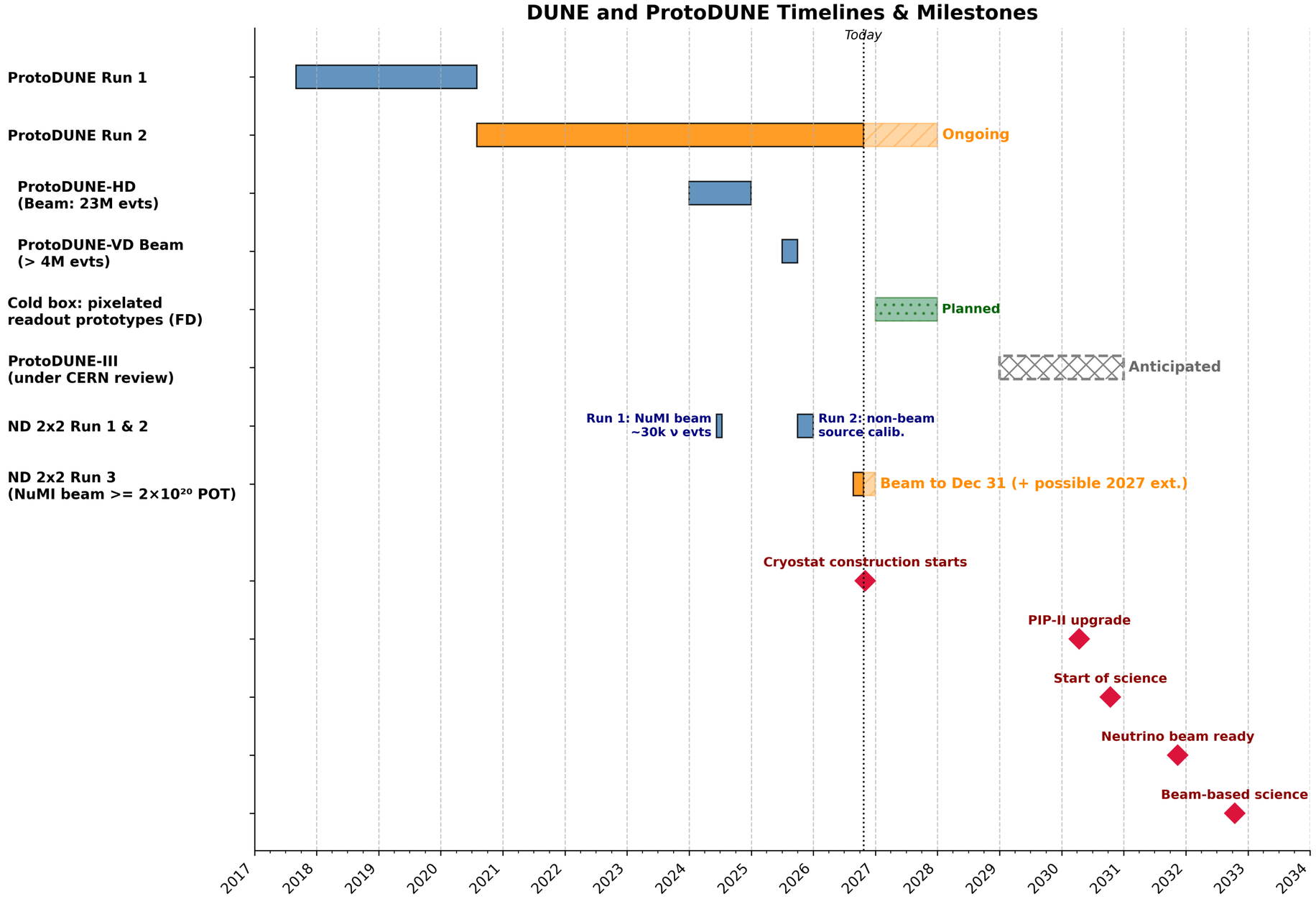
Early Physics Opportunities at DUNE

Sungbin Oh
Hanyang University

KPS 2026 Fall Meeting: Focus: Deep Underground Neutrino Experiment
23 October 2026

How Early?


DUNE and ProtoDUNE Timelines & Milestones
Today
ProtoDUNE Run 1
ProtoDUNE Run 2
Ongoing
ProtoDUNE-HD
(Beam: 23M evts)
ProtoDUNE-VD Beam
(> 4M evts)
Cold box: pixelated
readout prototypes (FD)
Planned
ProtoDUNE-III
(under CERN review)
Anticipated
ND 2x2 Run 1 & 2
Run 1: NuMI beam
~30k ν evts
Run 2: non-beam
source calib.
ND 2x2 Run 3
(NuMI beam >= 2×10²⁰ POT)
Beam to Dec 31 (+ possible 2027 ext.)
Cryostat construction starts
PIP-II upgrade
Start of science
Neutrino beam ready
Beam-based science
2017
2018
2019
2020
2021
2022
2023
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2033
2034

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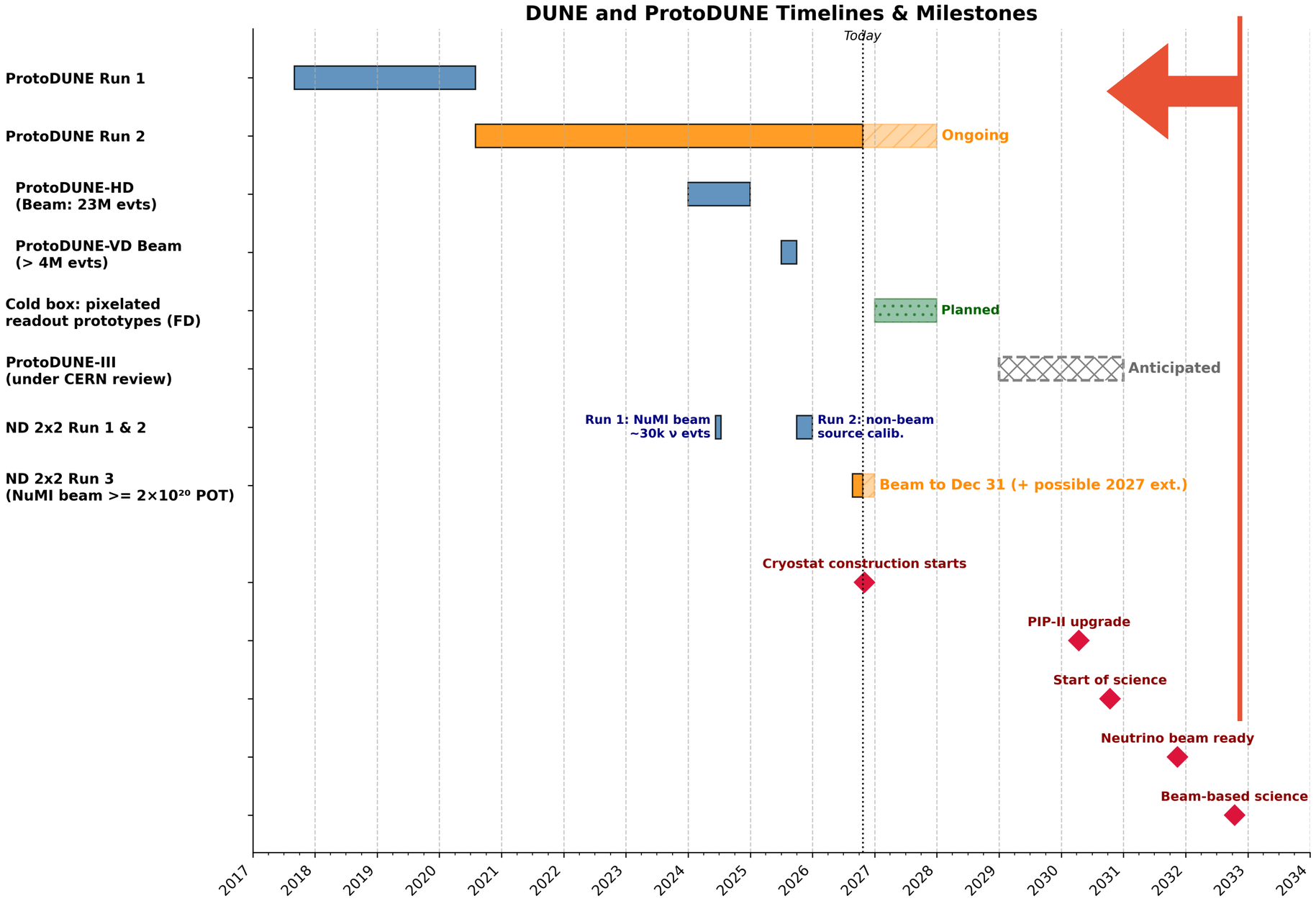
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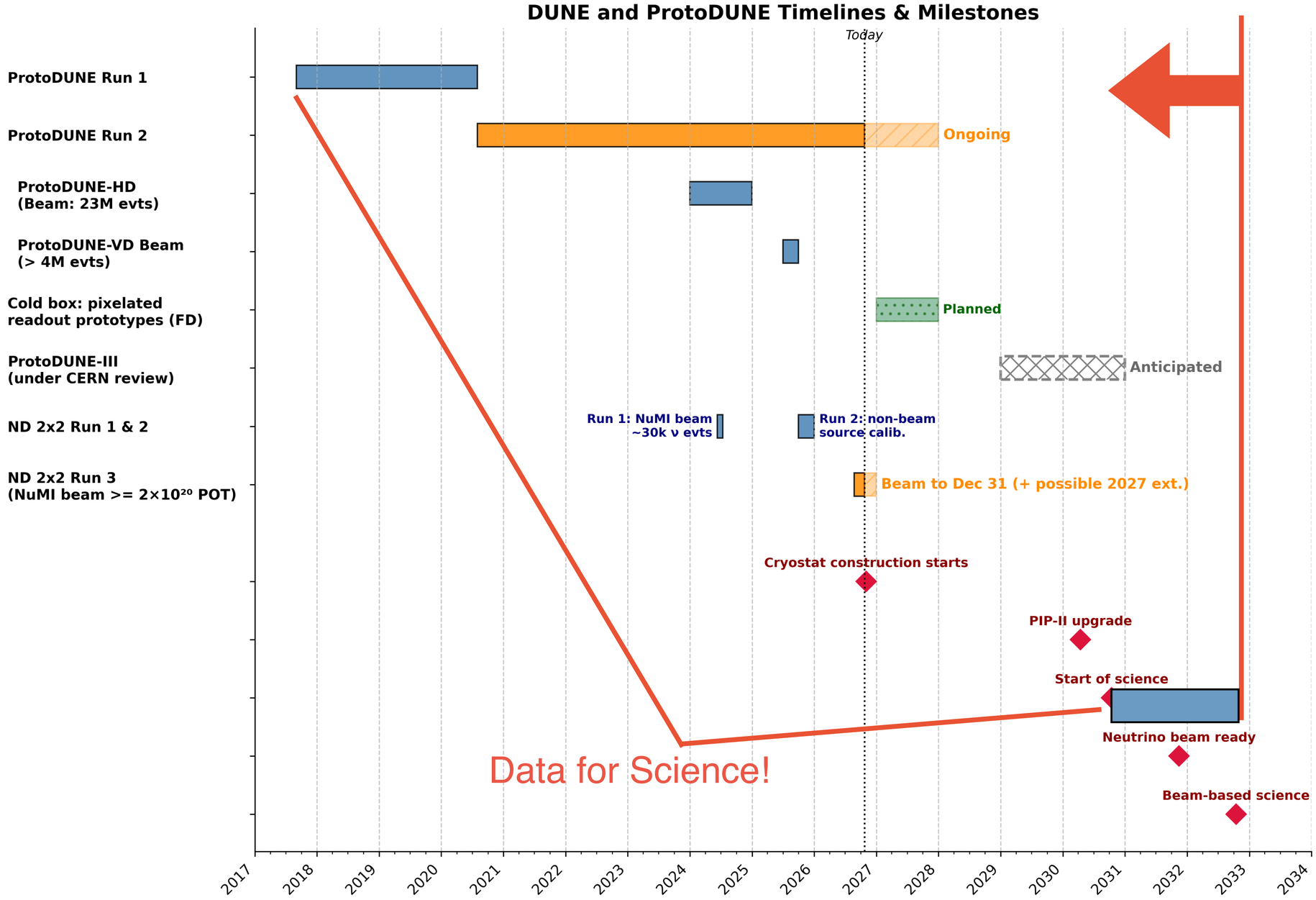
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Challenges in the Neutrino Oscillation Physics Program

