Status of the Short-Baseline Near Detector at Fermilab

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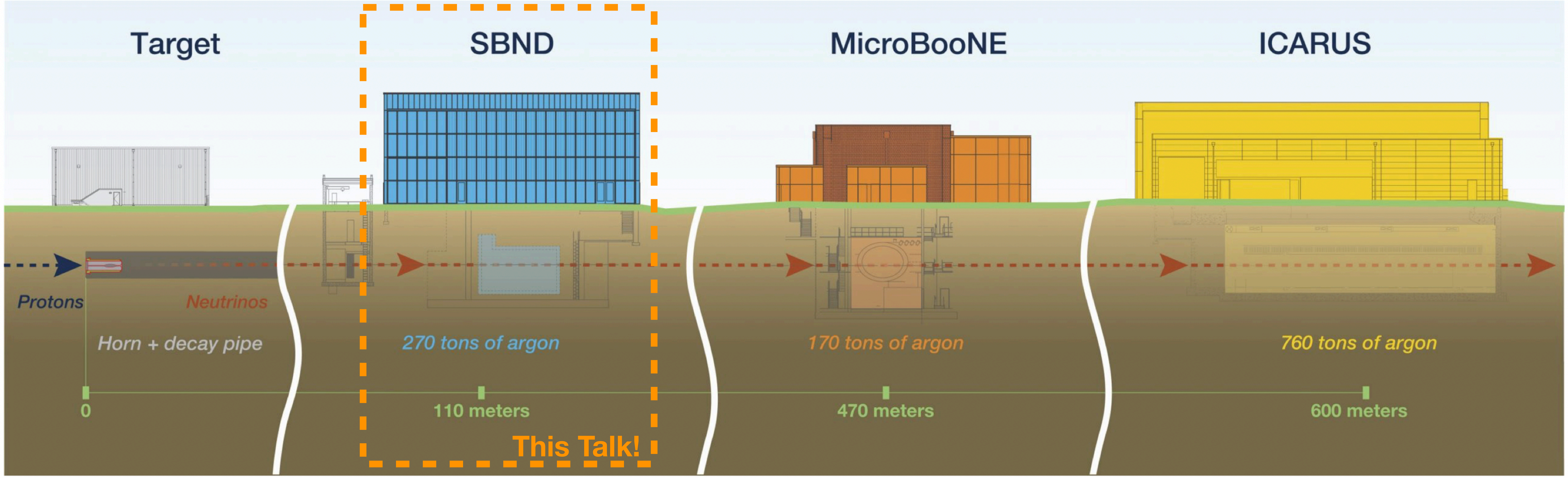
On Behalf of the SBND Collaboration
UC Santa Barbara

October 3rd, 2025

The 24th International Workshop on Next Generation Nucleon Decay and Neutrino Detectors (NNN25)

The SBN Program at Fermilab



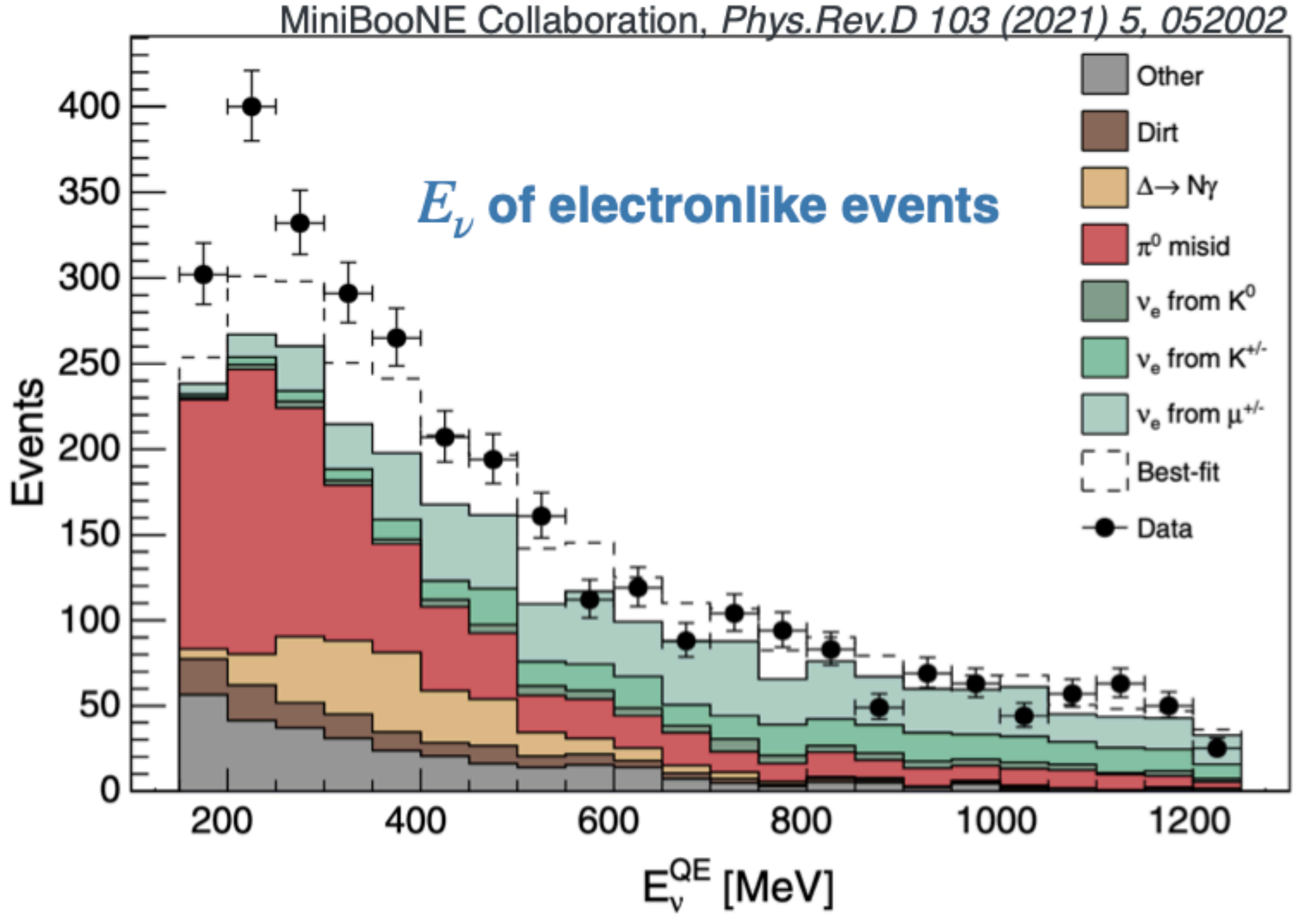
- The **S**hort **B**aseline **N**eutrino Program aims to resolve the low energy excess seen at MiniBooNE *(Phys. Rev. Lett. 121, 221801(2018))*
- Multi-detector facility sitting in the Booster Neutrino Beam at Fermilab → Pion decay-in-flight source *(PRD 79, 072002)*
  - Same as MiniBooNE!
- By using the same detector technology, target nucleus, and beamline, the SBN program can constrain systematic uncertainties to the %-level

The Short Baseline Near Detector (SBND)

- Liquid Argon Time Projection Chamber (LArTPC)
- Near detector of the SBN Program — 110 meters from the source
- Finished collecting our first run of neutrino data this summer (Run 1: December 2024 — July 2025)
  - ~3 million neutrino interactions!
- Physics goals:
  1. Constrain beam and cross section uncertainties for SBN sterile neutrino search
  2. Search for Beyond the Standard Model Physics and study rare processes
  3. Precision measurements of neutrino interactions on Argon (Cross sections)

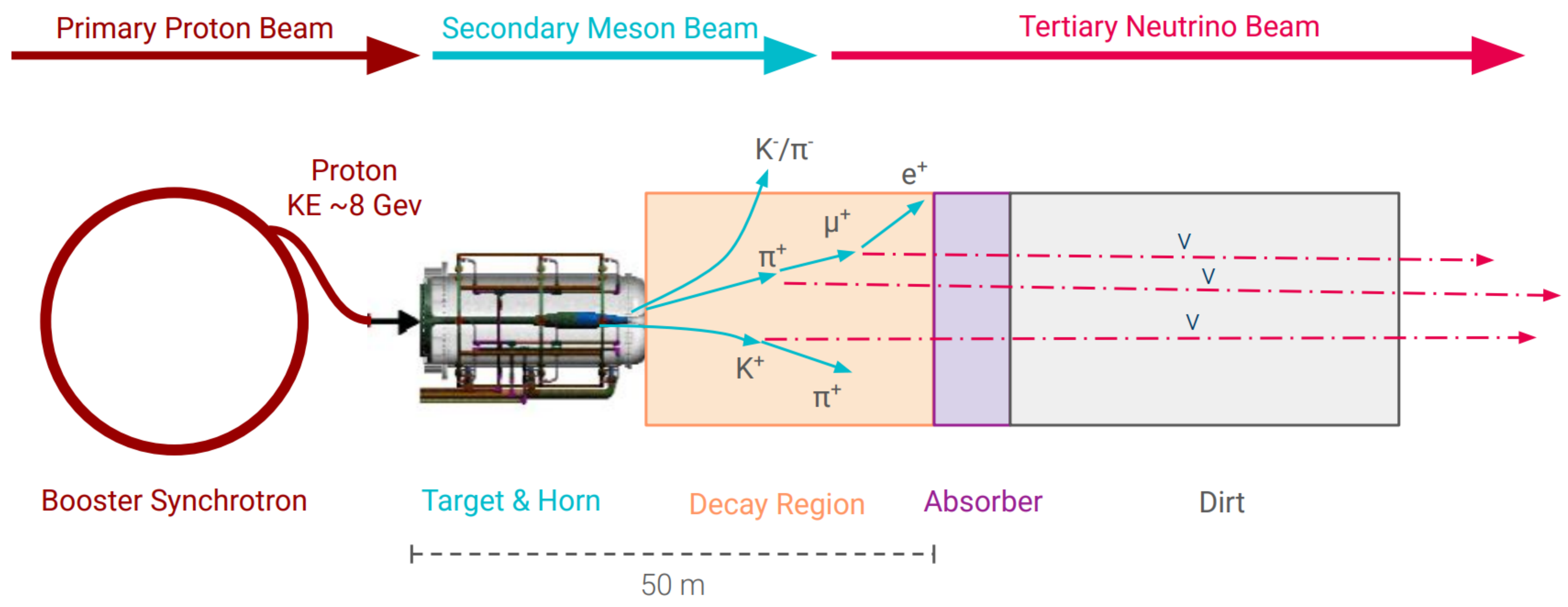
Physics Motivation

The SBN Oscillation Program



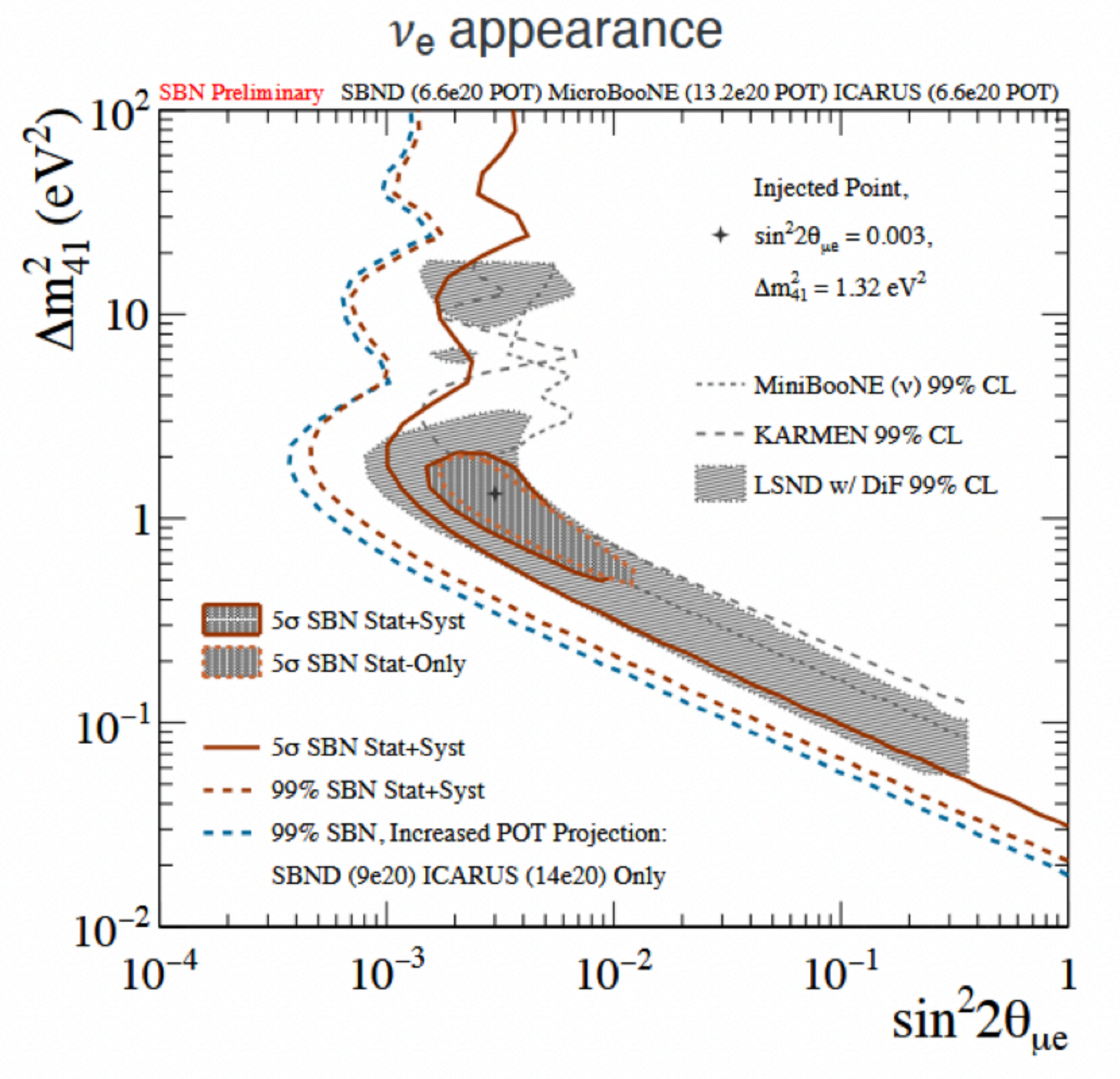
- Low energy excess in electron-like events was seen by MiniBooNE
- Used accelerator-based ν_μ dominated source
  - The **B**ooster **N**eutrino **B**eam (BNB)
- Motivates a search for sterile neutrinos at short baselines (~1eV scale in 3+1 model)

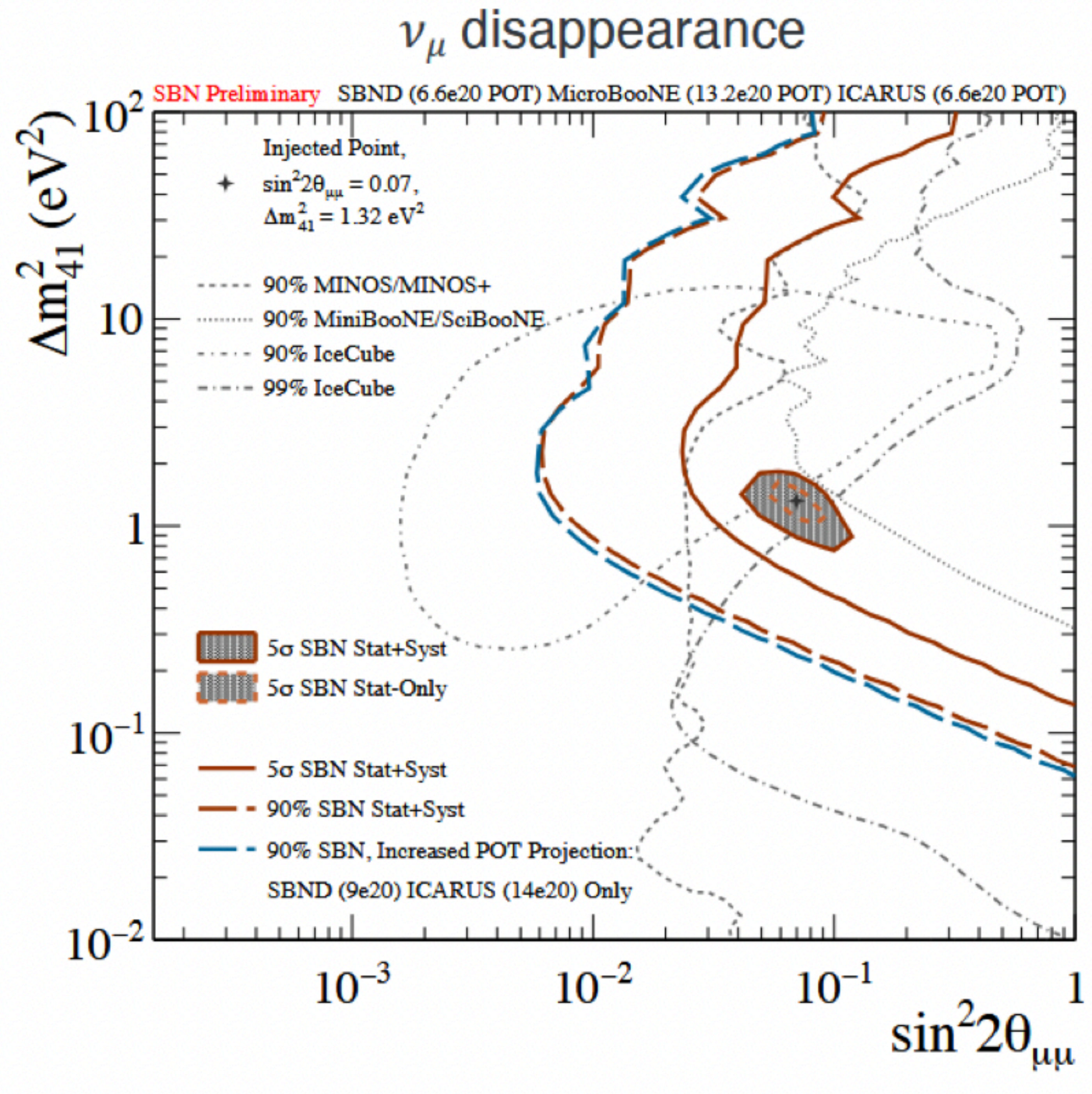
The Booster Neutrino Beam

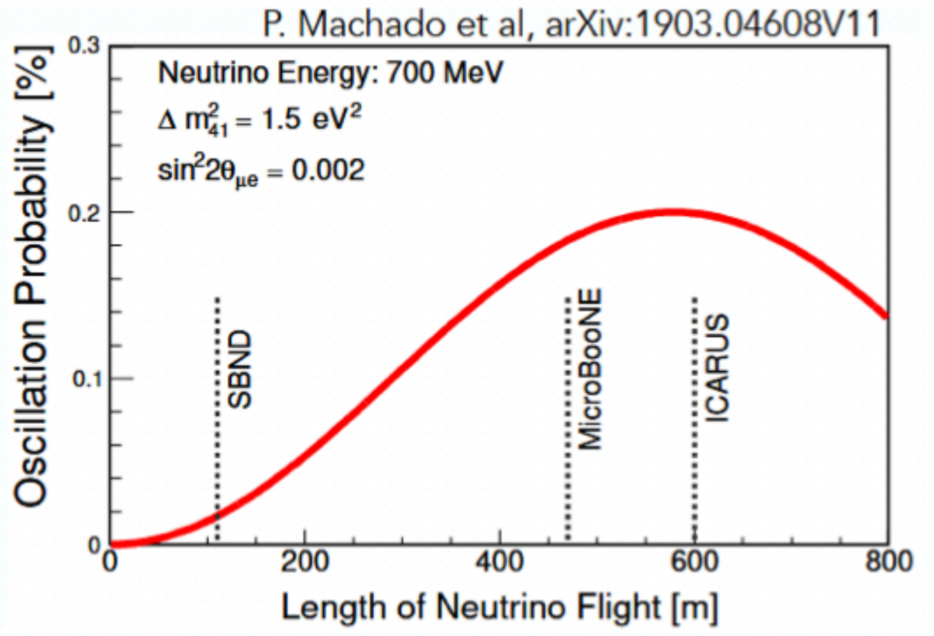


- **SBN program sits in the same beamline and has both a near (SBND) and far (ICARUS) detector with the same detector technology**
- **LAr-TPC provides much better particle ID**

The SBN Oscillation Program







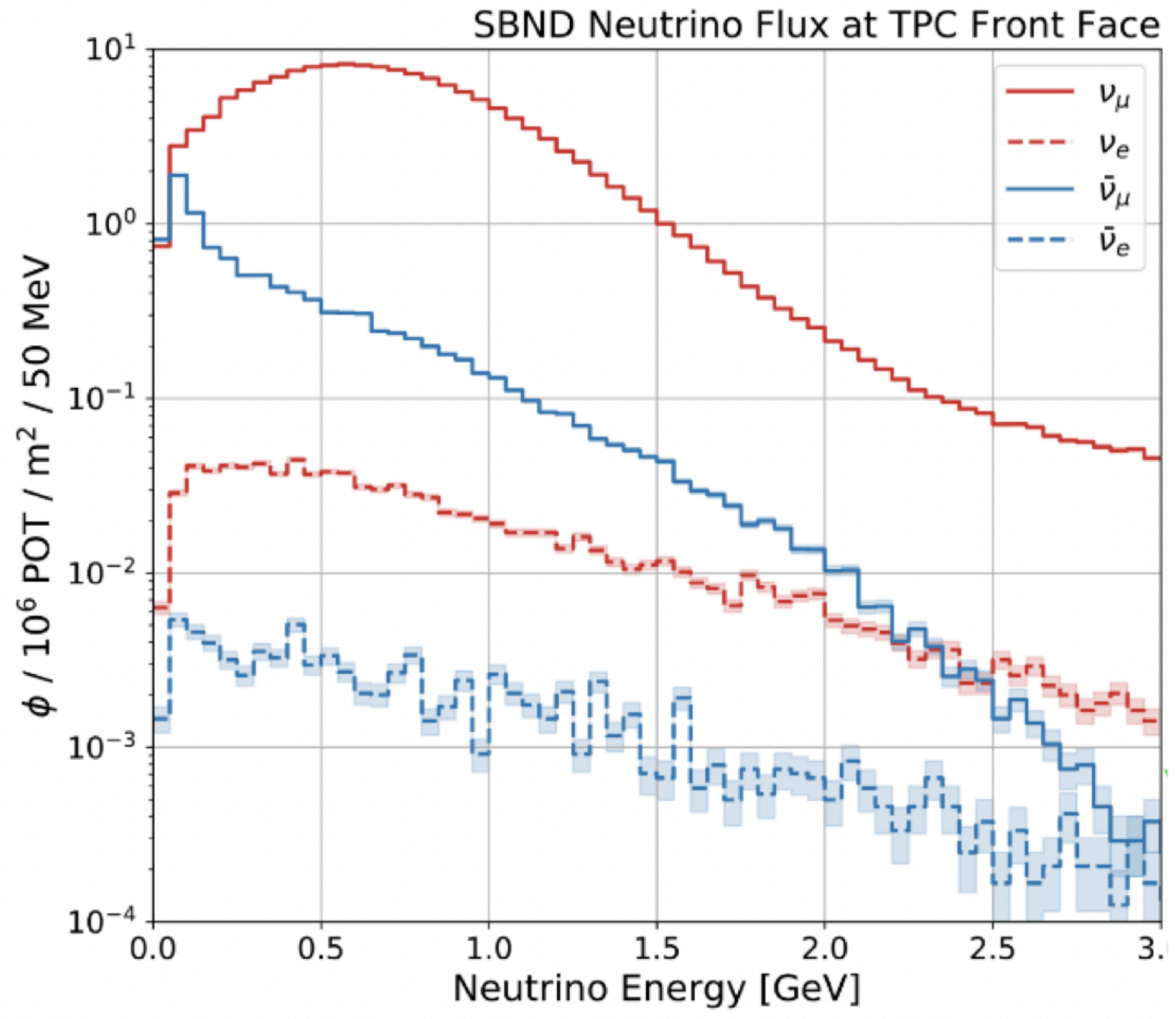
External contours from:
JHEP 08, 010 (2018)
Phys. Rev. D 85, 032007 (2012)
Phys. Rev. Lett. 122, 091803 (2019)
Phys. Rev. D 102, 052009 (2020)

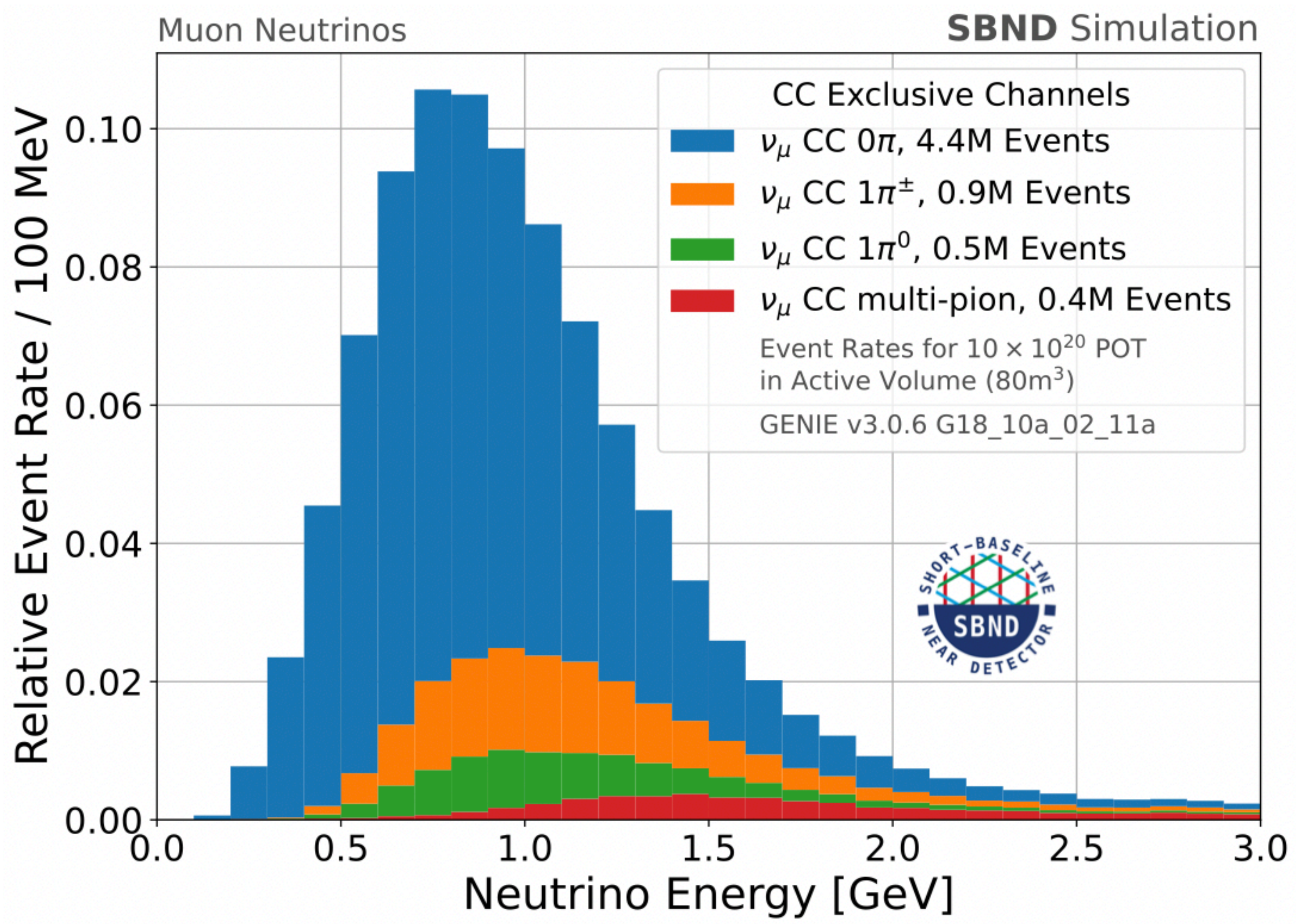
arXiv: 2504.00245

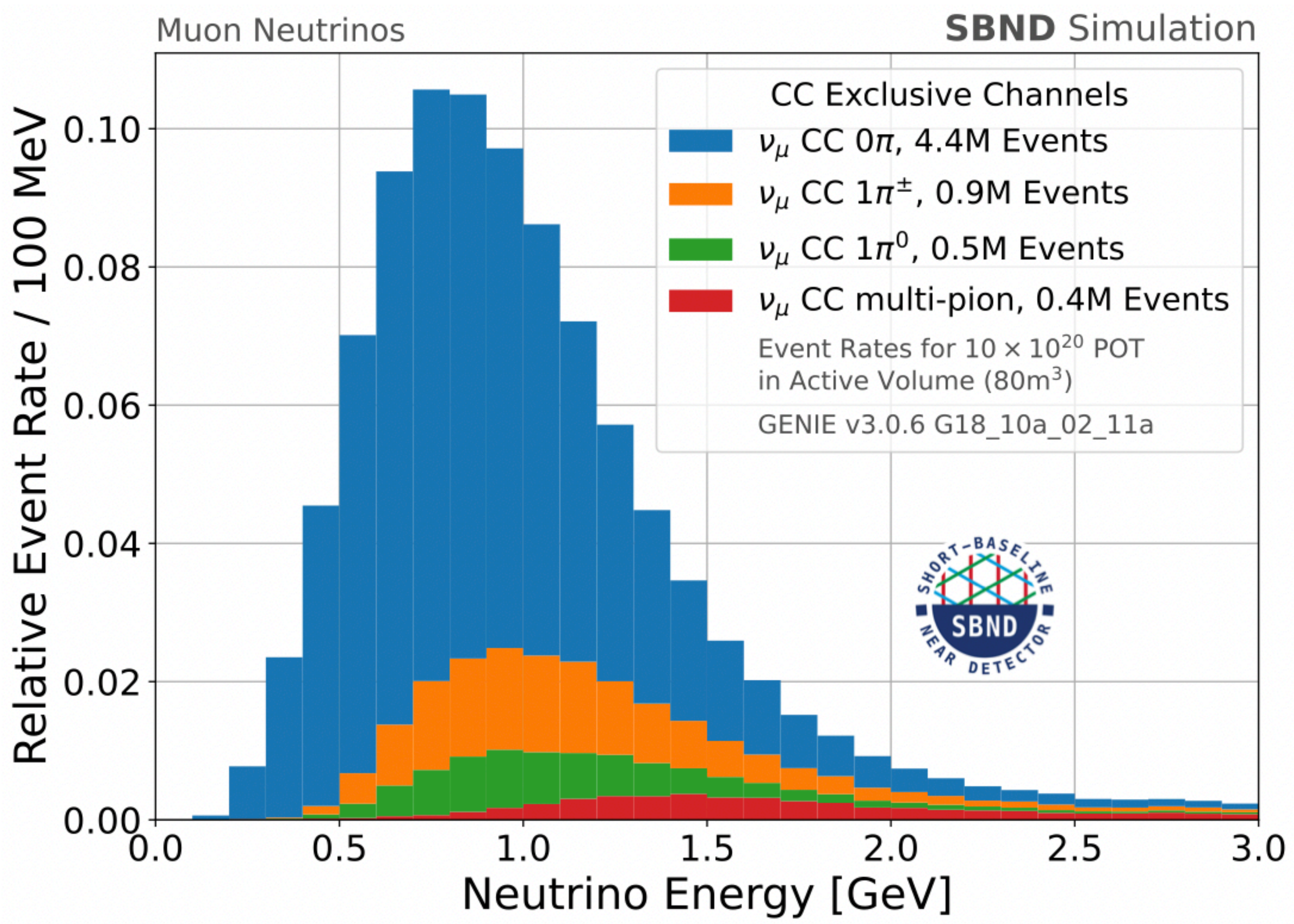
- SBND will constrain beam and cross section uncertainties as the near detector
- Need both ν_e appearance and ν_μ disappearance searches to conclusively address the sterile neutrino hypothesis

SBND Neutrino Flux

- SBND will collect unprecedented interaction statistics
  - **Currently have the world's largest $\nu-$Argon dataset**
  - Estimate ~2 million ν_μ CC and ~15,000 ν_e CC interactions per year → achieved in Run1 !
  - ~10 million neutrino interactions projected for the full data taking period of around 3 years



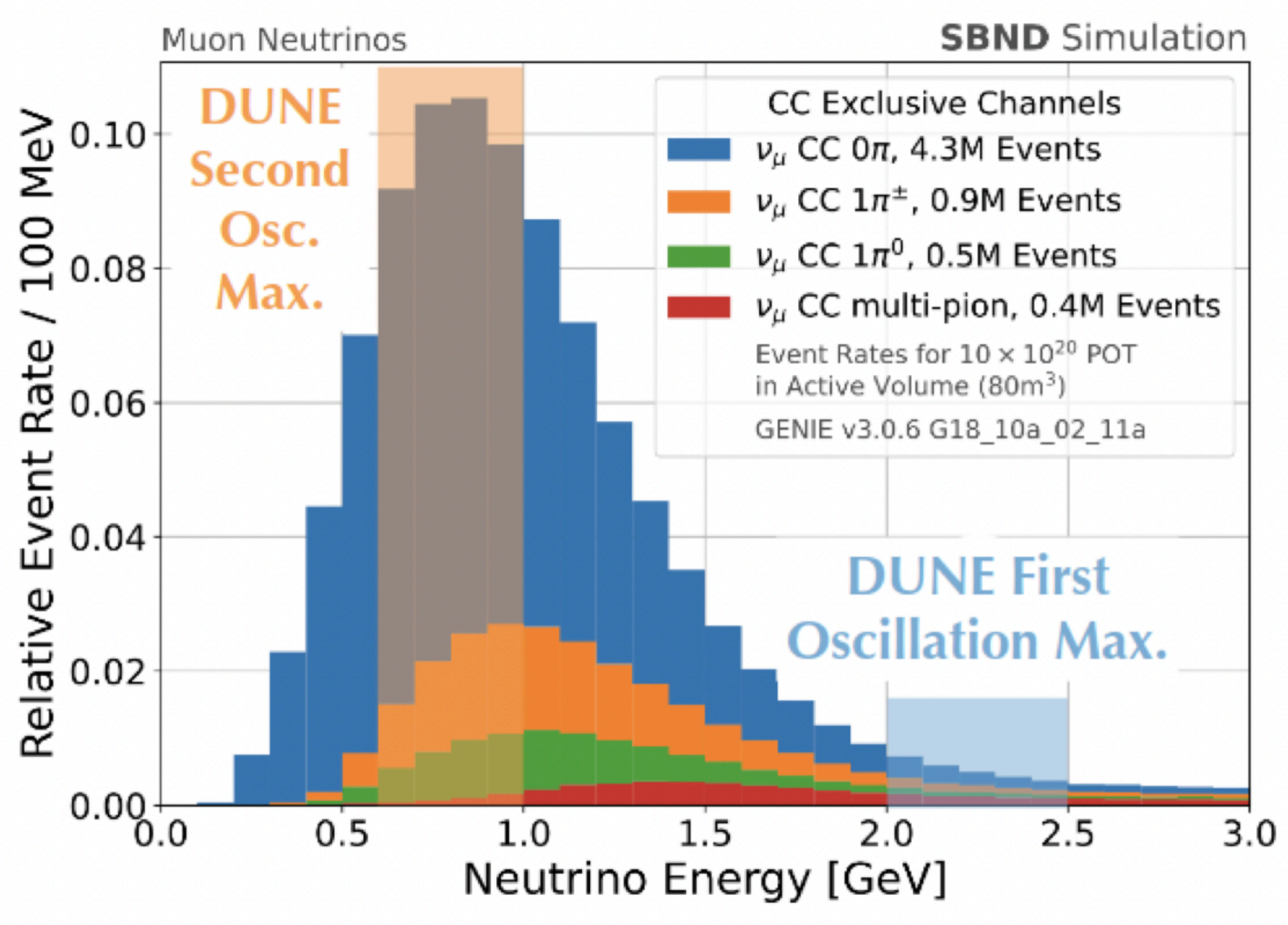


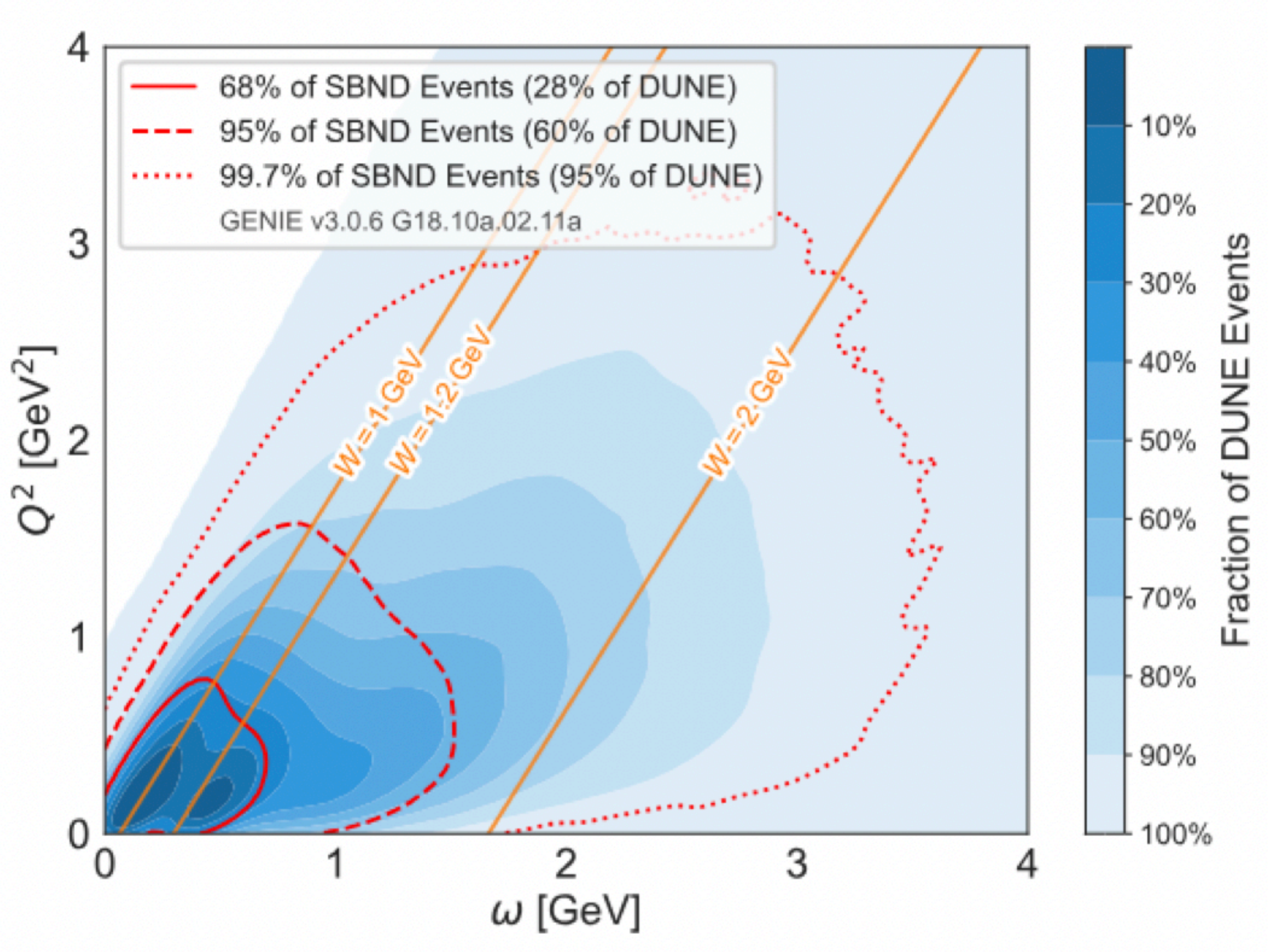


arXiv:2504.00245

SBND Neutrino Flux: DUNE Coverage

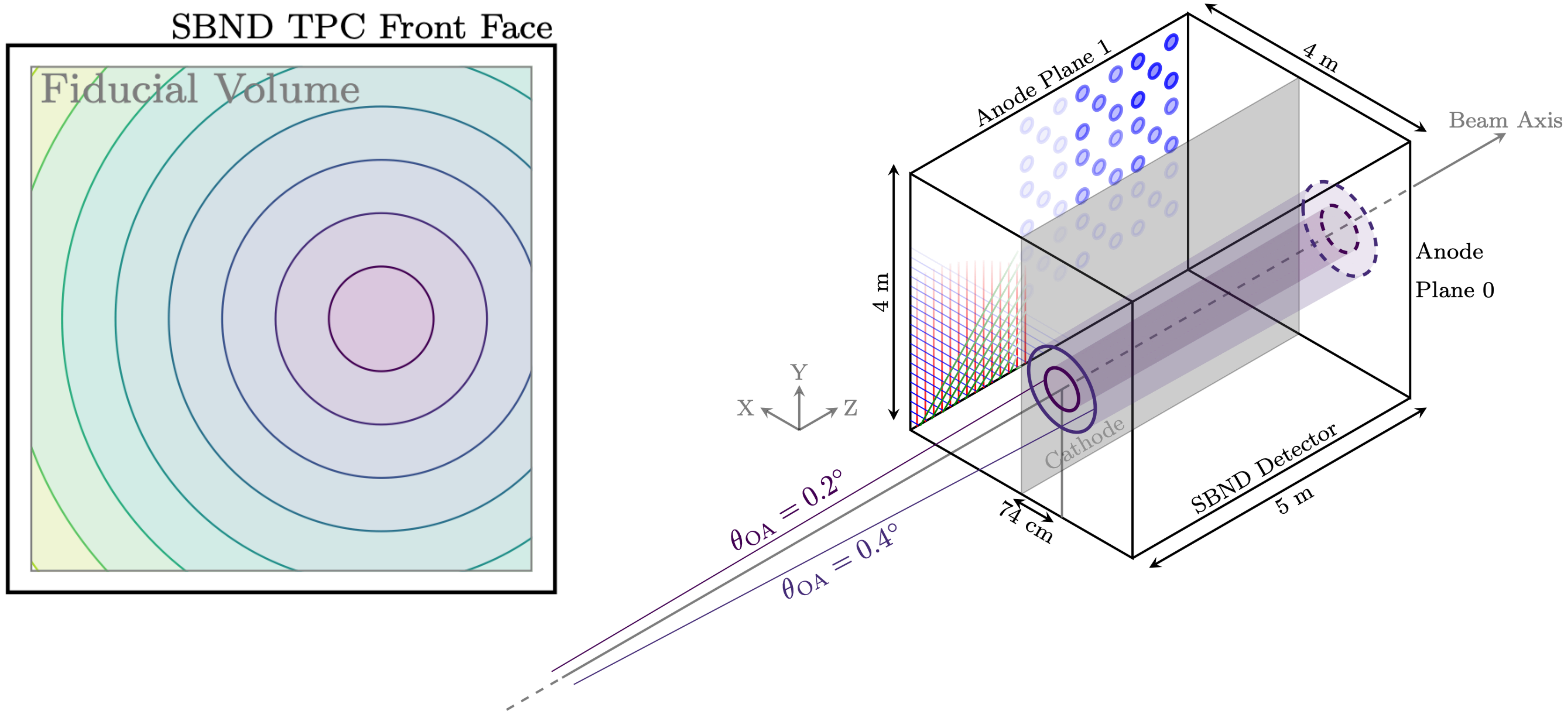
- SBND has significant kinematic phase space overlap with DUNE
  - BNB flux peaks near the second oscillation maximum for DUNE (~0.8 GeV)
  - SBND can be used to constrain DUNE cross section uncertainties

