Exploring the Nature of Neutrinos with the Deep Underground Neutrino Experiment (DUNE)

Prof. Bruce Howard (York University & Fermilab)
on behalf of the DUNE Collaboration

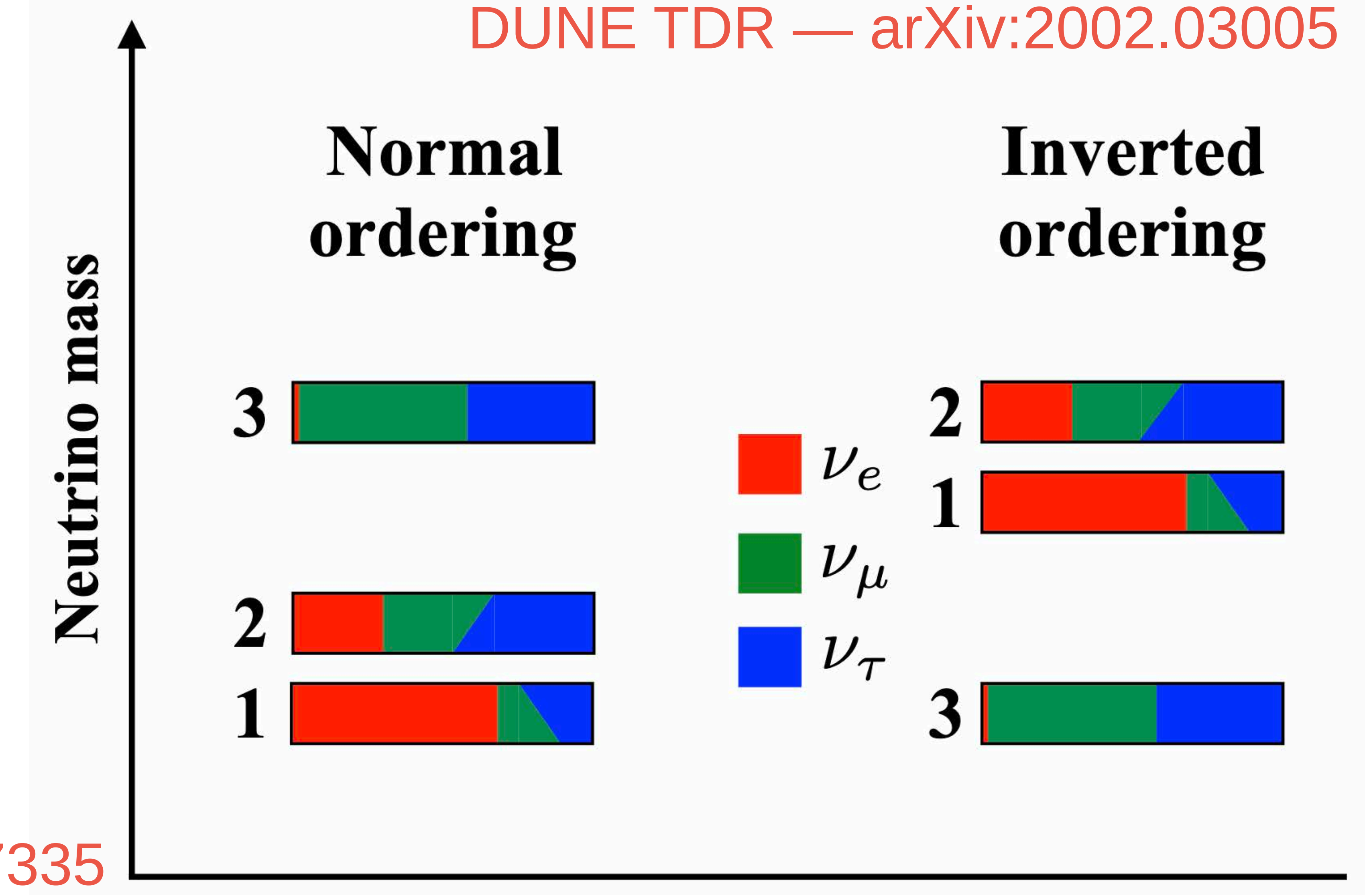
CAP Congress 2025
10 June 2025 | Saskatoon, Saskatchewan

This manuscript has been authored by FermiForward Discovery Group, LLC under Contract No. 89243024CSC000002 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics

Neutrinos/oscillation

- Neutrinos: *nearly* massless, neutral leptons proposed in 1930 and discovered mid-1950s
  - 3 flavours (e,μ,τ), superposition of 3 mass states
- Studies of solar (electron) neutrino flux (Ray Davis, 1960s on) consistently found fewer than expected
- Late 1990s/early 2000s: SNO (Ontario) and Super-Kamiokande (Japan) determine that neutrinos oscillate
- Neutrinos oscillate: created in 1 flavour, probability to later detect a given flavour evolves with time
  - Probability for oscillation evolves as L/E
  - Rotation angles, mass splitting dictate location and amplitude of probability dips
  - Complex phase encapsulates potential differences in $\nu, \bar{\nu}$ oscillations

DUNE TDR — arXiv:2002.03005

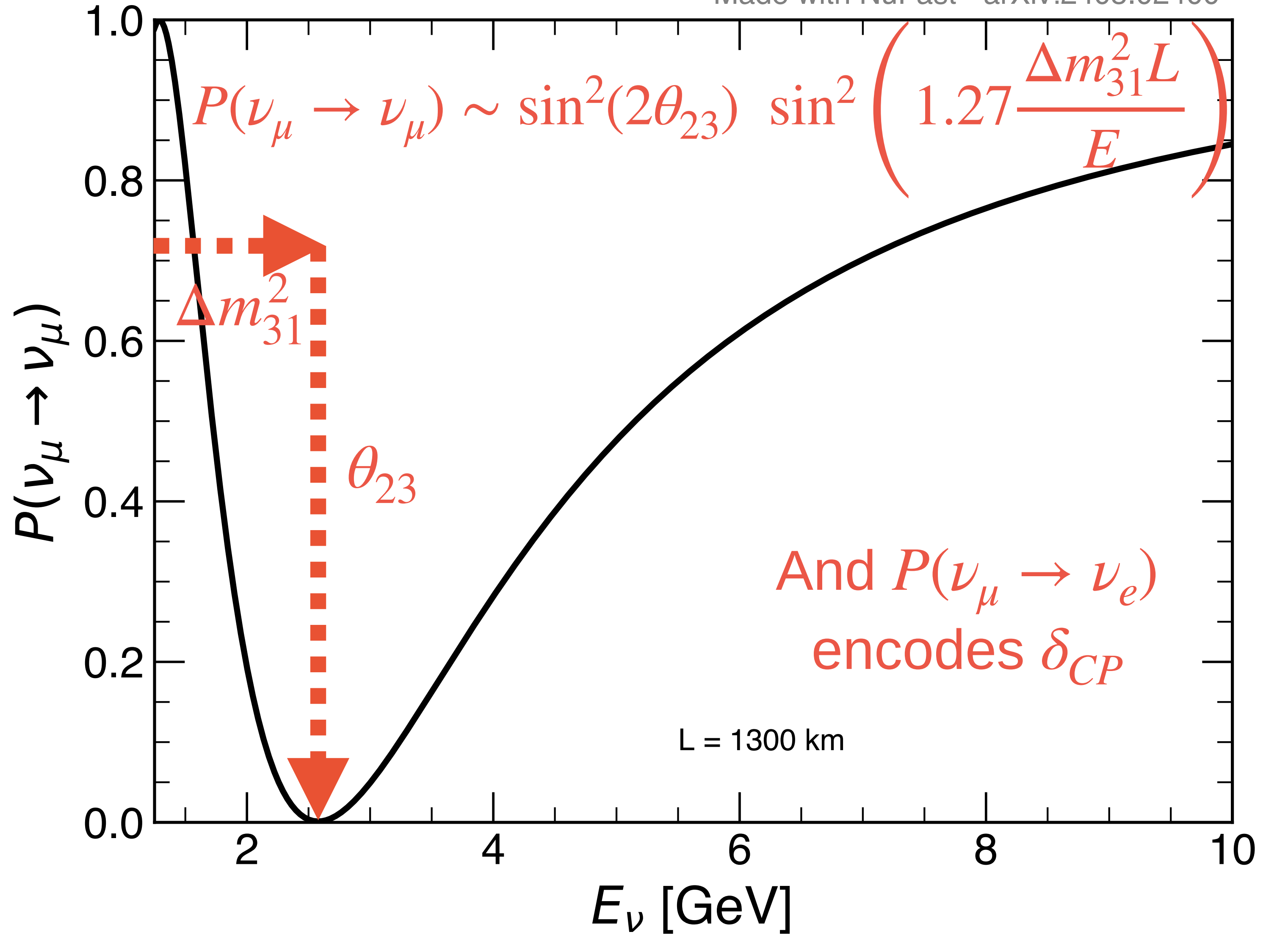


arXiv:1307.7335

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

Illustrative purposes

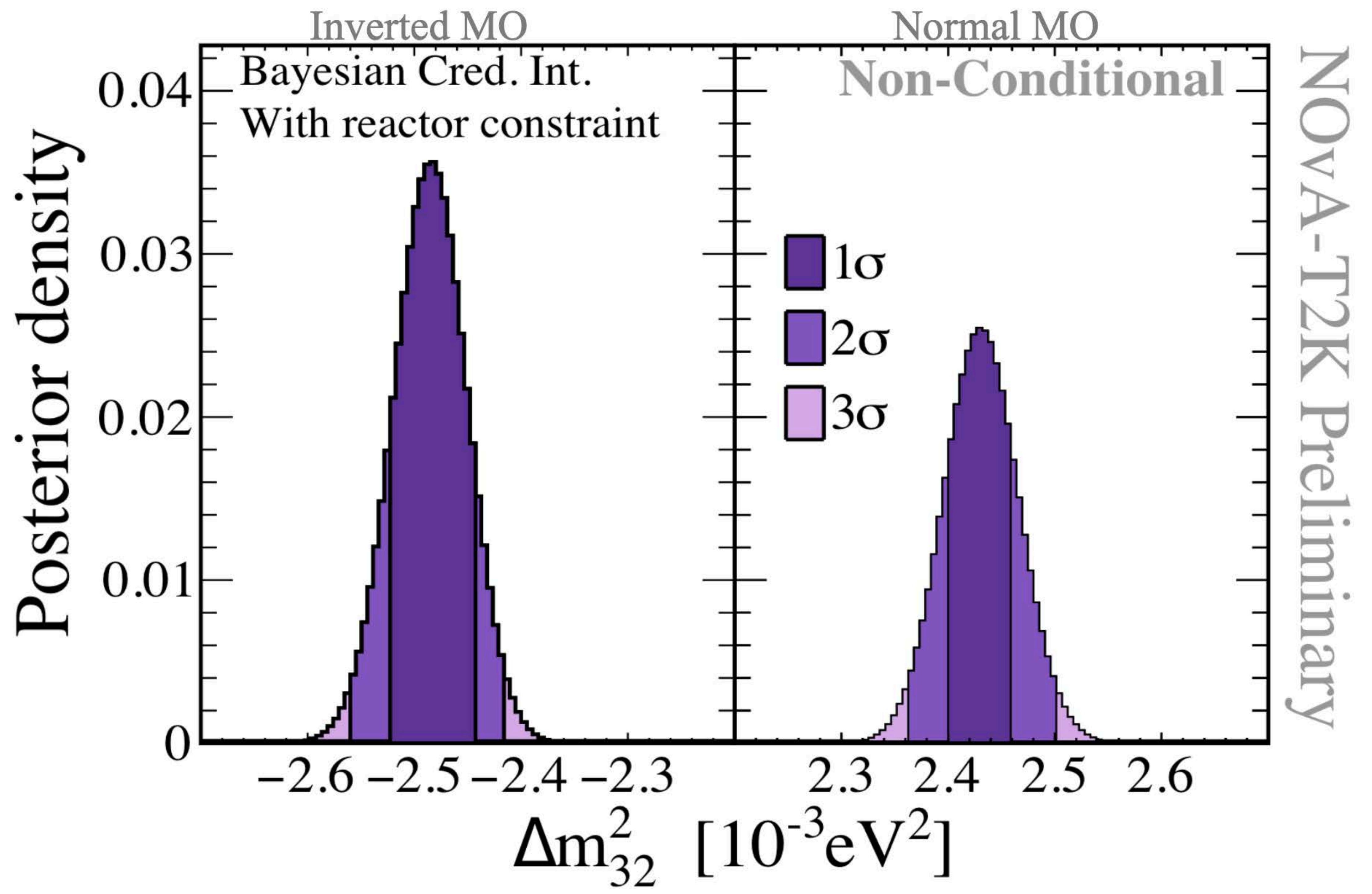
Made with NuFast - arXiv:2405.02400



Open questions in neutrino (oscillation)

- Several open questions related to neutrino oscillation:
  - **What is the sign of Δm^2_{31}?** Is m_3 heaviest (normal) or lightest (inverted), do ν follow the same mass ordering as other fermions?
  - **What are the precise oscillation parameters?**
  - **Is δ_{CP} not 0^o or 180^o, and if so what is it?** Do ν, $\bar{\nu}$ oscillate differently?
  - **Is three-flavour oscillation picture complete?**
    - Do parameters measured by different flavours and/or at different baselines and energies agree with each other? Are there more than the 3 flavours we know of?

Current generation (T2K, NOvA) joint analysis



From Zoya Vallari slides

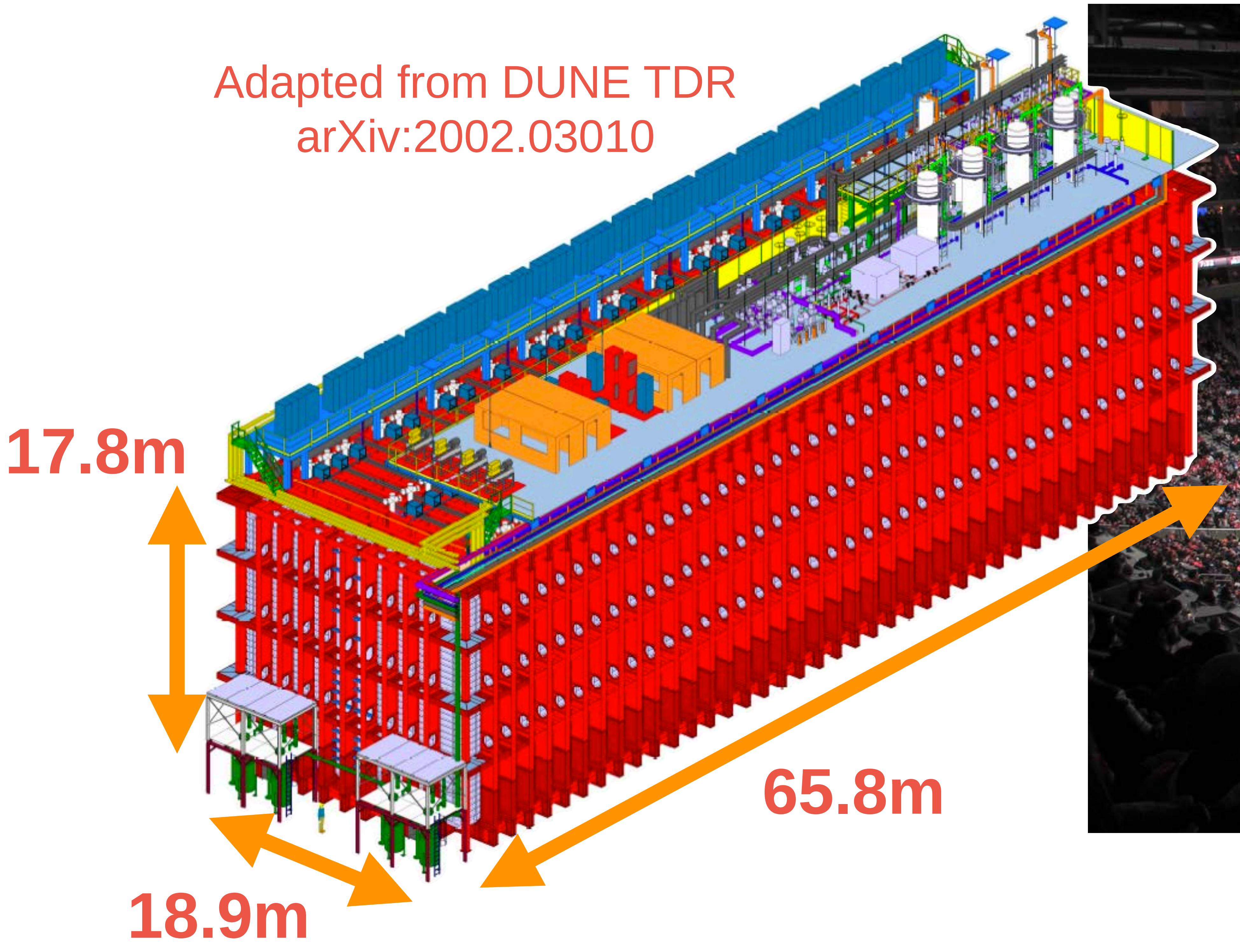
Solving problems of today with experiments of tomorrow

- Ways of making a more precise oscillation measurement in next generation?
  - **Higher event rates** → lower statistical uncertainties
  - **More sensitive measurements** → more precise detector and/or analysis techniques
  - **Better background rejection** → underground, detector technology
- **Better mass ordering sensitivity** → extra potential picked up by traveling through Earth enhances electron neutrino appearance probability (normal ordering) or anti-electron neutrino appearance (inverted ordering). DUNE will move to a longer baseline than current generation to have more sensitivity.
- **Wide-band beam** → see more of the oscillation spectrum, better constraint

DUNE

- International collaboration: ~1500 collaborators from over 30 countries
- Beam will originate at Fermilab, near Chicago, IL
- DUNE Far Detector in Lead, South Dakota (~1000 km south of Saskatoon)
  - Neutrinos travel 1300 km between Fermilab, Lead

Adapted from DUNE TDR arXiv:2002.03010



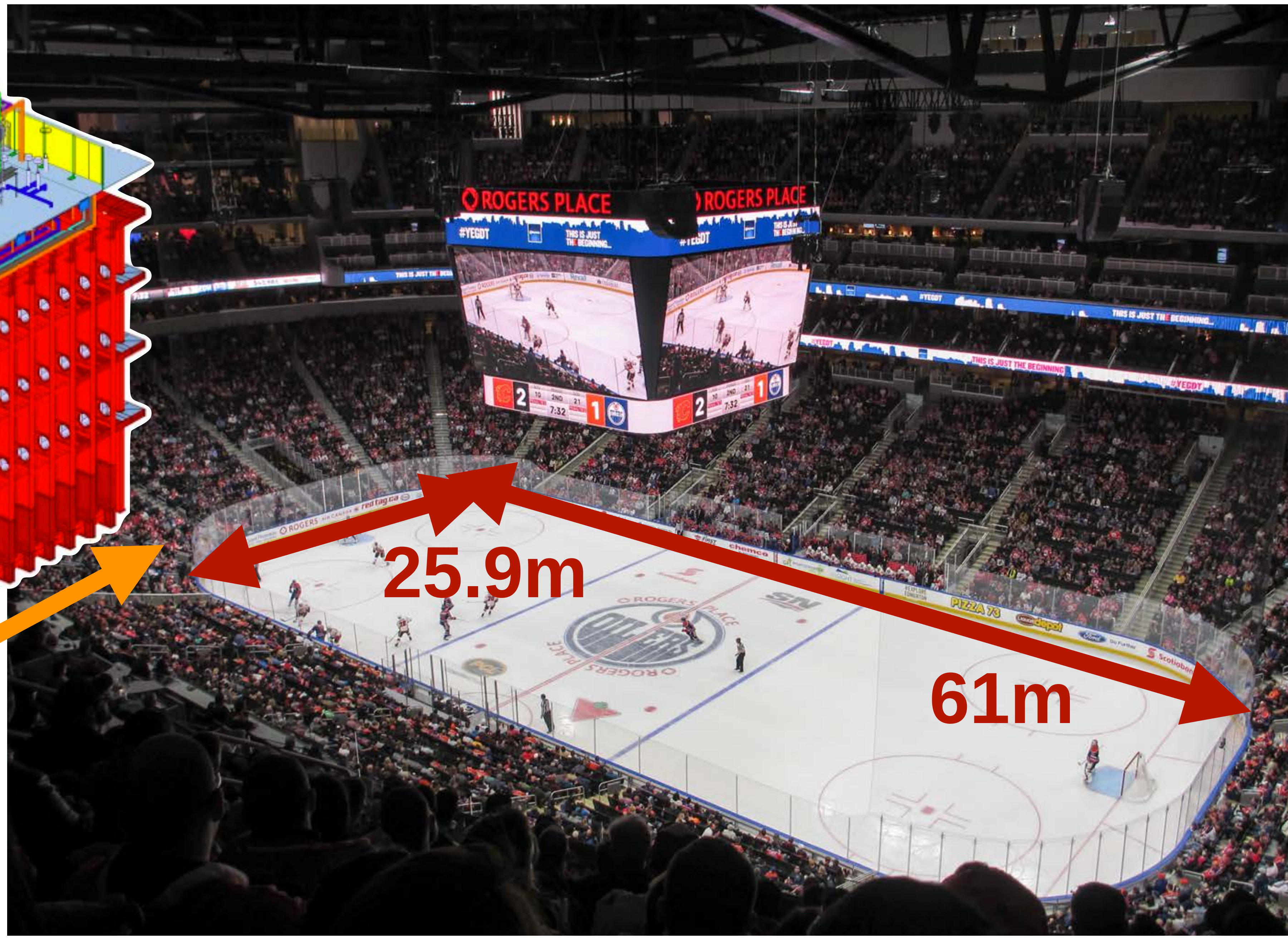
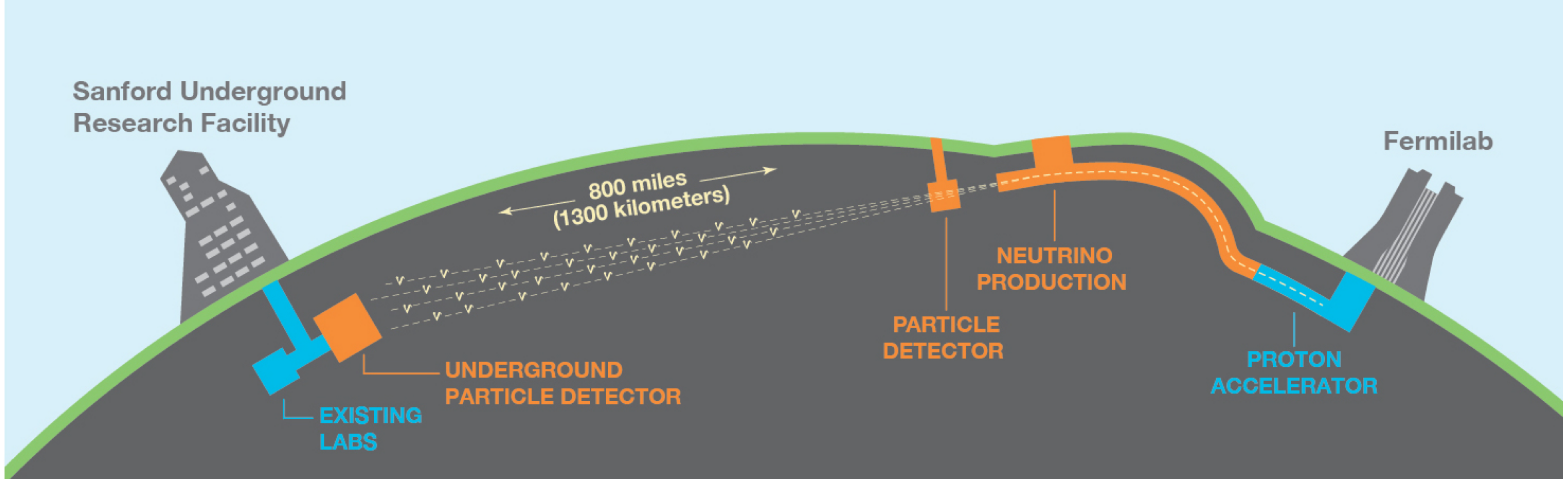


Photo by Mack Male, from Wikipedia
license: CC BY-SA 2.0, dimensions added



DUNE Timeline

- DUNE Far Detector caverns have been excavated
  - Detector construction phase starting - DUNE will start with two Far Detector modules
  - Far Detectors 1 and 2 installation expected to be complete and starting to operate ~2029
  - Near Detector and Beam follow, both being ready ~2031
  - DUNE accelerator oscillation program Phase I begins then
- Plan is to then implement a Phase II that will improve sensitivities. Technically limited schedule:
  - Far Detector Module 3: ~3 years after Phase 1 begins
  - Far Detector Module 4: ~5 years after Phase 1 begins
  - More Capable Near Detector: ~6 years after Phase 1 begins

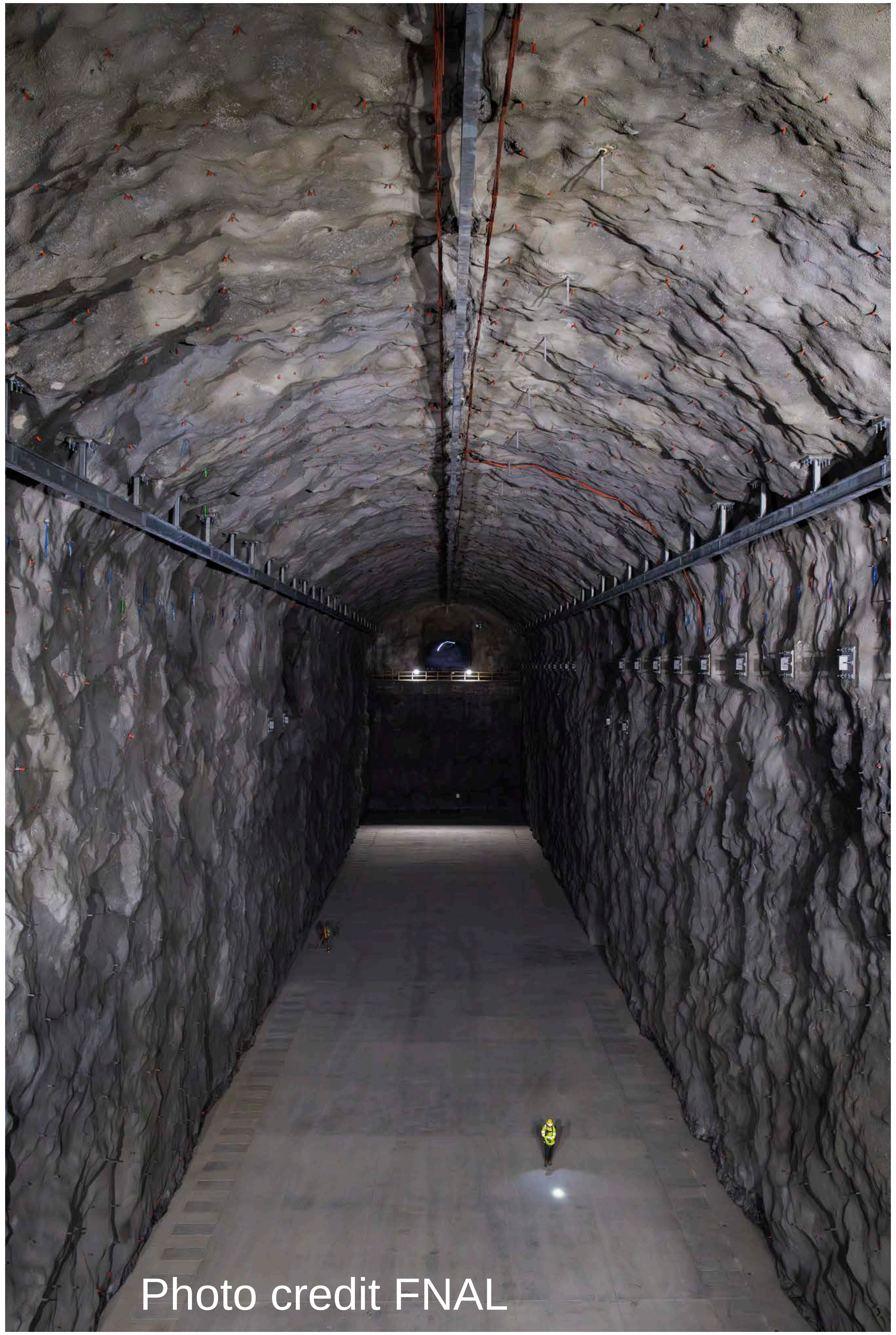
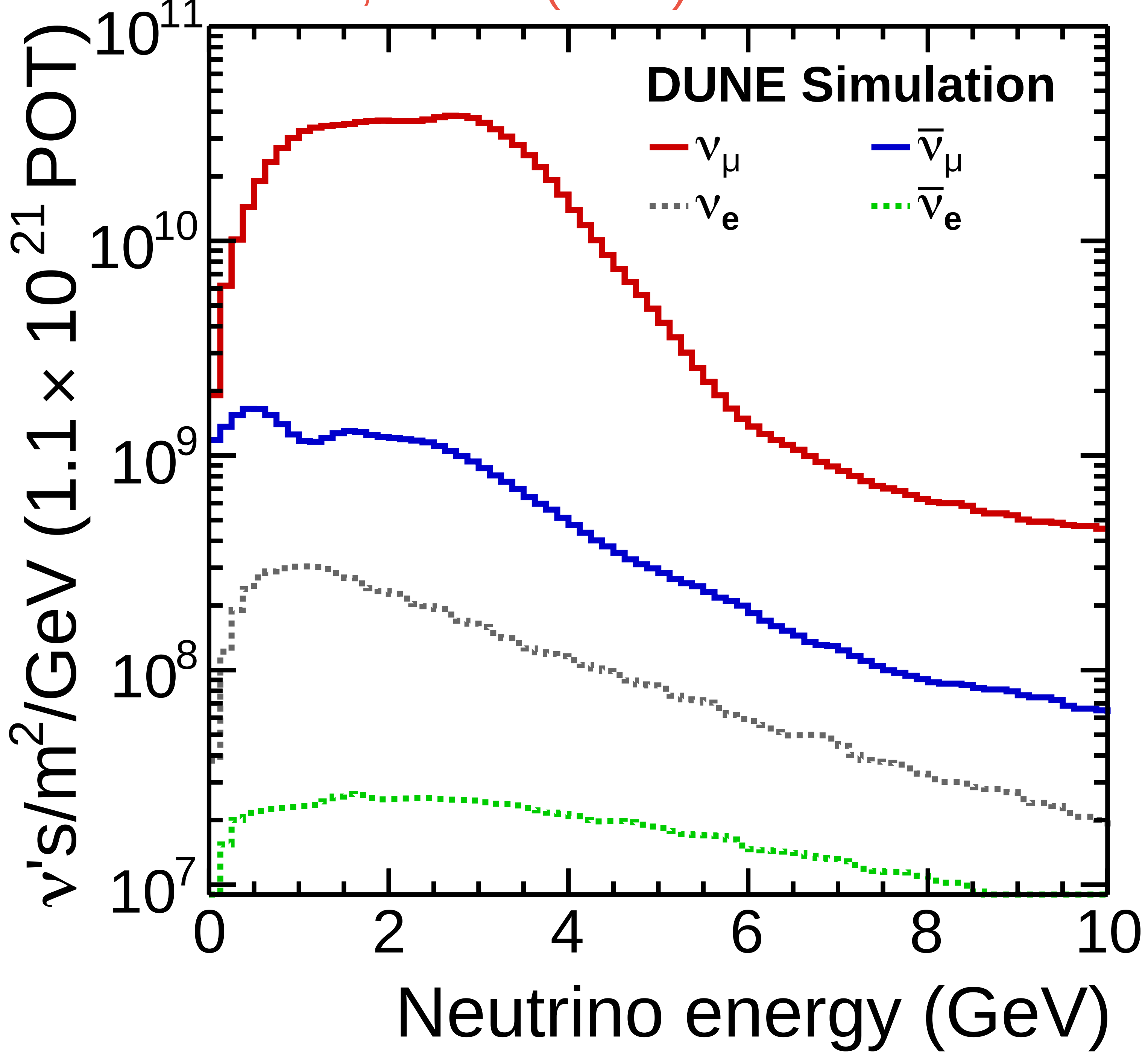


