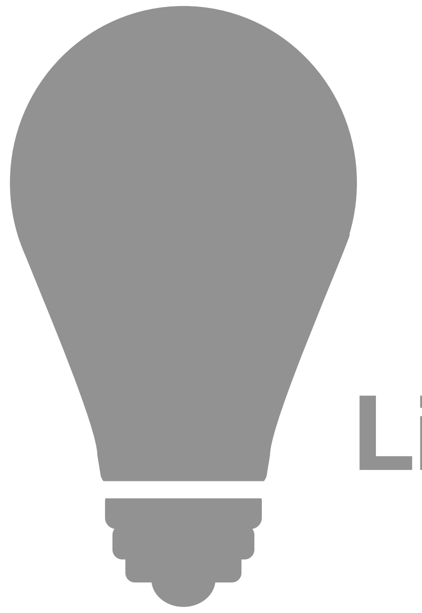


It's all about the yield of protons on the target, so relates to the "exposure" of the experiment and how many neutrinos we expect to see.

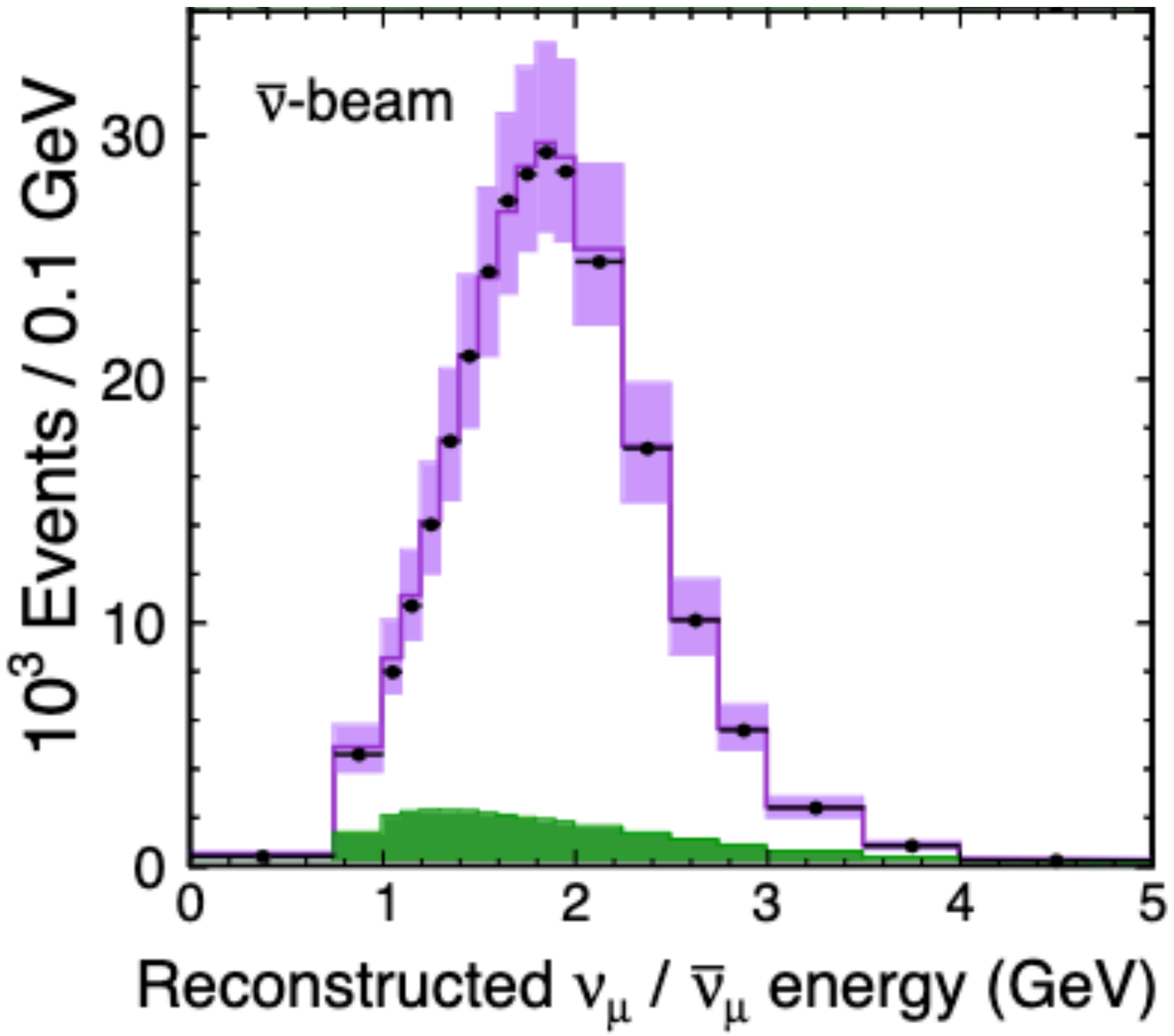
- **Main injector accelerates protons to E = 120 GeV**
- **Each spill sends about 5×10^{13} protons to target**
- **Spills are about 1.2-1.3 seconds apart**

120 GeV ~ 1.92×10^{-8} J so 1 spill is about 9.61×10^{5} J
Divide by 1.3 s → 740 kW



Lightbulb ~ 100 W → beam power ~ 7.4 thousand bulbs!

Characterize ν_μ , $\bar{\nu}_\mu$ and ν_e , $\bar{\nu}_e$ components of beam



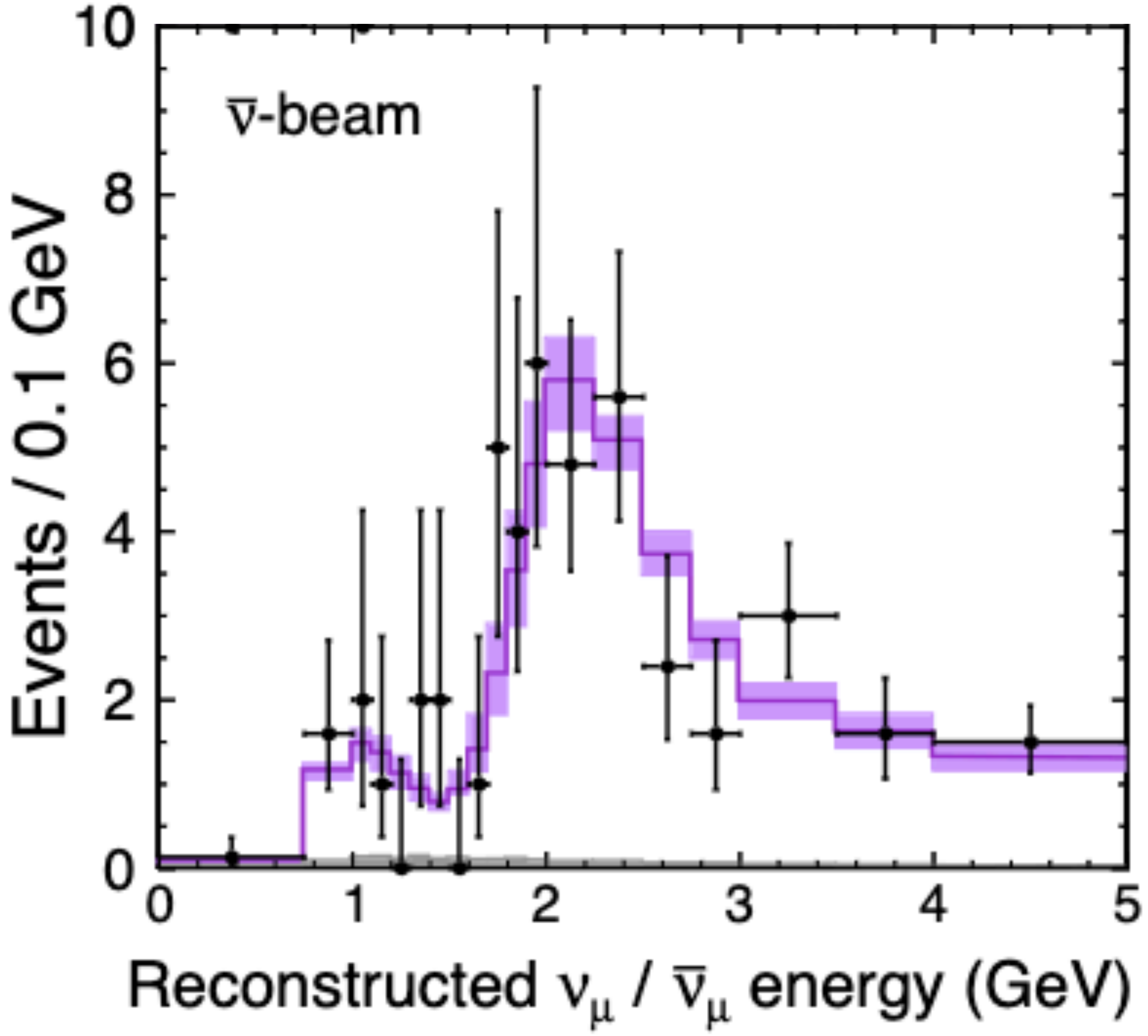
Can make corrections and adjustments to the prediction based on ND data to project (or extrapolate) to the FD

Adapted from

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

Characterize ν_μ , $\bar{\nu}_\mu$ and ν_e , $\bar{\nu}_e$ components of beam

Measure impact of oscillation



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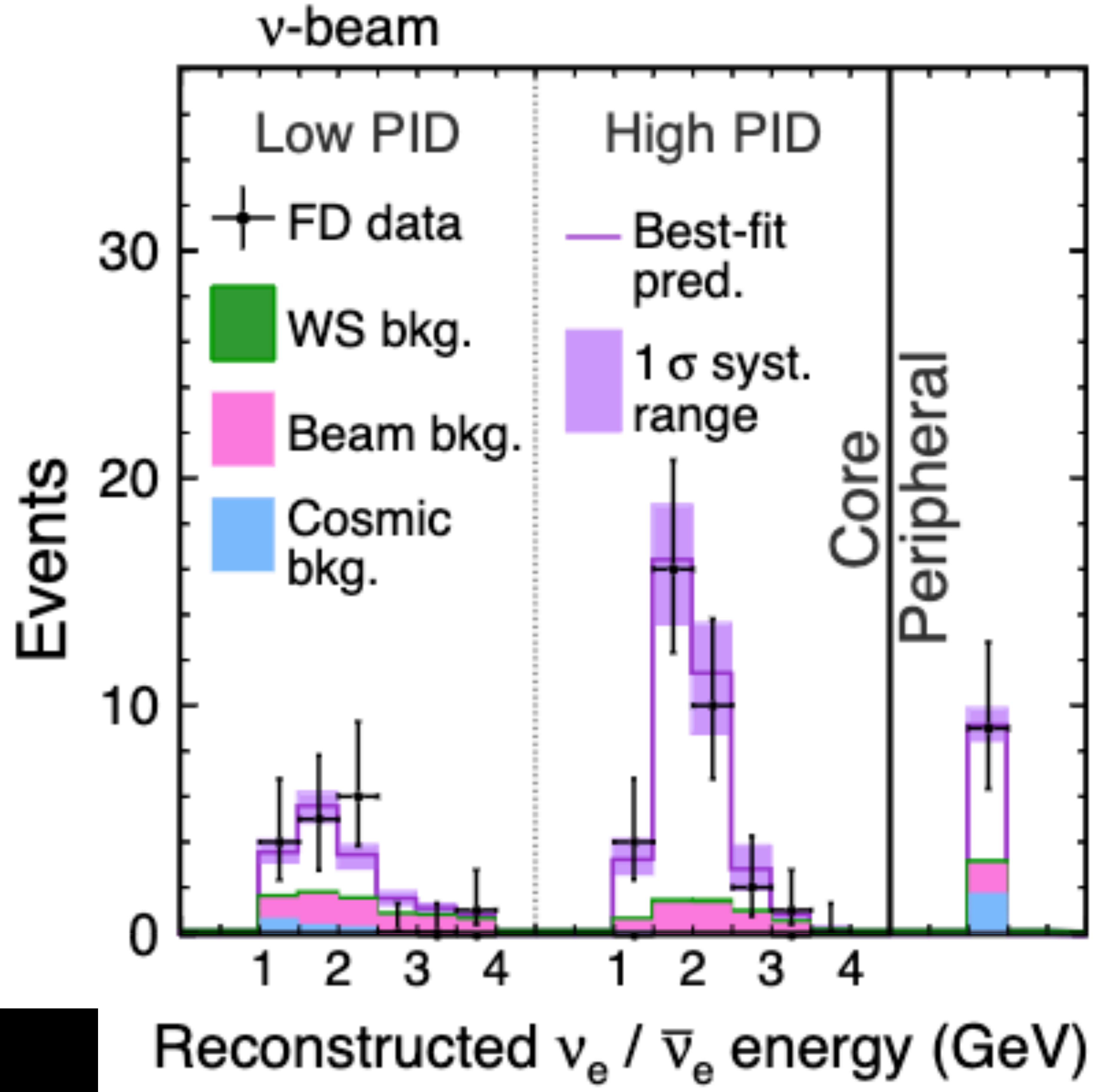

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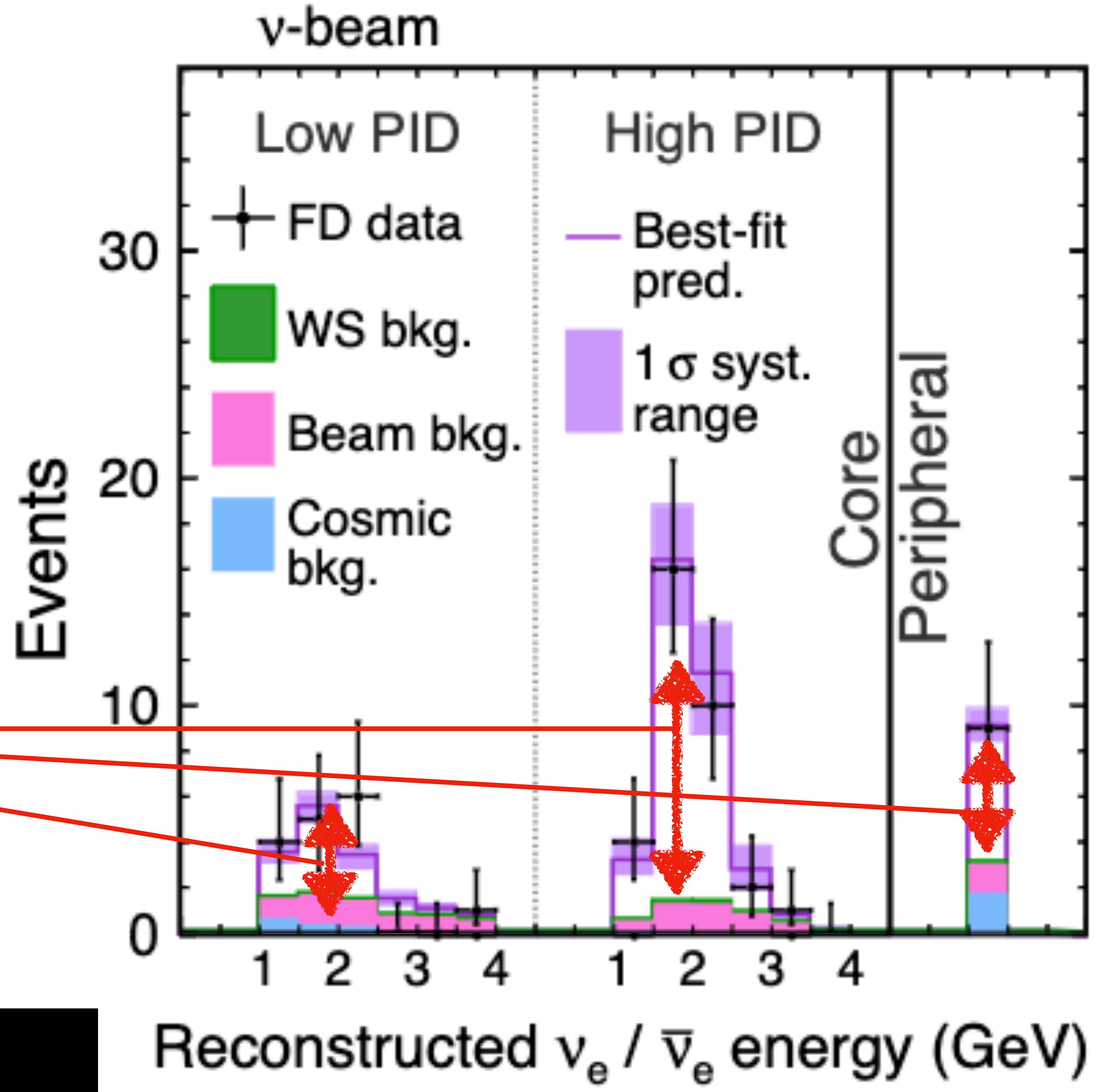
M. A. Acero et al. (NOvA). Phys. Rev. Lett. 123, 151803 (2019). arXiv:1906.04907

Sources

Characterize ν_μ , $\bar{\nu}_\mu$ and ν_e , $\bar{\nu}_e$ components of beam

Measure impact of oscillation

Oscillation ν_e appearance



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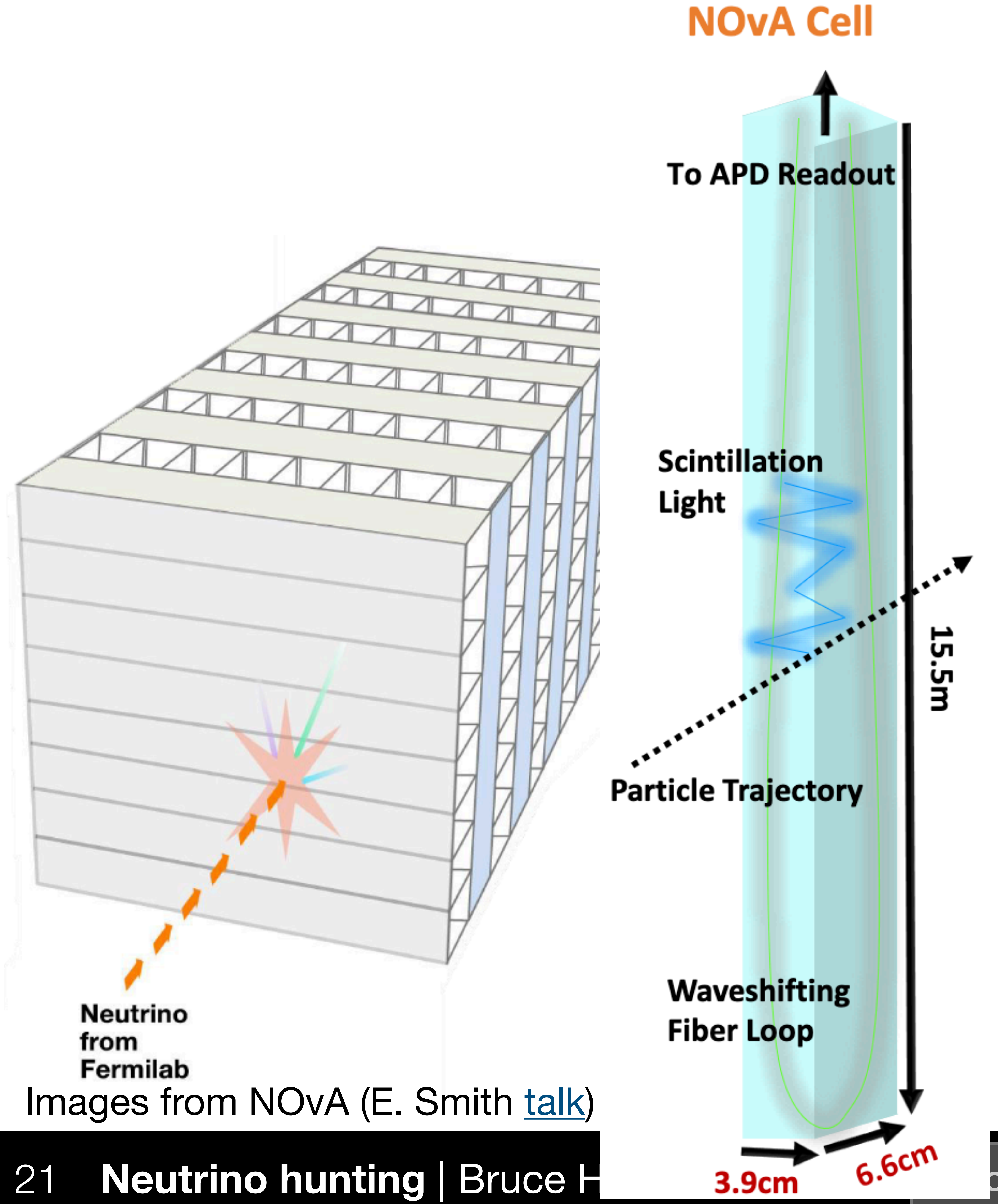
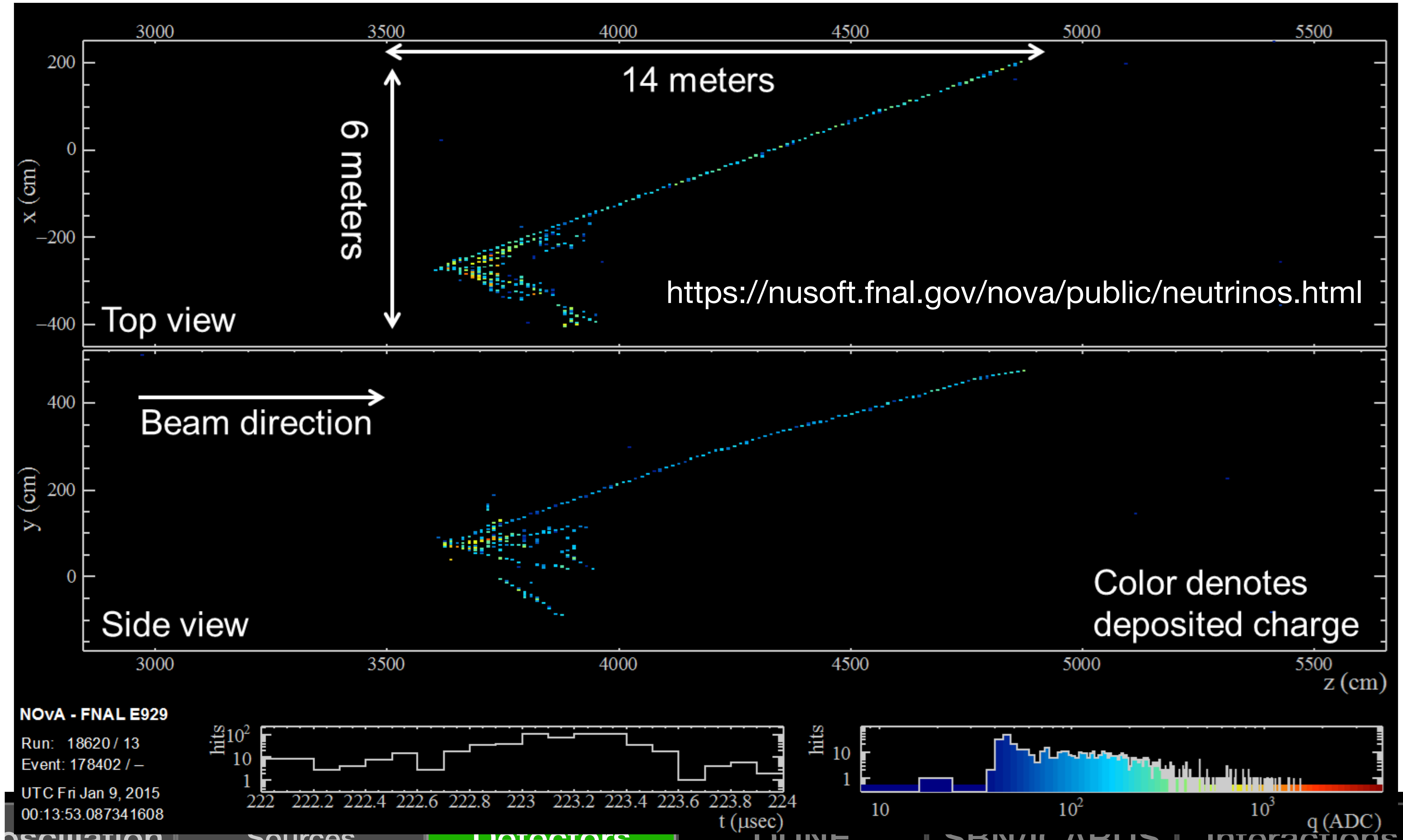
Choice of Detector Medium/Type



Images from NOvA (E. Smith talk)

A common detector functionality is "tracking calorimeter." NOvA is the current generation long-baseline oscillation experiment working with this type of detector.

Cells few cm wide. What if we could improve capabilities?



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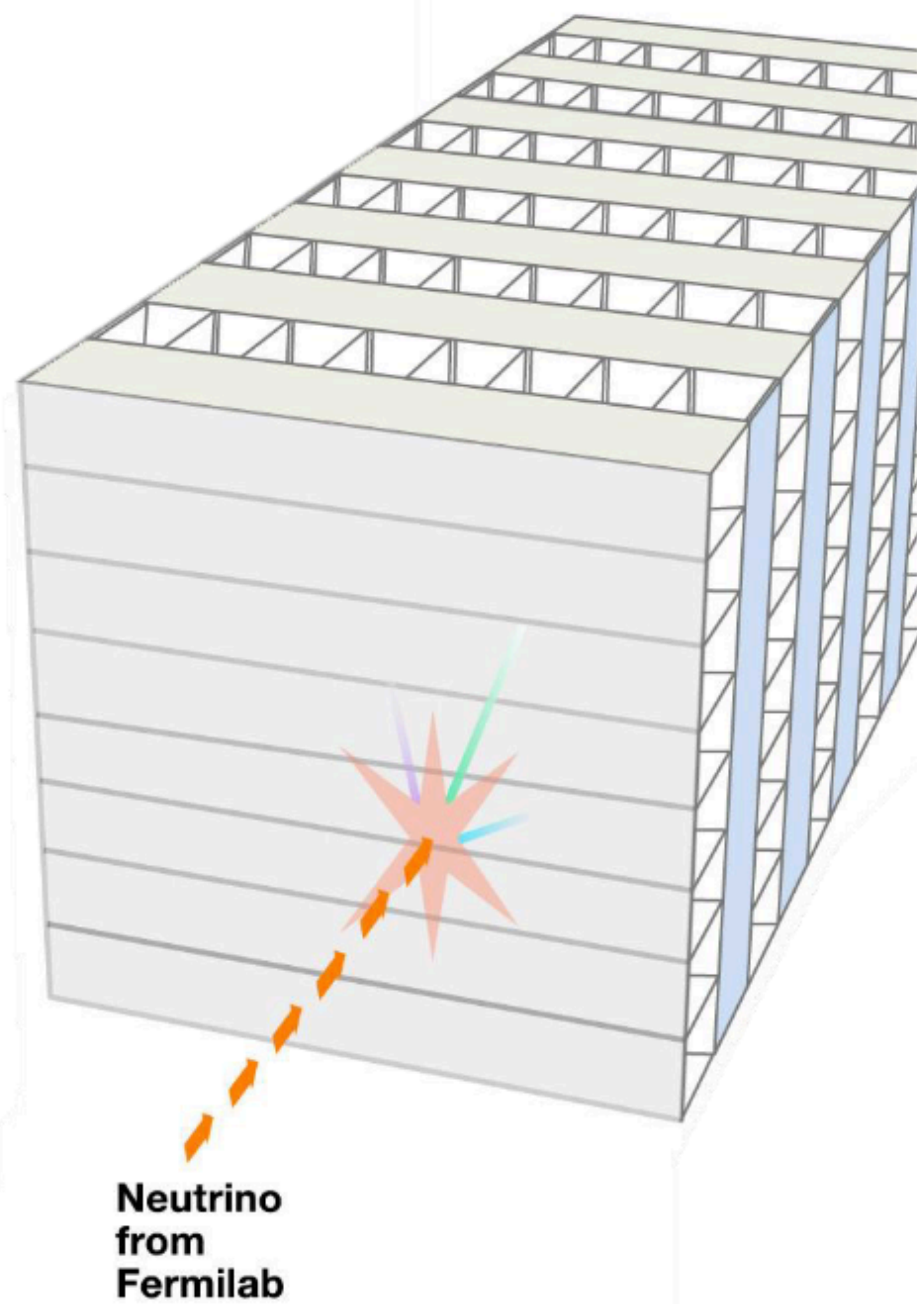
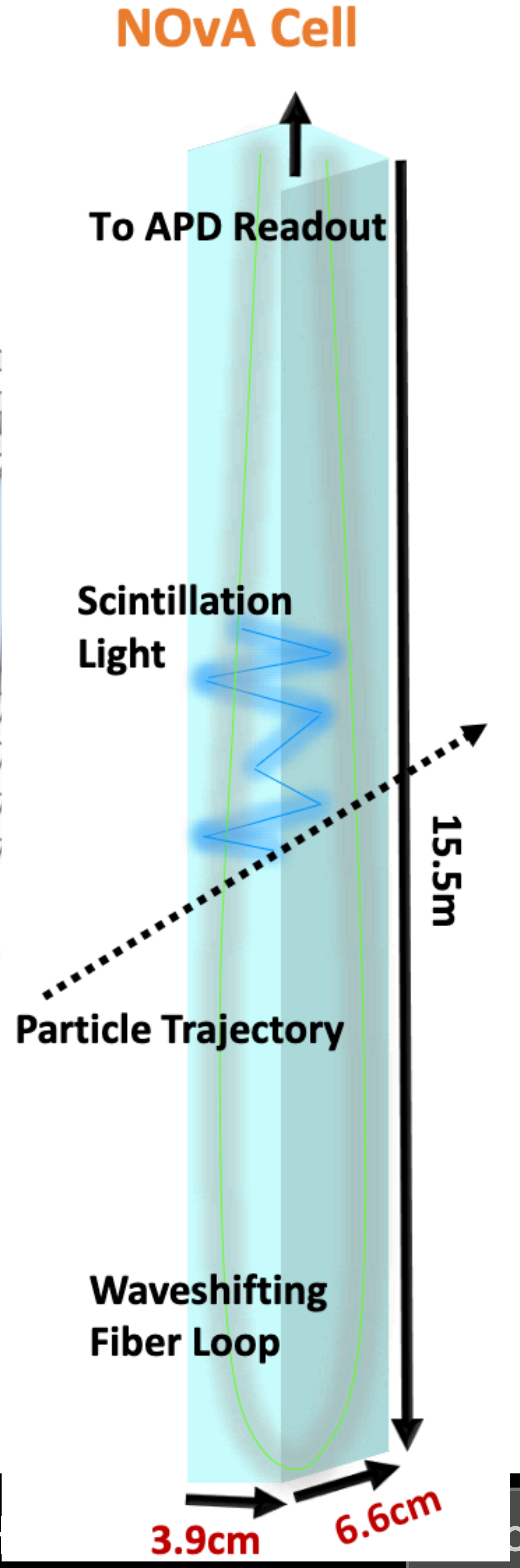
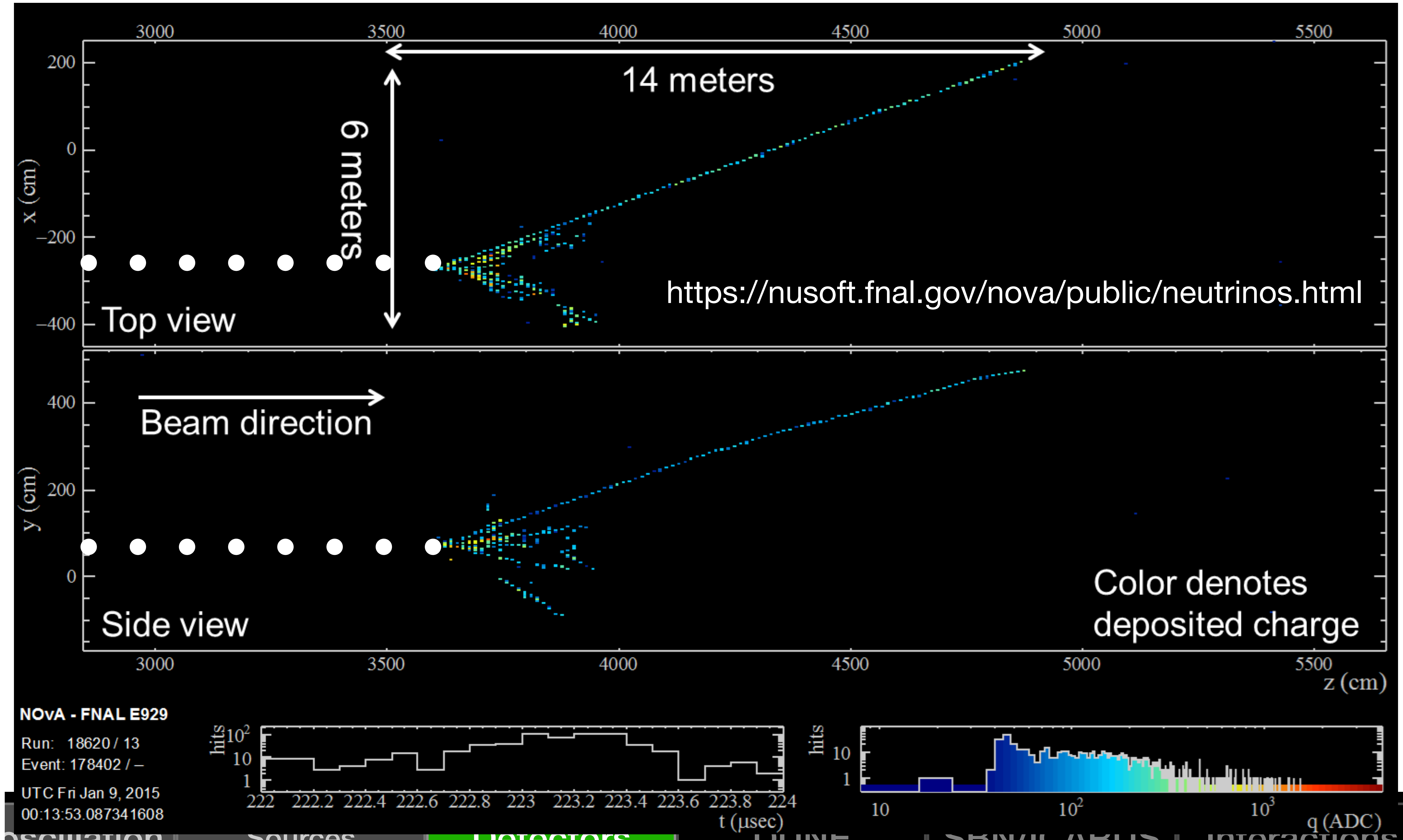
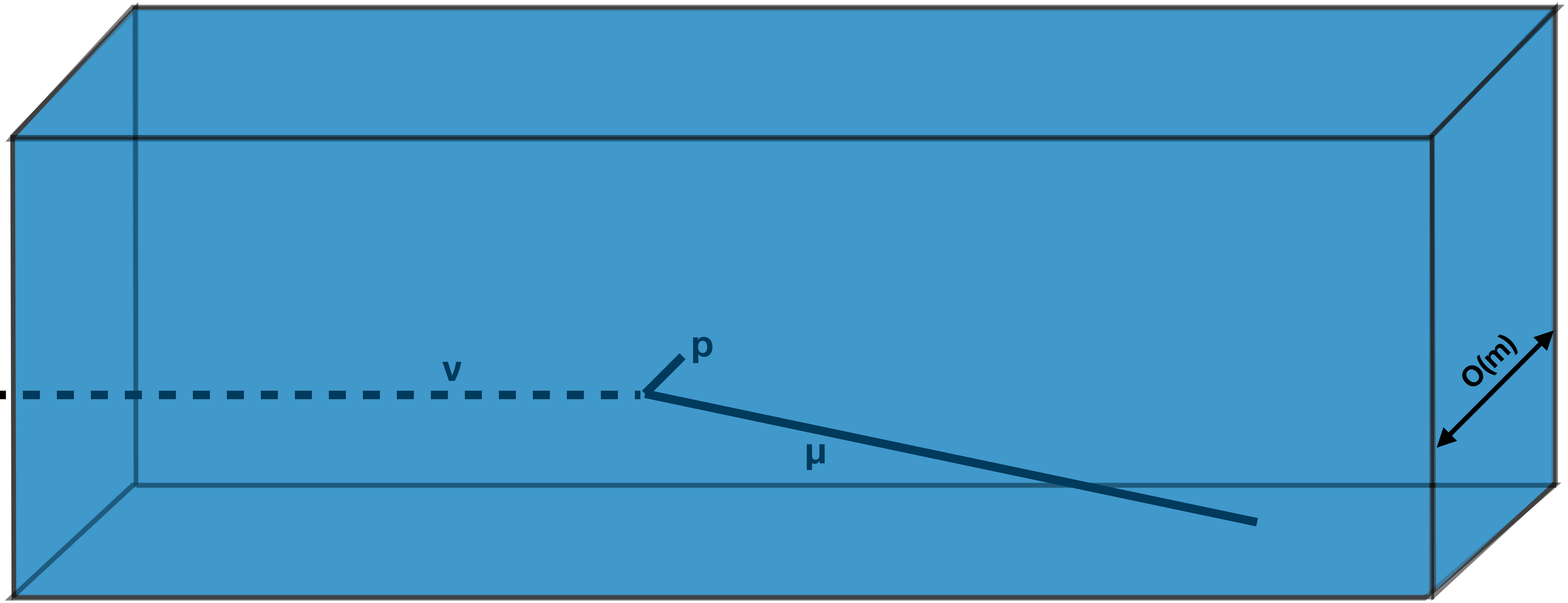






Images from NOvA (E. Smith talk)

Liquid Argon as Detector Medium



Liquid Argon as Detector Medium

Liquid Argon as Detector Medium

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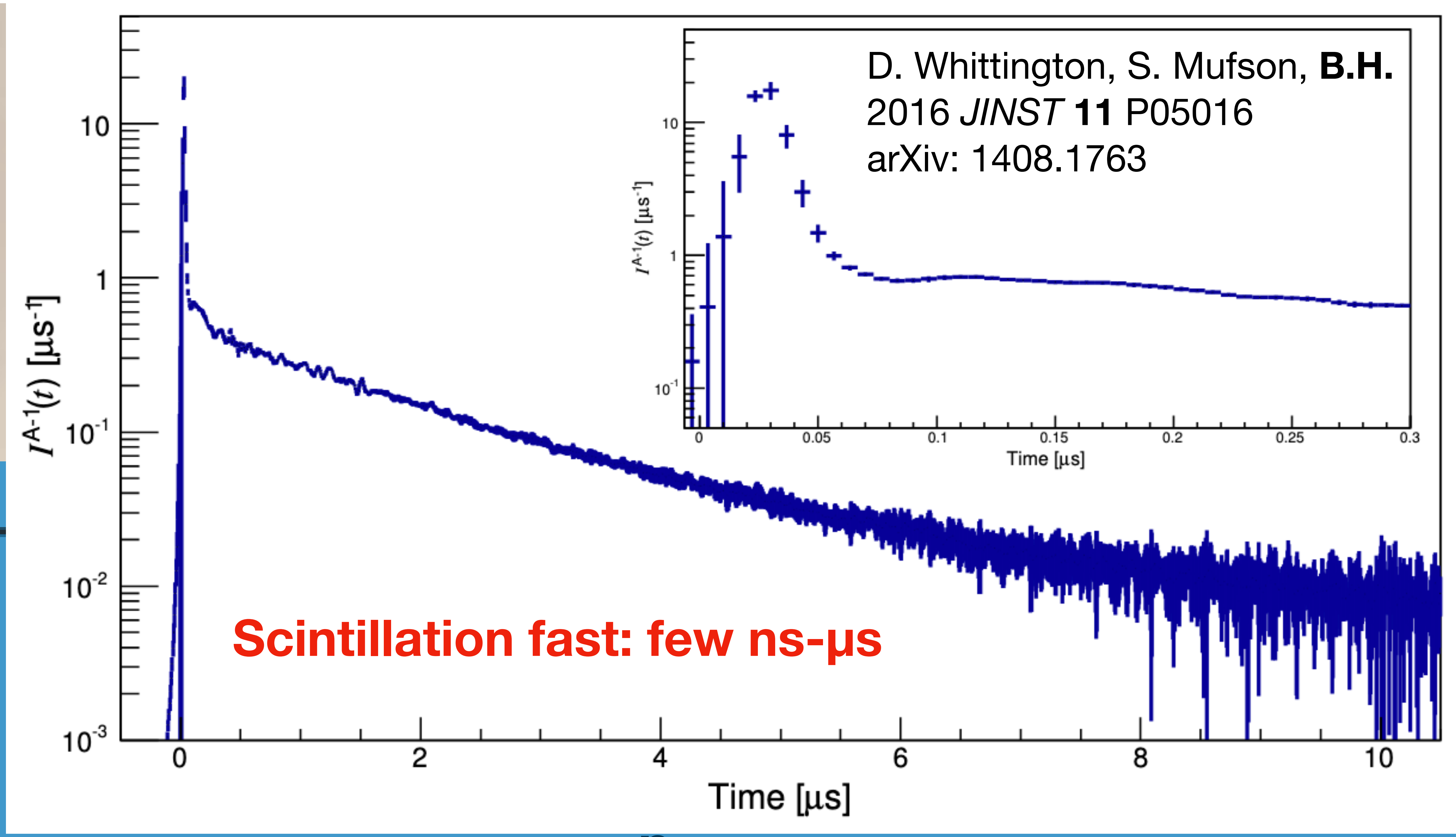
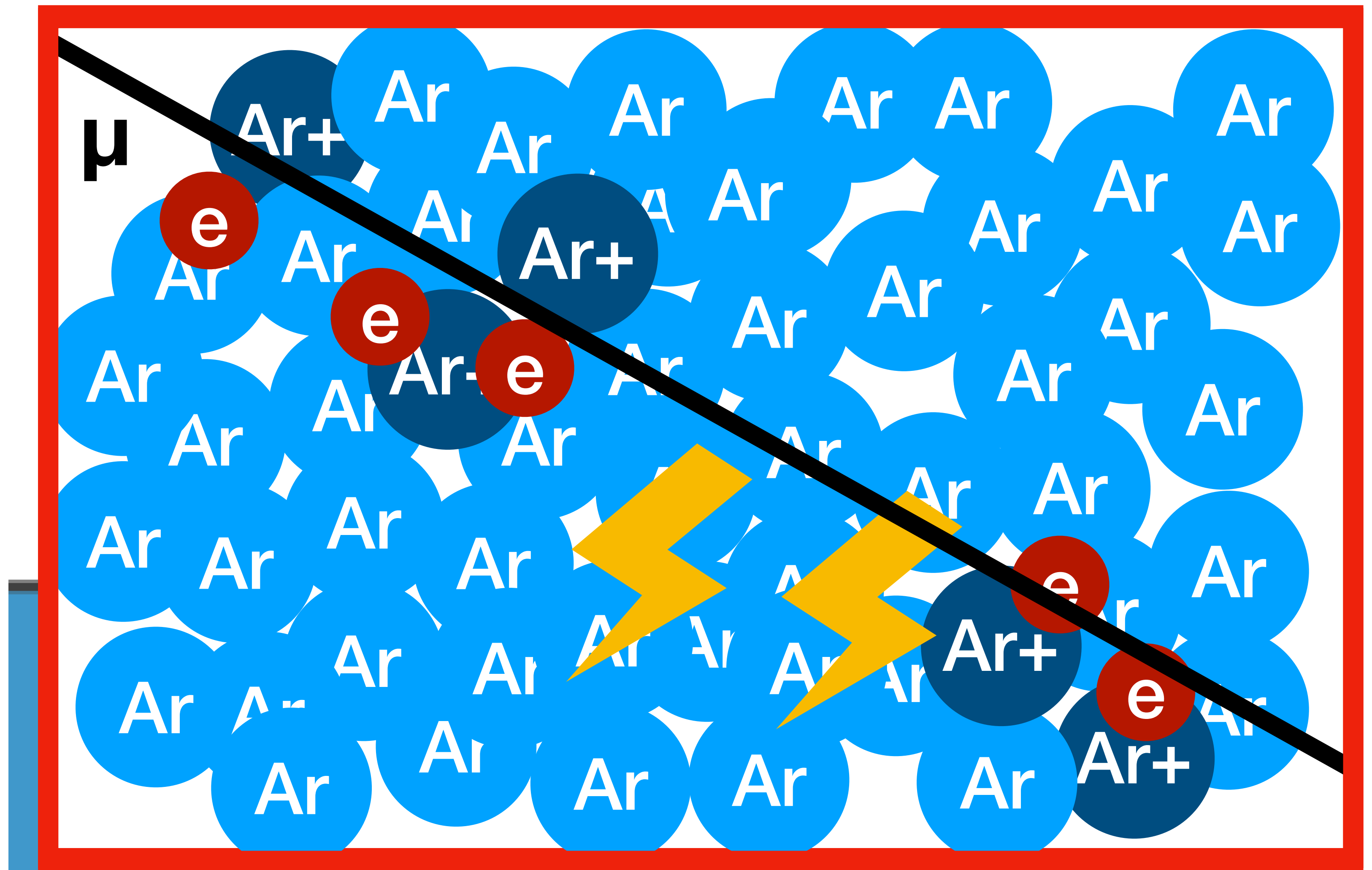
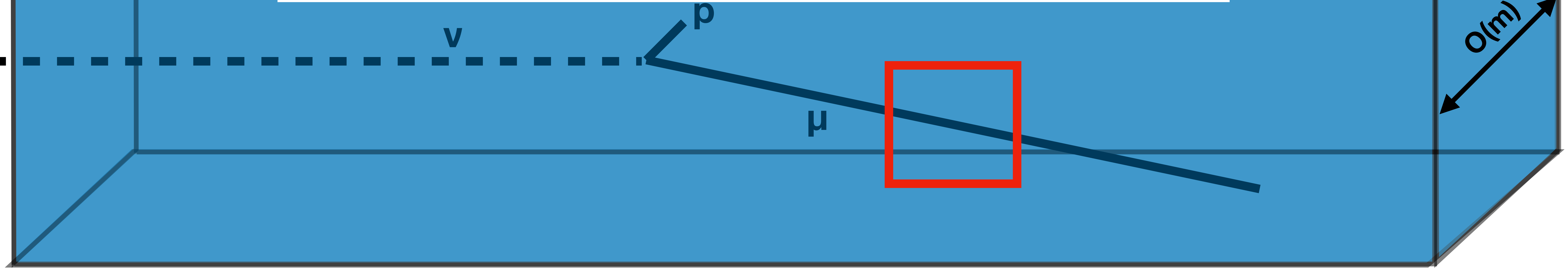
Liquid Argon as Detector Medium





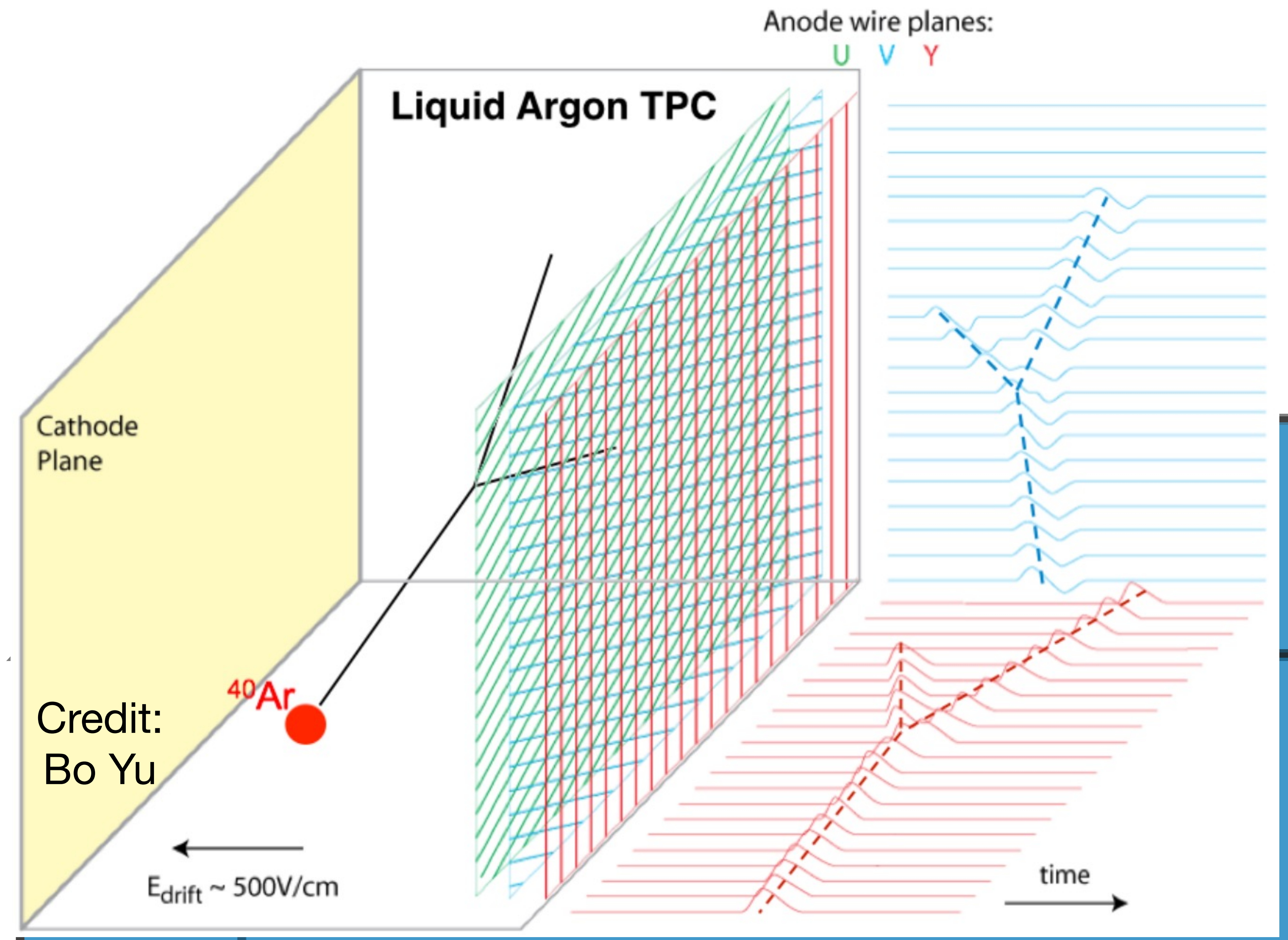


Scintillation

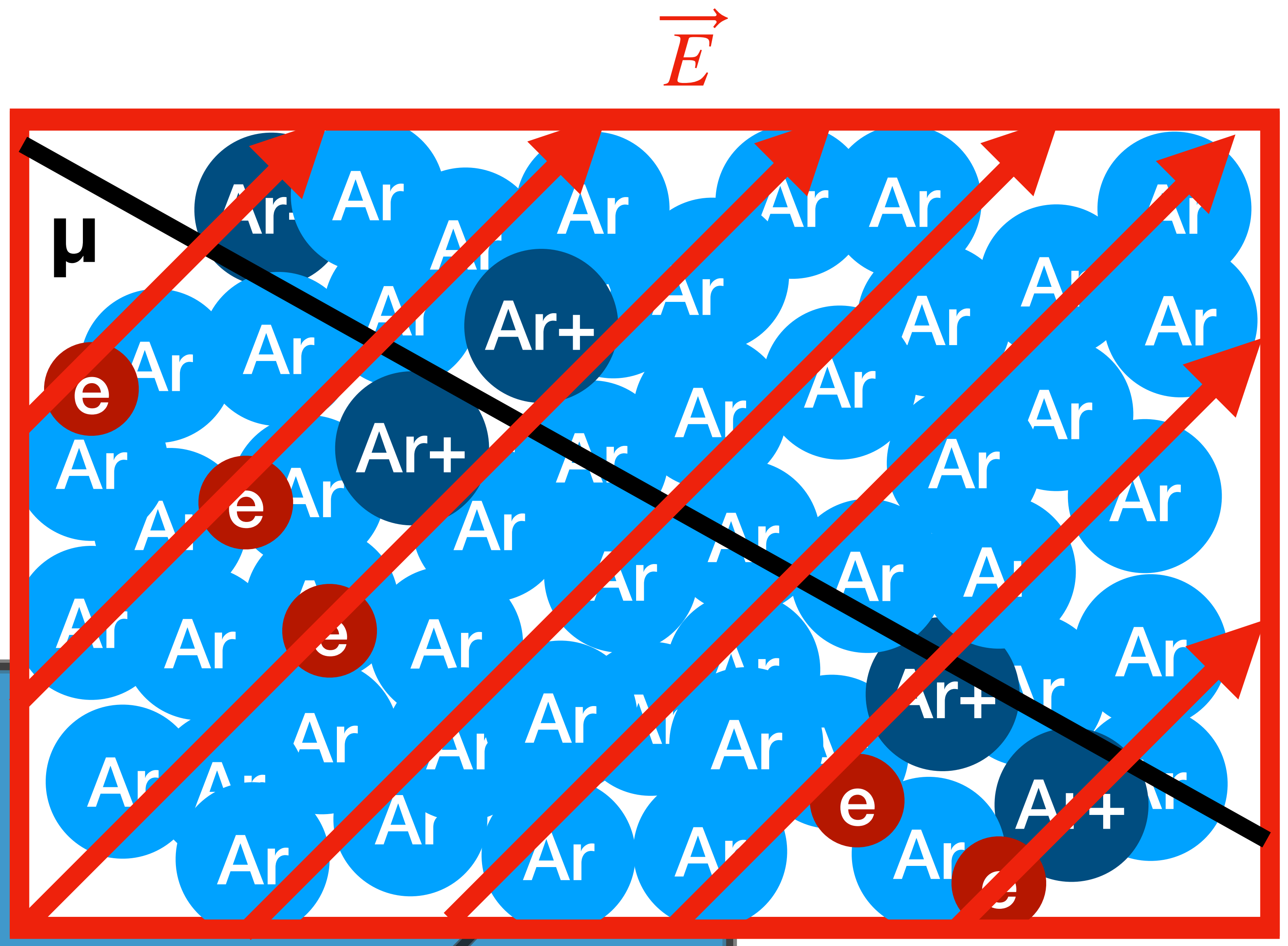
Fast (ns-μs)

Vacuum Ultraviolet

Liquid Argon as Detector Medium



Ionization drift much slower: ~1.6 mm/μs at E=500 V/cm



Ionization

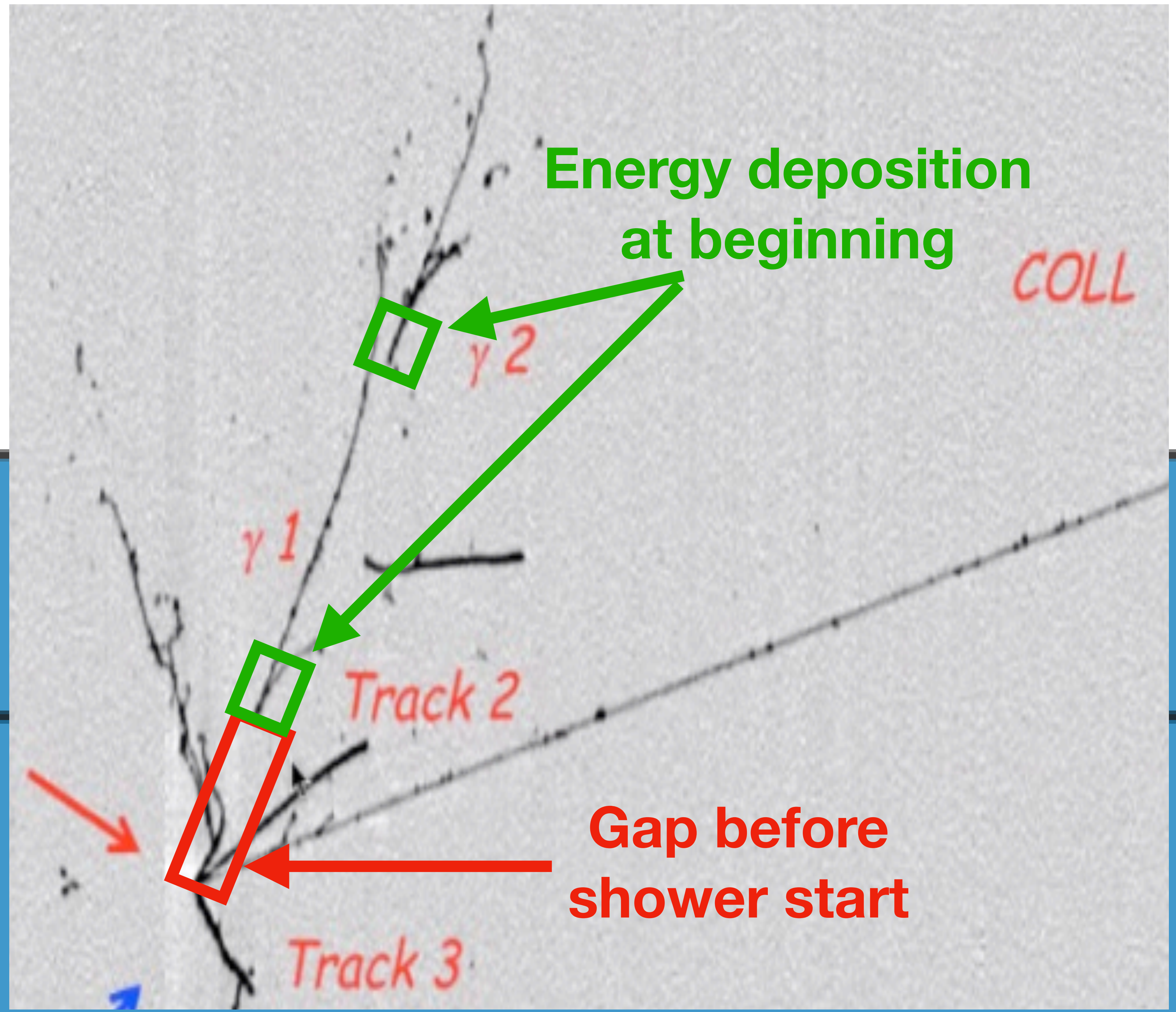
Tracking (wires, others ~mm apart)

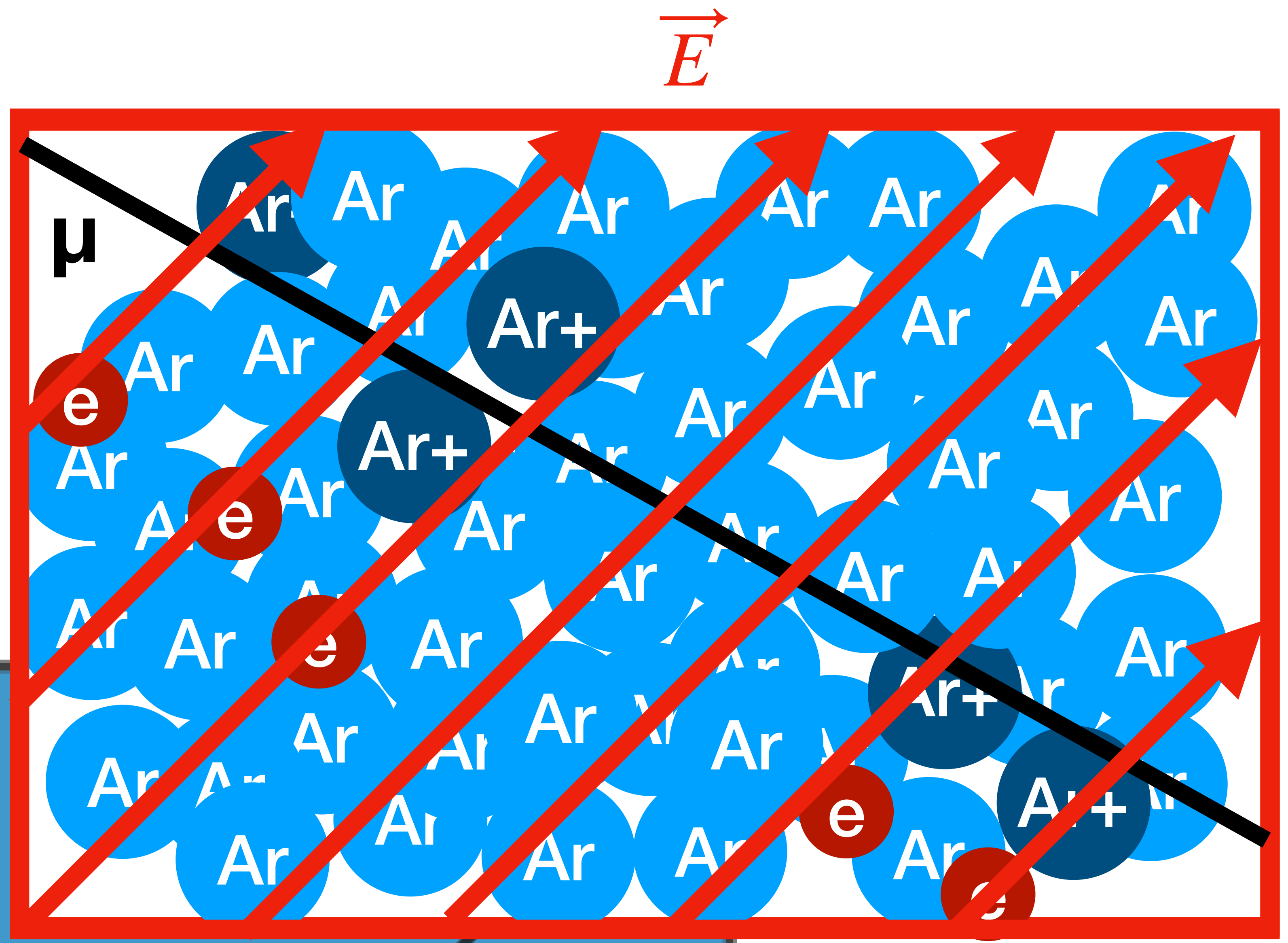
Charge proportional to energy

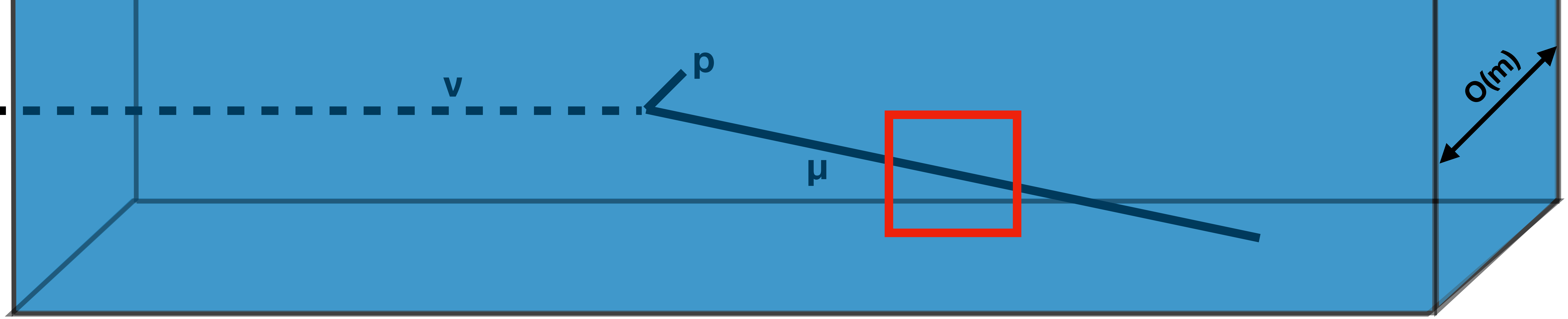
e/γ separation

Liquid Argon as Detector Medium

R. Acciarri et al.
arXiv:1503.01520







Ionization

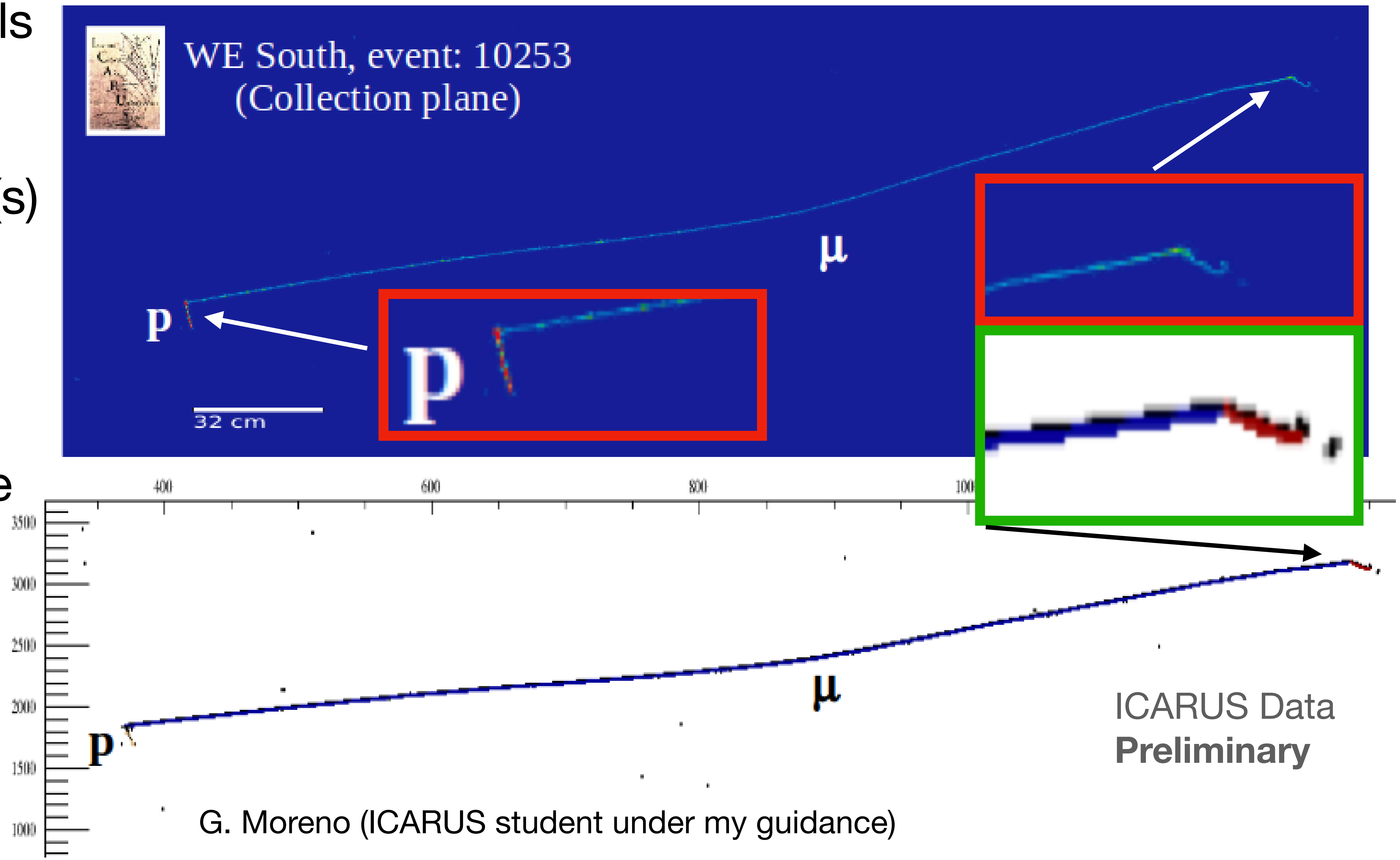
Tracking (wires, others ~mm apart)