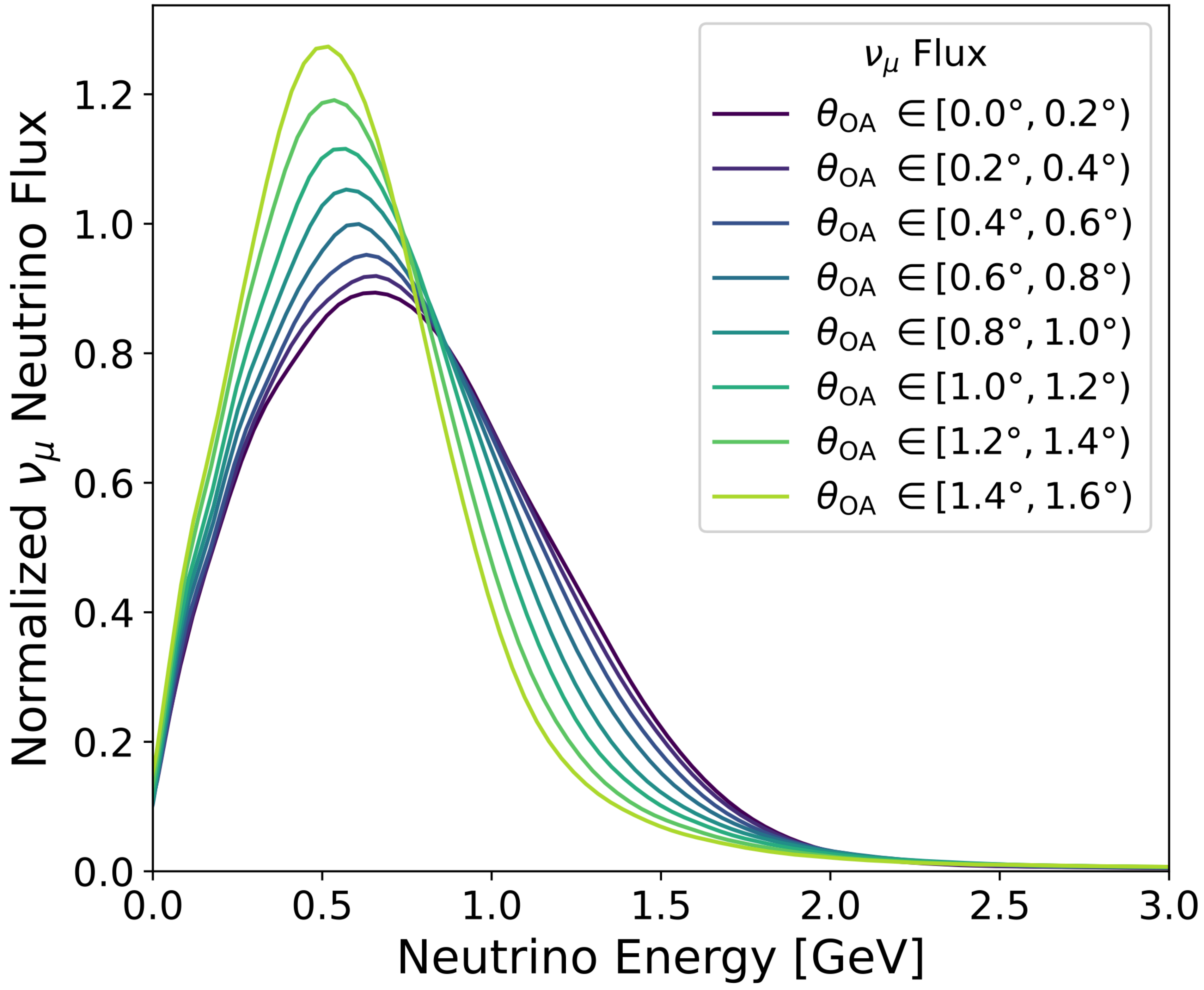




SBND Neutrino Flux: PRISM

- **P**recision **R**eaction **I**ndependent **S**pectrum **M**easurement: arxiv:2508.20239
- SBND sits 74 cm off-axis and its close proximity to the beam allows it to probe an angular range of [0, 1.6] degrees
- Neutrino energy spectrum changes with angle





Beyond the Standard Model (BSM)

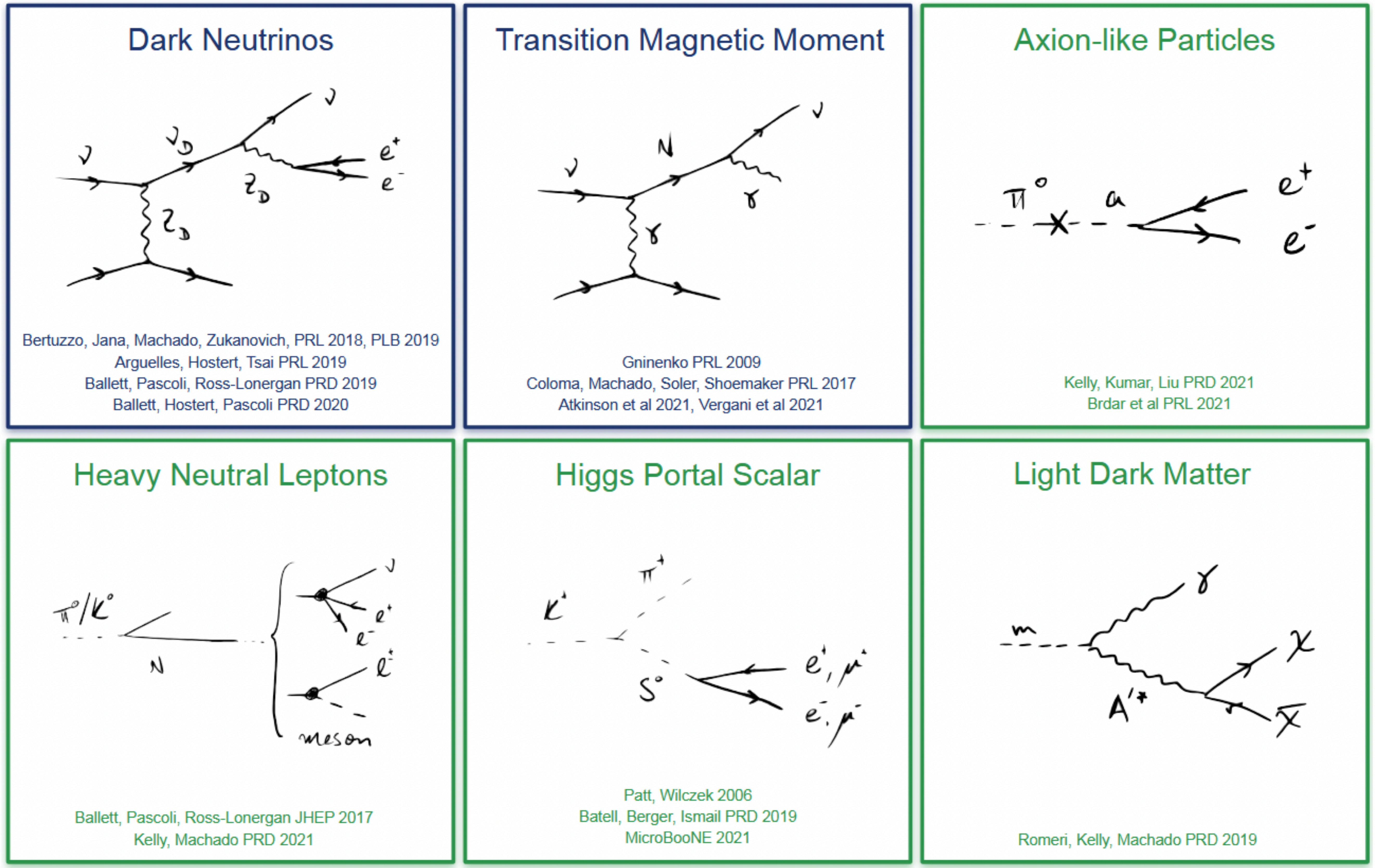
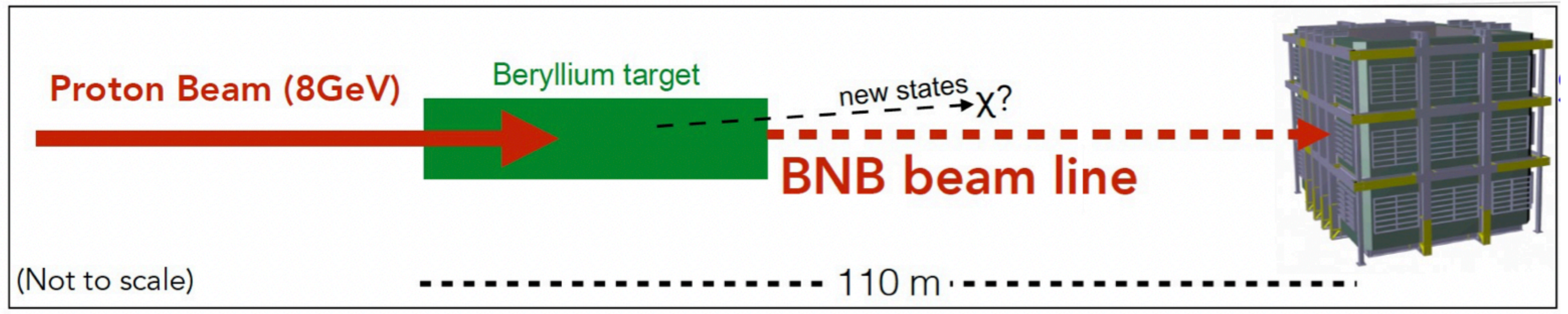


Image credit: Pedro Machado, Marco Del Tutto

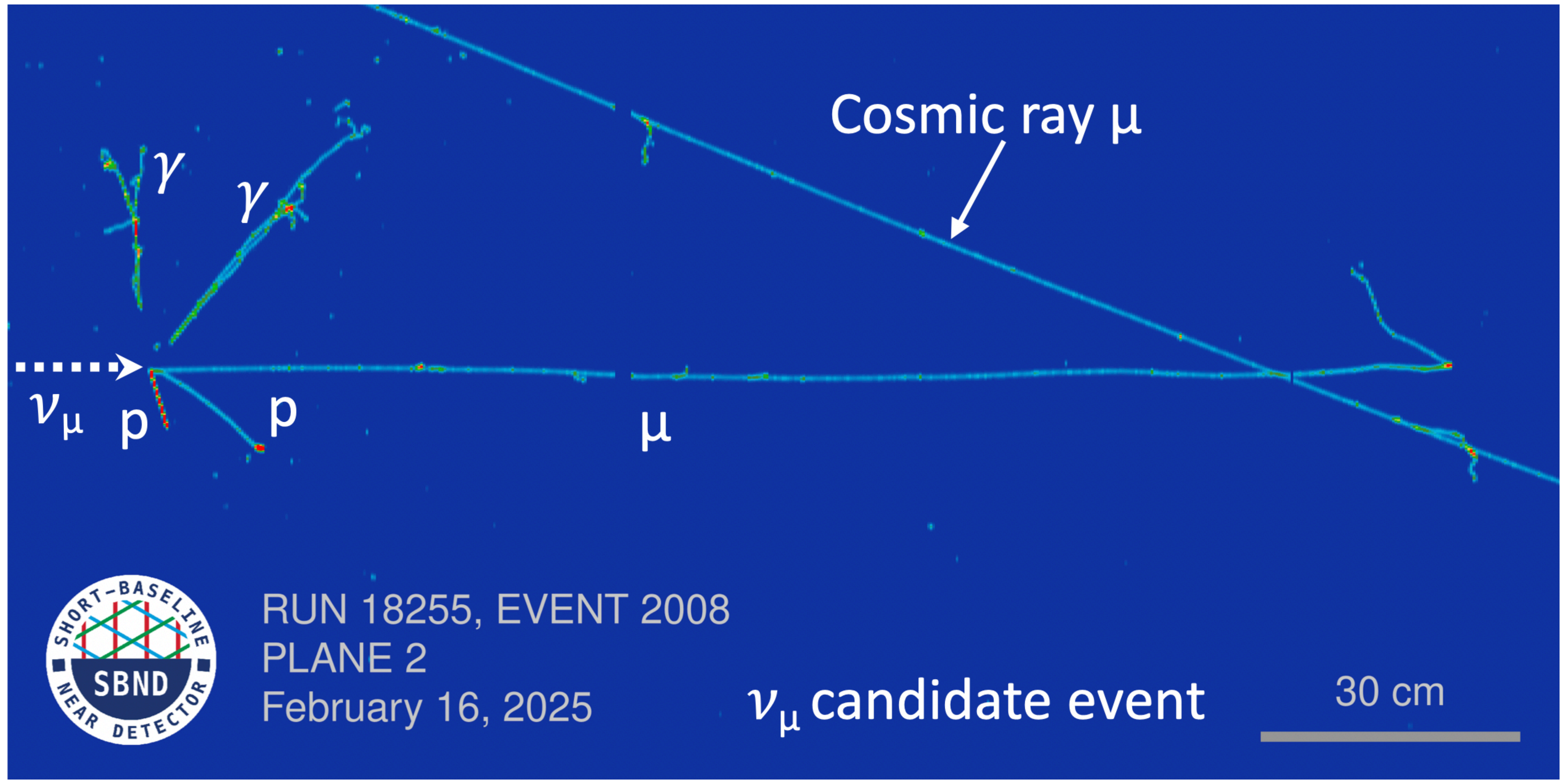


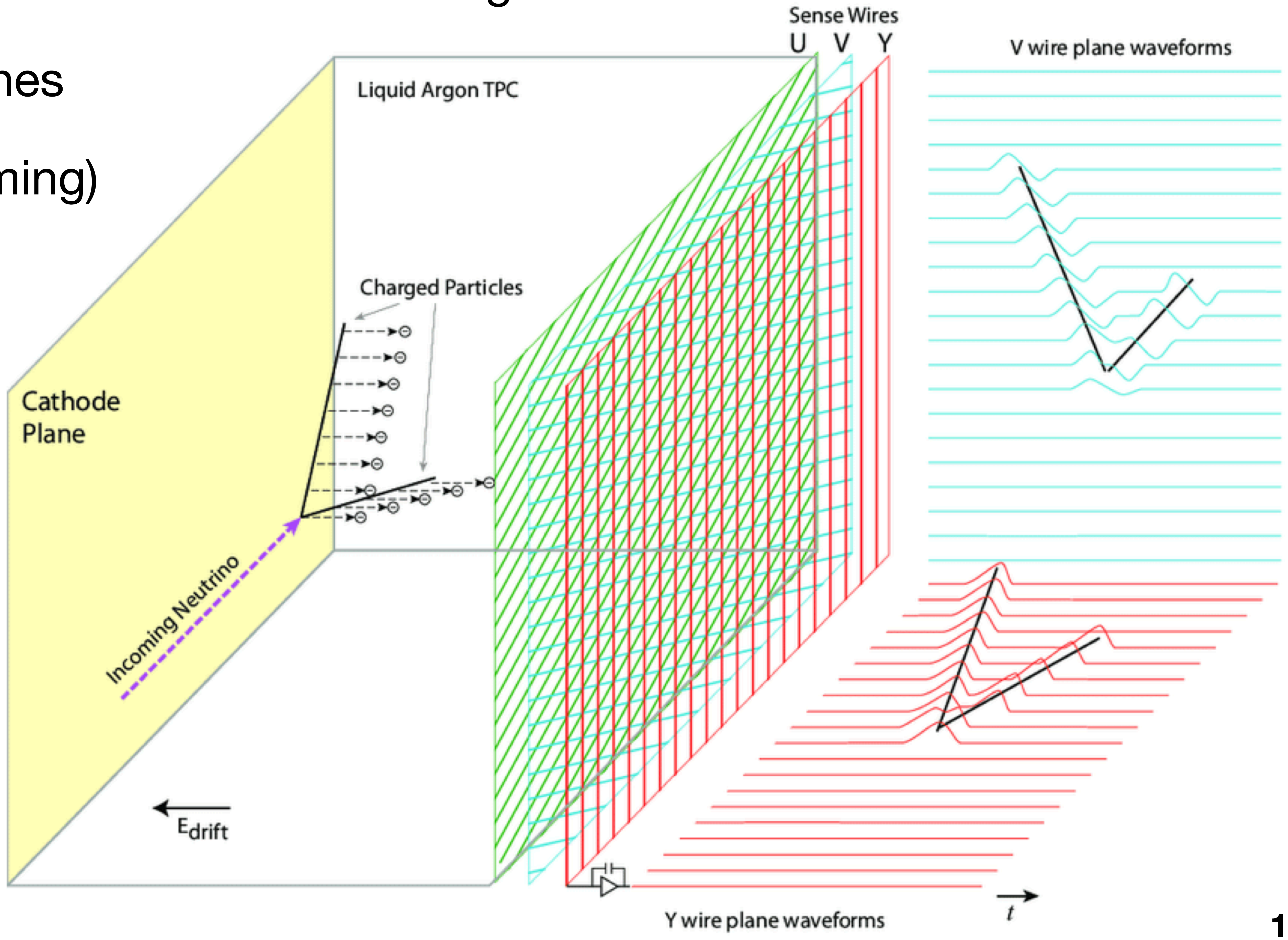
- SBND's proximity to the beam and high statistics enables BSM studies
- Developing advanced timing reconstruction based on scintillation light will help separate massive long-lived particles from neutrinos based on time-of-flight
- Competitive sensitivities to many dark sector particles

Detector Overview

Liquid Argon Time Projection Chambers

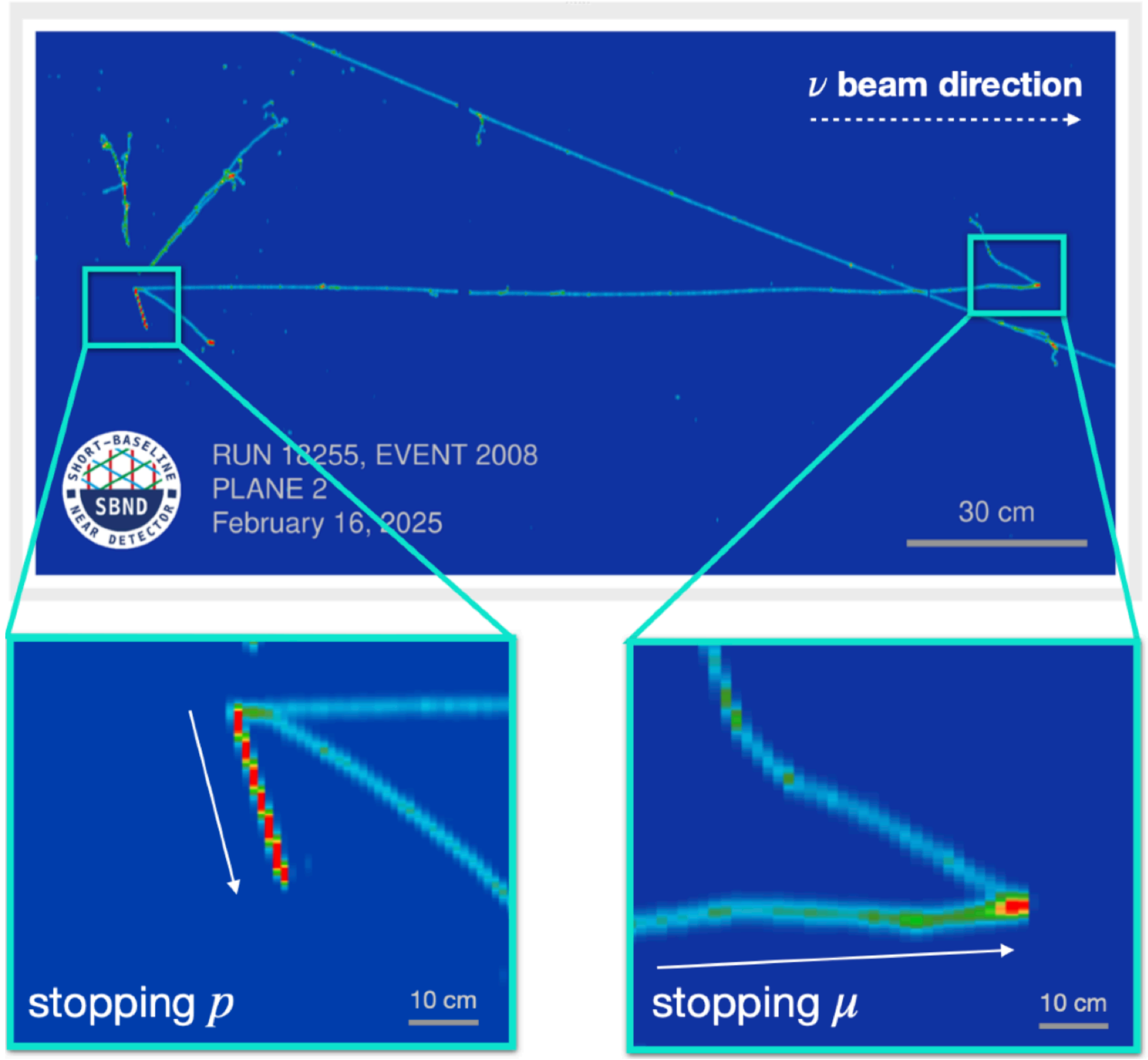
- **SBND** is a **L**iquid **Ar**gon **T**ime **P**rojection **C**hamber (LAr-TPC)
  - Charged particles deposit energy → producing ionization electrons and light
  - Ionization electrons drift towards wire readout planes
  - Scintillation light is recorded by PMTs (precision timing)
  - Millimeter-level 3D reconstruction





Why Use a LAr-TPC?

- **LAr-TPCs provide calorimetry and 3D tracking with fine-grained information**
  - Capable of identifying different species of particles
  - Particle Flow: parent vs daughter particles
  - Track vs Shower, Interaction Vertex, etc



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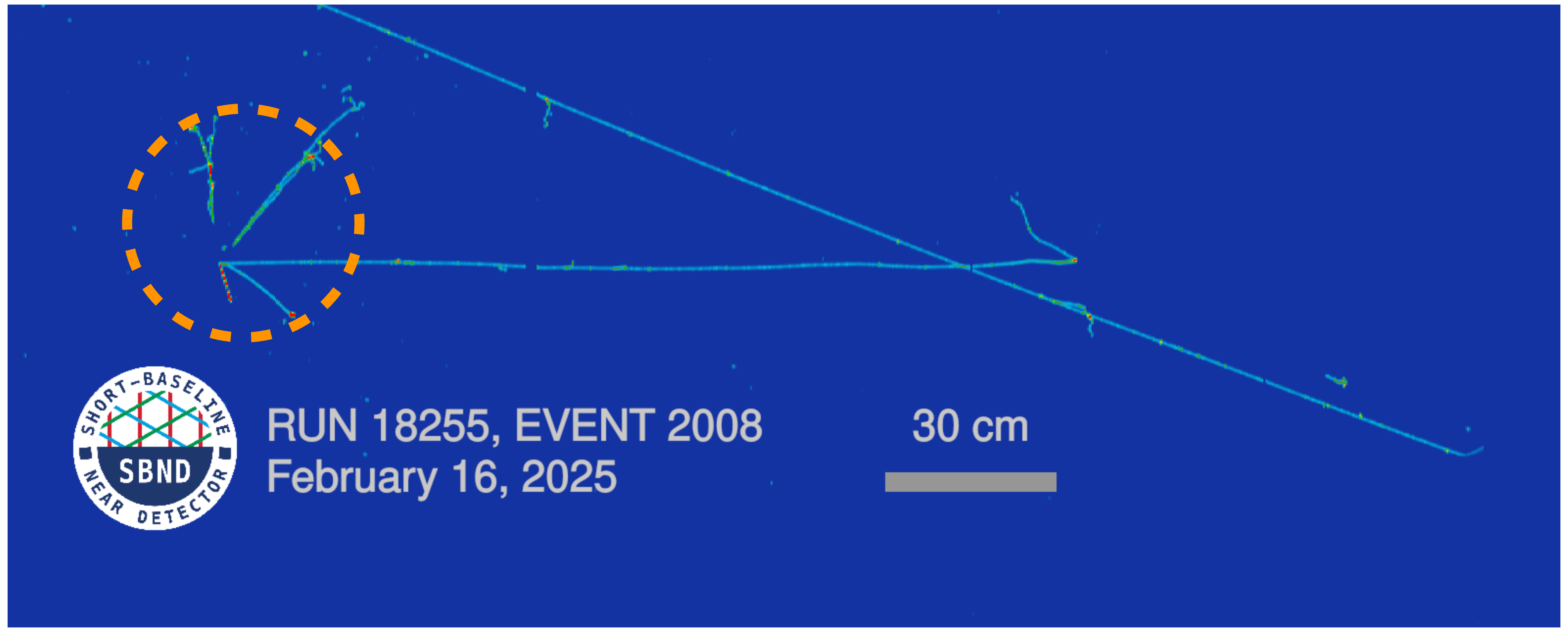
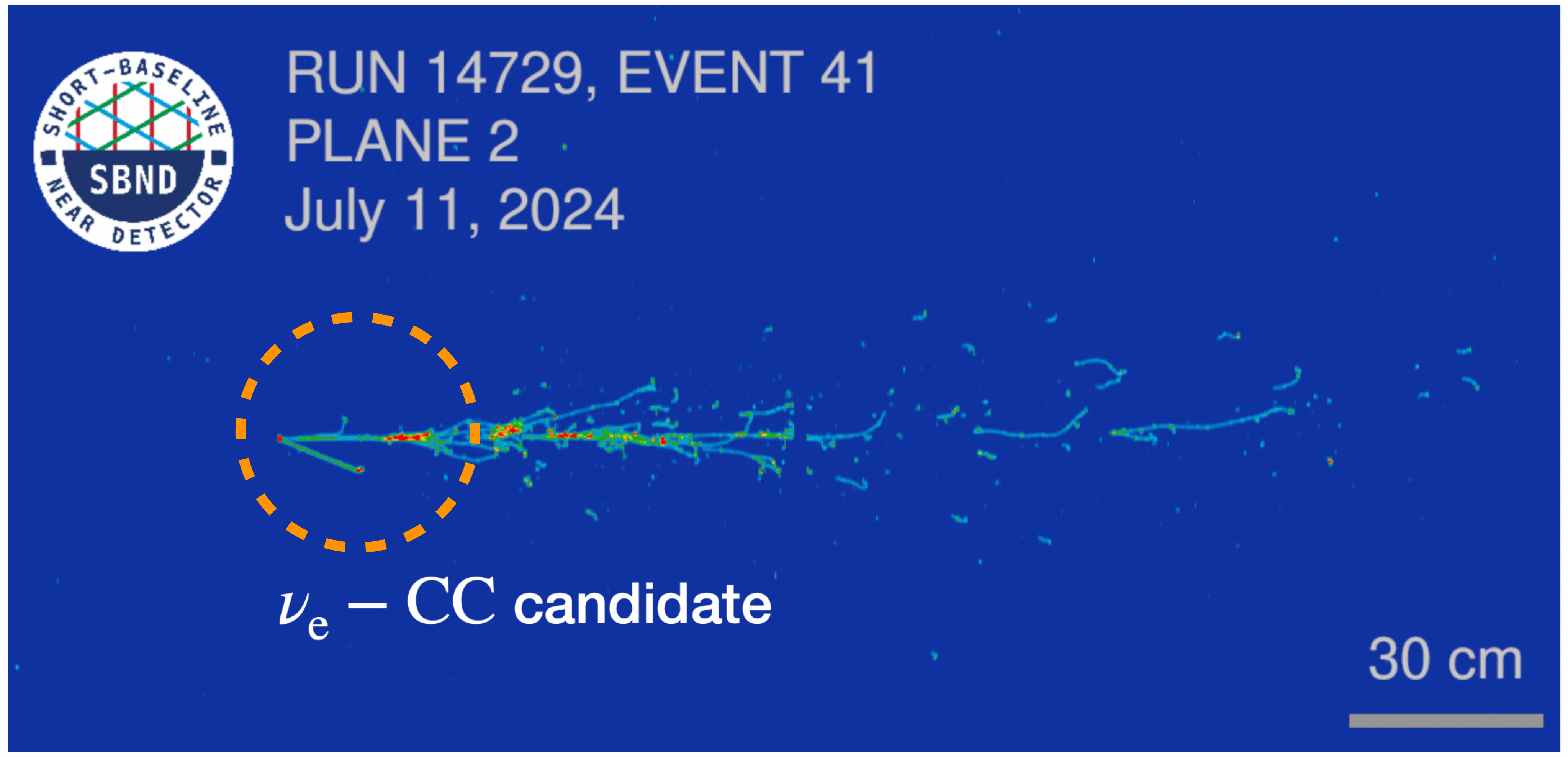
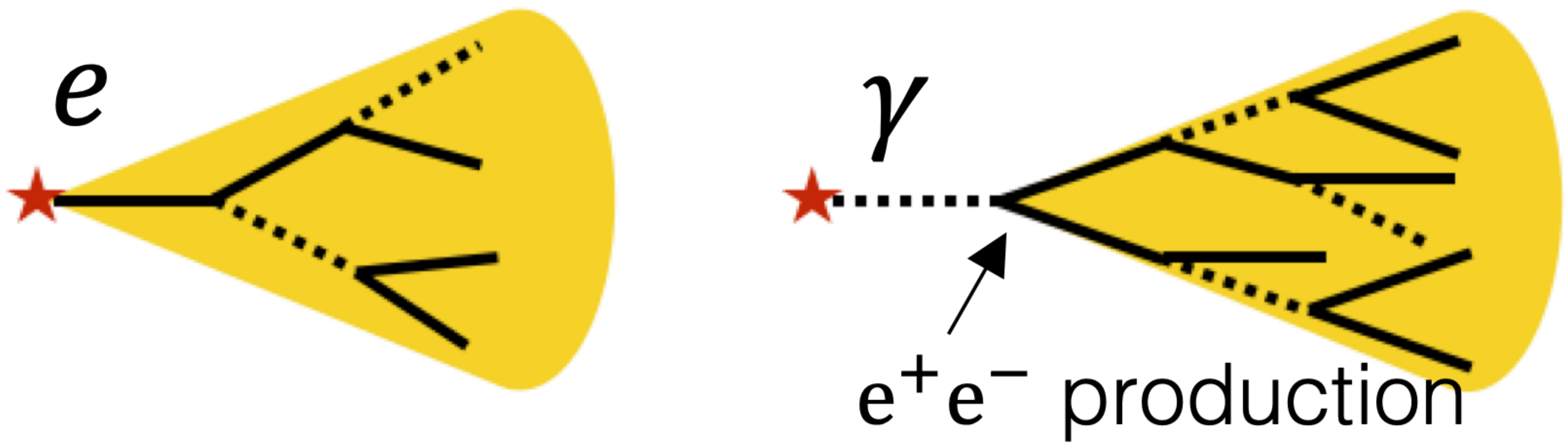
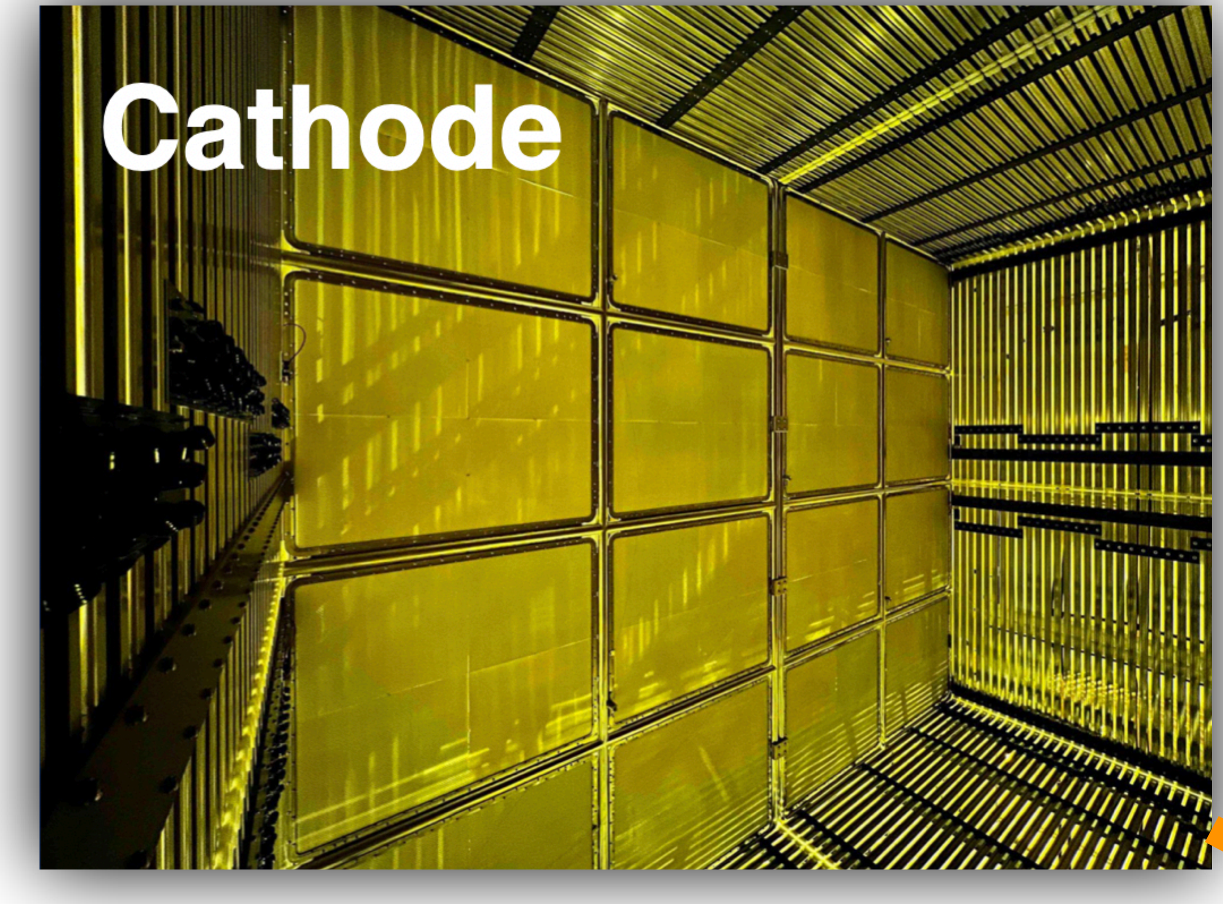
  - Track vs Shower, Interaction Vertex, etc
  - **Electron vs Photon Discrimination**
    - **Critical for oscillation program**



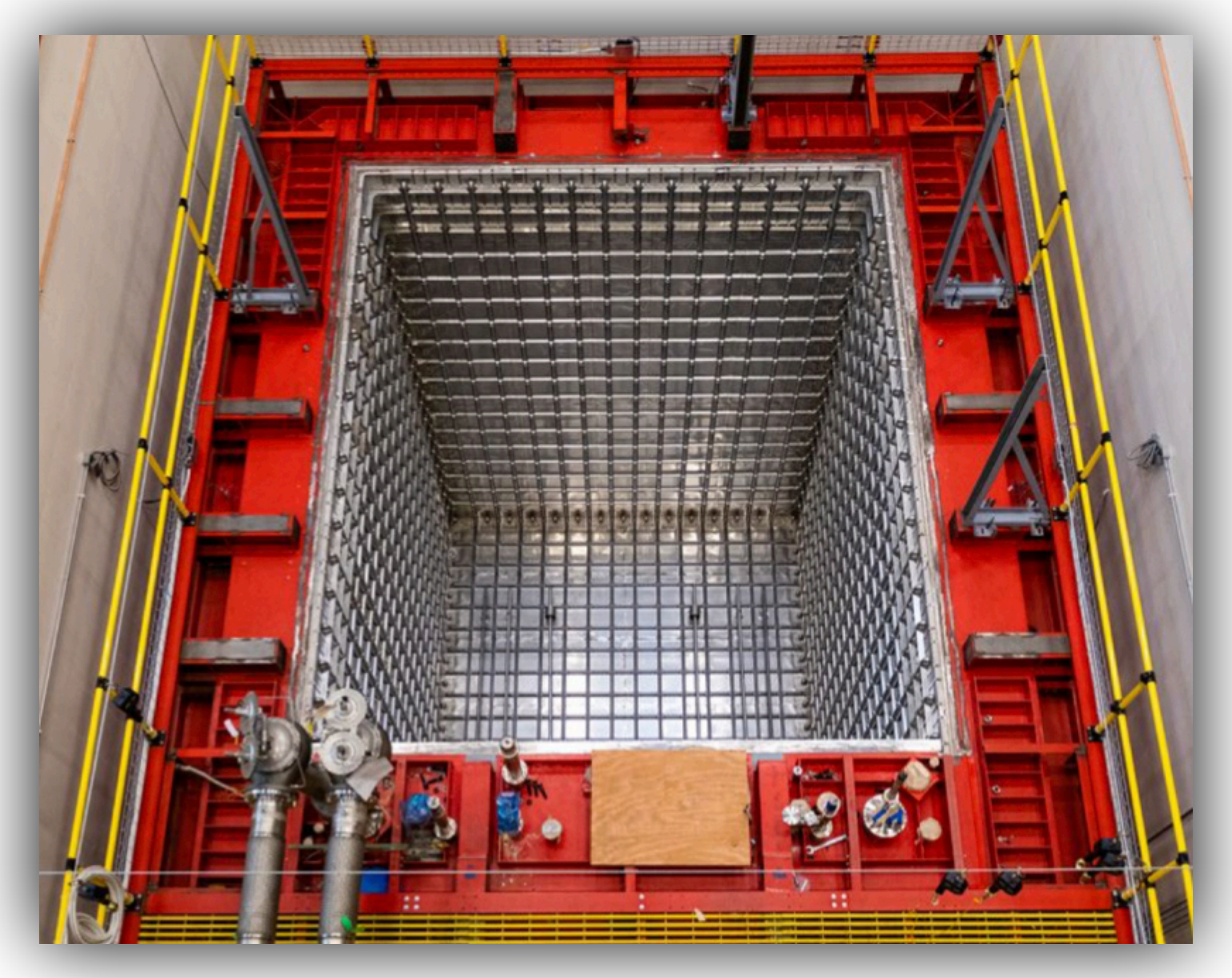




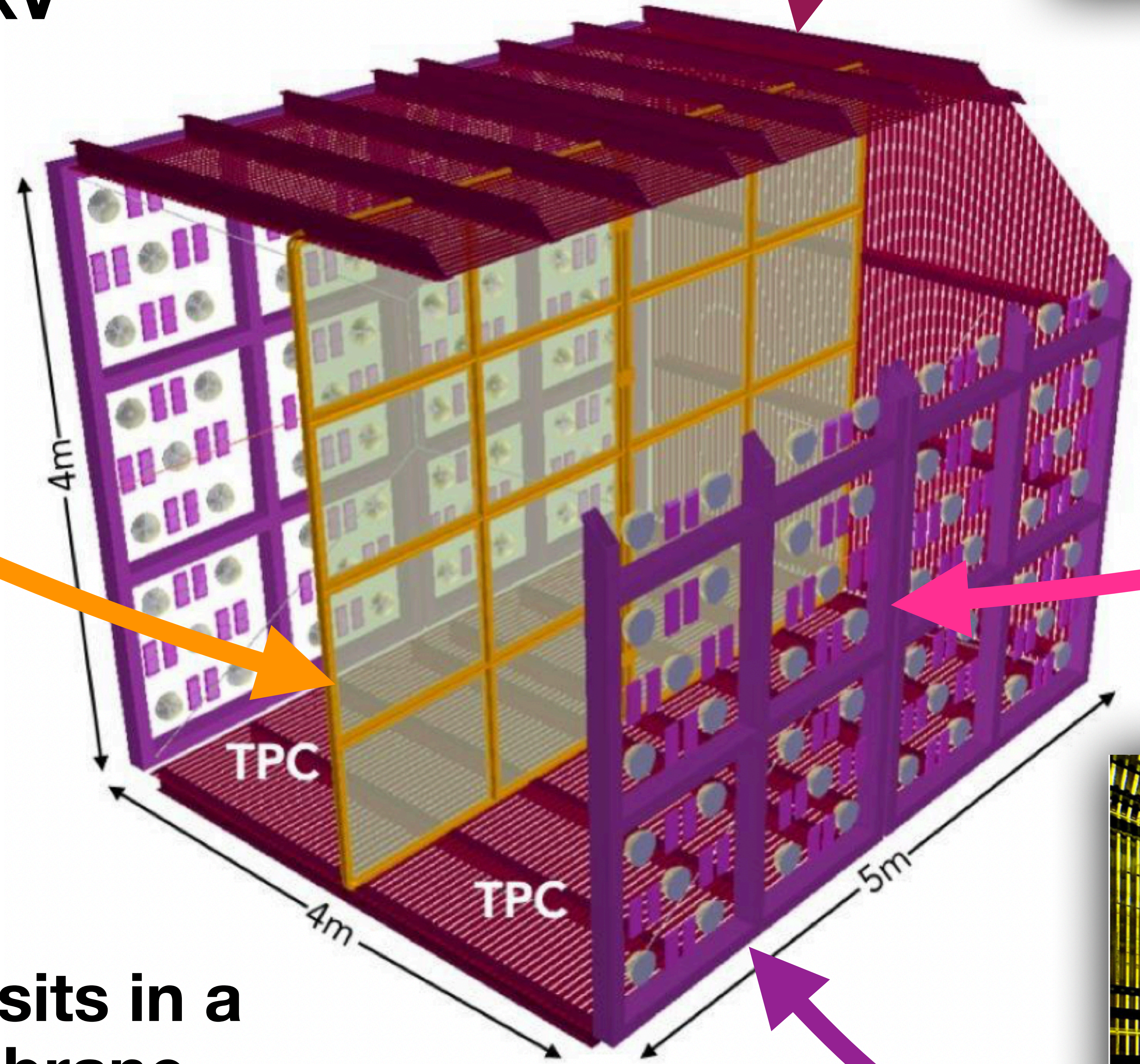
The SBND LAr-TPC

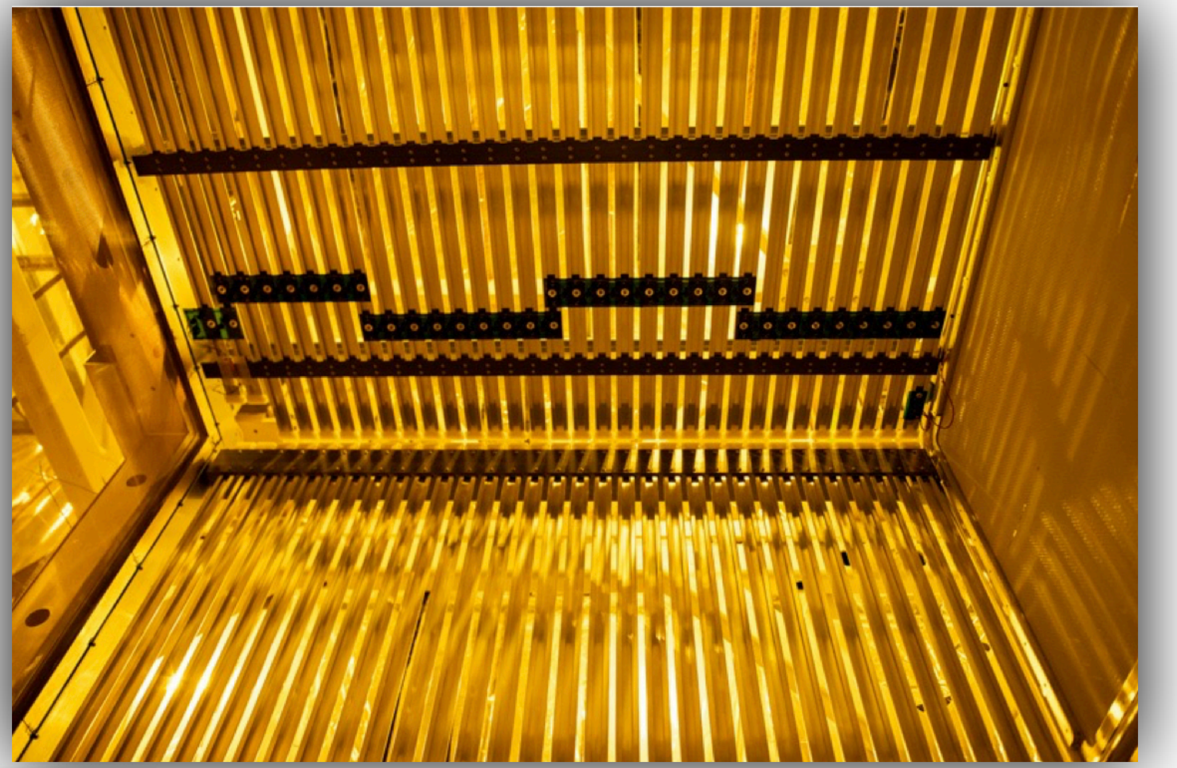


Biased at -100 kV

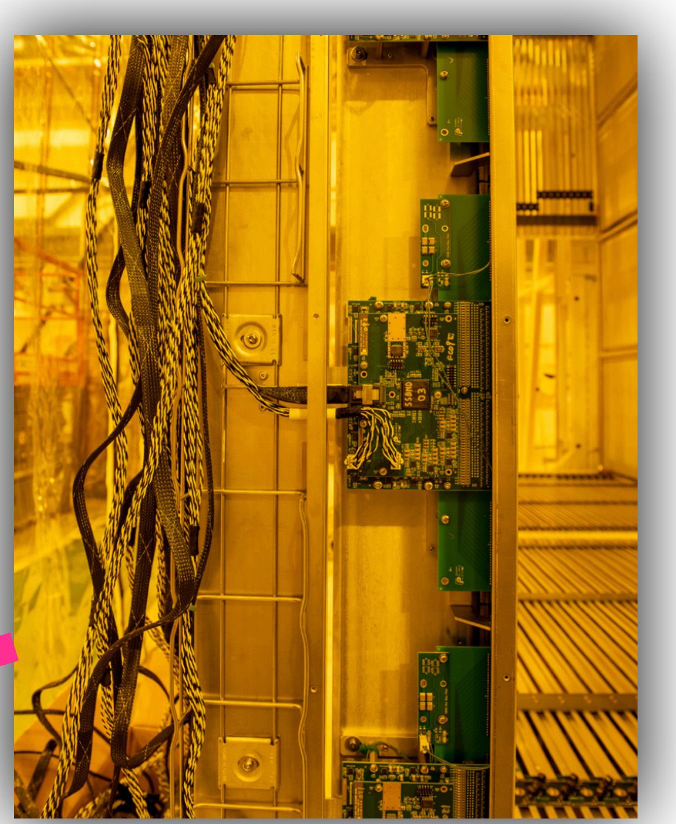


TPC sits in a membrane cryostat — same kind used in DUNE

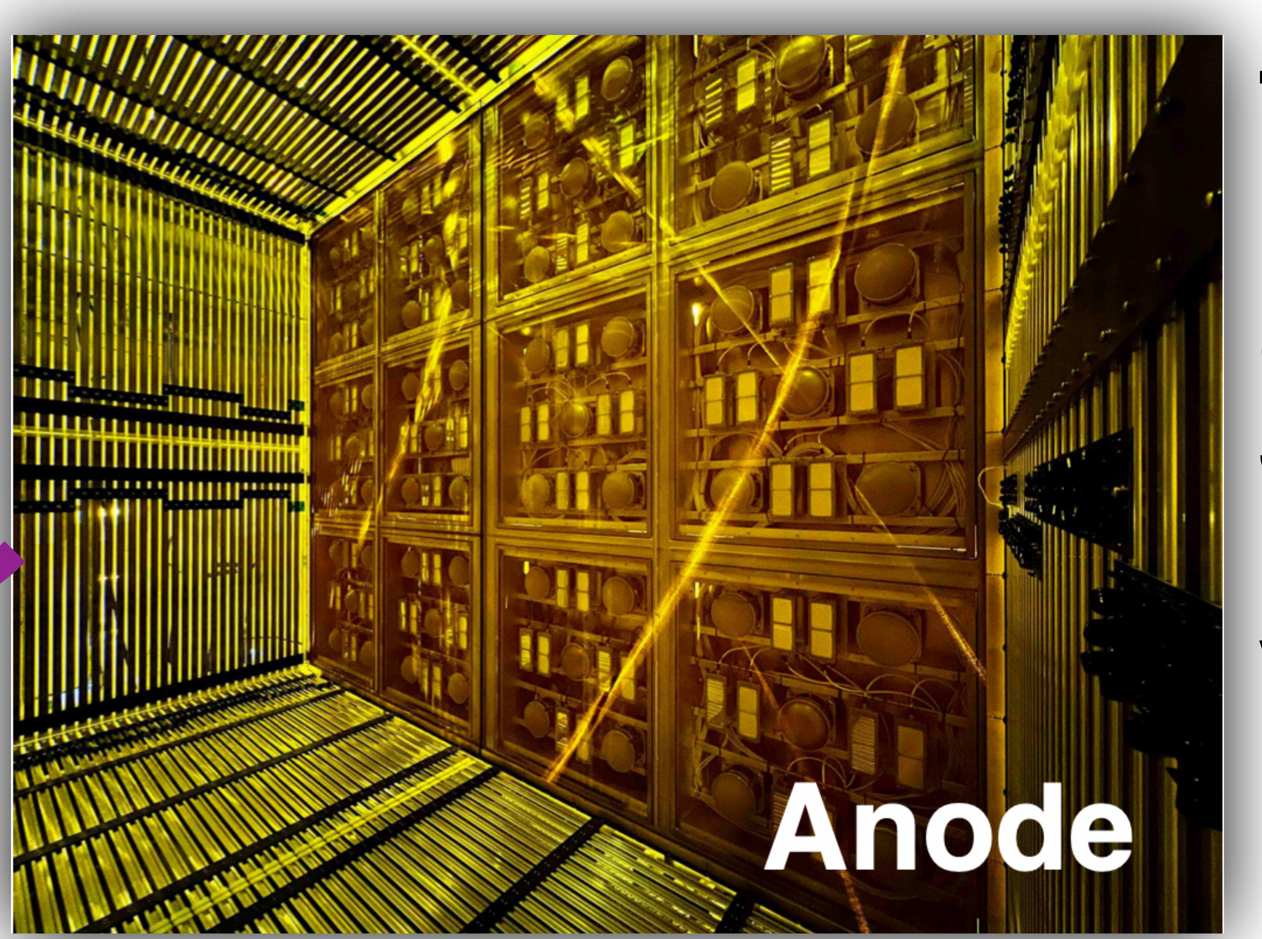




Field Cage for uniform 500 V/cm electric field



Cold electronics amplify and digitize at 89 K

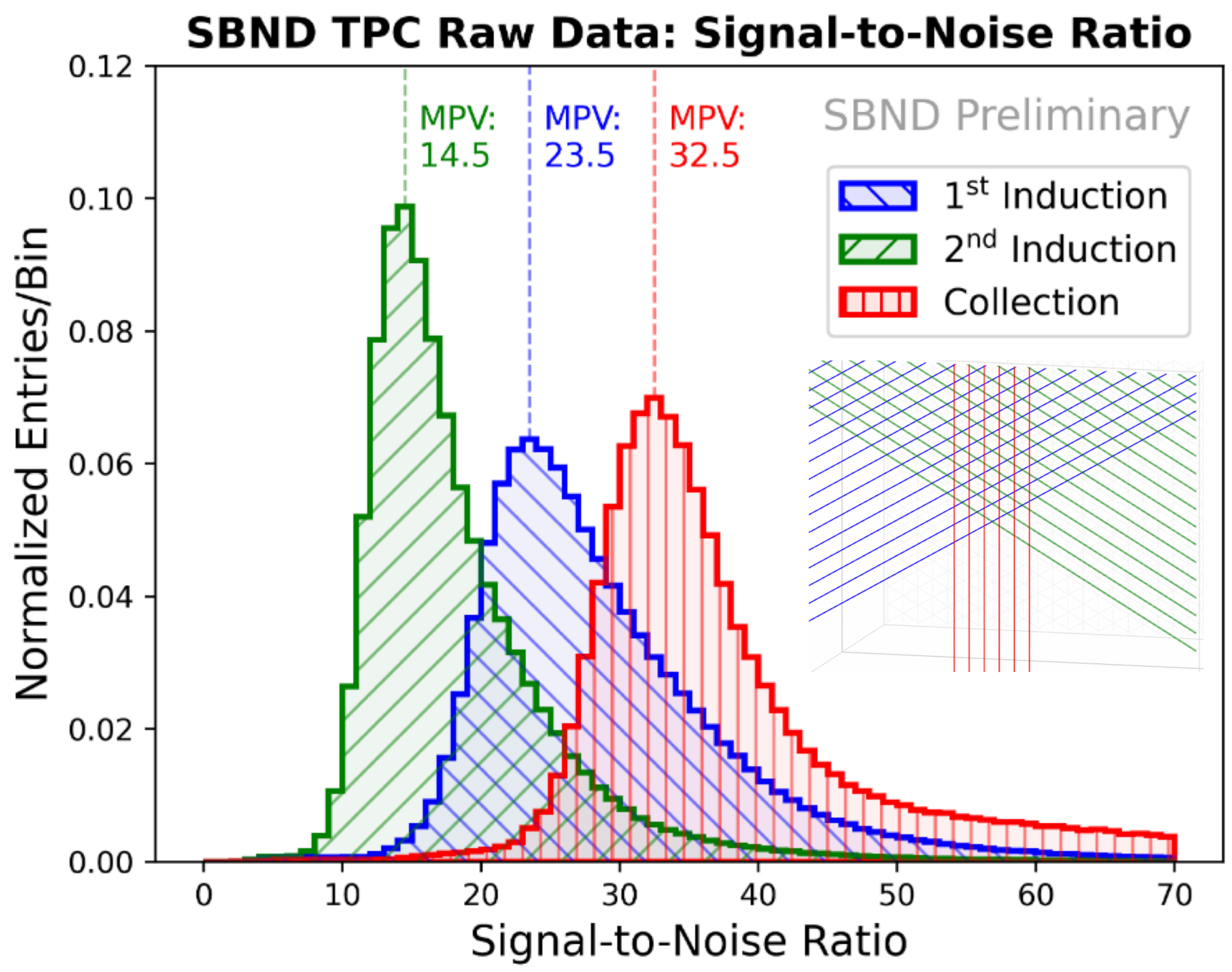


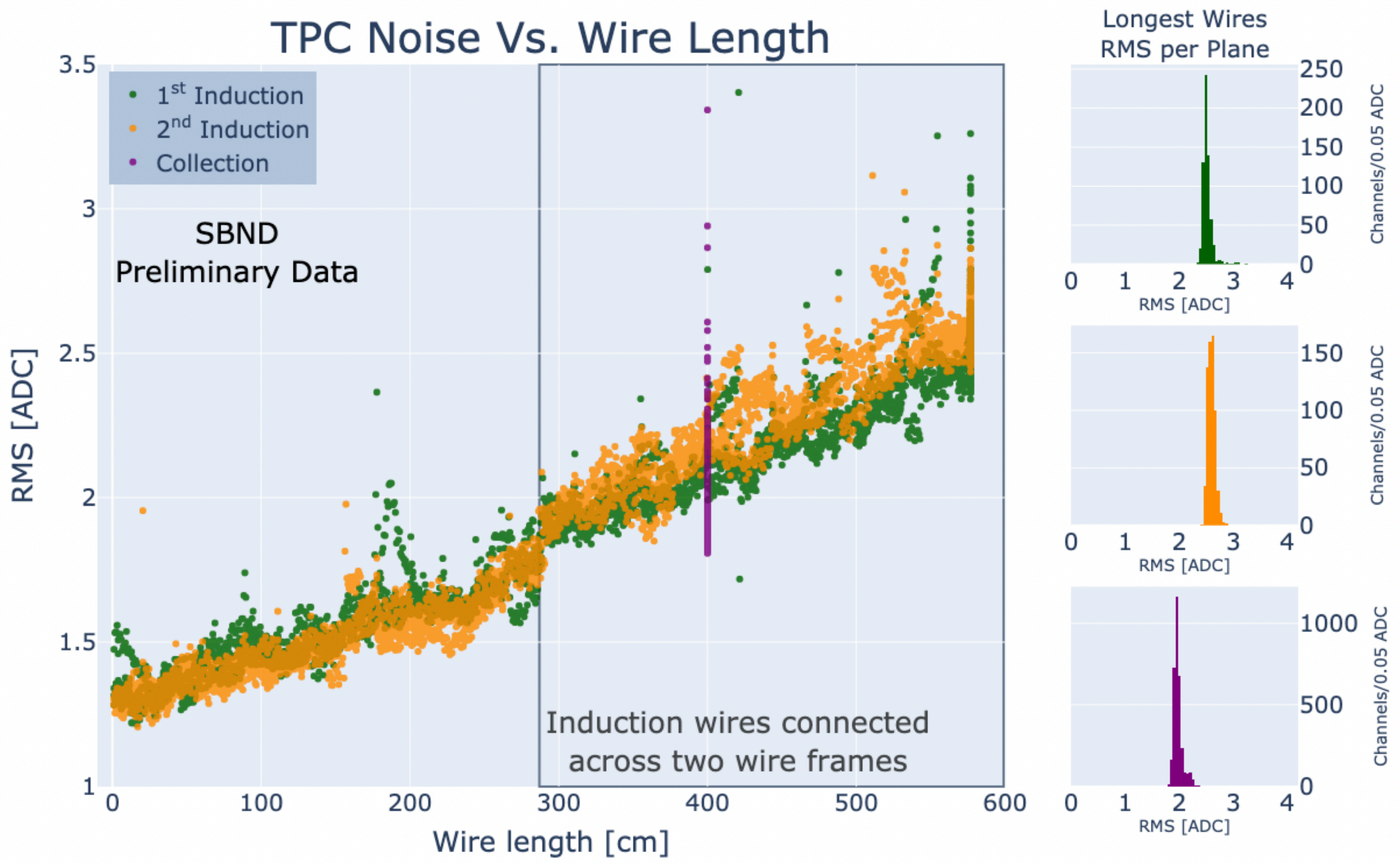
Held at ground

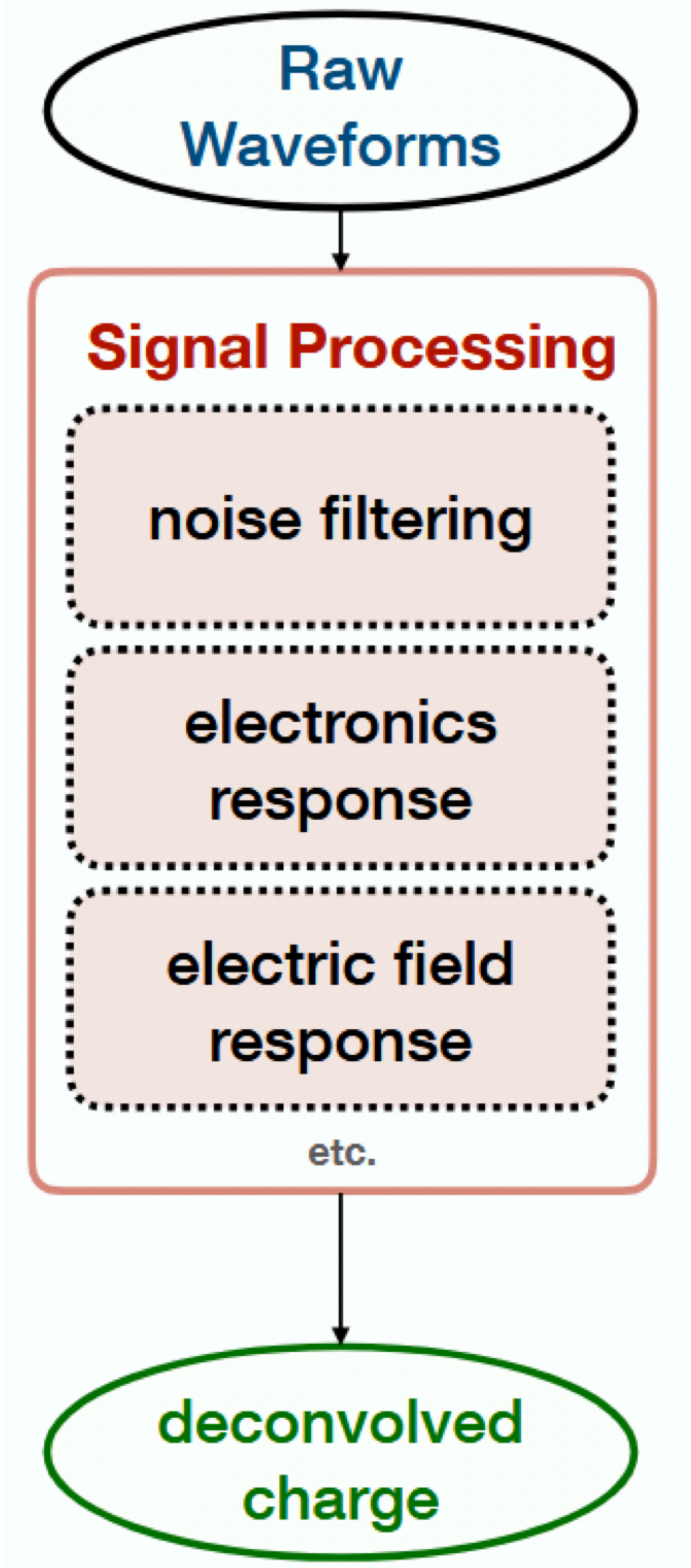
Three wire planes
$\theta = 0^{\circ}, \pm 60^{\circ}$
3mm spacing
11,264 total wires

JINST 15, P06033 (2020)

TPC Noise Performance

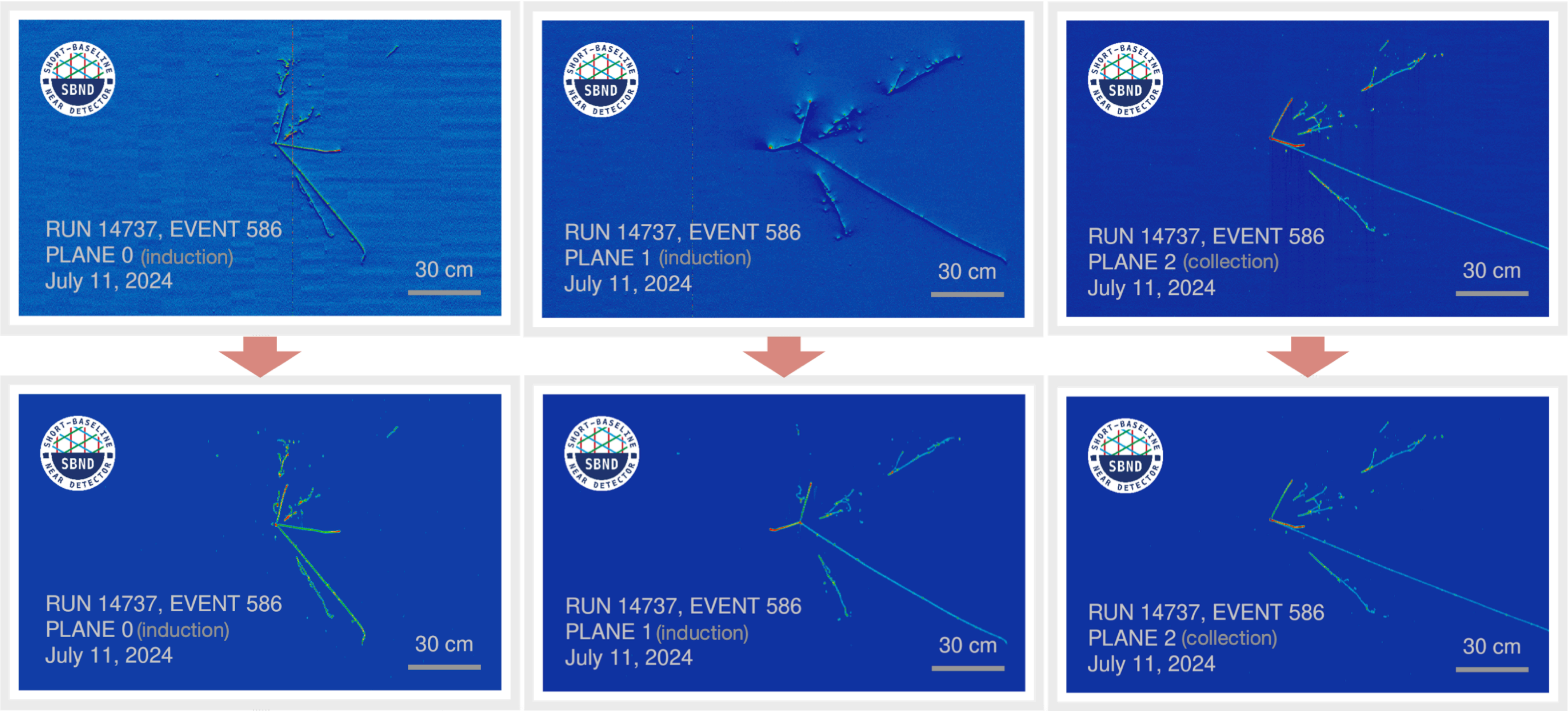






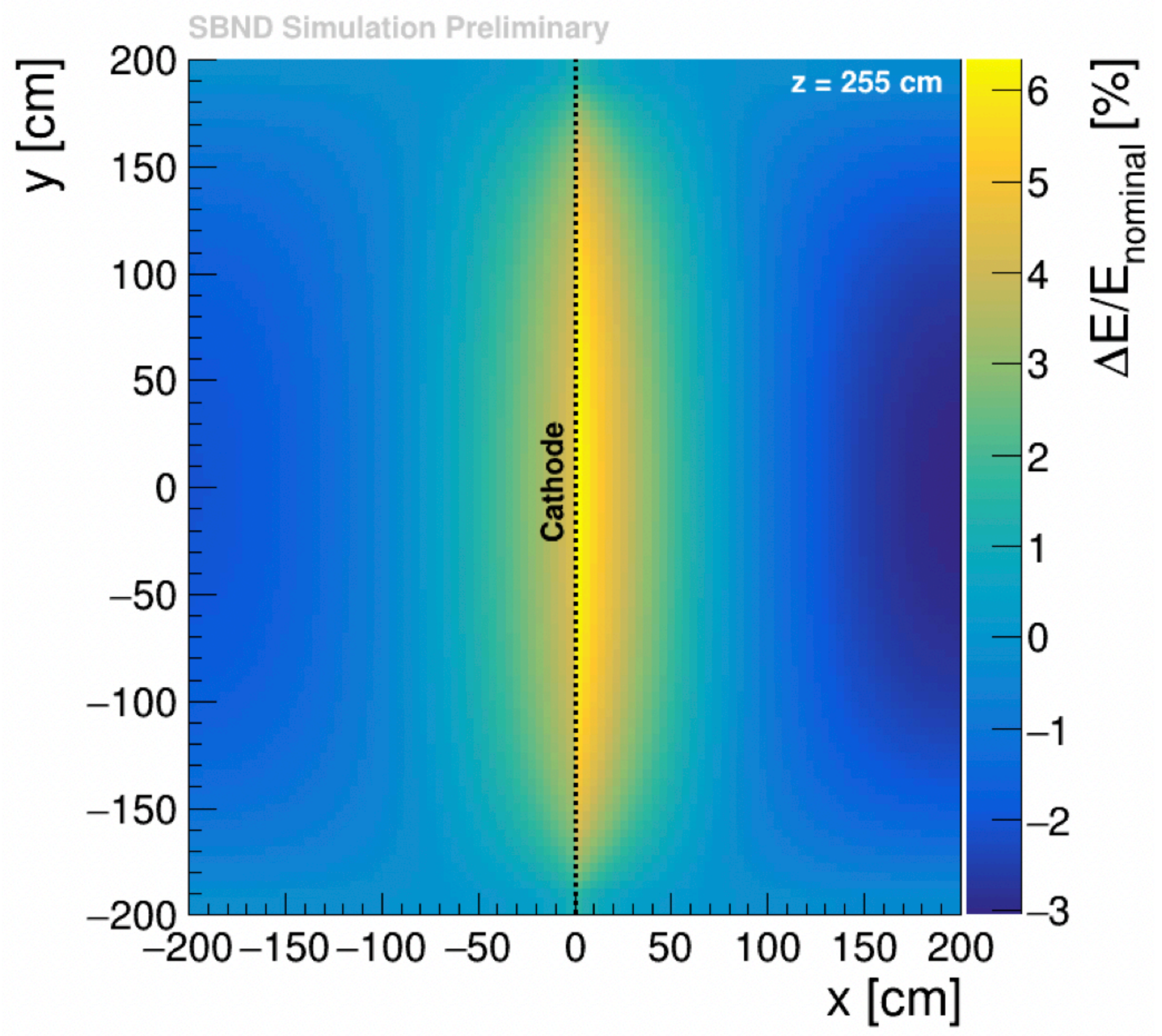
- For the longest wires, rms is less than 3 ADCs in general
- Excellent signal to noise ratio in raw data: 32.5 for the collection plane

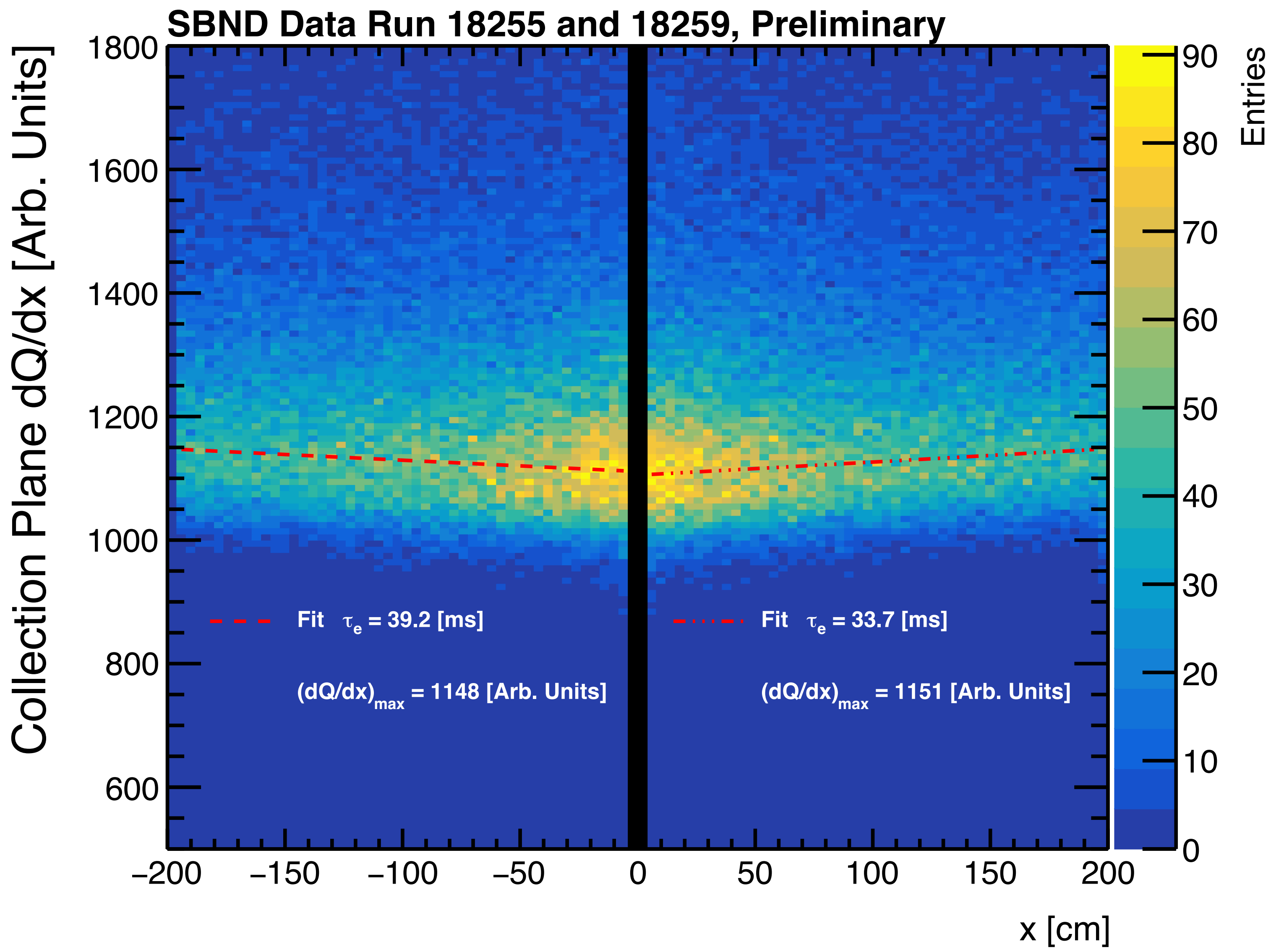
TPC Signal Processing

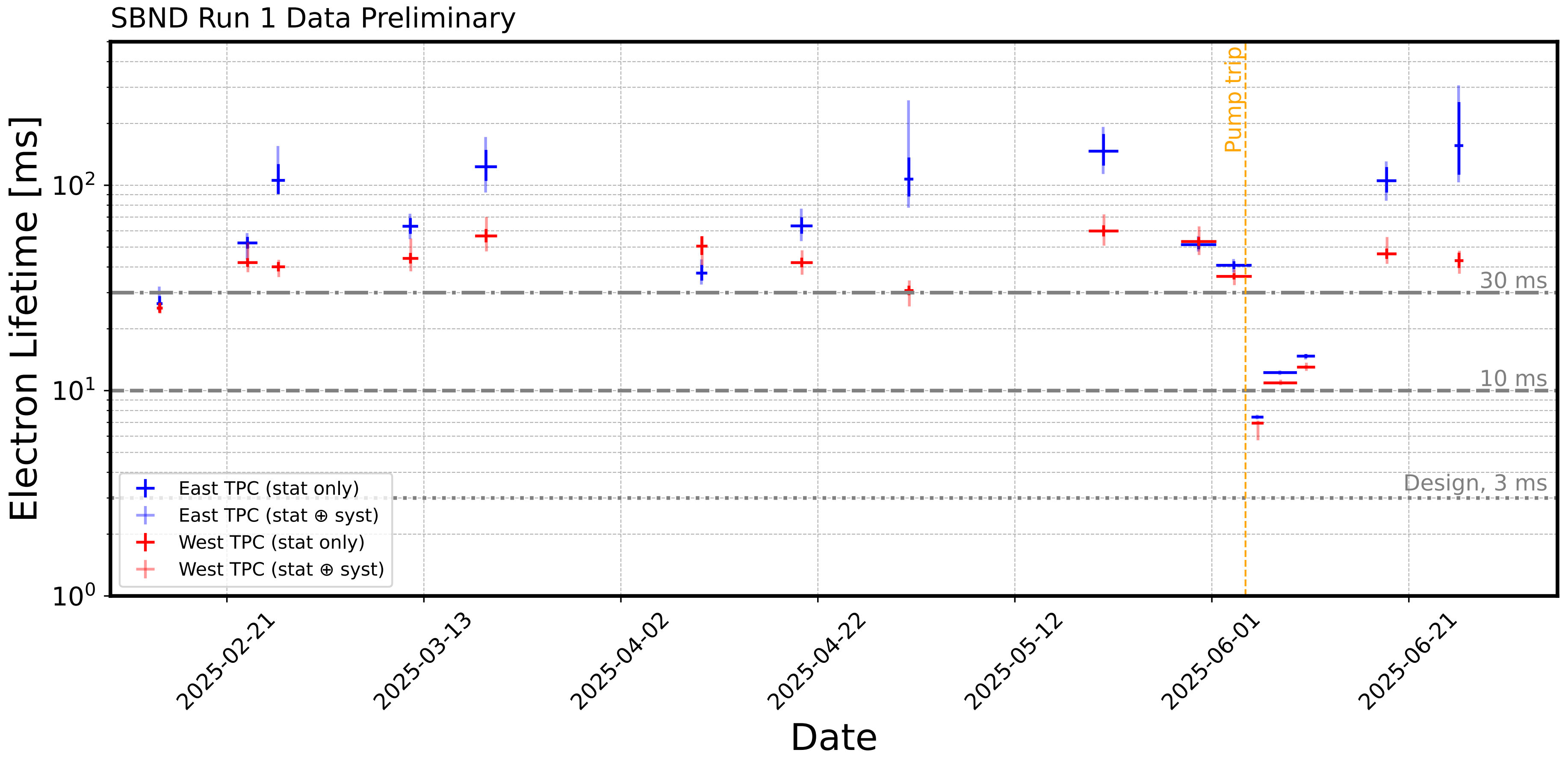


TPC Calibration

Space charge effect is well-calibrated: average effect is < 1cm across the detector

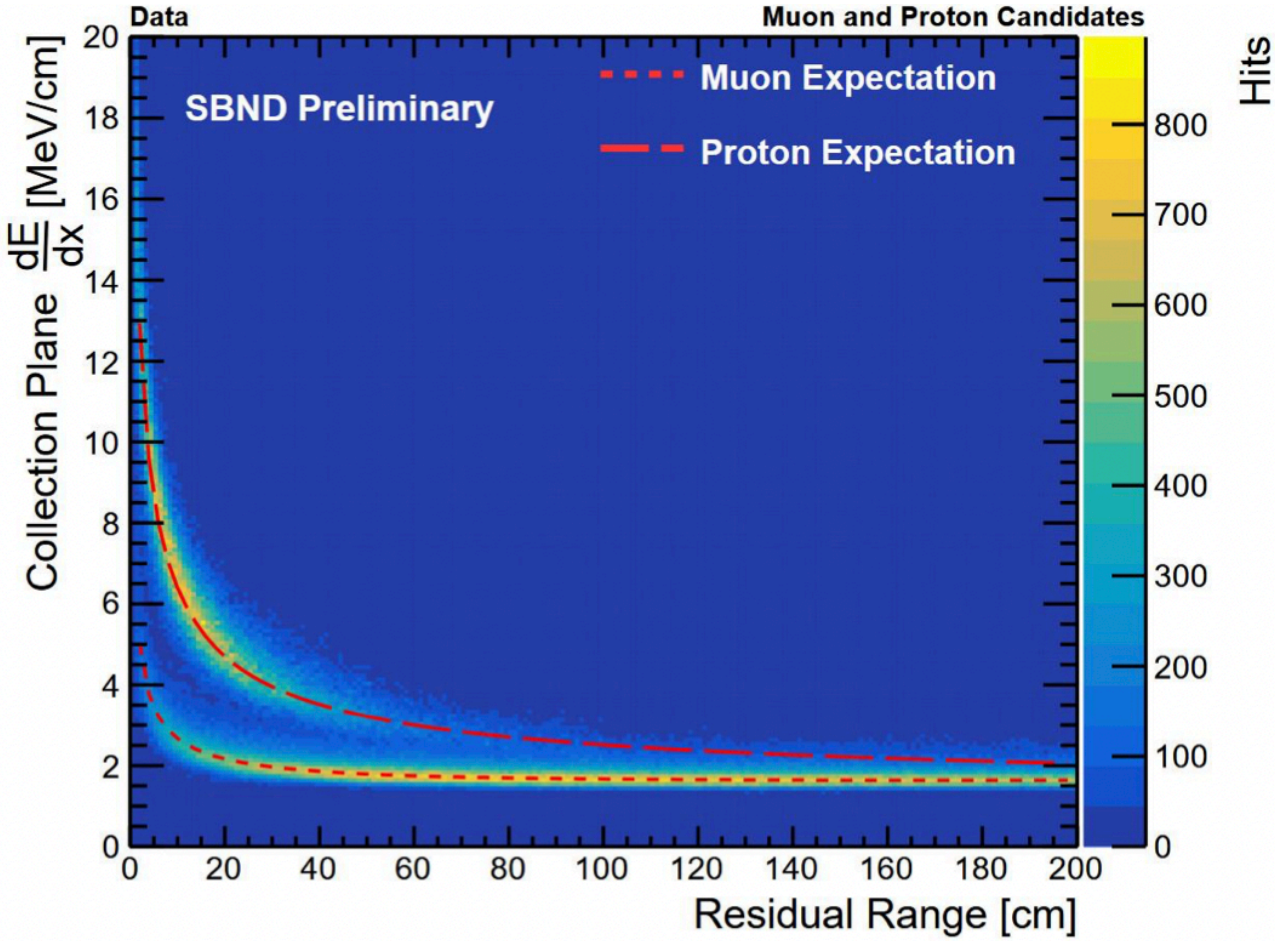




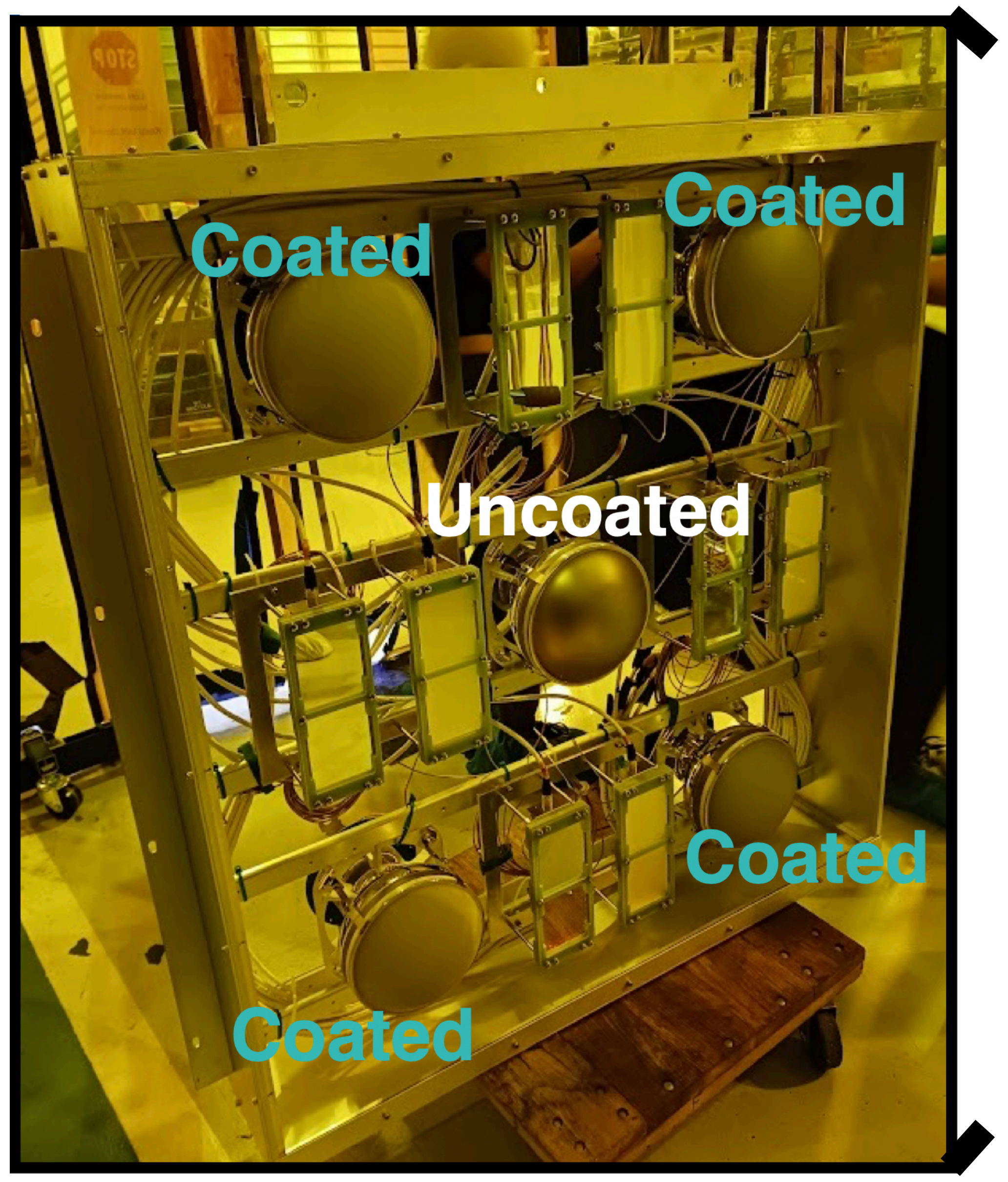


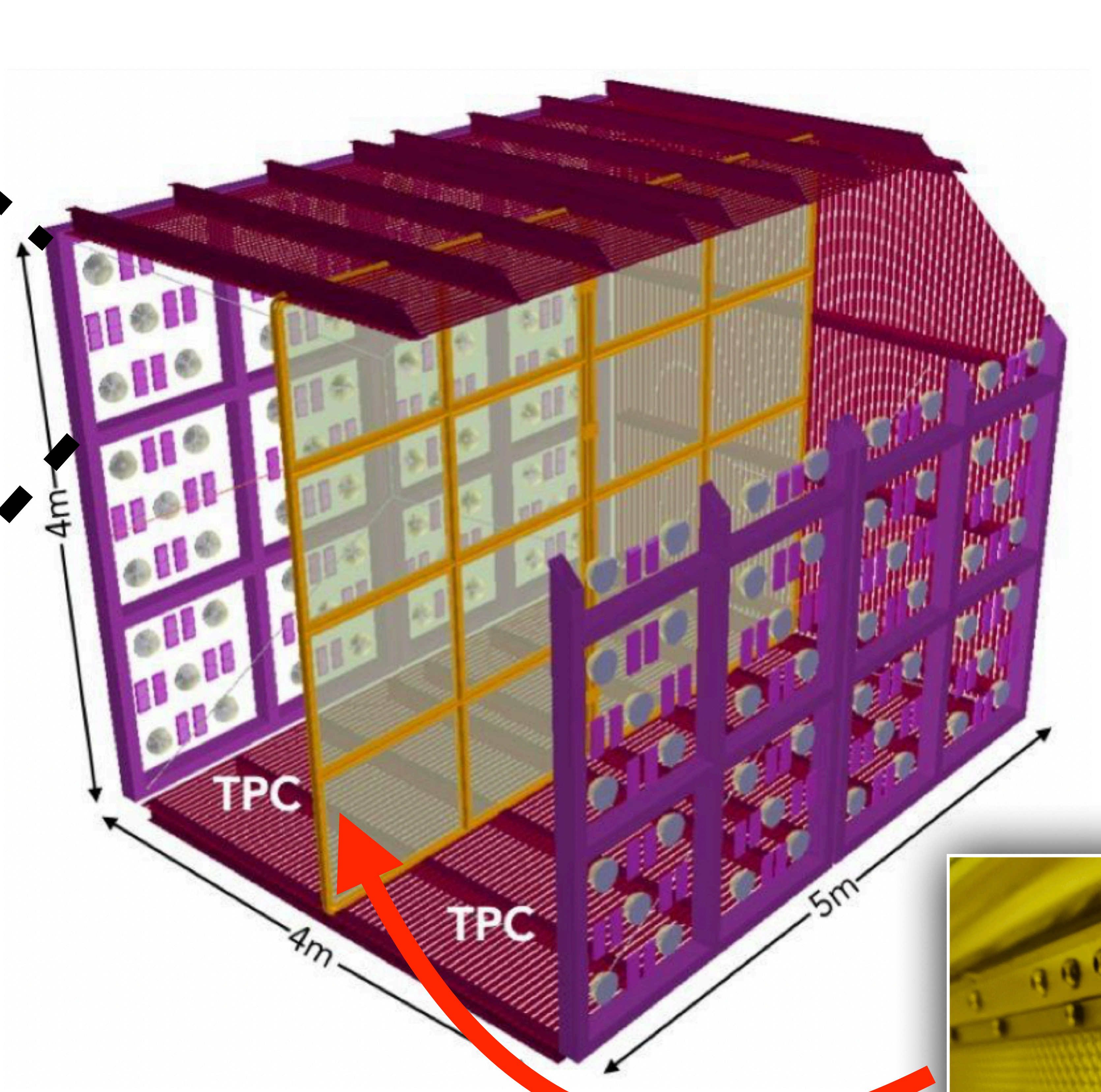
Electron lifetime is longer than 30 ms and stable!

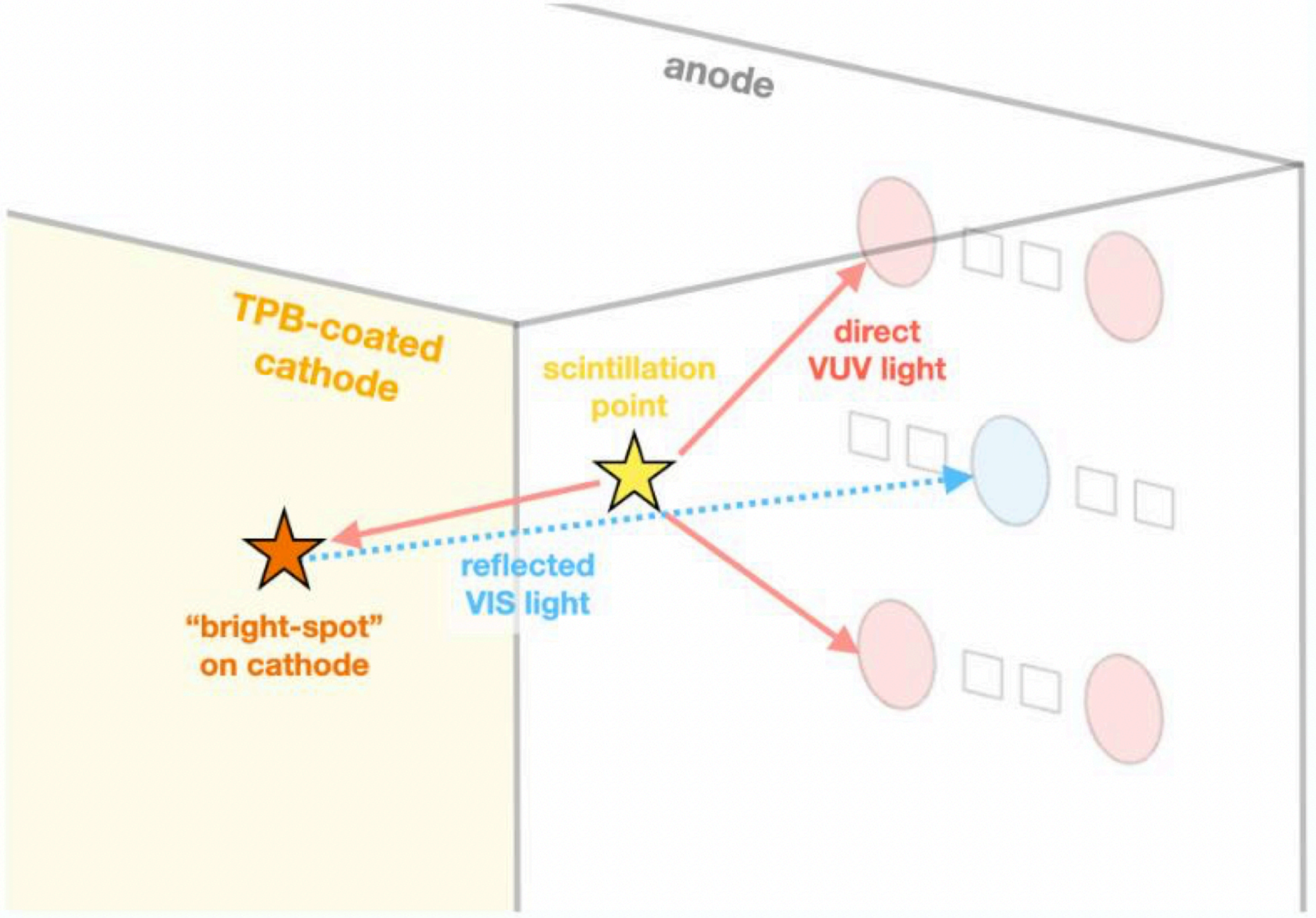
Muon and proton dE/dx after calibration agree well with expected Landau-Vavilov theory



The SBND Photon Detection System (PDS)





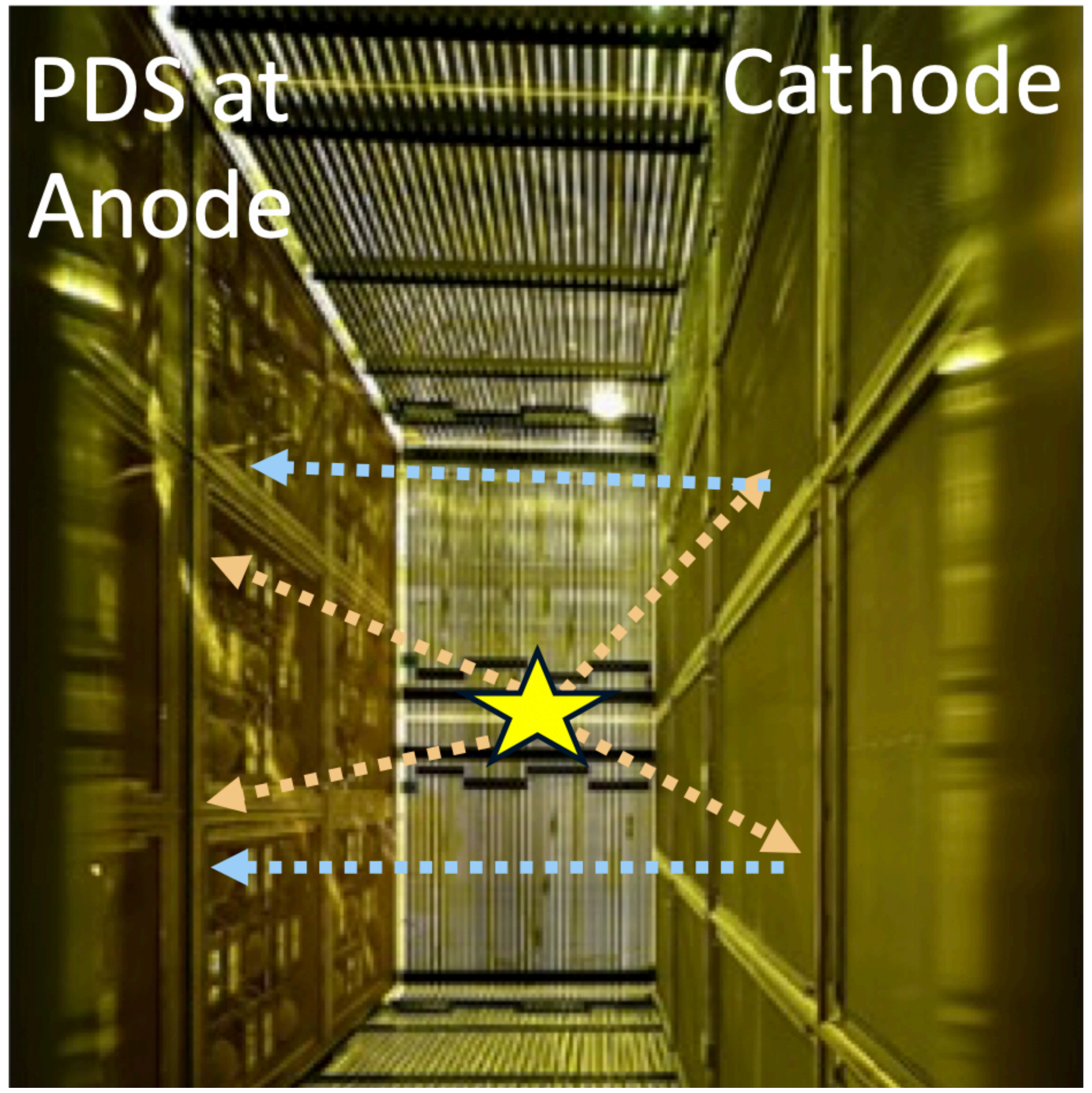


- Light Detection: 120 PMTs and 192 X-ARAPUCAs
  - Coated vs uncoated allows for independent spatial reconstruction
- Timing Resolution is ~O(1ns)

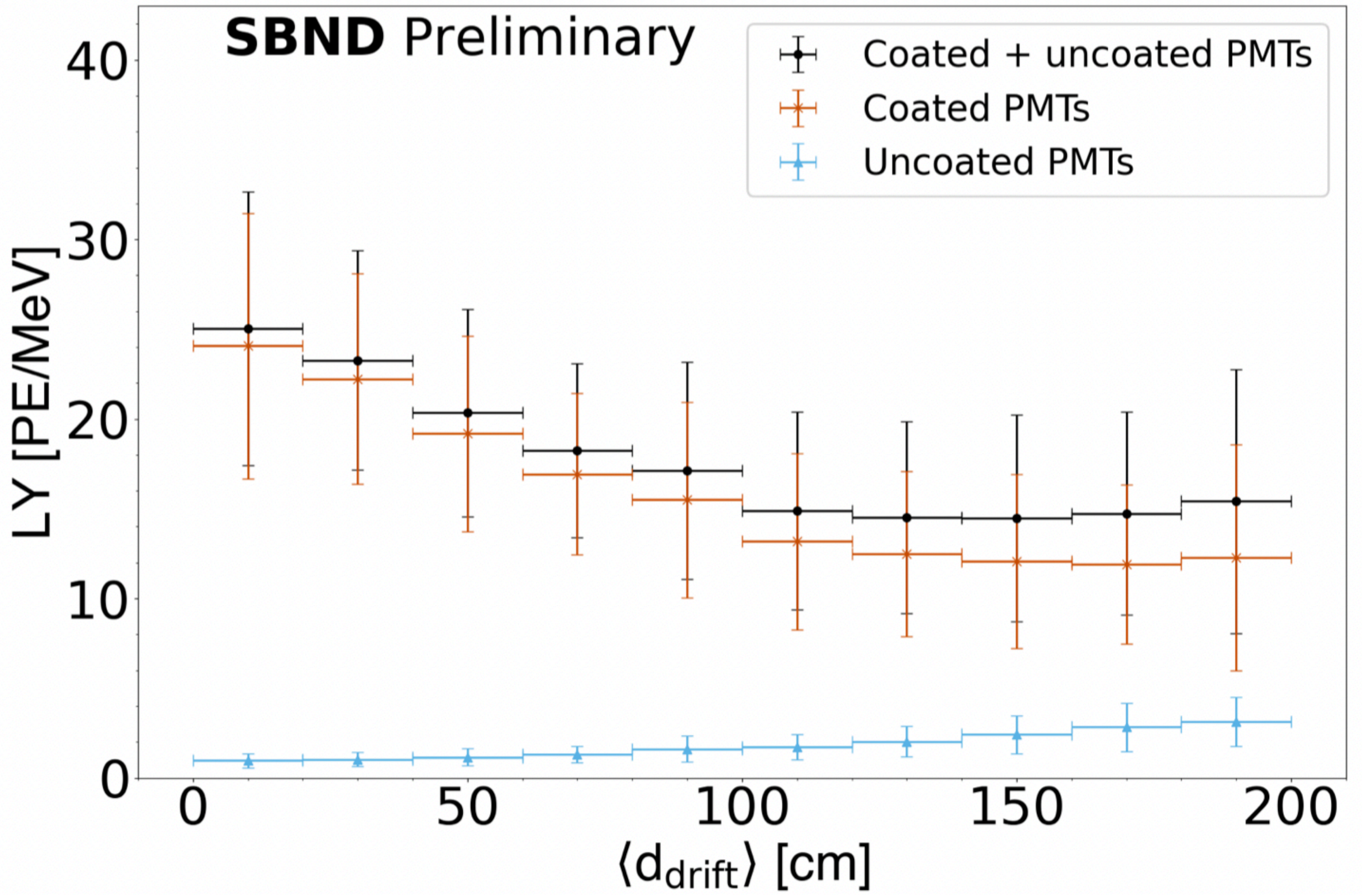
Wavelength shifting reflective foils at cathode

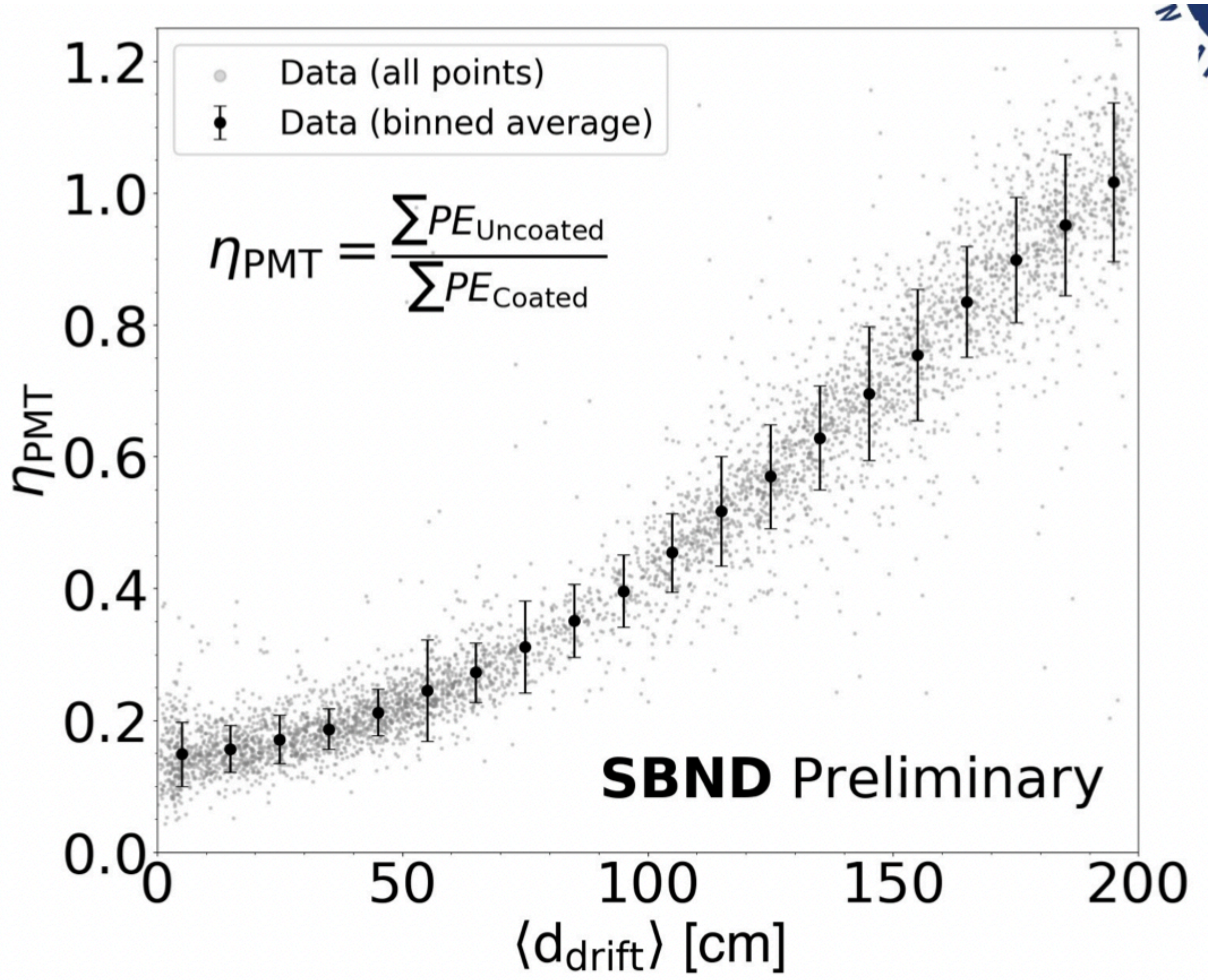
Increase uniformity of the light yield

PDS Performance



- Primary scintillation light is measured by the coated PMTs
- Uncoated PMTs measure the VUV scintillation light that reflects of the cathode
- Position reconstruction using the light: η_{PMT} is a proxy for drift distance

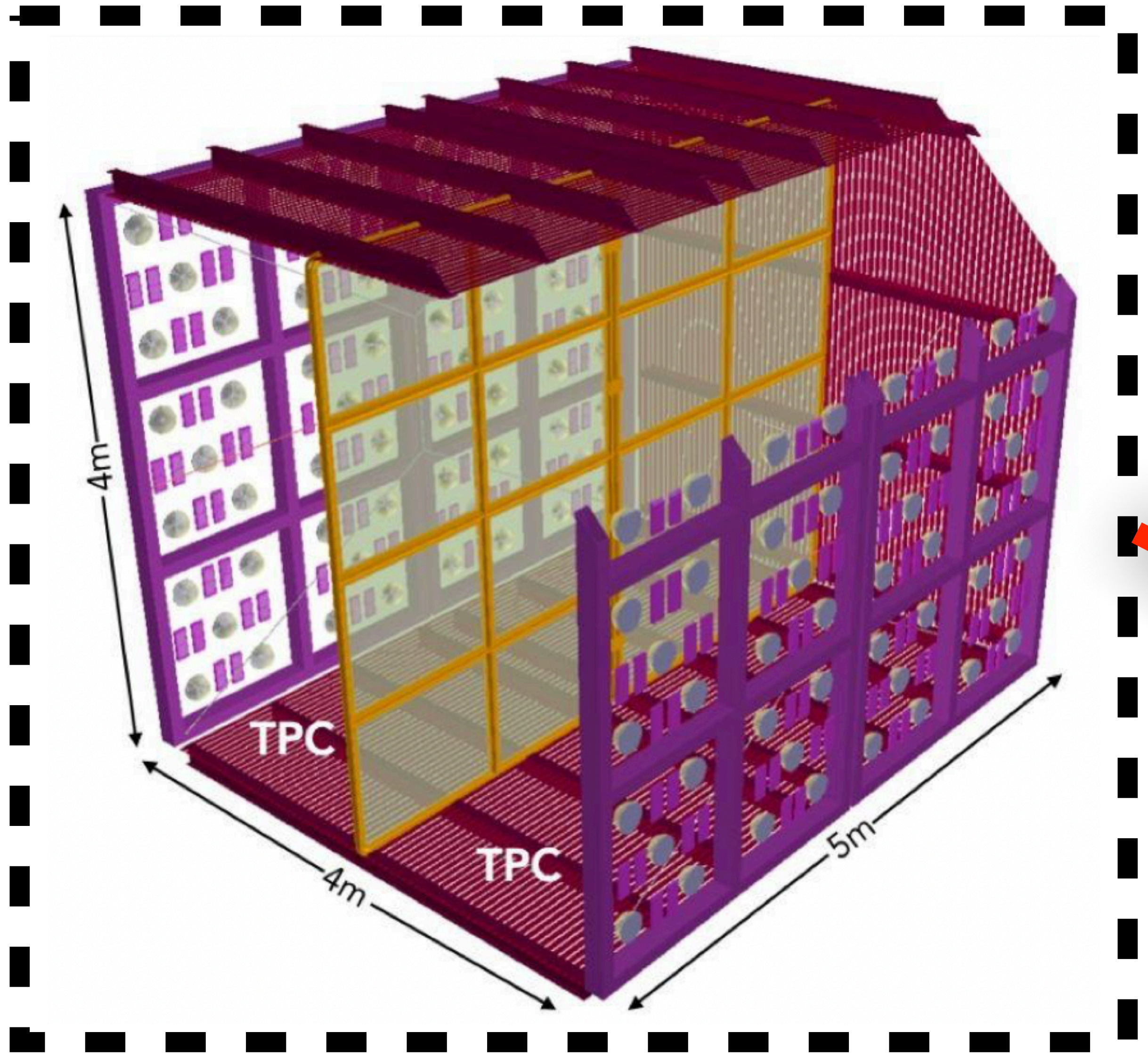


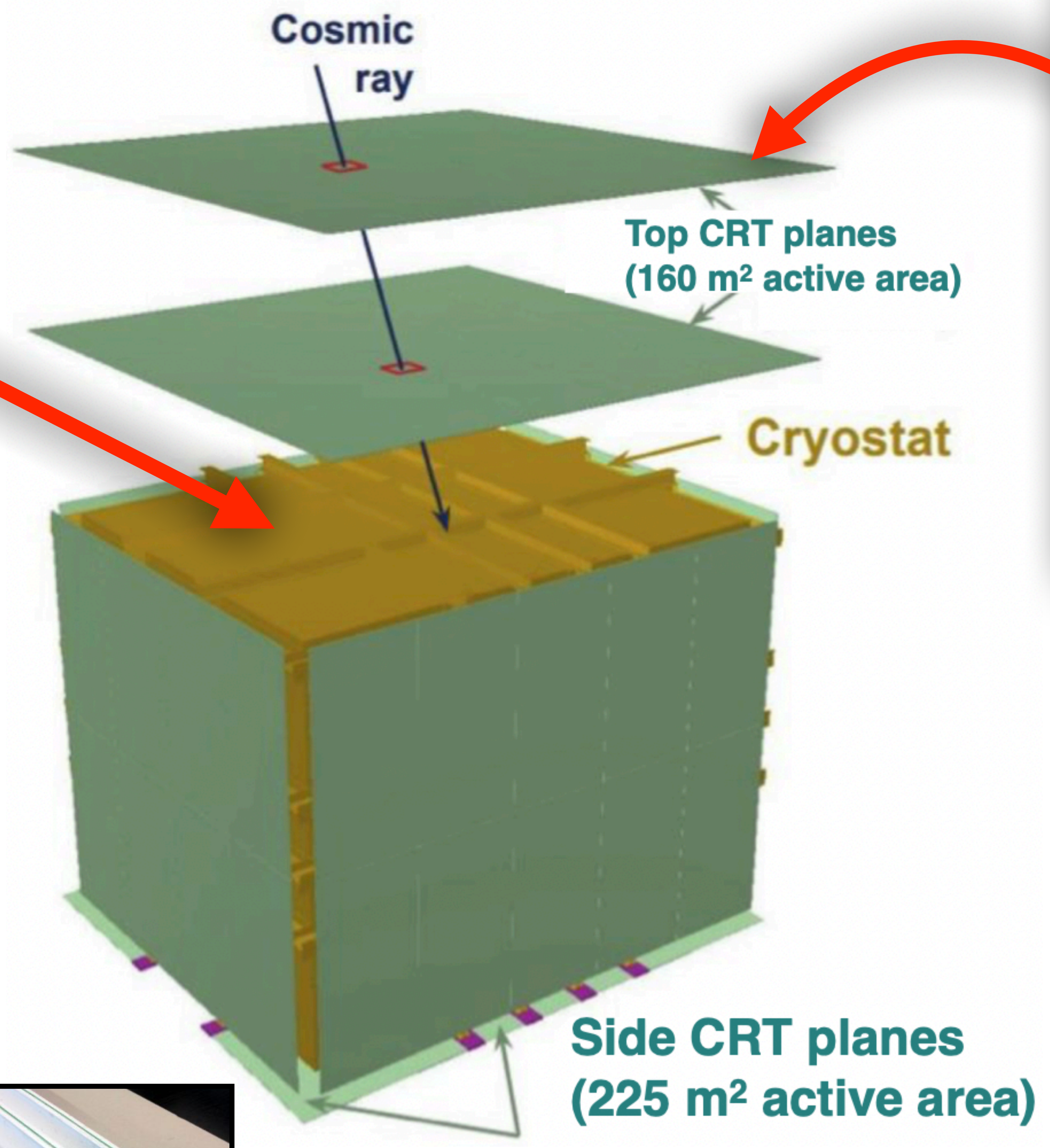


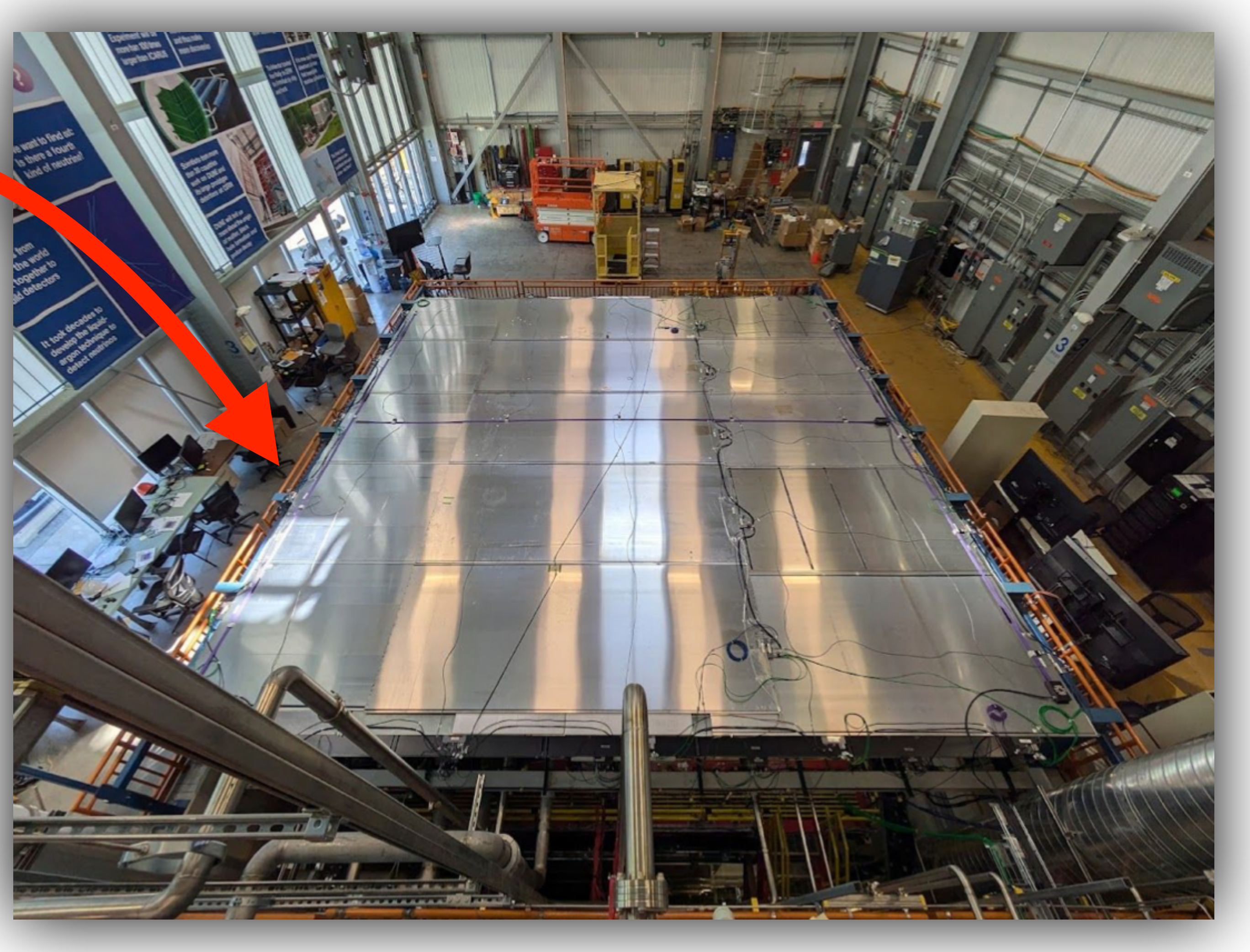
- The PDS has excellent timing resolution: ~O(1ns)
- Provides the basis for SBND's trigger system and can fully resolve the BNB spill structure (see next slides)

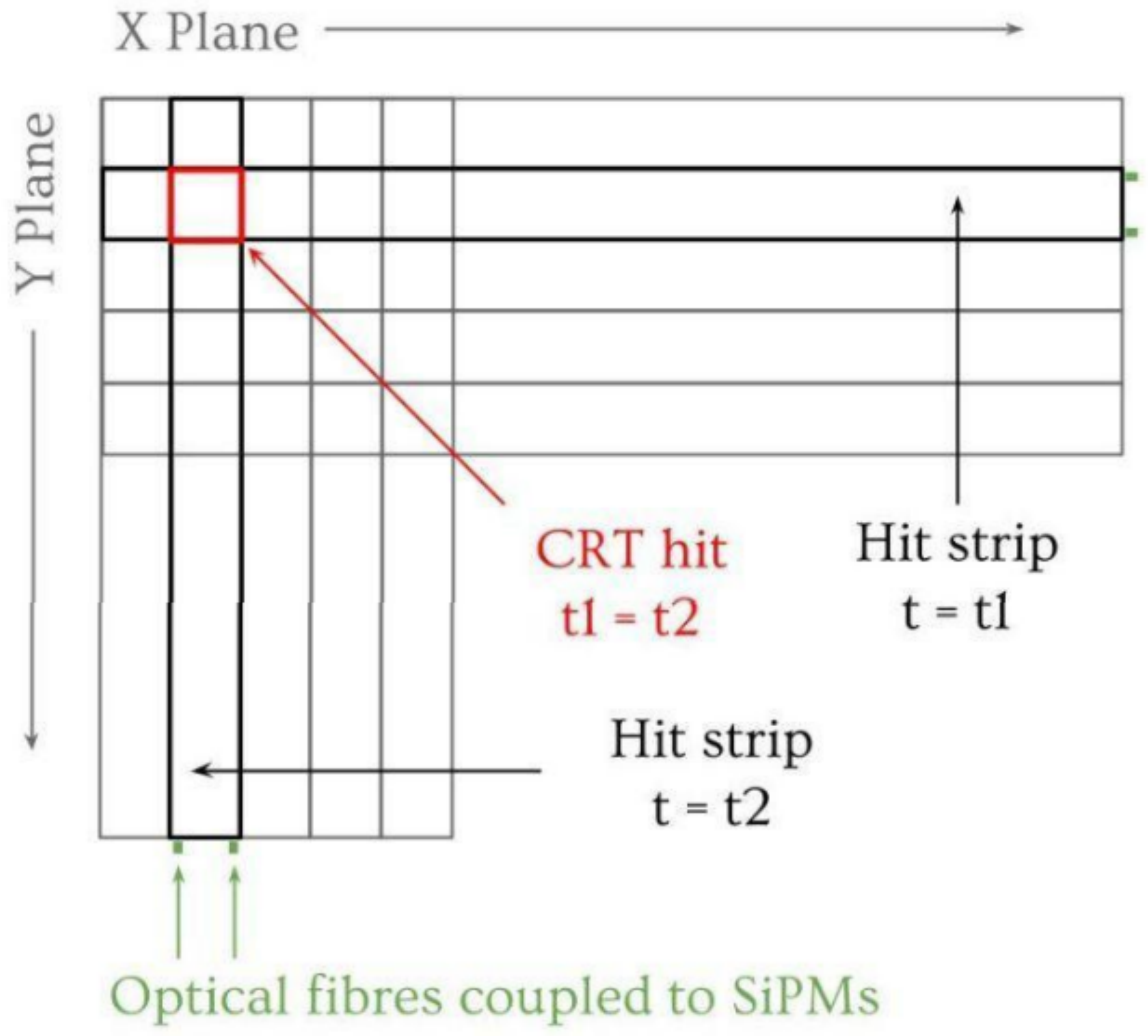
arxiv:2406.07514

The SBND Cosmic Ray Tagger (CRT)



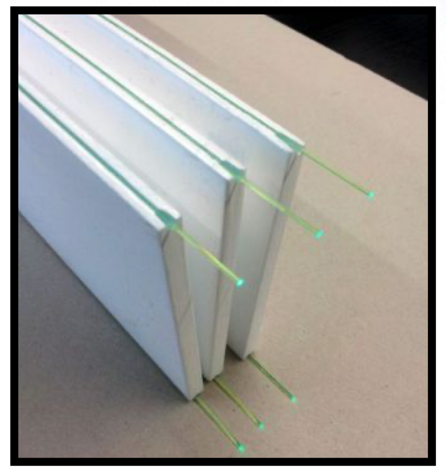






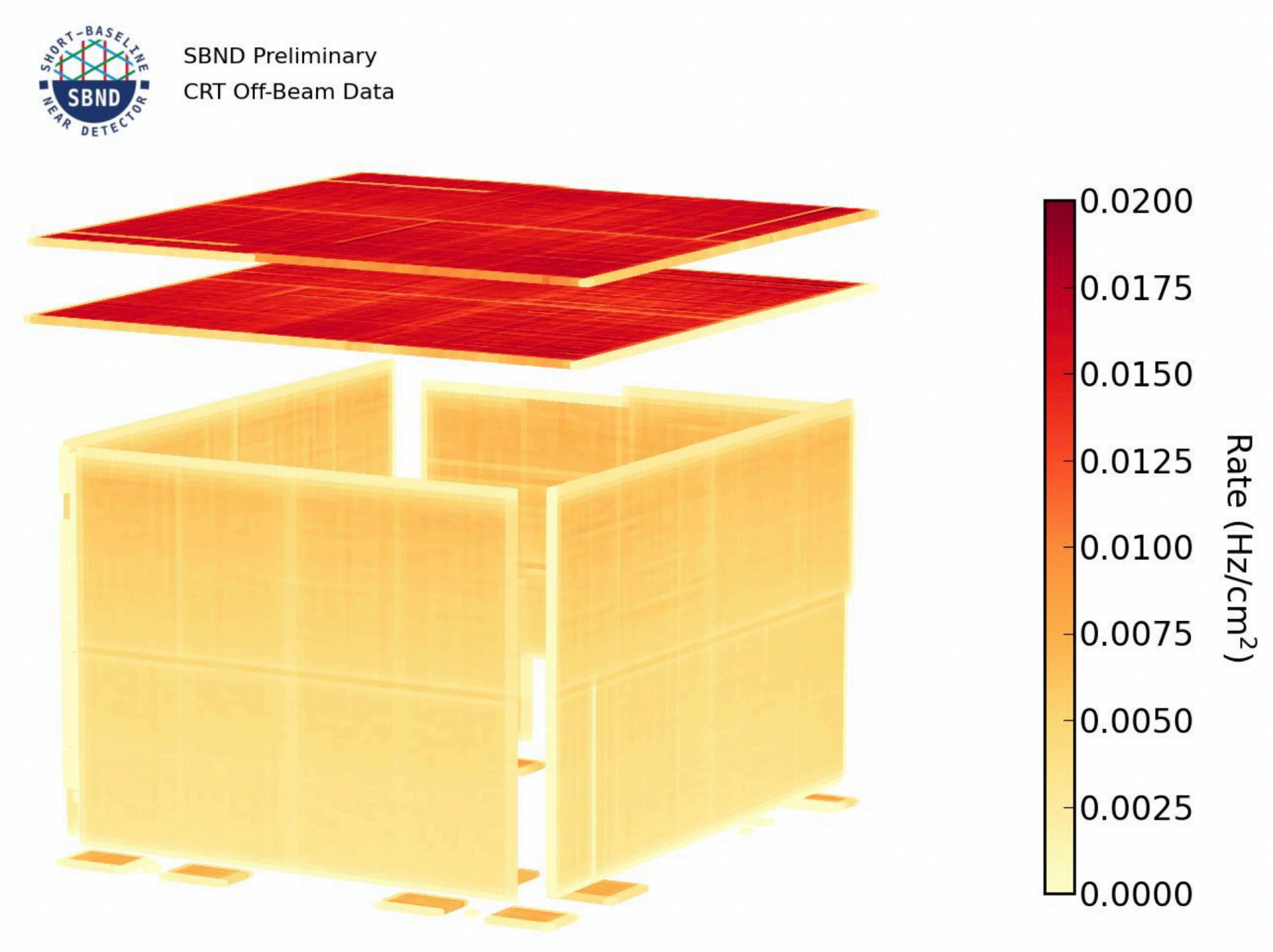
External particle tracker made of overlapping perpendicular scintillator bars:

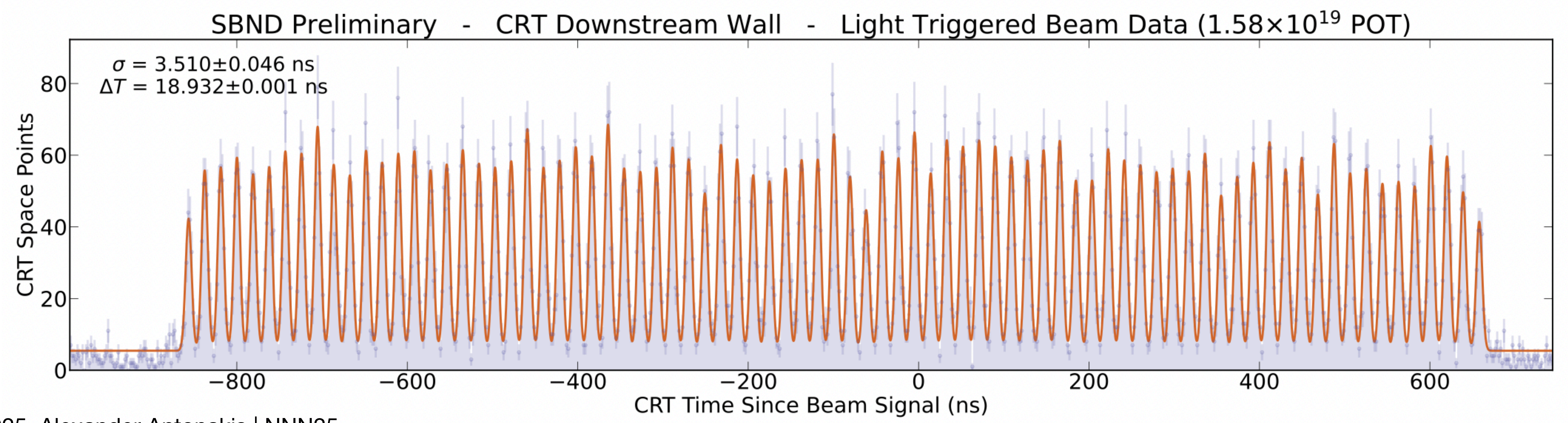
- **Wavelength shifting optical fibers**
- **Two Silicon Photomultipliers per bar for light detection**



CRT Performance

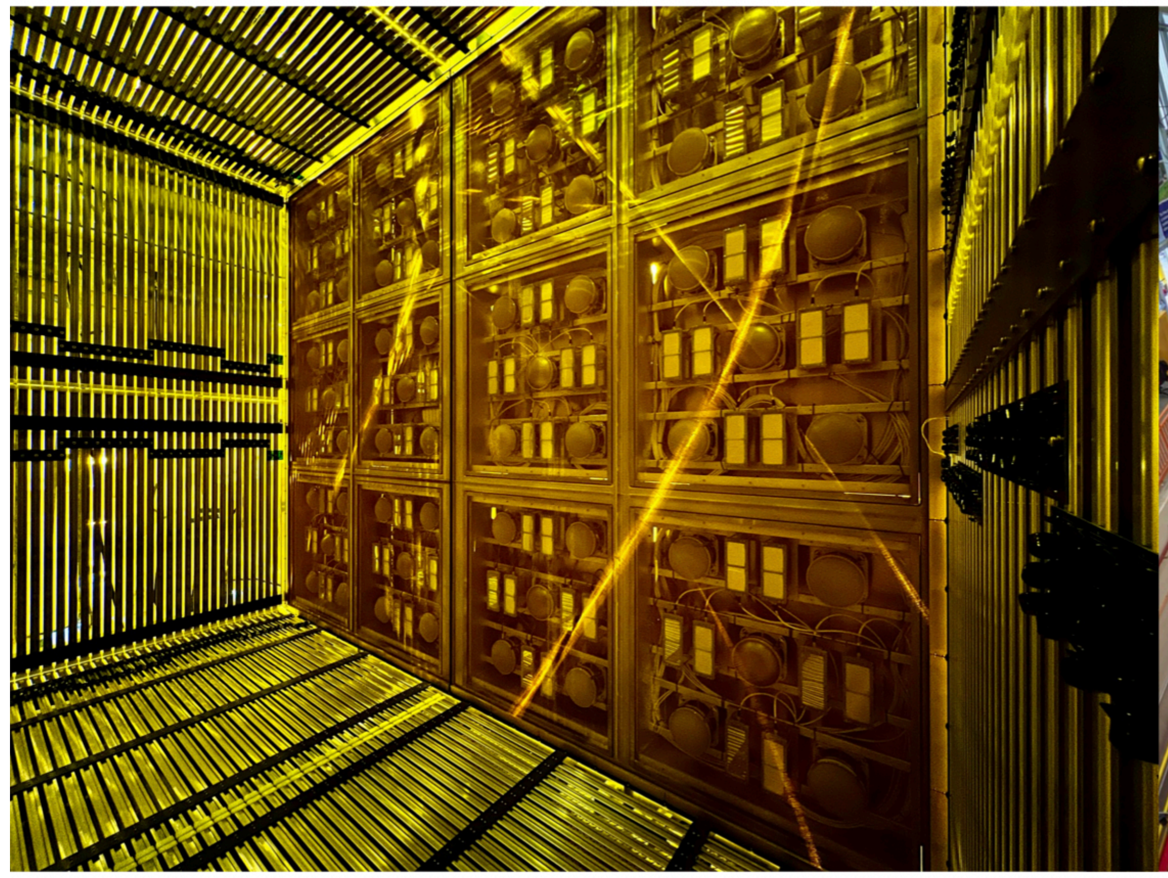
- SiPM voltage and gain calibration give a highly uniform response with excellent hit efficiency (> 90%)
- CRT can reproduce all 81 BNB proton bunches with ~3.3 ns timing resolution
- The CRT will be an excellent tool for cosmic rejection and vetoing neutrino interactions that happen outside the detector





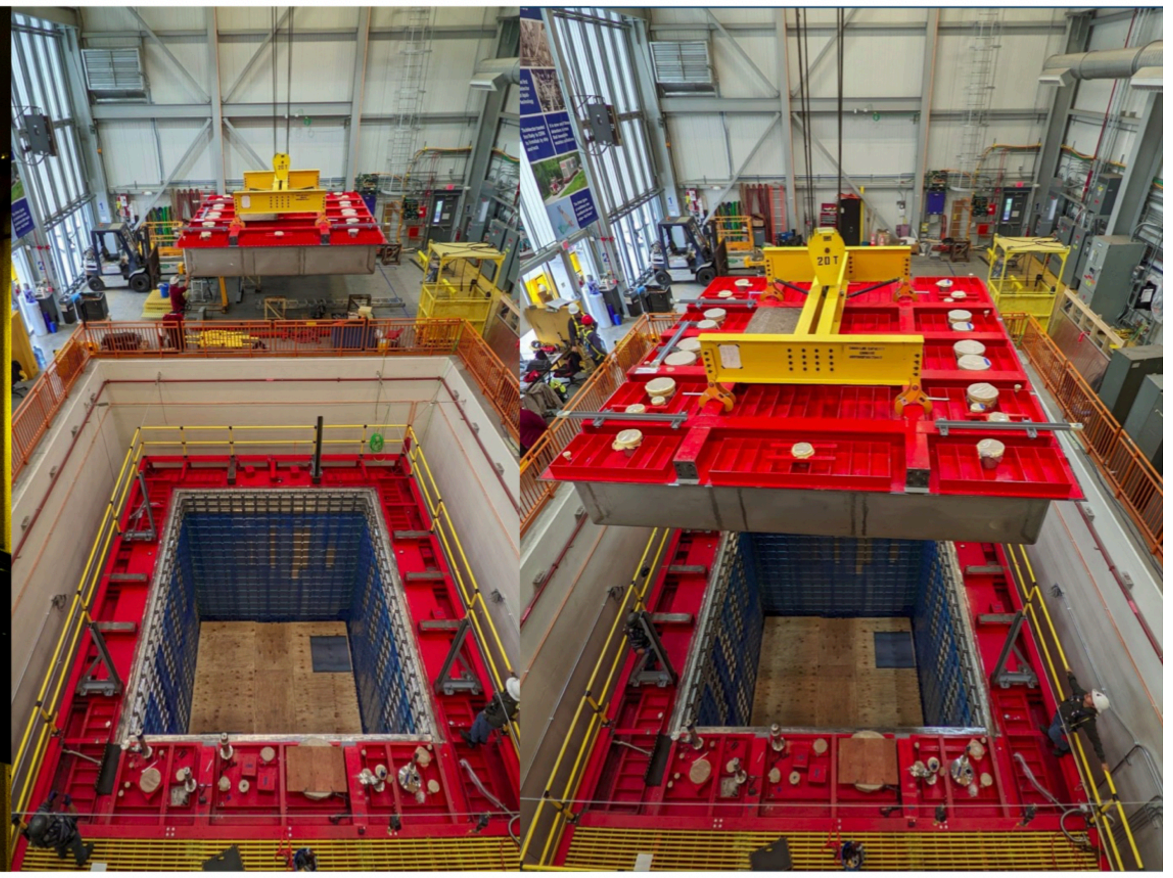
SBND Timeline

September 2022



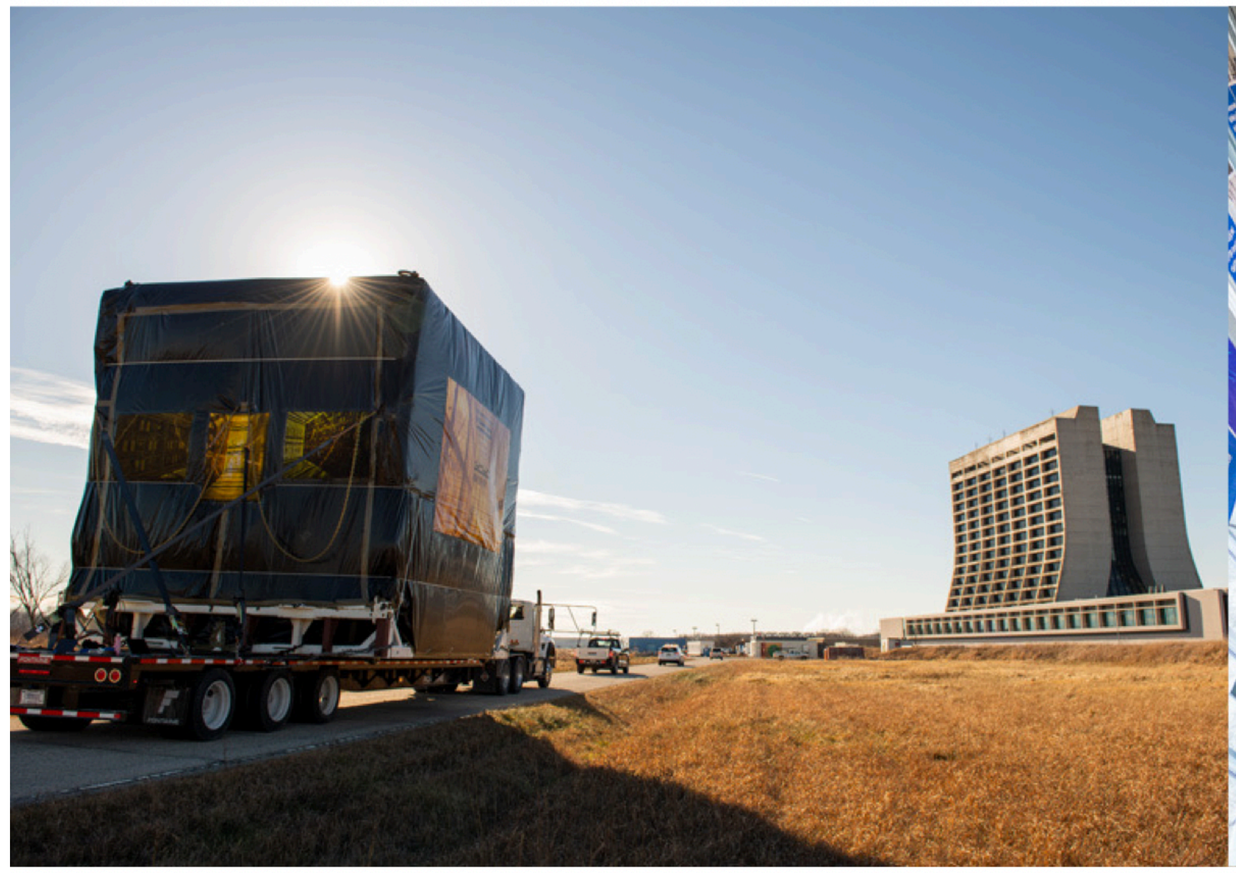
TPC and PDS Completed

October 2022



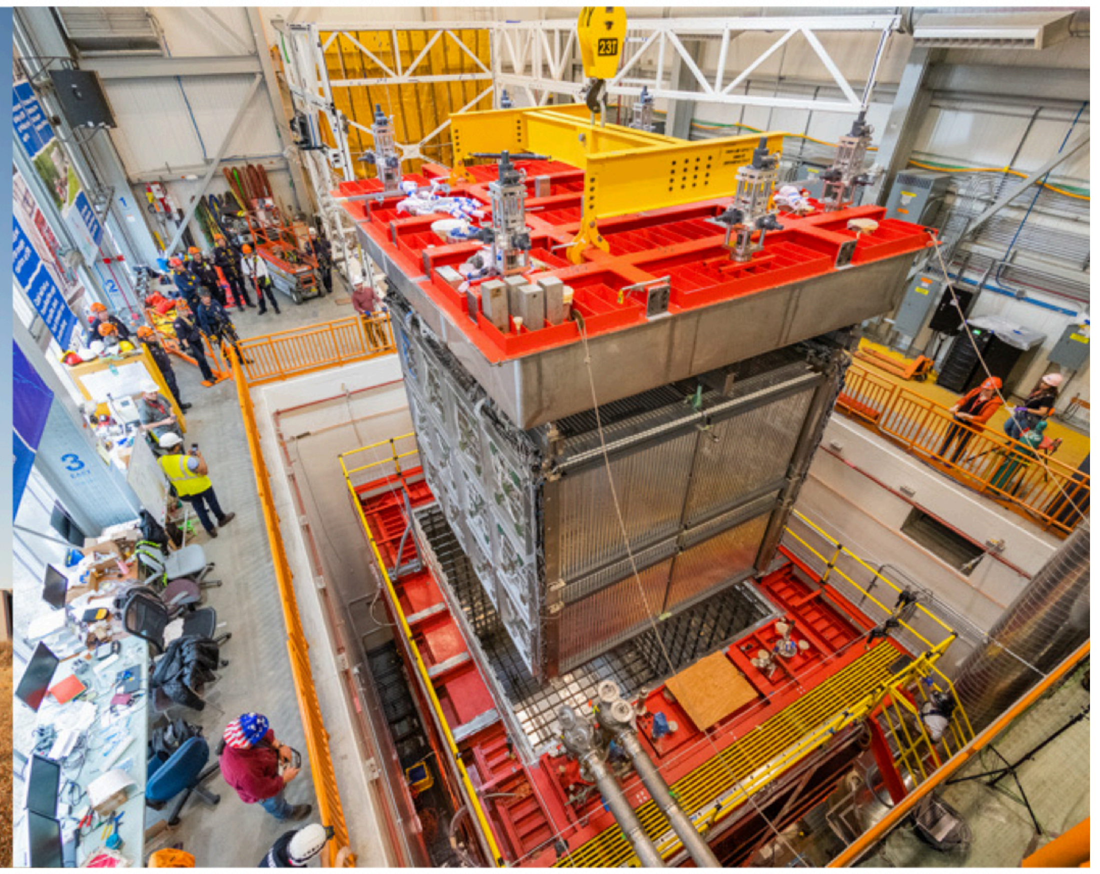
Cryostat Completed at ND Building

December 2022



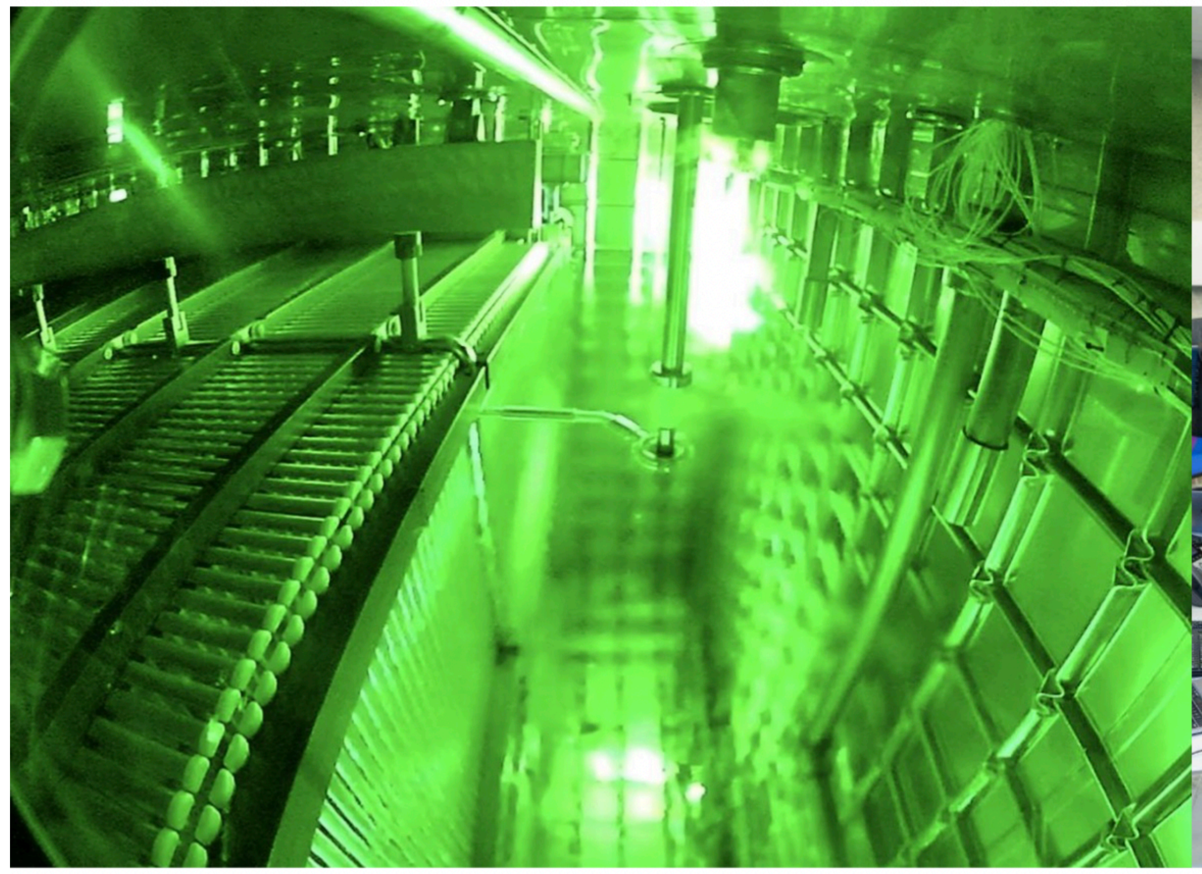
TPC Transported to ND Building

April 2023



TPC Lowered into Cryostat

March 2024



Detector Filled with LAr

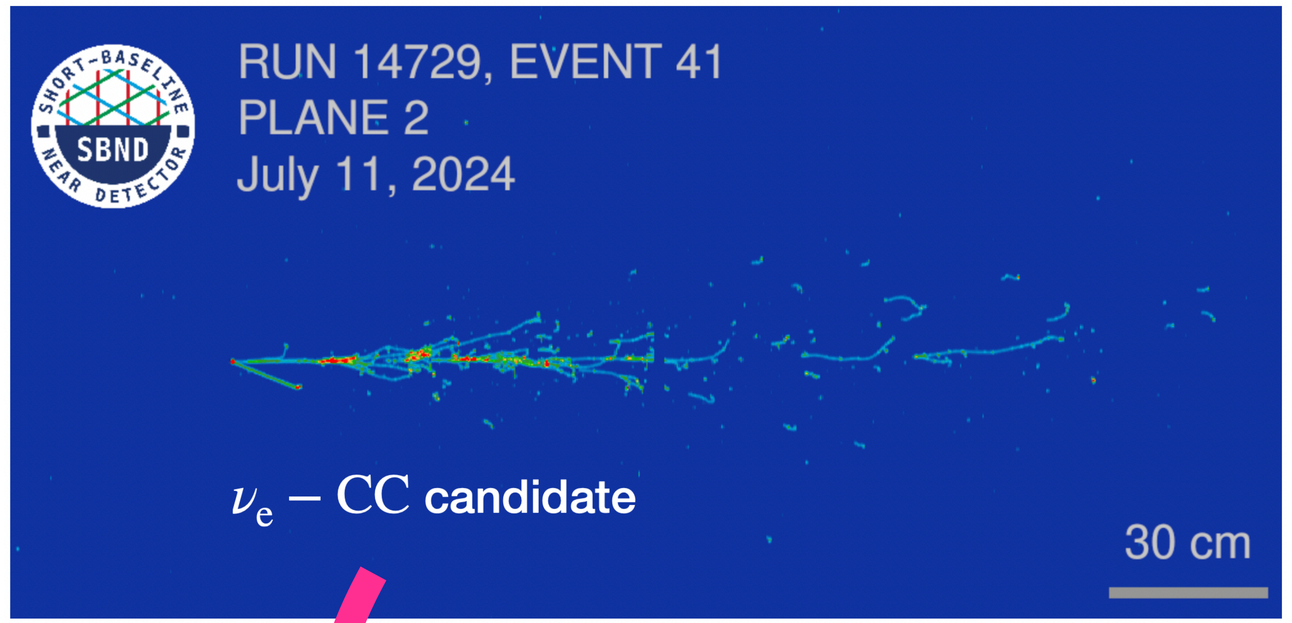
July 2024

Successfully Ramped to 500V/cm

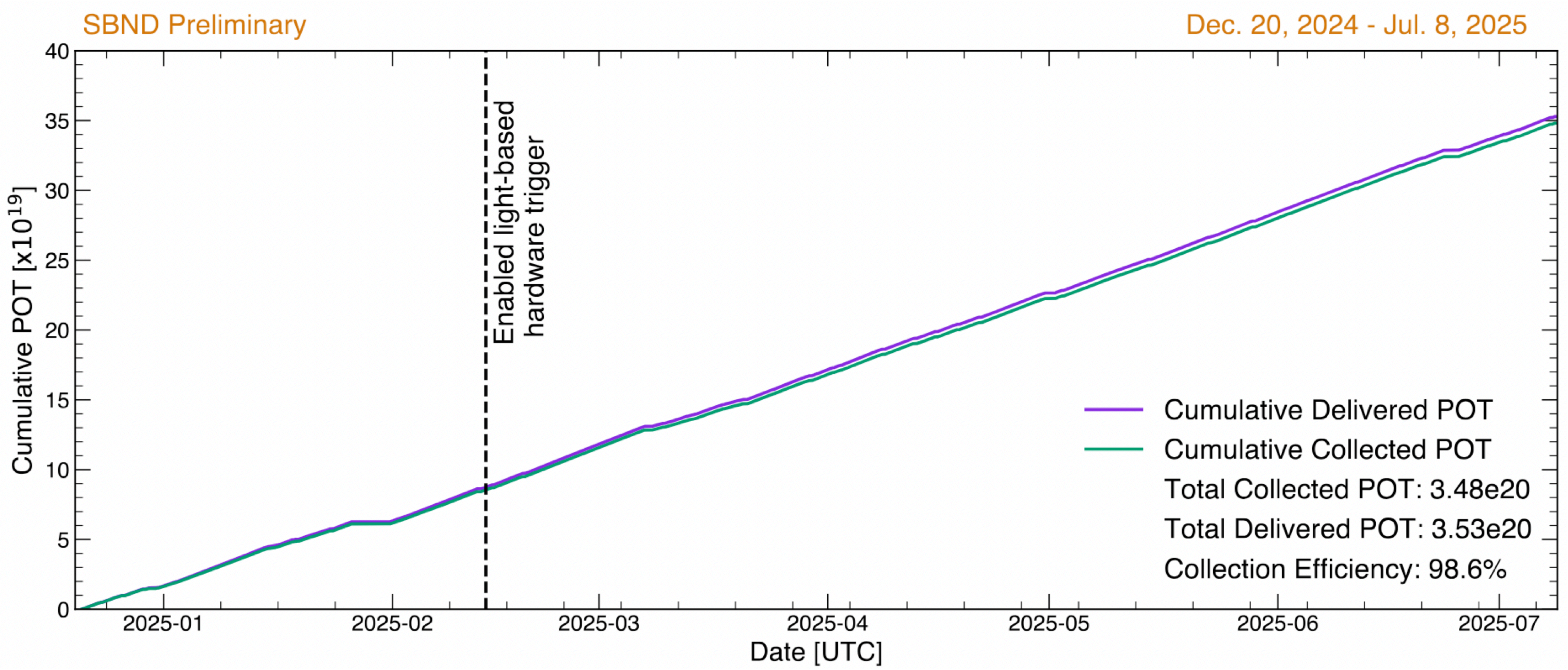
Physics data!

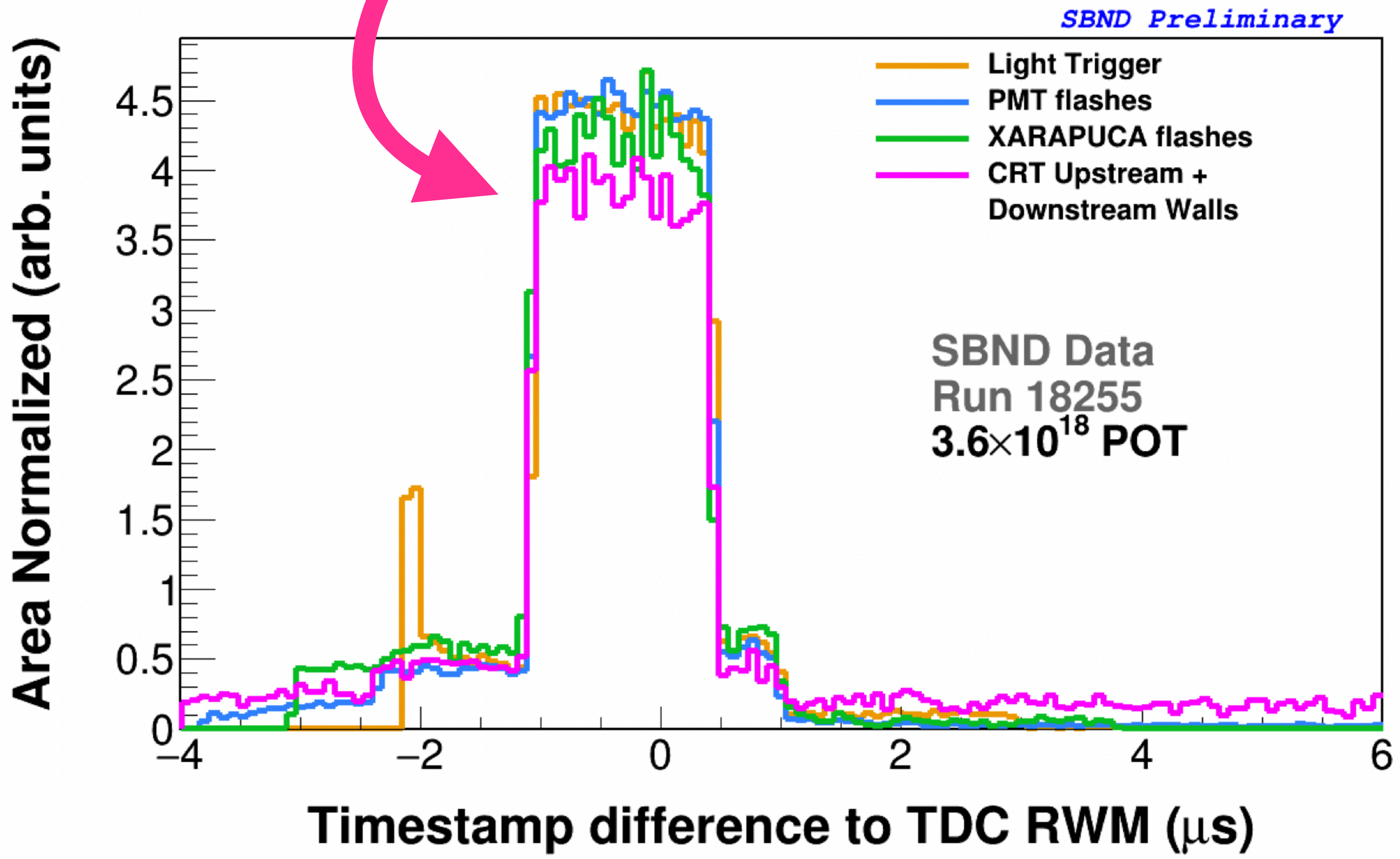
SBND Operations/Data Taking

- Run 1 data collection is complete (December 2024 — July 2025): ~3.5 x 10^{20} POT
- > 3 million neutrino interactions collected so far!
- Already have the world's largest ν−Argon interaction dataset



SBND Run 1 Cumulative POT





Status of First Analyses

SBND Cross Sections

- SBND's high statistics and LAr-TPC technology enables a broad cross section program
- Many analyses in progress:
  - ν_μCC Inclusive
  - ν_μCC1p0π
  - ν_eCC Inclusive

Previewed here and will be shown at NuInt 2025!

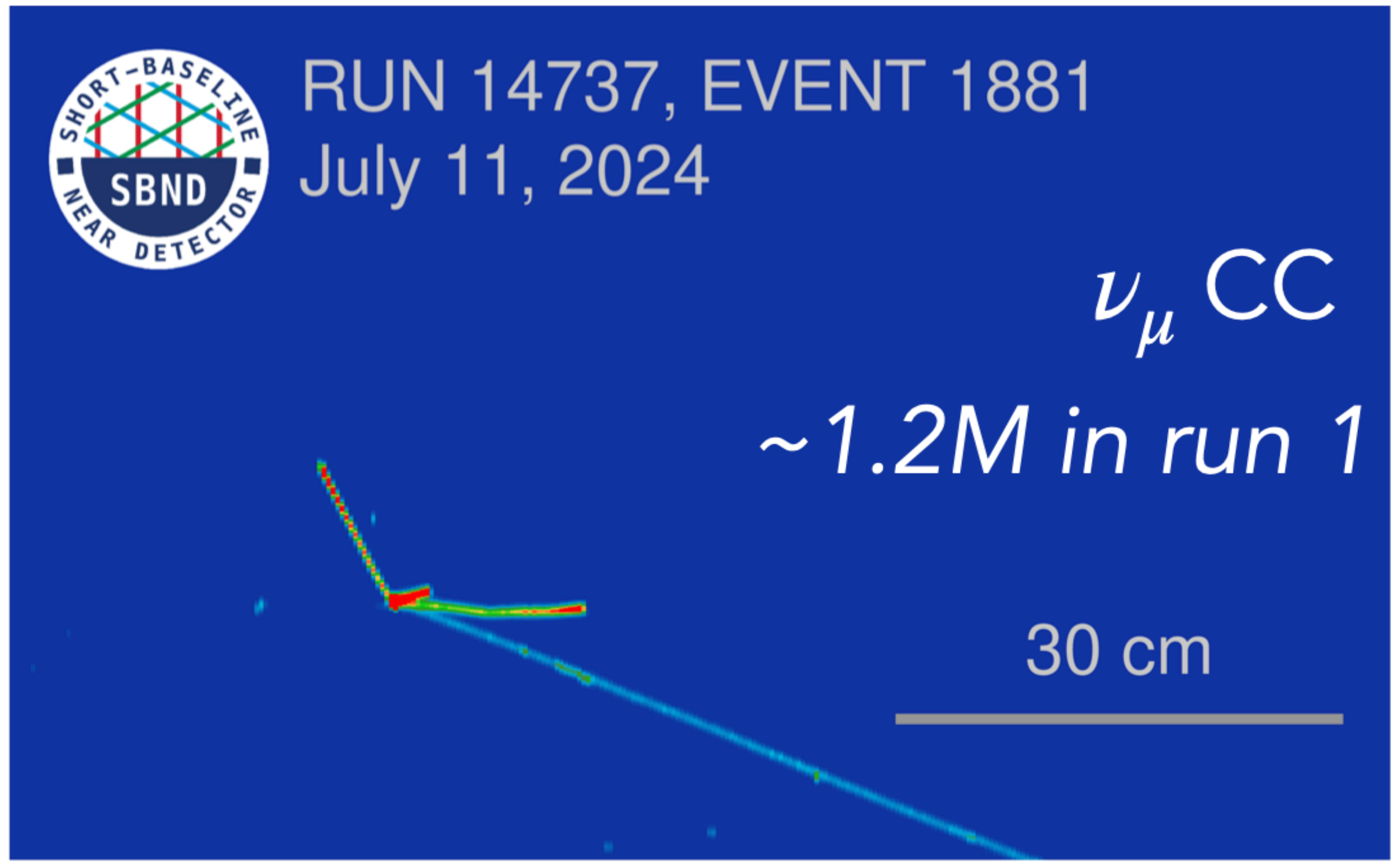
  - Coherent Pion Production
  - ν_μCC1$\pi^\pm$
  - NC1$\pi^0$1$\pi^\pm$
  - Resonance Production of Eta mesons
  - ν_μCC 2p0π
  - ν_μCCπ^0
  - ν_μCC Shallow Inelastic Scattering
  - ν_μCC QE hyperon production
  - Nuclear Cluster Production (deuterons, tritons, helions and alphas)
  - Neutrino-electron elastic scattering
  - μ decay at rest

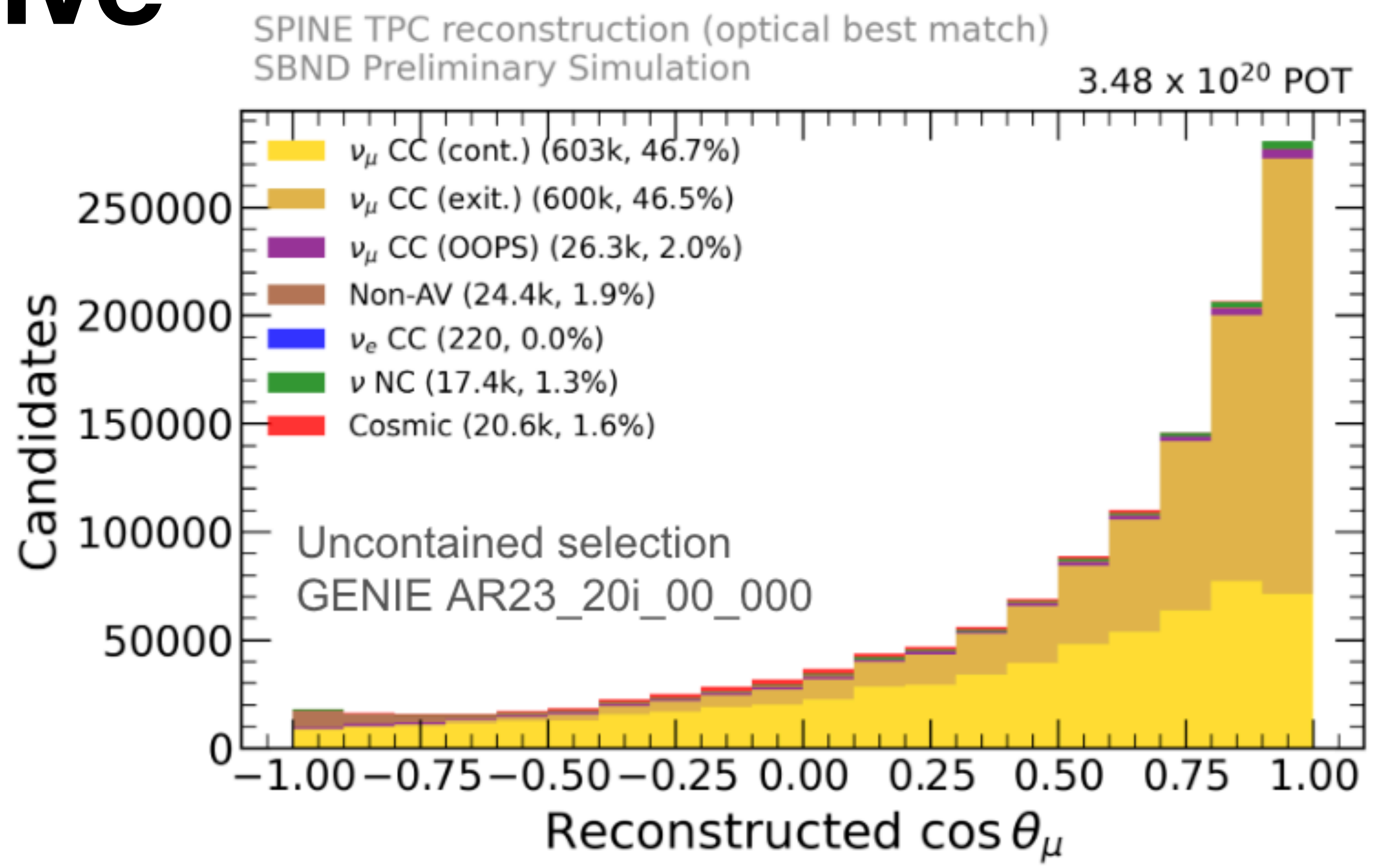
And many more …

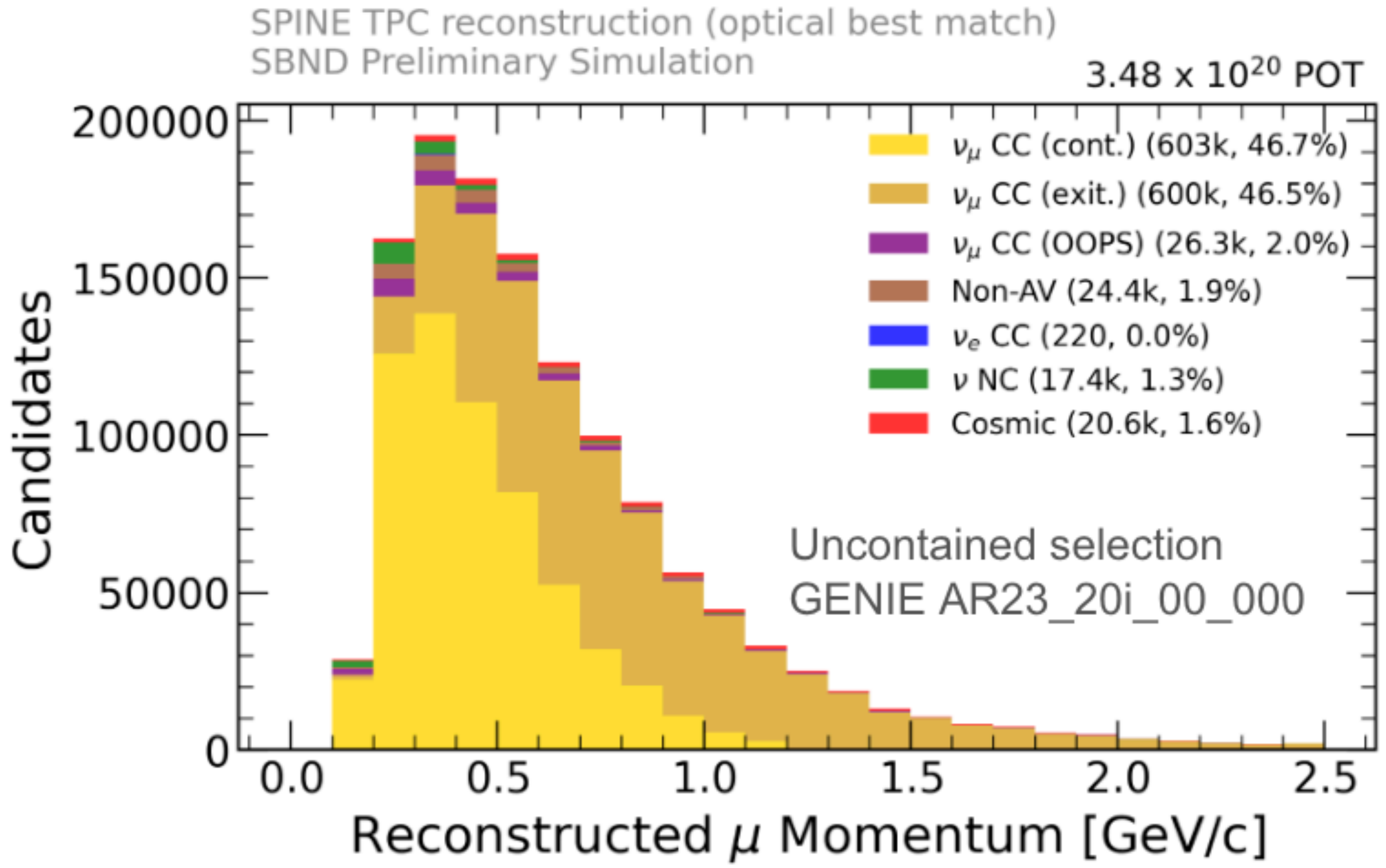
SBND Cross Sections: ν_μ CC Inclusive

- Early measurement can establish detector performance
  - Directly compare reconstruction algorithms
  - Excellent cosmic rejection as a surface detector
- Large statistics and low model bias in muon kinematics
- Multi-dimensional differential measurements
- High purity and efficiency

Purity = 93%
Efficiency = 79%







SBND Cross Sections: ν_μCC1p0π

- Targets the quasi-elastic mode and enables observation of low Q^2 effects
- Measurements in muon and proton kinematics as well as **T**ransverse **K**inematic **I**mbalance variables (TKI)
- Allows for the study of nuclear effects

Purity = 92.1%
Efficiency = 20.3%

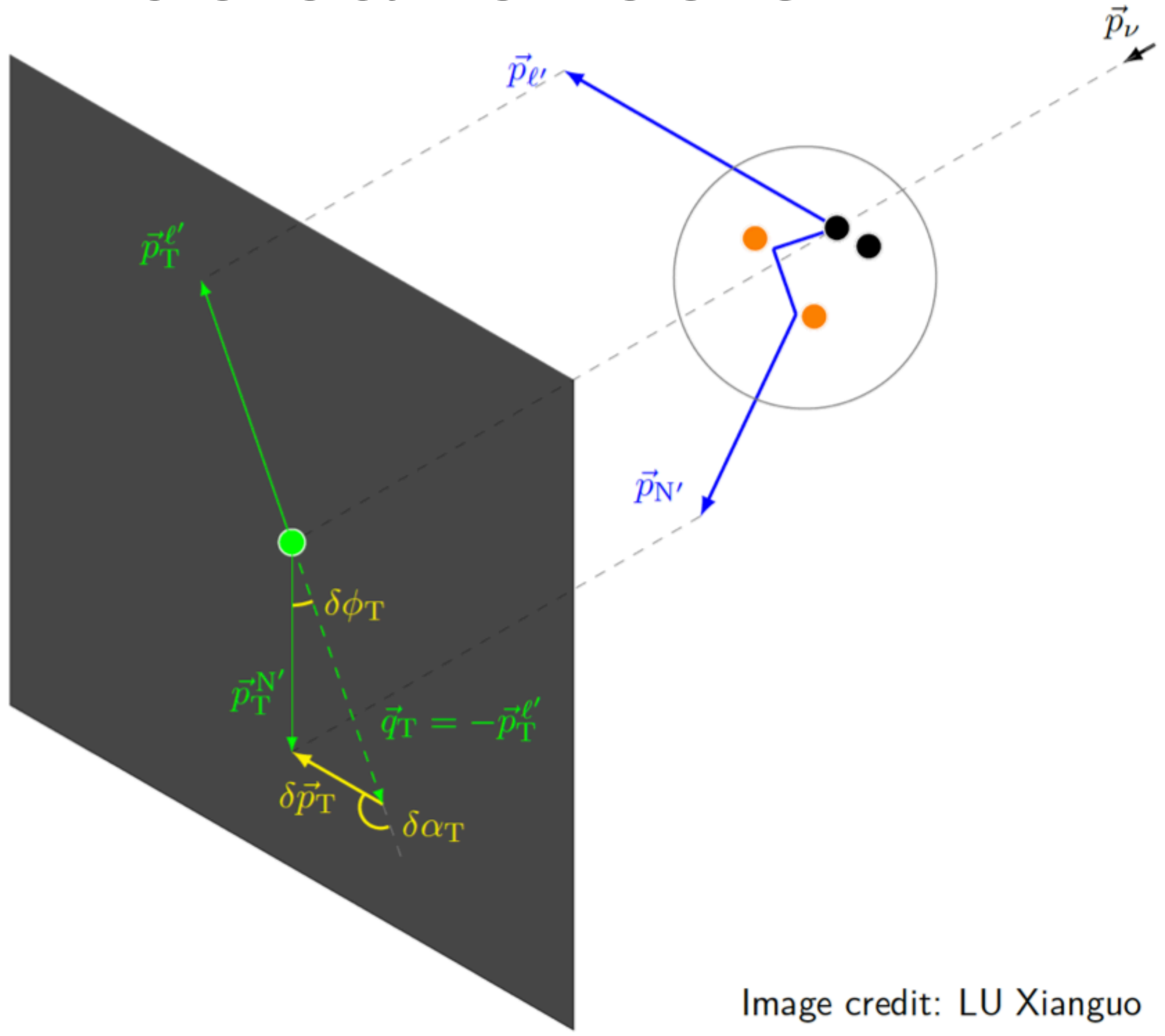
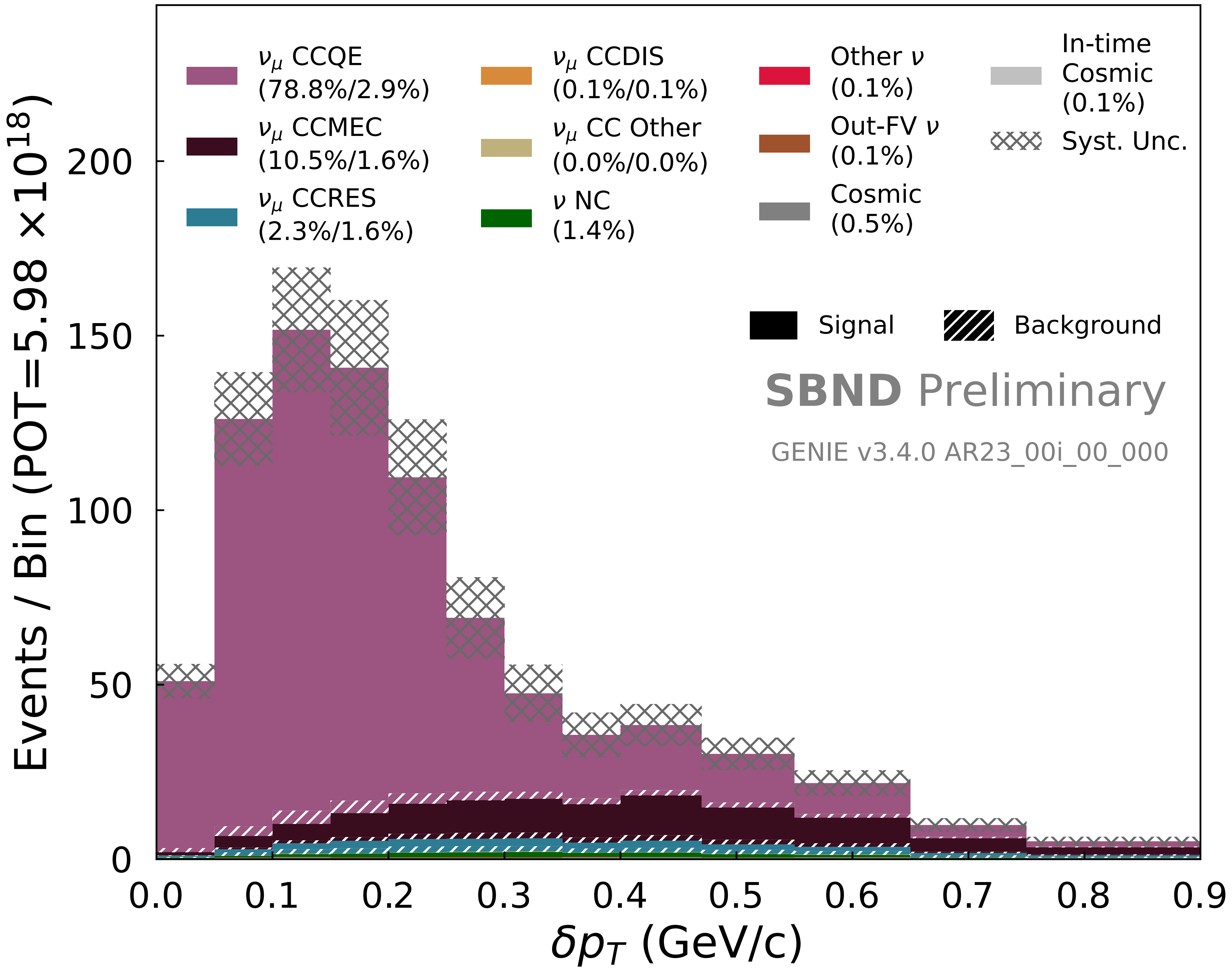
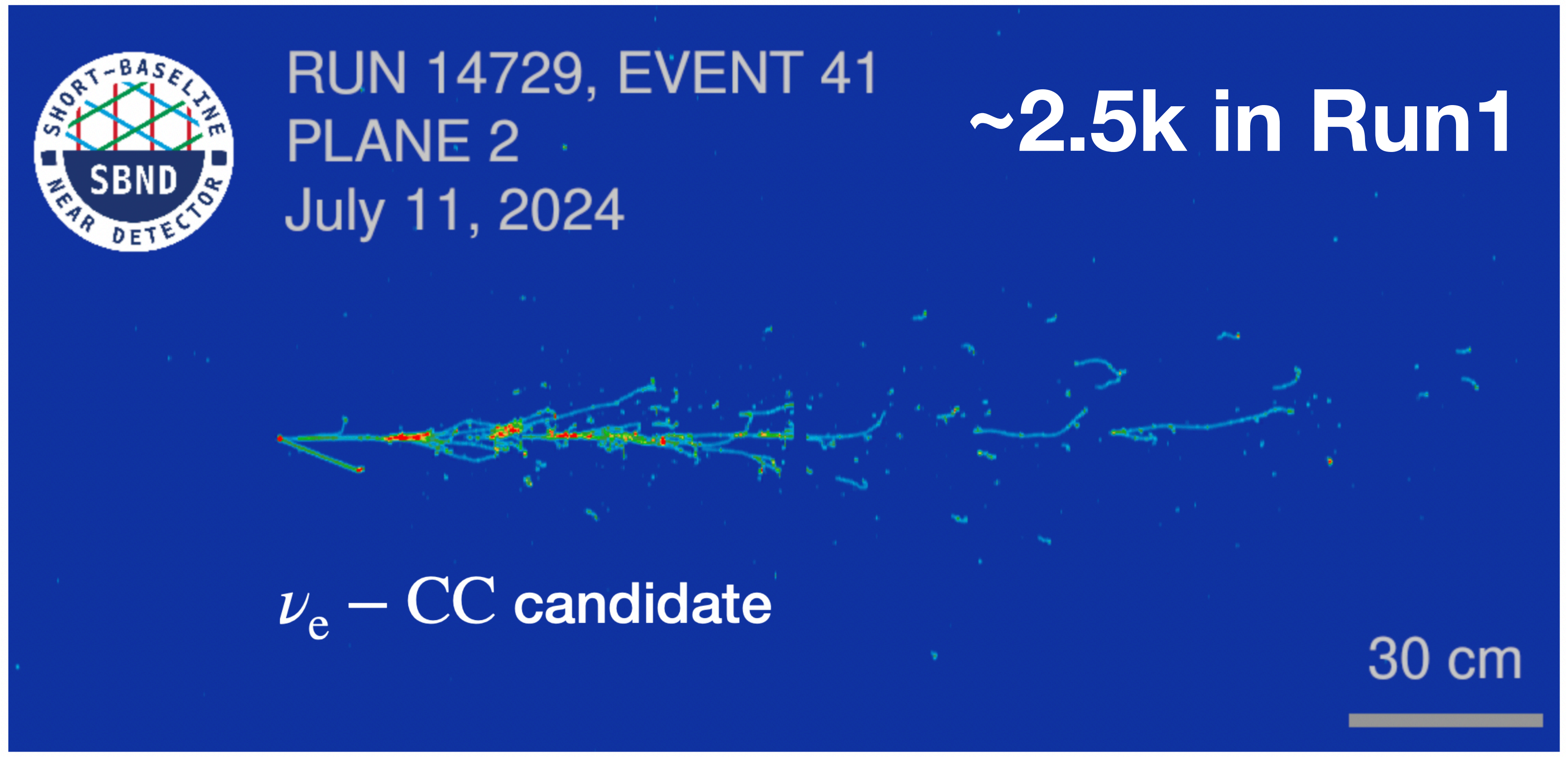


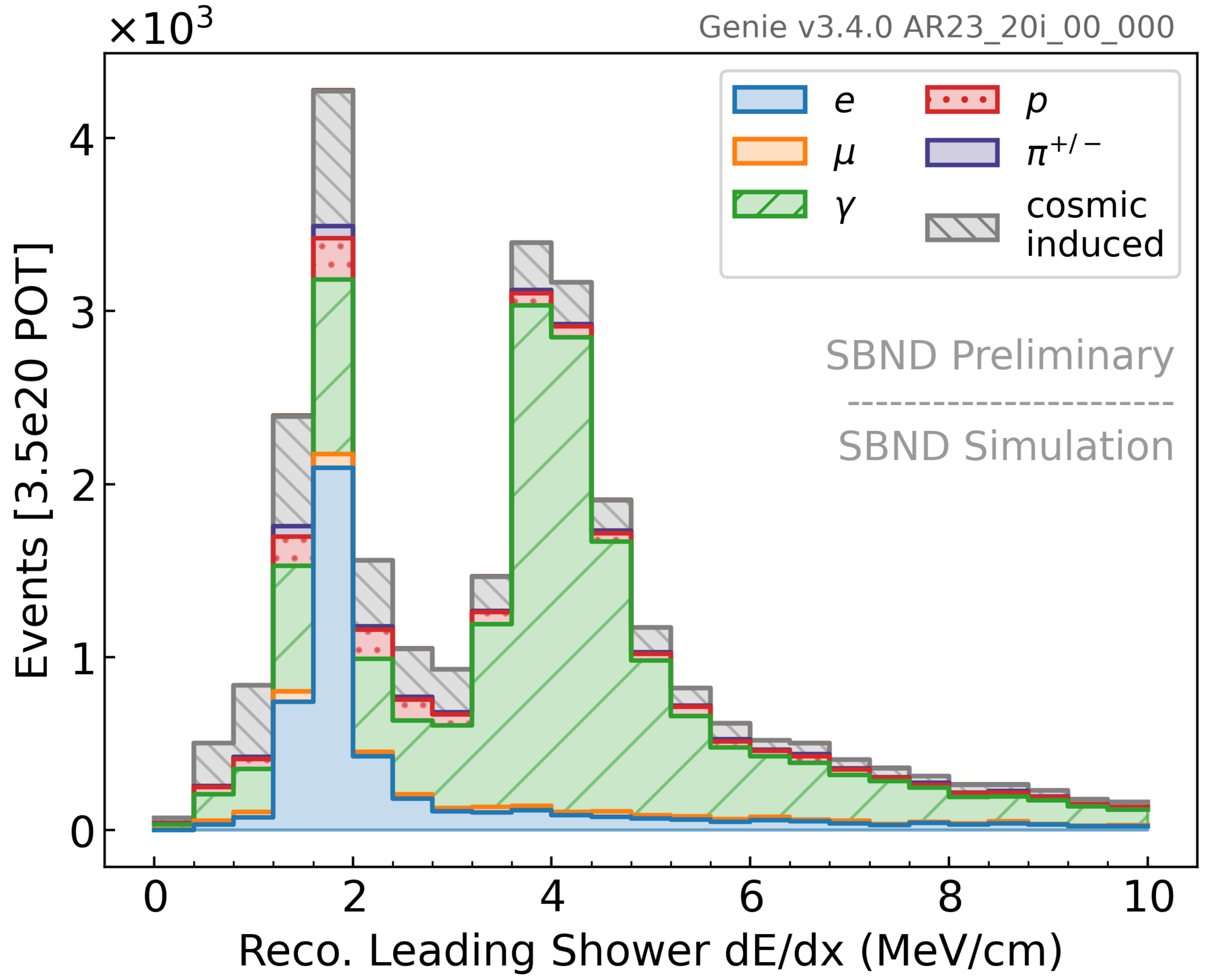
Image credit: LU Xianguo



SBND Cross Sections: ν_e CC Inclusive

- Despite small contribution to the BNB flux, still expect ~15,000 events/year
- Important for oscillation physics which uses the LAr-TPCs ability to distinguish between electrons and photons
- Variables such as the shower opening angle, dE/dx and distance between vertex and shower start help to select electrons
- Expect to have ~2.5k ν_e events after selection in Run1 dataset

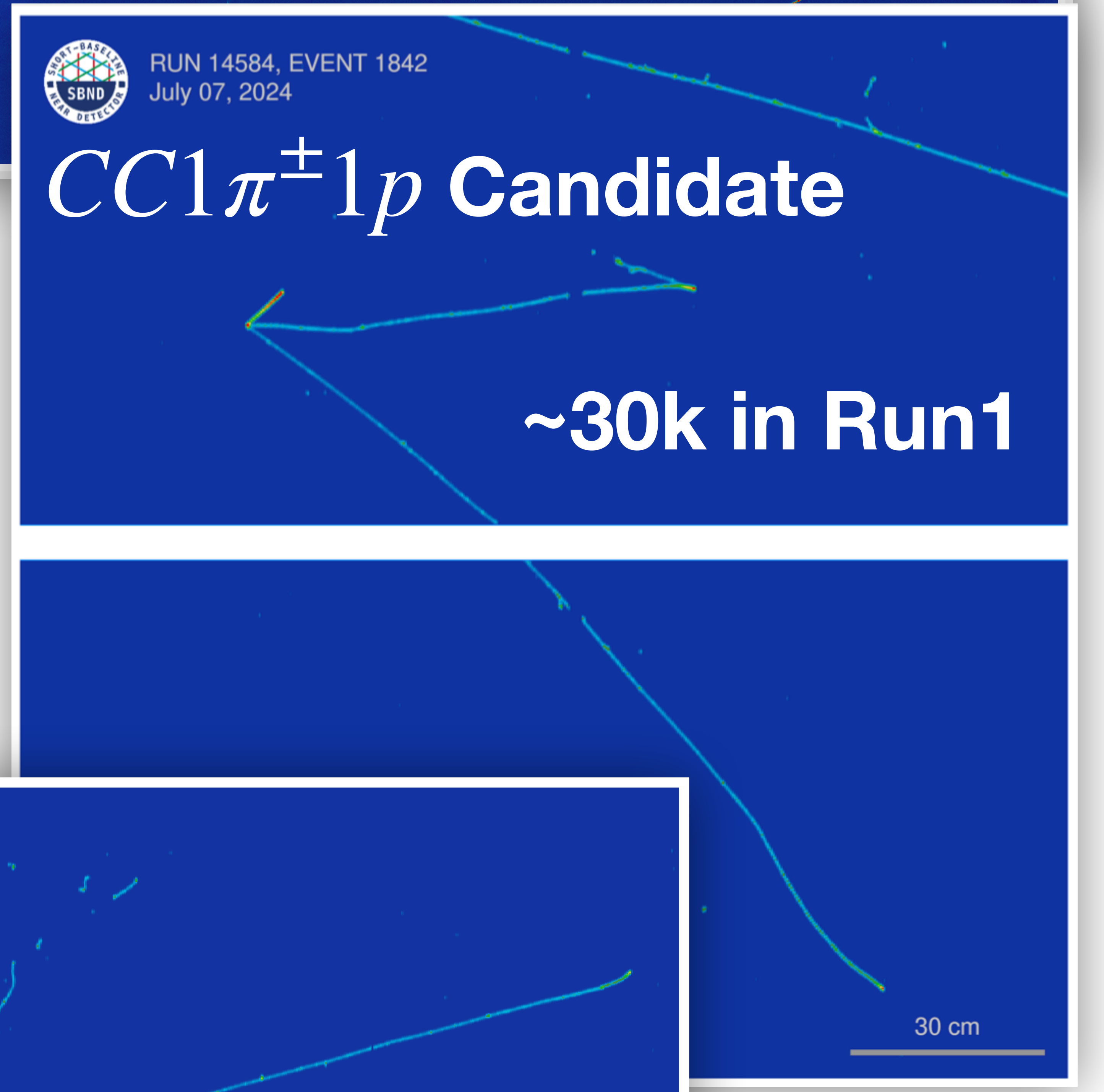




Purity = 62%, Efficiency = 27%

Other Analyses in Progress

- Longer term, SBND will be able to leverage the statistics to probe multi-dimensional cross sections and study rare processes
- Here are some select examples of ongoing analyses:
  - **Coherent Pion Production**
    - ~800 signal events with 6 months of data
  - ν_μ**CC**$1\pi^\pm$
    - Mostly probes resonance events and exudes shower topologies
  - **Resonance Production of Eta Mesons**
  - Probe resonances beyond the Delta baryon
  - 2 photon decay signal definition
  - Will quickly accumulate world leading statistics for a high precision measurement



Summary

- SBND has been taking physics data since December 2024 and we completed Run 1 in July 2025!
- We already have the world's largest dataset of $\nu-$Argon interactions
- Detector calibration and reconstruction shows great performance
- Wide physics program including the short-baseline oscillation program, detailed cross sections, rare processes and beyond the standard model searches
- First physics results being shown next week at NuInt 2025 !

Thank You!

The SBND Collaboration

updated May 2025

Including both scientific and technical personnel

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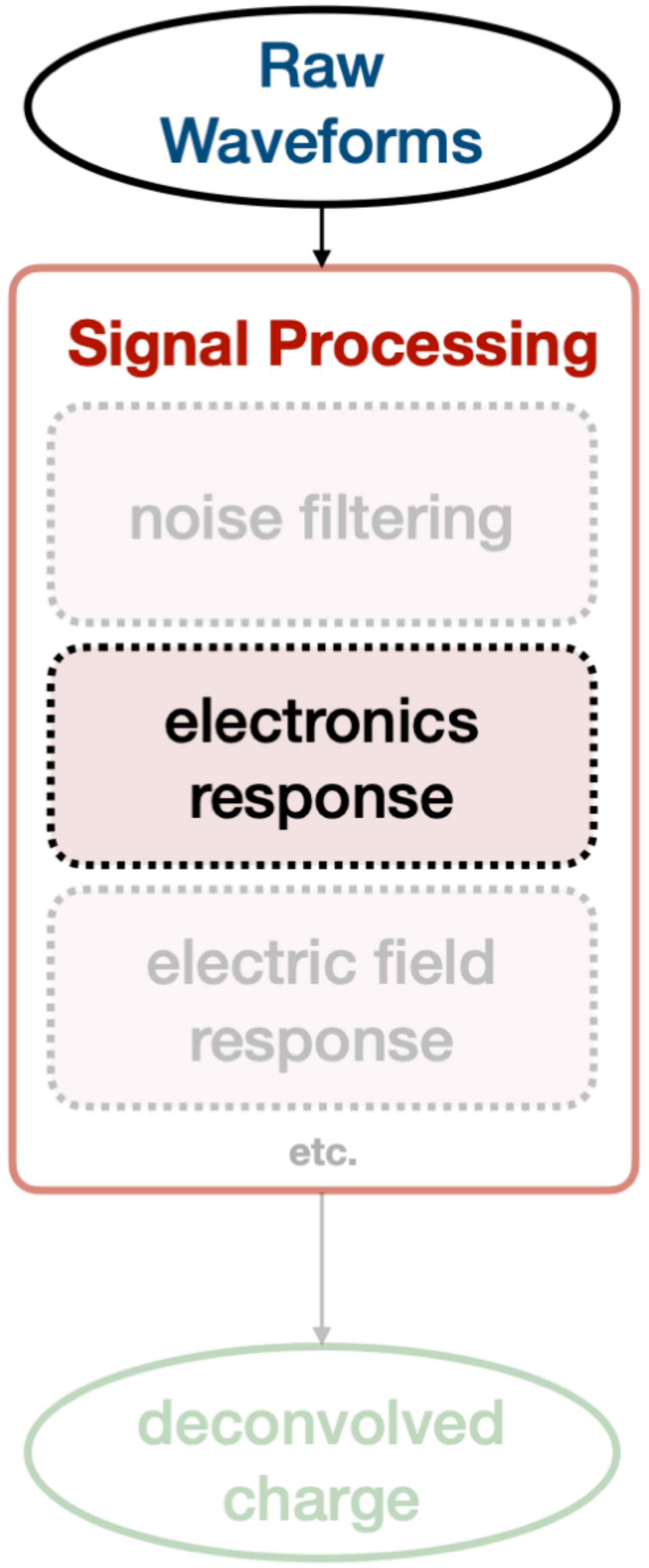
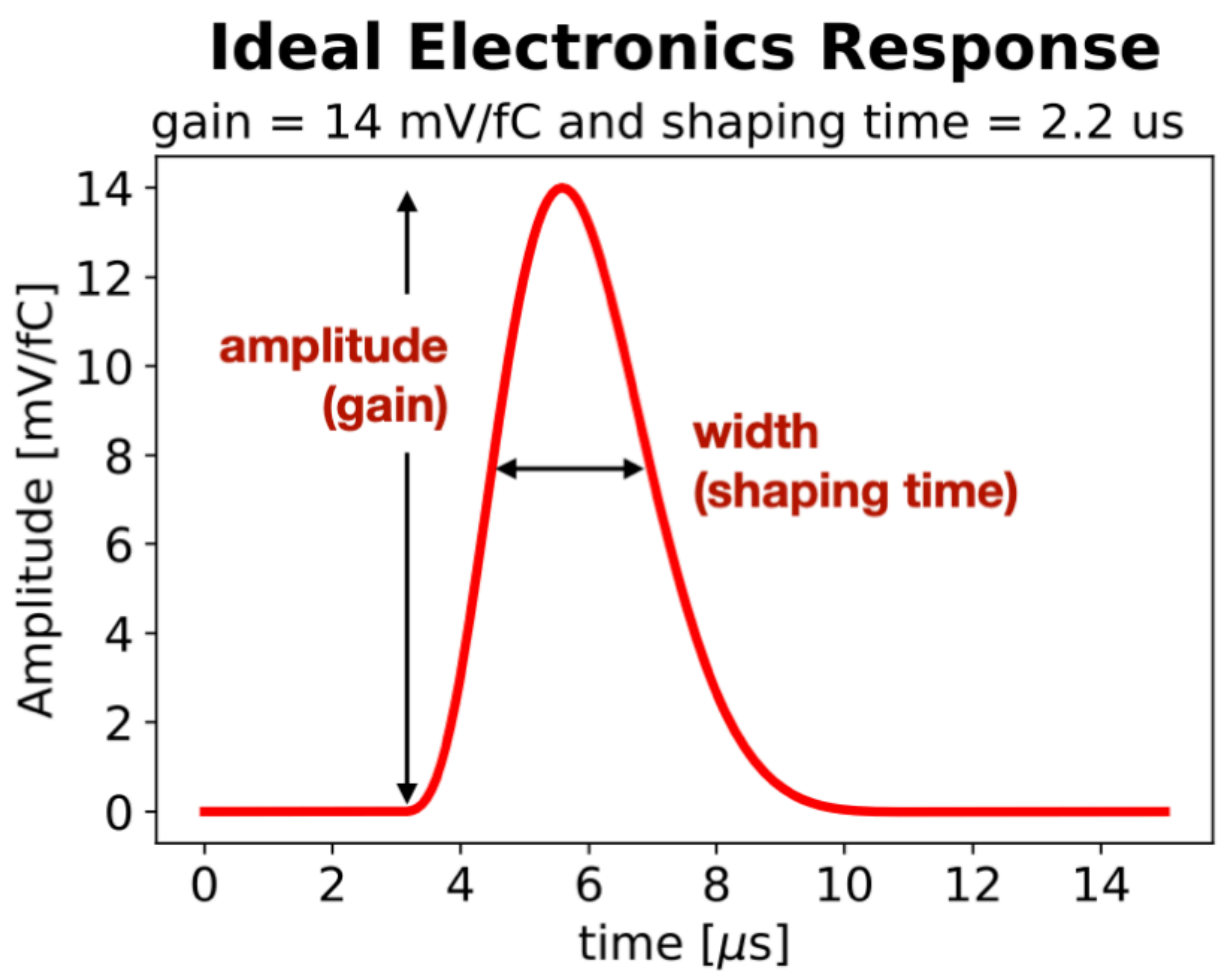
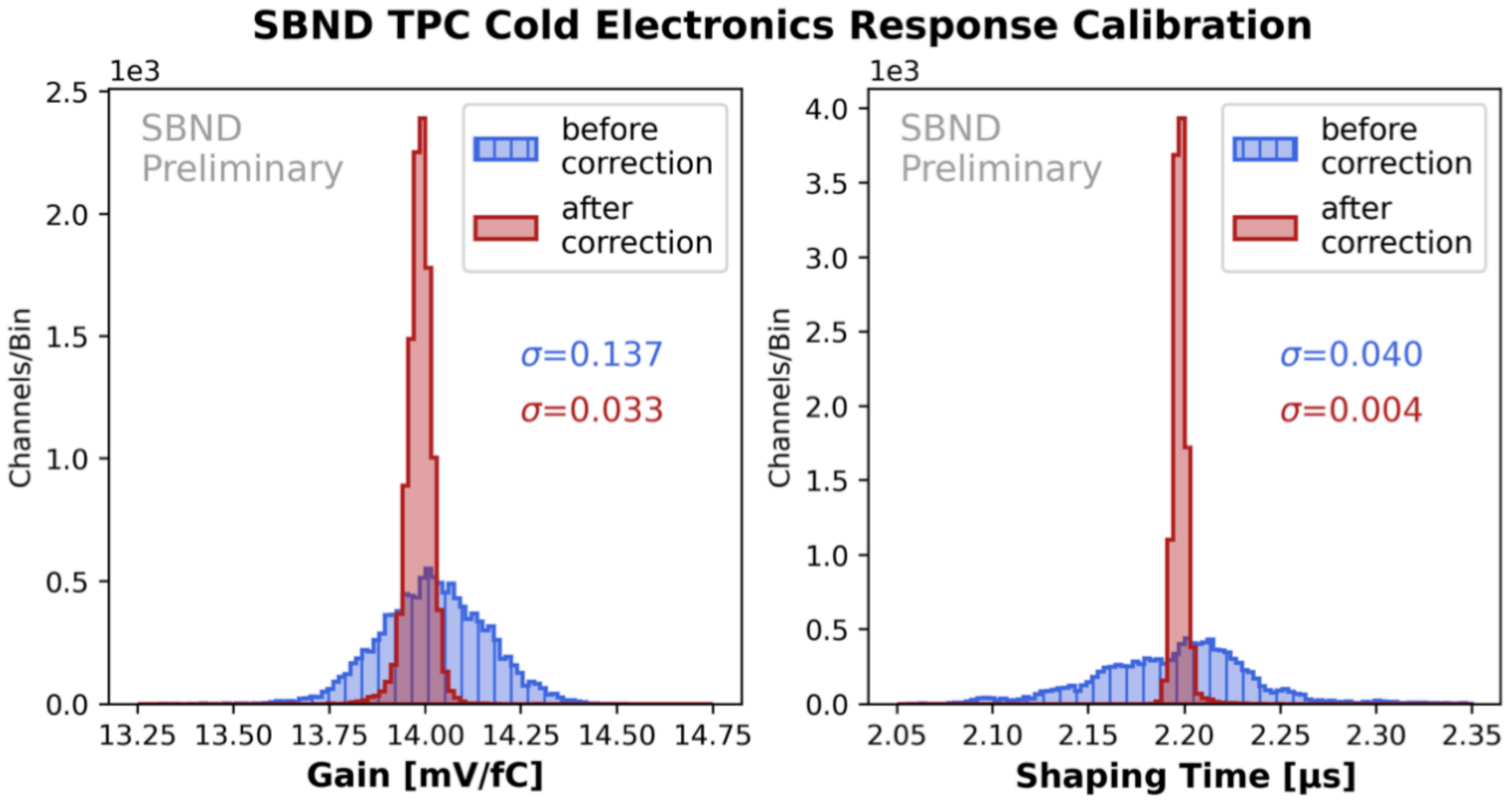
Tufts University: O. Alterkait, Z. Imani, T. Wongjirad
Virginia Tech: C. Mariani, G. Moreno-Granados, P. Roy
University of Warwick: A. Chappell, X. Lu, J. Marshall, A. Wilkinson

Backup

Signal Processing



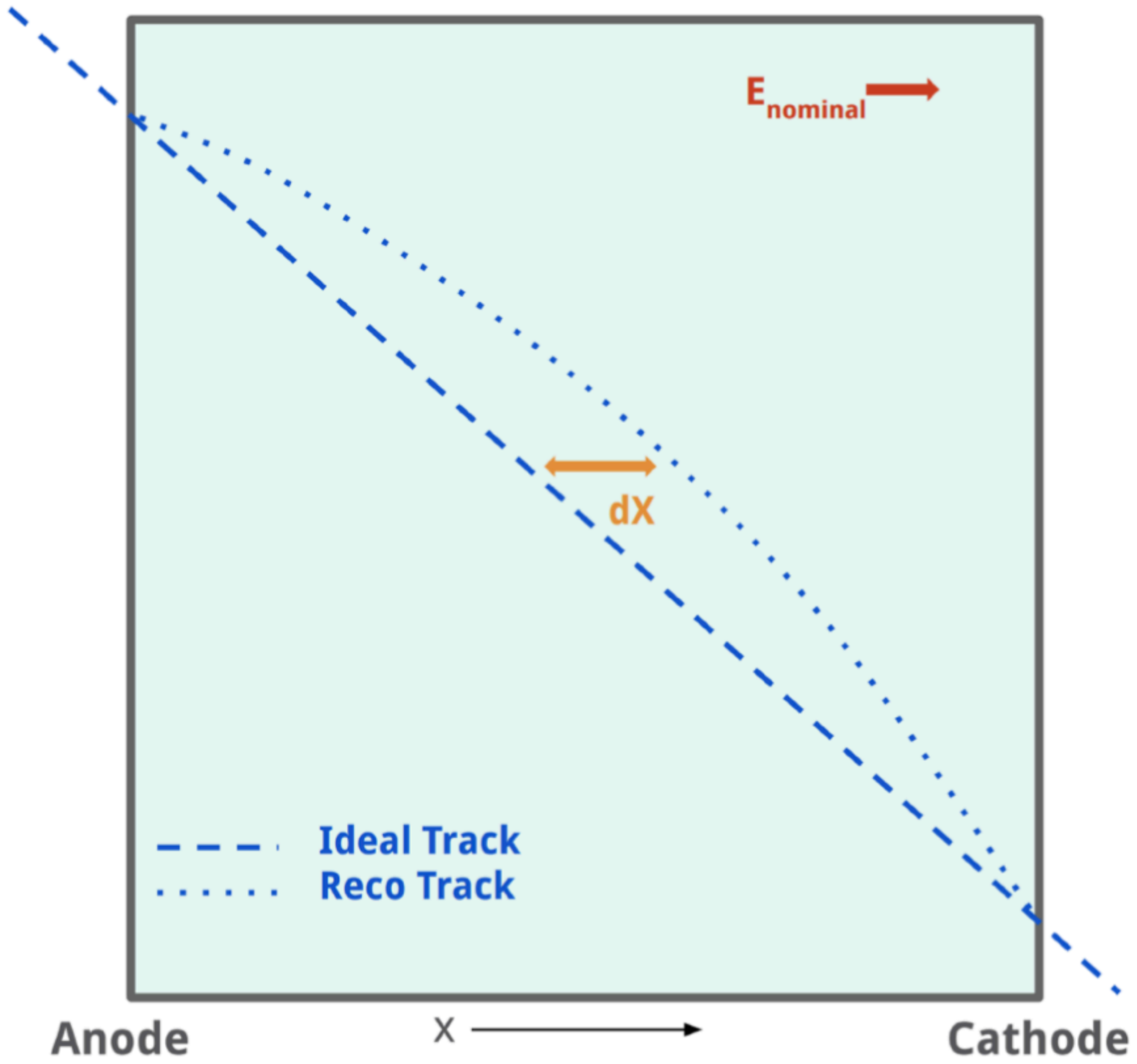


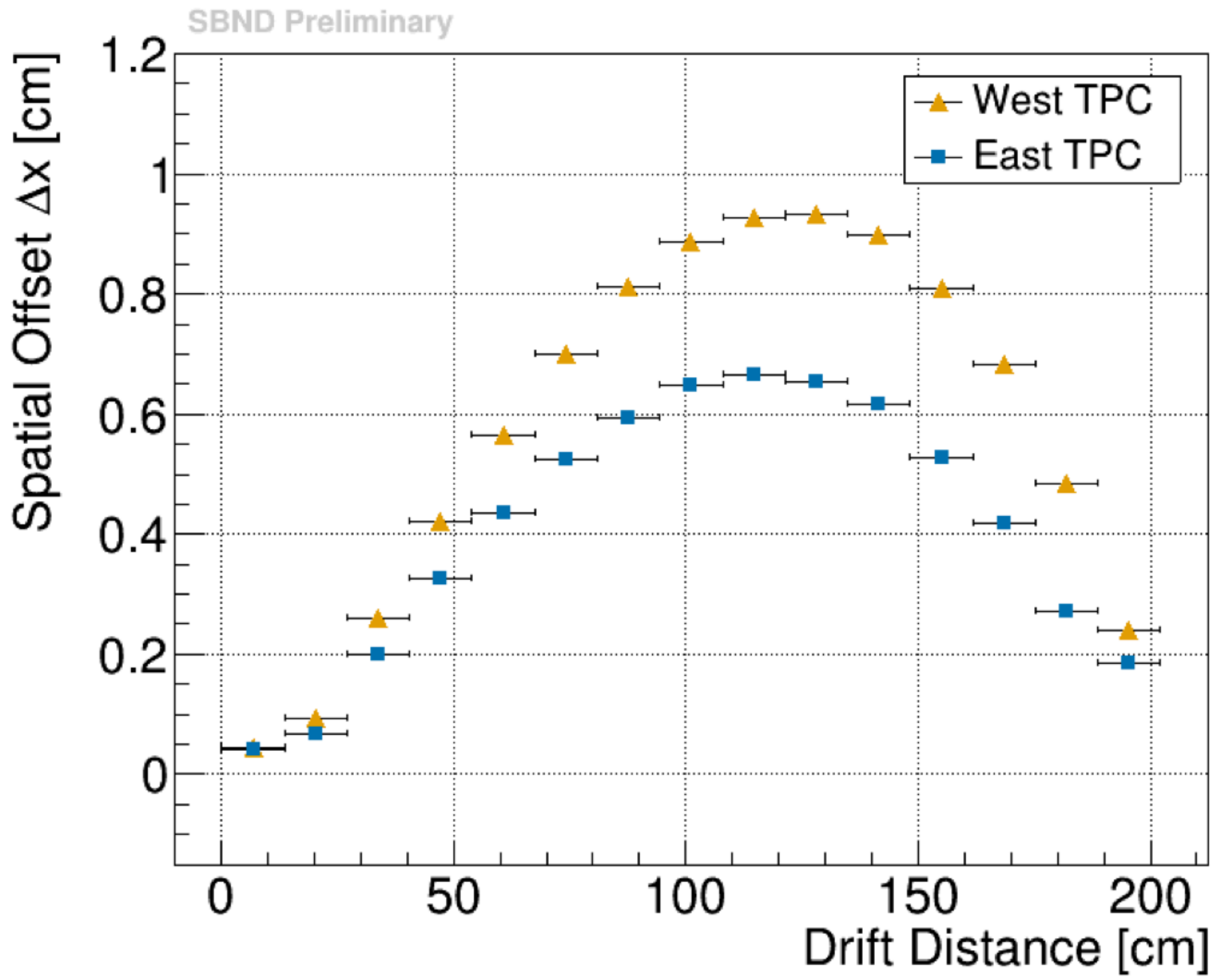


- Cold electronics are responsible for amplifying and shaping signals for each wire deconvolved charge
- Clear improvement in response uniformity after corrections from internal calibration source

Space Charge Effect

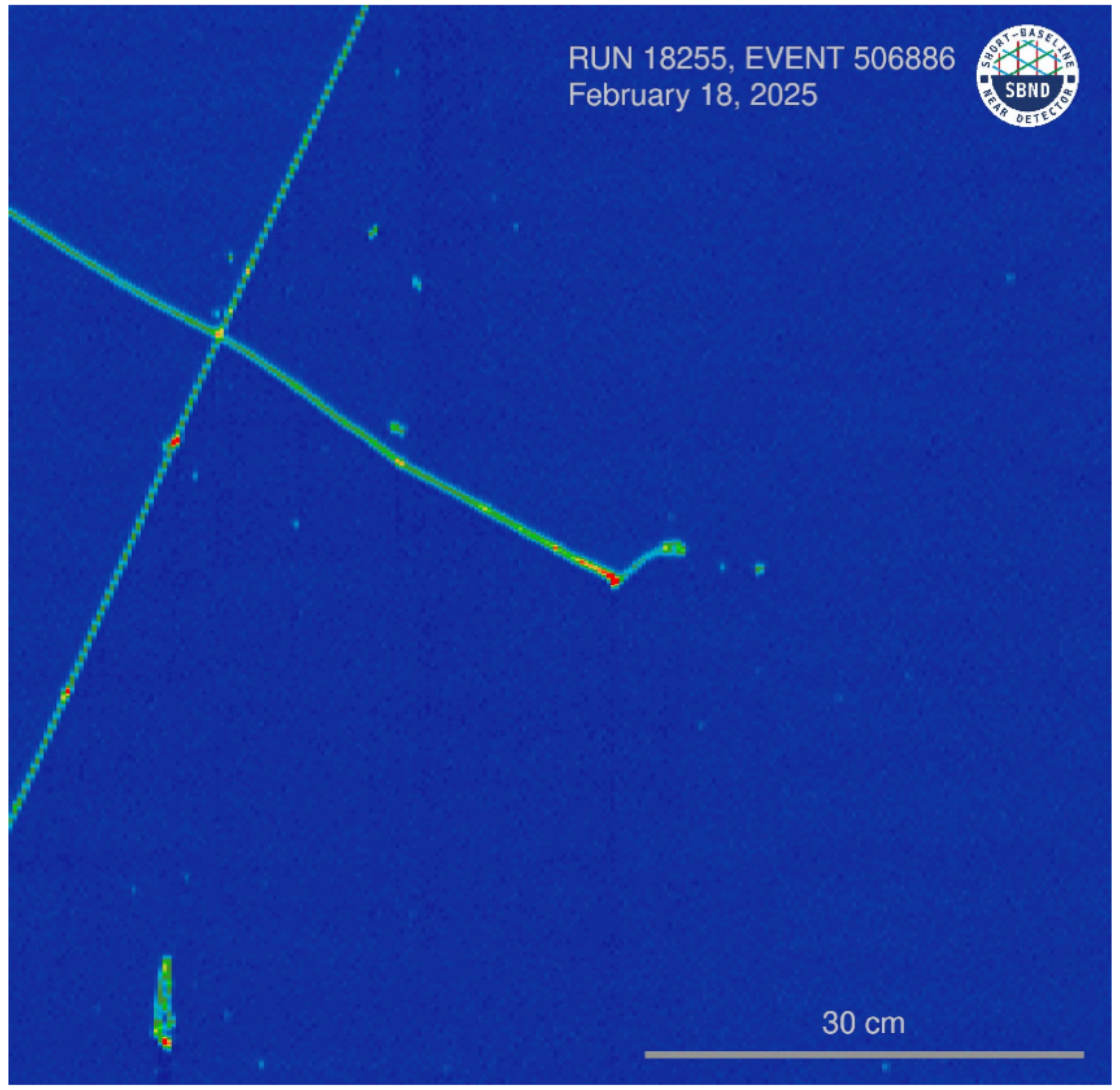
- One of the first steps in calibrating our TPC is characterizing the electric field, including distortions that come from accumulated Ar^+ ions, which is called the space charge effect
- The offsets due to space charge are on average <1cm across the detector, reflecting electric field distortions up to 6% of the nominal field

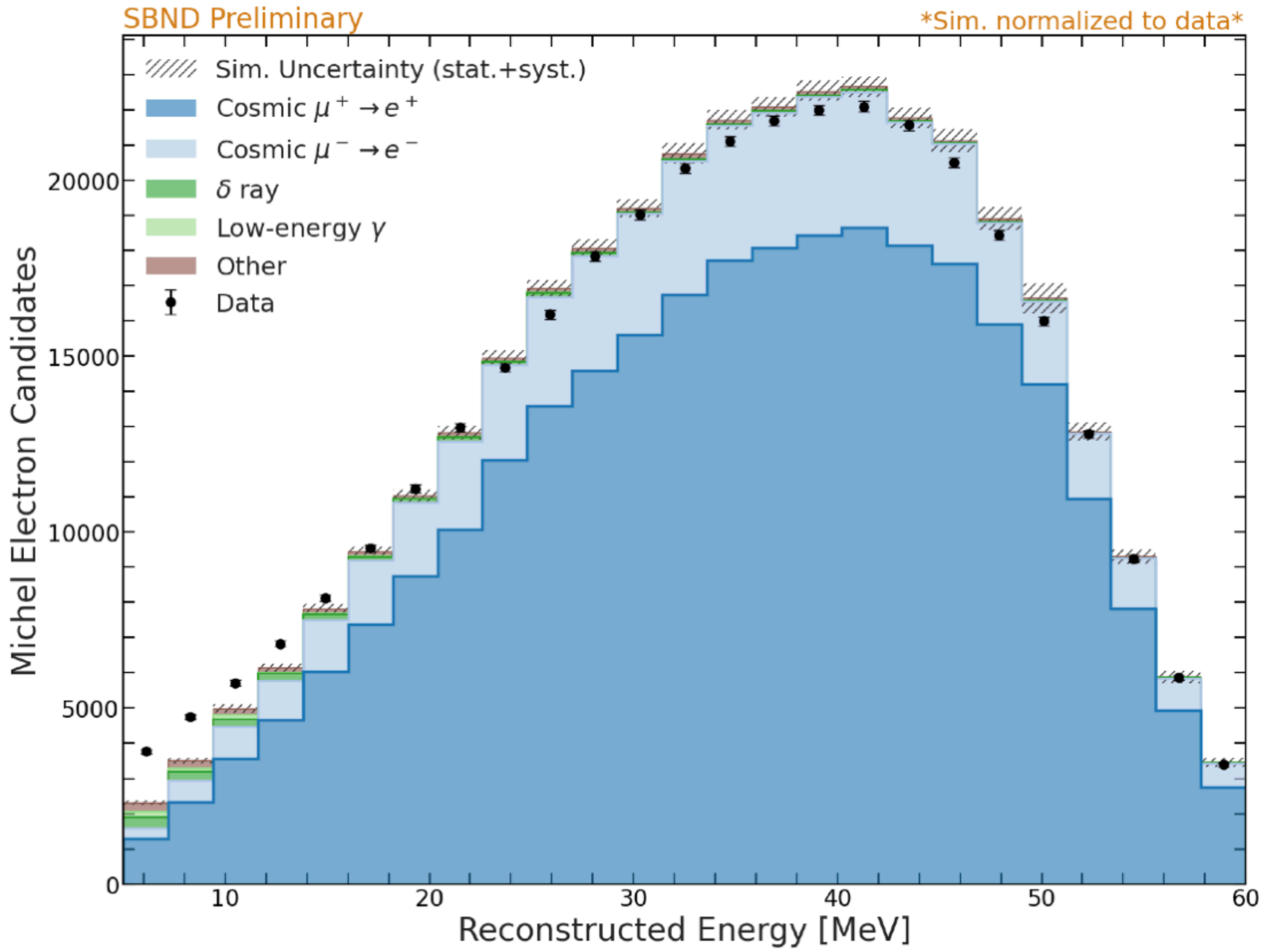




Michelle Spectrum

- Another valuable standard candle is the low-energy Michel electrons produced when muons decay at rest in the detector, which have a well-understood spectrum
- The Michel spectrum shows good agreement with simulation, indicating that we are able to accurately reconstruct these low-energy electrons in data





Flash Match (best match, whole detector) + SPINE (ML) TPC reconstruction
SBND Preliminary Simulation

Cut	Purity [%]	Efficiency [%]	Differential Efficiency [%]	Differential Purity [%]
No cut	3.05	100.0	n/a	n/a
Flash Match (best match, whole detector)	26.29	94.4	94.4	23.25
Fiducial	53.01	91.44	97.04	26.72
Has Muon	77.98	83.59	92.15	24.96
Start dE/dx	86.74	80.23	96.64	8.76
Flash Score	93.12	79.45	99.23	6.38

FIG. 7: Purity and efficiency after each cut of the uncontained selection.

ν_μ CC 1p0π Measurement

- Final state kinematics
  - One muon with $P_\mu \in [220, 1000]$ MeV/c
  - One proton with $P_p \in [300, 1000]$ MeV/c
  - No charged pion with $P_\pi > 70$ MeV/c
  - No neutral pions
  - Other particles not listed are allowed
- Measurement kinematic variables
  - μ and p momentum and direction relative to the beam
  - TKI variables: δp_T, $\delta\alpha_T$, $\delta\phi_T$
- Events required to be fully contained within the detector volume for this first analysis

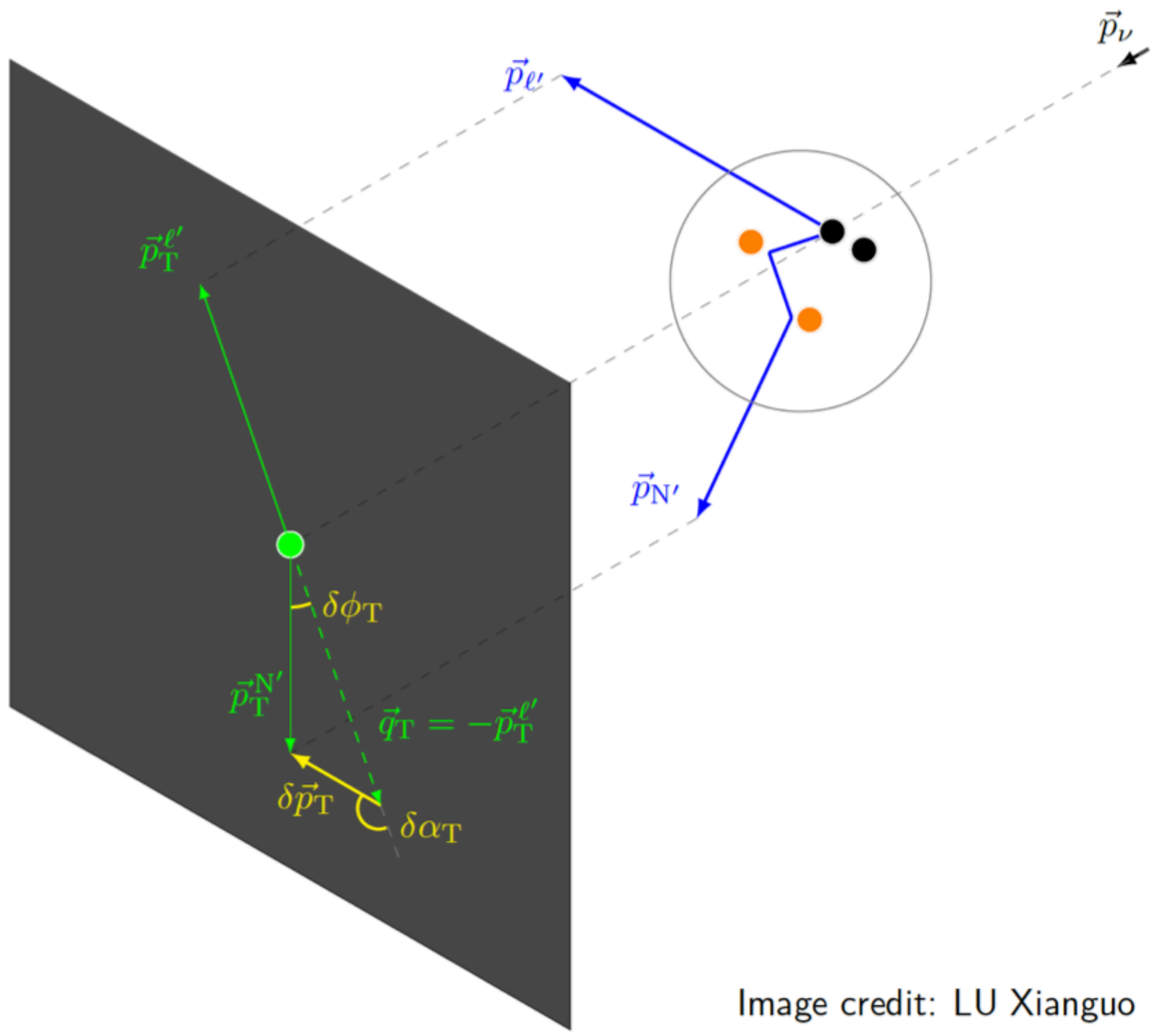


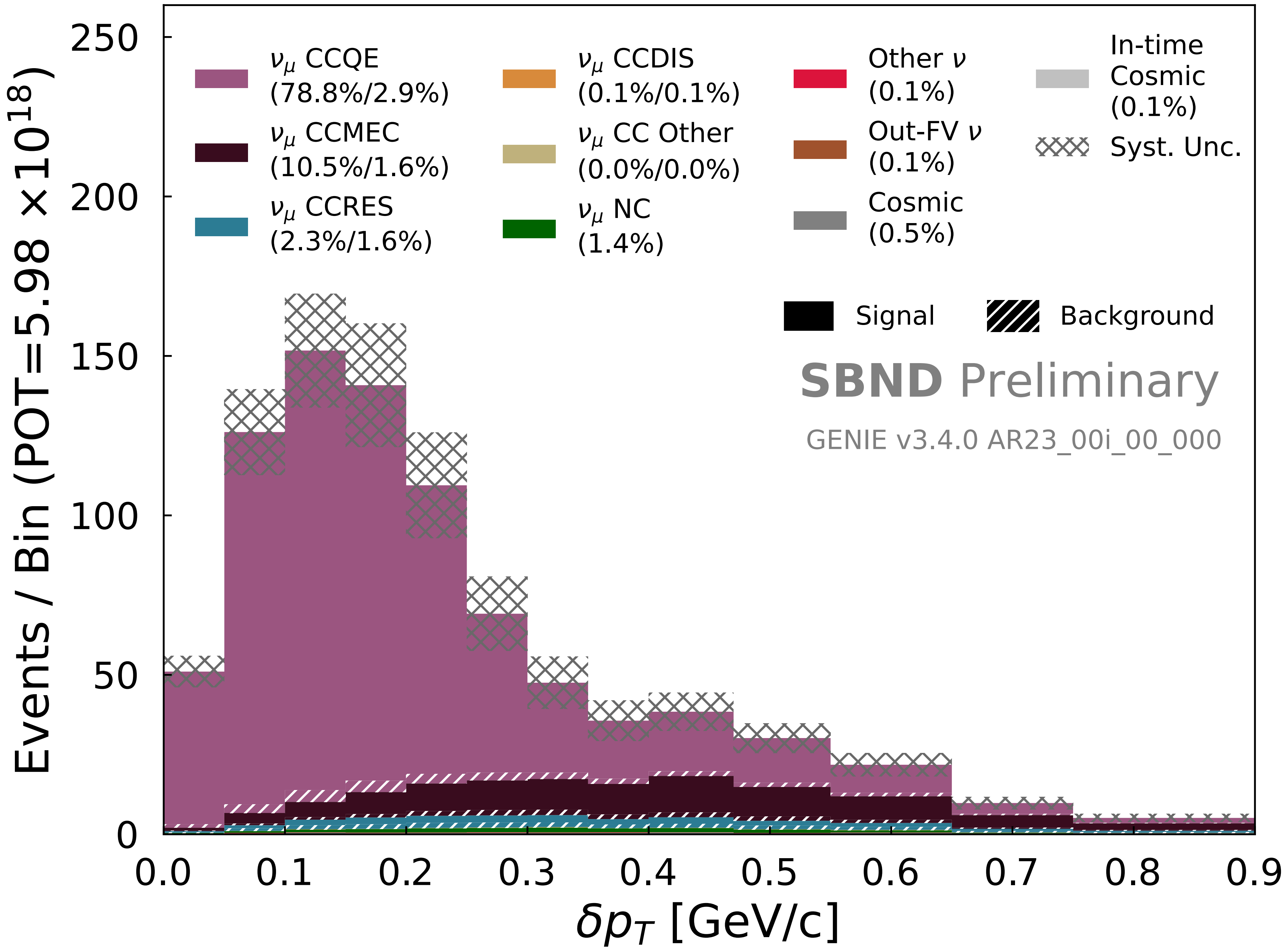
Image credit: LU Xianguo

ν_μ CC 1p0π Event Selection

- TPC-only event selection
  - Cosmic rejection
    - Select neutrino-like events
    - SBND benefits from lower cosmic background rates than other SBN detectors
    - Efficiency: 78.7%, signal purity: 20.7%, CCQE purity: 33.2%
  - 2-track topology selection
    - Select clean events with only two particle trajectories emerging from a common vertex
    - Efficiency: 26.3%, signal purity: 58.9%, CCQE purity: 62.7%
  - Muon-proton candidate selection
    - Identify events where the two tracks are classified as muon-like and proton-like using calorimetry-based PID scores
    - Efficiency: 20.3%, signal purity: 92.1%, CCQE purity: 81.7%

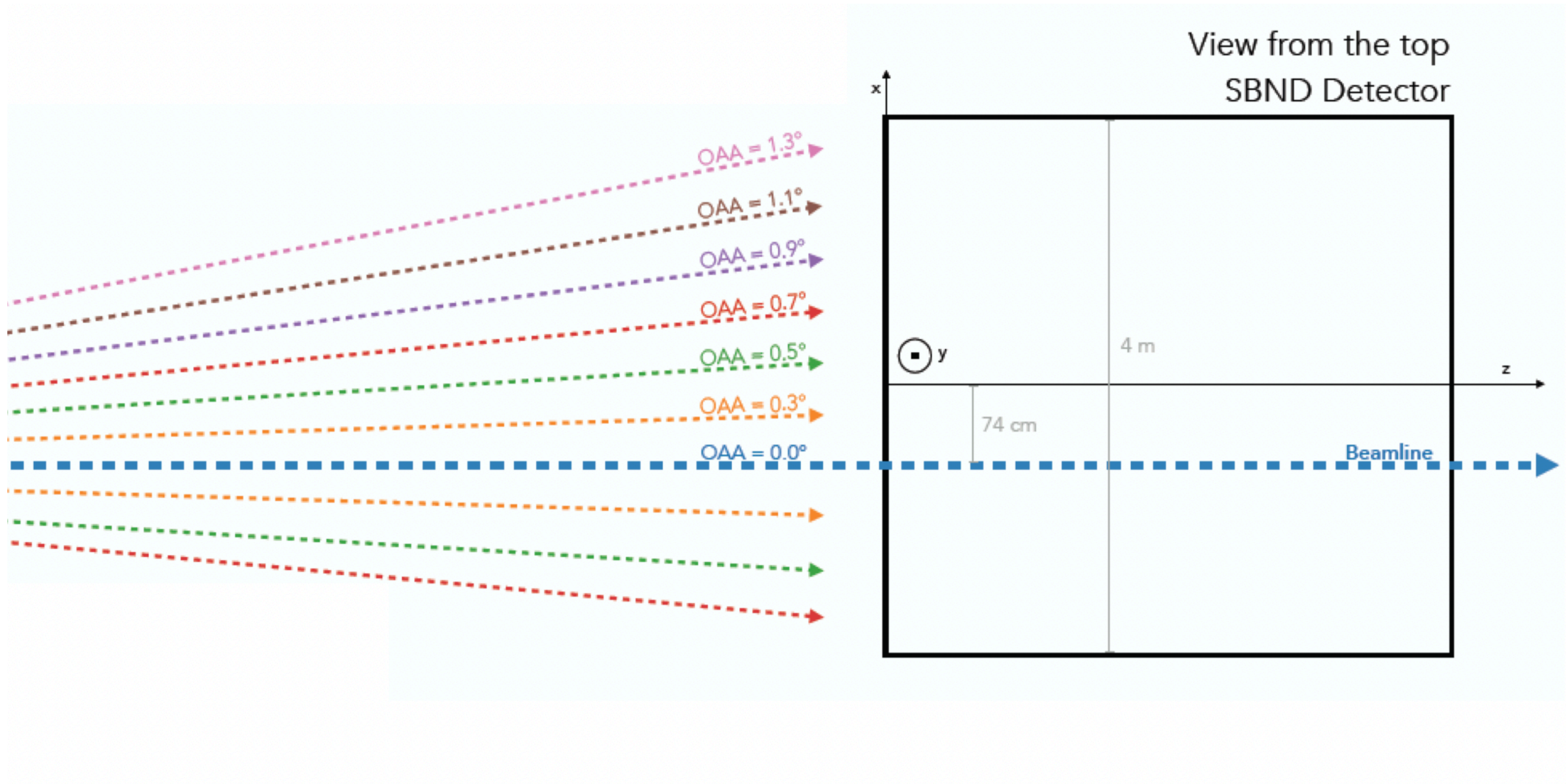
SBND Cross Sections: ν_μ CC 1p0π

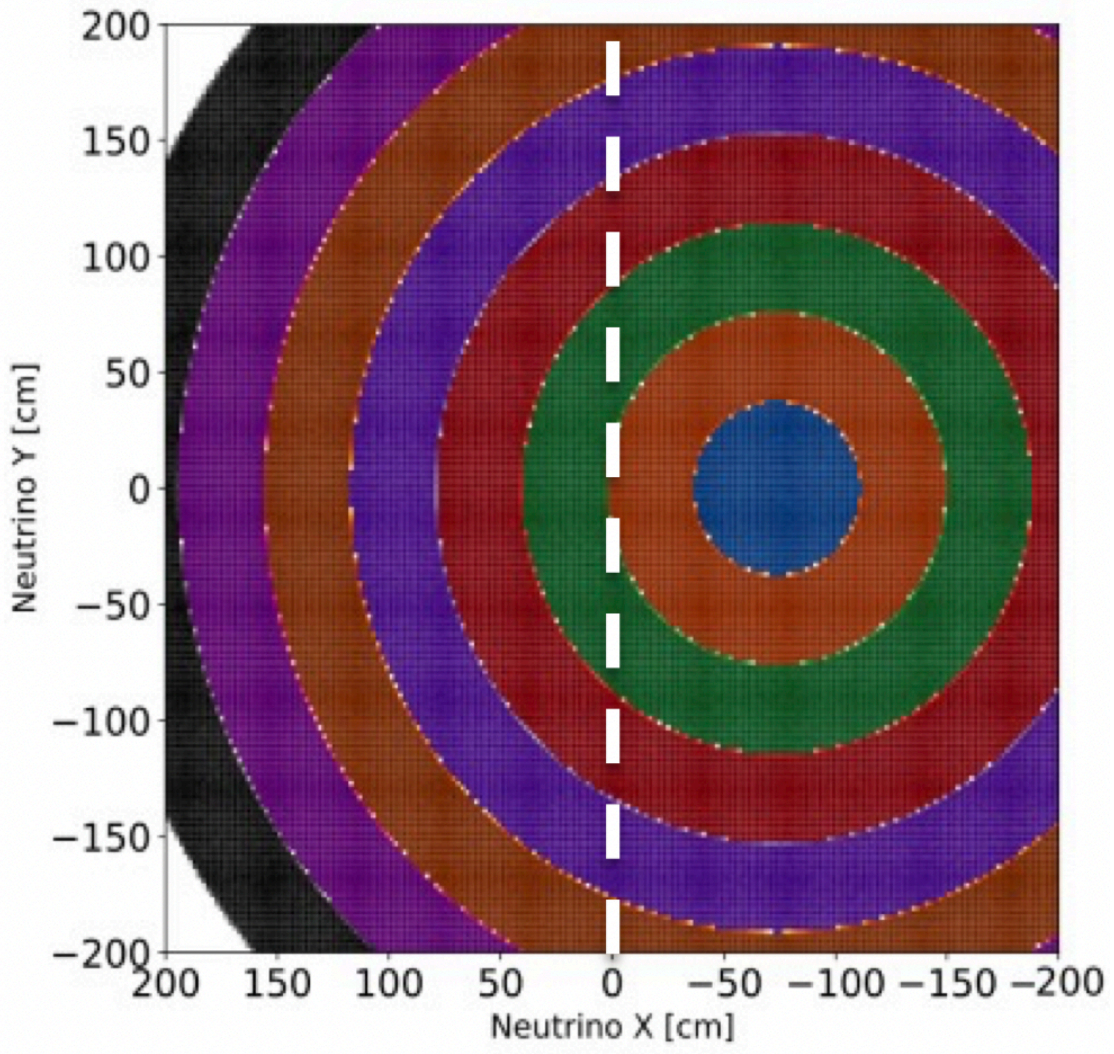
- Targets the quasi-elastic mode and enables observation of low Q^2 effects
- Measurements in muon and proton kinematics as well as **T**ransverse **K**inematic **I**mbalance variables (TKI)
- Allows for the study of nuclear effects
- Estimated 2 million signal events after 3 years of data taking
- 88 % purity at 38% efficiency

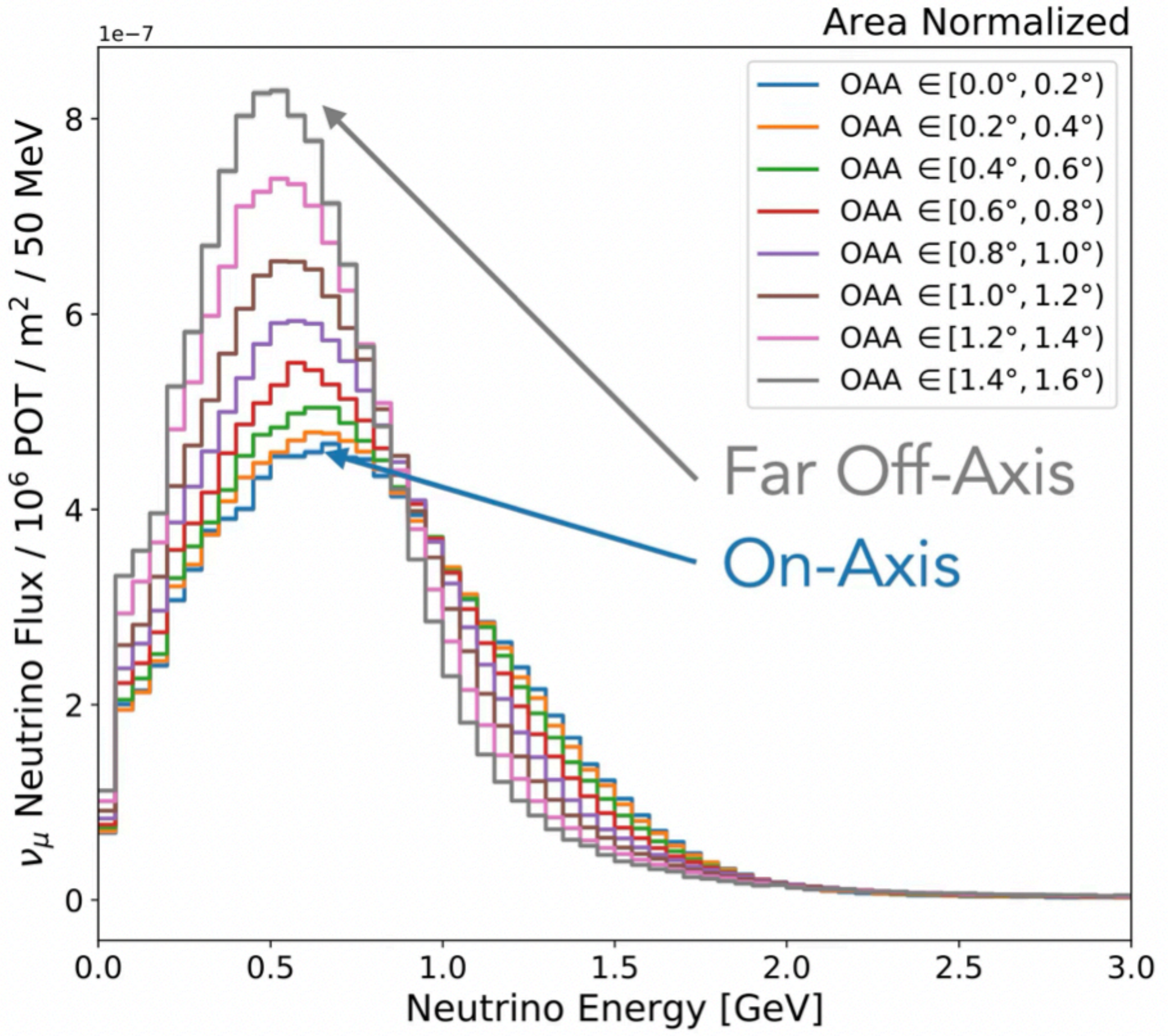


SBND Neutrino Flux: PRISM

- **P**recision **R**eaction **I**ndependent **S**pectrum **M**easurement: https://arxiv.org/abs/2508.20239
- SBND sits 74 cm off-axis and its close proximity to the beam allows it to probe an angular range of [0, 1.6] degrees
- Neutrino energy spectrum changes with angle







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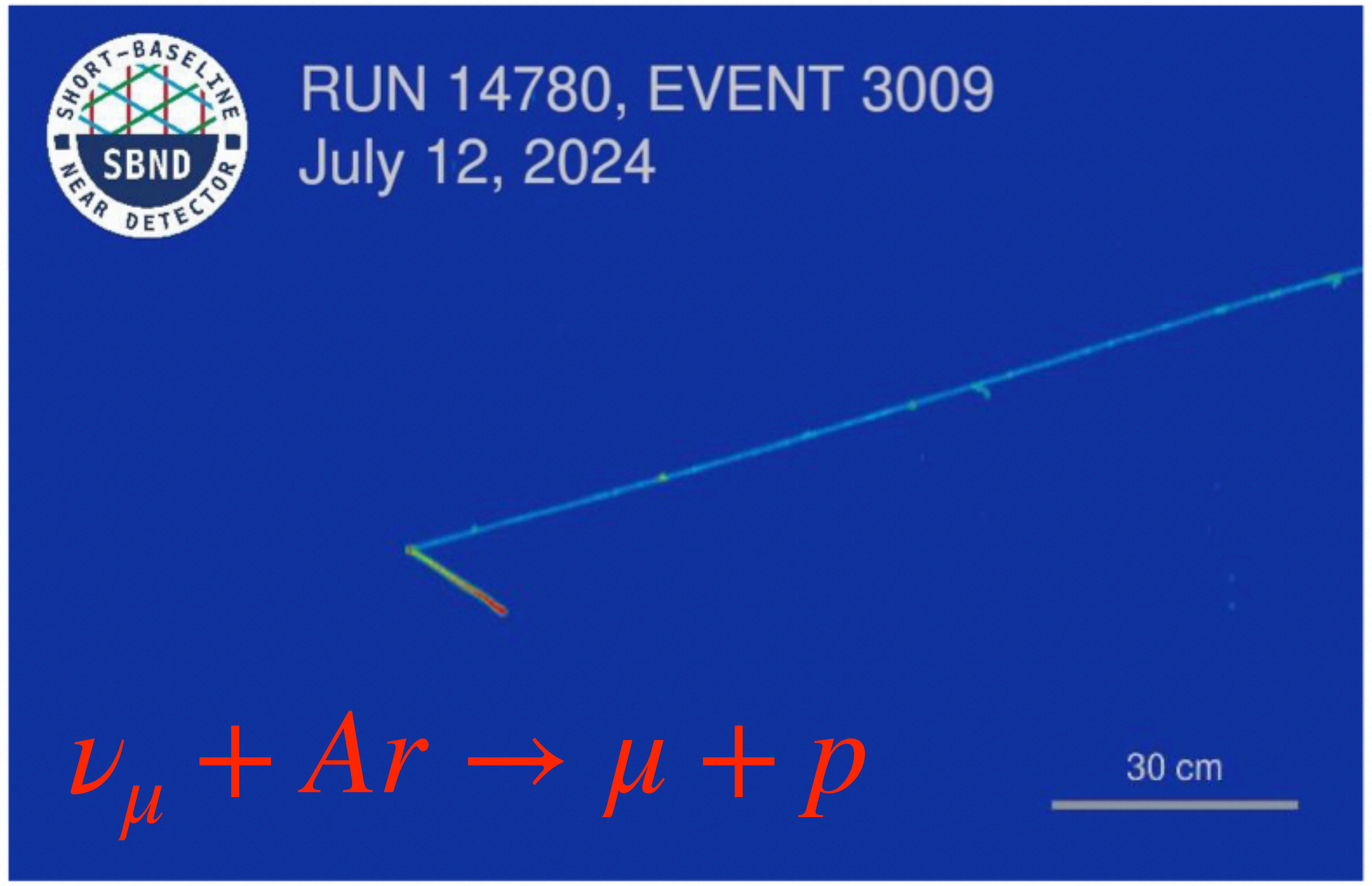
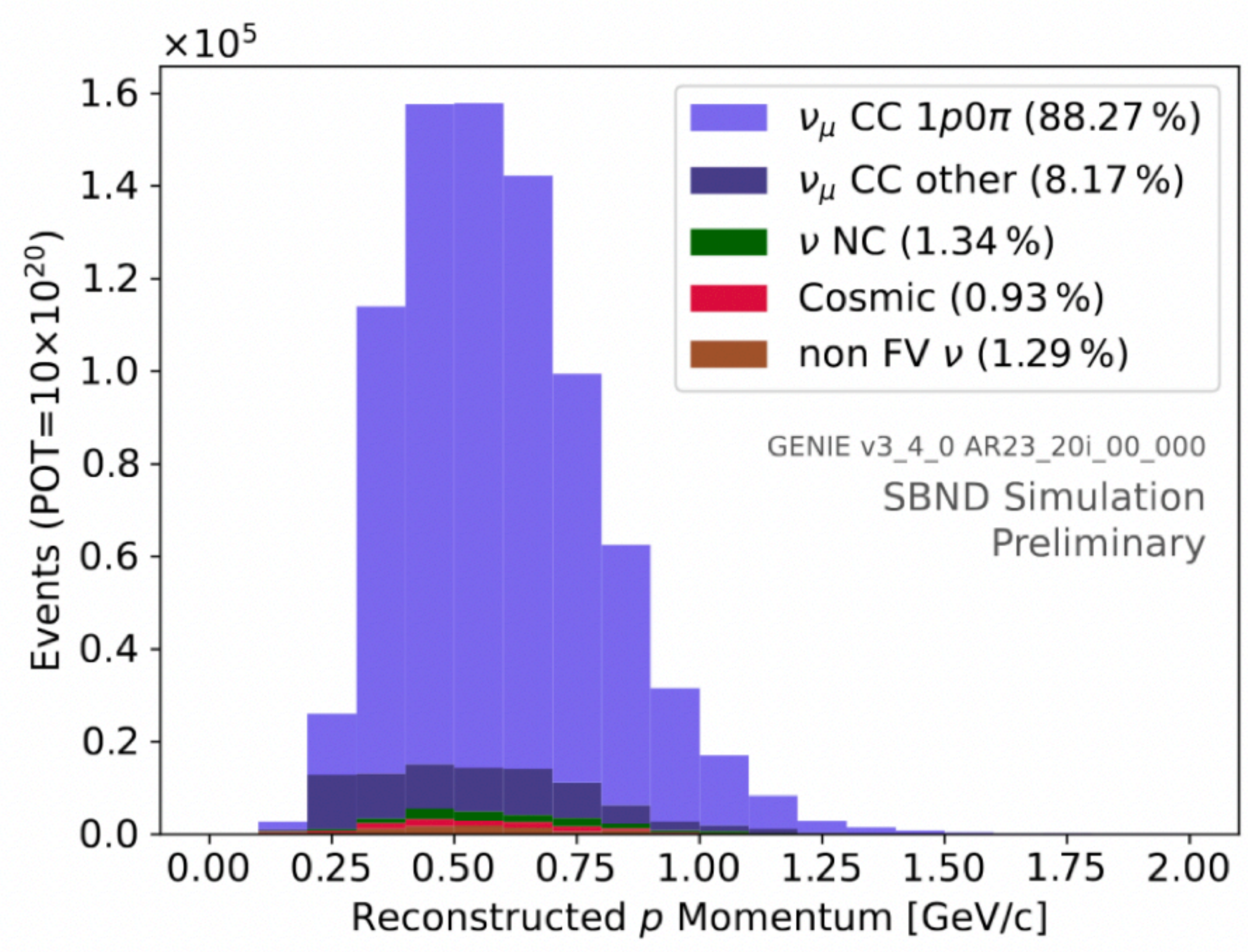
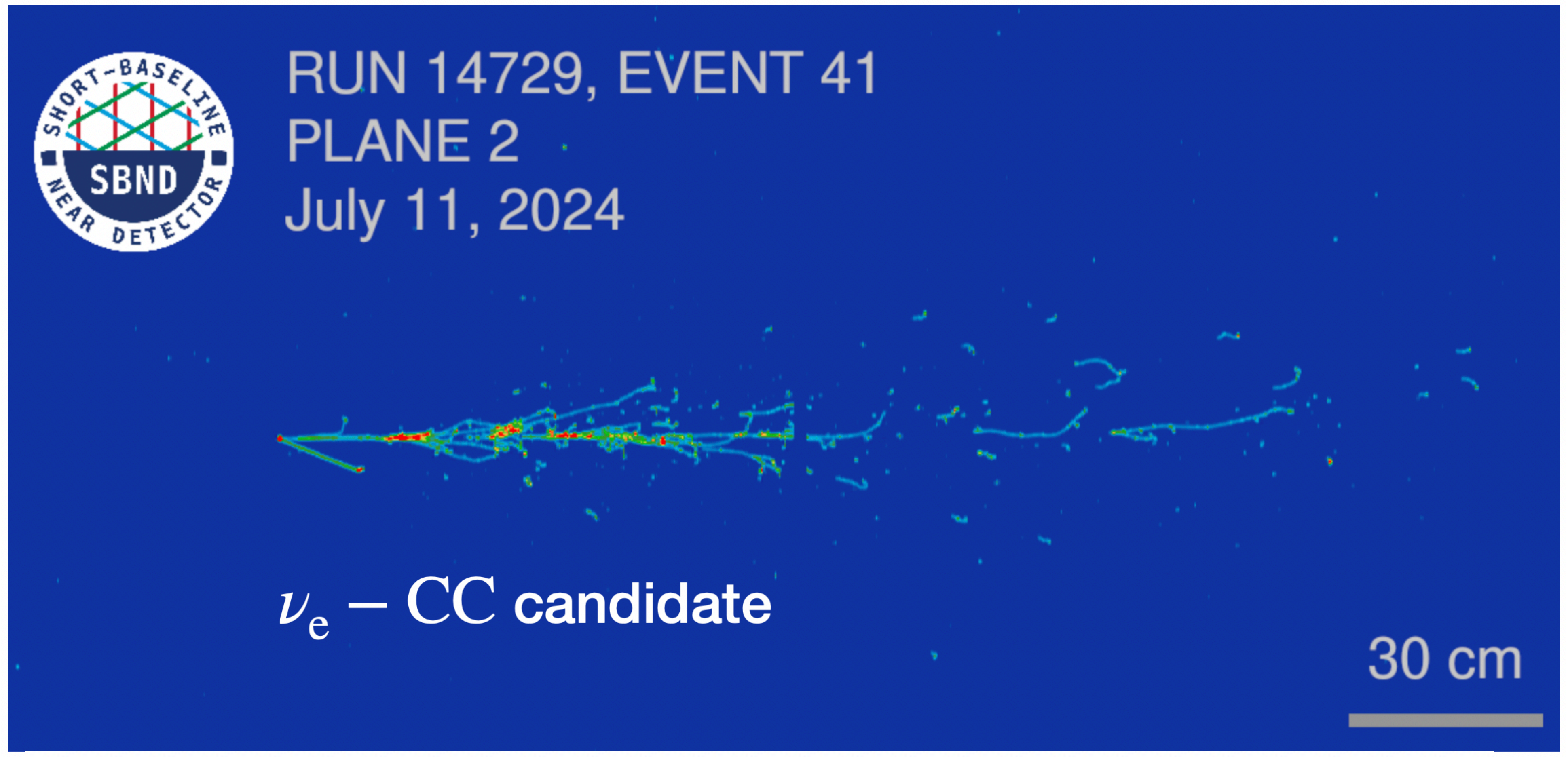
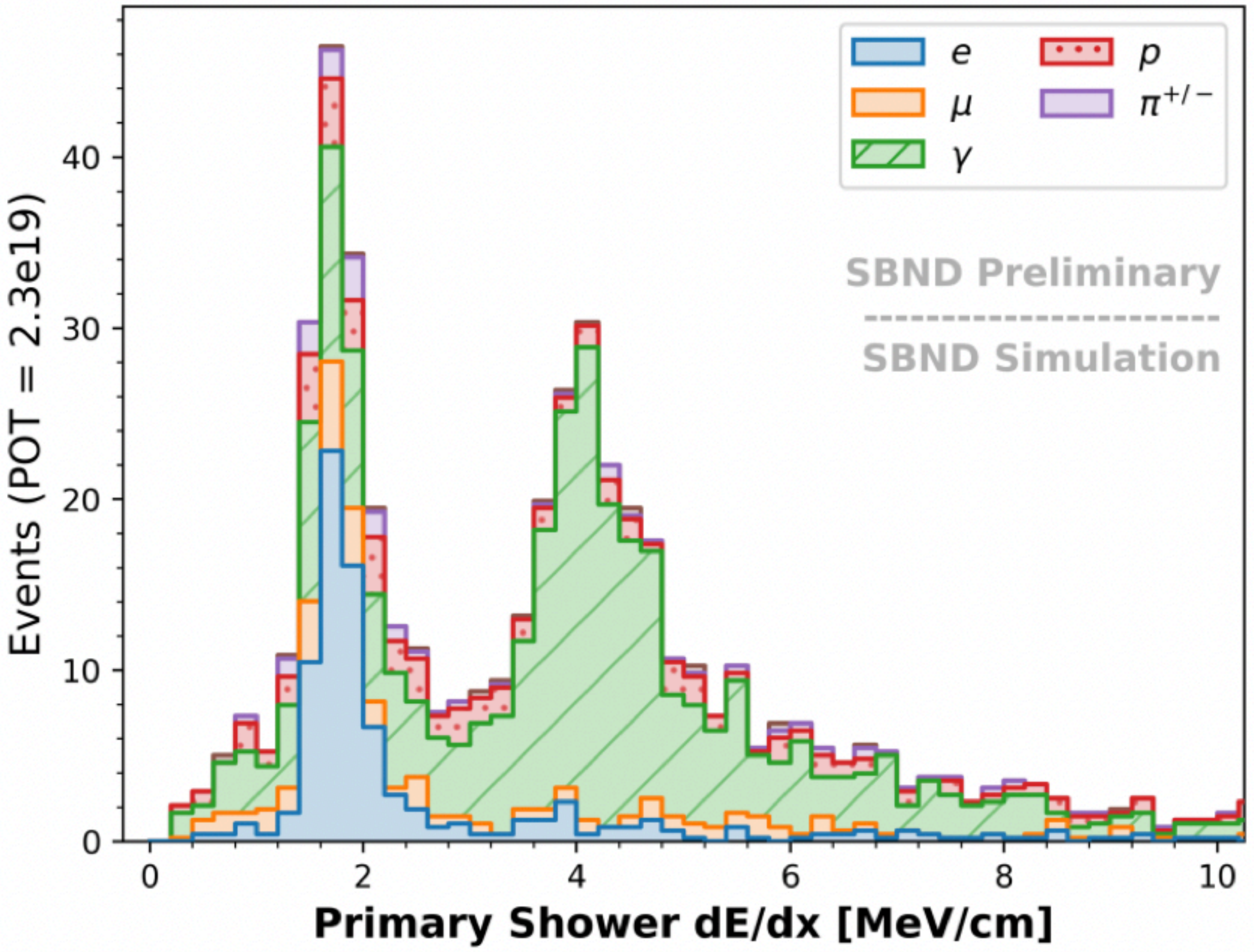




SBND Cross Sections: ν_e CC Inclusive

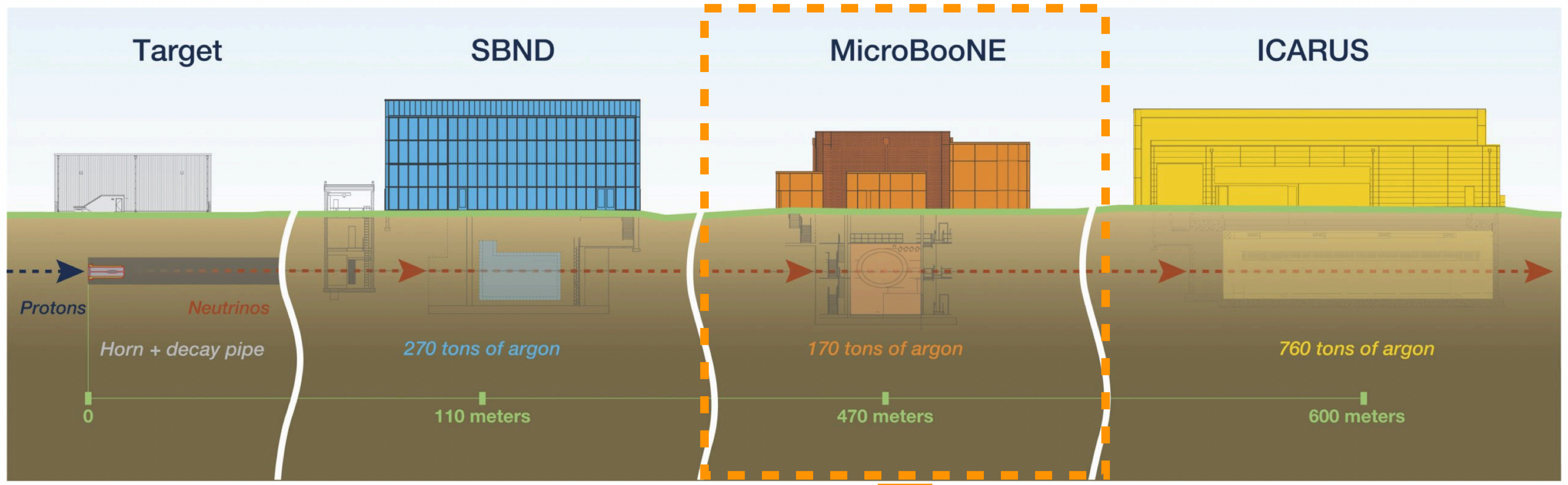
- Despite small contribution to the BNB flux, still expect ~15,000 events/year
- Important for oscillation physics which uses the LAr-TPCs ability to distinguish between electrons and photons
- Variables such as the shower opening angle, dE/dx and distance between vertex and shower start help to select electrons
- 78% purity and 31% efficiency for $E_e > 500$ MeV





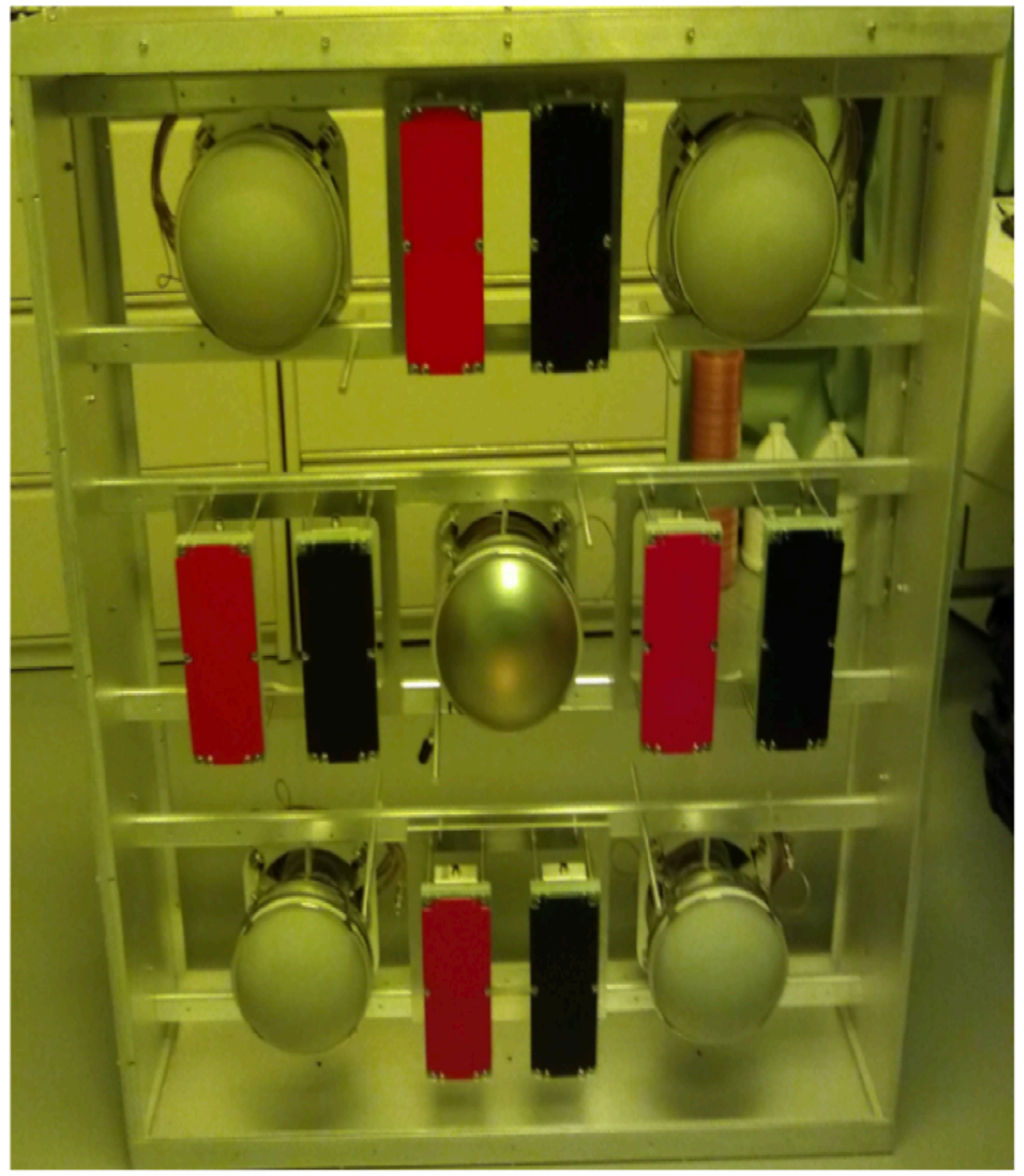
Why Use a LAr-TPC?

- **LAr-TPCs provide calorimetry and 3D tracking with fine-grained information**
  - Capable of identifying different species of particles
  - Particle Flow: parent vs daughter particles
  - Track vs Shower, Interaction Vertex, etc
  - **Generational Knowledge**
    - **LAr-TPCs are a well-understood technology and we benefit from the experience of many past experiments (ICARUS, ArgoNeuT, MicroBooNE …)**

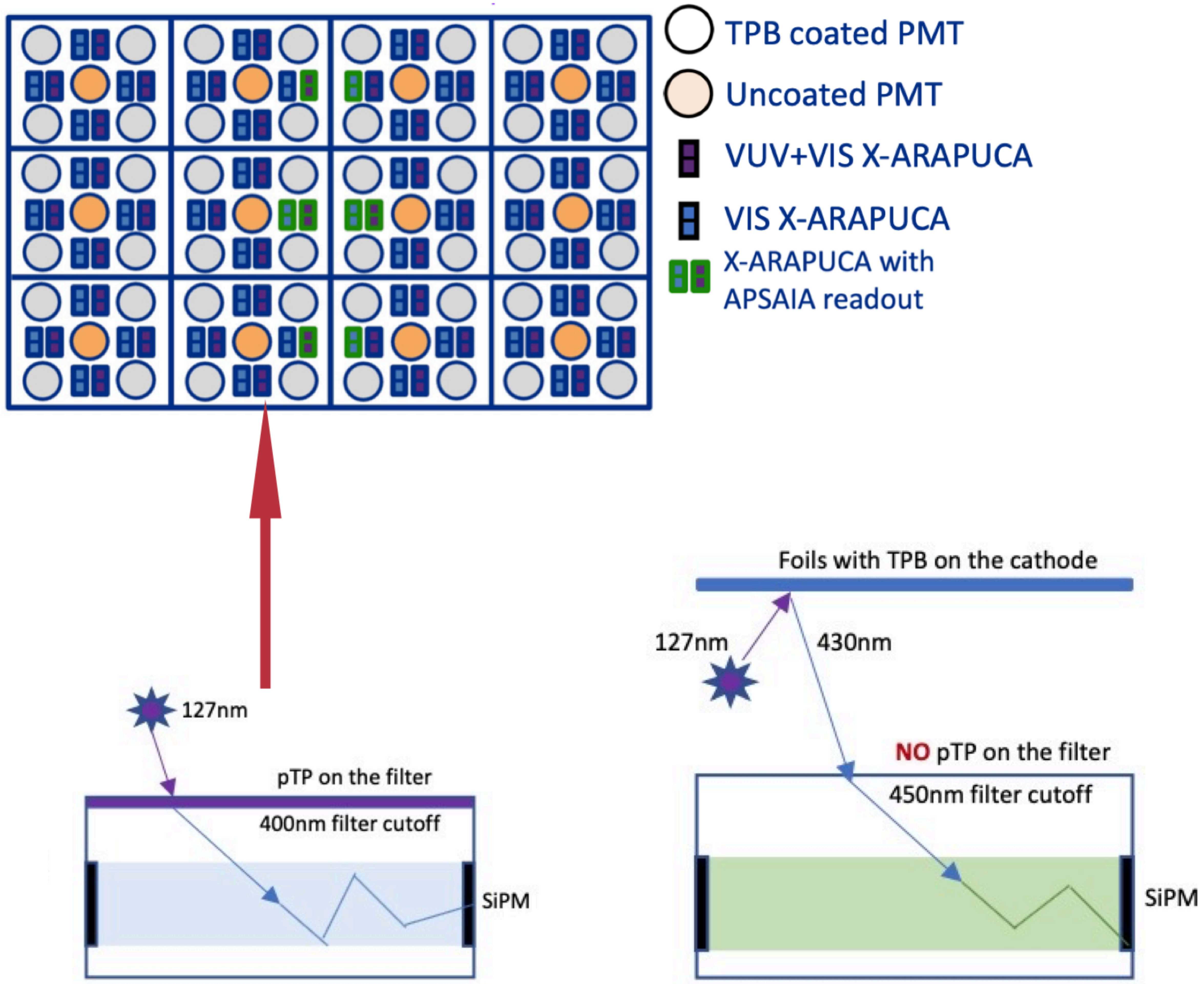


SBND Photon Detection System (PDS)

Modular system behind the APAs: "looking" inside the TPC with 24 modules (12 per side)



Each module has 5 8” PMTs (120 total) and 8 X-ARAPUCAS (192 total).



X-ARAPUCA's

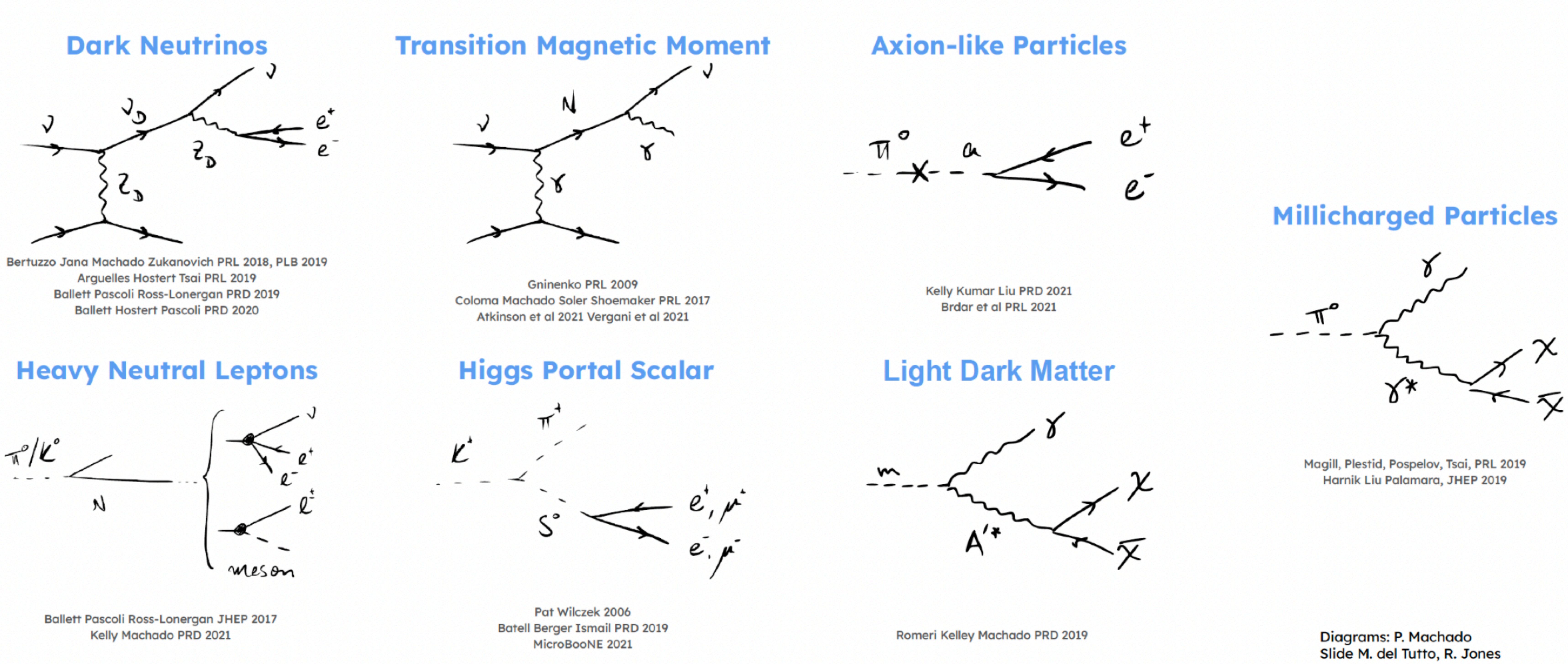
Alternative BSM Stuff

Beyond the Standard Model searches at SBND

- High-intensity proton beams (high-intensity neutrino beams)
- SBND's proximity to the target

→

- Access to various BSM scenarios as alternative to MiniBooNE's anomaly.
- Probe signatures for new physics scenarios in the neutrino sector and beyond.



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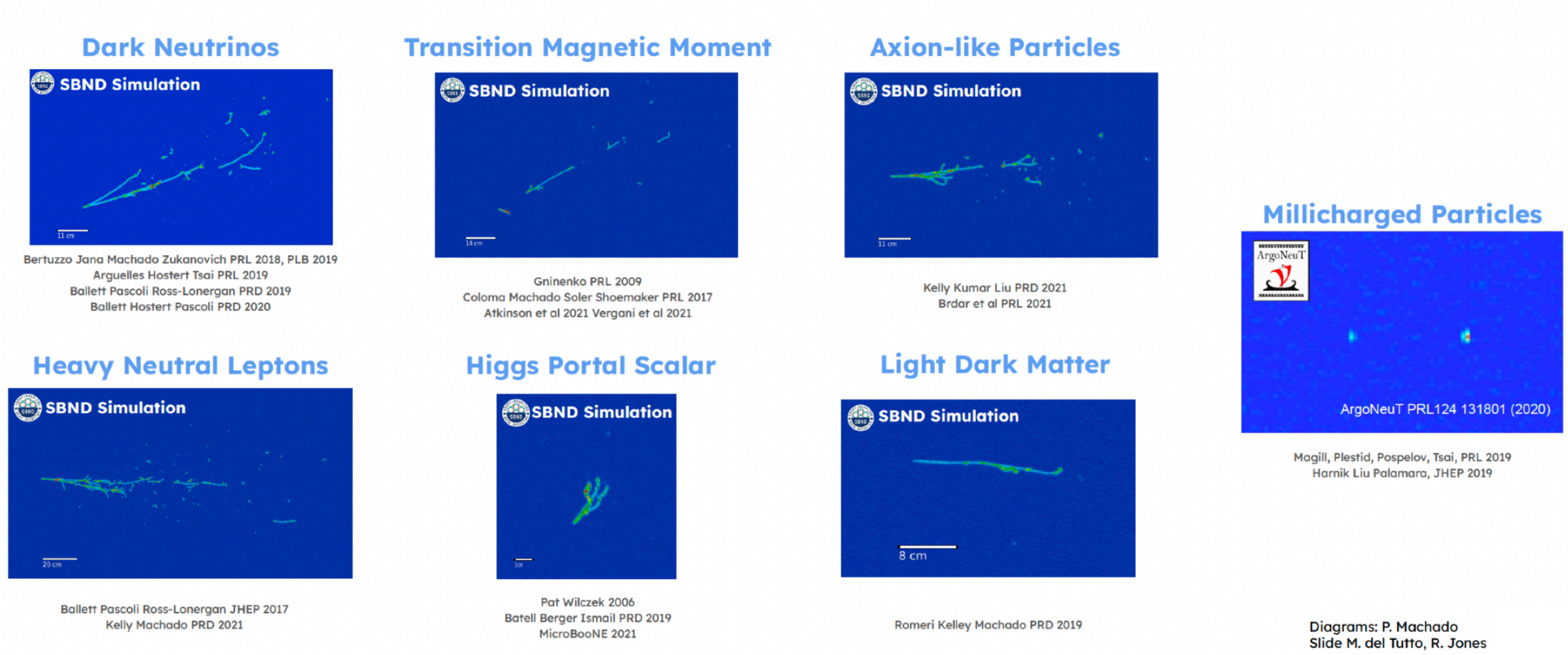
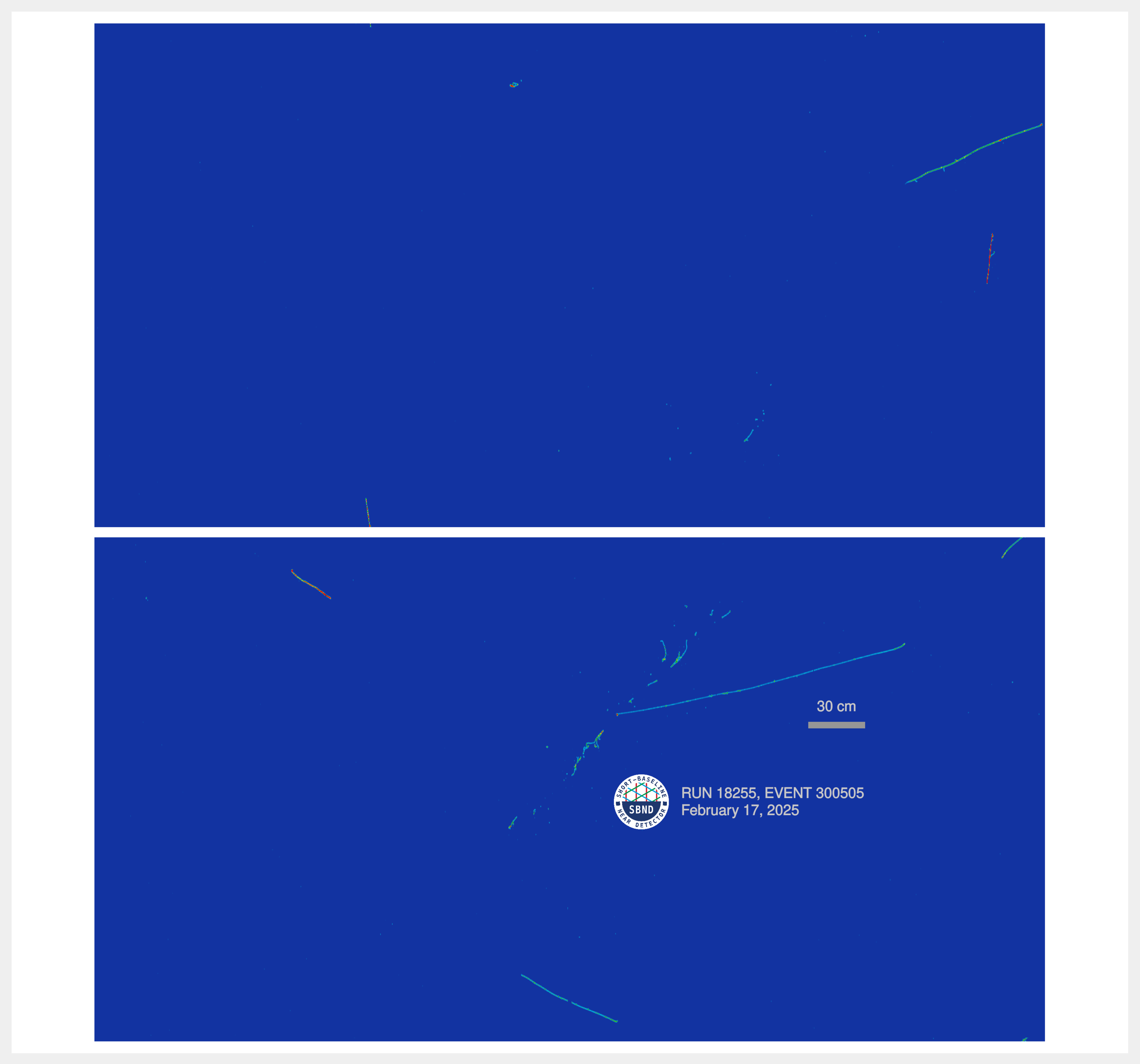
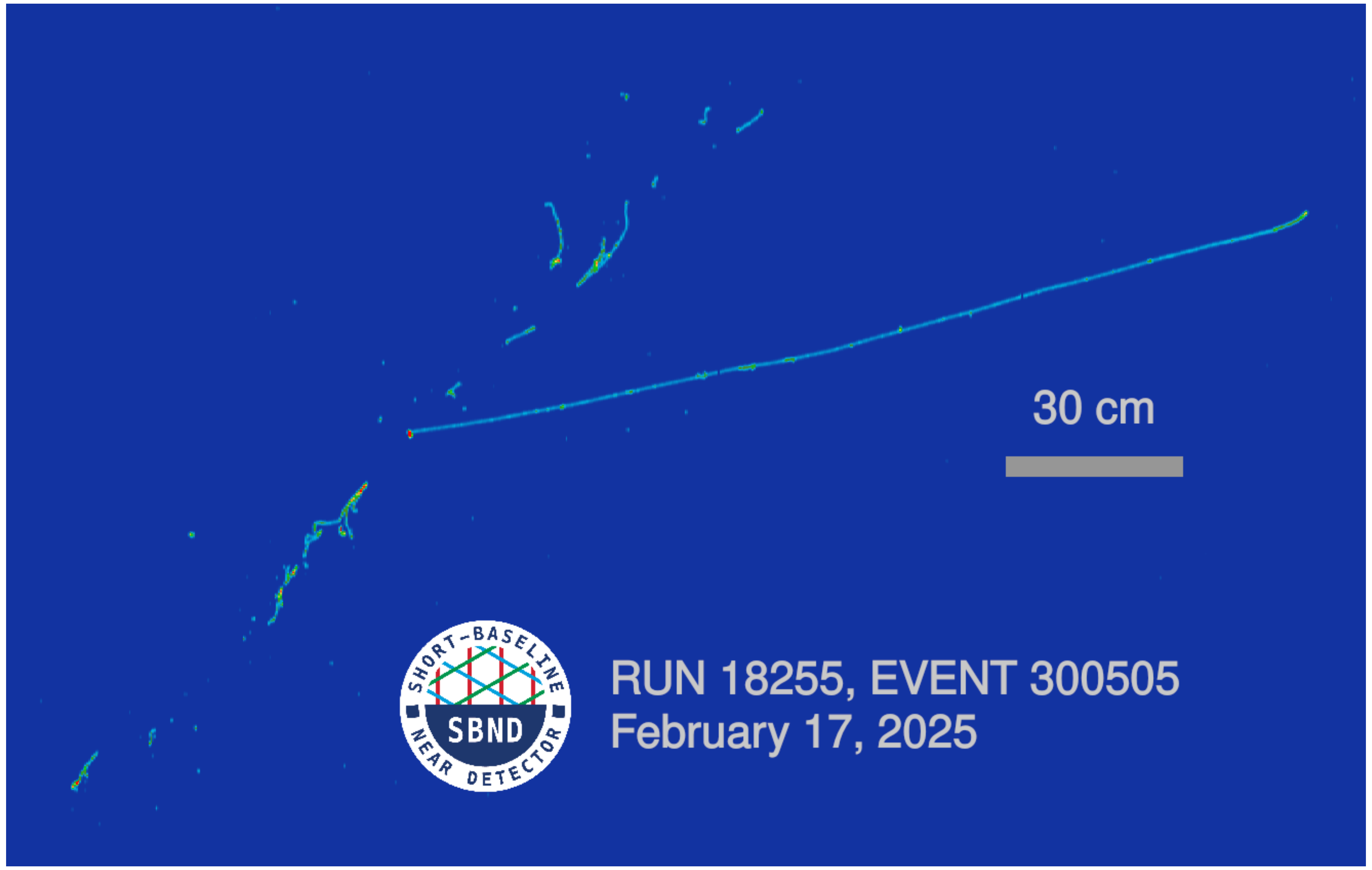


Coherent Candidate

Eta Meson Display





Pi0 Display