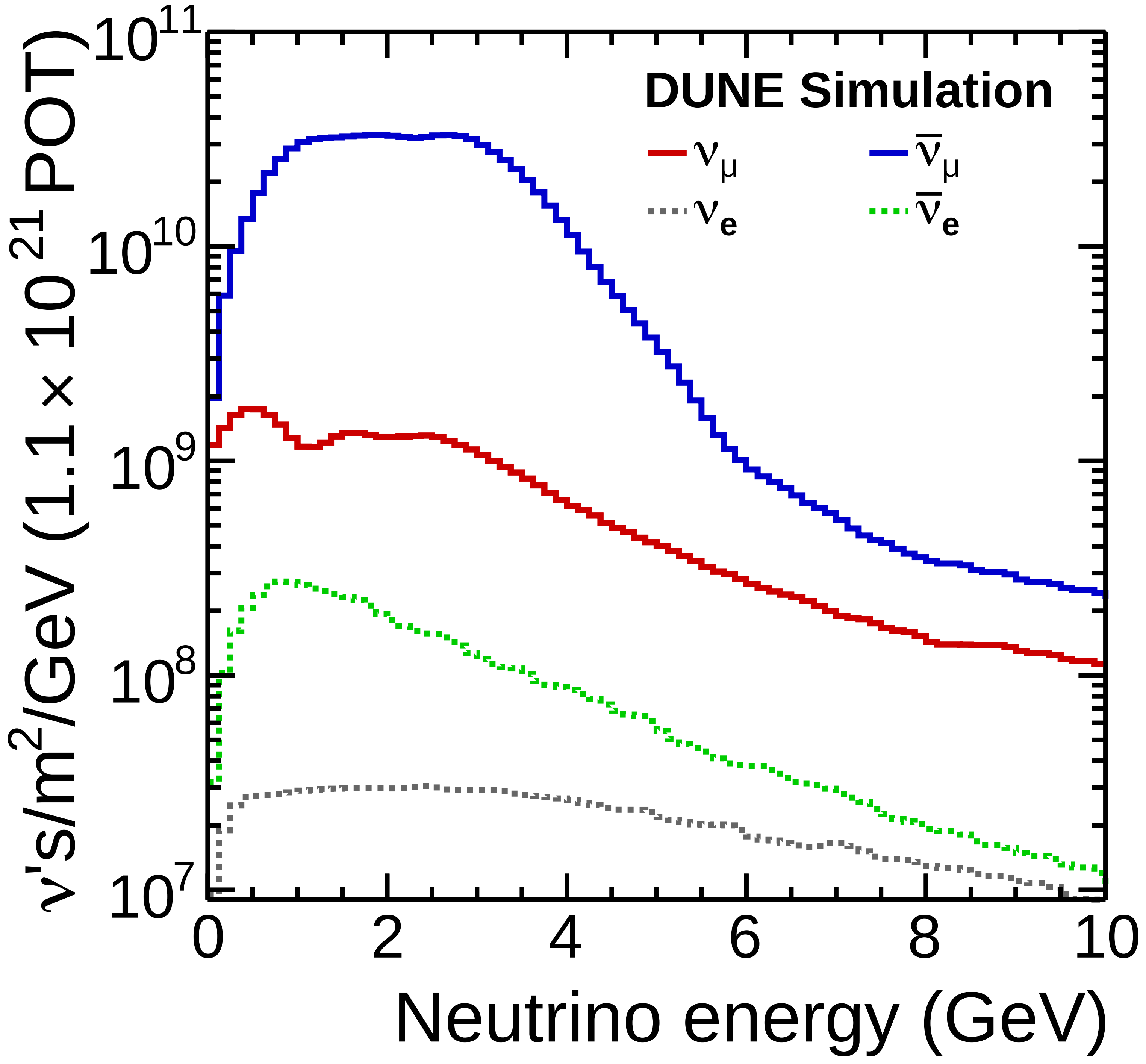
Photo credit FNAL

DUNE Flux and Measuring Oscillations

- Fermilab accelerator upgrades and new components to service DUNE will make the beam power be > 1 MW at beginning of full DUNE operations
- Broadband beam with flux peaked between ~1 and 5 GeV and achieves a good purity of flux

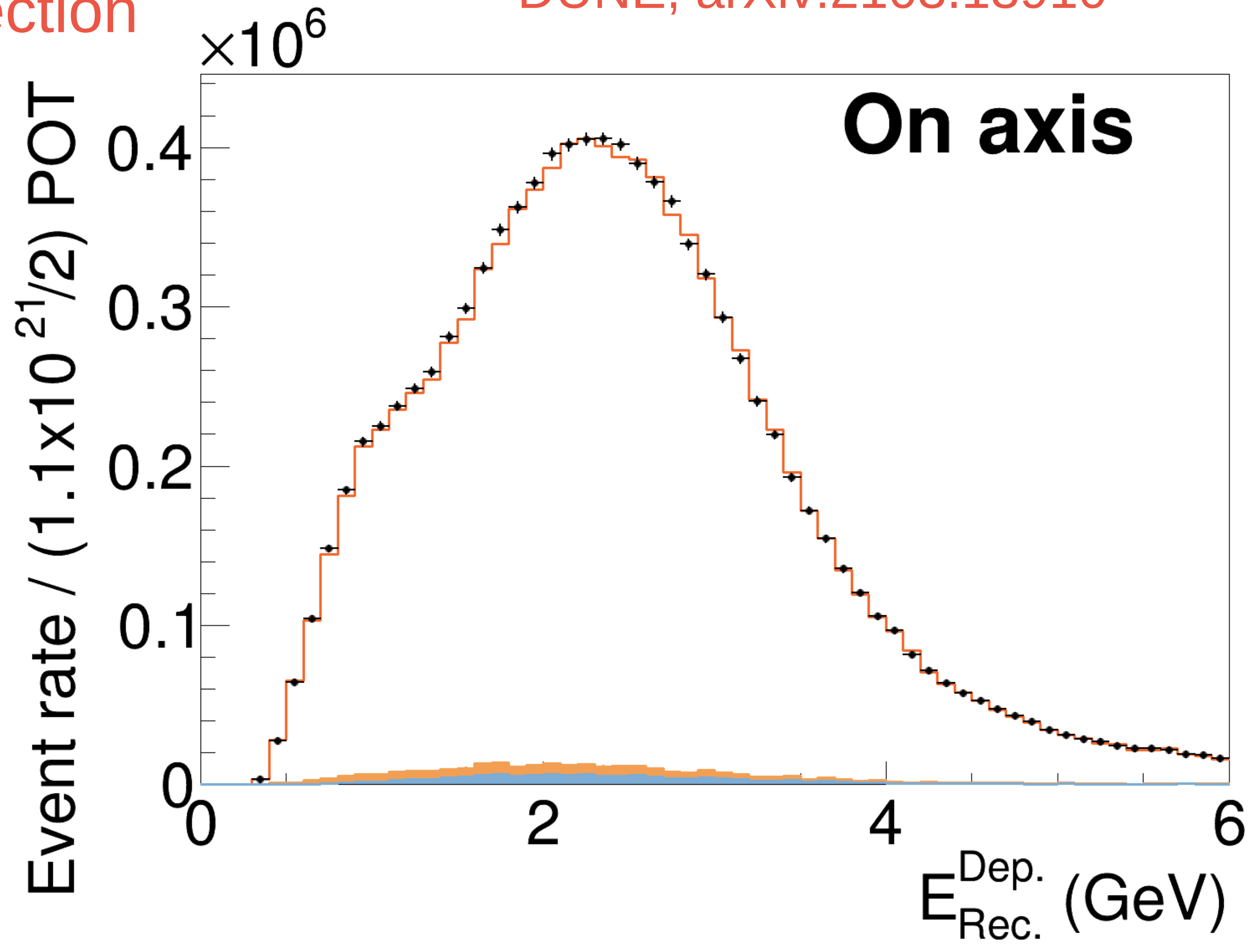
DUNE, EPJ C (2020) 80:978





Near Detector sees convolution of flux and cross-section

DUNE, arXiv:2103.13910



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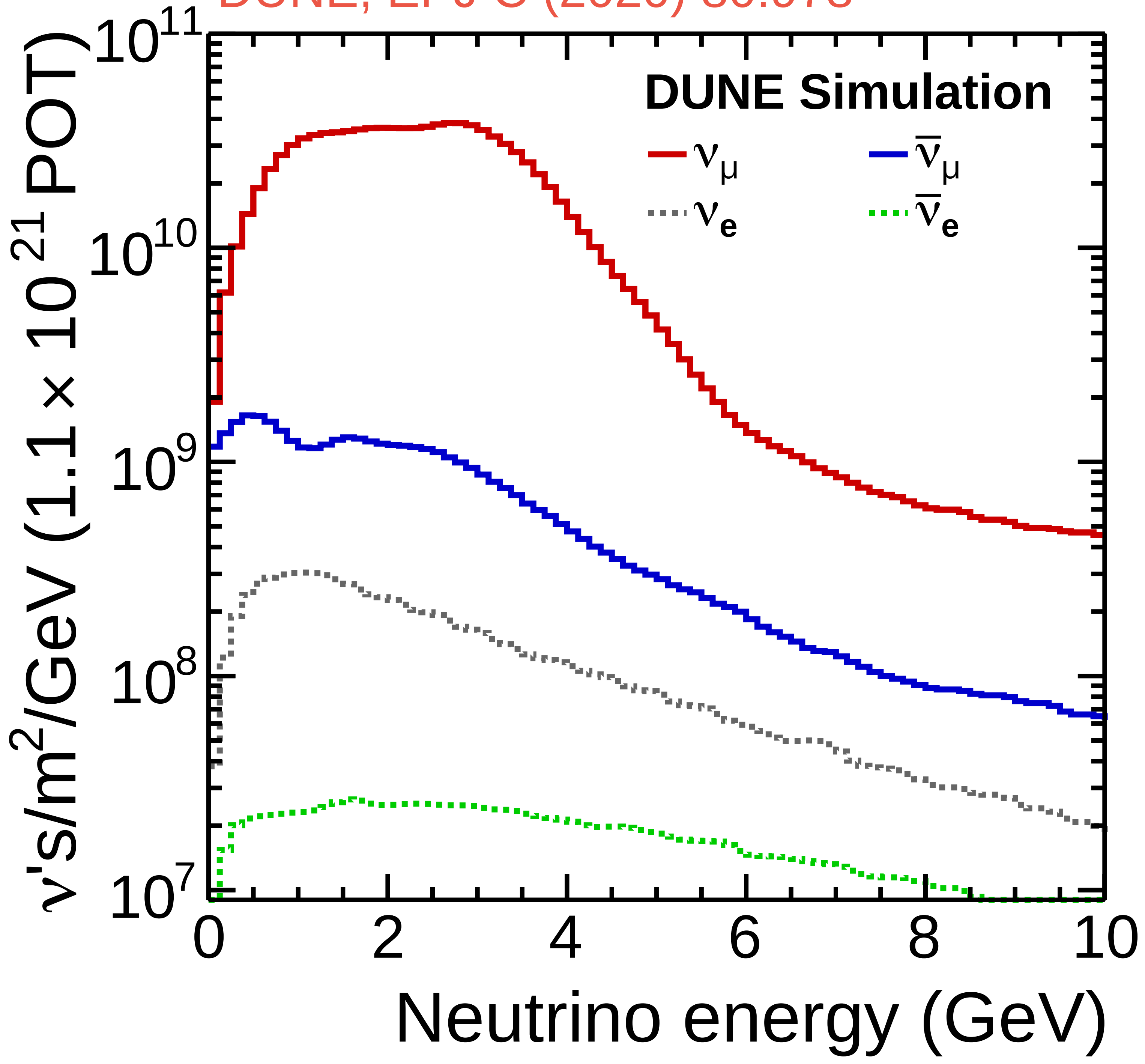
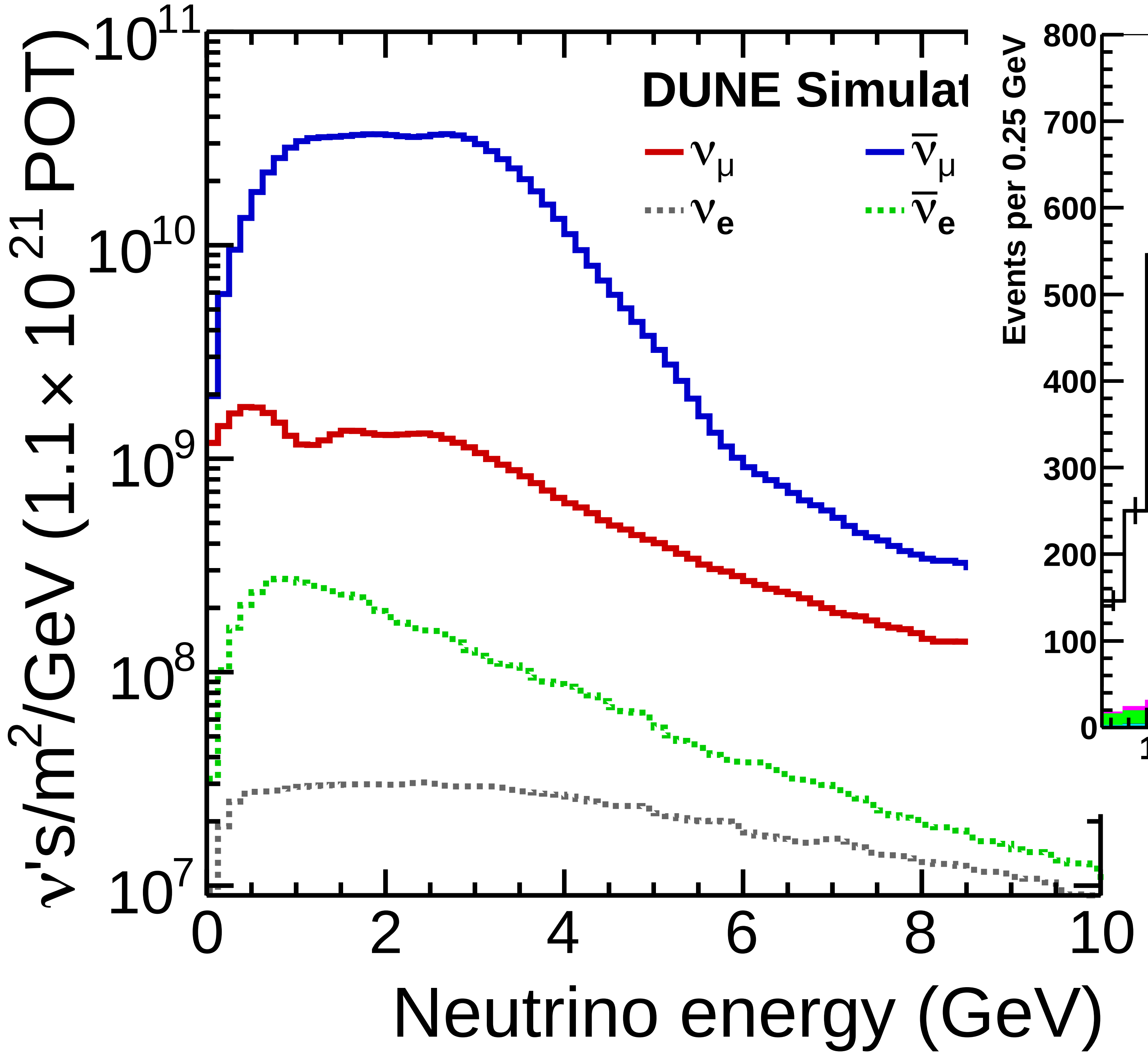
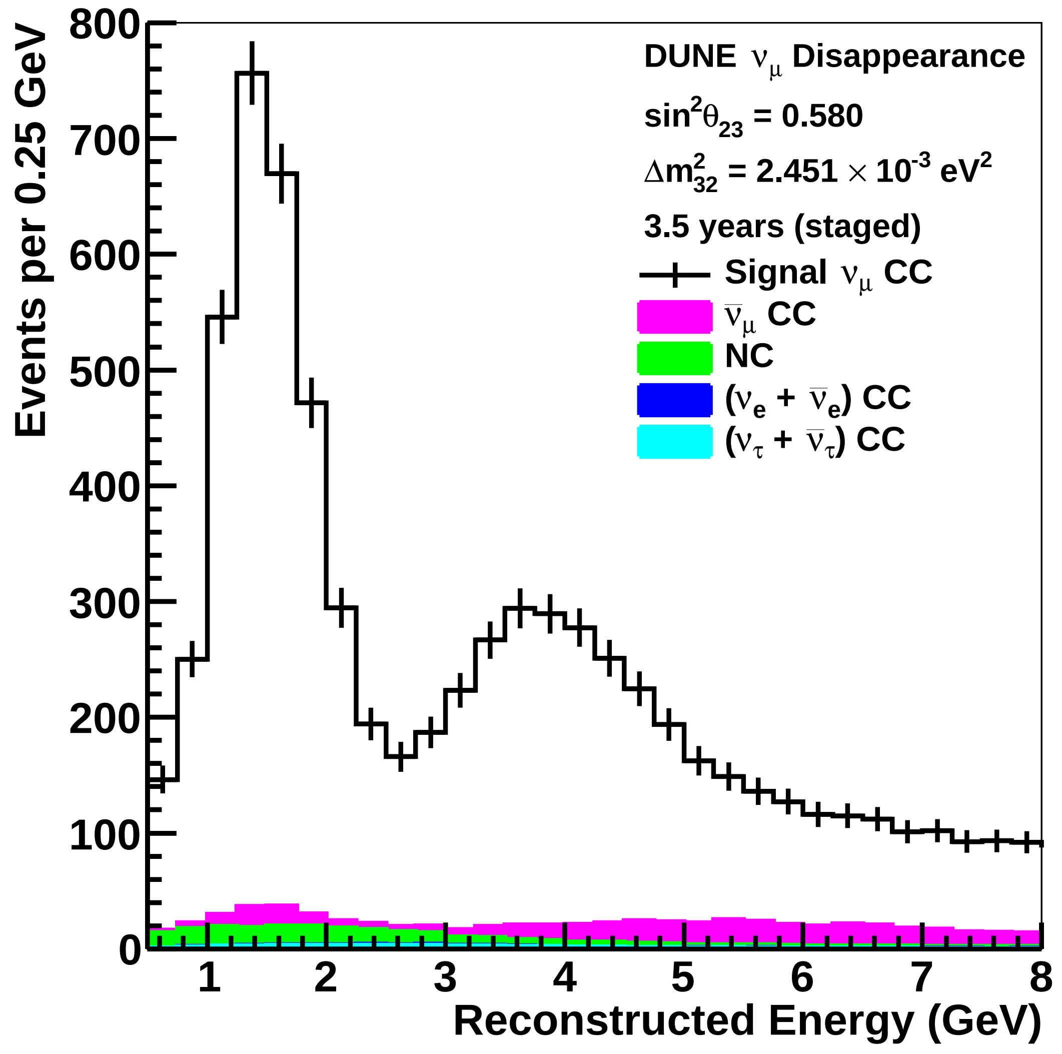
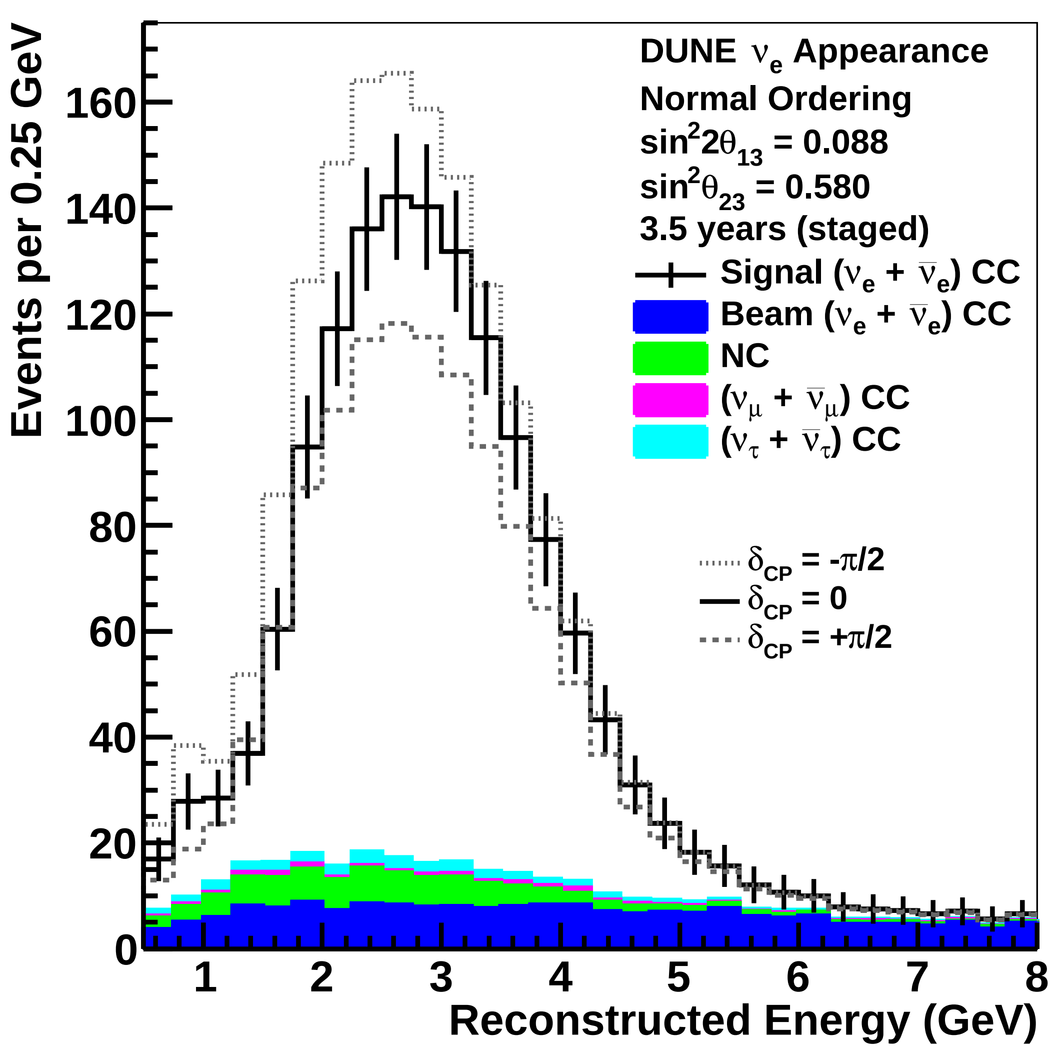




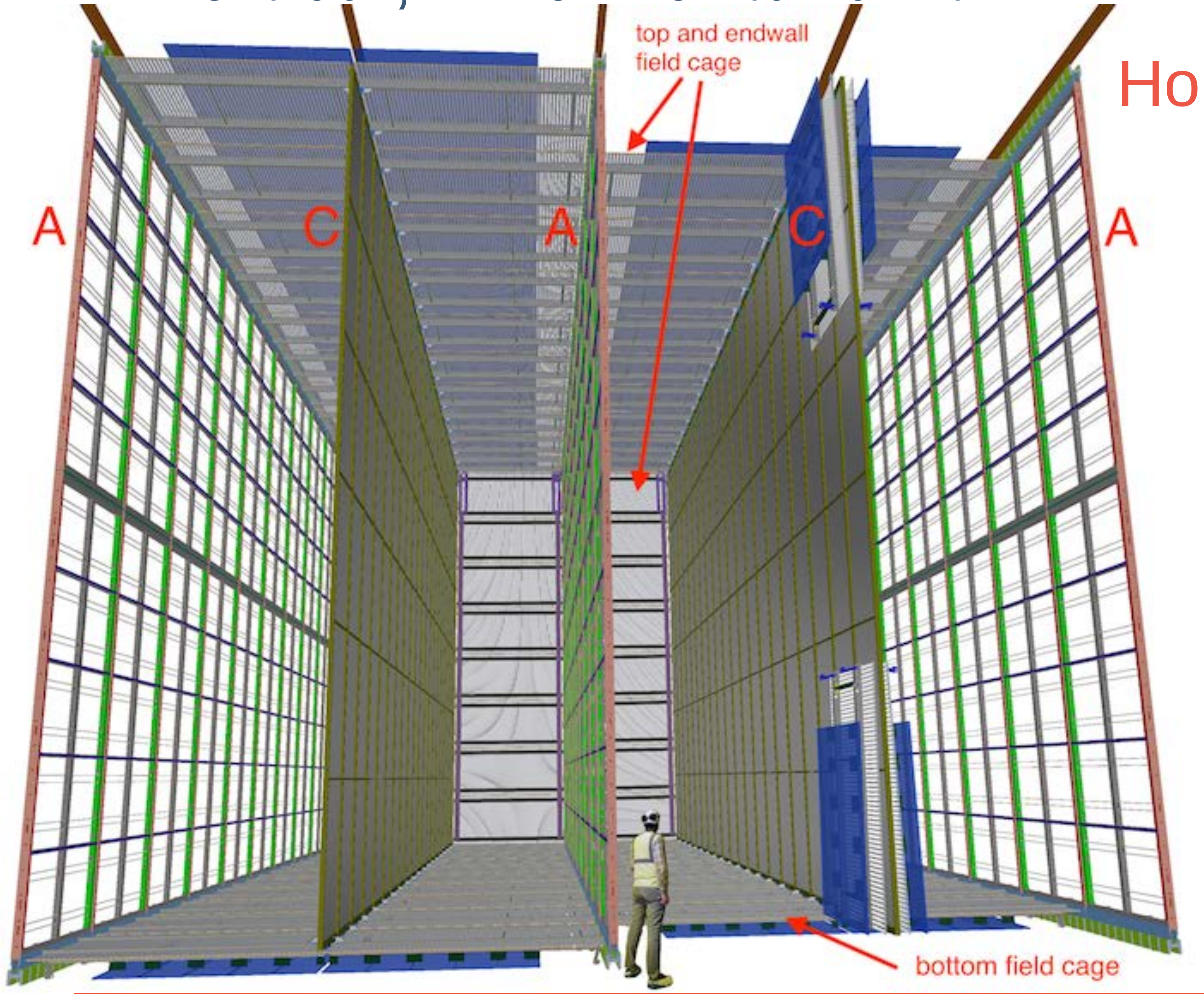




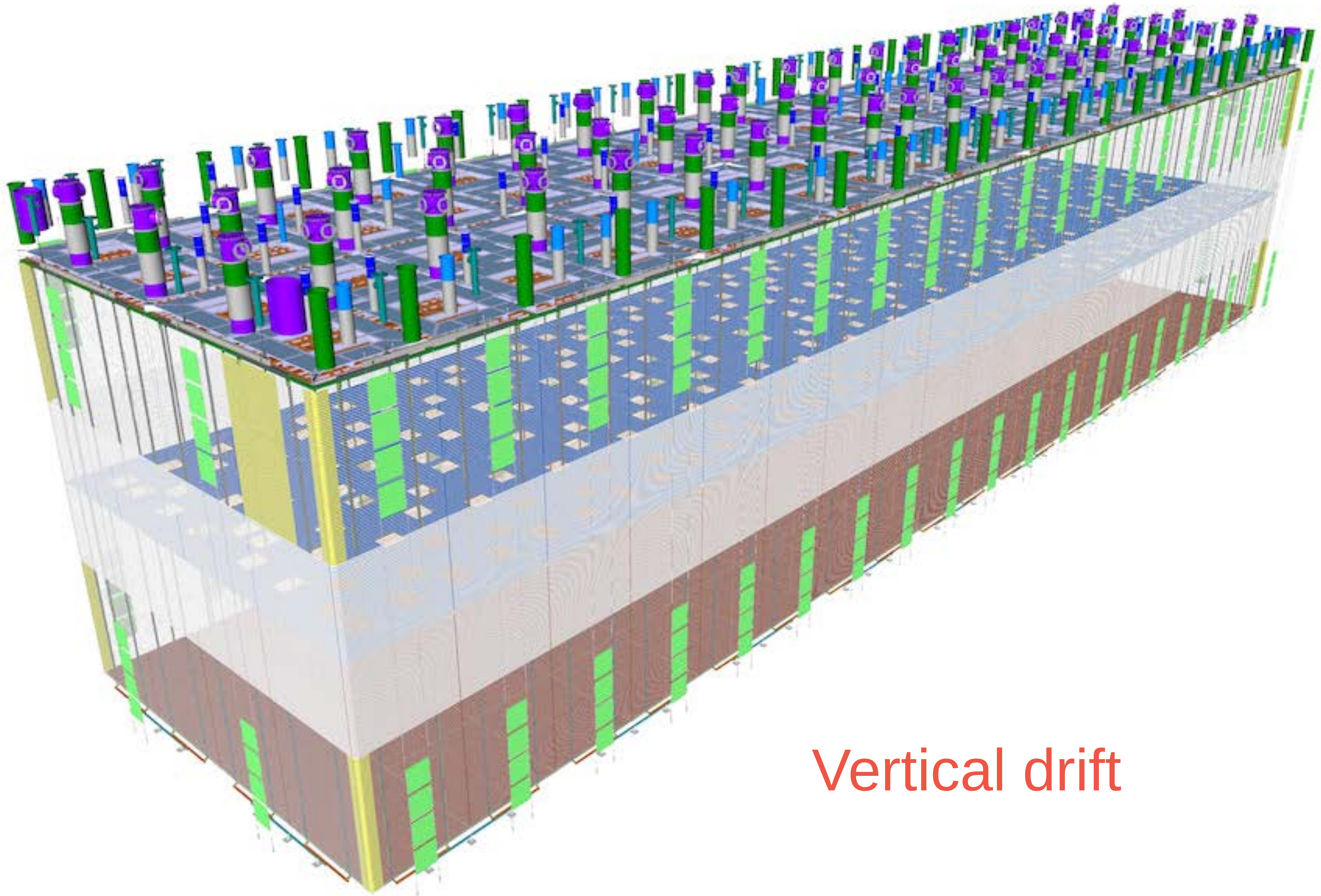
Far detector sees convolution of **oscillated** fluxes and cross-section!

DUNE Far Detector

- DUNE will start with 2 Far Detector modules, each 17 kt total volume
  - A 17 kt horizontal drift detector → 10 kt fiducial volume
- 2 similar yet different styles: Liquid Argon (LAr) time-projection chamber (TPC) but 1 vertical, 1 horizontal drift



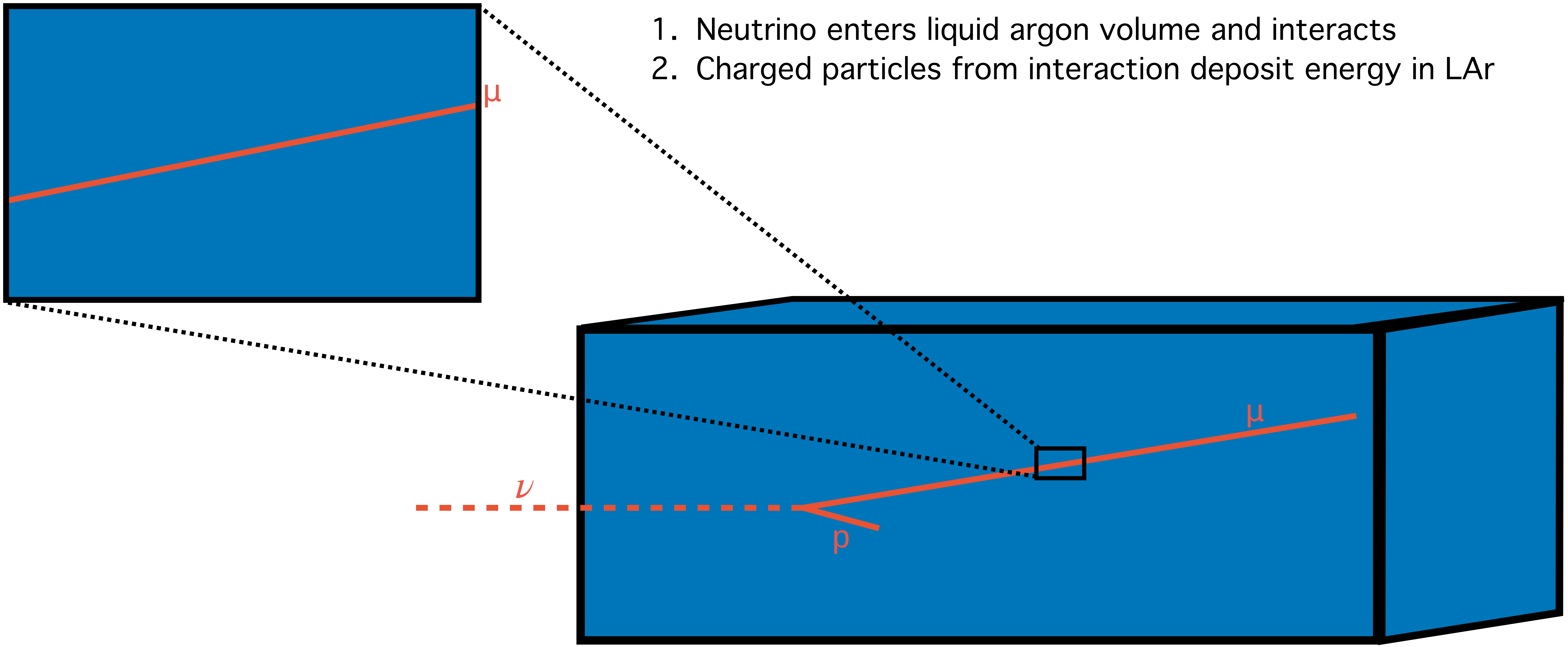
Horizontal drift



Vertical drift

Liquid Argon Time-Projection Chambers (LAr TPC)

