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SHORT-BASELINE NEAR DETECTOR SBND

Searches for Beyond the Standard Model Physics at the Short-Baseline Near Detector

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The University of Edinburgh

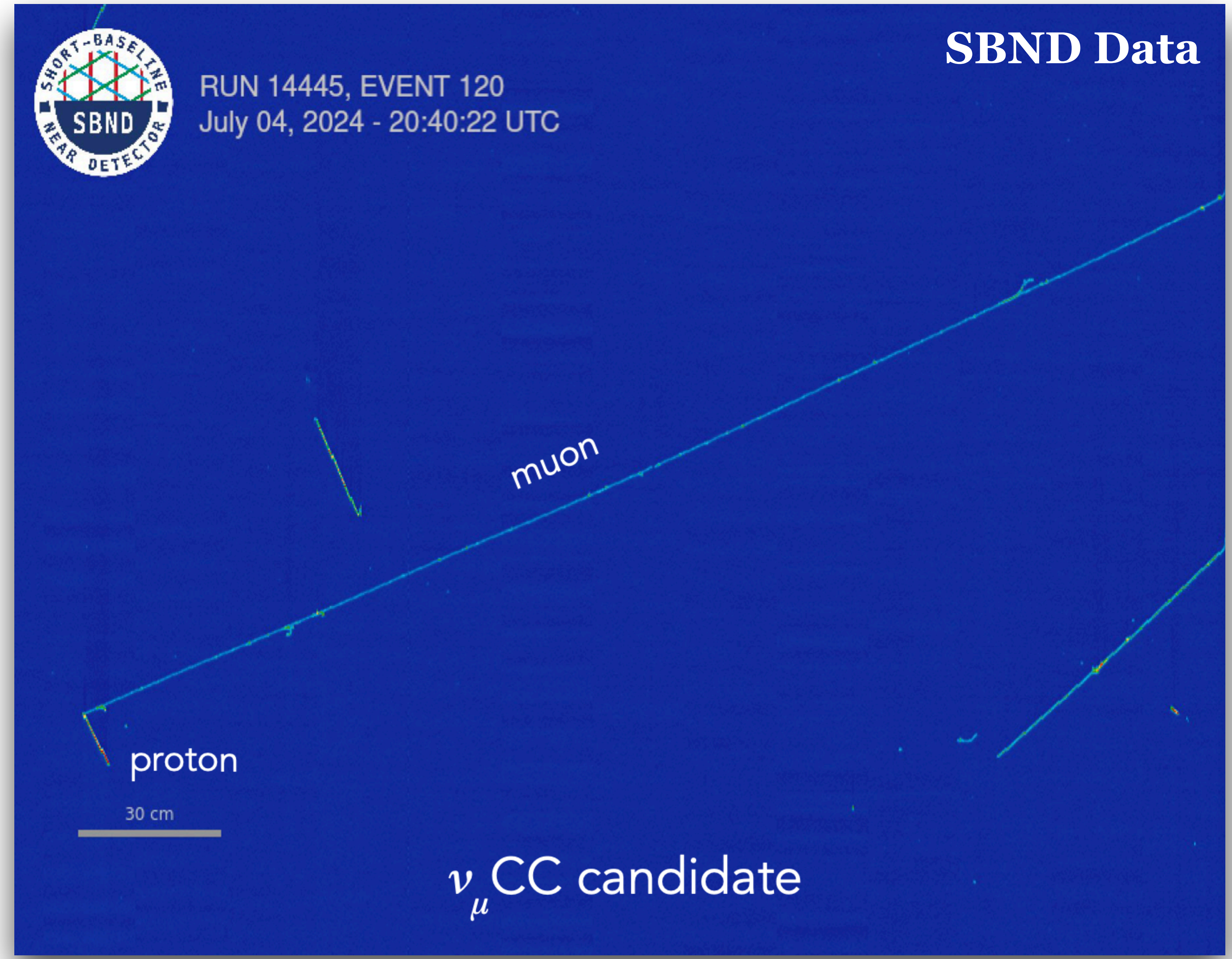
On behalf of the SBND Collaboration

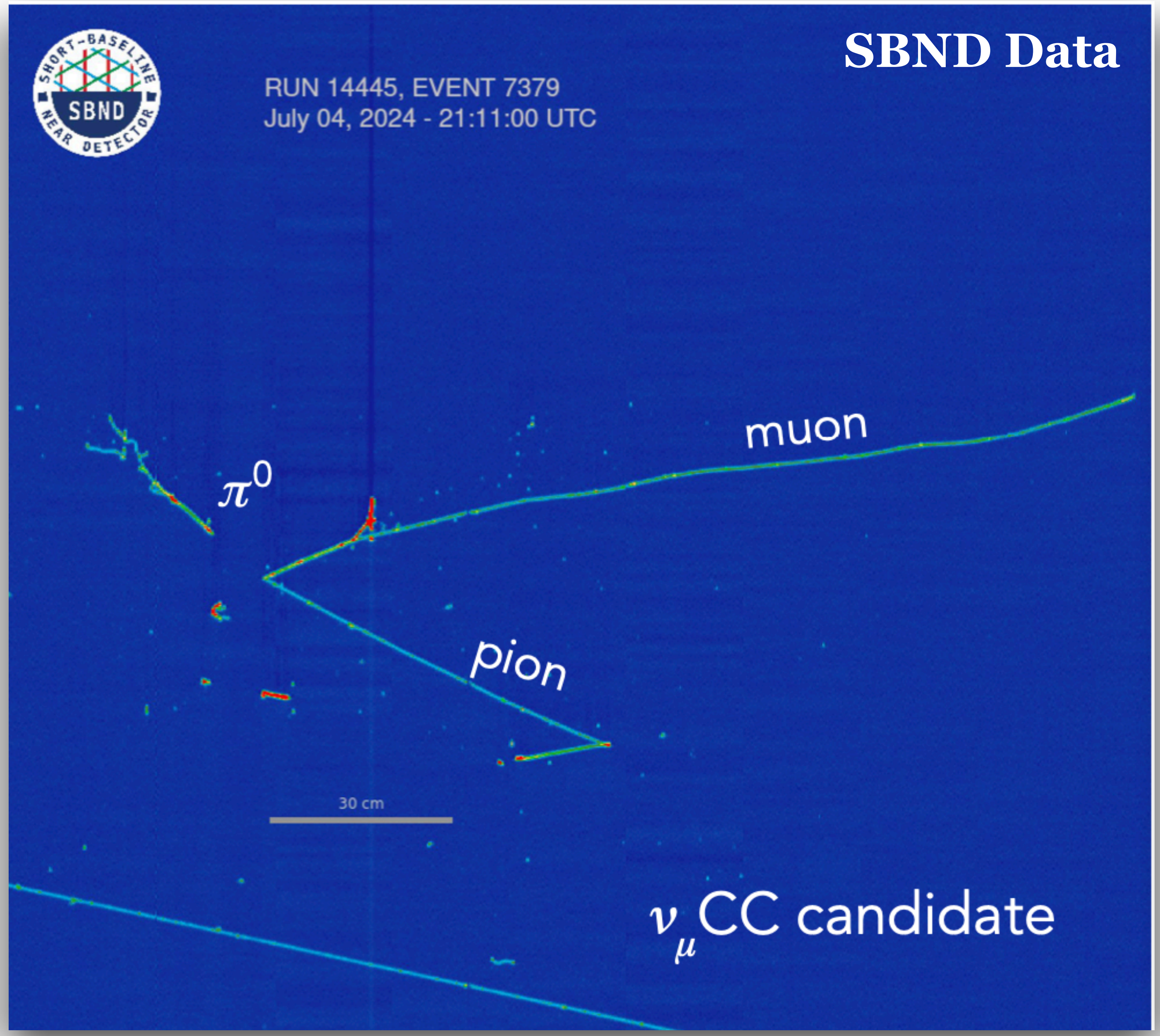
International Conference On High Energy Physics

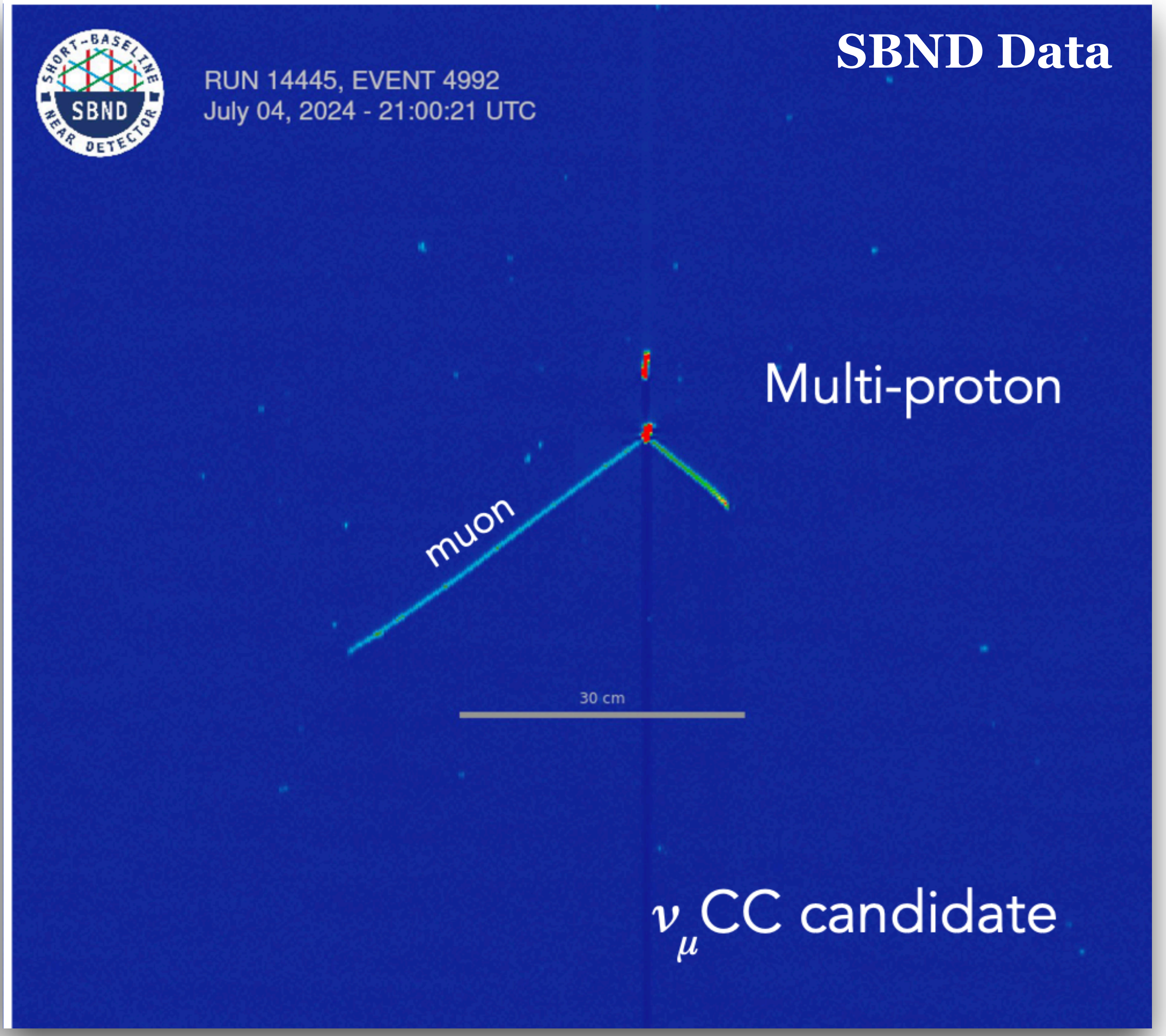
Prague, Czech Republic

July 18 - 24, 2024

SBND Data Event Display







SBND is now fully operational and has started to collect beam data from the 4th of July!
These are first-ever event displays from the early data collection :))

SBND Data Event Display

08:30 → 10:15 **Neutrino Physics** Panorama

10:00 **Status of the Short-Baseline Near Detector at Fermilab** 15m

The Short-Baseline Near Detector (SBND) is one of three Liquid Argon Time Projection Chamber (LArTPC) neutrino detectors positioned along the axis of the Booster Neutrino Beam (BNB) at Fermilab, as part of the Short-Baseline Neutrino (SBN) Program. The detector is currently being commissioned and is expected to take neutrino data this year. SBND is characterized by superb imaging capabilities and will record over a million neutrino interactions per year. Thanks to its unique combination of measurement resolution and statistics, SBND will carry out a rich program of neutrino interaction measurements and novel searches for physics beyond the Standard Model (BSM). It will enable the potential of the overall SBN sterile neutrino program by performing a precise characterization of the unoscillated event rate, and constraining BNB flux and neutrino-argon cross-section systematic uncertainties. In this talk, the physics reach, current status, and future prospects of SBND are discussed.

Speaker: Rodrigo Alvarez-Garrote (CIEMAT - Centro de Investigaciones Energéticas Medioambientales y Tec. (ES))

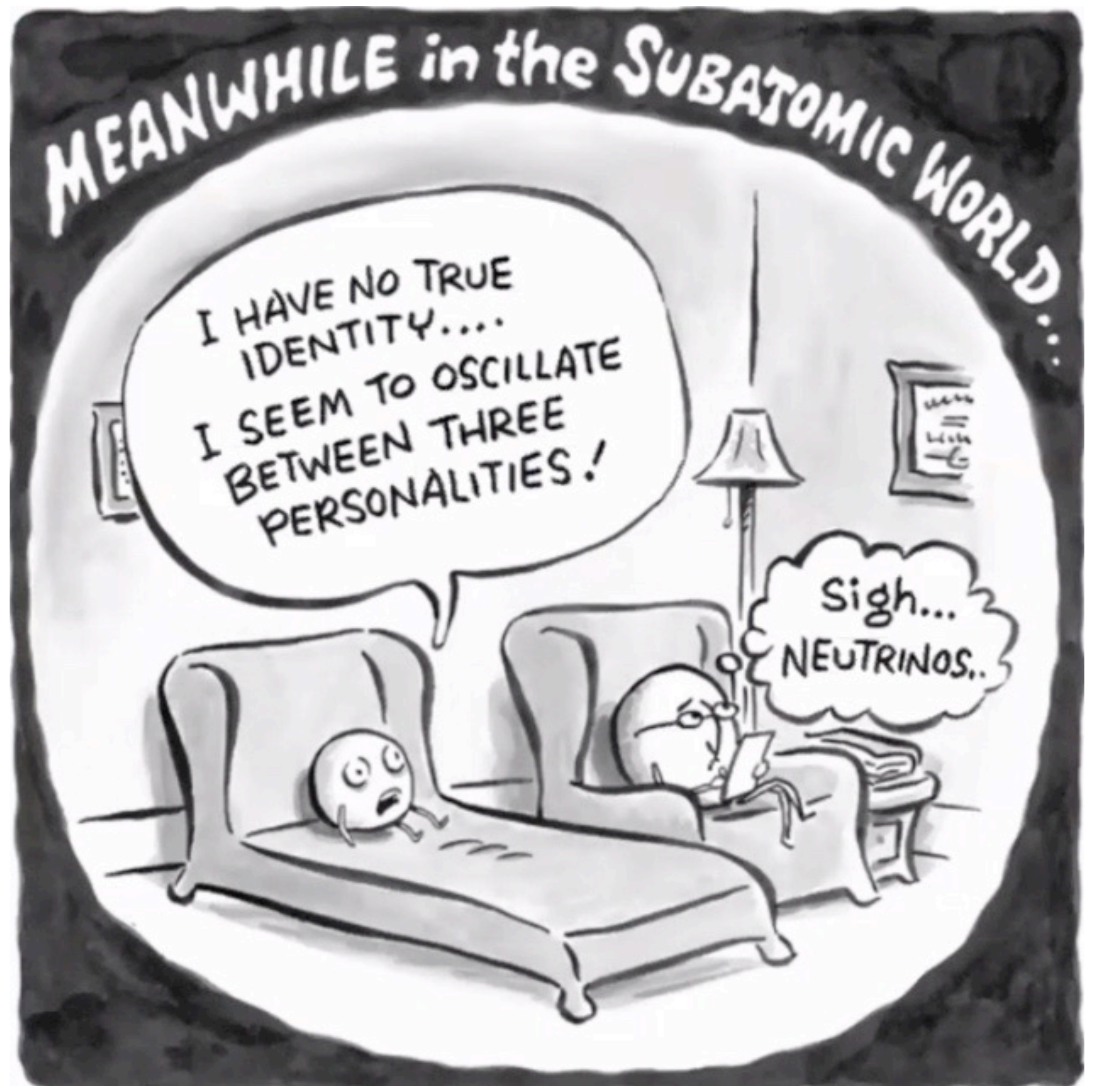
More details about SBND status can be found in Rodrigo Alvarez-Garrote's talk at 10 am today ;-)

Standard Model Neutrino

- Measurement of the Z boson at LEP shows there are three flavours of neutrino with SM weak interactions
- Neutrinos mix and oscillate among three different flavours, and the oscillation can be described by the PMNS matrix

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} .$$

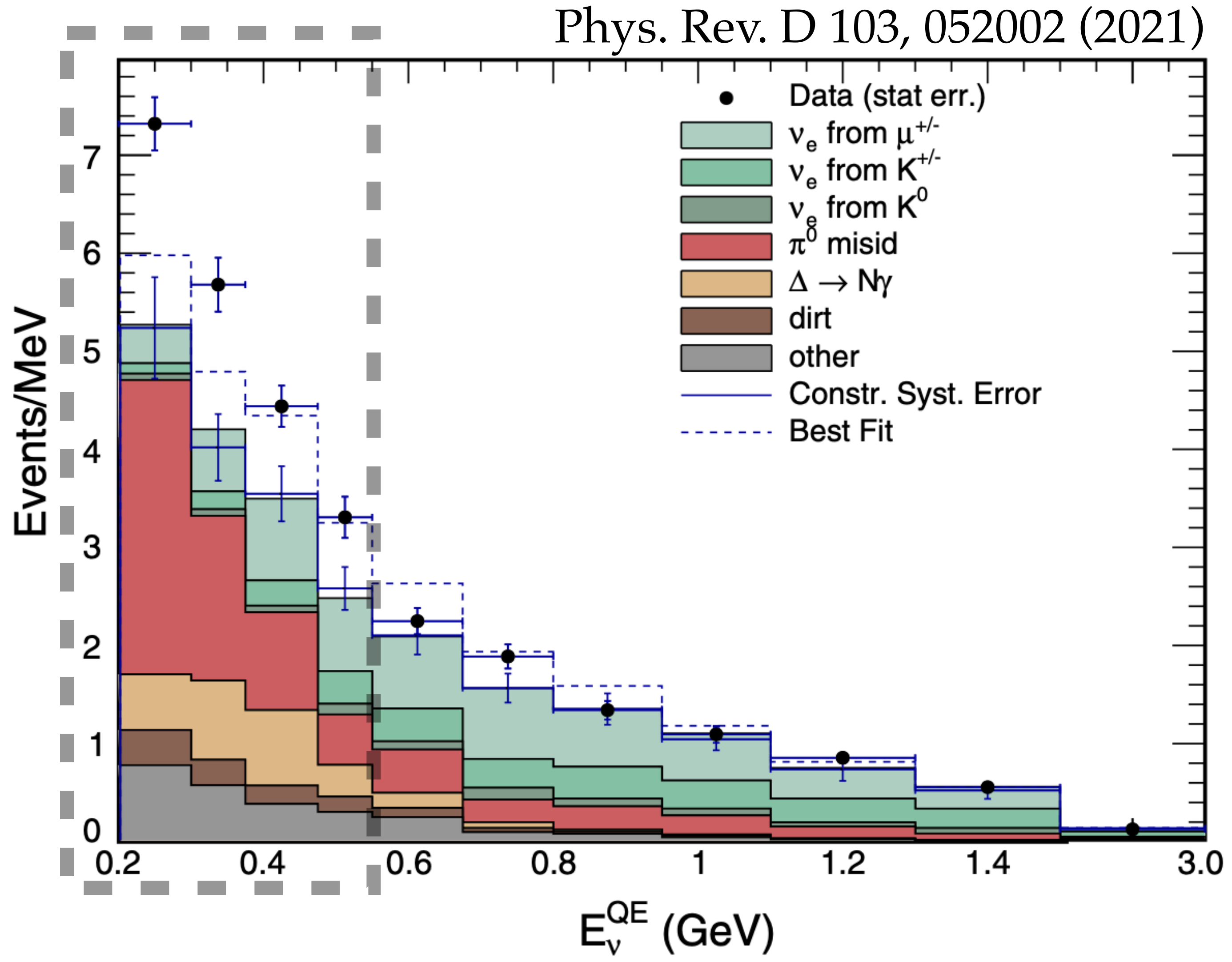
PMNS matrix



Standard Model Neutrino and Anomaly

- Measurements of the Z boson at LEP tell us there are three flavours of neutrino with SM weak interactions
- Neutrinos mix and oscillate among three different flavours, and the oscillation can be described by the PMNS matrix
- An outstanding anomaly for 10+ years: LSND & MiniBooNE both reported an excess of low energy events in their ν_e appearance searches:
  - one of explanations: sterile neutrinos oscillating into active neutrinos

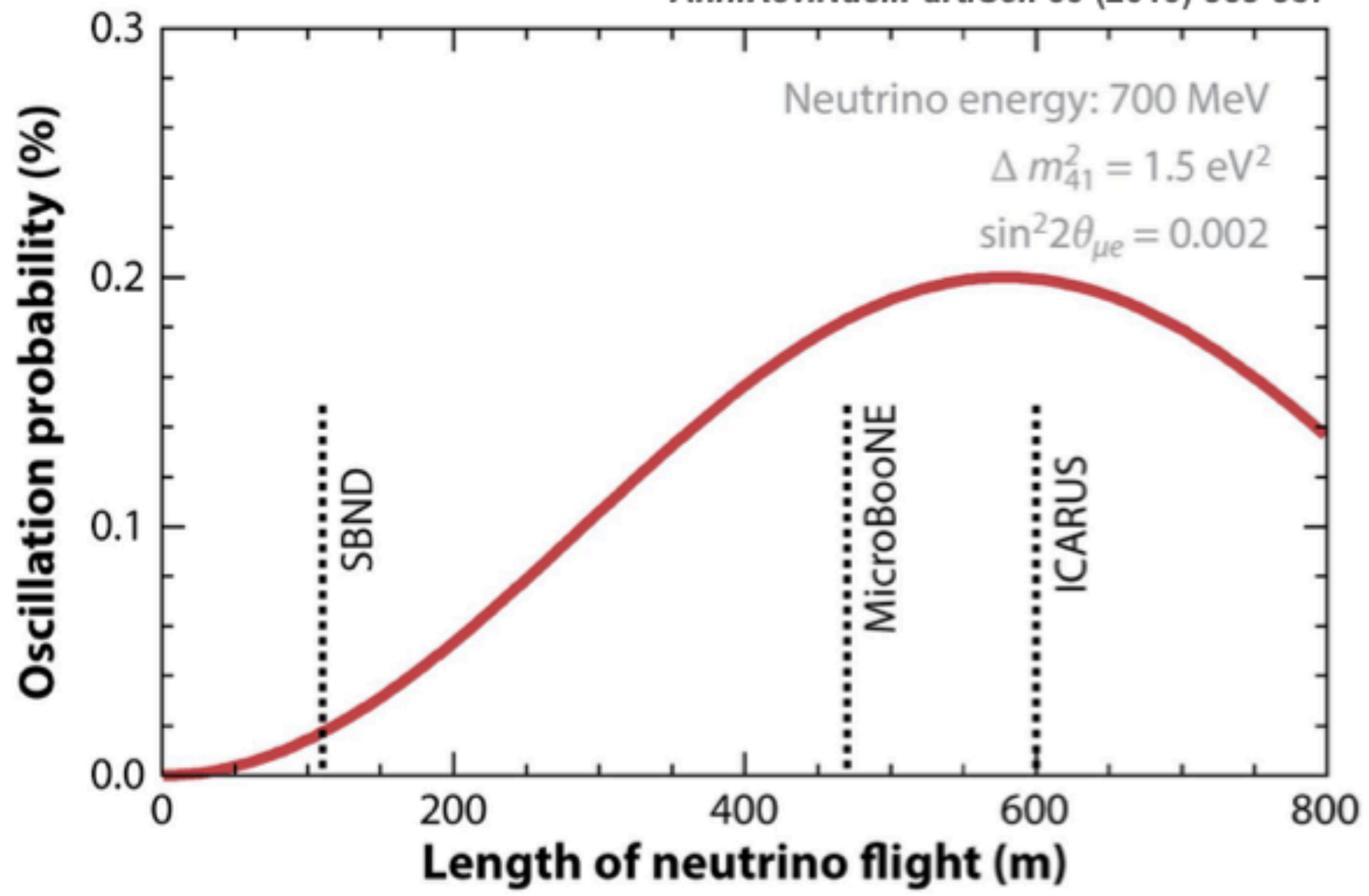
Phys. Rev. D 103, 052002 (2021)



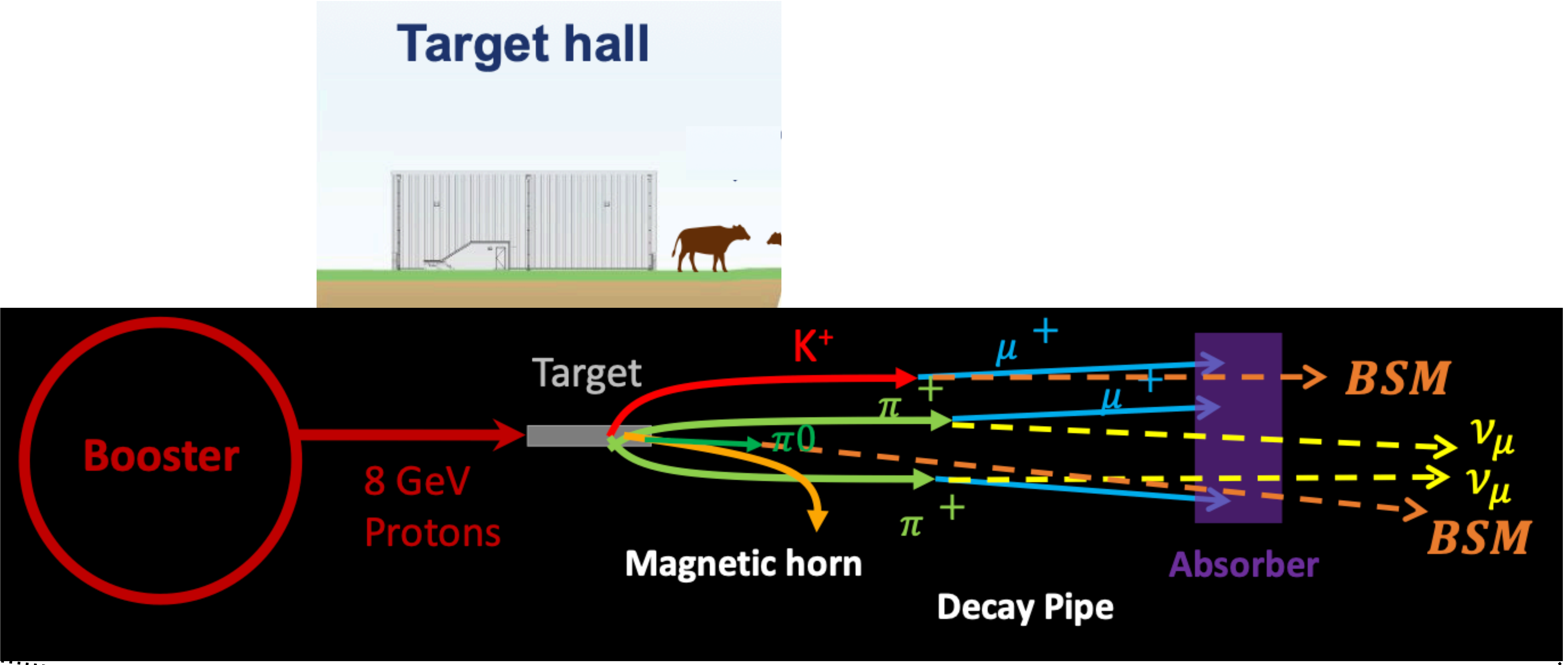
The Short Baseline Neutrino (SBN) program