Charge proportional to energy

e/γ separation

Reconstructing signals

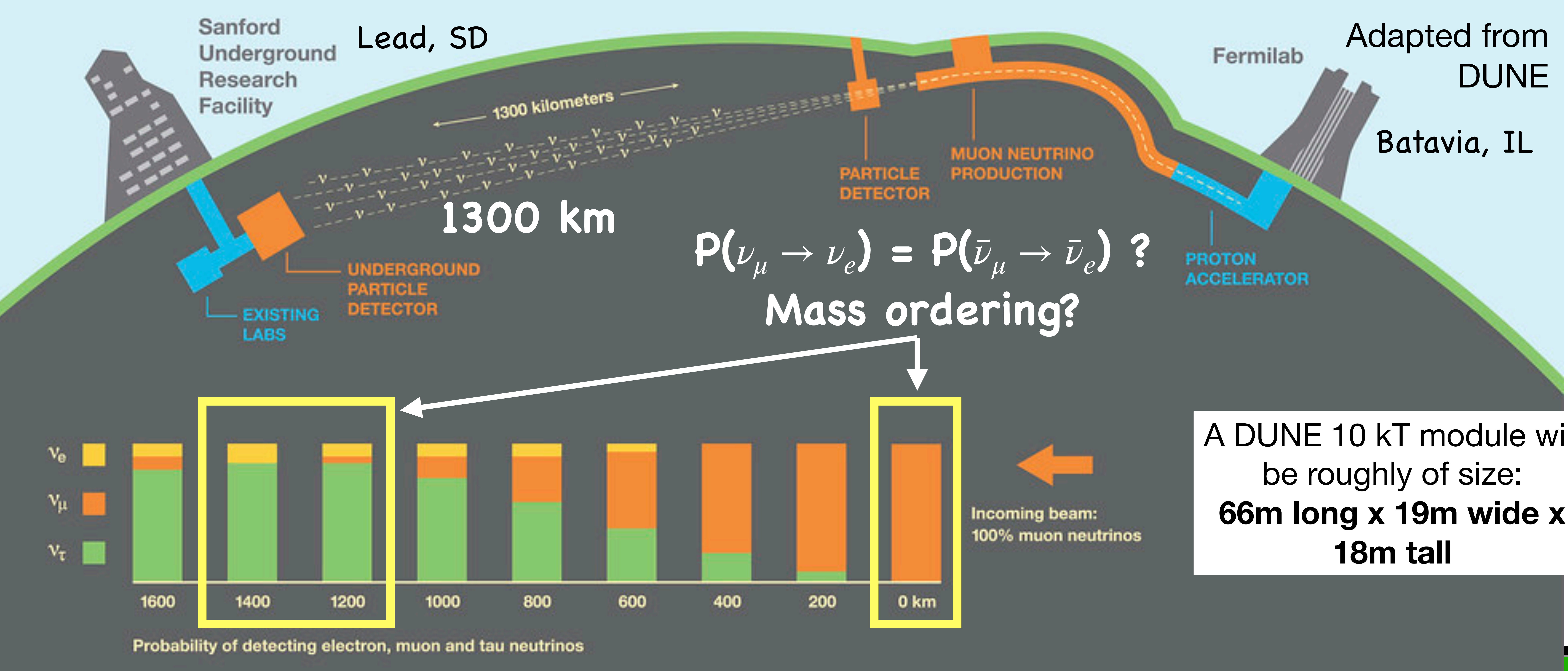
- Reconstruction: taking signals from elements of detector (e.g. wires) & building understanding of interaction(s)
- E.g. TPC reco in ICARUS w/ *Pandora*: commonly used in LAr TPCs
  - Using ICARUS as example due to my involvement in TPC reconstruction there



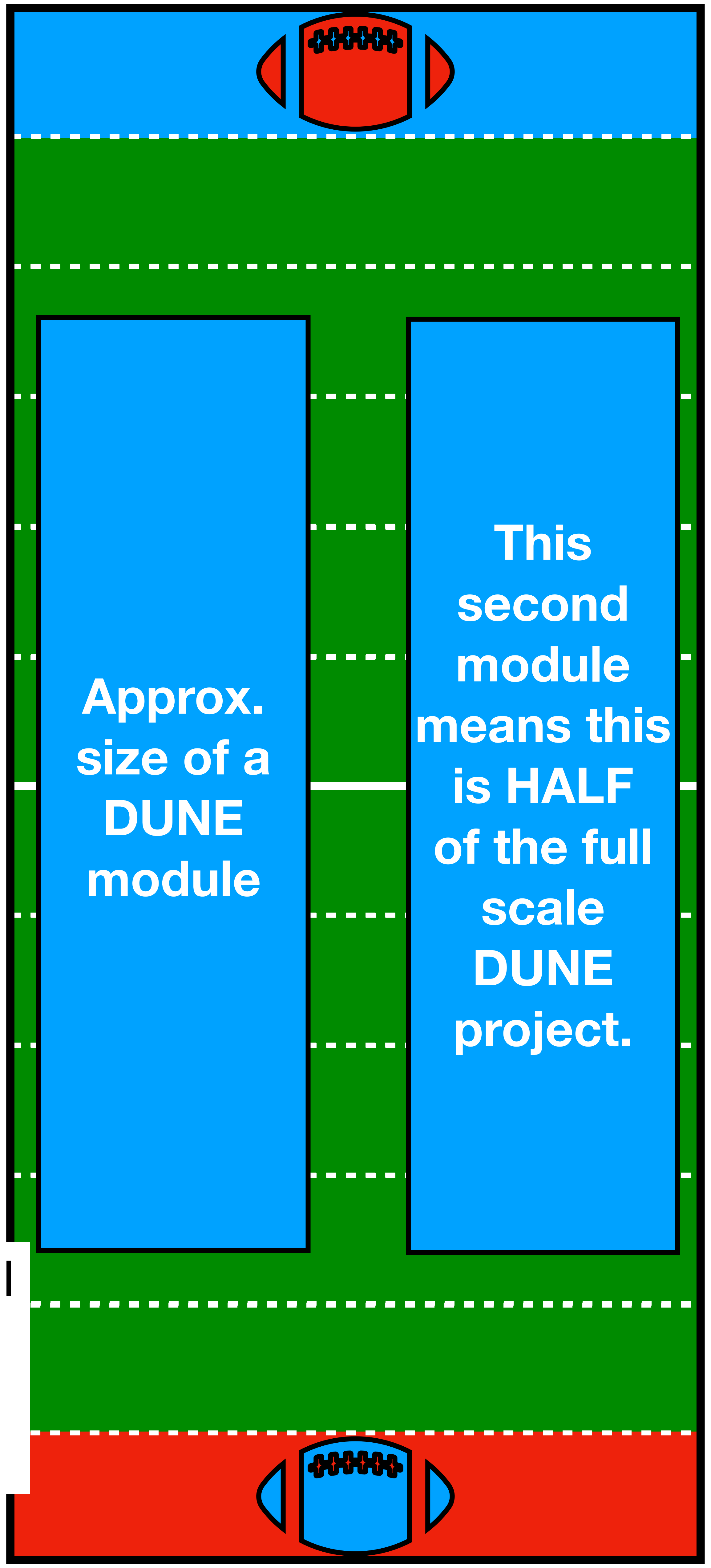
G. Moreno (ICARUS student under my guidance)

DUNE

- Will address questions in ν oscillation (and highly sensitive to other physics too)
- DUNE far detector will employ largest ever LAr TPC detectors, up to 40 kT of LAr: compare to NOvA far detector ~14 kT total



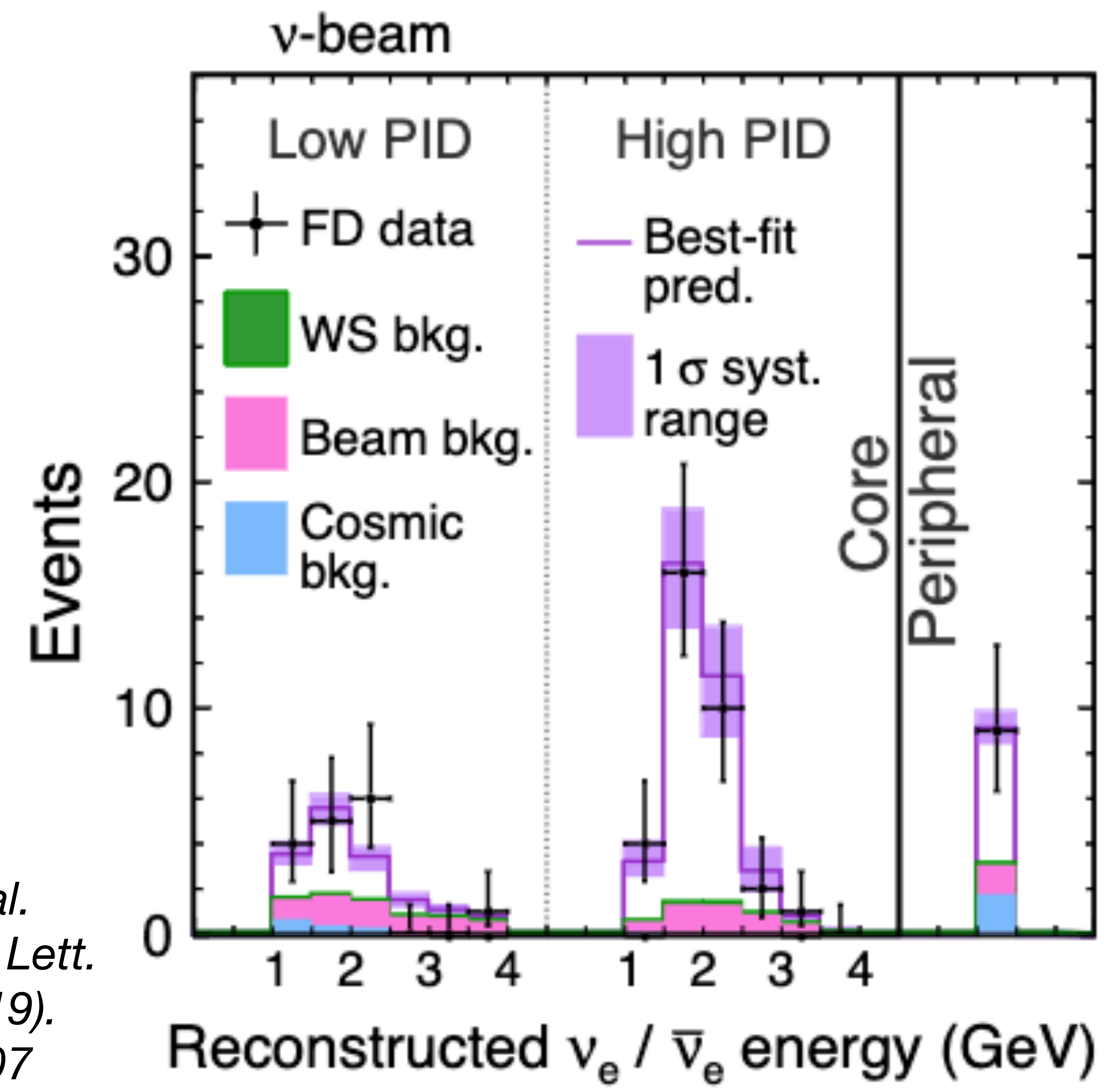
A DUNE 10 kT module will be roughly of size:
66m long x 19m wide x 18m tall



DUNE

- Will use improvements in beam and detector technology to make large advancements in oscillation analysis

Error bars here are statistical. We have lots of leverage in measurement here, as long as error bars on the measurement don't get too large!

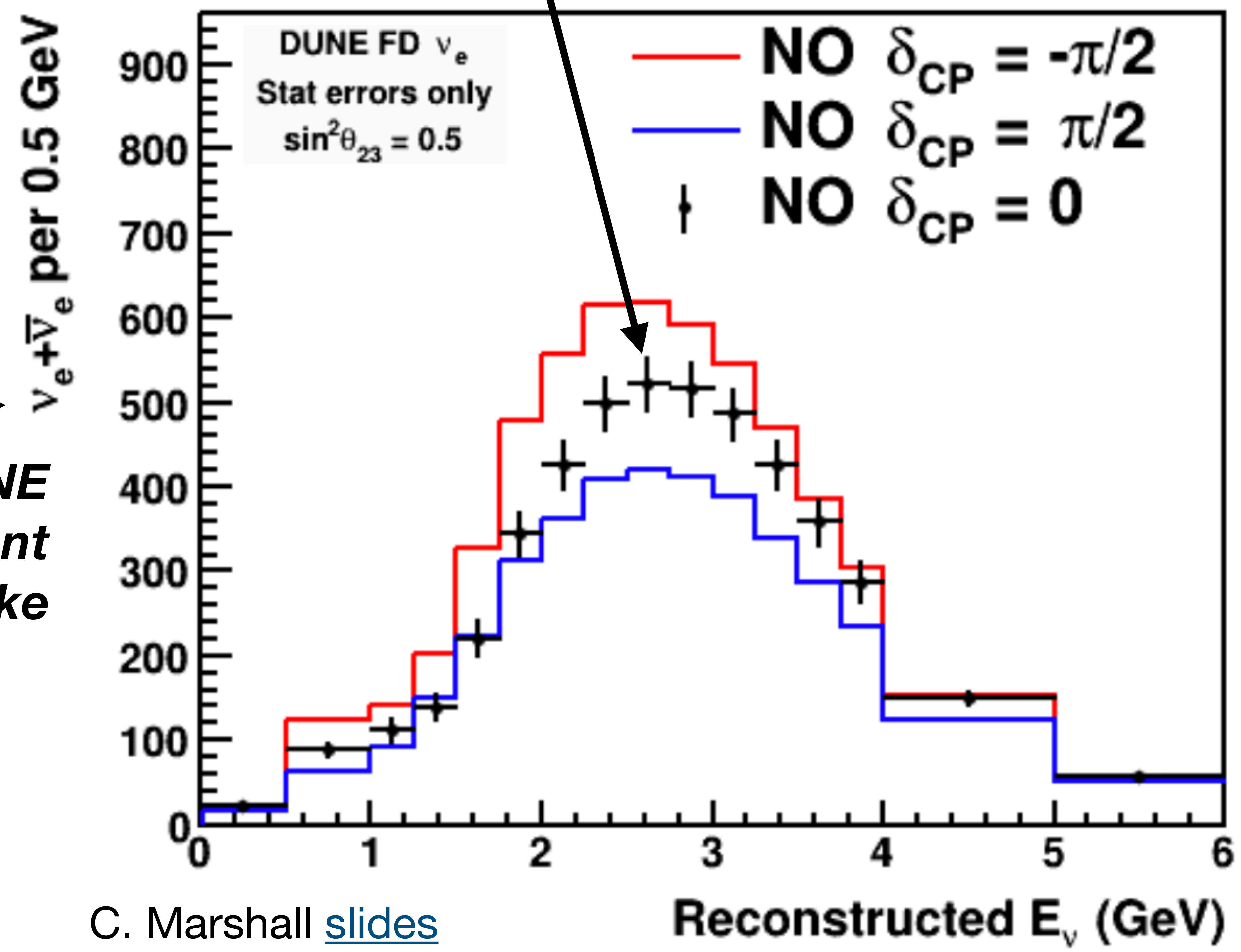


Adapted from

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

Reminder of a typical NOvA result with 10s-100 ν_e

What a future DUNE appearance measurement might look like



C. Marshall slides

DUNE in next few years

- DUNE is rapidly progressing:
  - Excavation of caverns ongoing in South Dakota preparing for installation of first two 10kT modules
  - Plan is for the first two 10 kT modules to be installed over second half of **2020s** with beam and Near Detector installed for **2031**

Image from C. Marshall NuFact slides

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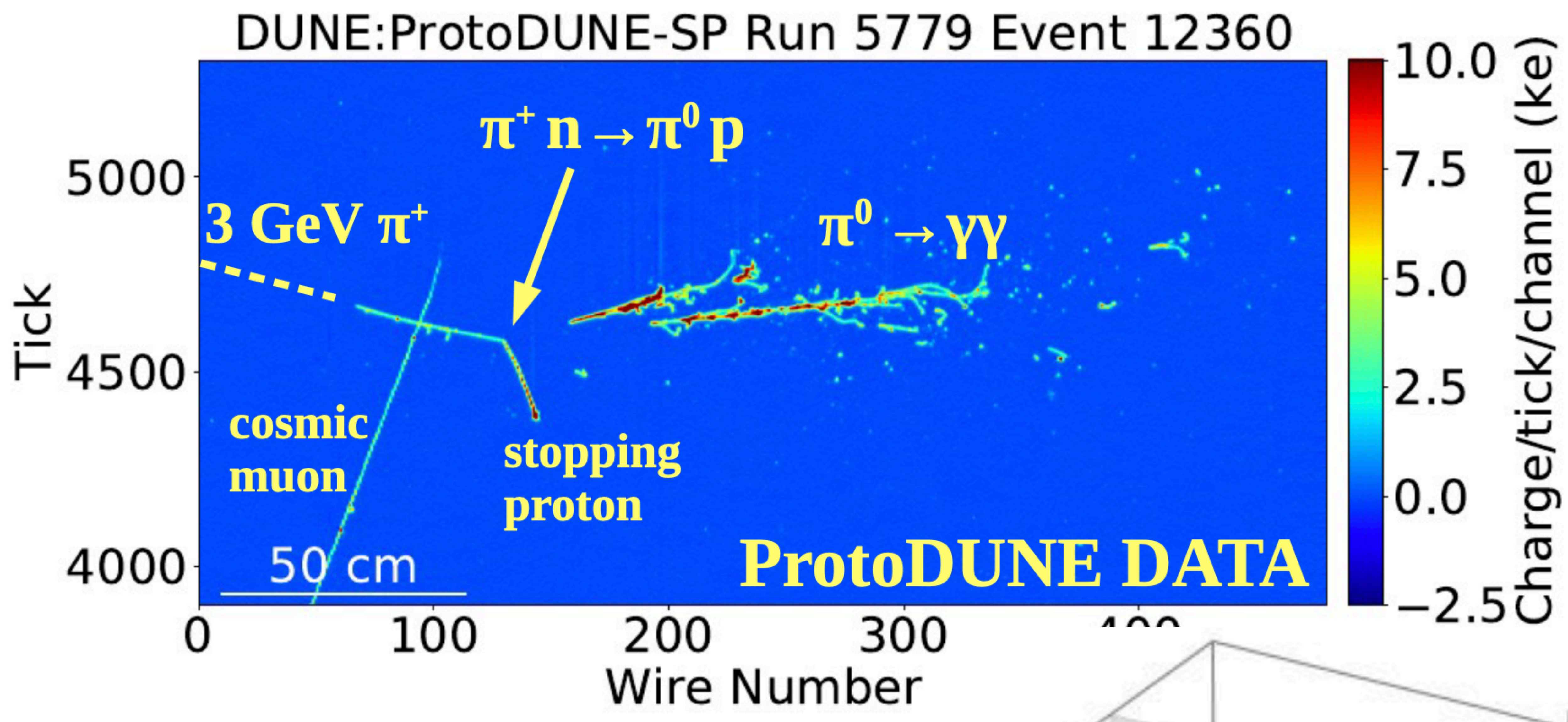
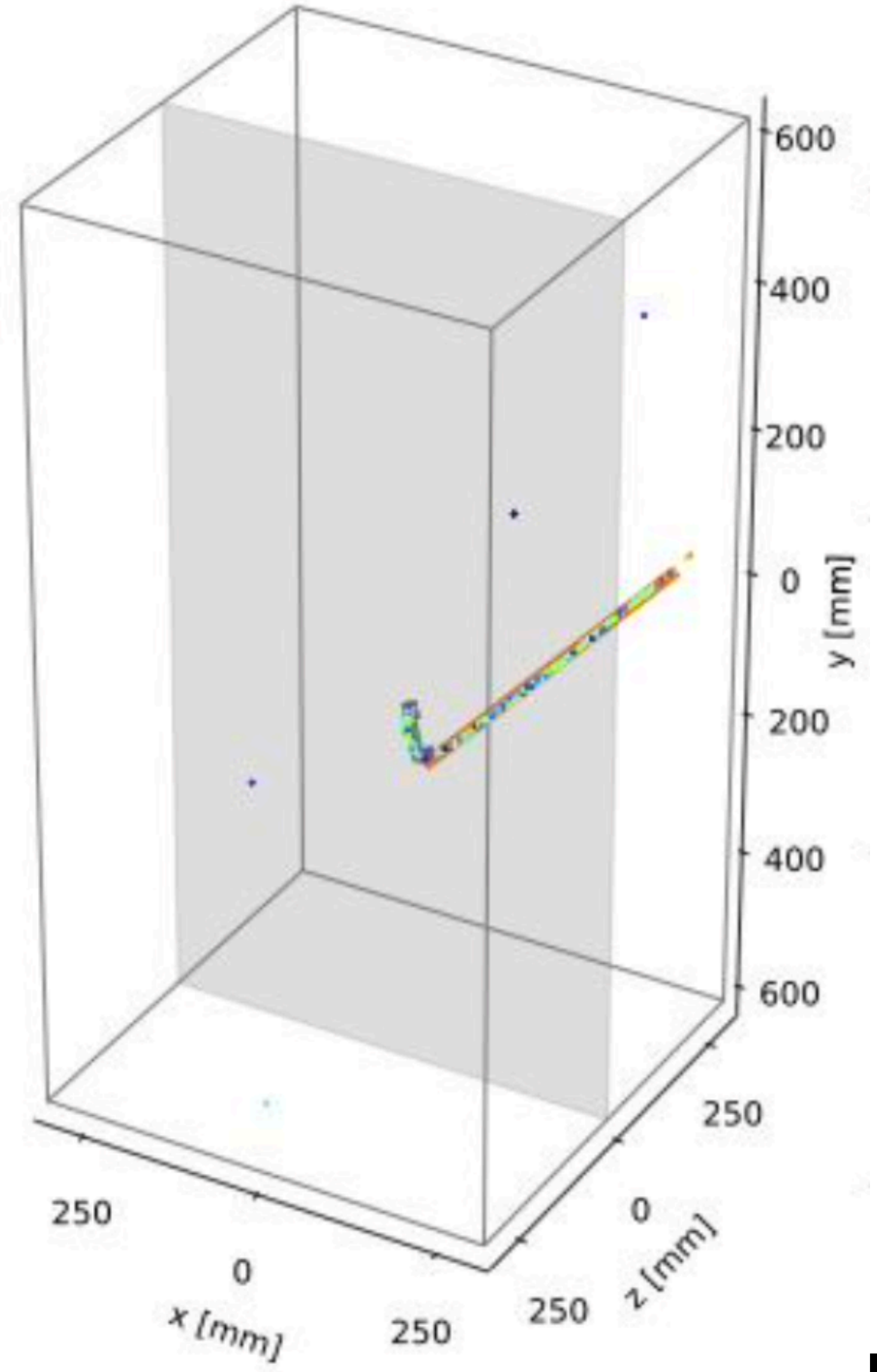
  - Excavation of caverns ongoing in South Dakota preparing for installation of first two 10kT modules
  - Plan is for the first two 10 kT modules to be installed over second half of **2020s** with beam and Near Detector installed for **2031**
- Meanwhile, analysis of data from Far Detector style modules in a test beam at CERN (“ProtoDUNE”) is ongoing, as are preparations for another run
- Also prototype detector runs will soon take place at FNAL, such as a prototype of the LAr TPC Near Detector



From C. Marshall NuFact slides

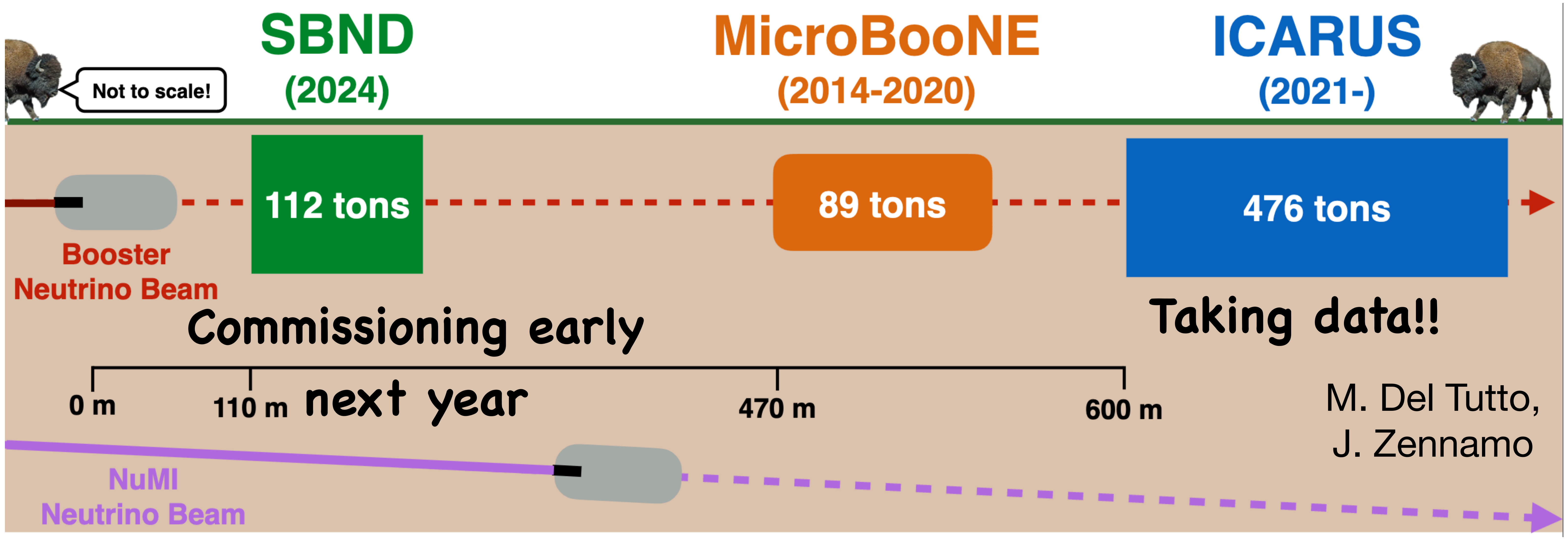


ND-LAr prototype data event

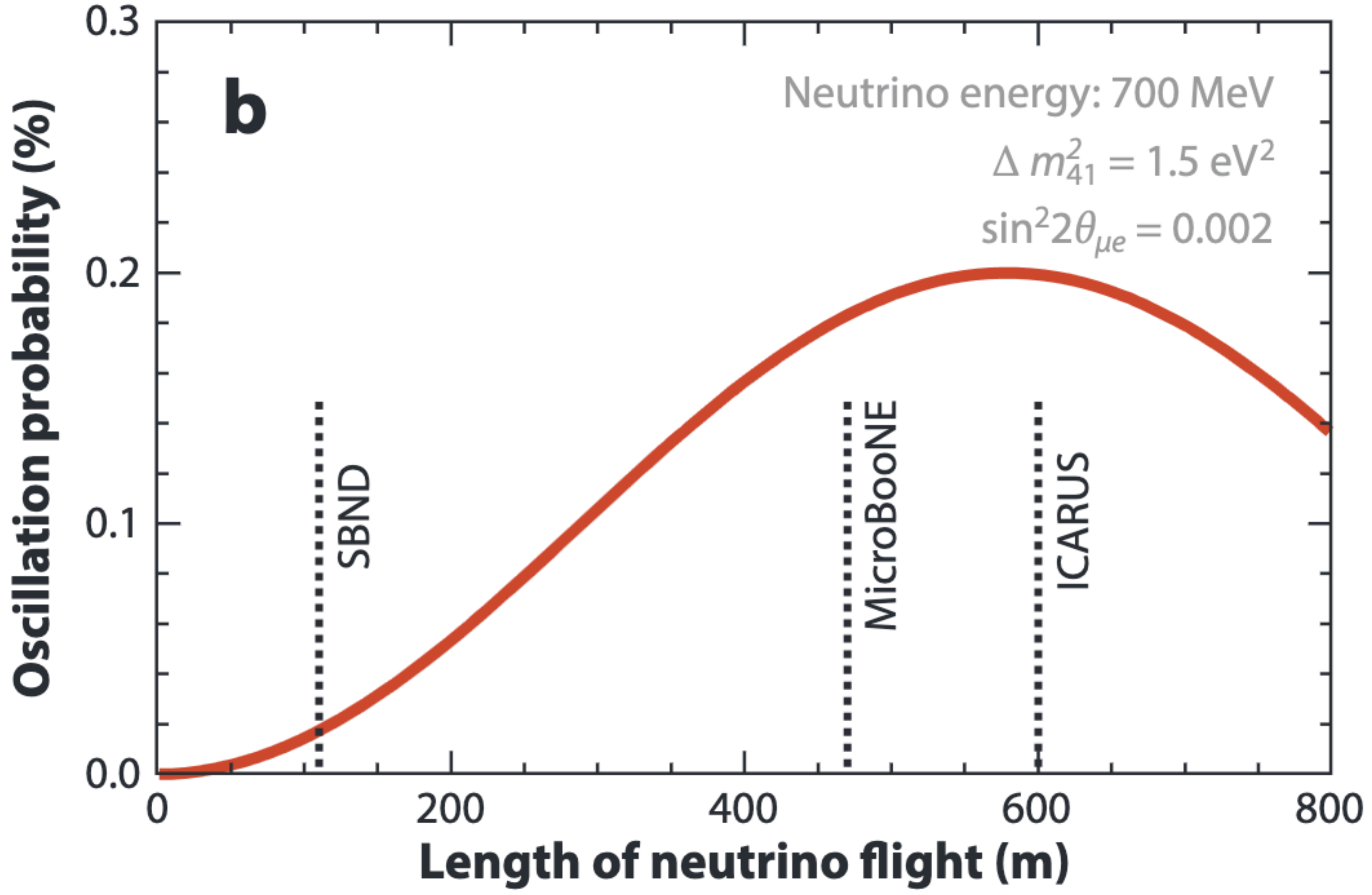
(Z. Hulcher slides)

SBN Program

- Short Baseline Neutrino program at FNAL, 3 LAr TPC detectors along BNB beam: **SBND and ICARUS will be running at the same time**
- Allows study like long-baseline, but for short-baseline anomaly
  - SBND=near det, ICARUS=far det
  - Main capability to study both ν_μ disappearance & ν_e appearance, and more



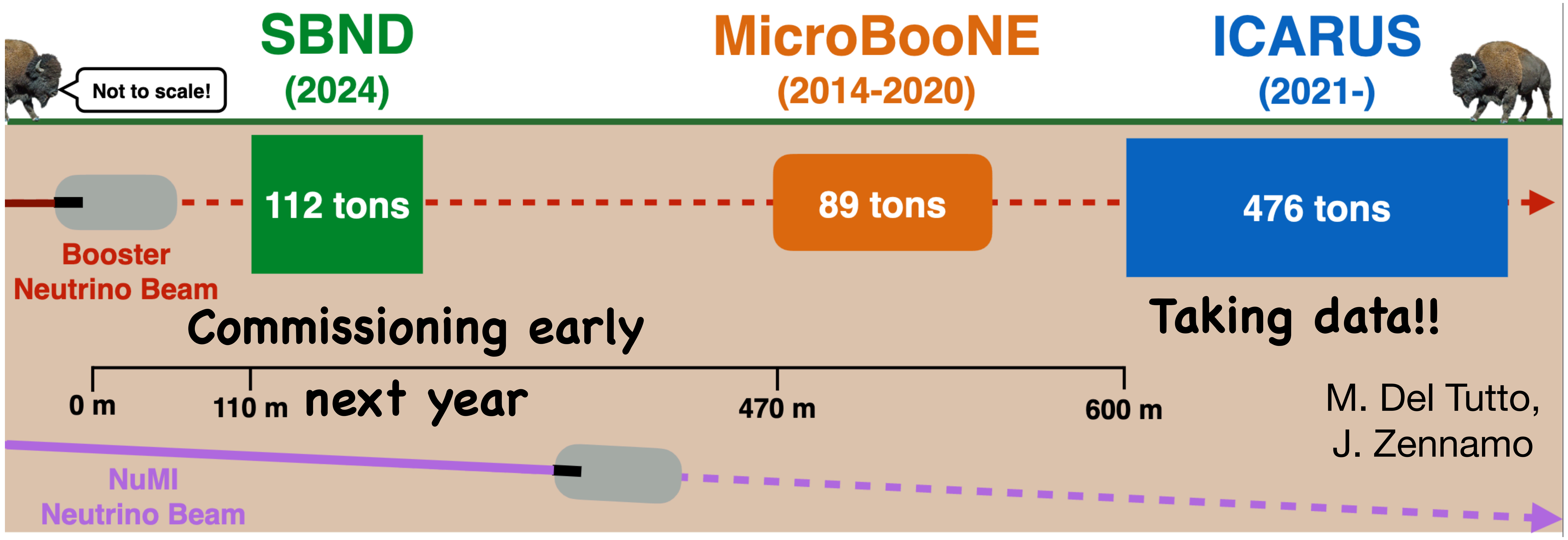
M. Del Tutto, J. Zennamo



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

SBN Program

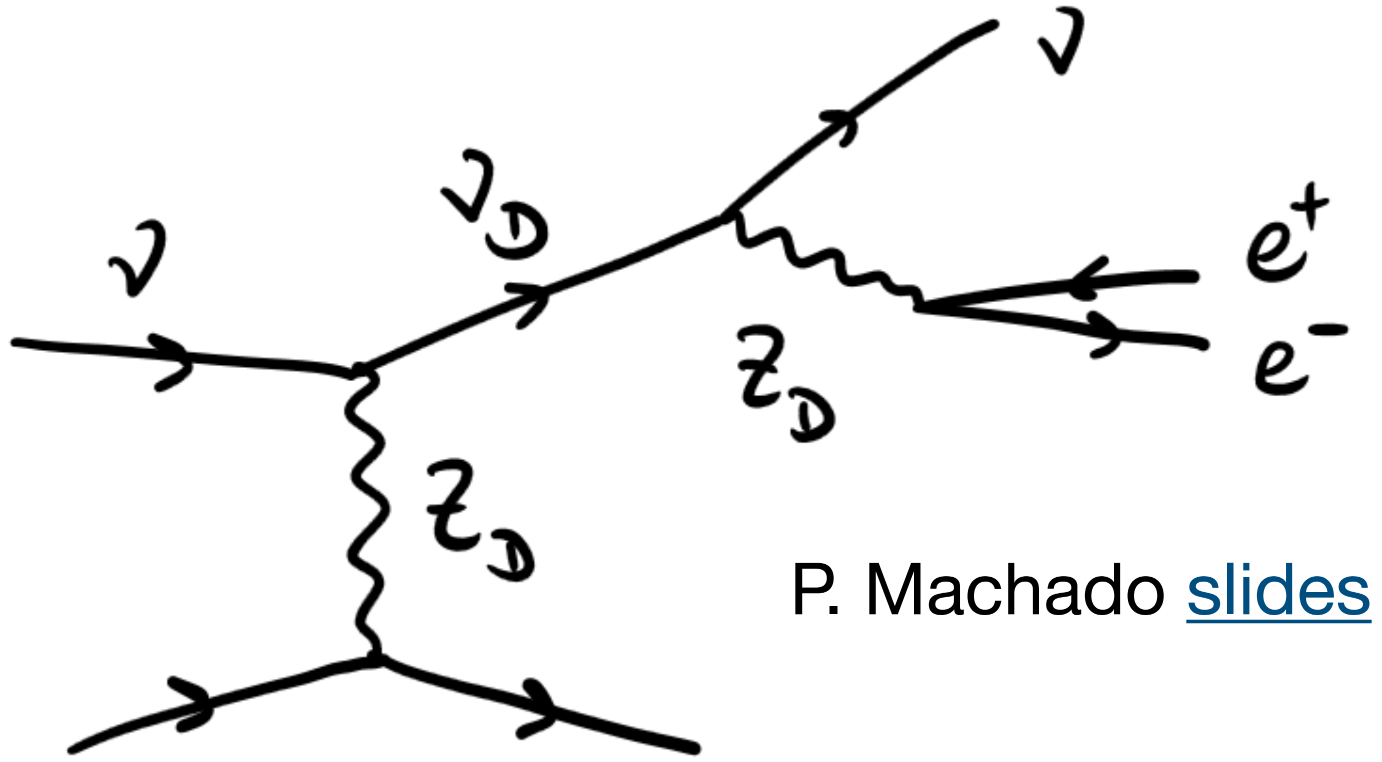
- If the anomaly isn't driven by sterile neutrinos, then what?
  - Could be a poorly constrained background: but SBN aims to improve this already
  - Could be poorly constrained decay processes: but MicroBooNE already investigated such a case
  - ***Could be other new physics?***
    - Models proposed that would lead to an e-like signature in MiniBooNE besides sterile that LAr TPCs may give the sensitivity to discover



M. Del Tutto, J. Zennamo

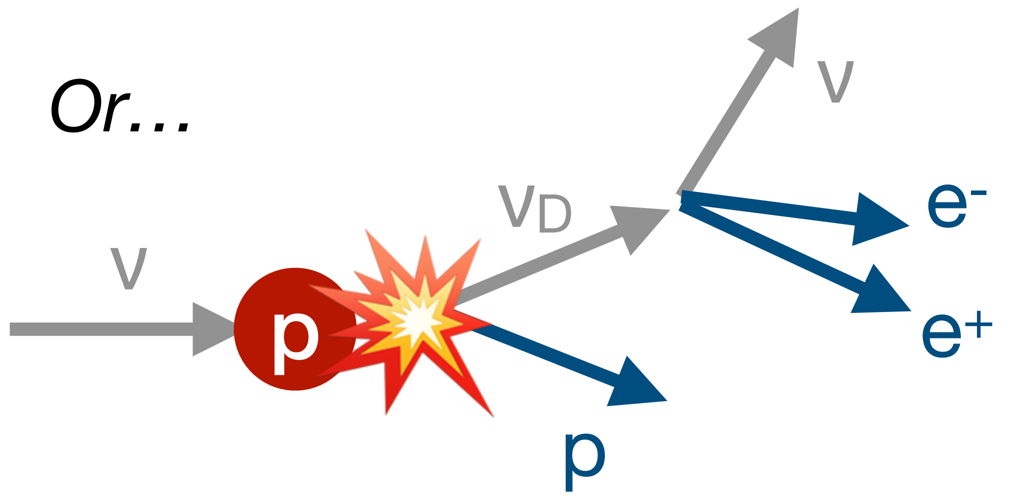
Model in a nutshell

Dark neutrinos with heavy Z_D



P. Machado slides

In case you like Feynman diagrams



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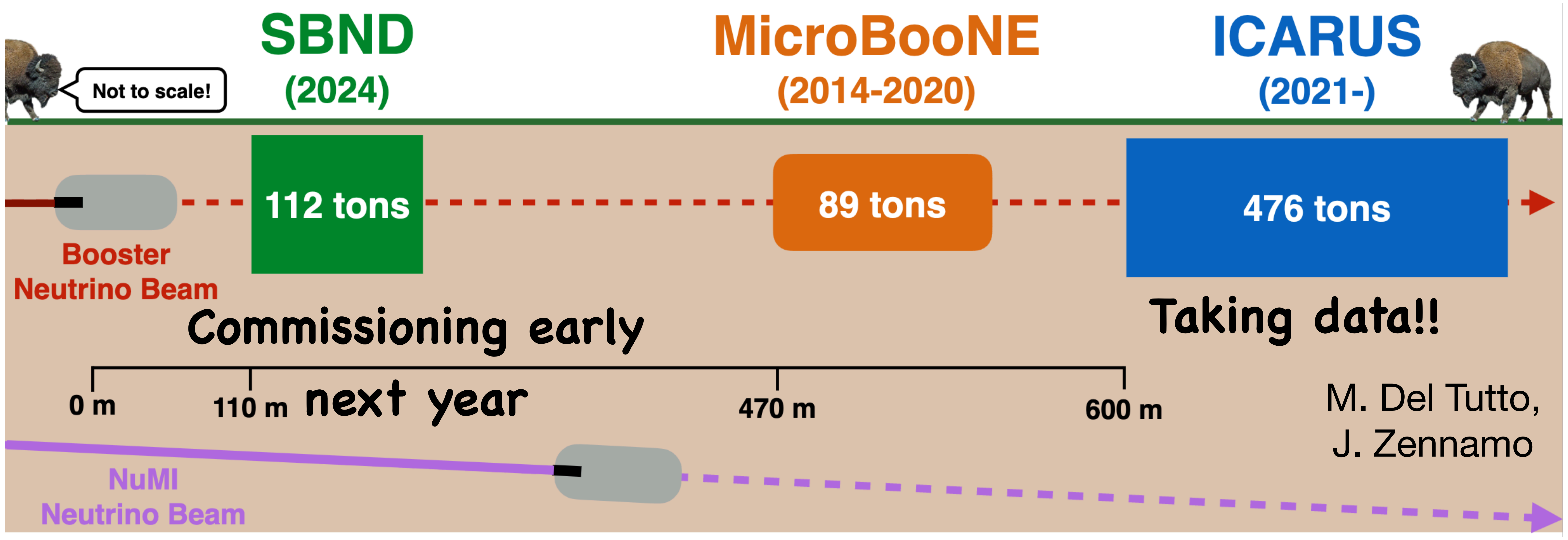

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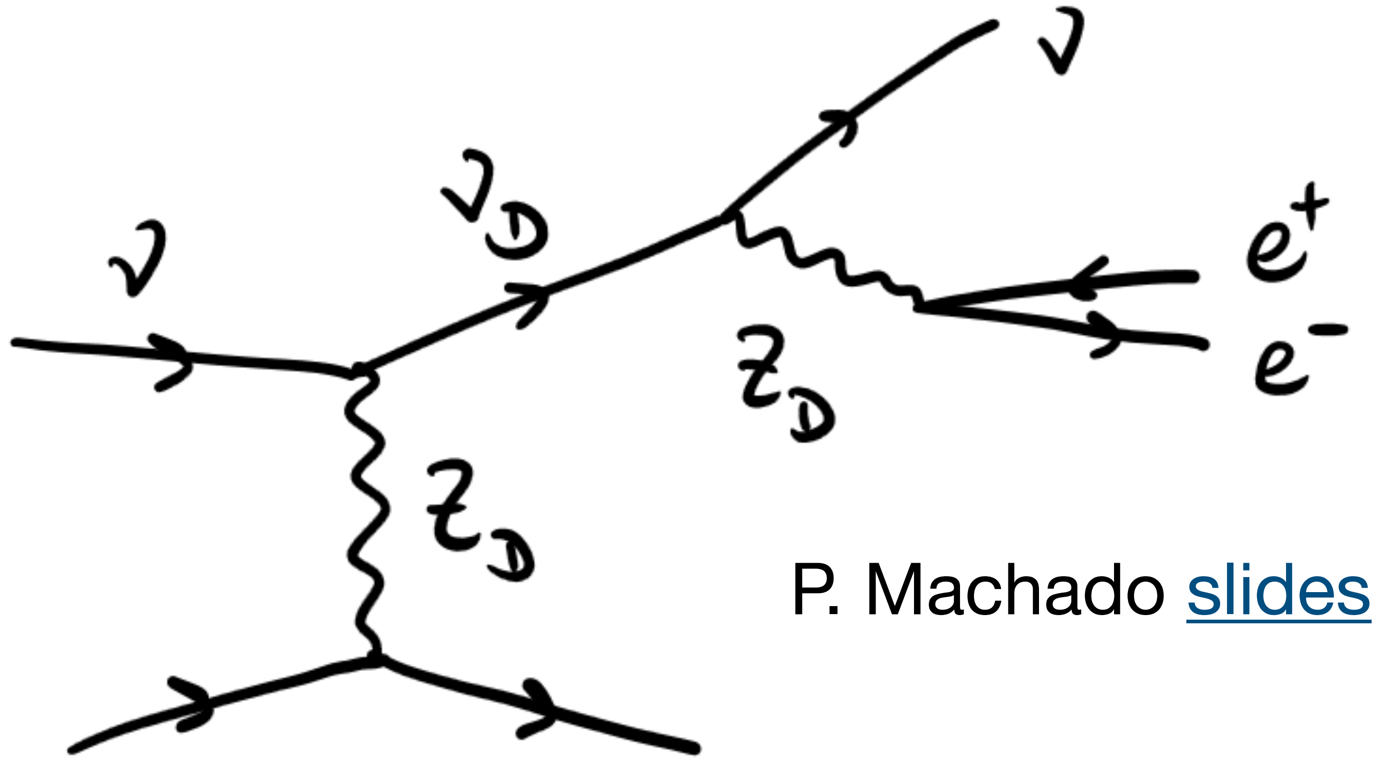
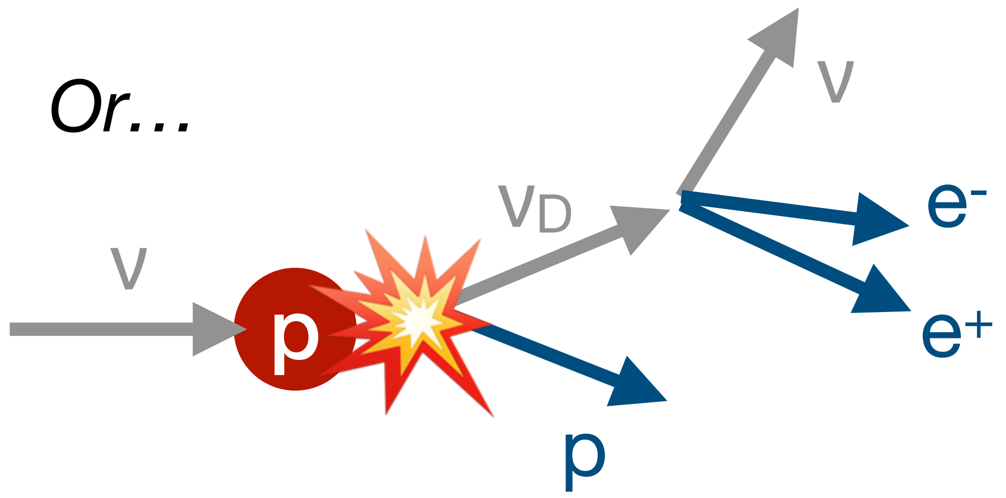


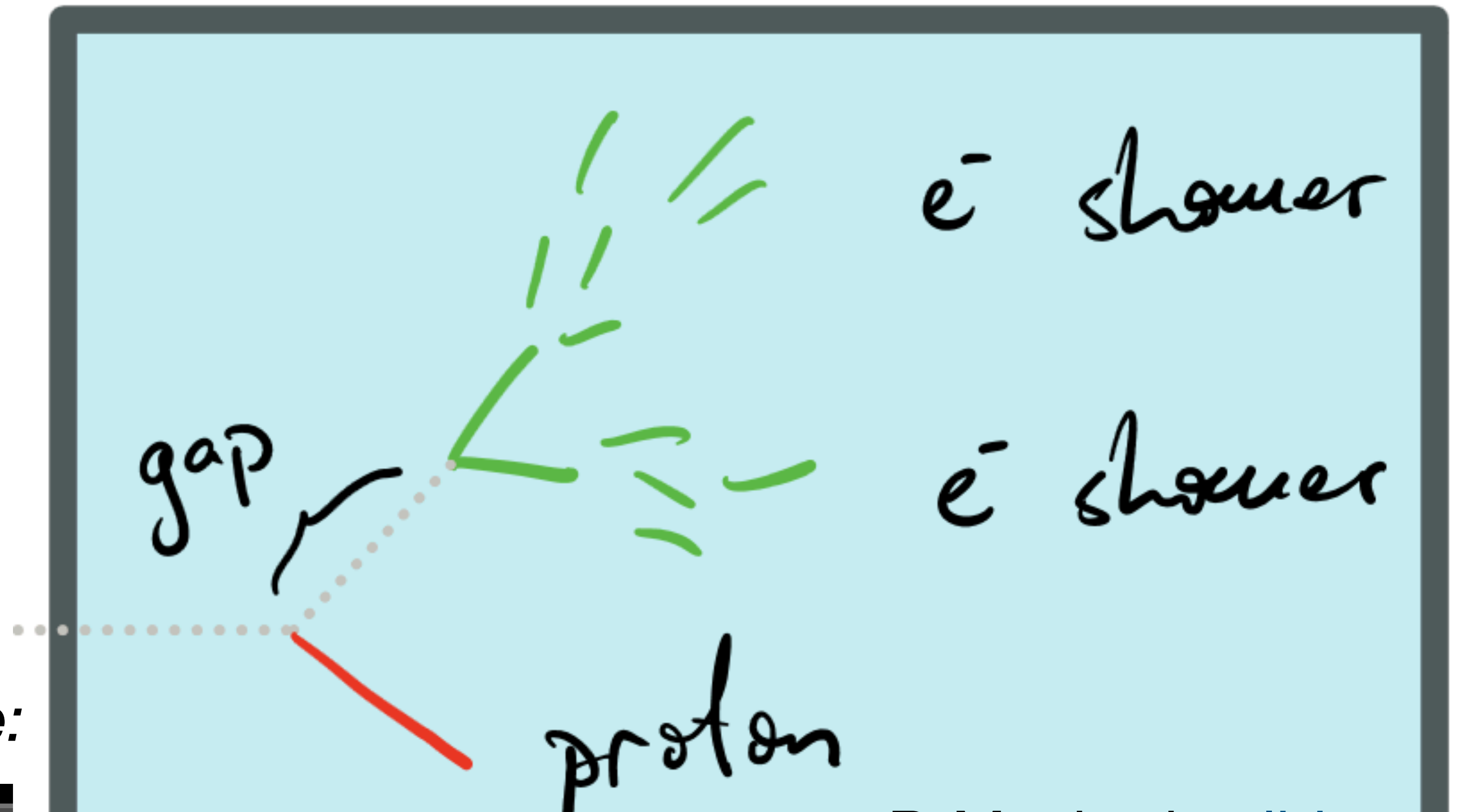
P. Machado slides

In case you like Feynman diagrams

Or…



And in our detector this would look like:

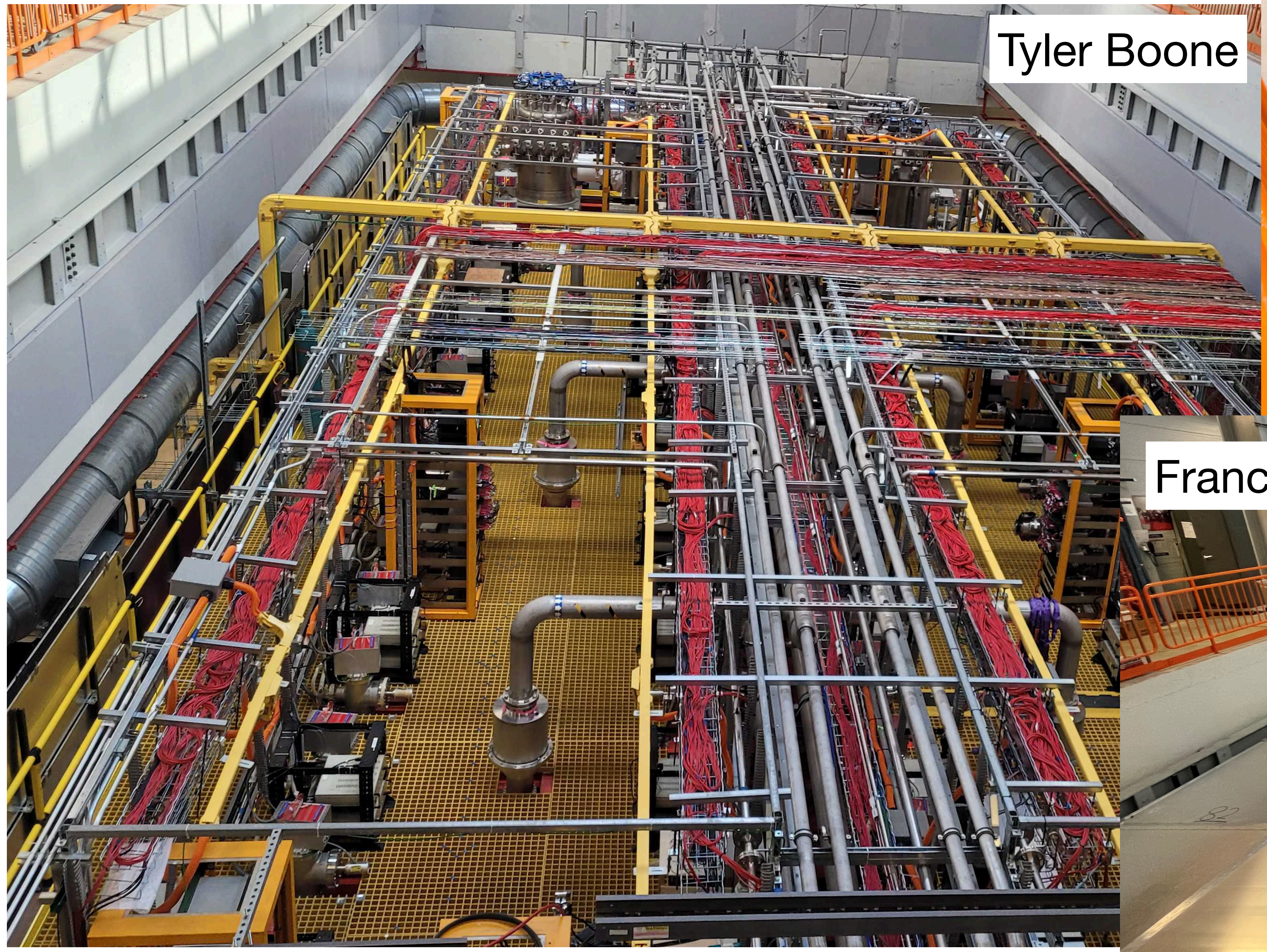


P. Machado slides

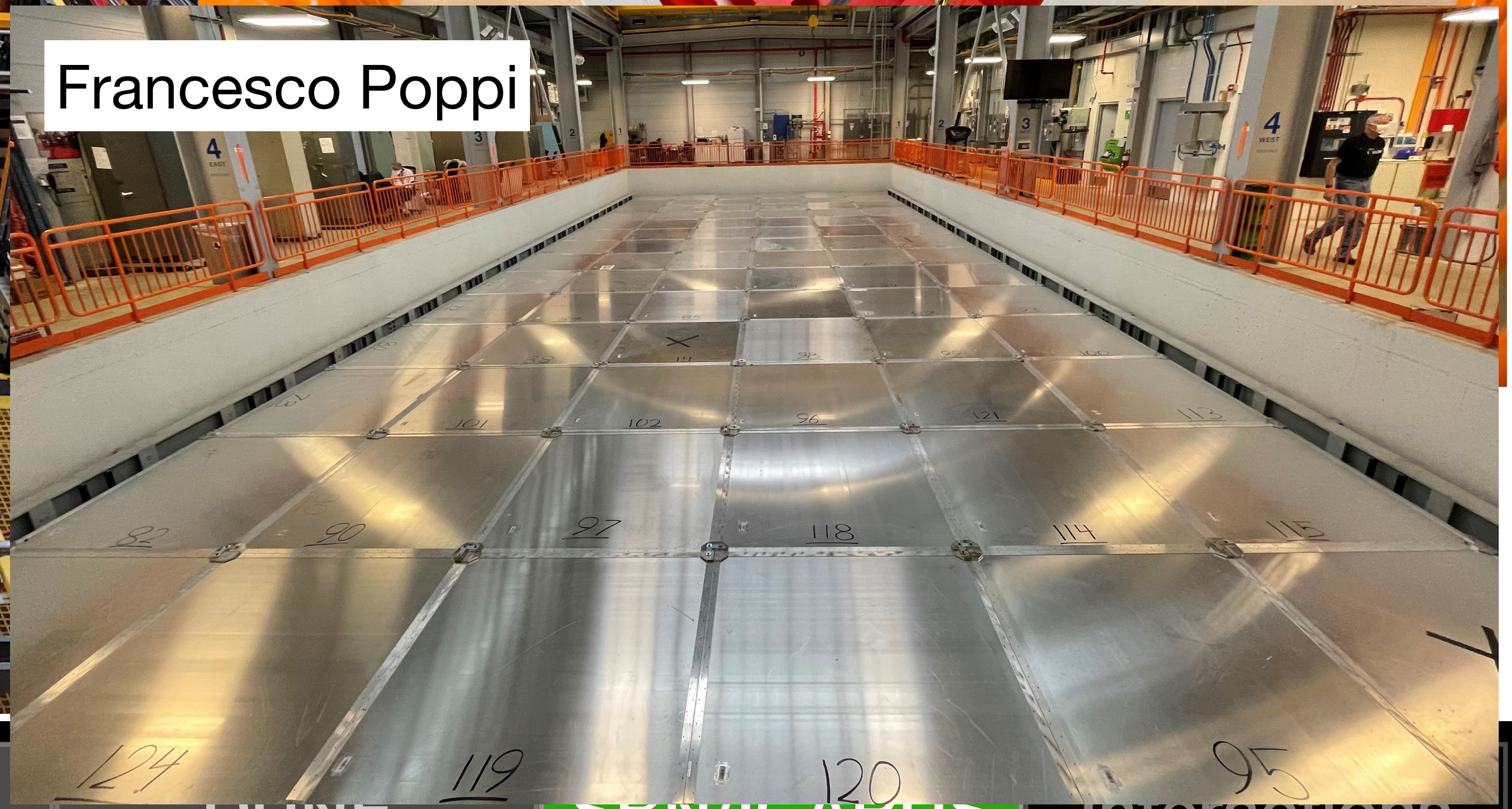
ICARUS @ FNAL

- 760 t LAr (0.760 kT): 476 t active volume with 2 modules, each 19.6 x 3.6 x 3.9 m^3: each with two 1.5 m wide TPCs
- 360 PMTs: trigger, match w/ other systems: ID beam activity
- Cosmic ray tagging system: reject cosmics:
  - Also combo of CRT + PMT with timing info, and overburden

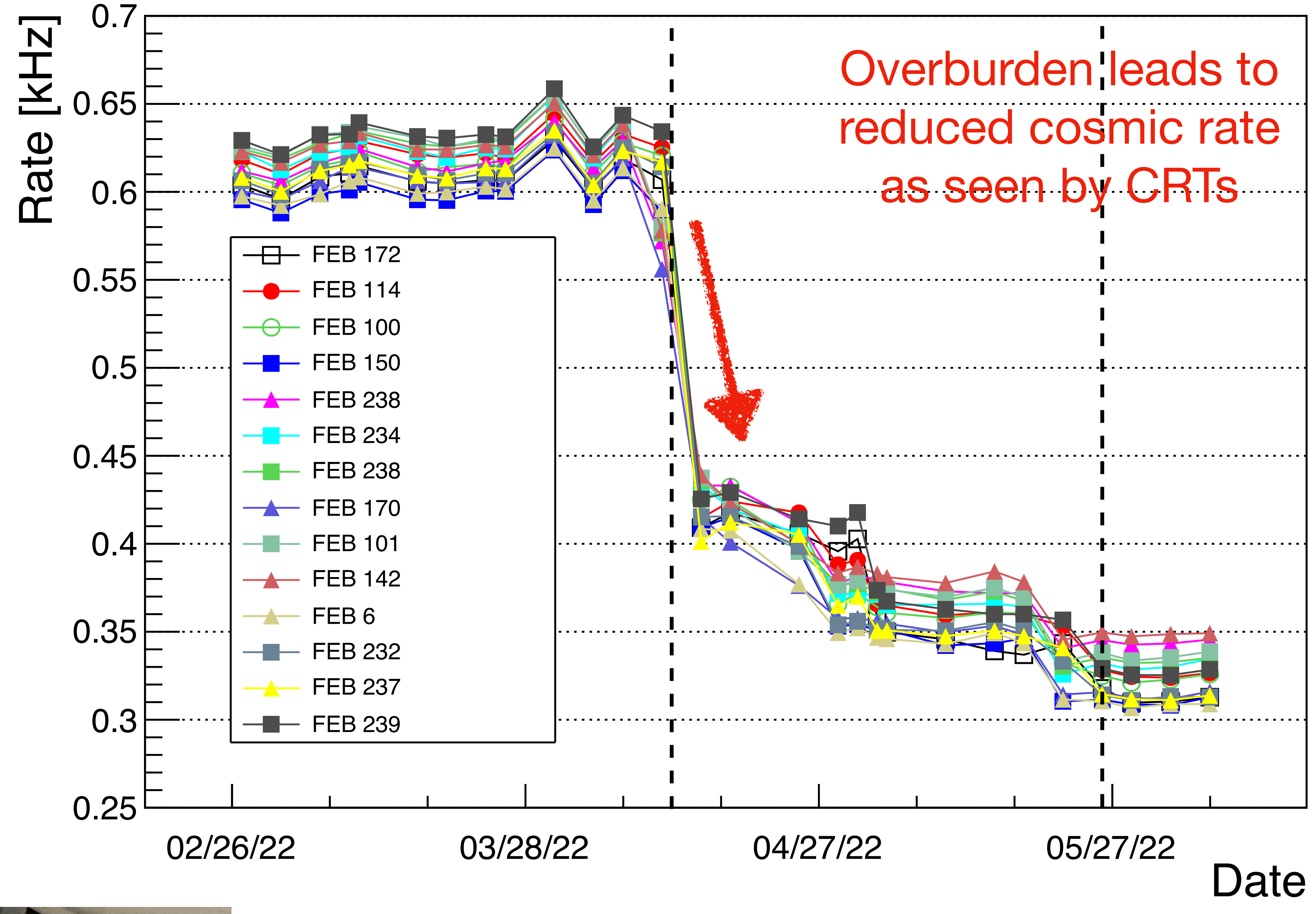

Photo: CERN


Tyler Boone

FNAL VMS


Francesco Poppi

ICARUS @ FNAL

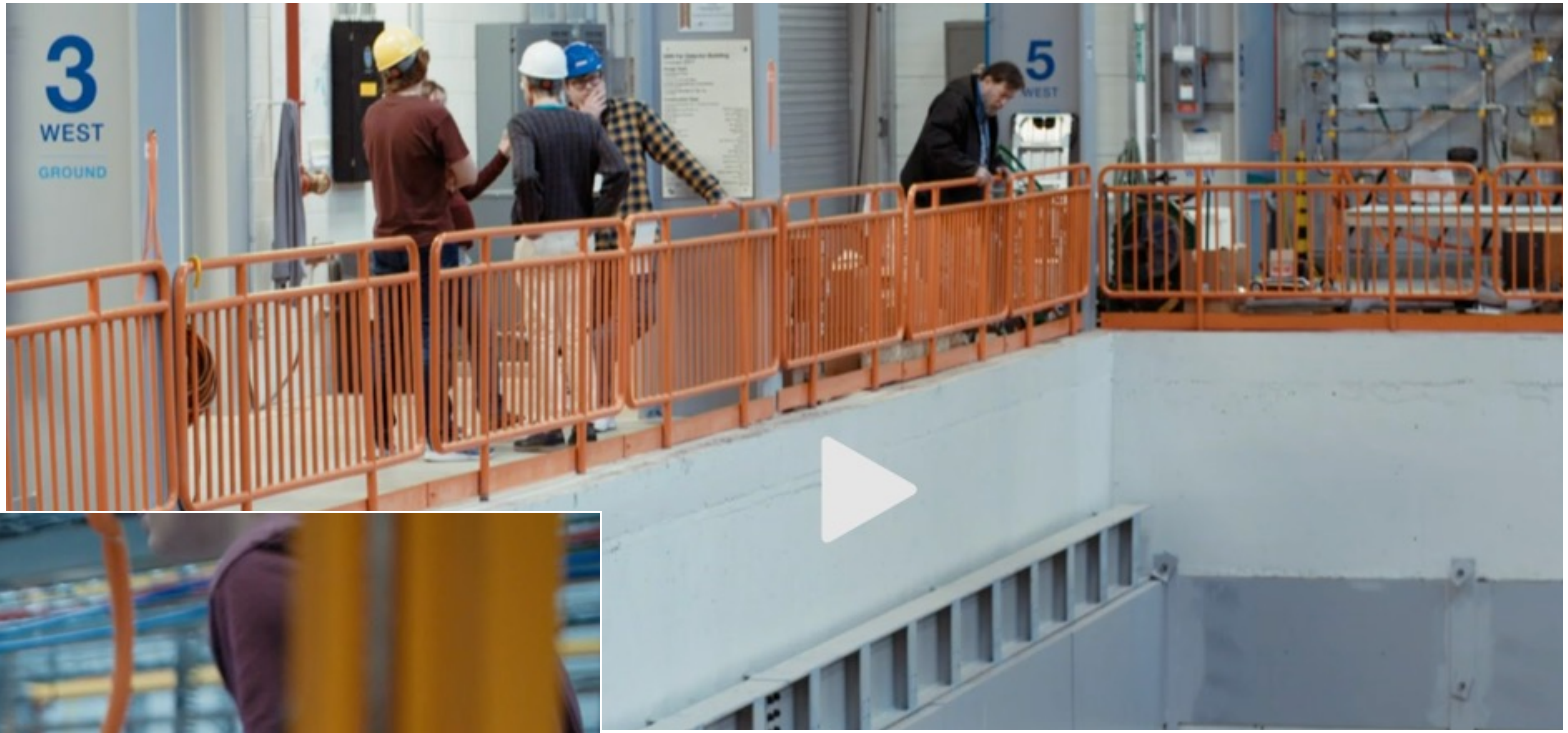


If you looked in the building now you'd see lots of concrete blocks!