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



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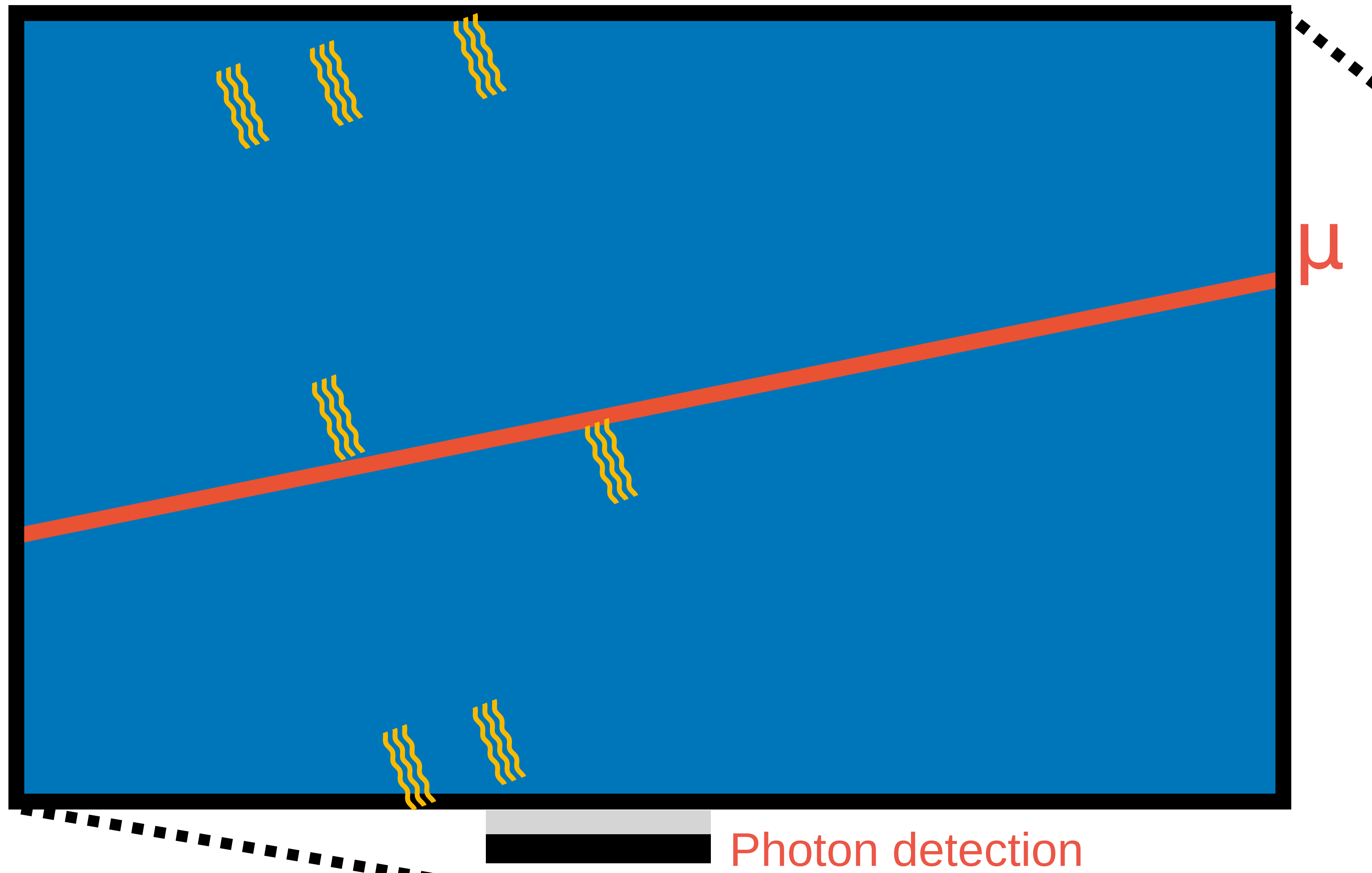
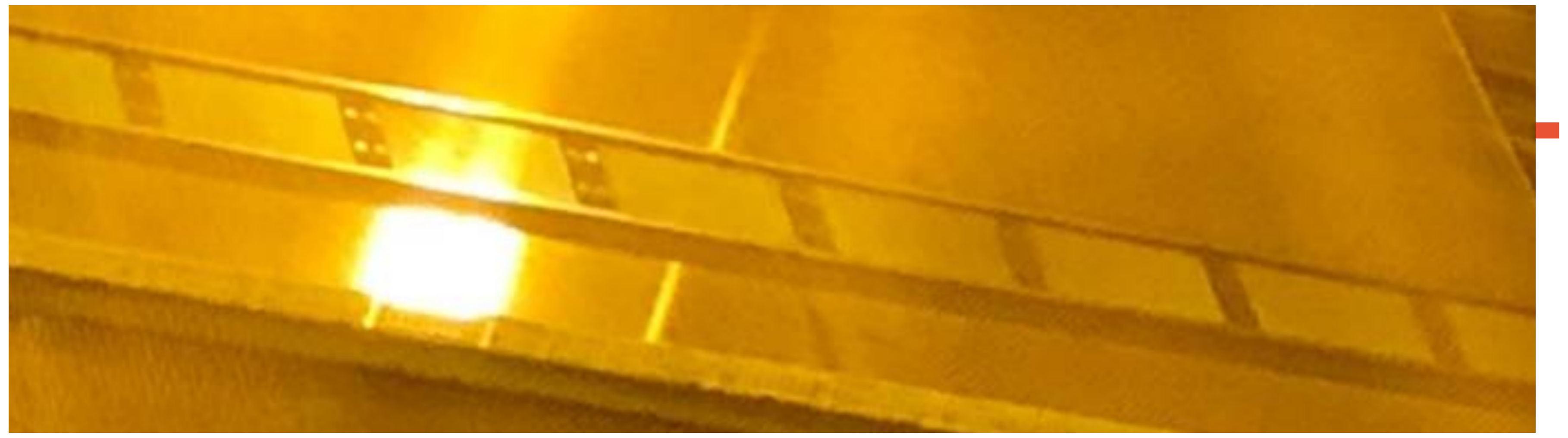
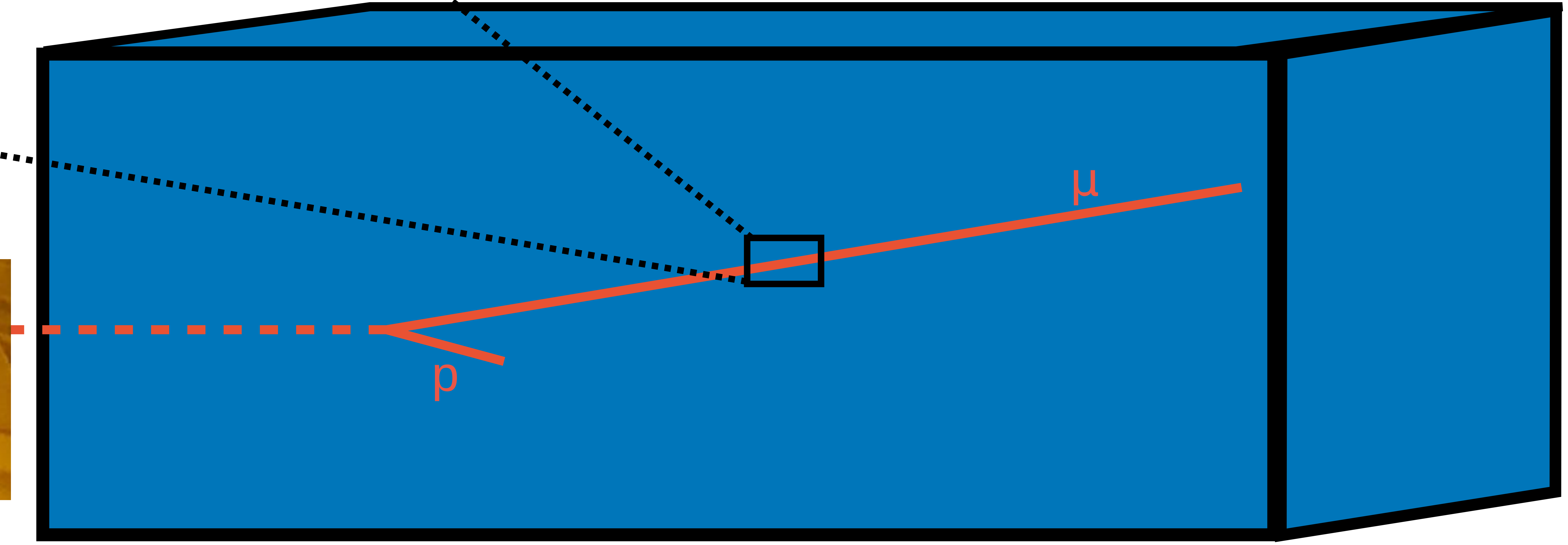


1. Neutrino enters liquid argon volume and interacts
2. Charged particles from interaction deposit energy in LAr
3. This leads to both ionization and scintillation
4. Scintillation: photon detectors, typically use wavelength shifters: 128nm→~vis ($v=c_{LAr}$, fast)

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



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



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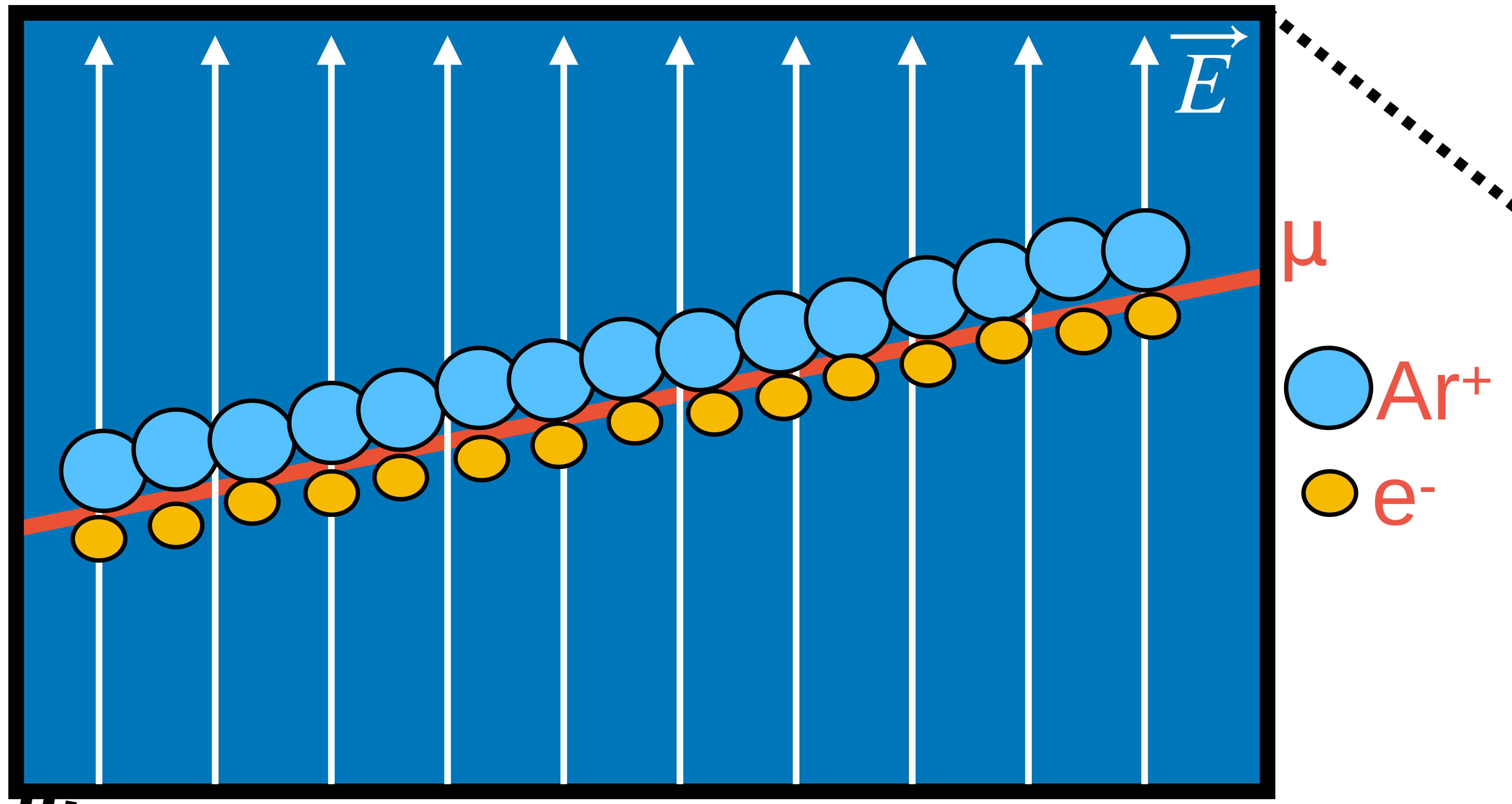

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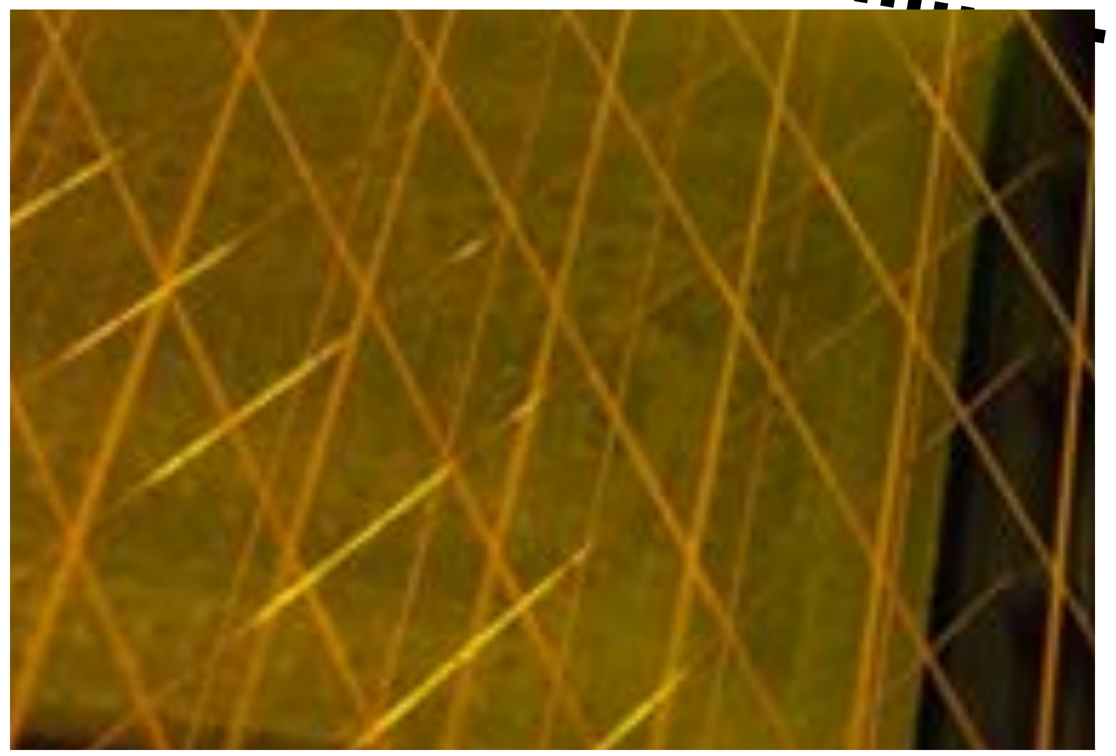
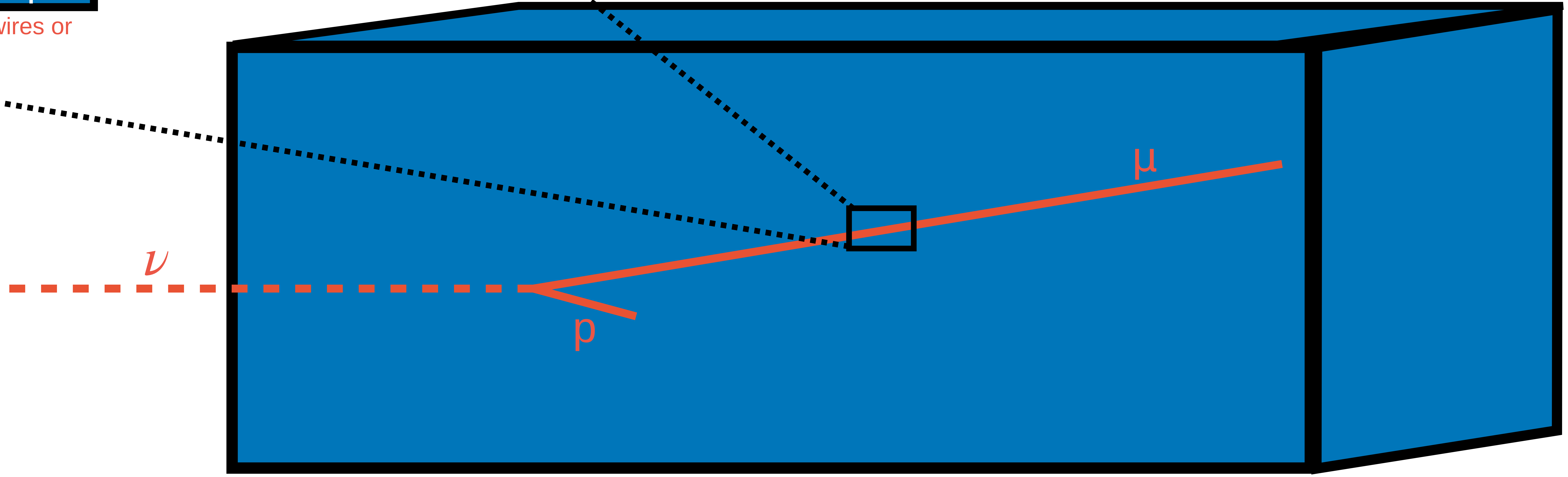
5. Ionization is drifted in electric field to sensing elements at the anode plane (v~0.16cm/μs, slow, hundreds μs to ms)





DUNE TDR
arXiv:2002.03010

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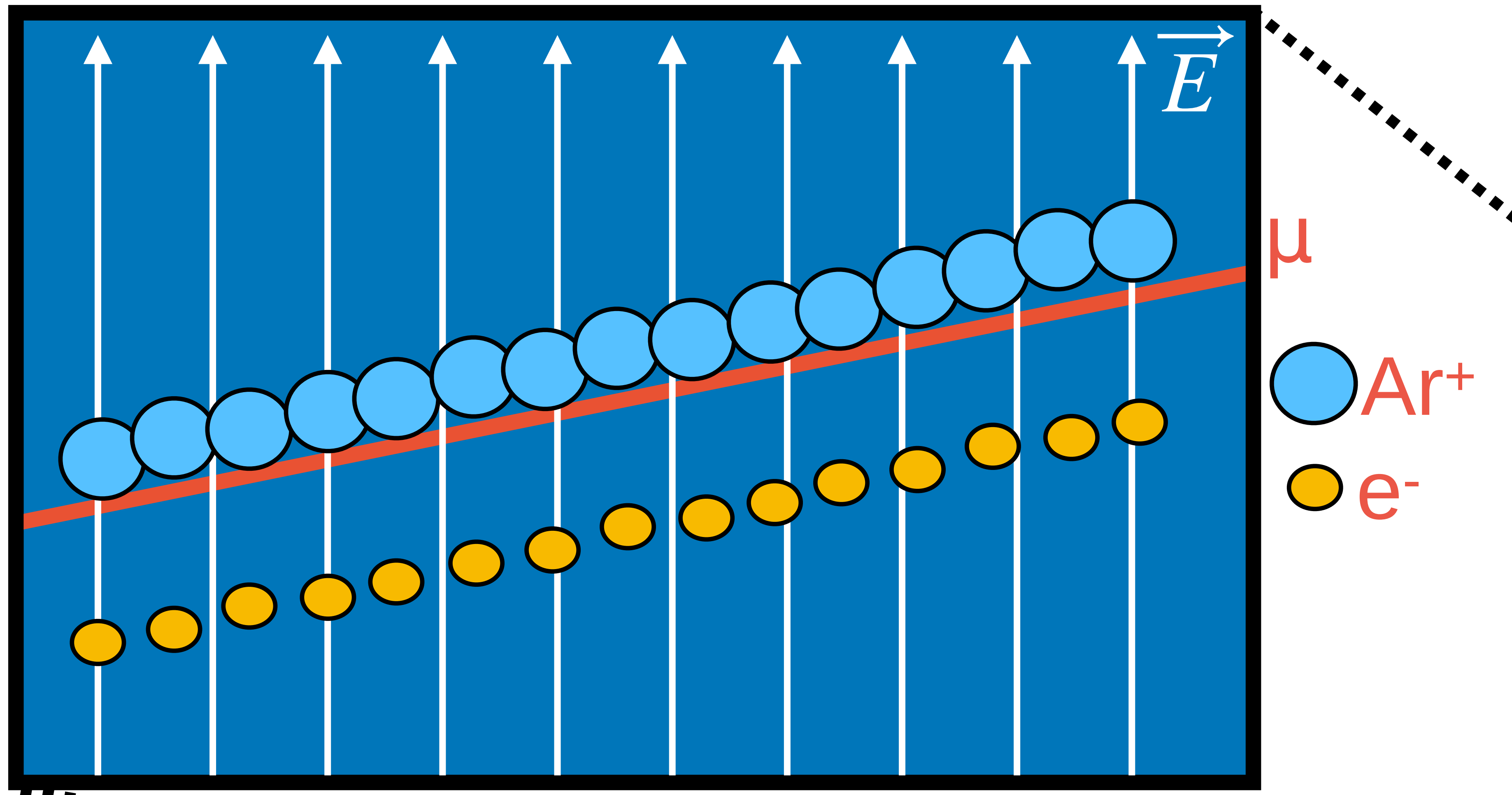

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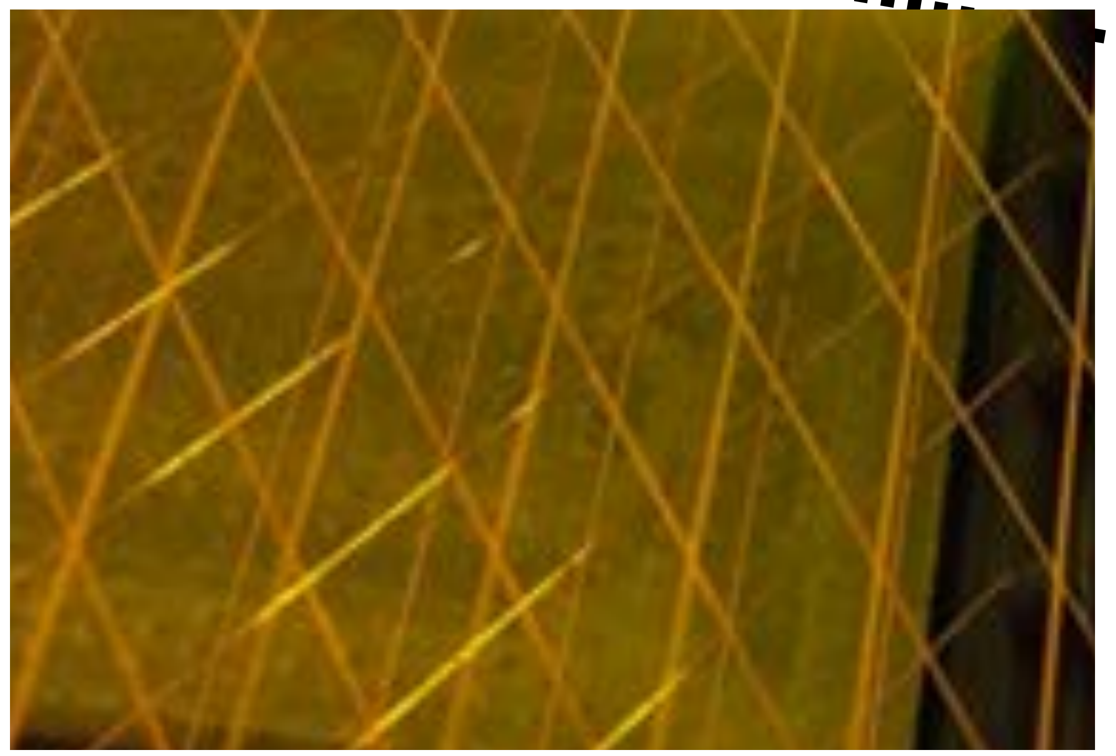
* Charge readout (wires or other readout)



DUNE TDR
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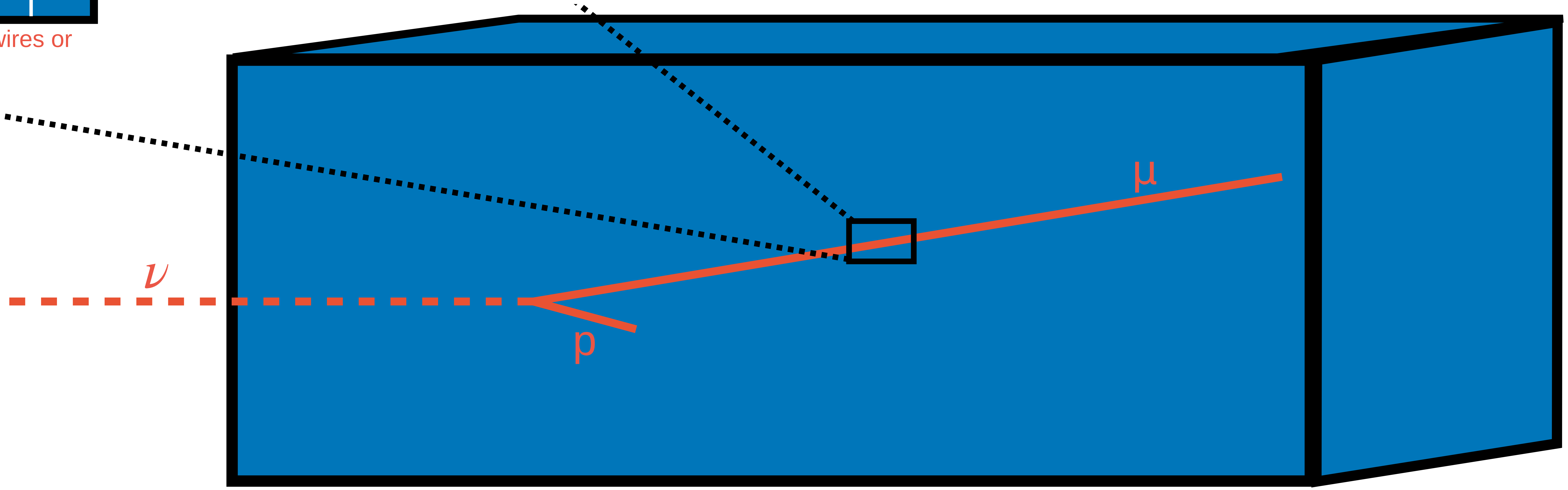

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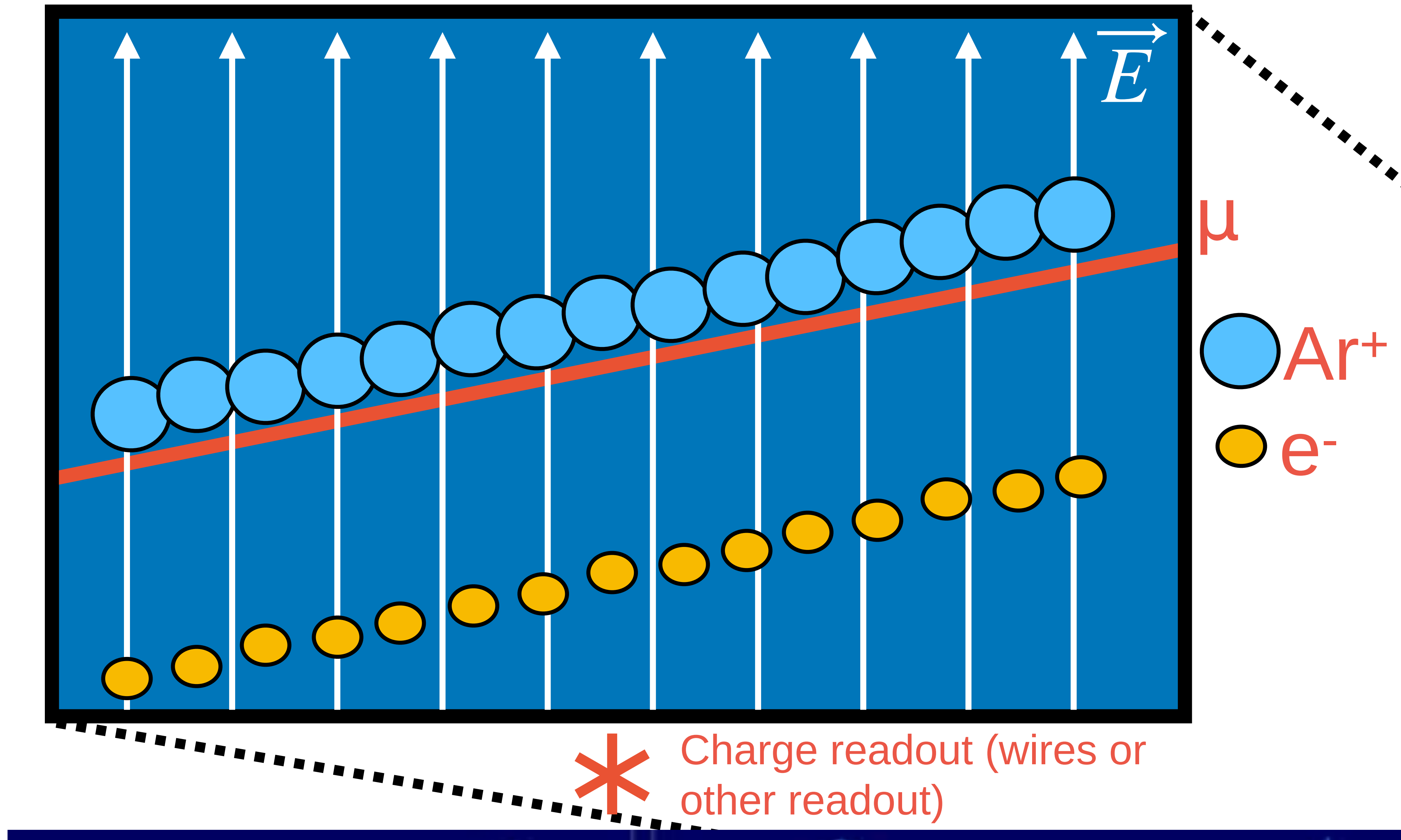

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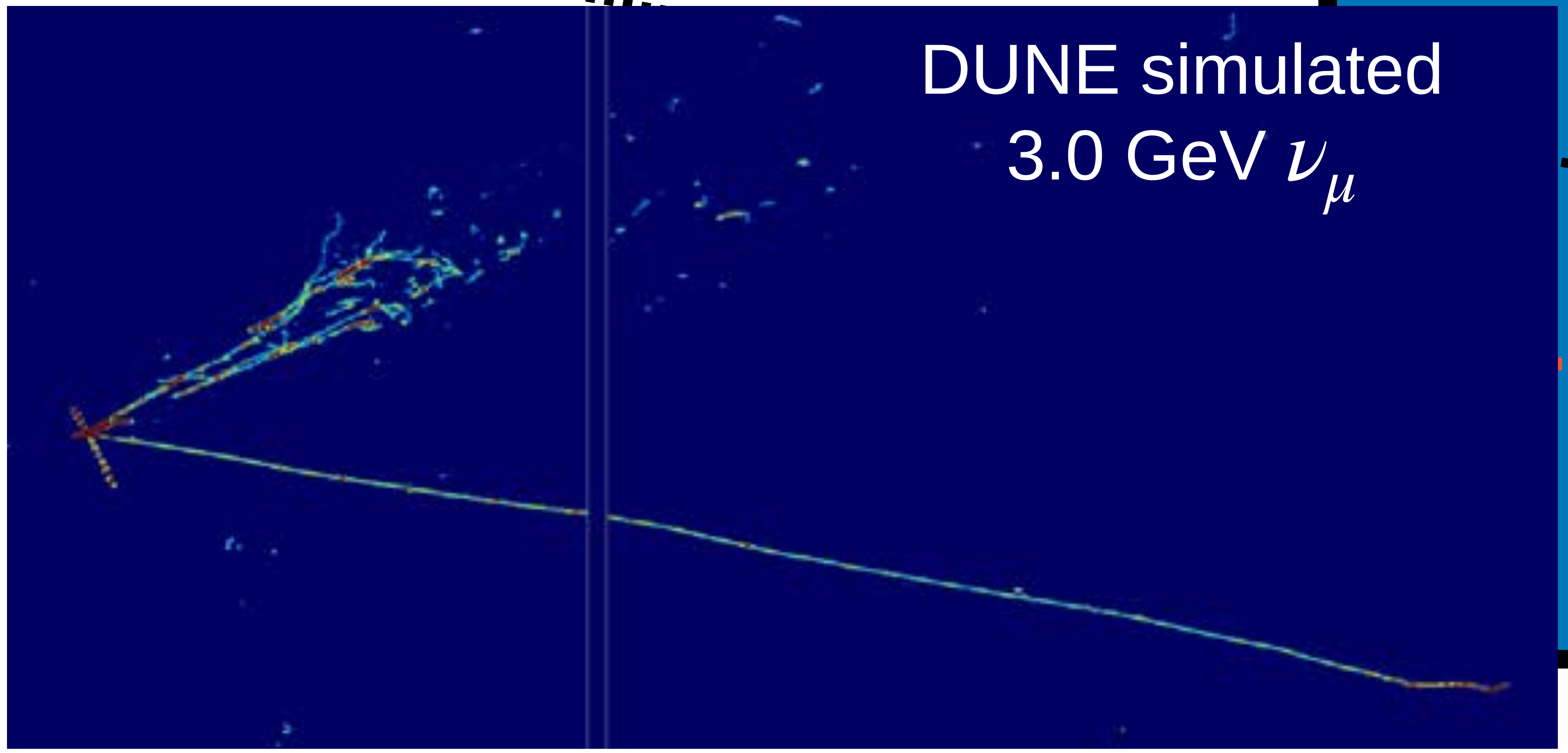
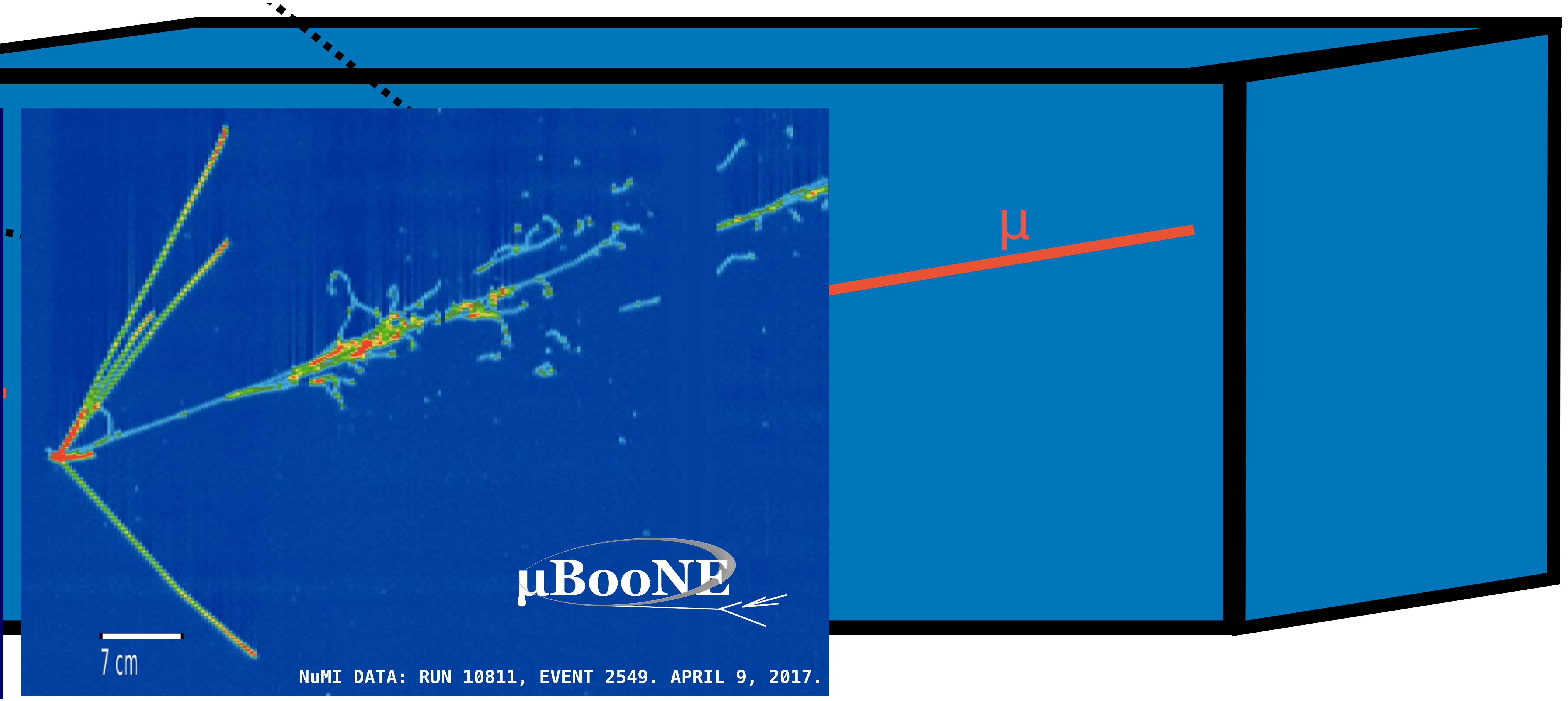
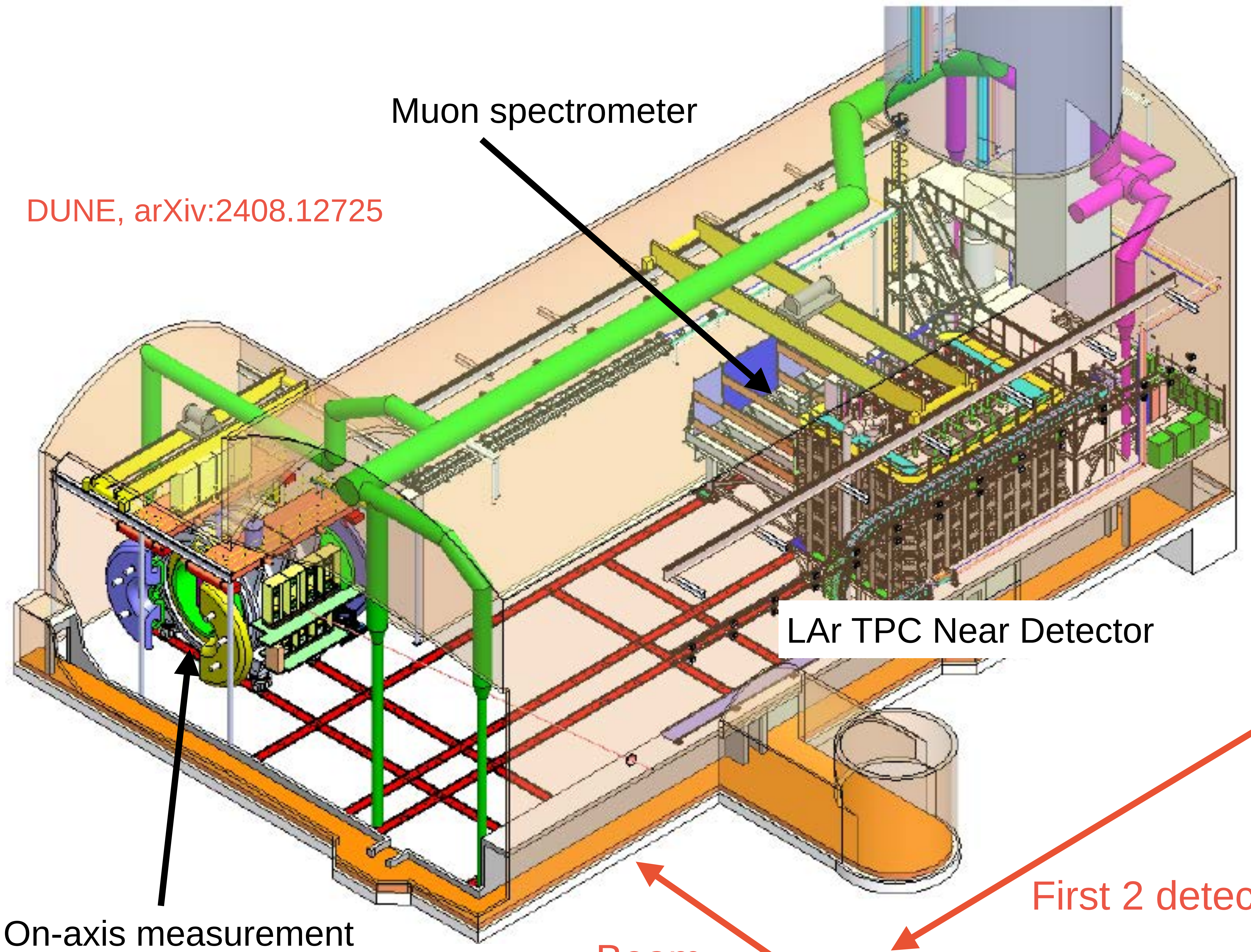