- The SBN program @ Fermilab is designed to address the possibility of eV-scale sterile neutrino oscillations with 5σ sensitivity
- Consists of three Liquid Argon Time Projection Chamber (LArTPC) detectors with different baselines
- Detectors are on-axis of intensive GeV neutrino beam line

P. Machado, O. Palamara, D. Schmitz
Ann.Rev.Nucl.Part.Sci. 69 (2019) 363-387



BSM Production for the SBN program



- Other than sterile neutrino, more **sub-GeV scale Beyond the Standard Model (BSM) physics** can be explored for SBN

Neutrino experiments energy landscape

Accelerator ν

PTOLEMY

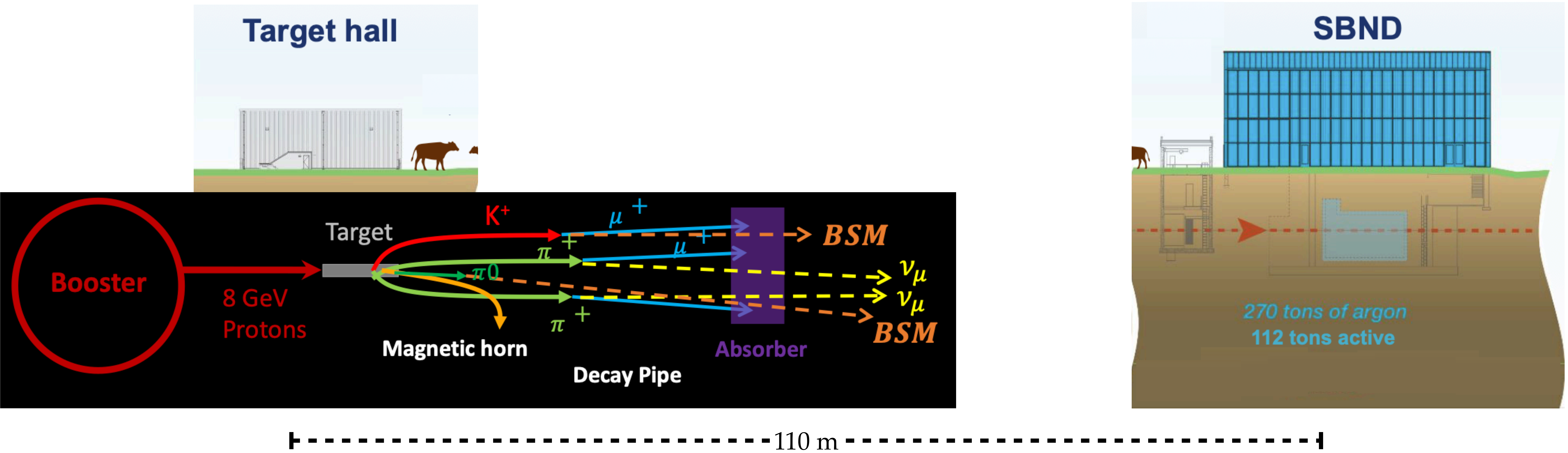
Solar ν

Collider

ICECUBE

...meV | eV | keV | MeV | GeV | TeV | PeV

BSM Production for the SBND



- The Short-Baseline Near Detector (SBND) is placed close (110 m) to the neutrino target:
  - high BSM production rate
  - more sensitive for heavier short-lived BSM particles

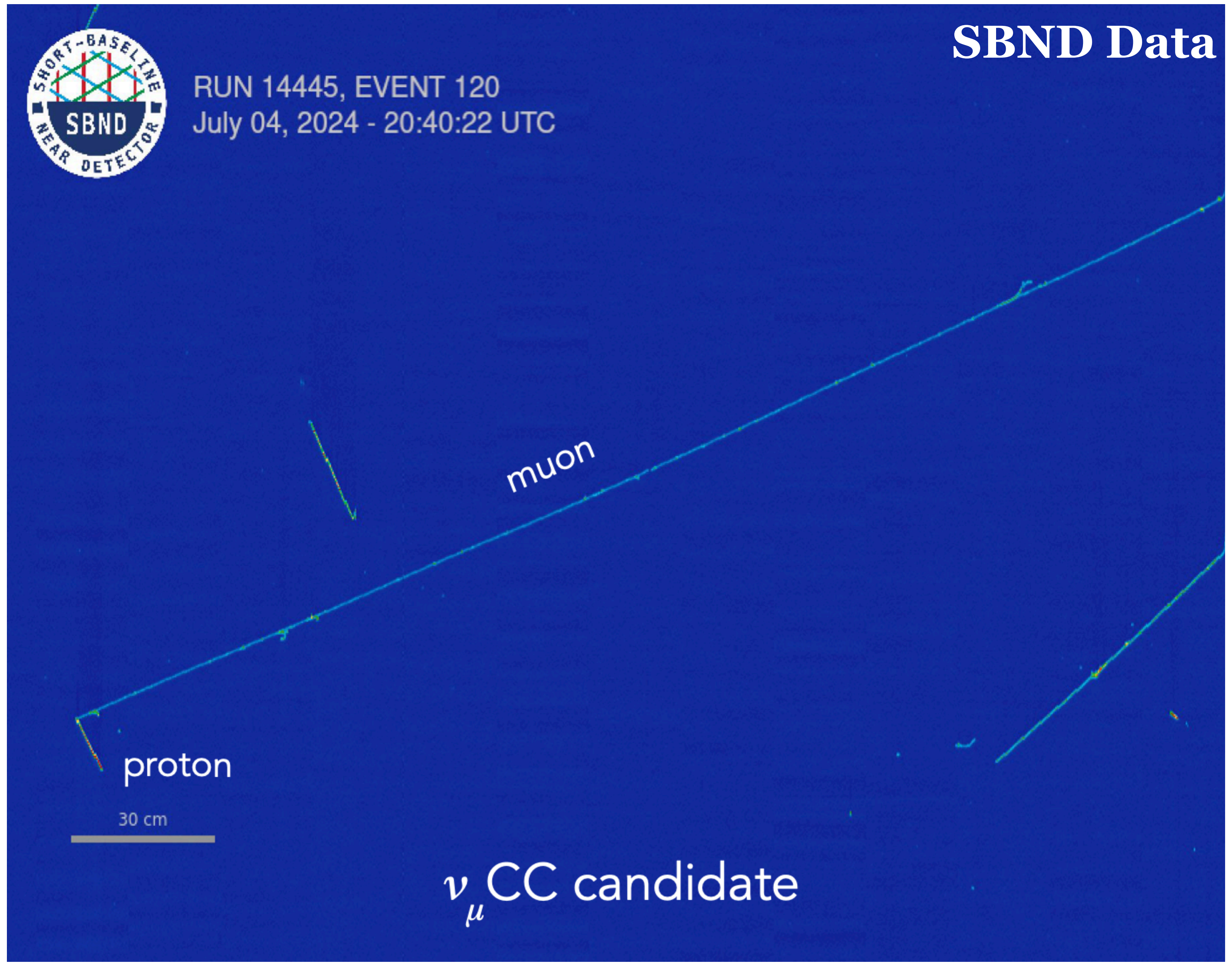
SBND

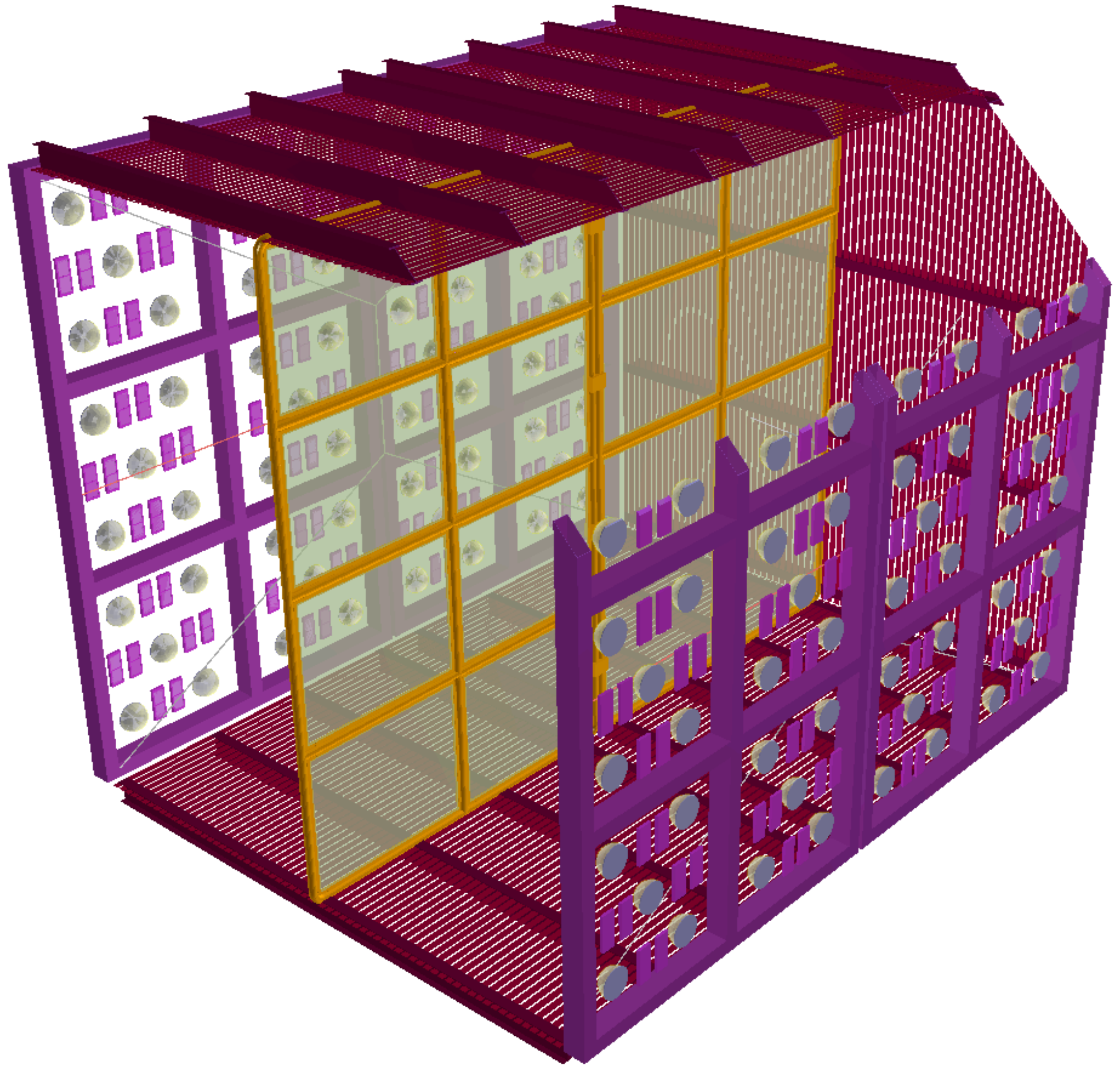
SBND as a LArTPC

LArTPCs:

- 3D reconstruction with mm-level resolution
- excellent particle identification
- low reconstruction thresholds, sub-MeV

Total dimension: 4m x 4m x 5m
Two Time Projection Chambers
with 112-tons of Argon





SBND as a LArTPC

LArTPCs:

- 3D reconstruction with mm-level resolution
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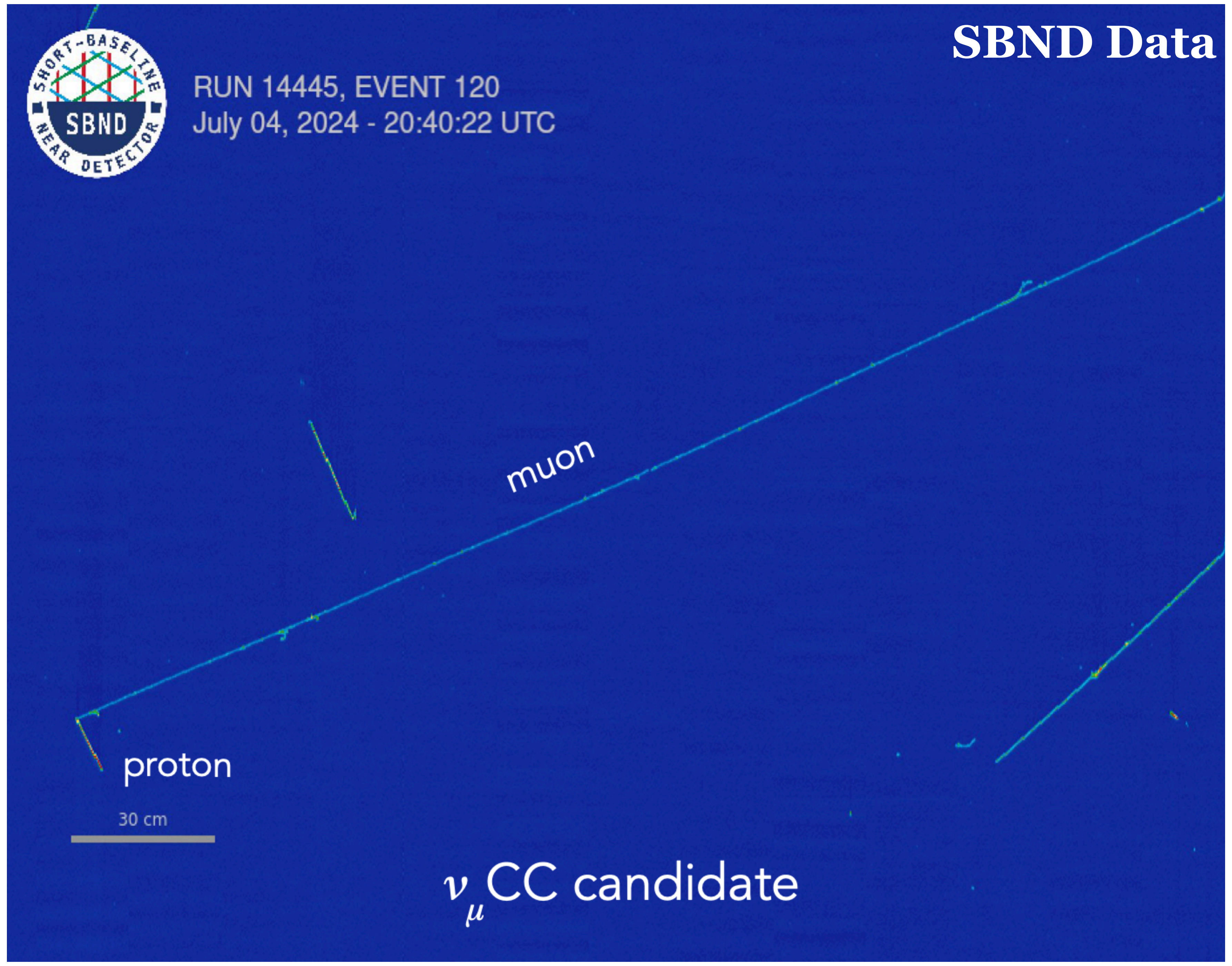

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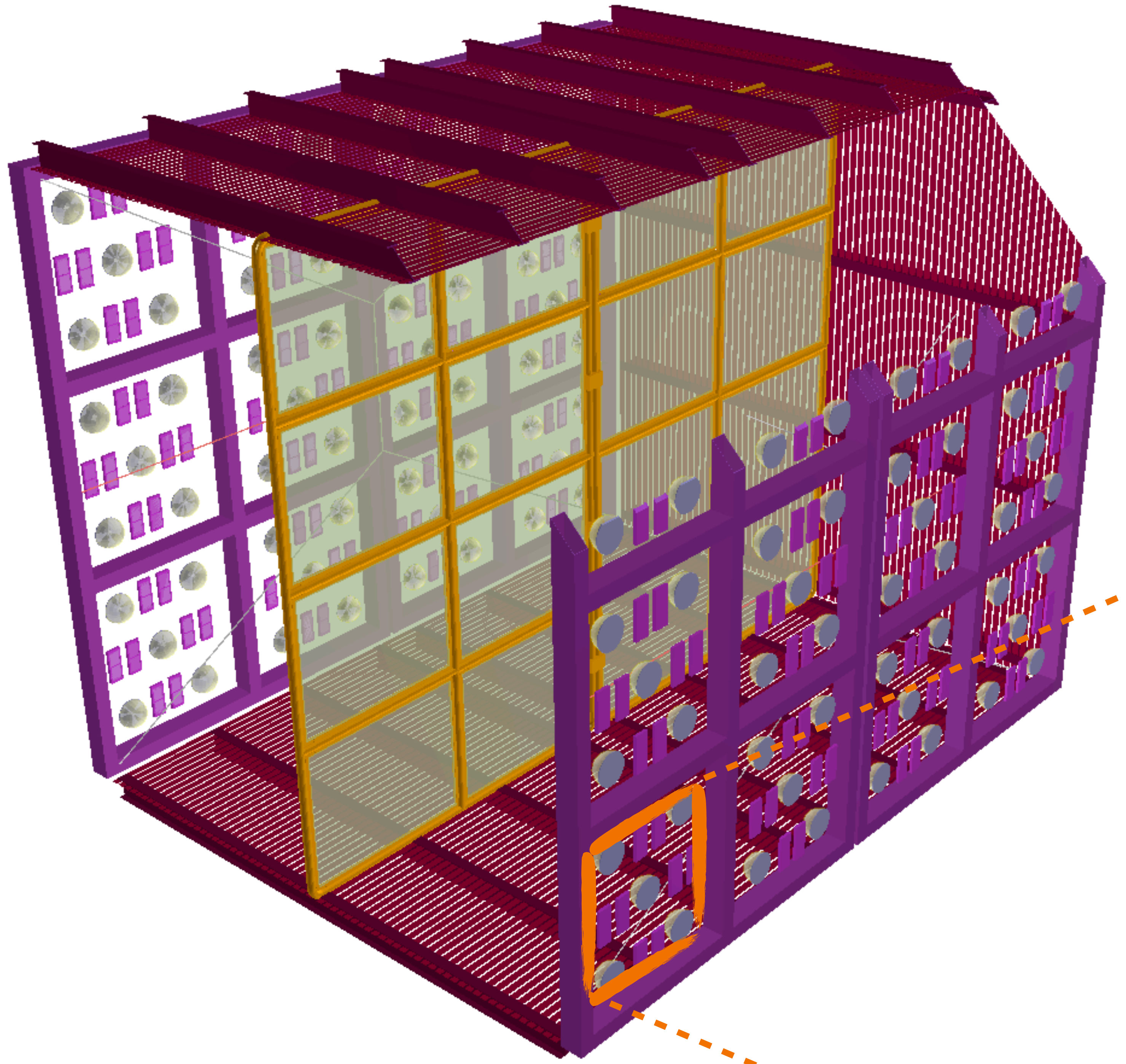
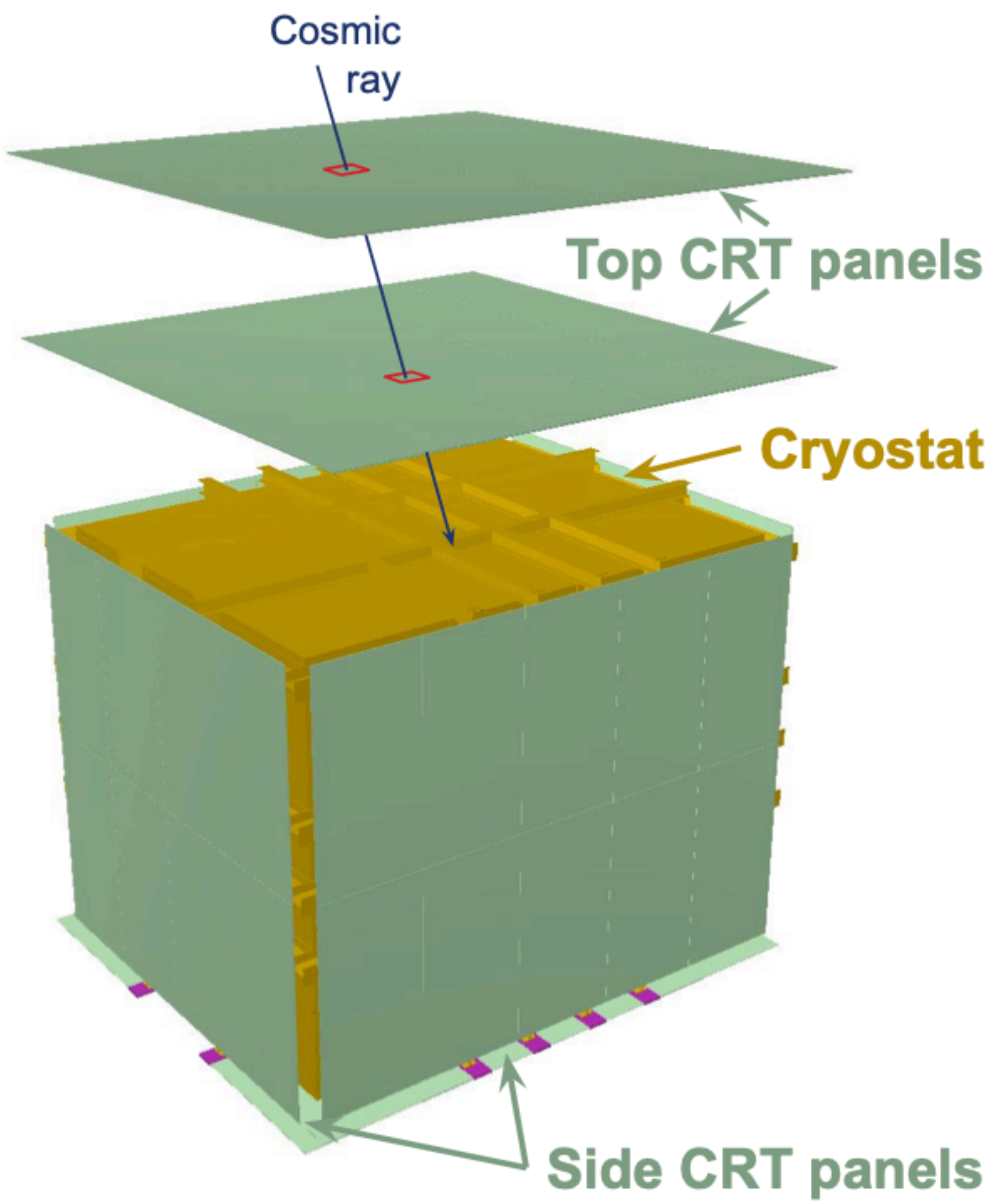


Photon Detection System:

- high and uniform light yield
- **excellent ns-timing resolution**

Cosmic Ray Tagger (CRT) System for SBND

- SBND is an **on-surface** detector and therefore is exposed to cosmic ray activities



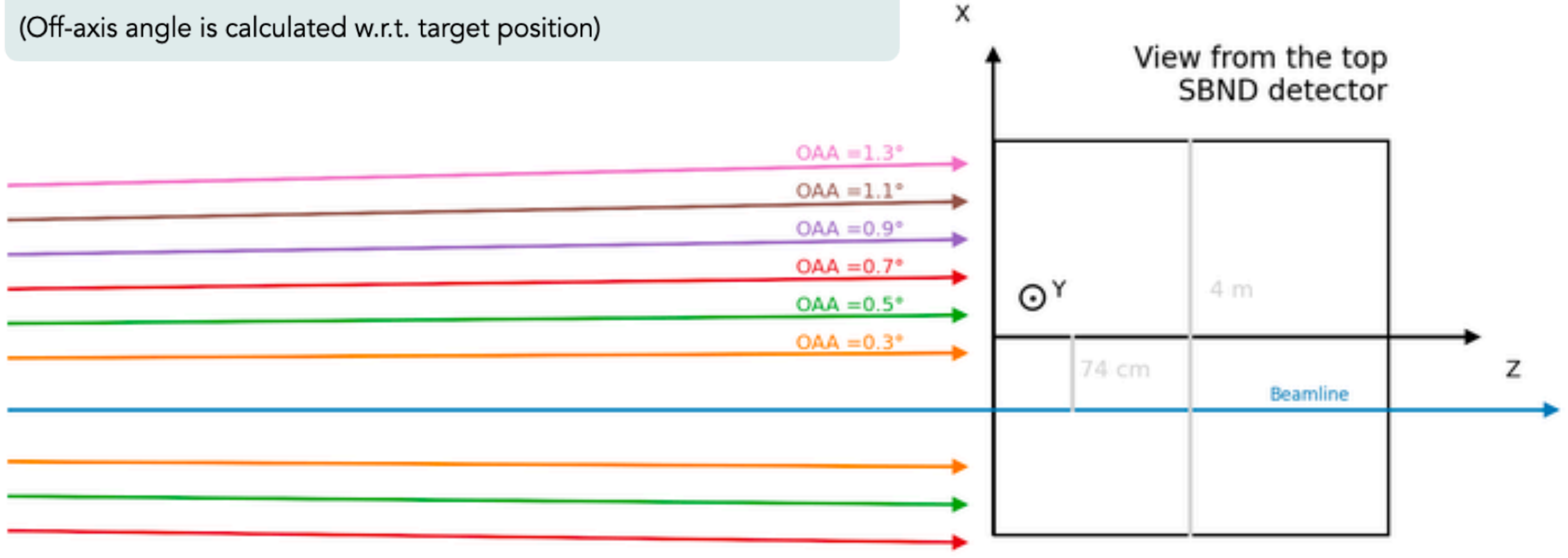
- To tag cosmics, the cryostat is surrounded by ~4π coverage of scintillator CRT panels.