An overburden to reduce cosmic rate…

ICARUS @ FNAL

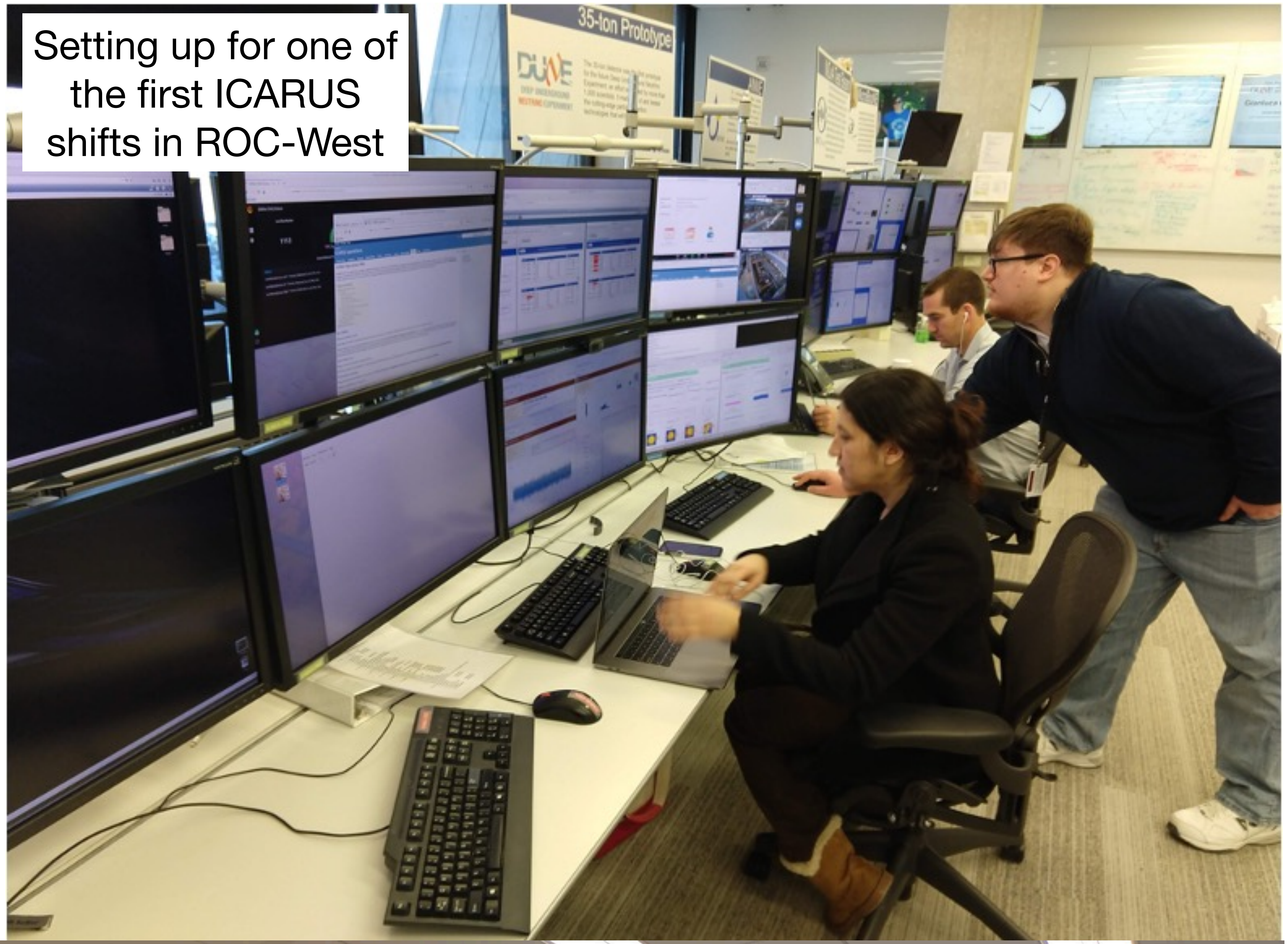
- And it turns out that sometimes when you work on a cool new program and detector area, you might end up in B-roll of a public science documentary… 🎥

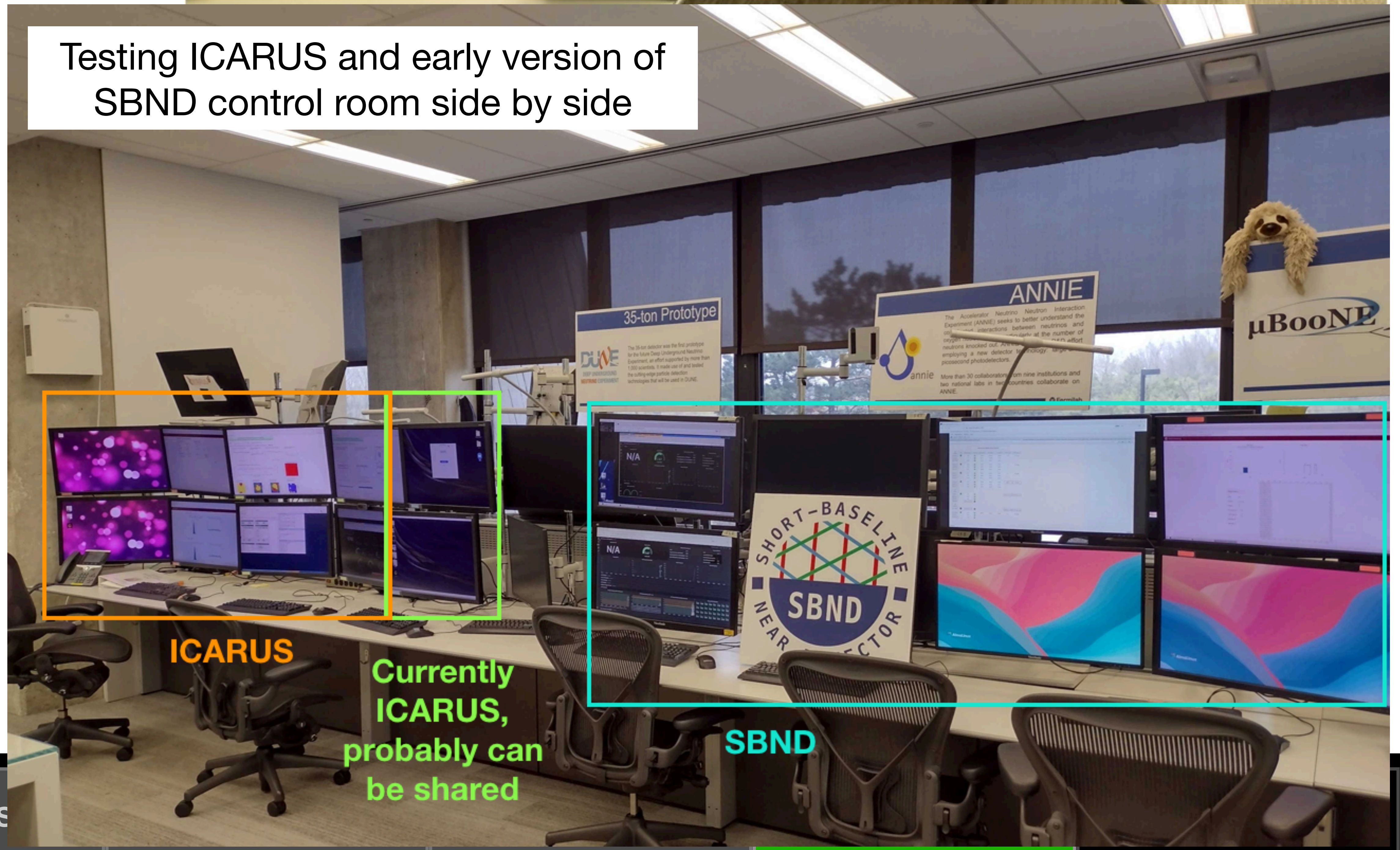


Screenshots from NOvA Particles Unknown (PBS)

Bringing ICARUS online

- Started 24/7 shifts at start of filling in Feb 2020: after 1 month, forced to move continue remote
- Following the fill, remote shifts continued and some additional installation tasks took place (e.g. installation of top CRT and overburden)
- Shifts now allowed back in ROC-West but
  - On, SBND we are now preparing for first operations including shifts and we are setting up in a way that enables local and remote shifts
- *For time I will not go much into it here, but would be happy to talk to folks about this. We should use the experiences of ICARUS and now SBND to guide and improve upon when bringing DUNE detector(s) online*

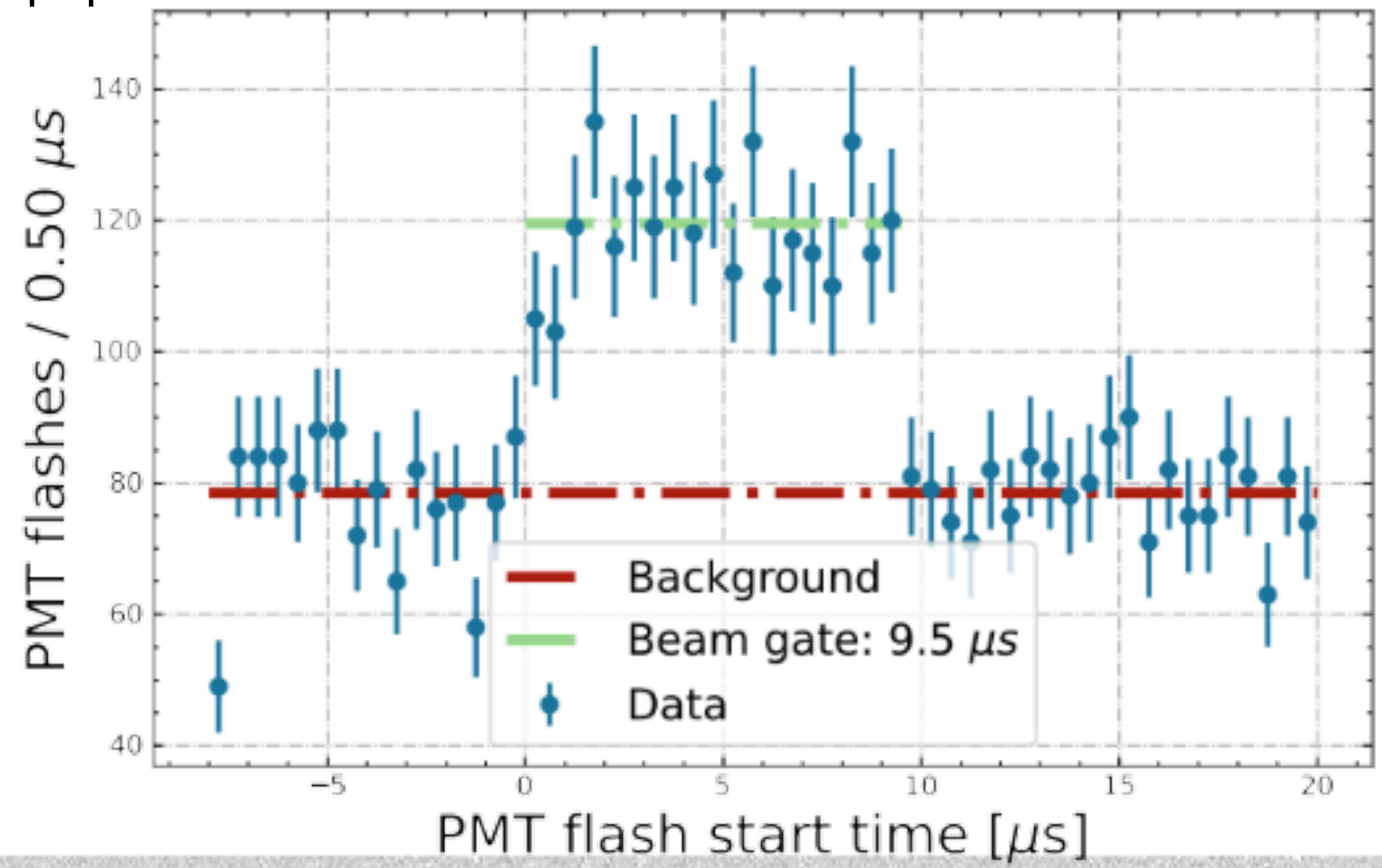


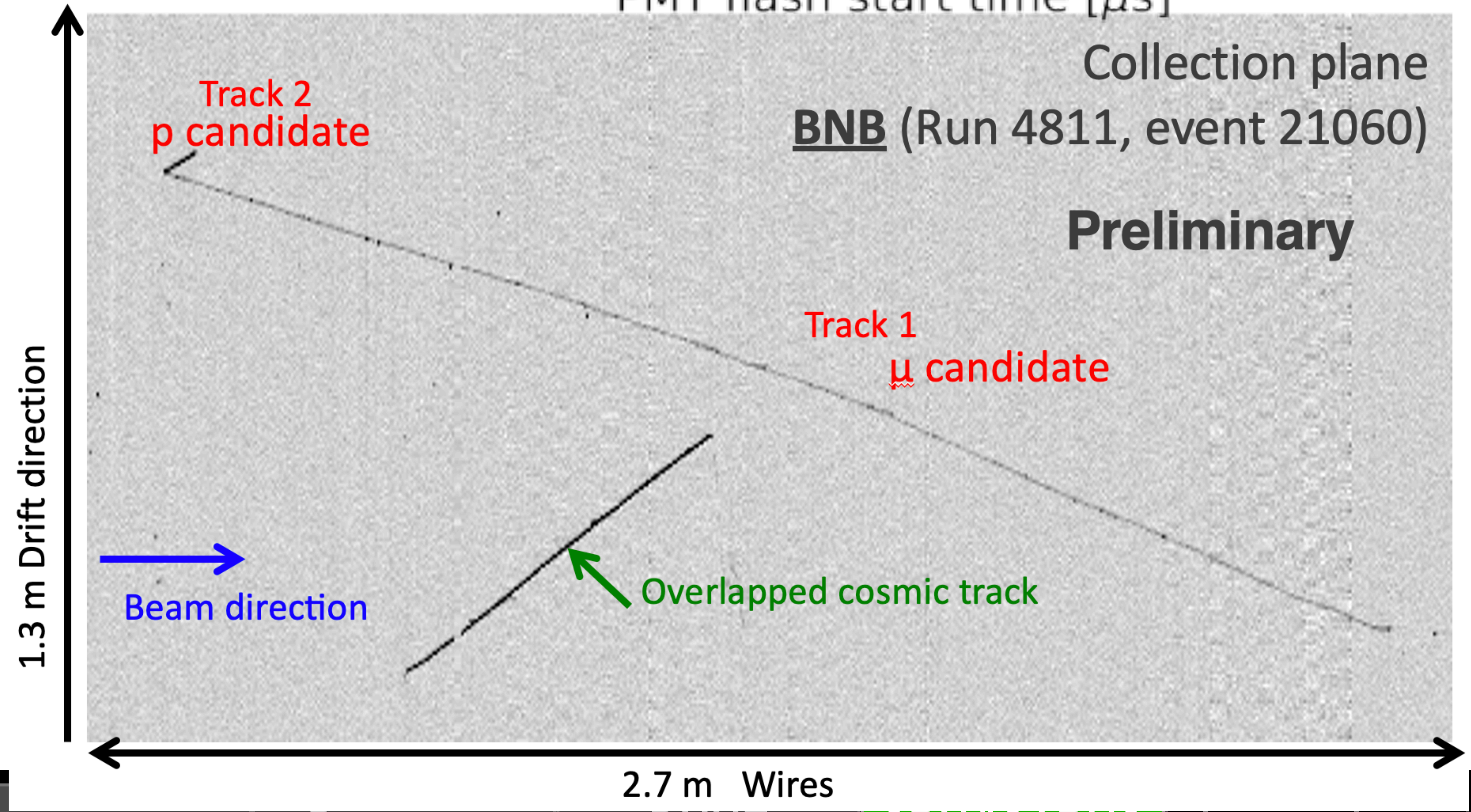


Bringing ICARUS online

- The different subsystems have undergone a set of commissioning & characterization studies to detail their performance:
  - *P. Abratenko et al, Eur. Phys. Journal C **83**, 467 (2023)*
- Few examples here of timing plots from PMT and a hand-scanned neutrino candidate that was one of the first ones found in ICARUS @ Fermilab.

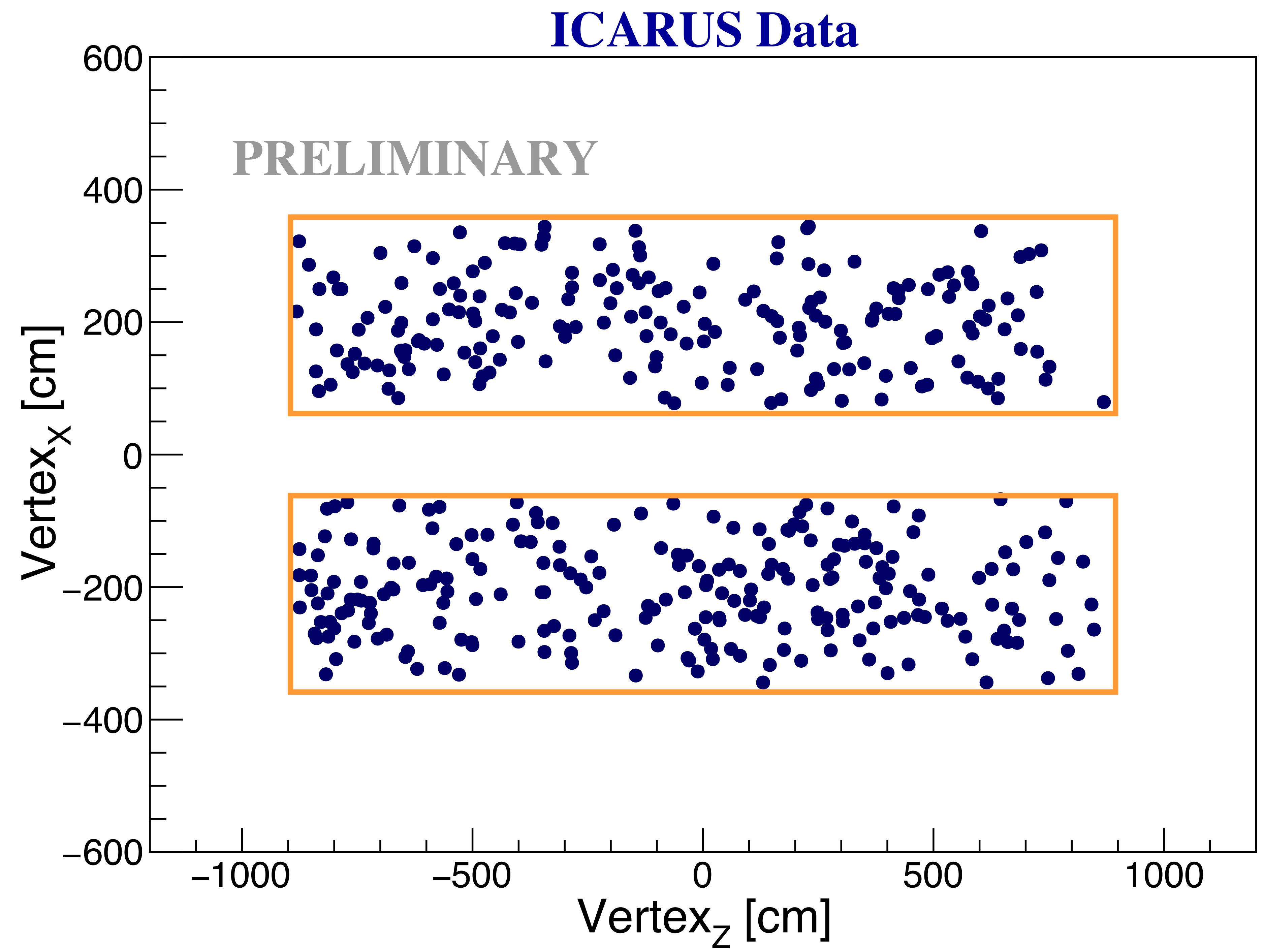
See paper for more details!

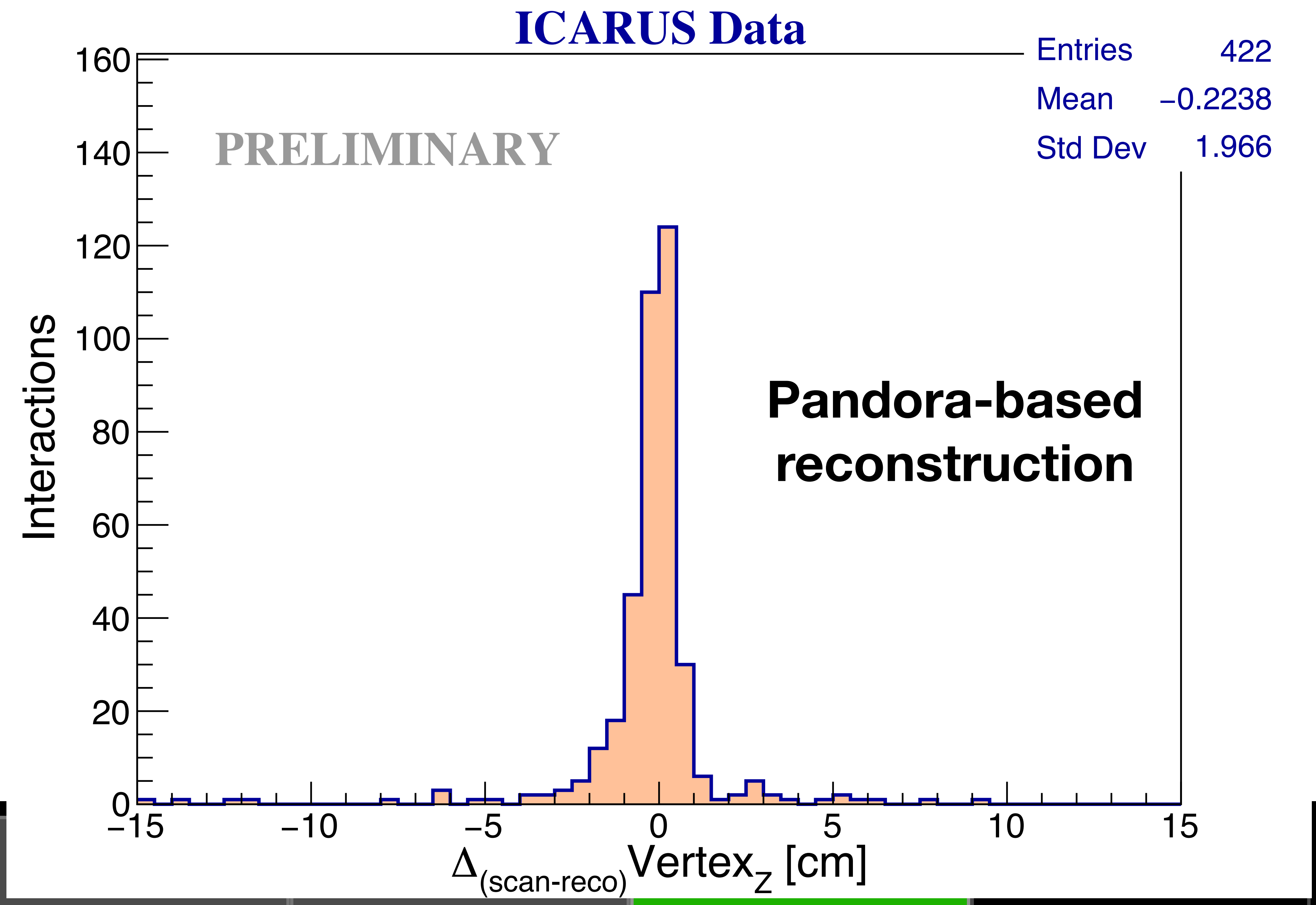


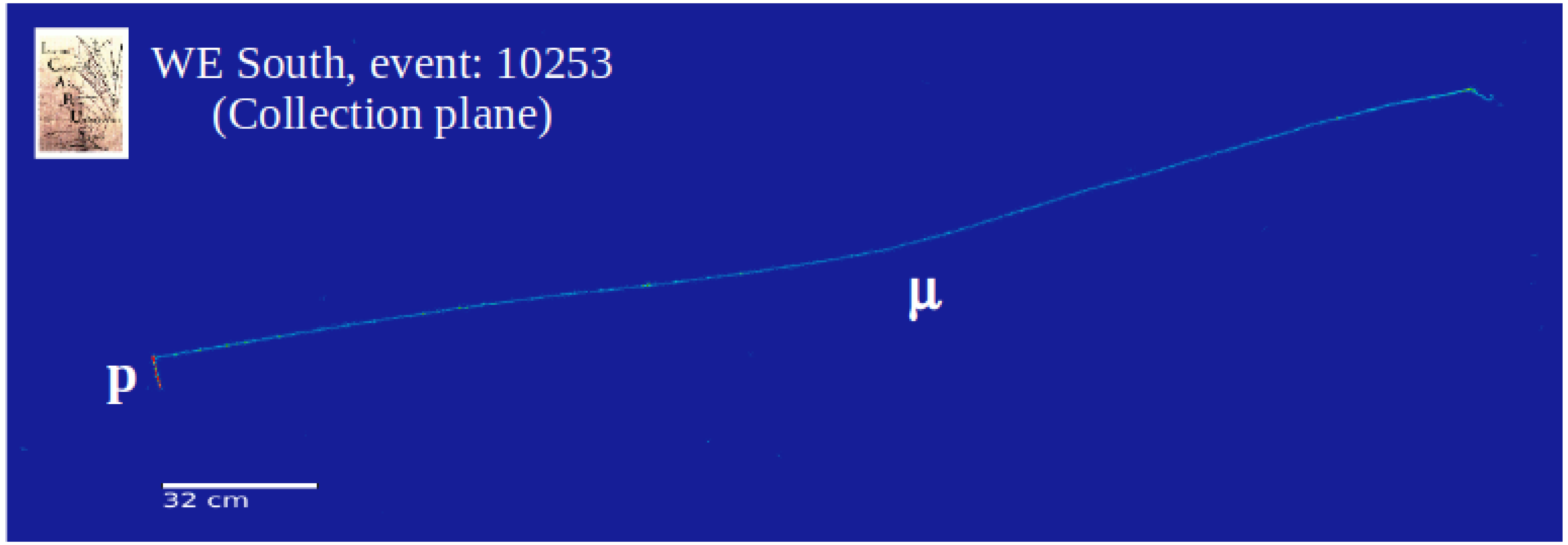


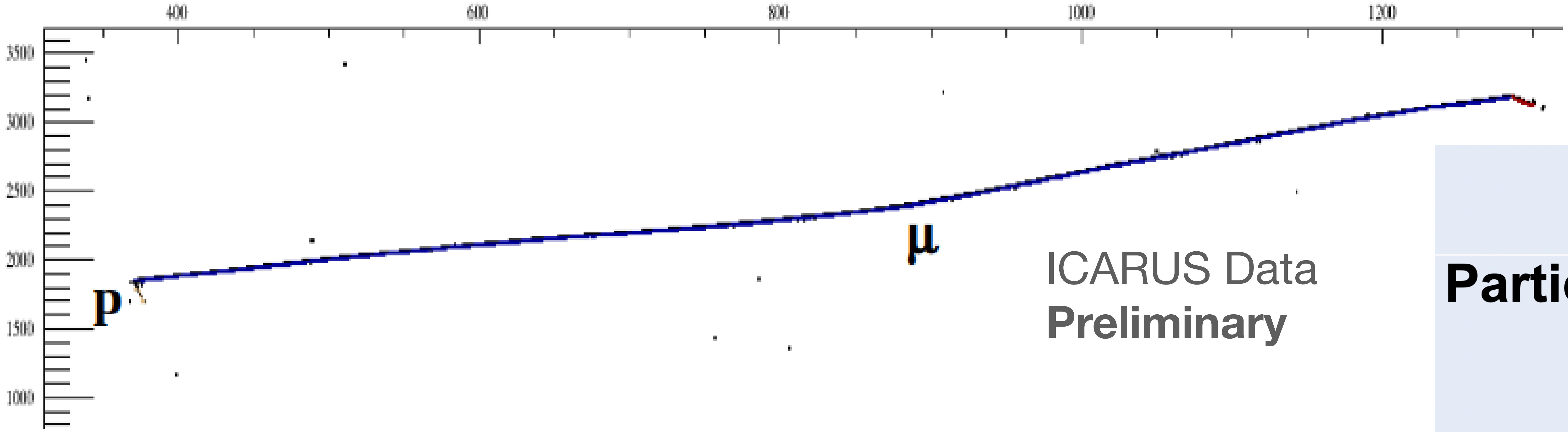
Bringing ICARUS online

- Use simulated samples of events, cosmic data, etc. to investigate the reco chain: validating & improving performance
  - Coordination w/ **hand-scanning** effort has provided very useful set of candidates to explore
  - Enabled also to check quality and ID areas needing improvement
- We have had vibrant group of interns, students, postdocs who contribute to the necessary studies and work to improve performance. Two reconstruction pathways in use:
  - Pandora-based reconstruction using the Pandora Pattern Recognition package (used in MicroBooNE/DUNE as well)
  - Also a group in ICARUS developing ML-based reconstruction
- The reconstruction effort is necessary in enabling the collaboration to do all the physics measurements!



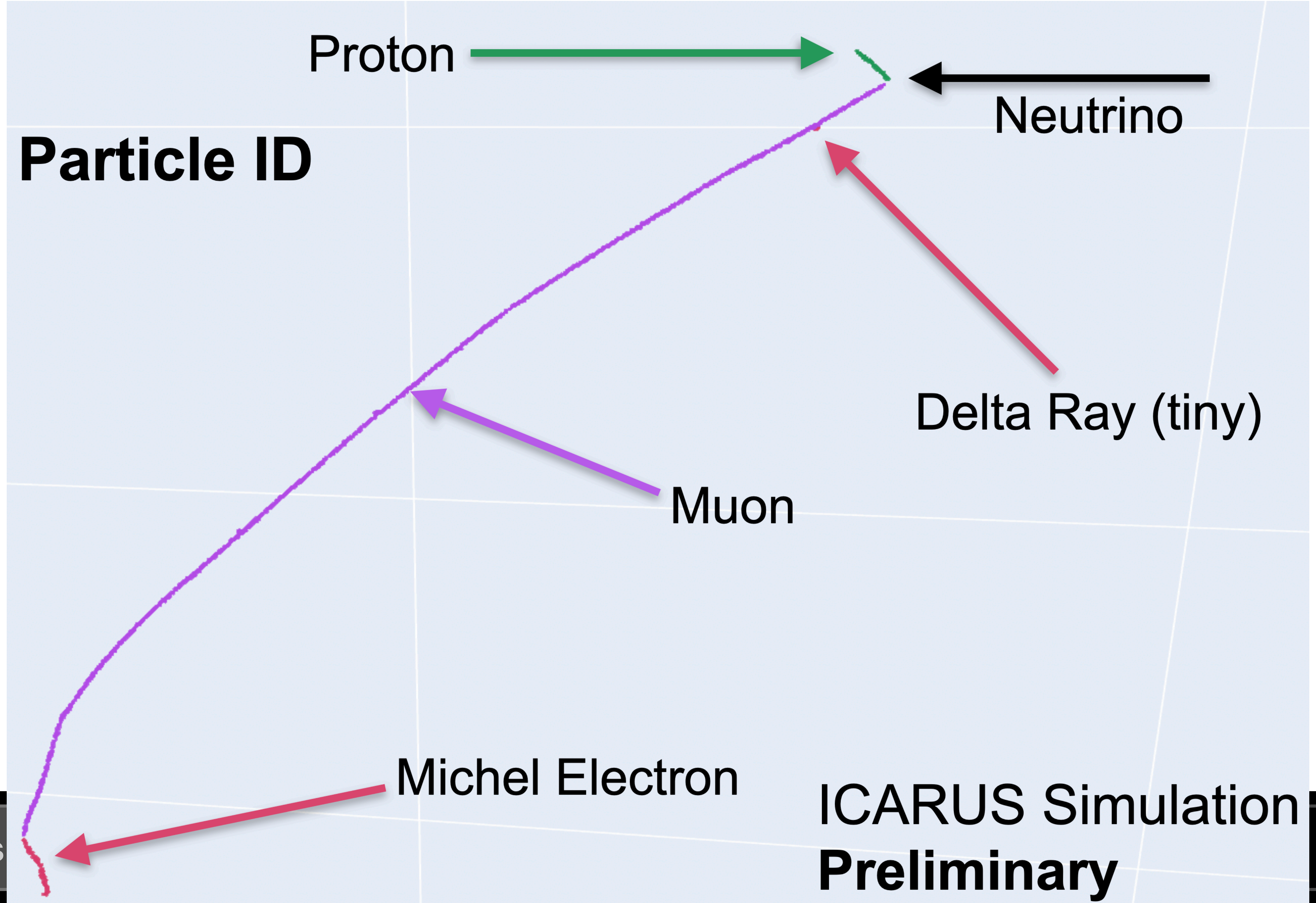






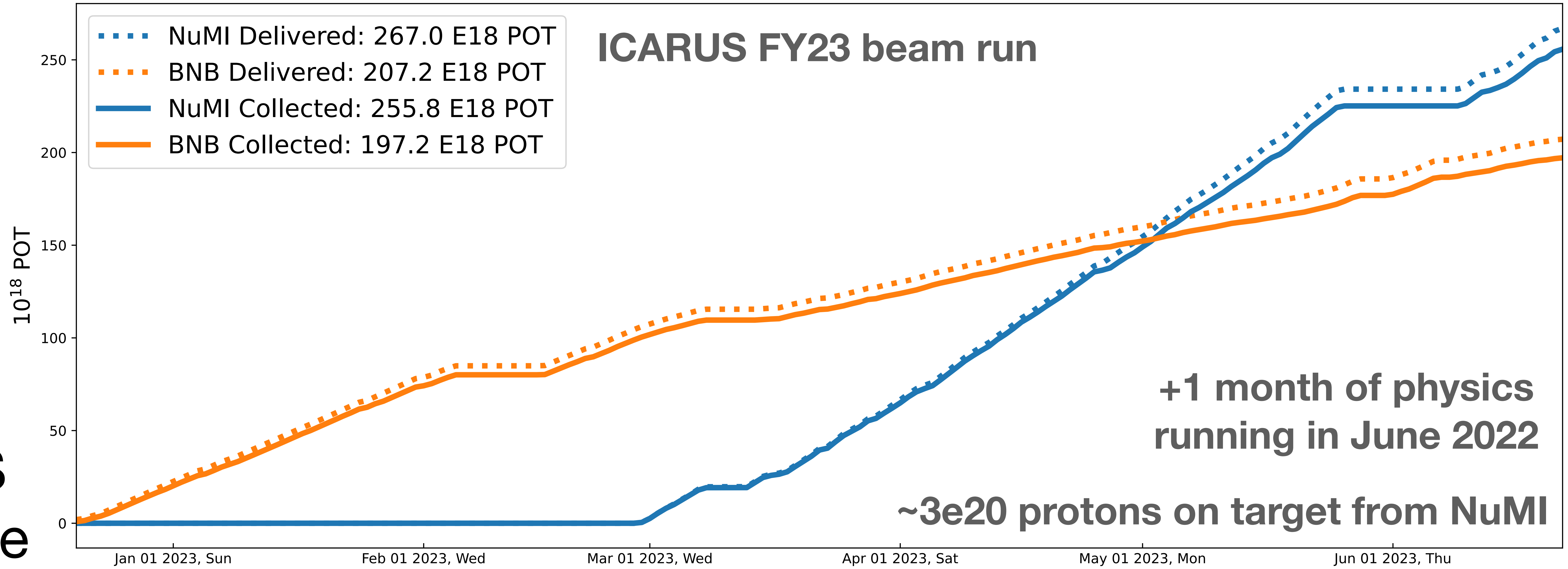
https://github.com/PandoraPFA

https://github.com/DeepLearnPhysics/lartpc_mlreco3d



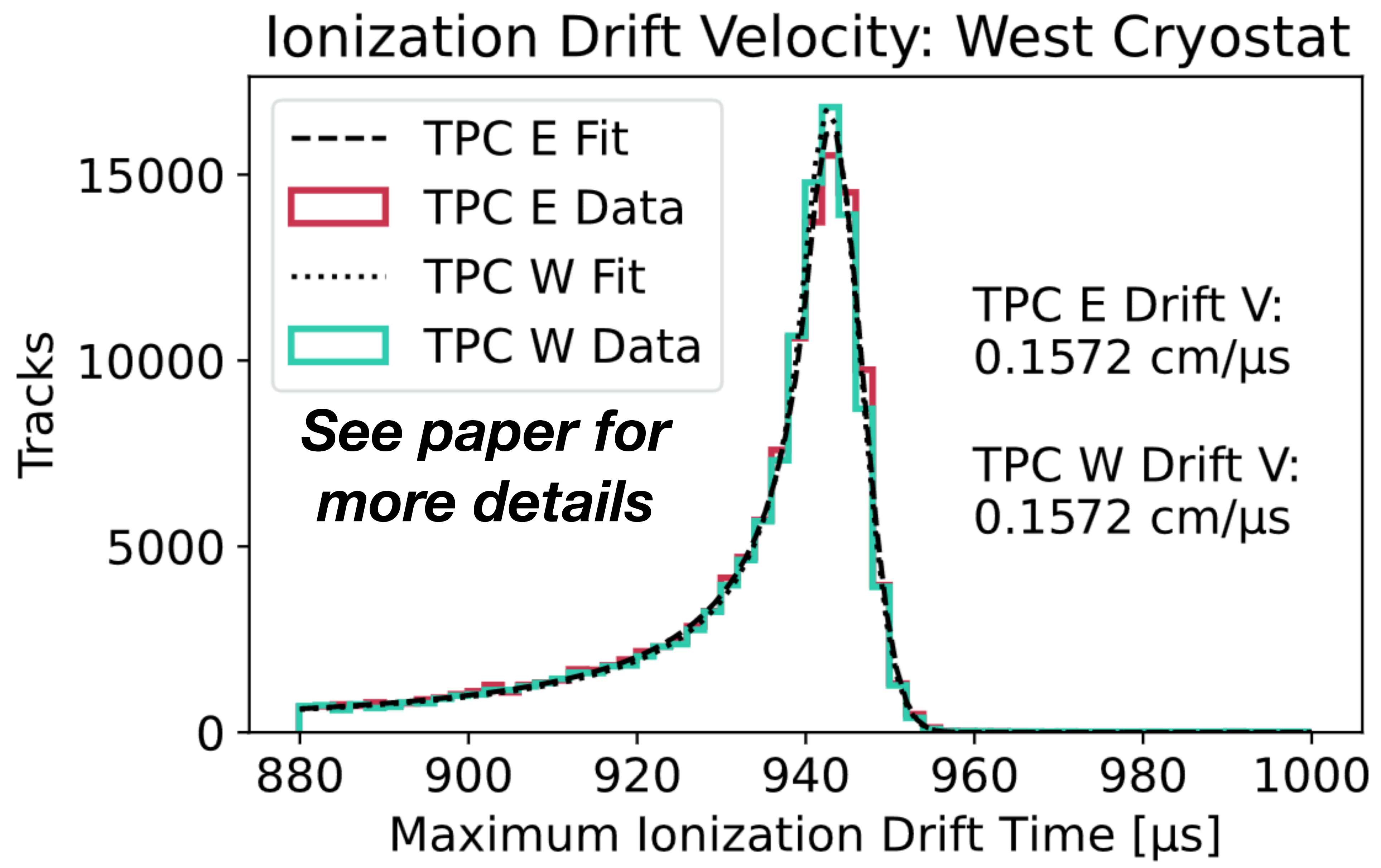
Bringing ICARUS online

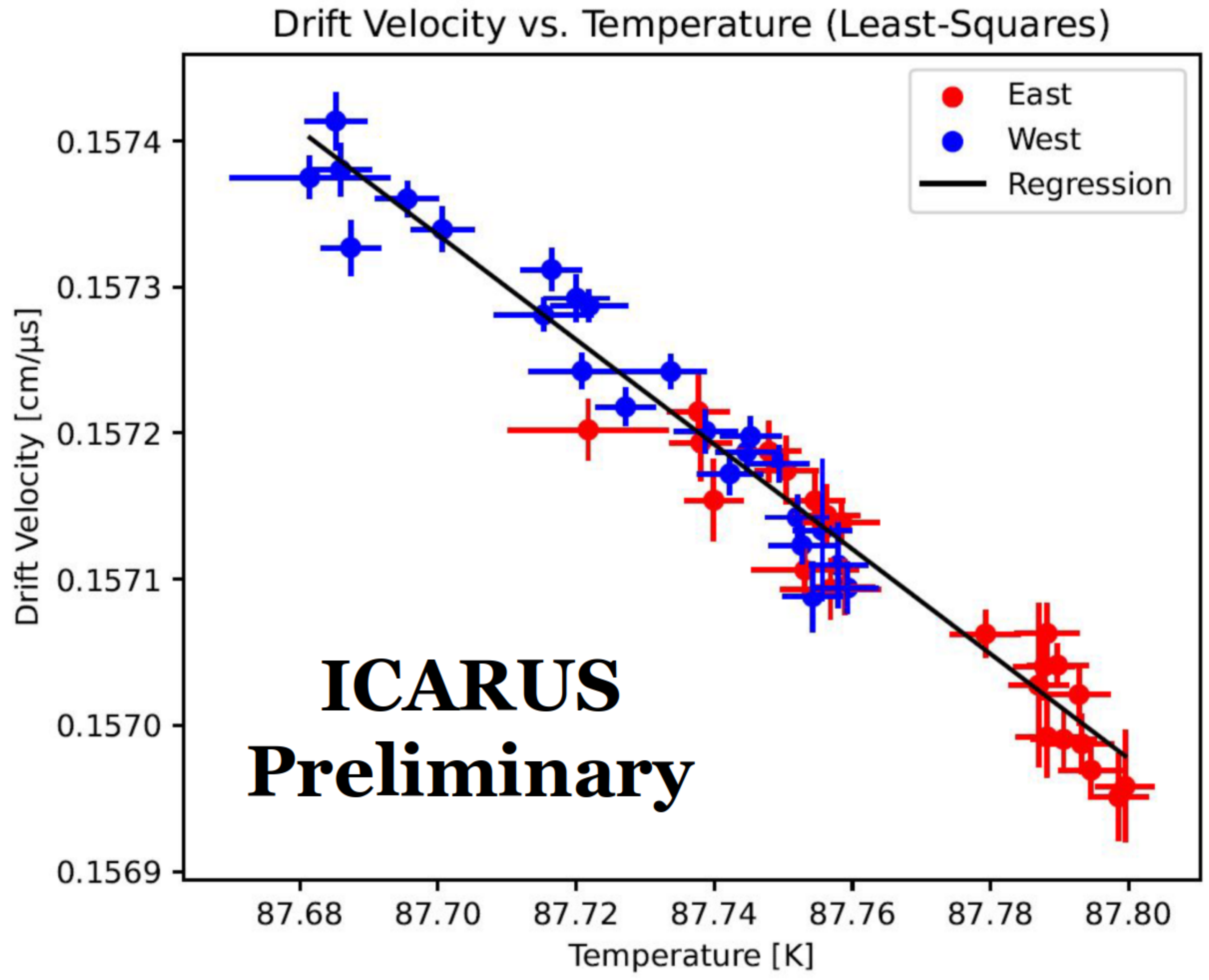
- Following the period of commissioning and final installations, completed in June 2022, we entered physics data-taking operations
  - Now have ~1 year of data and are actively pursuing first sets of physics results
- **SBND expected to take data starting next year**, though ICARUS is pursuing a single-detector ν_μ disappearance measurement in meantime
- But, what can we can do w/ the SBN detectors to prepare for next generation (e.g. DUNE):
  - For one, **experience with operating and analyzing data from LAr TPCs**
  - Also, **uncertainties related to ν interactions** will be a leading uncertainty in DUNE as it is now: ICARUS & SBND will be great help 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
- As an example of recent progress:
  - Drift velocity measured in the TPCs and appears in the EPJC article previously mentioned
  - Also, electron drift velocity in the TPC depends on LAr microphysics (T, ρ, etc.): a study was performed
    - Pressure sensors in detector are used to understand temperature
  - Many other studies: if there is an angular dependence of the particle trajectory with argon ion-electron recombination, diffusion of electrons as they travel to the wires, etc.

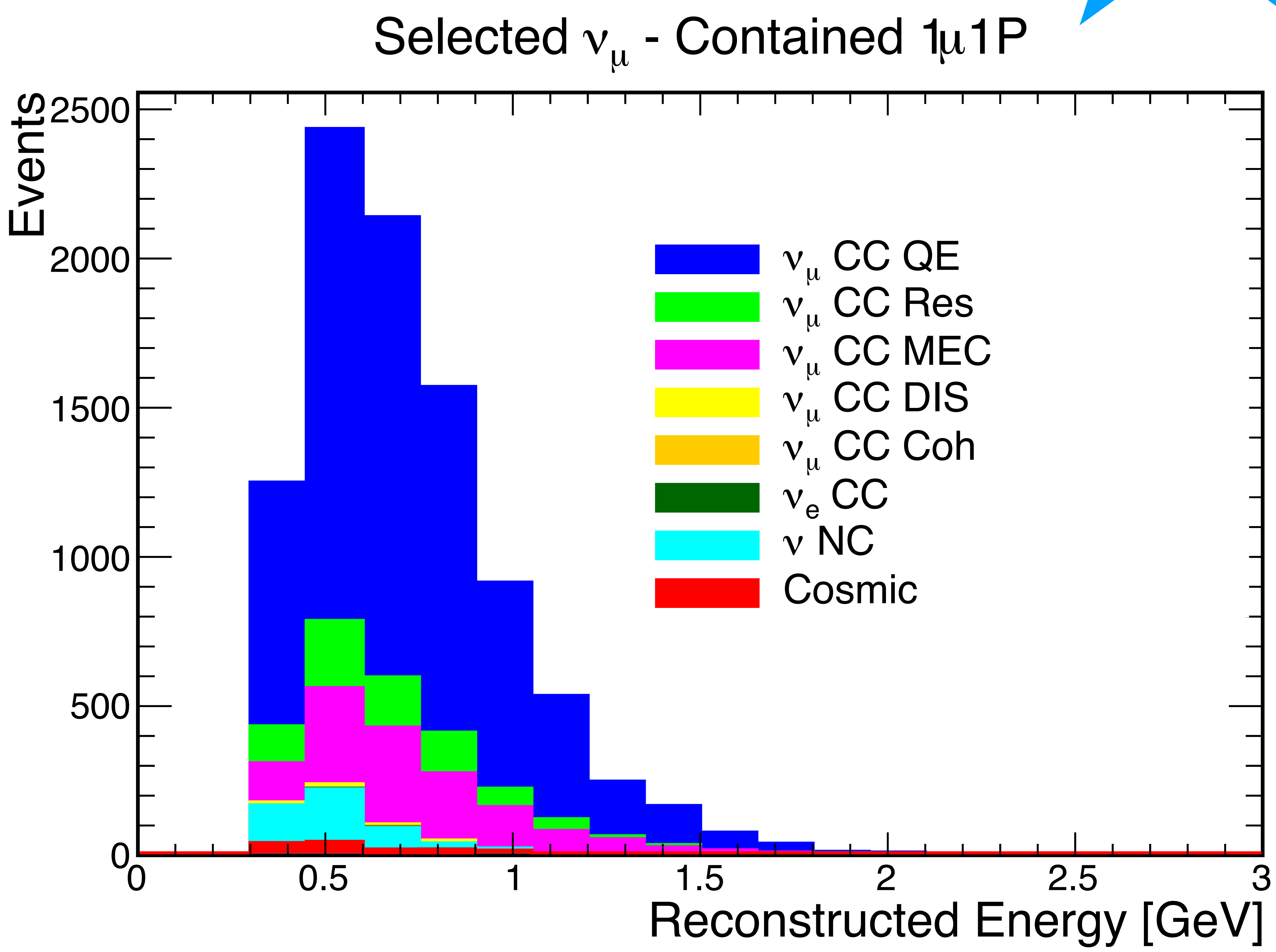




Progress toward oscillation analysis

??

- Working towards analysis with the data in hand or expected, will go over some of them now…
- An anticipation is that there could be a muon neutrino disappearance measurement first from the SBN program in advance of an appearance search
  - 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)

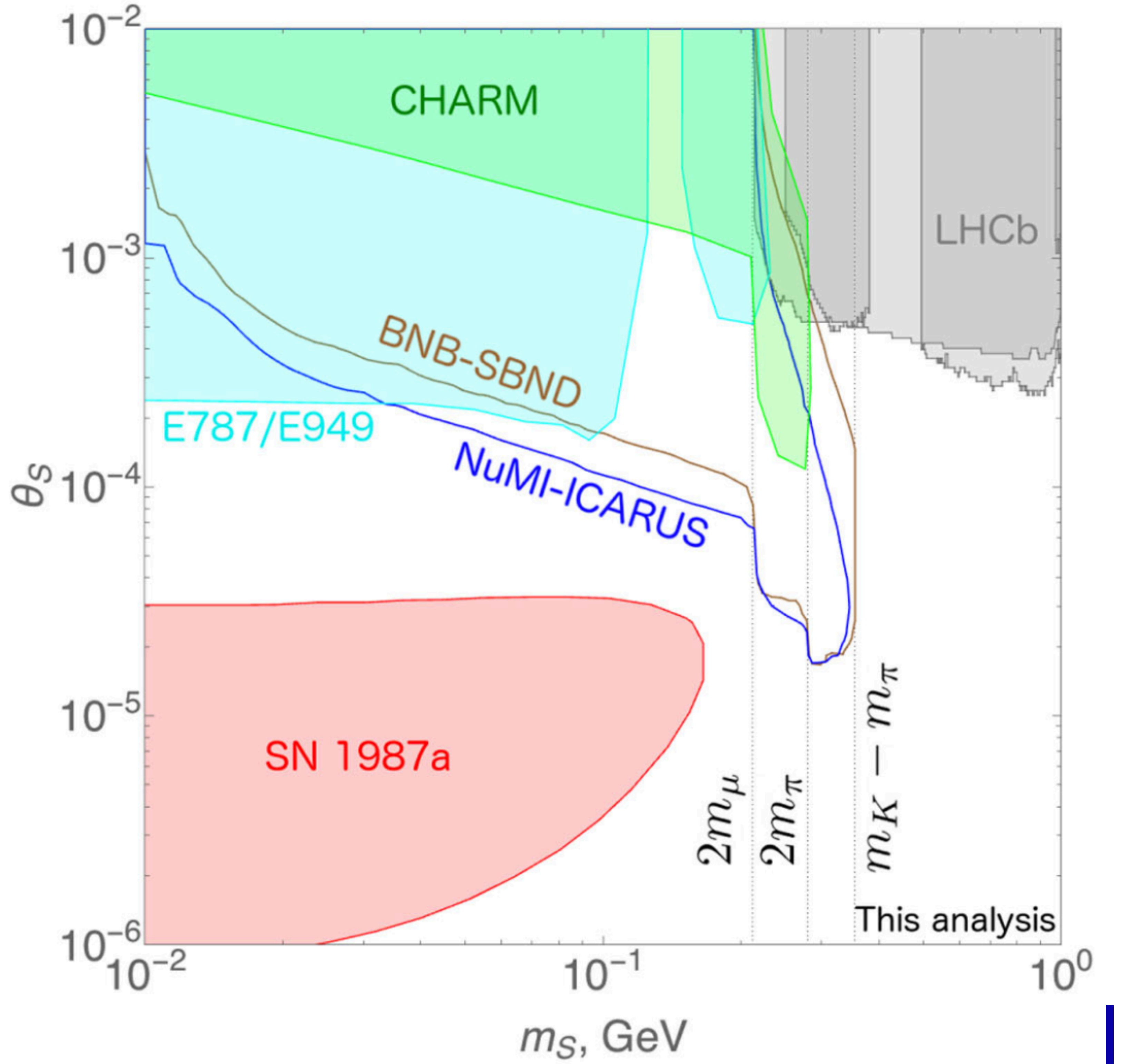


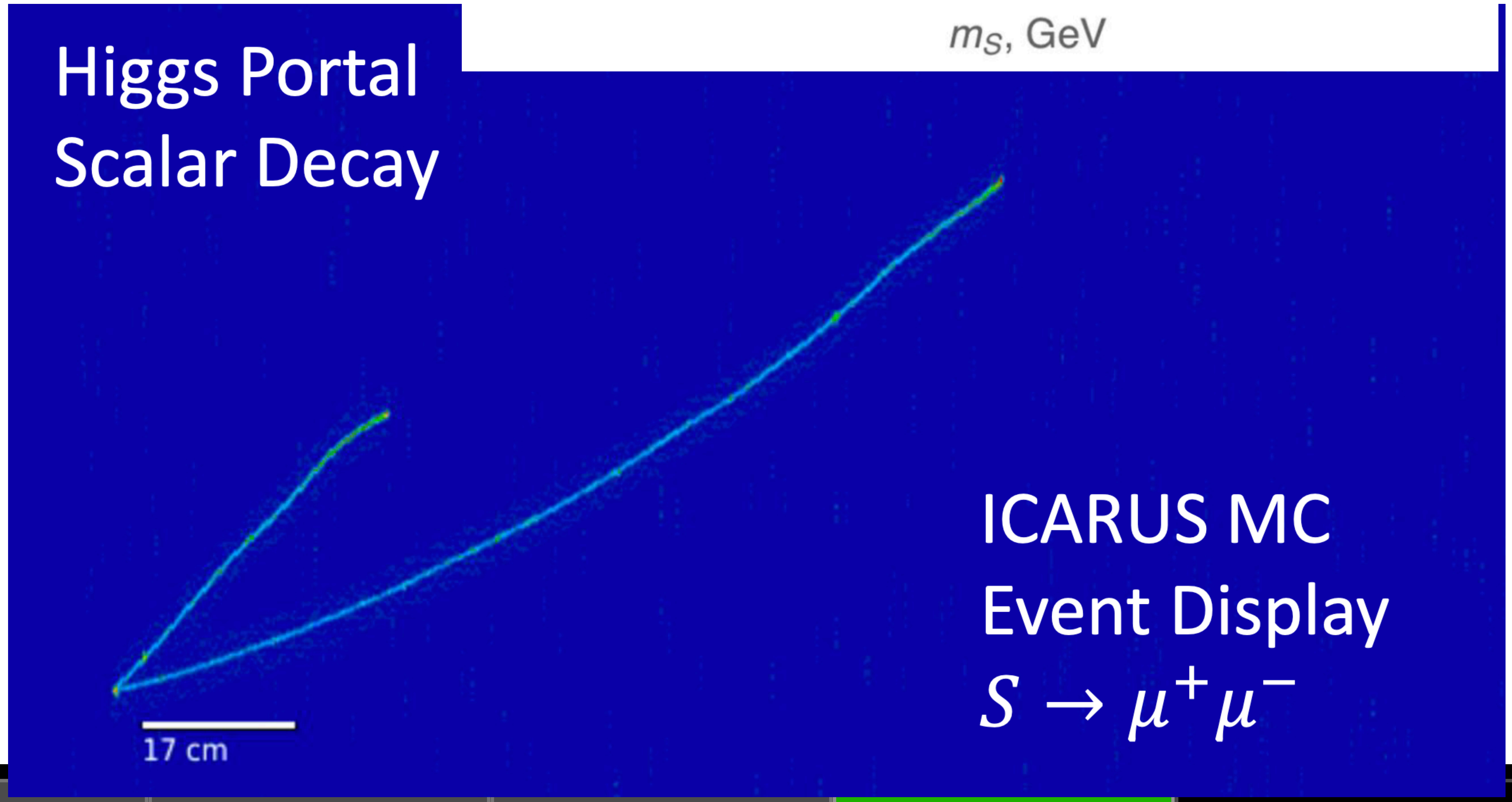
Showing plot from Pandora reco-based selection

NuMI BSM searchers

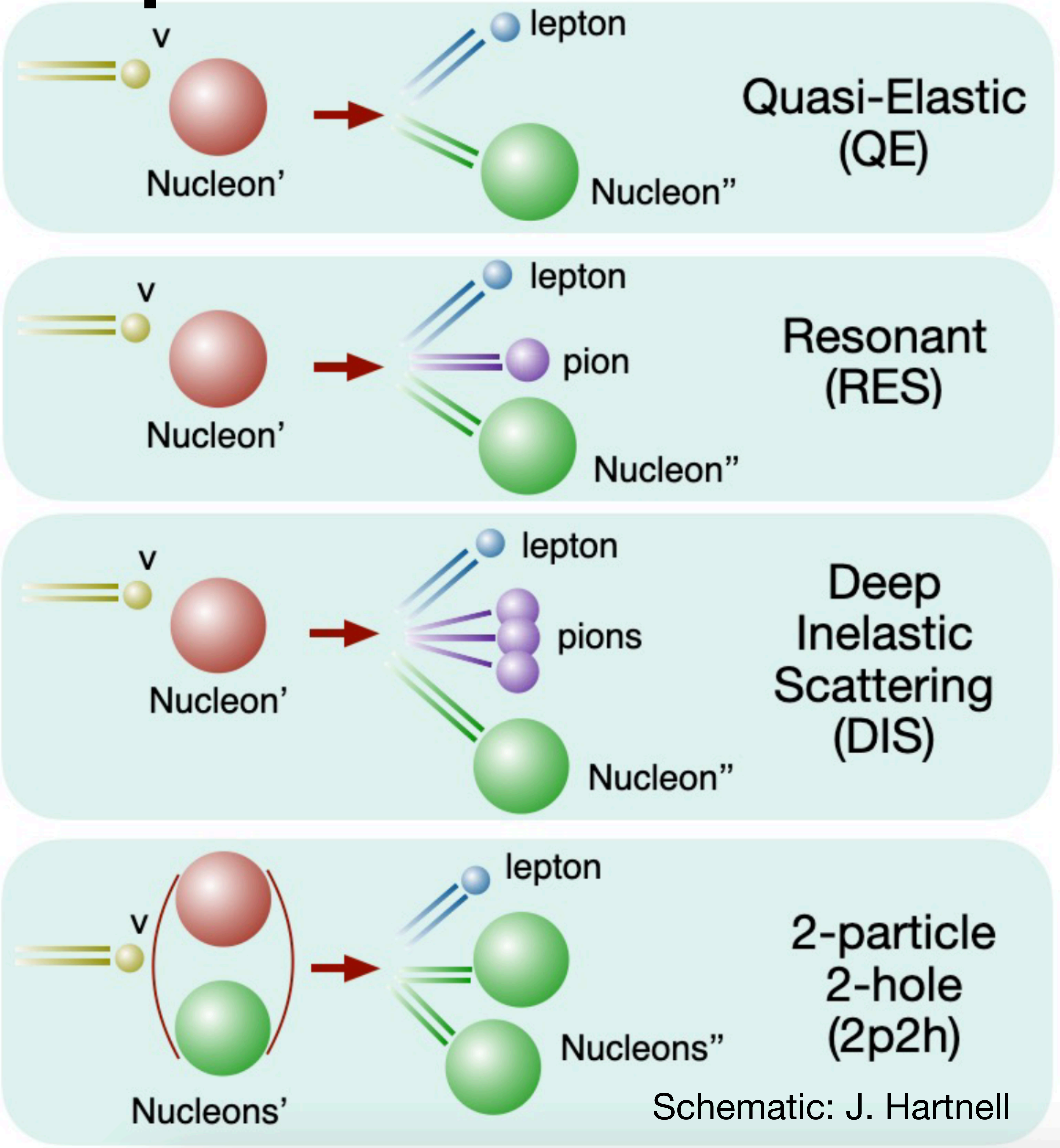
- As powerful beam off-axis and using LAr TPC tracking & calorimetry, also searching for Beyond Standard Model processes especially using NuMI beam at ICARUS
  - Enhanced by pointing capability, e.g. pointing back to target or beam dump
  - Looking for light dark matter
  - Also Higgs portal scalars,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

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



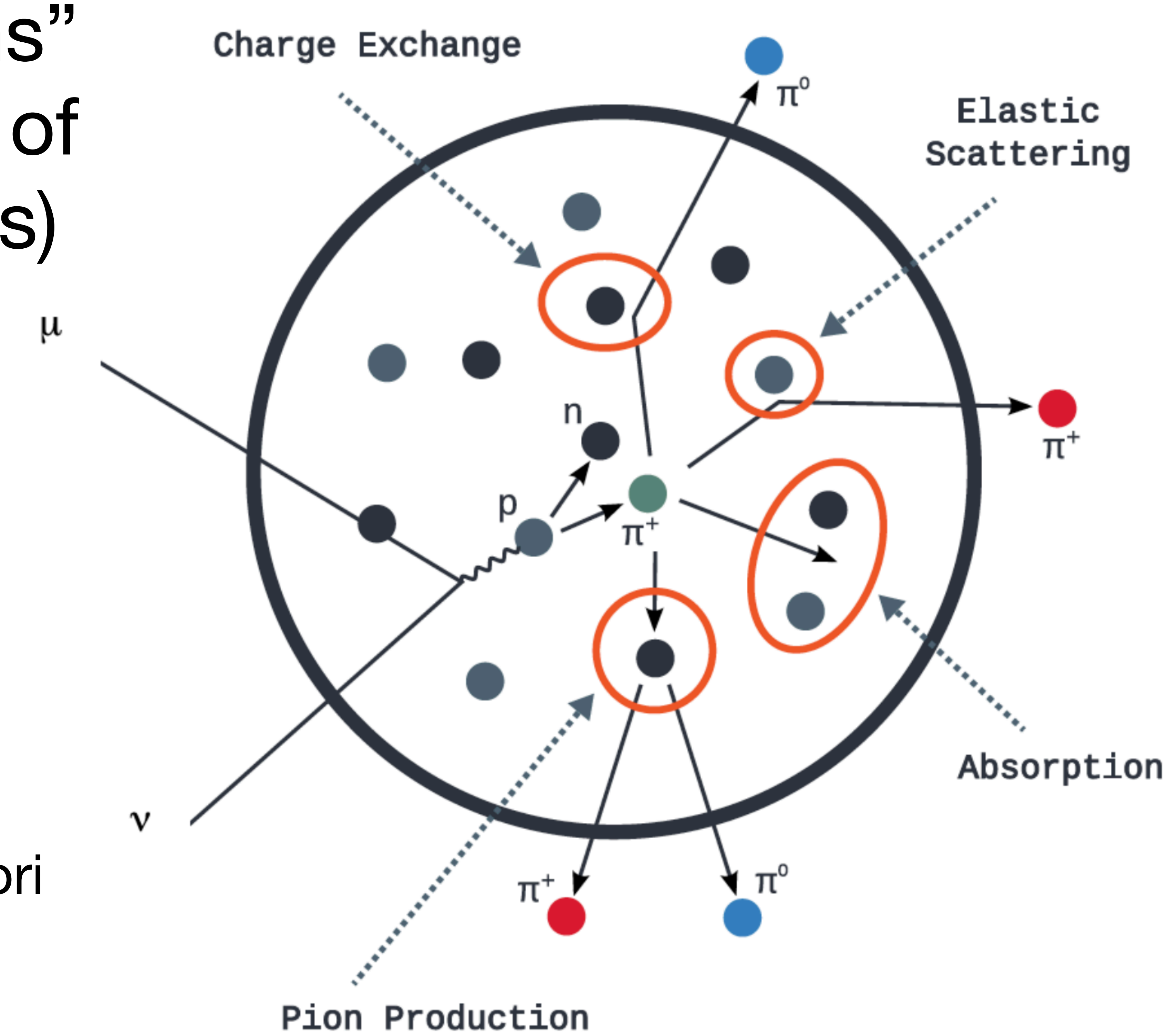


Impact of interactions



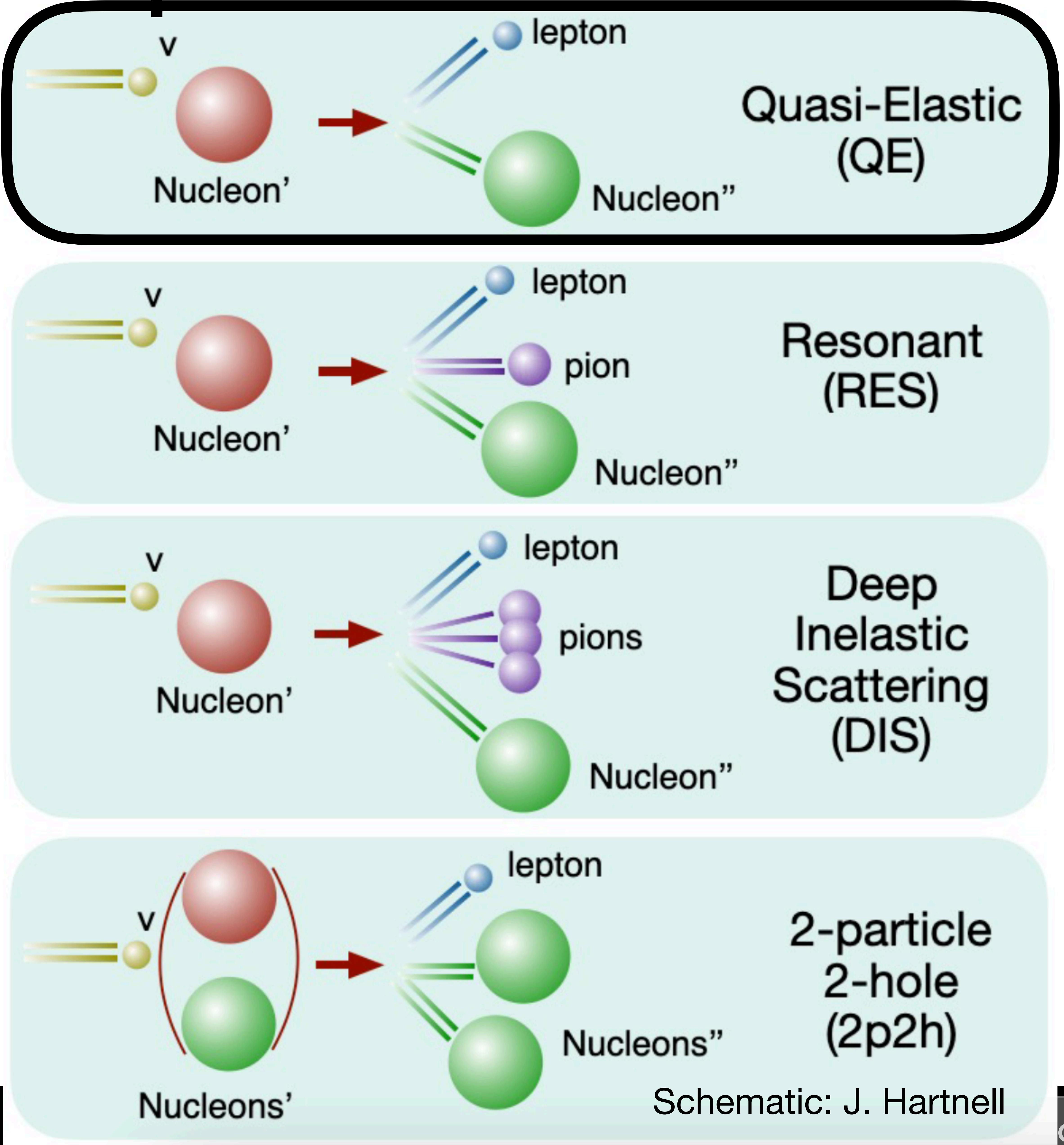
Schematic: J. Hartnell

- Oscillation goes as L/E: we know L and really need to measure **E**
- But we don't see the neutrino itself in our detector, only products of its interactions
  - Estimate E from energy of the products we **see**
  - Number of intricacies… we rely on our models of what happens and how often (i.e. neutrino "cross-sections" and dynamics of the interactions)



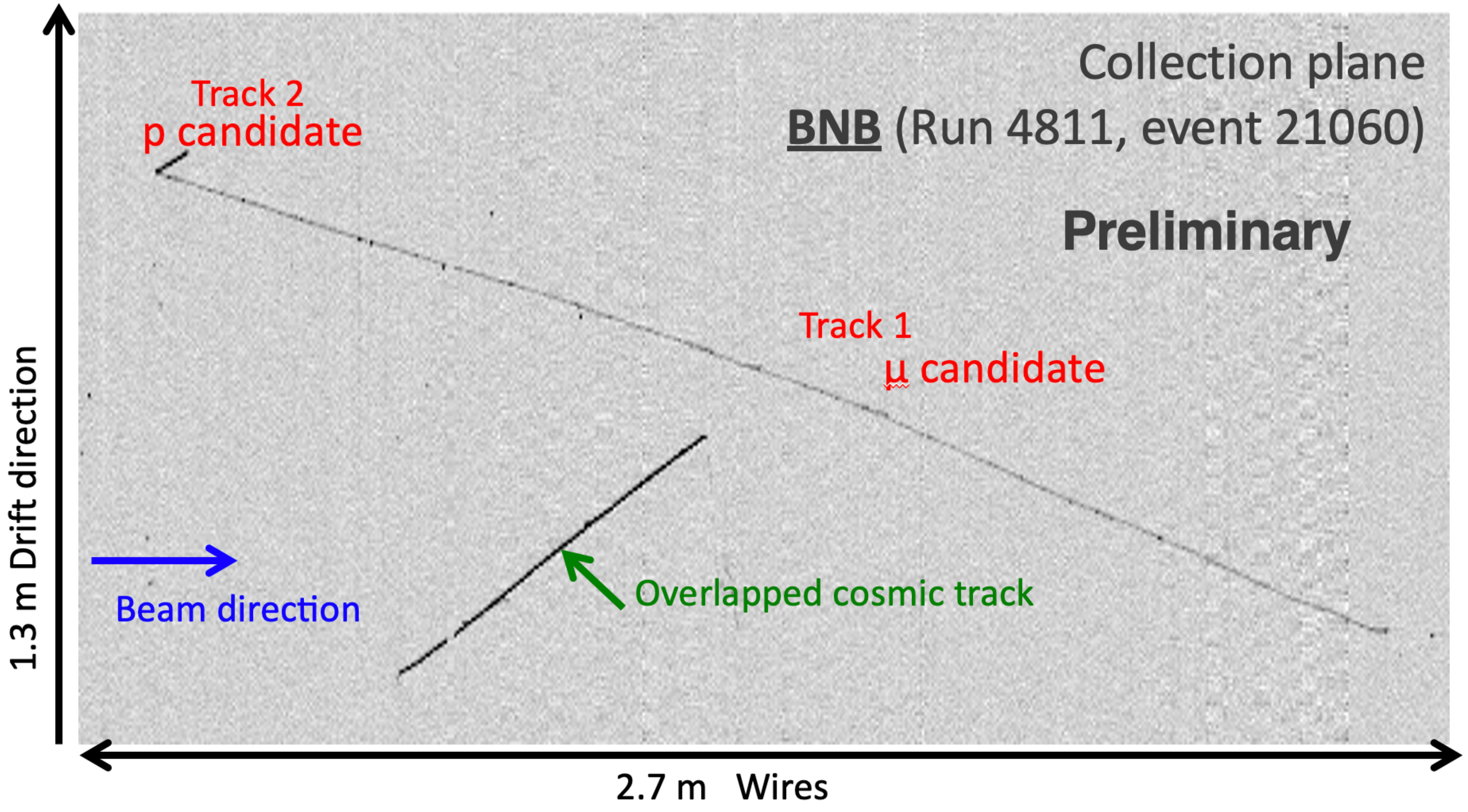
Schematic: T. Katori

Impact of interactions

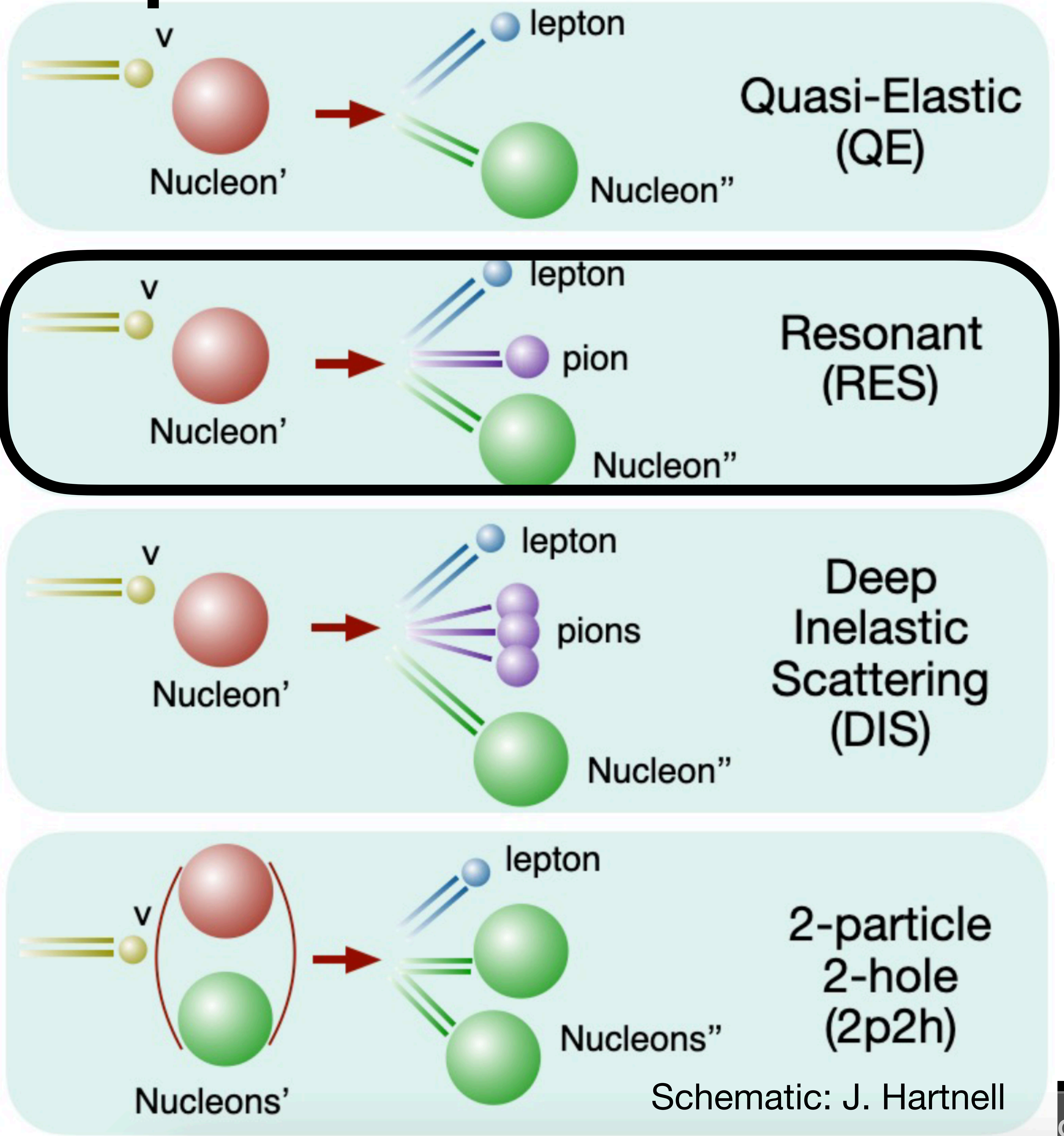


Schematic: J. Hartnell

A QE-like event in ICARUS!