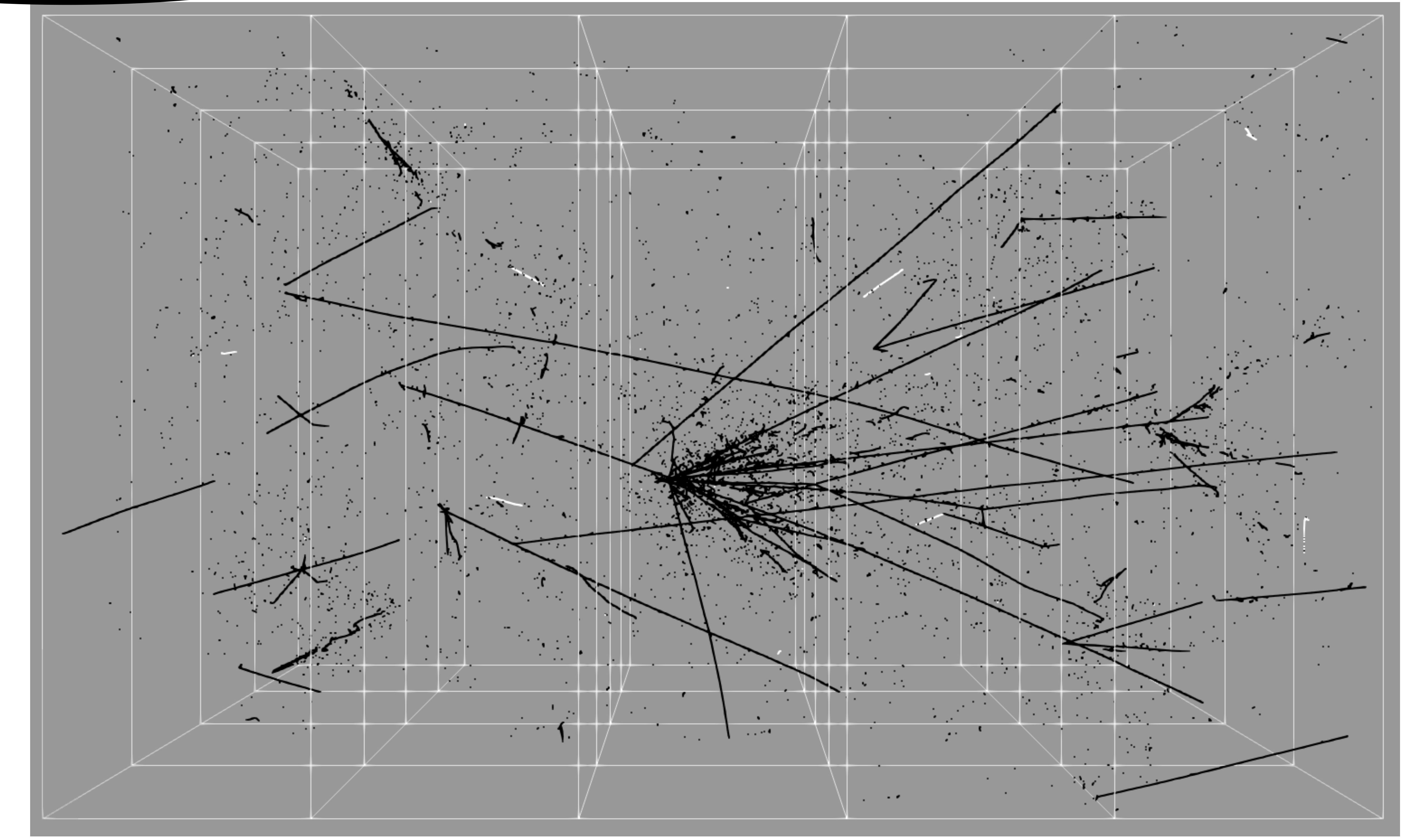
DUNE Near Detector

See next talk by **Noë Roy**

DUNE, arXiv:2408.12725



DUNE, arXiv:2103.13910



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

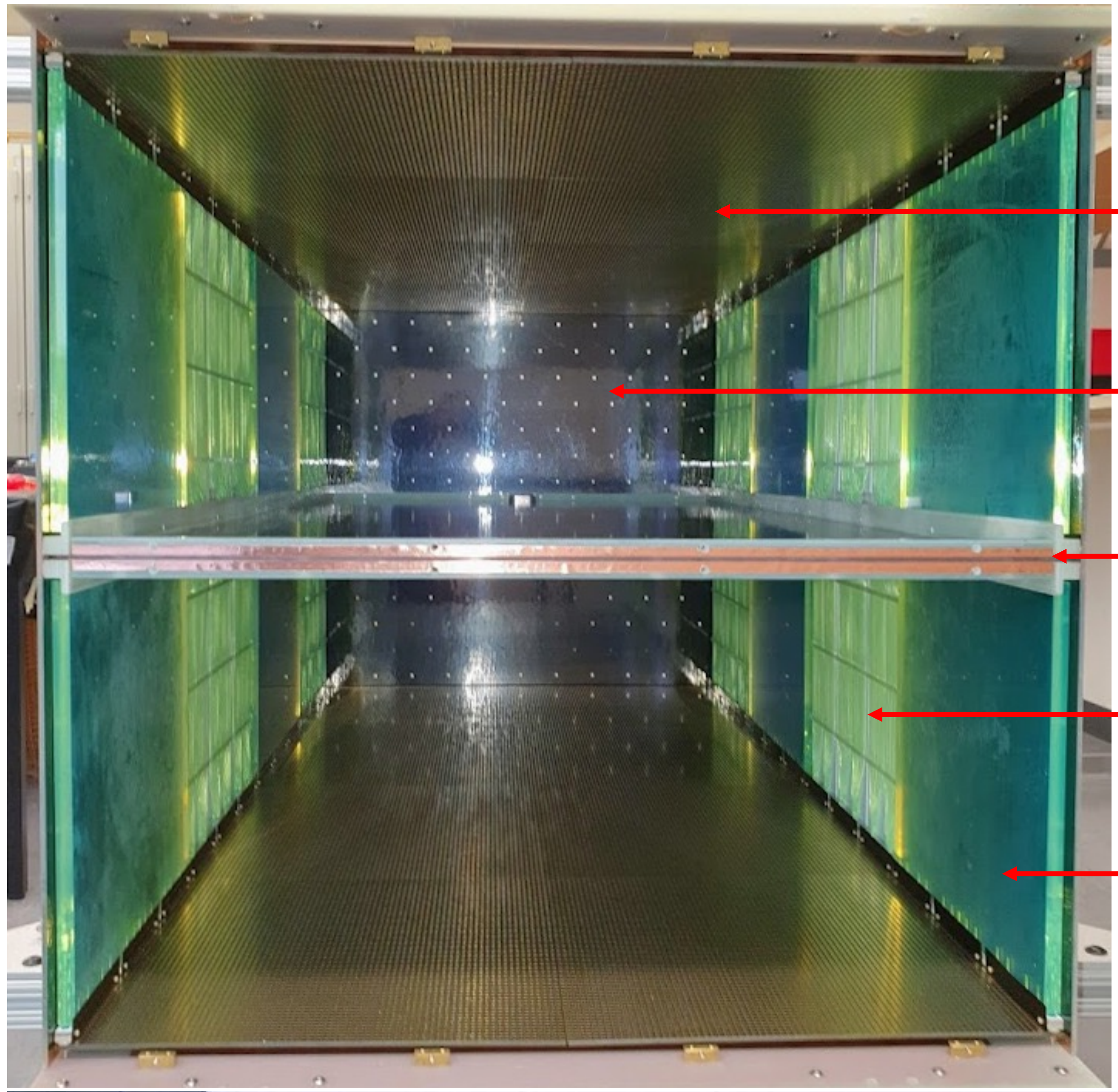
Beam

First 2 detectors can move off-axis (PRISM)

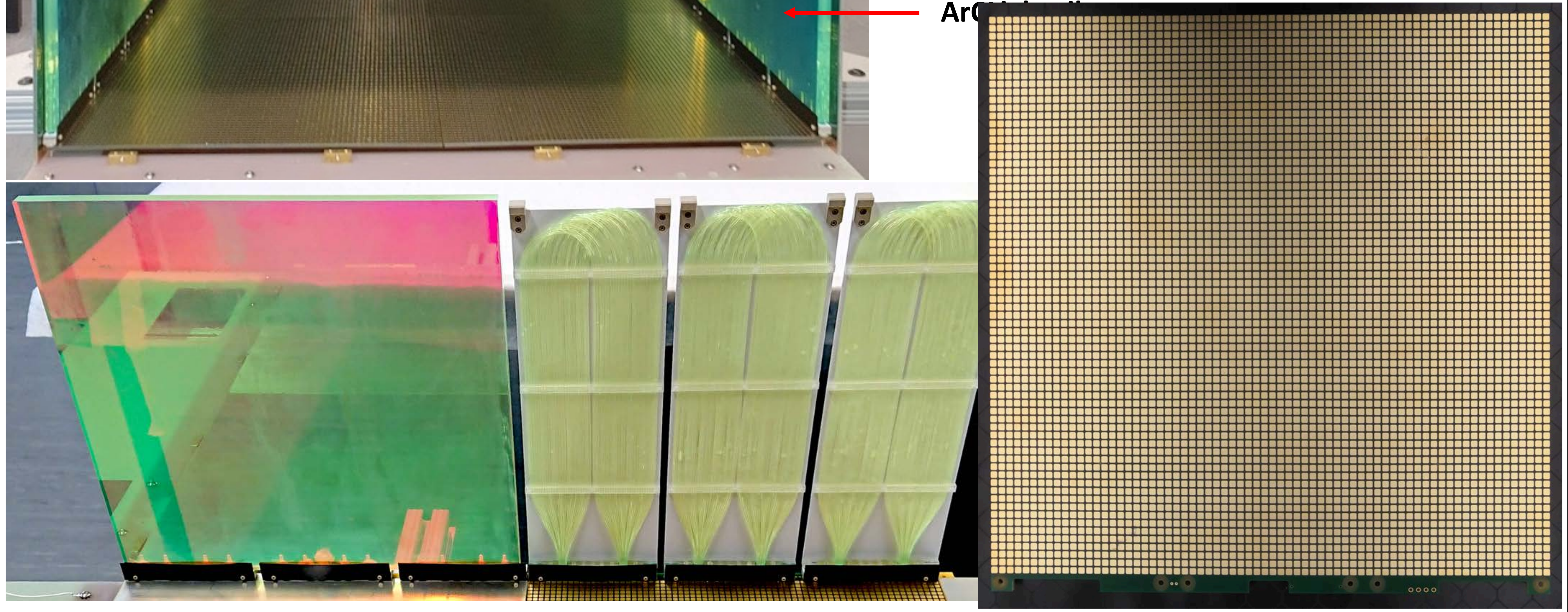
SAND remains on-axis - beam monitor

DUNE Near Detector

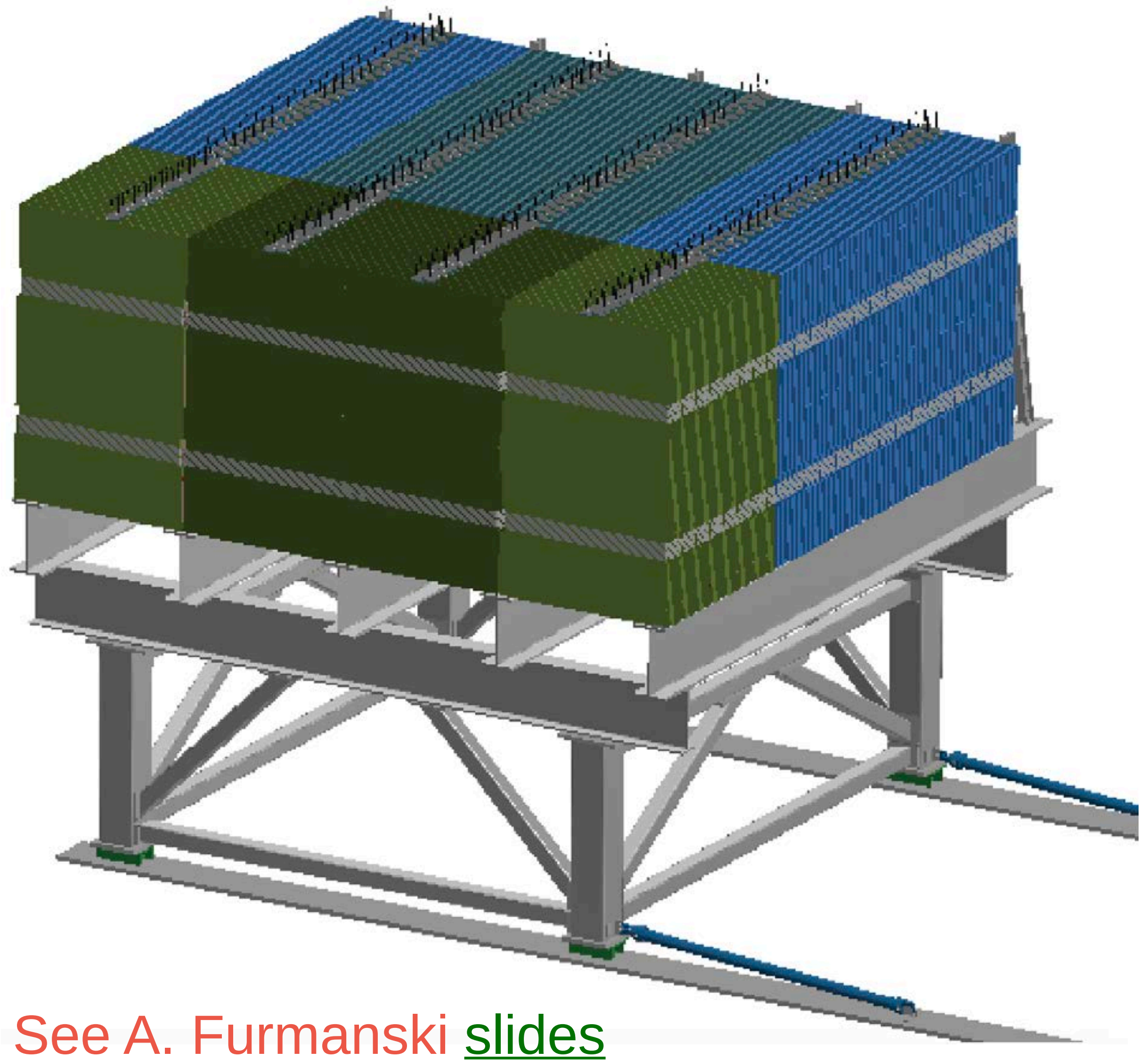
ND-LAr: segmented, pixelated LAr TPC



Instruments **2024** *8, 41*



TMS: Muon Spectrometer



See A. Furmanski slides

Moves with ND-LAr

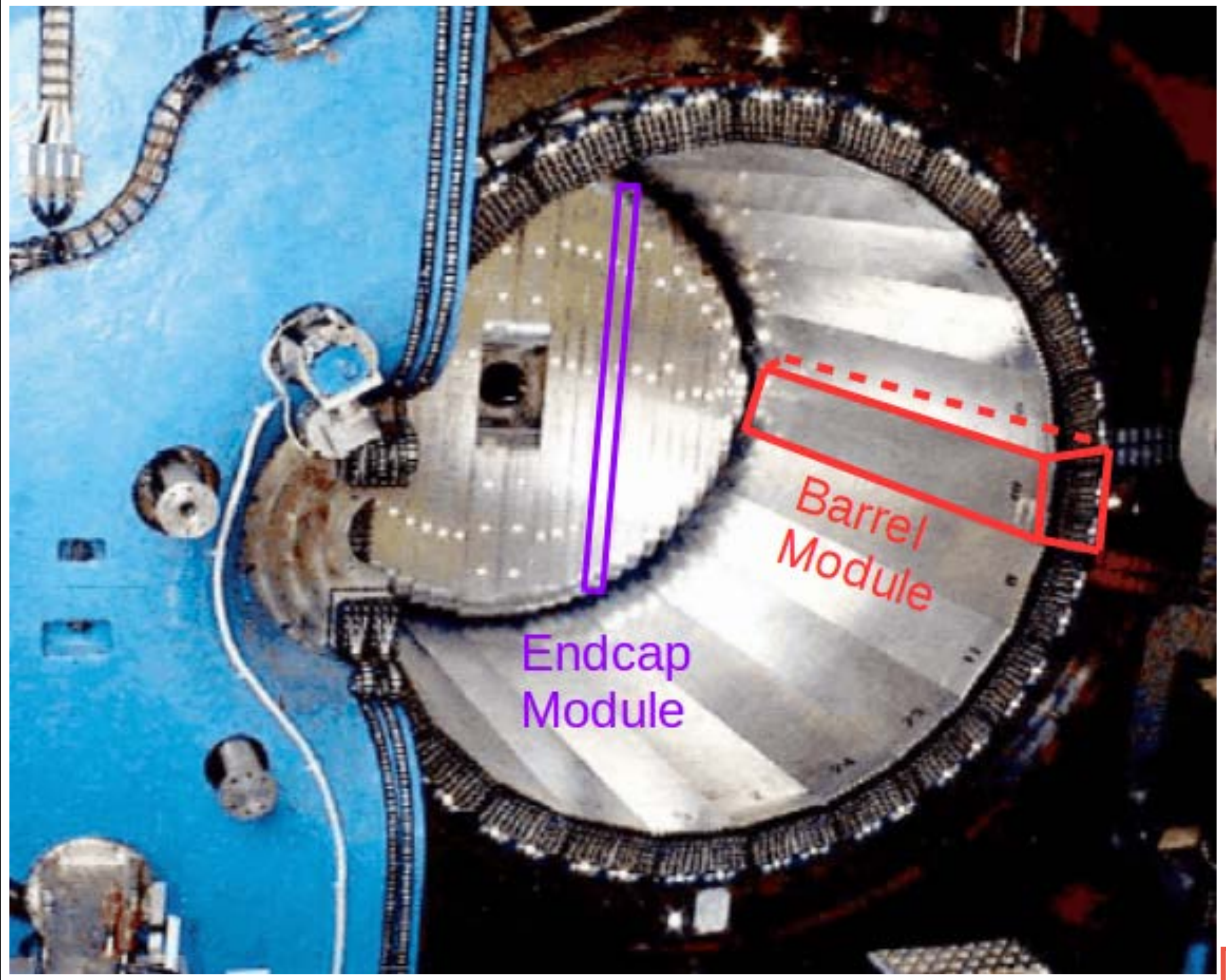
Sees many of the tracks that escape ND-LAr (i.e. largely energetic muons)

Scintillator + Steel: tracking and fast detection

Magnetized: sign selection

Also will see interactions in its material

SAND (System for on-Axis Neutrino Detection)



Reuses part of KLOE detector, with upgrades: also magnetized

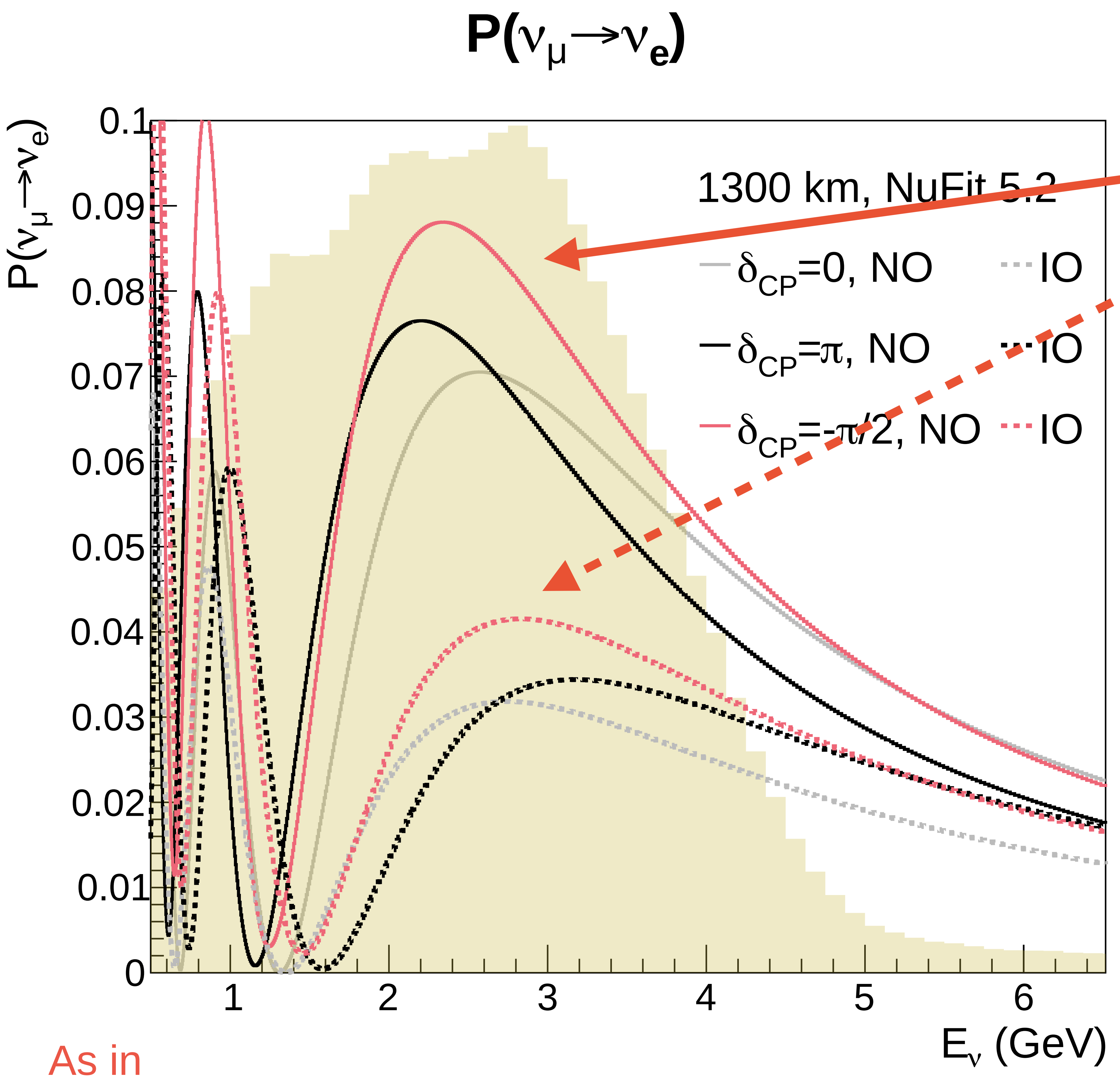
Remains on-axis: beam monitor

Measurements for flux constraint, cross-sections, etc.

DUNE ND CDR, arXiv:2103.13910

DUNE Sensitivities

Matter effect causes DUNE to pick up a large difference in oscillation probability depending on ordering, high sensitivity to mass ordering

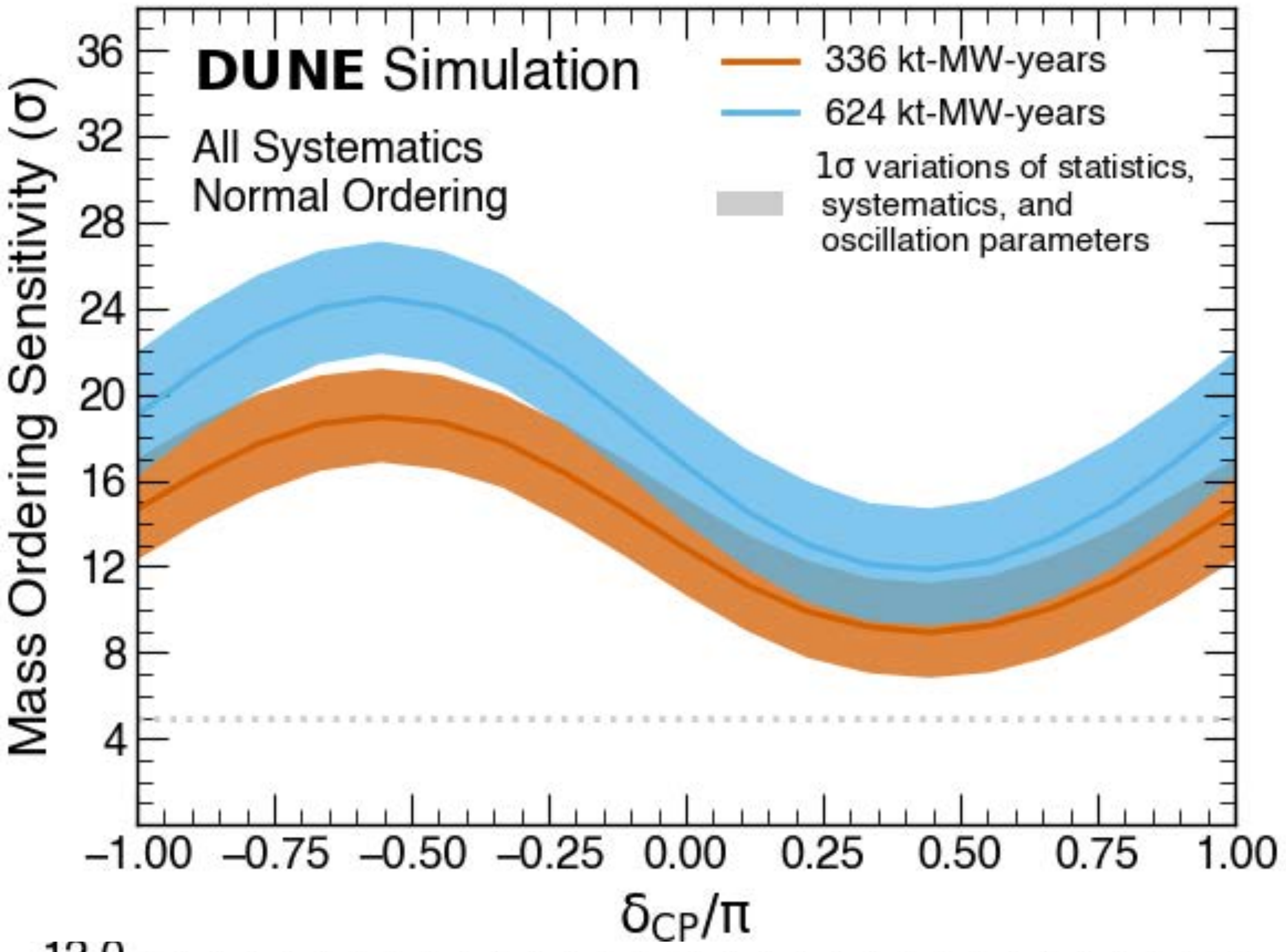


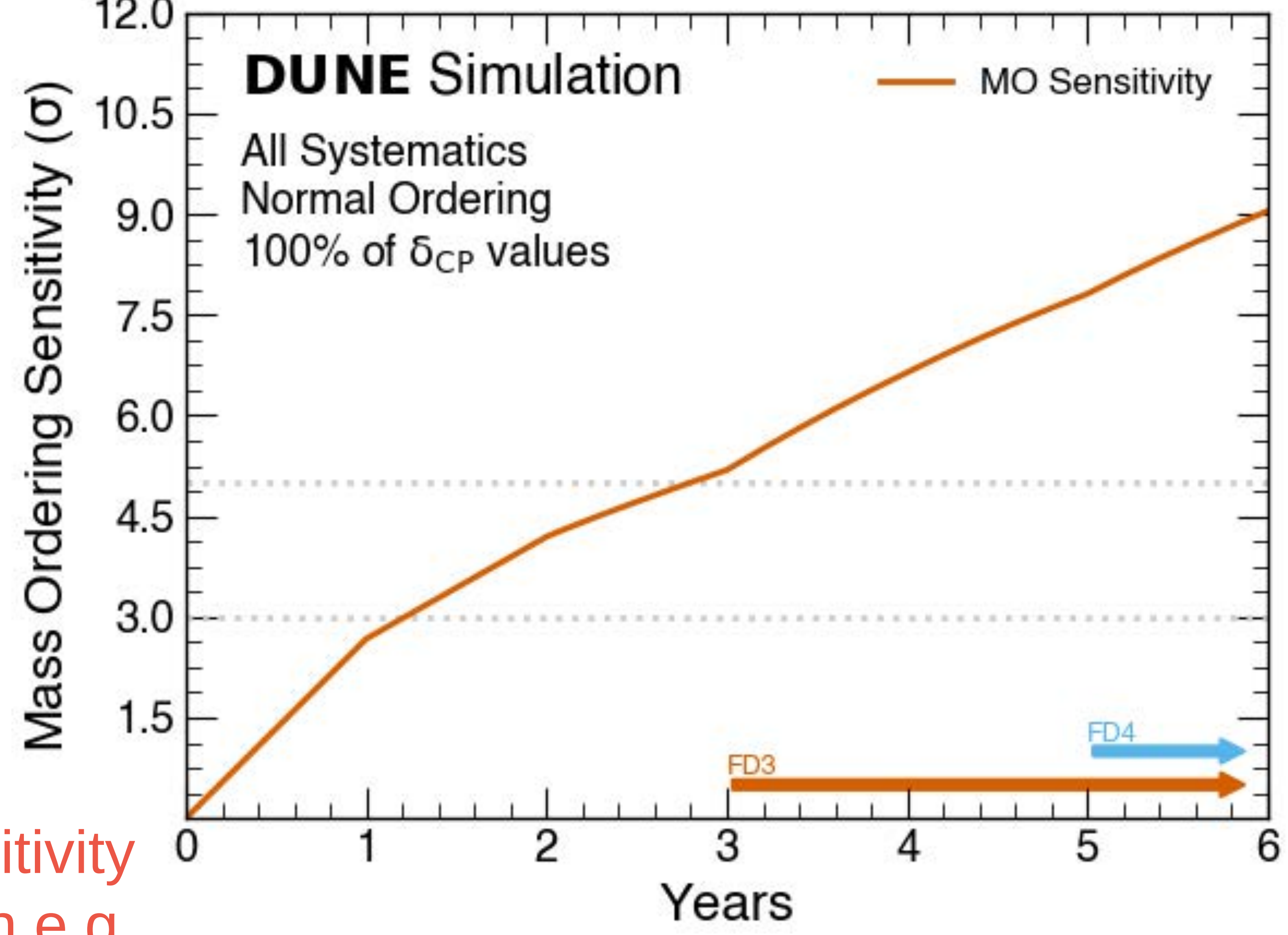
As in
Harris, Ilic, Konaka, Canadian Journal of Physics (2025)