Special handles for SBND BSM analysis

SBND PRISM

Precision **R**eaction **I**ndependent **S**pectrum **M**easurement

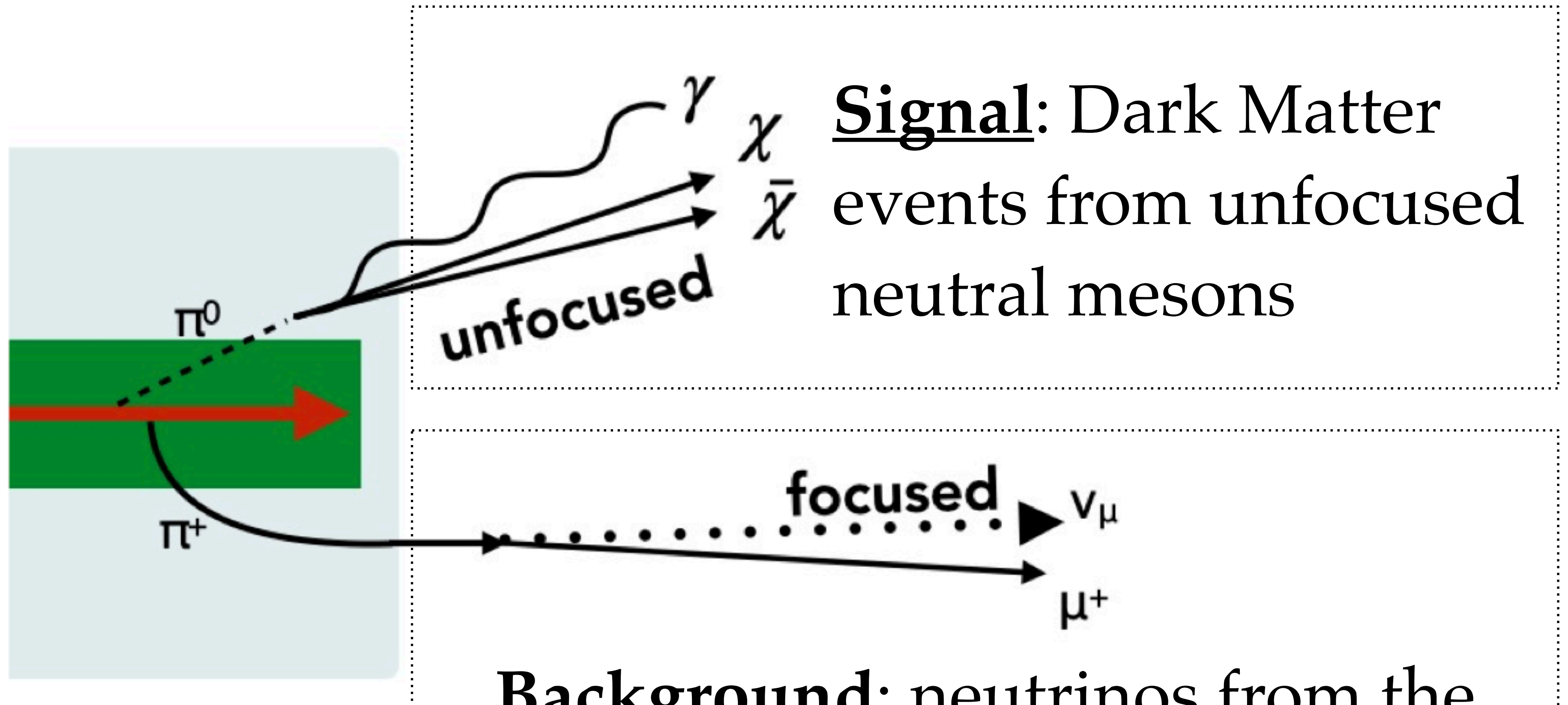
SBND sees neutrinos from several off-axis angles (OAAs)
(Off-axis angle is calculated w.r.t. target position)



- Close proximity to target -> larger solid angle coverage
  - Off-axis-angle range [0, 1.6°]
- SBND is intentionally positioned offset relative to the beam centre to leverage the PRISM concept

Application of SBND-PRISM:

- Constrain flux / xsec systematic uncertainty for SM neutrino background
- Higher BSM Signal / ν bkg. ratio with large off-axis-angle selection



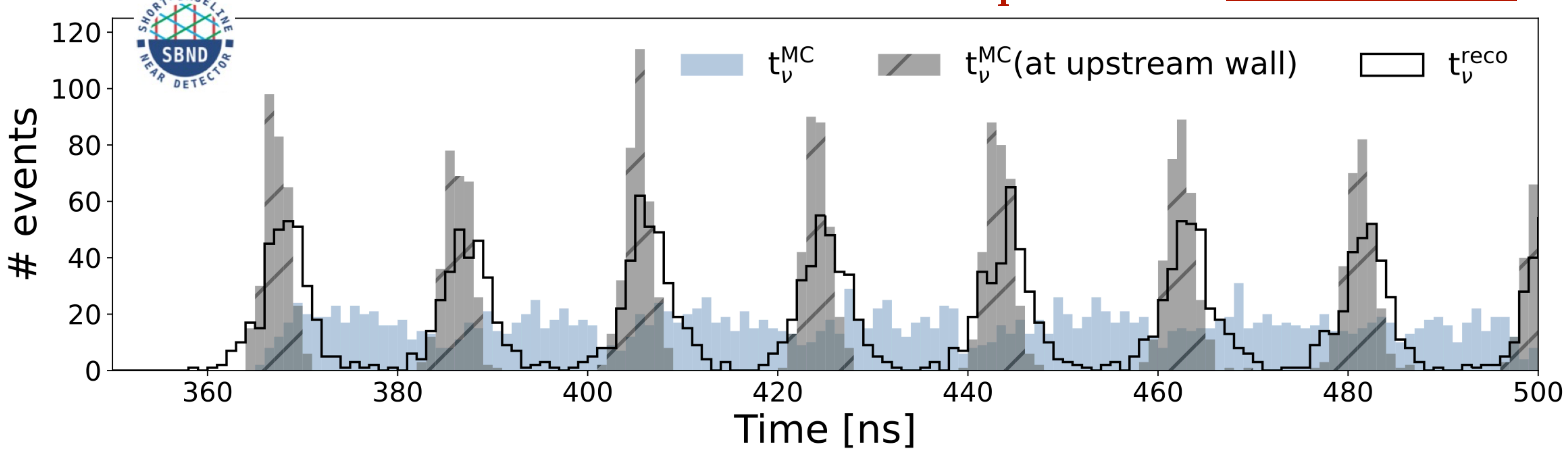
Signal: Dark Matter events from unfocused neutral mesons

Background: neutrinos from the focused charged mesons, events **decrease** with the off-axis angle

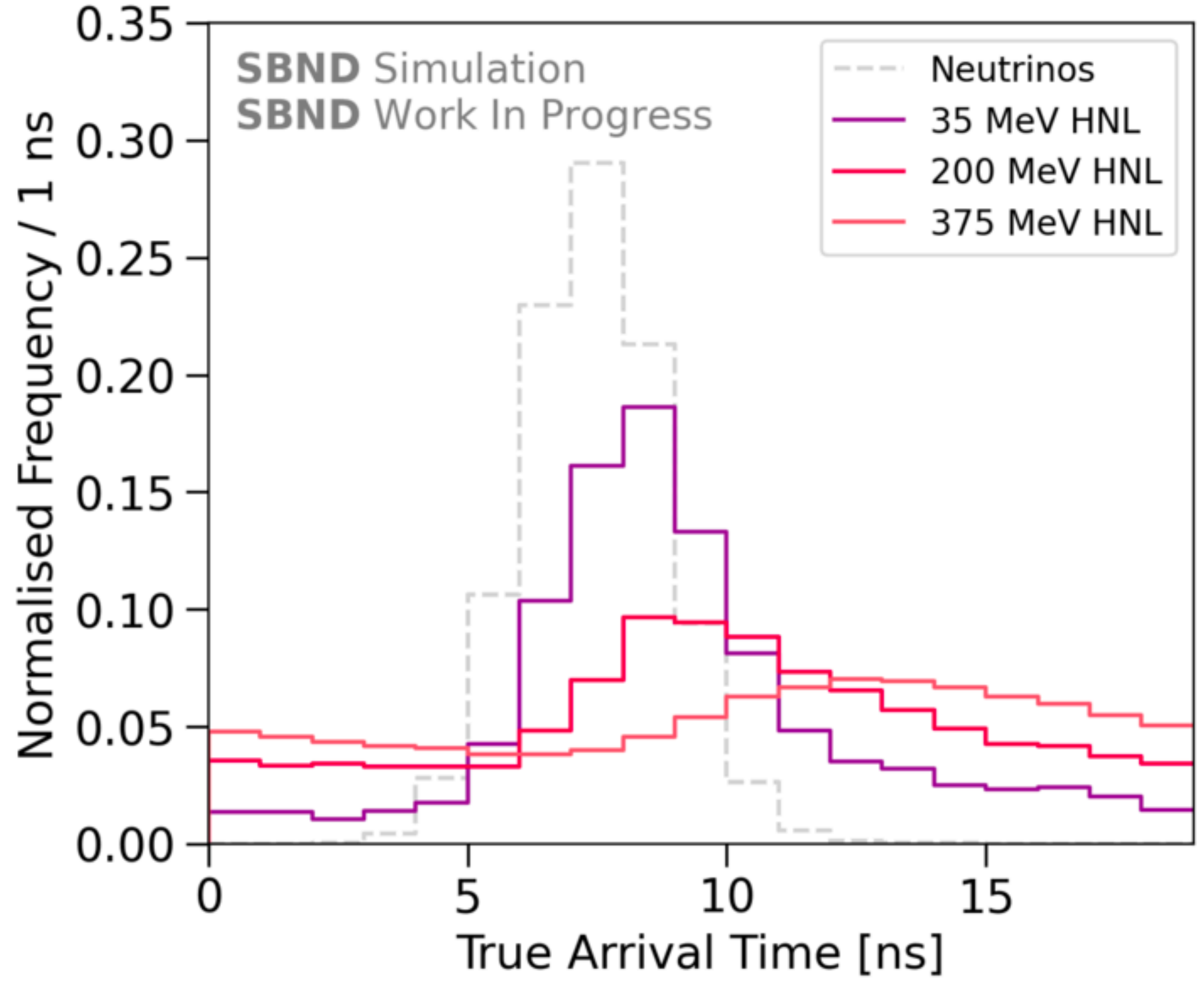
SBND - Precise Timing

Bunch structure of timing for ν production
2 ns ν bucket separate by ~18 ns gaps

SBND recent publication [arXiv:2406.07514]



The heavier mass the BSM particle is, the later it will arrive at the detector compared with ν



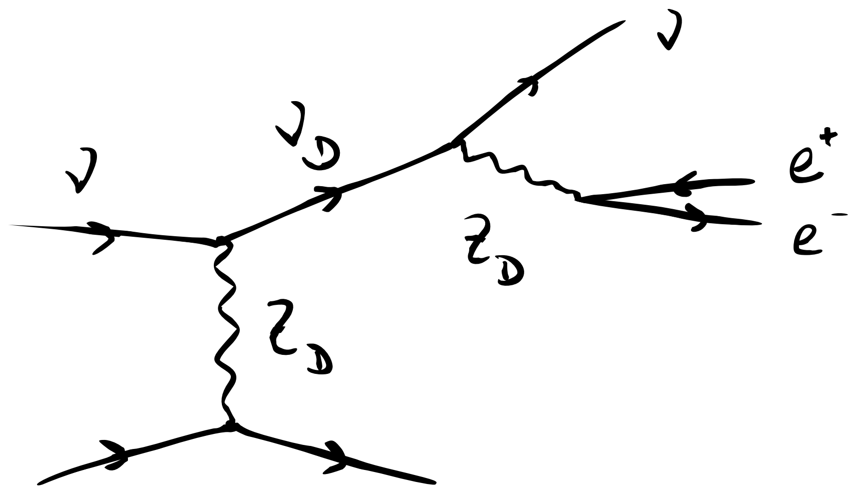
- SBND demonstrates the reconstruction of the ν beam bunch structure with simulation using its novel PDS design.
- BSM analyses in SBND are exploring the use of timing to increase the signal-to-background ratio

SBND BSM program

BSM program in SBND

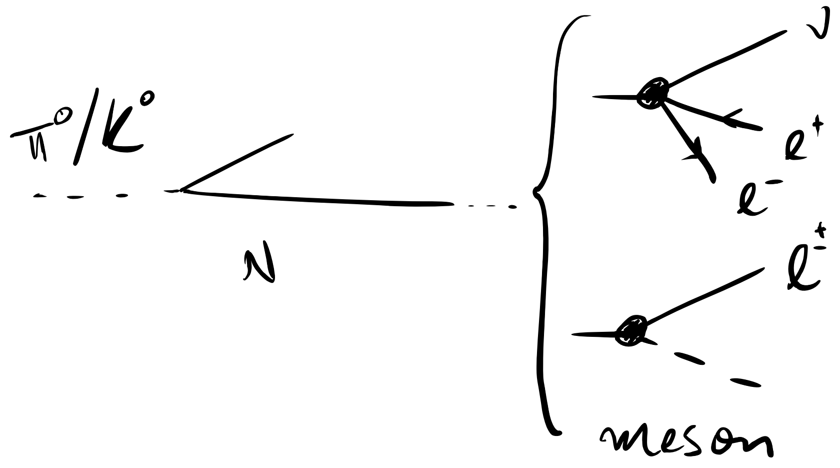
A non-exhaustive list of BSM particles produced at the Booster Neutrino Beam

Dark Neutrinos



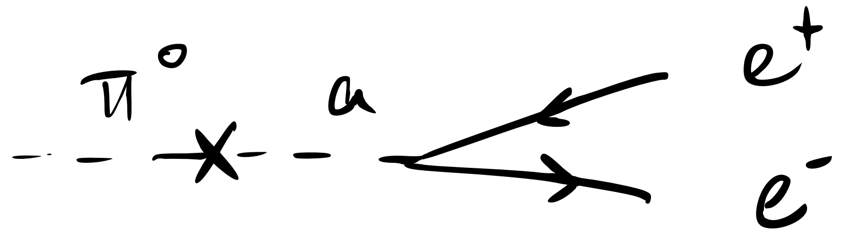
Bertuzzo Jana Machado Zukanovich PRL 2018, PLB 2019
Arguelles Hostert Tsai PRL 2019
Ballett Pascoli Ross-Lonergan PRD 2019
Ballett Hostert Pascoli PRD 2020

Heavy Neutral Leptons



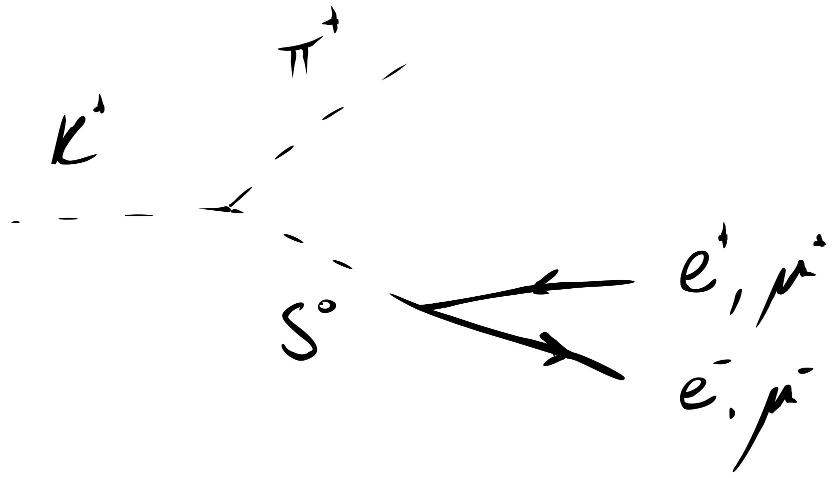
Ballett Pascoli Ross-Lonergan JHEP 2017
Kelly Machado PRD 2021

Axion-like Particles



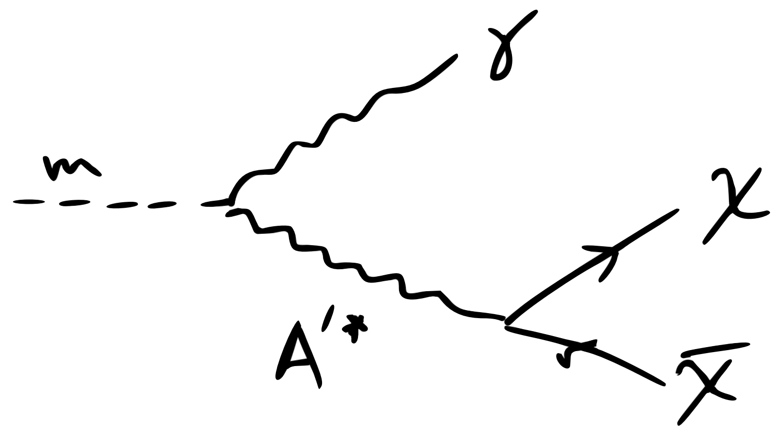
Kelly Kumar Liu PRD 2021
Brdar et al PRL 2021

Higgs Portal Scalar



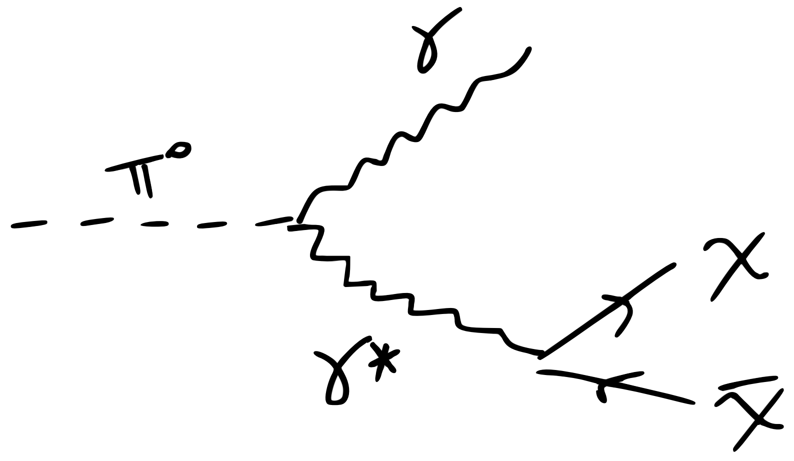
Pat Wilczek 2006
Batell Berger Ismail PRD 2019
MicroBooNE 2021

Light Dark Matter



Romeri Kelly Machado PRD 2019

Millicharged Particles



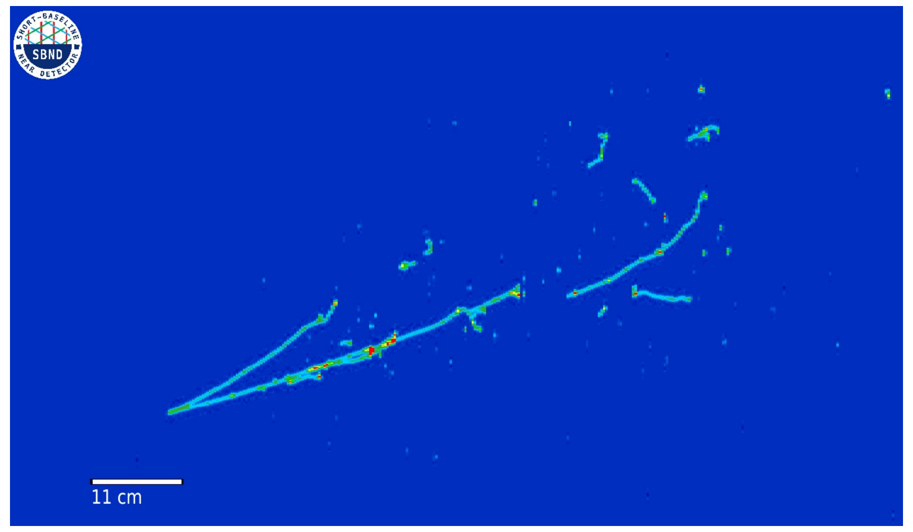
Magill, Plestid, Pospelov, Tsai, PRL 2019
Harnik Liu Palamara, JHEP 2019

Image credit P. Machado and M. Del Tutto

BSM program in SBND

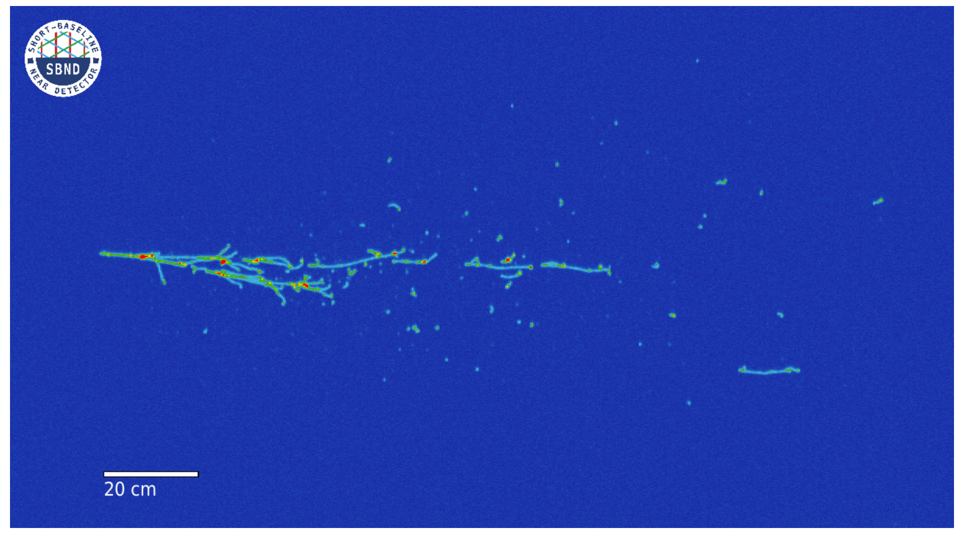
A non-exhaustive list of BSM particles produced at the Booster Neutrino Beam

Dark Neutrinos



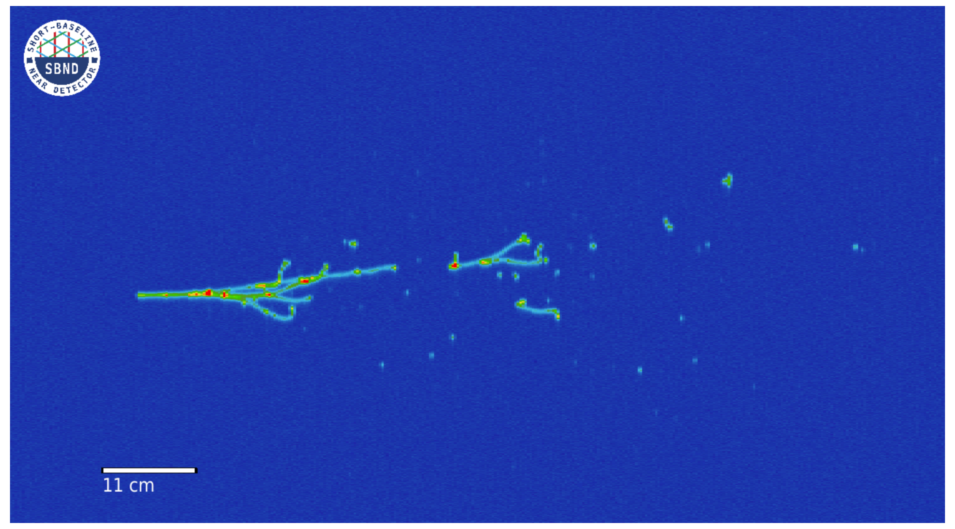
e+e- pair w/ or w/o hadronic activity

Heavy Neutral Leptons



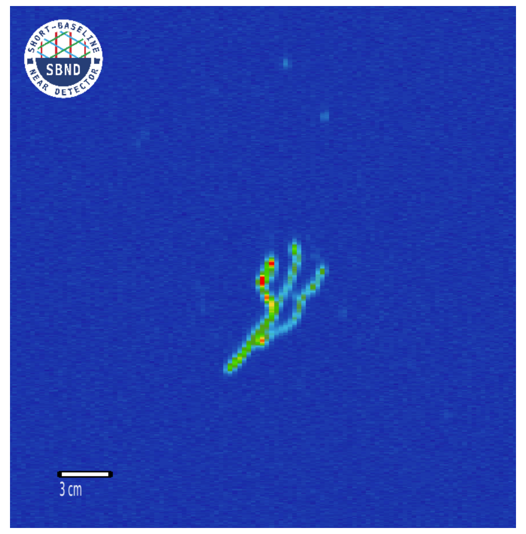
e^+e^-, $\mu^+\mu^-$, $\mu\pi$

Axion-like Particles



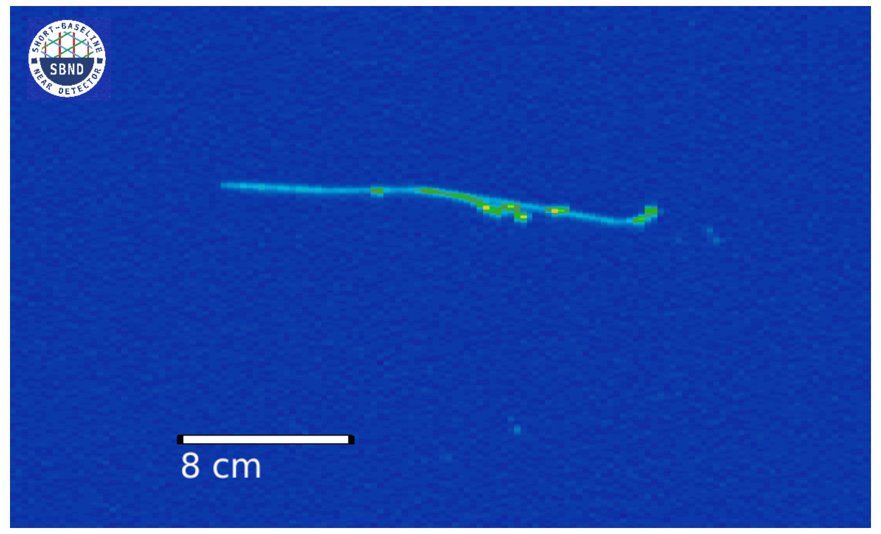
high-energy e^+e^-, $\mu^+\mu^-$

Higgs Portal Scalar



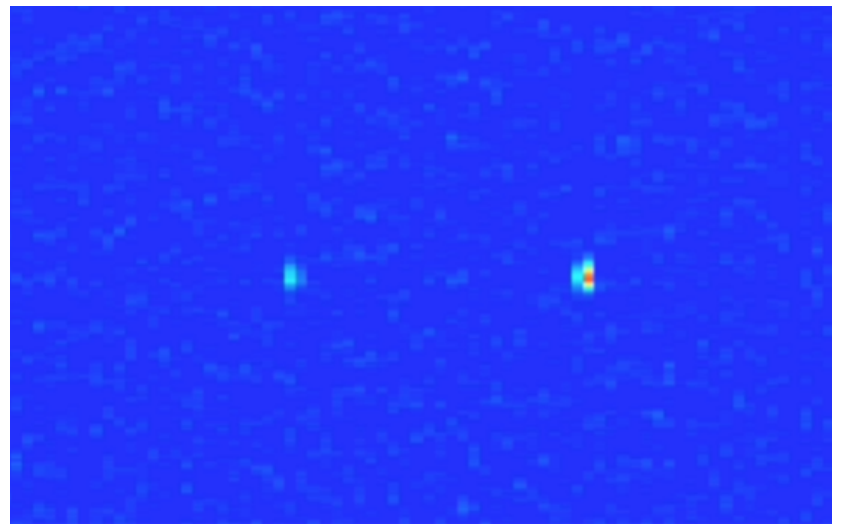
e^+e^-, $\mu^+\mu^-$, no hadronic activity