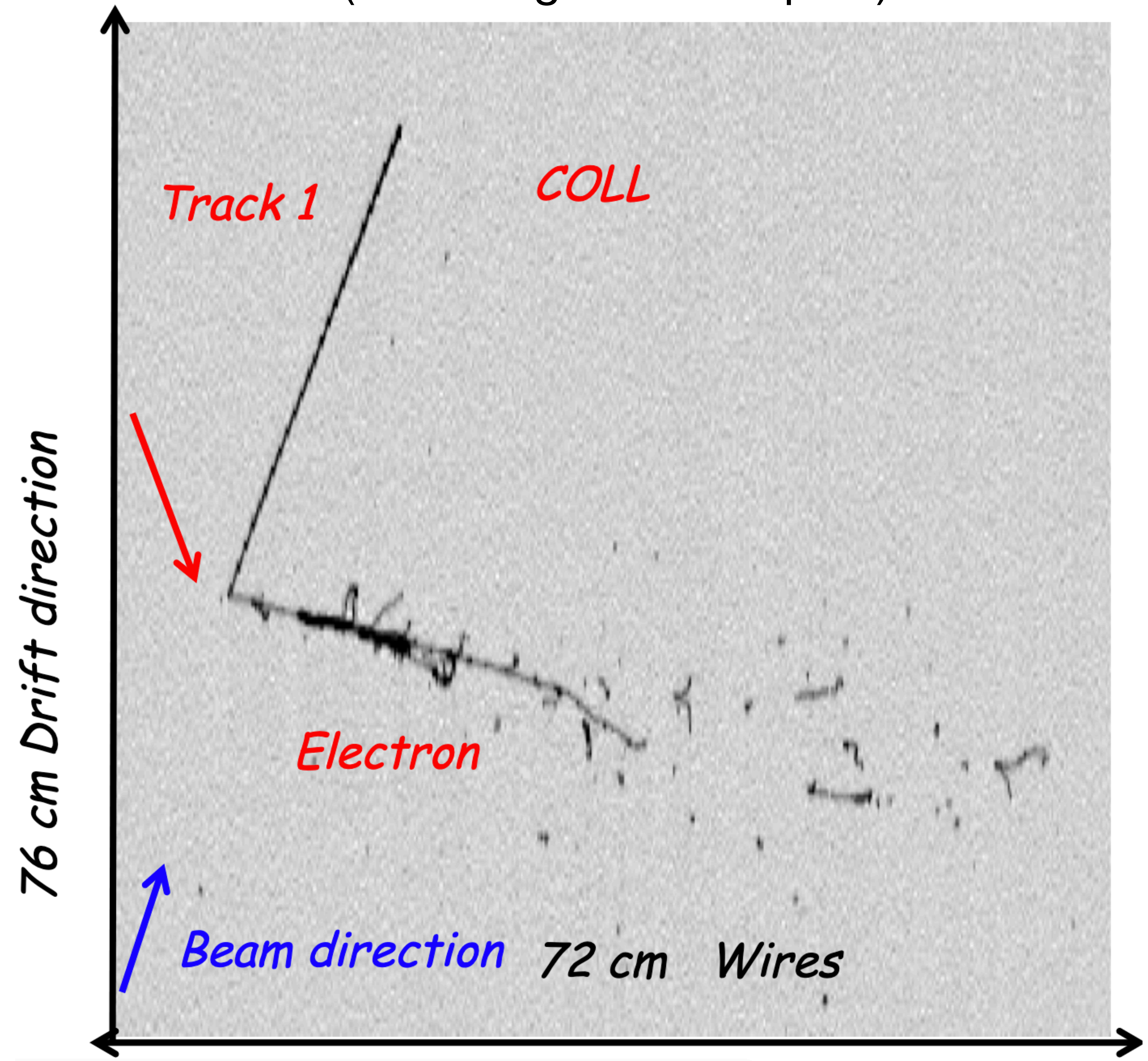


Impact of interactions



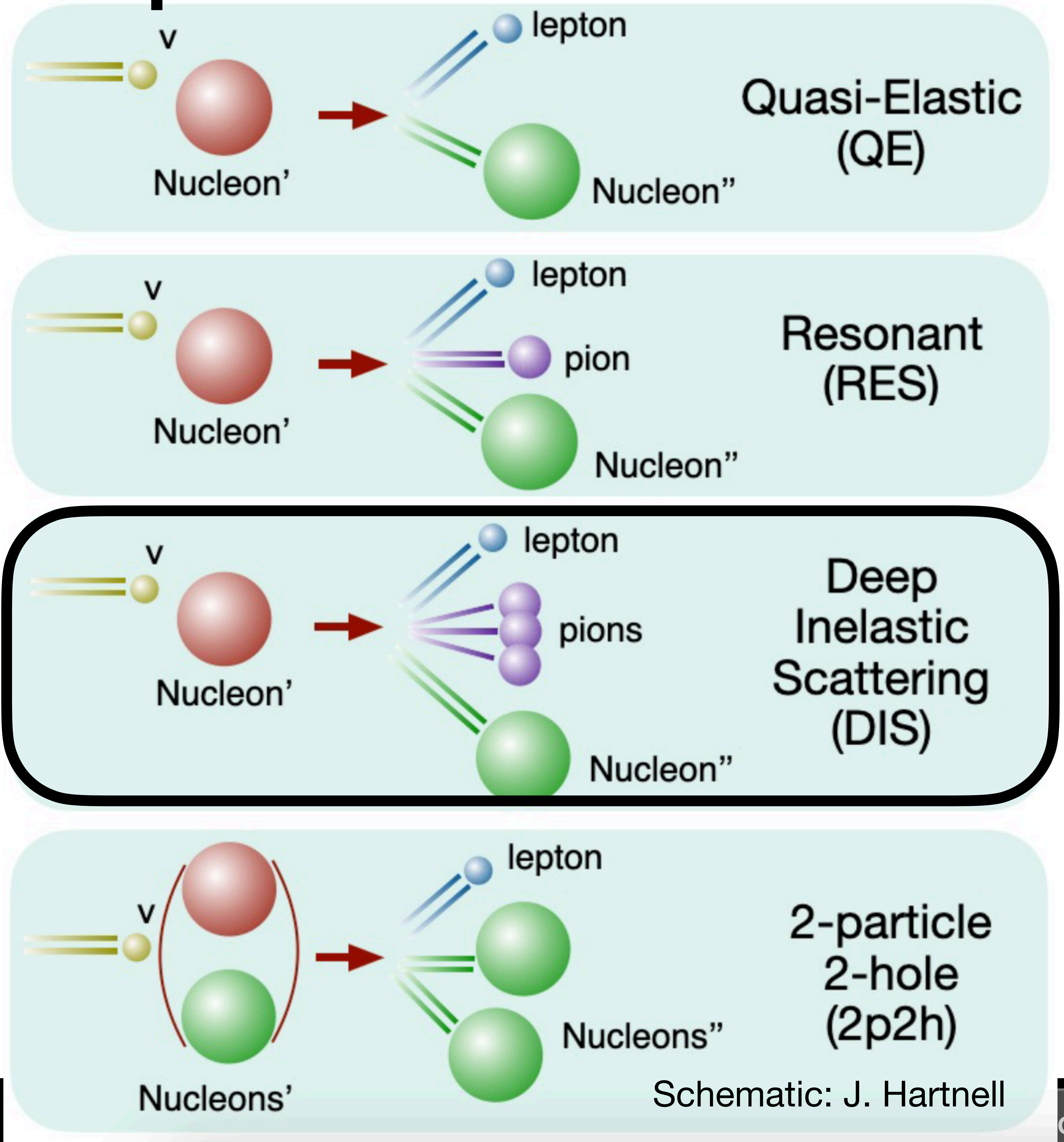
Schematic: J. Hartnell

A resonant-like event in ICARUS
(assuming track is a pion)

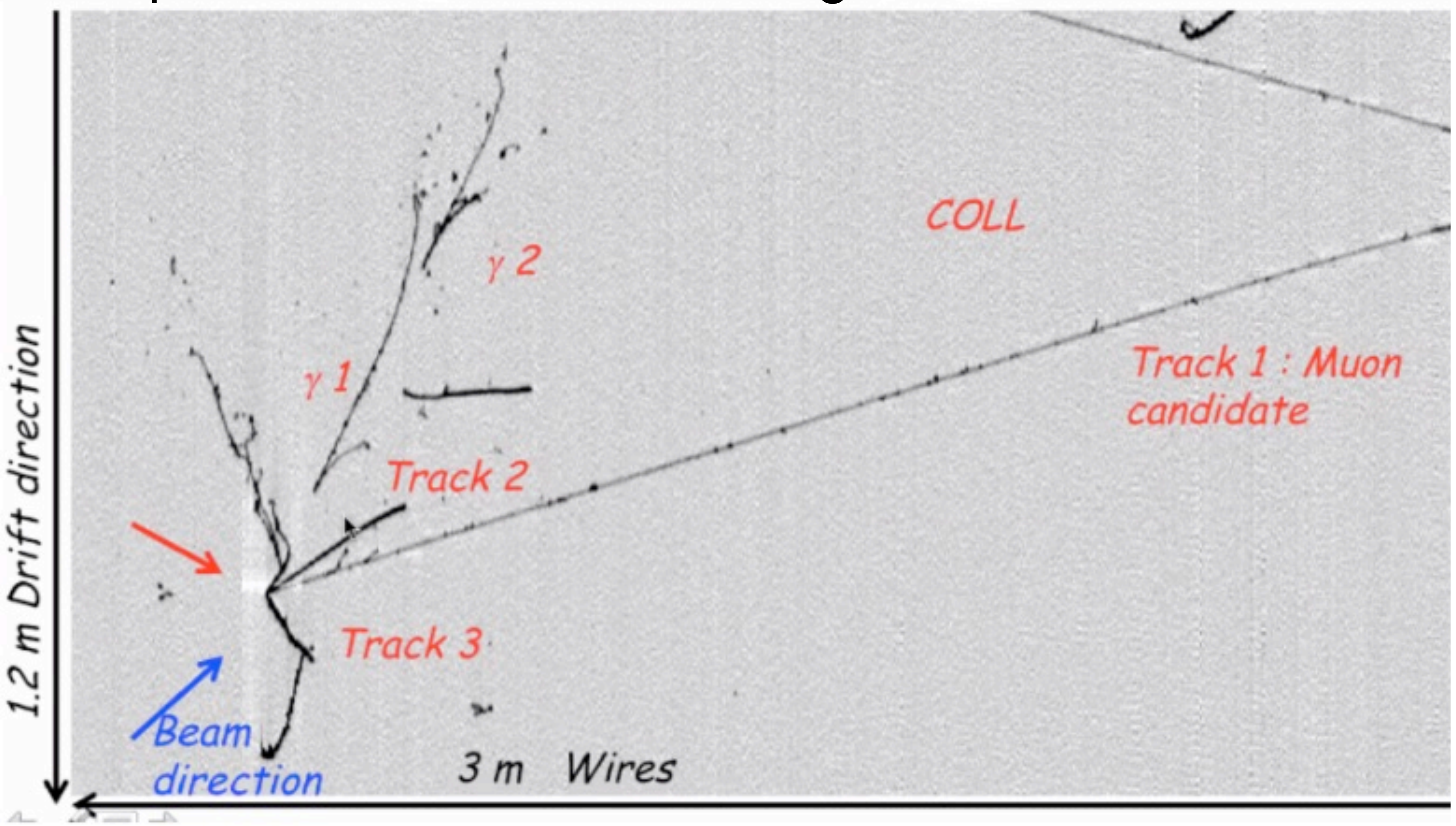


This is ν_e candidate, is like DUNE appearance signal

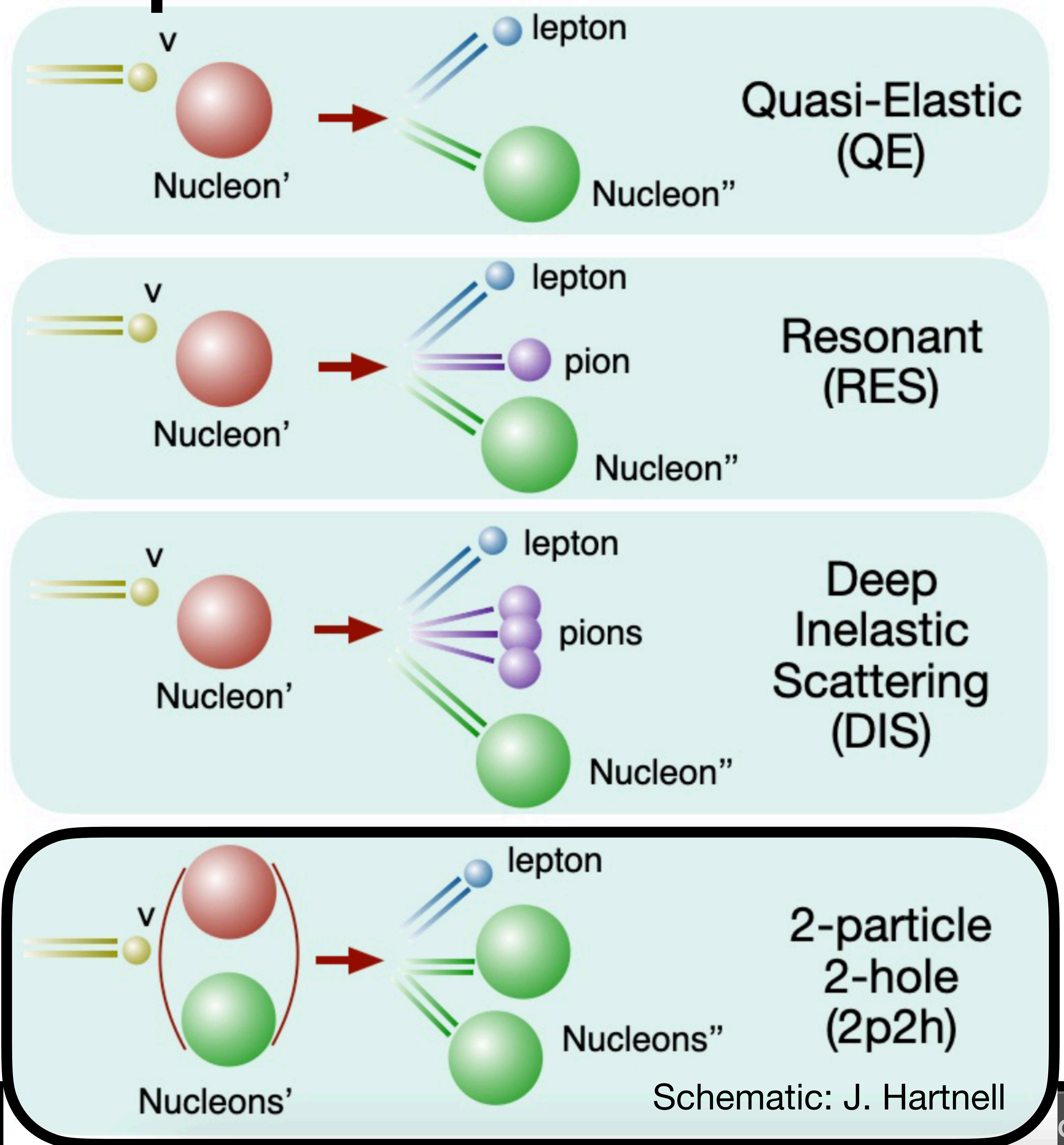
Impact of interactions



A possible inelastic scattering candidate in ICARUS

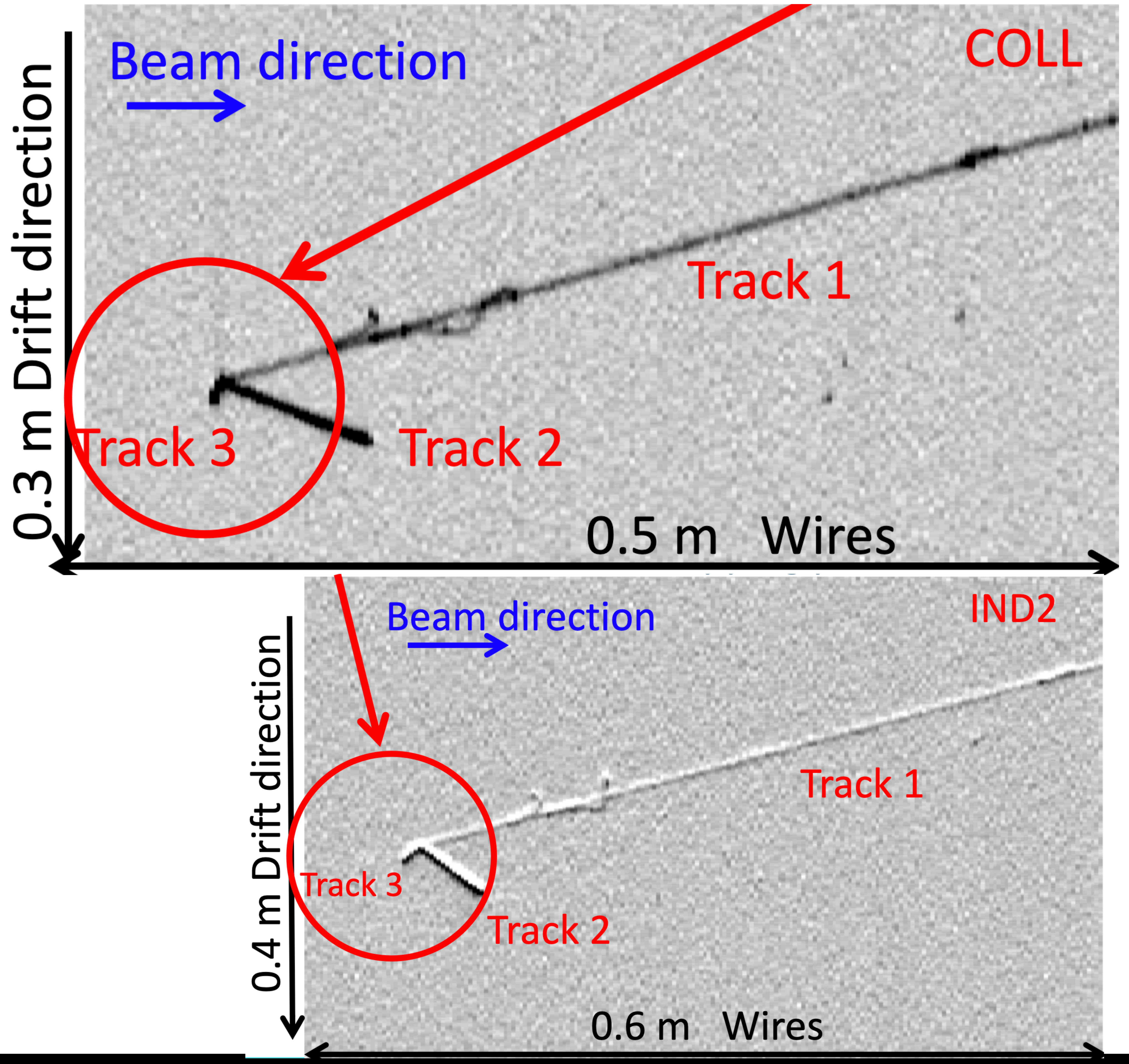


Impact of interactions



Schematic: J. Hartnell

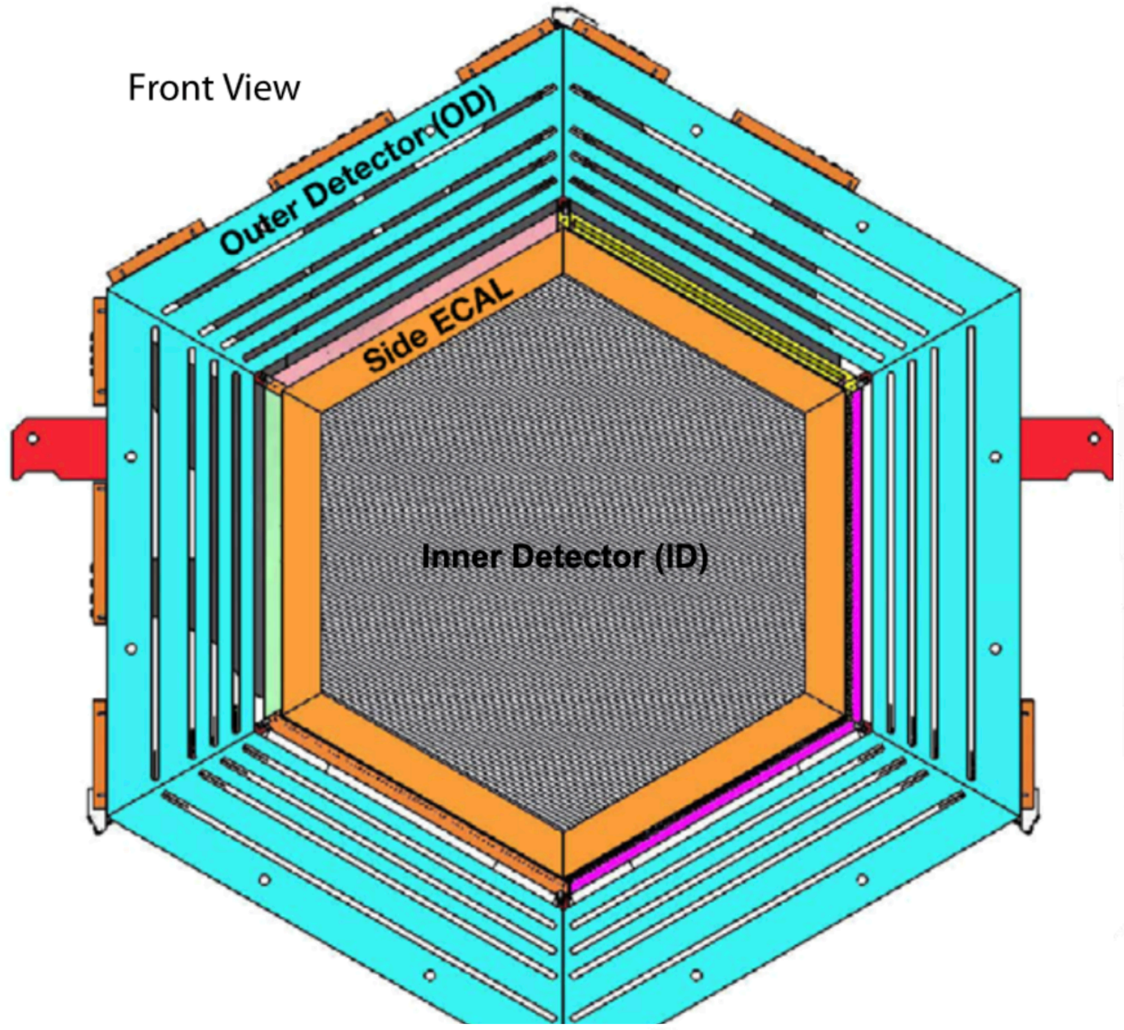
Interaction in ICARUS w/ 2 proton-like particles



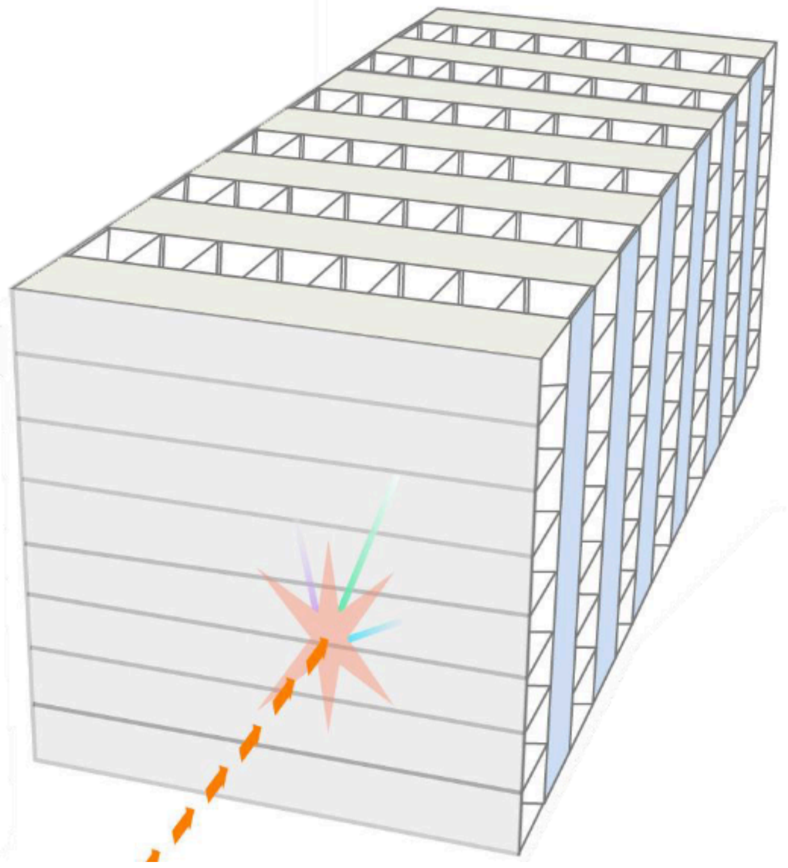
Impact of interactions

- In recent years a number of experiments are measuring interactions to put current models to test & drive new developments

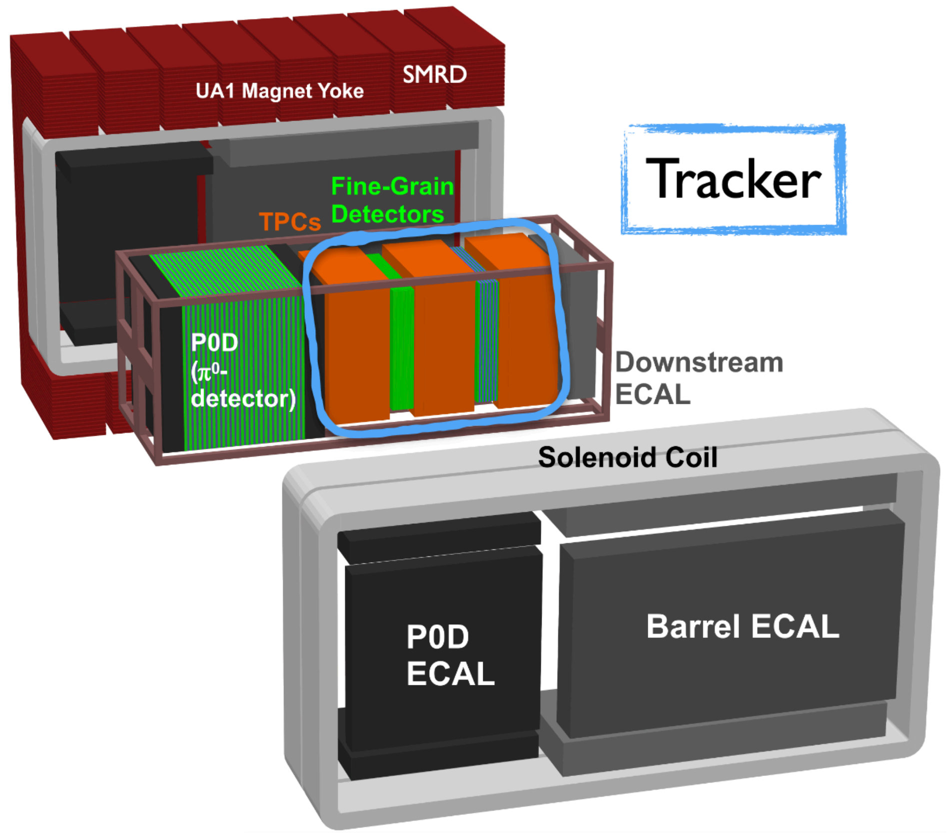
MINERvA: NIM A 743 (2014) 130–159



NOvA (E. Smith talk)



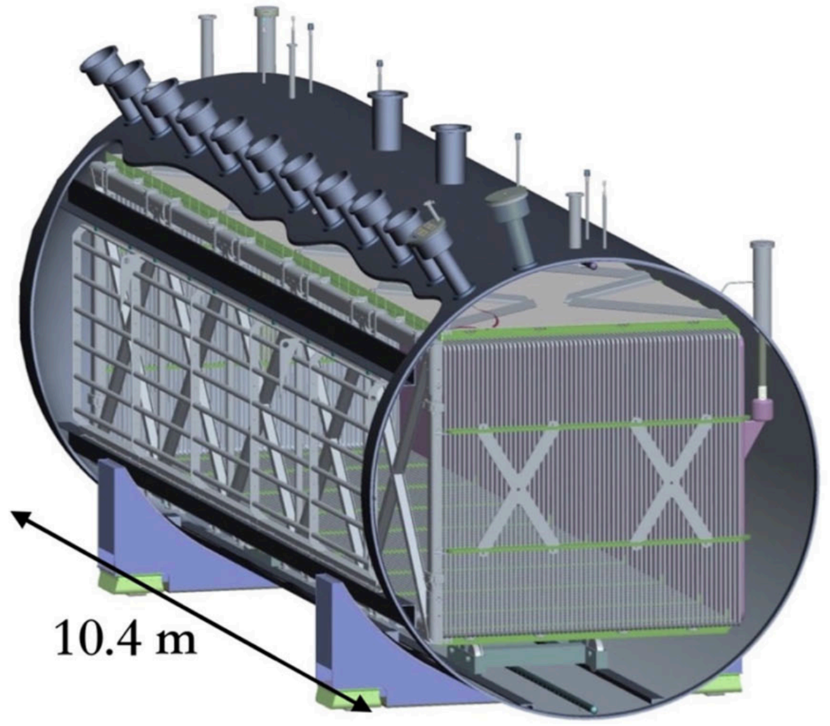
T2K (L. Magaletti talk)

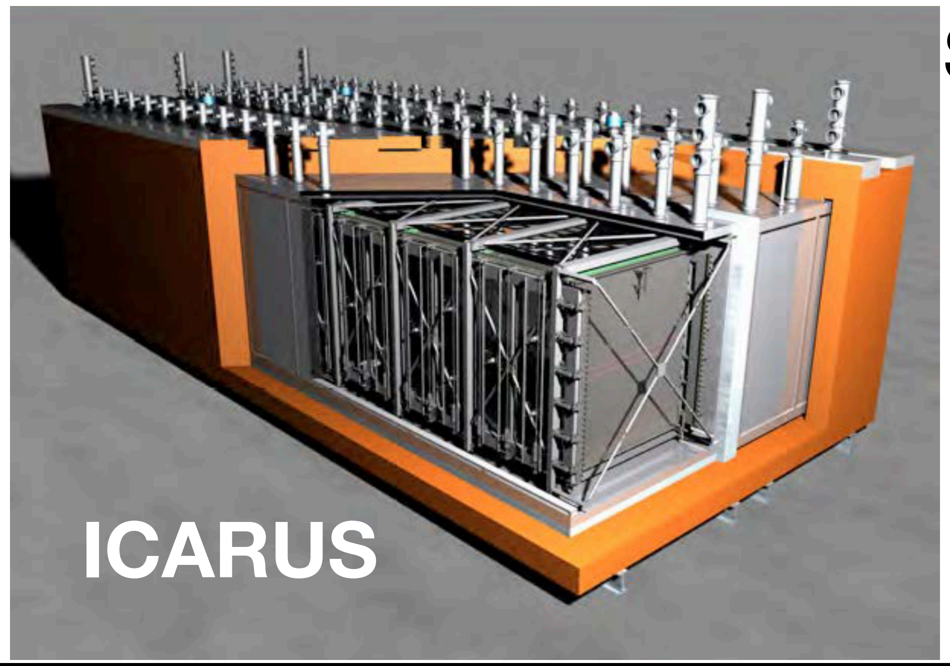


++ ICARUS & SBND:
More measurements on Ar!

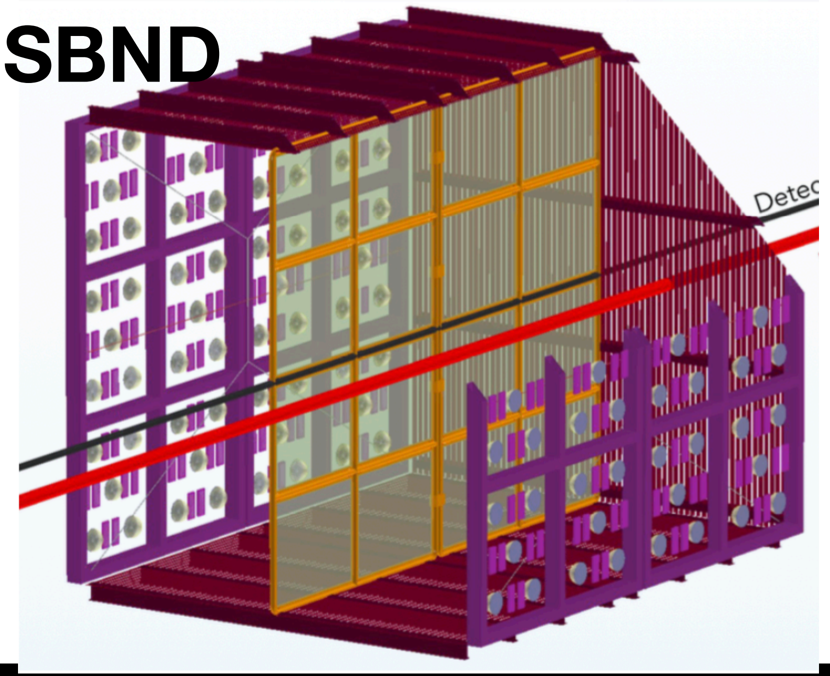
MicroBooNE:
Eur. Phys. J. C (2019) 79:673

ν-Ar !!





SBND

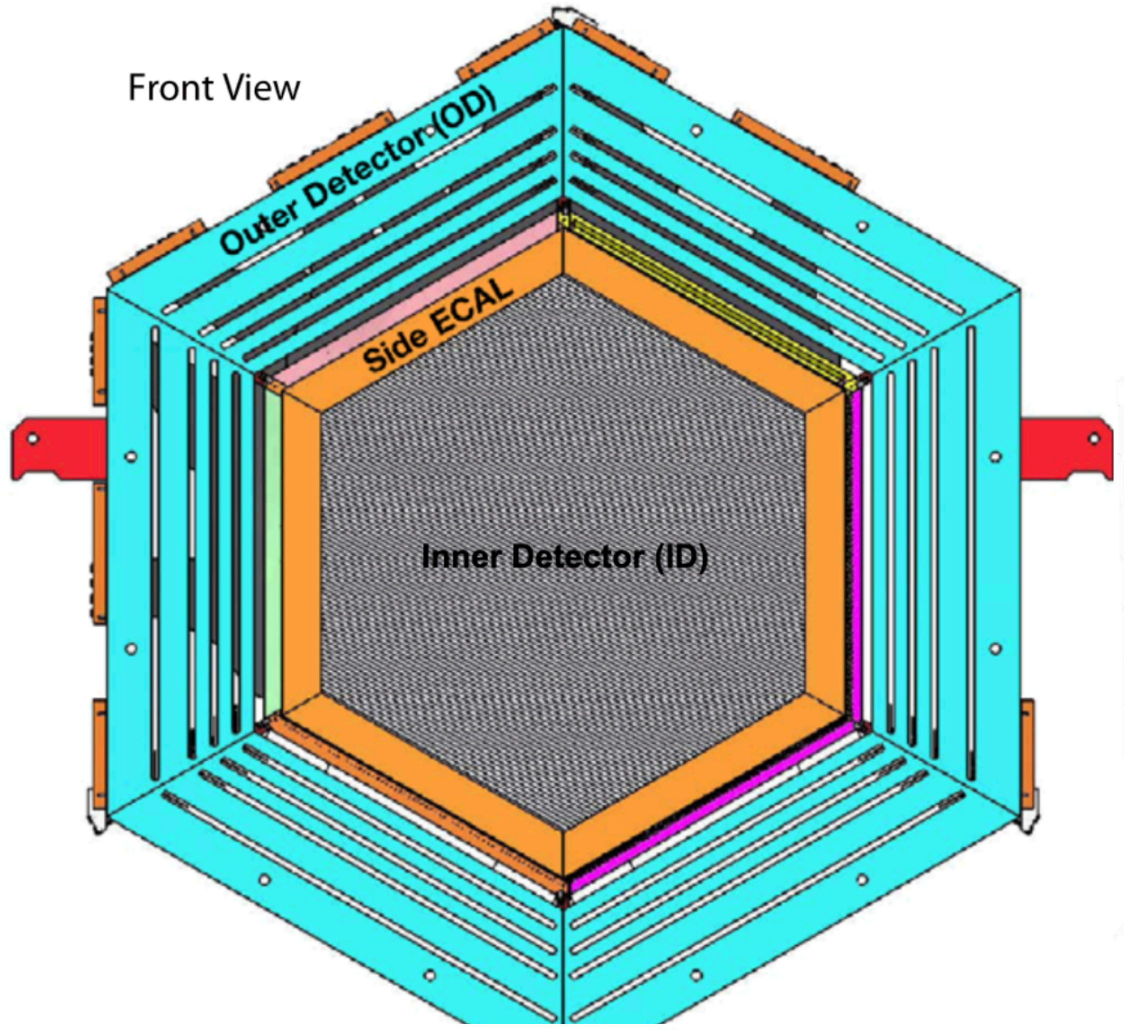


Impact of interactions

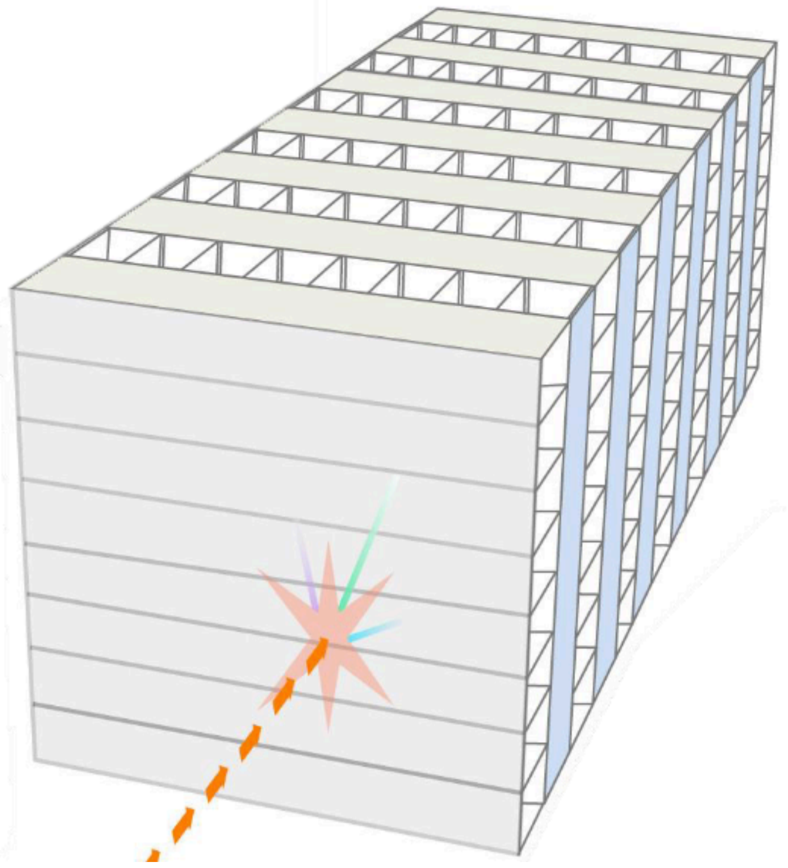
Unfortunately, at present there is plenty of disagreement between our models and data… Need more and better measurements driving and validating model developments

- In recent years a number of experiments are measuring interactions to put current models to test & drive new developments

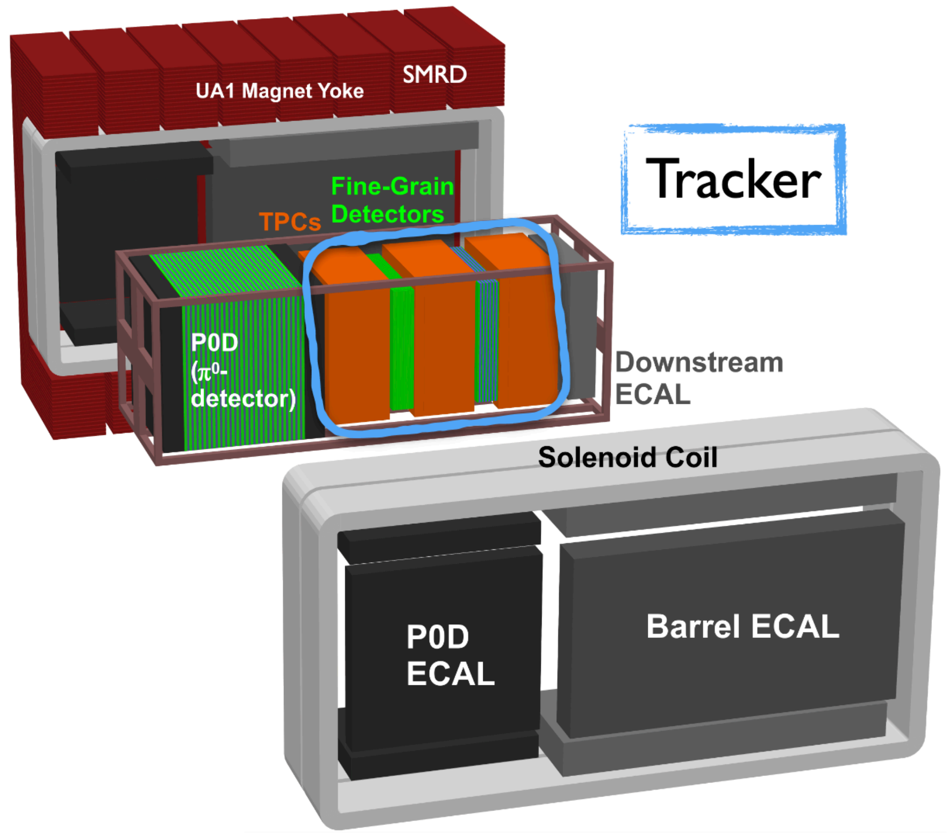
MINERvA: NIM A 743 (2014) 130–159



NOvA (E. Smith talk)



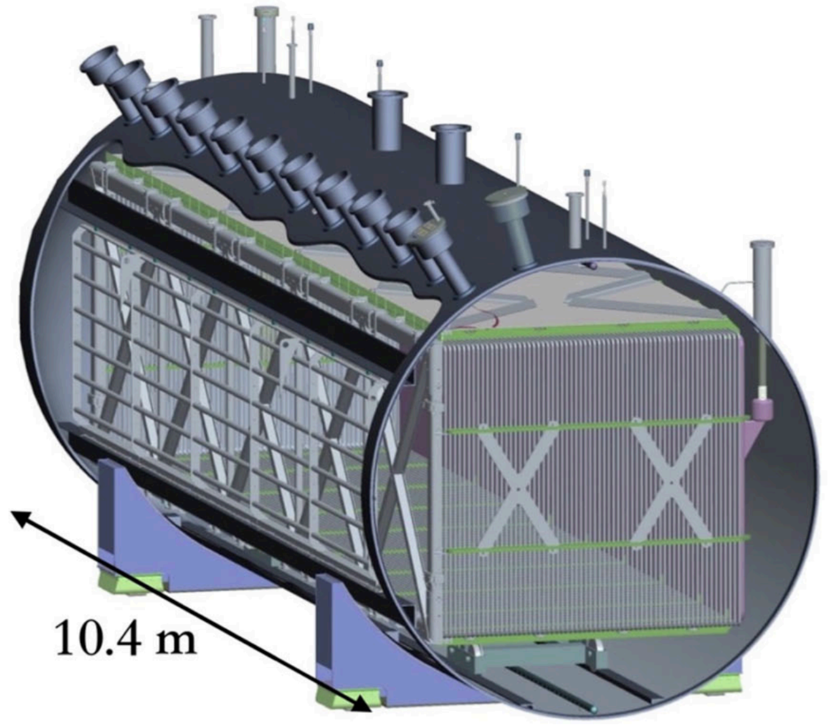
T2K (L. Magaletti talk)

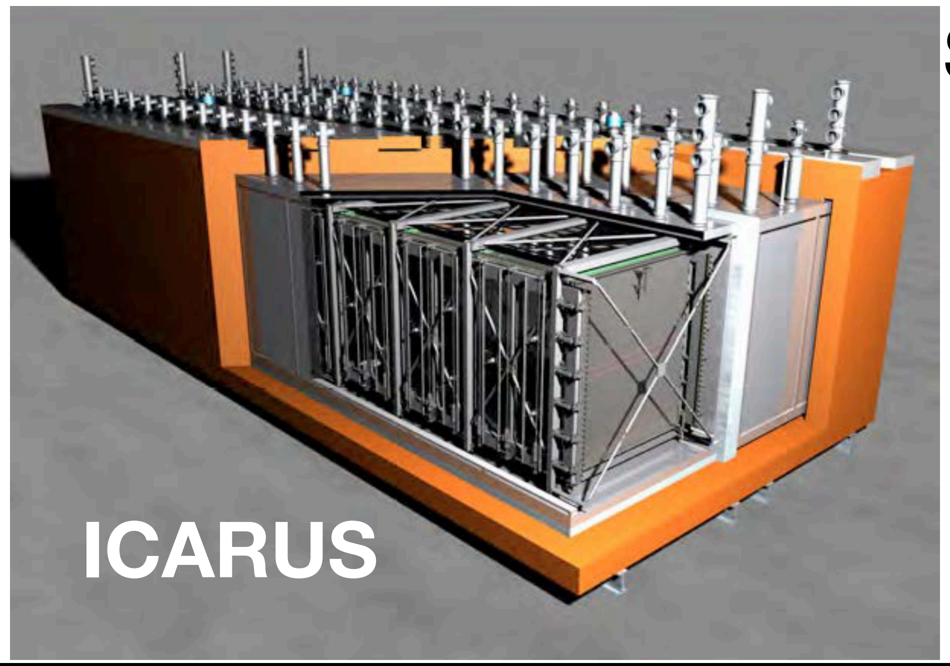


++ ICARUS & SBND:
More measurements on Ar!

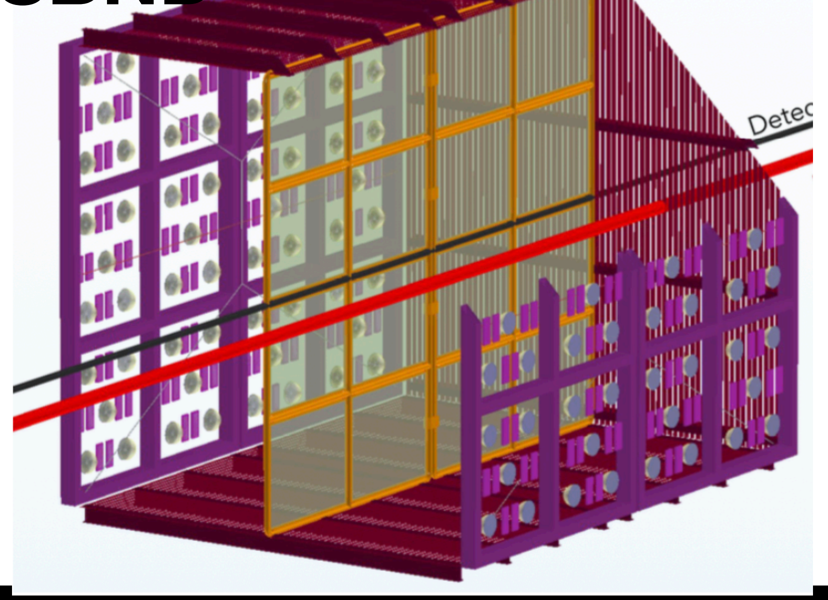
MicroBooNE:
Eur. Phys. J. C (2019) 79:673

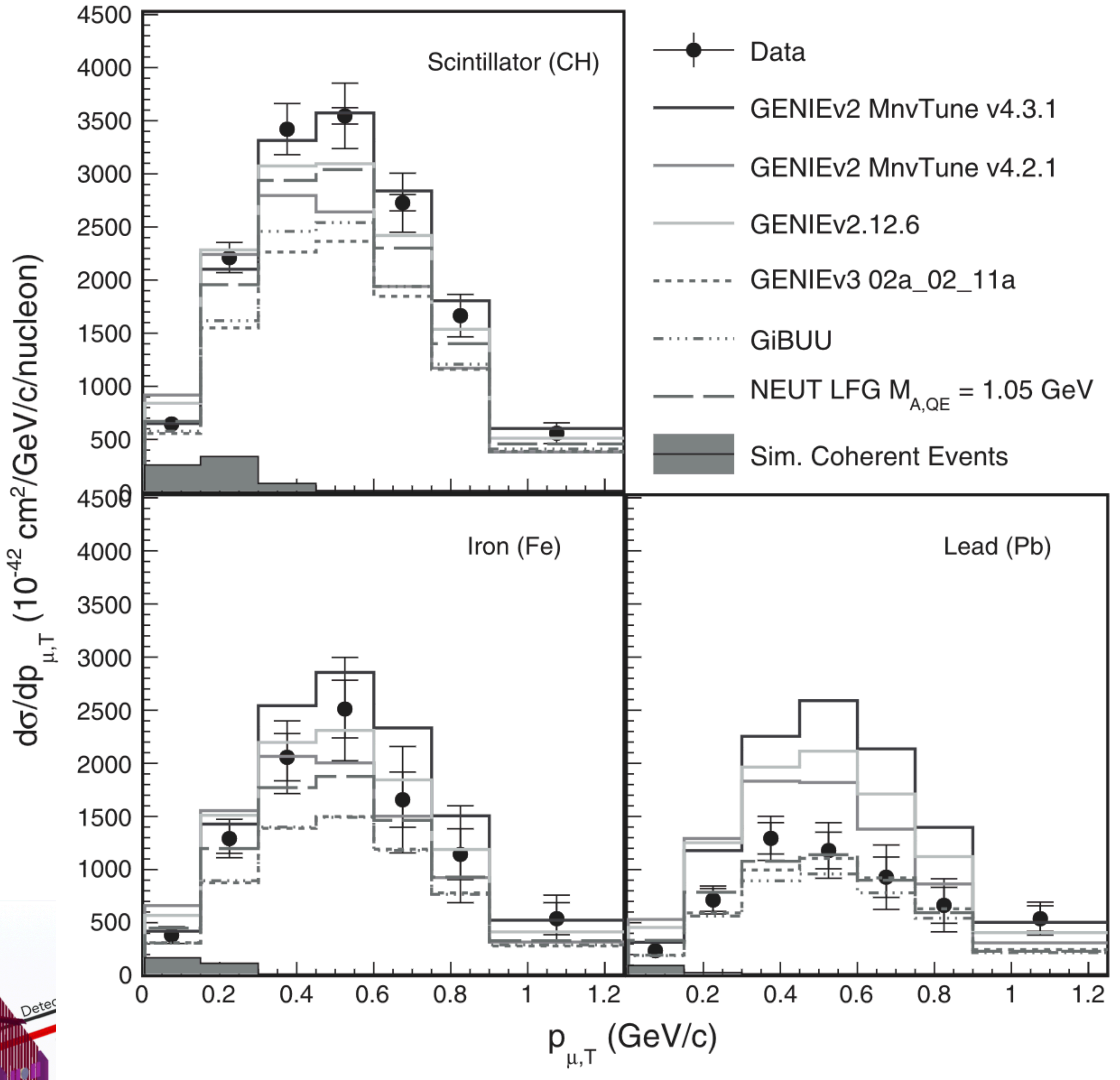
ν-Ar !!





SBND



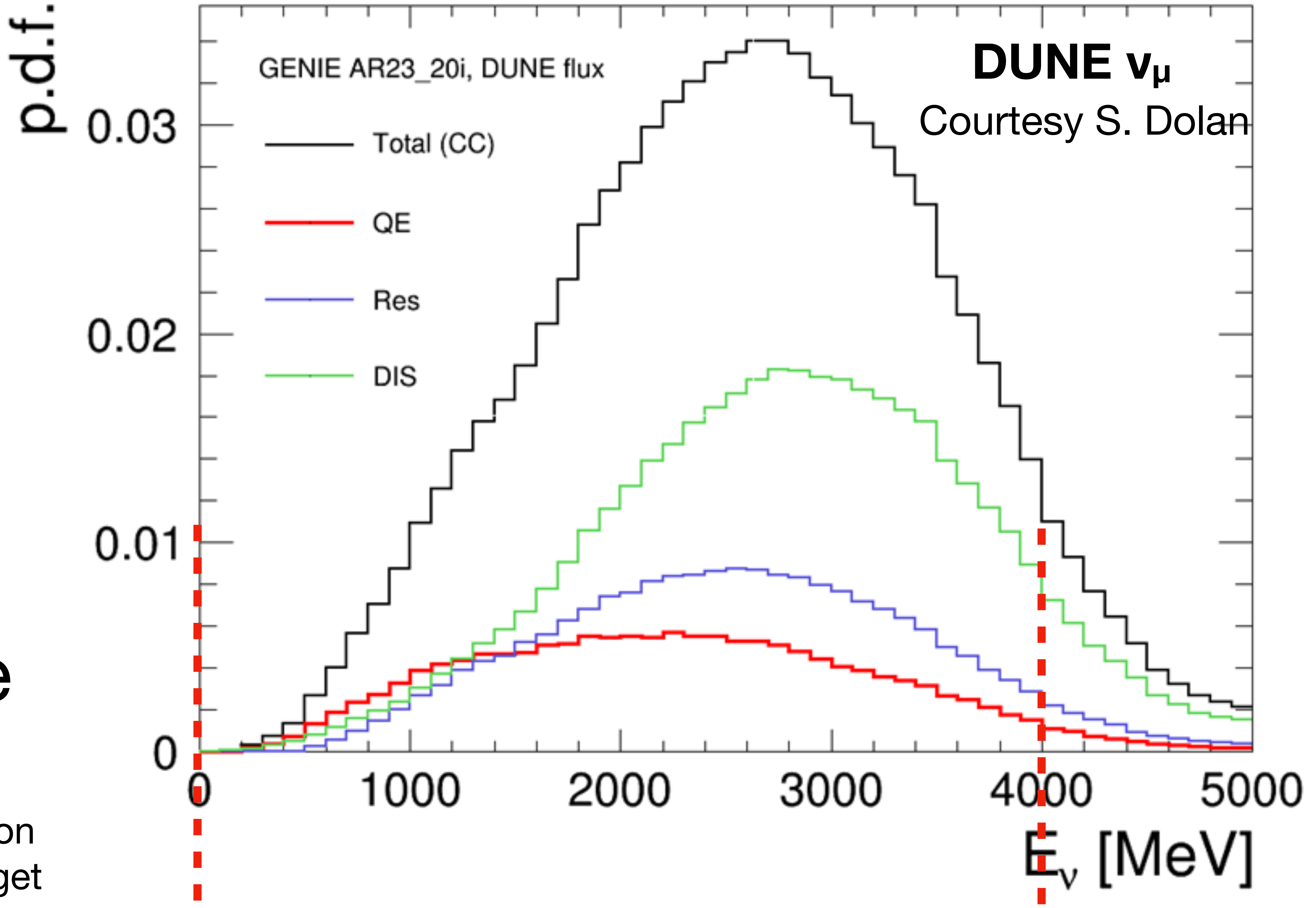


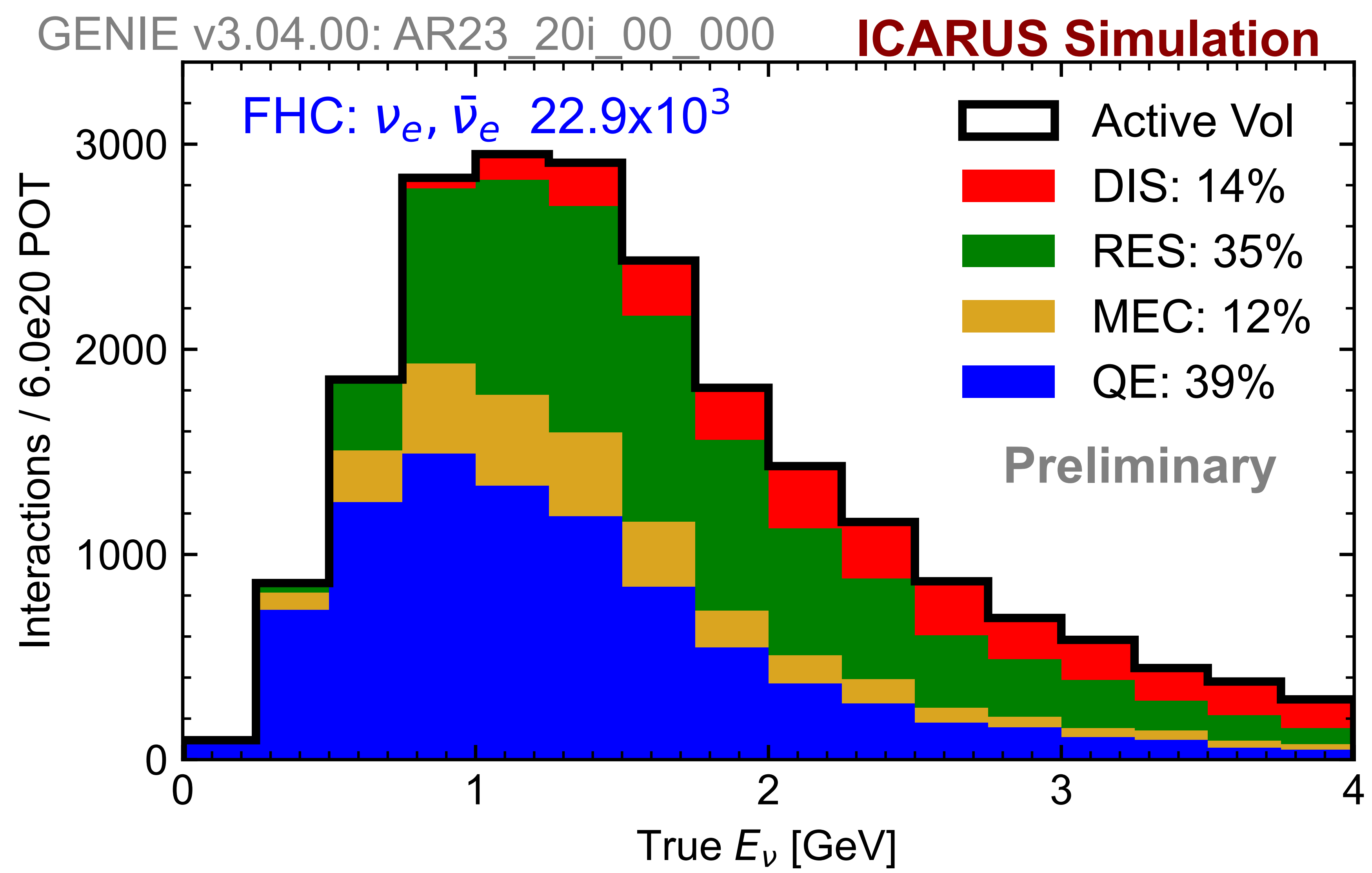
Transverse momentum of muon from MINERvA measurement studying muon neutrino interactions producing μ & charged π

A. Bercellie et al. Phys. Rev. Lett. **131**, 011801 (2023)

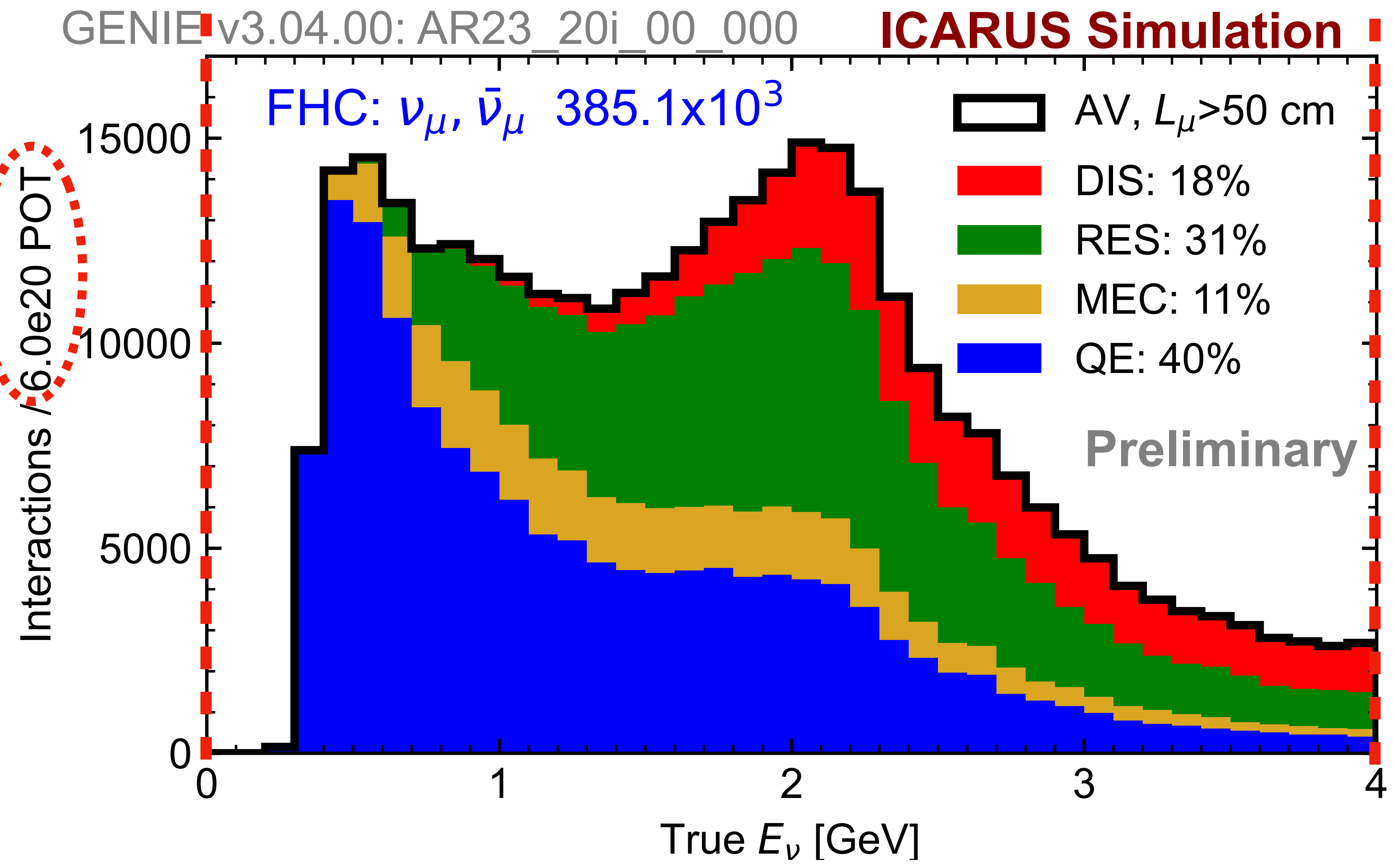
Studying interactions w/ ICARUS

- ICARUS sees NuMI ν: few deg. off-axis, ~800m from target: overlaps significant part of DUNE
- Using these ν to perform interaction studies & cross-section measurements:
  - Conducting first study with $\nu_\mu, \bar{\nu}_\mu$ on next slide and aim to conduct many more
  - Also significant amount of $\nu_e, \bar{\nu}_e$





Rough expectation of protons on target for 1 year

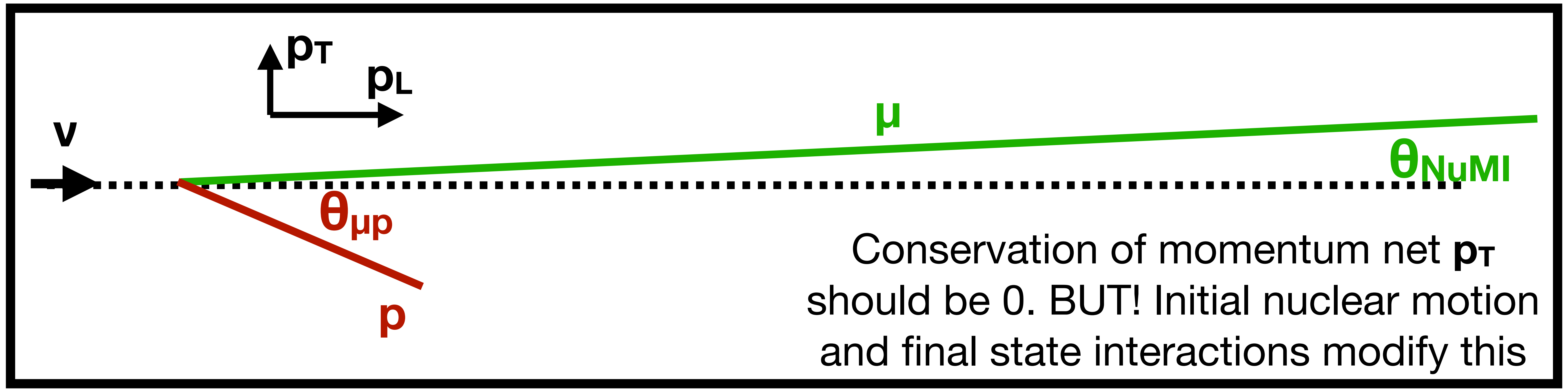


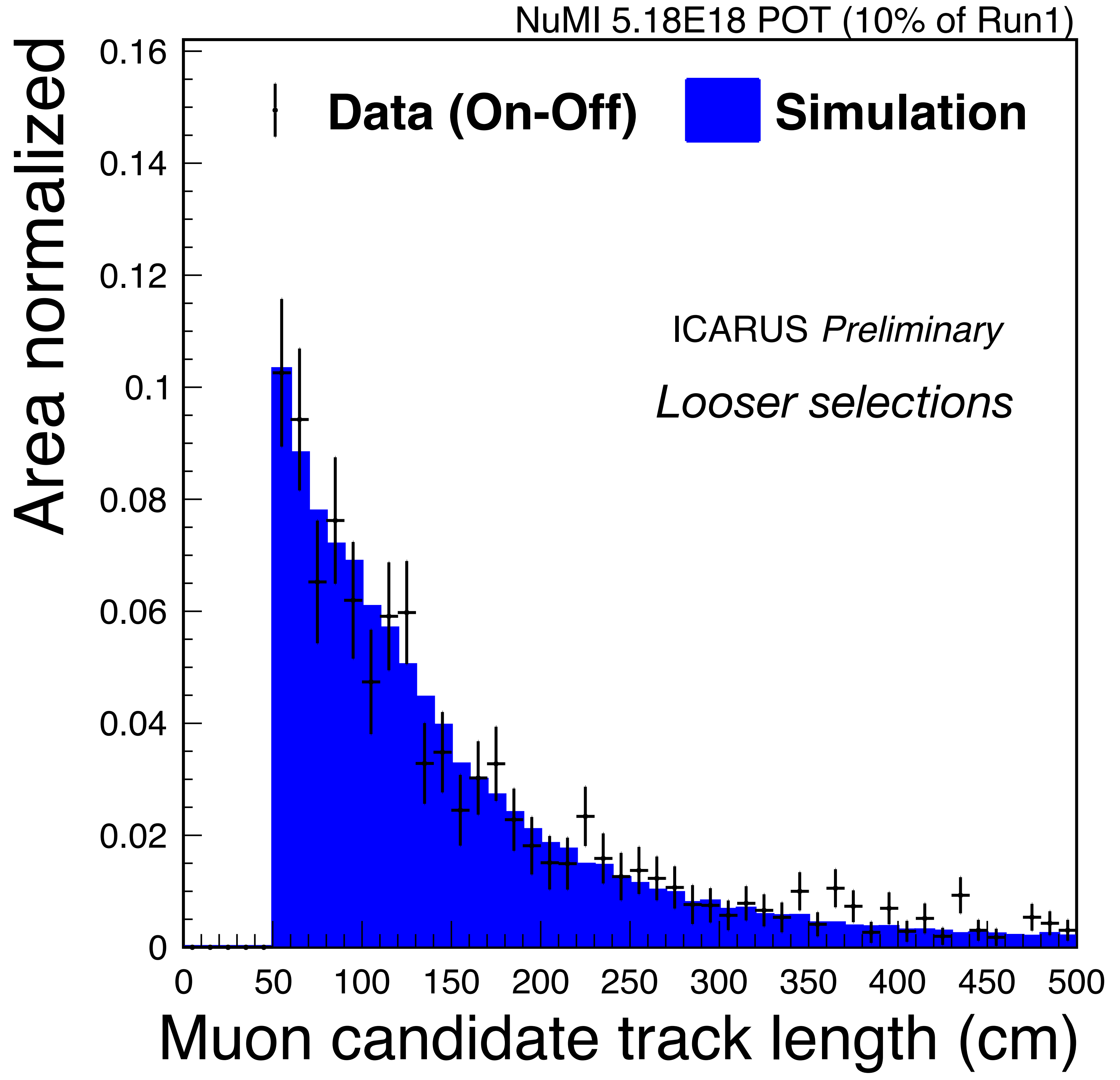
SBN and DUNE now using unified base model for event simulation!

Studying interactions with ICARUS

- Actively progressing towards first analysis targeting a cross-section for events with no pions (enhanced in QE, 2p2h)
  - Should be somewhat “cleaner” events as first target but still interesting physics
- Initial looks at some observables w/ data to study properties & selections promising:
  - Data/MC on μ and p
  - Data-Data comparisons of a somewhat different selection but validating idea of cosmic removal and ν signal

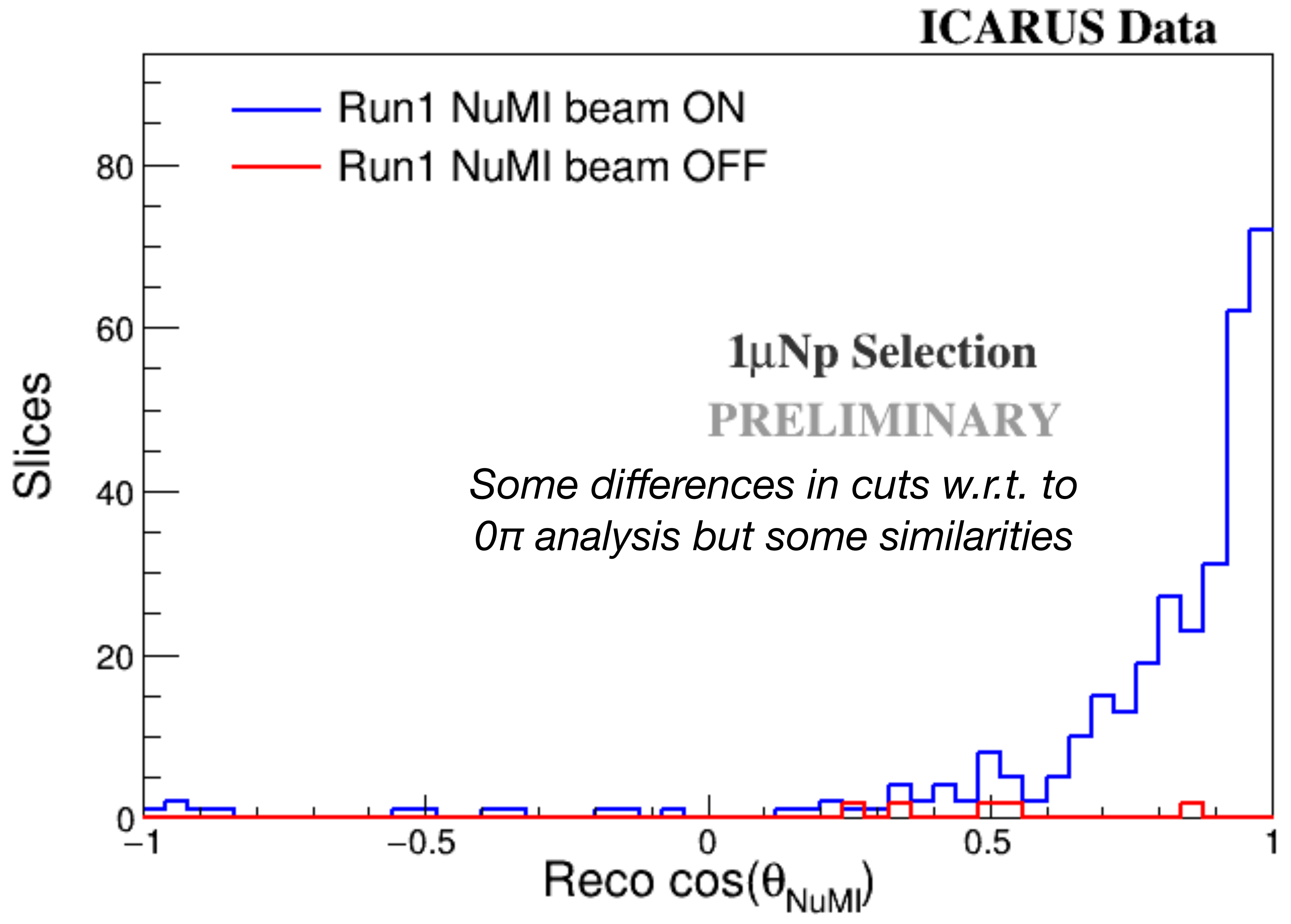
(Some) variables of interest:



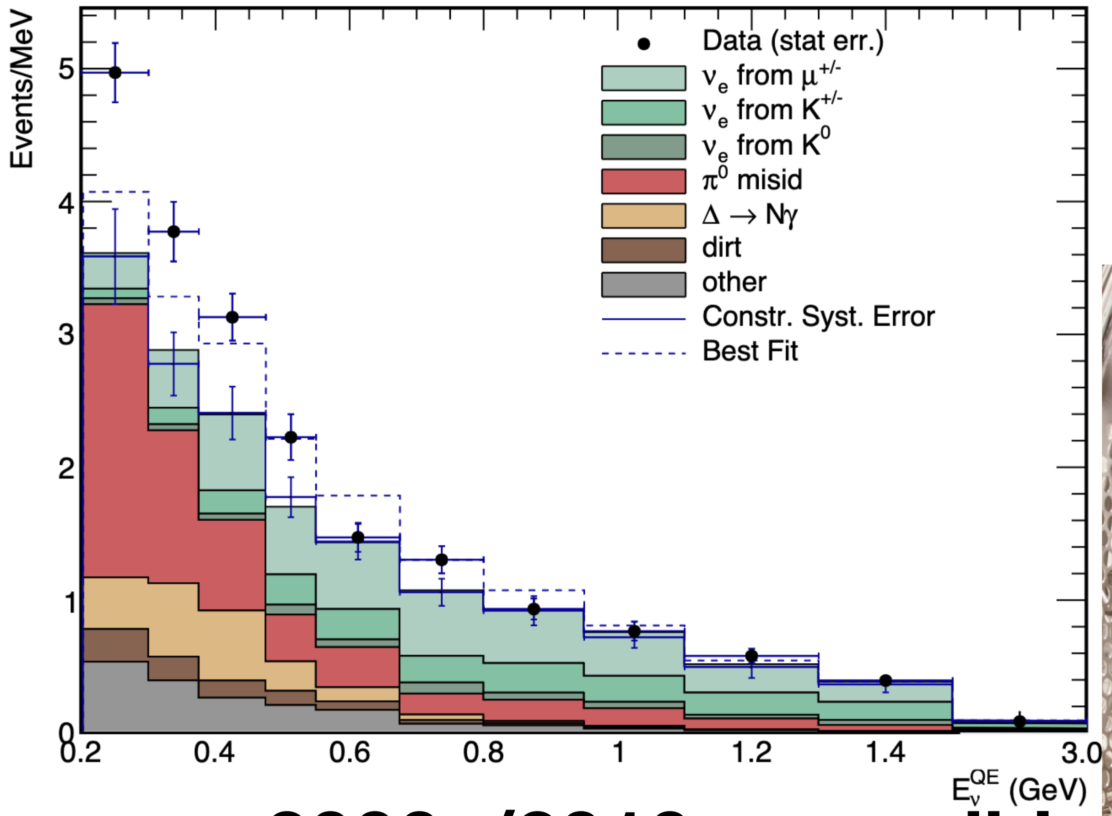


Studying interactions with ICARUS

- Should not just study ν-Ar interactions in "vacuum" but **using and feeding back into community tools**:
  - Unified **interaction simulation base model between SBN detectors and DUNE**
  - Use of **interaction uncertainties framework initially from DUNE**: can feed back/add new items to this based on our findings
  - **Neutrino flux** correction/uncertainty uses framework from NuMI experiments (**NOvA and MINERvA**)
  - **Particle re-interaction** uncertainties based on work from other experiments **DUNE and MicroBooNE**
  - **Fit & cross-section calculation** performed with tool produced for near detector fitting in T2K (Japanese current-generation long-baseline experiment)
- Analysis well under way, **targeting results next year**

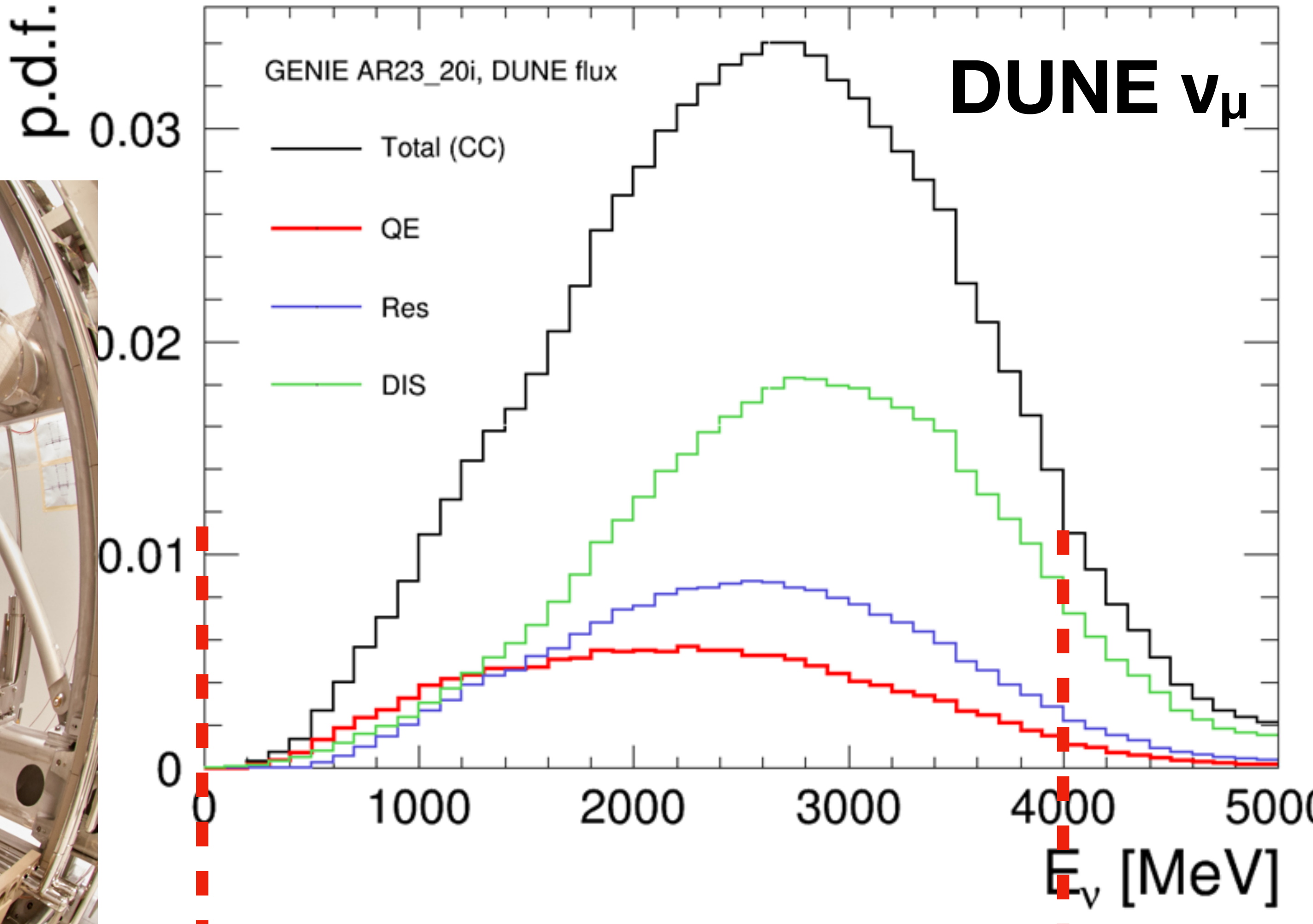


1930: Neutrinos proposed to explain β decay spectrum



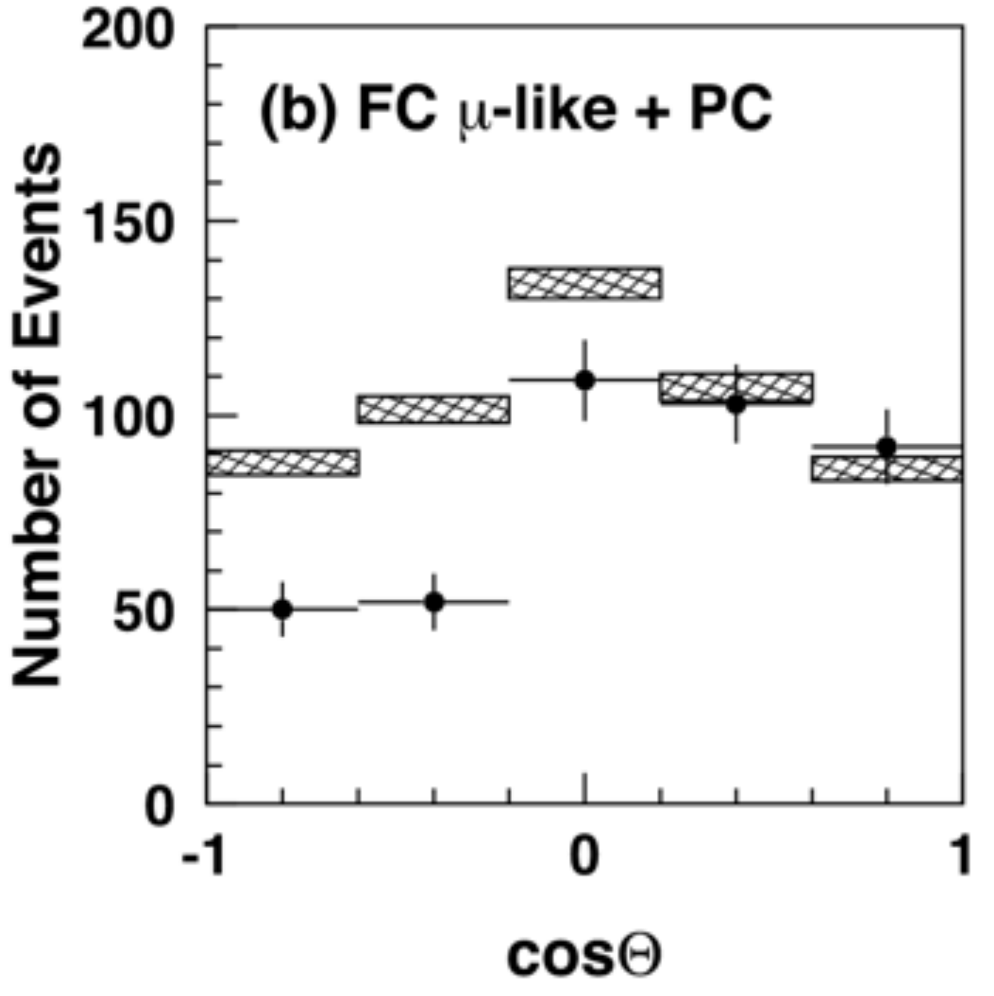
1950s: ν discovered

1960s: ν_μ discovered



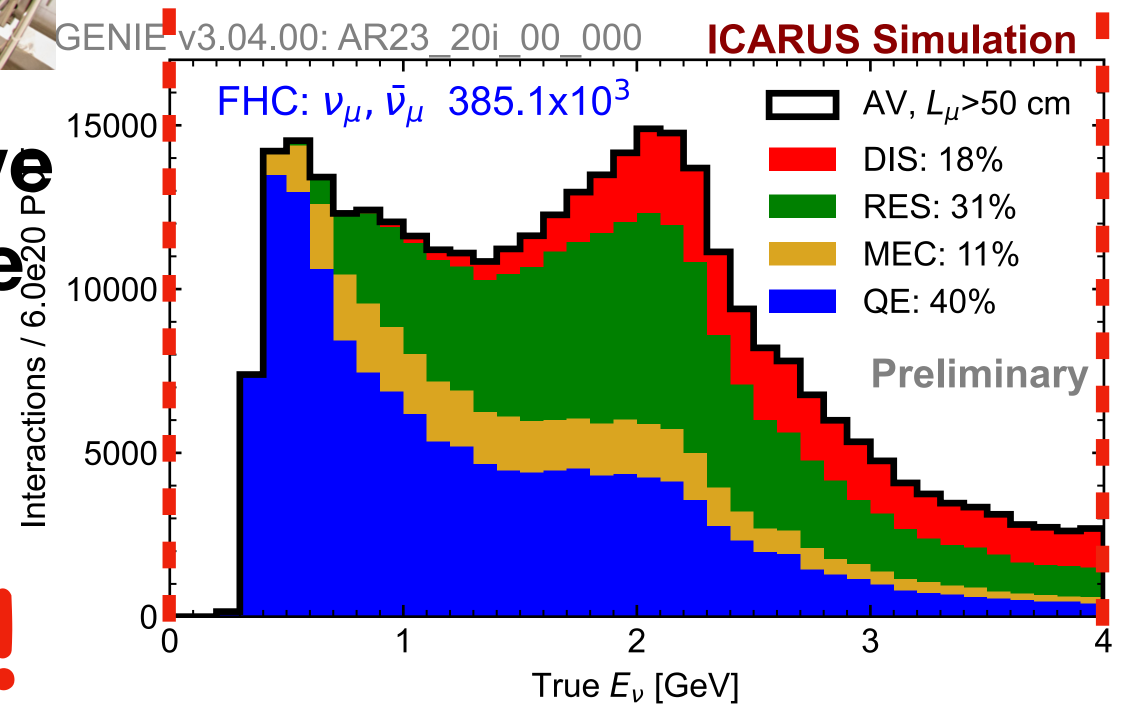
1990s: neutrino oscillation discovered

2000s/2010s: possible hints at >3 neutrinos in anomalies



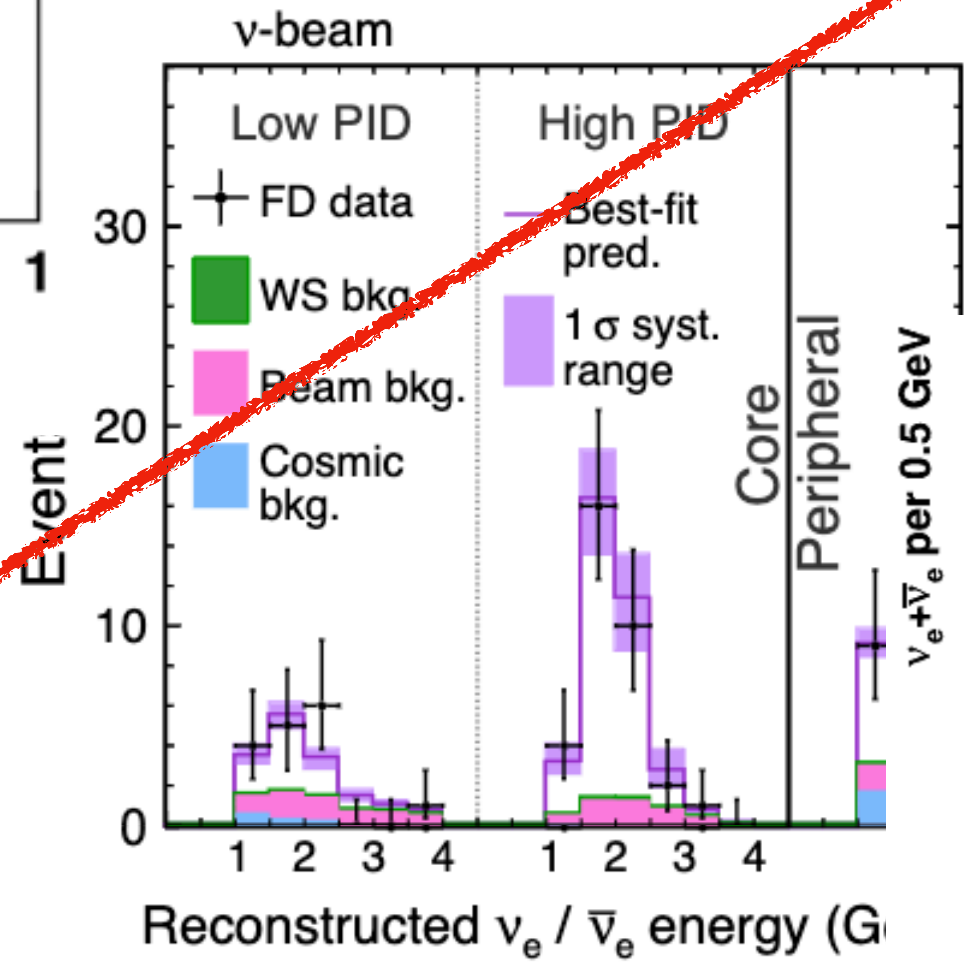
2010s/2020s: osc expts probe parameter space w/ better precision, but still more to learn:

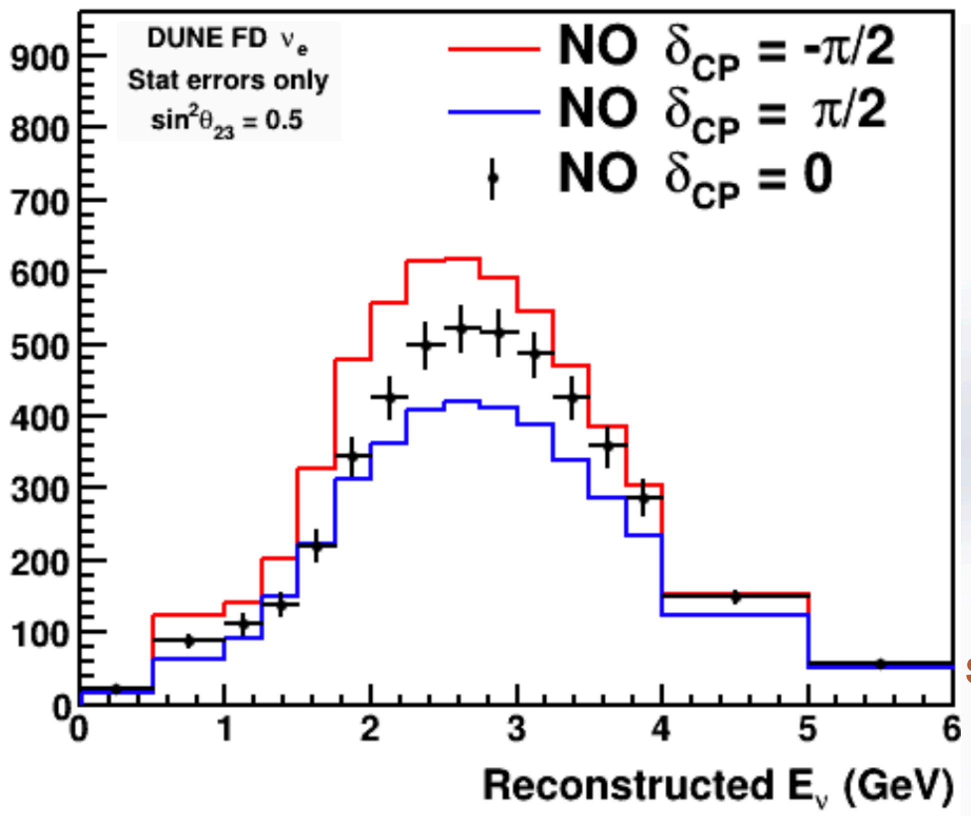
2020s: ICARUS & SBN will improve picture & LArTPC experience

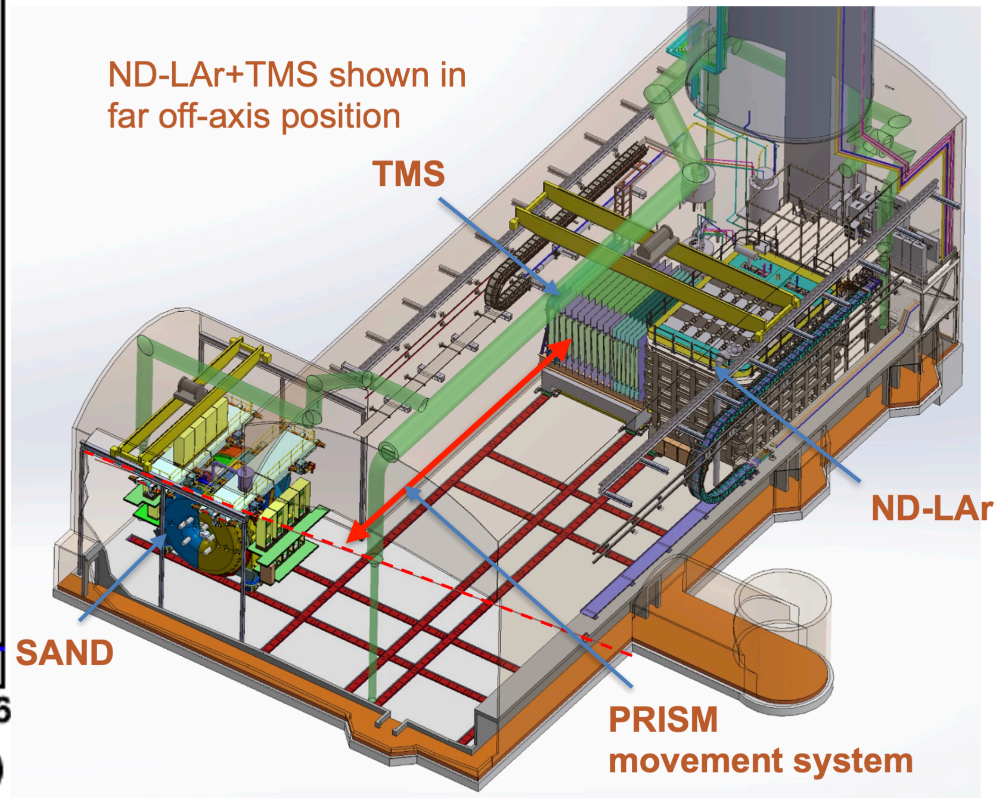


2030s: Next generation will produce precise osc results

Exciting times ahead!







You are here

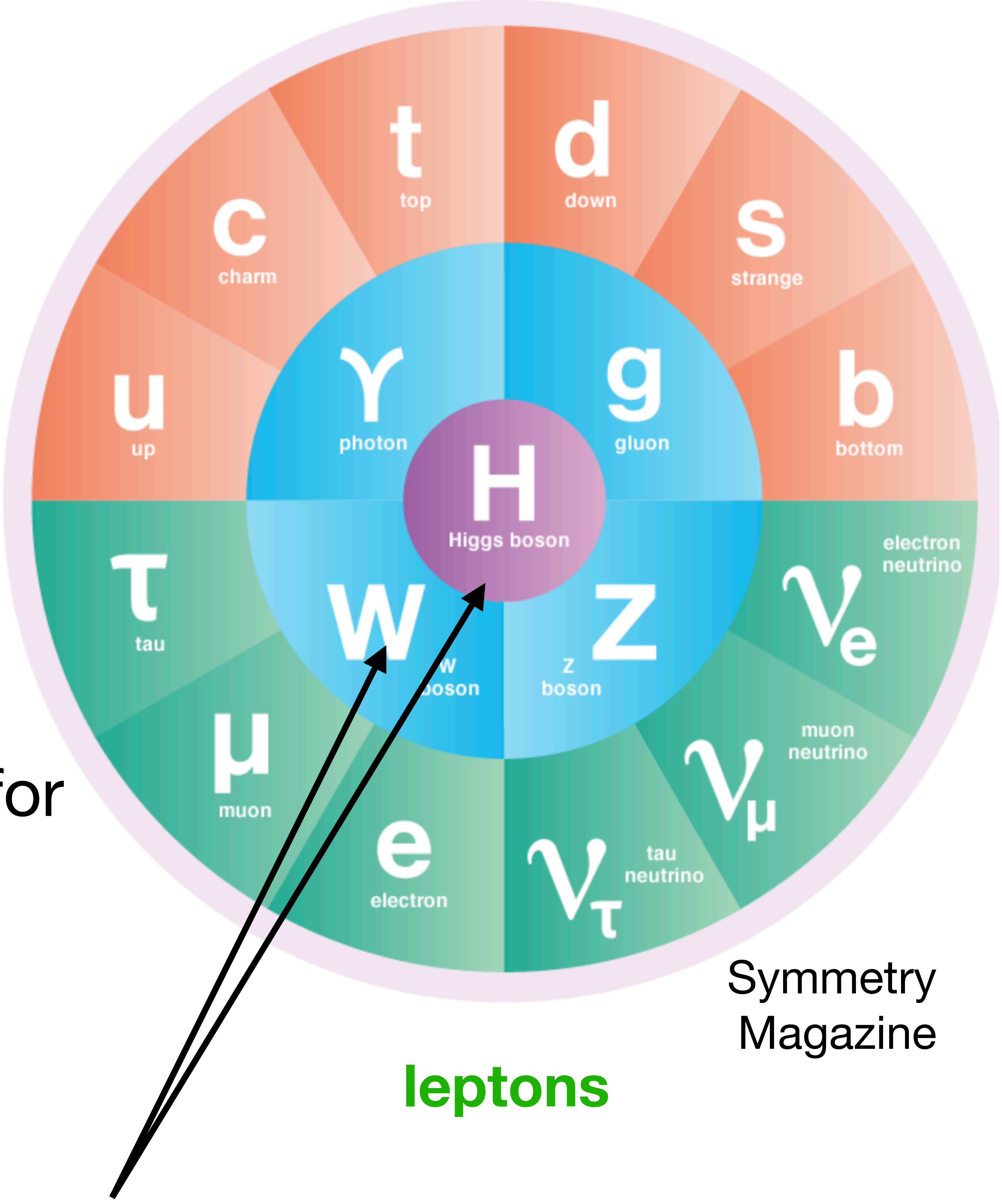
Summary & Conclusions

Backups

The neutrino

- Nearly massless, neutral, and only interact via the "weak force" (appropriate name): took time to discover them in nature
- 1950s: **e** coupled ν found $\boldsymbol{\nu_e}$ (Reines, Cowan)
- 1960s: $\boldsymbol{\nu_\mu}$ (Brookhaven)
- Early 2000s, $\boldsymbol{\nu_\tau}$ observed for first time (Fermilab)
- Measurements show 3 ν flavors expected
- That ***could*** have been the whole story…

quarks

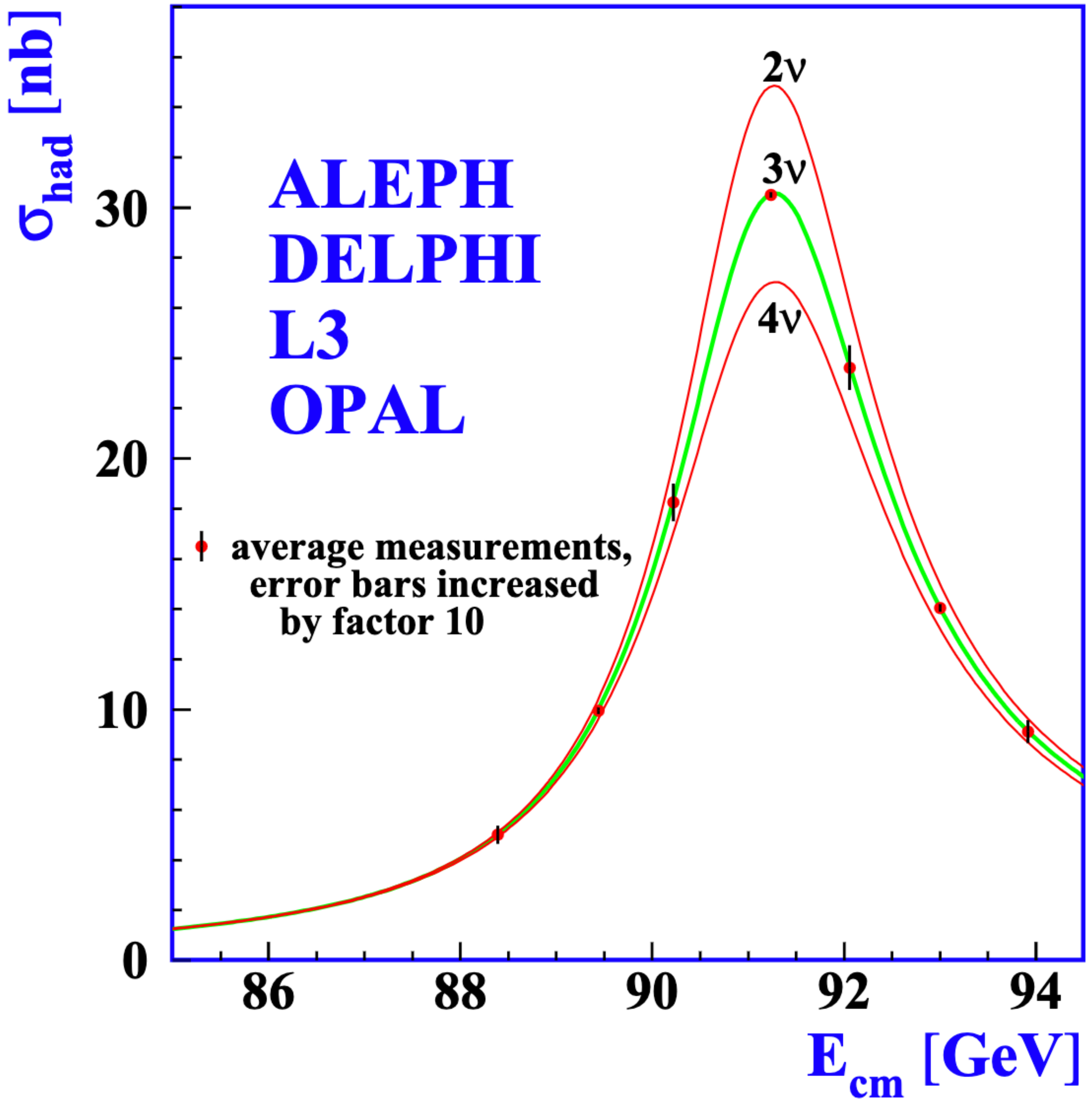


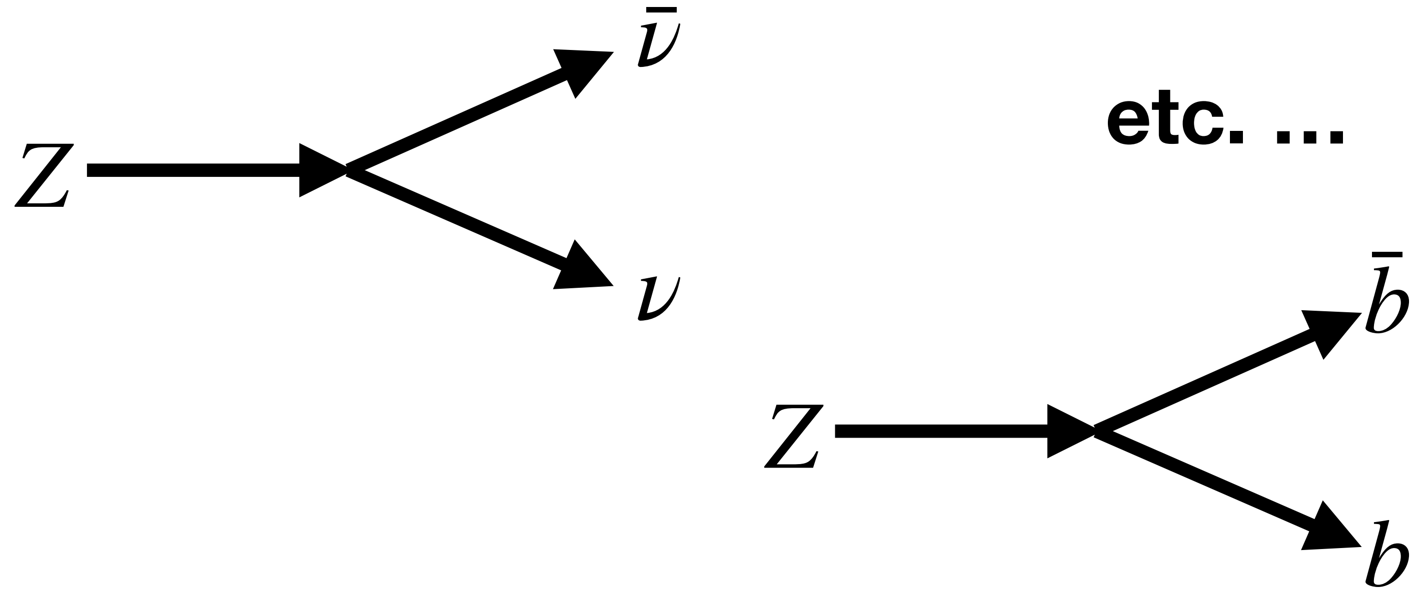
Symmetry Magazine

leptons

Bosons (force mediators)

"Precision electroweak measurements on the Z resonance"
Physics Reports **427** (2006) 257 – 454





Neutrino oscillation

- From these we know that the deficit is both flavor (ν_e, ν_μ, ν_τ) dependent and distance (L) dependent, and it turns out to be energy dependent as well
- These are signatures of what's called "neutrino oscillation"
  - Quantum mechanical interference between flavors and mass states (eigenstates)
  - Neutrinos created/detected via coupling to flavors, but propagate as the mass states

Neutrino oscillations with 2 flavors:

Flavors — U — Mass states

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\nu_\alpha = \cos\theta\nu_1 + \sin\theta\nu_2$$
$$\nu_\beta = -\sin\theta\nu_1 + \cos\theta\nu_2$$

$$P_{ab} = P(\nu_a \rightarrow \nu_b) = |\langle\nu_a|\nu_b(t)\rangle|^2$$

$$P_{\alpha\beta} = \left|\sum_{i=1}^{2}\sum_{j=1}^{2} U^*_{\alpha i} U_{\beta j} \langle\nu_j|\nu_i(t)\rangle\right|^2$$

QM time evolution: $e^{(E_2-E_1)t/\hbar}$

Taylor expand and $p_2 \sim p_1 \sim E$

Energy of mass state: $E_2 = \sqrt{m_2^2 + p_2^2} = p_2\sqrt{1 + \frac{m_2^2}{p_2^2}} \sim E + \frac{m_2^2}{2E}$

$$\rightarrow e^{\frac{(m_2^2 - m_1^2)t}{2E}} = e^{\frac{\Delta m_{21}^2 L}{2E}}$$

$(L = vt, \quad v \sim c \rightarrow 1)$
natural units

$$P_{\alpha\beta} = \sin^2 2\theta \sin^2\left(1.267\frac{\Delta m_{21}^2 L}{E}\right)$$

$m : [eV^2]$
$L : [m]$
$E : [MeV]$

For more details: See chapter 14 of R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022 083C01 (2022)

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- These are signatures of what's called "neutrino oscillation"
  - Quantum mechanical interference between flavors and mass states (eigenstates)
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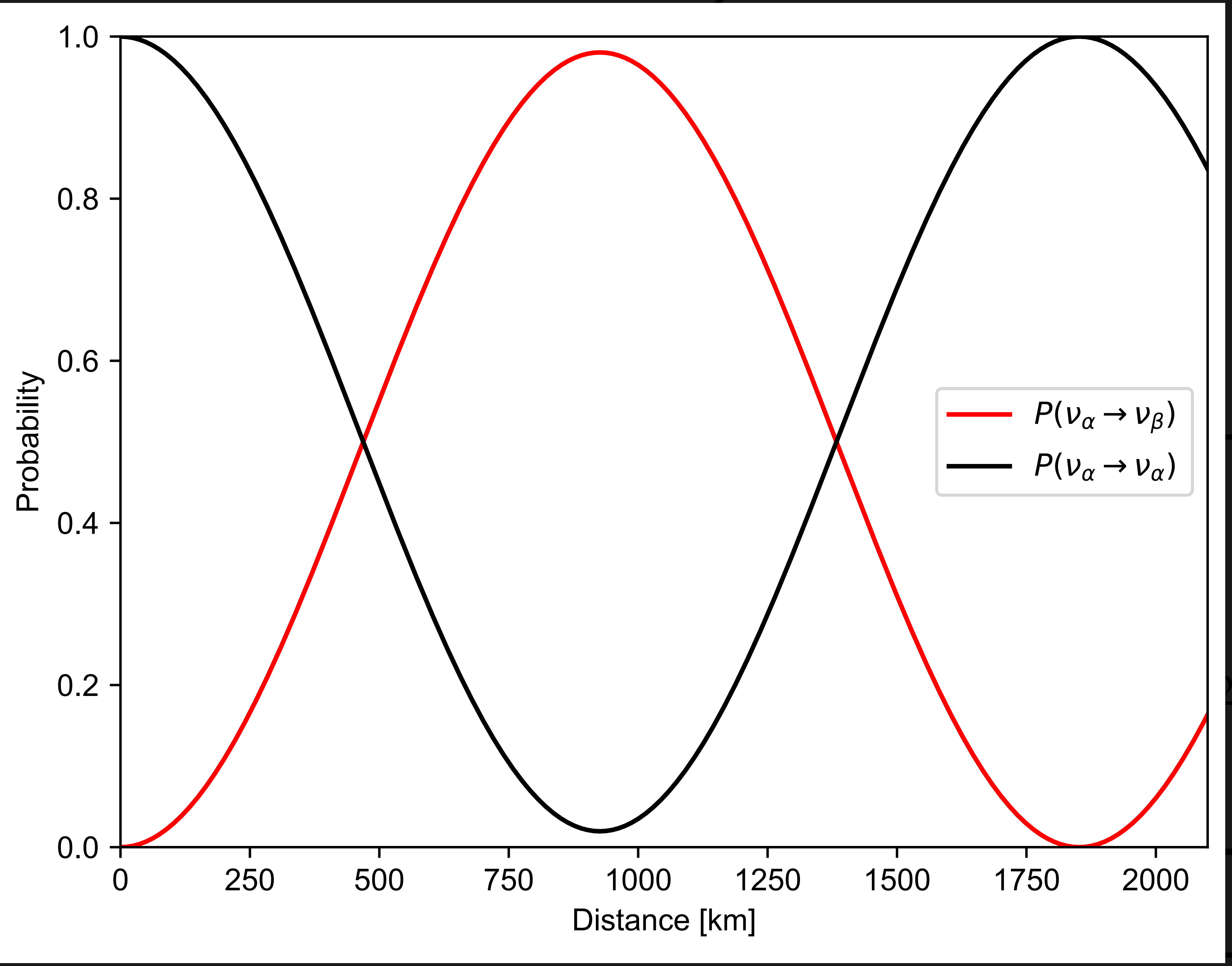
- In plot, have an oscillatory effect for mass splitting 10^{-3} eV^2. For GeV ν, this takes ~100s to ~1000s of km to be maximal → **"long baseline"**

Flavors U Mass states

Neutrino oscillations with 2 flavors:

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$



Drawing out $P_{\alpha\beta}$ and $P_{\alpha\alpha} = 1 - P_{\alpha\beta}$:

Fixed E (1.8 GeV)

L in range 0 - 2.1 km

θ≅49^0

Δm^2=2.41x10^{-3} eV^2

NOTE the oscillatory nature!

See PDG

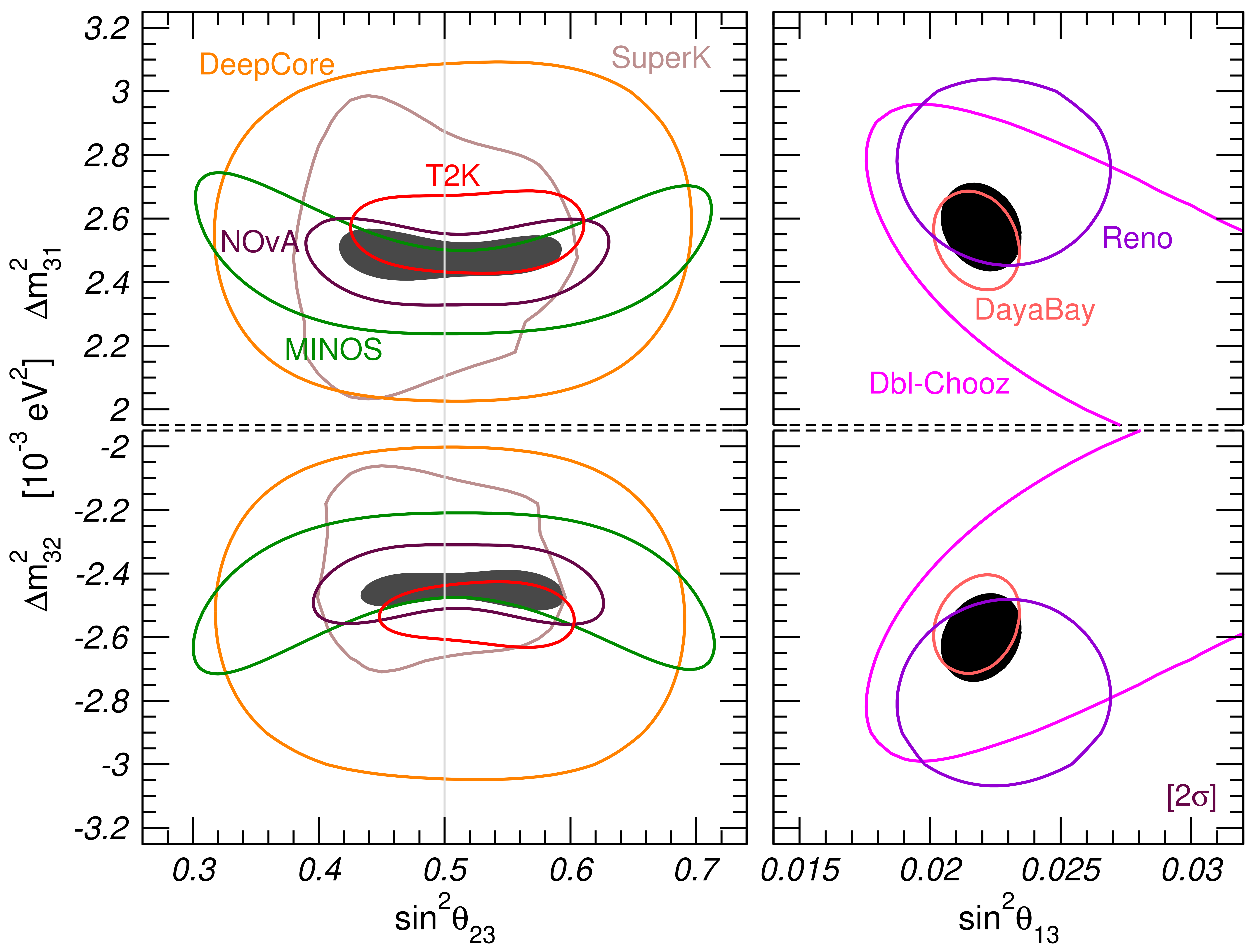
$$P_{\alpha\beta} = \sin^2 2\theta \sin^2\left(1.267\frac{\Delta m_{21}^2 L}{E}\right)$$

$m : [eV^2]$
$L : [m]$
$E : [MeV]$

Neutrino oscillation

- Past decades have brought us long way
- Major open questions still, though:
    - **Some values need better study (θ_{23} close to 45^0, on which side?)**
      Fully/precisely measure the mixing parameters!
    - **Sign of Δm_{32}? (We have Δm^2_{32})**
      Is m_3 the lightest or heaviest?
    - **Is δ_{CP} different from 0?**
      Do neutrinos and antineutrinos behave differently?
    - **Do we see same parameters from experiments at very different regimes? (test assumptions)**
      Is the 3 neutrino picture complete?
- Need next generation to answer these definitively…

NuFIT 5.2 (2022)



JHEP 09 (2020) 178, NuFIT 5.2 (2022), www.nu-fit.org

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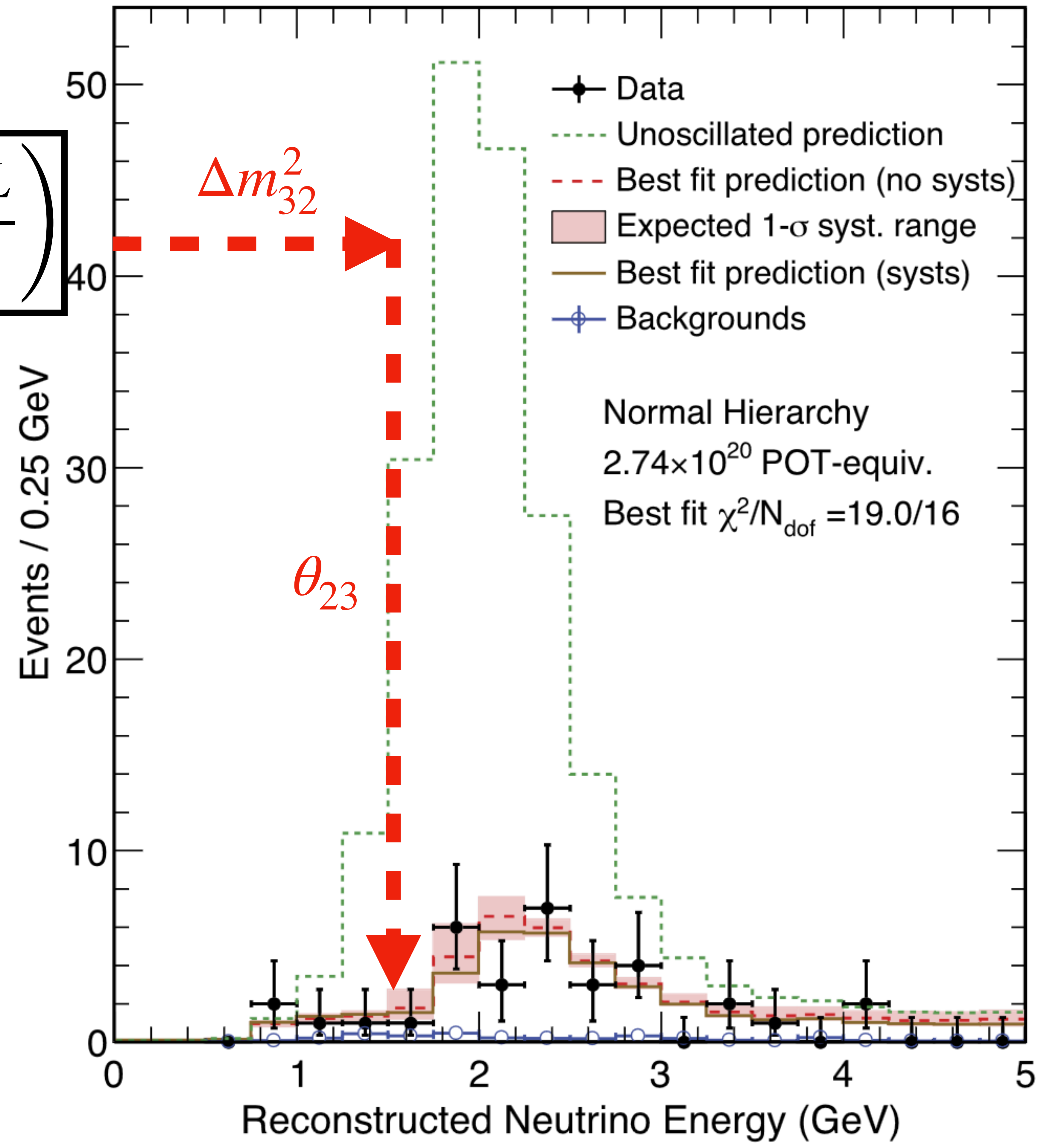
$$P_{\mu\mu} \sim \sin^2 2\theta_{23} \sin^2\left(1.267\frac{\Delta m^2_{32} L}{E}\right)$$

At long baselines, looking for ν_μ disappearance approx. reduces to 2ν

Figure from: M.D. Messier. Nuclear Physics B 908 (2016) 151–160



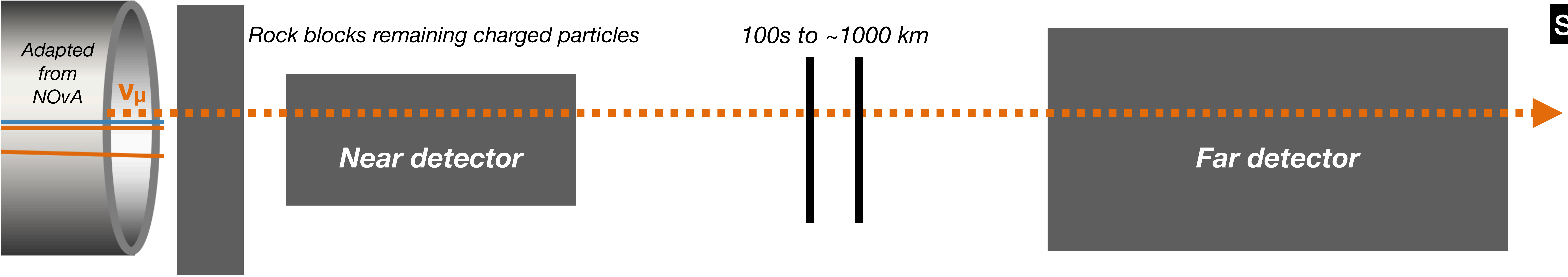
M.D. Messier. Nuclear Physics B 908 (2016) 151–160

$$P(\nu_\mu \to \nu_e) = P_{\text{atm}} + 2\sqrt{P_{\text{atm}} P_{\text{sol}}}(\cos\Delta_{32}\cos\delta_{\text{CP}} \mp \sin\Delta_{32}\sin\delta_{\text{CP}}) + P_{\text{sol}}$$

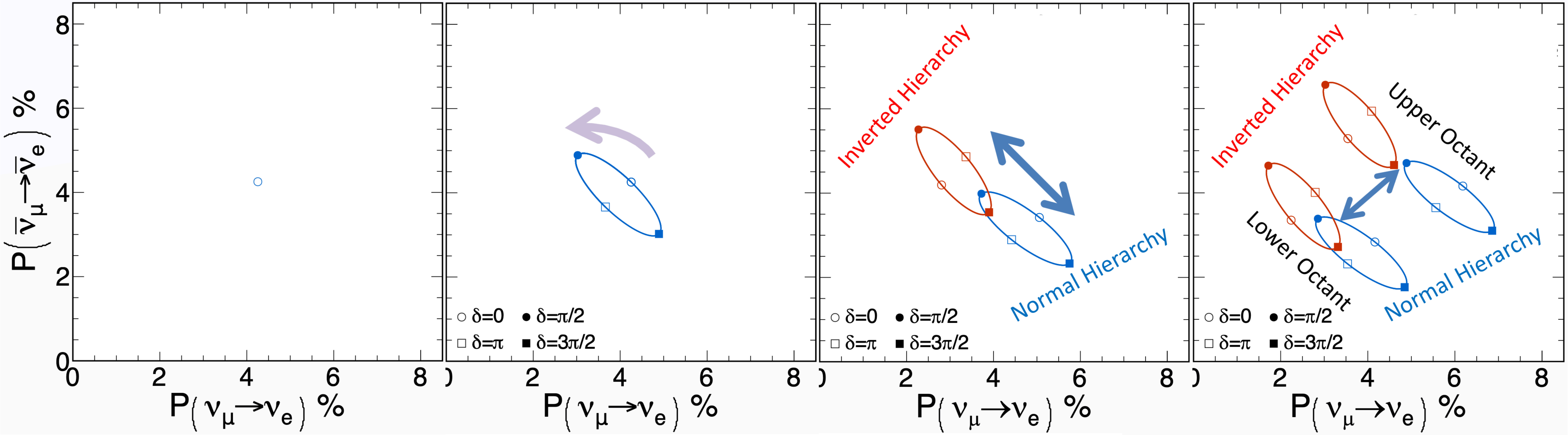
$$\sqrt{P_{\text{atm}}} = \sin\theta_{23}\sin 2\theta_{13}\frac{\sin(\Delta_{31} - aL)}{\Delta_{31} - aL}\Delta_{31}, \quad \Delta_{32} \simeq \Delta_{31} = \frac{1.27\Delta m^2_{32} L}{E} \simeq 1.1$$

$$\sqrt{P_{\text{sol}}} = \cos\theta_{23}\sin 2\theta_{12}\frac{\sin(aL)}{aL}\Delta_{21} \quad \Delta_{21} = \frac{1.27\Delta m^2_{21} L}{E} \simeq 0.04,$$

Sources



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



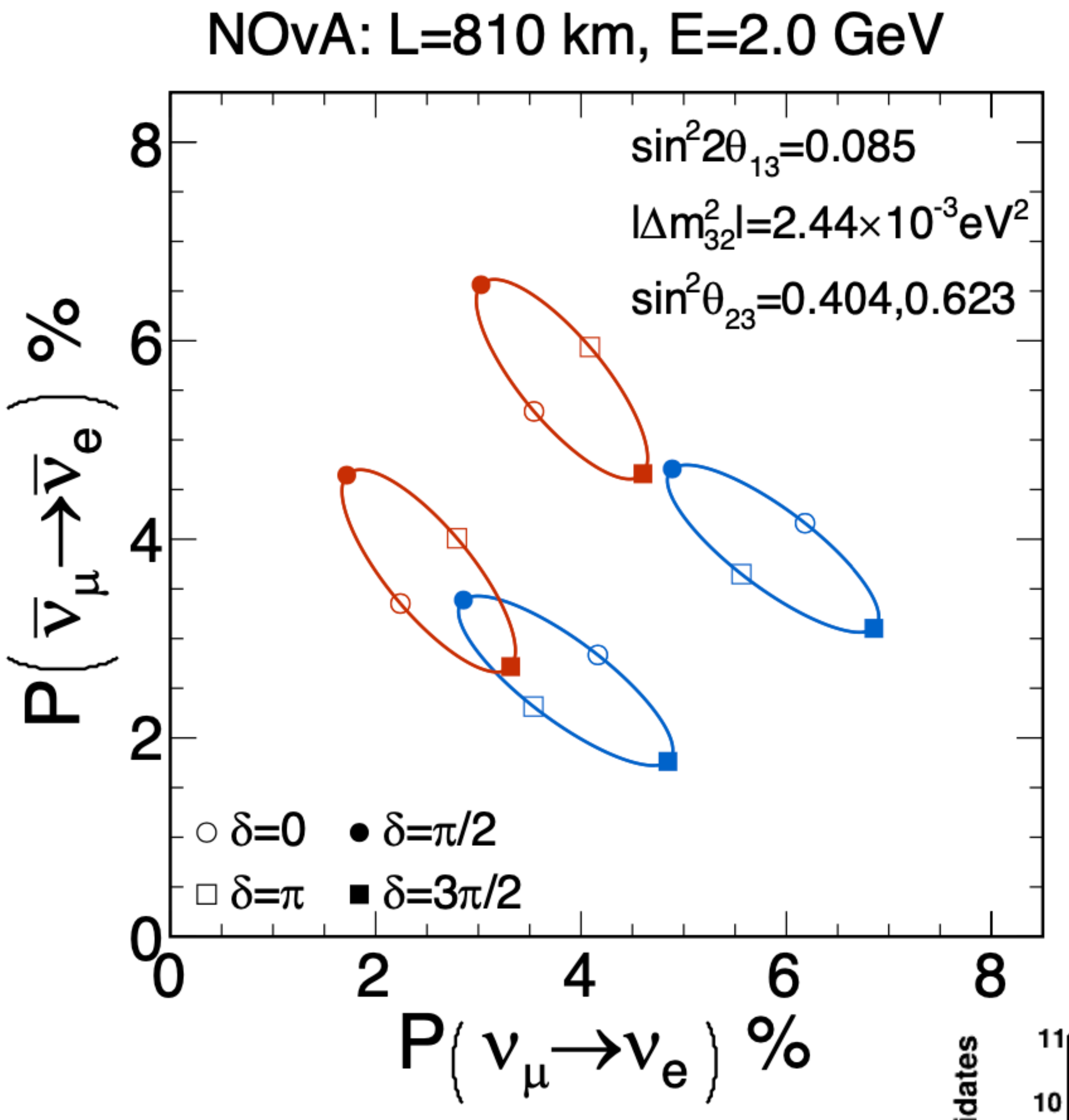
With no CP-violation and in vacuum: oscillation same for nu and anti-nu

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

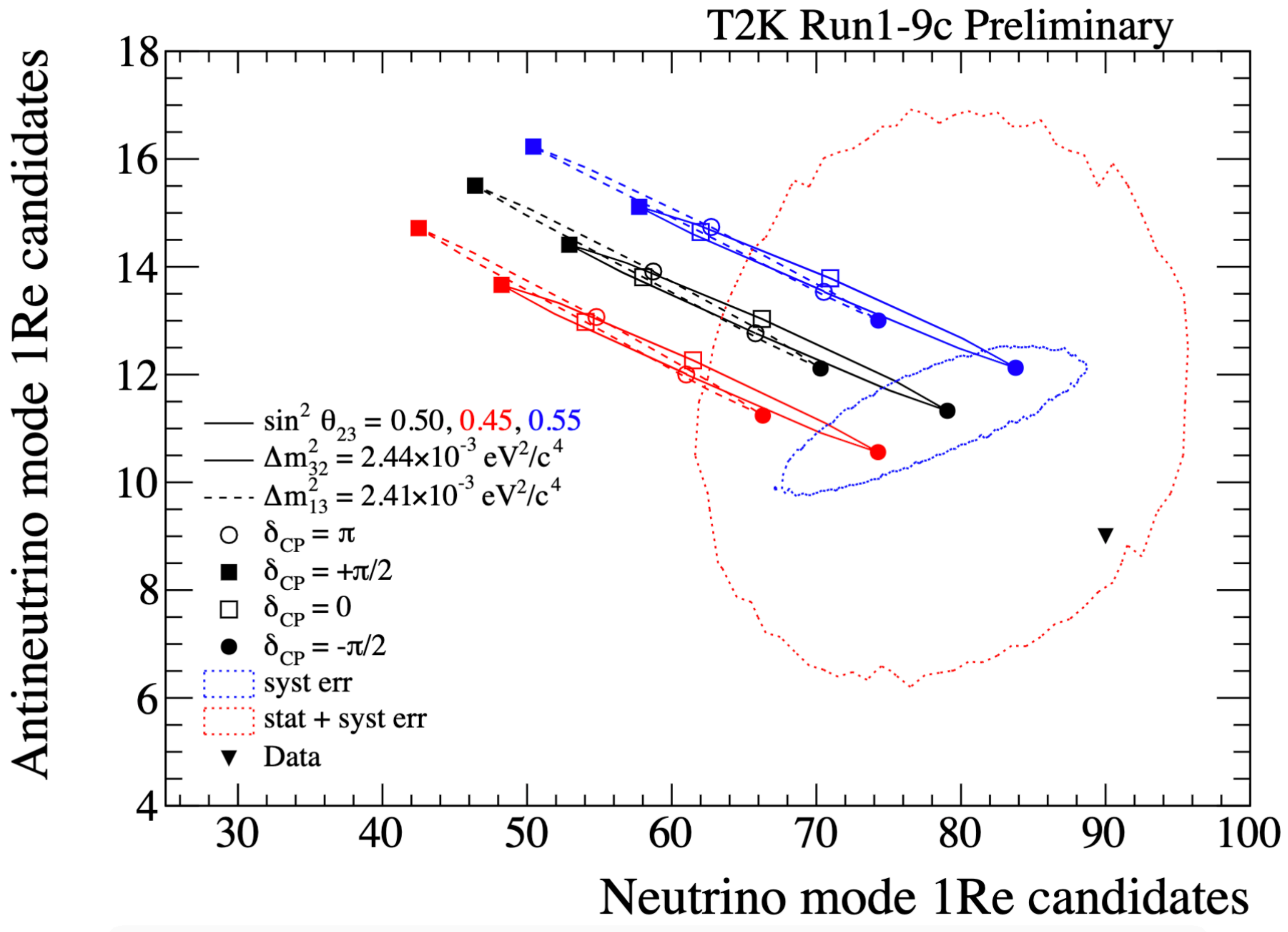
Not vacuum: enhancement of one & depletion of other based on mass ordering

θ_{23} creates overall enhancement or depletion

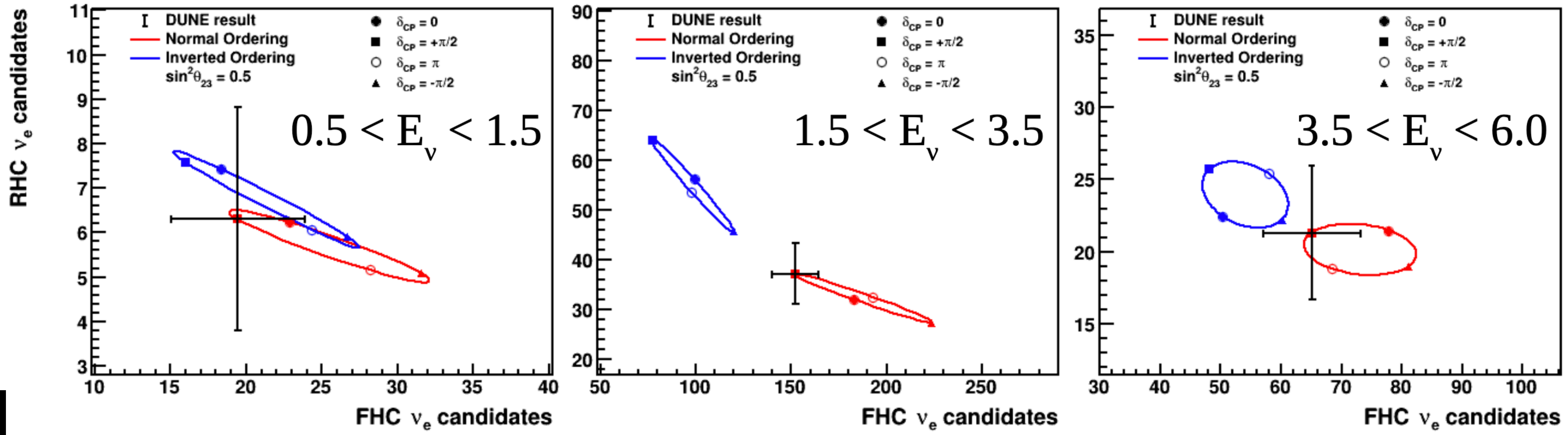
From NOvA



From T2K



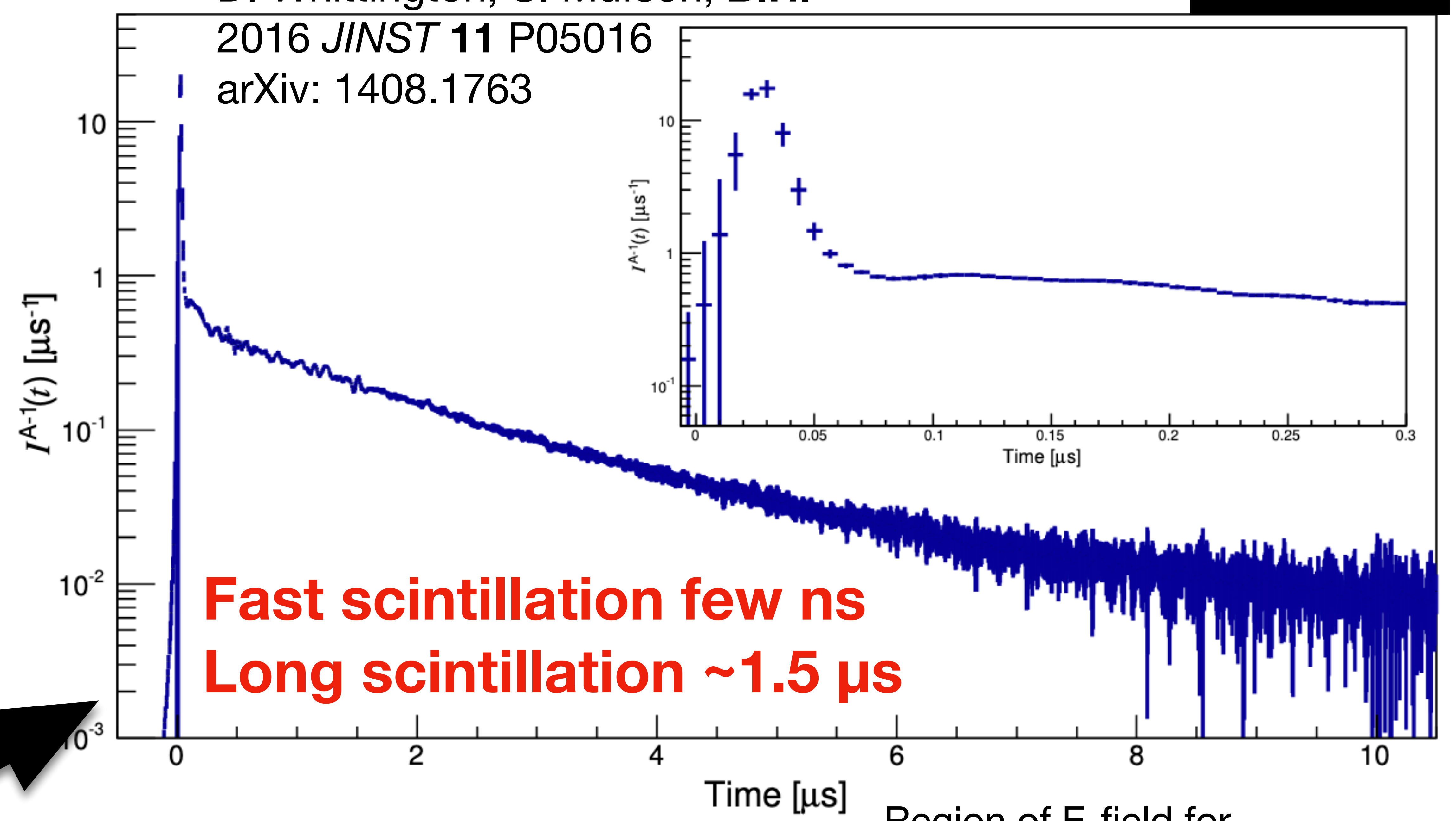
From DUNE, slices of neutrino energy



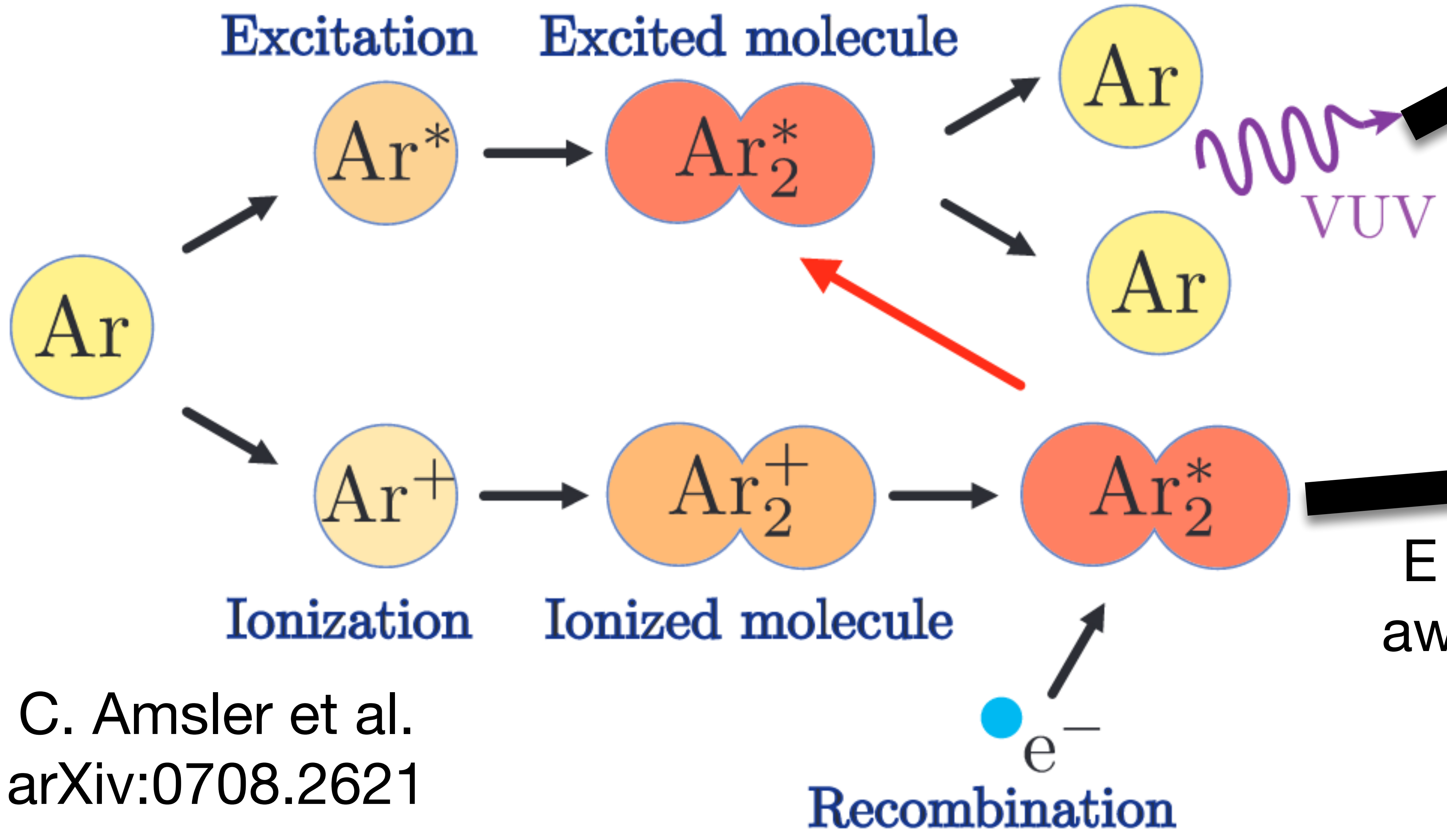
Liquid Argon as Detector

- 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



Few different paths to excite Ar dimers, lead to scintillation

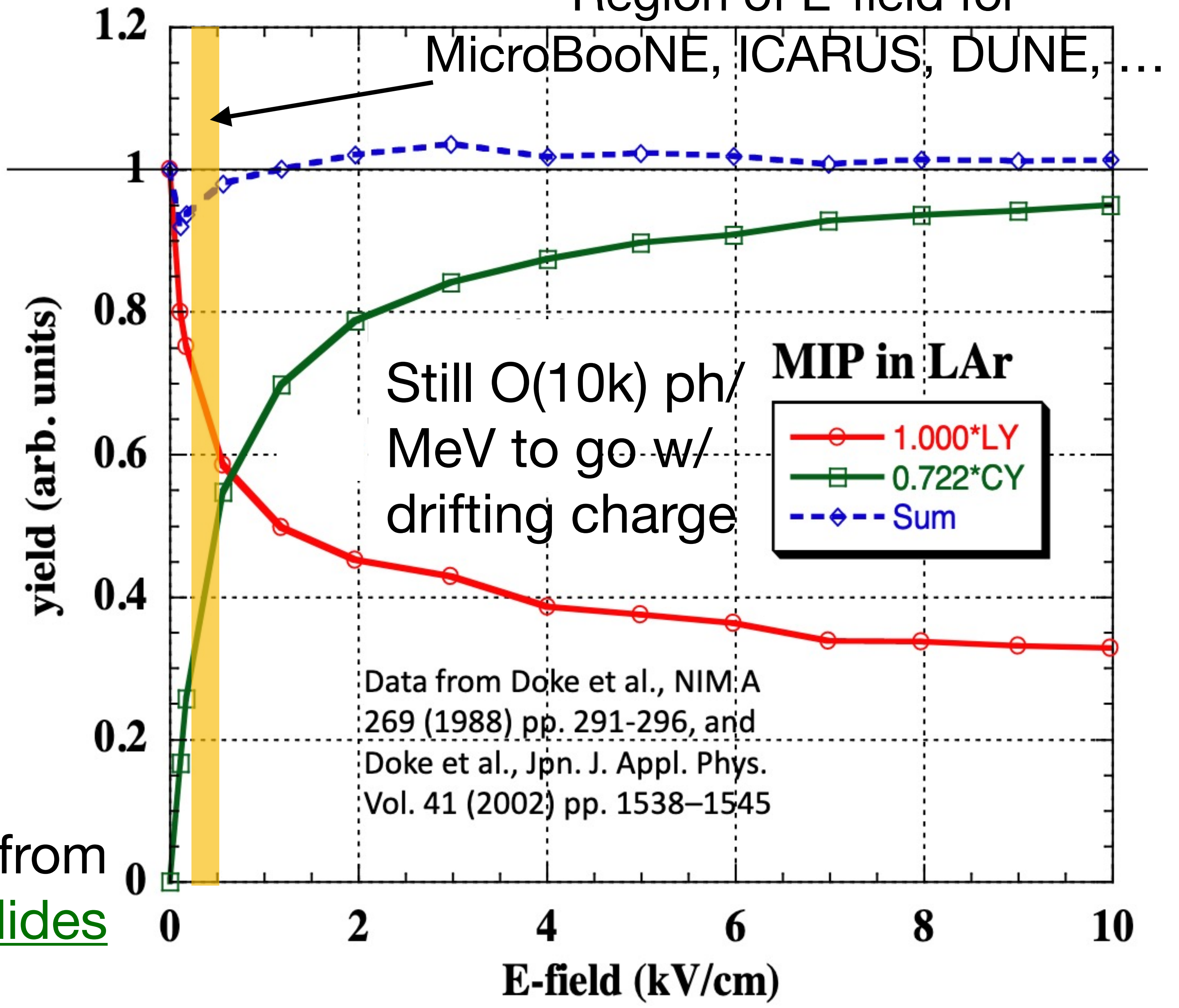


C. Amsler et al.
arXiv:0708.2621

Scintillation production happens on 2 timescales

E field pulls ionization away, reducing amount of recombination

Region of E-field for MicroBooNE, ICARUS, DUNE, …

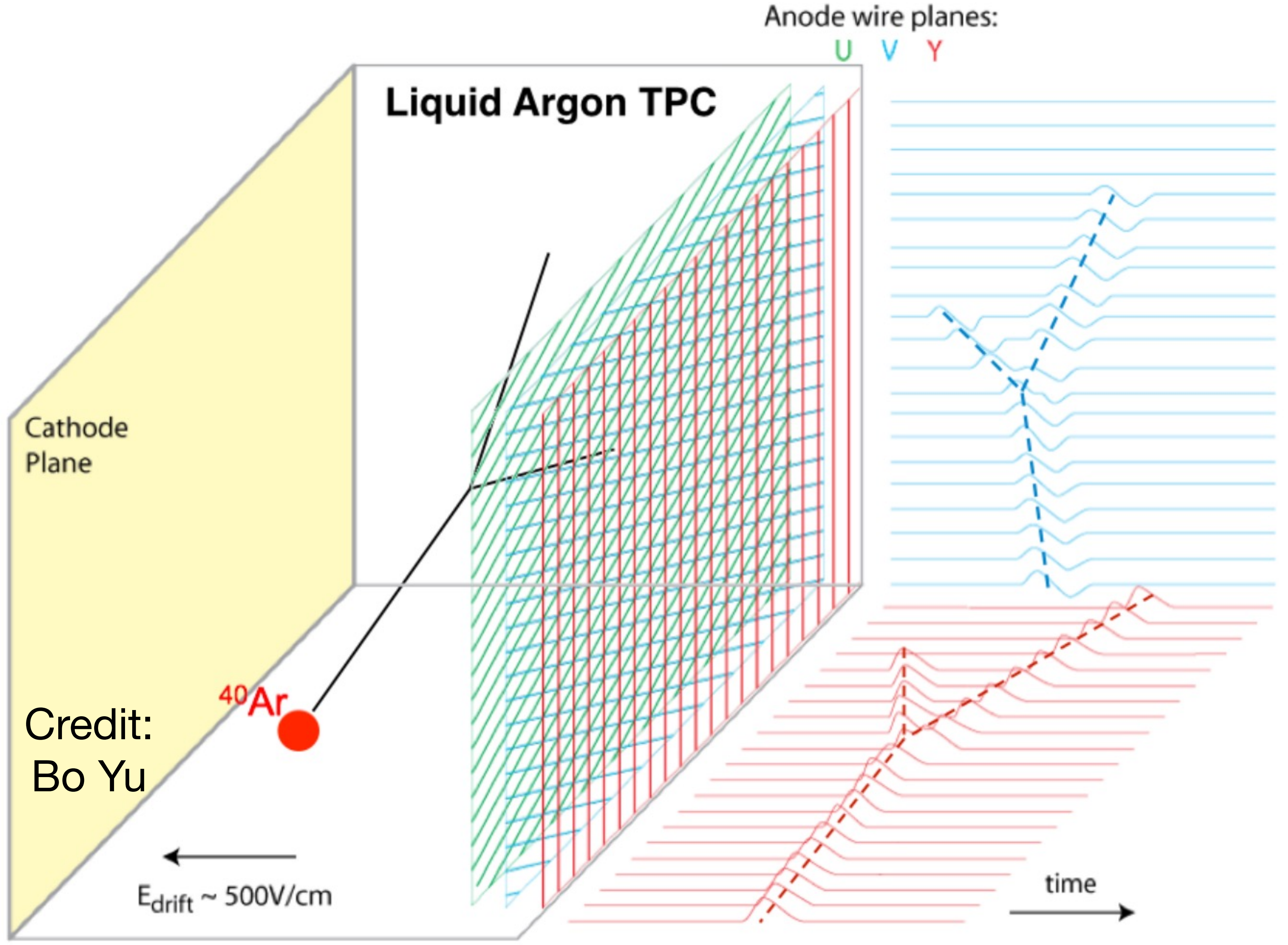


Still O(10k) ph/MeV to go w/ drifting charge

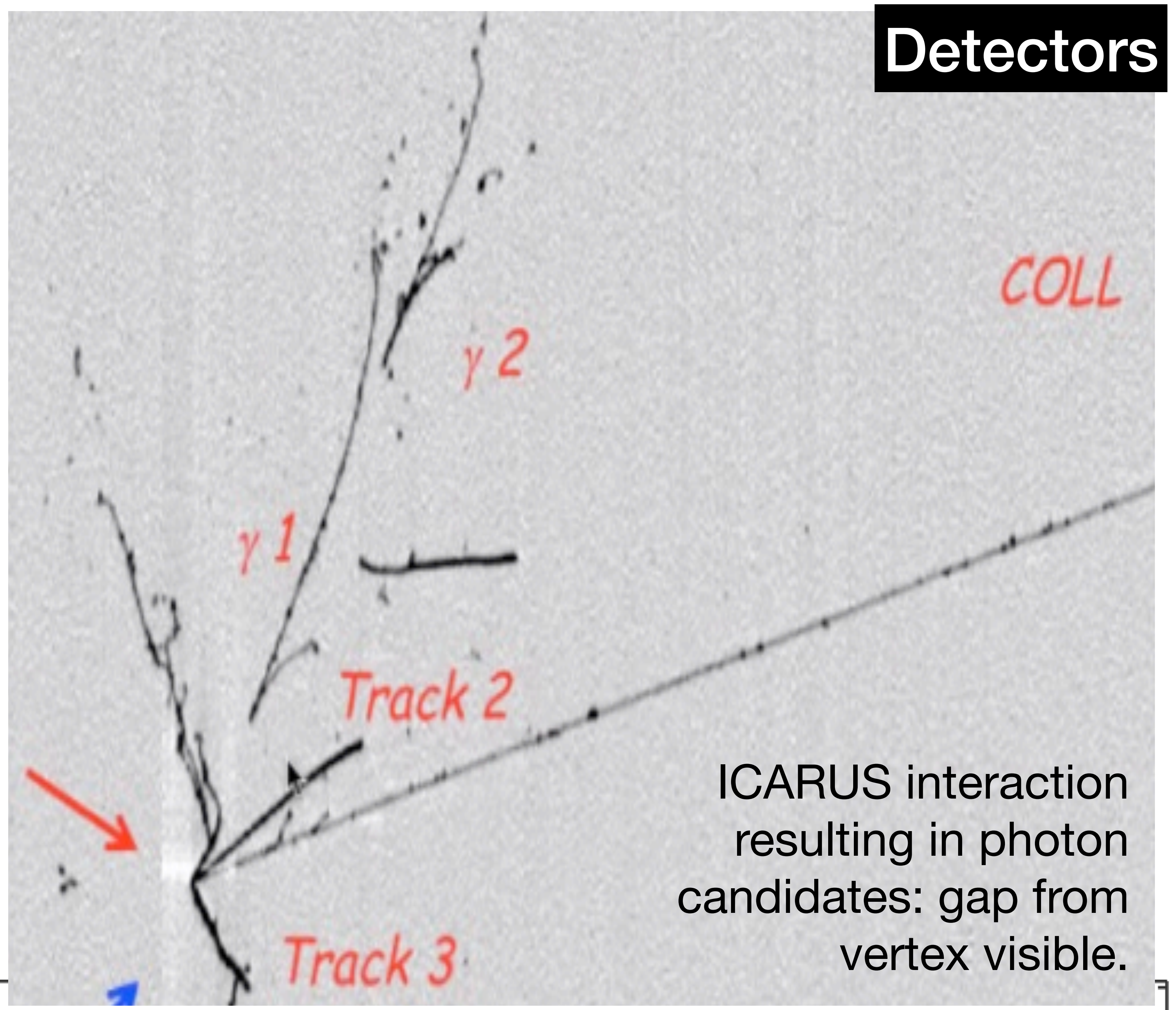
Adapted from M. Szydagis slides

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

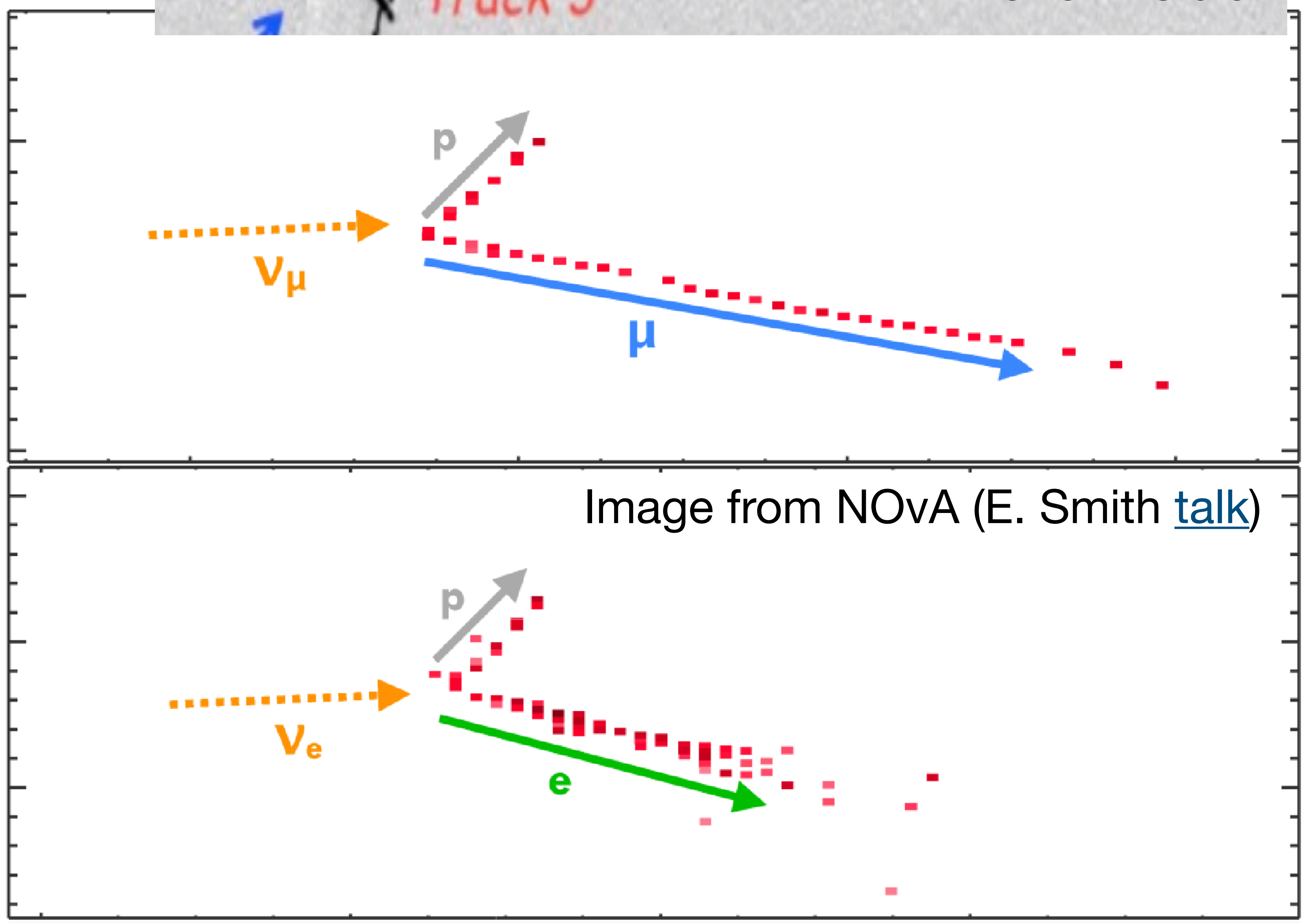


Image from NOvA (E. Smith talk)

LAr Time-Projection Chamber

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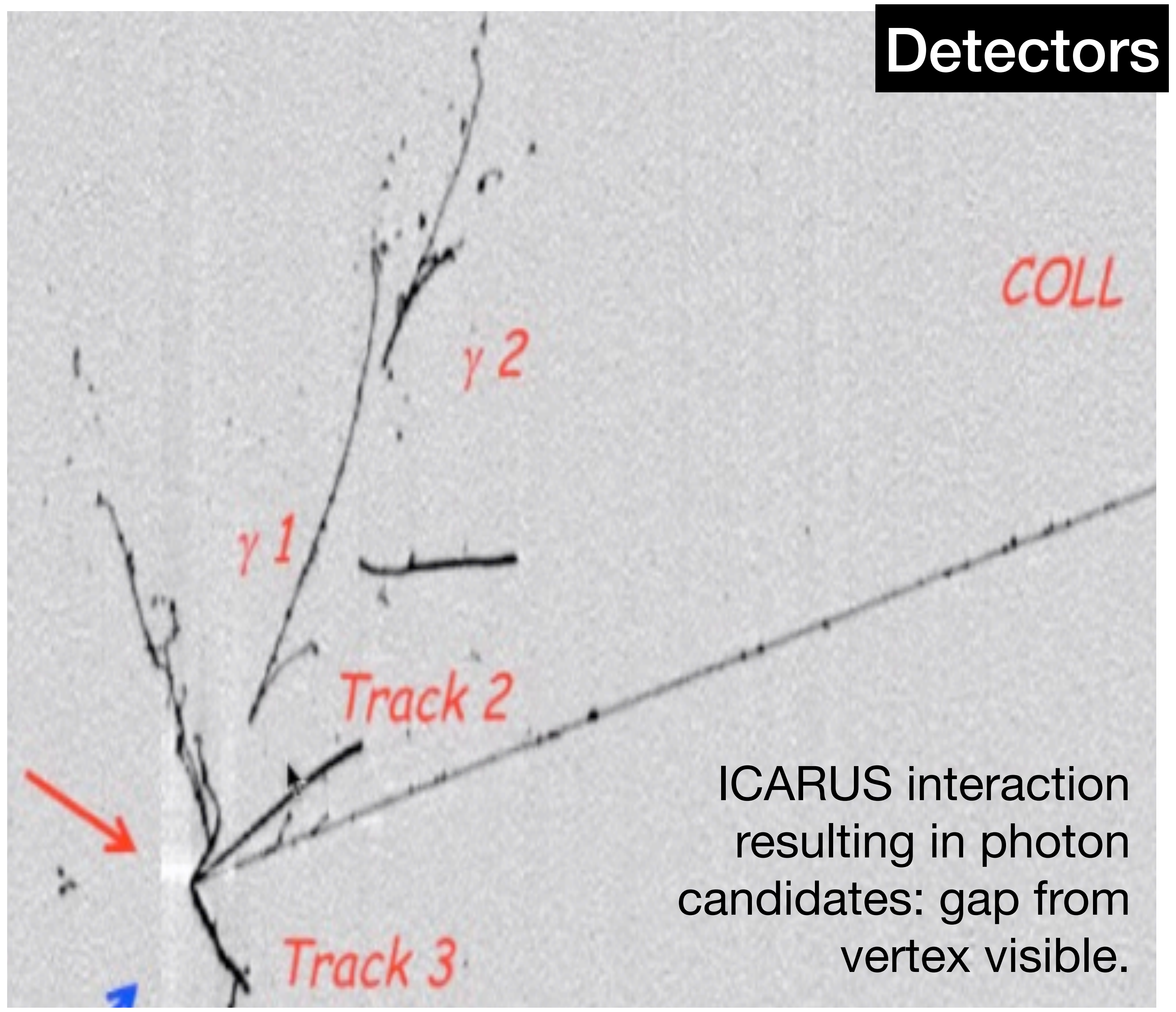

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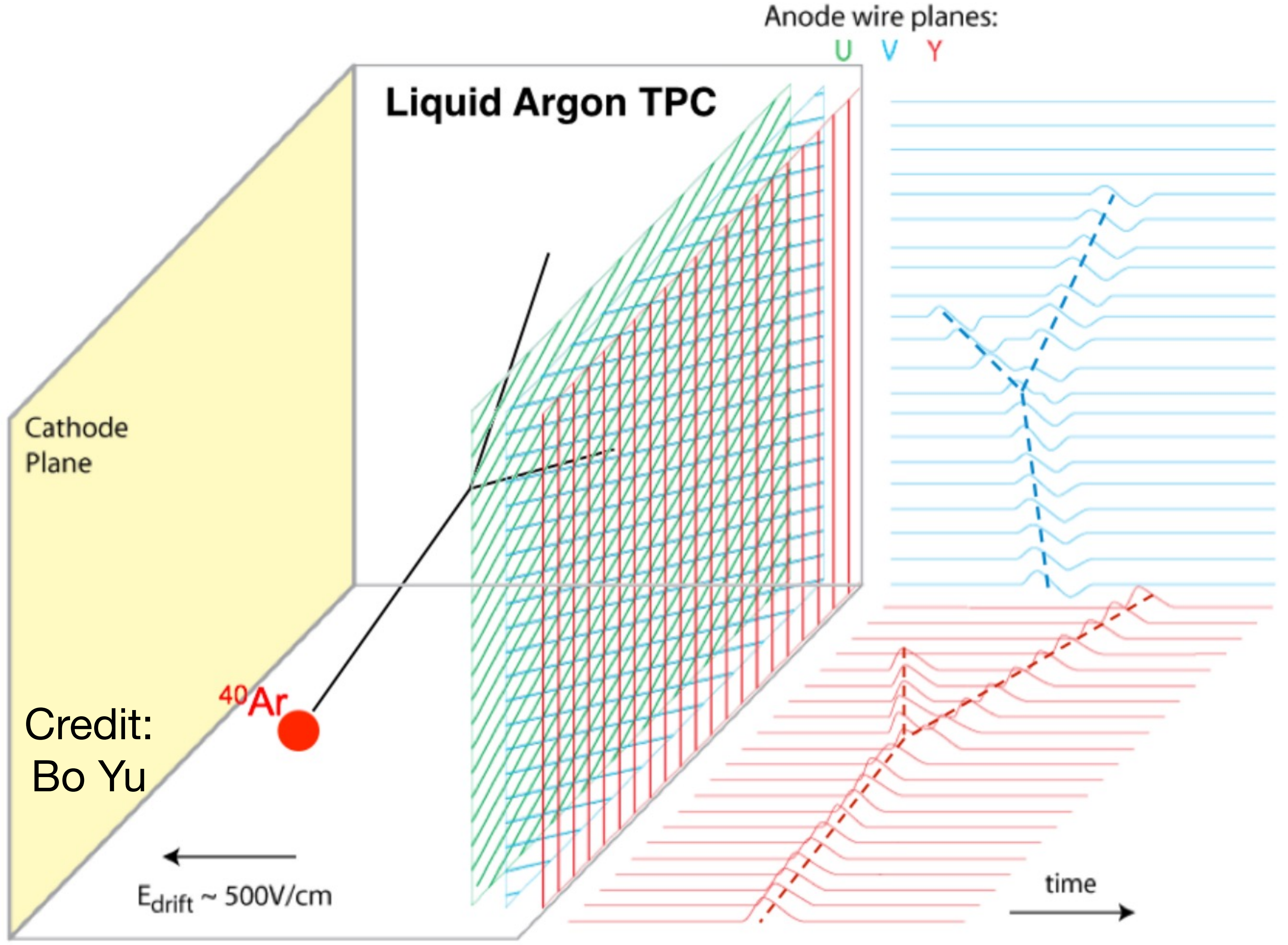
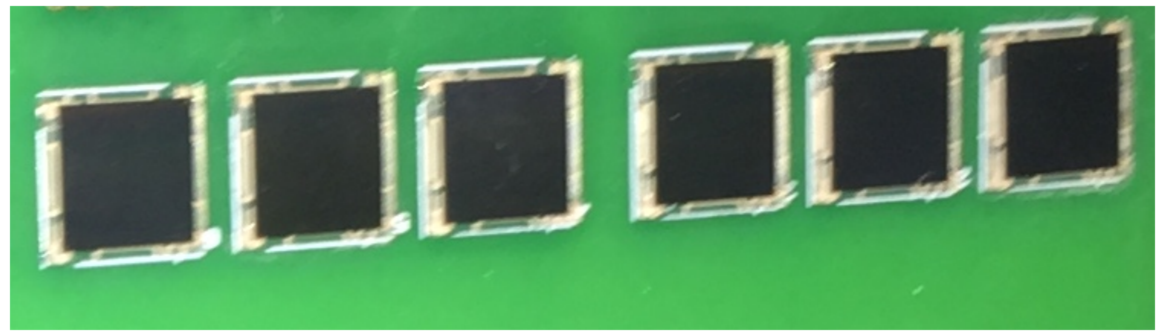


Credit: Bo Yu

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

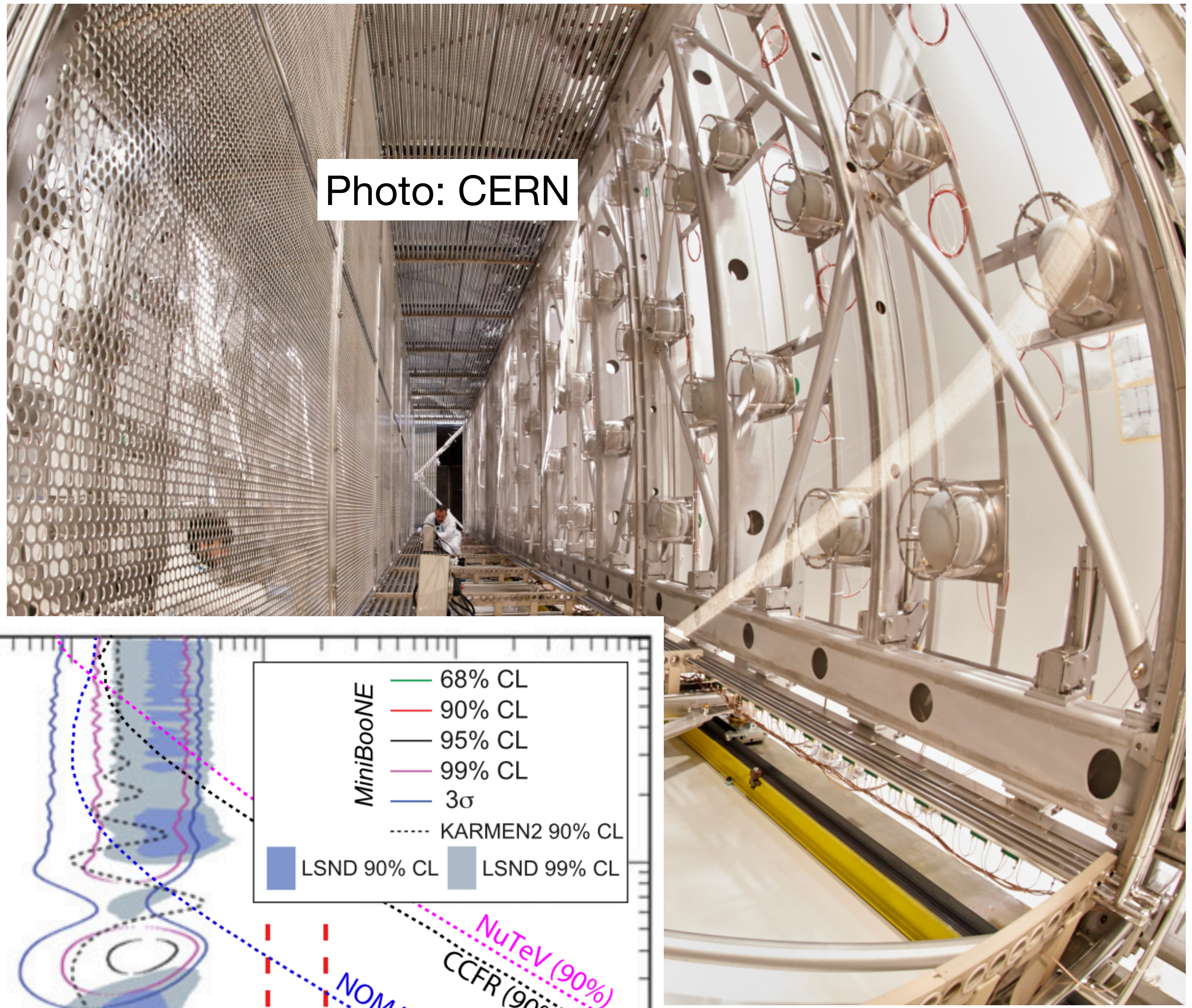


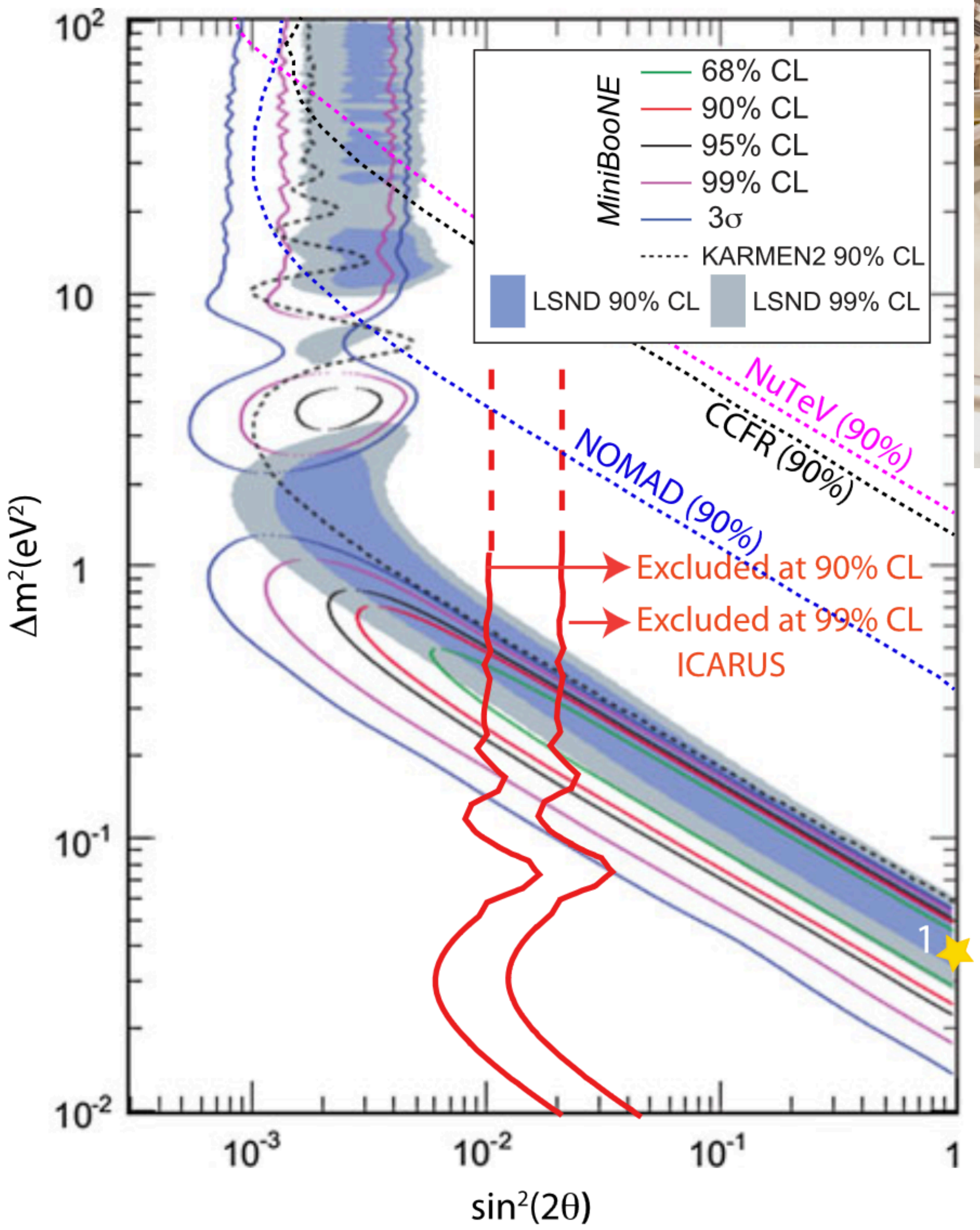
6x6 mm^2 silicon photomultipliers (SiPMs) arranged in line. These are optical SiPMs, but (V)UV sensitive SiPM options also now exist.

- 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



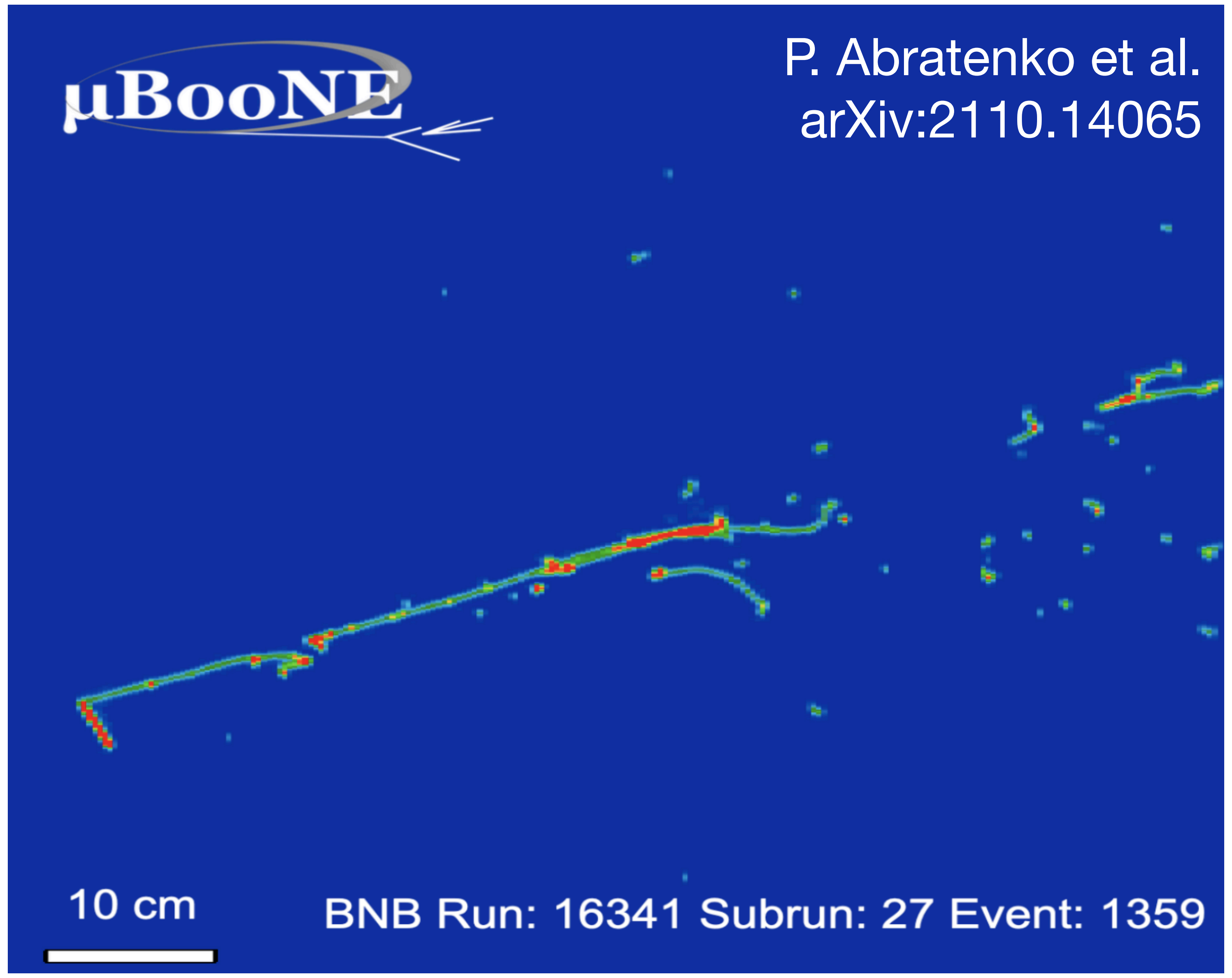


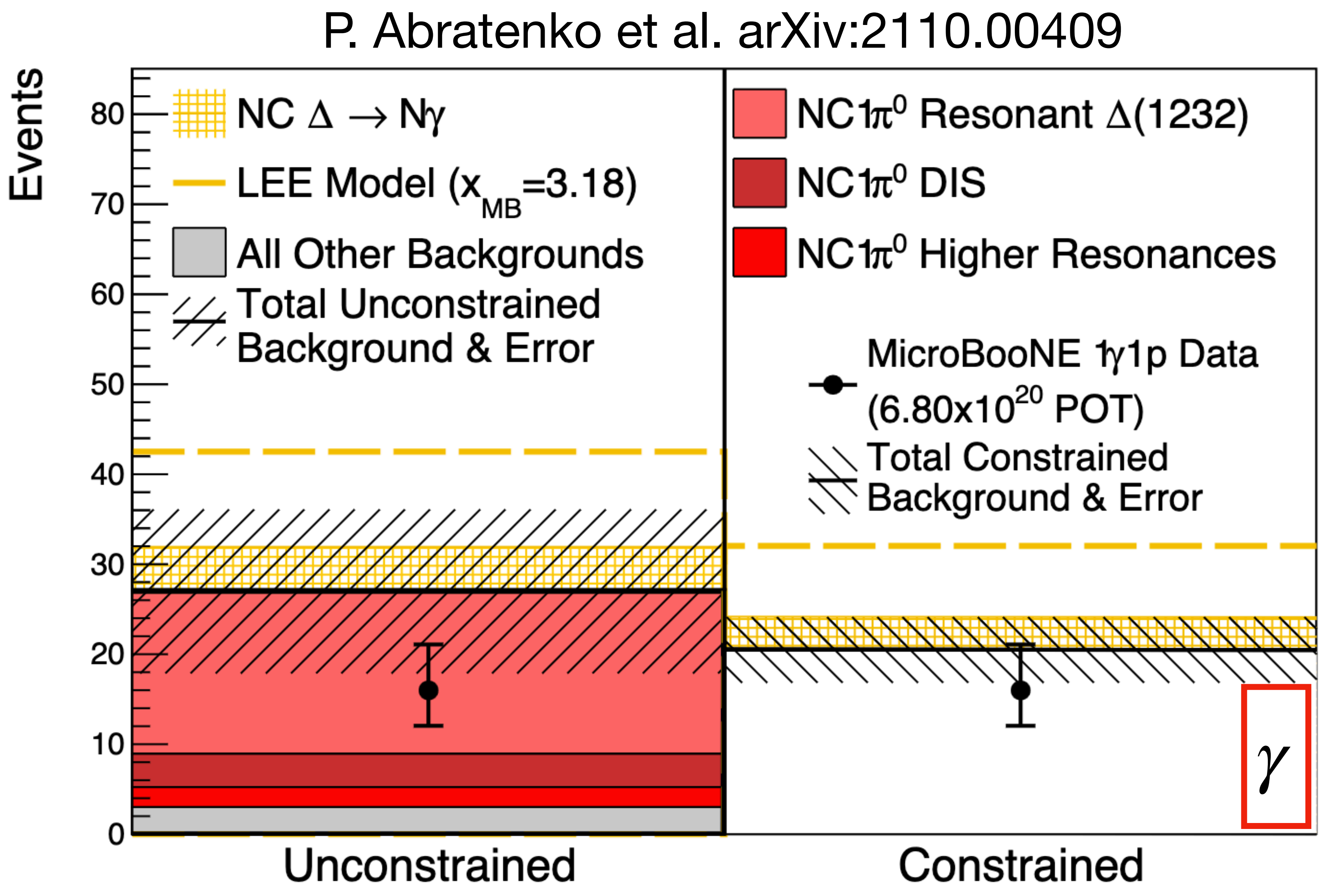
ICARUS at LNGS

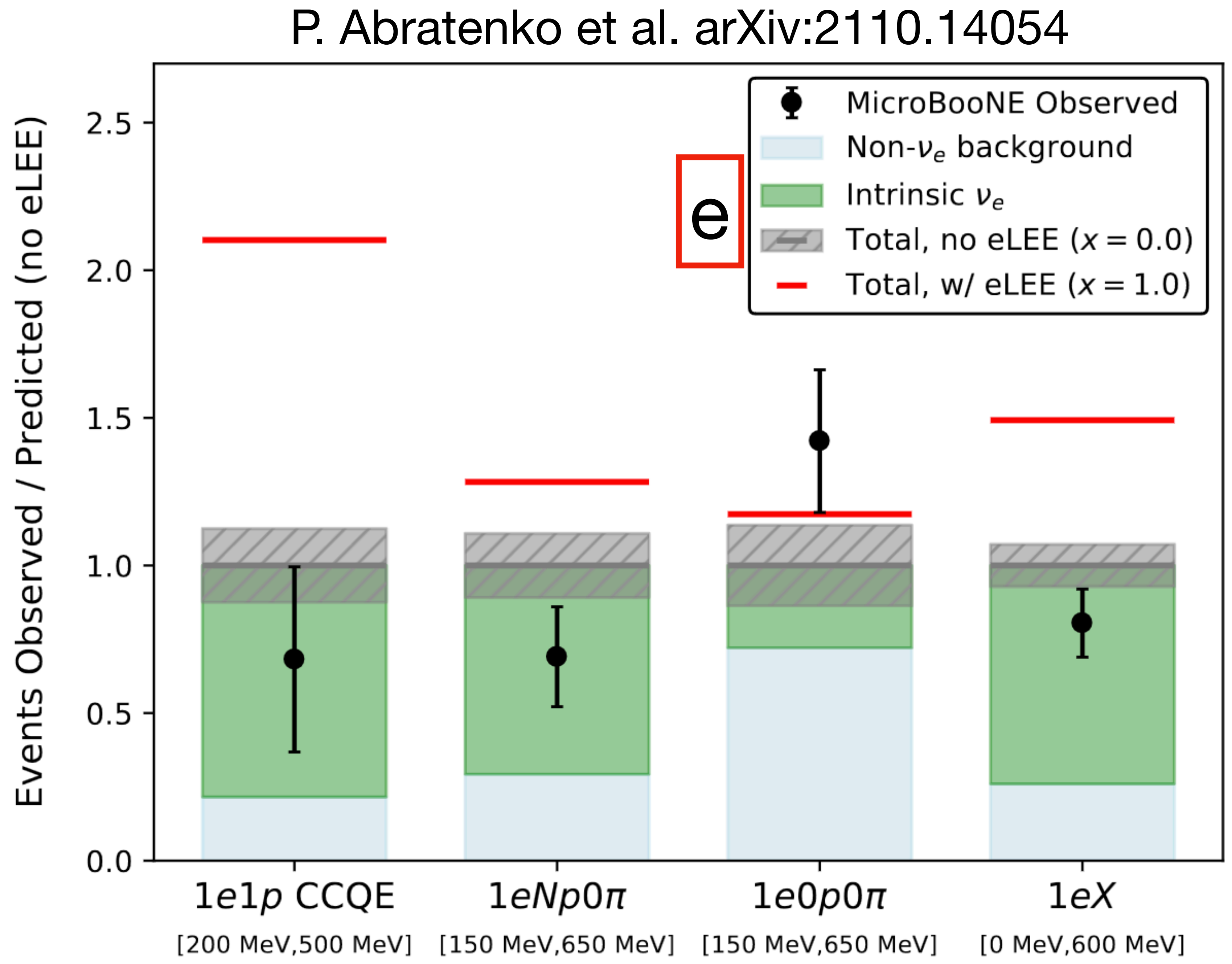
M. Antonello et al. Eur. Phys. Journal C **73**, 2345 (2013)

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

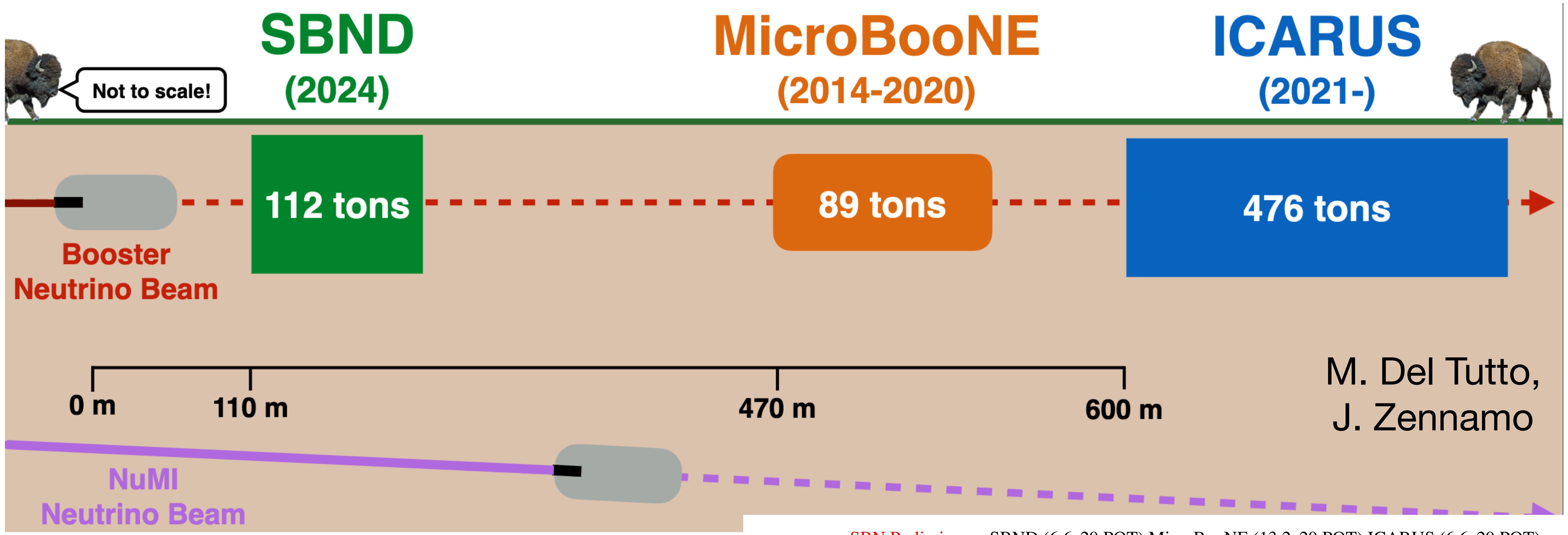


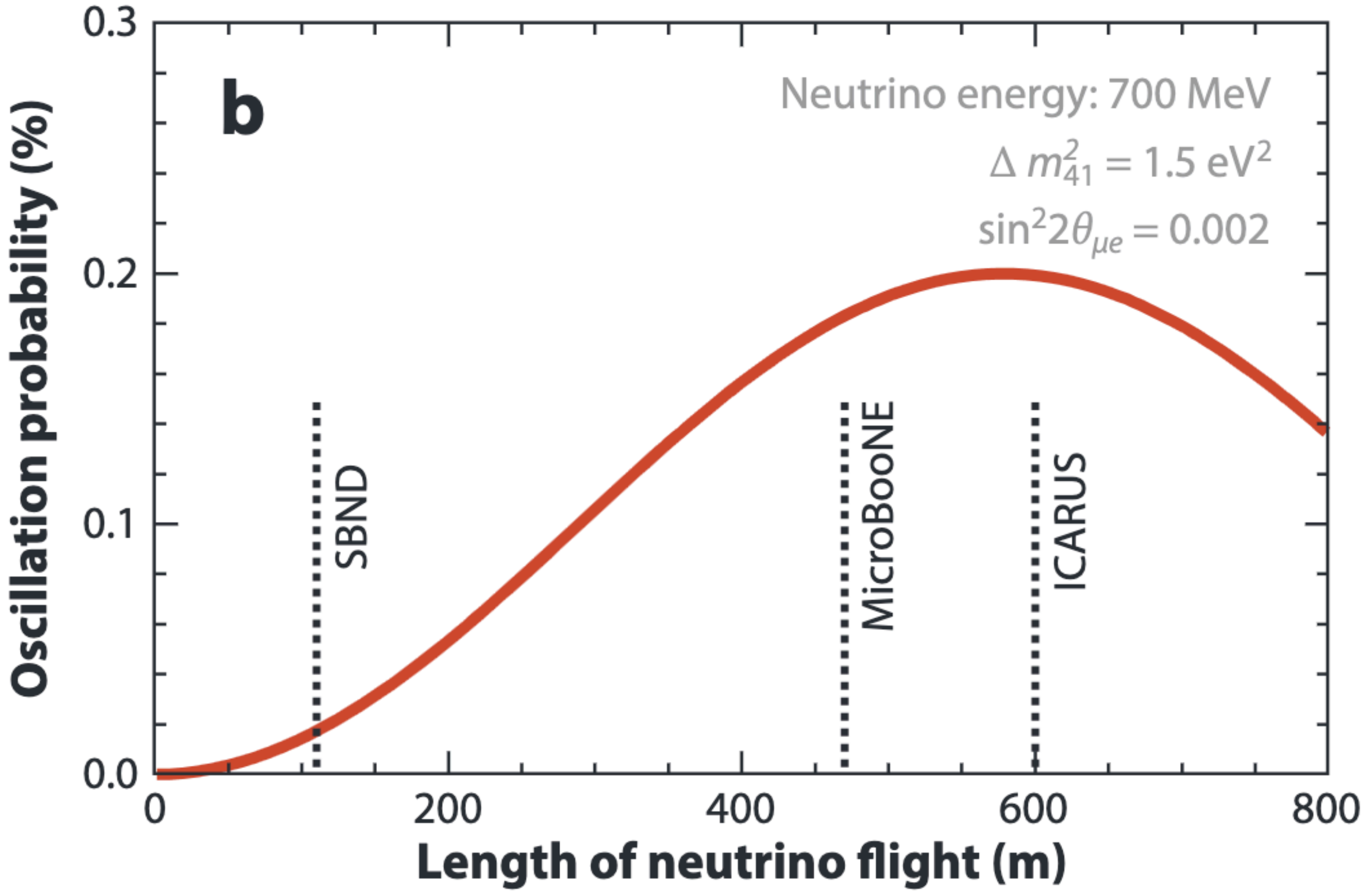




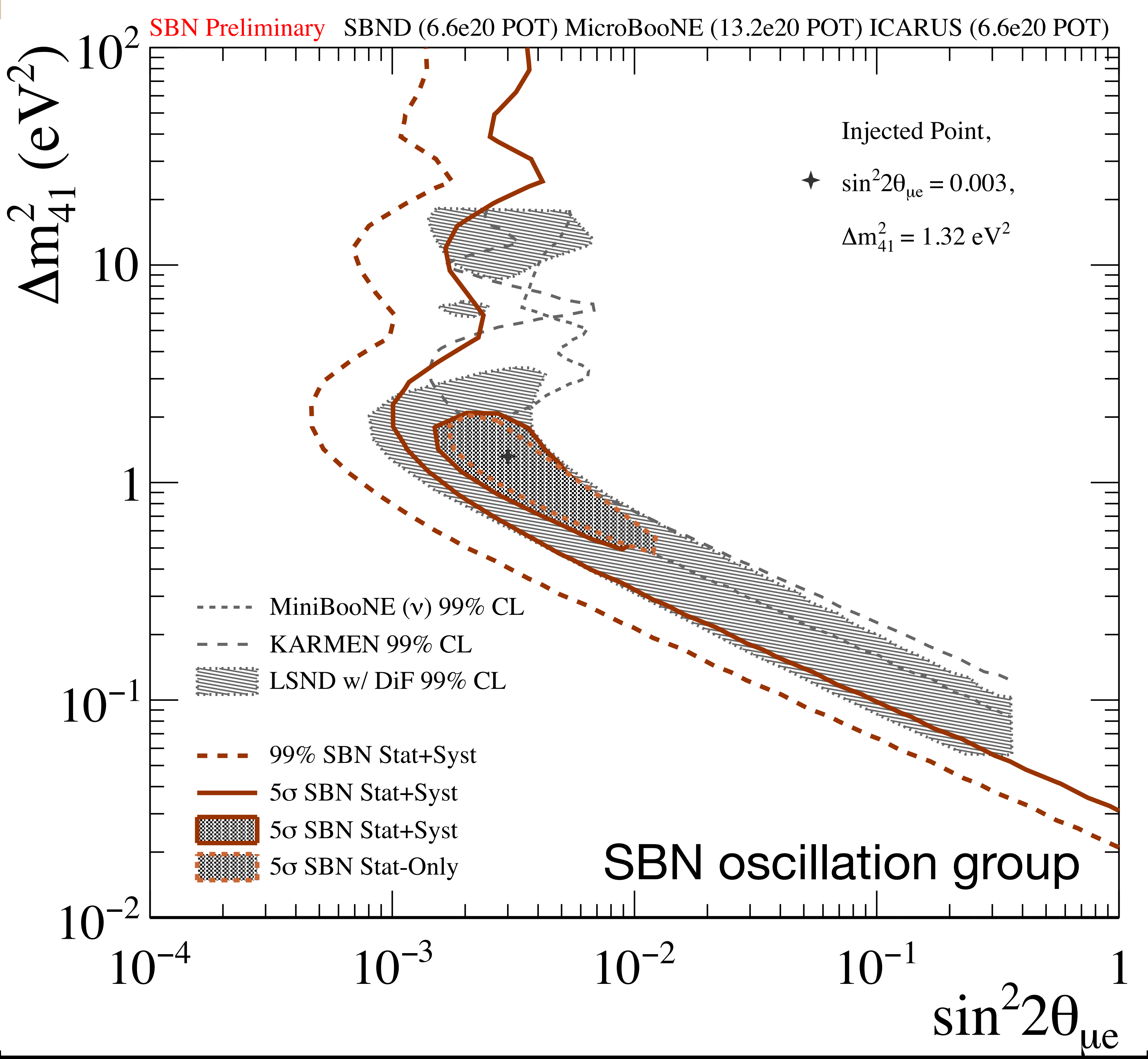
SBN Program

- 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)



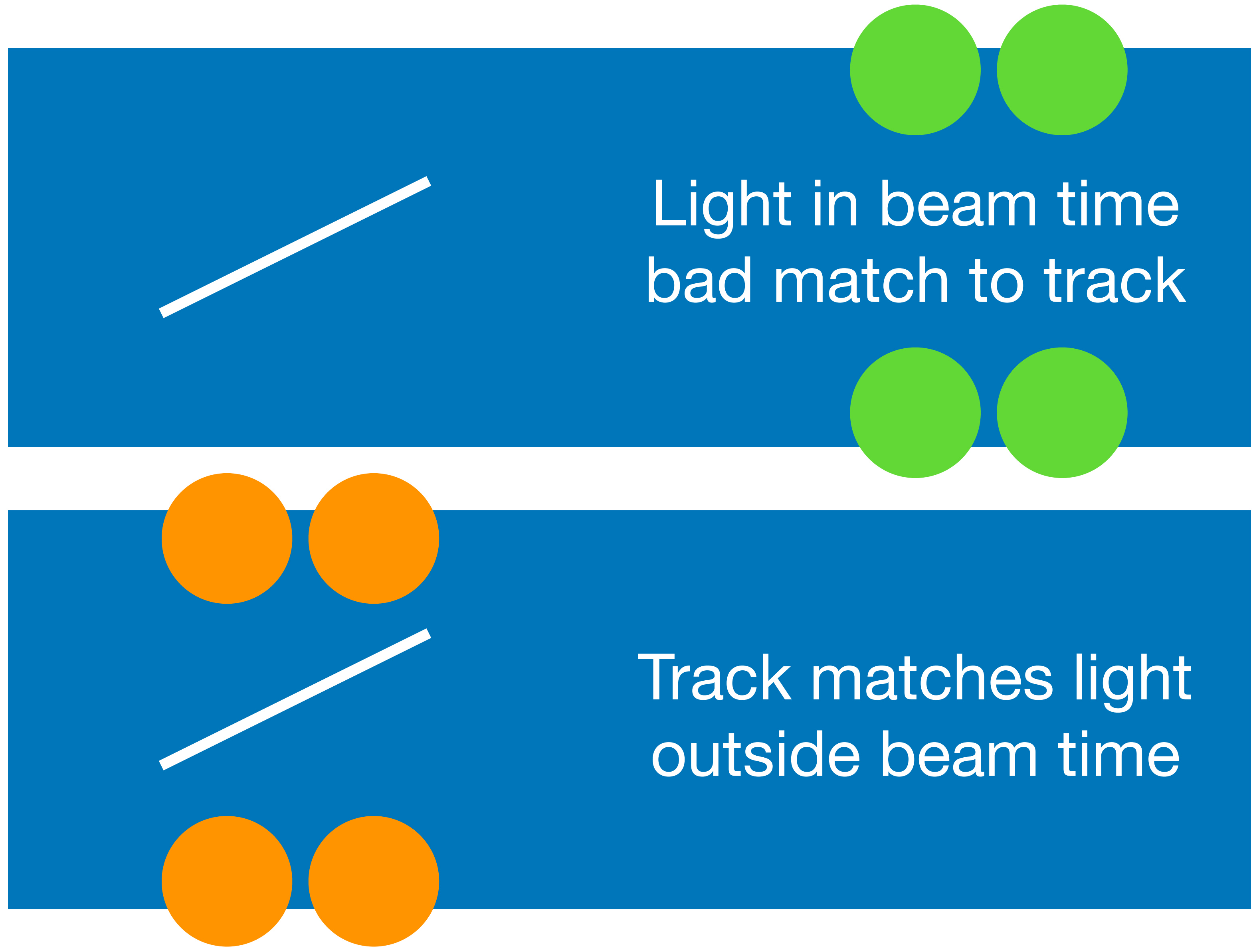


Possible oscillation signature under a set of parameters. P. Machado, O. Palamara, D. Schmitz. Annu. Rev. Nucl. Part. Sci. (2019). doi: 10.1146

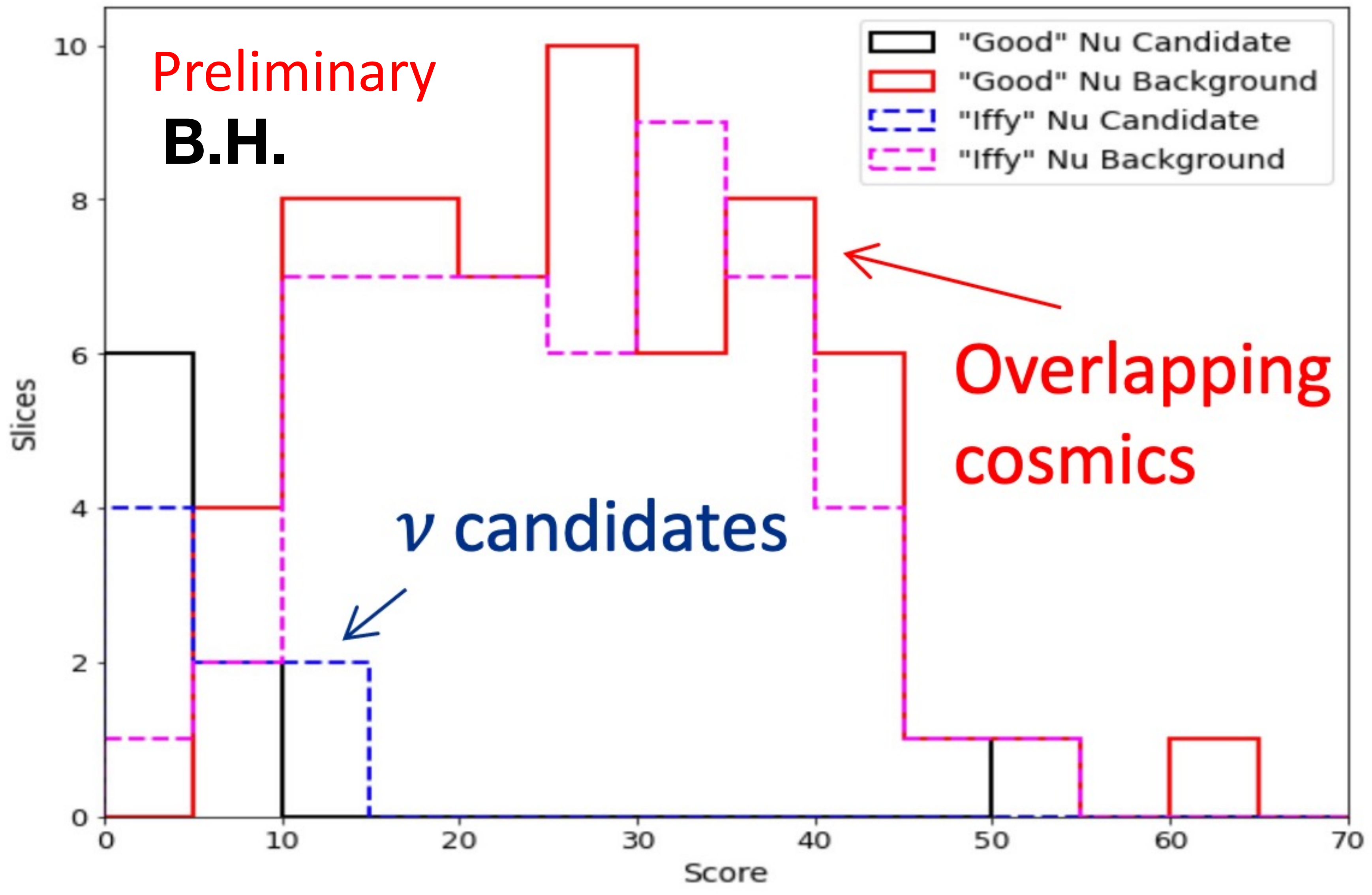


Cosmic Mitigation in ICARUS

- 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

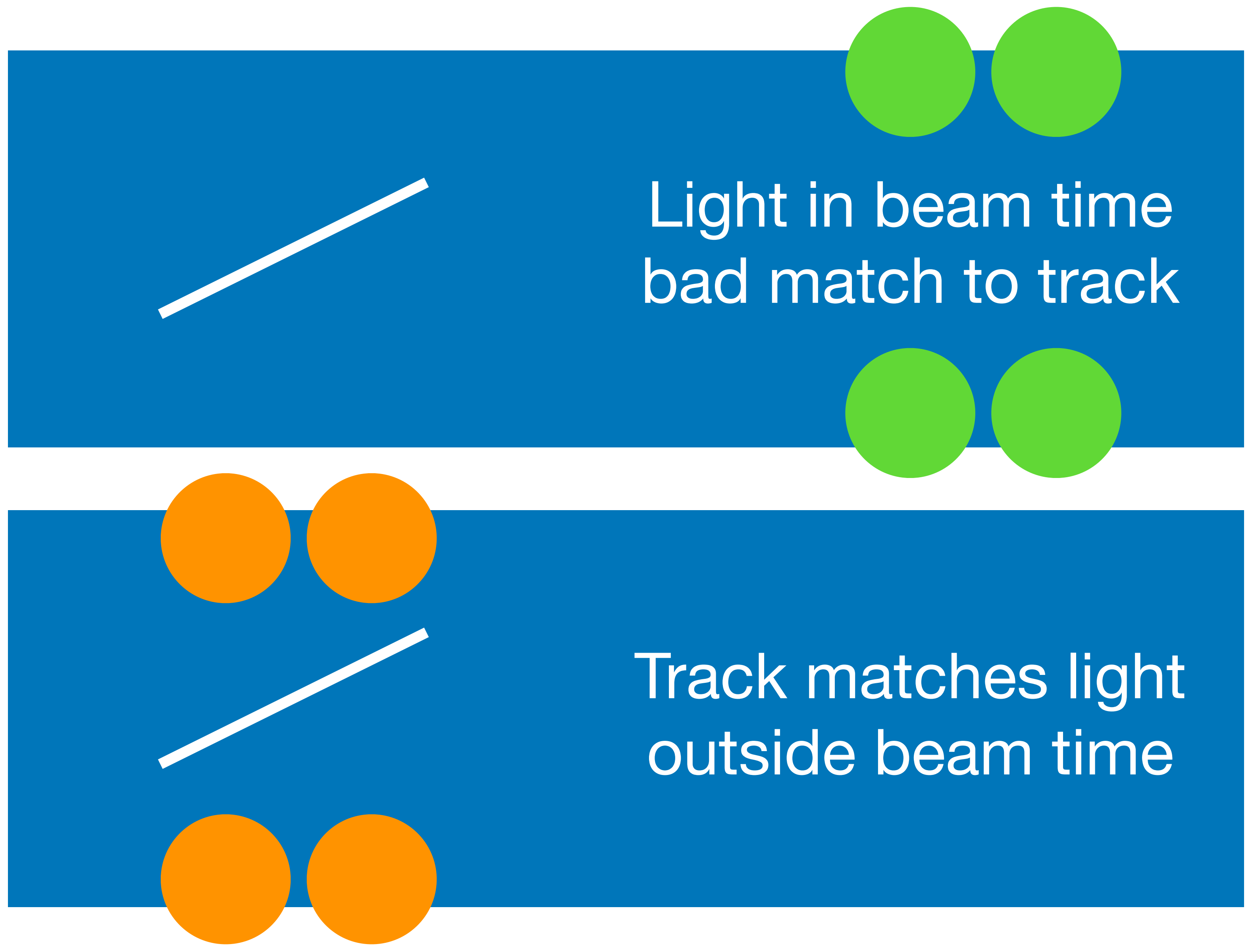


Early look I made with a few hand-scanned events from commissioning: will talk more about commissioning/operating ICARUS shortly



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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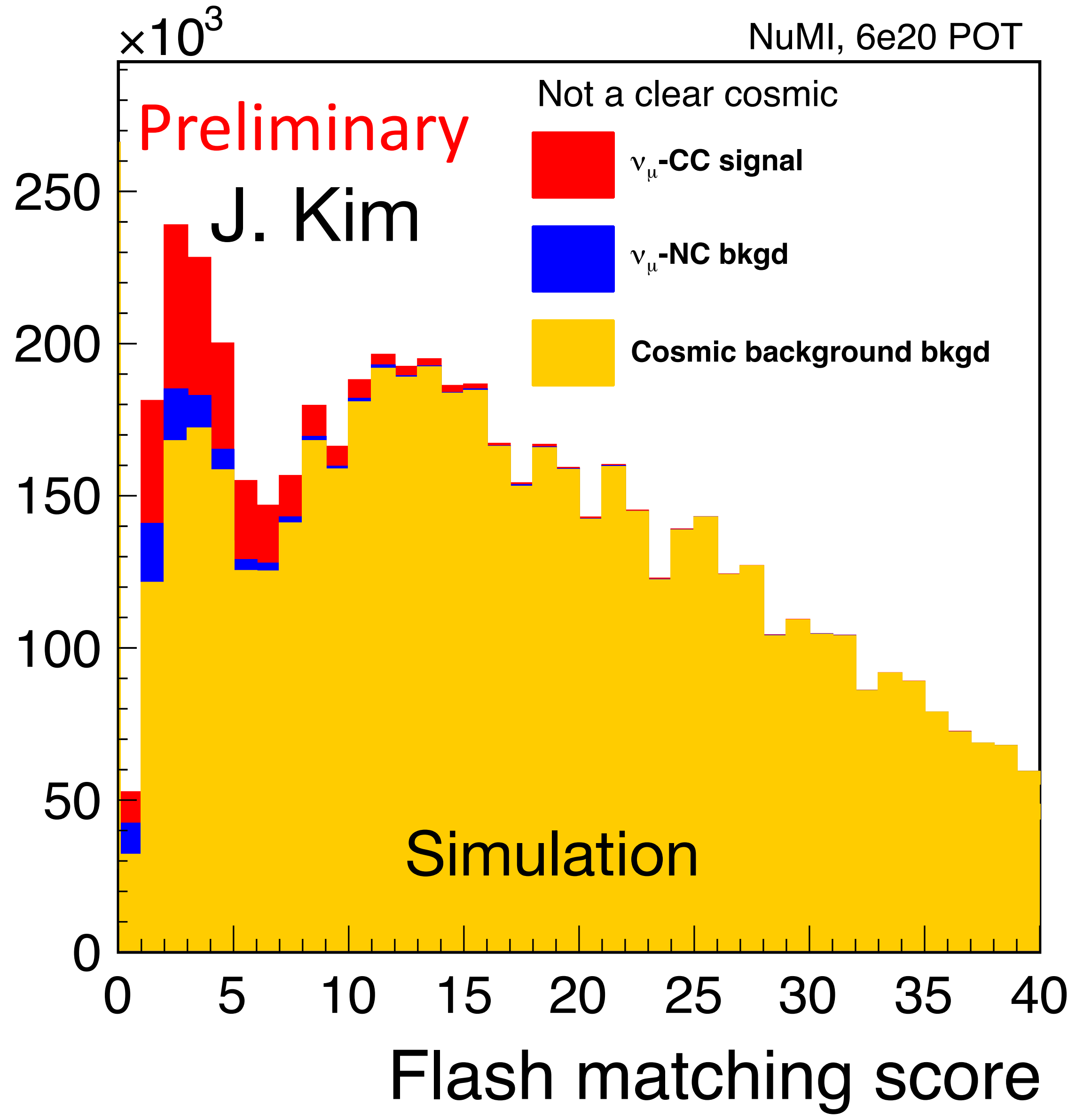
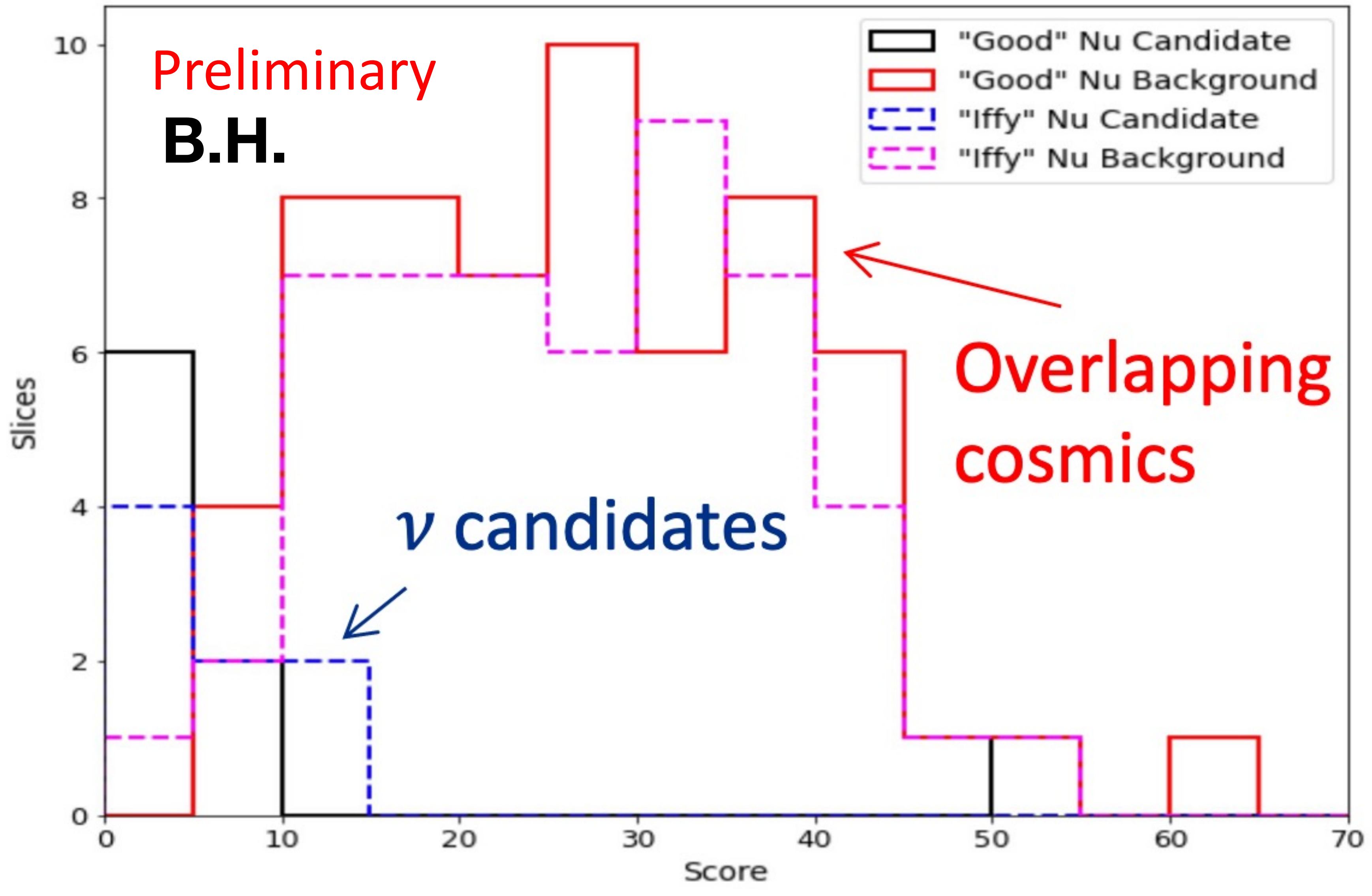
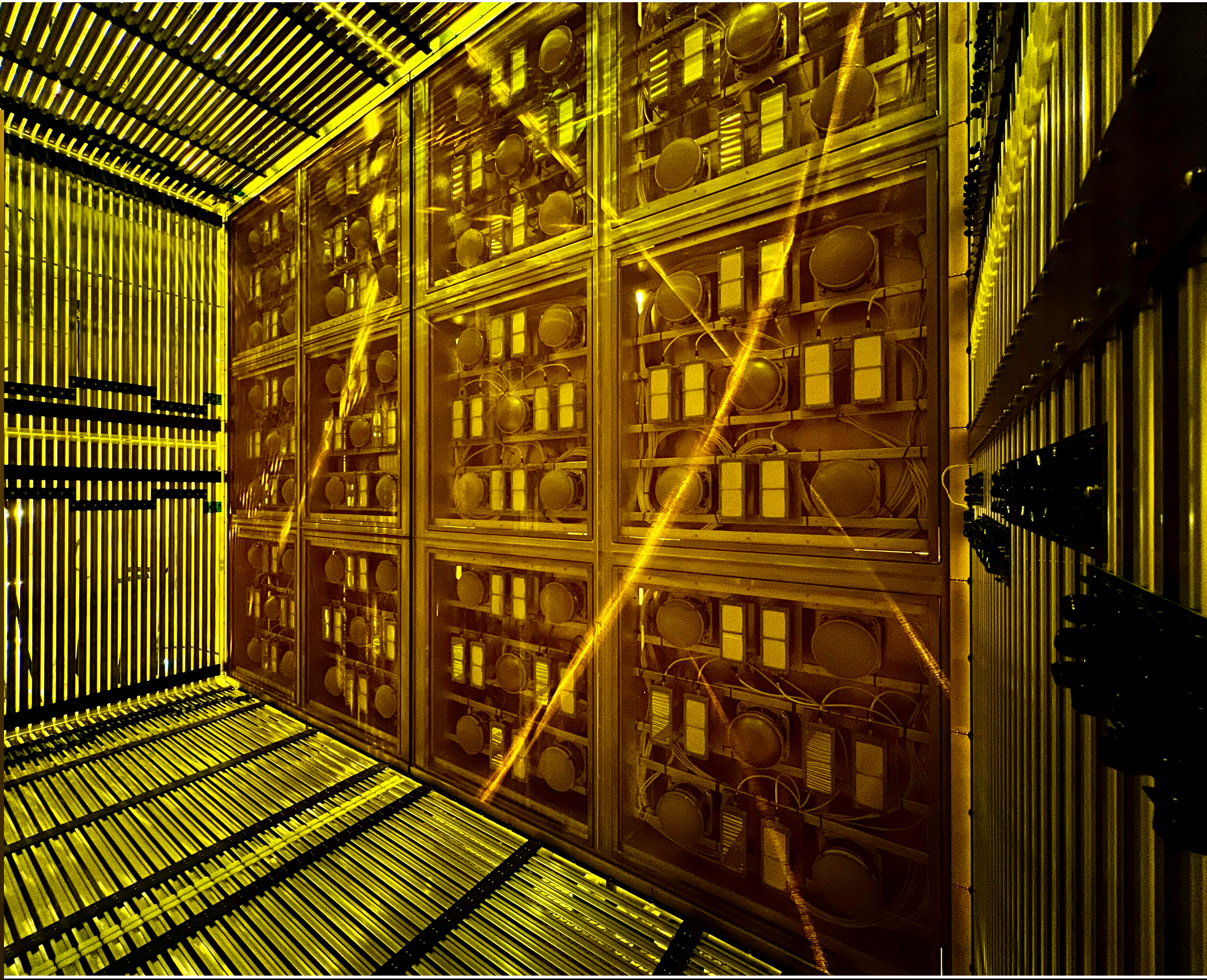


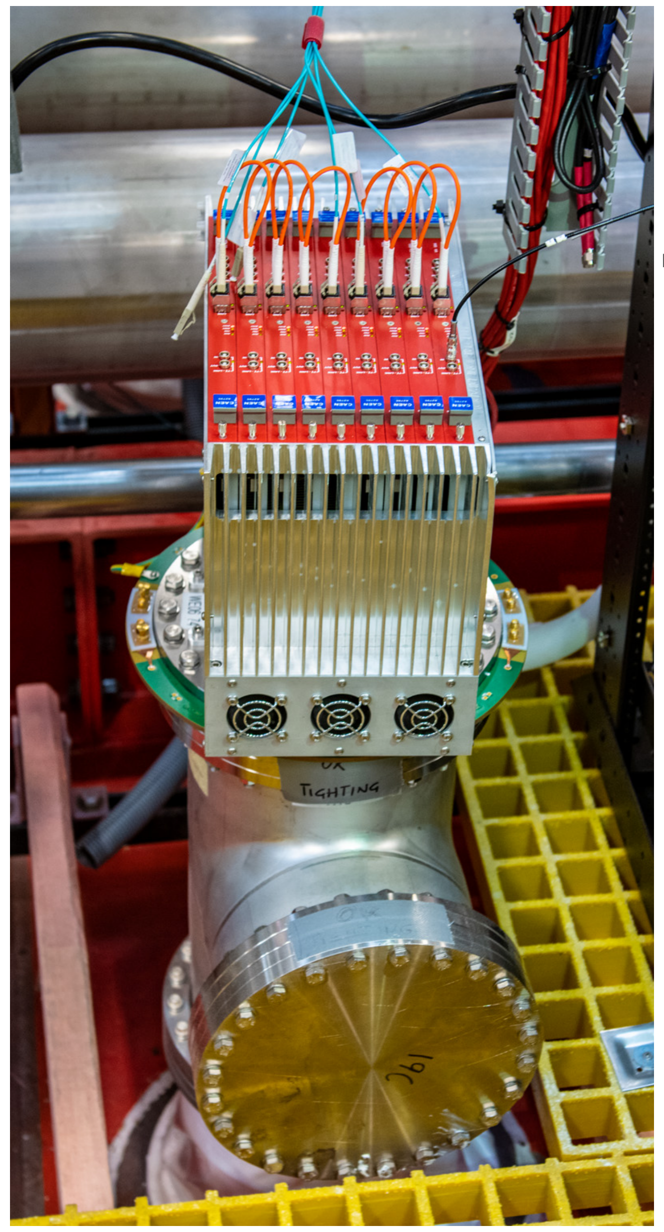


SBND @ FNAL



Photos: Mônica Nunes

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

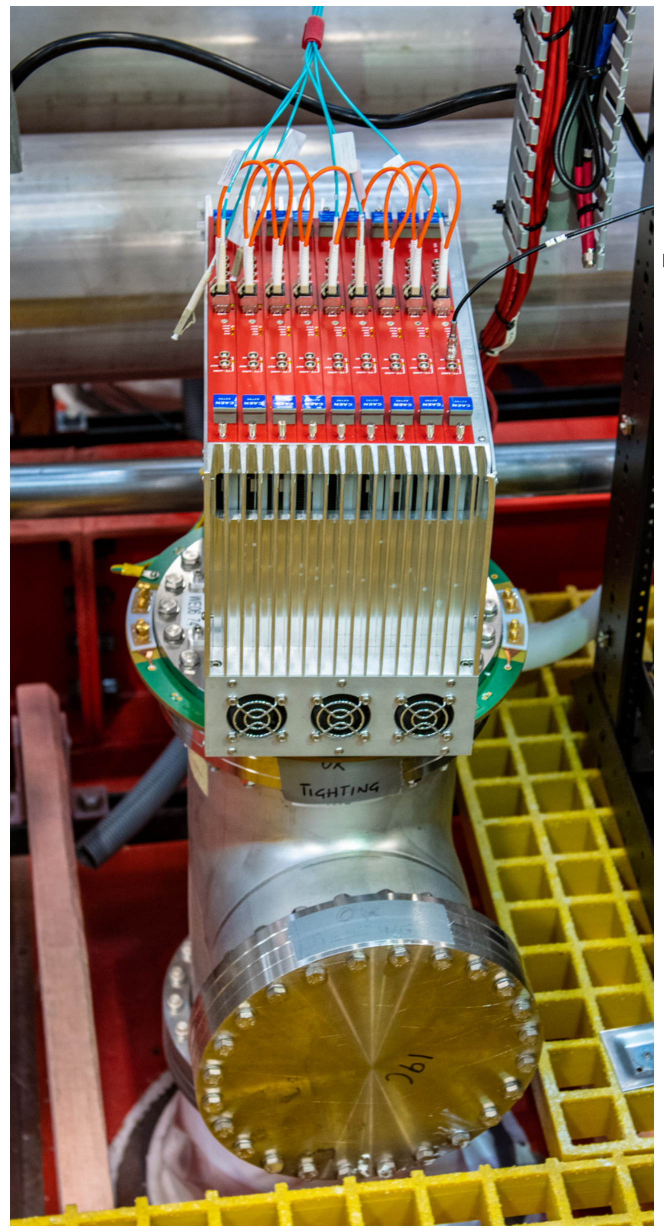
→ **Machine Learning Reco**

Pandora → Track Reco & downstream reco like calo

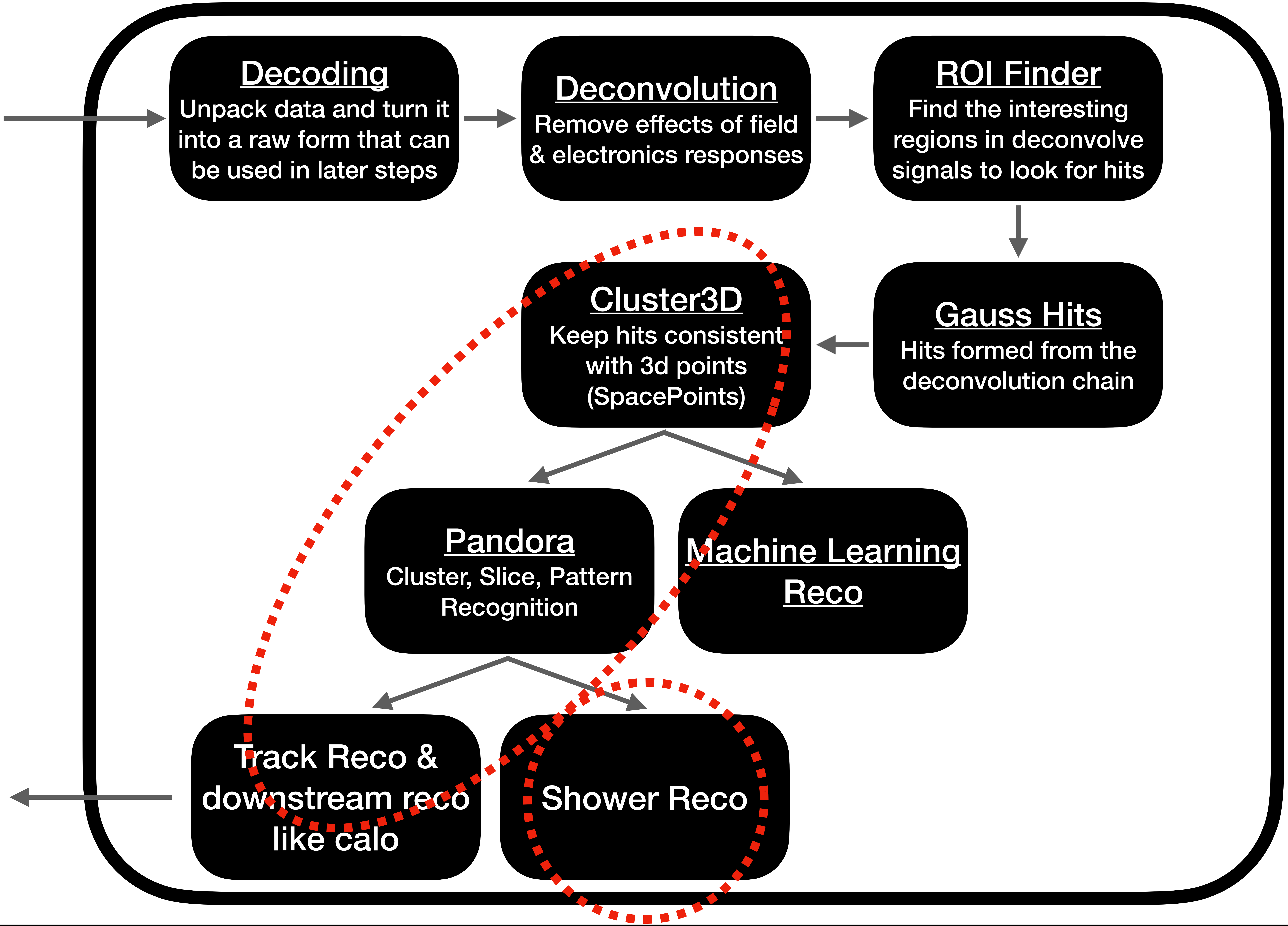
Pandora → Shower Reco

Track Reco → ANALYSIS

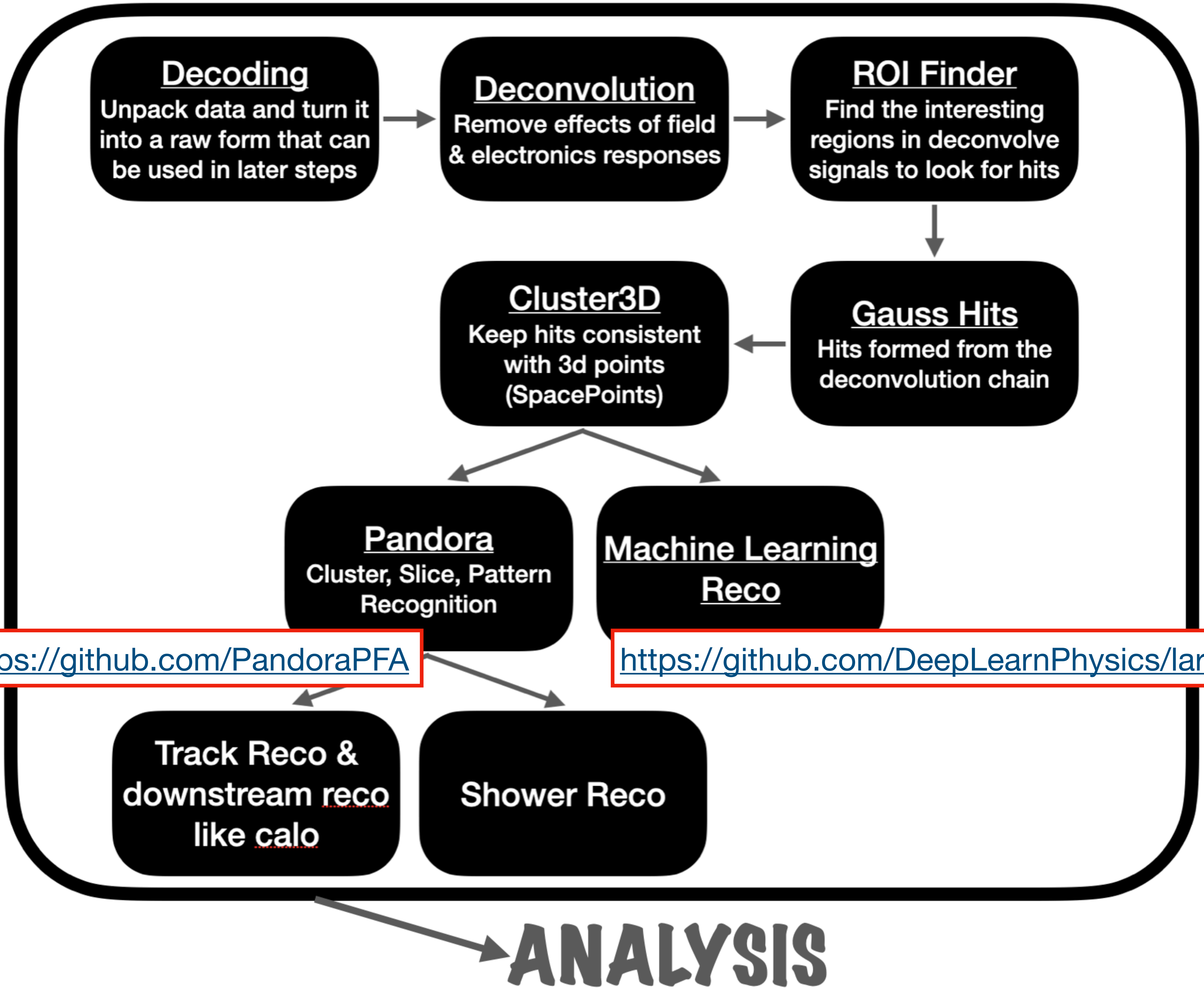
ICARUS TPC Reco

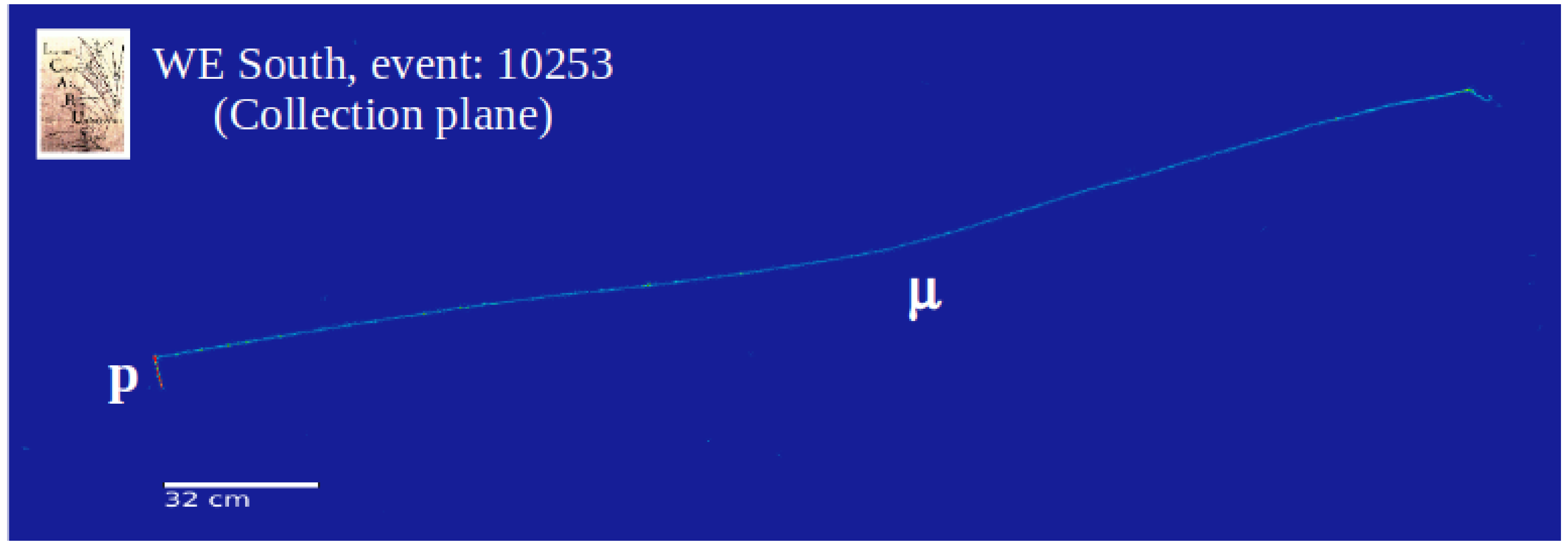


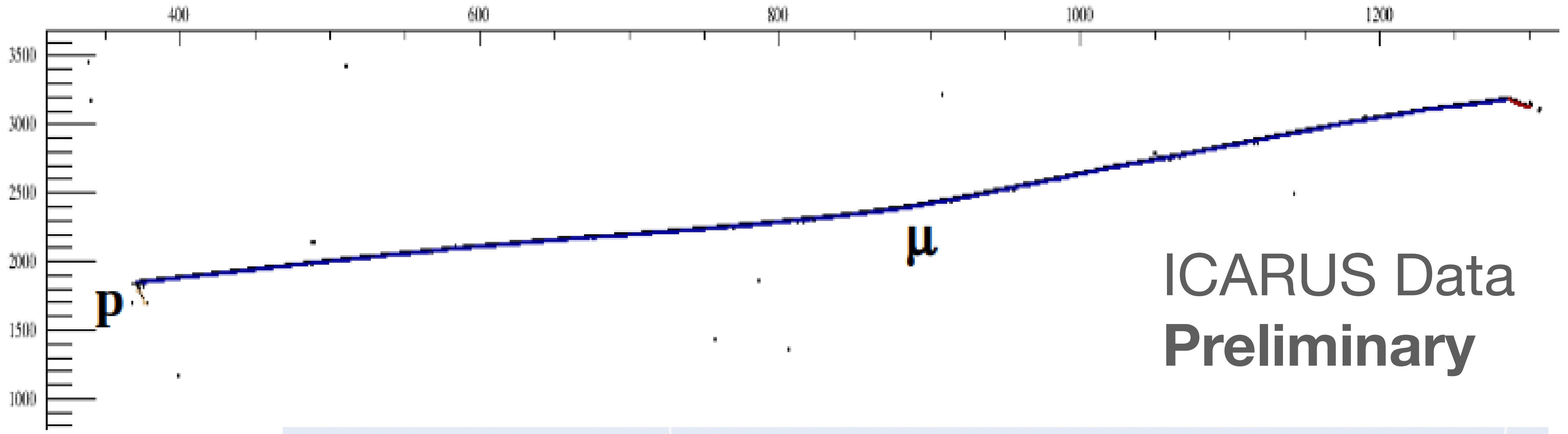
FNAL VMS

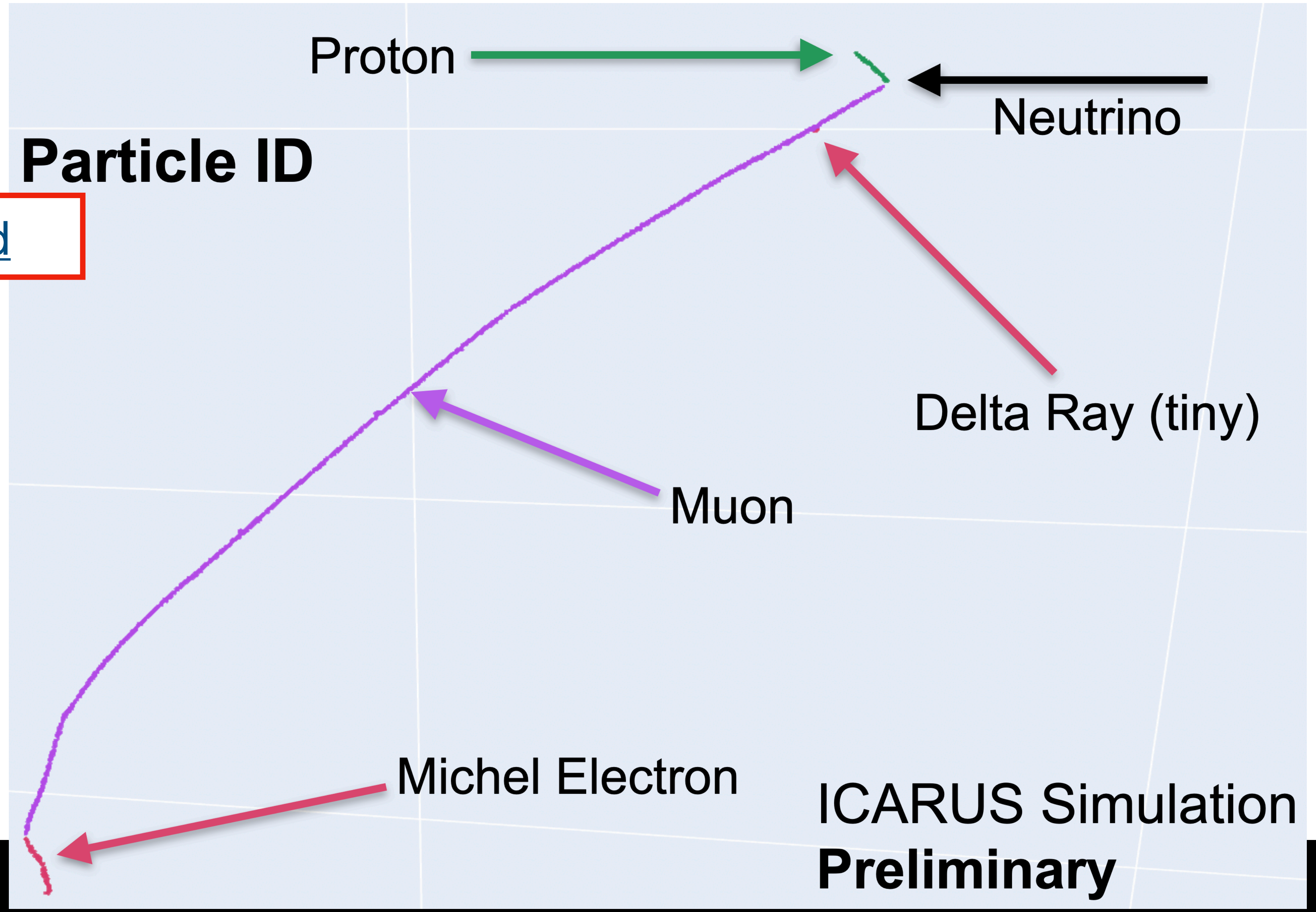


TPC Reconstruction



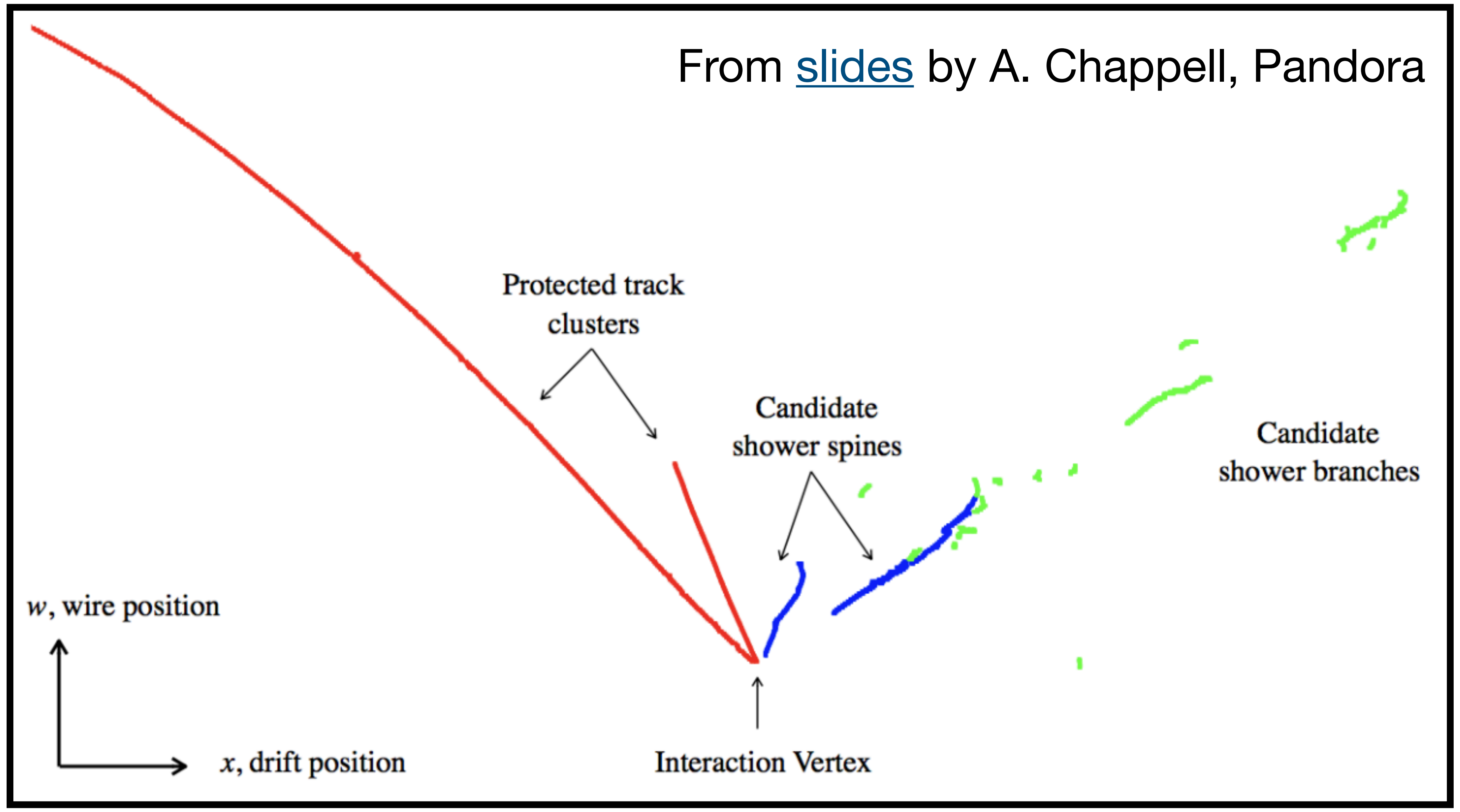






ICARUS TPC Reco

- 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.

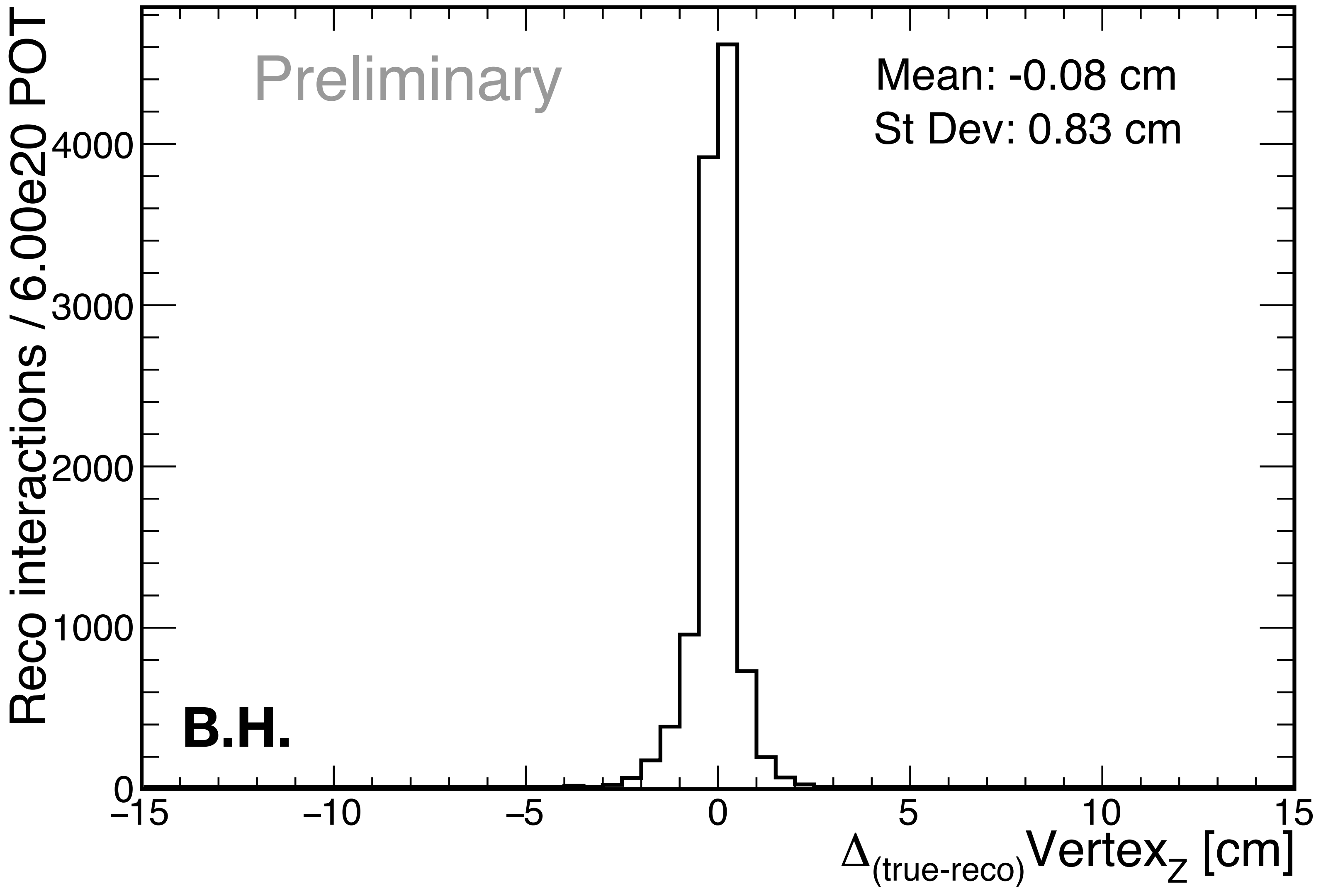


ICARUS TPC Reco

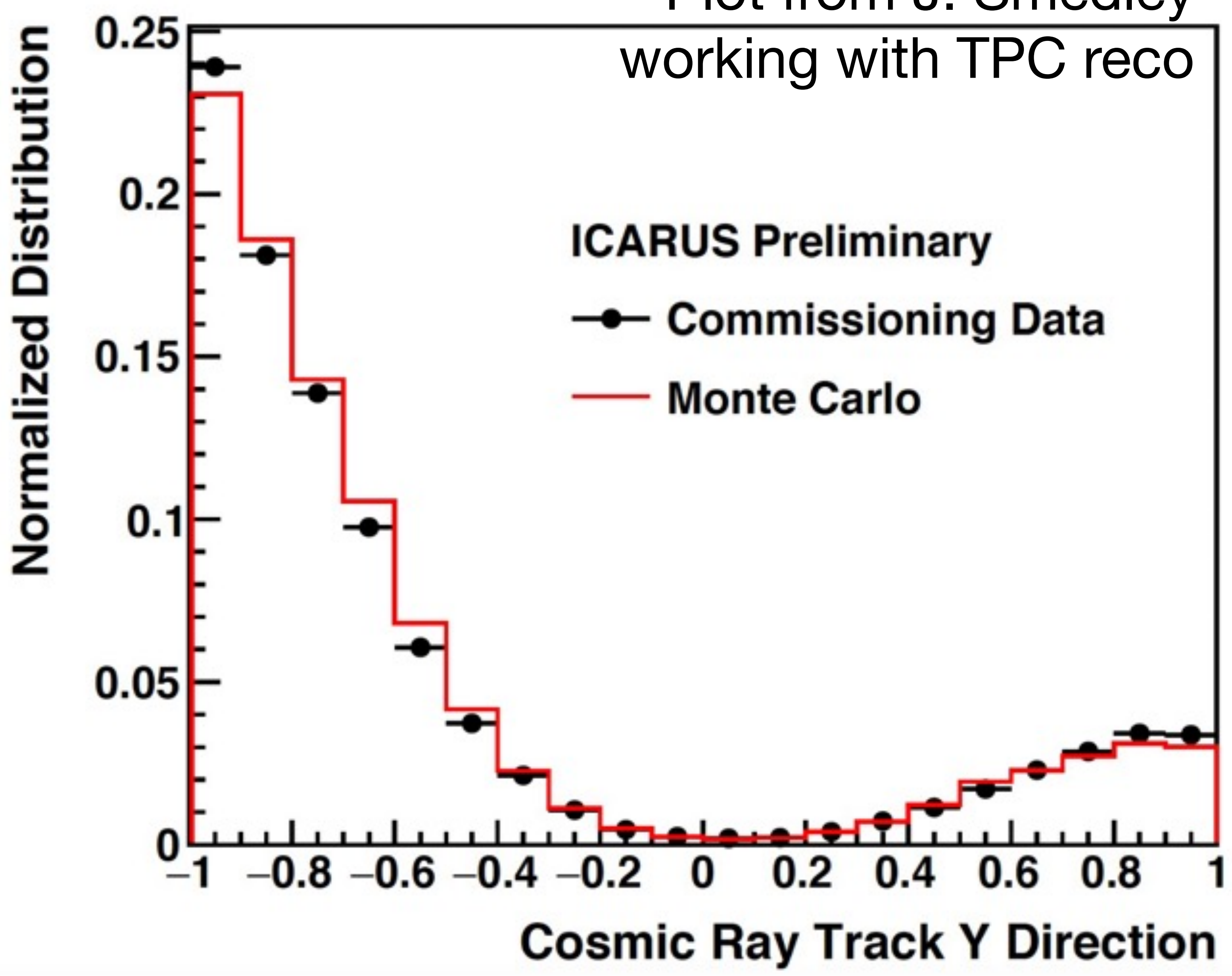
- Use sim & data to understand quality of reco, **identify areas needing improvement, and then work to address them**
- We have had vibrant group of interns, students, postdocs who contribute to the necessary studies and work
- Examples of activity in the group:
  - Evaluating reco w/ events from hand-scan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

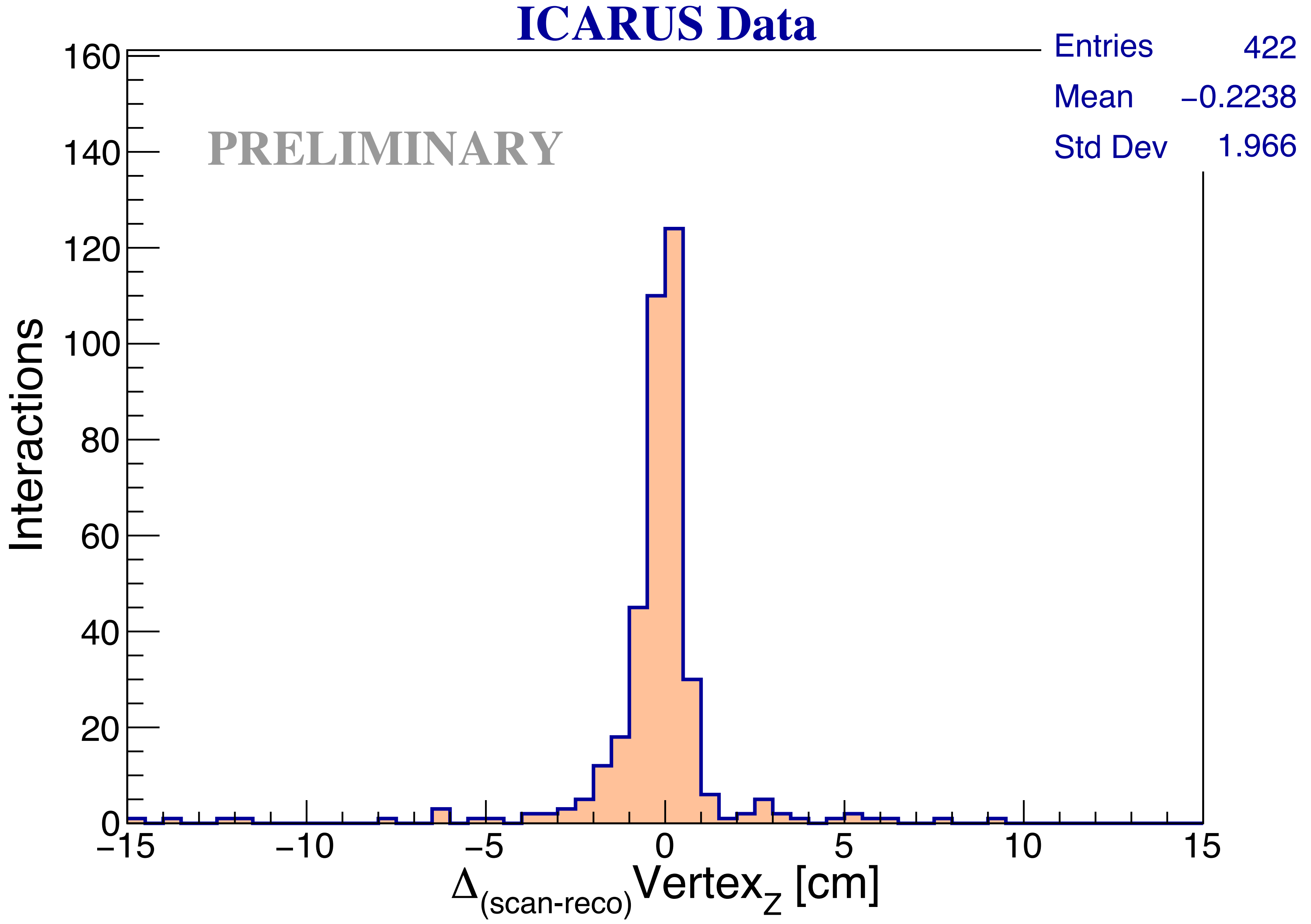
Set of MC events with a muon and proton that pass some cuts on reconstruction.

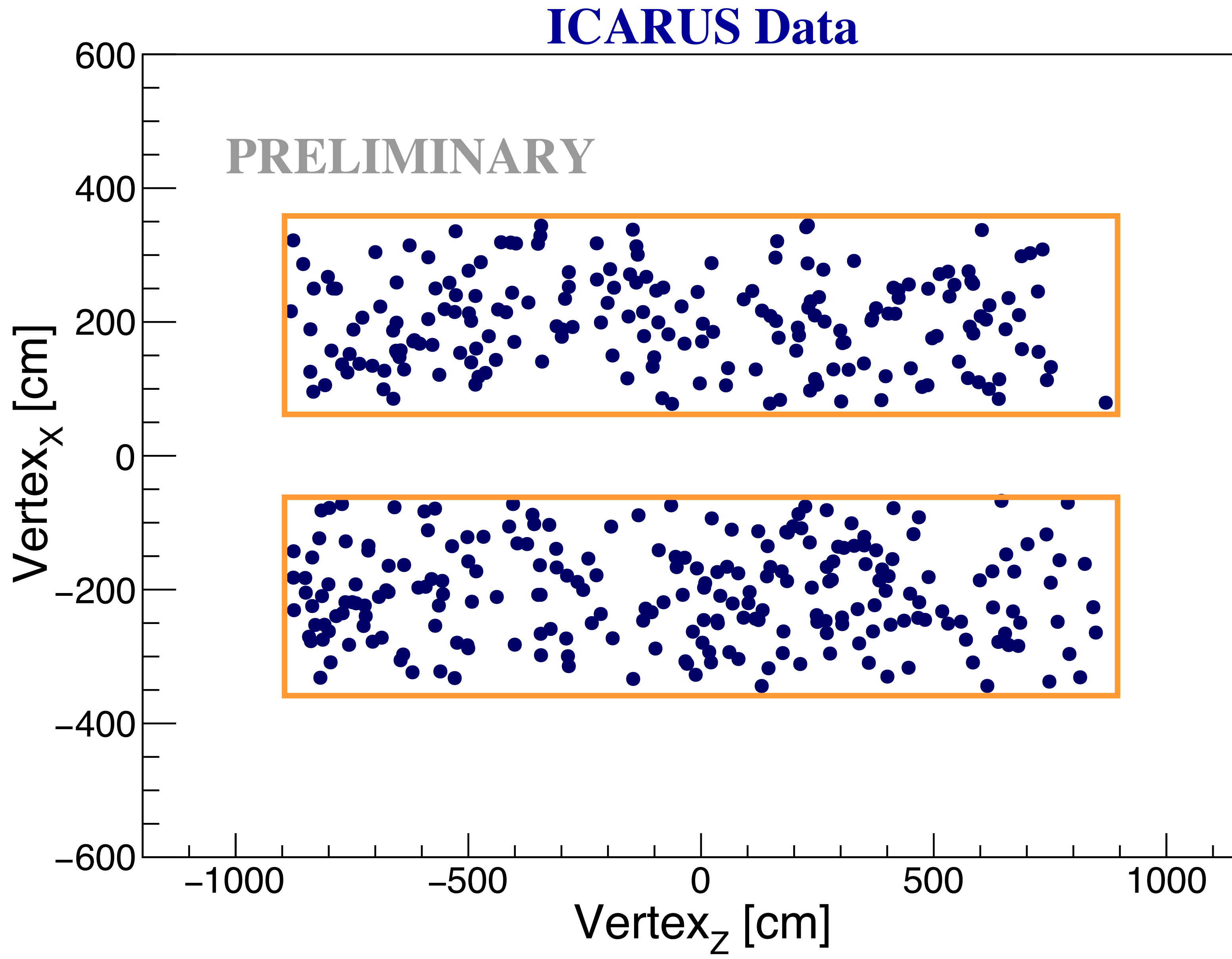
ICARUS Simulation



Plot from J. Smedley working with TPC reco



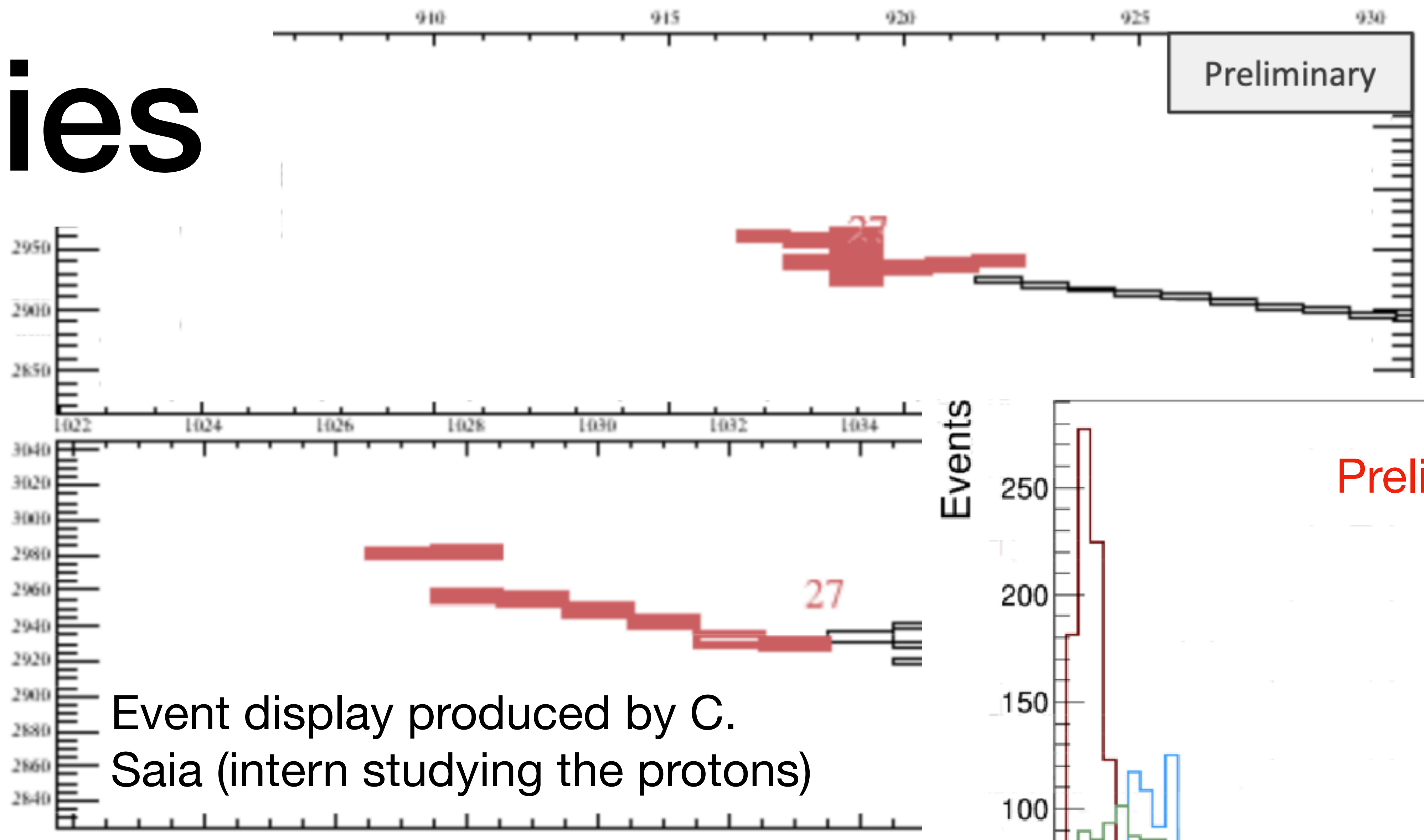




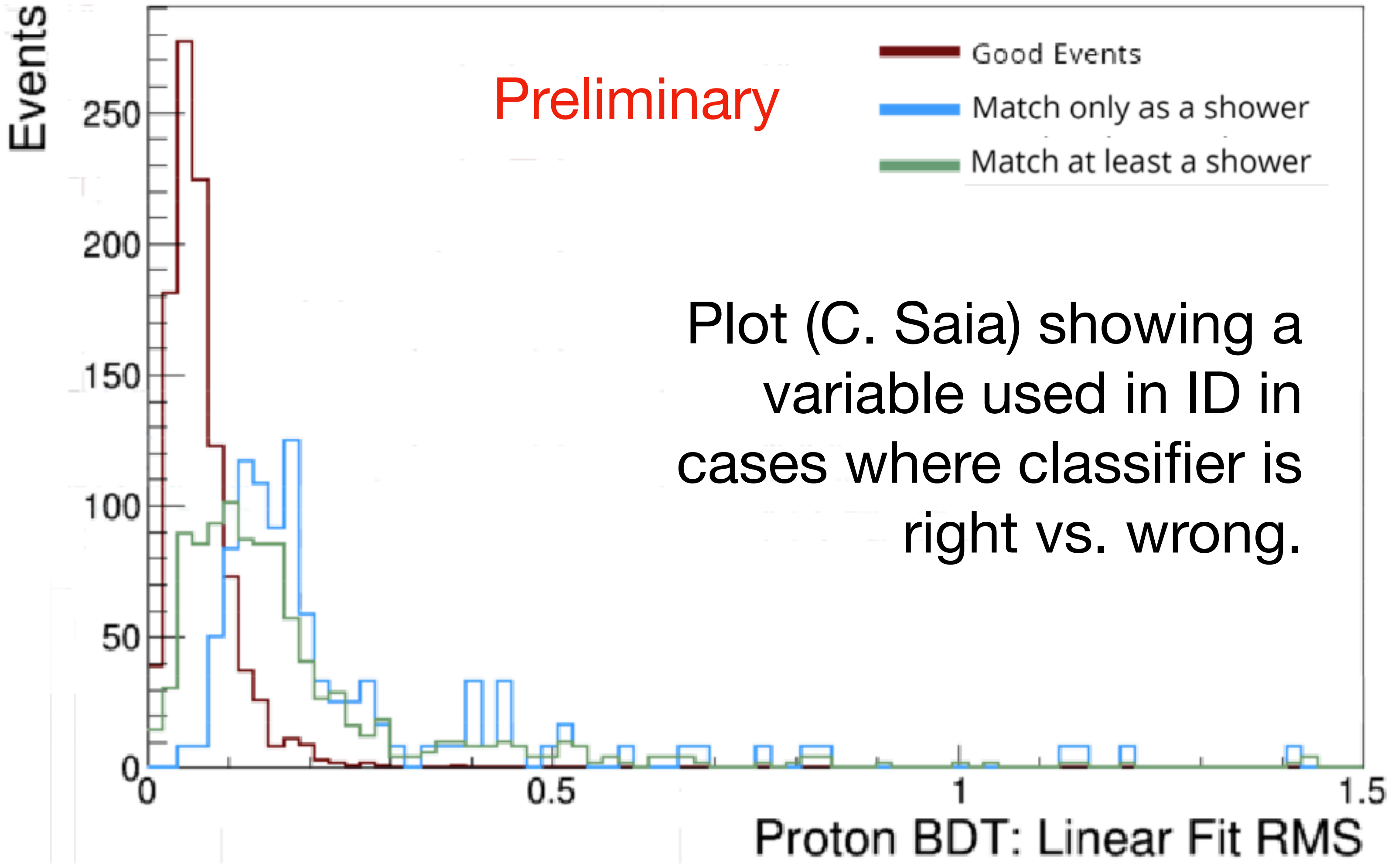
Plots from G. Moreno investigating a set of hand scanned DATA events for similar reconstruction quality checks (Note that some of the same signal and reco quality cuts not made here.)

Addressing Pathologies

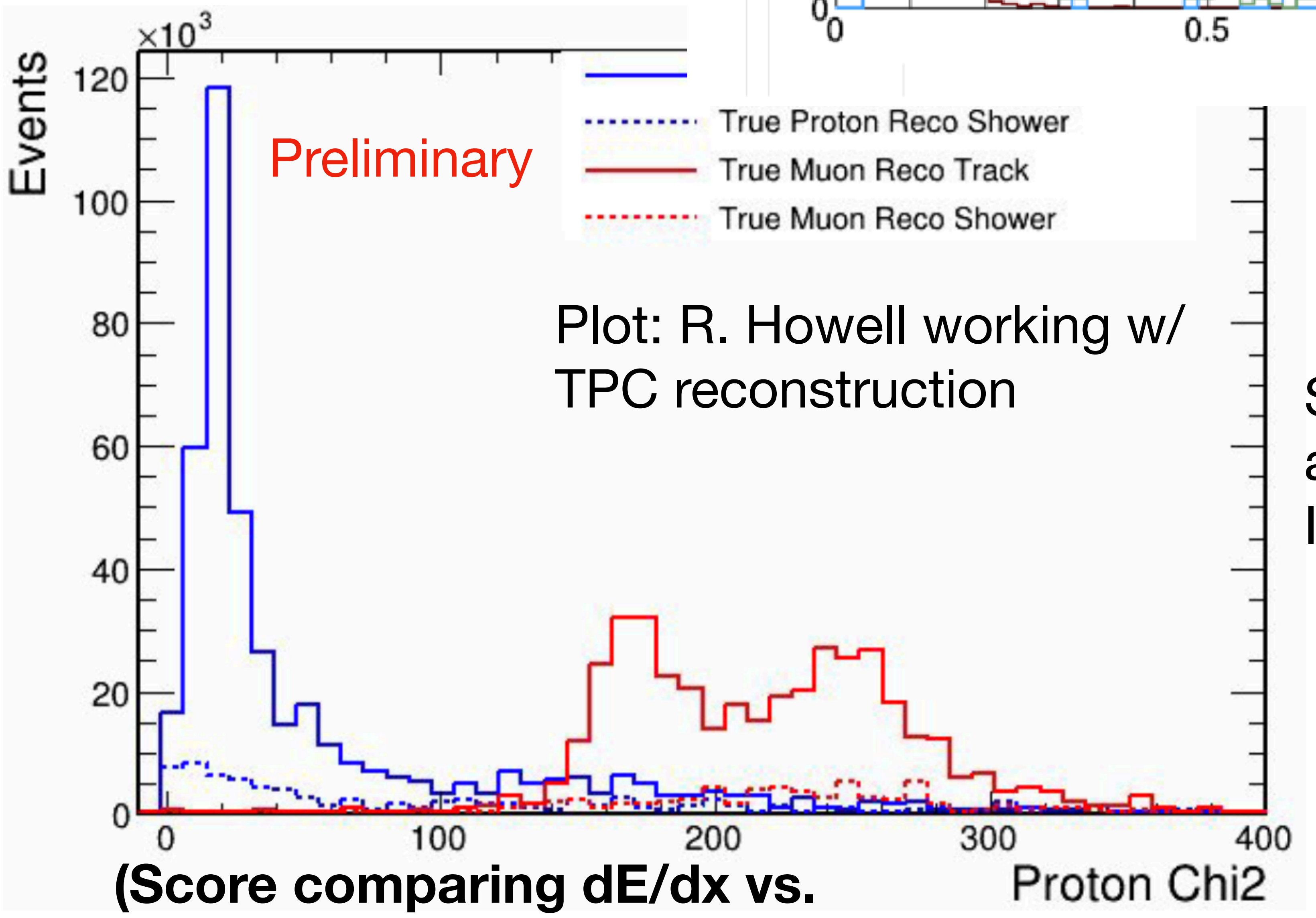
- Sometimes reco can get tricked by protons and mis-classify as showers. We worked to address:
  - We added to Pandora & our analysis files to **enable saving feature variables** used in track-shower identification
    - **<u>In</u>** Pandora: available for others!
  - Try **track AND shower fit**, save 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))



Event display produced by C. Saia (intern studying the protons)



Plot (C. Saia) showing a variable used in ID in cases where classifier is right vs. wrong.

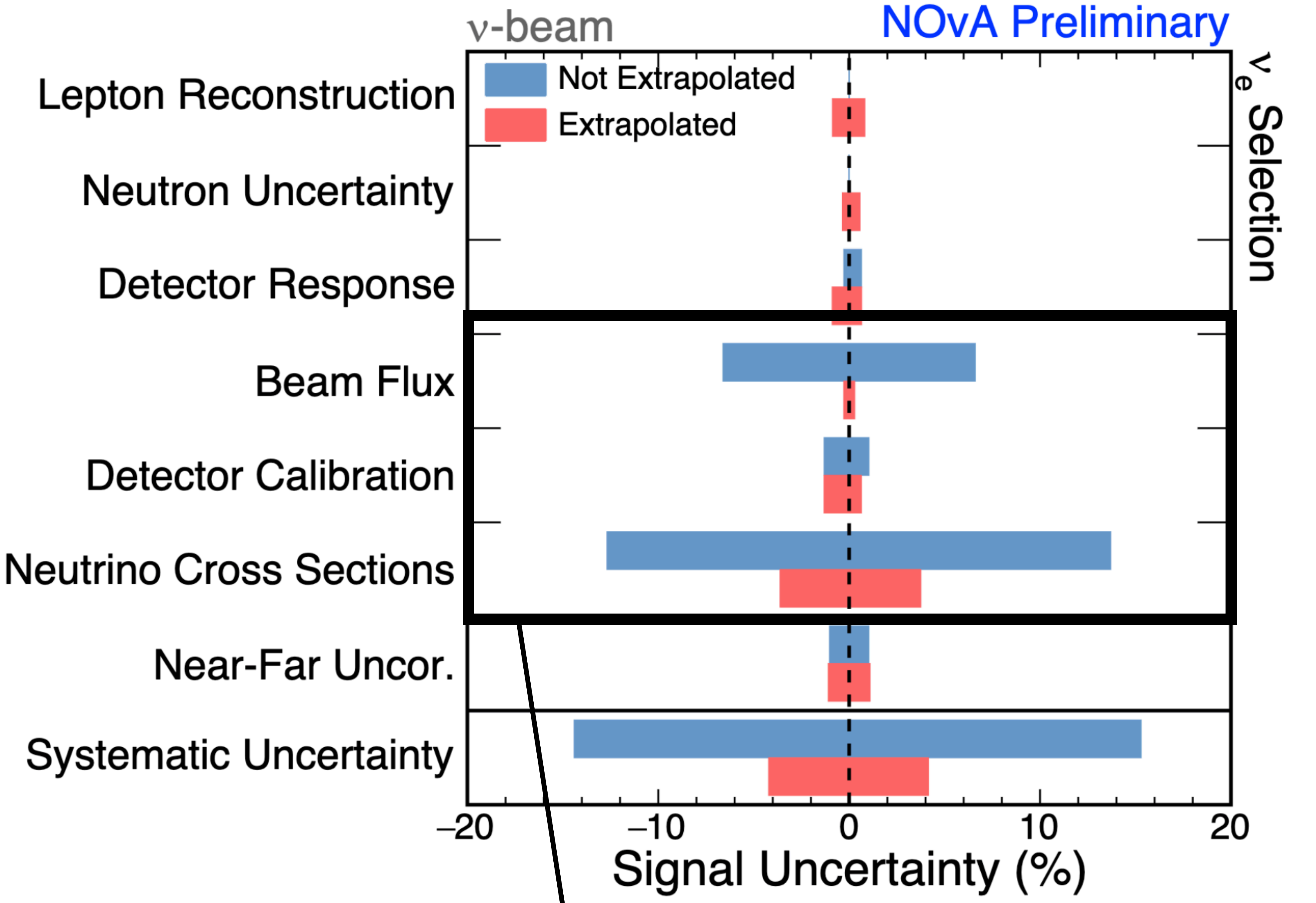


Plot: R. Howell working w/ TPC reconstruction

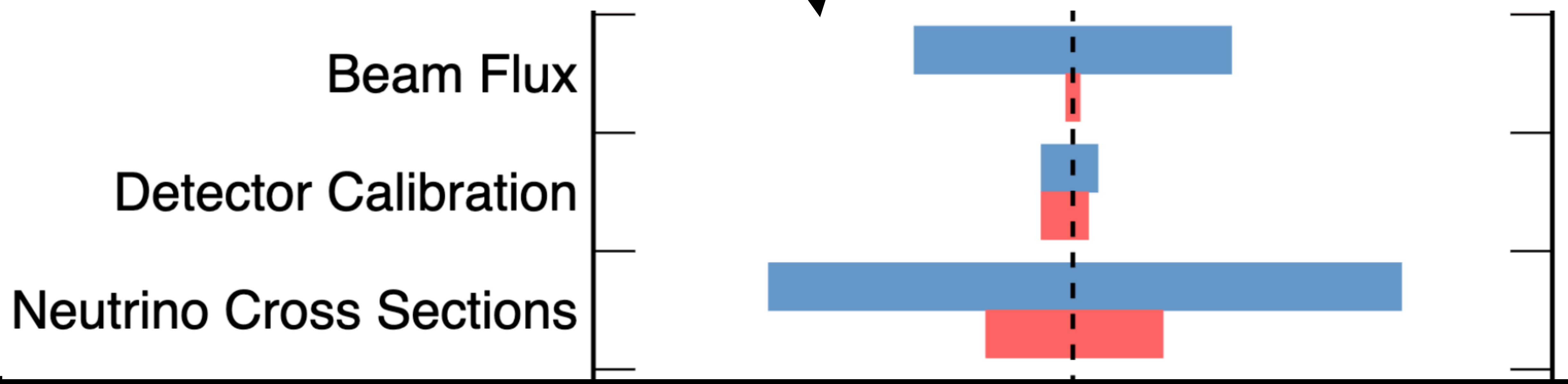
(Score comparing dE/dx vs. residual range to expected curve)

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

Impact of interactions

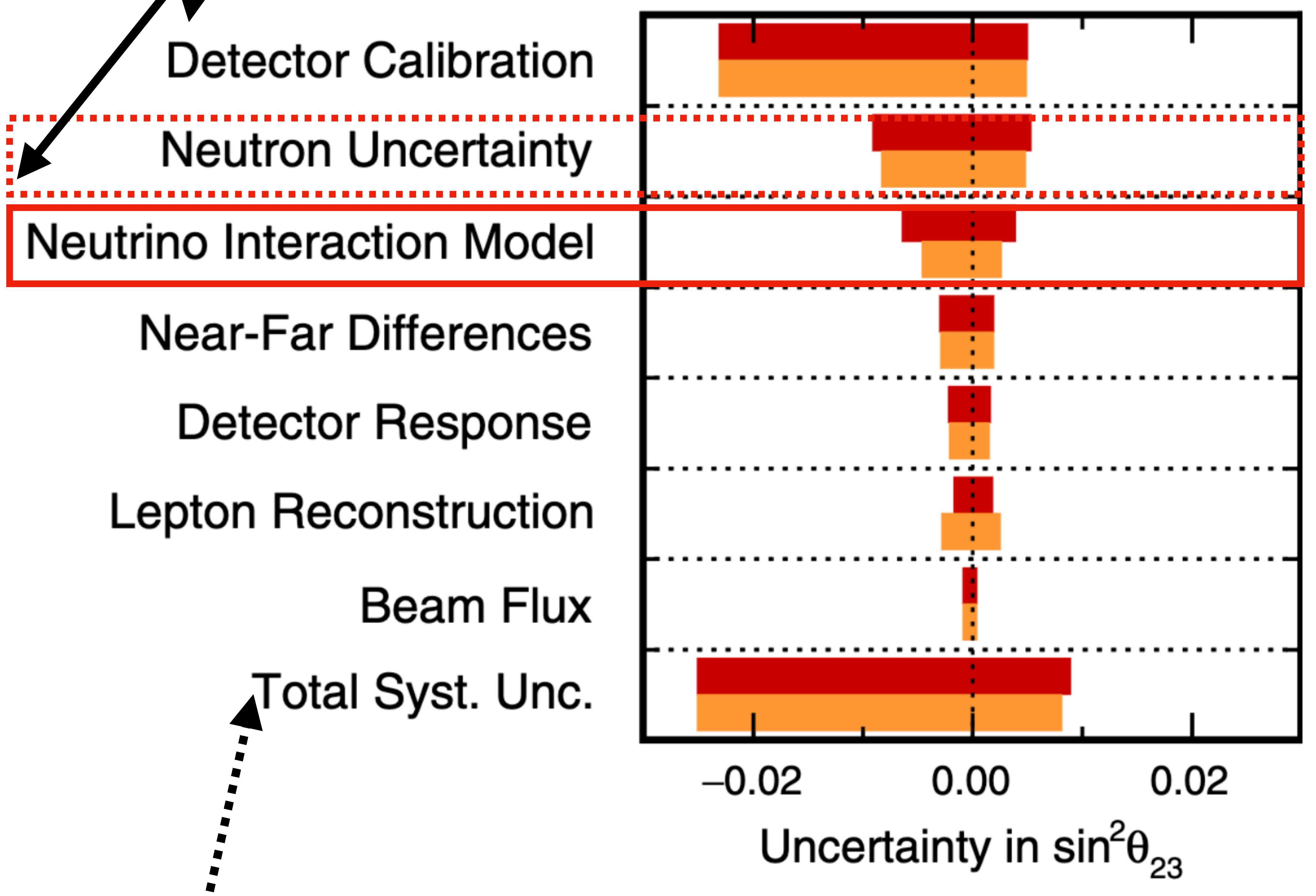


E. Cataño-Mur
NNN23 slides



Different detector type but also this is partly covered by "experience"

Really need to improve here, also DUNE different medium so need more meaurements with Ar

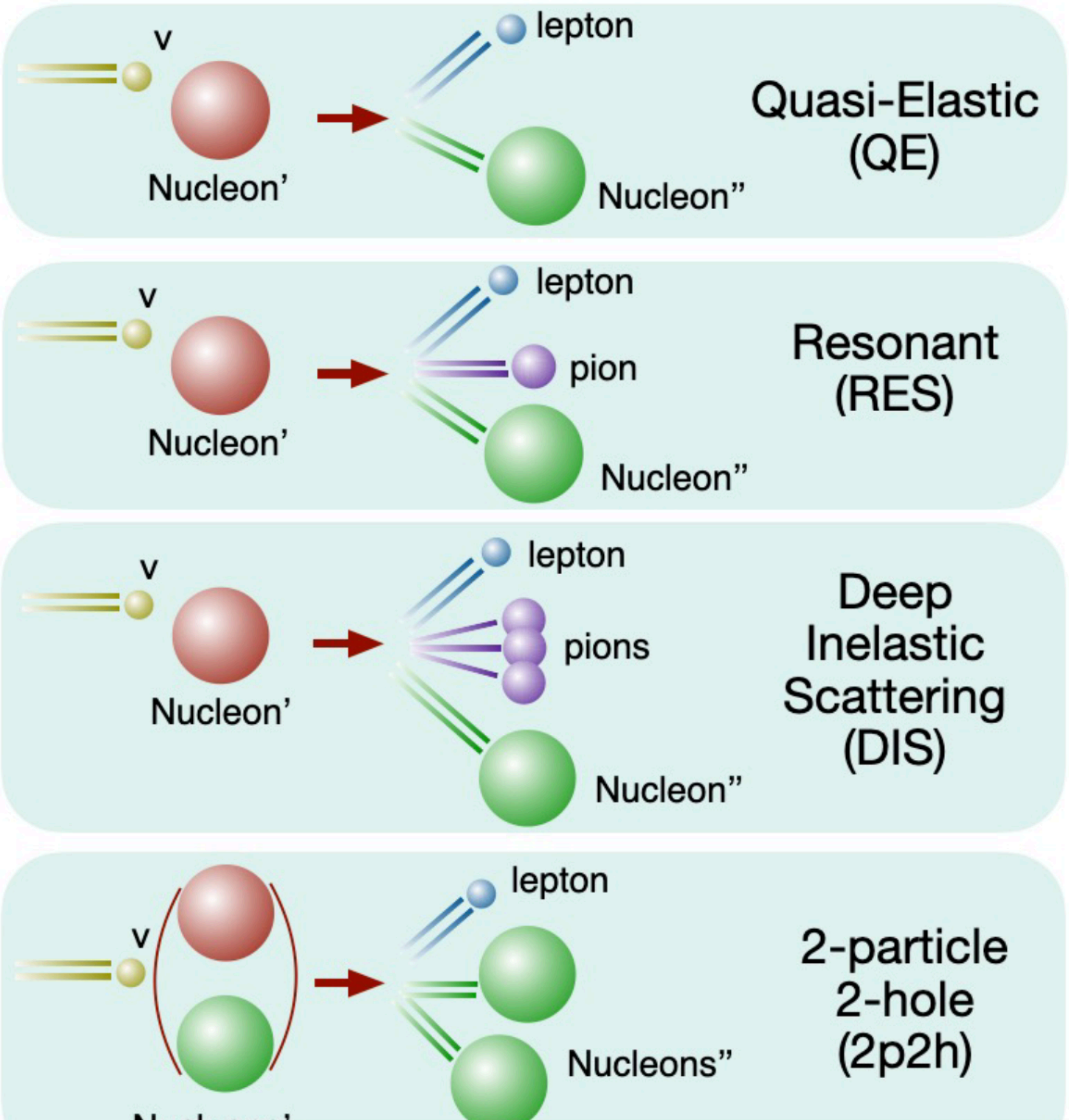


NOvA: M.A. Acero et al Phys Rev D 106, 032004 (2022)

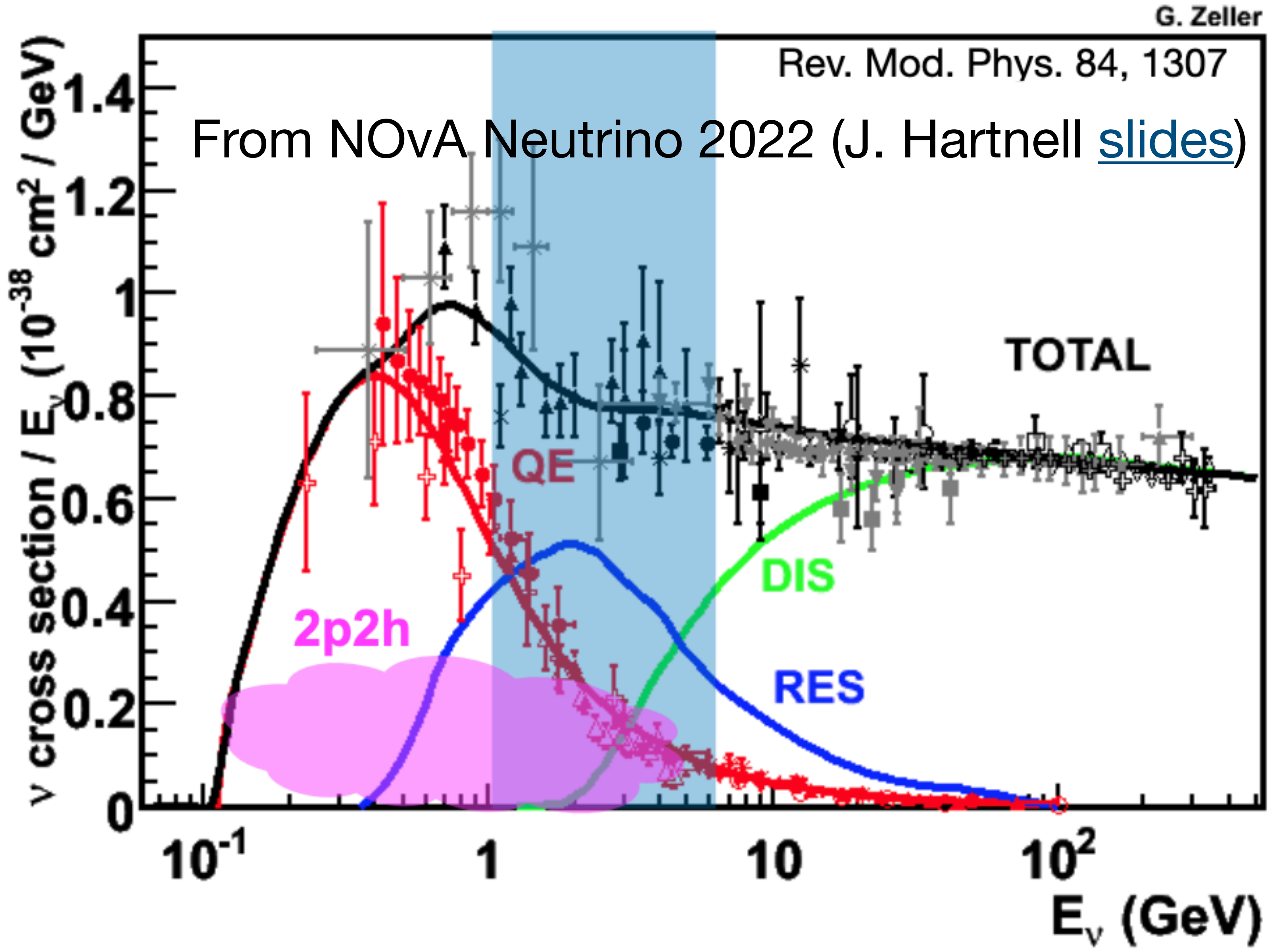
DUNE will have significantly higher statistics

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

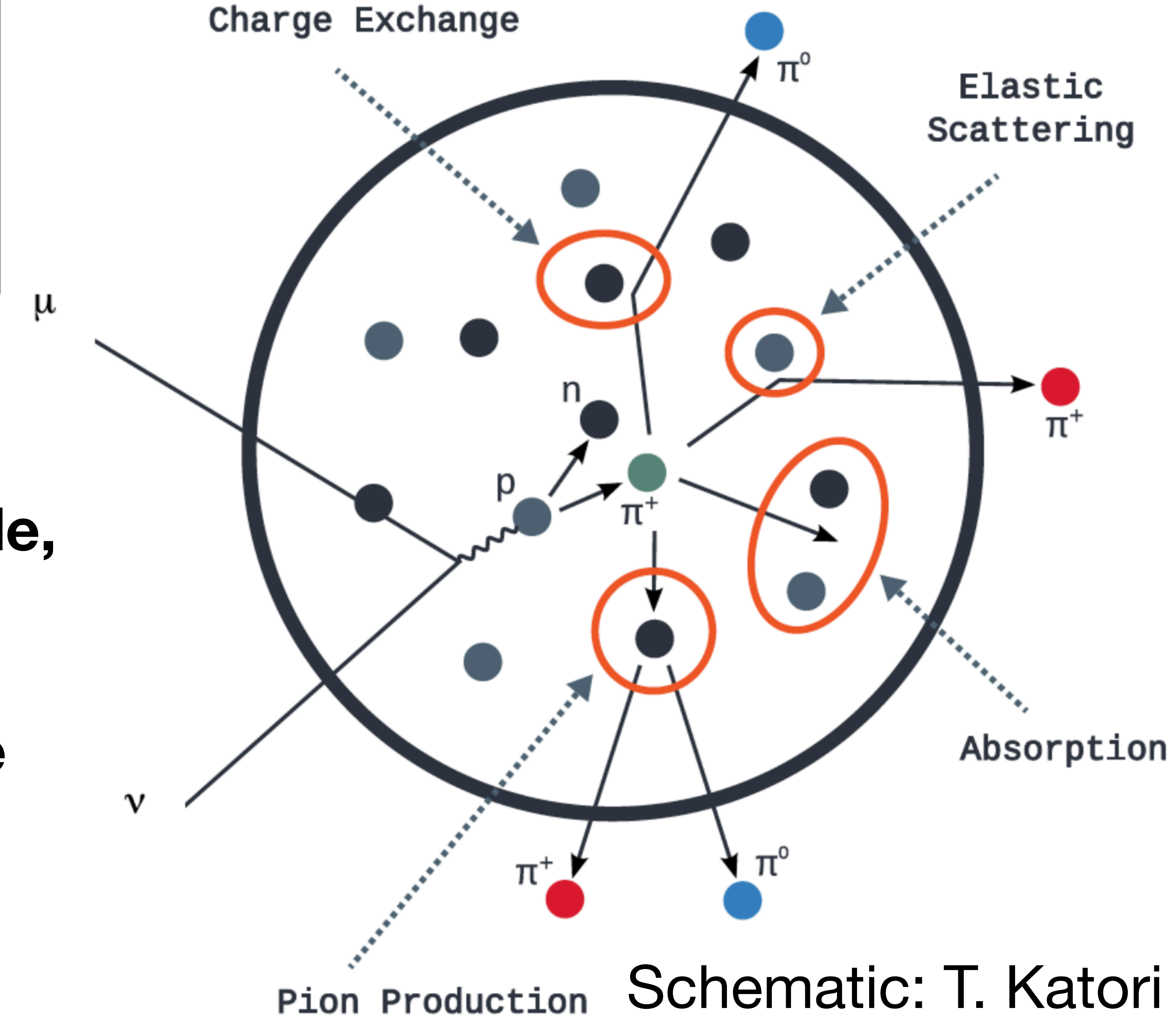


Particles/yields expected depend on mode, therefore so does the energy resolution.

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

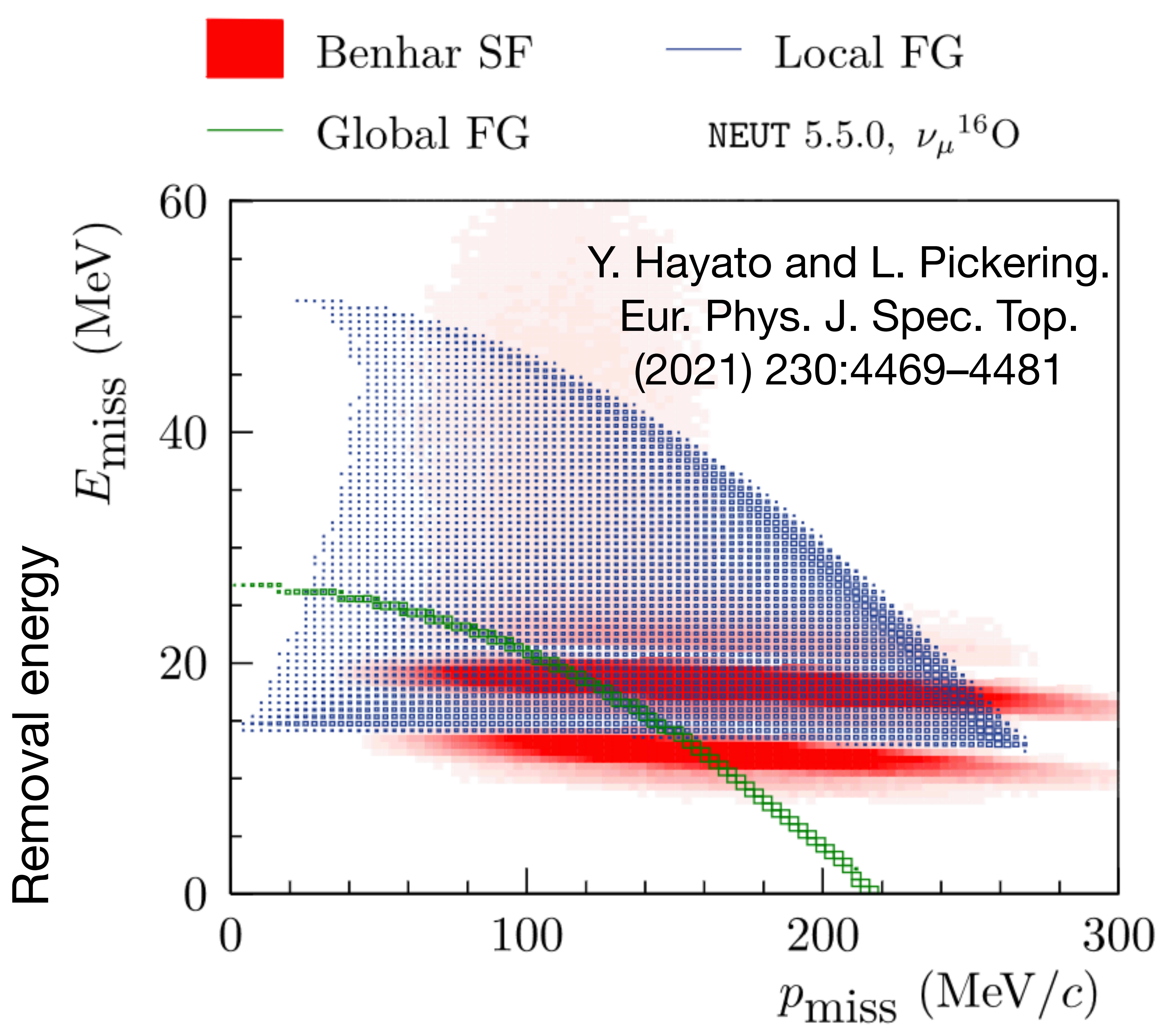
Due to nuclear medium, particles may have "Final State Interactions" (FSI).

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



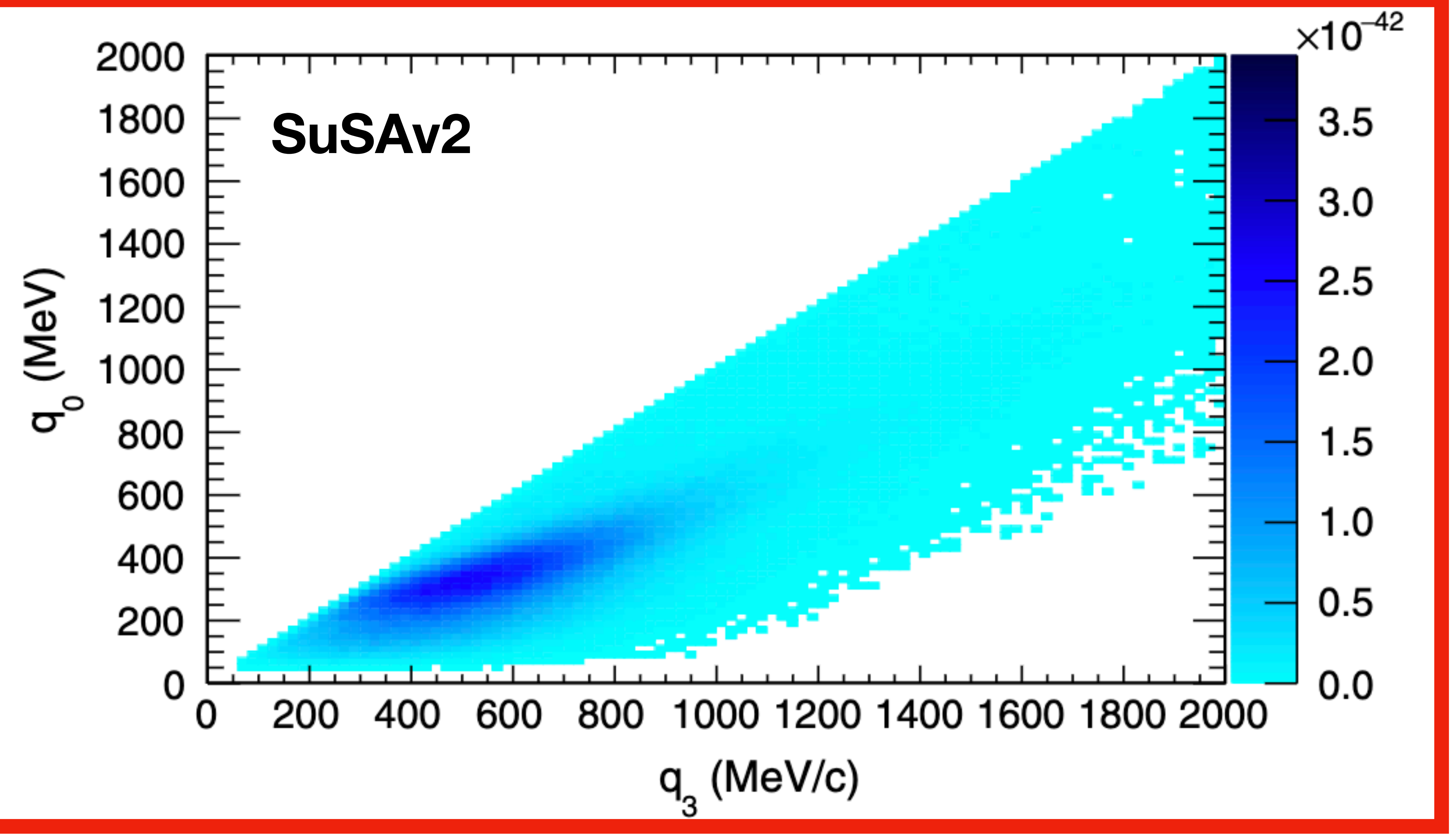
Schematic: T. Katori

GENIE version

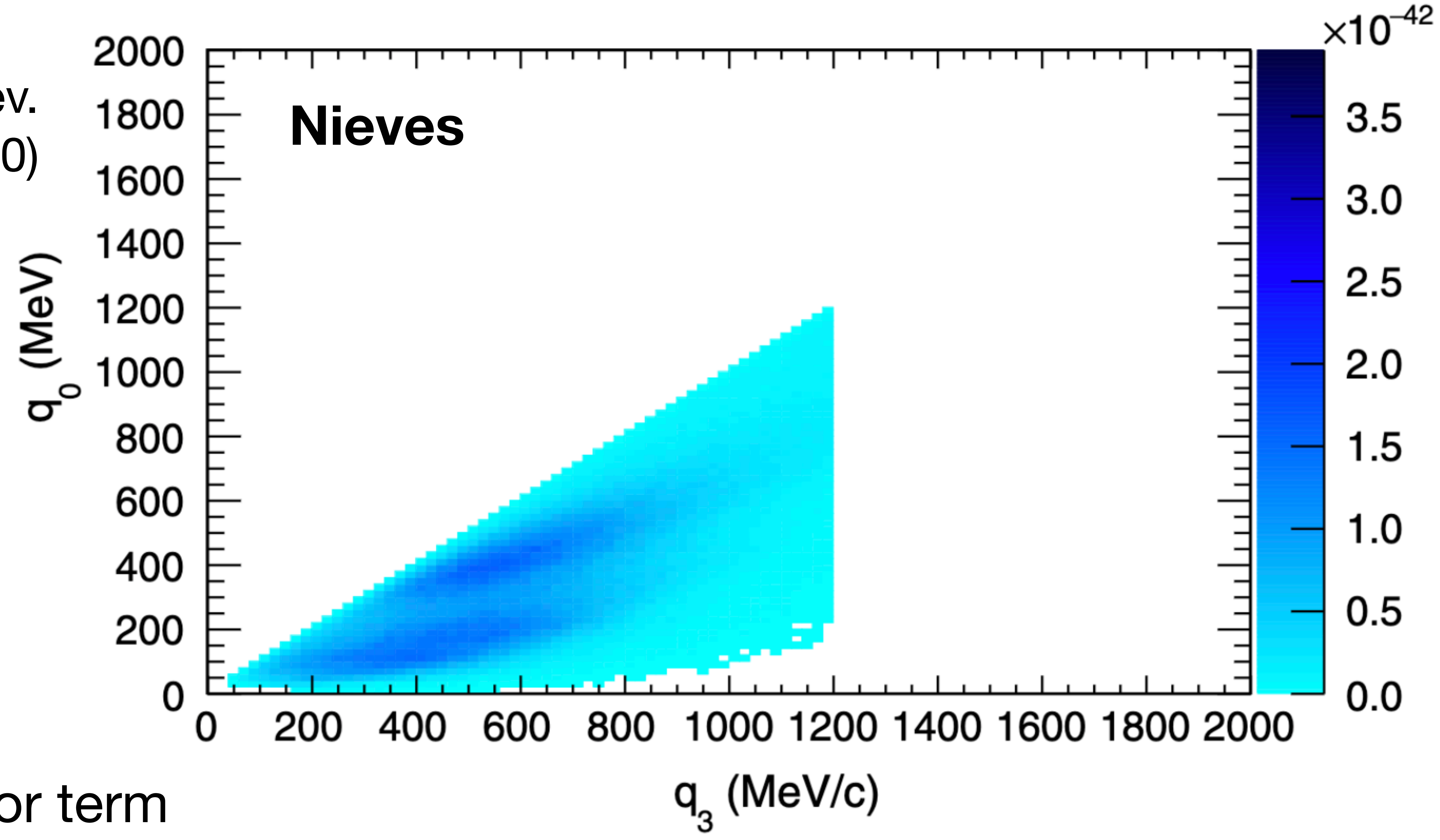


Our GENIE version is more like the Local Fermi Gas model here but with a short range correlations tail extending below 15 MeV Emiss

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)

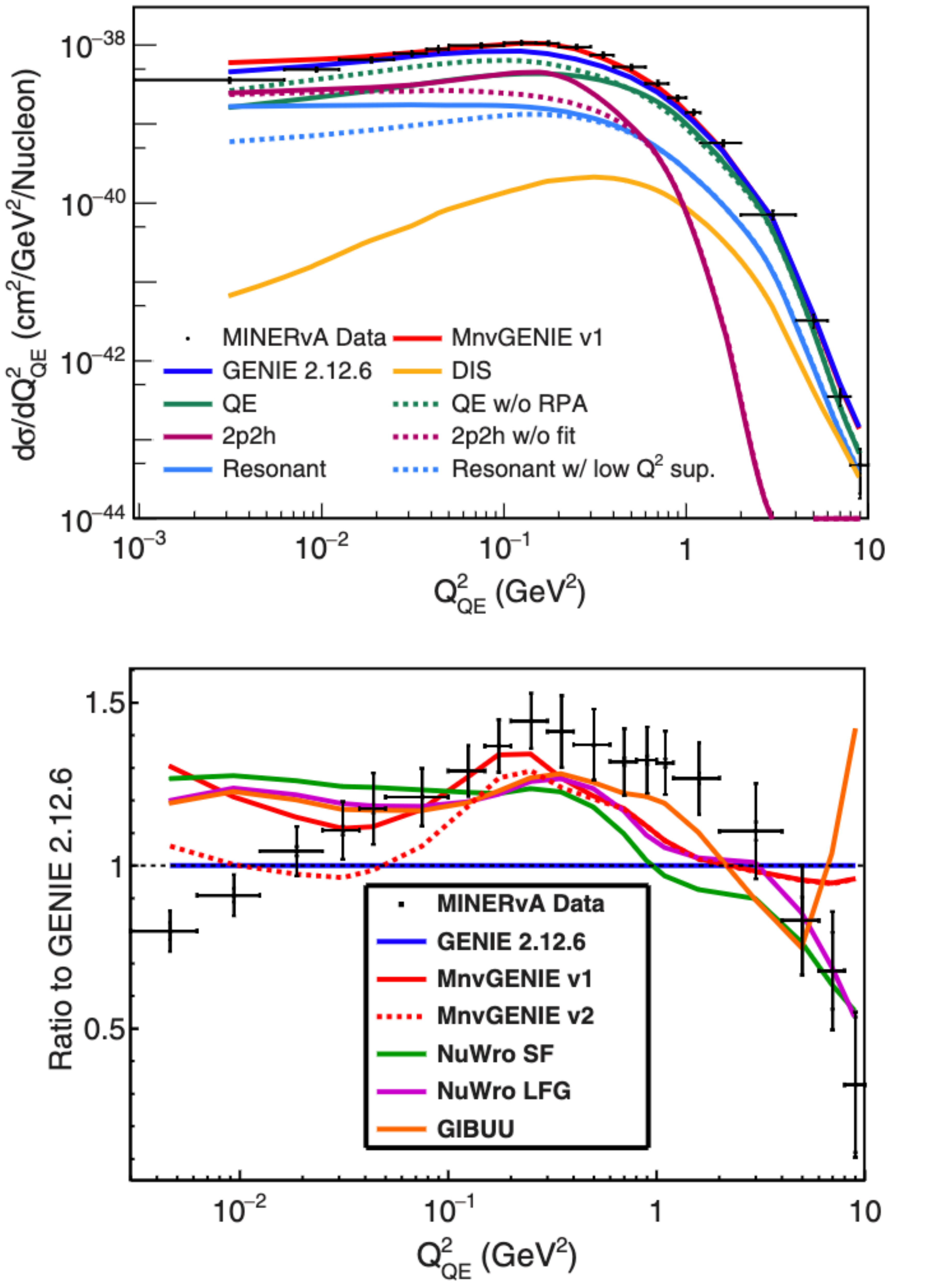
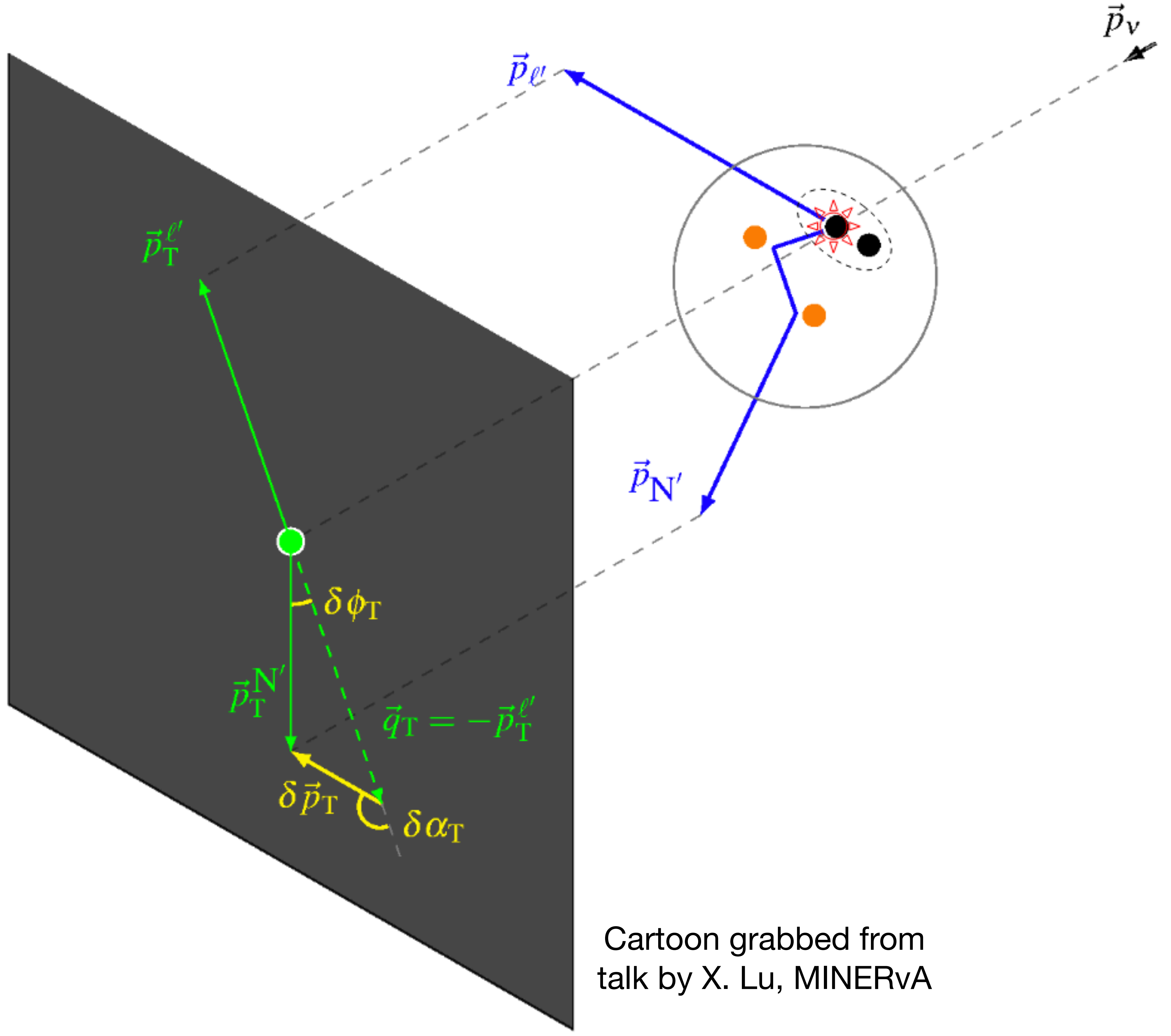


FIG. 5. Top: Differential cross section as a function of Q^2. Bottom: Generator predictions compared to data. All are plotted as ratio to the predictions of unmodified GENIE 2.12.6.

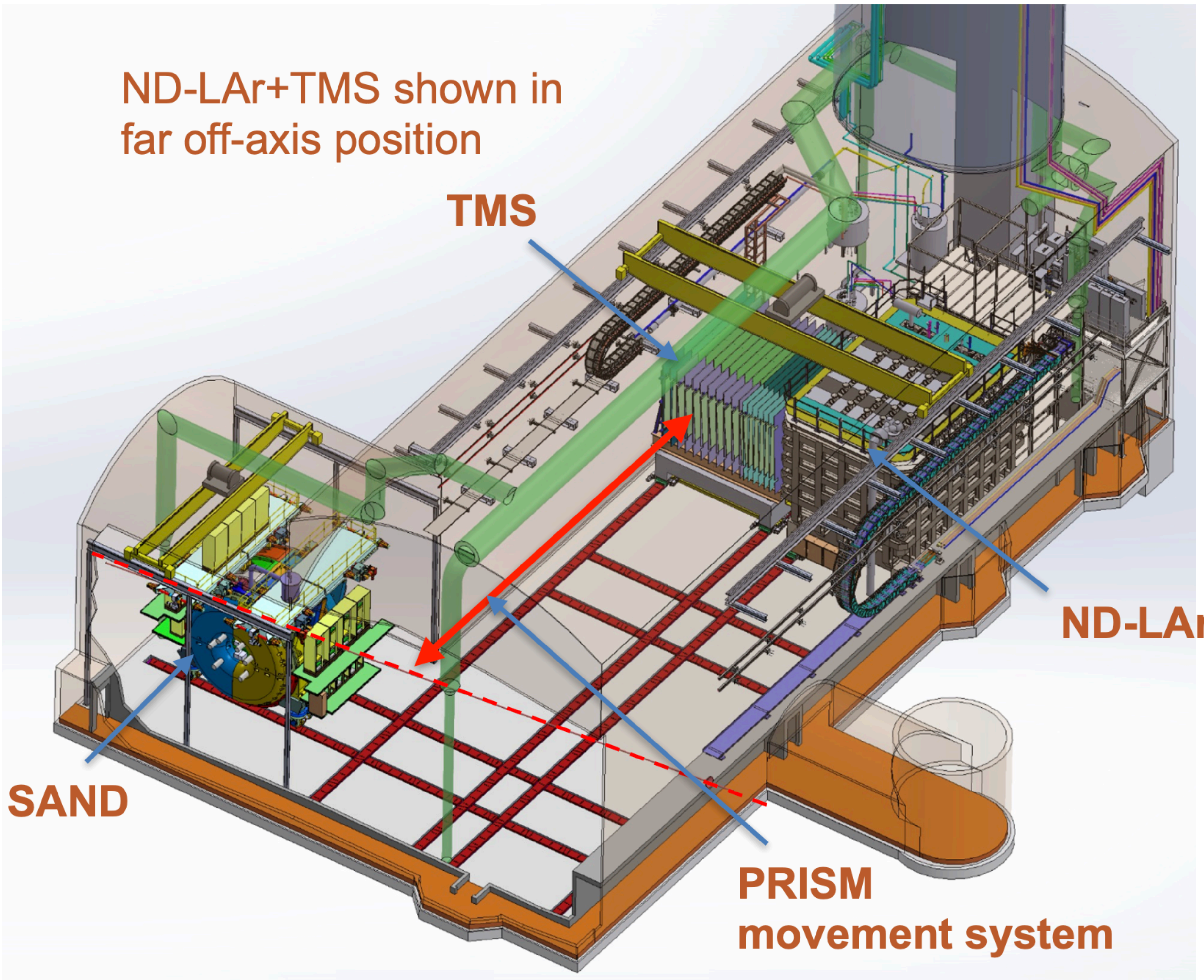
Cartoon of transverse kinematic imbalance



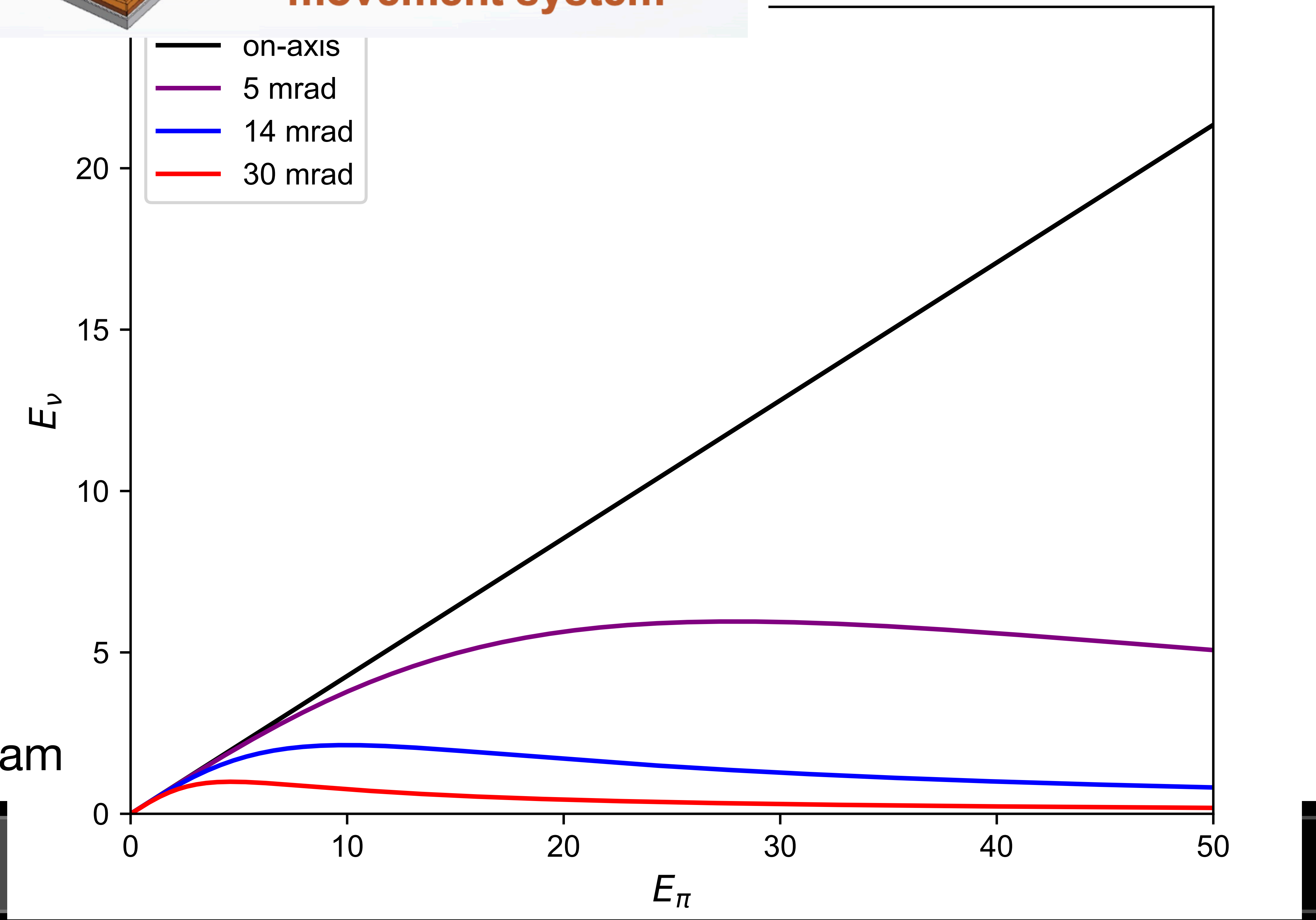
Cartoon grabbed from
talk by X. Lu, MINERvA

DUNE

- Needs own capable Near Detector: characterize ν flux, perform more measurements/model developments w/ unprecedented statistics, etc.
  - Ultimate plan comprises of **multiple detectors** including LAr TPC and a Gas Argon TPC
  - High pileup: pixelated readout for LAr TPC portion instead of wires
  - GAr: less dense Ar → low E particles travel further → lower thresholds for e.g. protons
  - Capability to move parts **off-axis**



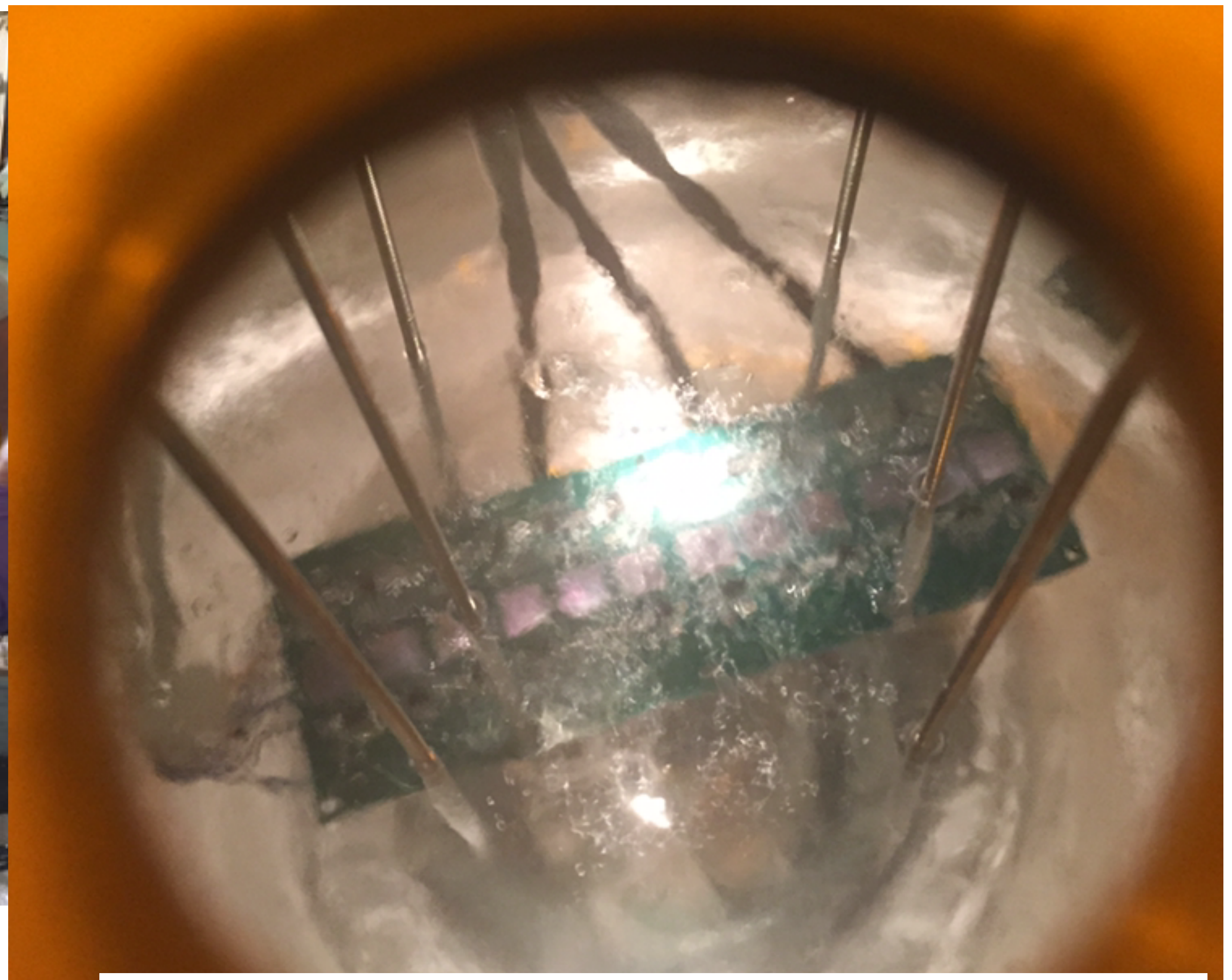
Schematic of DUNE Near Detector (H. Tanaka slides)



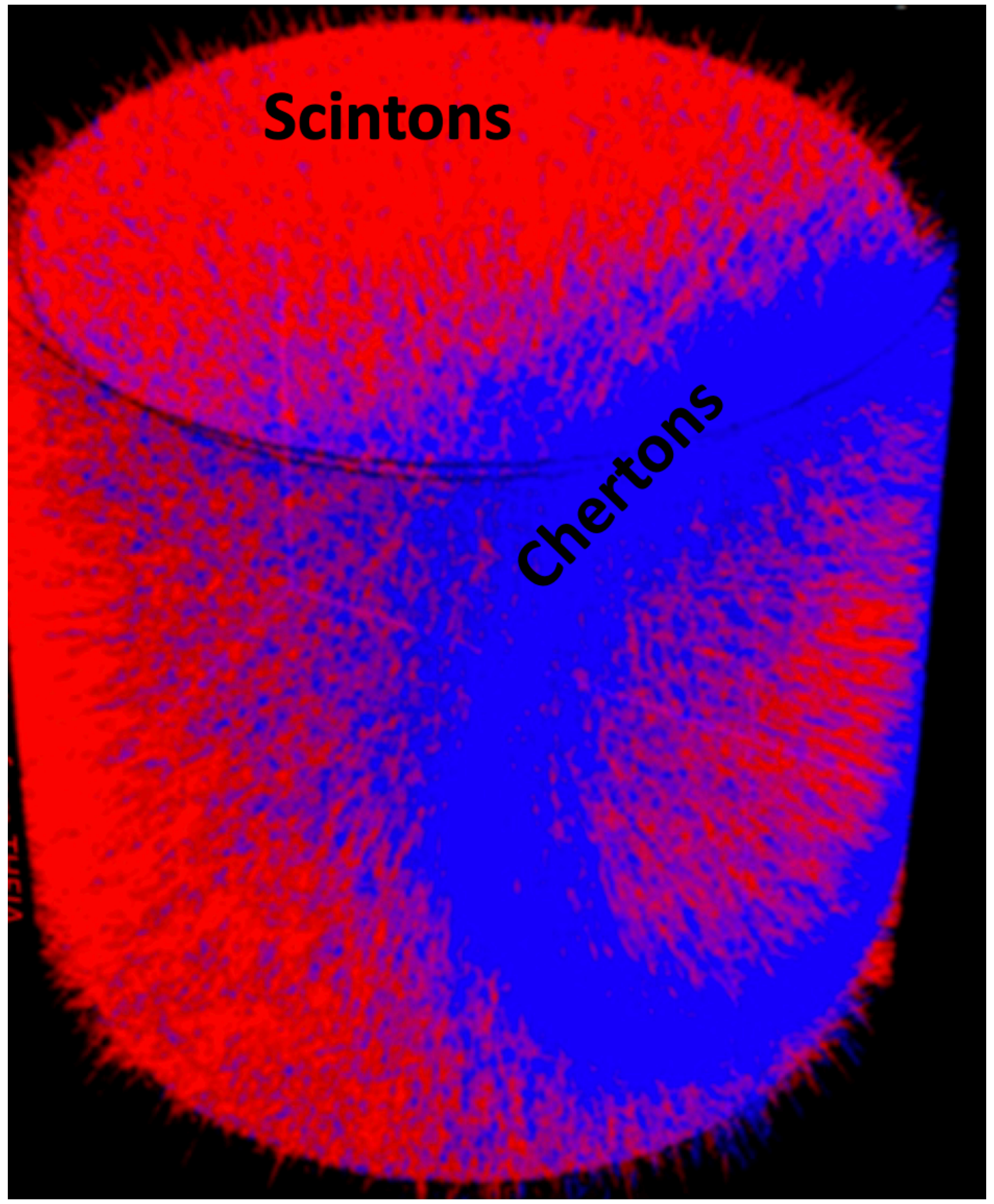
Neutrino energies change at different angles from the beam

DUNE

- Though building on a few decades of LAr TPC prototyping and operations, DUNE is really pushing forward the detector type
  - R&D to improve and solve unique needs in many areas
  - Examples:
    - ND pixelated readouts: smaller space / channel
    - FD scintillation detectors
    - “Module of Opportunity”: 4th module of 10kT can be different tech to provide complimentary and/or extended reach



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



Idea of one Module of Opportunity: WbLS with THEIA

M. Wurm slides