Ultimate DUNE volume ~40 kt

Beam will start at ~1 MW and be upgradable to ~2 MW in end

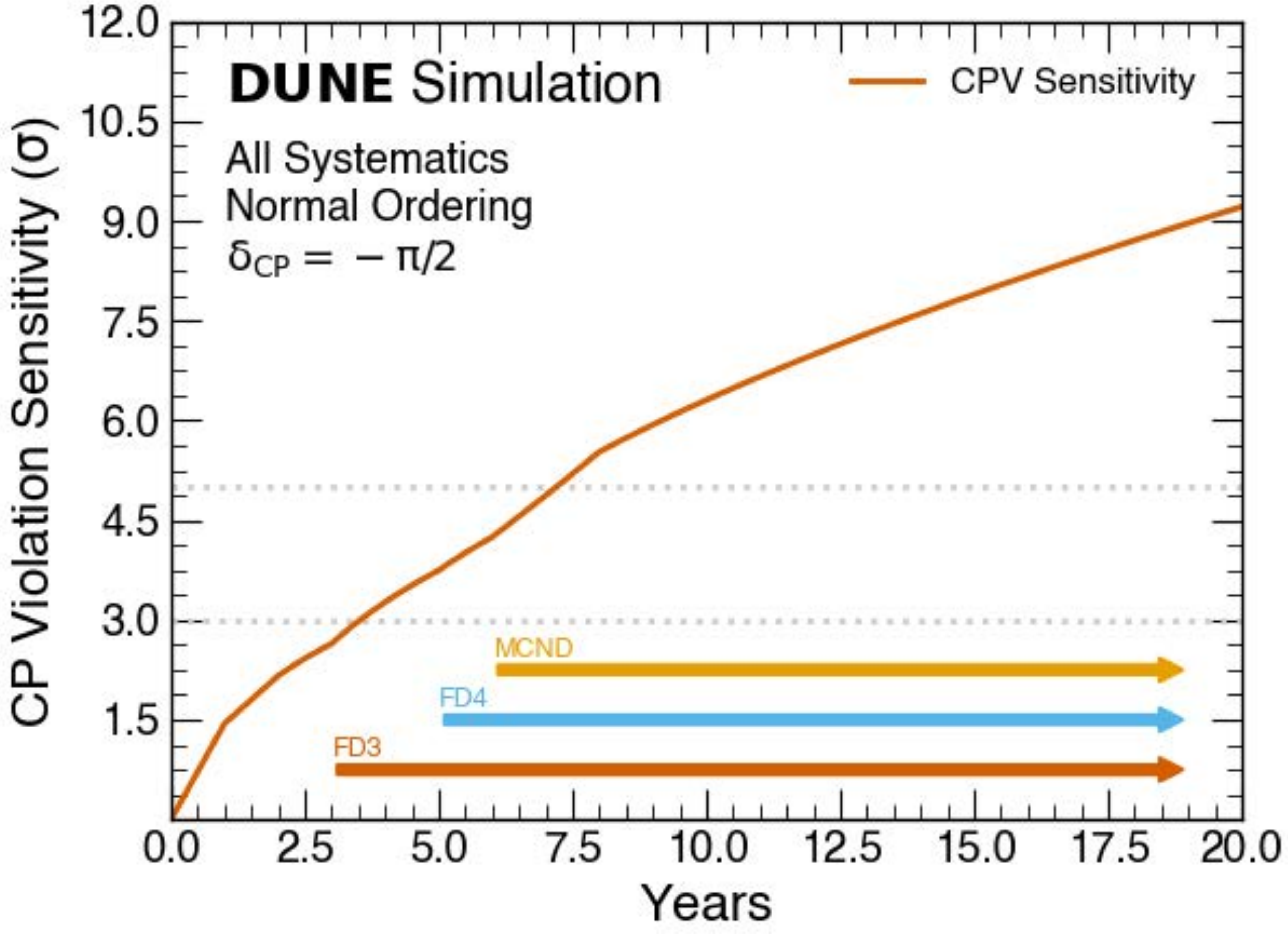
DUNE sensitivity vs timeline interpretation (2024)

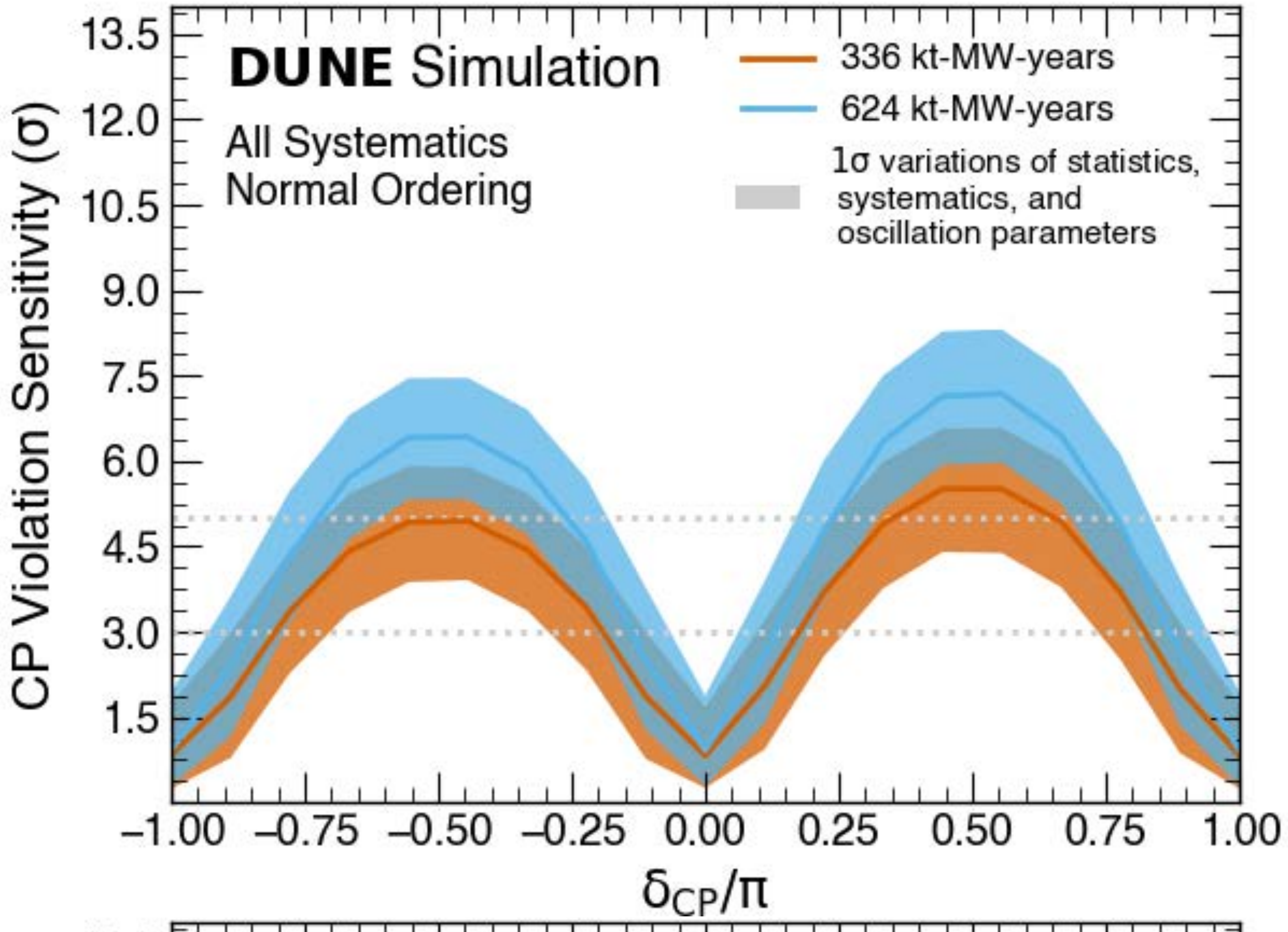


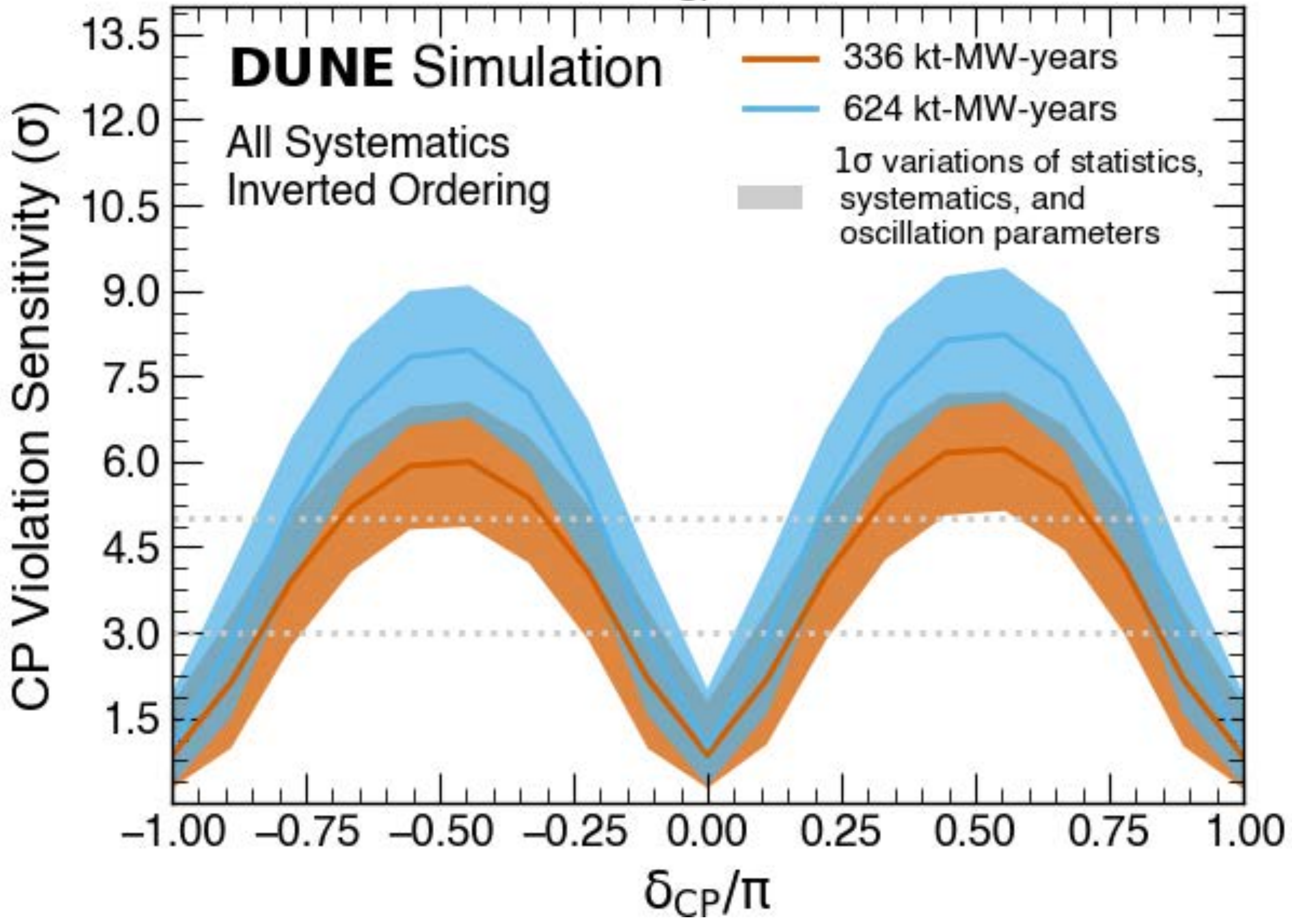


Updated versions of sensitivity plots, see analysis details in e.g.
DUNE, EPJ C (2020) 80:978
DUNE, PRD **105**, 072006 (2022)

DUNE Sensitivities







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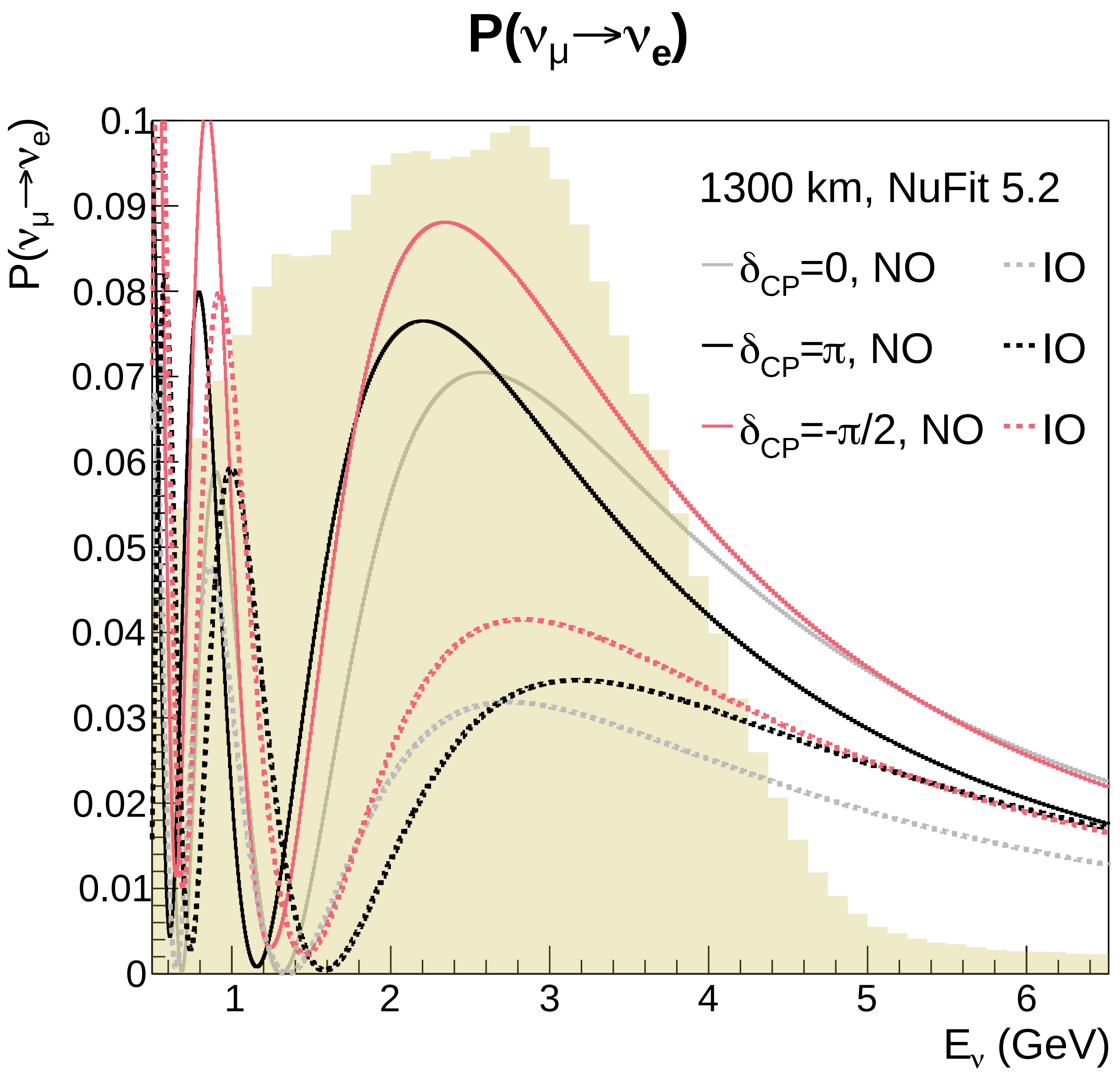
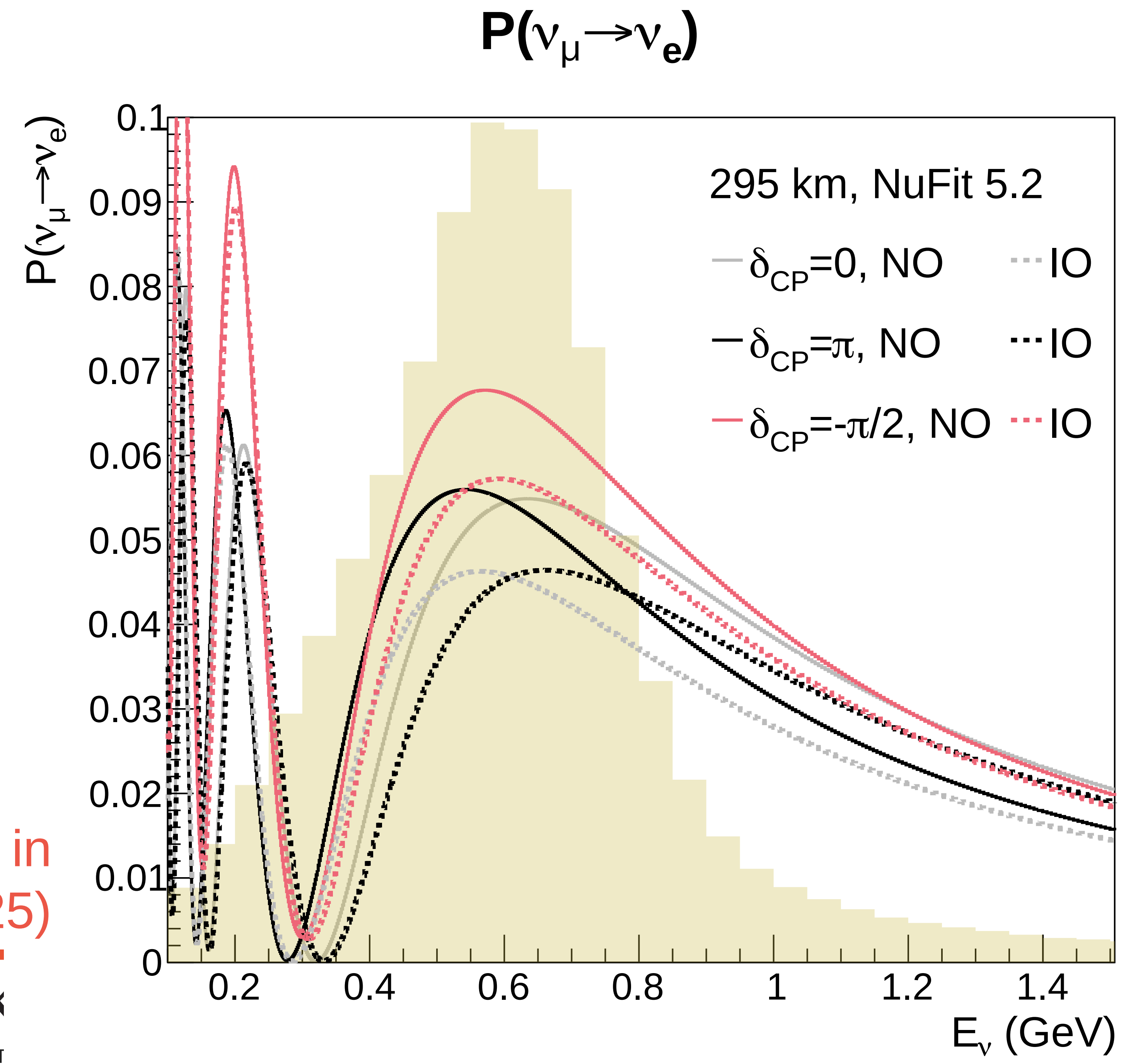
DUNE, PRD **105**, 072006 (2022)

DUNE & Hyper-Kamiokande

- Hyper-Kamiokande: next-generation neutrino oscillation experiment in Japan
  - Both DUNE and HK will measure oscillation probabilities for neutrinos, and similar ratio of L/E (in peak)
  - But very different experimental setups:
    - Different length scales (DUNE 1300 km, HK 300 km)
    - Different beam energy (DUNE broad 1-5 GeV, HK ~600 MeV)
    - Different primary detection medium (DUNE liquid Argon, HK water) and detector type (DUNE TPC, HK Čerenkov)
- This longer length scale for DUNE makes it especially sensitive to mass ordering over HK, though HK does retain δ_{CP} sensitivity
  - Both together give best sensitivity to δ_{CP} and overall complementary measurement of oscillations



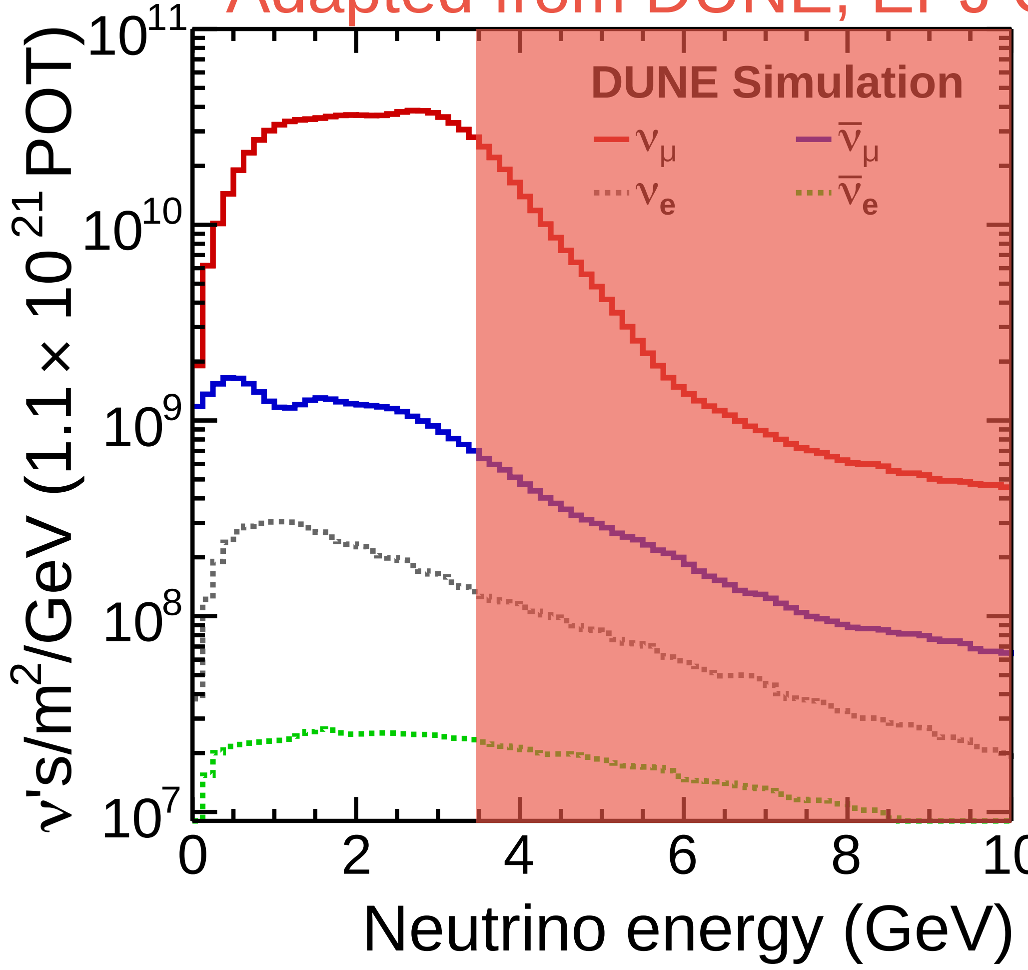


As in
Harris, Ilic, Konaka, Canadian Journal of Physics (2025)

DUNE & Hyper-Kamiokande

- DUNE's wide-band beam, and higher E_ν enable some key additional points:
  - Potential to see 2nd oscillation peak or at minimum a large amount of a full oscillation period
  - Higher E → chance to study ν_τ appearance also
- DUNE will also reach current generation sensitivity on mixing angles being very well measured by reactors (θ_{13})
- Stringent tests of the three-flavour oscillation paradigm
- Complementary non-beam physics: e.g. each is most sensitive to different interactions of supernova neutrinos, provide complementary channels in case of a nearby supernova
- Canada-based researchers are participating in both programs

Adapted from DUNE, EPJ C (2020) 80:978

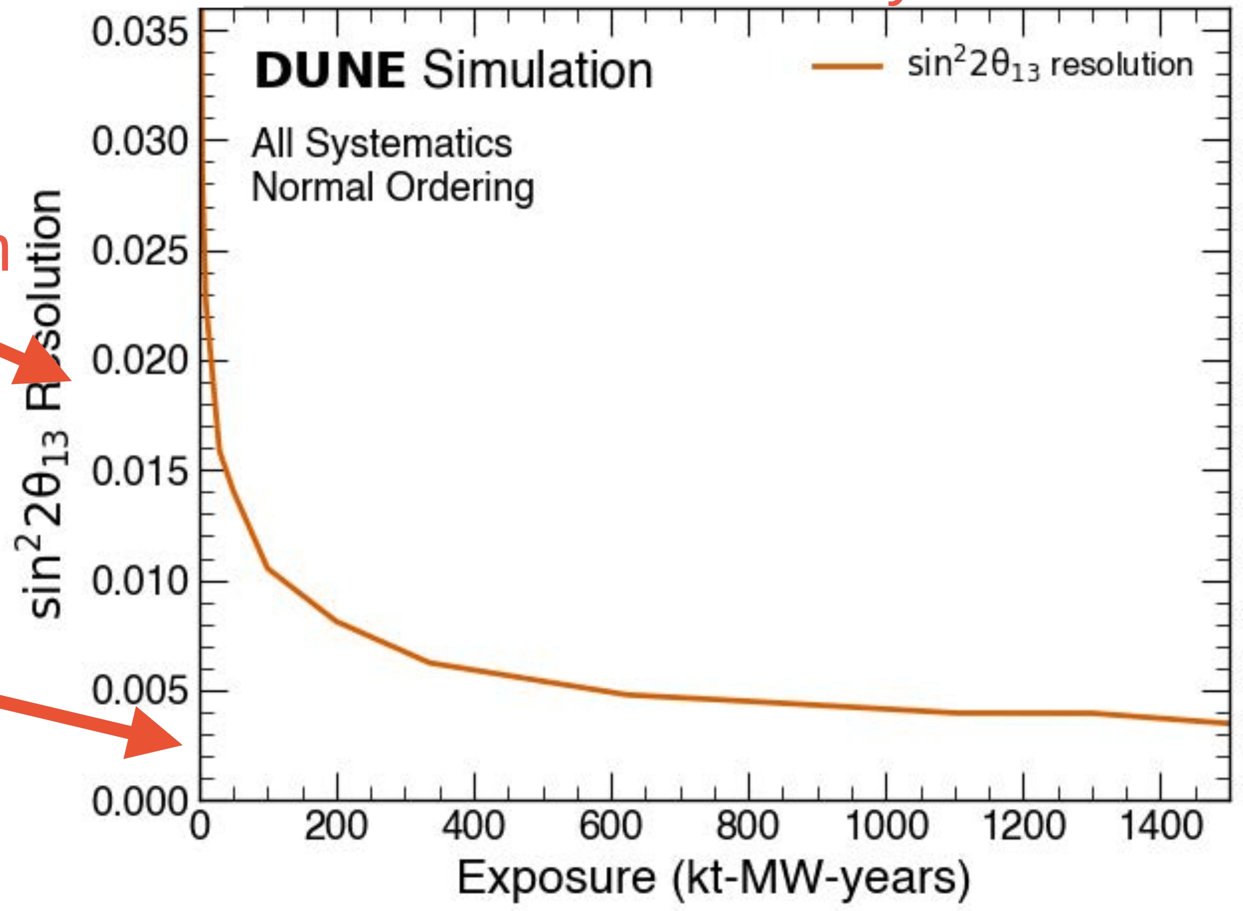


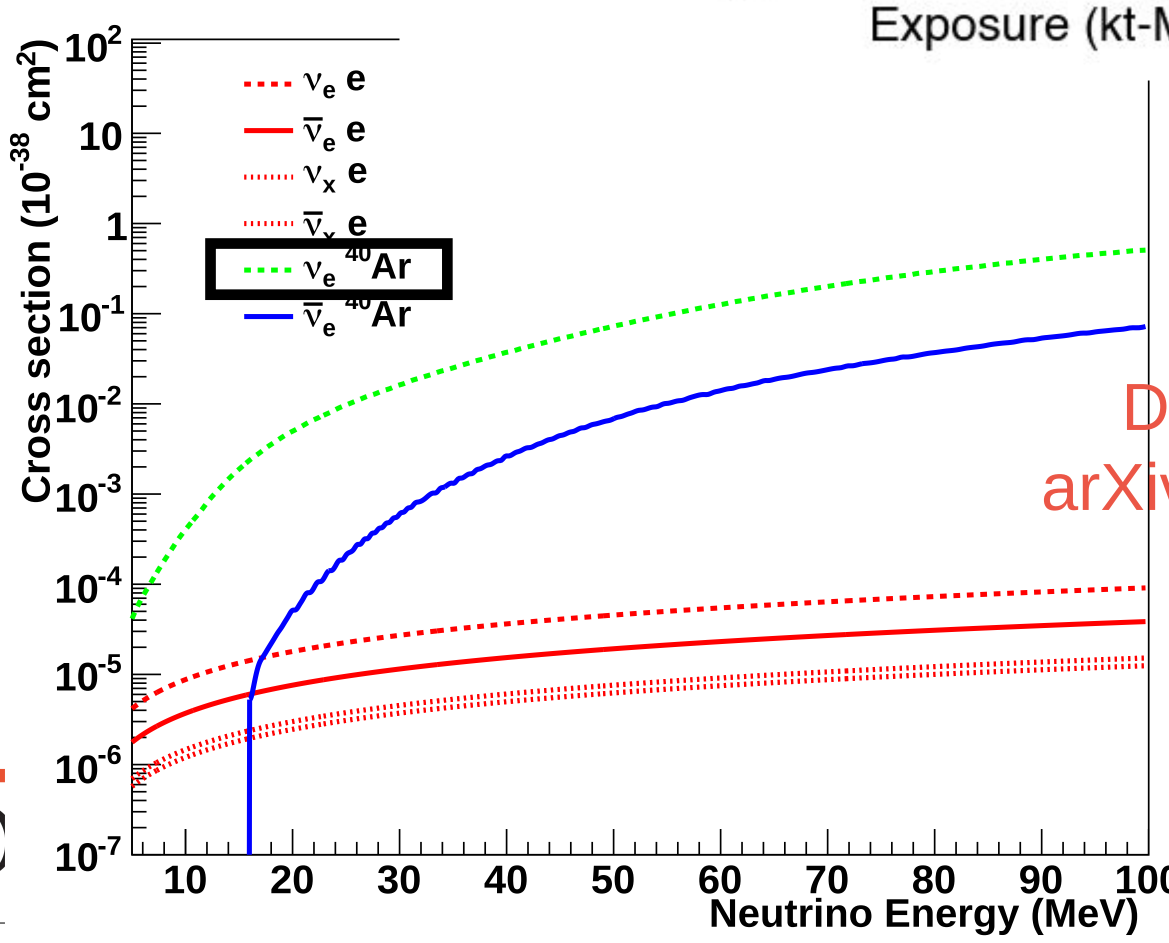
Can produce ν_τ

DUNE sensitivity as before

~NOvA resolution

Daya Bay resolution





DUNE TDR, arXiv:2002.03005

What about the years leading up to DUNE?