Light Dark Matter



electron scattering

Millicharged Particles



blips/faint tracks

Image credit P. Machado and M. Del Tutto

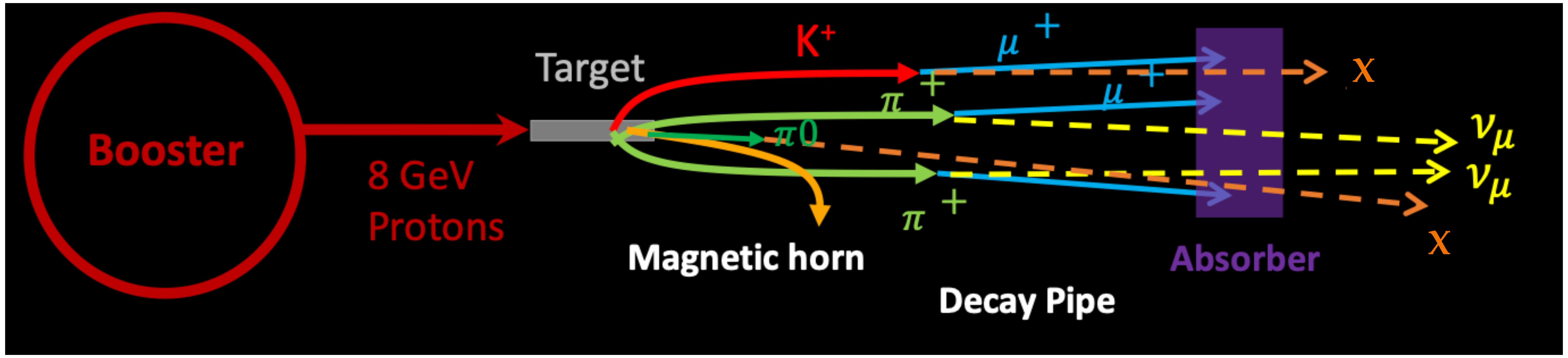
Model-independent Search in SBND

Search driven by experimental observables

Explore sensitivity to a generic long-lived massive particle X based on **experimental observables** (ie. event rates at different final-states) and **general BSM parameters** (e.g. branch ratio, mass)

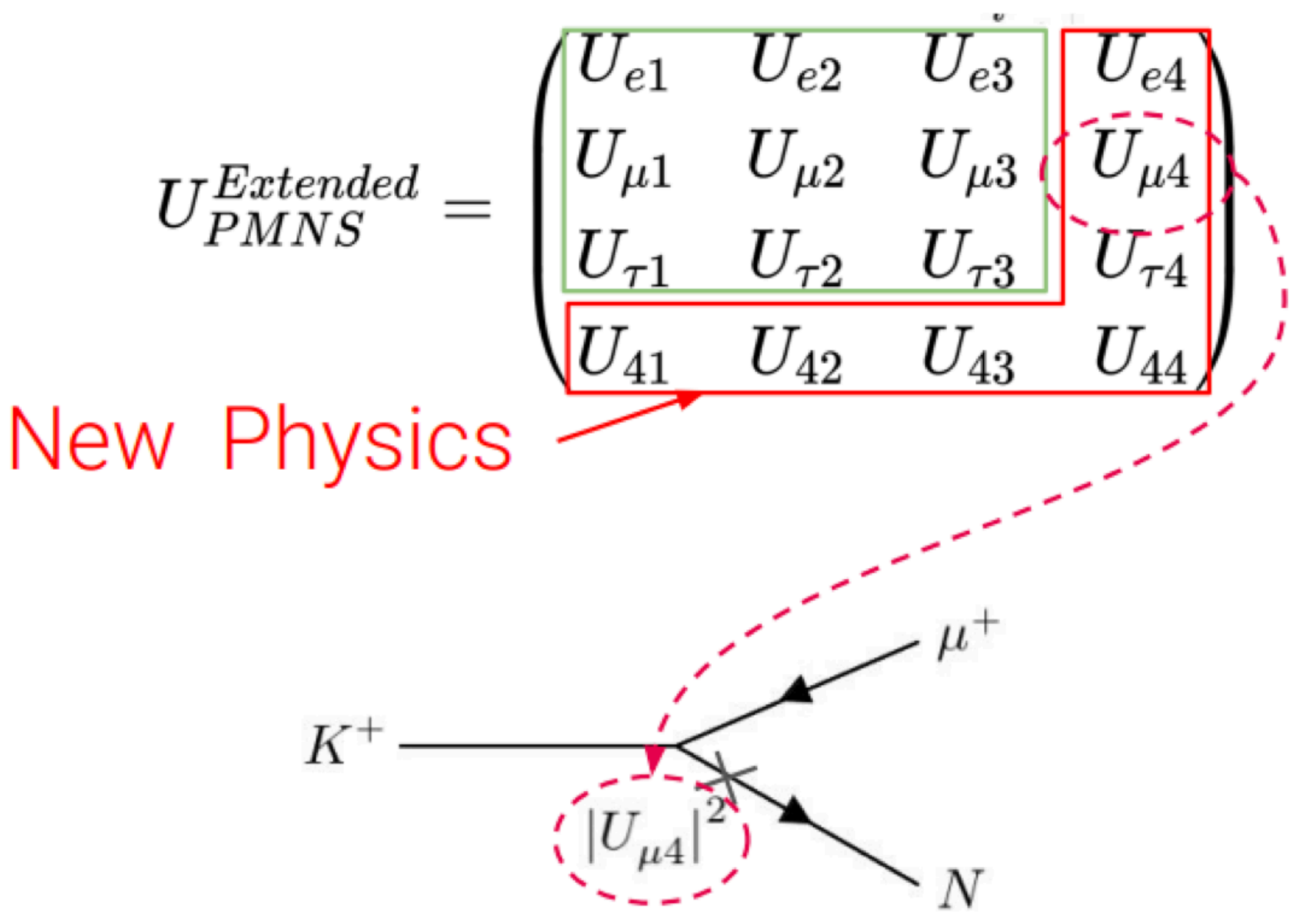
Advantages

- A simplified, unified sensitivity is defined by experimental observables
- This maximise discovery potential, which is needed for BSM field



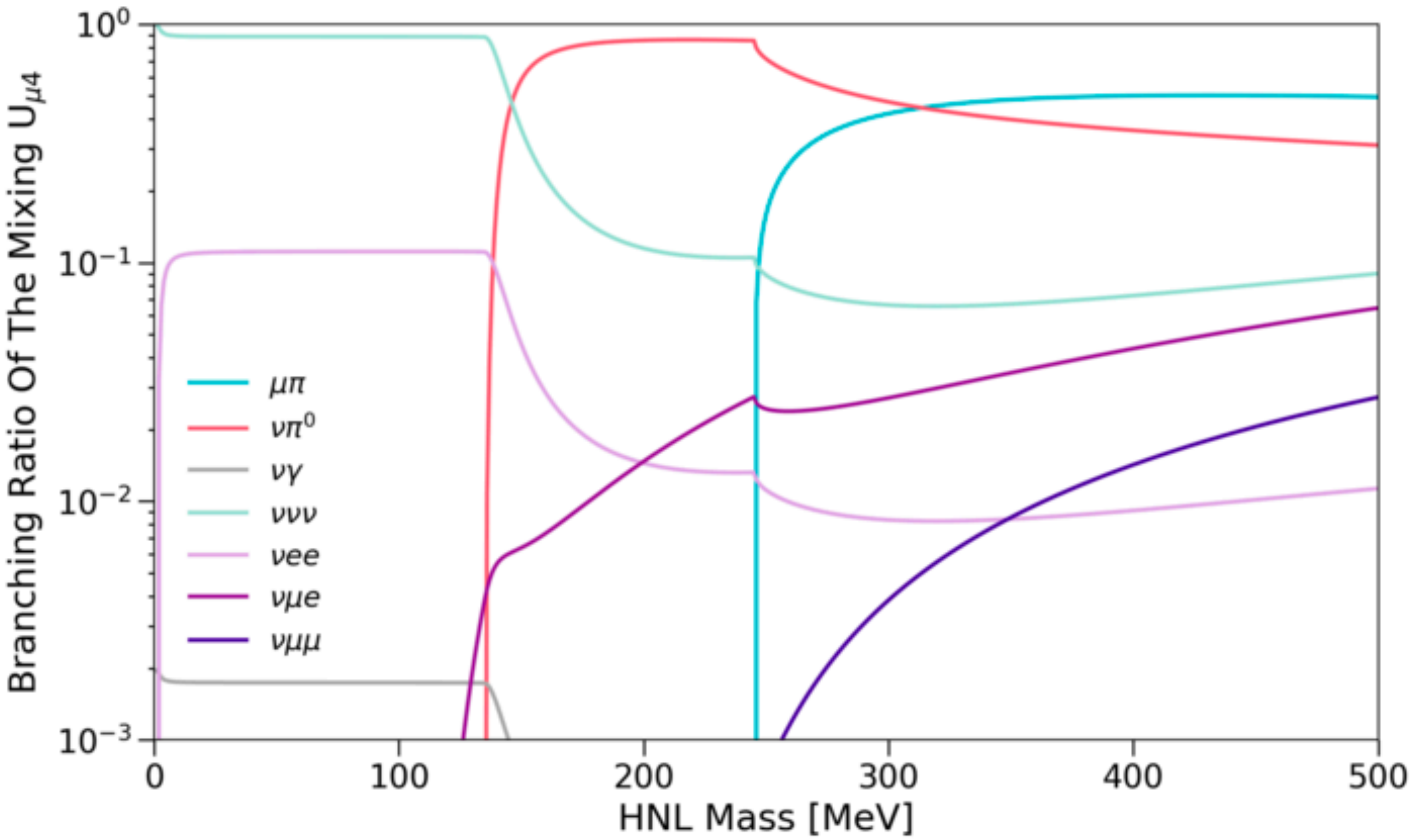
Heavy Neutral Lepton (HNL)

Production



HNL can be produced from K^+decay up to ~500 MeV in the neutrino beam

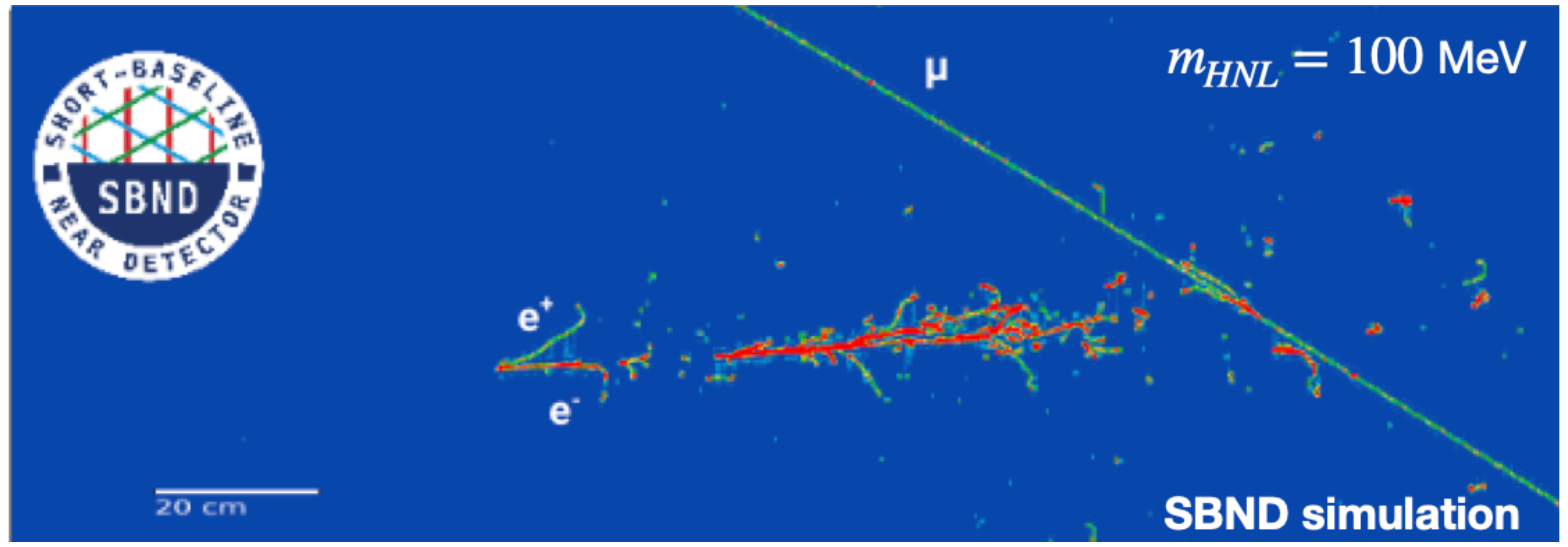
Decay



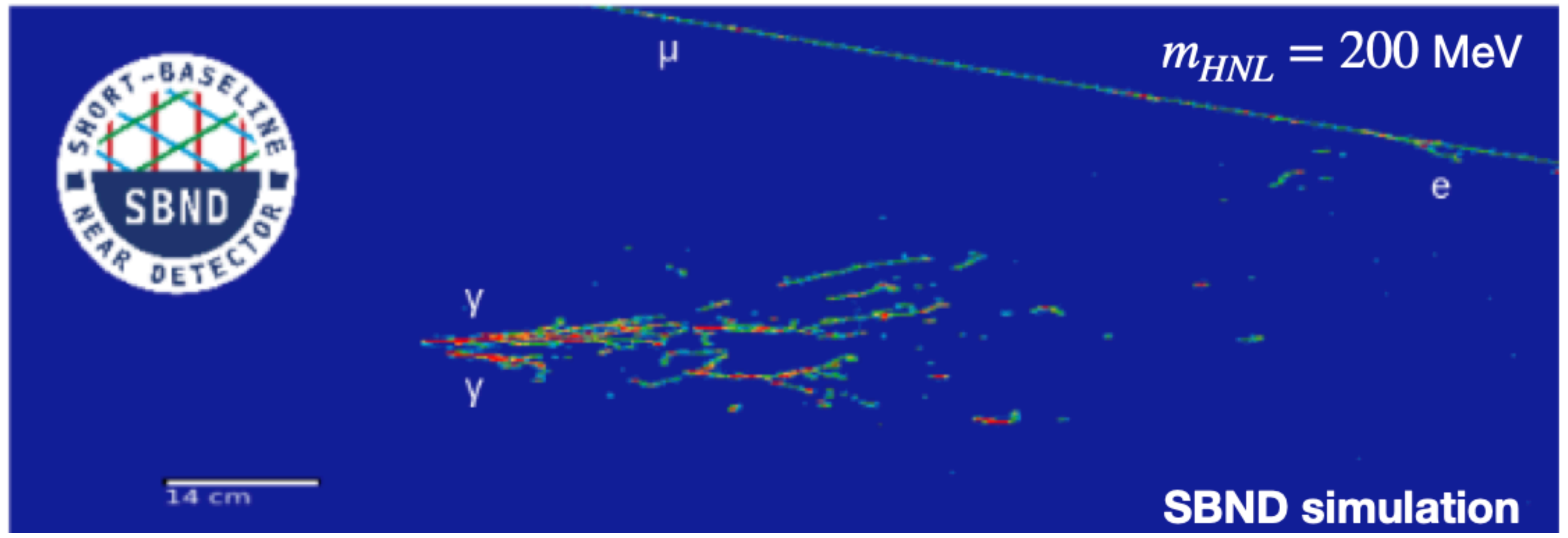
HNL then decays to SM particles with rate $\propto |U_{\alpha4}|^4, \alpha = e, \mu, \tau$

Heavy Neutral Lepton (HNL)

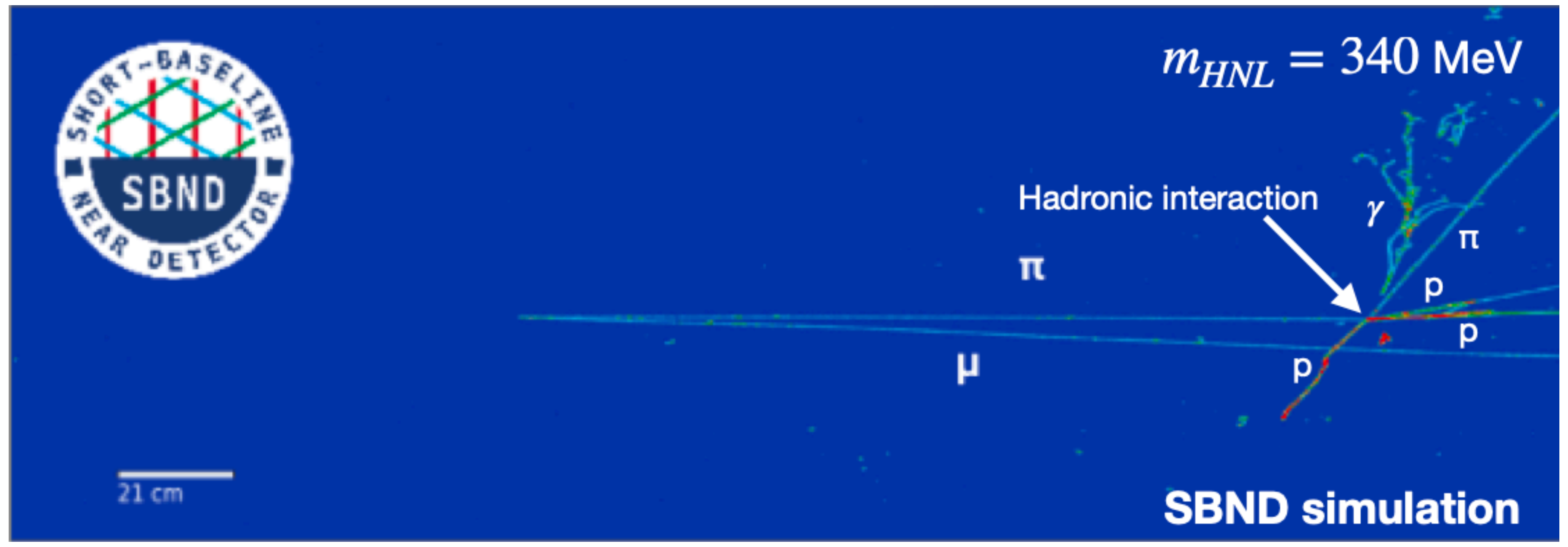
$HNL \rightarrow \nu ee$



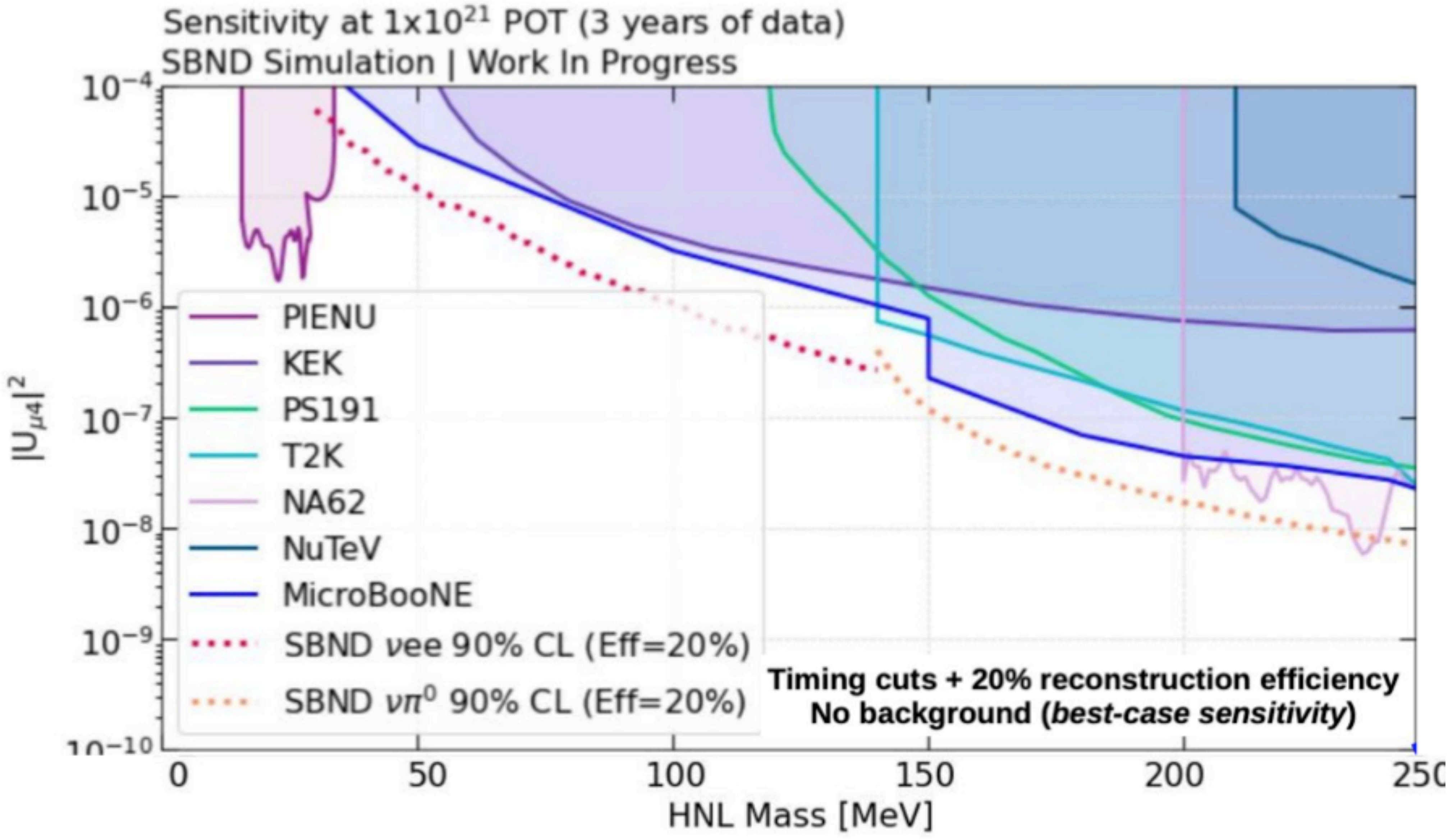
$HNL \rightarrow \nu \pi^0$



$HNL \rightarrow \mu \pi$



Preliminary truth-based sensitivity



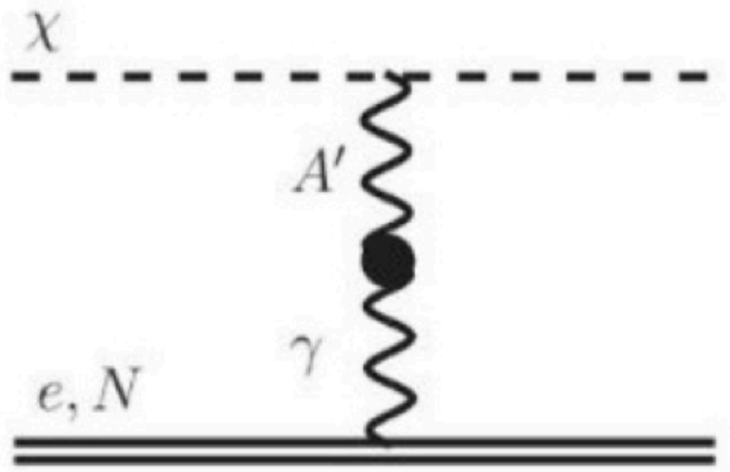
Current Status for HNL in SBND:

- Three channels are under consideration
- ns-timing handle is used for HNL analysis
- With realistic background consideration, reconstruction effect, and machine-learning based event selection

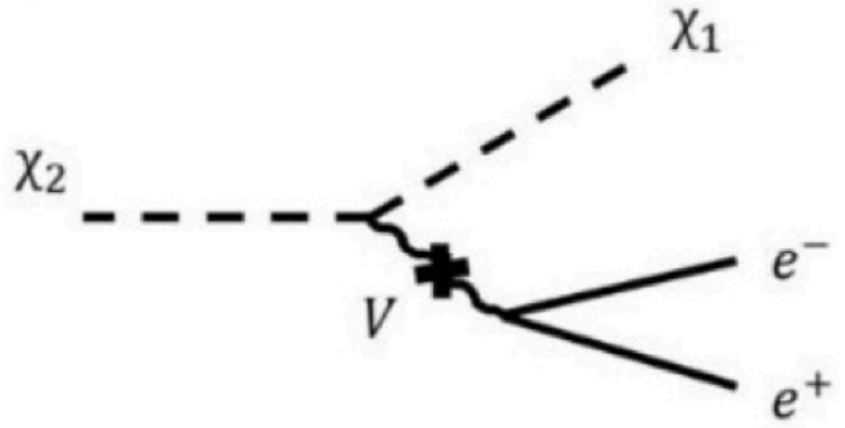
Sensitivity calculations will be out soon! Stay tuned!