Near Detector

$$N_{ND}(E_\nu^{reco.}) = \int \Phi_\nu(E_\nu)\sigma(E_\nu)\epsilon(E_\nu)dE_\nu$$

Far Detector

$$N_{FD}(E_\nu^{reco.}) = \int \Phi_\nu(E_\nu)P_{osc.}(E_\nu)\sigma(E_\nu)\epsilon(E_\nu)dE_\nu$$

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Original Flux | Obs. | Cross section | Detector effect

Reality is complicated

Challenges in the Neutrino Oscillation Physics Program

Near Detector $$N_{ND}(E_\nu^{reco.}) = \int \Phi_\nu^{ND}(E_\nu) P_{osc.}^{ND}(E_\nu) \sigma(E_\nu) \epsilon^{ND}(E_\nu) dE_\nu$$

Far Detector $$N_{FD}(E_\nu^{reco.}) = \int \Phi_\nu^{FD}(E_\nu) P_{osc.}^{FD}(E_\nu) \sigma(E_\nu) \epsilon^{FD}(E_\nu) dE_\nu$$

Reality is EVEN more complicated

Challenges in the Neutrino Oscillation Physics Program

Far Detector $$N_{FD}(E_{\nu}^{reco.}) = \int \Phi_{\nu}^{FD}(E_{\nu}) P_{osc.}^{FD}(E_{\nu}) \sigma(E_{\nu}) \epsilon^{FD}(E_{\nu}) dE_{\nu}$$

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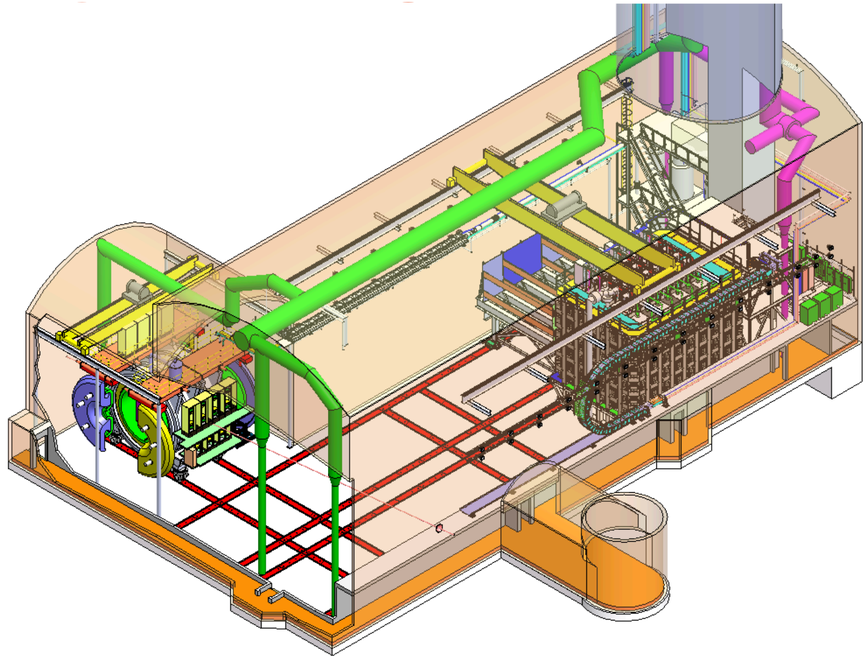
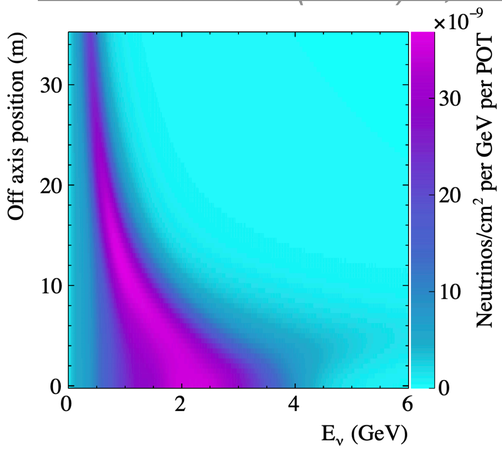
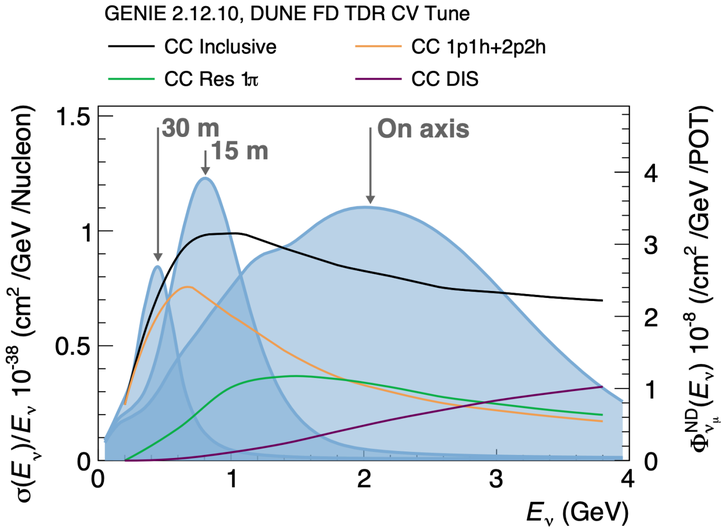
The Movable Near Detector Component (ND-LAr)
will constrain uncertainties → **But not "Early"**



Instruments 5 (2021) 4, 31





Challenges in the Neutrino Oscillation Physics Program

Far Detector $$N_{FD}(E_\nu^{reco.}) = \int \Phi_\nu^{FD}(E_\nu) P_{osc.}^{FD}(E_\nu) \sigma(E_\nu) \epsilon^{FD}(E_\nu) dE_\nu$$

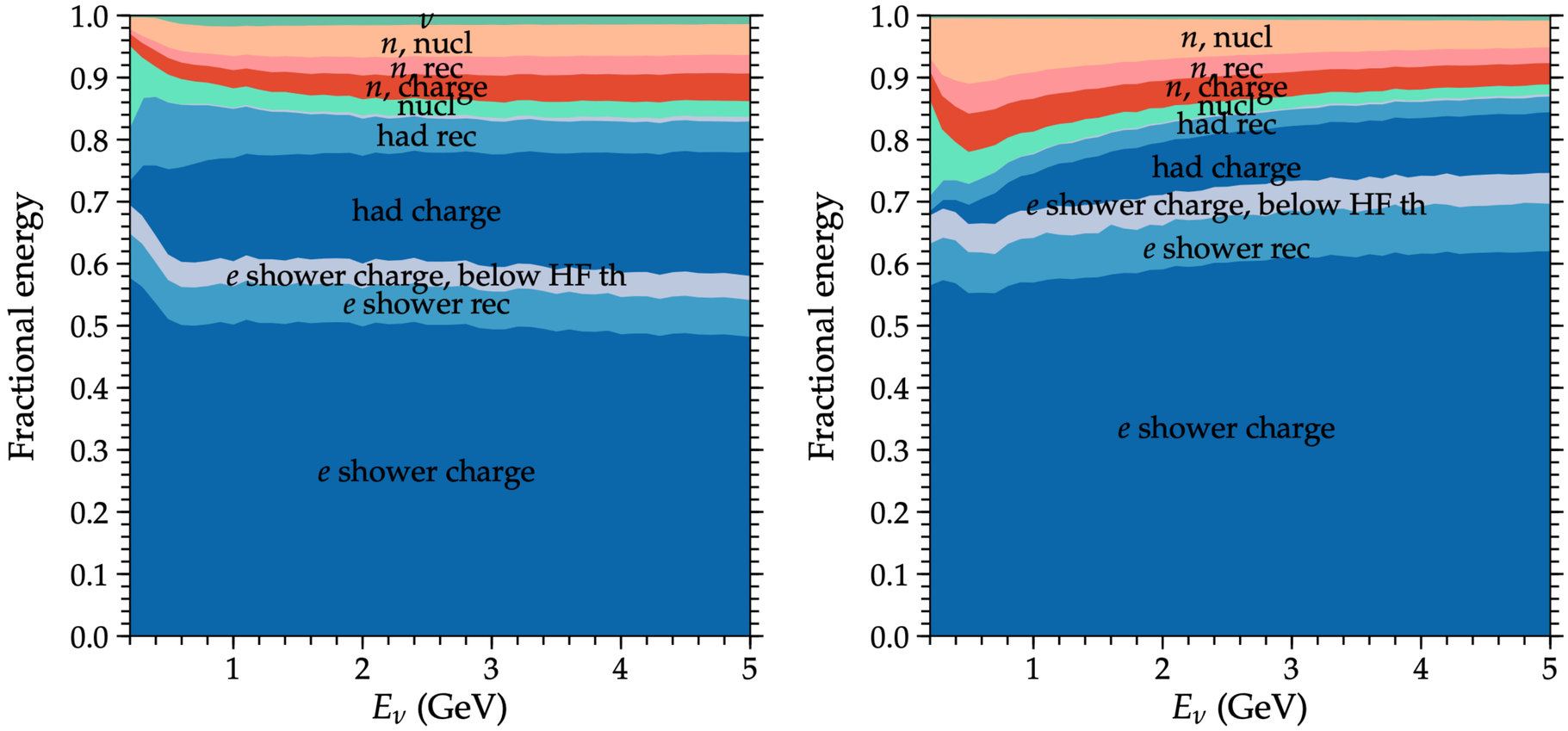
Final state particles kinematics: O

$$\sigma(E_\nu)\epsilon(E_\nu) = \int \frac{d\sigma(E_\nu)}{dO} \epsilon(O \mid E_\nu) dO$$

We can tackle this **right now**!

Hadrons are Important!

- For charged-current ν_e-argon interactions at the DUNE far detector
- Fraction of hadronic energy deposition is significant: ~ 30 – 40%



Alexander Friedland, Shirley Weishi Li, *Phys.Rev.D 99 (2019) 3, 036009*

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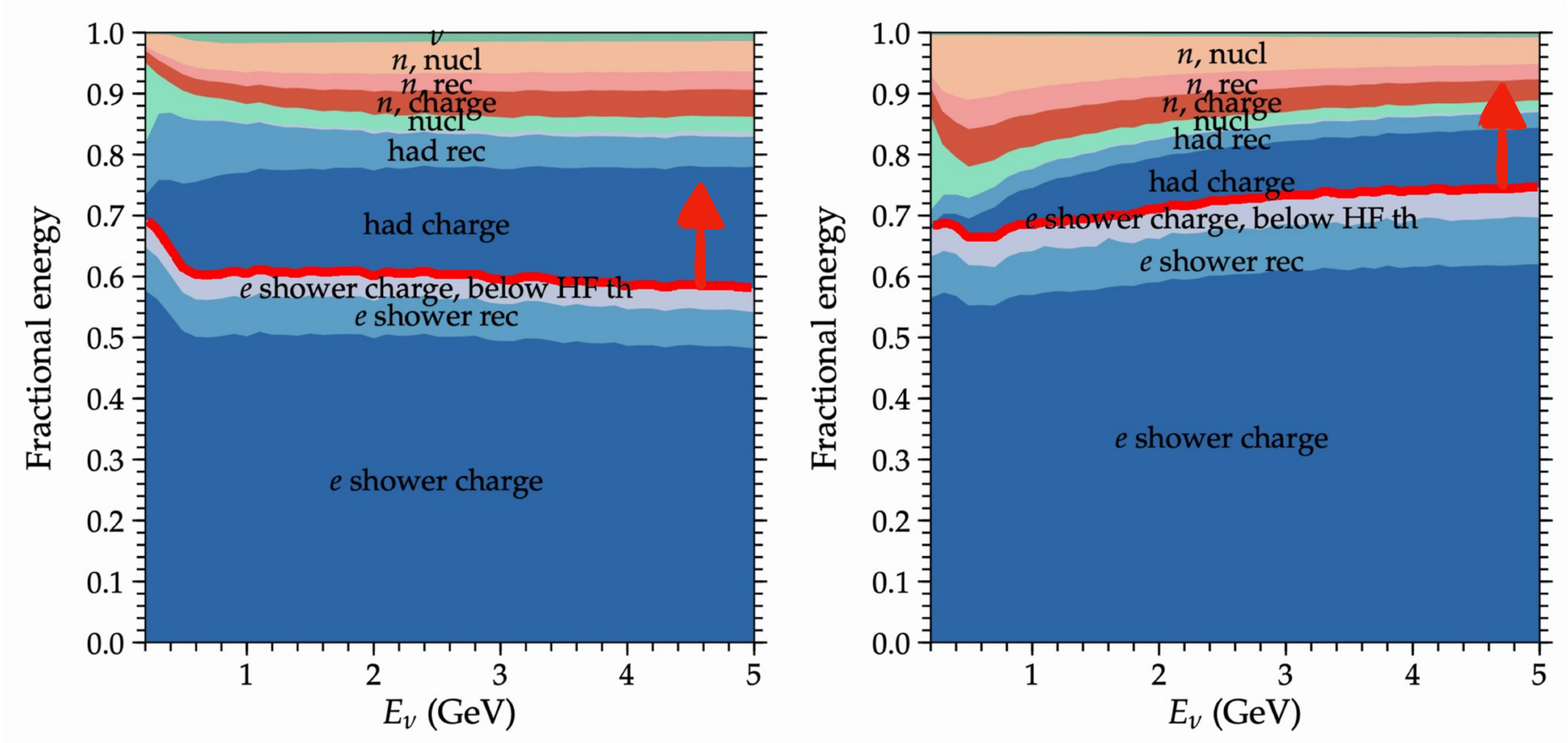

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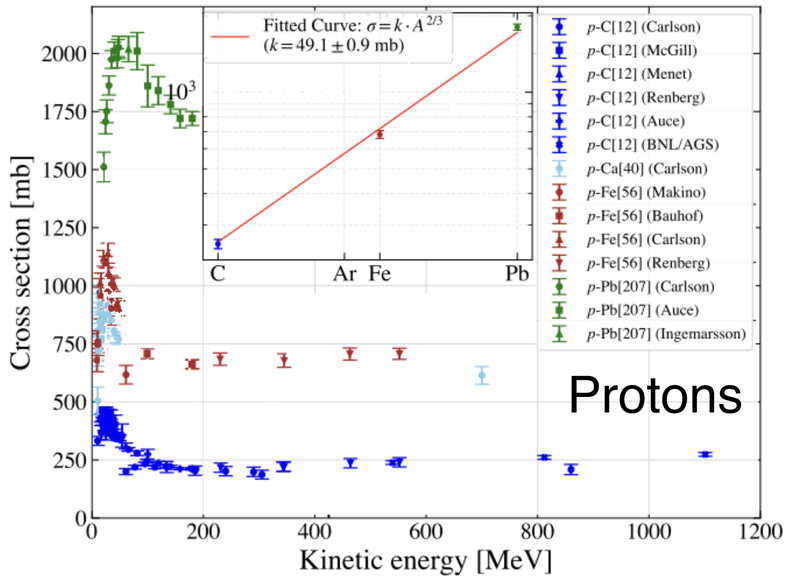
Hadrons are Challenging!

- Understanding their **propagation** in liquid argon
  - Measurements of hadron-argon interactions are sparse



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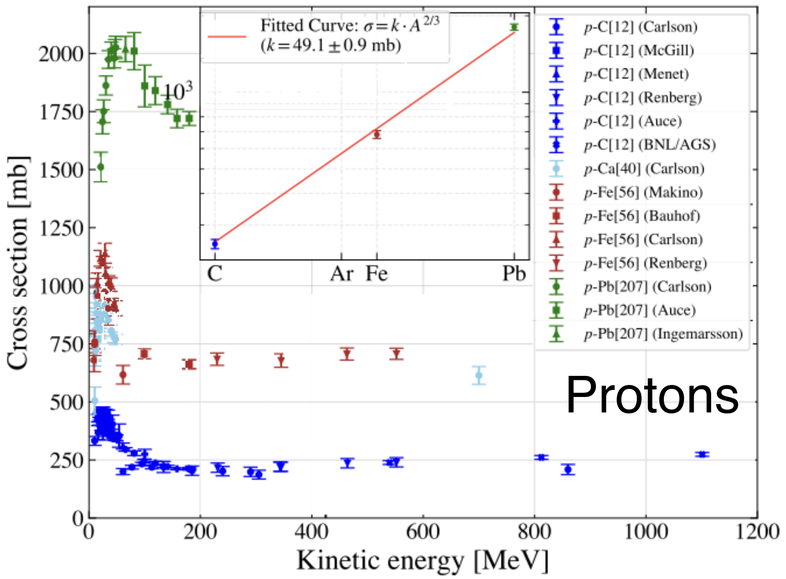
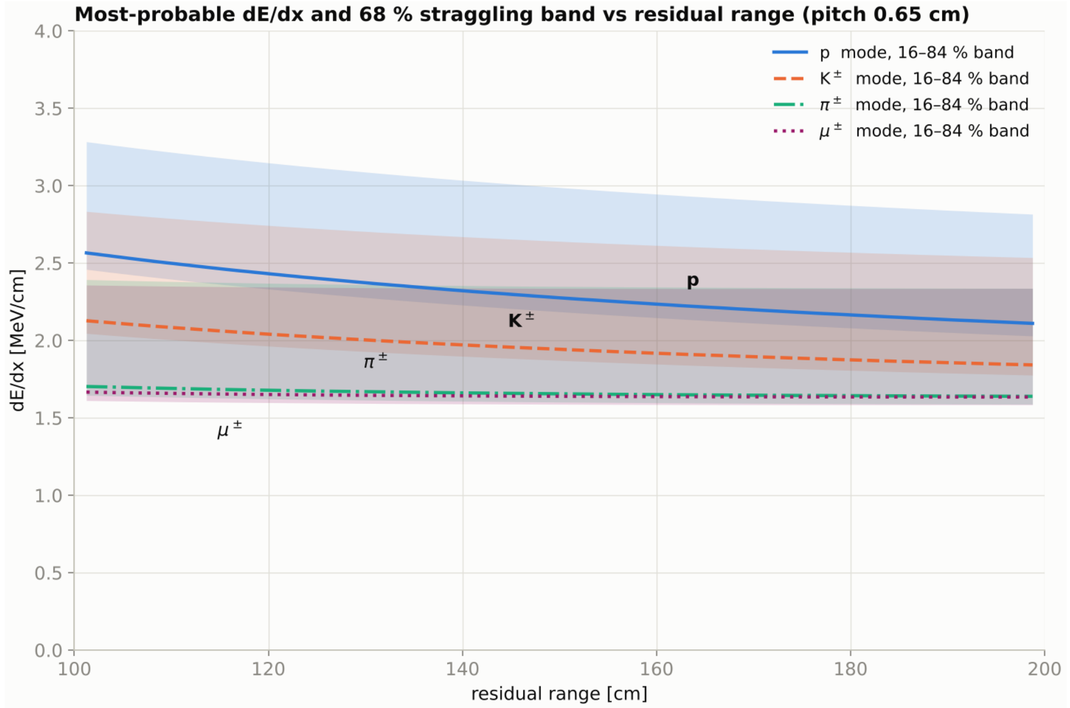
  - Measurements of hadron-argon interactions are sparse

- Information lost from inelastically interacting hadrons
  - Energy **reconstruction**
  - Particle identification (**PID**)

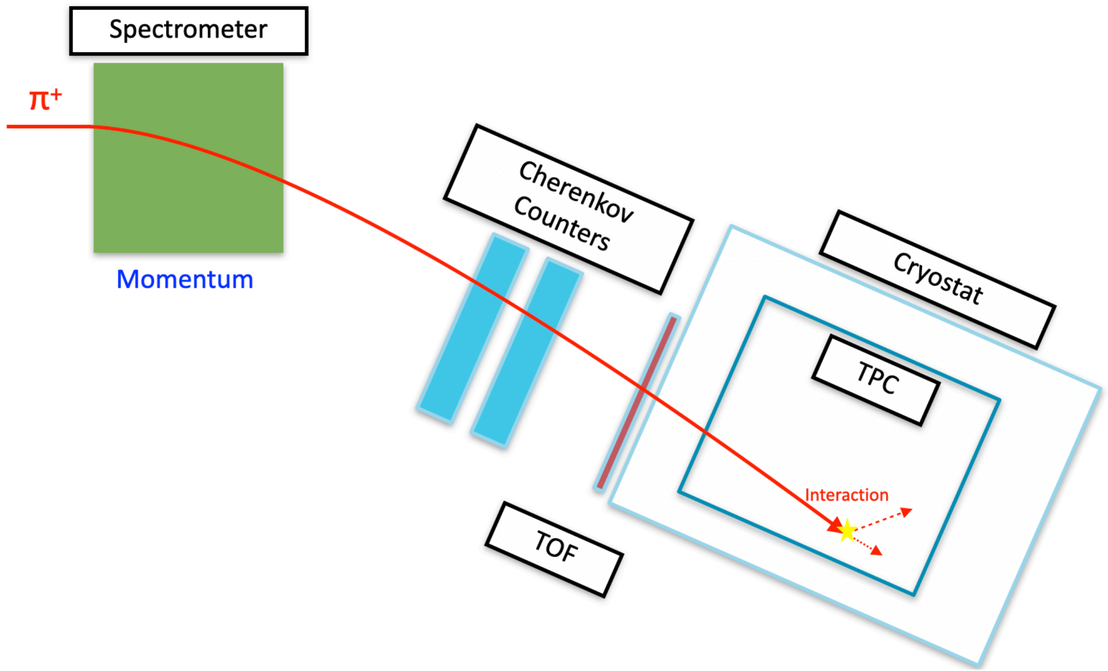




Opportunities for Hadrons: ProtoDUNEs!

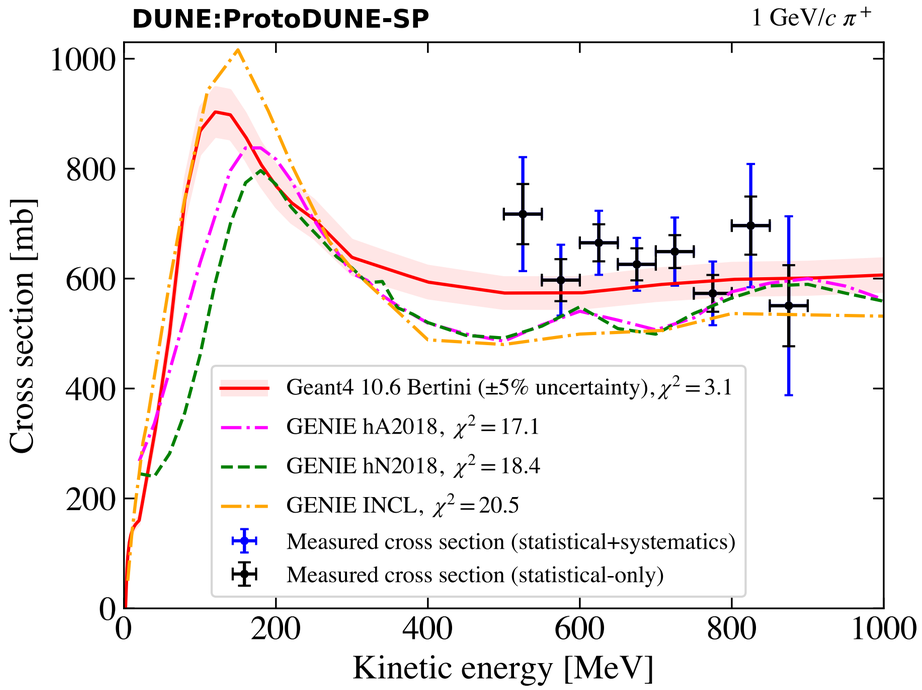
- Hosted by the CERN Neutrino Platform
- DUNE far detector prototypes
- Exposed to momentum-analyzed hadron beams
- Run 1 with the beam (2018): produced many results, with more coming soon
- Run 2 with the beam (2024 - 2025): data is available for further studies!

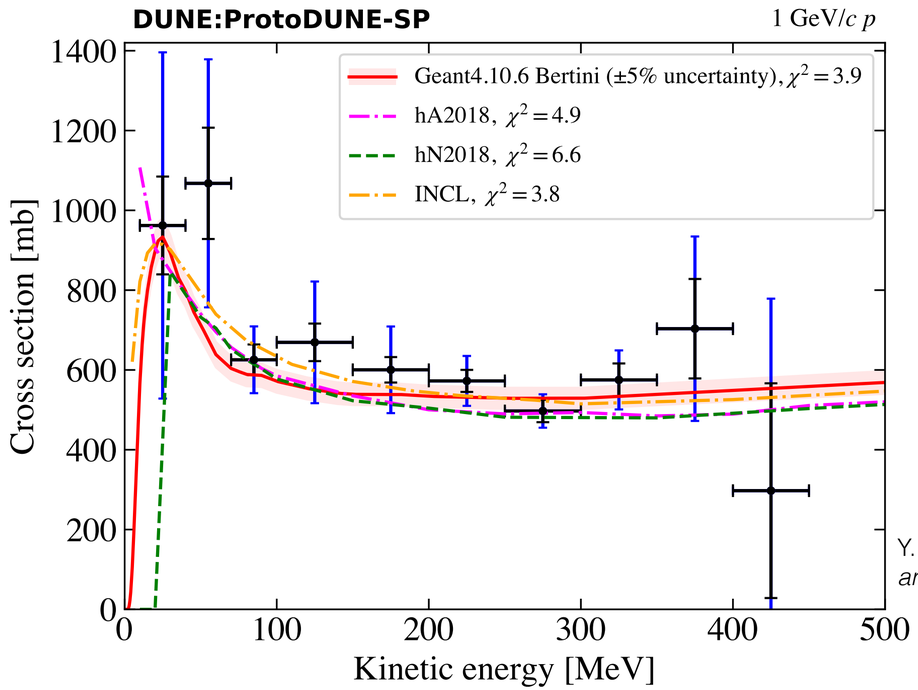
Phys.Rev.D 110 (2024) 9, 092011
Phys.Rev.D 113 (2026) 5, 052004
Phys.Rev.D 113 (2026) 11, 112002
arXiv:2511.11925, submitted to *PRL*



Opportunities for Hadrons: (1) Interaction with Argon

- Charged pion–argon interaction cross-section measurements using the ProtoDUNE Run 1 data
  - First measurements in this kinetic energy region
  - A **first measurement at the Δ-resonance peak** would be very interesting
- Proton–argon interaction cross-section measurement: large uncertainties at low kinetic energy
  - **Improved proton track end-point reconstruction** will be very helpful!



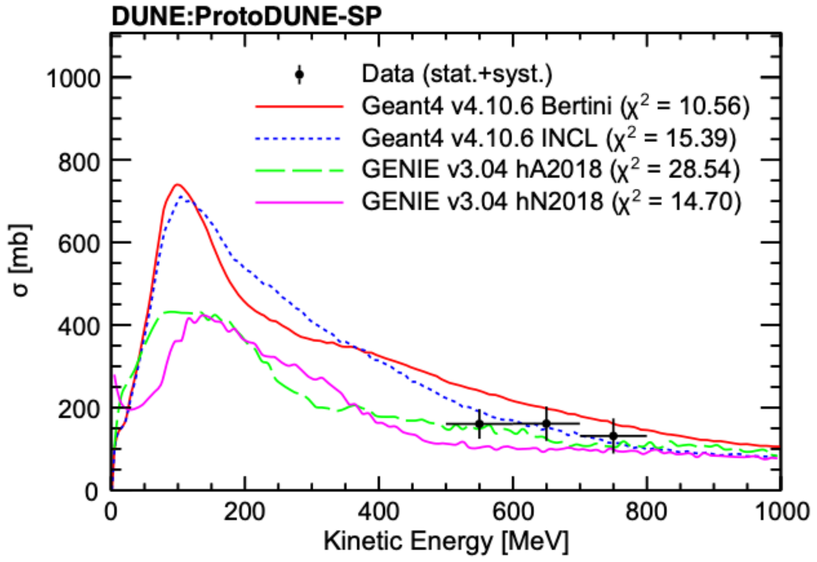


Y. Liu, S.B. Oh et al. DUNE collaboration, *arXiv:2511.11925 (submitted to PRL)*

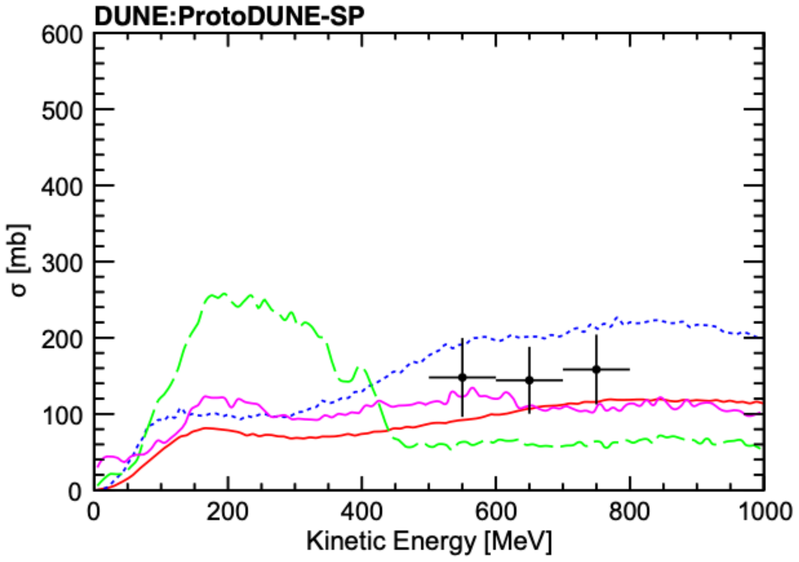
Opportunities for Hadrons: (1) Interaction with Argon

- Exclusive cross-section measurements are also very important
  - Direct impact on neutrino energy resolution and its uncertainty

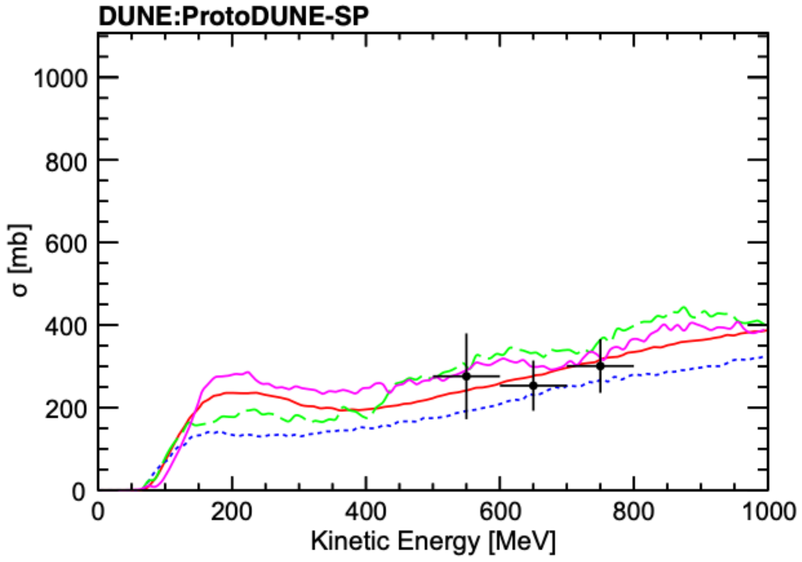
- Below are results from ProtoDUNE Run 1 data
  - More data from Run 2 is available now for further studies in exclusive channels



(a) Absorption



(b) Charge Exchange

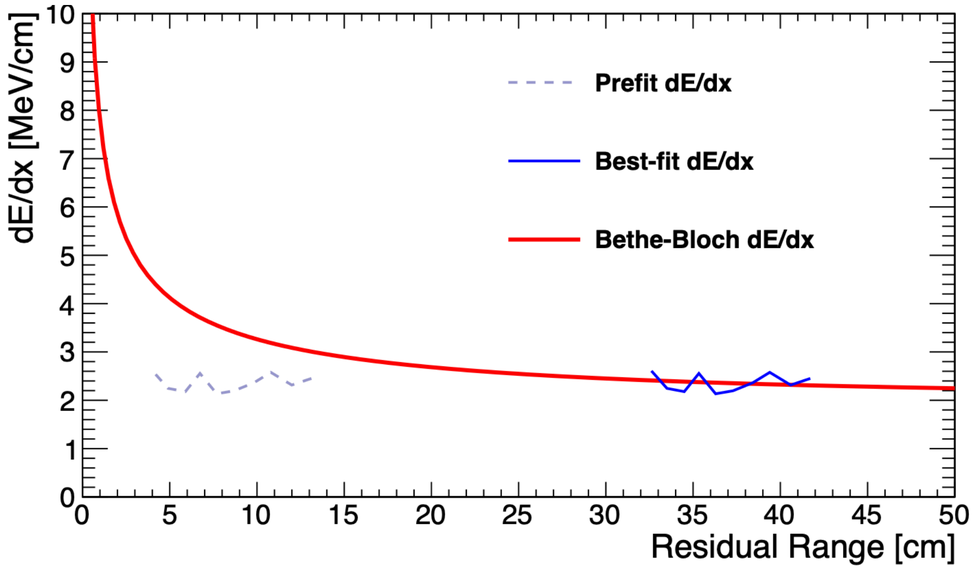


(c) Other Interactions

J. Calcutt et al. DUNE collaboration, *Phys.Rev.D* 113 (2026) 11, 112002

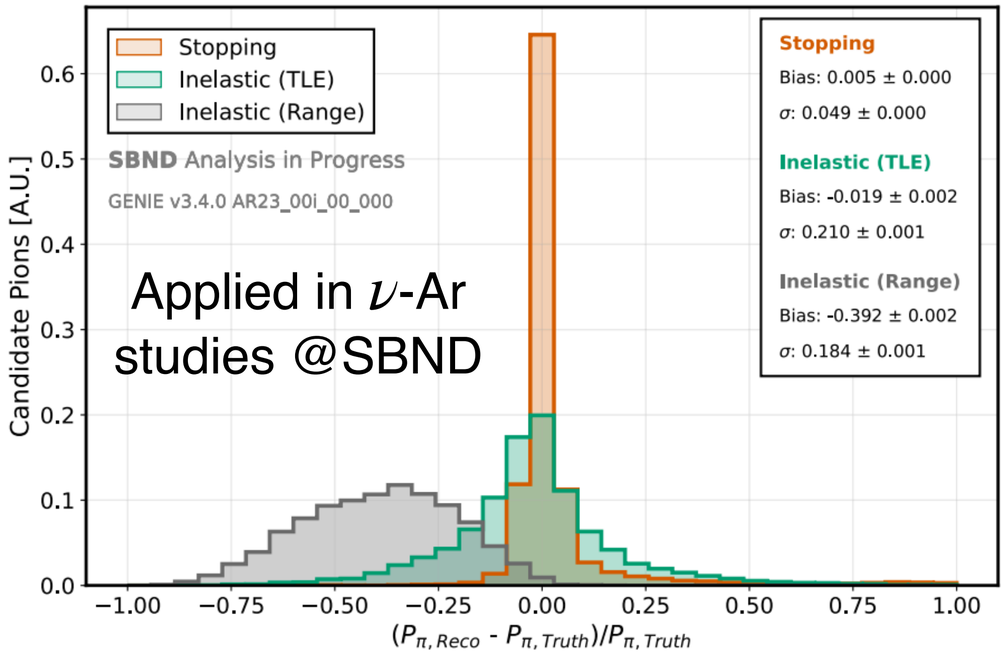
Opportunities for Hadrons: (2) Reconstruction and PID

- Energy reconstruction for inelastically interacting charged pions
  - A novel method was developed using the ProtoDUNE Run 1 data
  - Uses both position and calorimetric information



S.B. Oh et al. DUNE collaboration, *JINST* 20 (2025) 02, P02021

Presented @ Neutrino 2026



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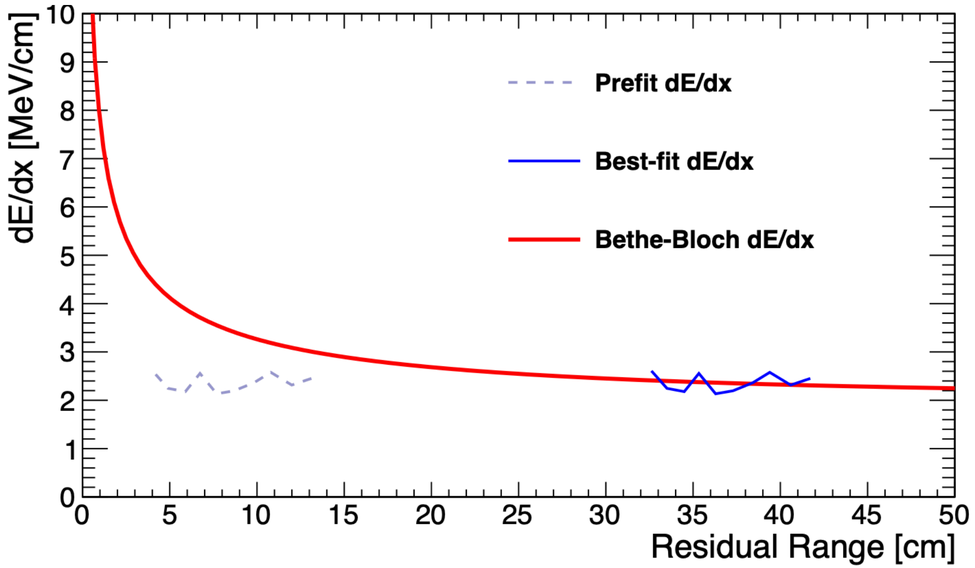

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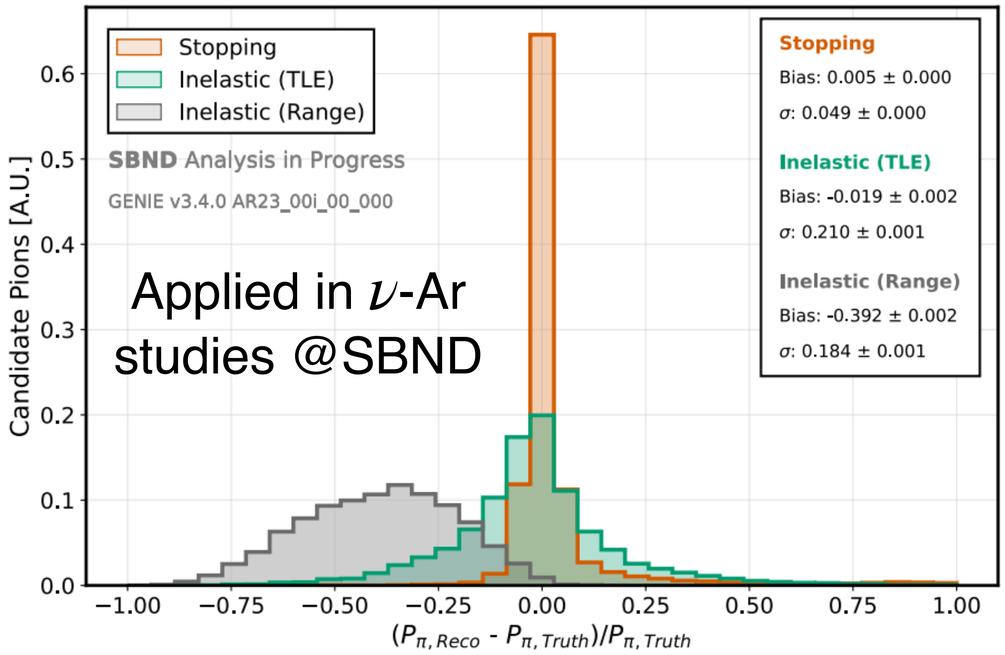

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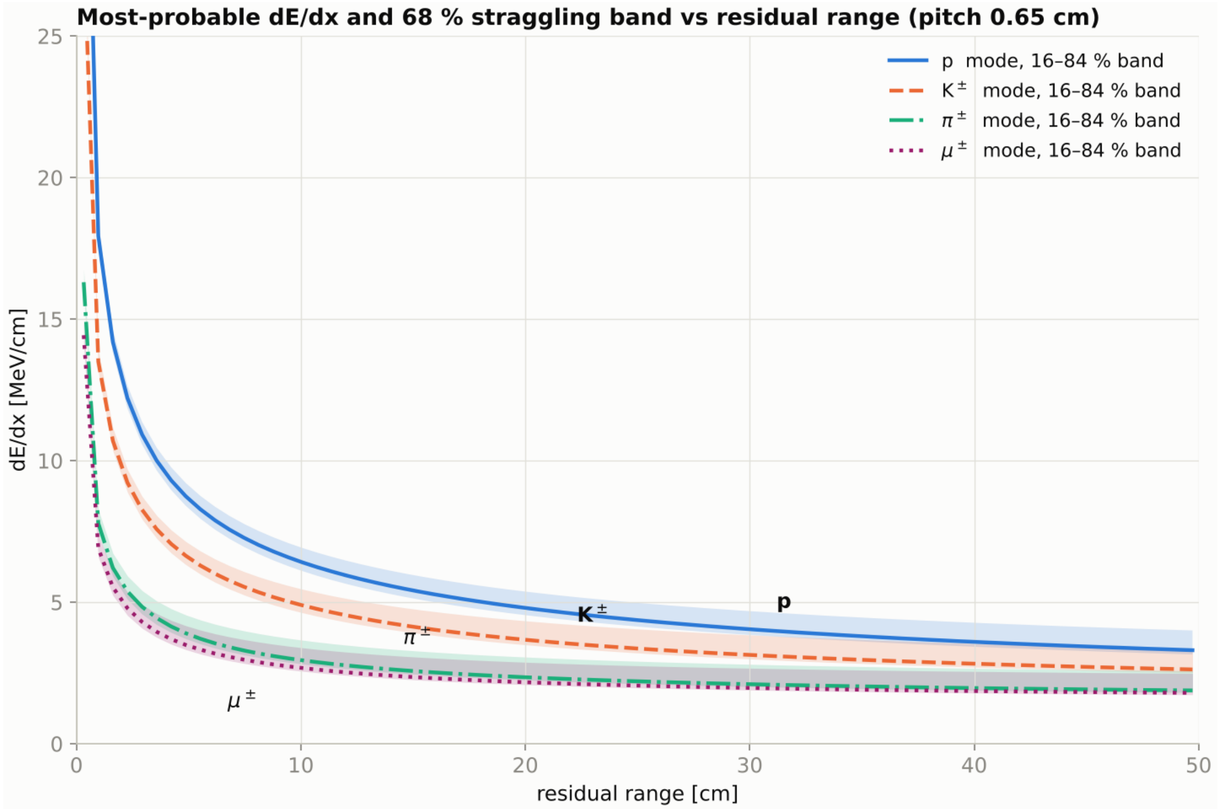

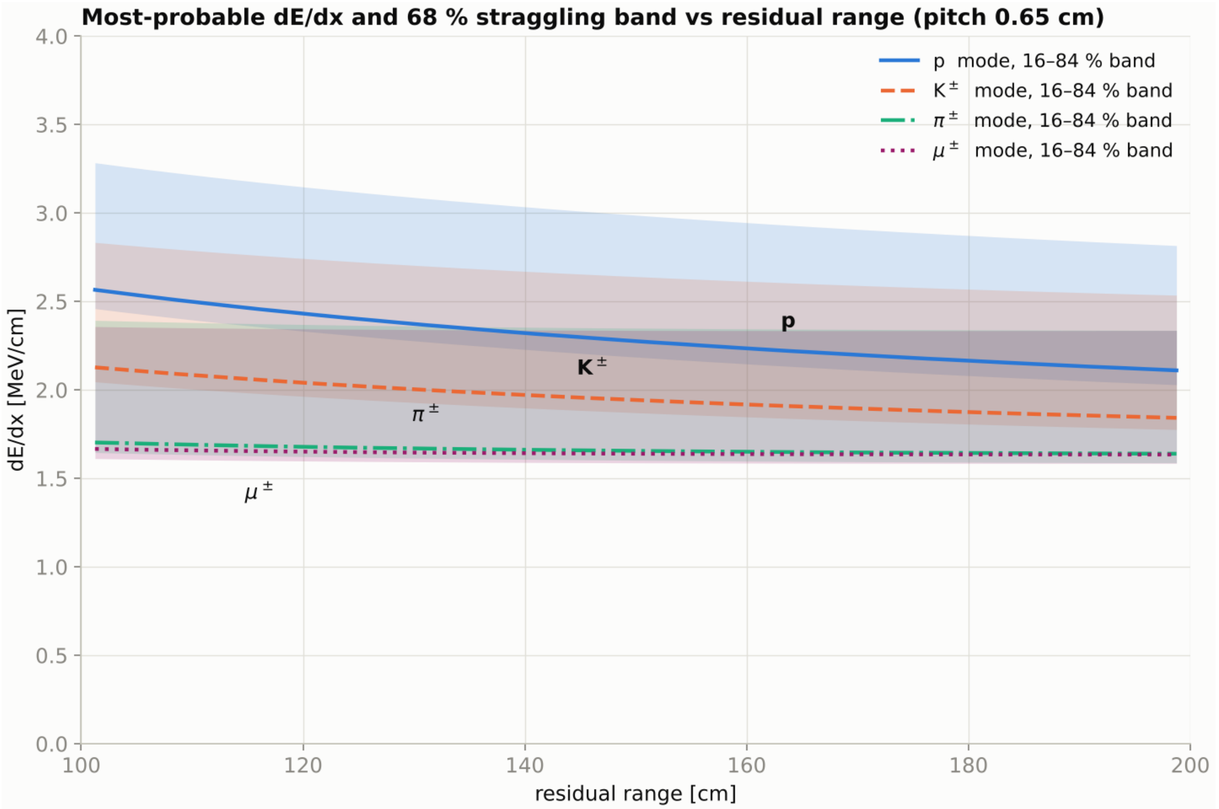

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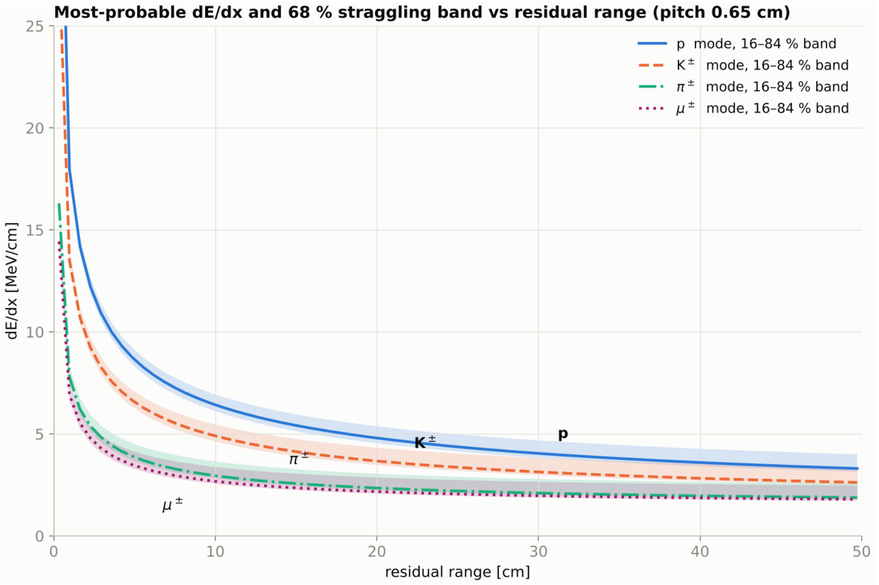
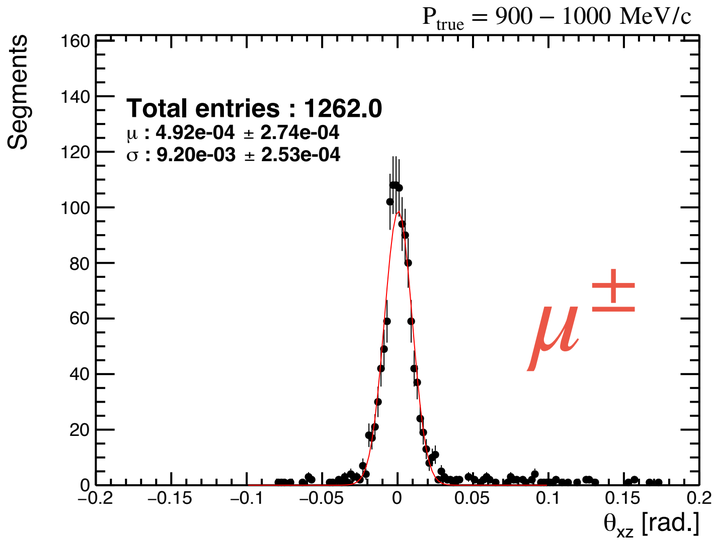
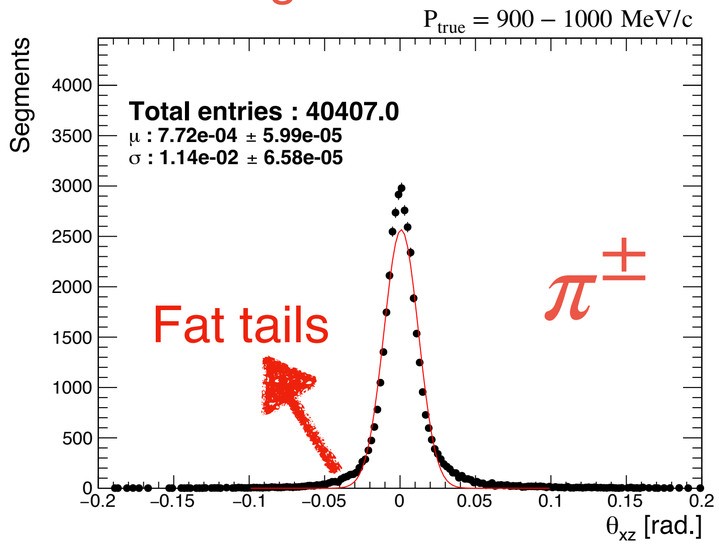
- Energy reconstruction for inelastically interacting charged pions
  - A novel method was developed using the ProtoDUNE Run 1 data
  - Uses both position and **calorimetric** information
    - **Multiple scattering angle** is a promising variable
    - Mass- and energy-dependent; EM only (μ) vs. EM + Strong (p, $\pi^{\pm}$); excellent angular resolution ~ $\mathcal{O}$(mrad.)



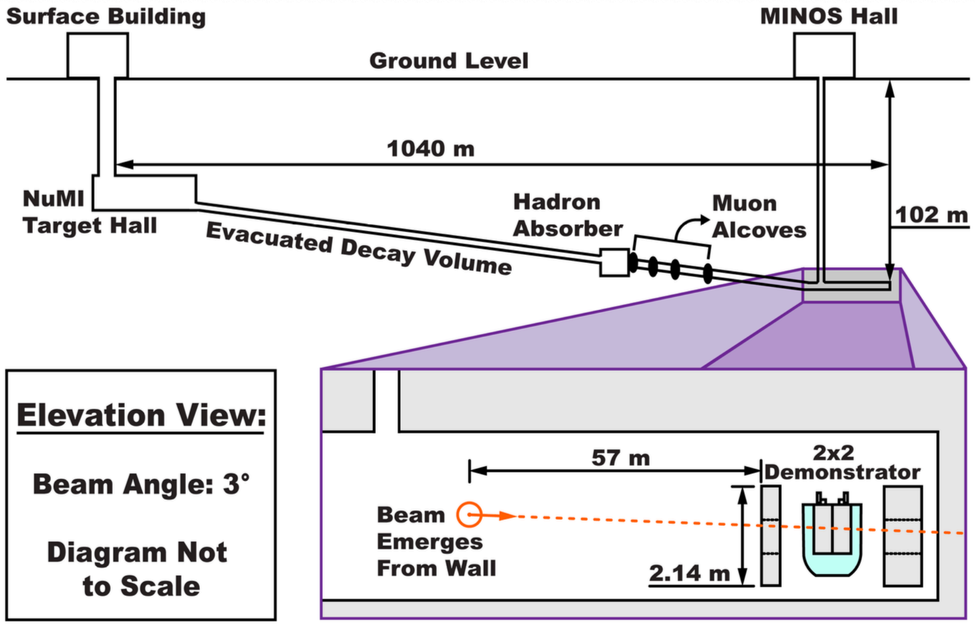
Geant4 Simulation for 14 cm segment in LAr

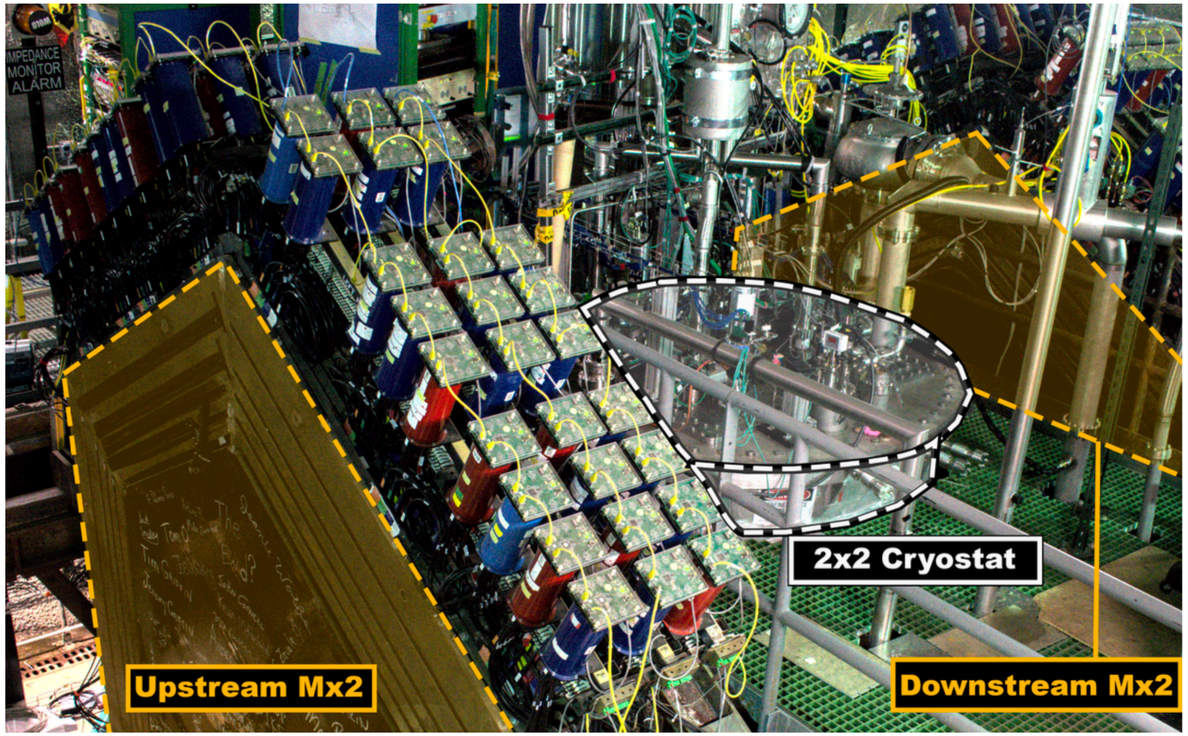




Opportunities at Near Detector Prototype: The 2x2 Demonstrator

- Demonstration of ND-LAr design with 4 modules at ~ 60% scale: pixelated charge readout!
- Installed in the Minerva detector hall
- Run 1 (2024): NuMI data (~ 4.5 days, ~ 30k ν) and cosmic data
- Run 2 (2025): calibration data (neutron & γ sources, ^{220}Rn injection …)
- Run 3 (2026 - 2027): more NuMI and cosmic data

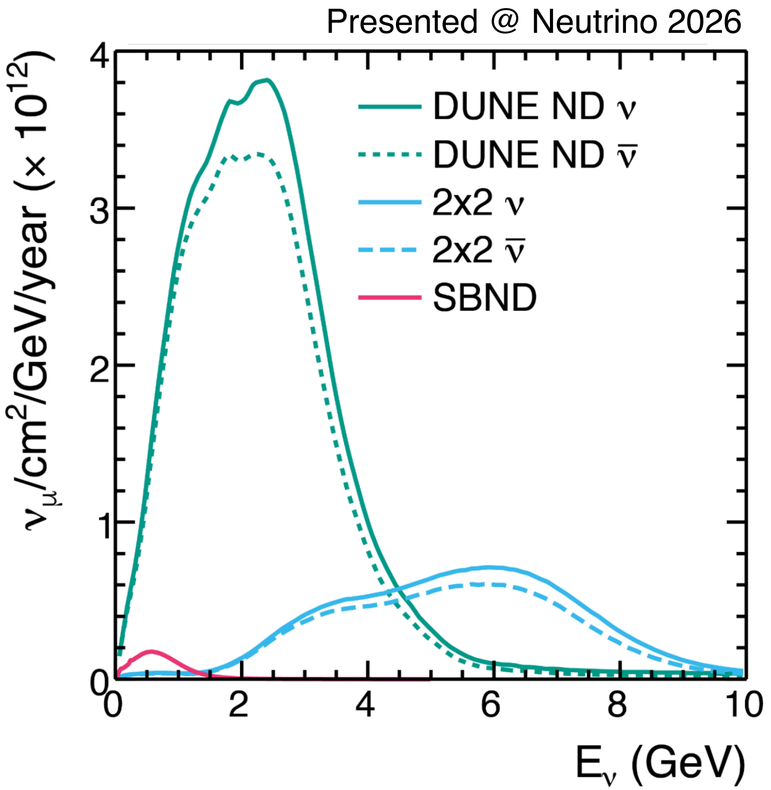


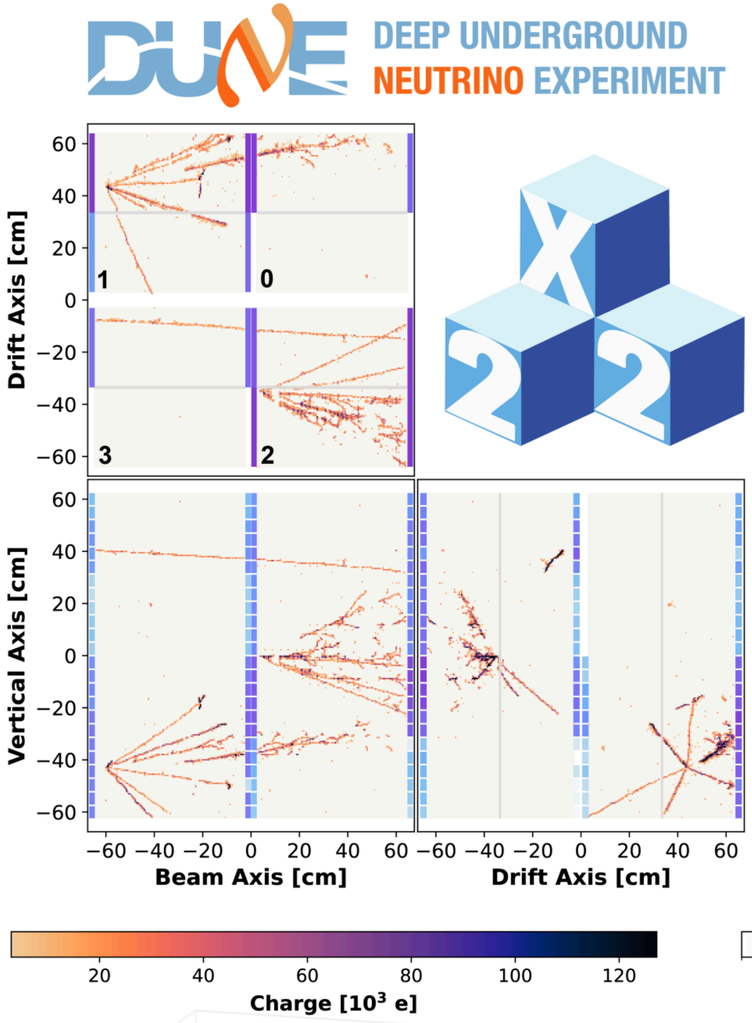


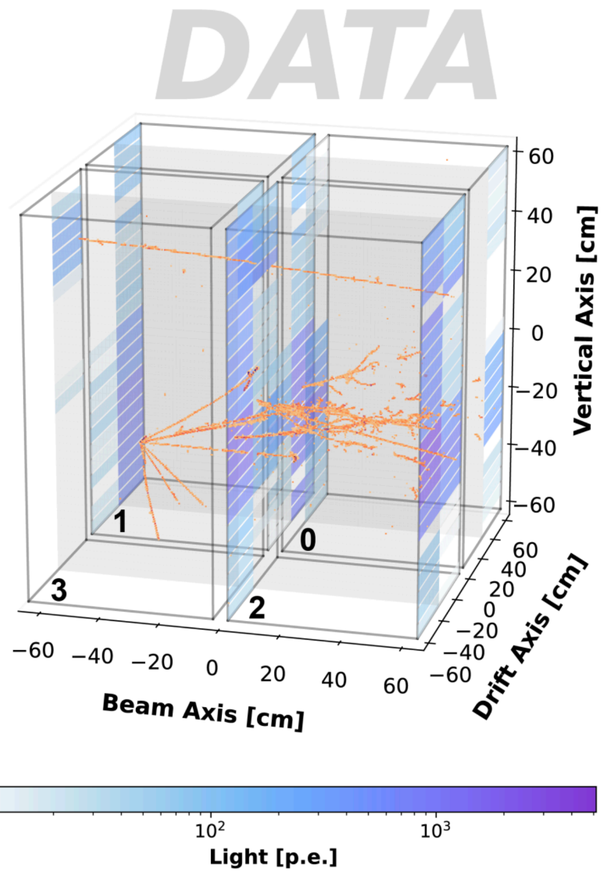
DUNE collaboration, *Instruments* 10 (2026) 1, 18

Opportunities at Near Detector Prototype: The 2x2 Demonstrator

- $\nu - \mathrm{Ar}$ studies using the NuMI beam
- Testing beyond the standard model scenarios
- Reconstruction & calibration studies





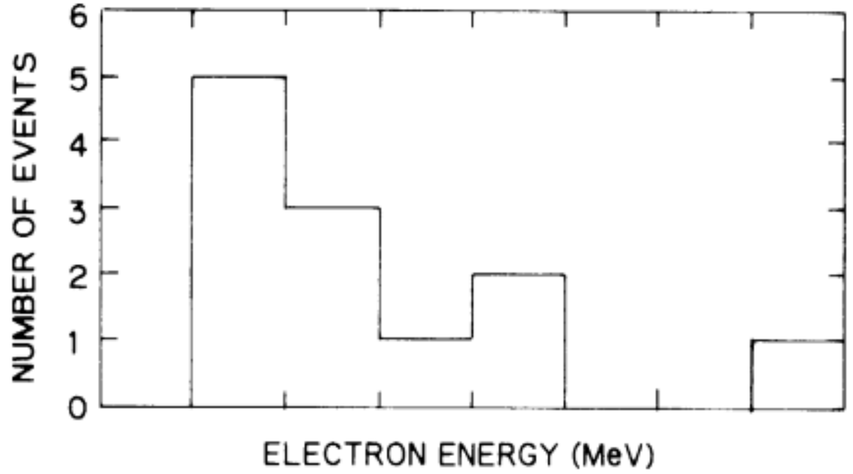


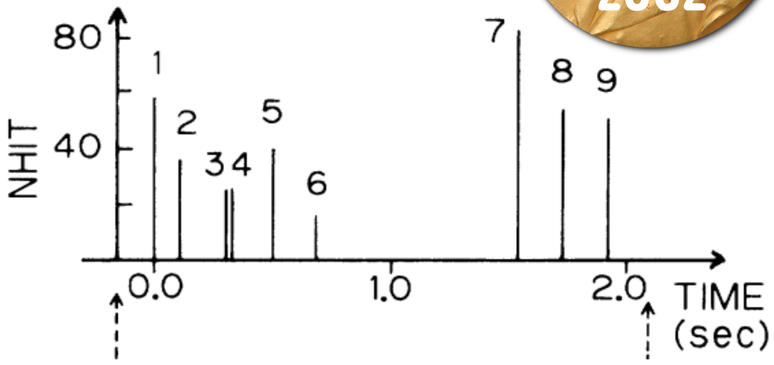
DUNE collaboration, *Instruments* 10 (2026) 1, 18

Opportunities in FD1: (1) Core-Collapse Supernovae

- Core-collapse supernovae produce neutrino bursts
  - Observed only once: SN 1987A, 12 electron events by Kamiokande-II
- The next neutrino burst from a core-collapse supernova will be observed by many neutrino telescopes
  - DUNE far detector modules are also neutrino telescopes

Credit:
NASA, ESA, CSA, M. Matsuura (Cardiff University),
R. Arendt (NASA's Goddard Spaceflight Center & University of Maryland, Baltimore County),
C. Fransson (Stockholm University), J. Larsson (KTH Royal Institute of Technology), A. Pagan (STScI)

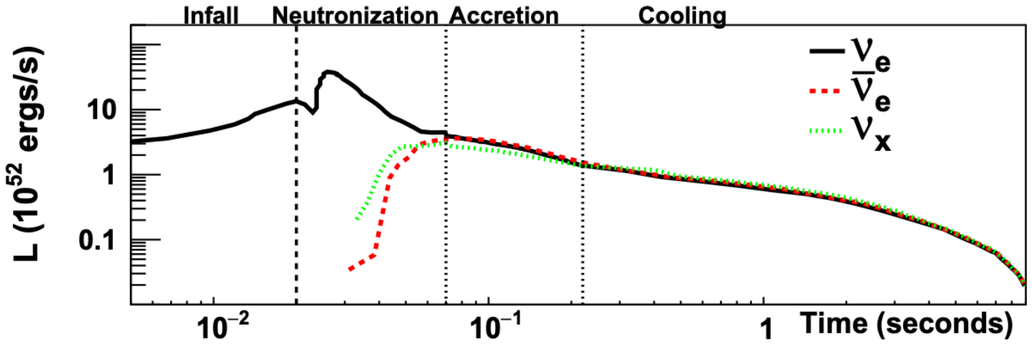


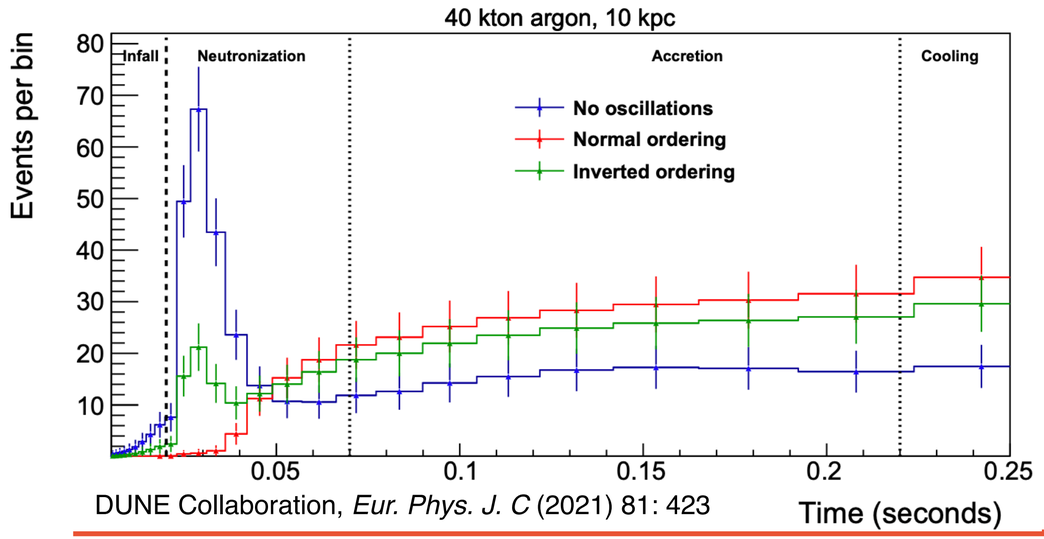


Hirata, K et al., *Phys.Rev.Lett.* 58 (1987) 1490-1493

Opportunities in FD1: (1) Core-Collapse Supernovae

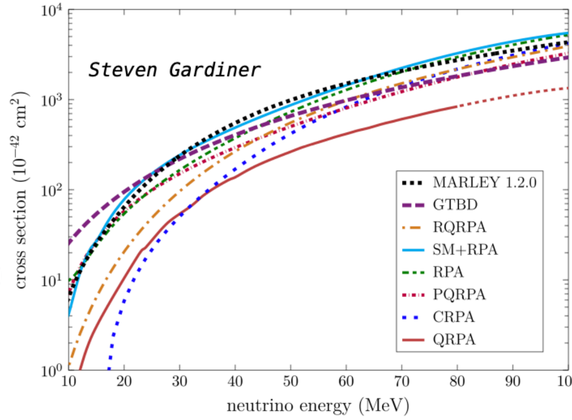
- DUNE has a unique sensitivity to ν_e from the neutrino burst: ν_eCC ($\nu_e + \mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$)
  - A big advantage for probing the early neutrinos from the burst!





DUNE Collaboration, *Eur. Phys. J. C* (2021) 81: 423

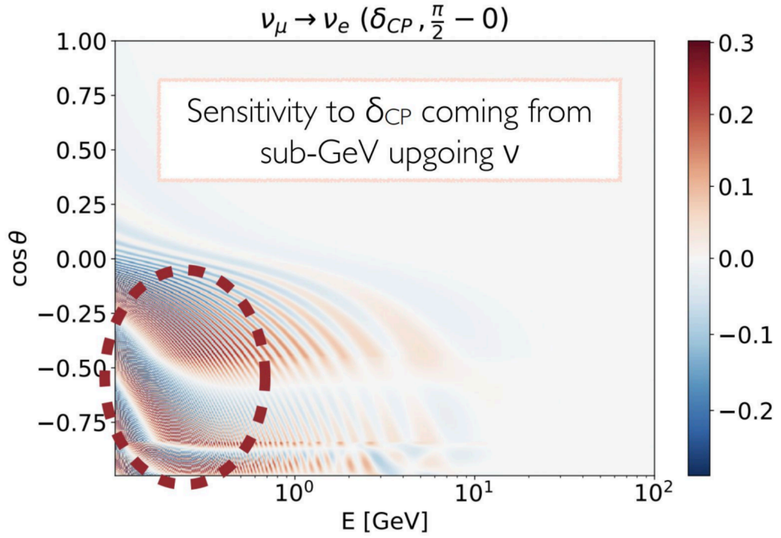
- **But there are many challenges (= opportunities)**
  - Cross-section modeling
    - No measurement yet!
      - SBND: ν_e from μDAR
    - Dedicate event generator (MARLEY)

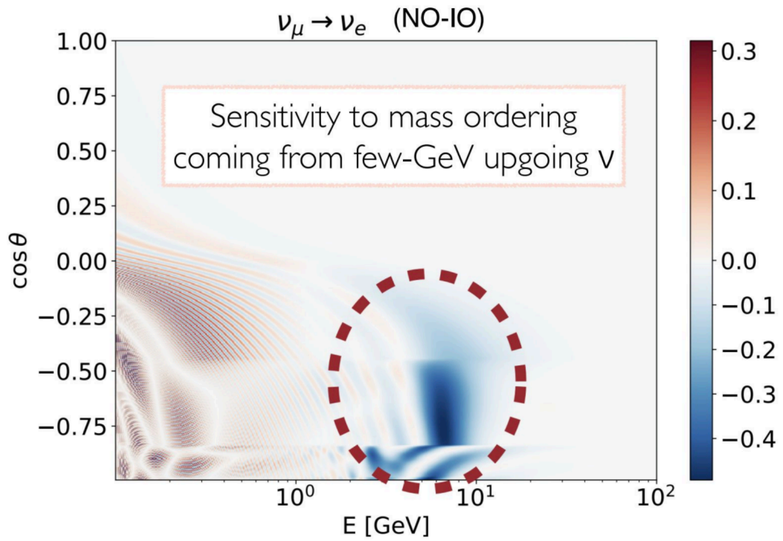


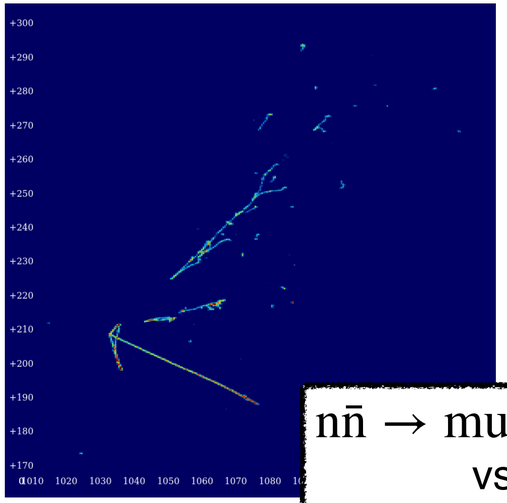
  - Triggering and data streaming systems
  - Reconstruction: low-energy electrons and de-excitation photons
  - Supernova pointing
    - Improving $\nu_e + e^- \rightarrow \nu_e + e^-$ selection purity is the key

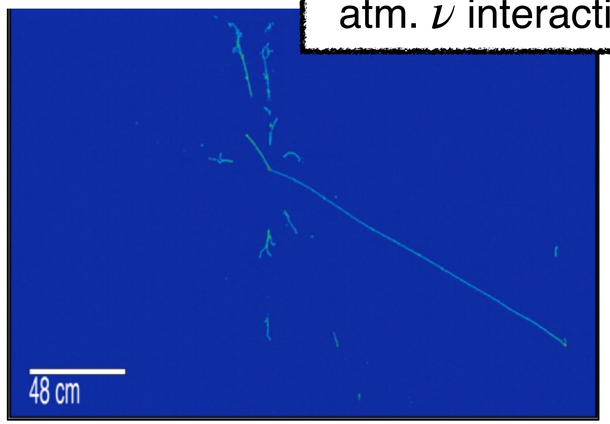
Opportunities in FD1: (2) Atmospheric Neutrinos

- Atmospheric neutrinos offer rich physics
  - $E_\nu < 1$ GeV: upward-going ν_e provides sensitivity to δ_{CP}
  - $E_\nu \approx \mathcal{O}(1\ \text{GeV})$: sensitivity to mass ordering
  - Main background for beyond the standard model searches
    - e.g., dark matter and baryon number violation







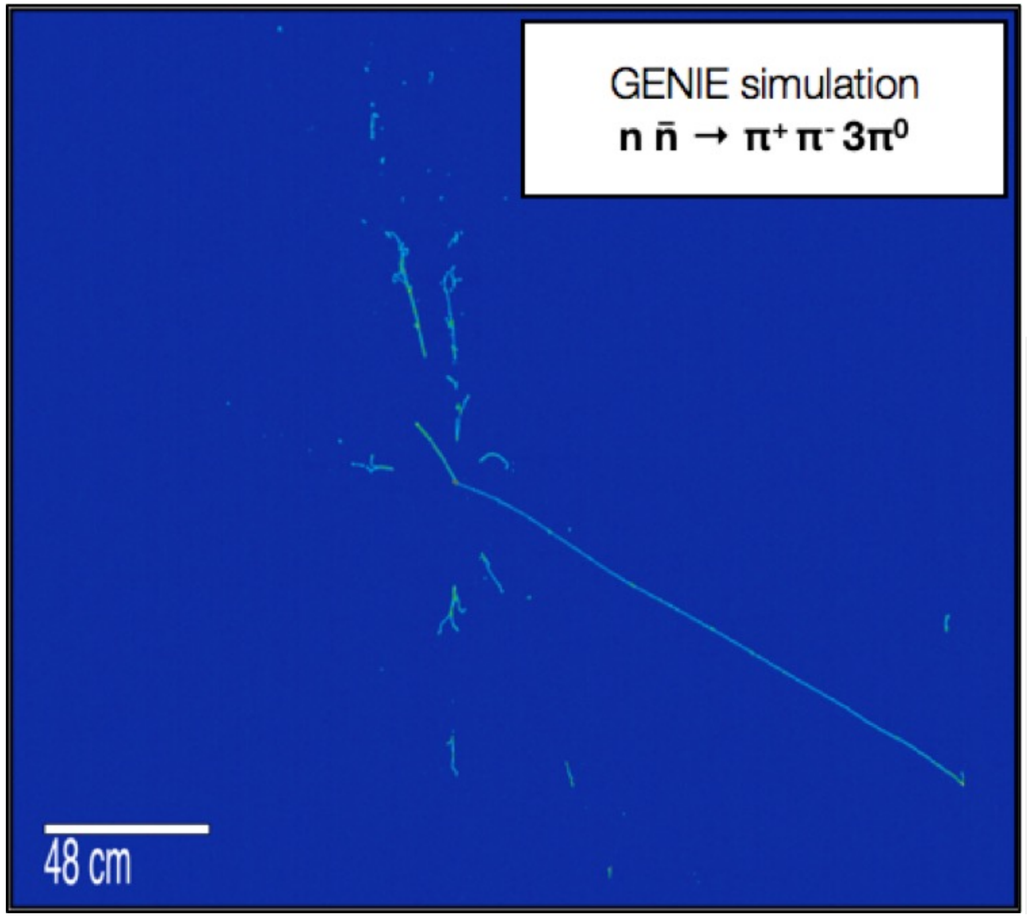


$n\bar{n} \to$ multi pions
vs.
atm. ν interaction

- Neutrino reconstruction study for FD-HD was published in July 2026, *Eur.Phys.J.C* 86 (2026) 7, 904
  - Opportunities in FD-HD sensitivity and a full suite of FD-VD (1st module) studies

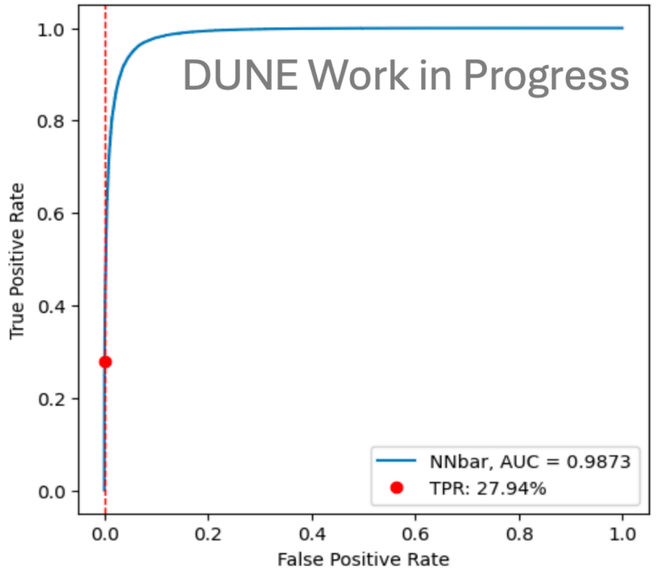
Opportunities in FD1: (3) Baryon Number Violations

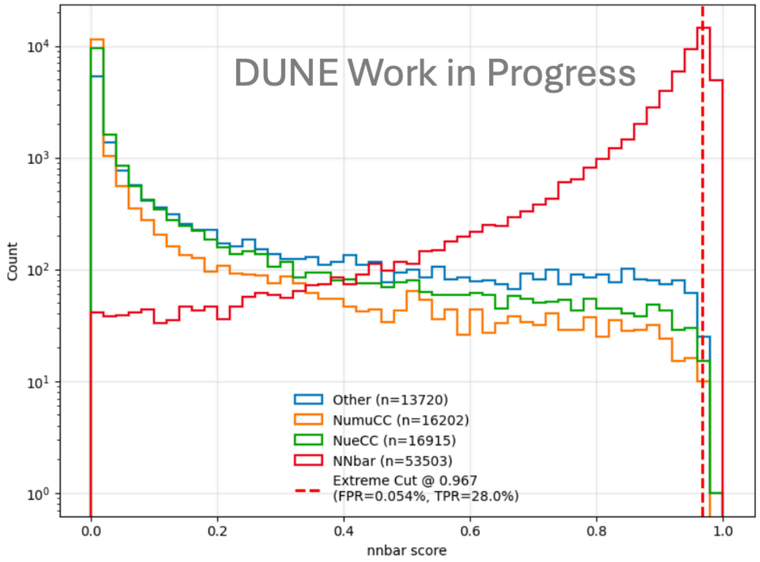
- DUNE has low hadron energy thresholds, mm-scale position resolution, and precise calorimetry
  - Could provide world-class sensitivities to baryon number violation searches



- A recent study for $n - \bar{n}$ oscillation using a TransformerCVN architecture achieved 3× the signal efficiency at the same background rejection, relative to the DUNE TDR
  - Scaling by $\sqrt{3}$ leads to a $\tau_{n-\bar{n}}$ limit of ~ 10^9 s (400 kt·yr)

K. Yu @ Neutrino 2026





Summary

- DUNE construction is progressing well
  - There are physics opportunities before the beam-based science program starts

- **Hadrons** are important for the DUNE long-baseline neutrino oscillation physics program
  - About 30% to 40% of neutrino interaction energy is deposited by hadrons
  - Hadron propagation & interaction modeling, energy reconstruction and particle identification are challenging
  - There are imminent physics opportunities with the DUNE FD prototype detectors to tackle them

- There are also physics opportunities with the first DUNE FD module
  - To realize DUNE's unique sensitivity to ν_e from core-collapse supernova neutrino bursts
    - Modeling and reconstruction of $\nu_{\mathrm{e}} + \mathrm{Ar} \rightarrow \mathrm{e}^- + {}^{40}\mathrm{K}^*$ events
    - Triggering and data streaming systems
    - Selection purity for $\nu_{\mathrm{e}} + \mathrm{e}^- \rightarrow \nu_{\mathrm{e}} + \mathrm{e}^-$ process is key for pointing performance
  - Atmospheric neutrinos offer rich physics; first far detector module (FD-VD) studies are wide open
  - A recent $n - \bar{n}$ oscillation study shows promising performance; analyzing the first FD data will be exciting

Back Up