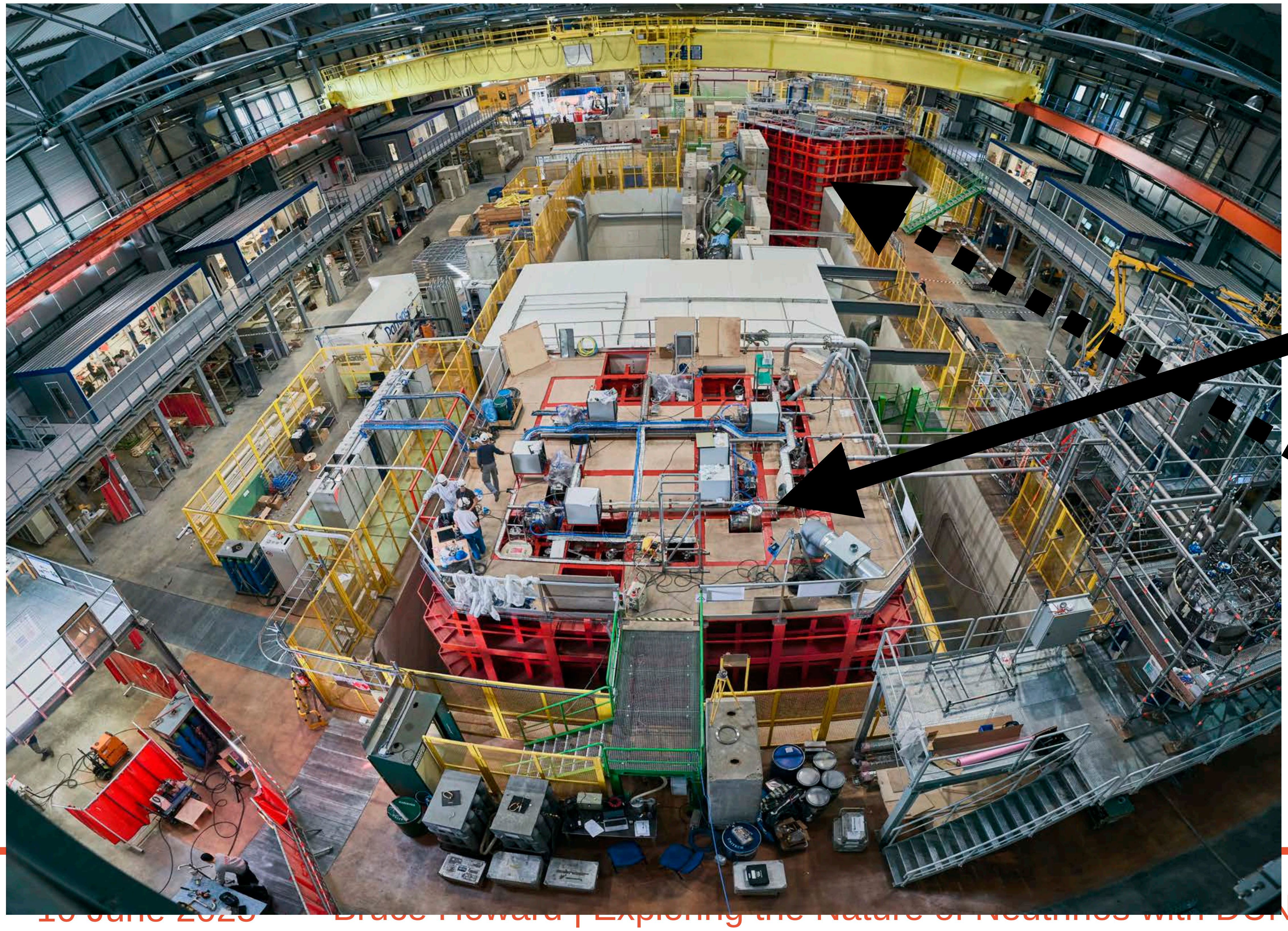
- In the time leading up to the full realization of DUNE, in addition to the constructing of the detectors and preparing for the delivery of physics, there is an active suite of ongoing efforts with smaller scale LAr TPCs within DUNE and around the community

- DUNE is operating a number of prototype experiments for the near and far detector modules
  - Also chances to do physics with these smaller LAr TPCs
  - More on these in the next slides

- There is another experimental program at Fermilab using LAr TPCs: Short Baseline Neutrino Program

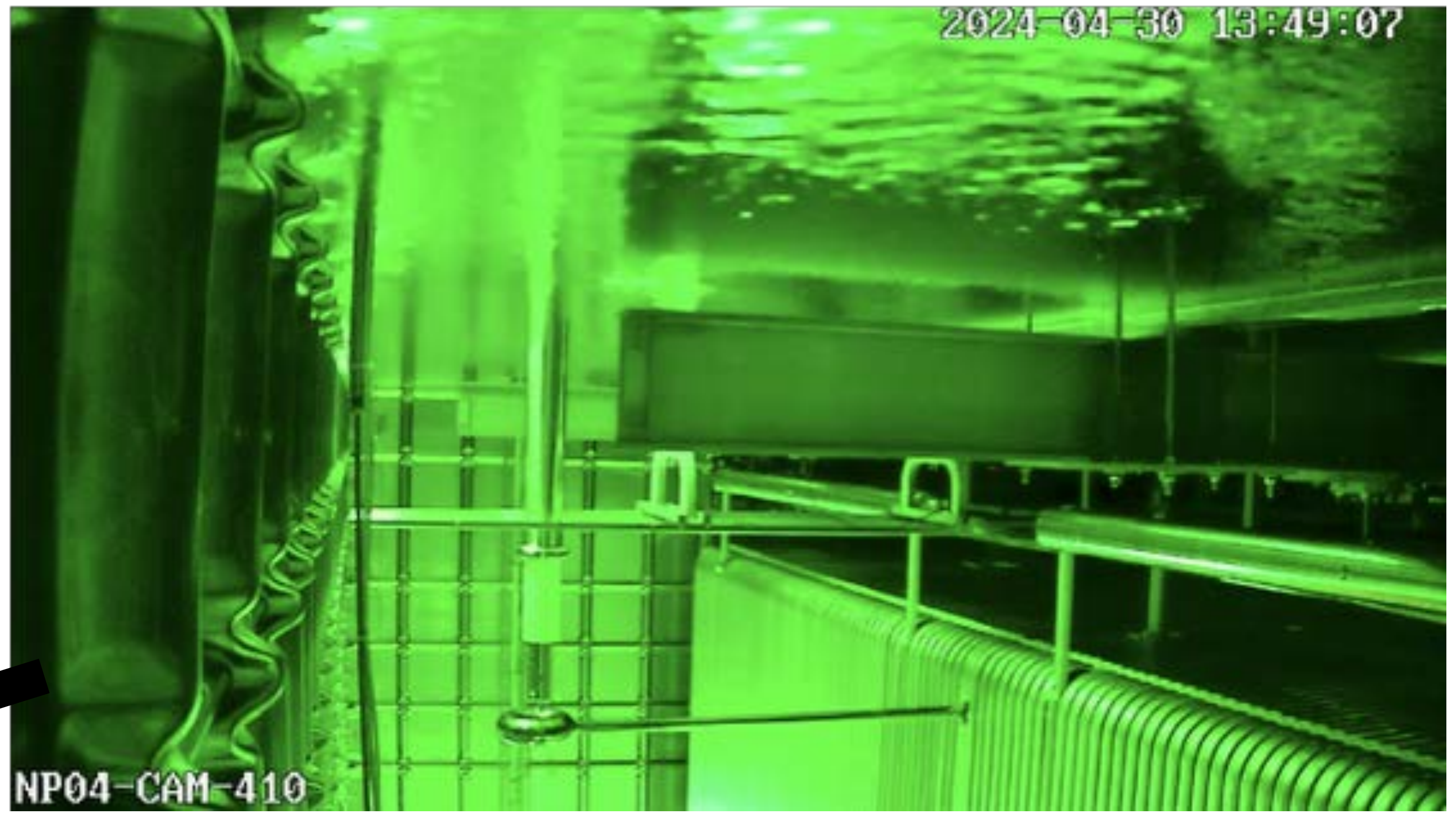
ProtoDUNEs at CERN

- To test DUNE style horizontal and vertical drift detectors, prototypes at CERN have been operating in charged particle beam
  - Horizontal drift data-taking over a few run periods, and now filling complete (2025) to test vertical drift as well

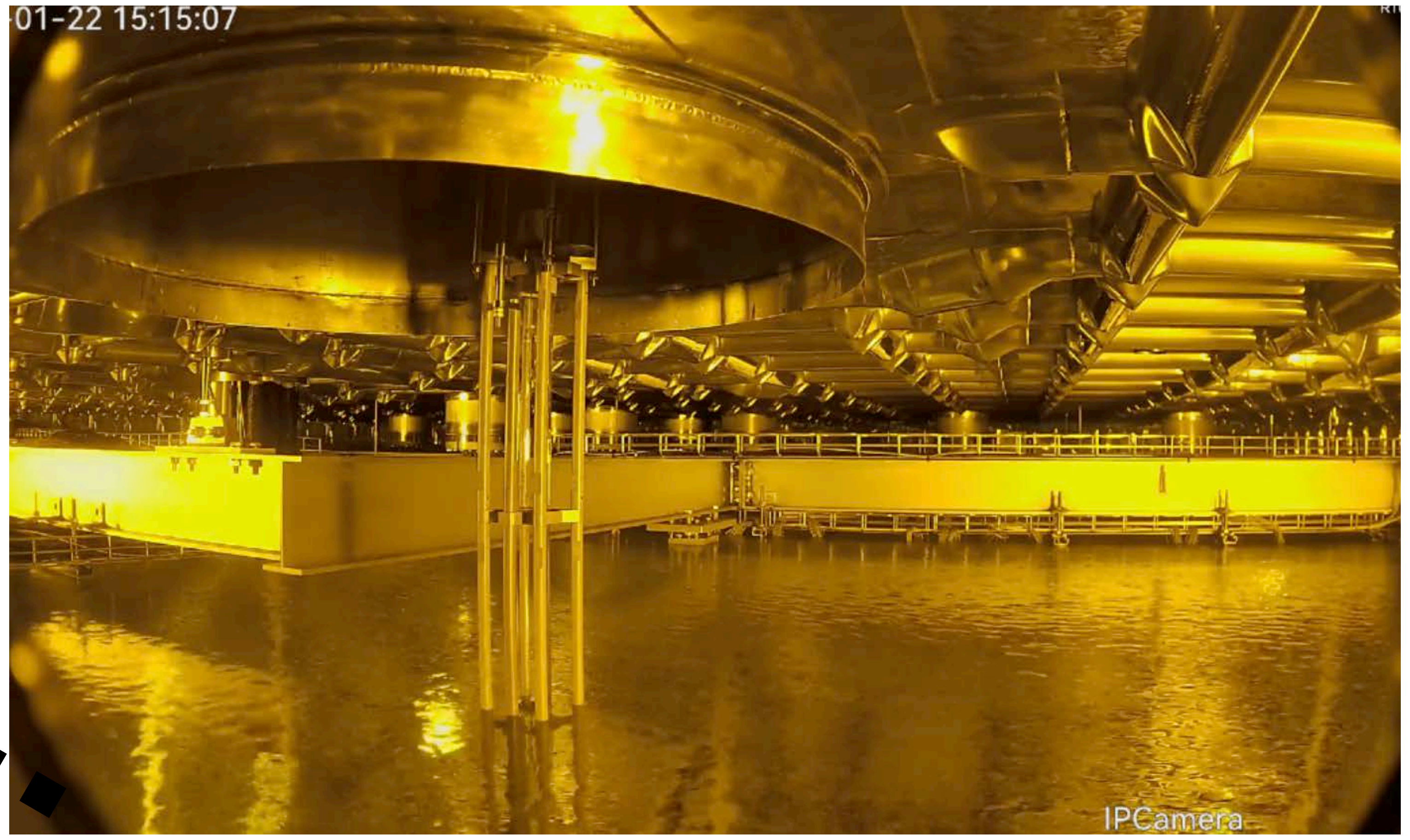


ProtoDUNE hall, photo: CERN

LAr in horizontal drift detector for last year’s tests



LAr in vertical drift detector for this year’s tests



ProtoDUNEs at CERN

- Serves as an important test of hardware for DUNE Far Detector modules
- Also, study events with charged particles and Ar
  a) Reconstruction and algorithms for analyzing data
  b) Measure particle-Ar interactions

First results on ProtoDUNE-SP liquid argon time projection chamber performance from a beam test at the CERN Neutrino Platform [2007.06722], JINST **15** P12004 2020

Design, construction and operation of the ProtoDUNE-SP Liquid Argon TPC [2108.01902], JINST **17** P01005 2022

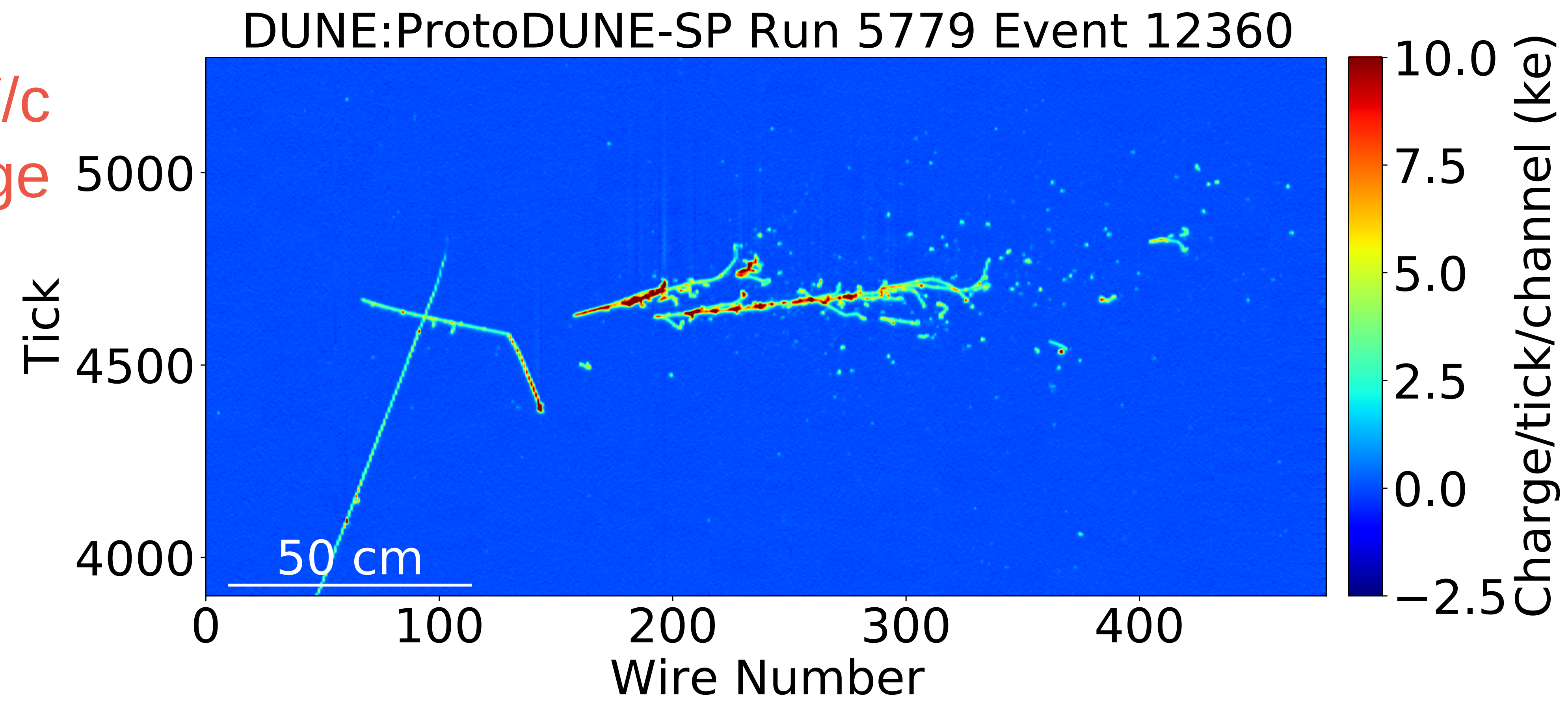
Reconstruction of interactions in the ProtoDUNE-SP detector with Pandora [2206.14521], EPJC (2023) 83:618

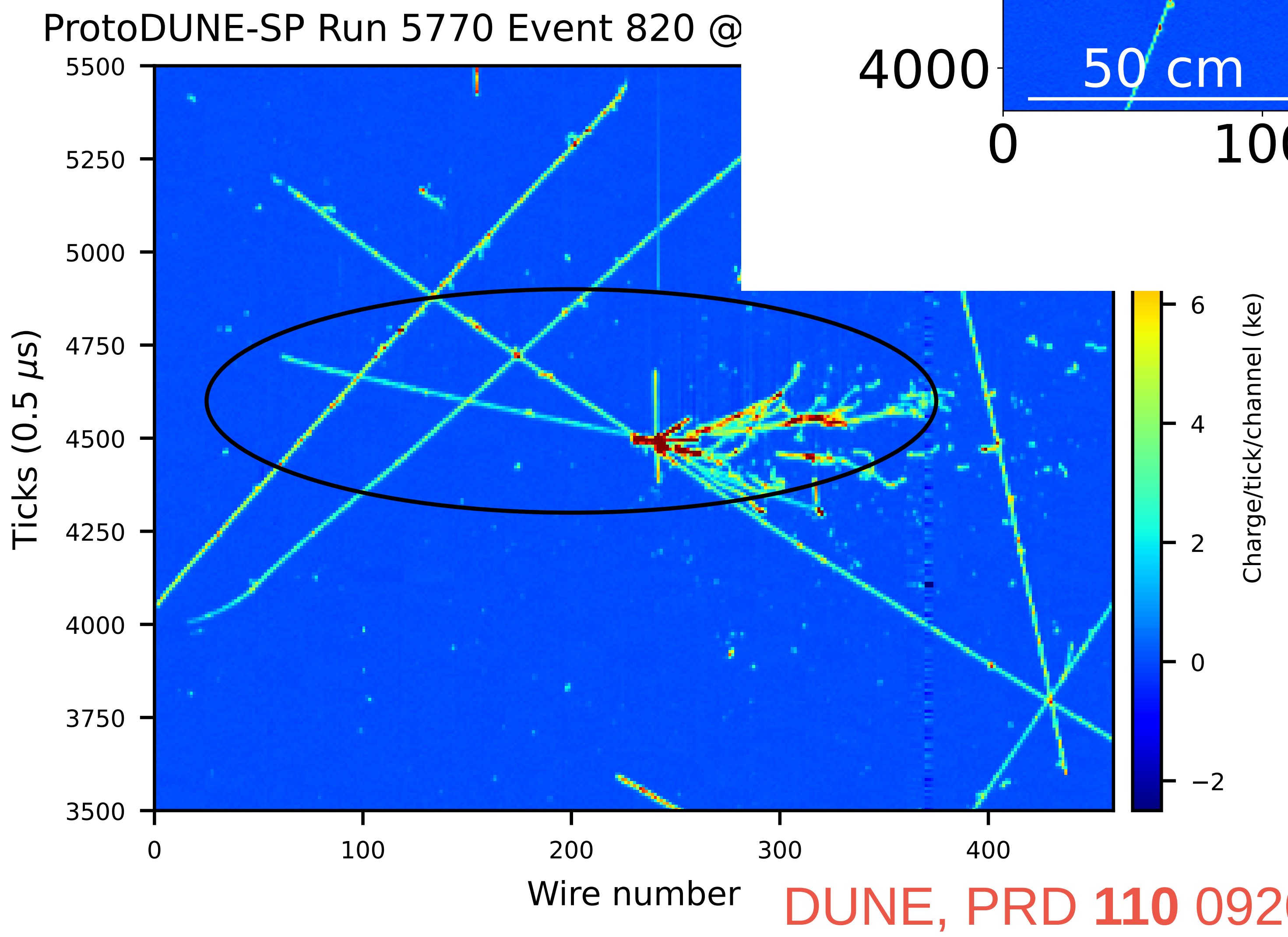
First Measurement of the Total Inelastic Cross-Section of Positively-Charged Kaons on Argon at Energies Between 5.0 and 7.5 GeV

and more! [2408.00582], PRD **110** 092011 (2024)

DUNE, JINST **15** P12004 2020

Candidate for a 2 GeV/c pion charge-exchange





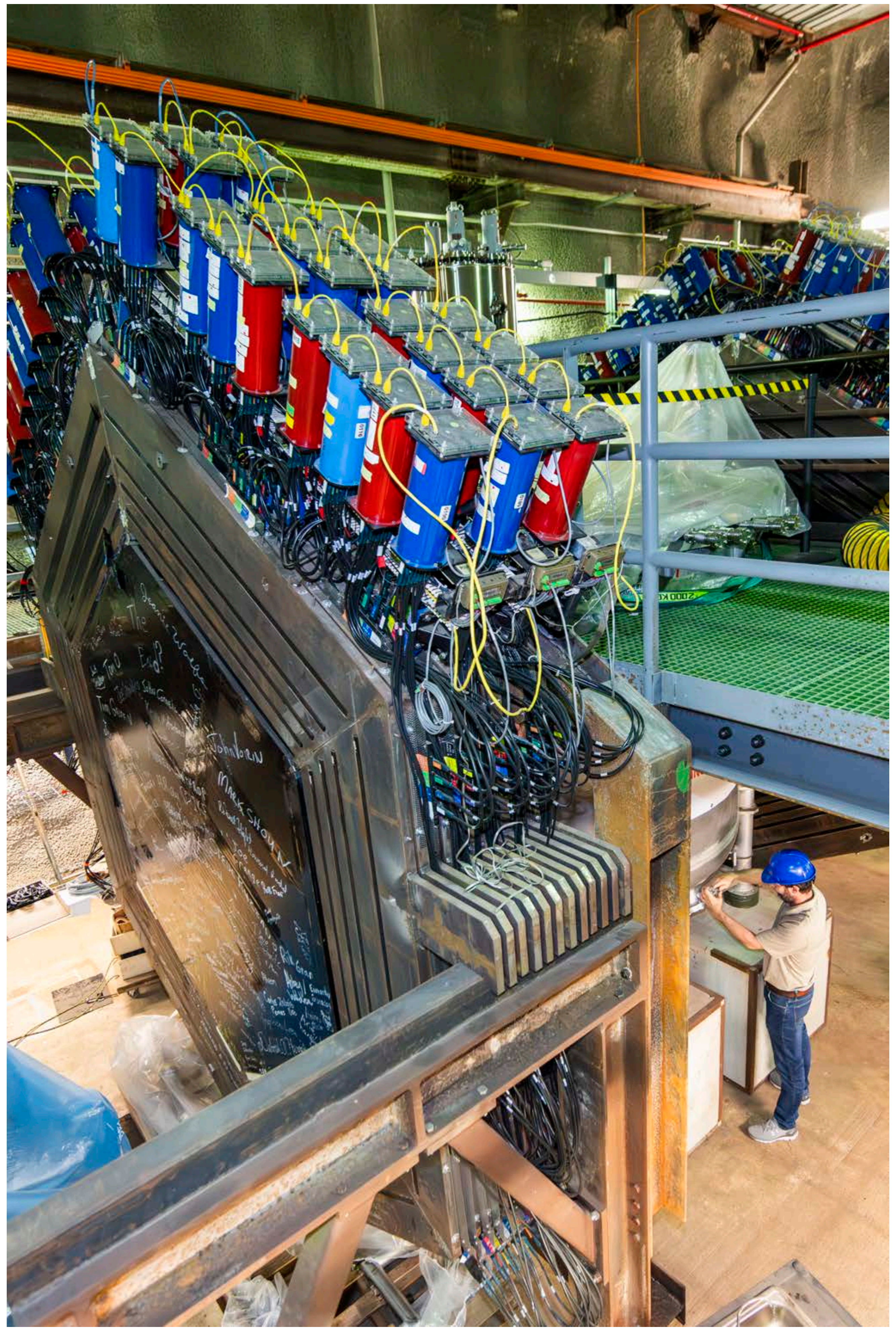
Candidate for inelastically interacting kaon

DUNE, PRD **110** 092011 (2024)

DUNE Near Detector Prototypes

- 2x2 at Fermilab: smaller segmented, pixelated LAr TPC
  - Repurposed scintillating tracker planes tag muons from interactions in the rock and to catch muons that leave 2x2
  - 2x2 operated in NuMI ($\bar{\nu}$) beam, Fermilab at end of 2024 beam run
  - Thousands of interactions to study
  - Working to study detector performance, and study the $\bar{\nu}$-Ar interactions
- Upgraded & larger single module “Full Scale Demonstrator” (FSD) module was operated in the Fall 2024 at Bern with cosmic ray exposure

Photos: Fermilab VMS



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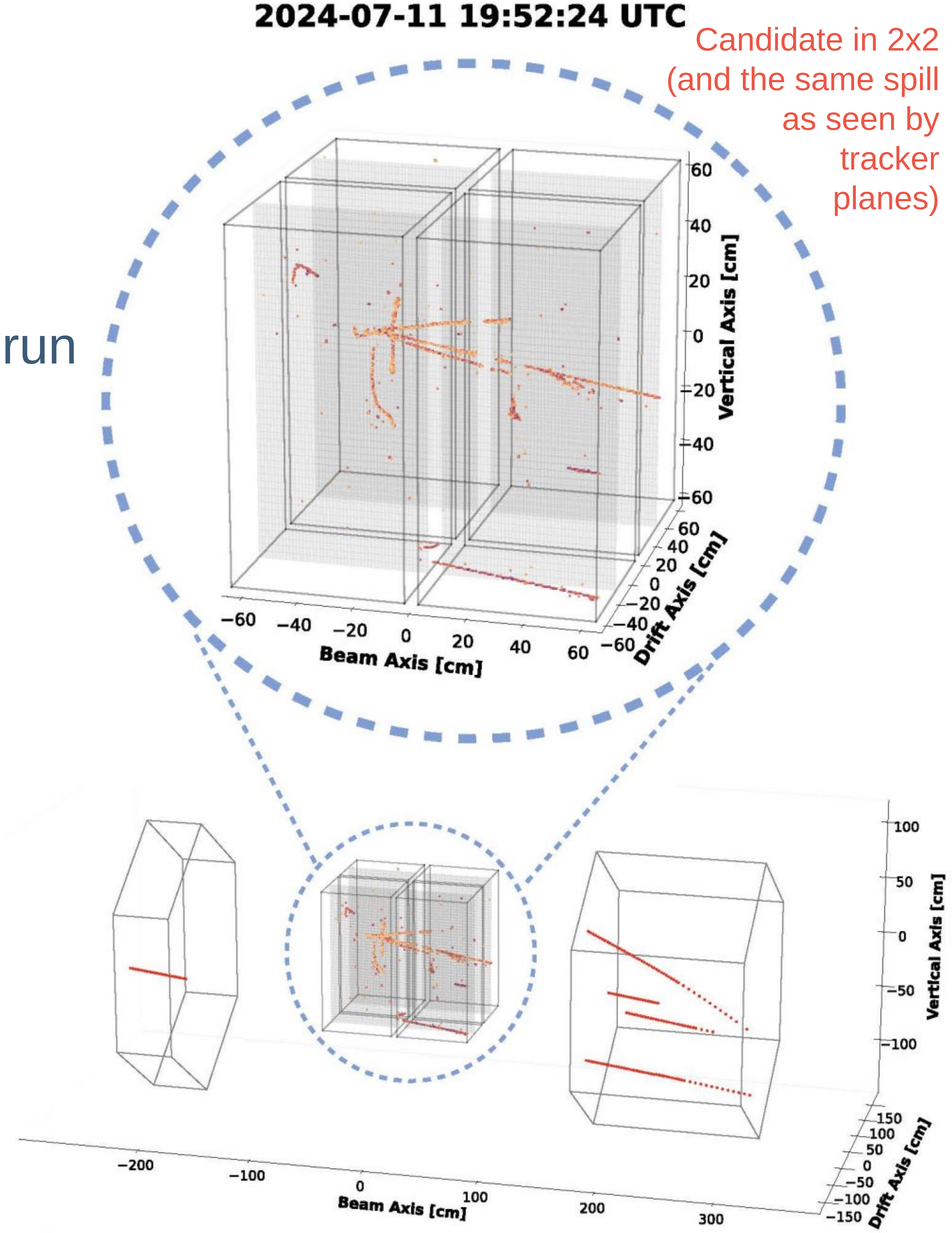
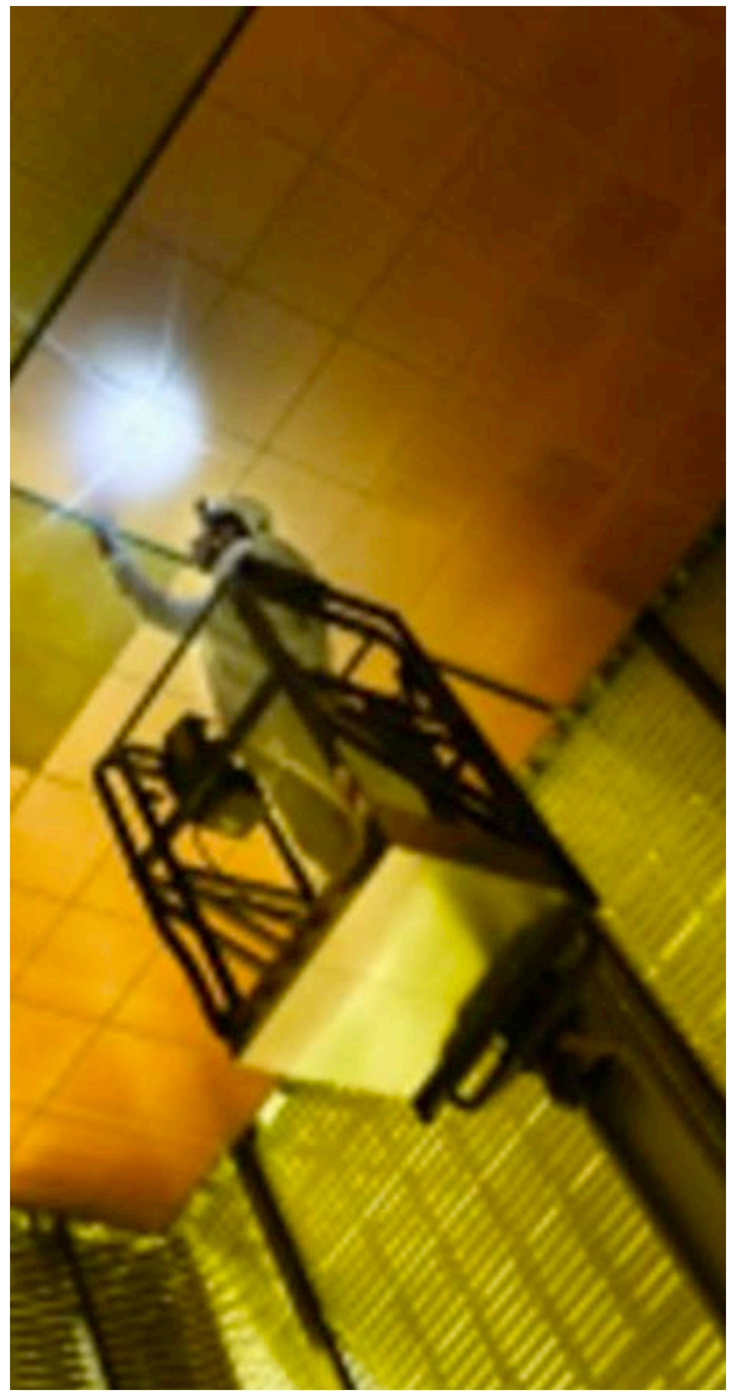
Phot

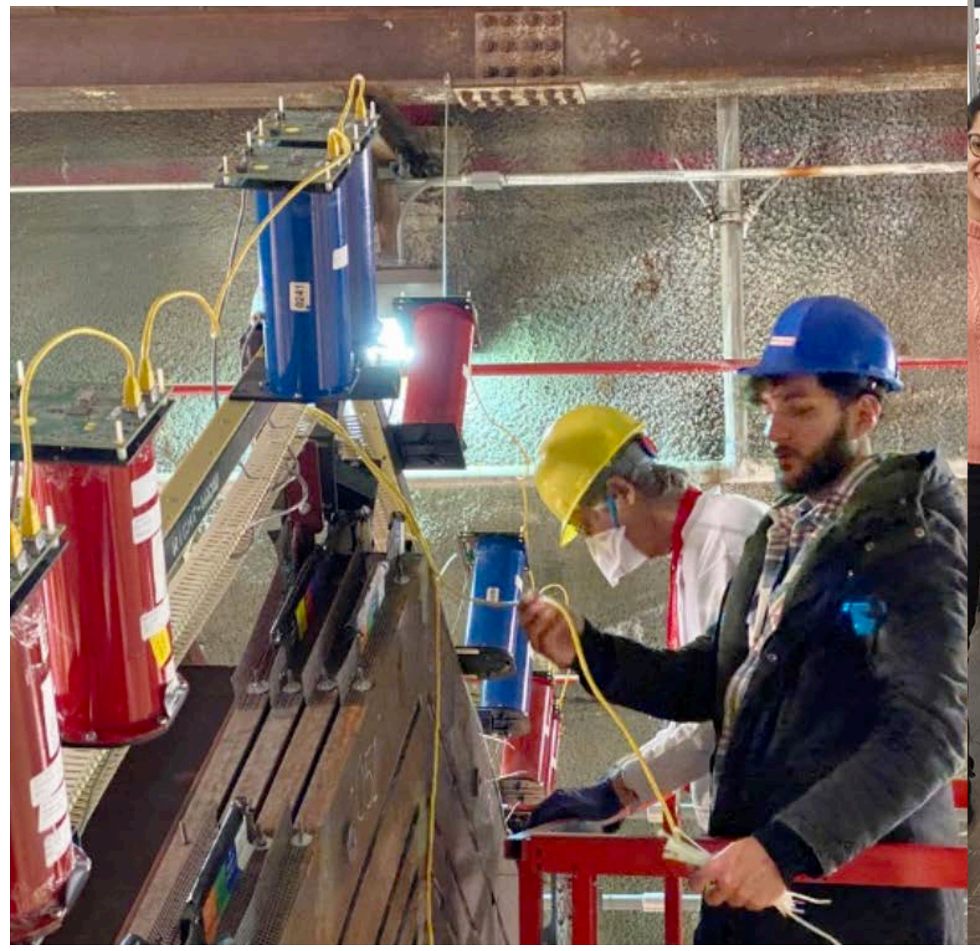


Candidate in 2x2 (and the same spill as seen by tracker planes)