Light Dark Matter and Milli-charged particle

Scattering/Decay

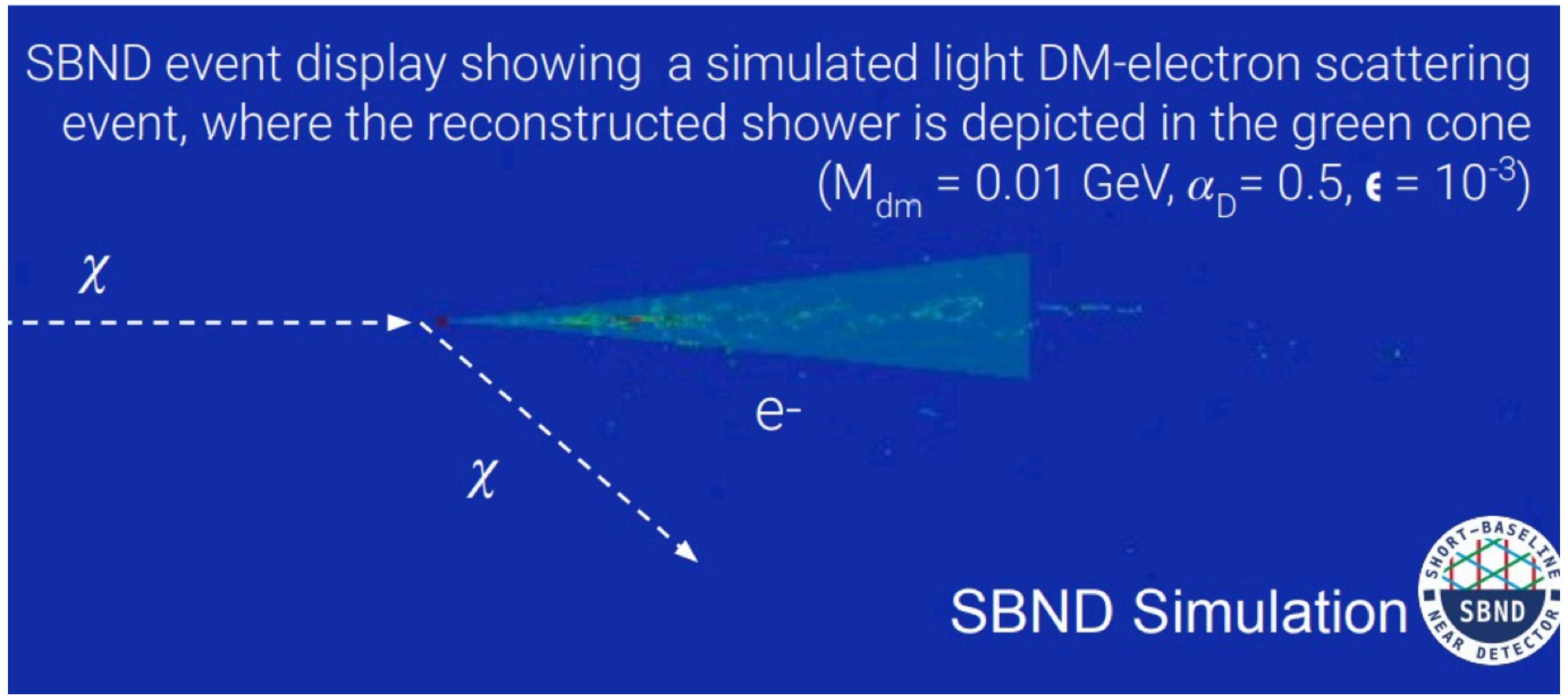


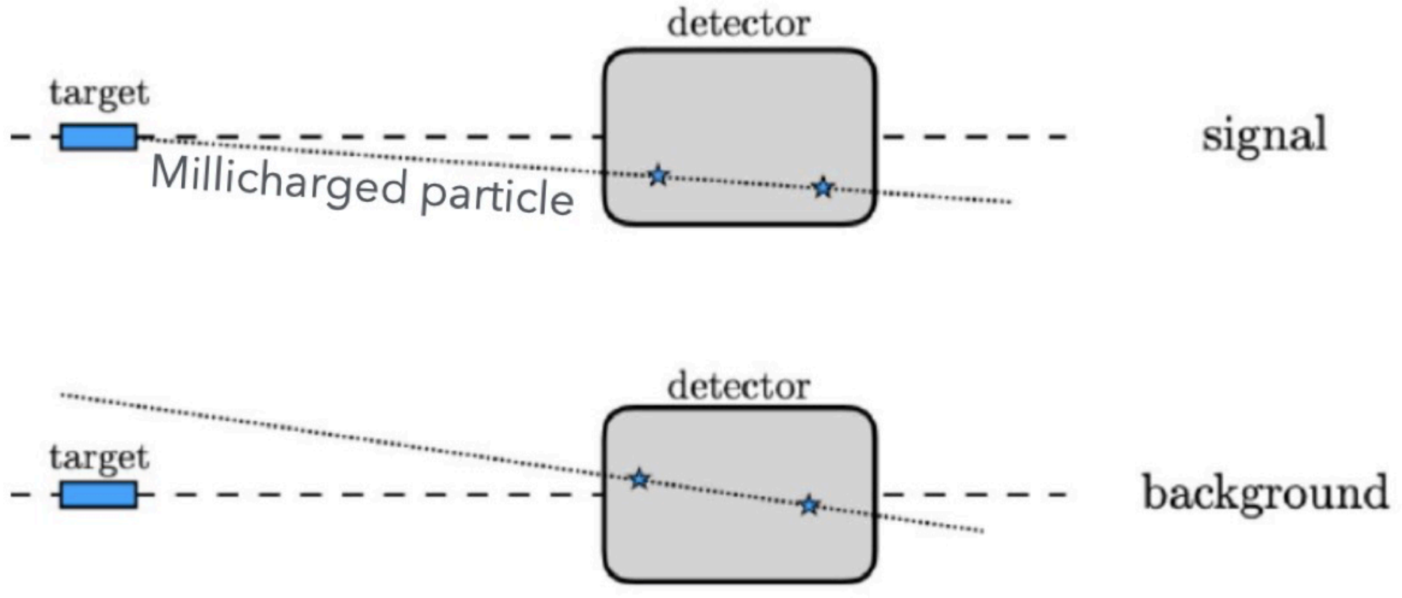
NC elastic scattering with e⁻ or nucleon



Decay to dark photon, and subsequently into an e⁺e⁻ ("dark trident")

Both channels are being explored in SBND, search for signature with EM showers without hadronic activity



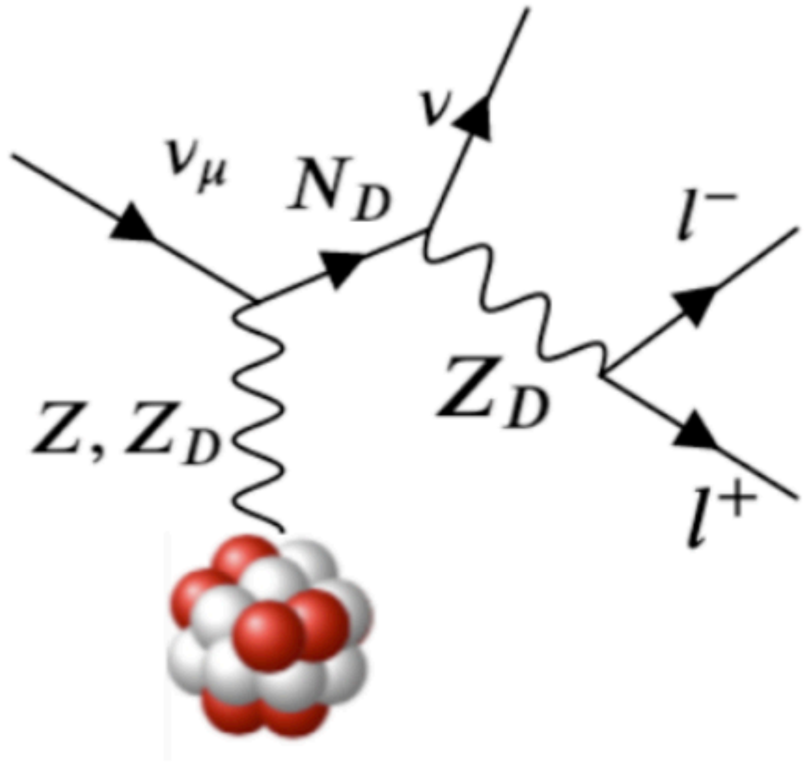


Signature in the SBND

- Milli-charged particle appears as *blips* or *faint tracks* pointing back to the target
- This is under development in SBND to search for up to 3 hits pointing back to the neutrino beam target

Dark Neutrino

The dark neutrino model is an alternative way to explain MiniBooNE low energy anomaly



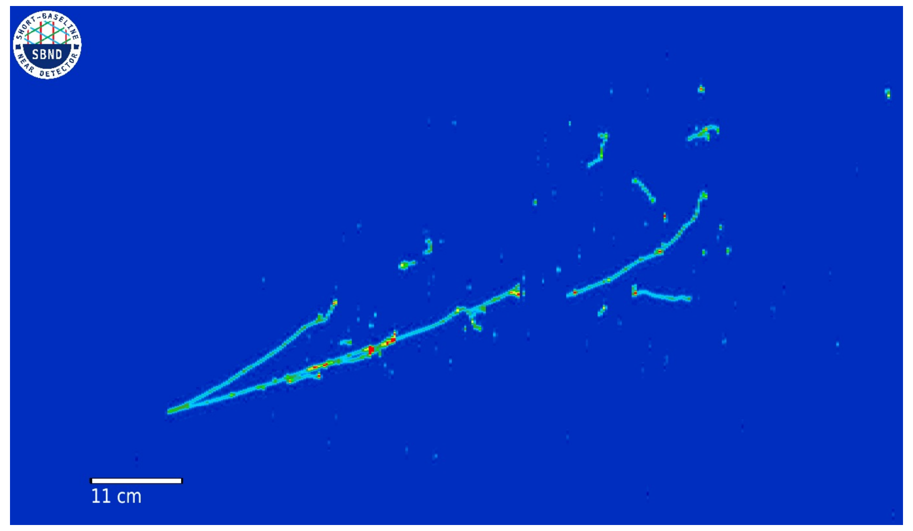
Decay

- Dark neutrino decays to a dark gauge boson Z_D, which will further decays into di-leptons

Production

- Dark neutrino is produced via ν-nucleon scattering in the neutrino beam line

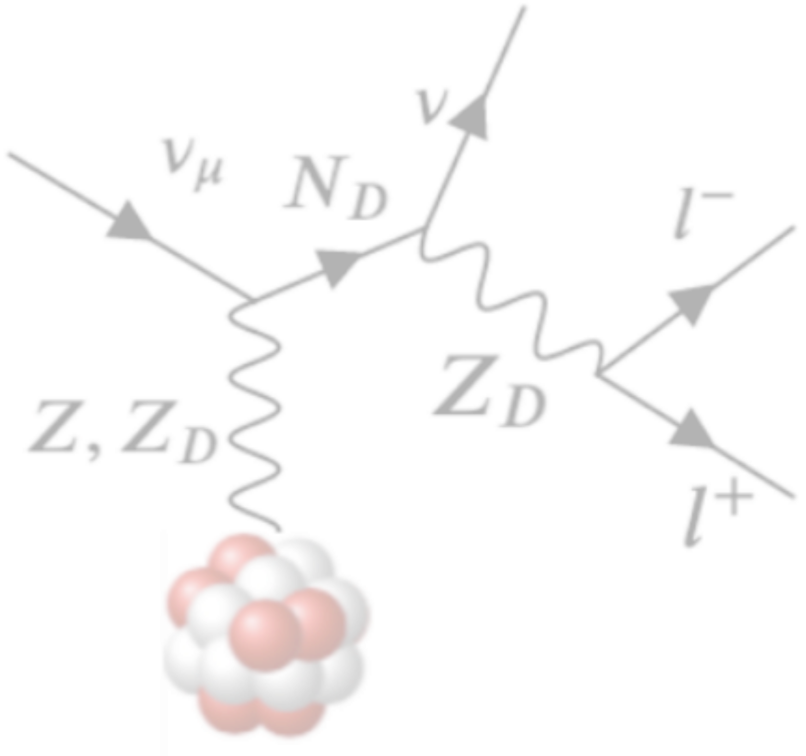
Dark Neutrinos



e+e- pair w/ or w/o hadronic activity

Dark Neutrino in the SBND CRT Beam Telescope

The dark neutrino model is an alternative way to explain MiniBooNE low energy anomaly

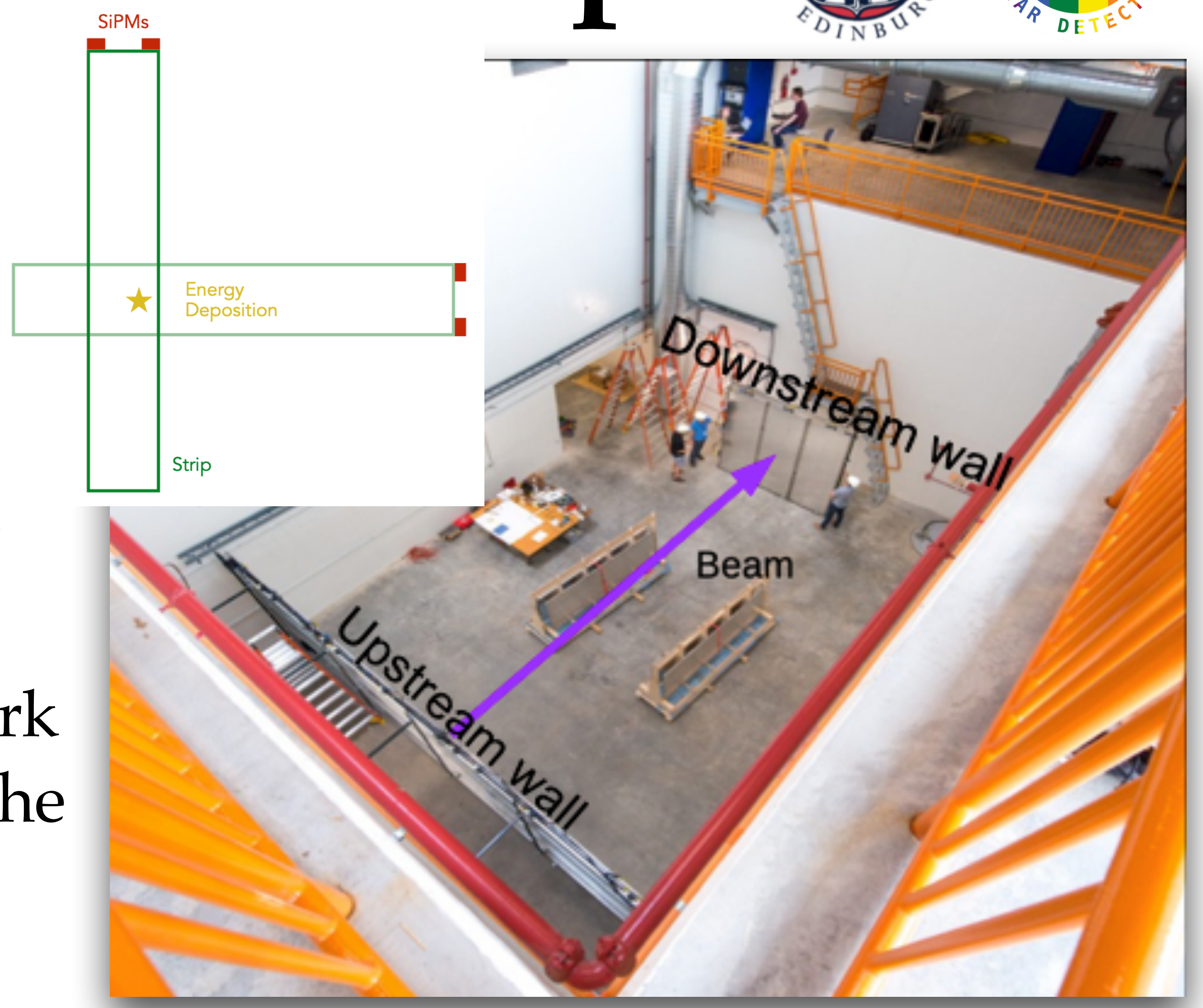


Decay

- Dark neutrino decays to a dark gauge boson Z_D, which will further decays into di-leptons

CRT Beam Telescope Data

- SBND installed the Beam Telescope with the CRT modules and collected data from 2017 to 2018
- Di-lepton pairs from the dark neutrino can be tagged by the CRT detector



Production

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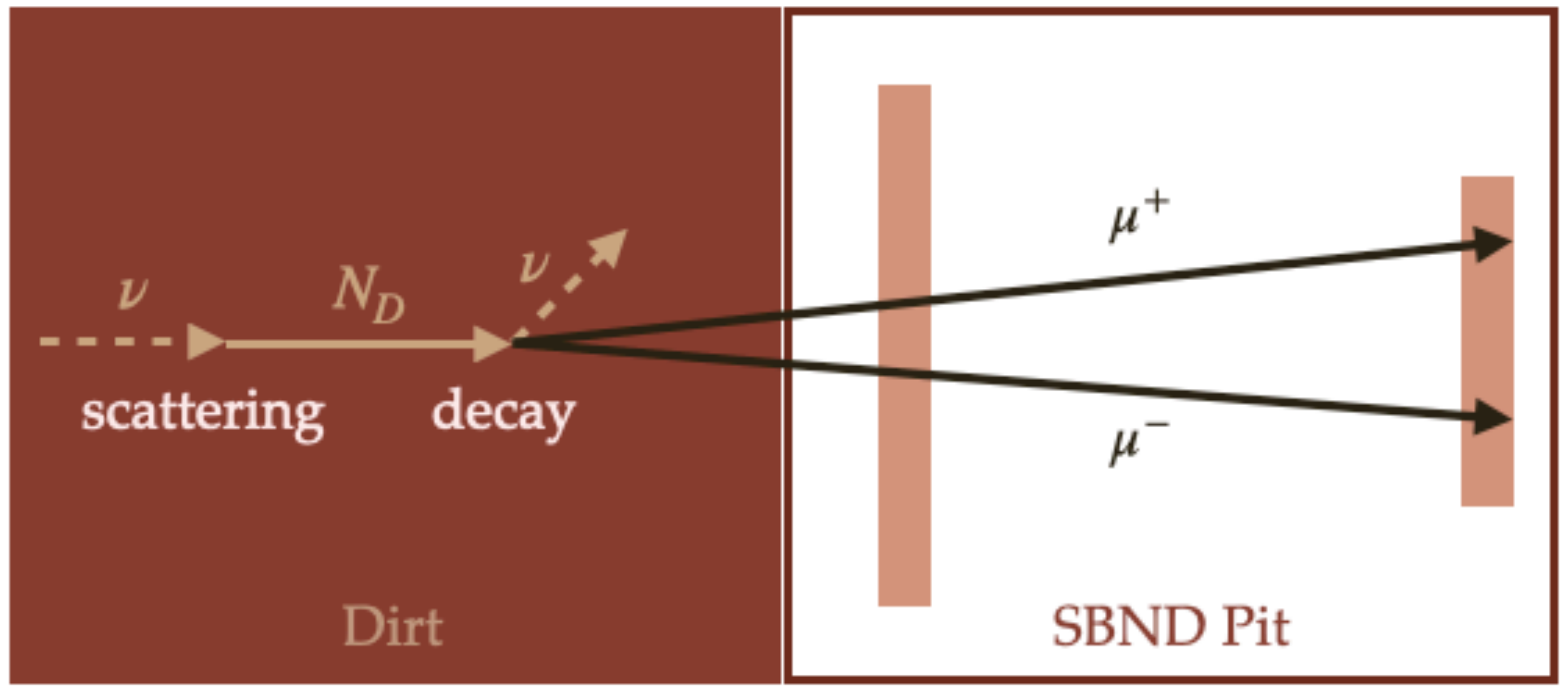
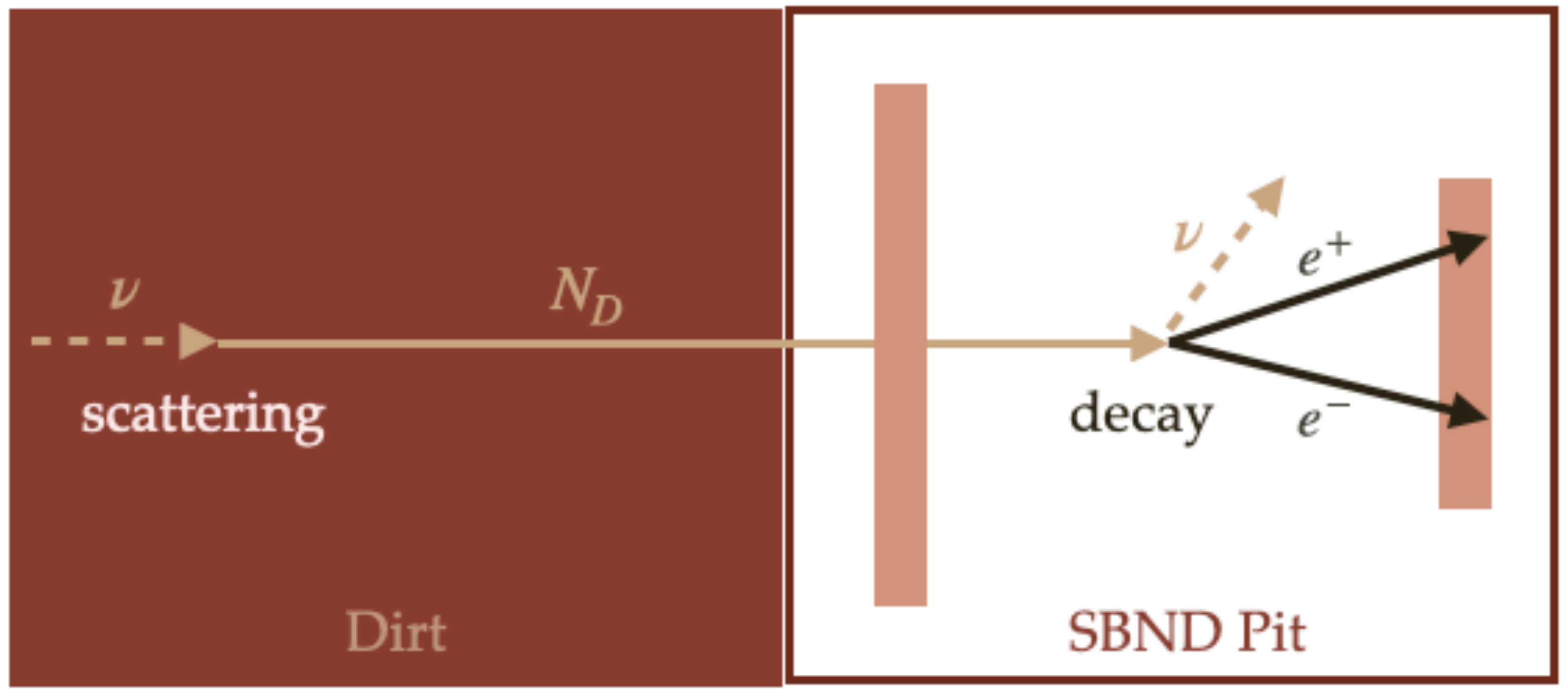
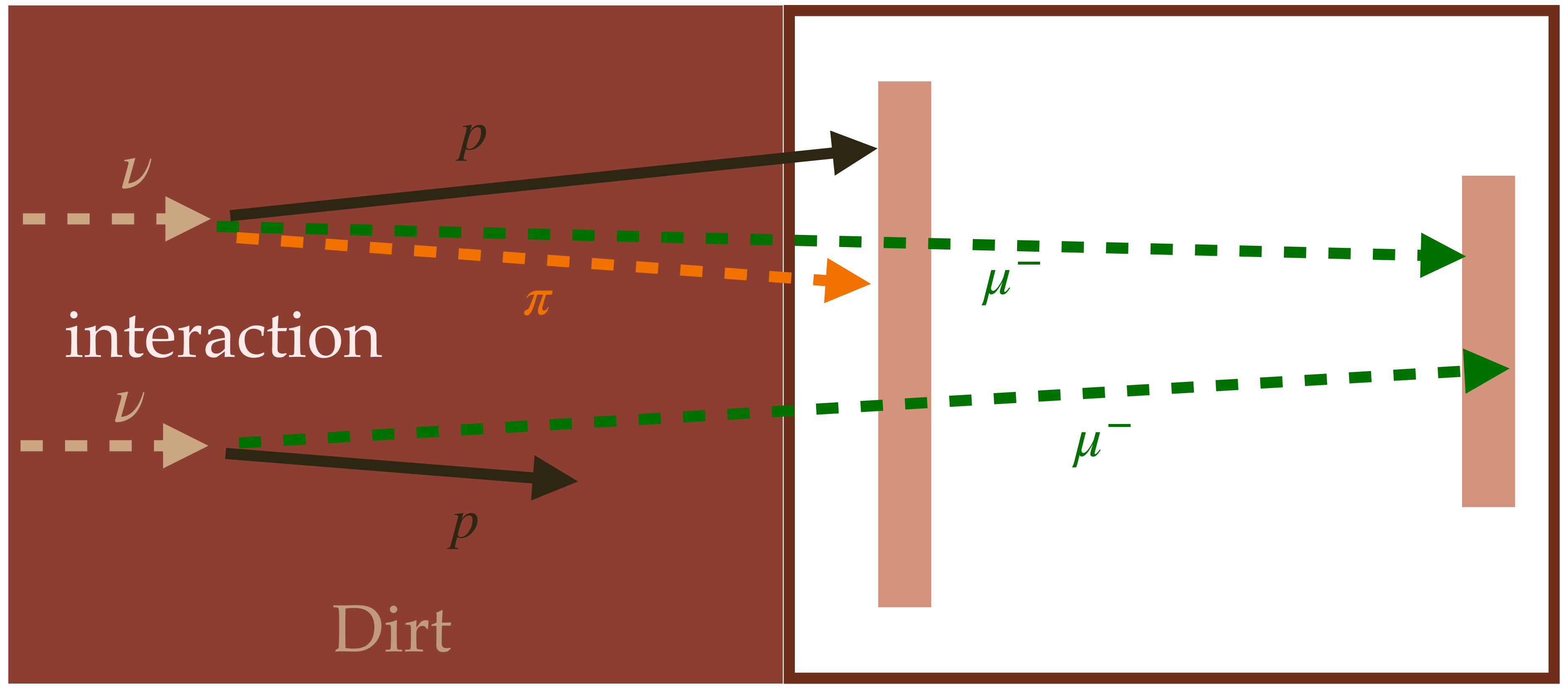
Short-lived dark neutrinos

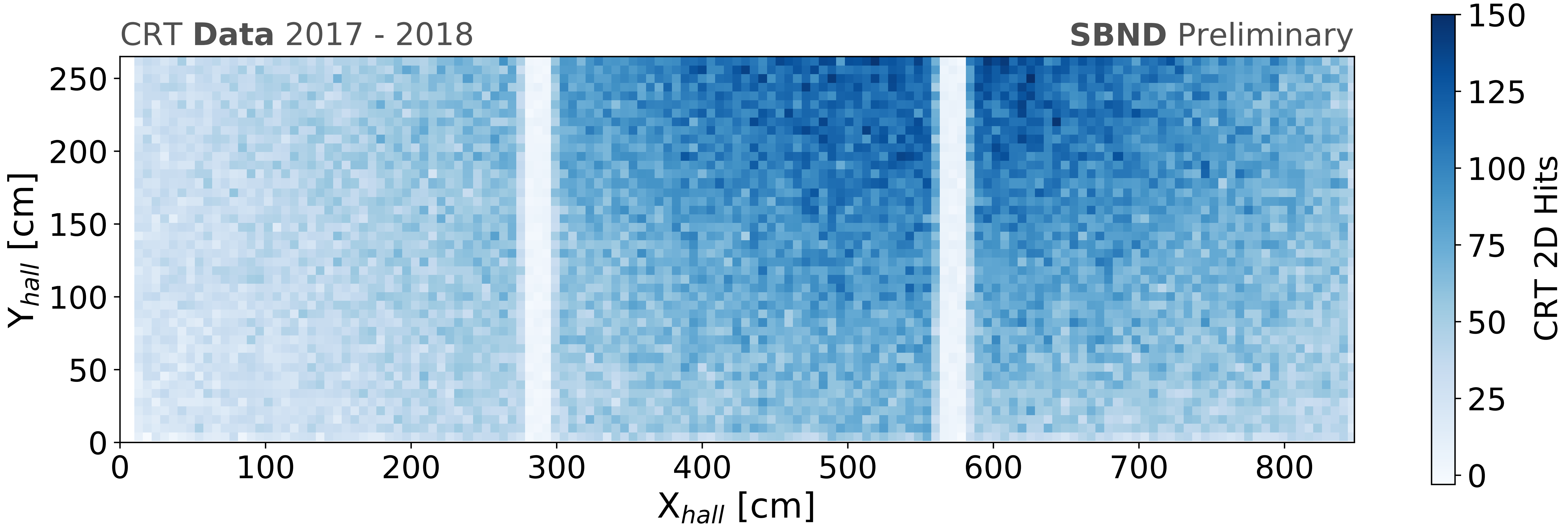


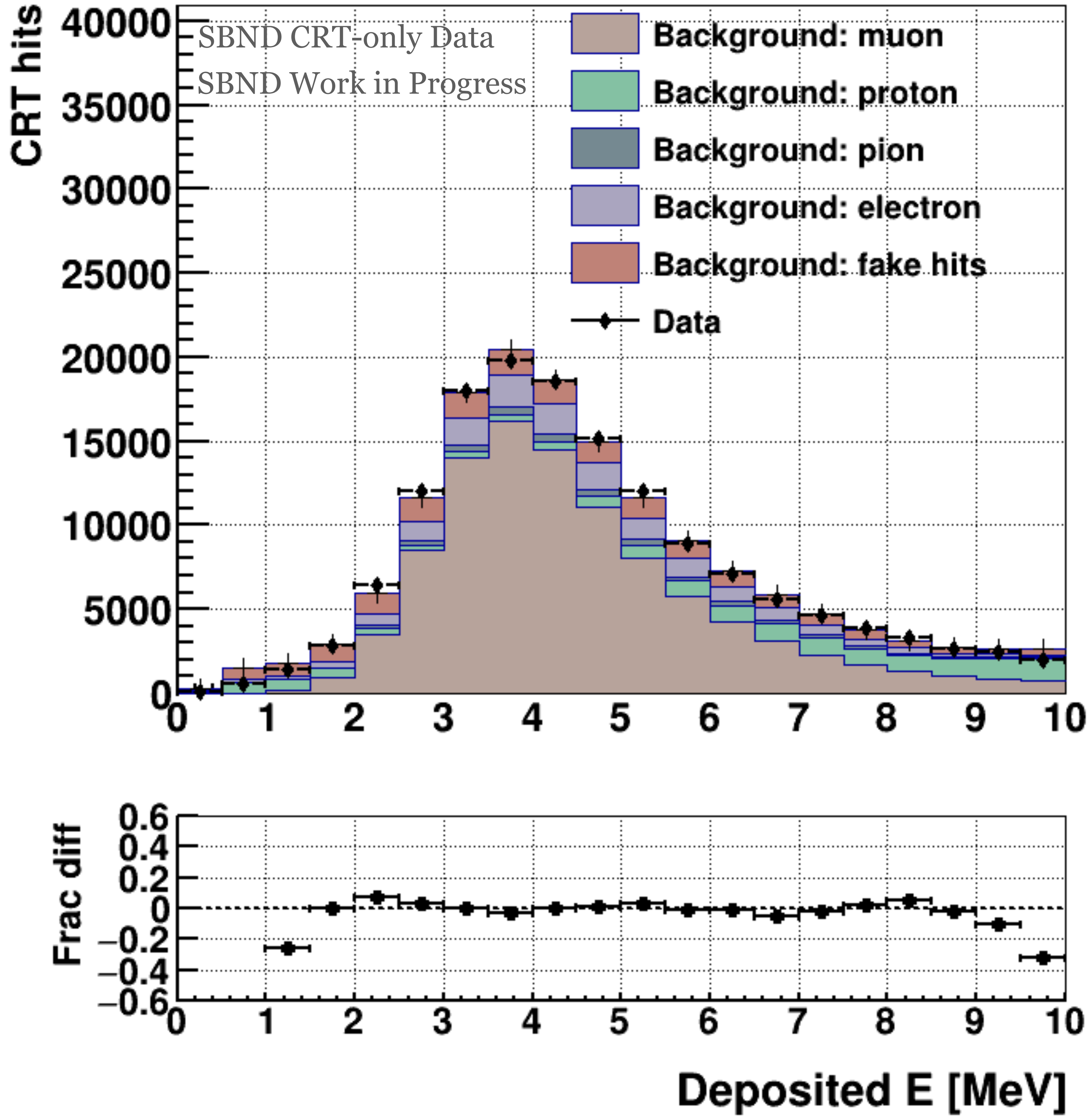
Long-lived dark neutrinos



Background Validation for Dark Neutrino







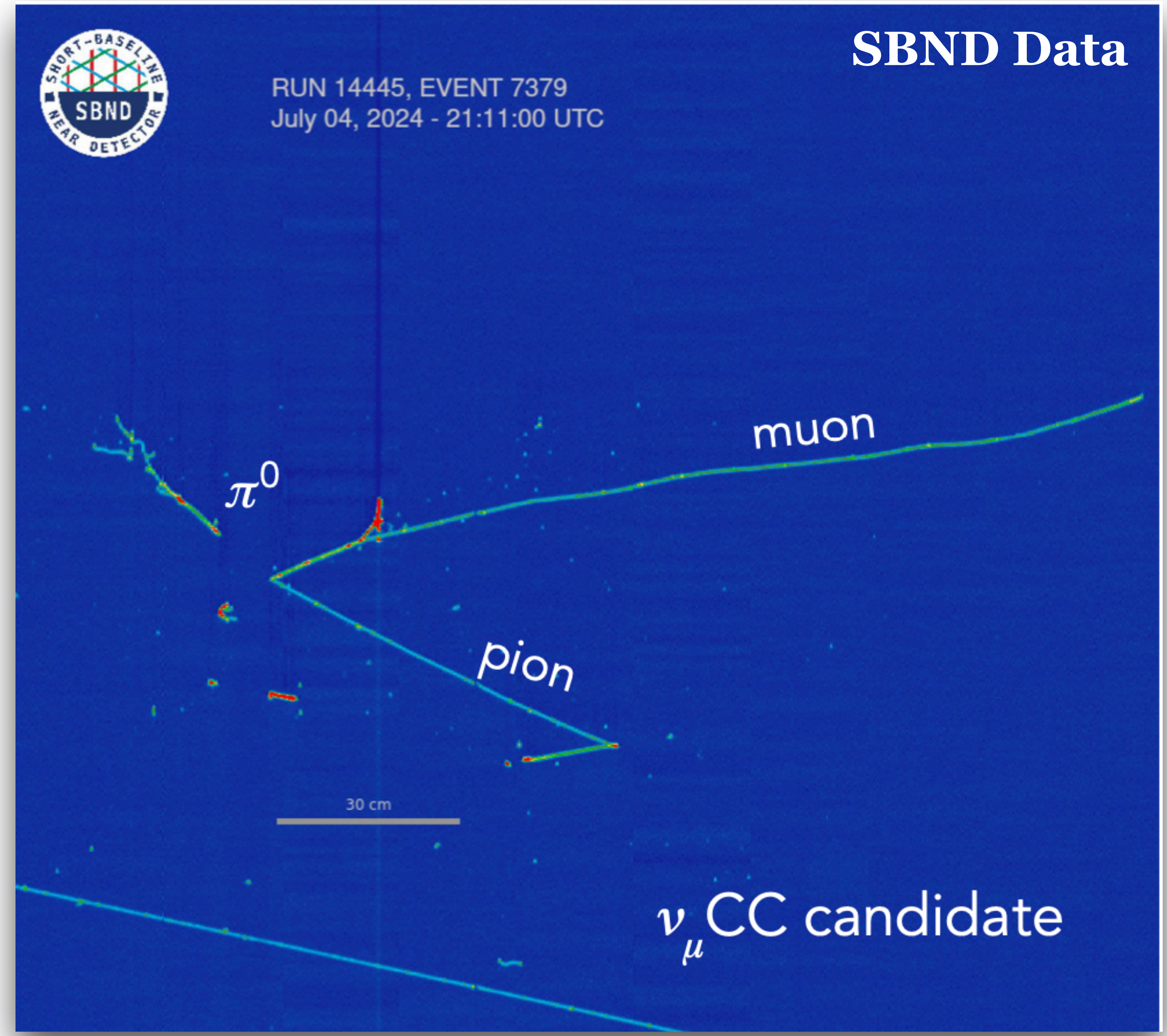
Neutrino Beam Structure is observed from the CRT data

Simulation shows a good agreement with the CRT data

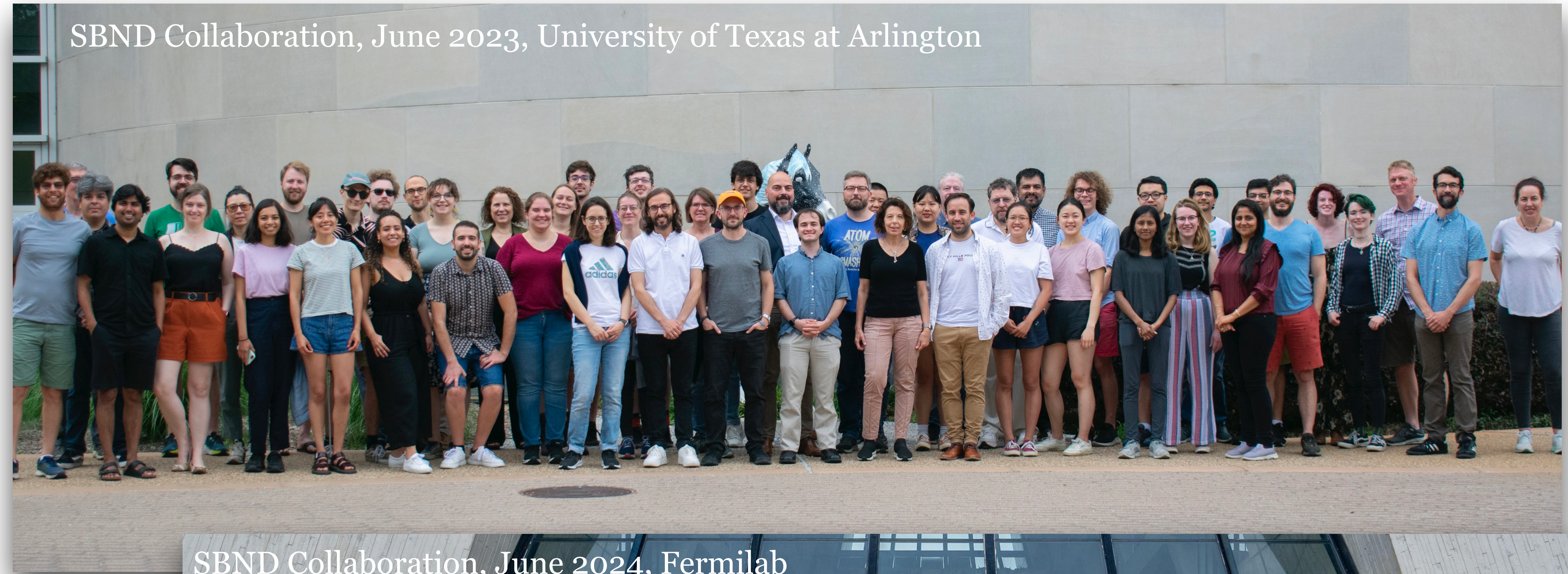
This is an ongoing analysis, results will be out soon! Stay tuned!

Summary

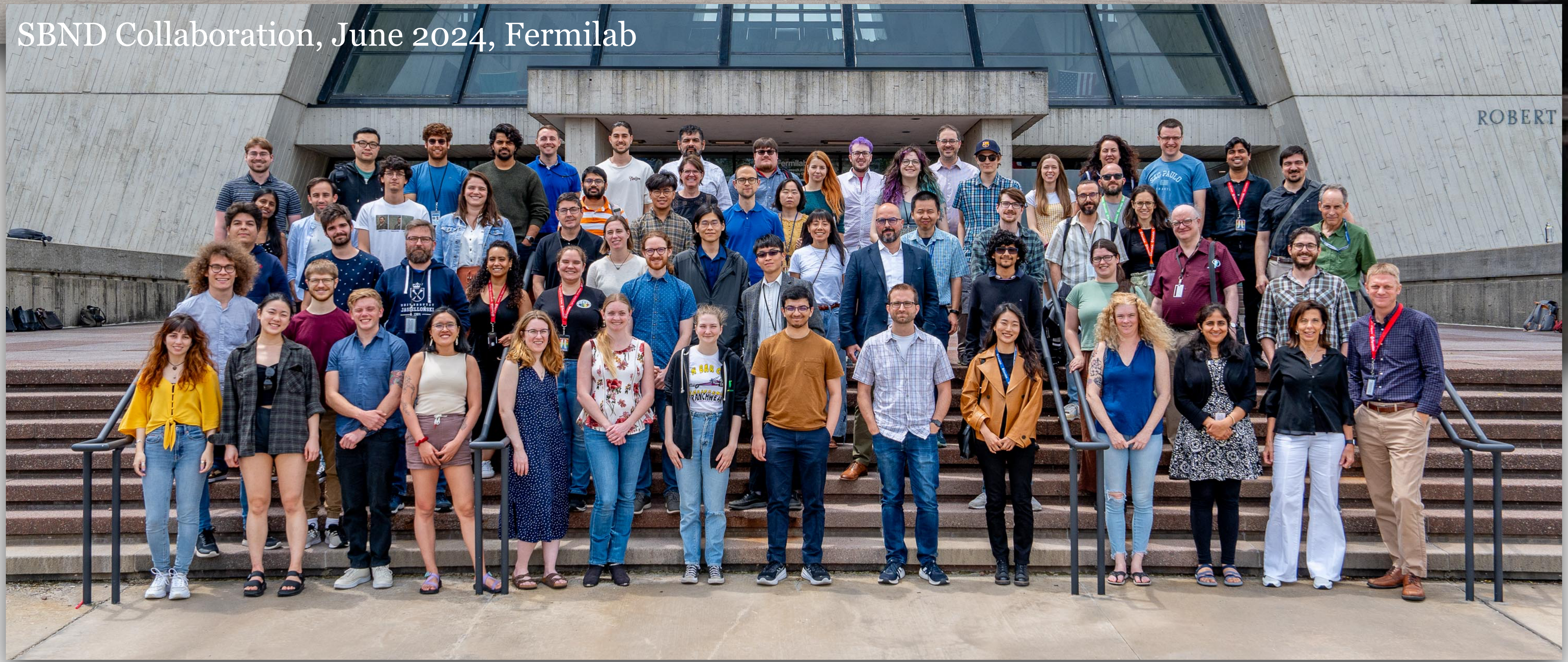
- Short Baseline Neutrino Detector (SBND) is in a unique position to sub-GeV BSM physics:
  - high BSM production rate due to the proximity to the neutrino target
  - SBND-PRISM for systematic constrains and s/B optimisation
  - ns-timing resolution provides a handle for low background
- SBND has a rich BSM program:
  - Model-independent to maximise discovery potential, enabling comparisons across experiments
  - Model specific: HNL, Light Dark Matter, Dark ν, Milli-charged particle, QCD axion
- <u>**Data taking in SBND has started**</u> after many years of hard work! The BSM sensitivity paper for SBND is in-progress



非常感谢！ :)) *Thank you very much! Děkuji mnohokrát!*


SBND Collaboration, June 2023, University of Texas at Arlington


SBND Collaboration, December 2024, Sao Paulo



SBND Collaboration, June 2024, Fermilab

Stay tuned for SBND!

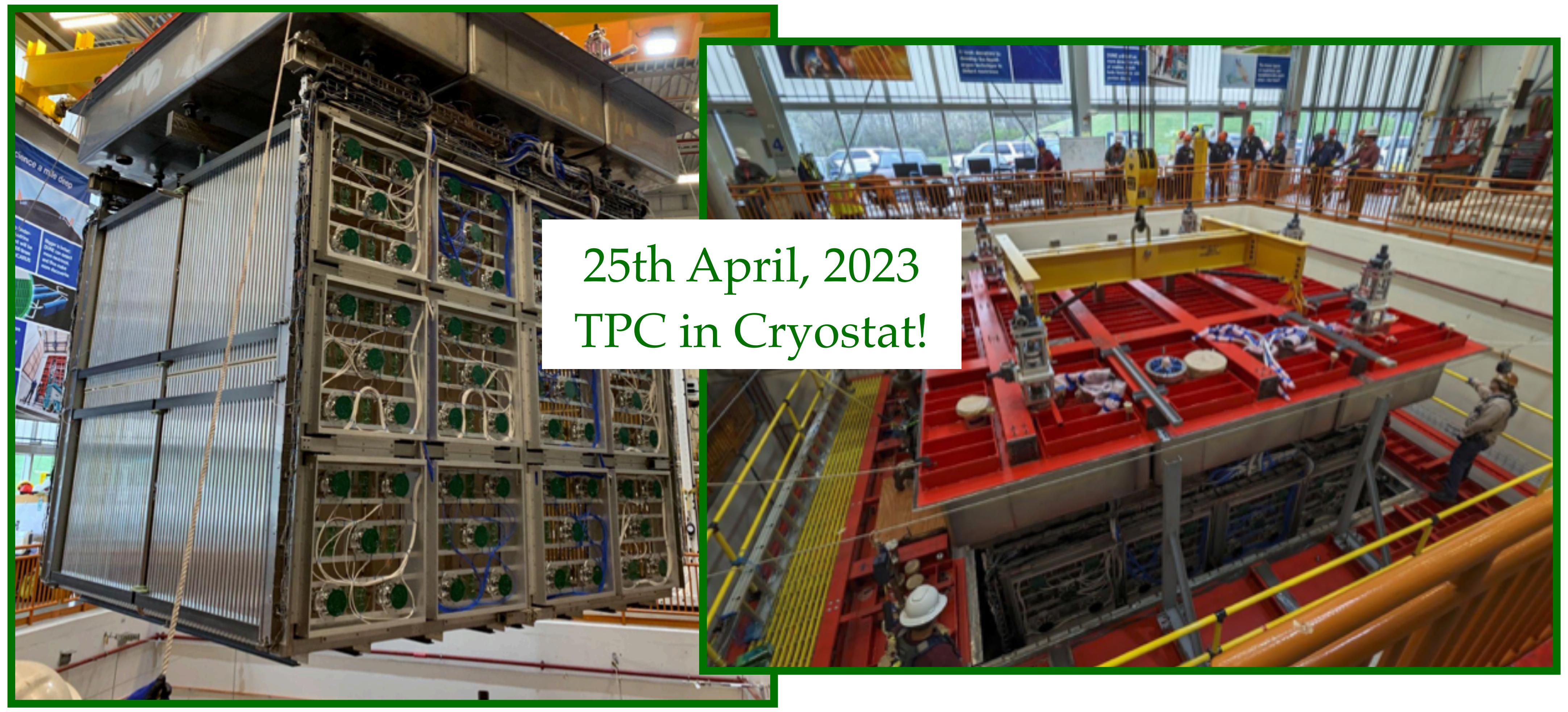
Backup

SBND Milestones

13th June, 2022 TPC + PDS System Assembly done!

18th May, 2023, first wall of CRT installed!

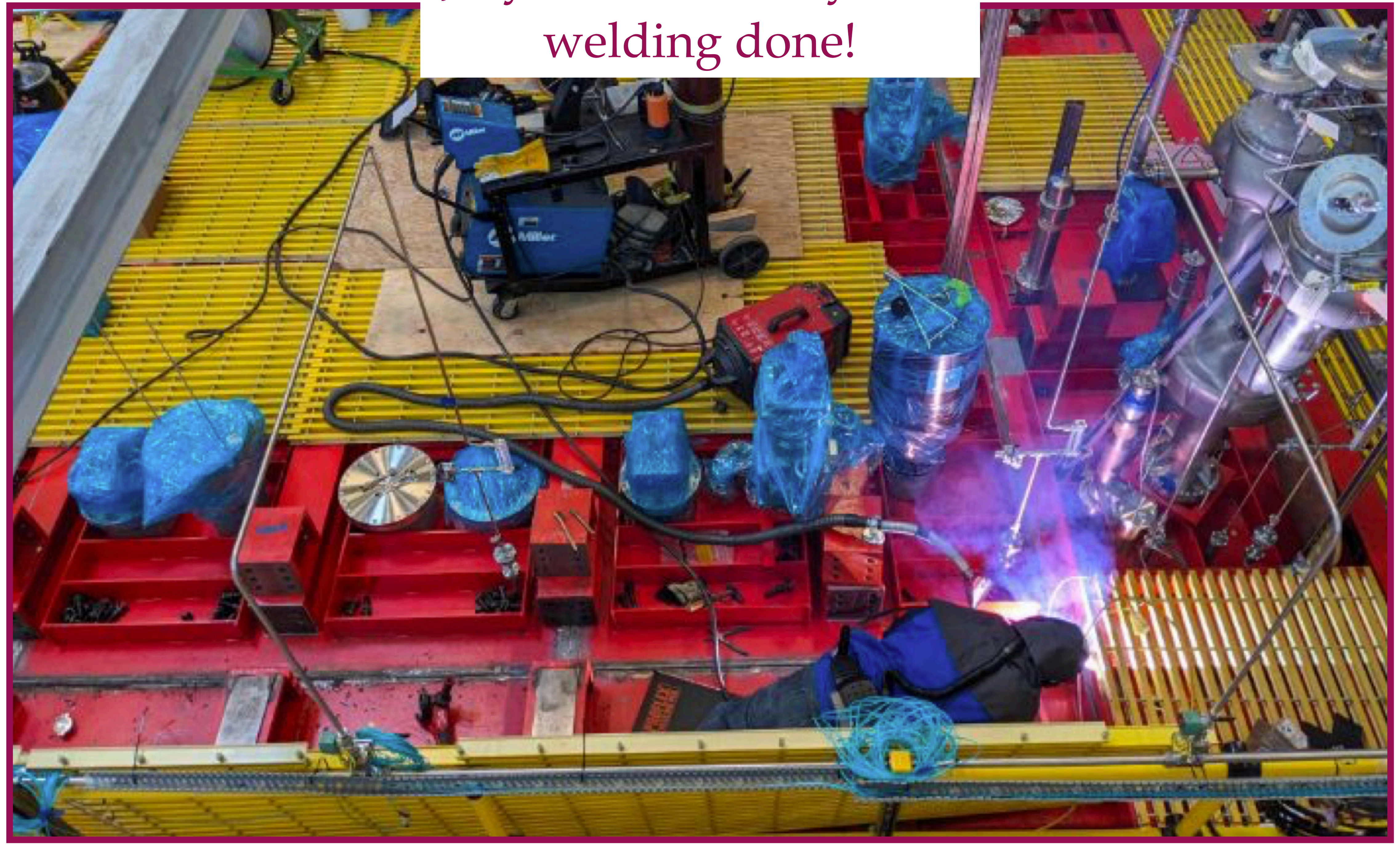
1st, December 2022, TPC in SBND building!



25th April, 2023 TPC in Cryostat!

SBND Milestones

July 19th, 2023 Cryostat welding done!



1st December, 2023 cryogenics installation done!

SBND Milestones

LAr filling completed
March 2024

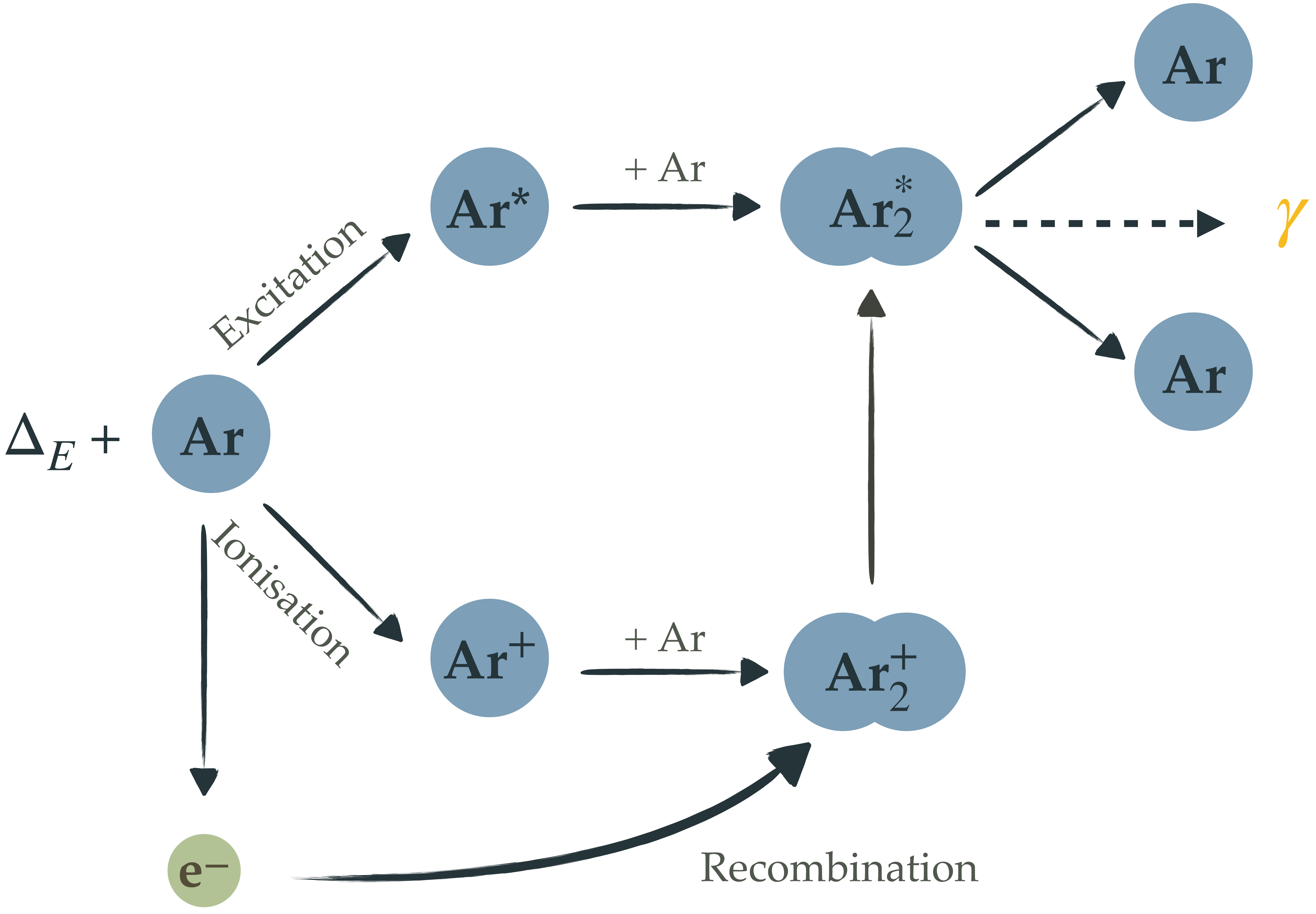
North and East CRT modules installed

April 2024

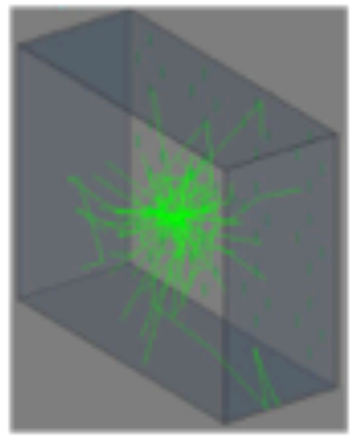
Ramp up to nominal TPC voltage

July 2024

Liquid argon scintillation light

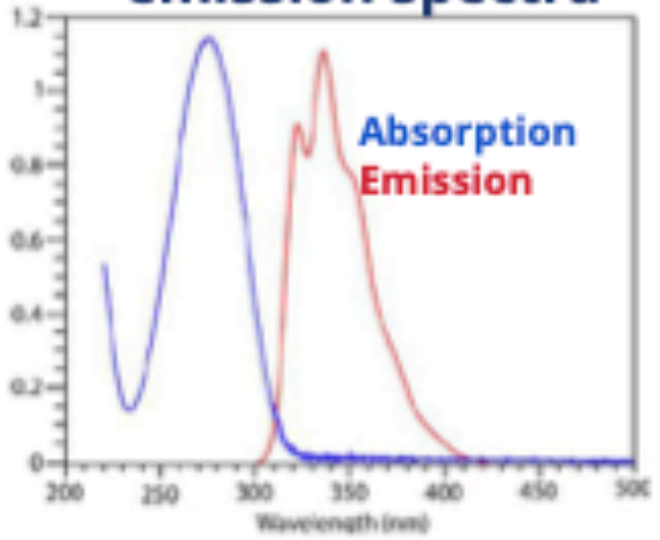


VUV Light



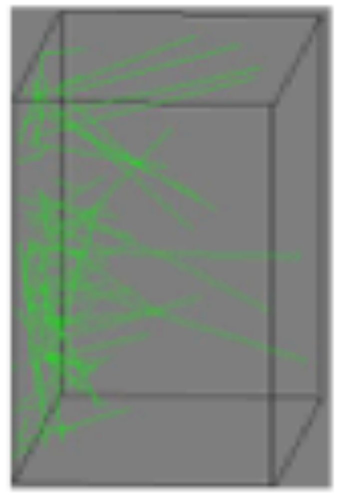
- Directly produced in LAr volume
- Rayleigh scattering length ~1 m
- TPB & P-Terphenyl (pTP) coating of PDS sensors

pTP absorption & emission spectra



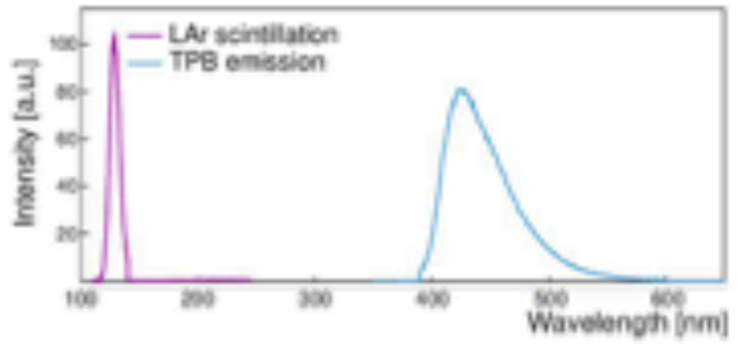
Nuclear Science Symposium (pp. 2228-2233), 2008

Visible Light



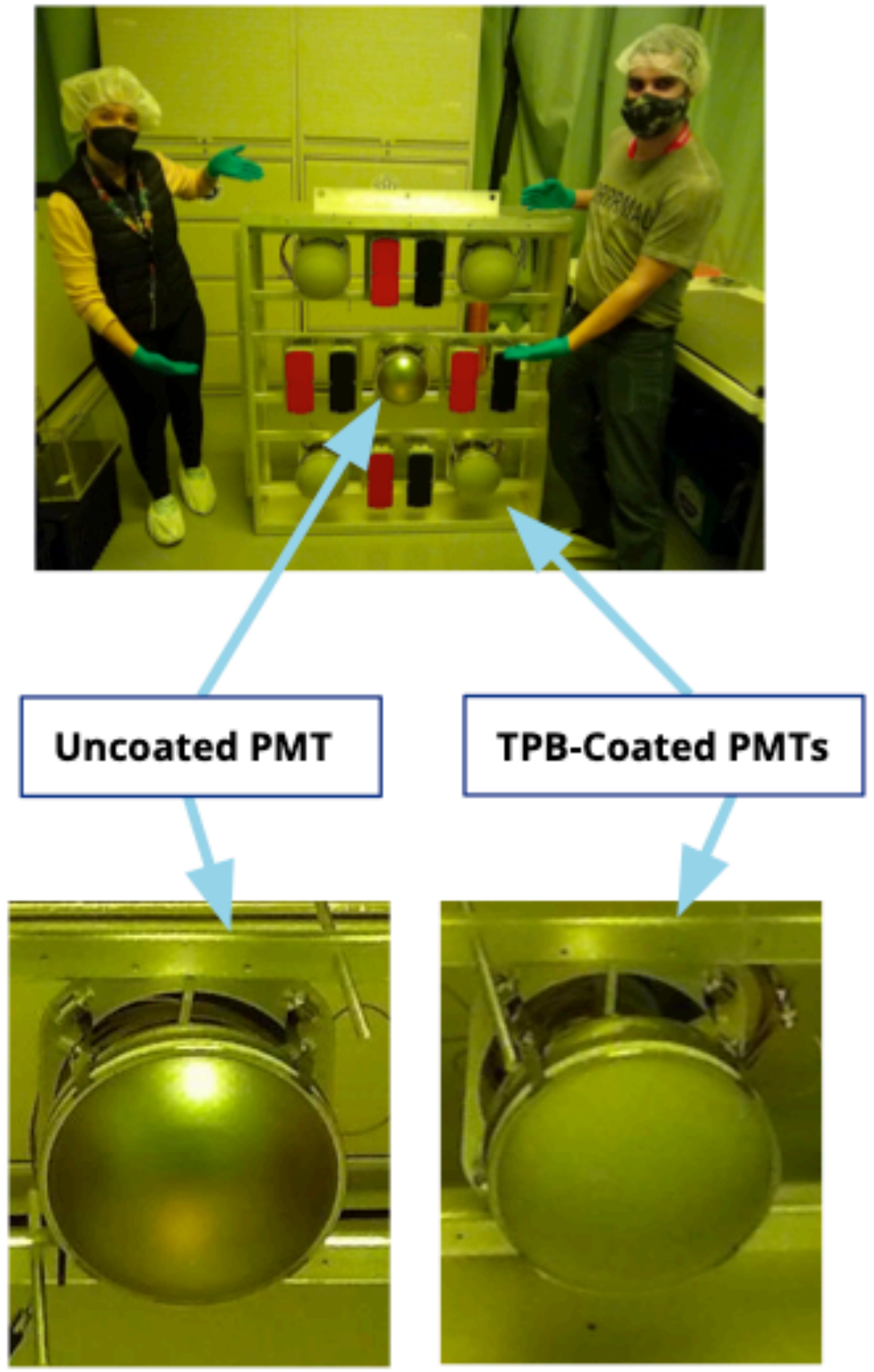
- Re-emitted by TPB foils in the cathode plane
- Rayleigh scattering length ~20 m

TPB emission spectra



Eur.Phys.J.C 82 (2022) 5, 442

PDS: PhotoMultiplier Tubes



Left & right: uncoated and coated PMTs installed in PDS Box

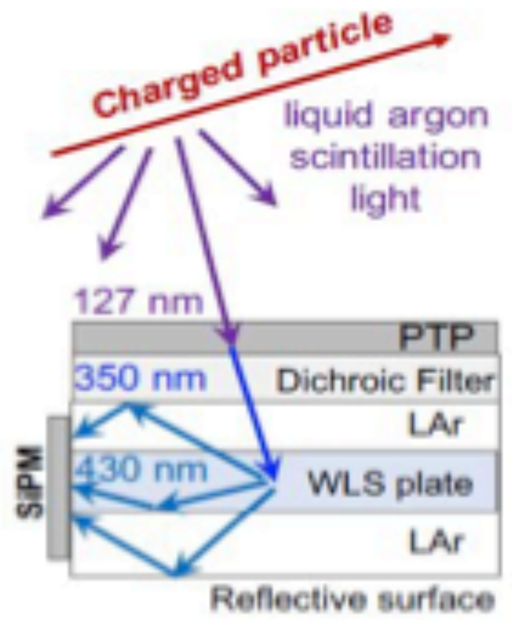
- ➔ 120 total 8" Hamamatsu R5912 PMTs
  - ◆ 96 TPB coated PMTs (VUV +visible light)
  - ◆ 24 uncoated PMTs (visible only)
- ➔ 500 MHz CAEN readout.
- ➔ PMT system already tested and characterized by CCM experiment
- ➔ Used for trigger building.

PDS: X-ARAPUCAs

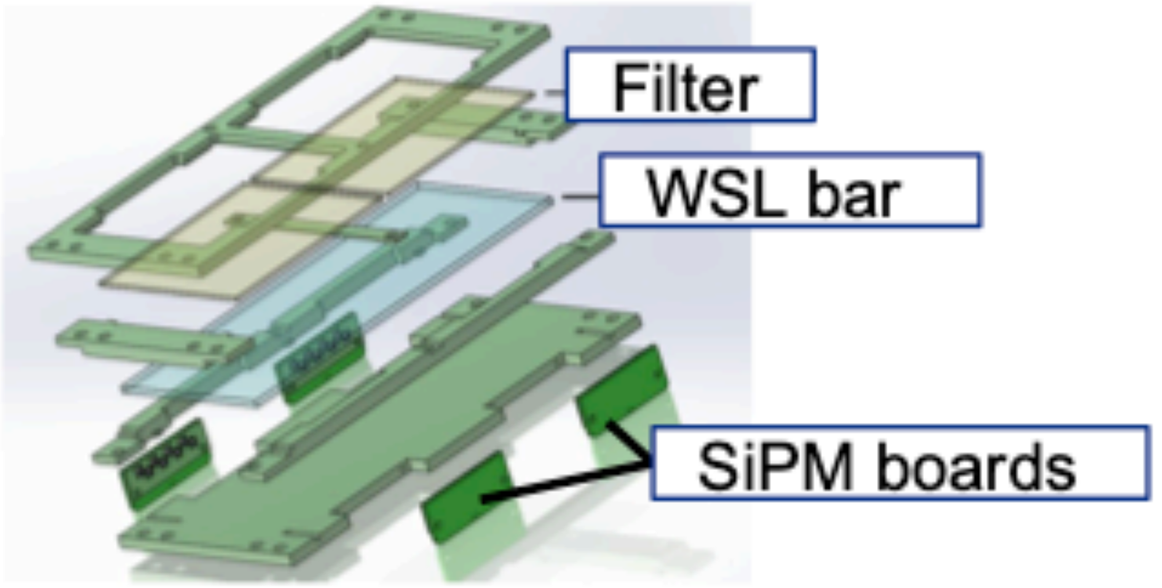
SiPMs	WLS Bar	Filter	Modules in SBND
SensL MICROFC-30050-SMT	Eljen 286	pTP coated 400 nm cutoff	88
SensL MICROFC-30050-SMT	Eljen 280	450 nm cutoff	88
HPK 6050-VE	Glass to power B.	pTP coated 400 nm cutoff	6
HPK-VE 6050-VE	Glass to power G.	450 nm cutoff	6
HPK 6050-HS (↓bias,↑PDE)	Glass to power B.	pTP coated 400 nm cutoff	2
HPK-HS 6050-HS (↓bias,↑PDE)	Glass to power G.	450 nm cutoff	2

SBND X-ARAPAPUCA configurations

- ➔ **New scalable technology under development.**
- ➔ **Photons get trapped inside the module, increasing collection area. Side SiPMs collect the photons.**
- ➔ **Cut-offs allow for light source discrimination (450nm filter lets only visible light through)**
- ➔ **CAEN readouts: 12-bit / 62.5 MHz**
- ➔ **Important R&D for future experiments (DUNE PDS is only X-ARAPUCA based).**



X-ARAPUCA operating principle. Nucl. Instrum. Meth. A, 985 (2021)

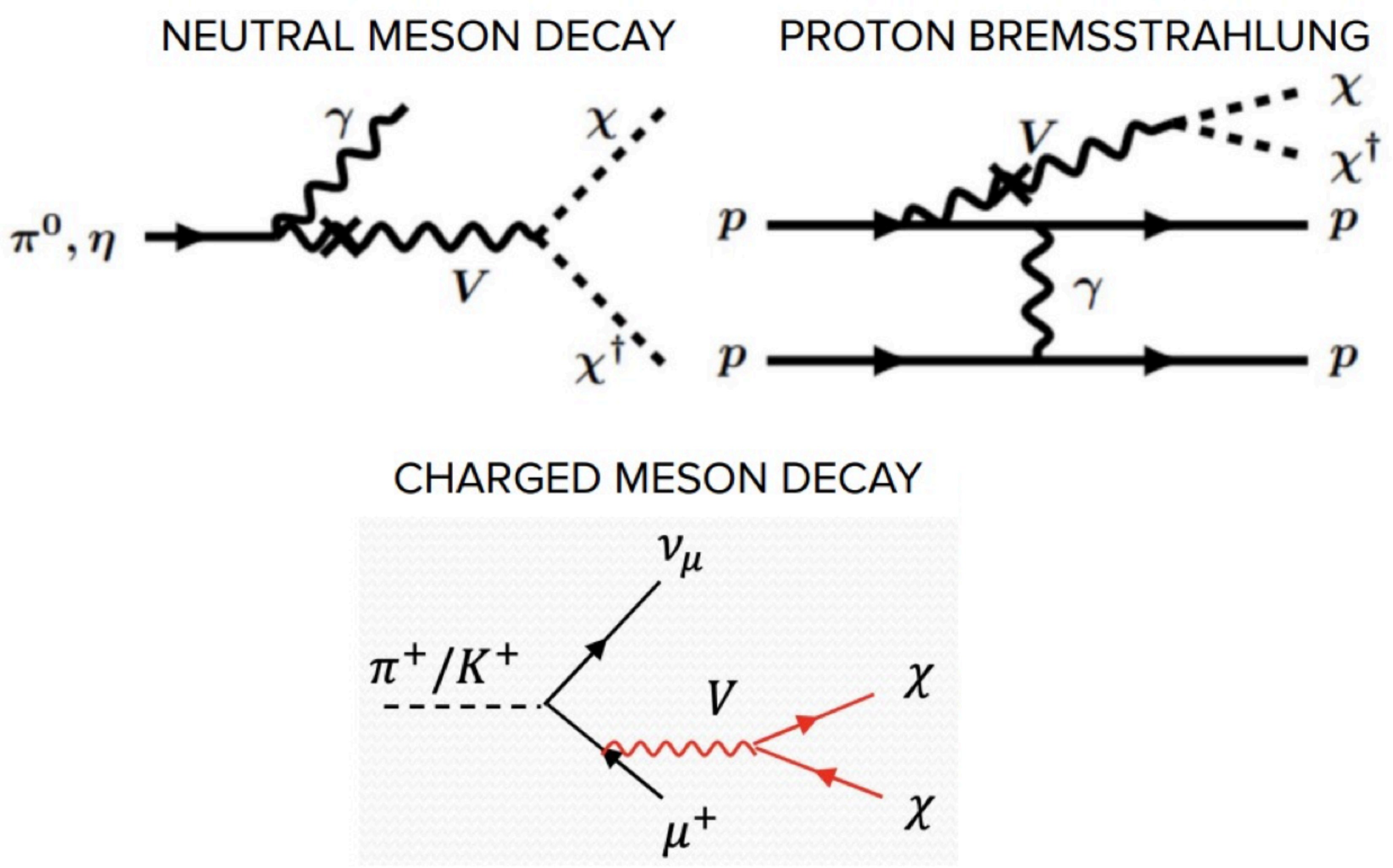


Left: SBND X-ARAPUCA mechanical scheme. Right: mounted module

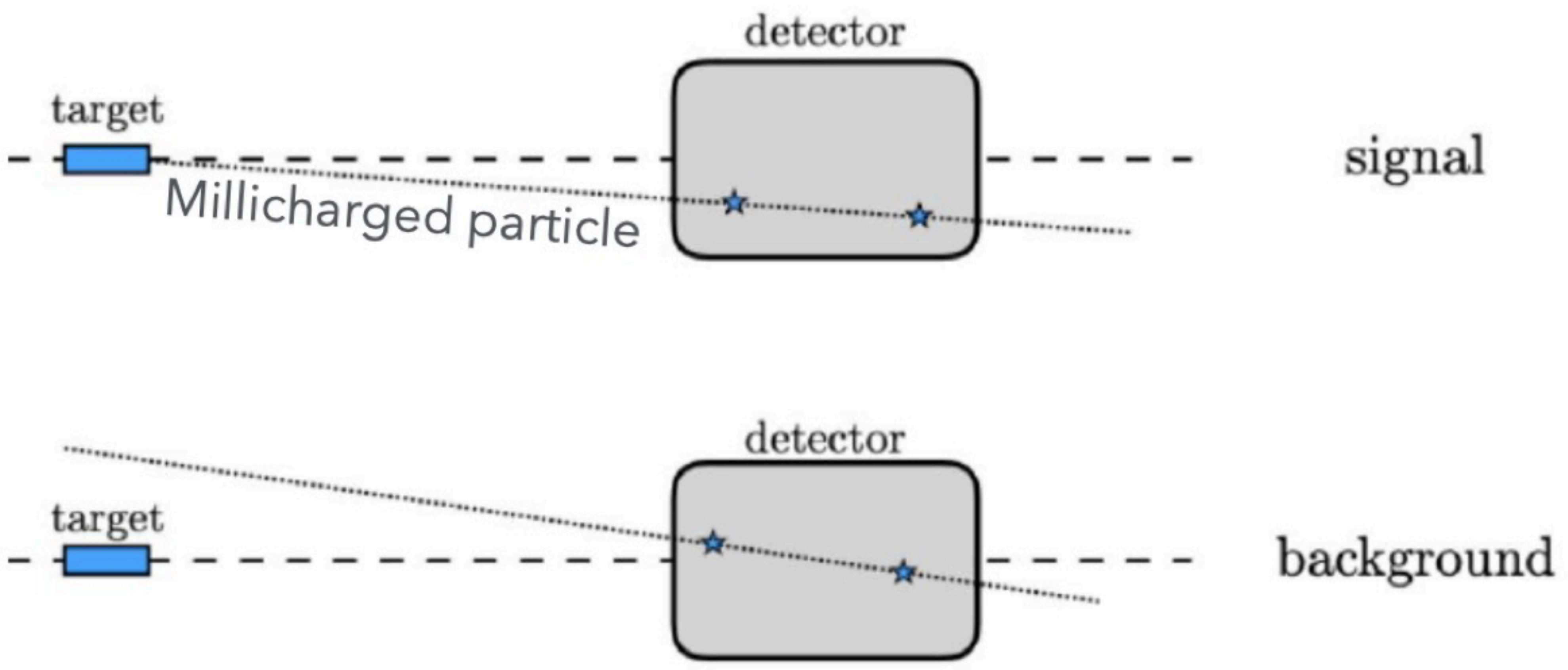
Light Dark Matter and Milli-charged particle

Production

[PRD 95, 035006 (2017)]



Sub-GeV Dark Matter can be produced from neutral/charge meson decay and proton Bremsstrahlung in the neutrino beam

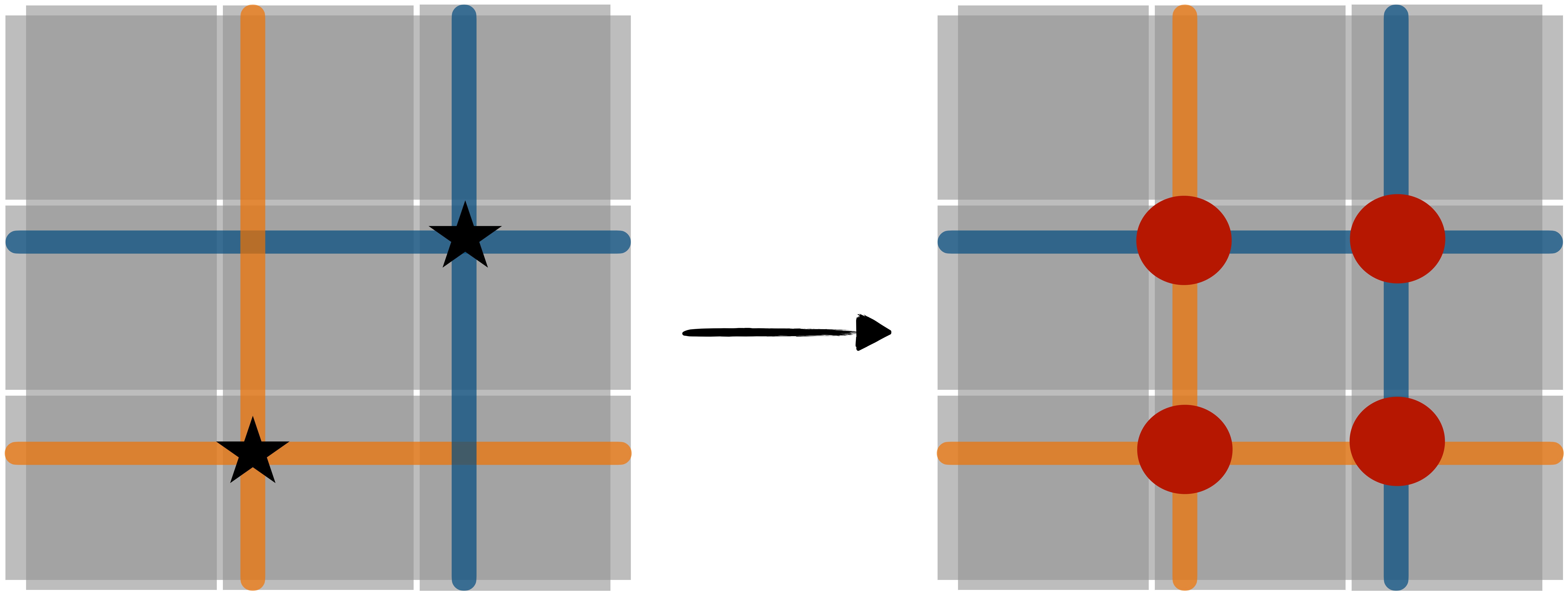


Hypothesised particles with **fractional electronic charge**, motivated by a cosmological anomaly (EDGES)

Production

- Milli-charged particle is produced by neutral meson decay in the neutrino beam

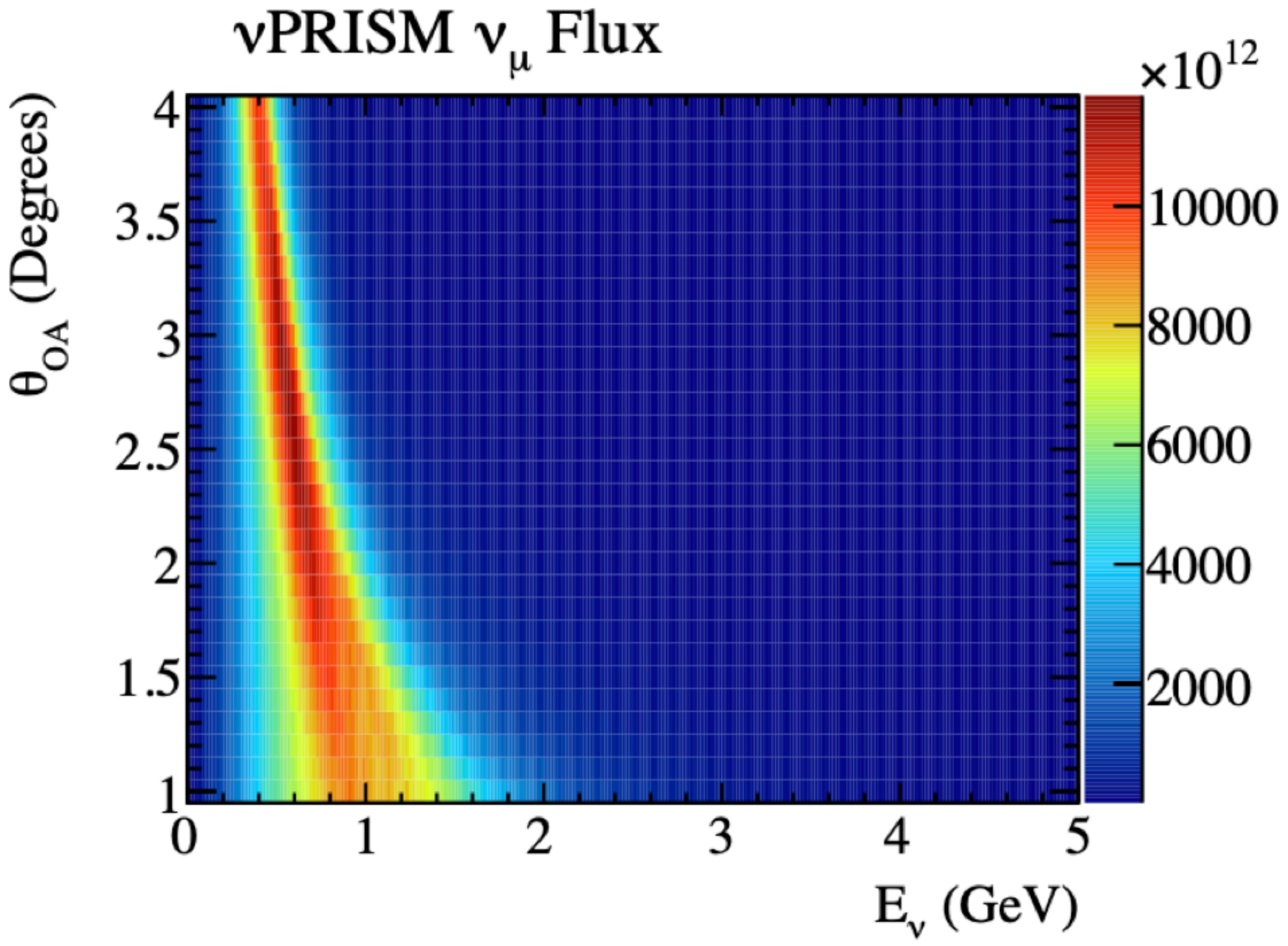
CRT hit reconstruction

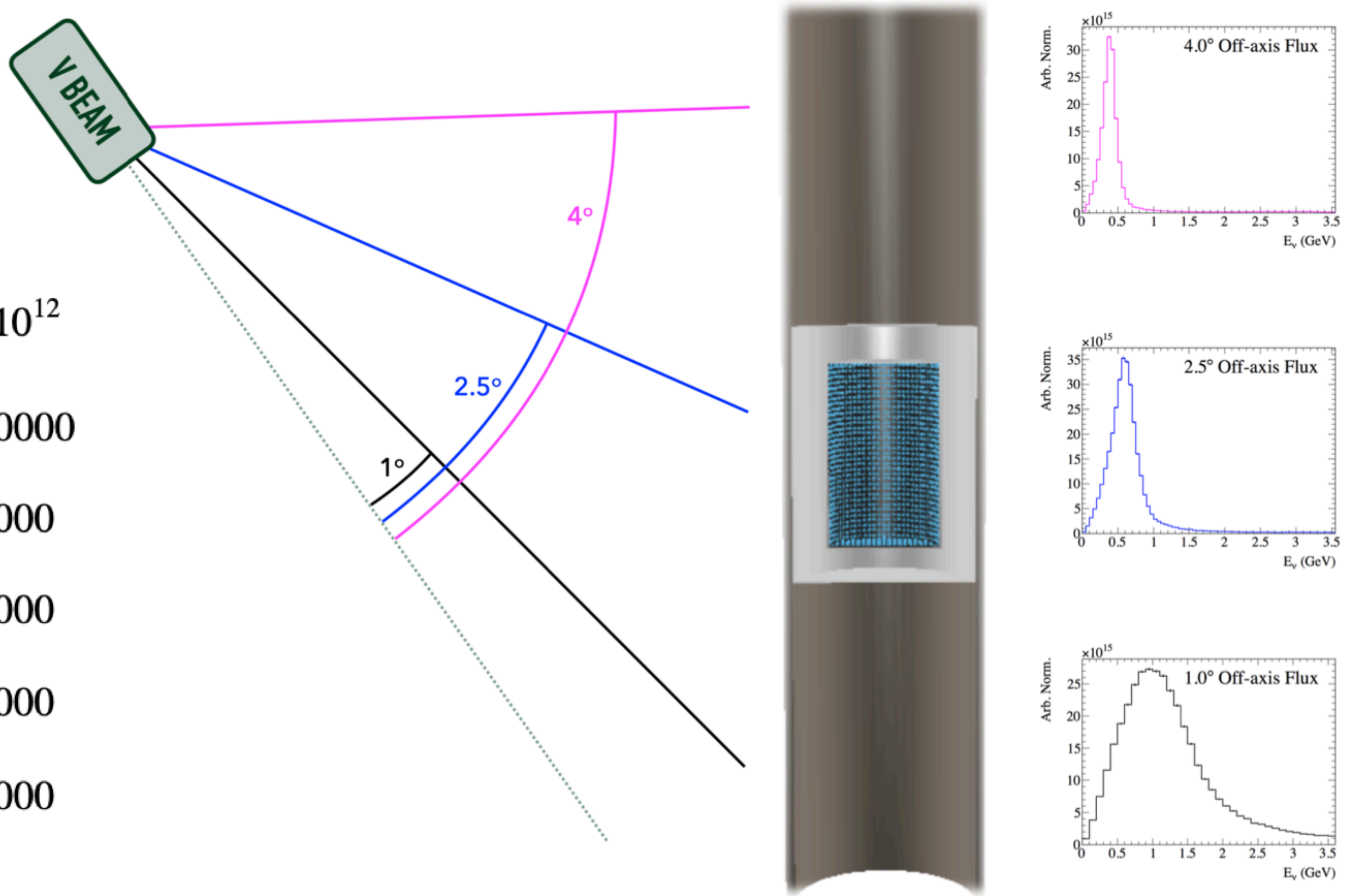


✦ NuPRISM

- Water Cherenkov detector moves through a cylindrical chamber
- 1 km downstream of the neutrino target
- Scans upto 4 degrees from the neutrino beam axis

[nuPRISM Collaboration], arXiv:1412.3086 [physics.ins-det]





SBND PRISM

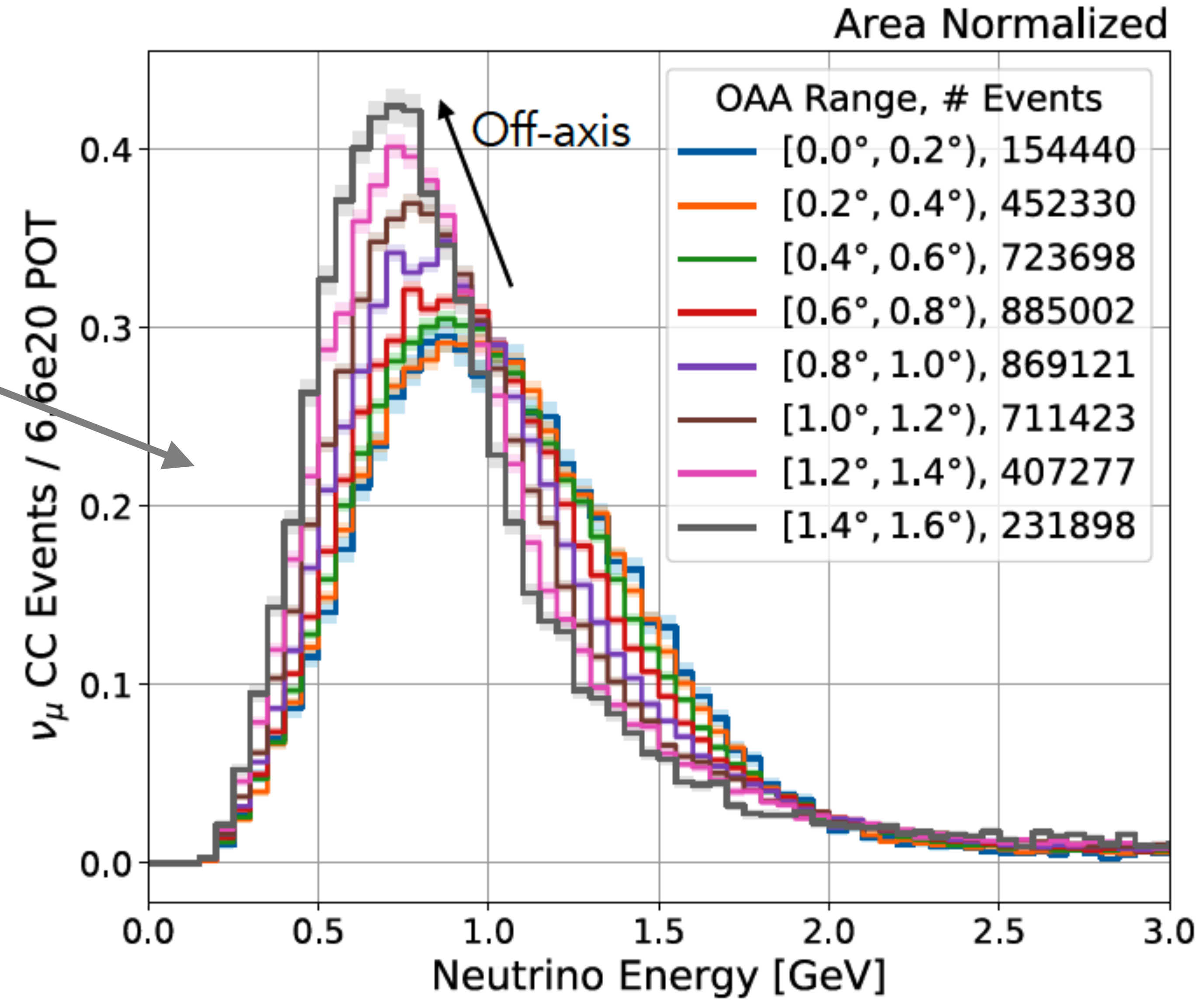
The **Muon** neutrino energy distributions are affected by the off-axis position [ν_μ come predominantly from two-body decay].
Larger off-axis angle → lower mean energy.

The **Electron** neutrino energy distributions also change, but they are less affected by off-axis position [ν_e come from three-body decay].

Muon and electron neutrino spectra change in a different way!

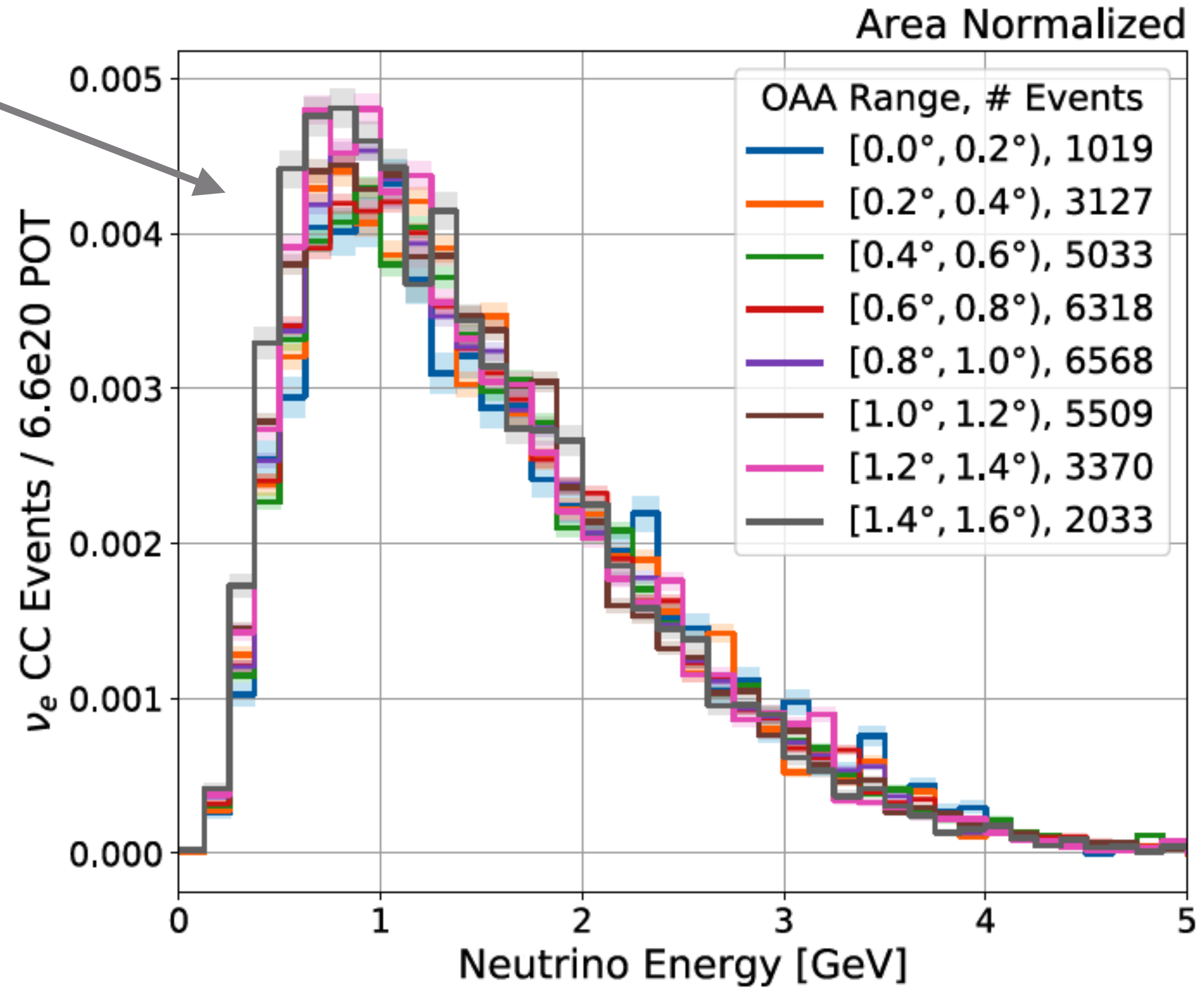
Leveraging the different behaviour of muon and electron neutrinos in the OAA regions, we can improve sensitivity for sterile neutrino searches.

Neutrino Fluxes in Off-Axis Angle (OAA) regions



Muon neutrino

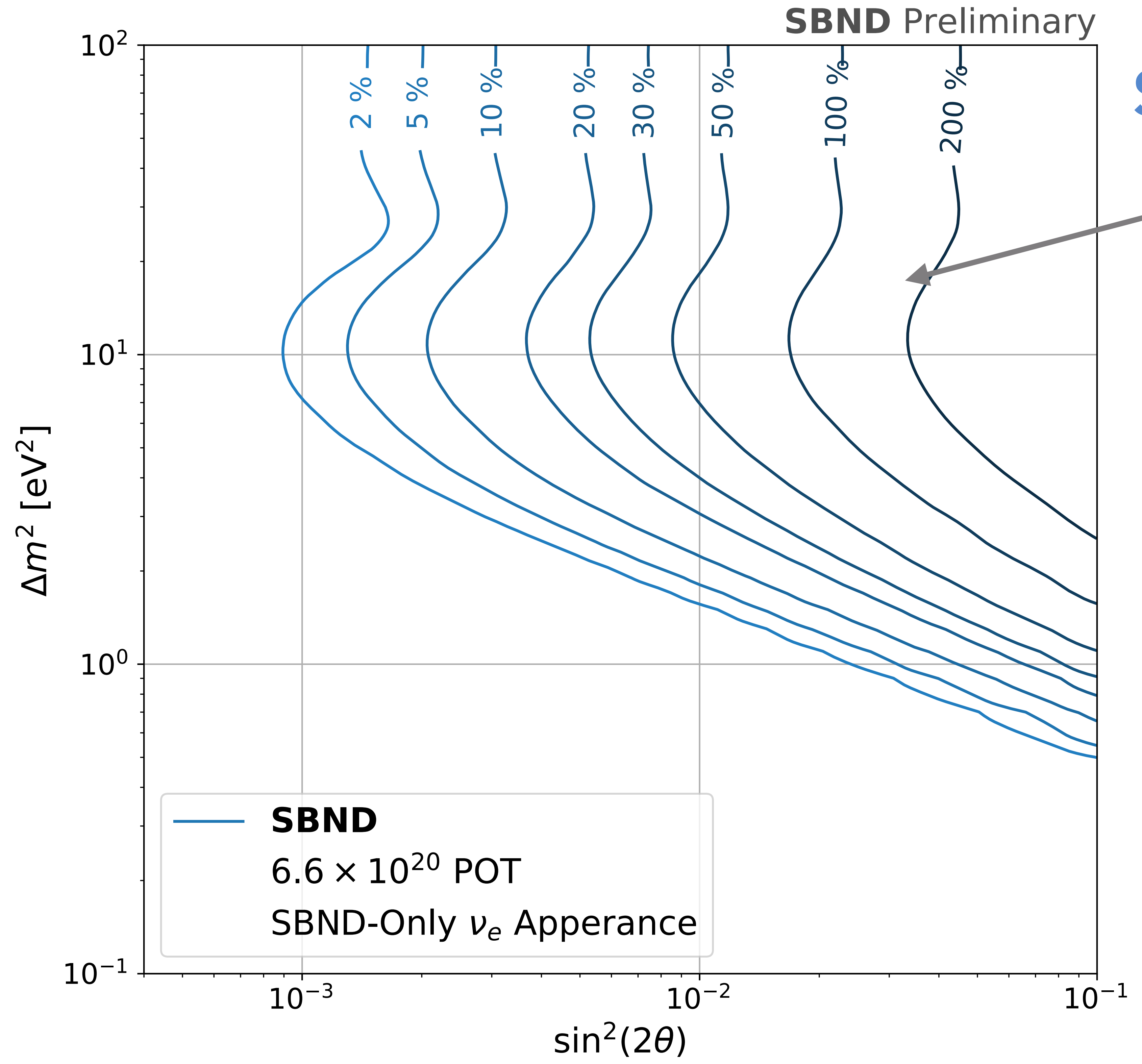
High event statistics in all off-axis regions.



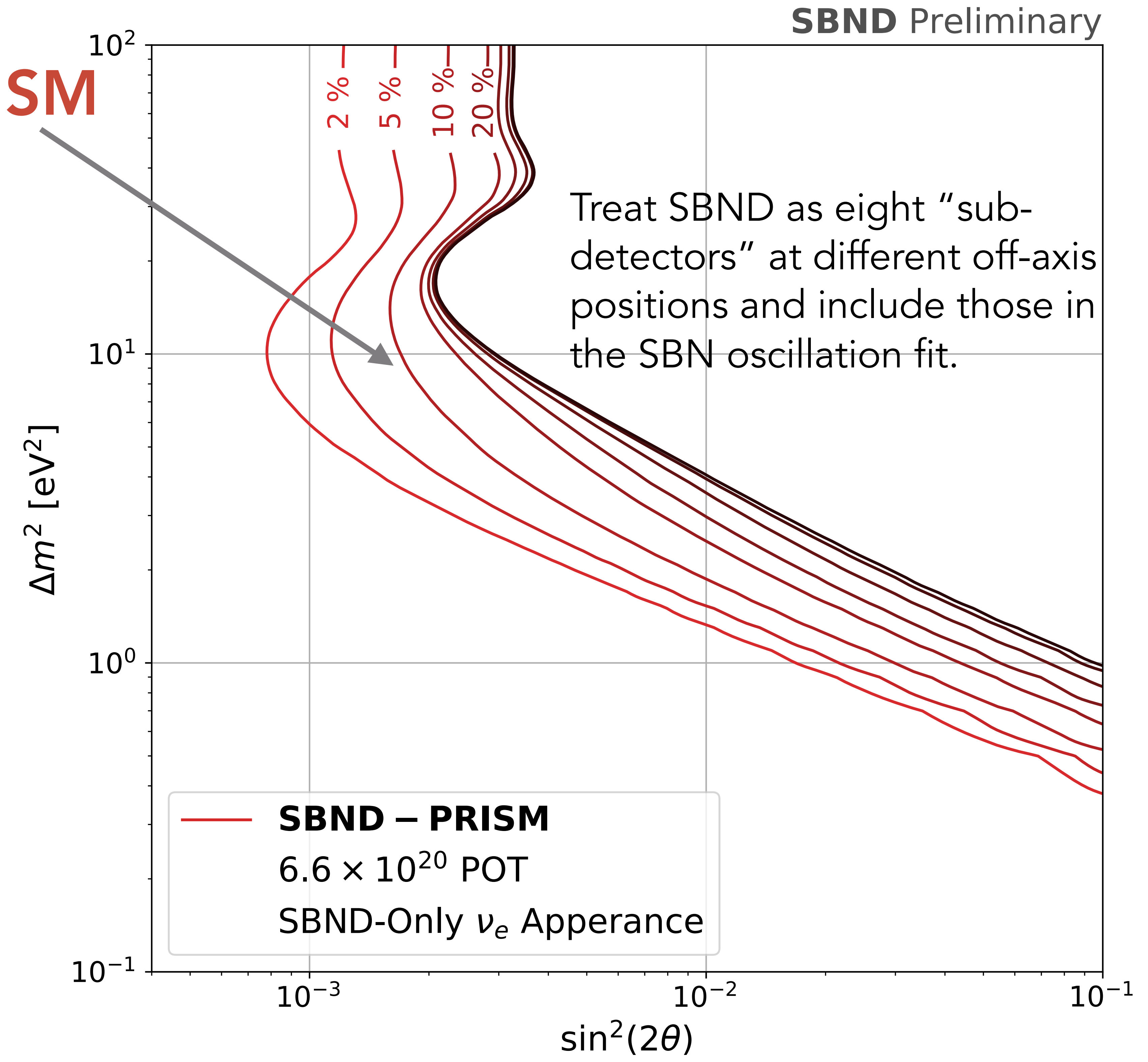
Electron neutrino

EFFECT OF SBND-PRISM ON OSCILLATION ANALYSES

SBND-only - simplified Oscillation Analysis (ν_e Appearance)



SBND as a single detector vs **SBND-PRISM**



Curves include neutrino flux plus 2-to-200% systematics on total cross section.

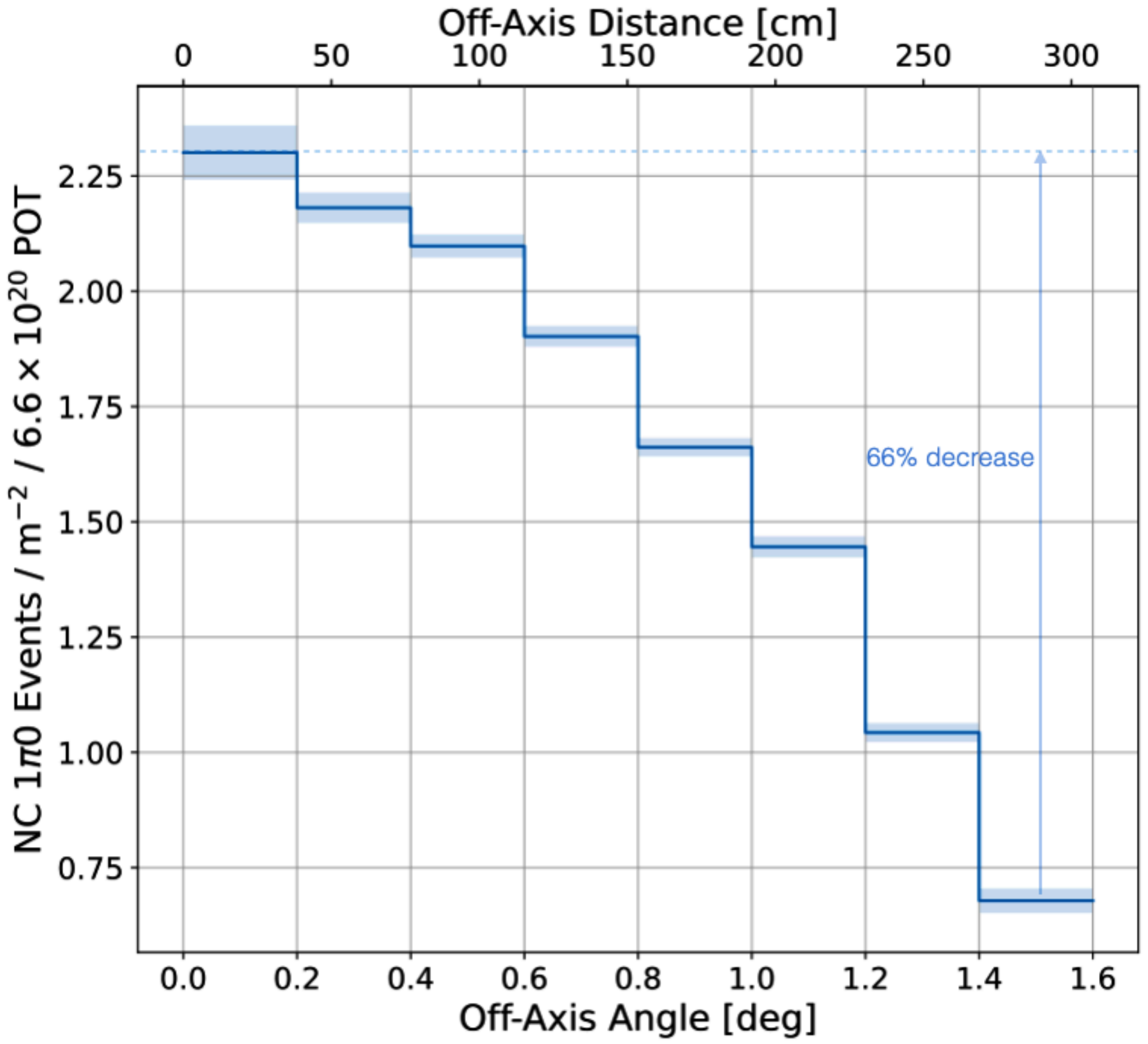
- Improvement in sensitivity by exploiting SBND-PRISM.
- Using the PRISM technique the neutrino interaction model is over-constrained, becoming ~ insensitive to cross section model uncertainties above 20%. Robust against large cross-section uncertainties.

Study of the effect of SBND-PRISM on SBN Sterile neutrino oscillation sensitivities is ongoing.

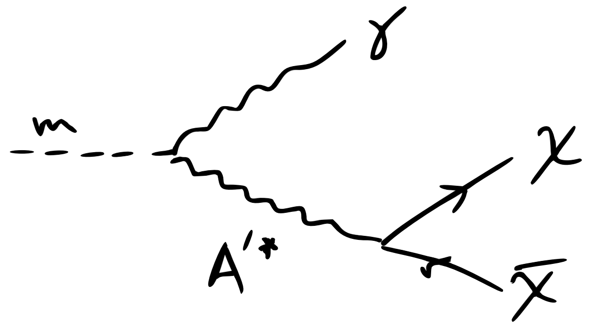
SBND-PRISM TO MITIGATE BACKGROUNDS

An example: electron neutrino measurements

Main background for electron neutrino: NC 1 π^0 events.

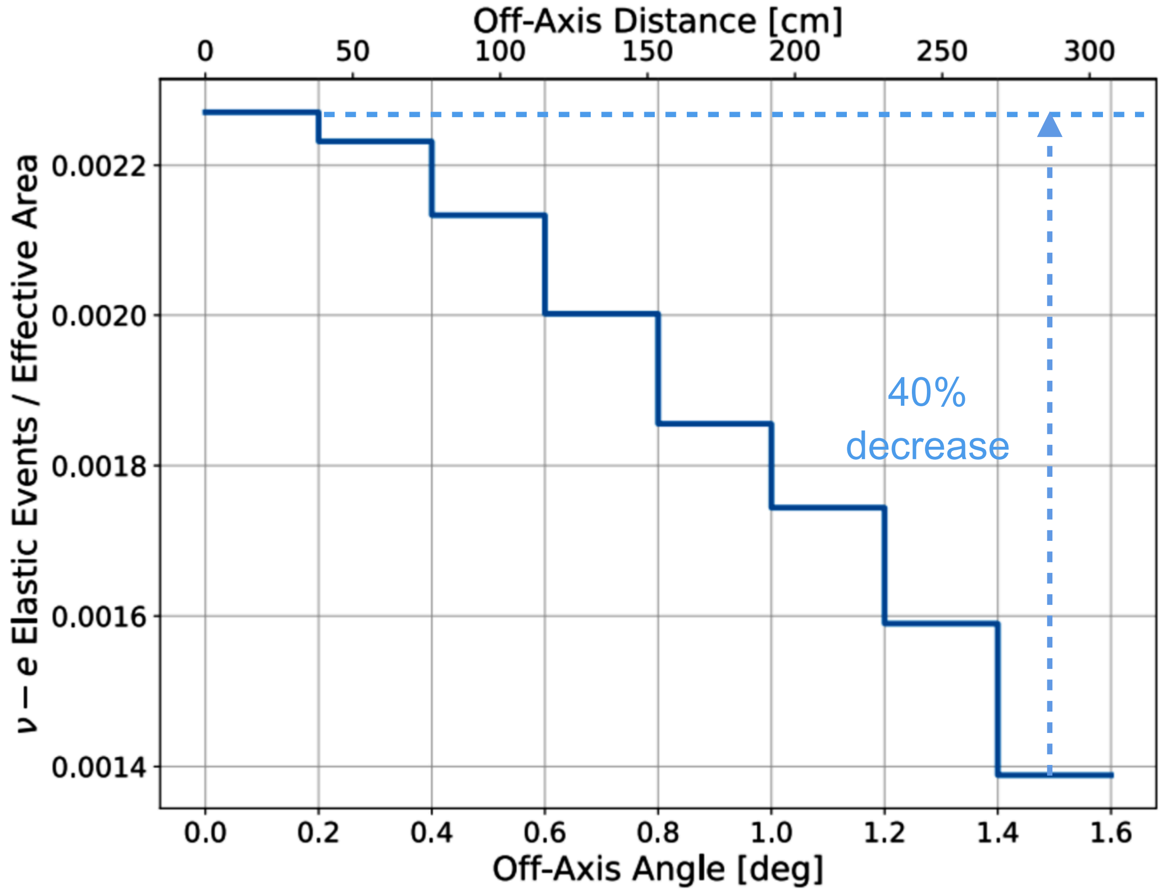


Another example: search for Light (sub-GeV) **Dark Matter**

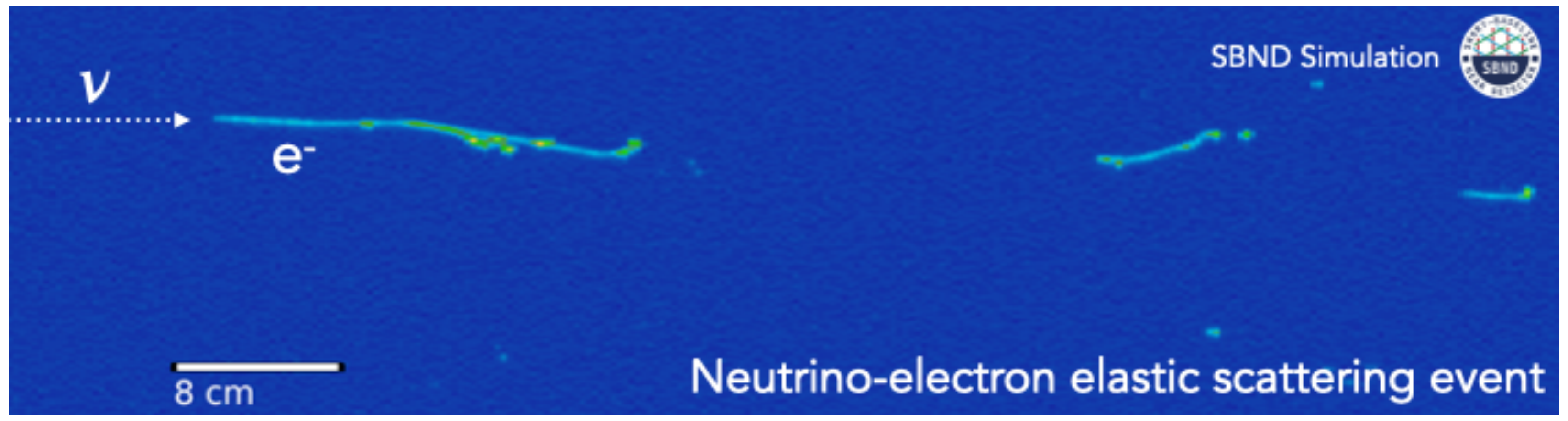


Dark photons, produced by the decay of neutral meson (pions, etas) in the target and decay into dark matter.

The dark matter, through the dark photon, **scatter off electrons in the detector**.



- **Signal**: DM elastic scattering electron events. DM comes from neutral (unfocused) mesons.
- **Background**: neutrino-electron elastic scattering. Neutrinos come from two-body decays of charged (focused) mesons.



SBND-PRISM provides a natural way to **reduce backgrounds by looking off-axis**.