Understanding neutrinos with accelerator beams and liquid argon time-projection chambers: ICARUS and DUNE

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on behalf of the DUNE and ICARUS collaborations

WNPPC 2026
14 February 2026 | Banff, Alberta

Contents

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- Accelerator beams
- Liquid argon time-projection chambers
- DUNE
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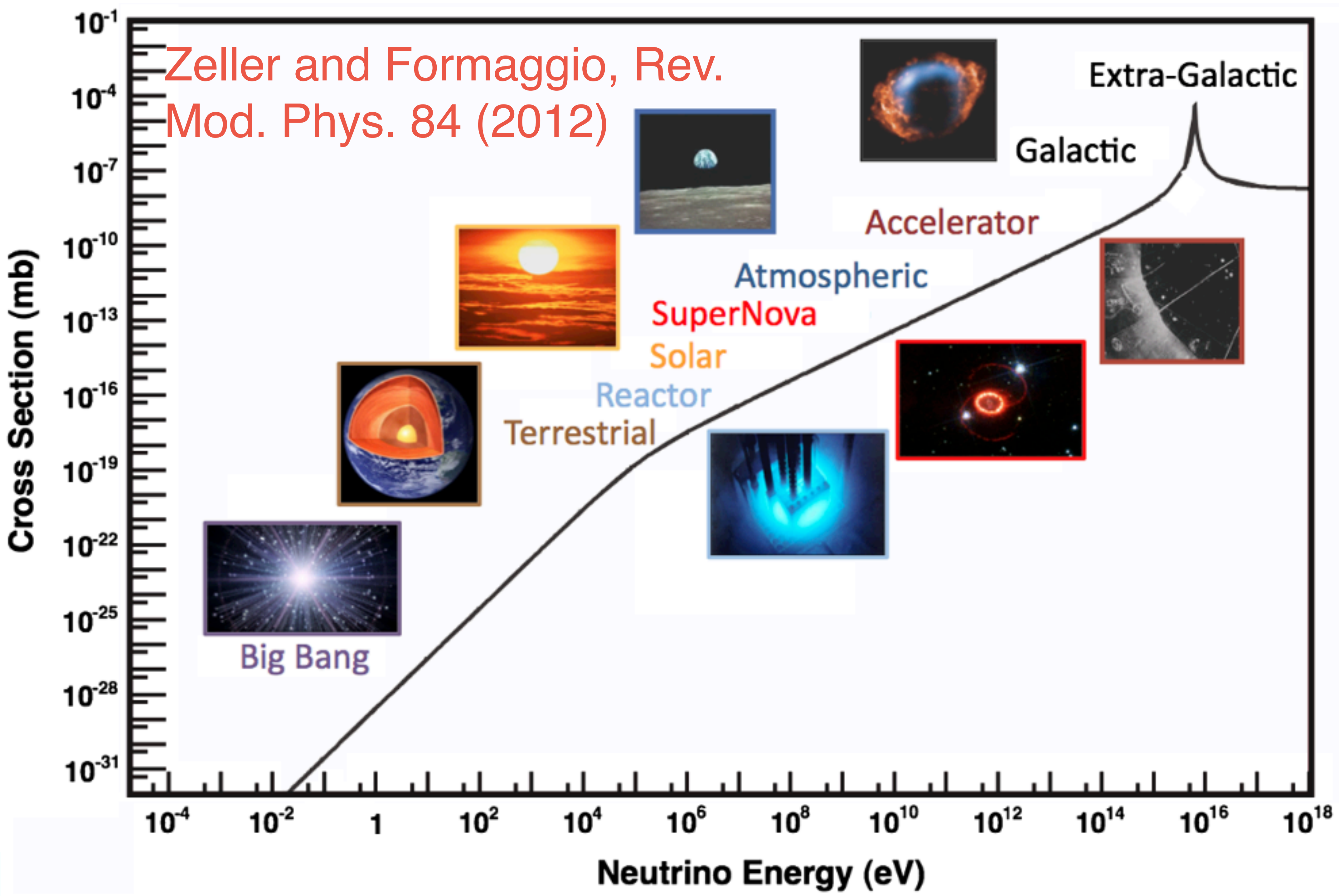
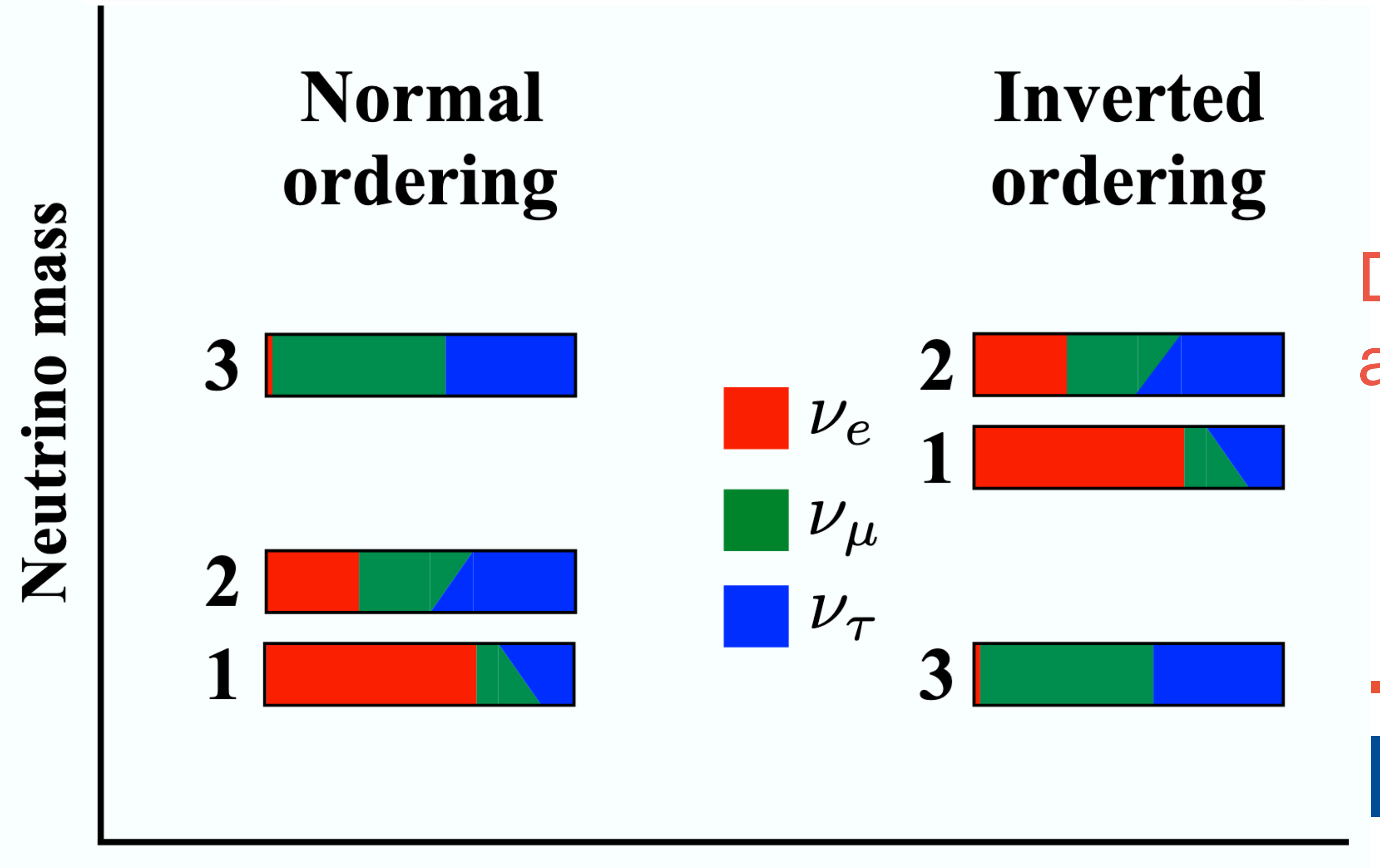
Neutrinos

- Neutrinos: *nearly* massless, neutral leptons proposed in 1930 and discovered mid-1950s
- Studies of solar (electron) neutrino flux (Ray Davis, 1960s on) found fewer than expected
- Late 1990s/early 2000s: SNO (Ontario) and Super-Kamiokande (Japan) determine that neutrinos oscillate
  - 3 flavours (e,μ,τ), superposition of 3 mass states
  - created in 1 flavour, probability to later detect a given flavour evolves with time
  - Probability for oscillation evolves with time for the neutrino, distance/energy (L/E)





DUNE TDR — arXiv:2002.03005

Neutrinos

- Mixing angles, mass differences dictate probability
- Complex phase potential differences in $\nu, \bar{\nu}$ oscillations

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

3x3 matrix with 3 mixing angles and a complex phase

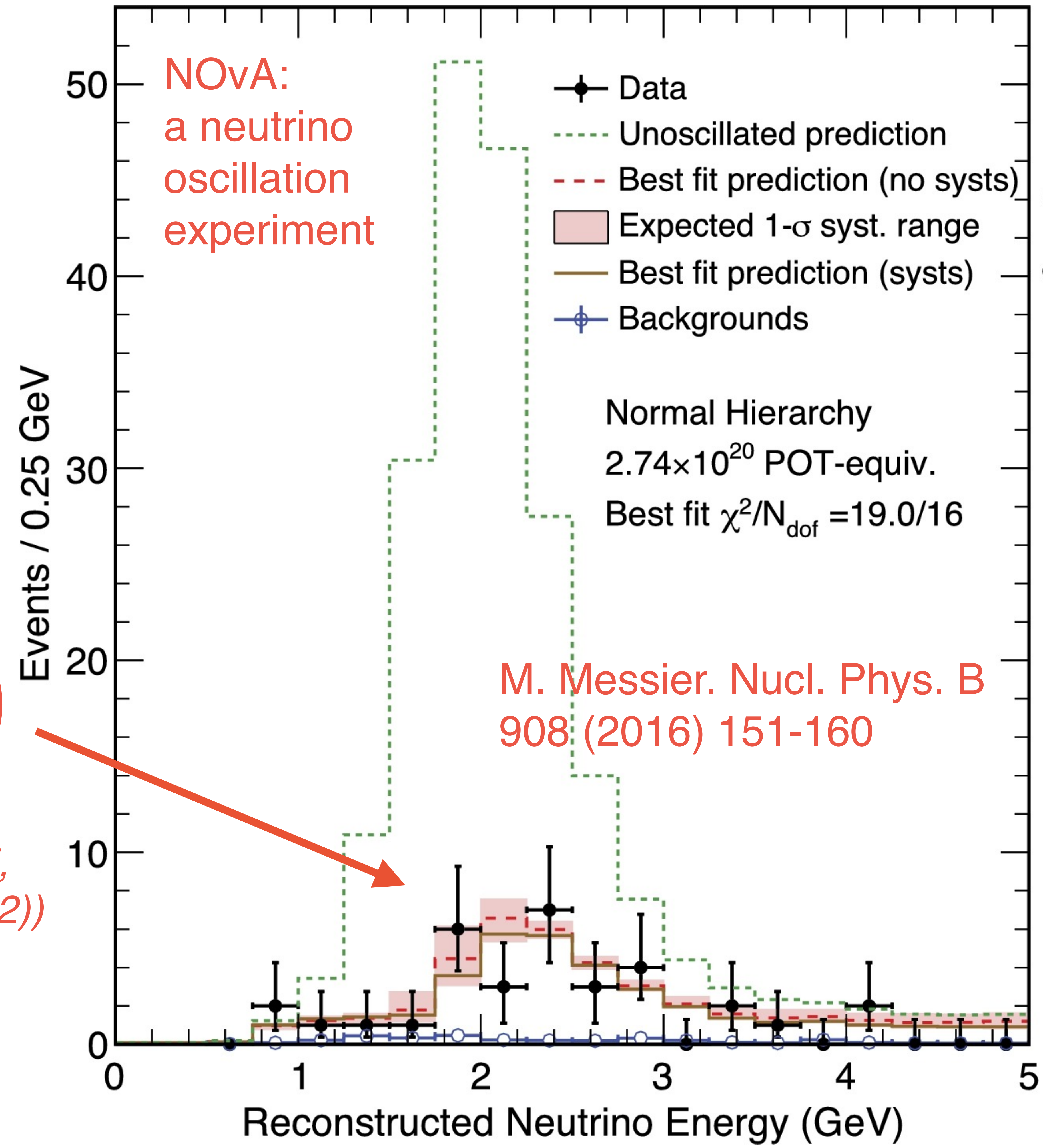
$$P(\nu_\mu \to \nu_\mu) \sim 1 - \sin^2(2\theta_{23})\ \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

*(See T2K, PhysRevD **85**, 031103(R) (2012))*

DUNE CDR vol2, arXiv:1512.06148

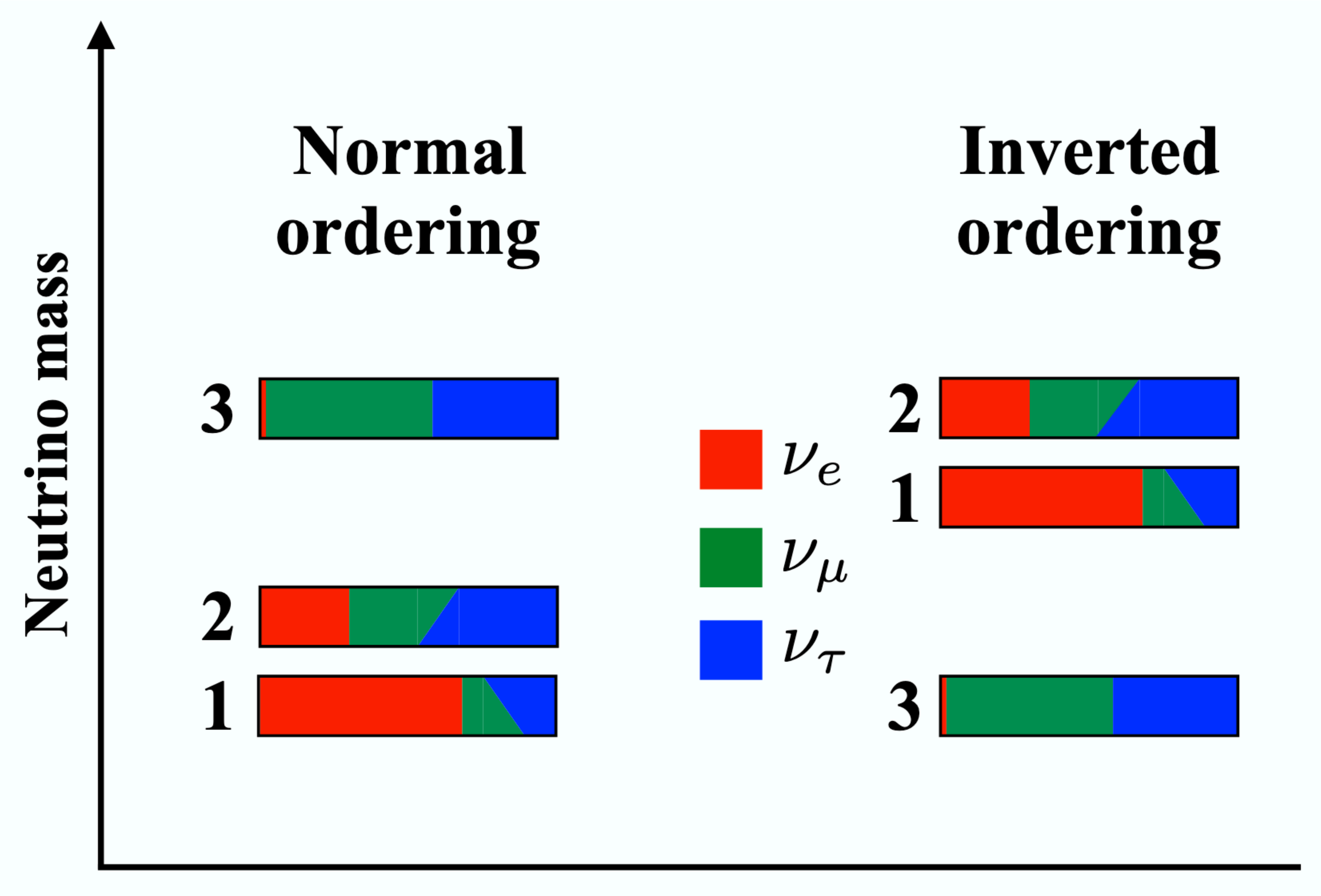
$$\begin{aligned} P(\nu_\mu \to \nu_e) \;\simeq\; & \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 \\ & + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{\mathrm{CP}})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

a *encodes matter effects picked up from electrons in Earth. Changes sign for $\nu, \bar{\nu}$*



Open questions

- Several open questions related to neutrino oscillation:
  - **Is three-flavour oscillation picture complete?**
    - Do parameters measured by different flavours, different baselines, different energies agree with each other?
      - If yes: what are the precise oscillation parameters?
      - If no: what are we missing?
    - Are there more than the 3 flavours we know of? (e.g. sterile neutrinos)
  - **What is the sign of Δm_{31}?** Is m_3 heaviest (normal) or lightest (inverted), do ν follow the same mass ordering as other fermions?
  - **Is δ_{CP} not 0^o or 180^o, and if so what is it?** Do ν, $\bar{\nu}$ oscillate differently?



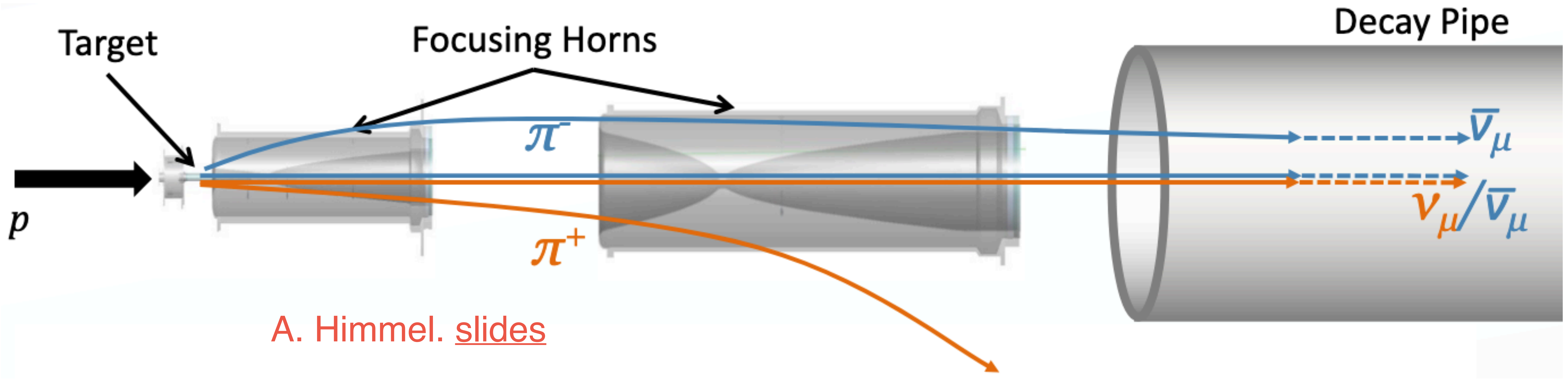
DUNE TDR — arXiv:2002.03005

Next steps

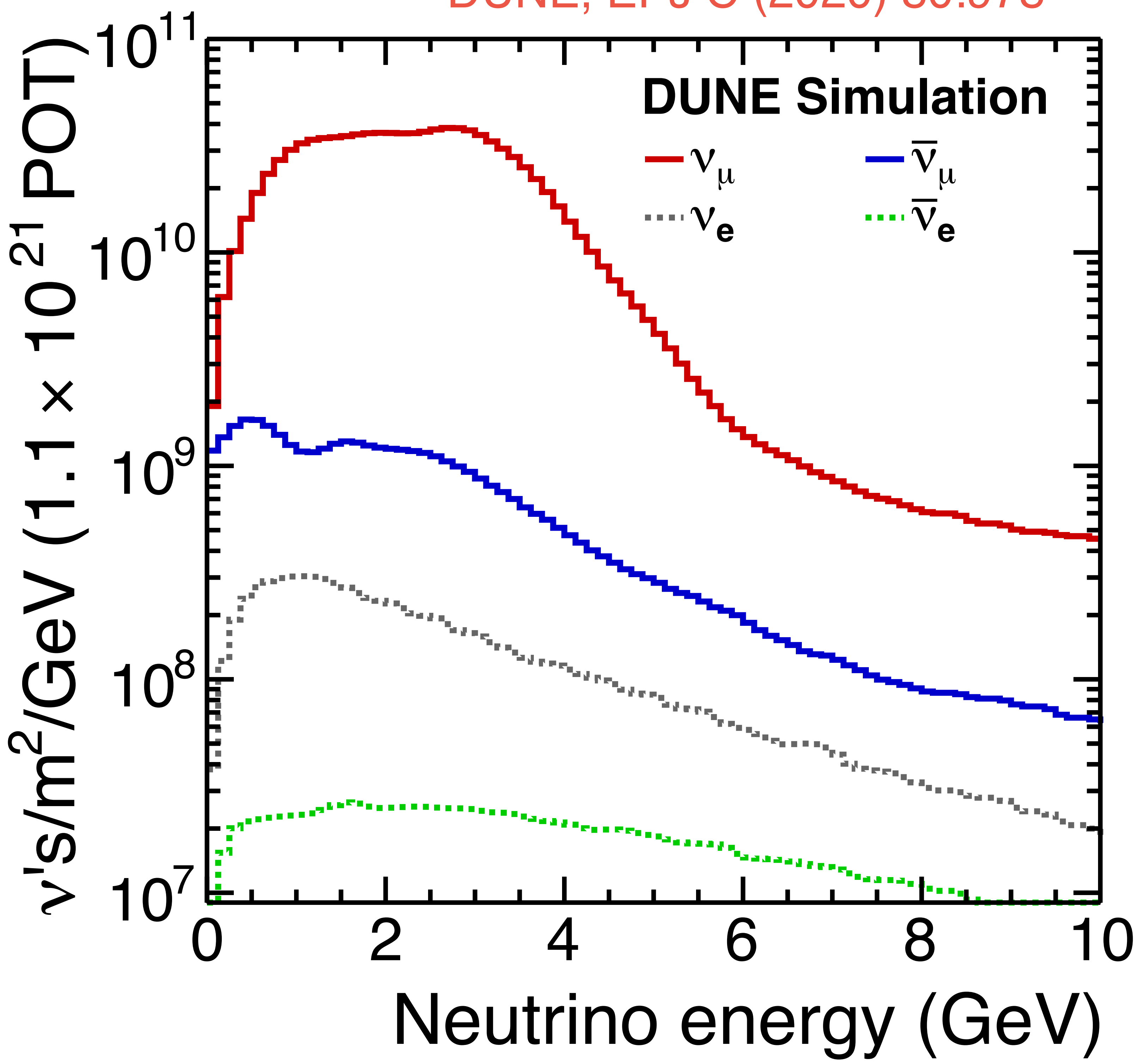
- Ways of making a more precise oscillation measurement in next generation?
  - **Higher statistics** (choice of source - energy/flavour, detector sizes/locations)
  - **Better measurements** (detector technology)
  - **Improved analysis** (limiting systematic uncertainties (e.g. on the neutrino flux, neutrino interactions), better analysis techniques)
- Two approaches to this problem for long-baseline oscillation experiments:
  - One avenue of approach is to build a more massive detector and collect higher statistics this way in a narrower band beam (e.g. Hyper-Kamiokande)
  - Another is to build a more sensitive detector along with a wide band beam to see a larger portion of L/E (e.g. DUNE)

Source: accelerators

- We can control the direction and timing of the beam, and the energy, "sign," and flavour composition of the resulting neutrinos



A. Himmel. slides



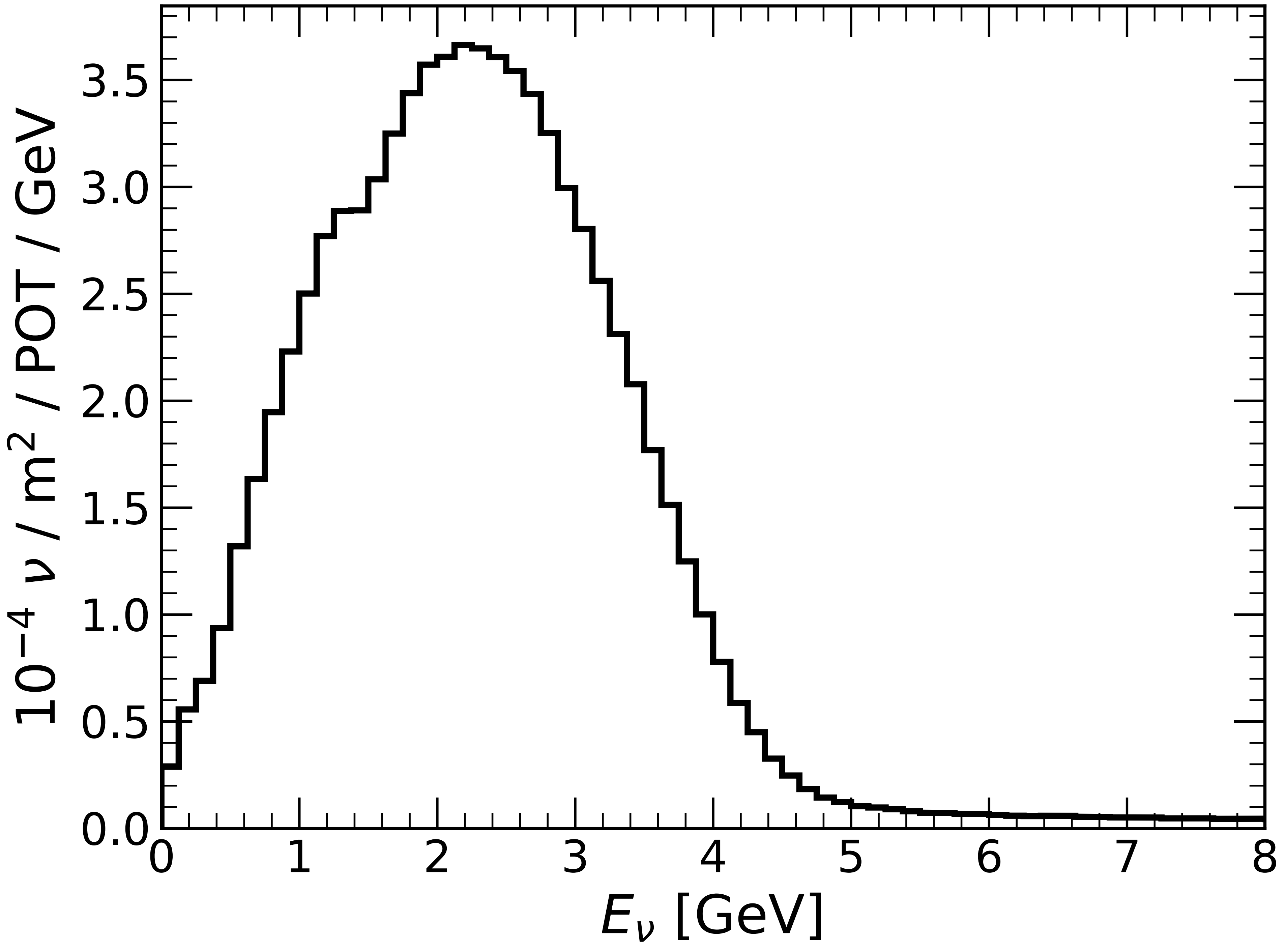
DUNE, EPJ C (2020) 80:978

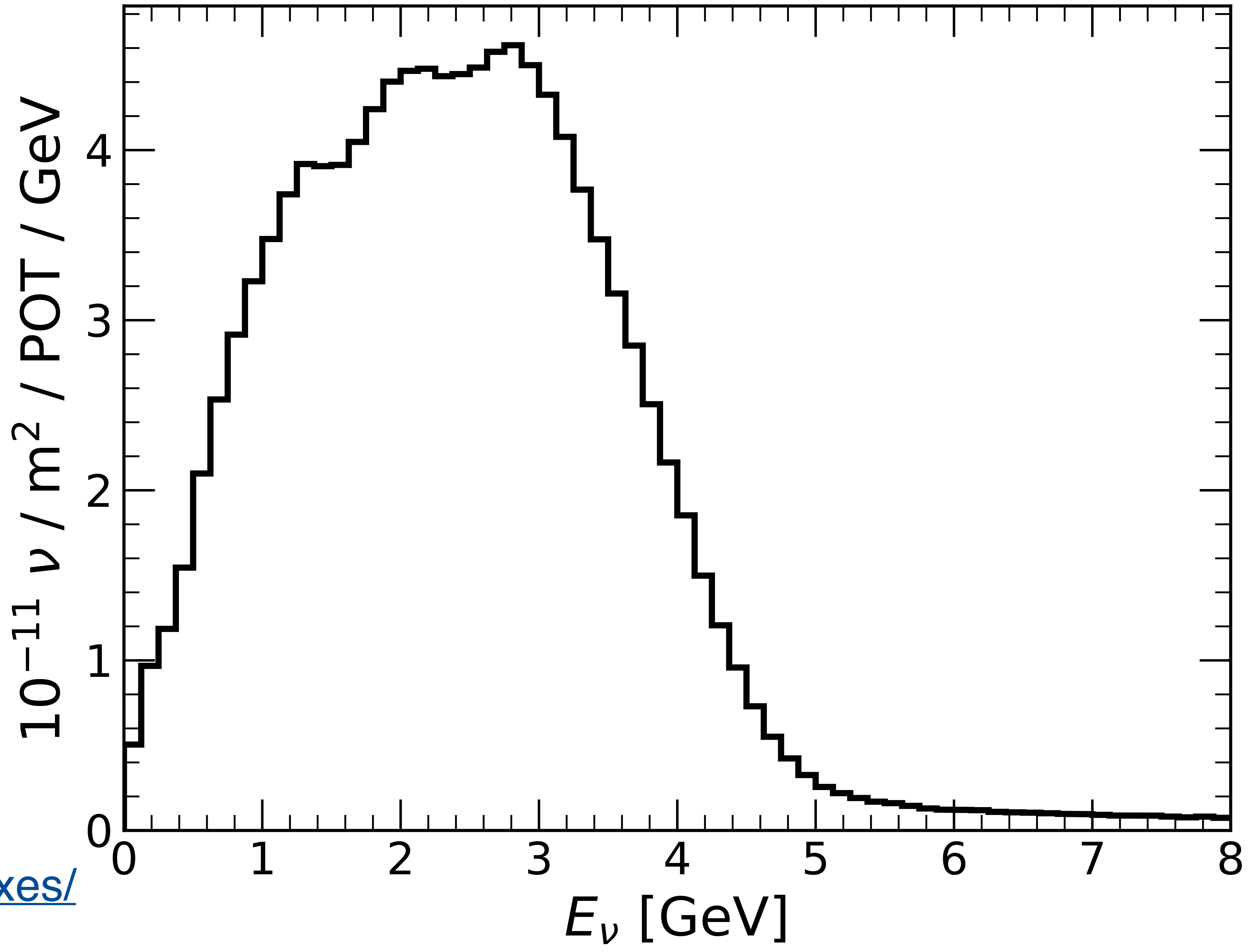
- Main source in this setup $\pi \rightarrow \mu + \nu_\mu$
  - But also $K \rightarrow \mu + \nu_\mu$, $K \rightarrow \pi^0 + e + \nu_e$, $\mu \rightarrow e + \nu_e + \nu_\mu$

Oscillation experiments

Small contamination of other flavours

Small contamination of other flavours





DUNE TDR-era flux:
https://glaucus.crc.nd.edu/DUNEFluxes/
Oscillation probabilities NuFast:
https://github.com/PeterDenton/NuFast-LBL

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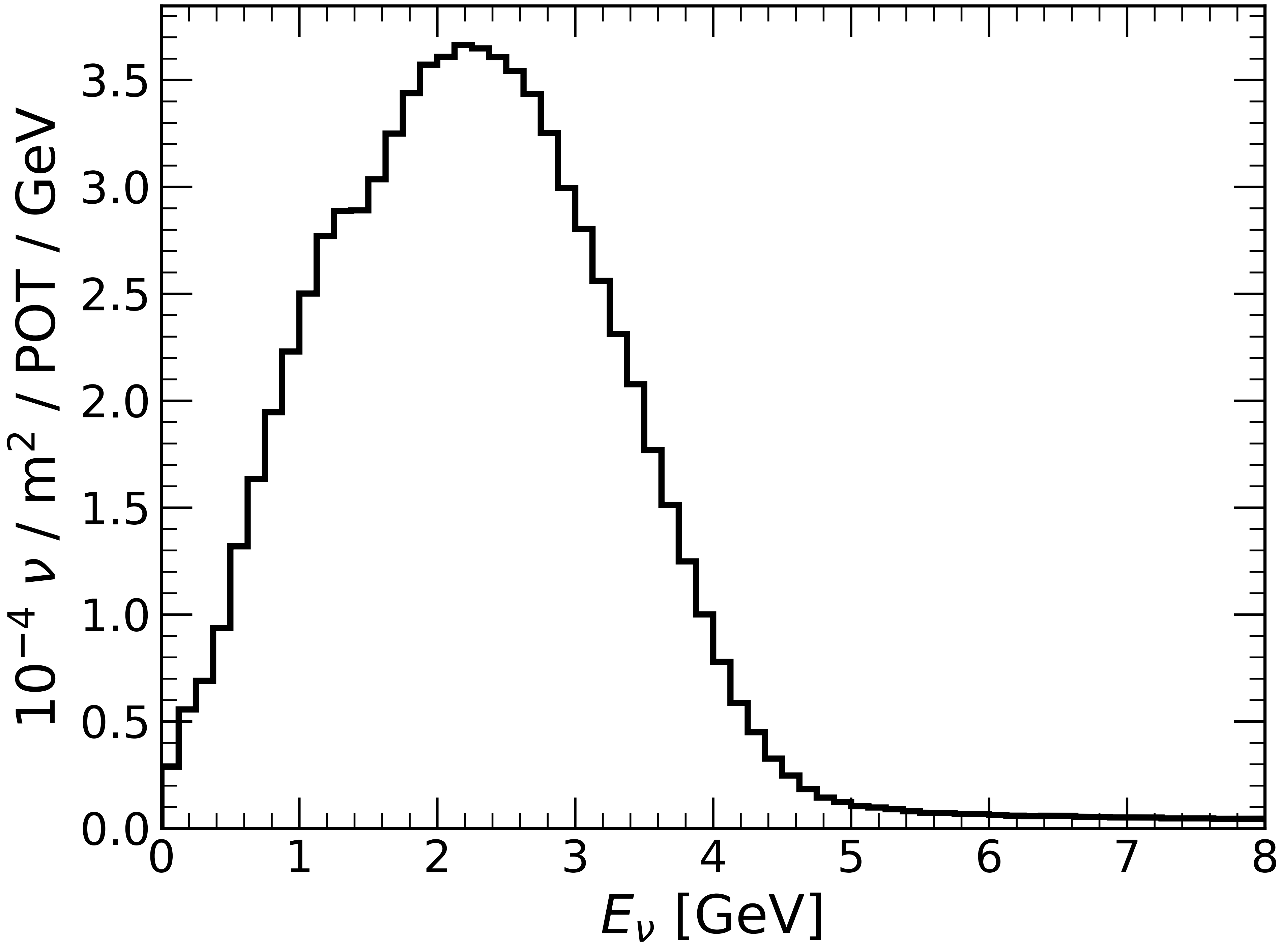

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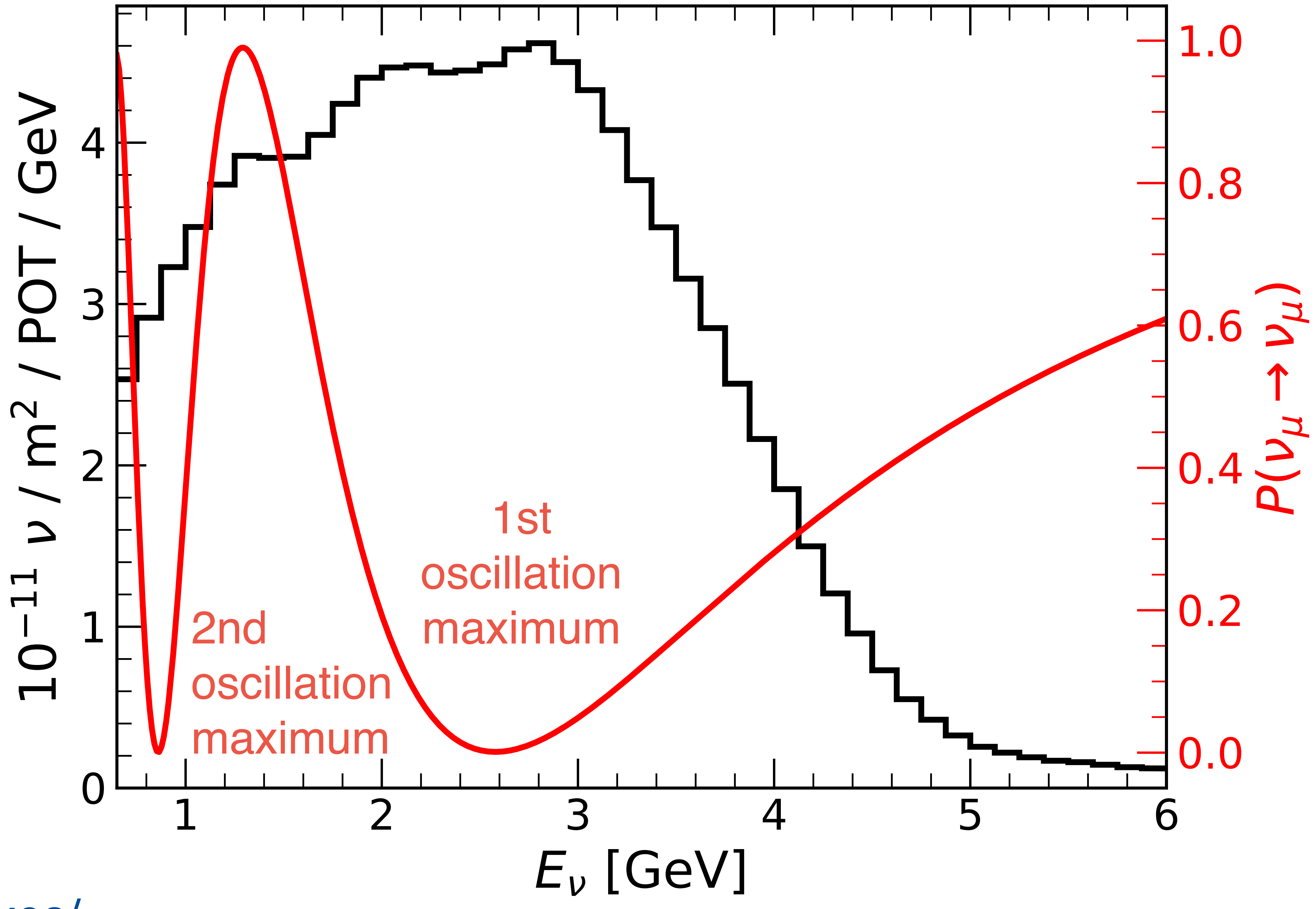

NOTE zoomed in axis

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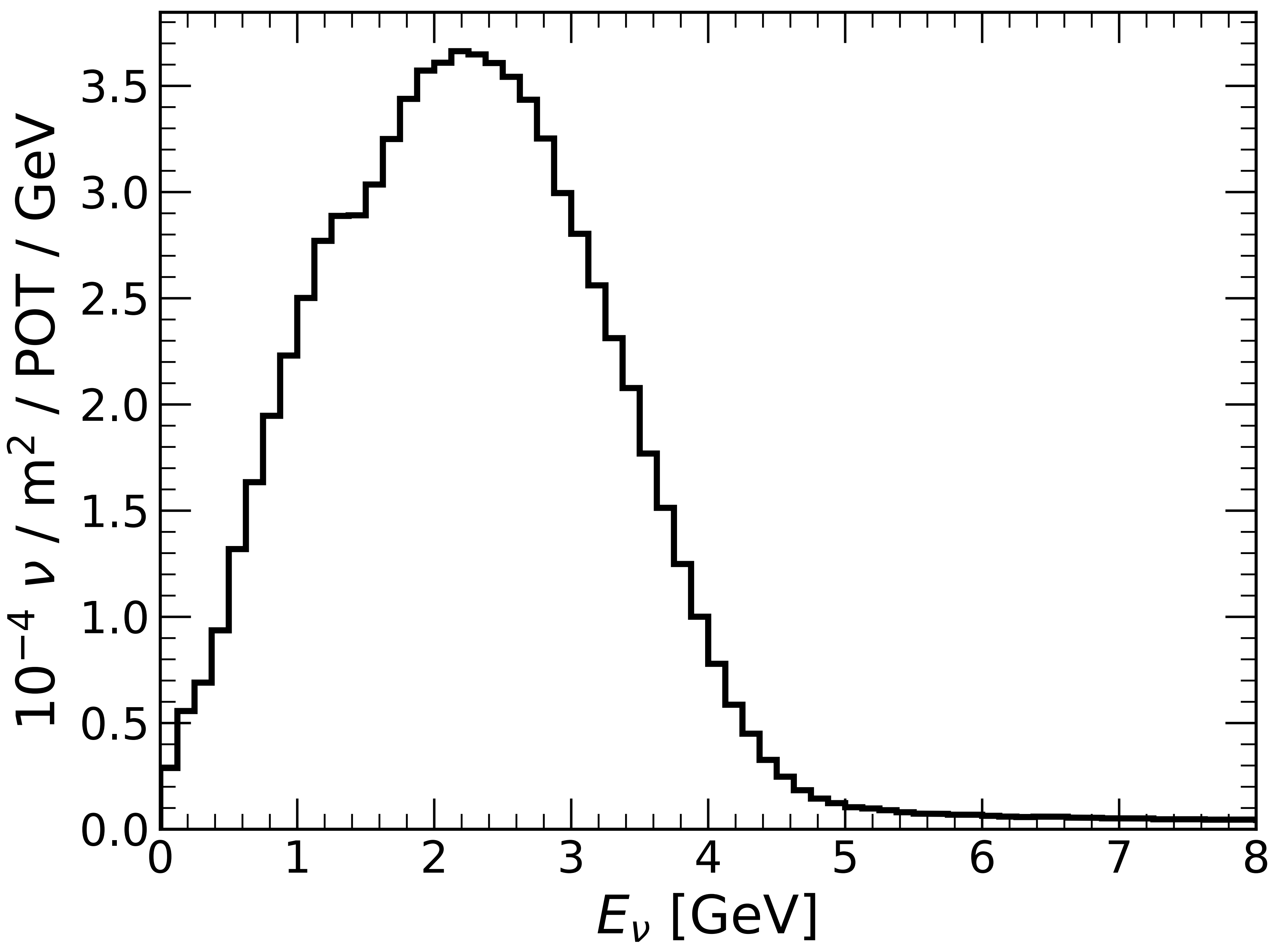

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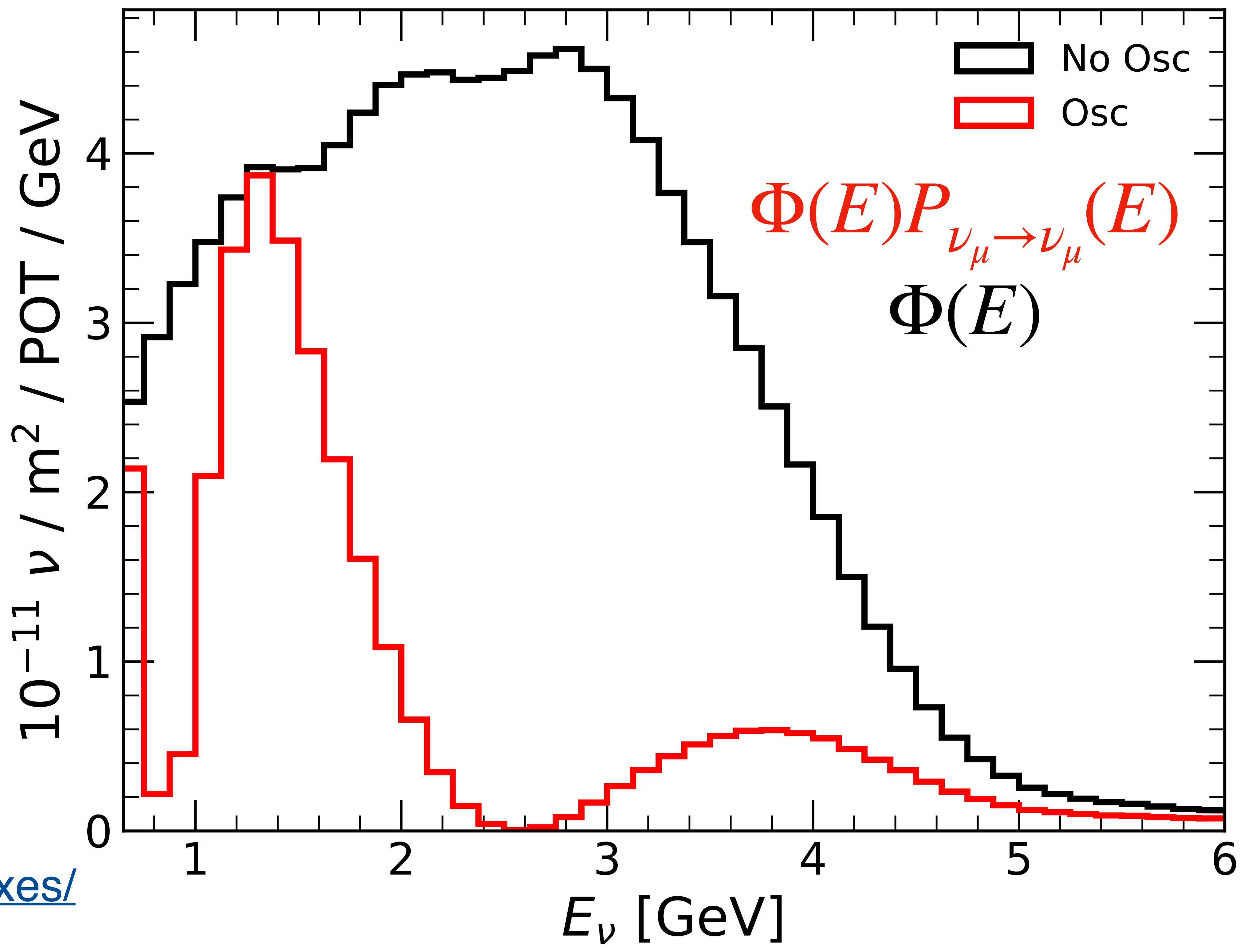

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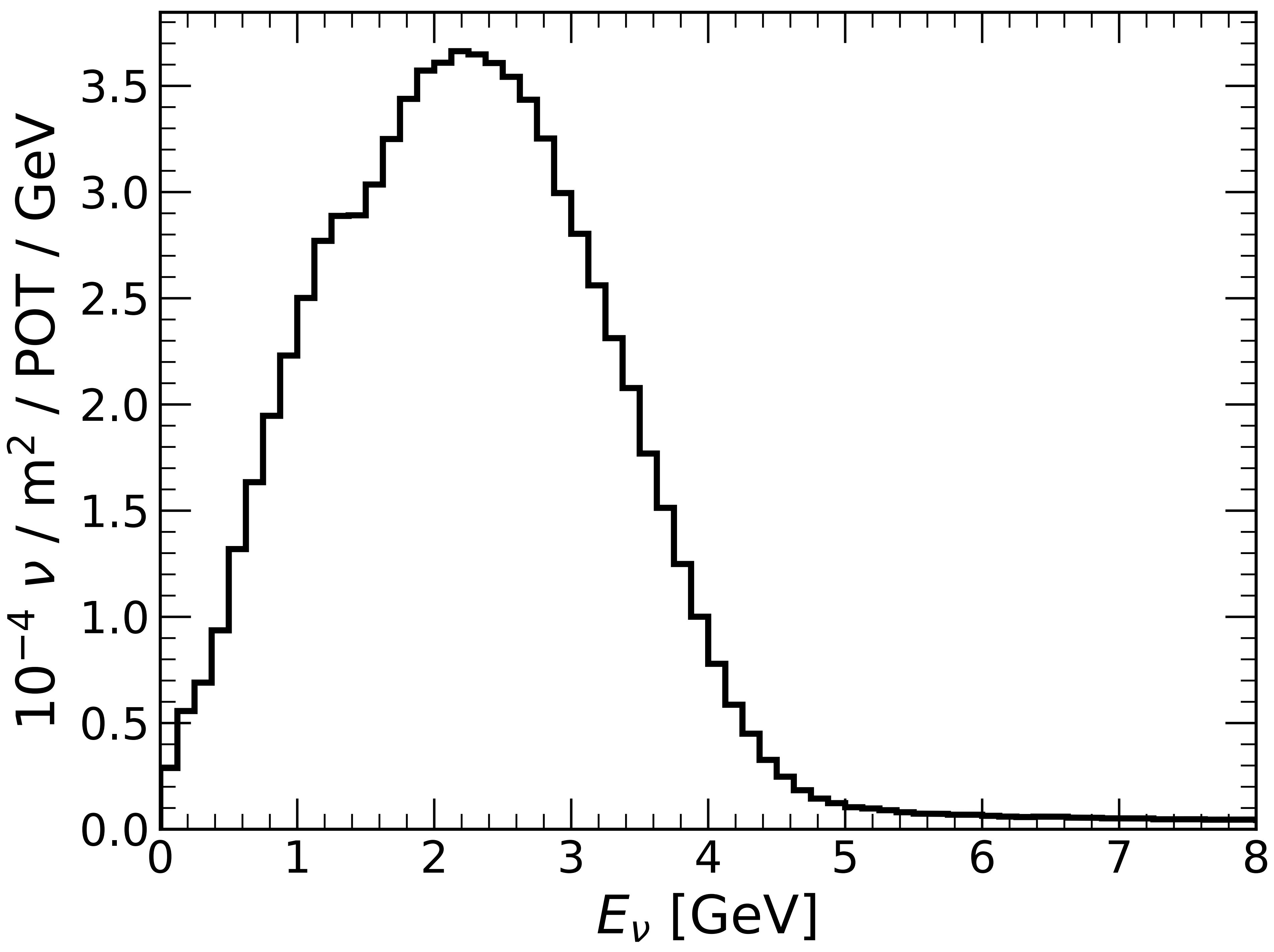

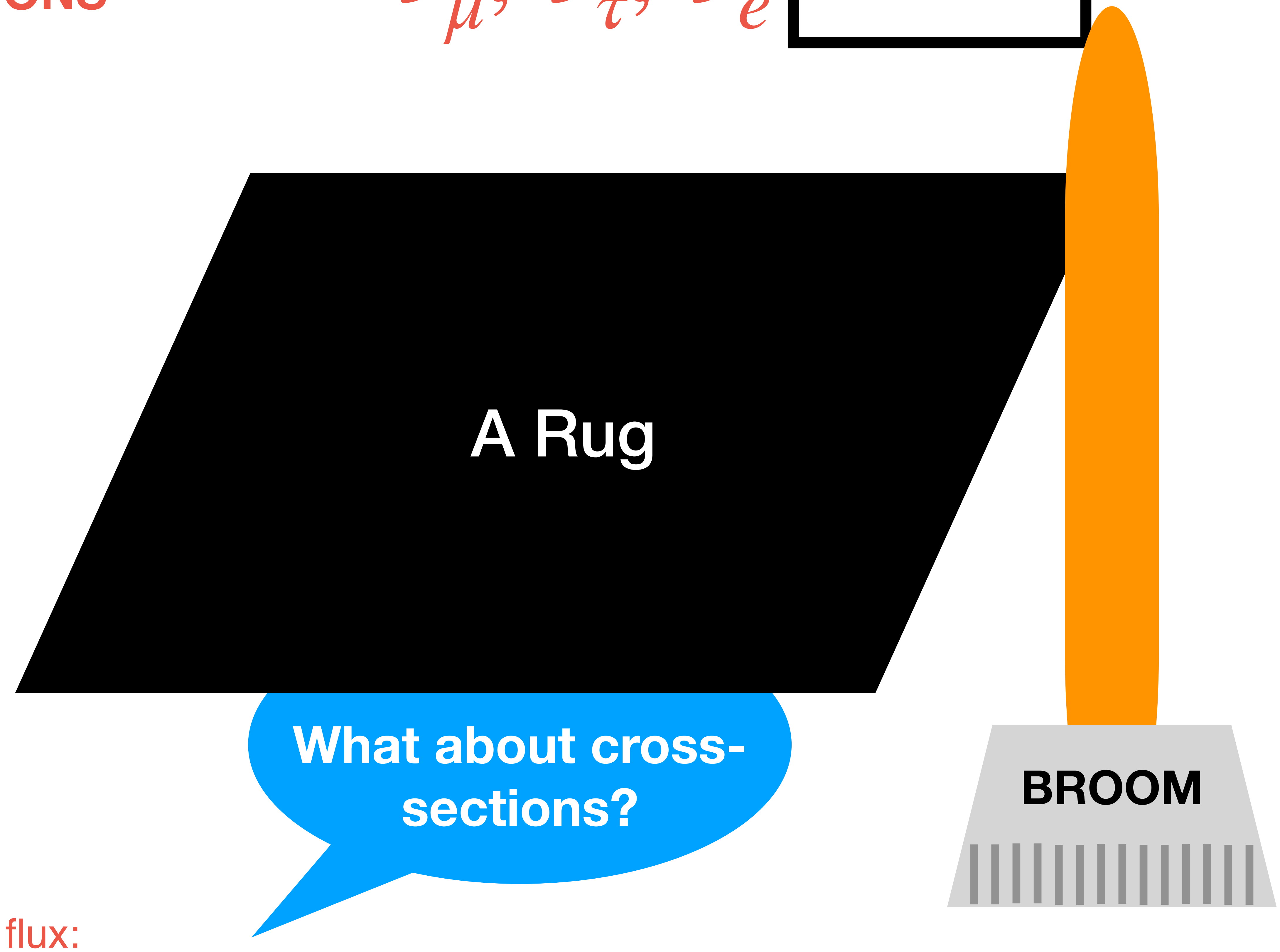

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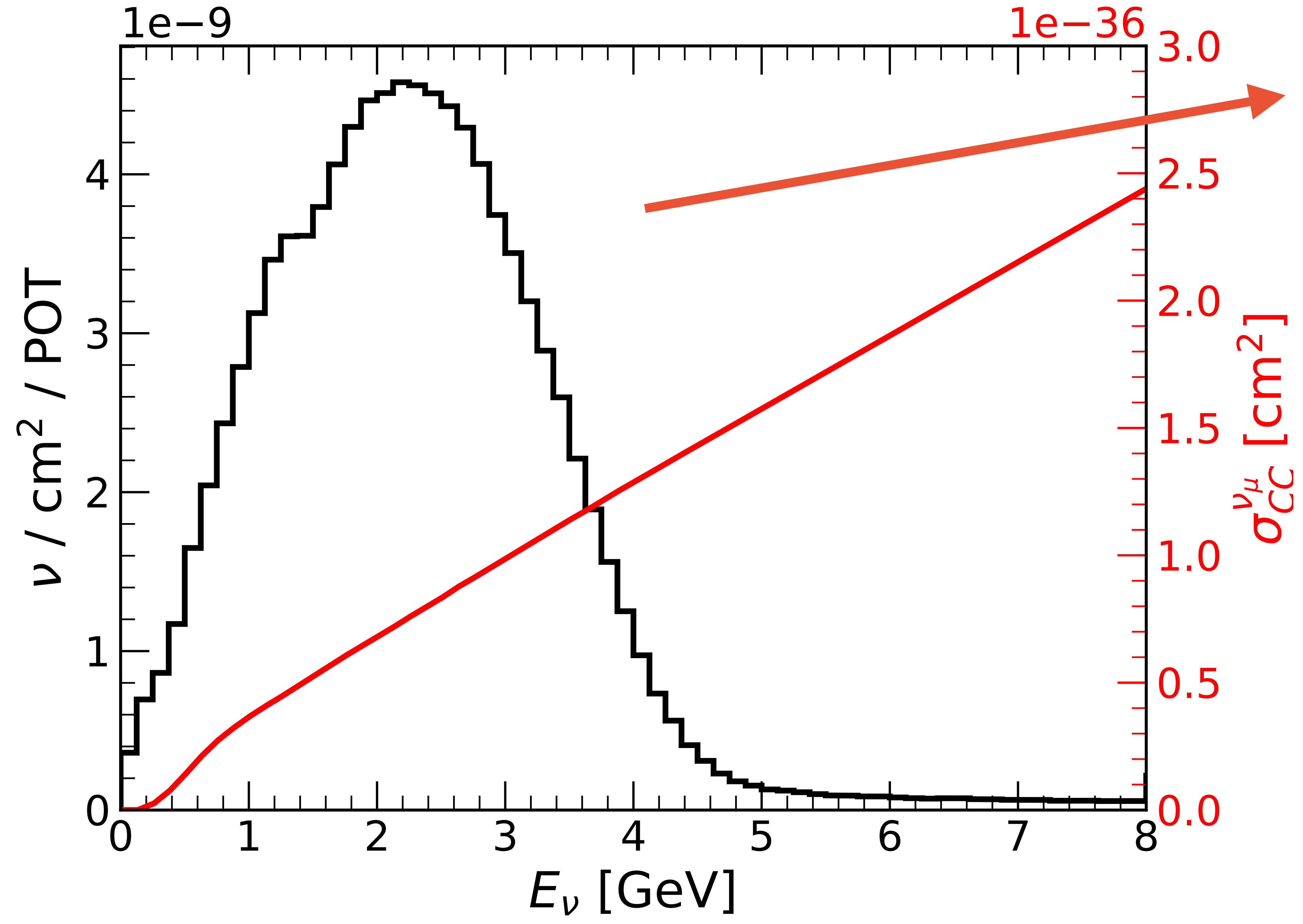

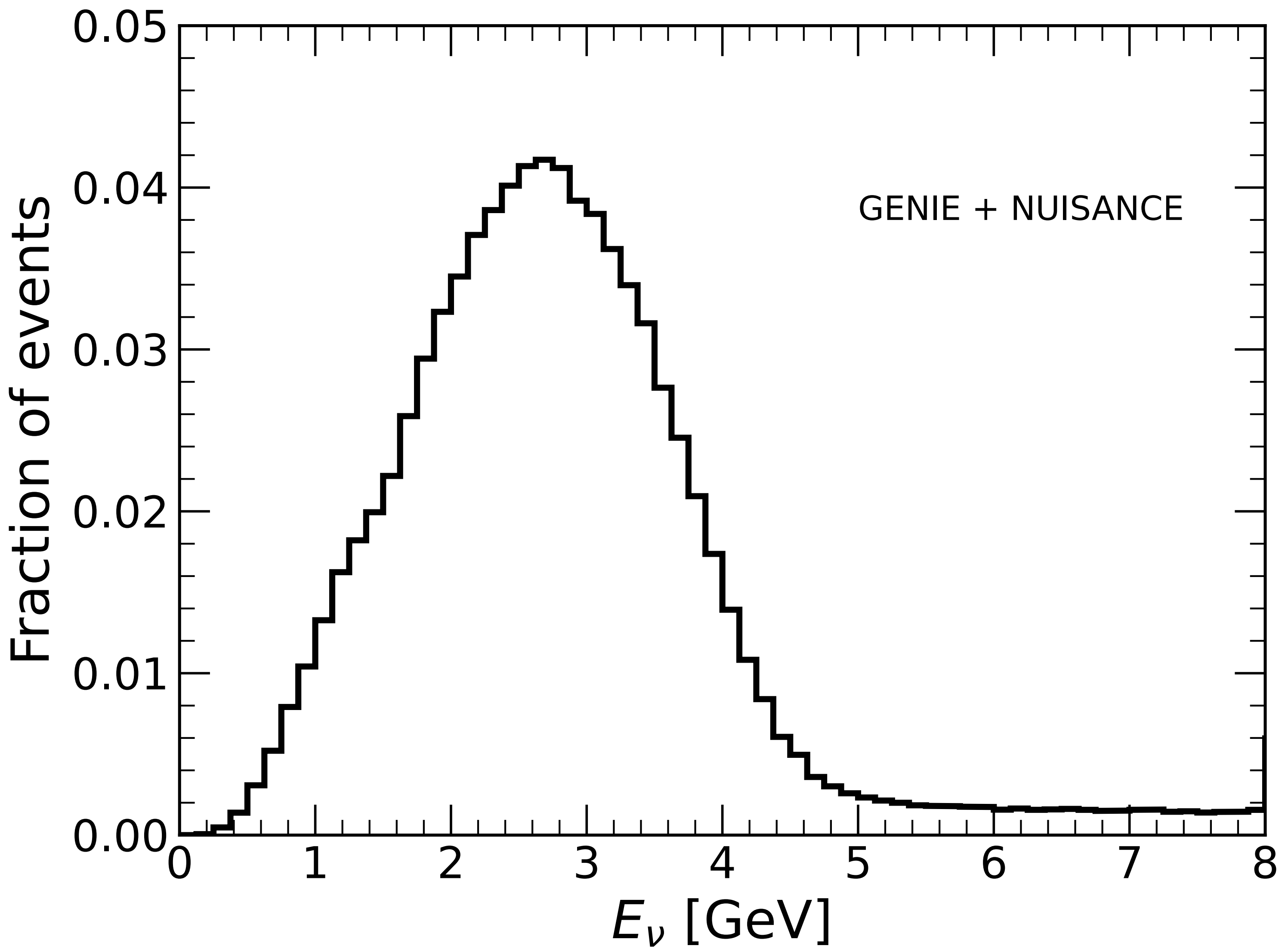

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https://github.com/PeterDenton/NuFast-LBL
Cross-sections: **GENIE v3 Ar23**
NUISANCE: repository

NEAR DETECTOR events:

$$\Phi(E)\ \sigma_\nu(E)$$

FAR DETECTOR events:

$$\Phi(E)\ P_{osc}(E)\ \sigma_\nu(E)$$

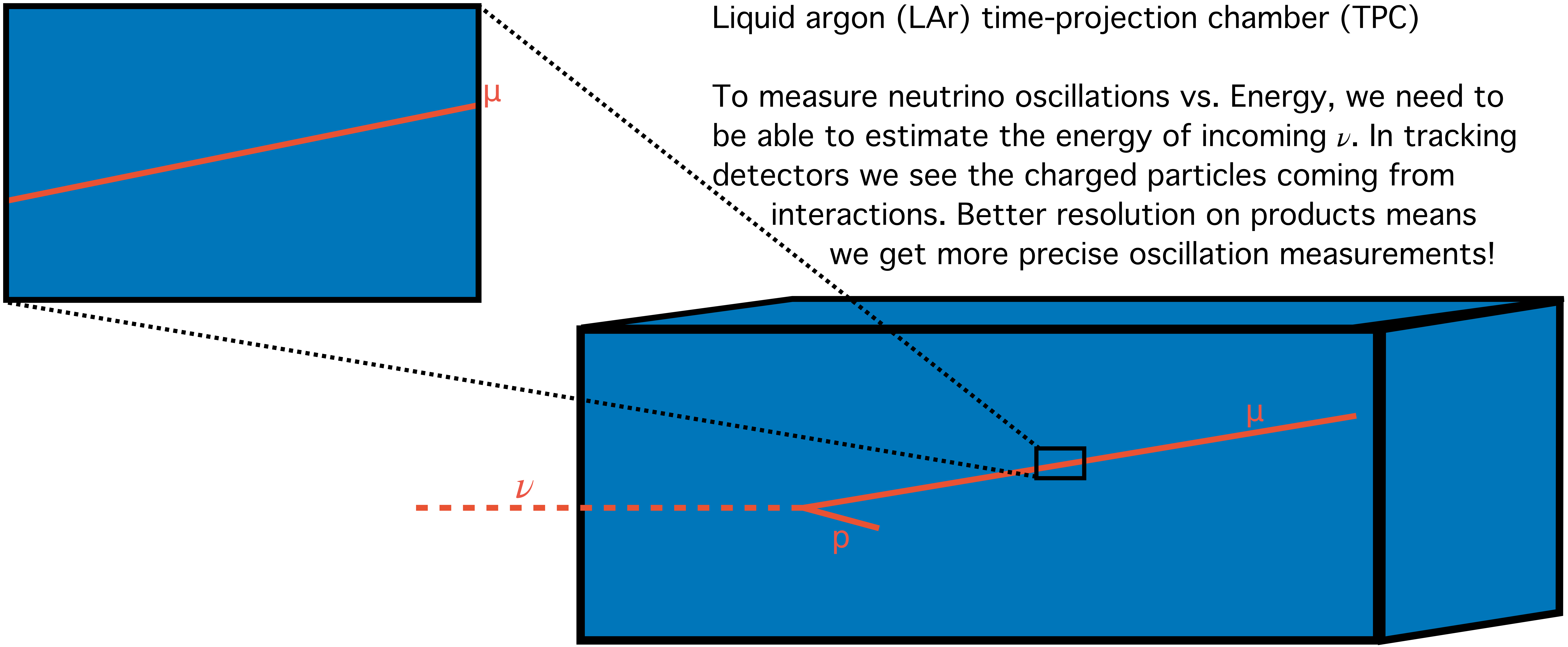
And/so we also need to consider:
- Flux Far ≠ Flux Near
- Flavour/sign x-sec differences
- We estimate E by what we see (resolution for different channels)

Here we rely on **interaction models** that feed into our simulations. Need to perform measurements to test and inform models!

Detector Choice: LArTPC

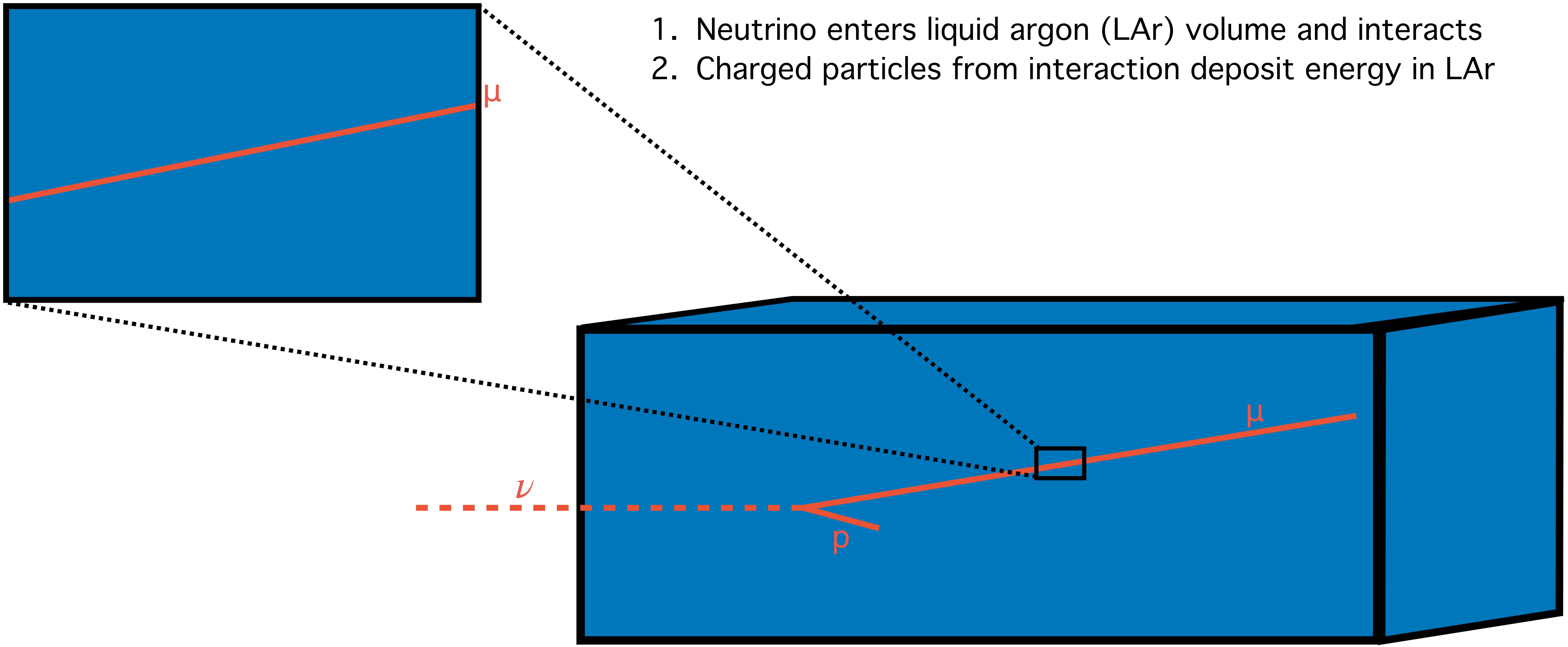
Liquid argon (LAr) time-projection chamber (TPC)

To measure neutrino oscillations vs. Energy, we need to be able to estimate the energy of incoming ν. In tracking detectors we see the charged particles coming from interactions. Better resolution on products means we get more precise oscillation measurements!



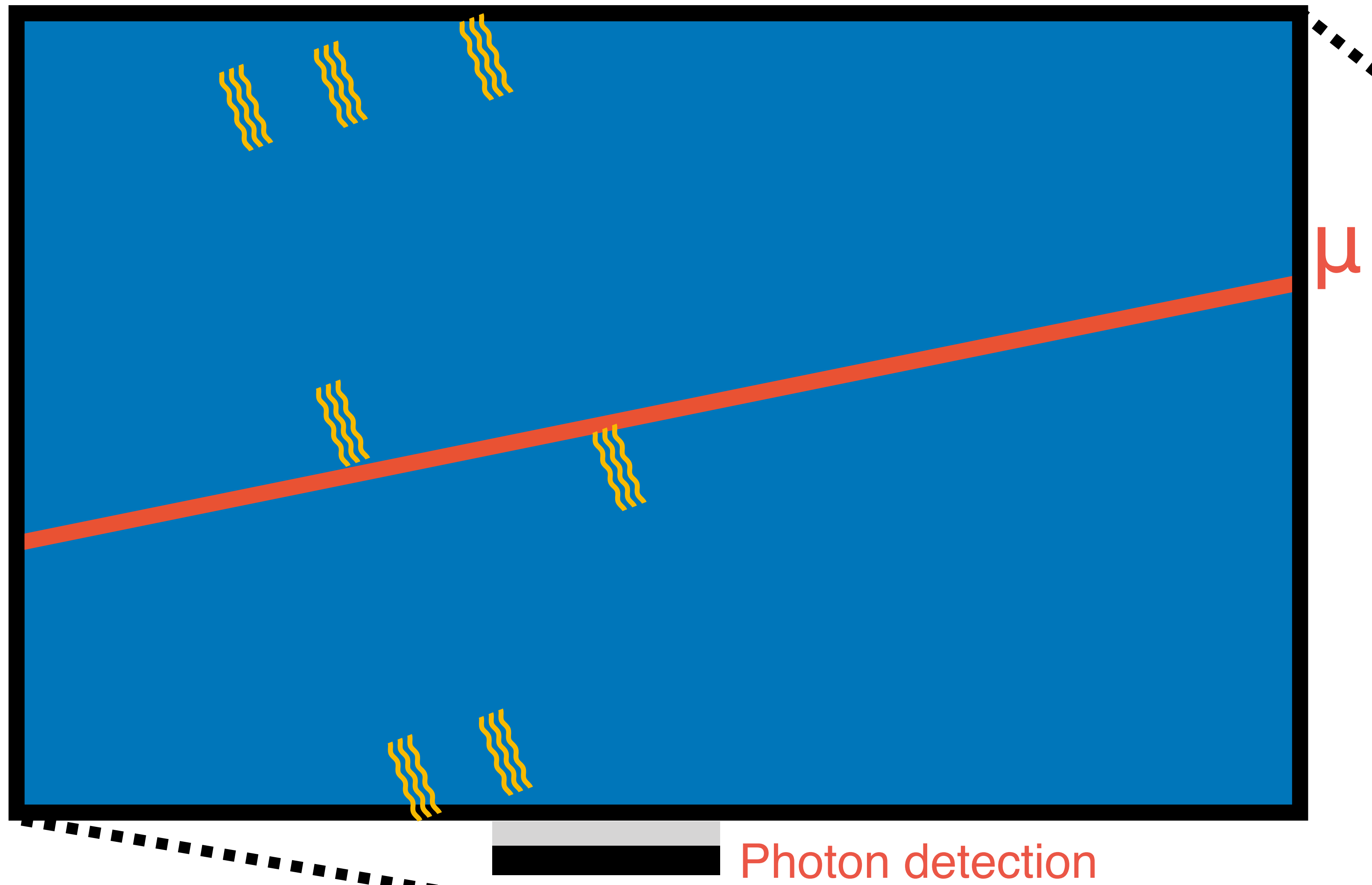
Detector Choice: LArTPC

1. Neutrino enters liquid argon (LAr) volume and interacts
2. Charged particles from interaction deposit energy in LAr

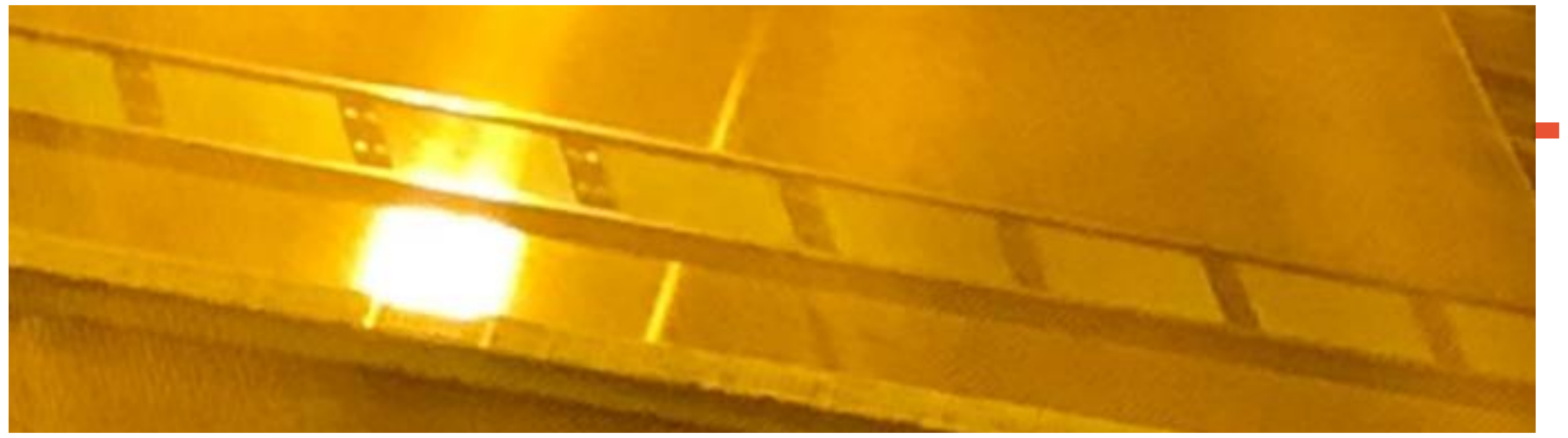


Detector Choice: LArTPC

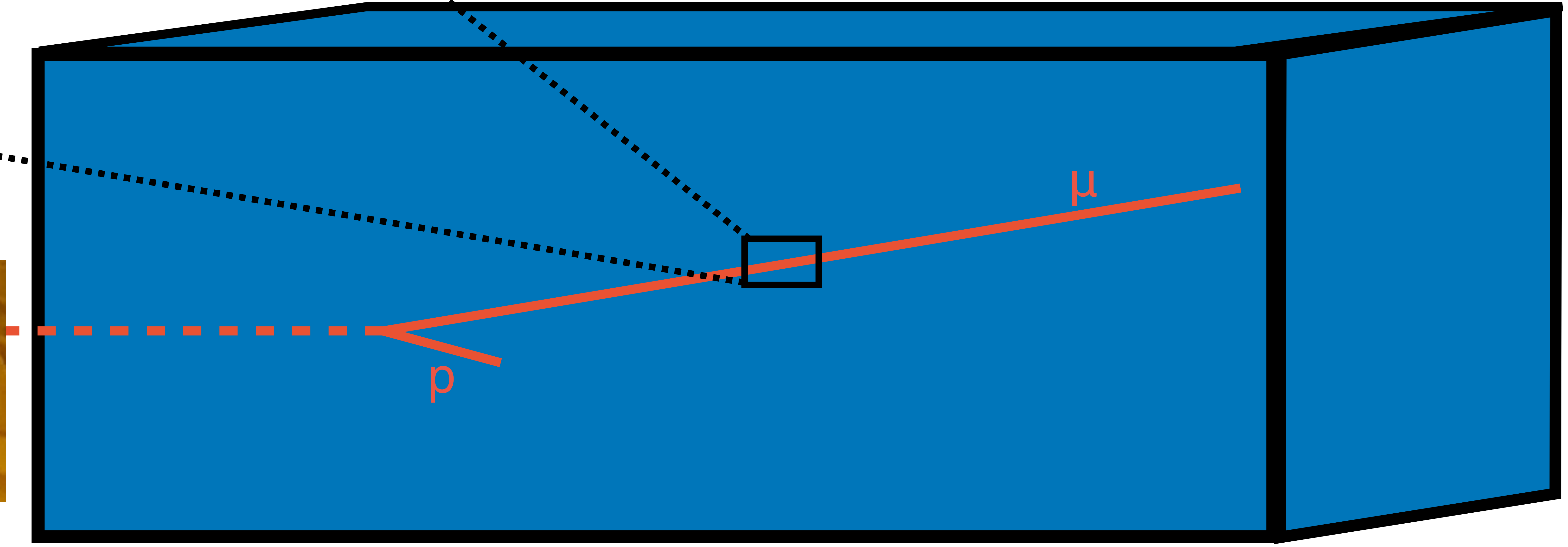
1. Neutrino enters liquid argon (LAr) volume and interacts
2. Charged particles from interaction deposit energy in LAr
3. This leads to both ionization and scintillation
4. Scintillation: photon detectors, typically use wavelength shifters: 128nm→~vis ($v=c_{LAr}$, fast)



Traditional: PMTs coated with wavelength shifter (ICARUS, photo CERN)



Also can use flatter photon detectors, e.g. w/ SiPMs
Shown: ProtoDUNE, JINST **17** P01005 (2022)



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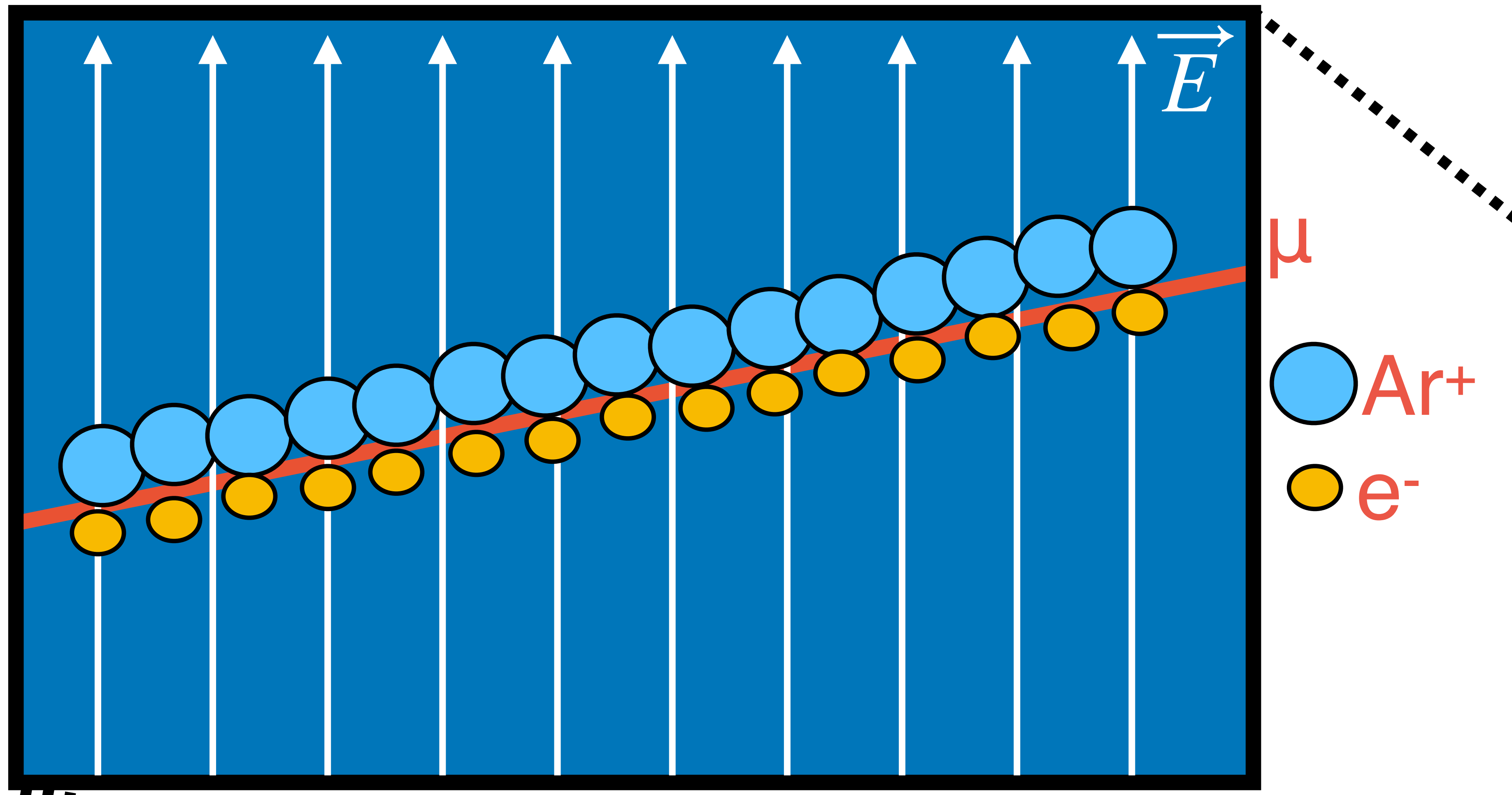

* Charge readout (wires or other readout)

DUNE TDR
arXiv:2002.03010

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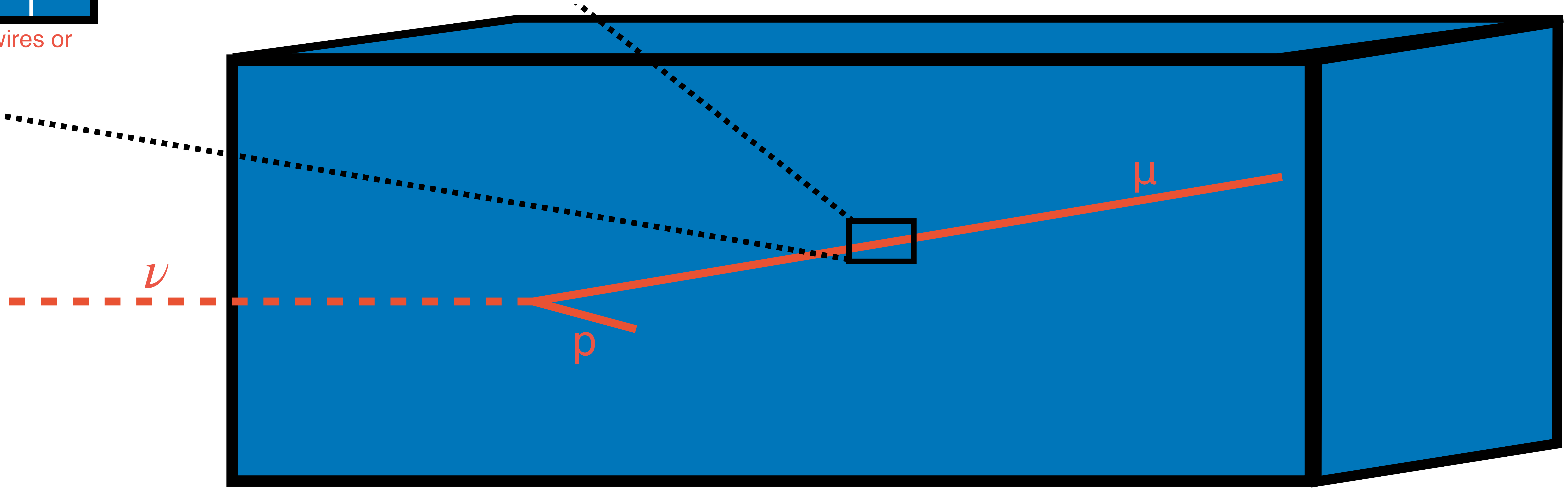
5. Ionization is drifted in electric field to sensing elements at the anode plane (v~0.16cm/μs, slow, hundreds μs to ms)



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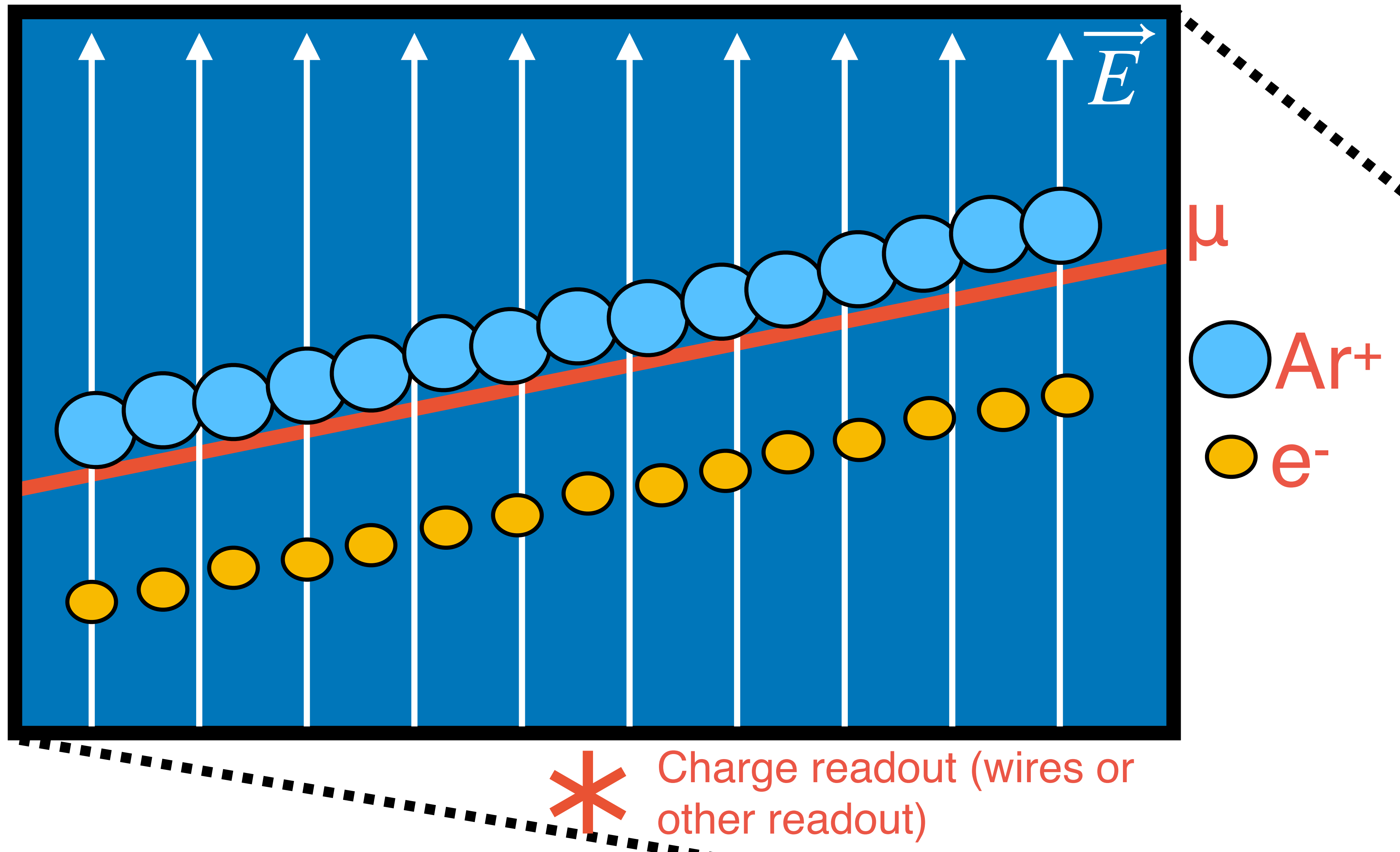

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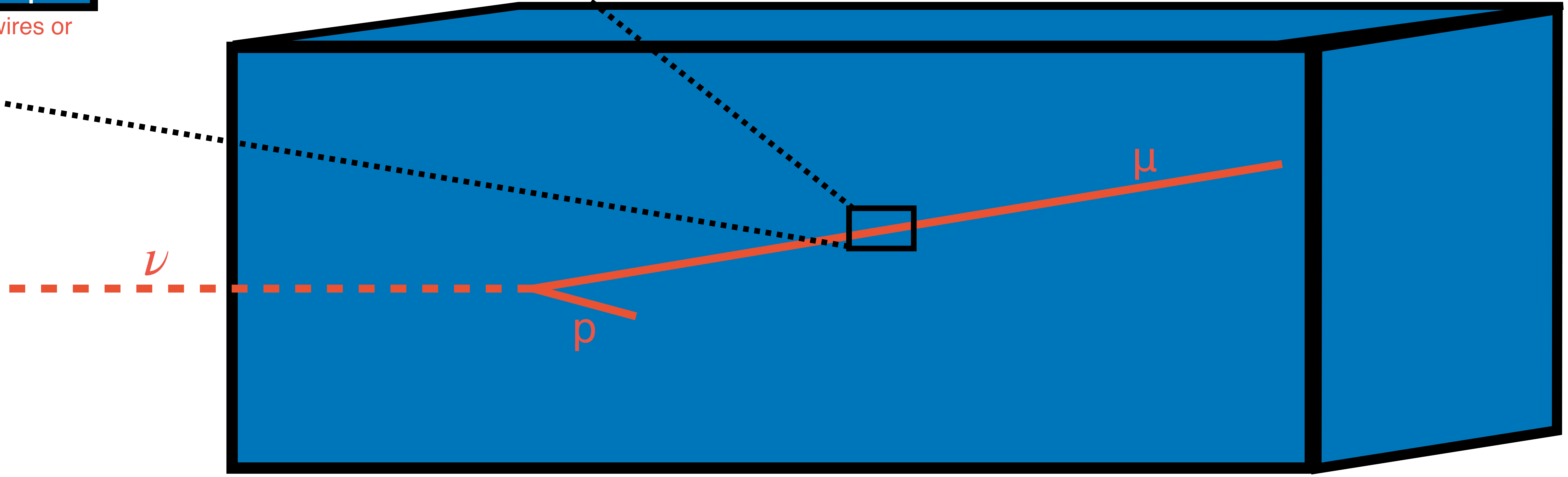

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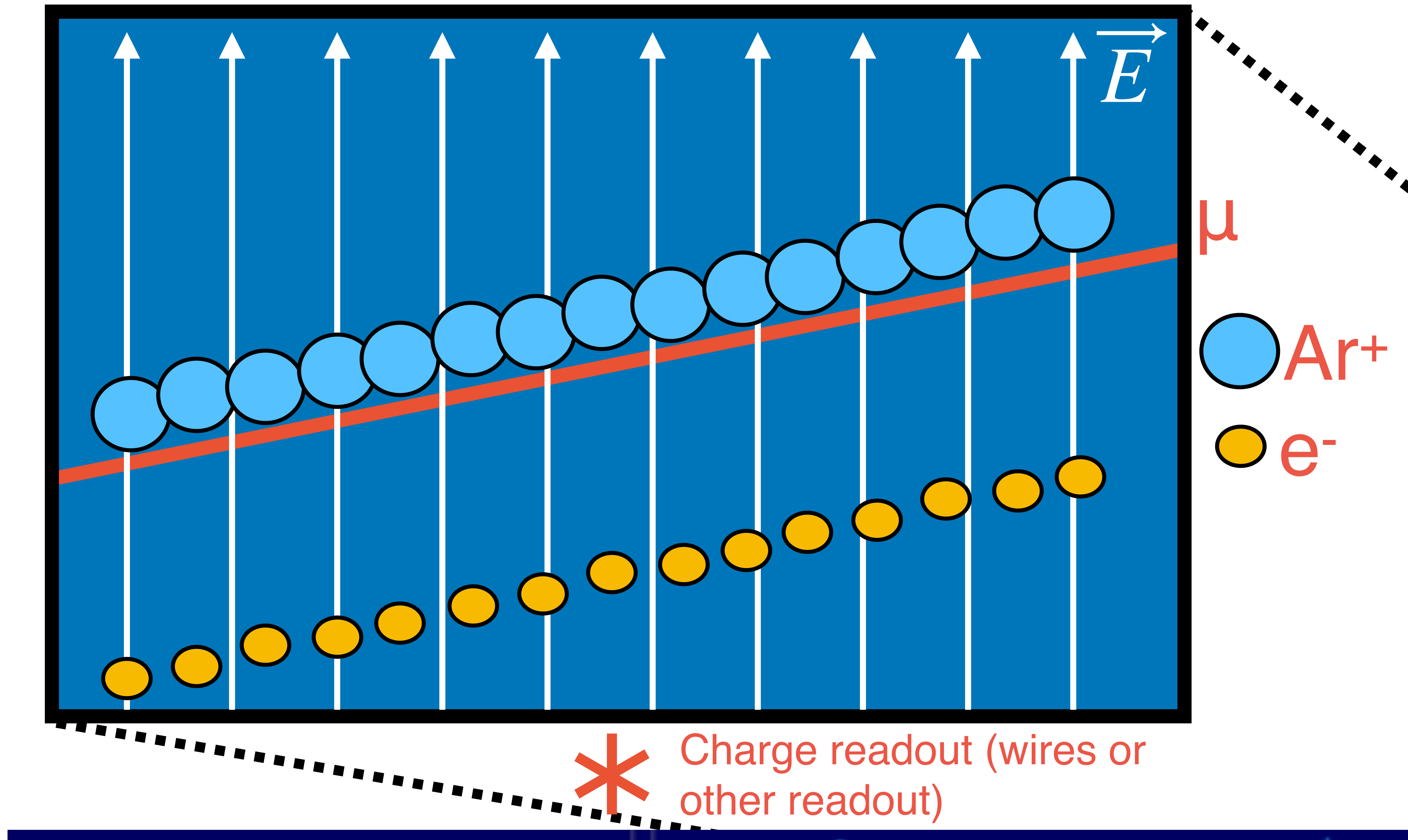

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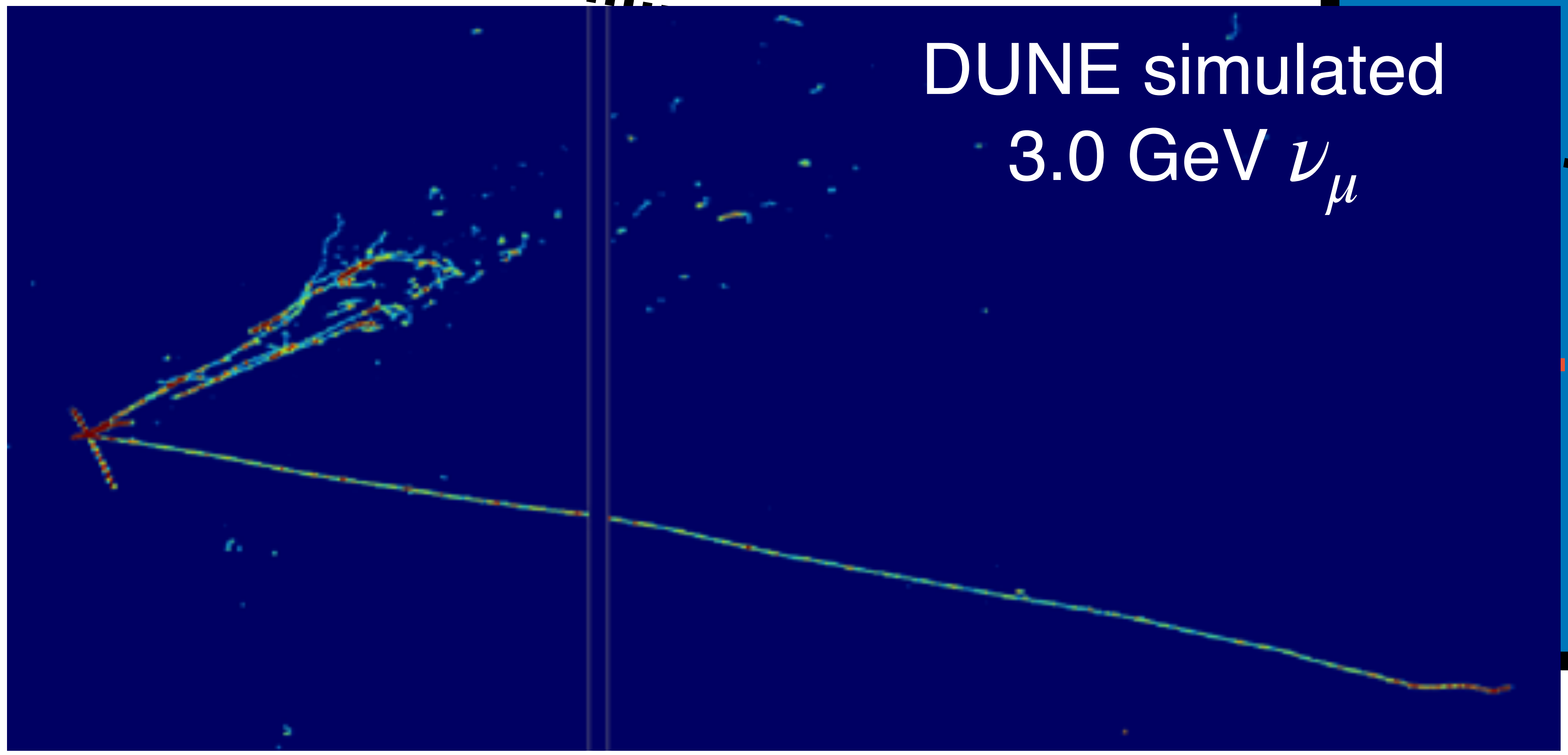
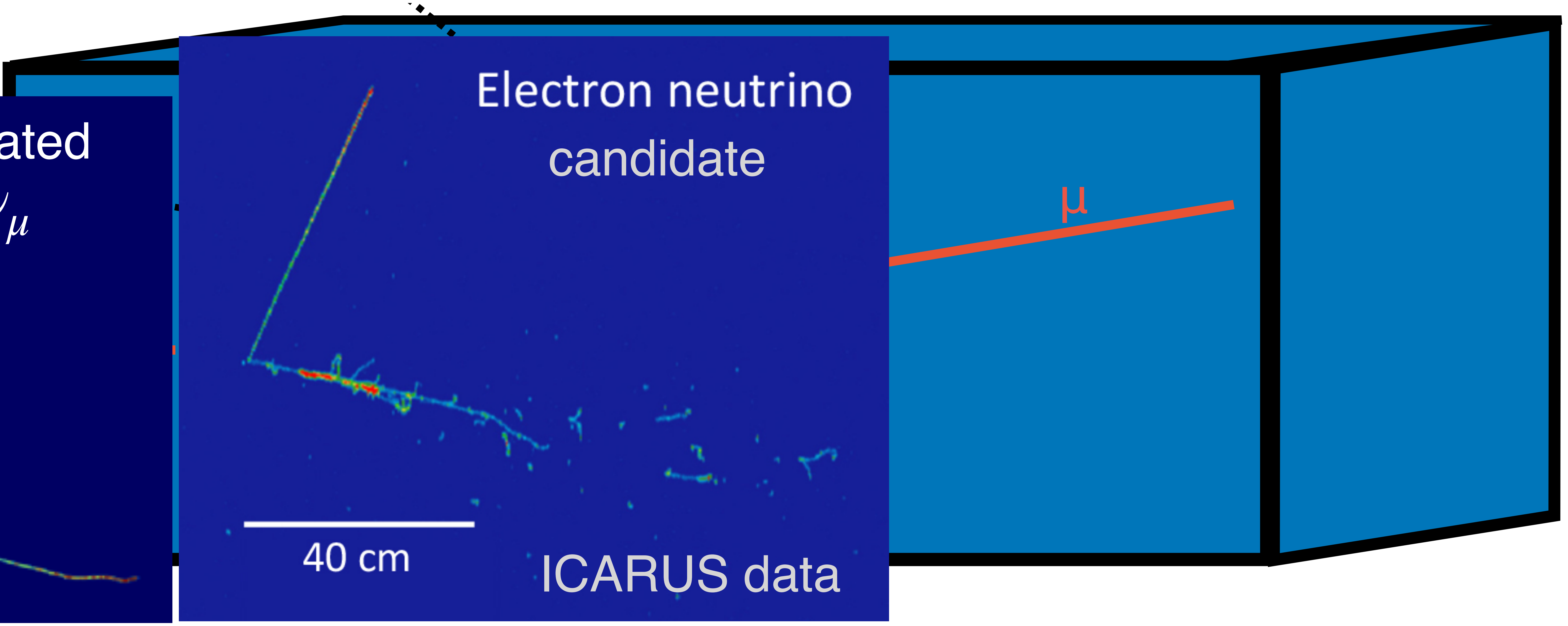
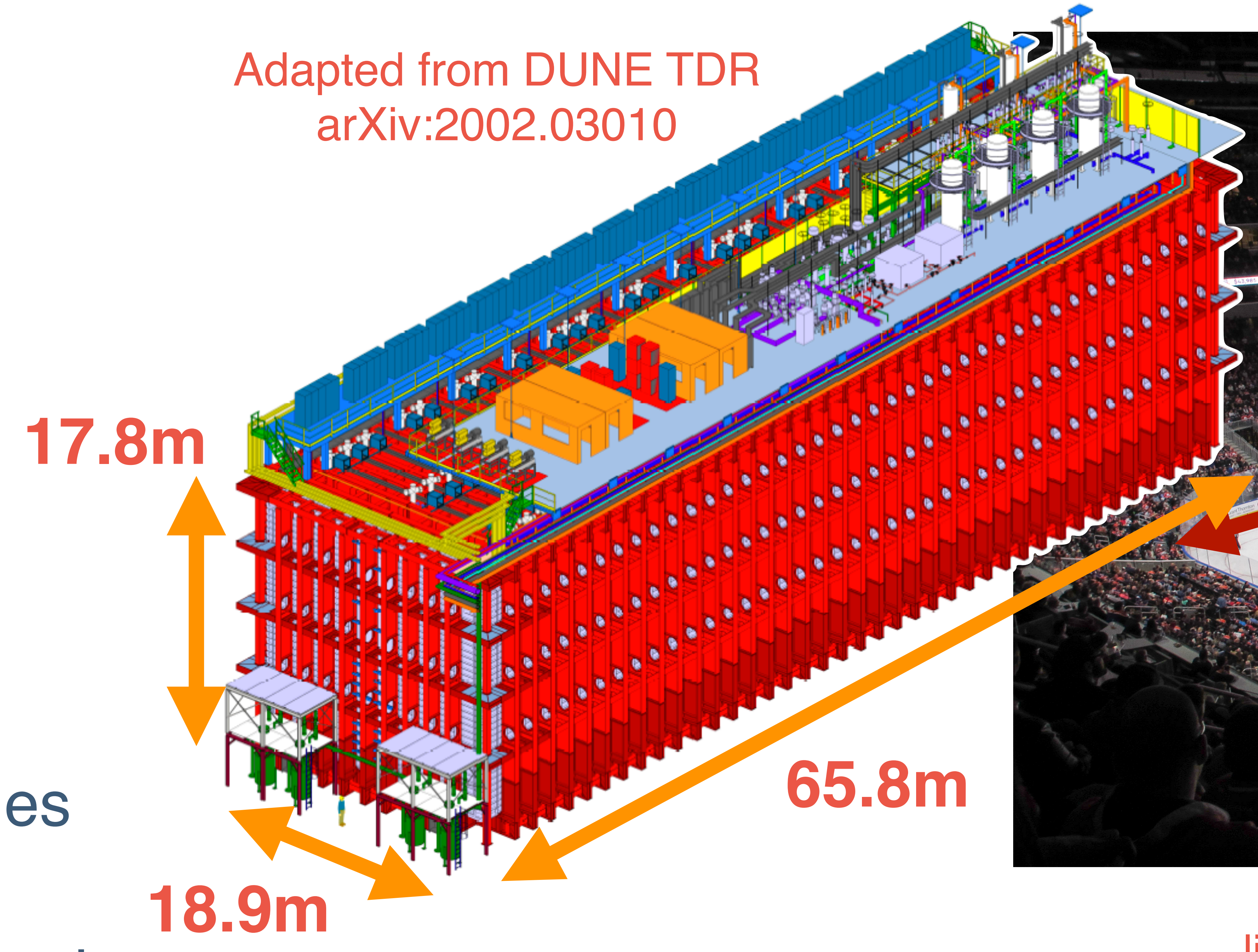




Deep Underground Neutrino Experiment

- DUNE:
  - **Higher event rates:**
    → intense beam, large detectors
  - **Sensitive:**
    → use LAr TPCs
  - **Background rejection:**
    → underground
- ~1500 people, > 30 countries
- Beam will originate at Fermilab, near Chicago, Illinois
- Far Detector (FD) in Lead, South Dakota (south of Sask.)
  - Neutrinos travel 1300 km between Fermilab, Lead

Adapted from DUNE TDR
arXiv:2002.03010



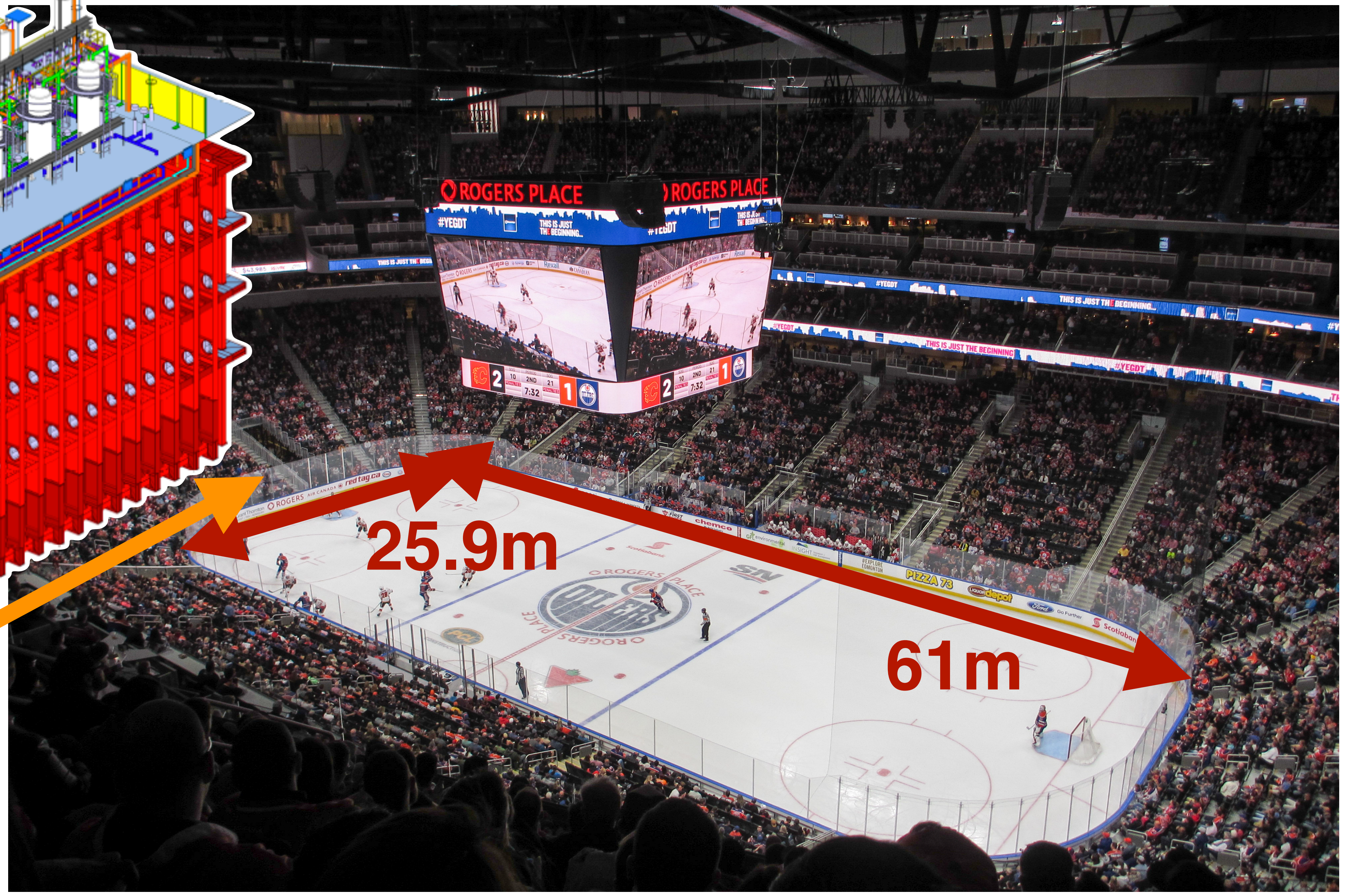


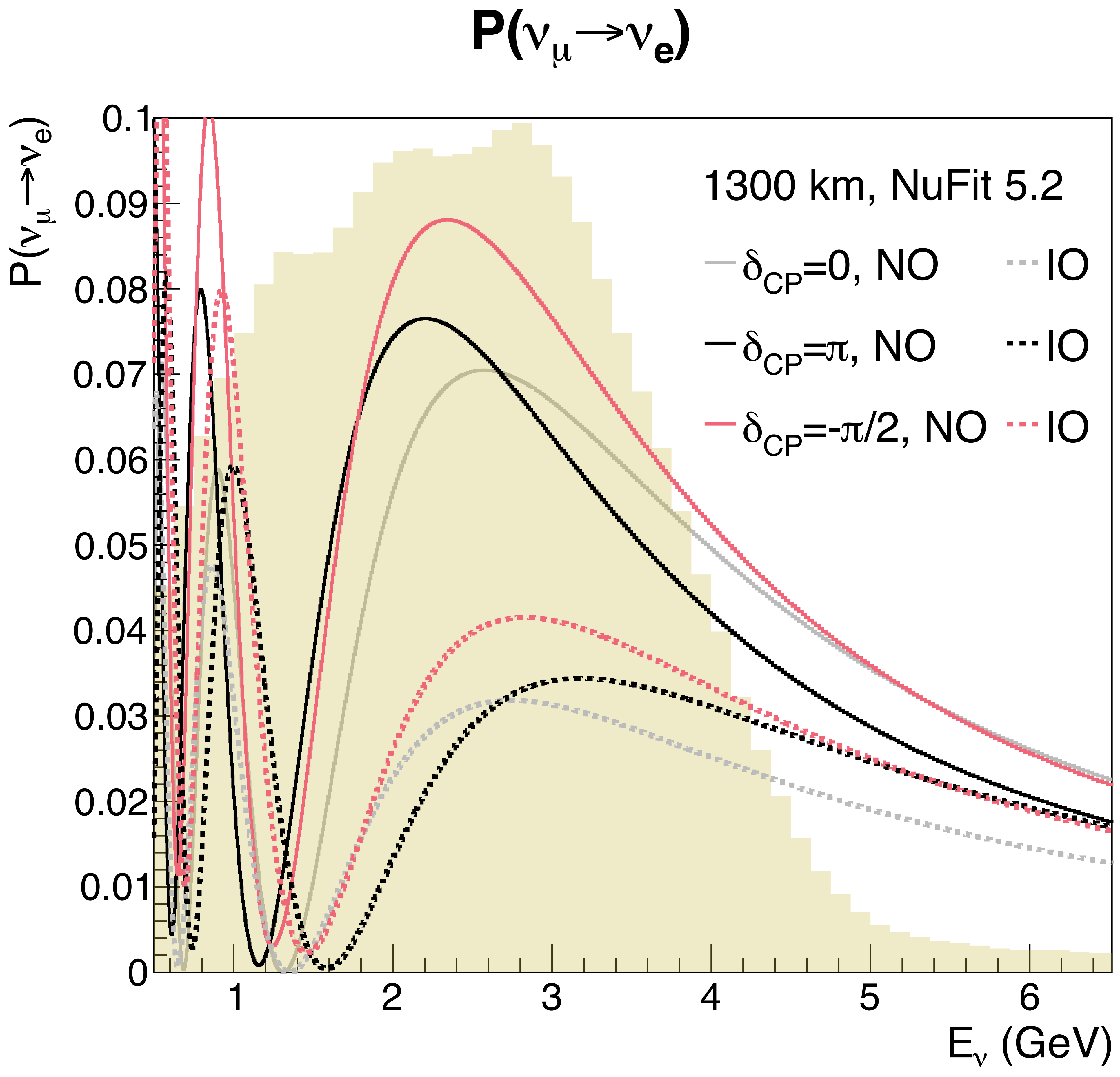
Photo by Mack Male, from Wikipedia
license: CC BY-SA 2.0, dimensions added

Each DUNE Far Detector module will be 17,000 tons of LAr (10,000 fiducial)

DUNE will put in 2 of these modules at first, expanding to up to 4 modules

Unique physics reach

- DUNE's setup enables a unique physics reach amongst the next generation
  - Stringent tests of the three-flavour oscillation paradigm
- Matter effect causes DUNE (1300 km) to pick up a **large** difference in oscillation probability depending on ordering, high sensitivity to mass ordering (> 5σ in a few years)
- Significant sensitivity to CP violation as well (> 5σ for regions of parameter space)
- DUNE's wide-band beam, and higher E_ν enable some key additional points:
  - Potential to see 2nd oscillation peak or at least large amount of a full oscillation period
  - Measure several oscillation parameters in one experiment
  - Higher E → chance to study ν_τ appearance



As in
Harris, Ilic, Konaka, Canadian Journal of Physics (2025)

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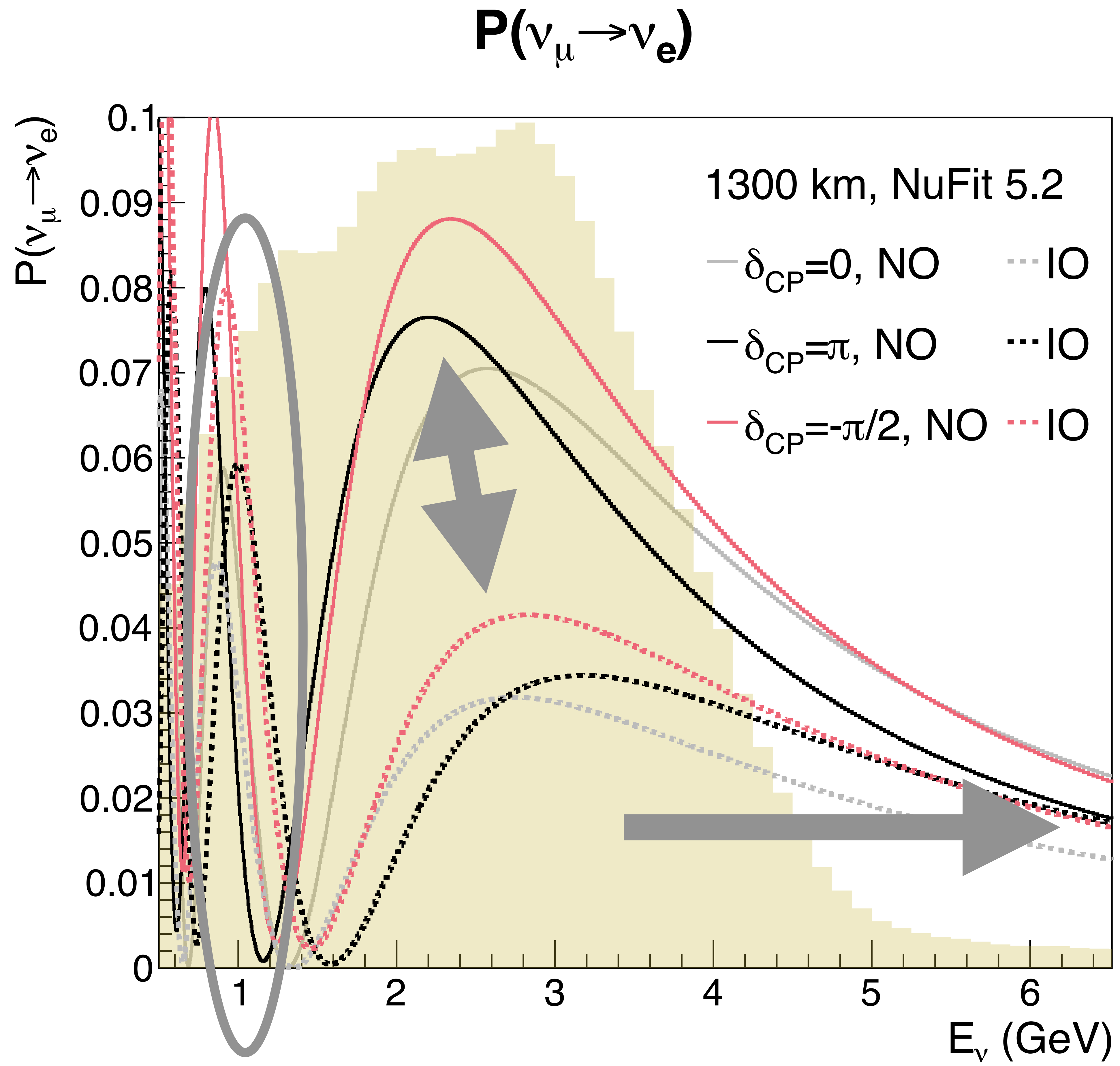
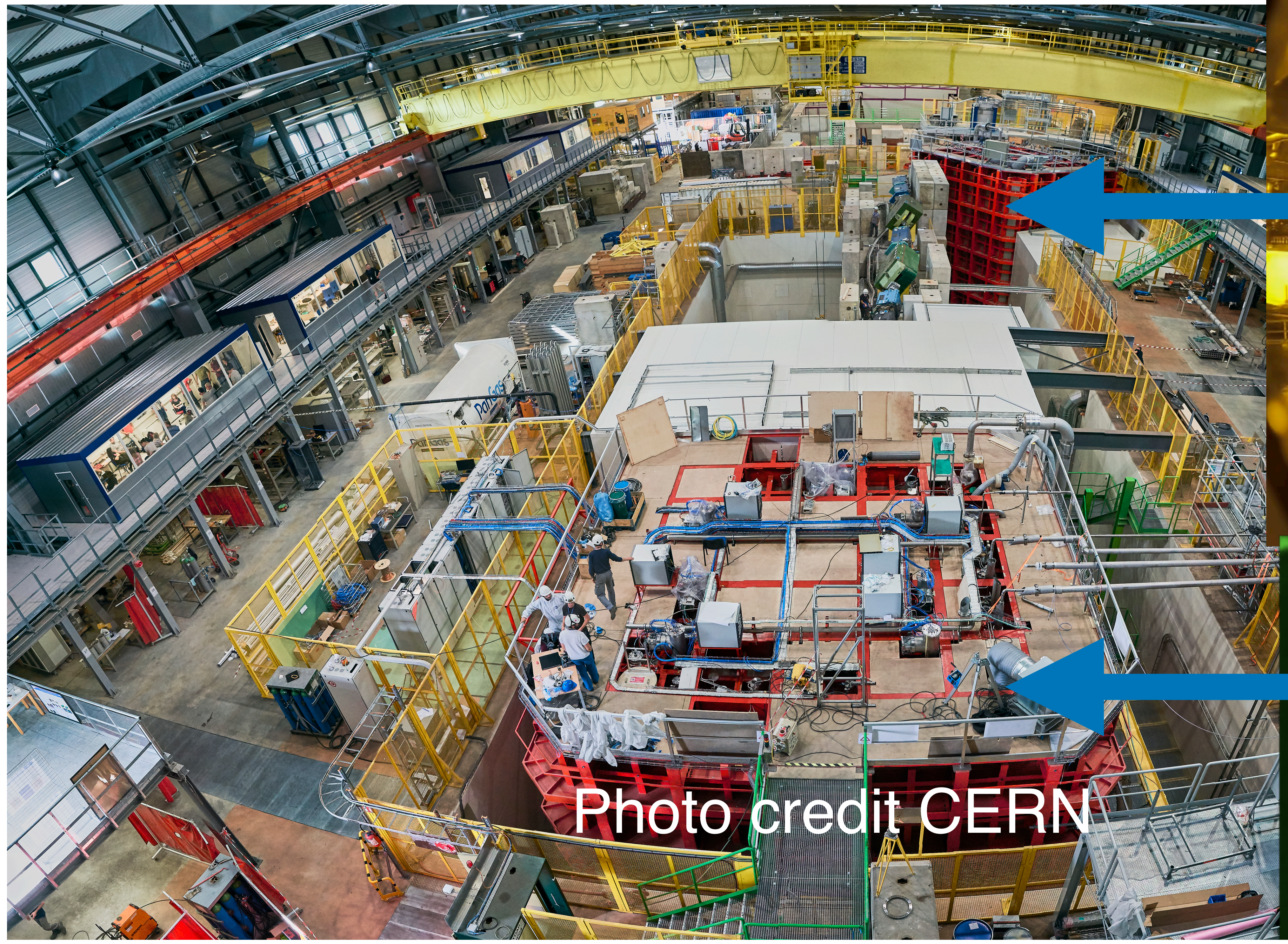
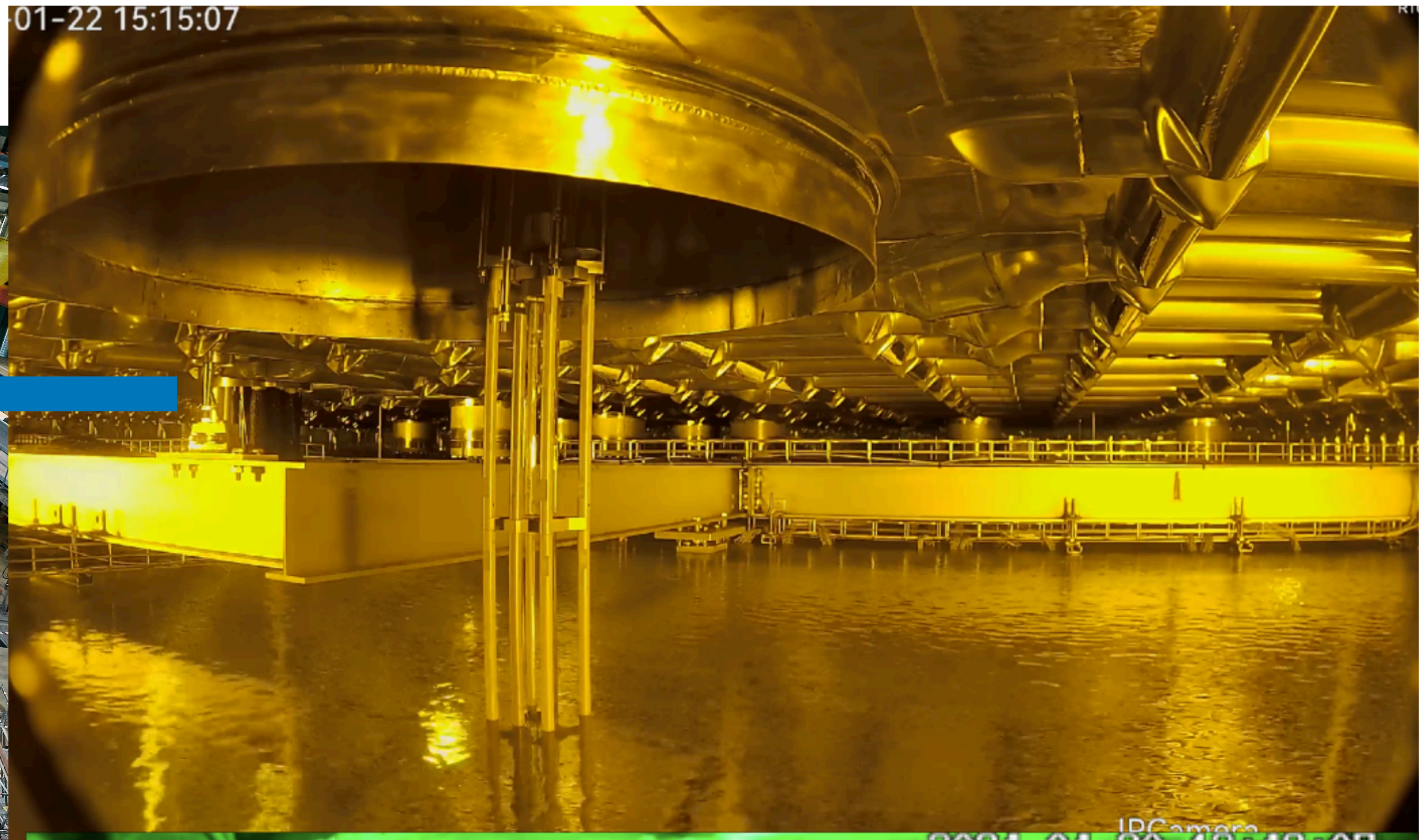


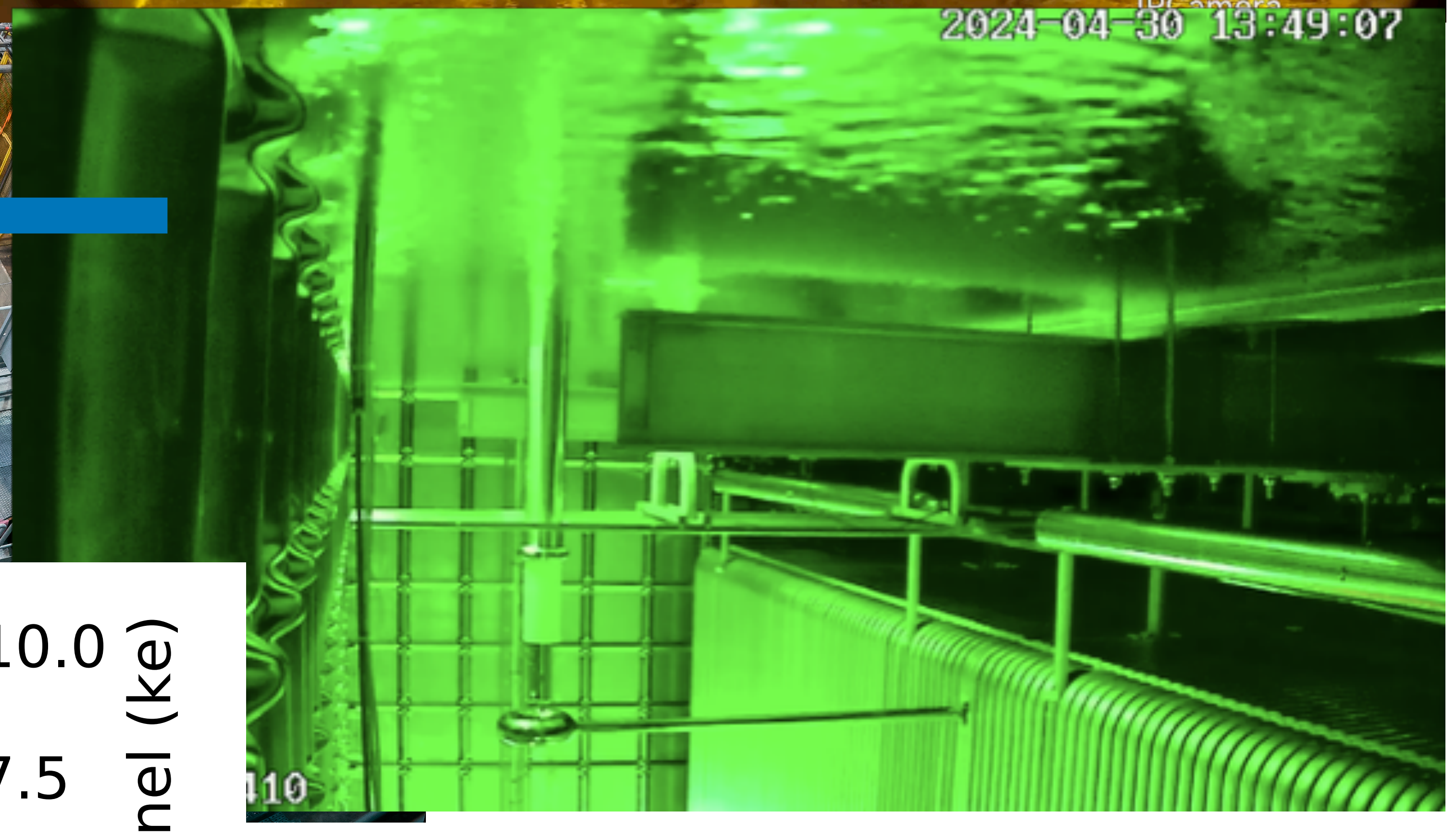
As in
Harris, Ilic, Konaka, Canadian Journal of Physics (2025)

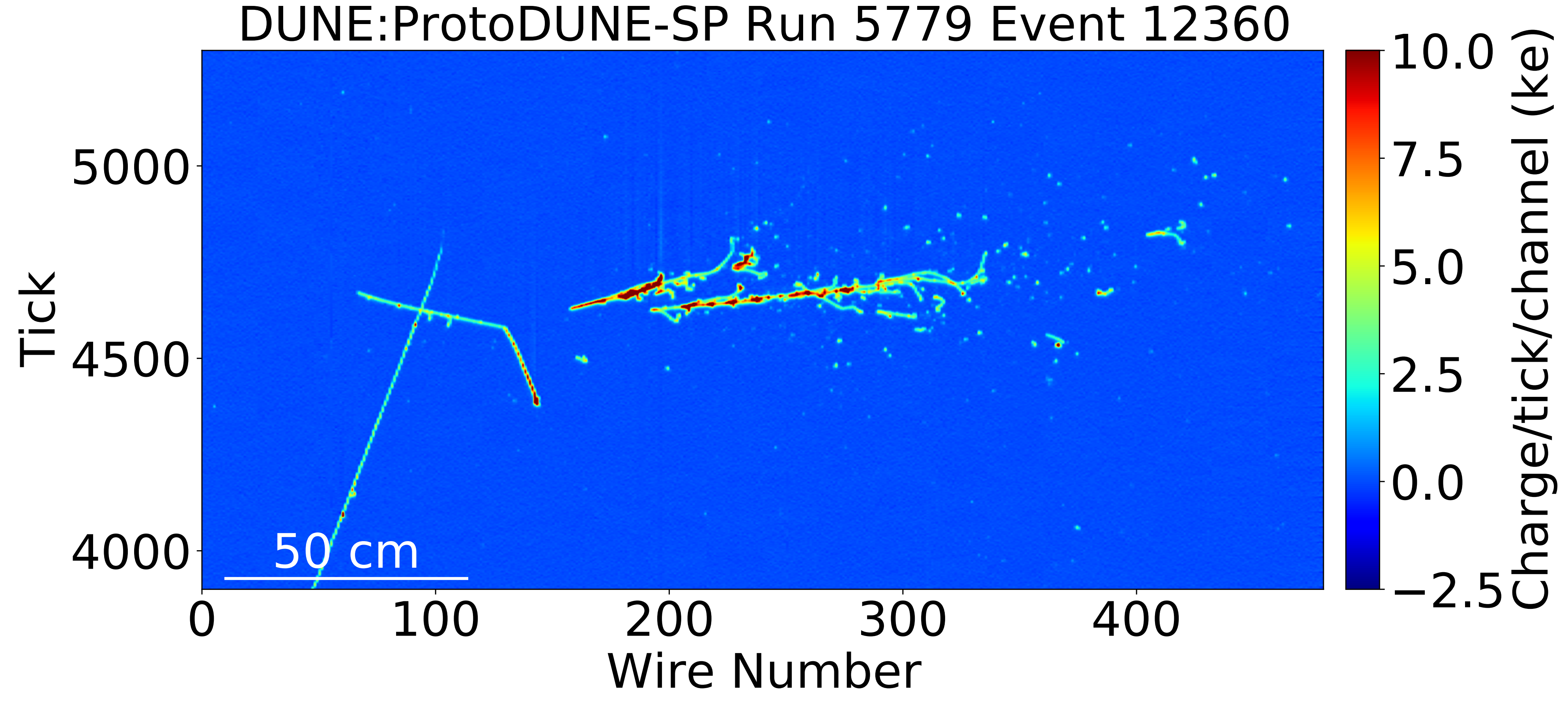
DUNE FD Status

ProtoDUNE testing FD prototypes





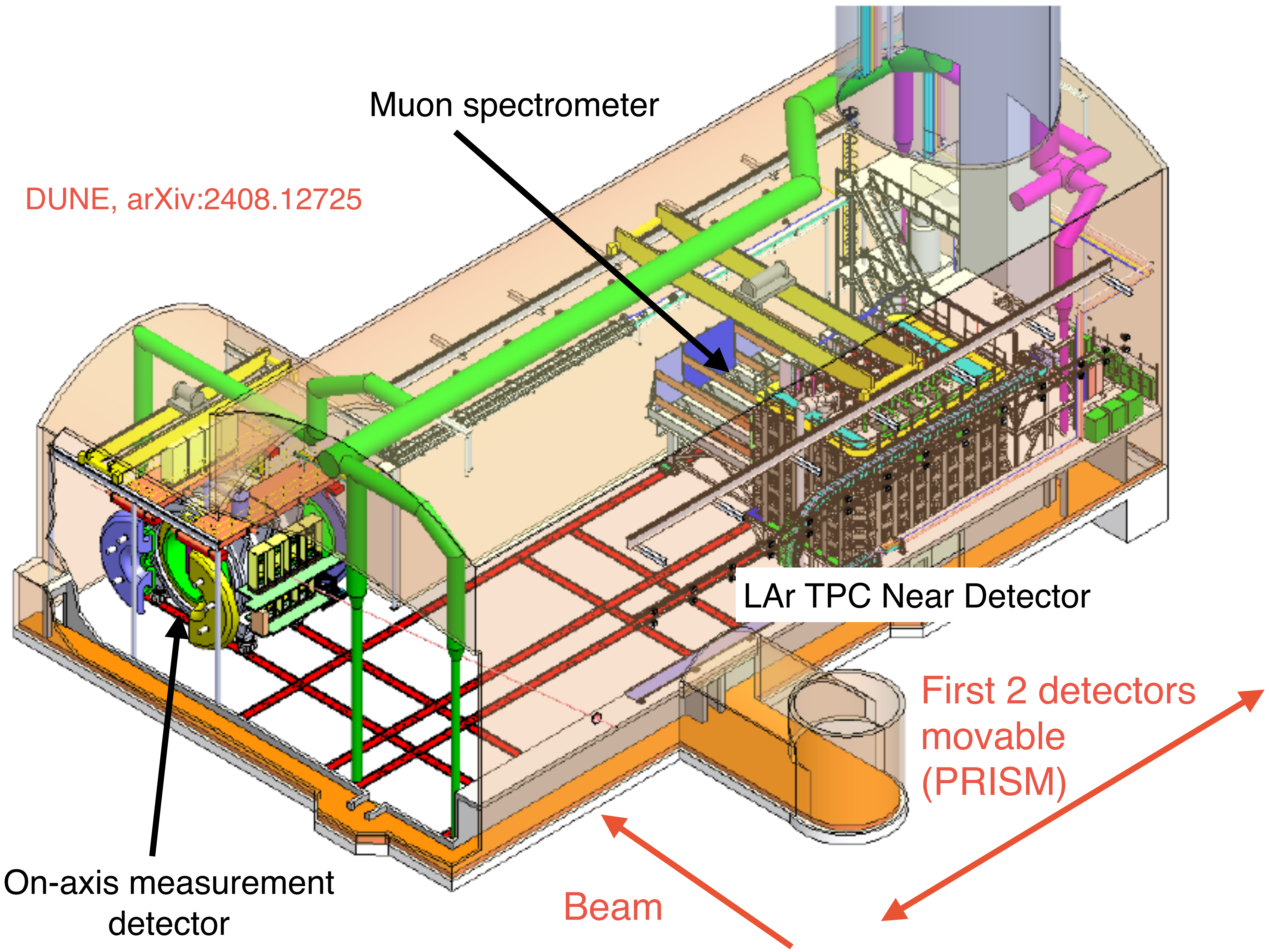


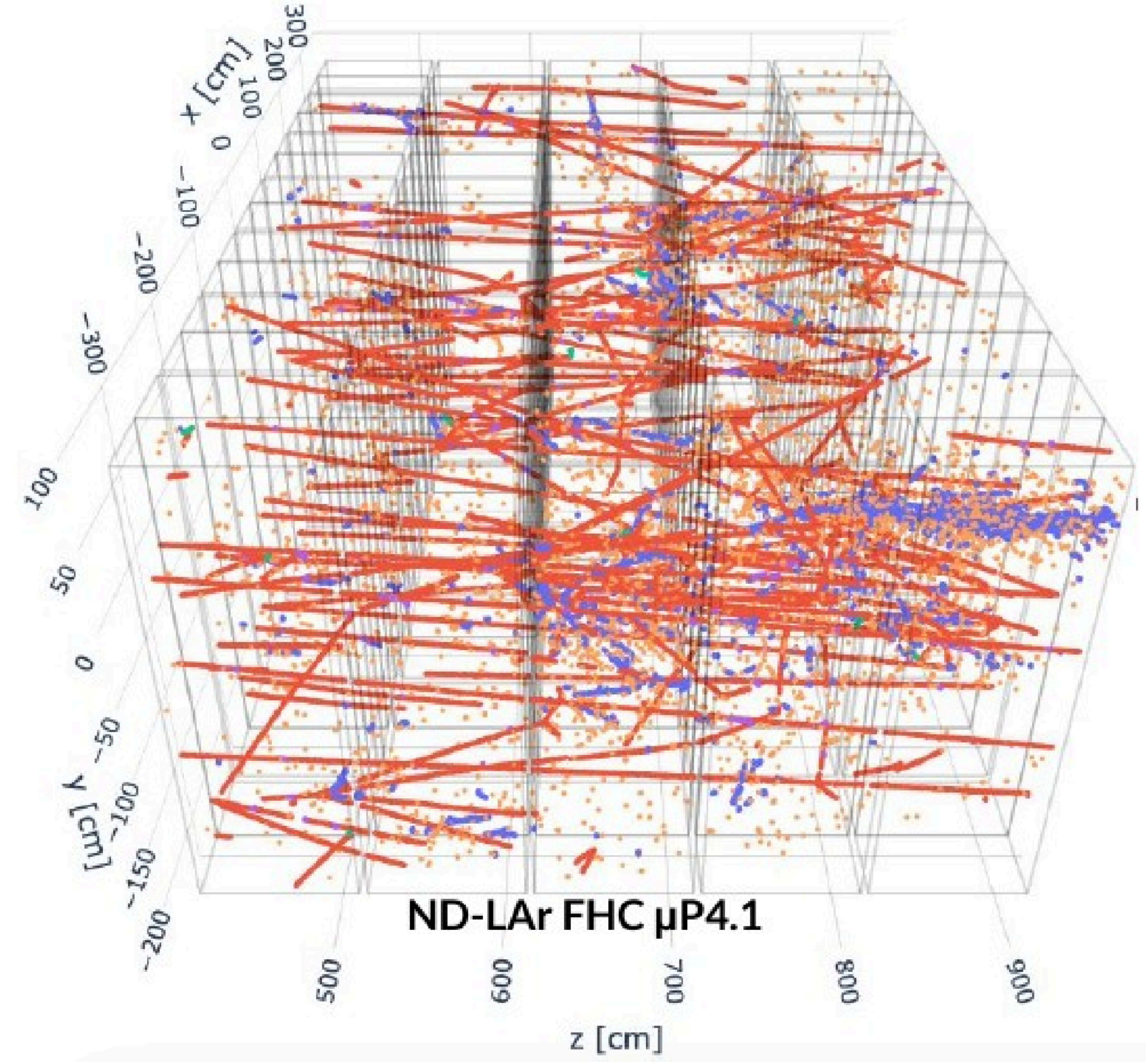


DUNE, JINST **15** P12004 2020

DUNE Near Detector

DUNE, arXiv:2408.12725



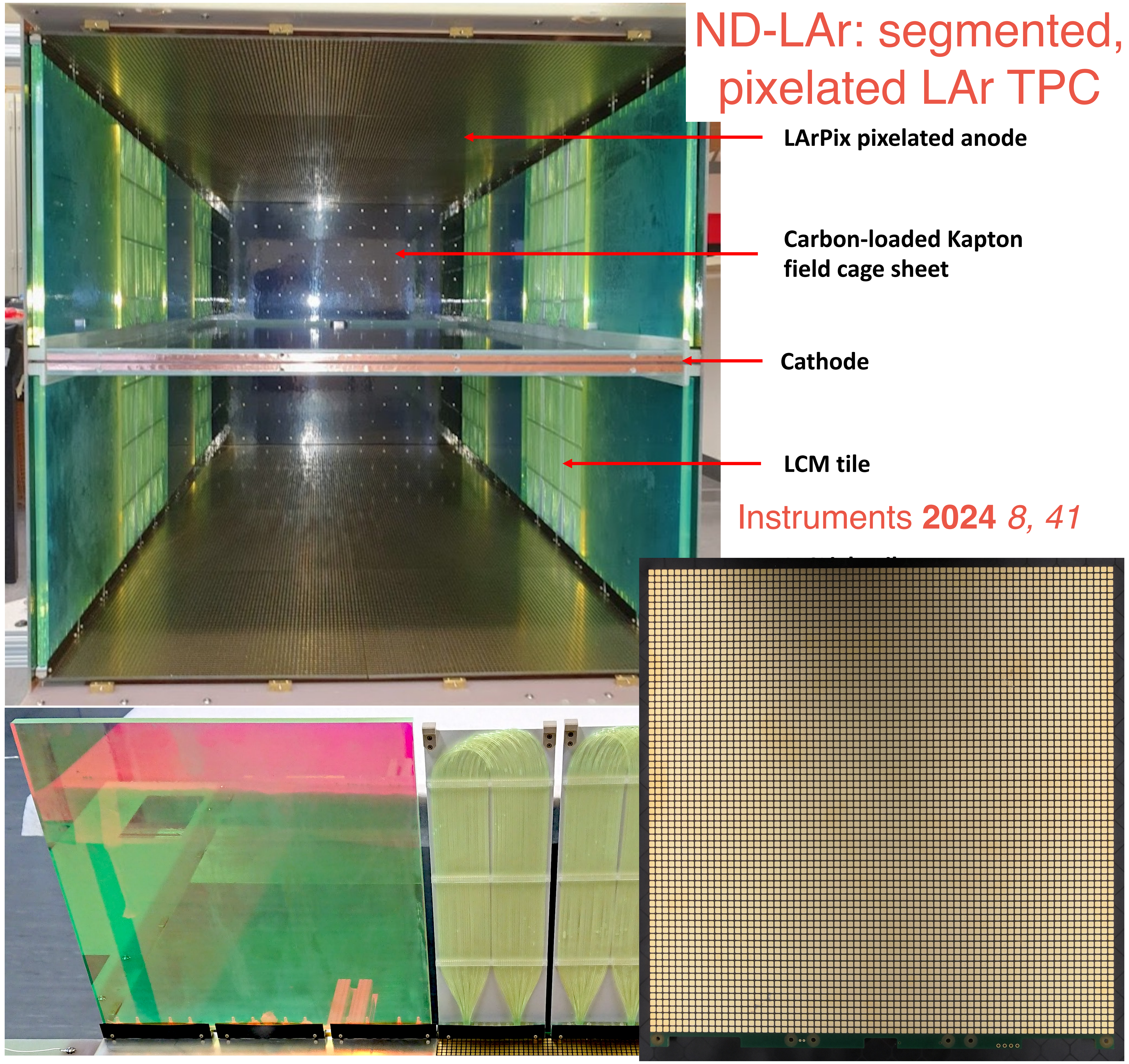


Challenges of a LAr TPC Near Detector (ND-LAr):

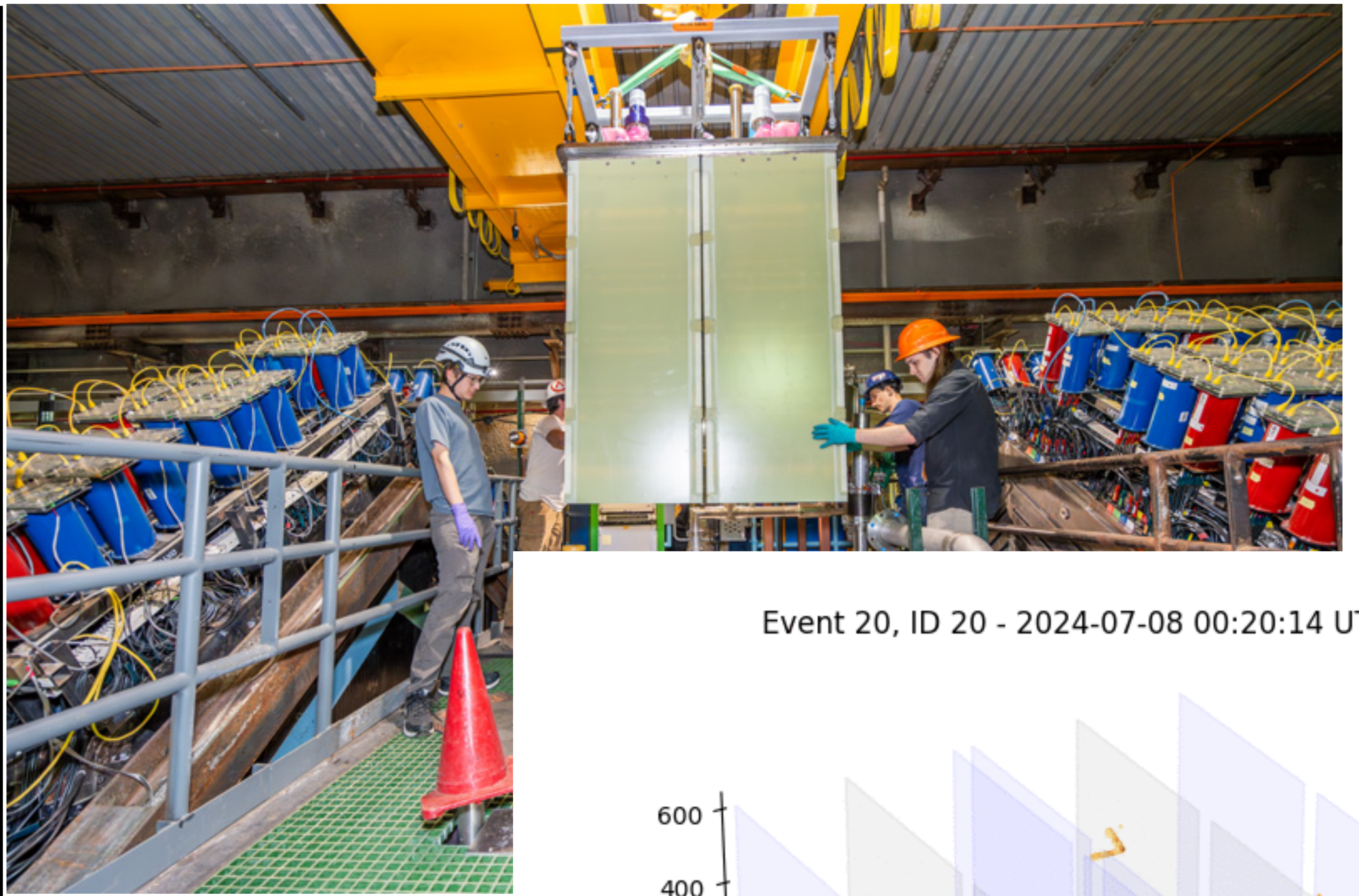
- Slow detector: pileup from being near beam
- Also pileup: traditional wire LArTPCs will have many hits on a given long wire → confusion
- Higher energy muons will escape ND-LAr

DUNE Near Detector

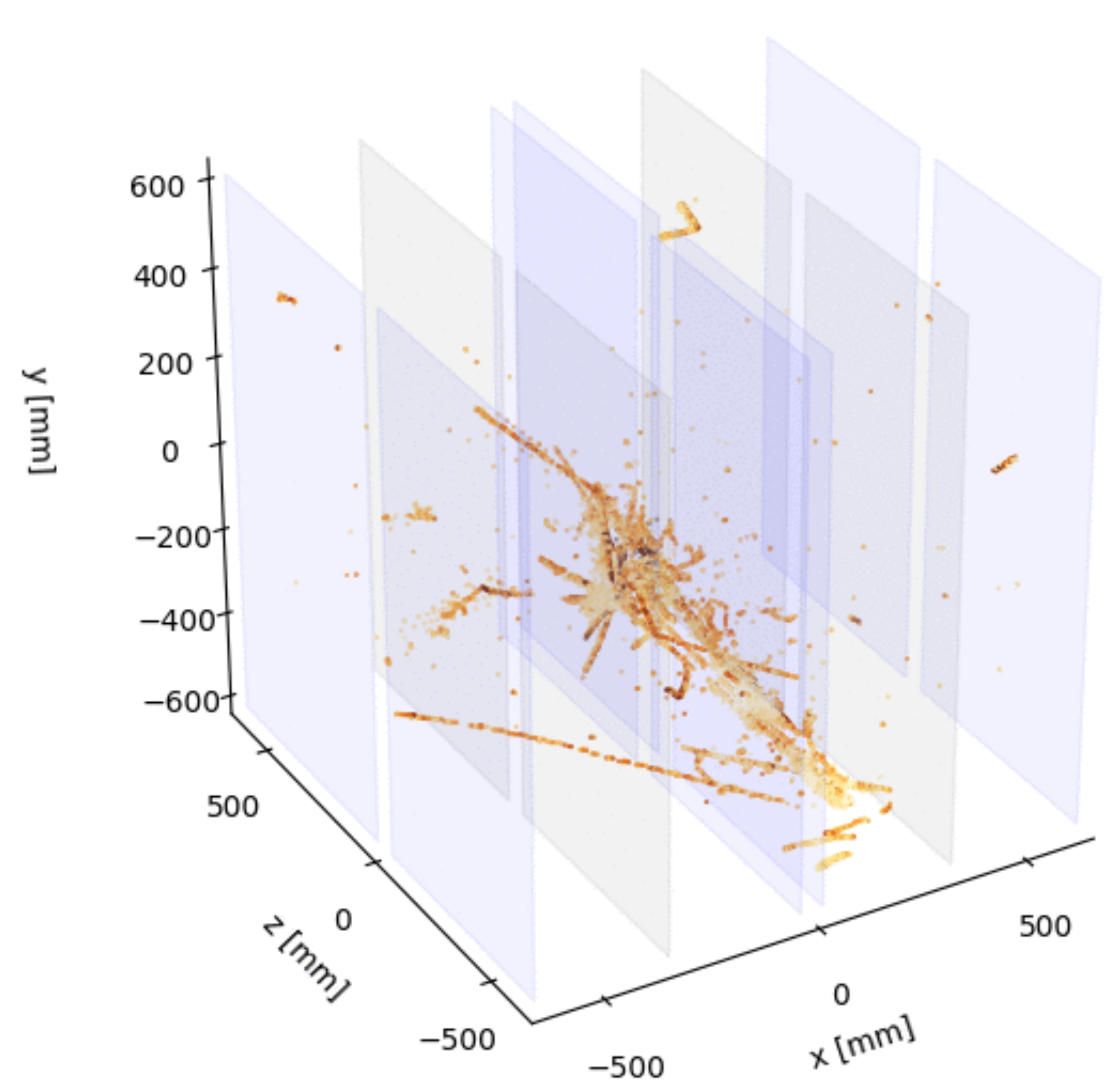
ND-LAr: segmented, pixelated LAr TPC



Instruments **2024** *8, 41*



Prototype operated at Fermilab in summer 2024 in a neutrino beam & this past Fall w/ radioactive sources.



DUNE-Canada

- Currently comprised of York University (Toronto), University of Toronto
  - 3 faculty, w/ postdocs, graduate students & undergraduate students involved
- Strong contributions to both Near, Far Detectors:
  - Data acquisition, ProtoDUNE
  - Far Detector physics: ν_τ appearance, low energy (e.g. solar ν), non-standard interactions, atmospheric ν
  - Near Detector (esp. the LAr TPC but also connections to other systems): prototypes, simulation, calibration, reconstruction and analysis
  - Making use of Digital Research Alliance resources to push forward DUNE here in Canada
    - Helping DUNE to perform oscillation sensitivity analyses and improve neutrino interaction predictions
- New members welcome

Short Baseline Neutrino (SBN) Program

ICARUS

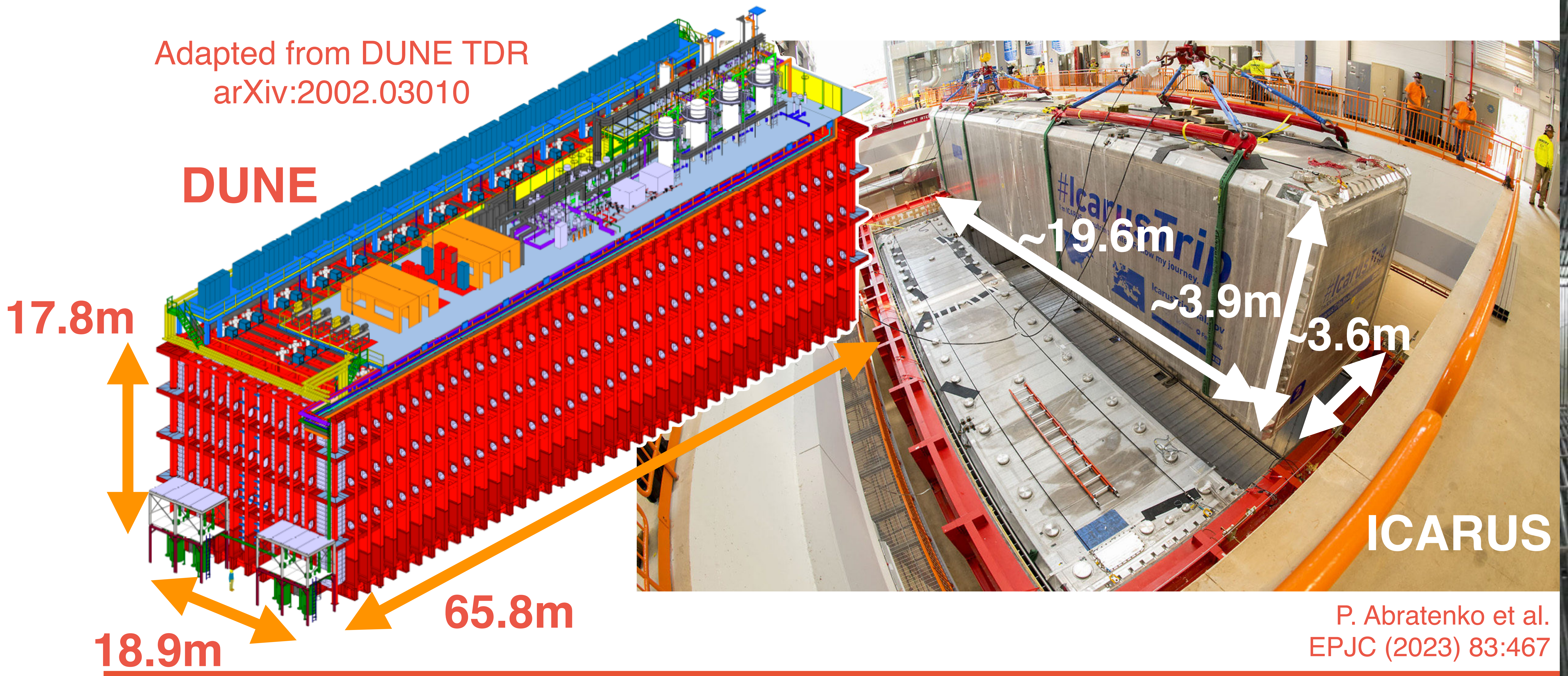
Italy, USA, Brazil, **Canada** (York U), CERN, India, Mexico

Installed at FNAL, filled w/ LAr in 2020, began taking physics data in 2022

760t LAr (476t active), **~1/20 DUNE module** (still one of the biggest)

4 TPCs (1.5 x ~3.1 x ~19 m^3), each 90 PMTs (trigger), external cosmic tagger

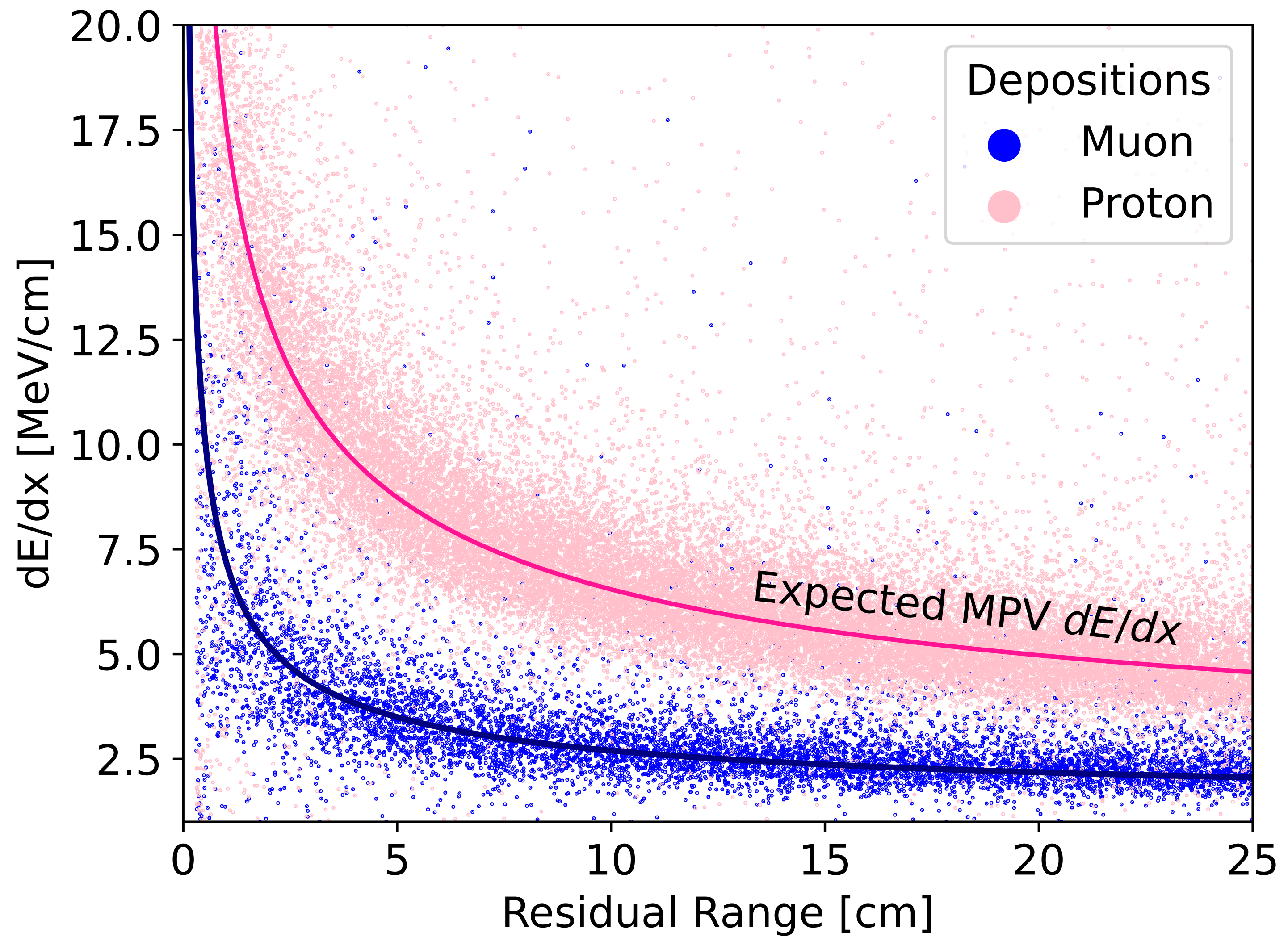
Adapted from DUNE TDR arXiv:2002.03010



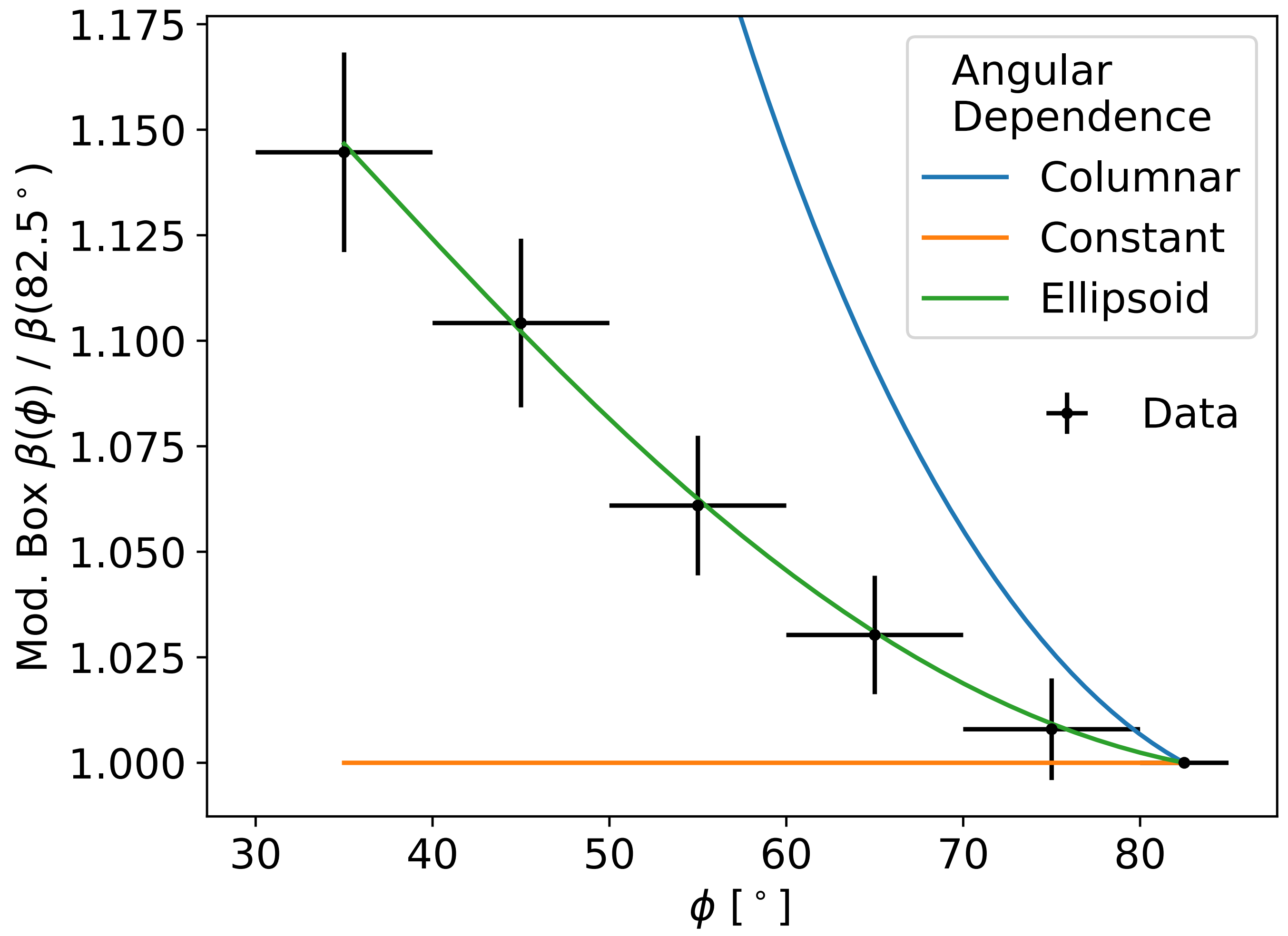
P. Abratenko et al. EPJC (2023) 83:467

ICARUS so far

- *Excellent* opportunity to gain experience in operating, calibrating, analyzing such data to prepare for DUNE
- Conducting key physics measurements (and training students & postdocs)
  - Primary goal: look for oscillations on a short baseline (clarify the sterile neutrino picture)
    - ICARUS-only measurement recently presented in seminar at Fermilab, publication in preparation
    - SBND also now operating → 2 detector studies to follow
  - Also studying **neutrino interactions** (briefly discussed here)
    - Publication of first measurement results in preparation
  - Also searching for BSM signatures (PRL 134 (2025) 151801)

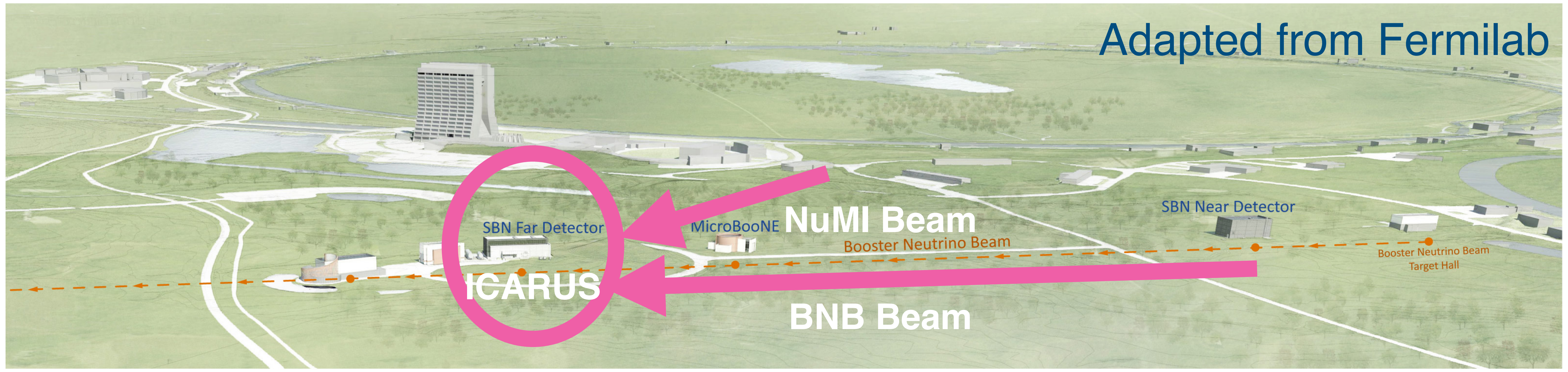


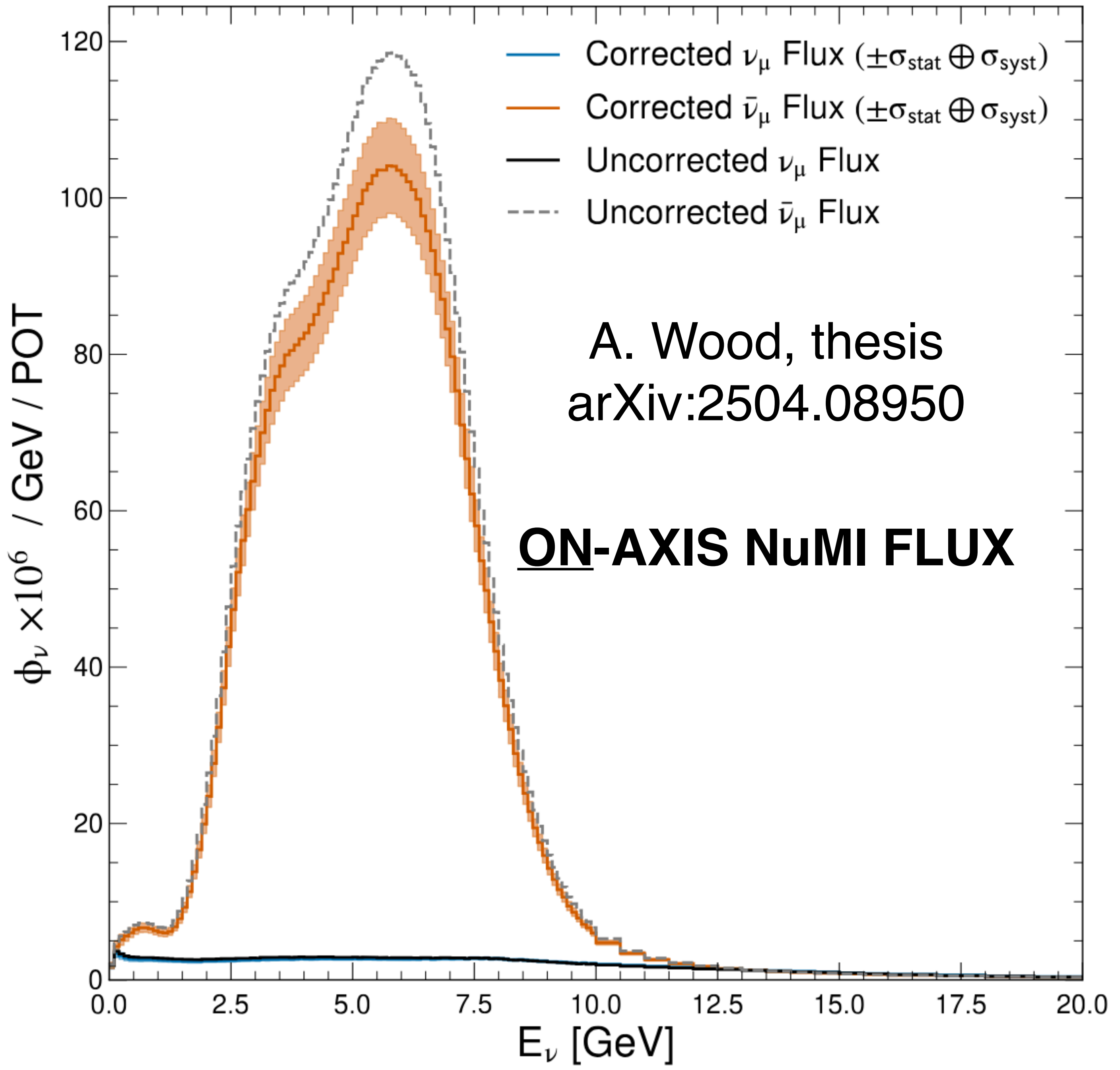
JINST **20** P01033

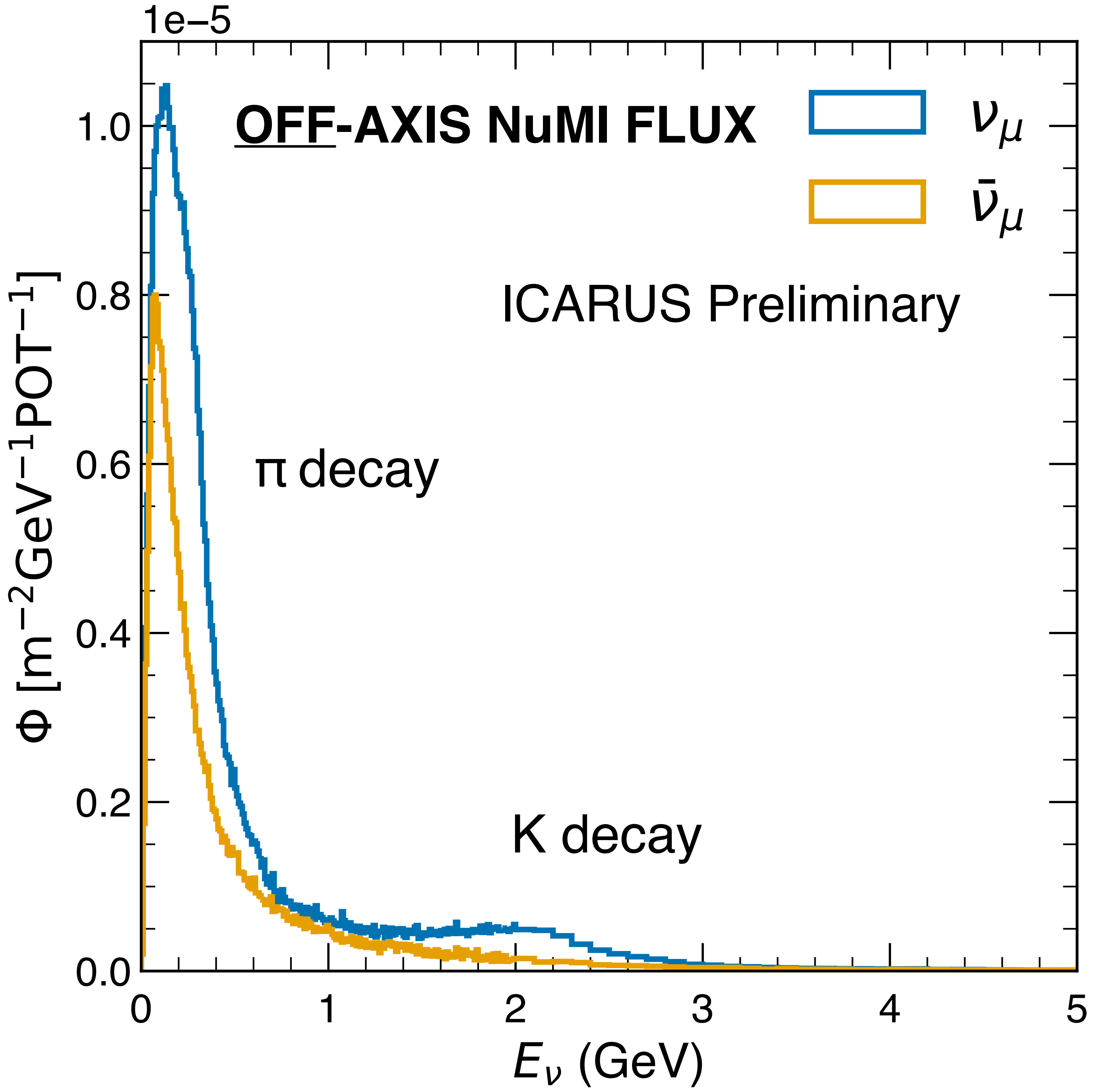


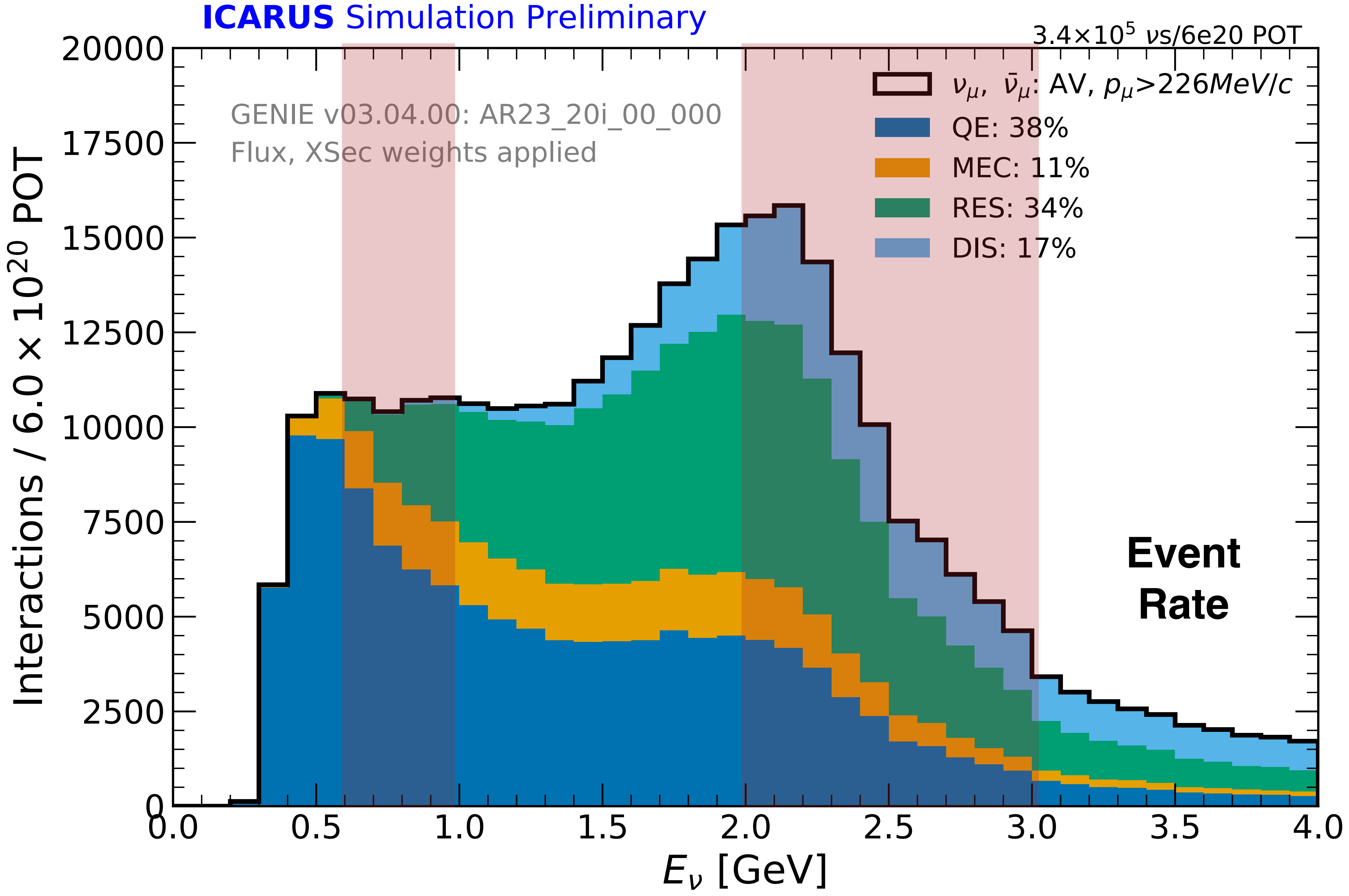
NuMI beam for ICARUS

- ICARUS ~6 degrees off-axis (100 mrad) off-axis of NuMI beam line
  - 120 GeV protons, graphite target
  - On-axis peak flux ~6 GeV
  - Electron neutrino component also!







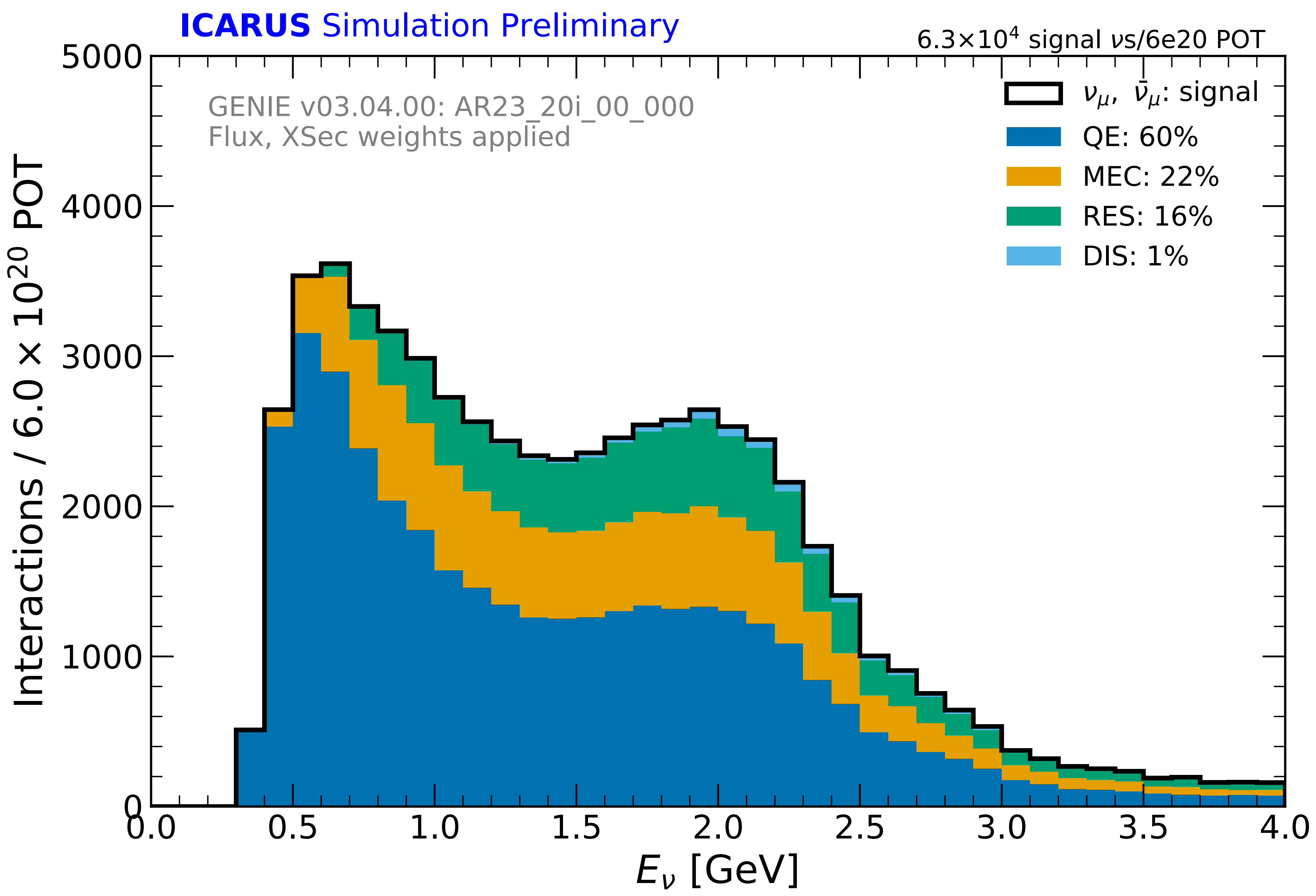


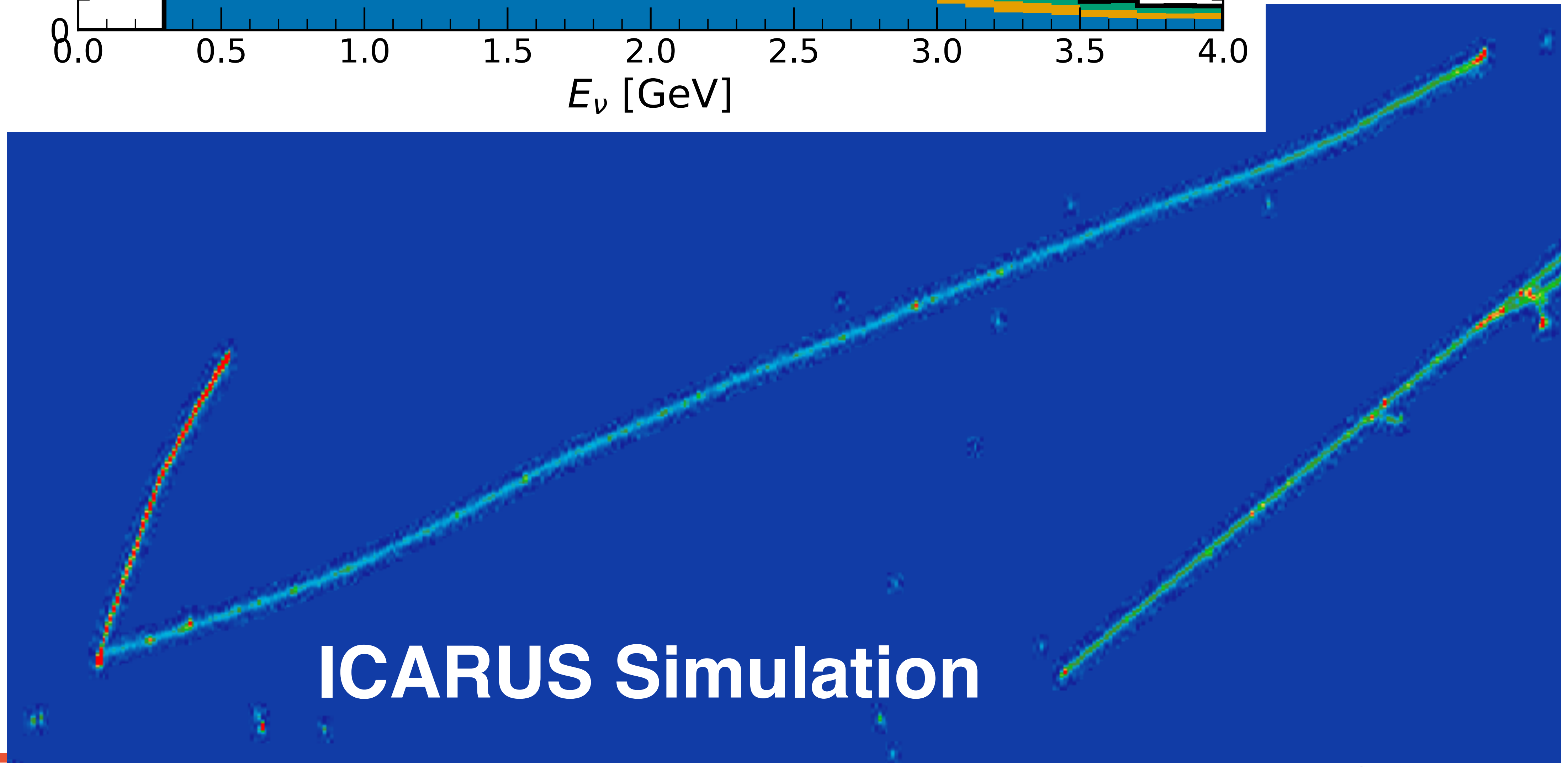
Cross-sections with NuMI

- First cross-section with NuMI at ICARUS: targeted a signature with 1μ, at least 1p, and 0π in final state
  - Quasi-elastic-like (QE-like)
  - 0π in could be because none produced, or because of final state interactions (FSI)

- Signal selection: look at reconstructed particles, select if matching signal criteria
  - Reject if: tagged as cosmic by reconstruction (Pandora), photon-like showers (π^0), extra minimum ionizing tracks ($\pi^\pm$)

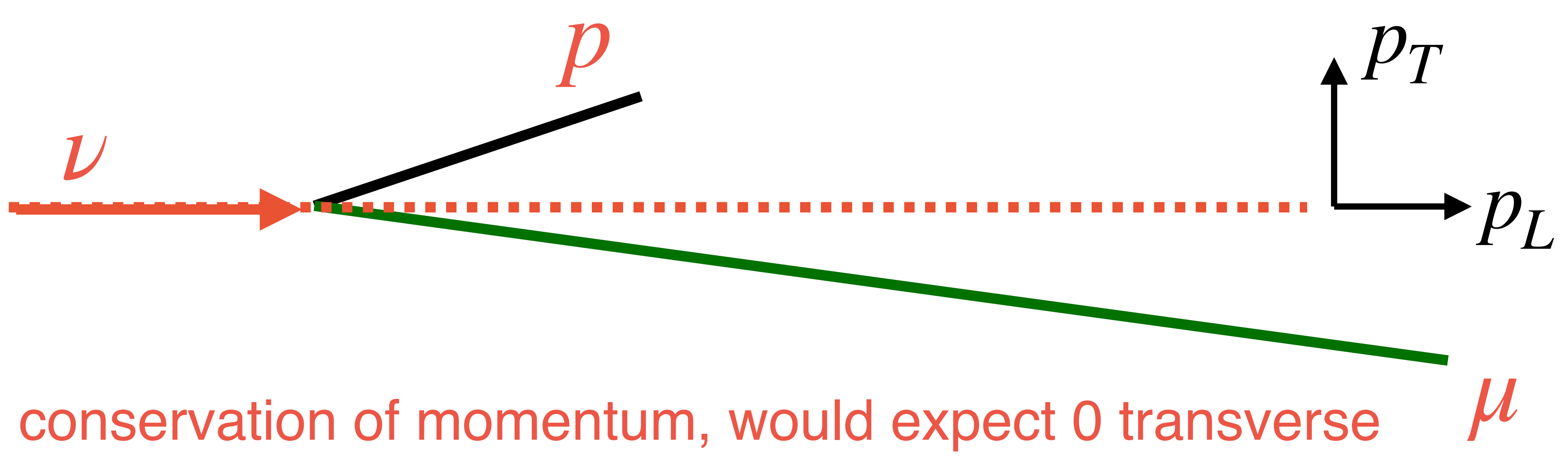
- Sideband: flip $\pi^\pm$ rejection cut, **require** a second minimum ionizing track (length > 10 cm)



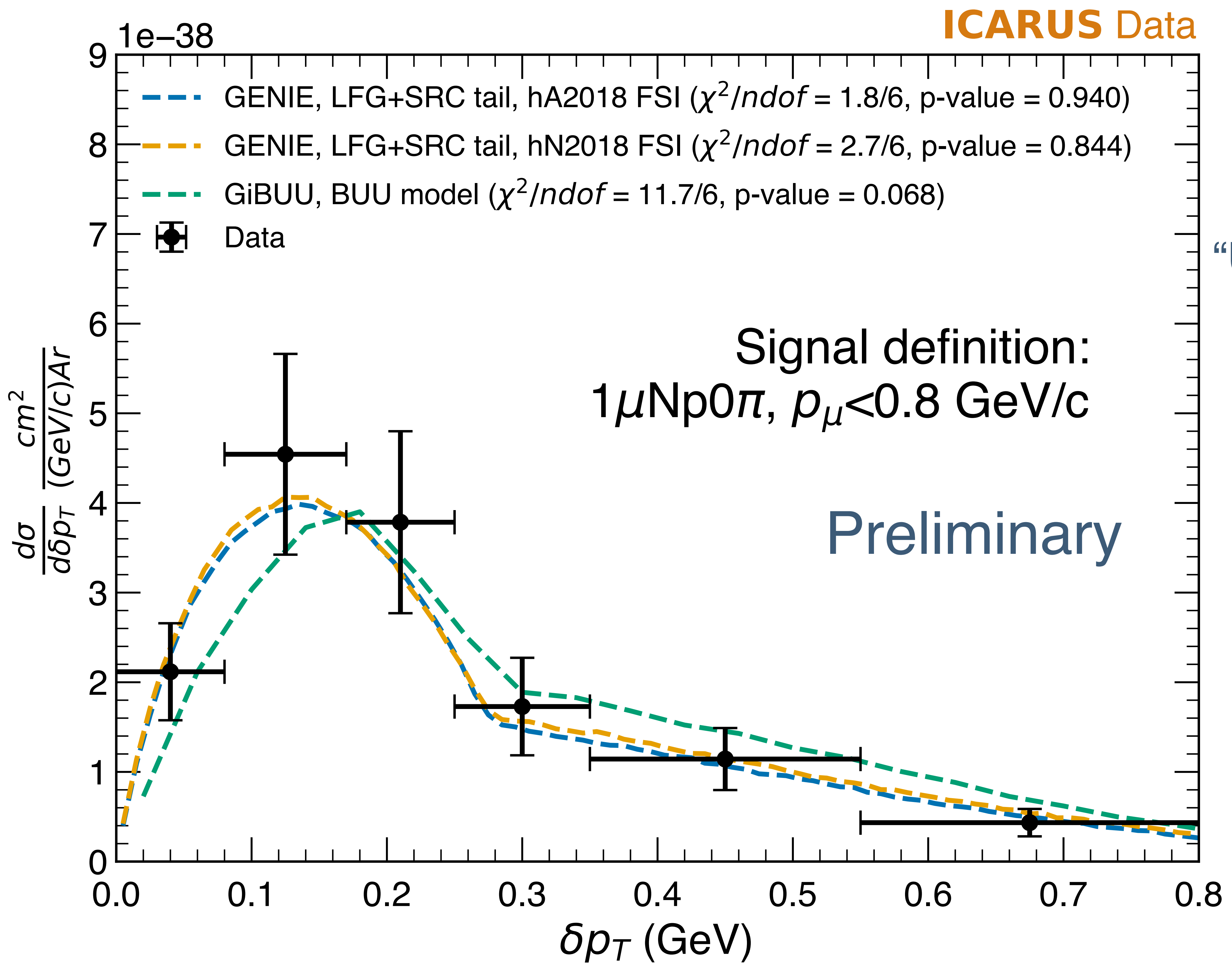


Cross-sections with NuMI

- We use a fitting tool (GUNDAM) initially developed within T2K to fit signal, sideband concurrently. Then from there we use it to extract cross-section.
- Cross-section result(s) & comparison to different generator models
- Showing here one of our 4 variables



From conservation of momentum, would expect 0 transverse momentum. BUT initial motion of the nucleons in the nucleus and final state interactions modify this!



"Unaccounted momentum"

- This is just the first, many more cross-sections to study and can study these in more detail

Conclusions

- Still many open questions and under-explored parameters with neutrino oscillation
  - The current generation of oscillation experiments is doing a good job of pushing forward our knowledge, but will not be able to address everything
- Liquid argon time-projection chambers (LAr TPC): tracking-calorimeters w/ sensing elements a few mm apart → sensitive detectors!
- DUNE will place very large LAr TPCs deep underground (Far Detector) and a sensitive Near Detector to perform measurements and constrain the oscillation measurements
  - Mass-ordering (long-baseline), possible CP violation, ν_τ measurements and testing unitarity
- ICARUS is a currently operating LAr TPC (~1/20 size of a DUNE Far Detector module)
  - Main goal is to clarify the question of sterile neutrinos **but** also provides important experience with these detectors and the ability to study neutrino interactions to test models for use in DUNE.
  - First cross-section measurement performed: many more interaction channels, variables to investigate
- Lots of data and training for students and postdocs on these programs, and Canadian involvement is pushing forward these programs!

Acknowledgements

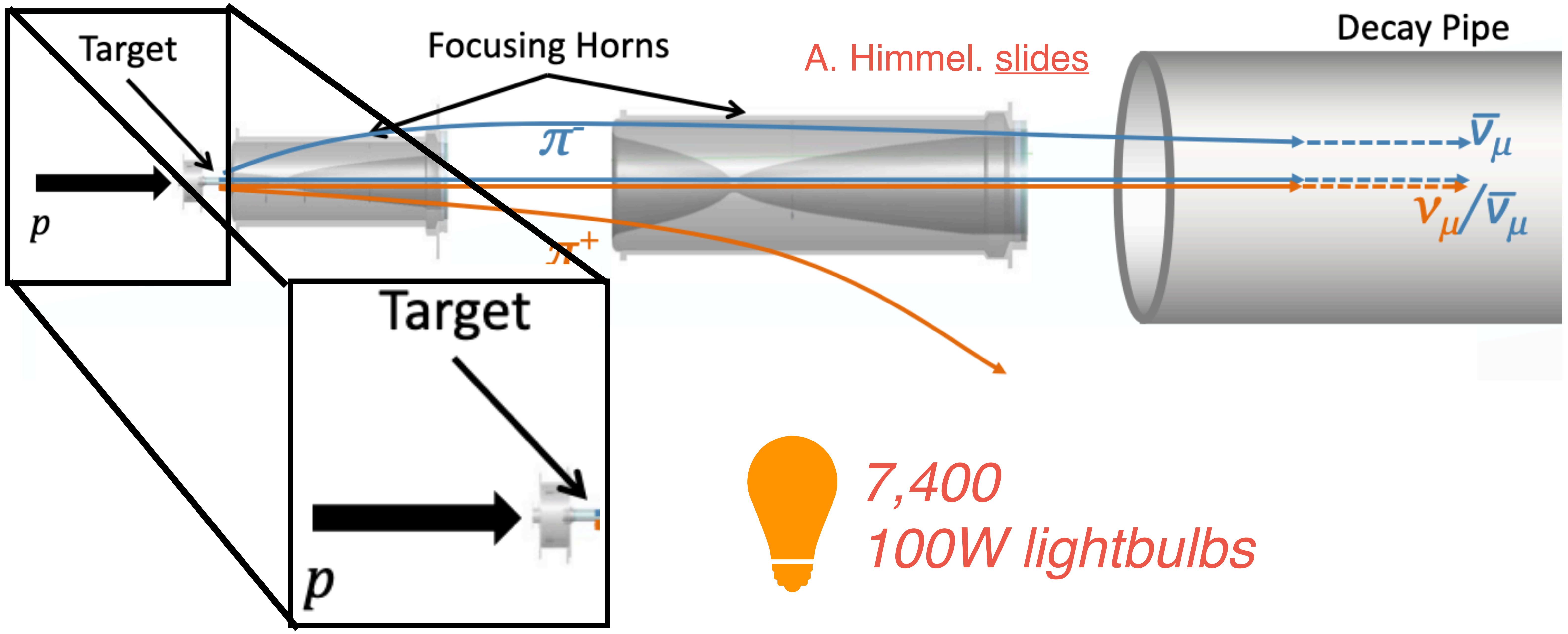
DUNE efforts in Canada are supported by NSERC, CFI, IPP, and Digital Research Alliance, as well as funds from our universities. MRS support is received from University of Montreal and McGill University.

This document was prepared by DUNE and ICARUS using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, Office of High Energy Physics HEP User Facility. Fermilab is managed by Fermi Forward Discovery Group, LLC, acting under Contract No. 89243024CSC000002.

Backup

Source: accelerators

- One way of getting more neutrinos: more protons hitting the target!
- "Protons on target" overall, and beam itself is often quoted based on **power:**



A. Himmel. slides

7,400
100W lightbulbs

It's all about yield of protons:

E=120 GeV protons (~1.92x10^{-8} J)

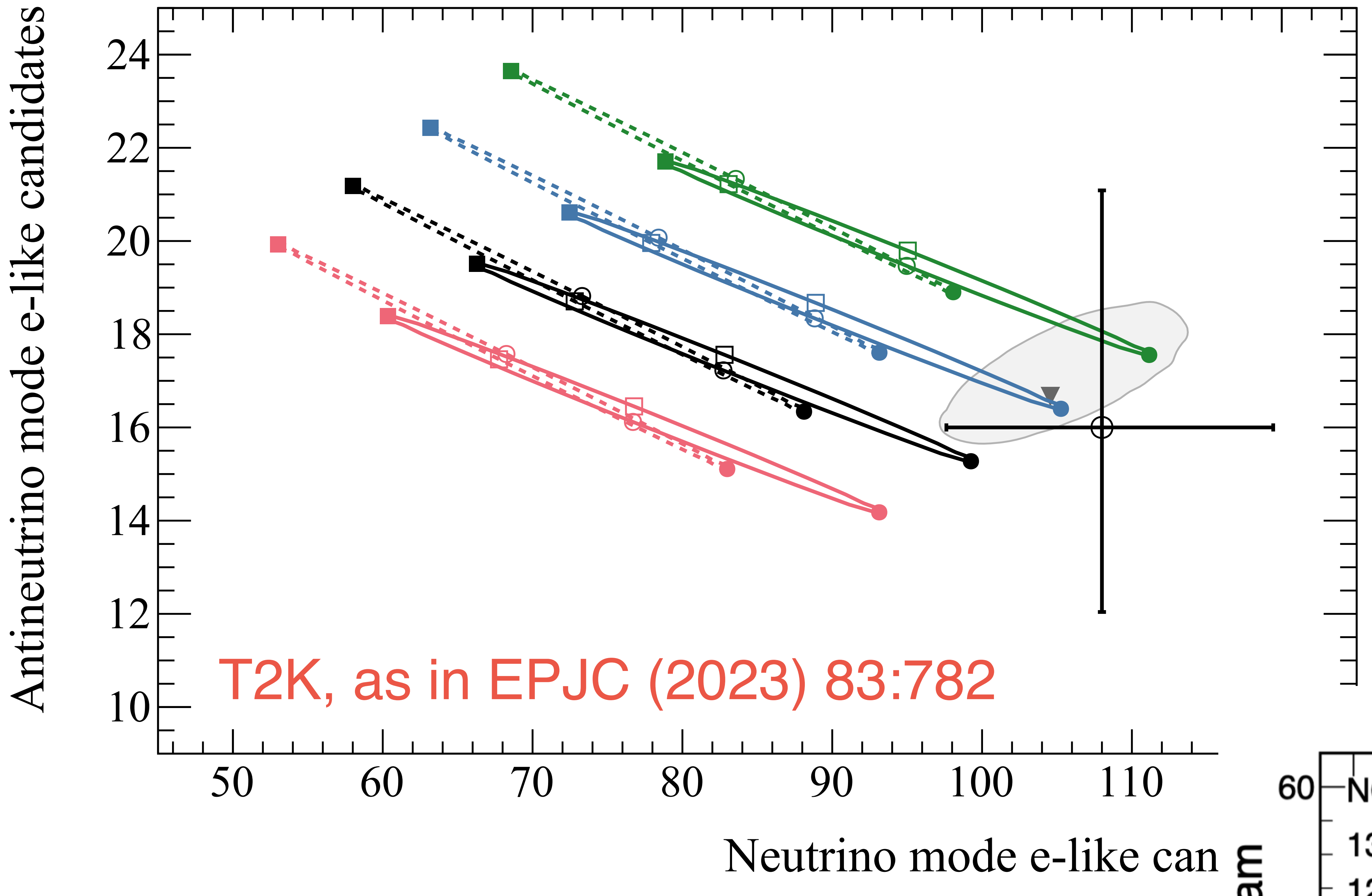
N=1 "spill" sends ~5x10^{13} protons

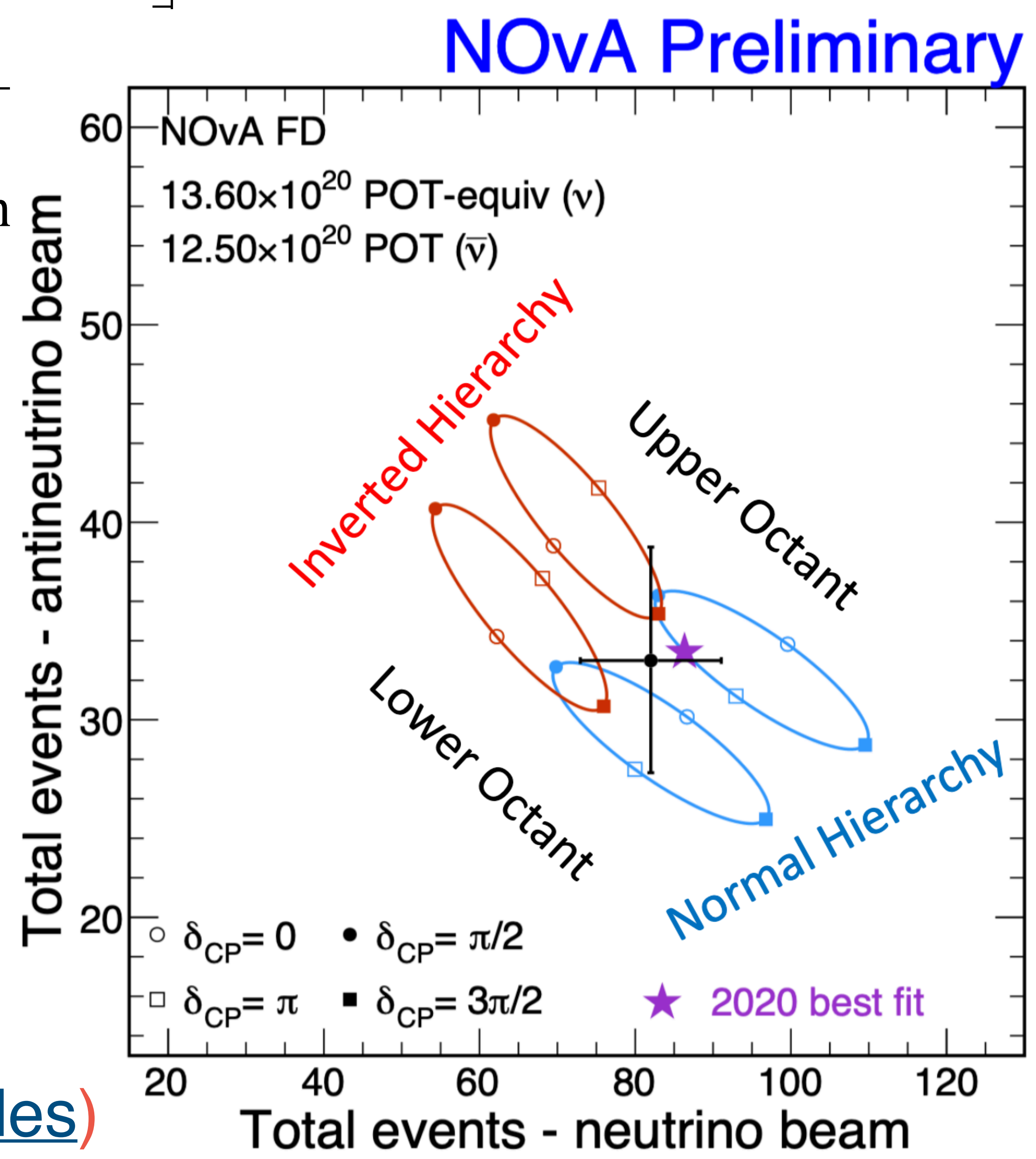
T=Spills ~1.2-1.3 seconds apart

P = N*E / T ~ 740 kW

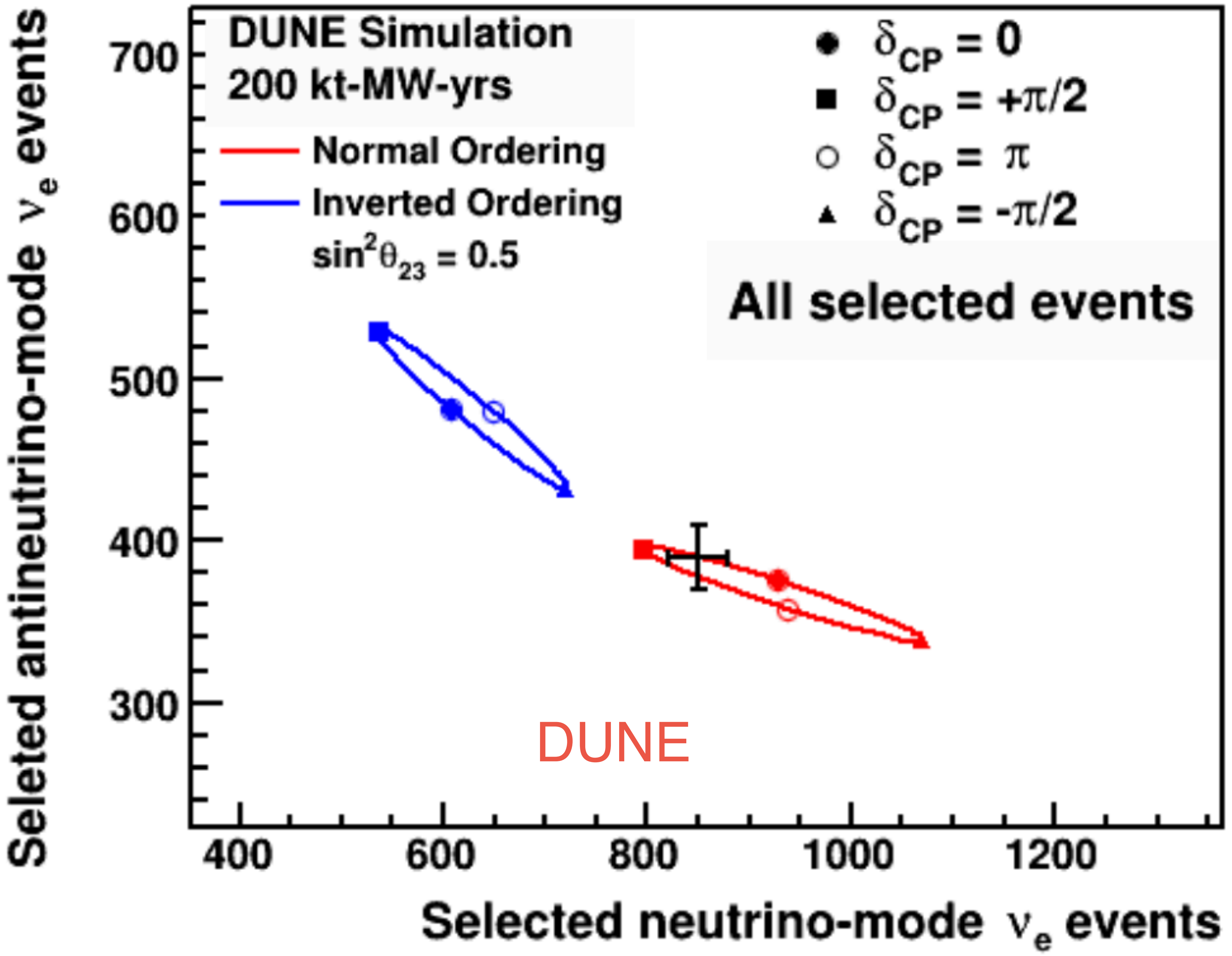
- Current generation beam at Fermilab has run ~700 kW (pushed up to ~900 kW). Next generation intends to start ~1.2 MW, possibly reach 2+ MW

See C. Marshall colloquium





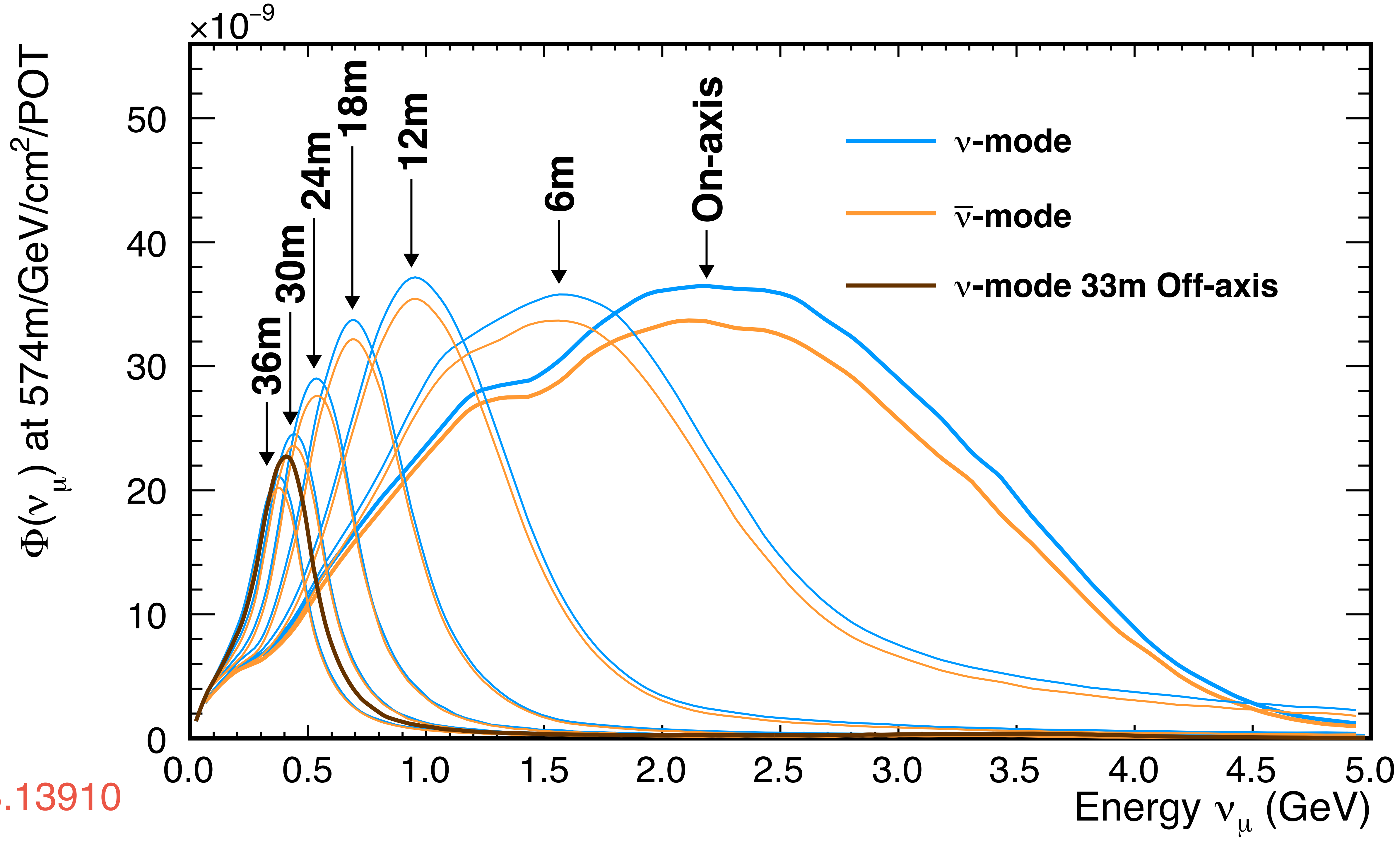
A. Himmel, Neutrino 2020 (slides)



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

arXiv:1307.7335

DUNE PRISM



DUNE, arXiv:2103.13910

Unfolding to i true bin

Signal events in j reco bin (i.e. bkgd subtracted)

$$\left(\frac{d\sigma}{d\delta p_T}\right)_i = \frac{\sum_j U_{ij} N_j^{sig}}{\epsilon_i \Phi N_{Ar} (\Delta \delta p_T)_i}$$

Efficiency

Flux

Targets

Bin size

See article on mathematic methods in cross-sections arXiv:2401.04065 [hep-ex]