DUNE-Canada 🇨🇦

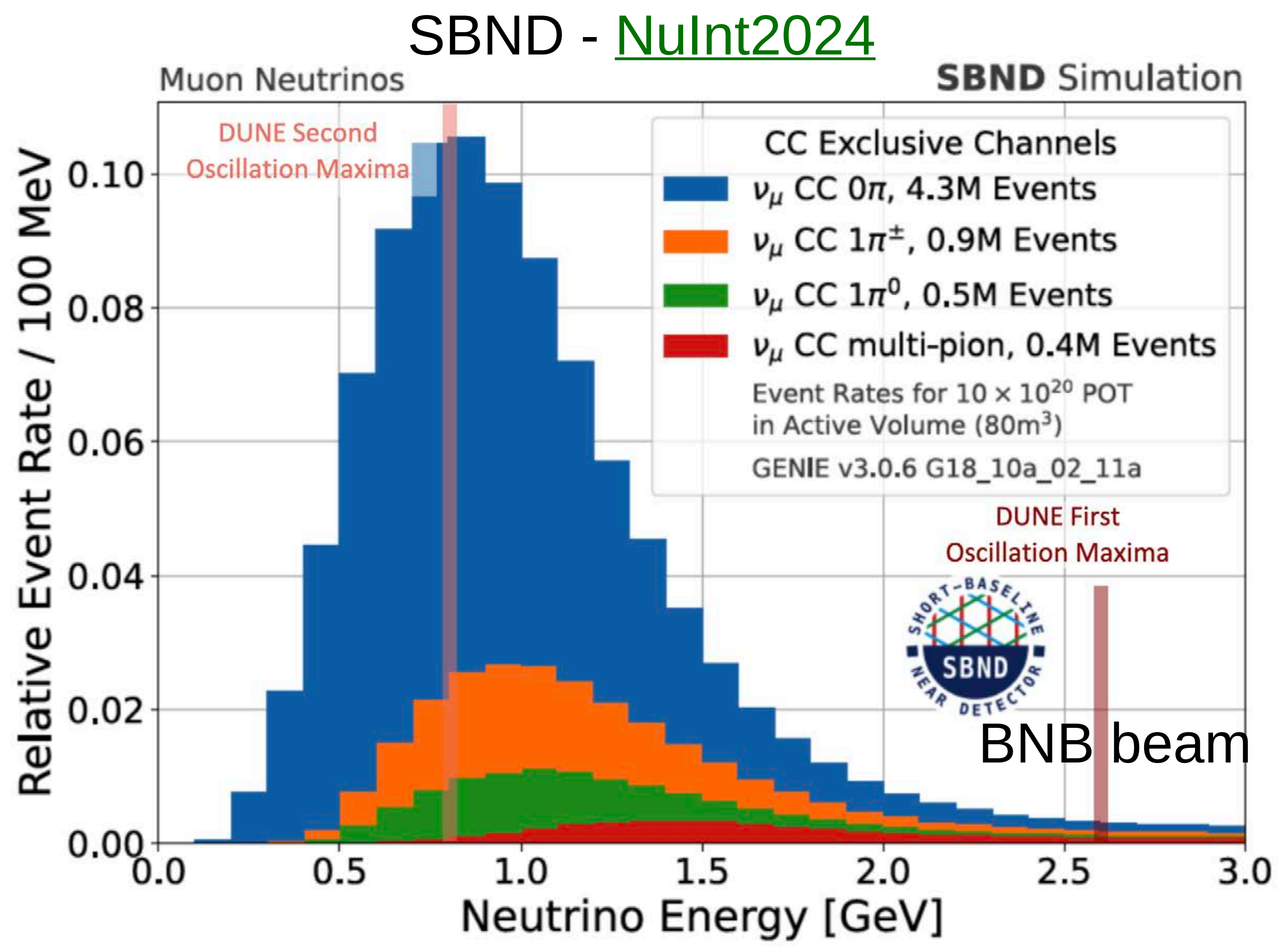
- Current institutions collaborating on DUNE in Canada:
  - York University (Toronto), University of Toronto (Toronto)
  - 3 faculty, w/ postdocs, graduate students & undergraduate students involved
- Between the groups, coverage in both Near and Far Detectors:
  - Data acquisition, ProtoDUNE
  - Far Detector physics: ν_τ appearance, low energy (e.g. solar ν), non-standard interactions
  - Near Detector (esp. the LAr TPC but also connections to other systems): prototypes, simulation, calibration, reconstruction, analysis
  - Also, Digital Research Alliance resources are helping DUNE to perform oscillation sensitivity analyses

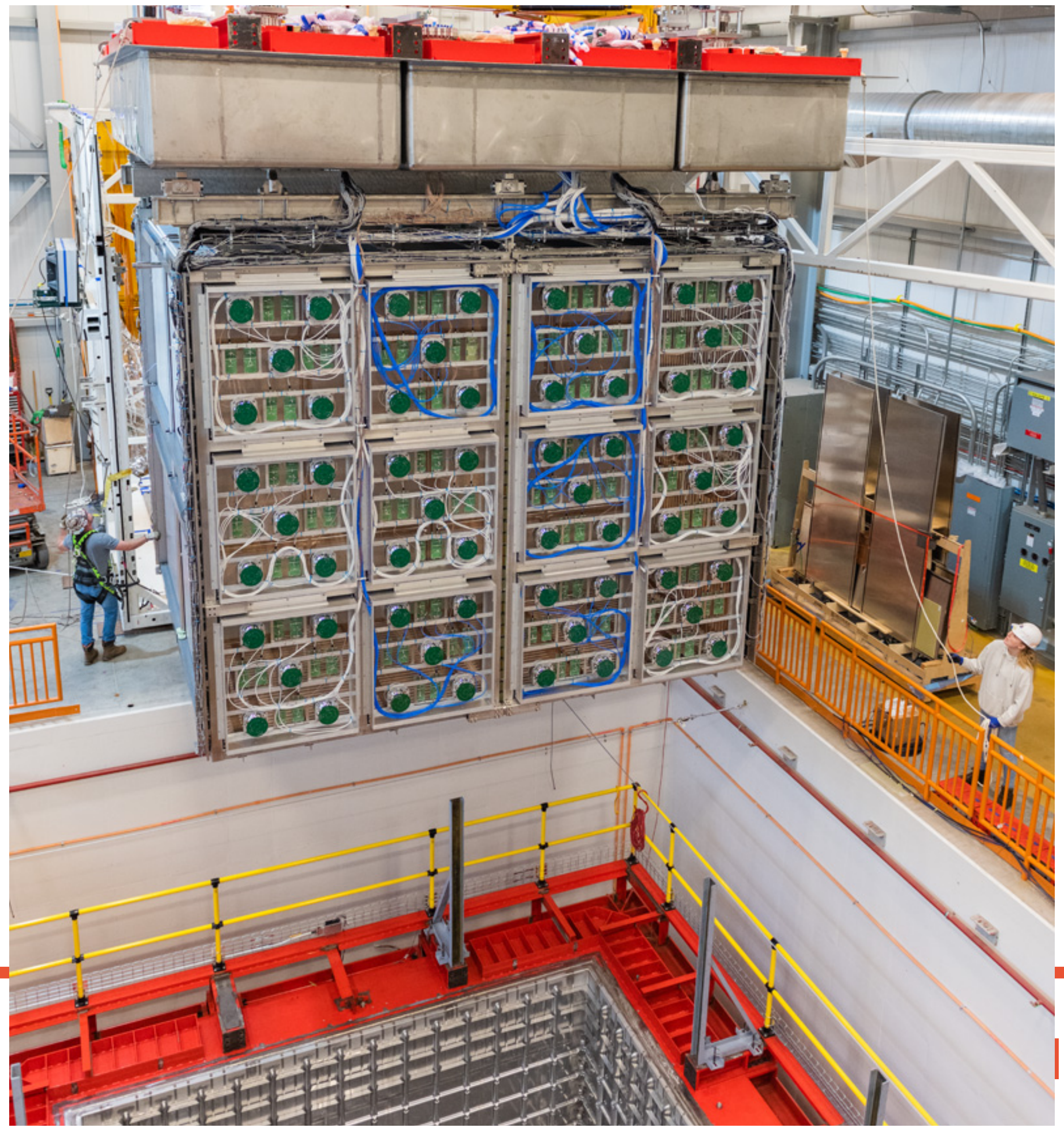




Other liquid argon experiments

- Smaller LAr TPCs have been operating at Fermilab
  - Studying excess of electron-like candidates at short baselines in other experiments (e.g. sterile ν?)
- Additionally, an opportunity to e.g.:
  - Gain experience w/ these detectors (operating, analyzing)
  - Conduct neutrino interaction measurements to help constrain model inputs for early DUNE measurements

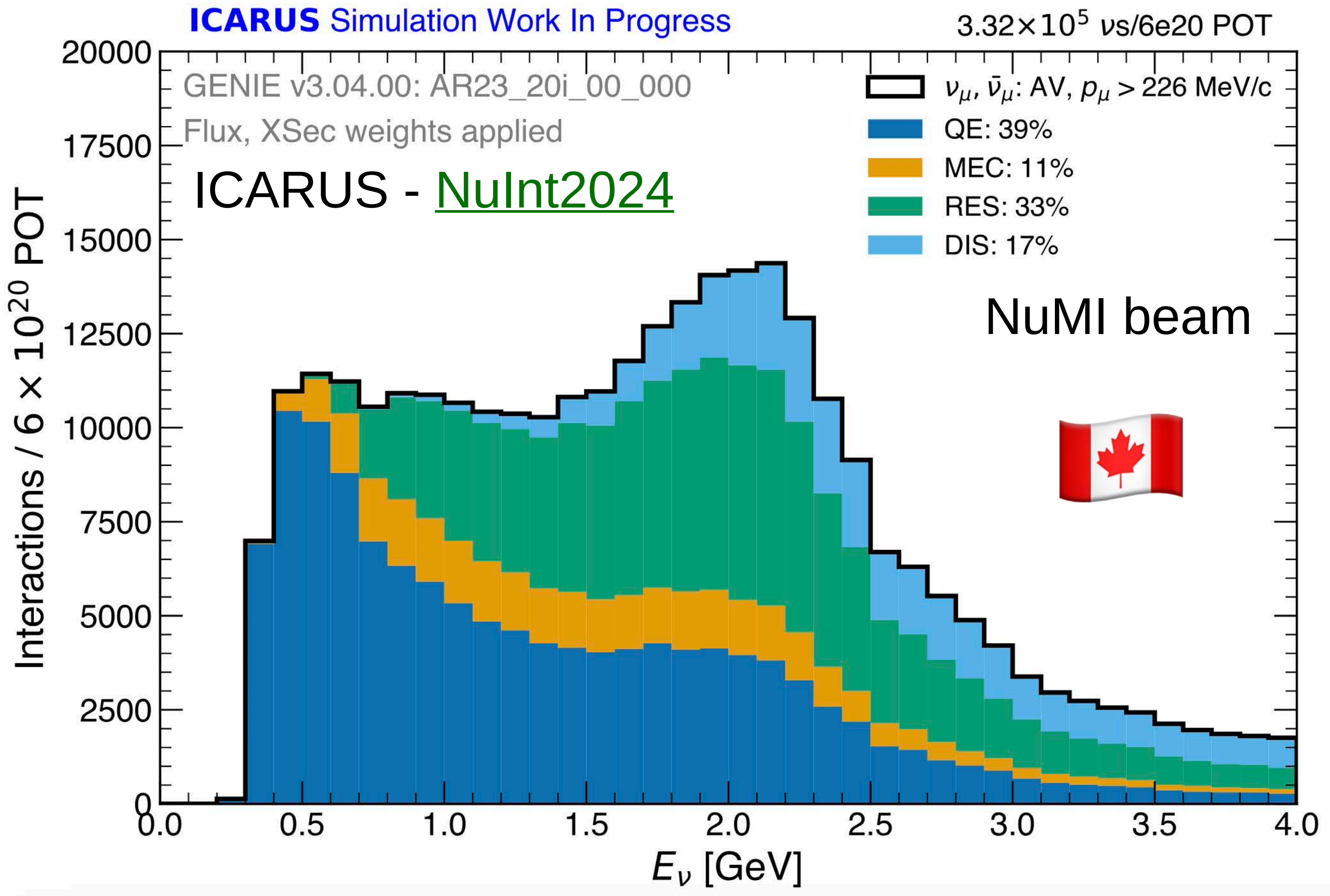




MicroBooNE (not shown) is another LAr TPC that ran at Fermilab

SBND, photo credit FNAL

ICARUS, photo credit CERN

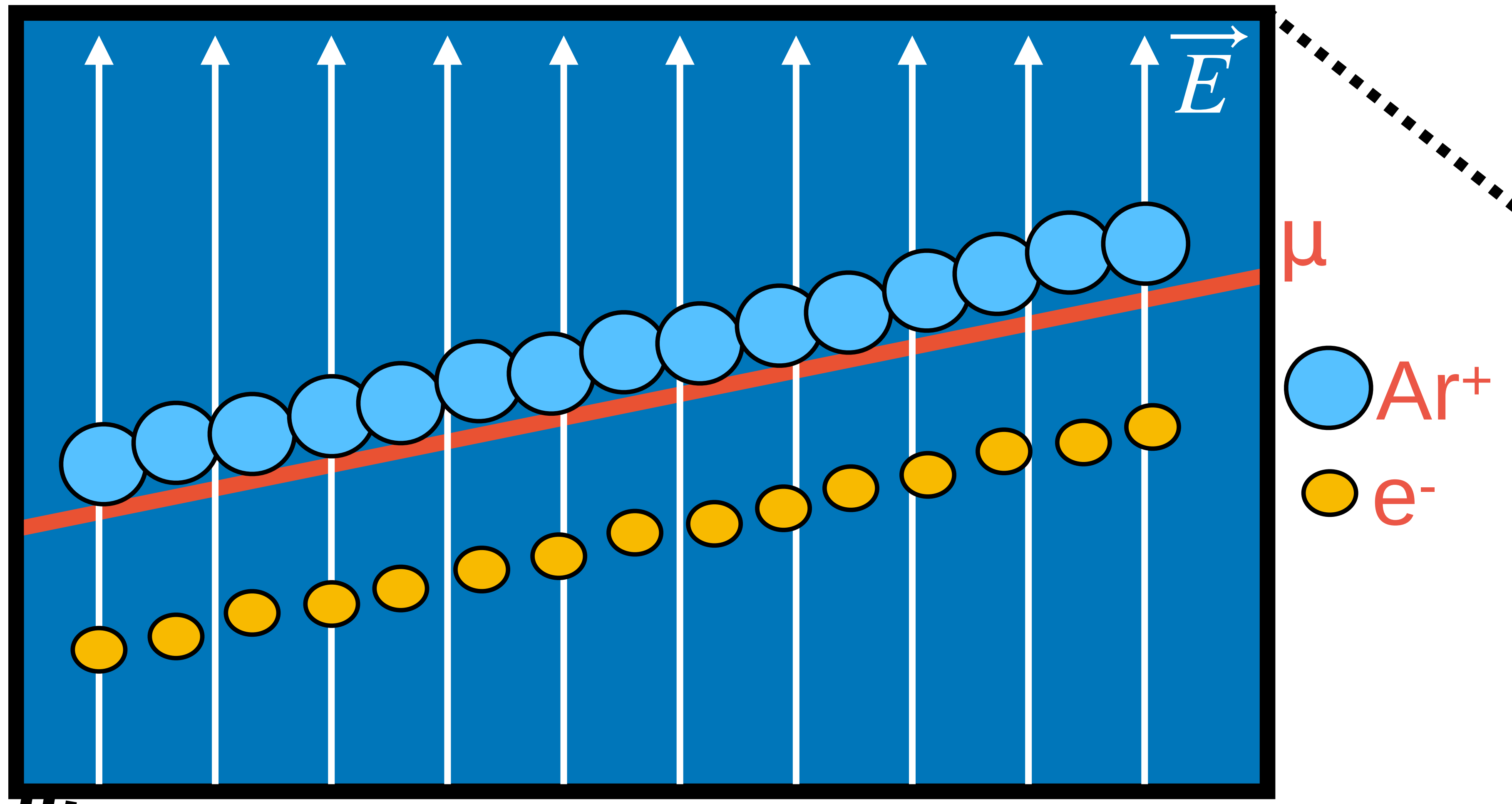


Conclusions

- DUNE will deploy LAr TPC detectors in Lead, South Dakota and a near detector at Fermilab, and leverage these to study neutrino oscillations
- Prototypes of Near and Far Detector technologies have been operating in test beams and neutrino beams: are demonstrating and driving the technology, software, and producing analysis
- DUNE Far Detector cavern excavations basically complete, next is constructing the far detector modules
  - Far Detectors to start operating around the end of the decade
  - Near Detector and Beam to follow and start DUNE's full oscillation program in early 2030s
- The next generation of neutrino oscillation experiments will address open questions related to neutrino oscillations
  - Realizing the full DUNE program will bring a test of the three-flavour neutrino oscillation paradigm and precise measurements of oscillation, as well as a platform for other rare event searches
  - Researchers in Canada are working towards this realization

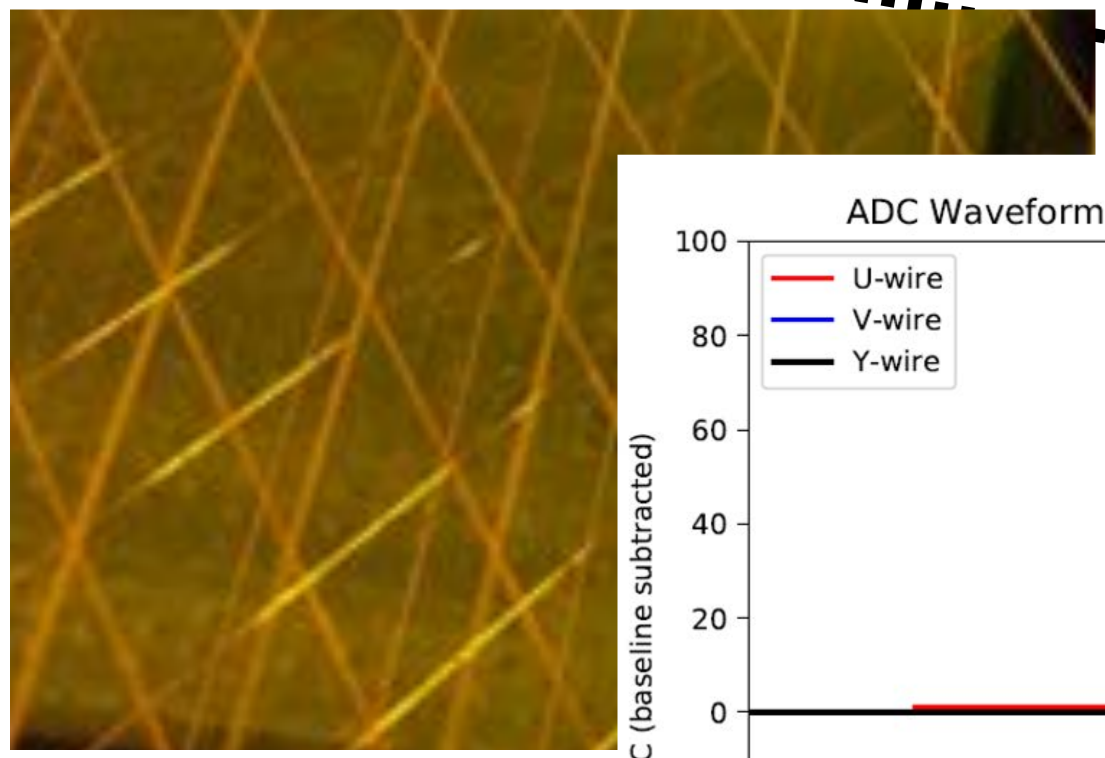
Backup

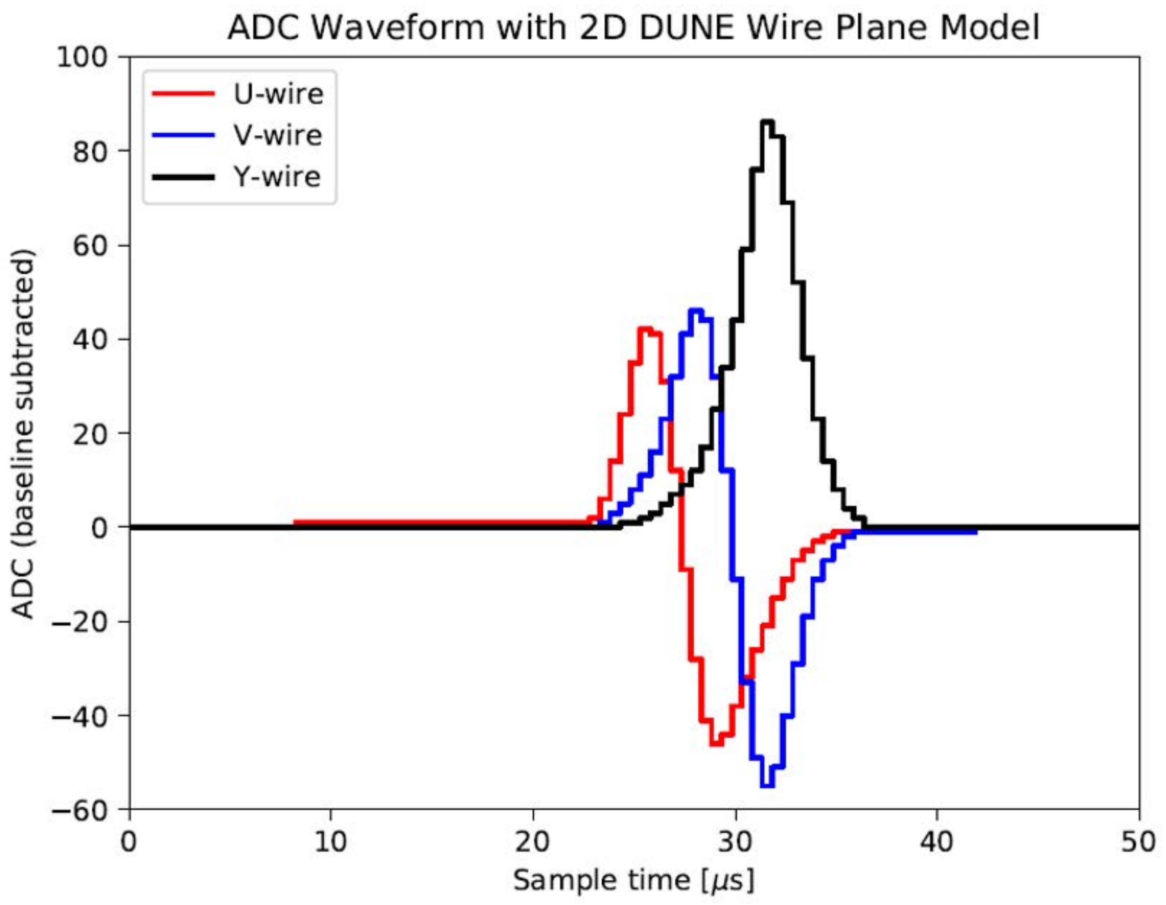
Liquid Argon Time-Projection Chambers (LAr TPC)



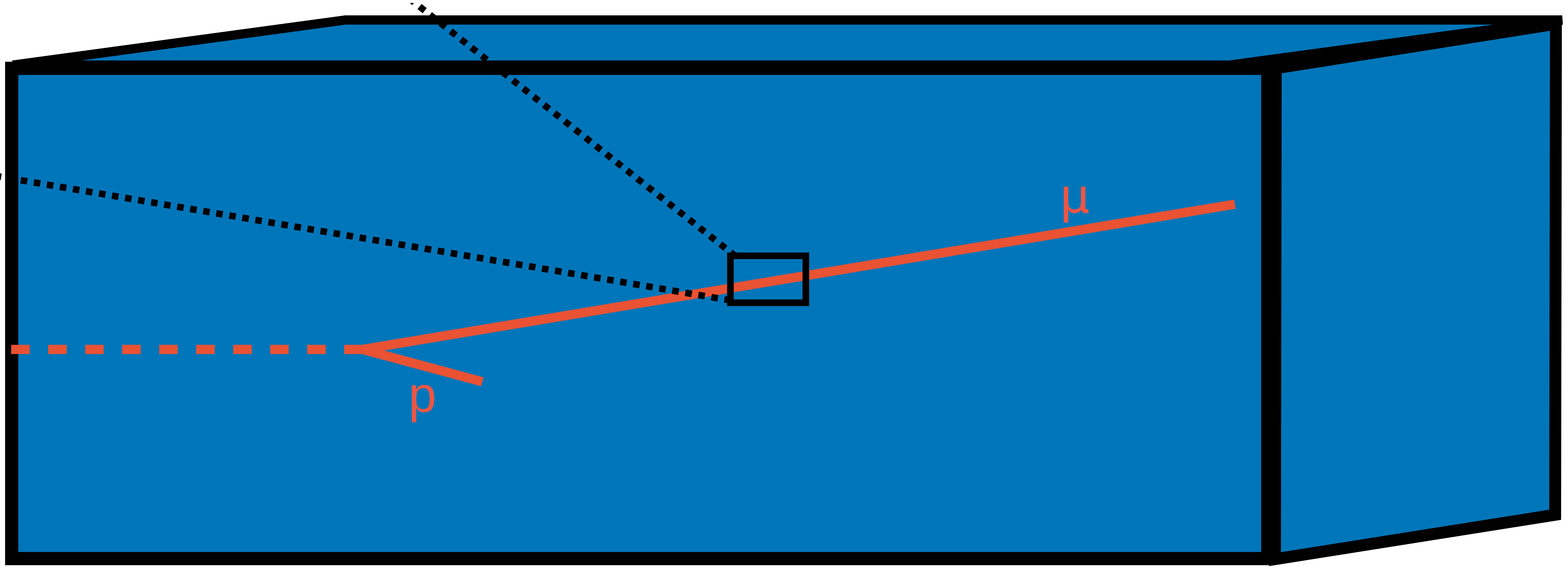
1. Neutrino enters liquid argon volume and interacts
2. Charged particles from interaction deposit energy in LAr
3. This leads to both ionization and scintillation
4. Scintillation: photon detectors, typically use wavelength shifters: 128nm→~vis ($v = c_{LAr}$, fast)
5. Ionization is drifted in electric field to sensing elements at the anode plane (v~0.16cm/µs, slow, hundreds µs to ms)

* Charge readout (wires or other readout)





DUNE TDR
arXiv:2002.03010



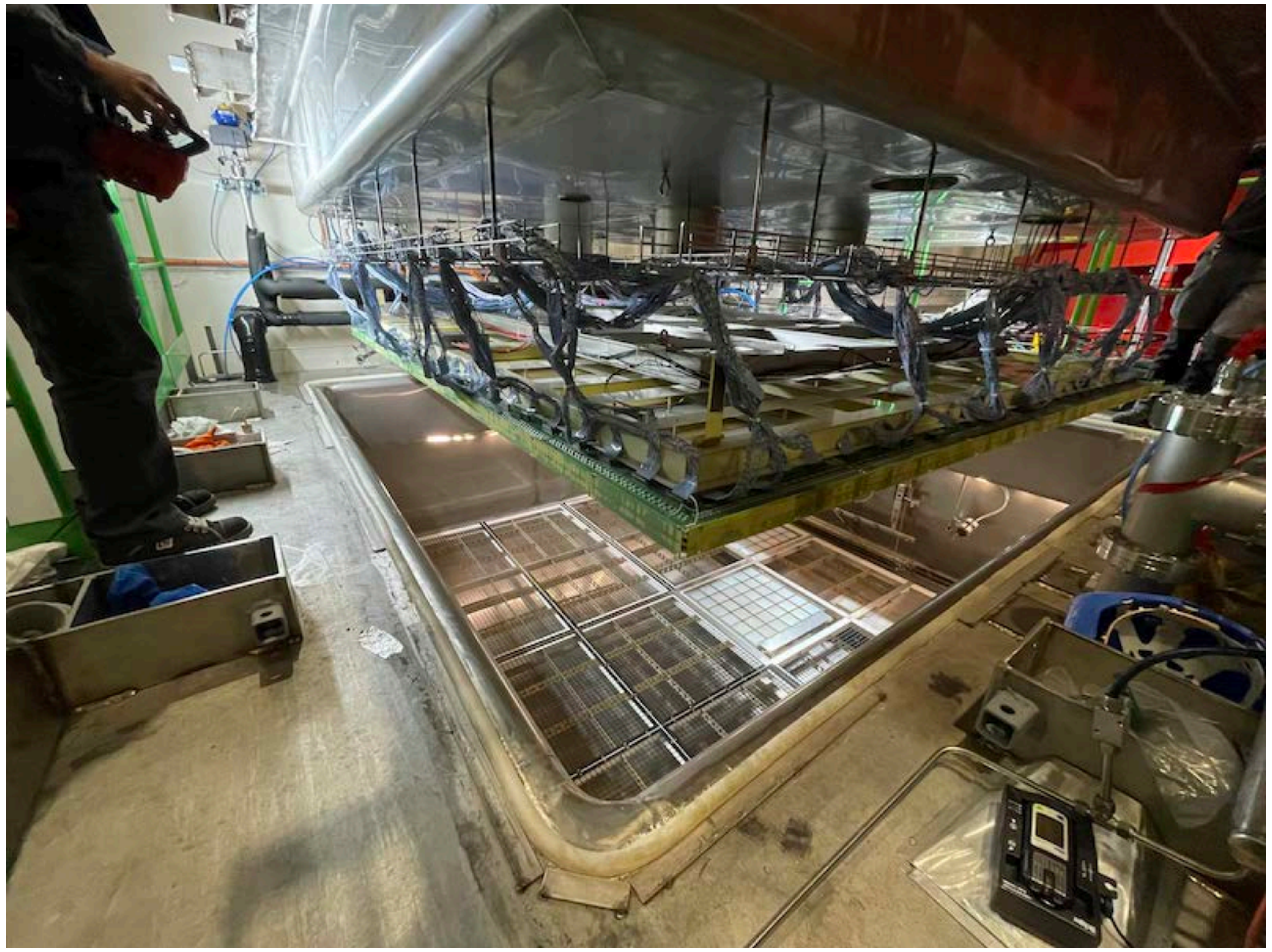
DUNE Far Detector

Anode Plane Assembly (unit) for wire-based TPC of horizontal drift module.
150 of these in a 17 kt module → 384,000 sense wires

DUNE TDR arXiv:2002.03010

Vertical drift builds on updated LAr TPC readout: Charge Readout Planes using PCB with electrodes reading out charge signals

Cathodes horizontal: photon detectors on cathodes

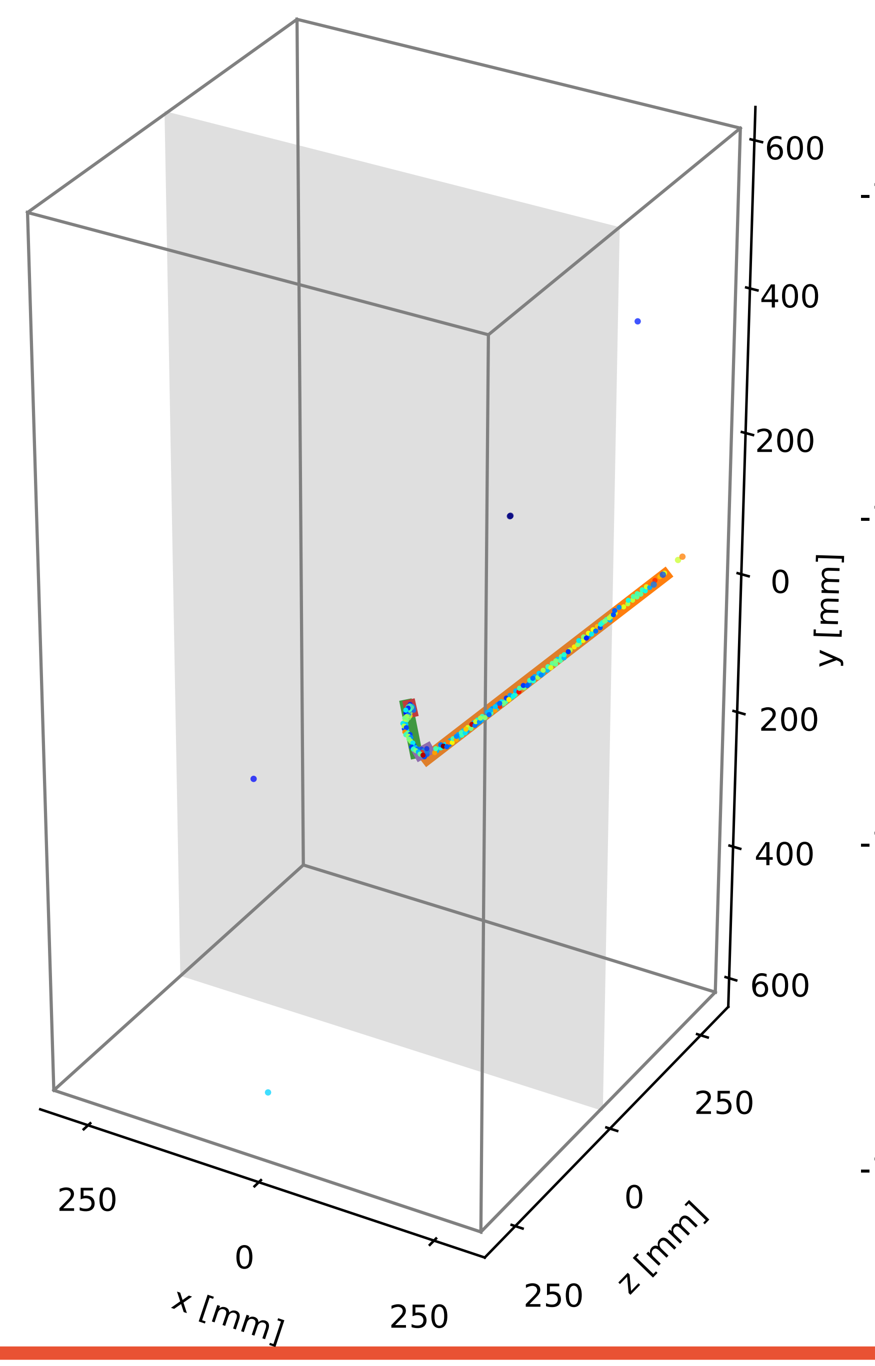


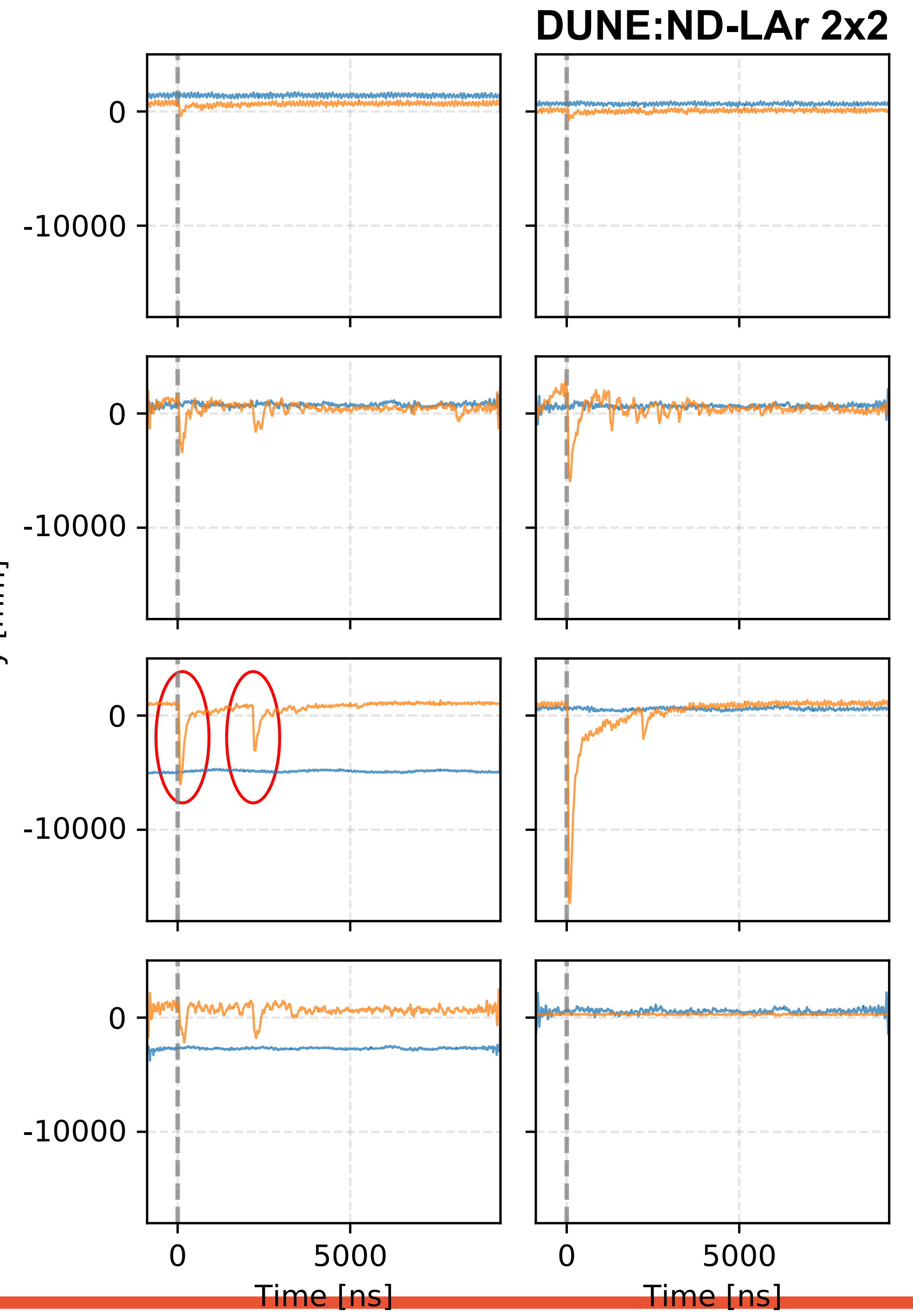
DUNE VD TDR arXiv:2312.03130

- Large liquid argon volume nearly a mile underground = sensitive and low backgrounds: atmospheric neutrinos, supernova neutrinos, possibly solar neutrinos, searches for BSM physics

DUNE Near Detector Prototypes

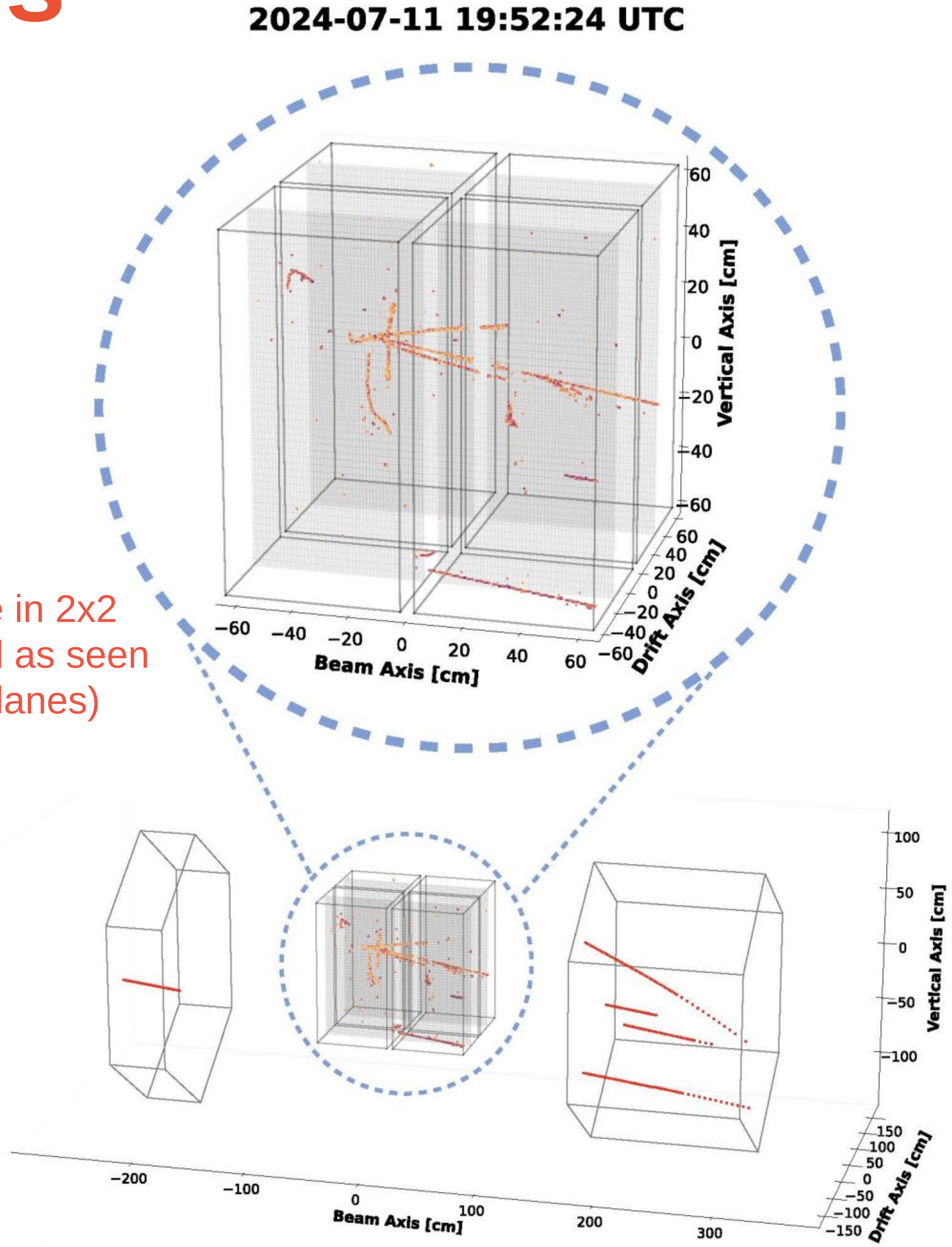
- 2x2 operated in NuMI ($\bar{\nu}$) beam, Fermilab, for ~1 week during the 2024 beam run
  - Thousands interactions to study
  - Working to study detector performance, and study the anti-neutrino argon interactions





Module 0 prototype event

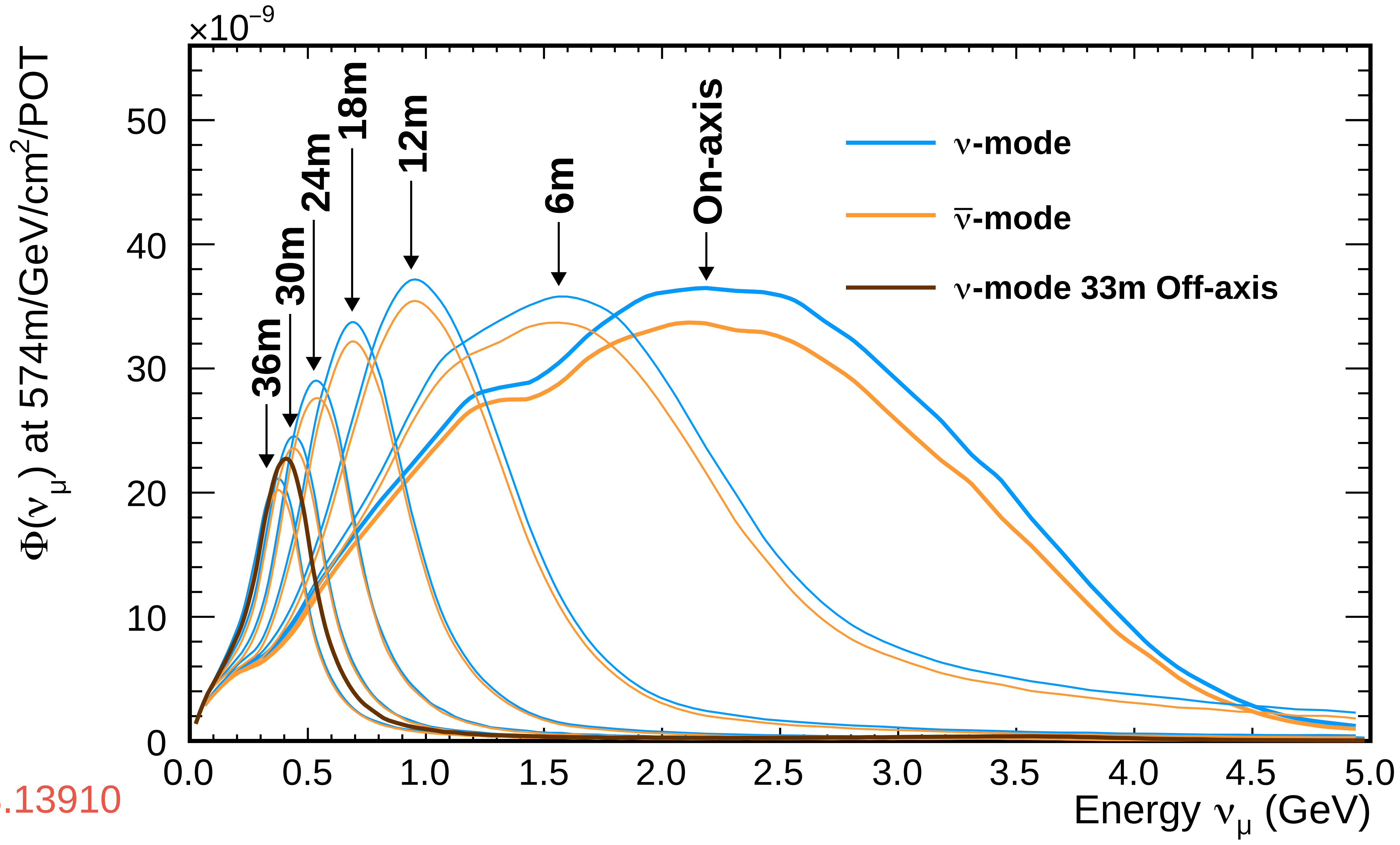
Instruments **2024** *8, 41*



Neutrino candidate in 2x2 (and the same spill as seen by the MINERvA planes)

DUNE PRISM

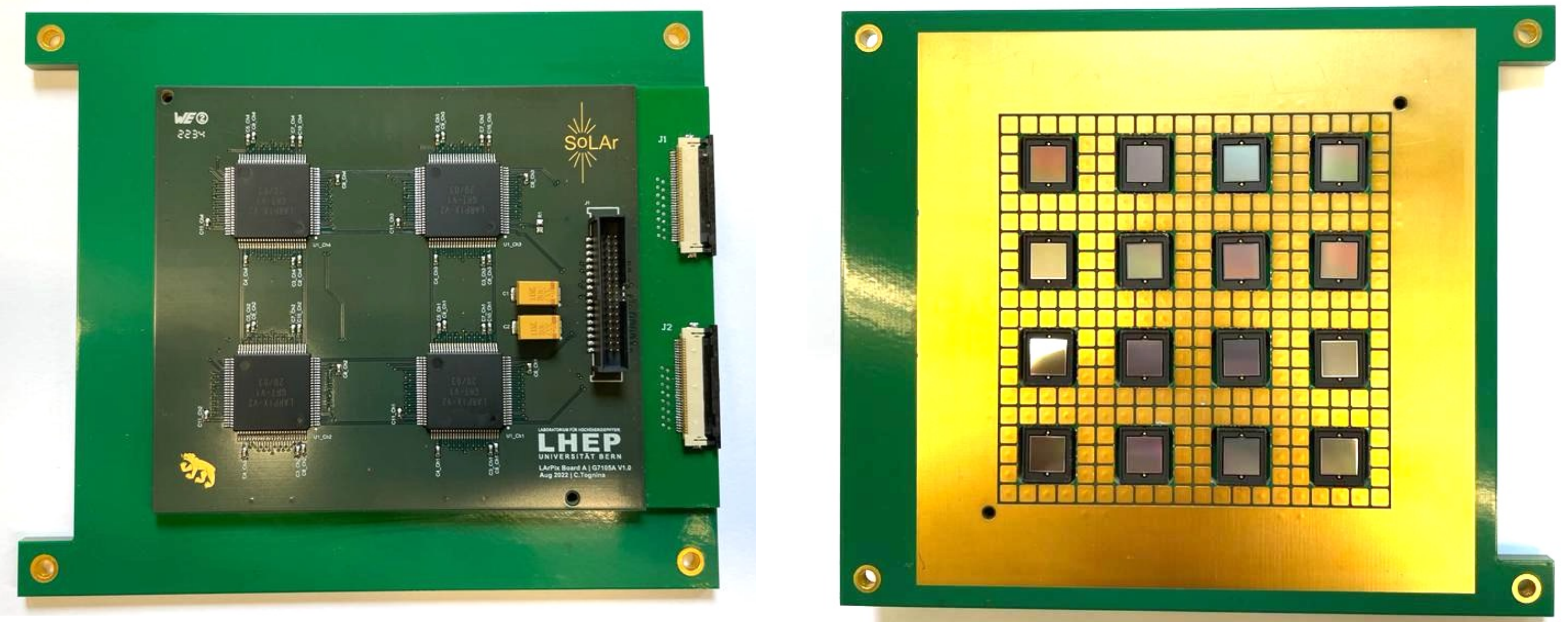
- Mentioned Near Detector spectrum is convolution of flux, cross-section
  - Even though you get a large amount of near-far cancelation from similar detector and same medium, it doesn't cancel entirely
  - Due to oscillation, far flux ≠ near flux → cross-section uncertainty still matters
- Due to hadron decay kinematics, flux at near site also changes if one moves off-axis.
- Move near detector off-axis to sweep a wide range of fluxes & disentangle these effects in the analysis
- SAND stays on-axis, keeps track of beam variances



DUNE, arXiv:2103.13910

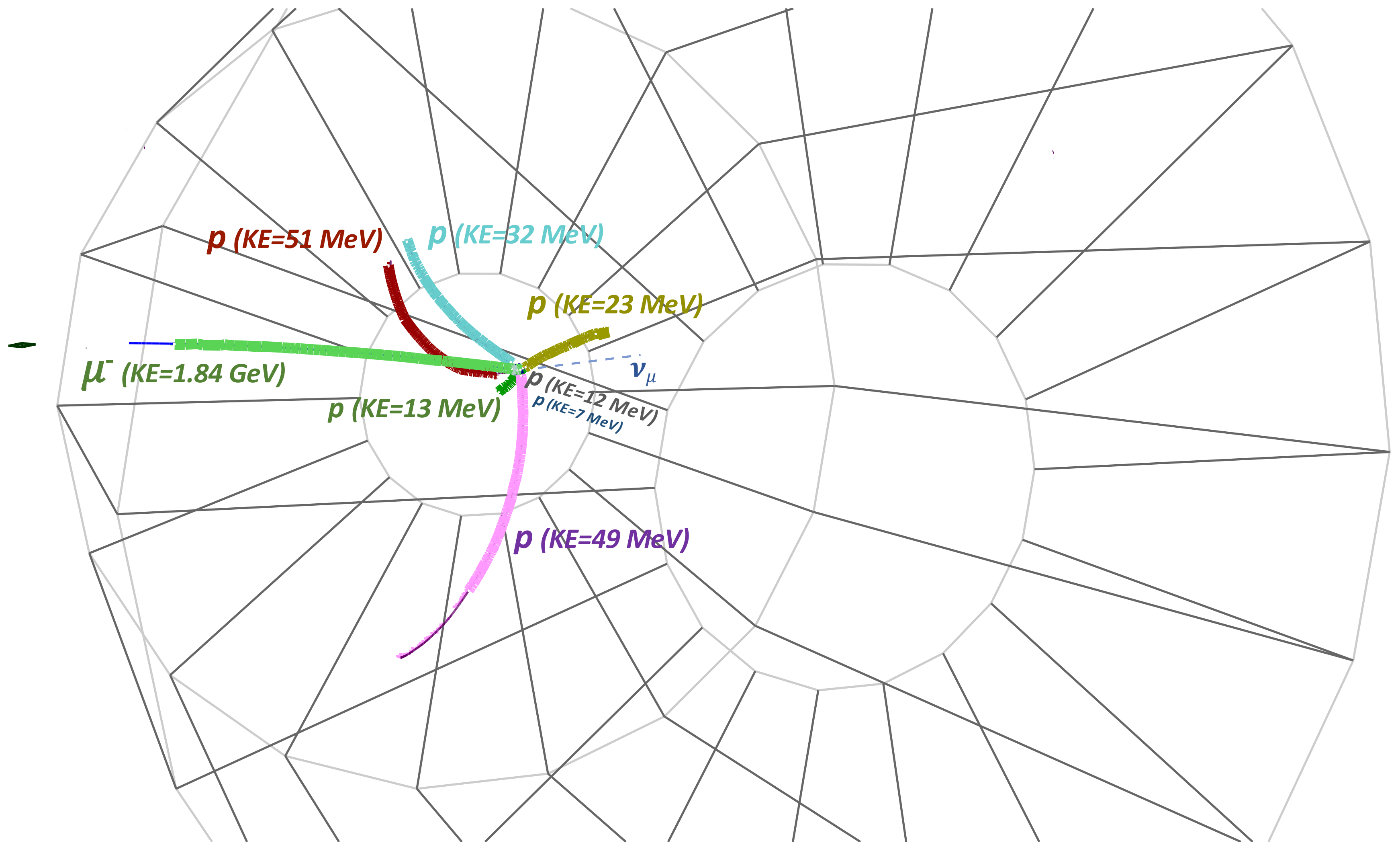
DUNE Phase II

- Far Detector Module 3: baseline is to make another vertical drift LAr TPC but possibly with some improvements
- Far Detector Module 4: “Module of Opportunity” → must preserve oscillation sensitivity but encourages enabling additional physics sensitivity
  - Baseline again vertical drift LAr TPC
  - Options include possible improved LAr TPC designs (e.g. a pixellated Far Detector) or even non-LAr options possible (e.g. water-based liquid scintillator, WbLS)
- More Capable Near Detector: replace TMS with a gaseous Ar TPC
  - More ν-Ar interactions
  - Still functions as a spectrometer for muons leaving ND-LAr
  - Less dense medium → particles of same energy travel further:
    - Lower thresholds! Easier to study low energy proton production in interactions e.g.
- See DUNE Phase II: Scientific Opportunities, Detector Concepts, Technological Solutions (arXiv:2408.12725, JINST **19** P12005 (2024))



Prototype of SoLAr, a pixellated LAr TPC tile meant to enable both light and charge detection

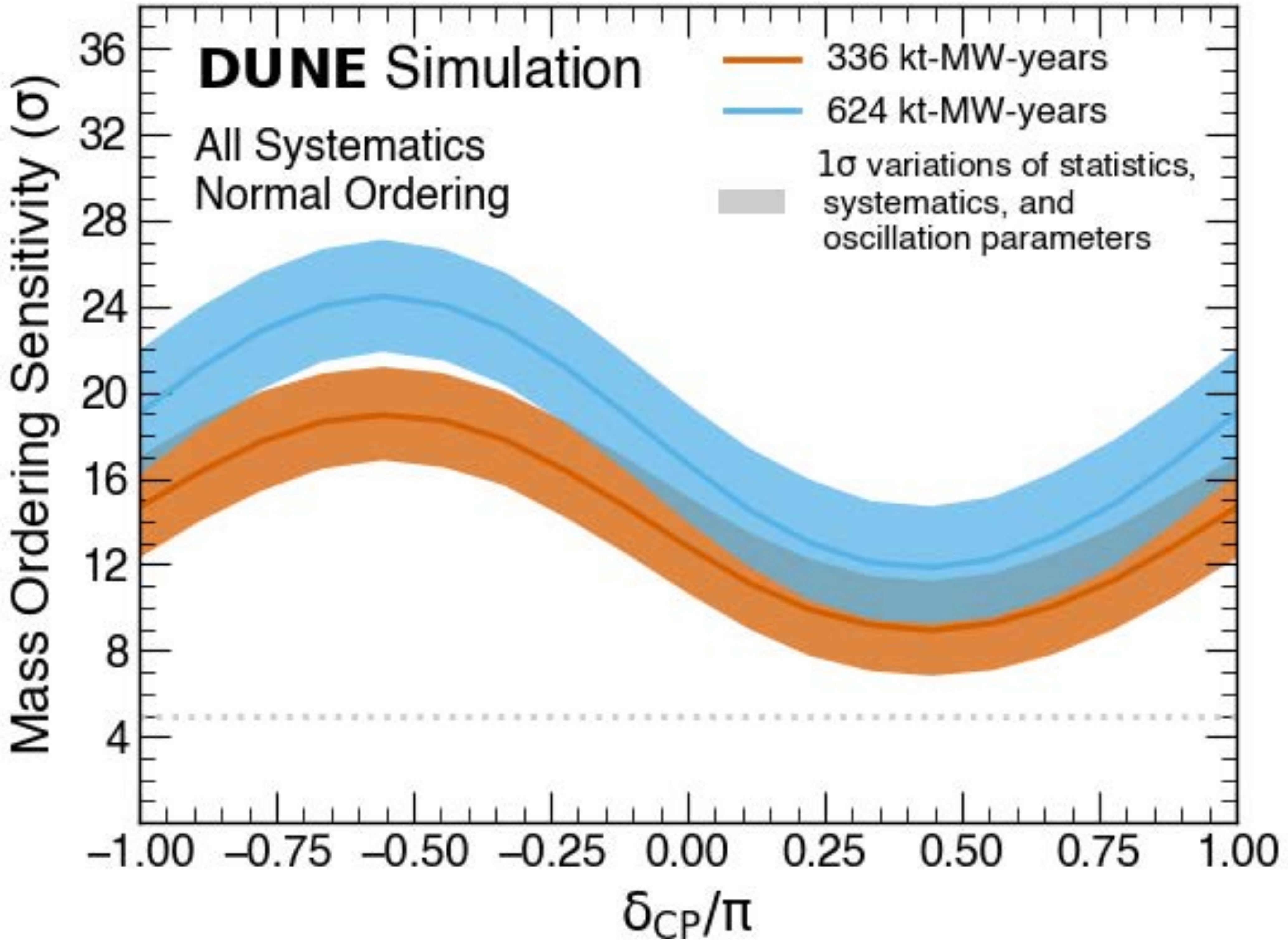
JINST **19** P12005 (2024)

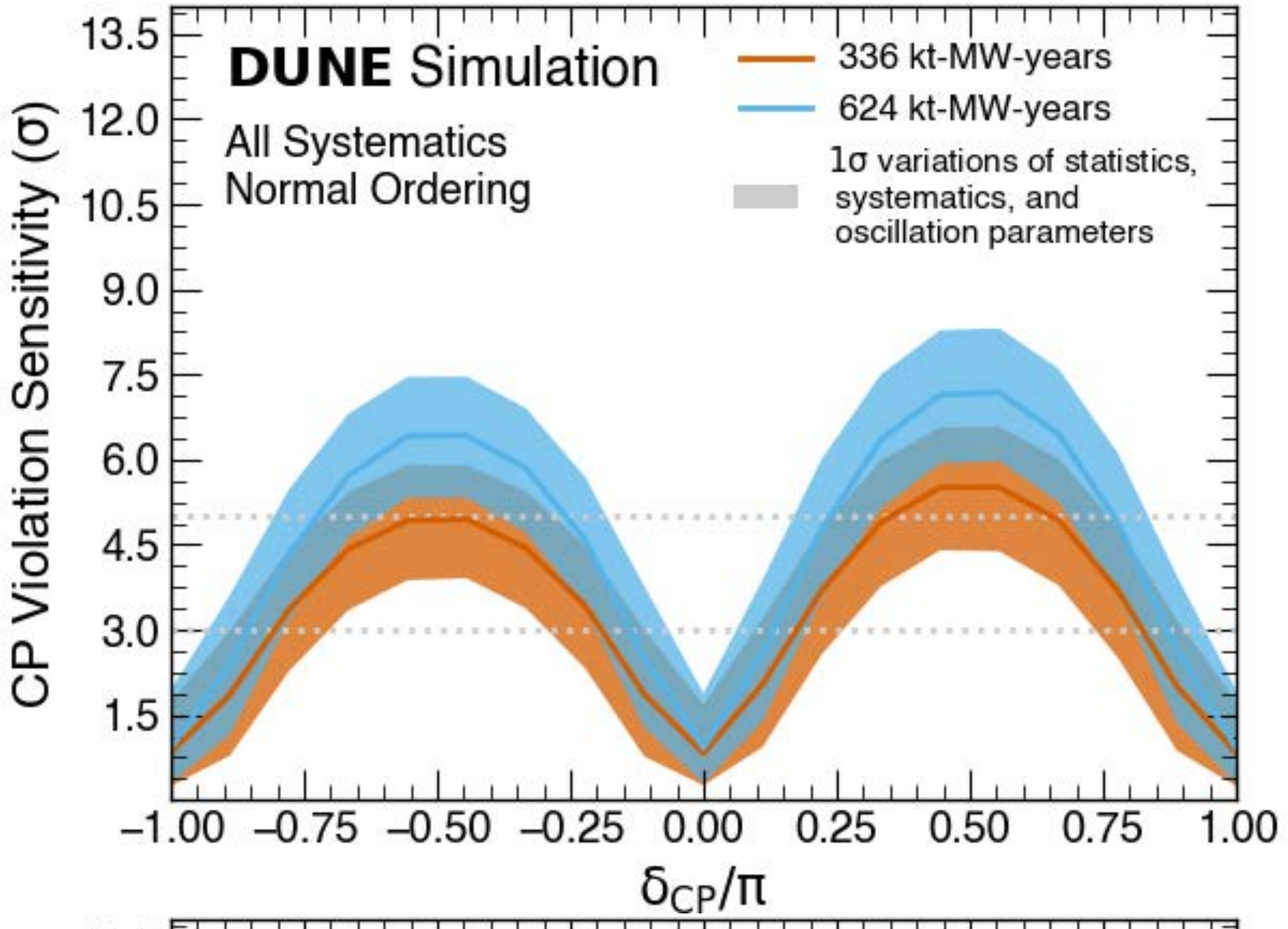


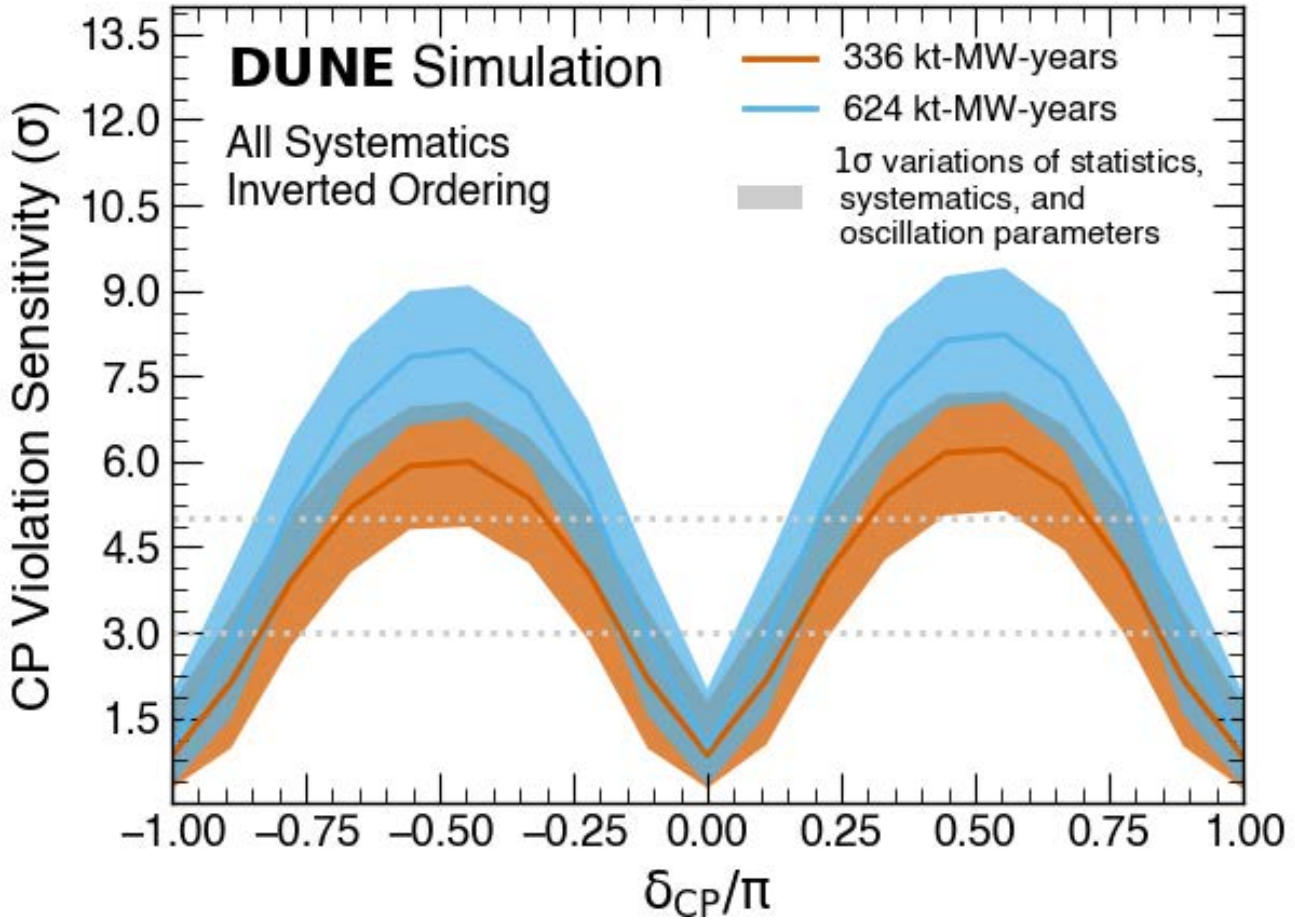
GAr TPC simulation: low energy protons are more easily resolvable (20 MeV proton < 1 cm in LAr)

arXiv:2203.06281

DUNE Sensitivities







Ultimate DUNE volume ~40 kt

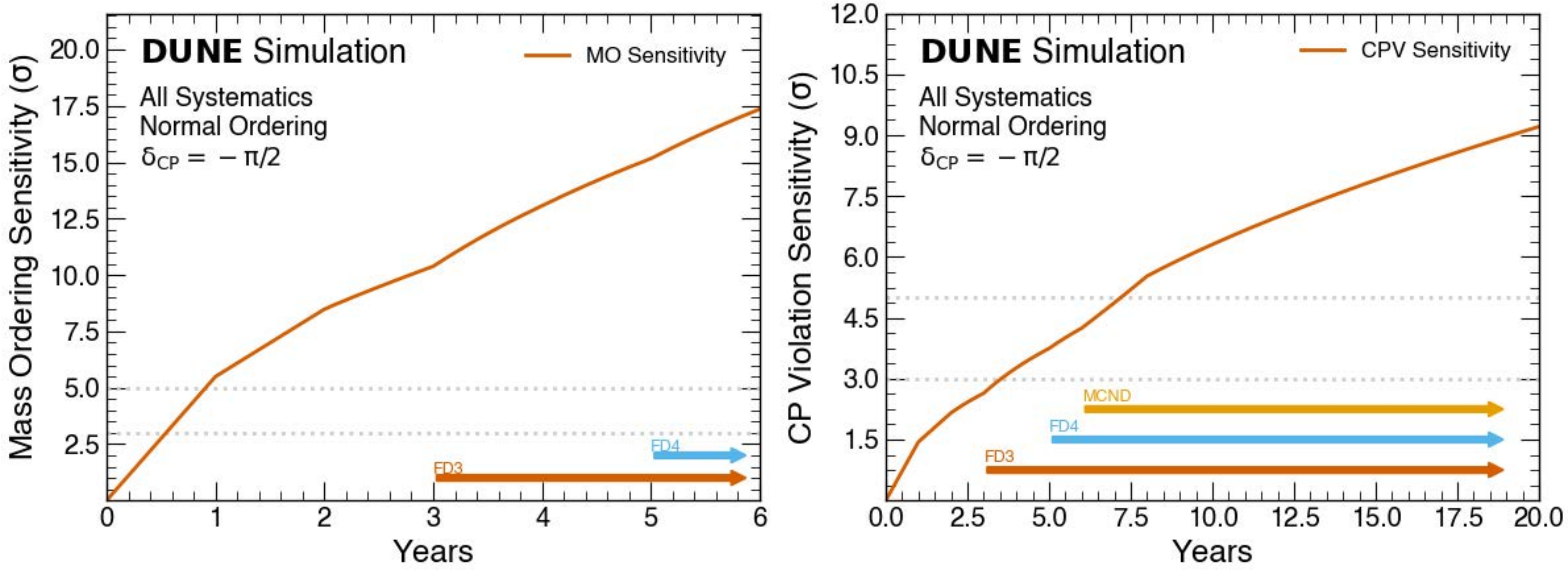
Beam will start at ~1 MW and be upgradeable to ~2 MW in end

Updated versions of sensitivity plots, see analysis details in e.g.
DUNE, EPJ C (2020) 80:978
DUNE, PRD **105**, 072006 (2022)

DUNE Sensitivities

DUNE sensitivity vs timeline reinterpretation (2024)

Assuming favourable nature:



Over a range of δ_{CP} values: