Precision Measurements of Neutrino-argon Interactions in the Short-Baseline Near Detector Experiment

Theoretical Physics Uncertainties to Empower Neutrino Experiments
Institute for Nuclear Physics Workshop, Seattle, November 2nd, 2023

Ornella Palamara
Fermilab & Yale University

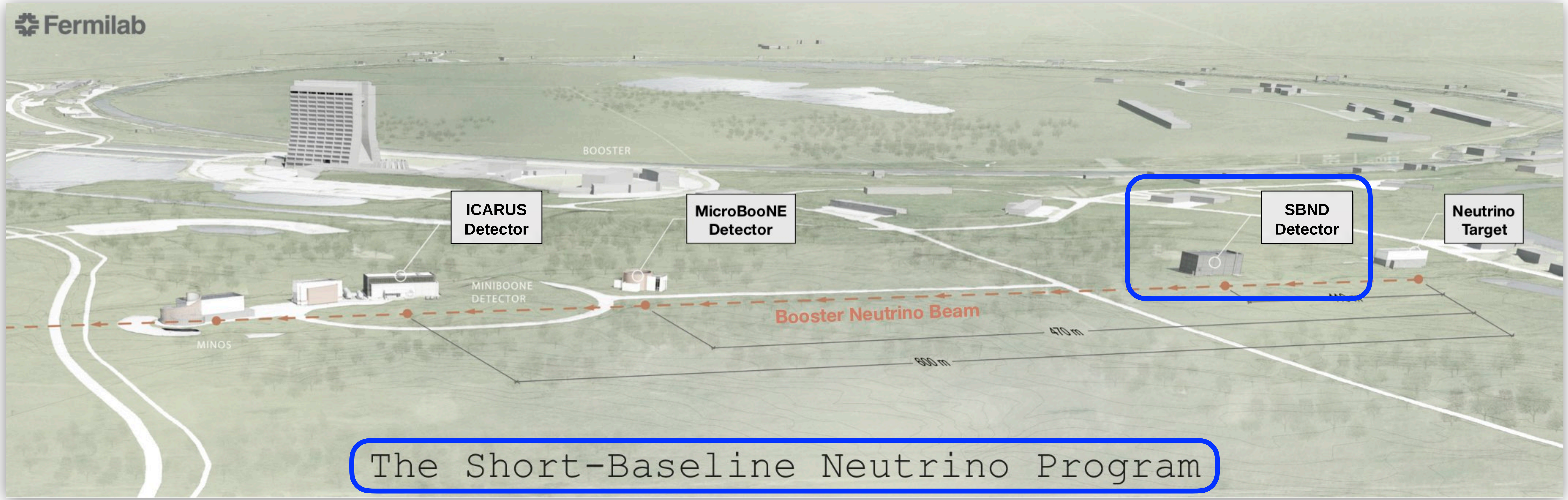
OUTLINE

Short-Baseline Neutrino (**SBN**) Program at Fermilab

Short-Baseline Near Detector (**SBND**): status, timeline and key features

Neutrino Interaction Physics at SBND: statistics, capabilities and SBND-PRISM

eV-scale Sterile Neutrinos searches at SBN and New Physics Searches at SBND



SHORT BASELINE NEUTRINO PROGRAM

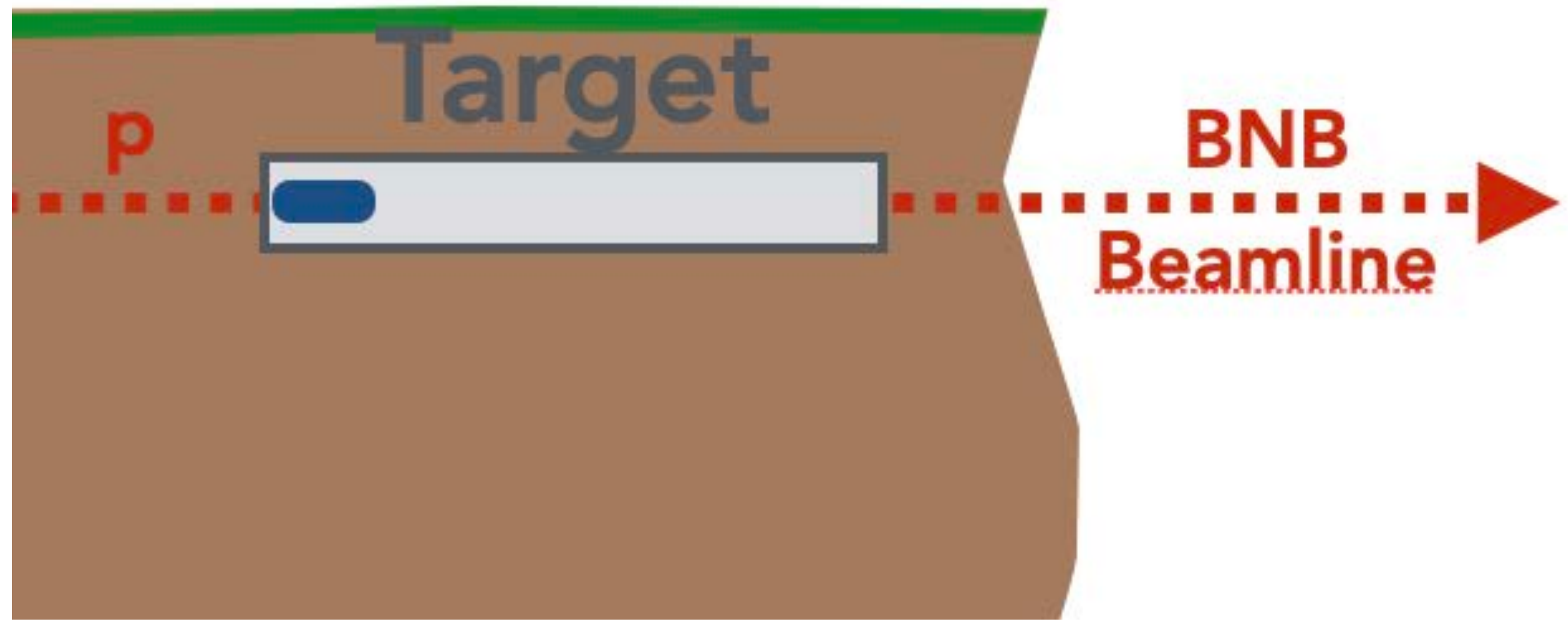
A program designed for **Sterile Neutrino** searches: same neutrino beam, nuclear target and detector technology to reduce systematic uncertainties to the % level.

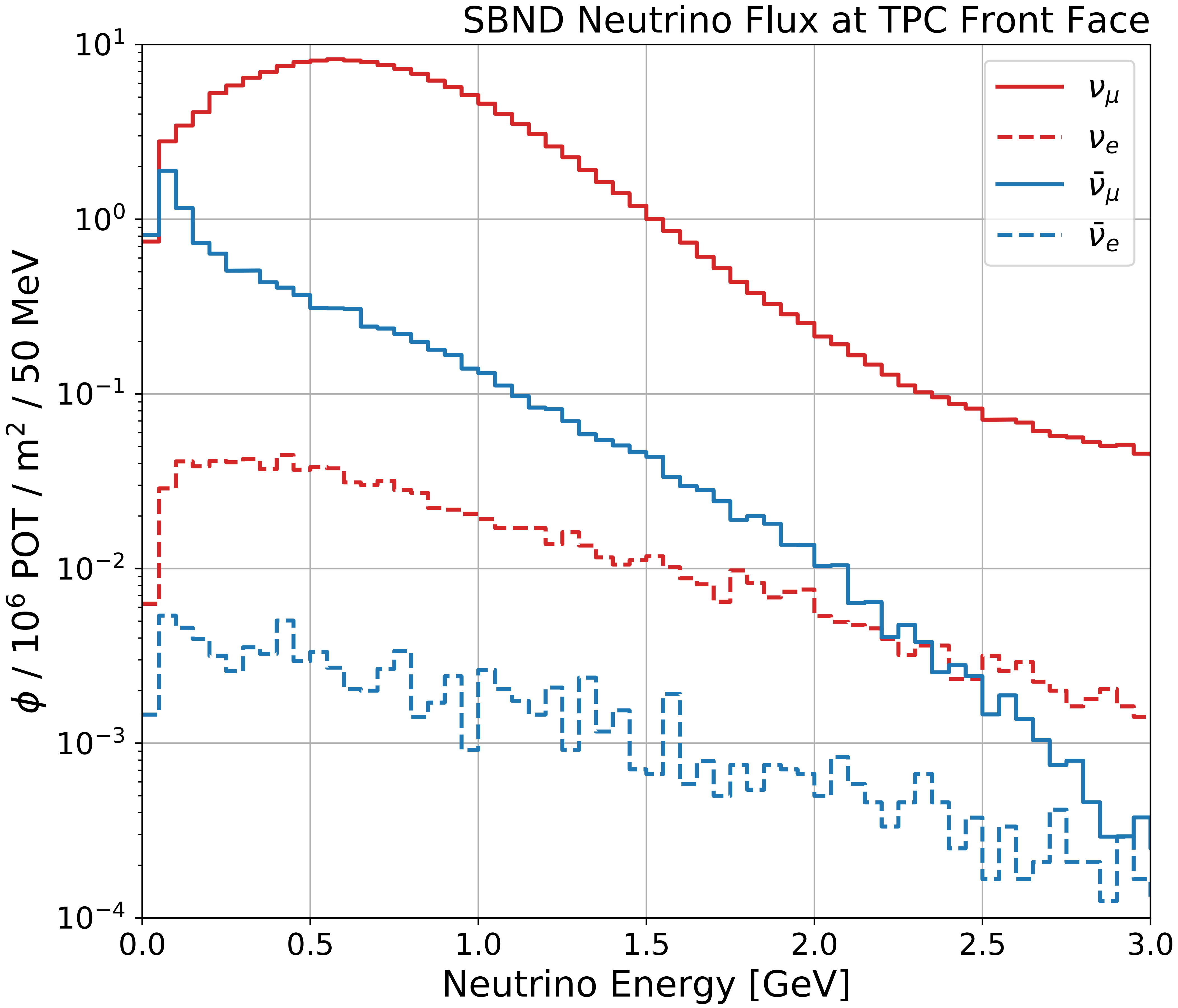
But large mass LAr detectors and proximity to intense beams enables a **broad physics program**.

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

Booster Neutrino Beam

High-intensity neutrino beam from 8 GeV proton beam on Be target





Neutrino flux at the SBND front face

Mean muon-neutrino energy: ~0.8 GeV

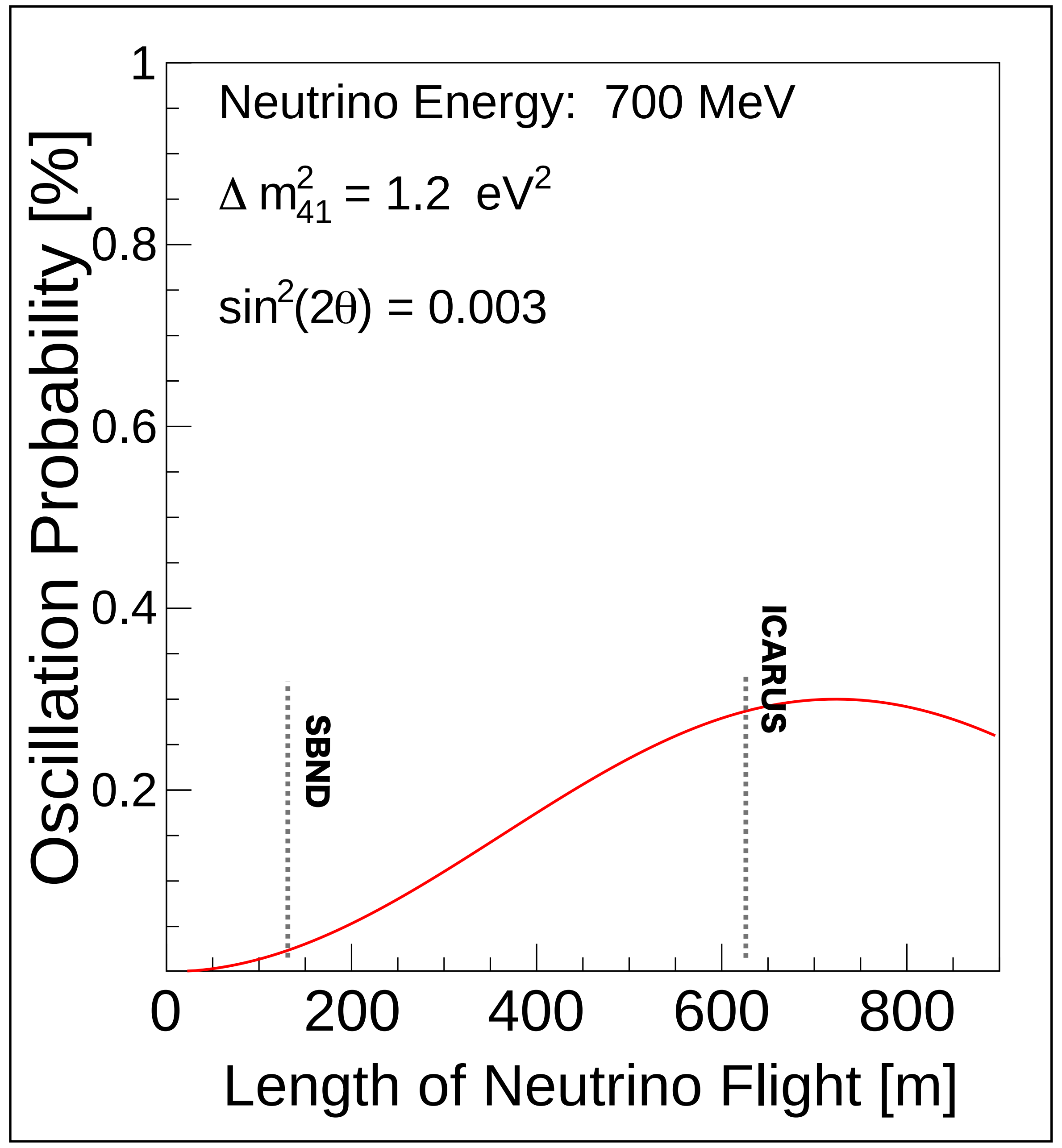
Beam composition:

ν_μ (93.6%)

$\bar{\nu}_\mu$ (5.9%)

ν_e+$\bar{\nu}_e$ (0.5%)

What makes the SBN Program Unique?



LAr Technology

Event **imaging**

High-resolution **tracking**

Fine granularity **calorimetry** and **particle identification**

Electron-γ separation

Low energy threshold

ns-level timing resolution

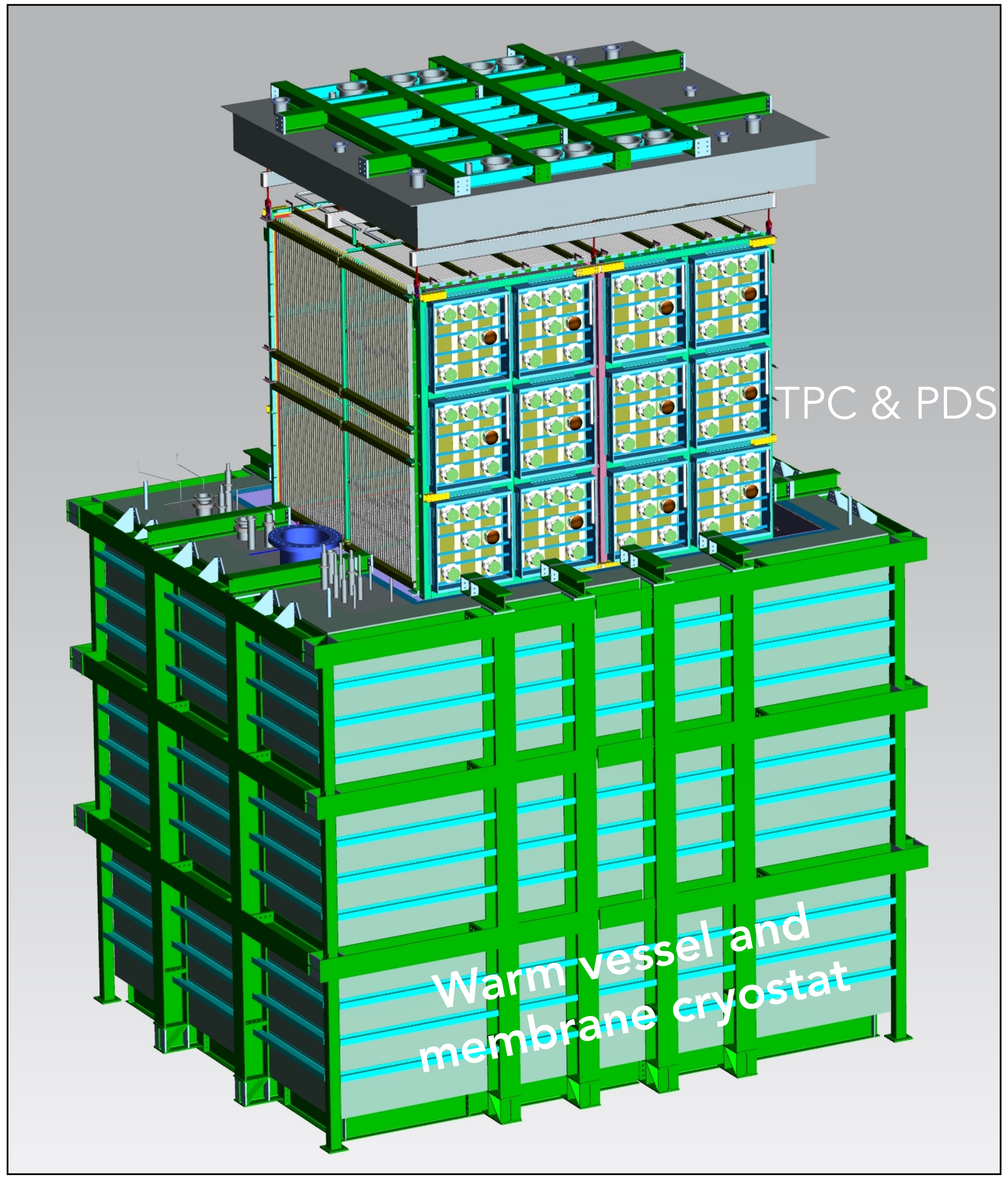
Near detector - SBND

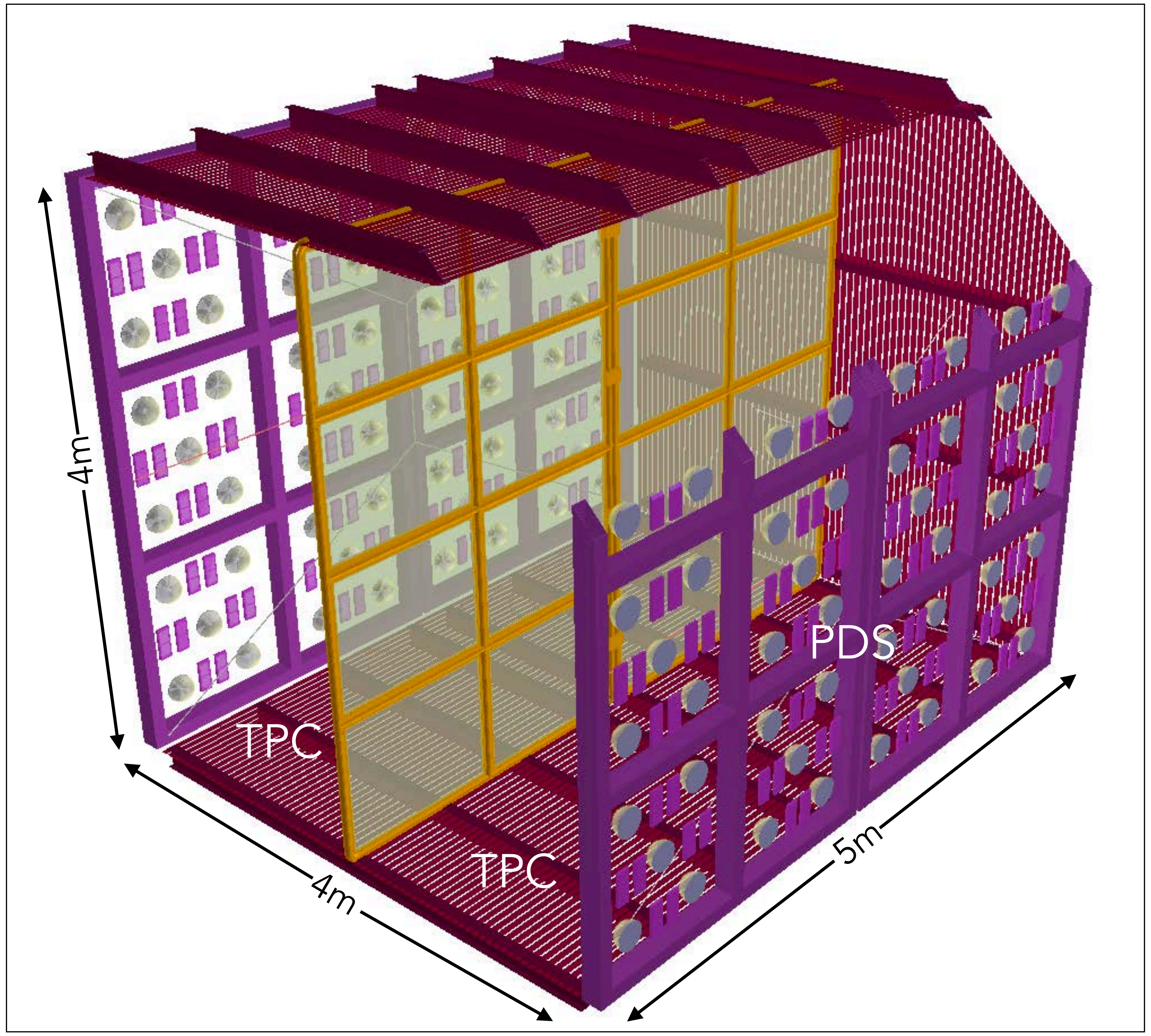
Crucial for oscillation searches.
Sitting close to the neutrino source, SBND plays a **unique role.**
It sits before oscillations turn on @eV-scale → it characterizes the beam and **addresses the dominant systematic uncertainties**

Far detector - ICARUS

Given its far location and large mass provides big exposure to oscillated neutrinos, allowing for a **high sensitivity oscillation search**

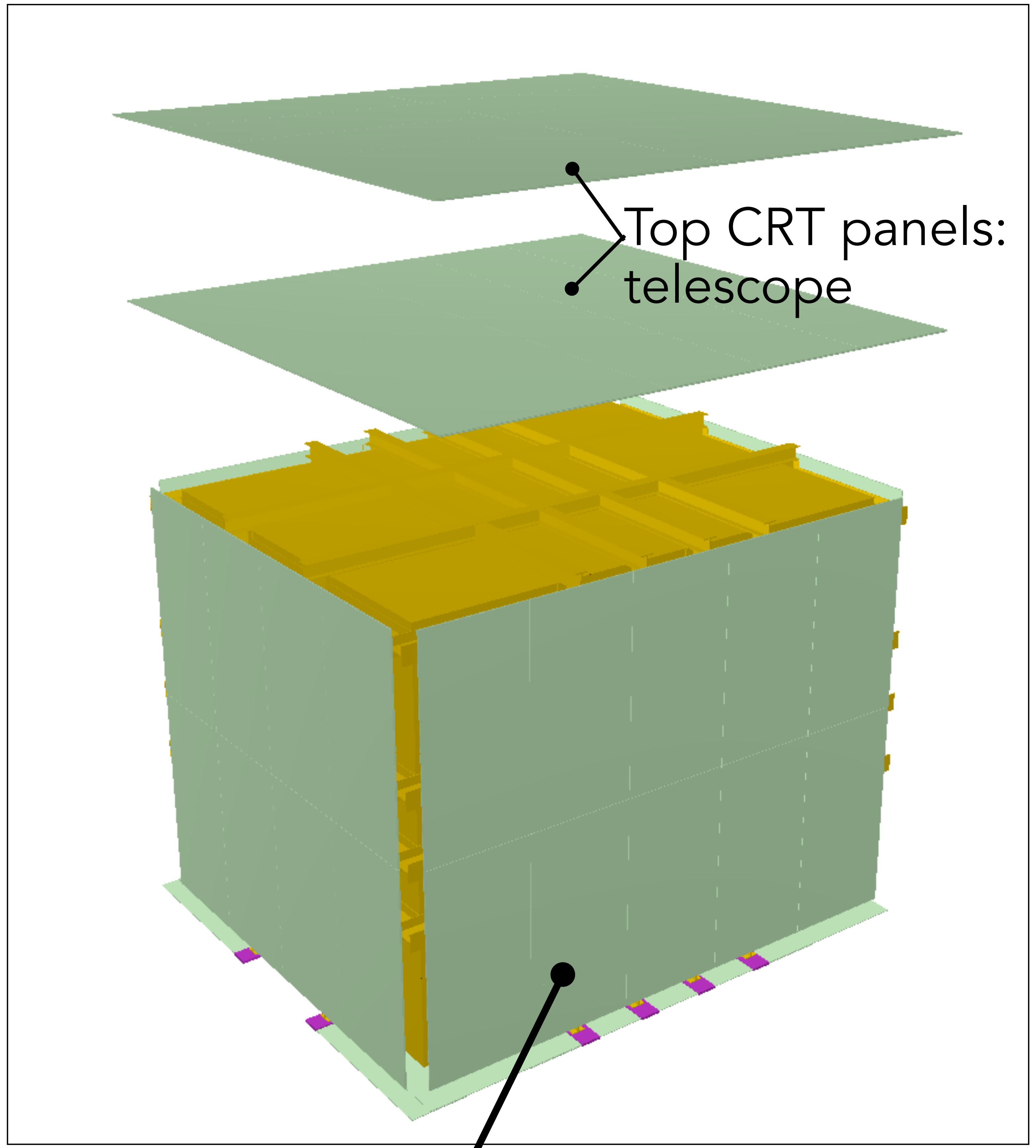
SBN Near detector: SBND





Two Time Projection Chambers and Photon Detection systems

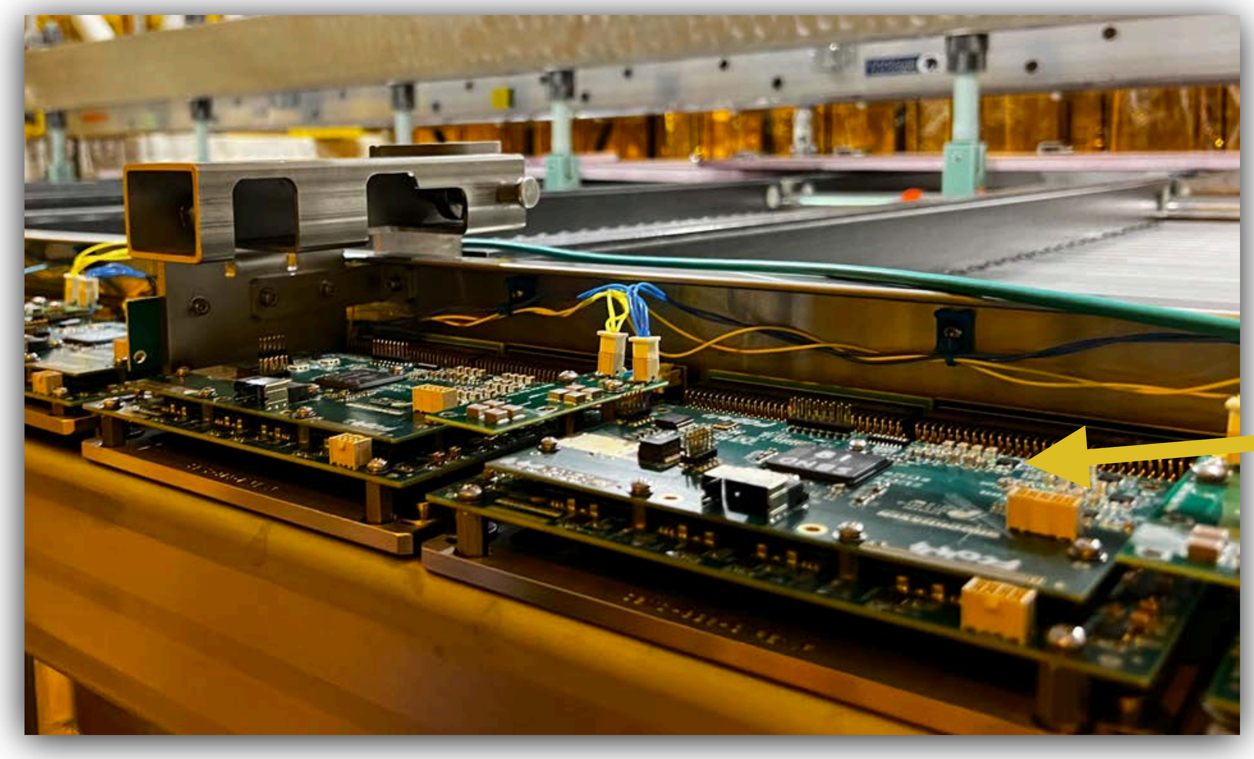
Cryostat surrounded by a Cosmic Ray Tagger system for cosmic ray rejection



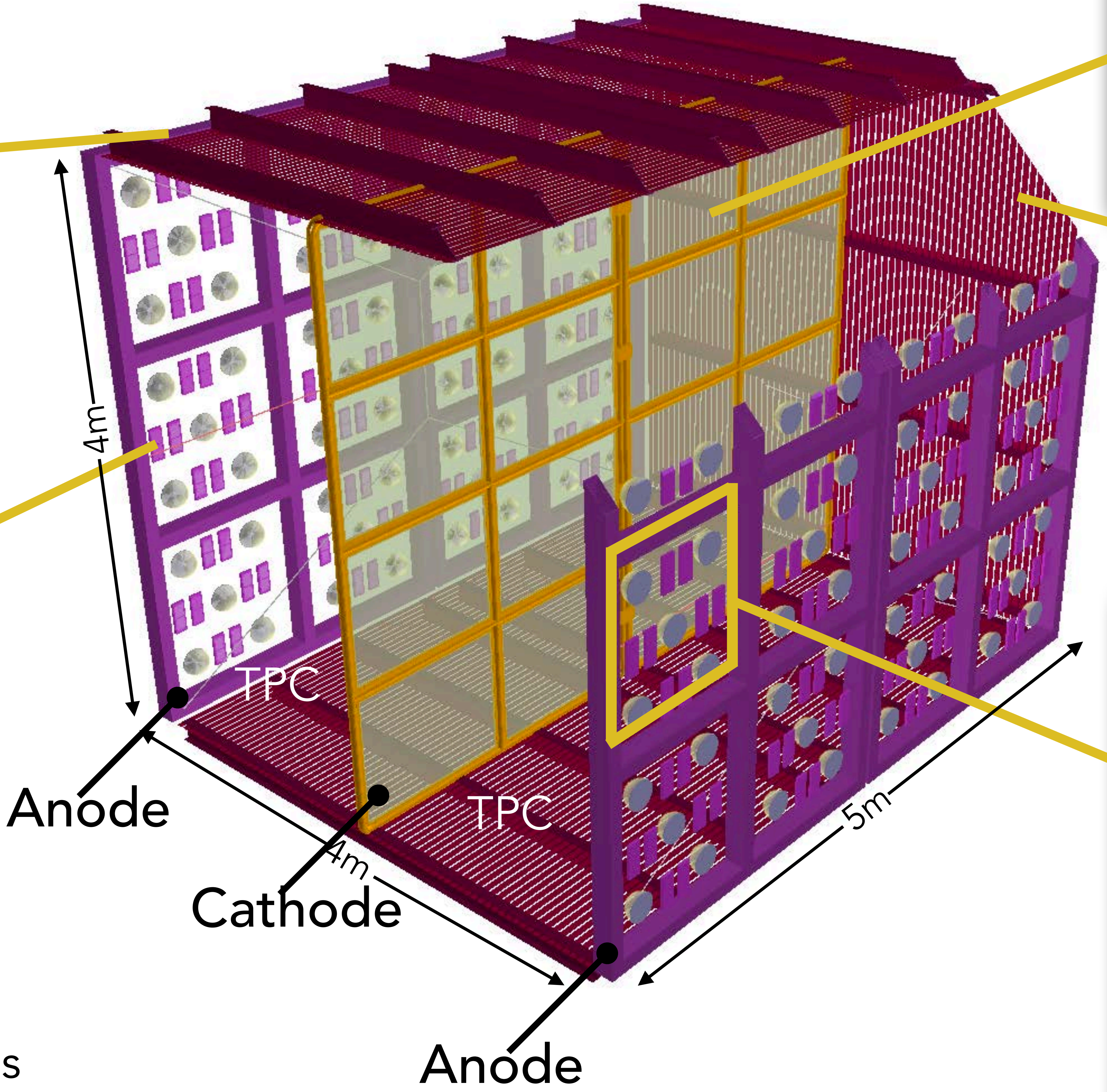
Panels made of scintillator strips

SBND DETECTOR: TPC AND PDS

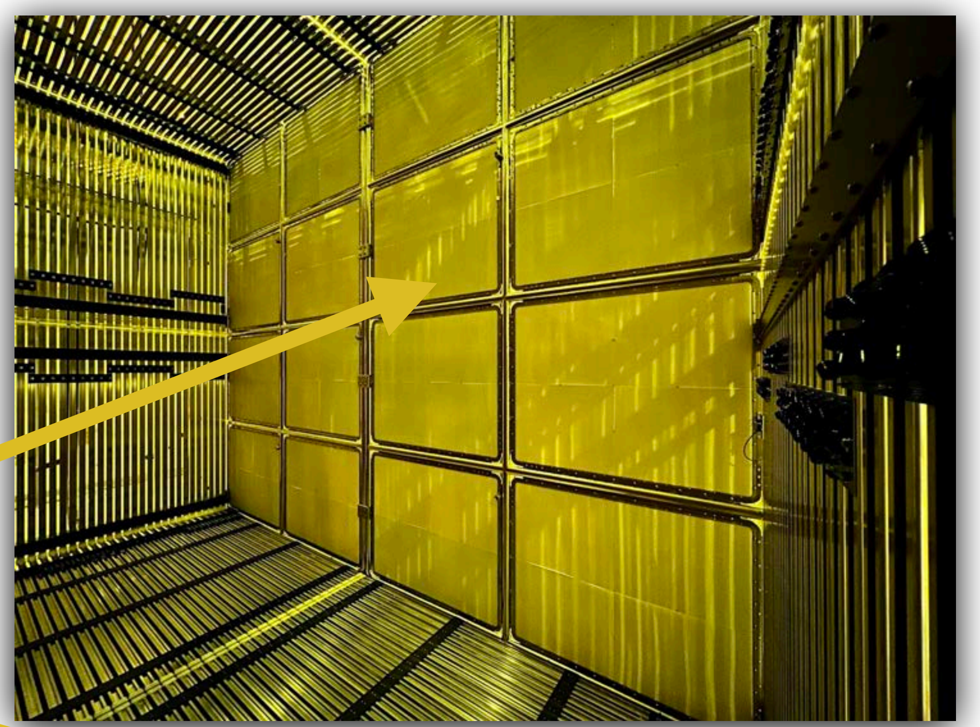
TPC Cold electronics



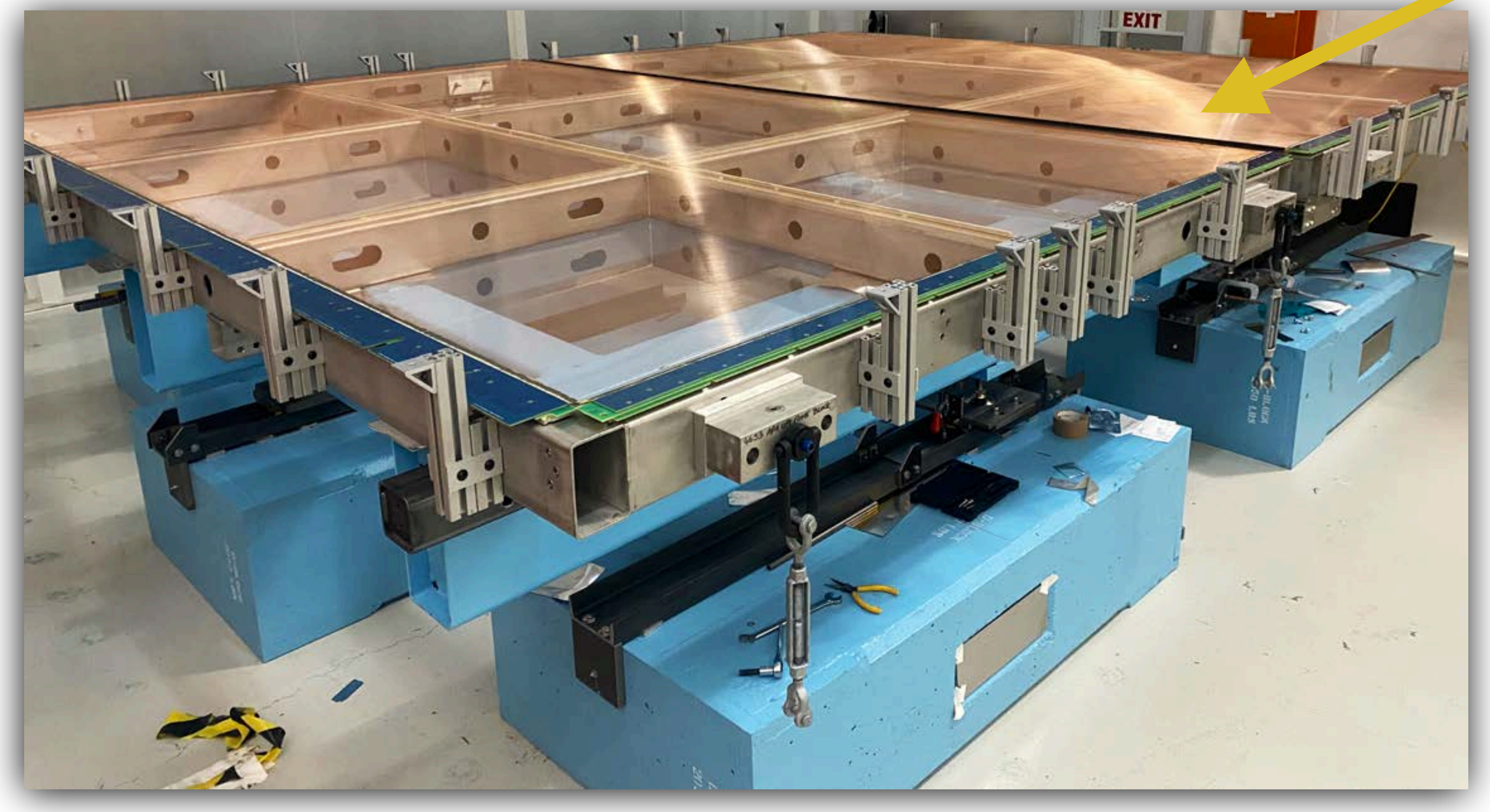
Two Time Projection Chambers
Total dimension: 4m x 4m x 5m



CPA-Cathode
covered with TPB
coated reflectors



Field Cage

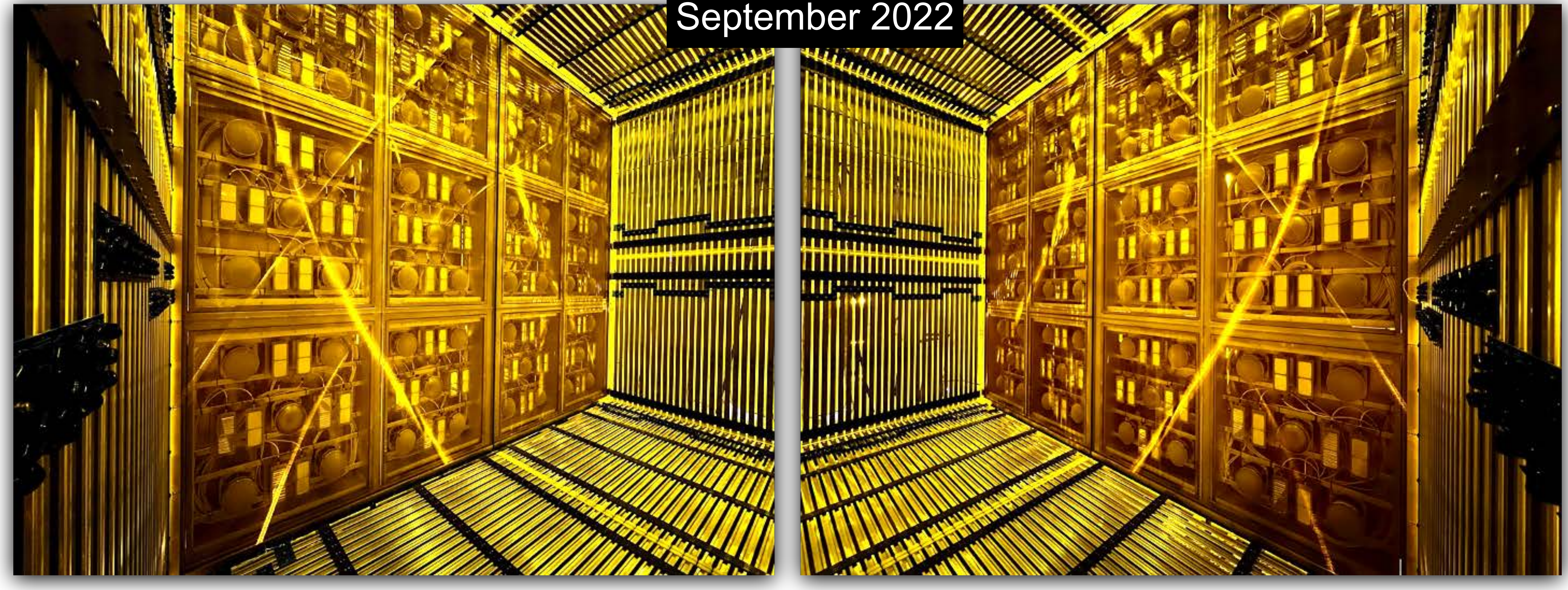


APA-Wire Planes- 3 planes, ~11000 wires

Photon Detection Systems: 120 PMTs, 192 X-Arapucas

SBND Status

September 2022

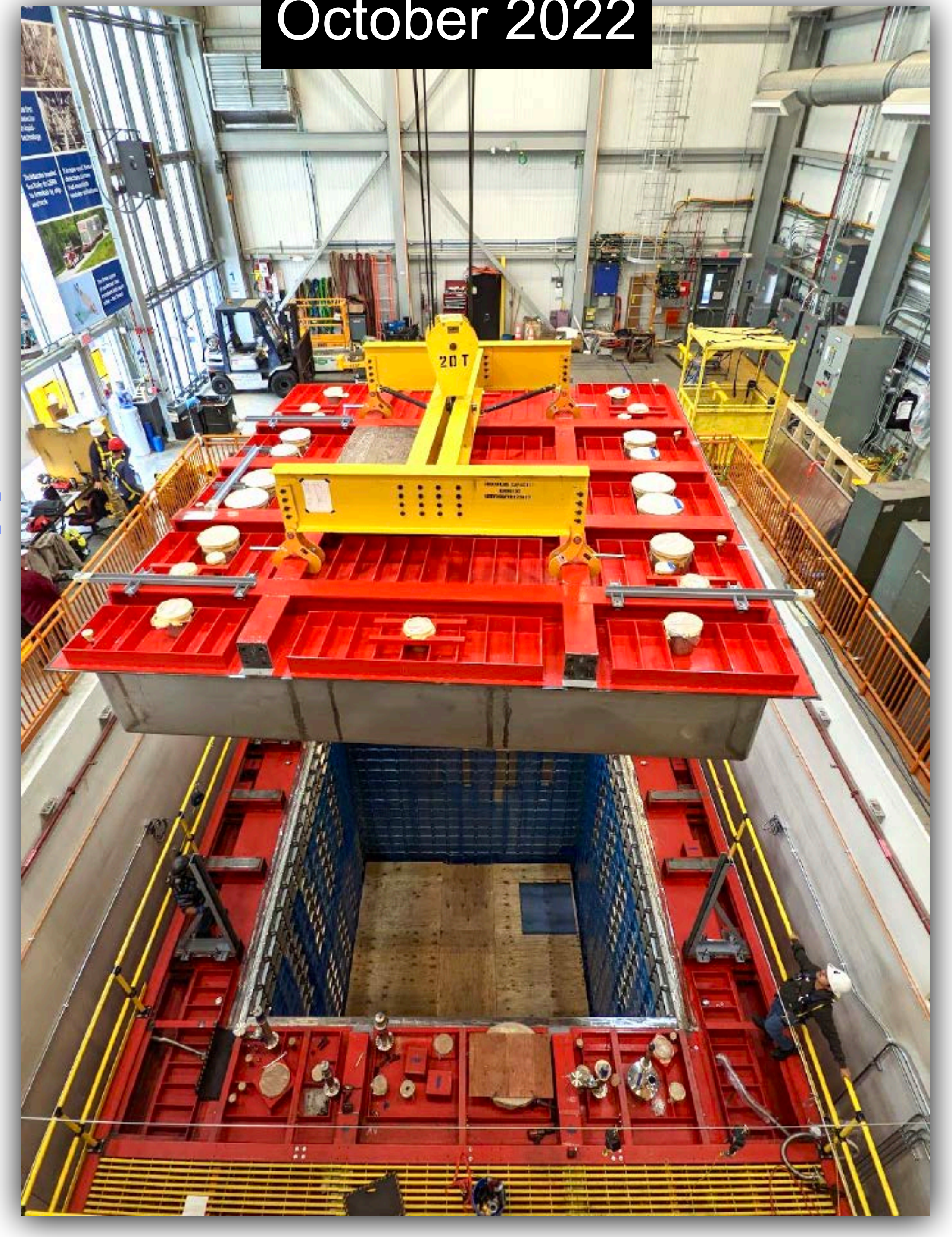


SBND detector completed

SBND cryostat completed

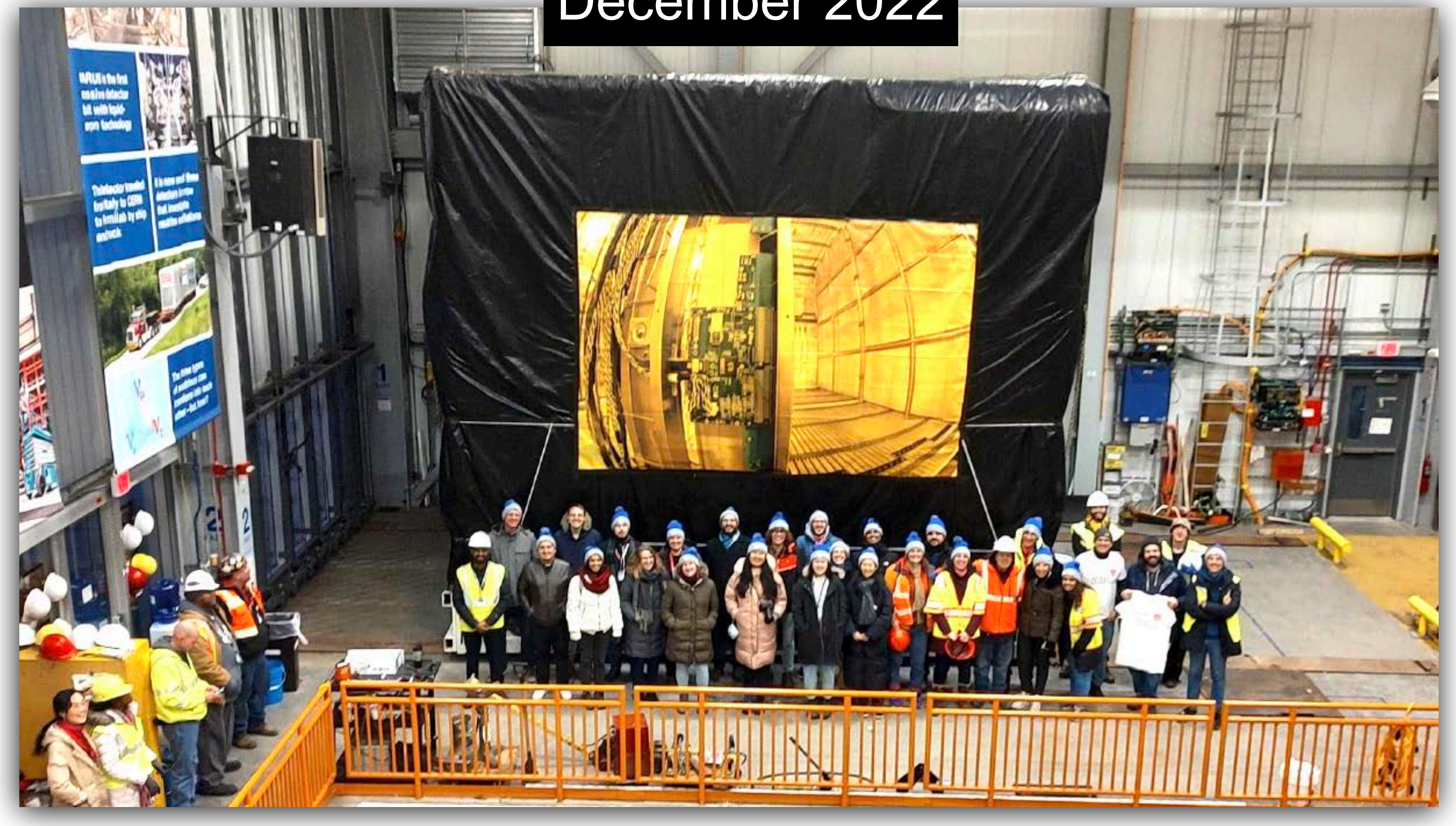
Membrane cryostat

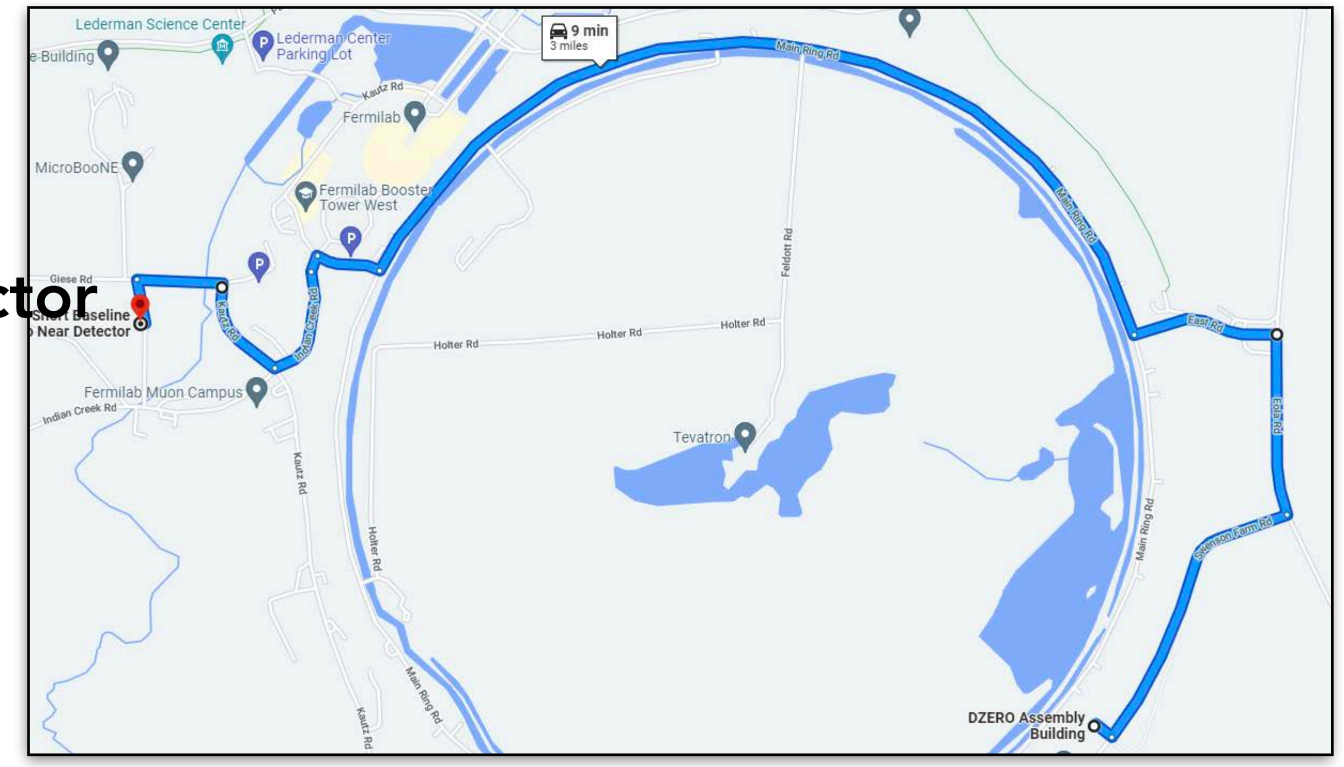
October 2022



SBND detector move

December 2022





SBND Detector Building

DAB

SBND Status

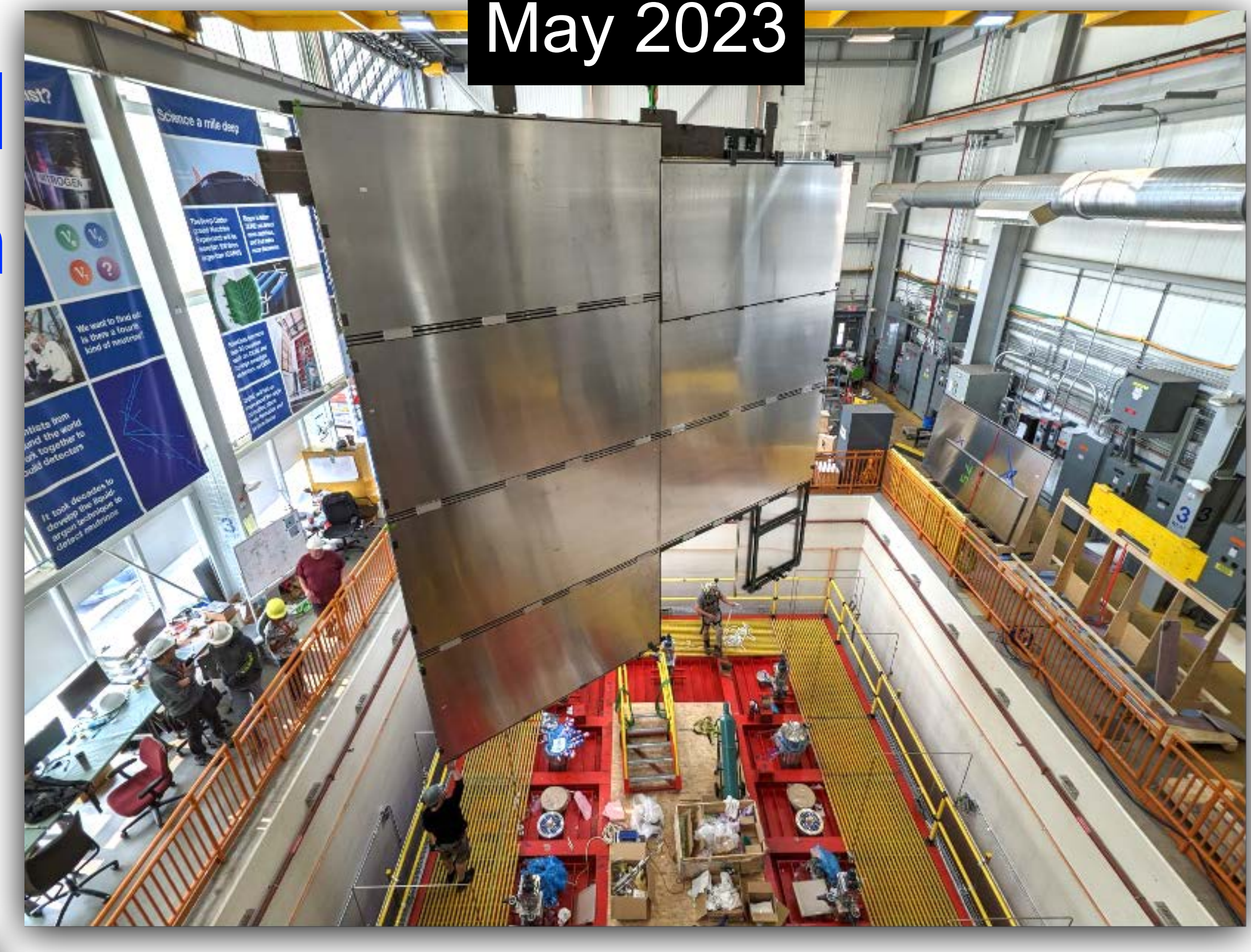
April 2023

Video - Fermilab creative service

SBND detector rigging into the cryostat

CRT North Wall installation

May 2023



October 2023

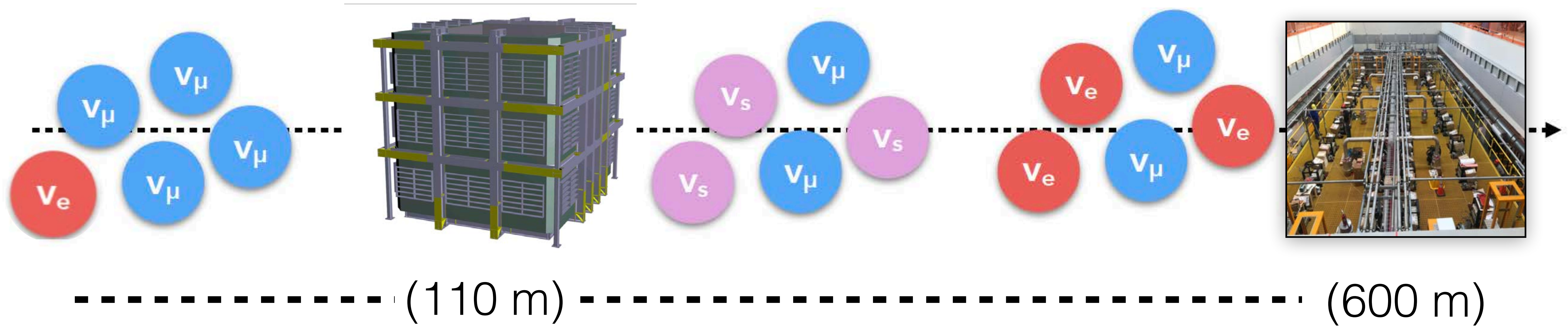
Expected to begin operations in early **2024**

Running **until** the Fermilab **accelerator long-shutdown** in 2027, SBND is expected to collect **10-13 × 10^{20} POT**
[this is x2 the assumed exposure in the SBN proposal (6.6 × 10^{20} POT)]

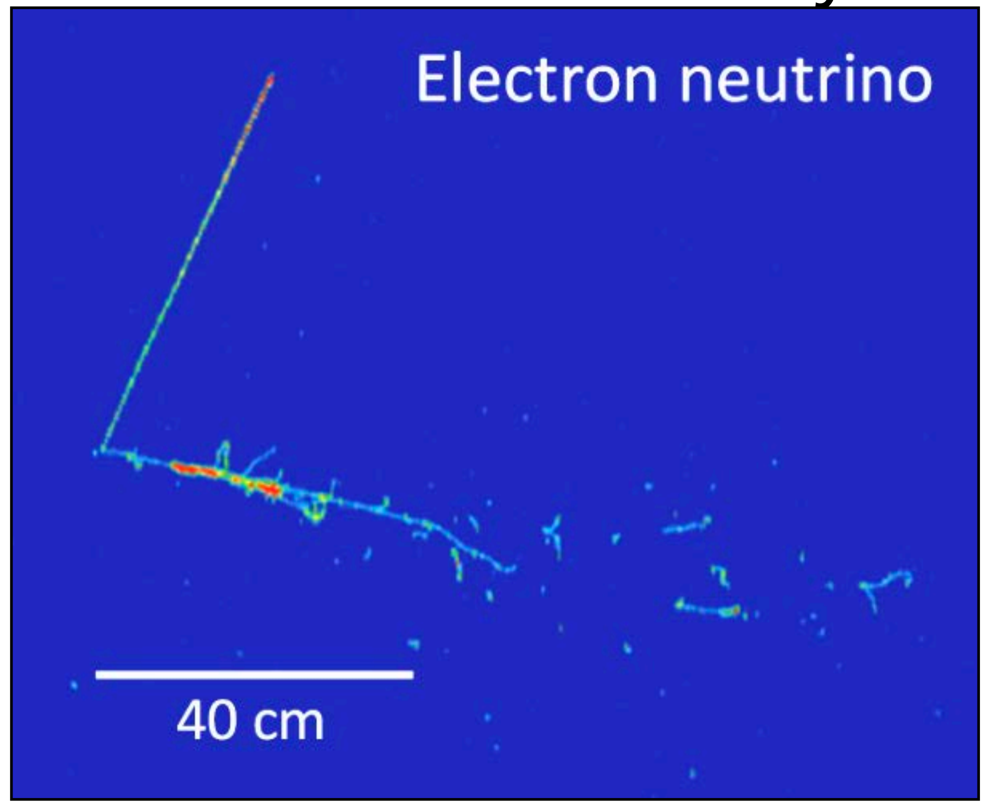
We have started considering the **physics potential of extending the run after the long-shutdown** (2029+), run in anti-neutrino mode?

SBND - A Broad Physics Program

eV-scale sterile neutrinos: searches for physics beyond the three-neutrino mixing with **multiple-detectors at different baselines.**



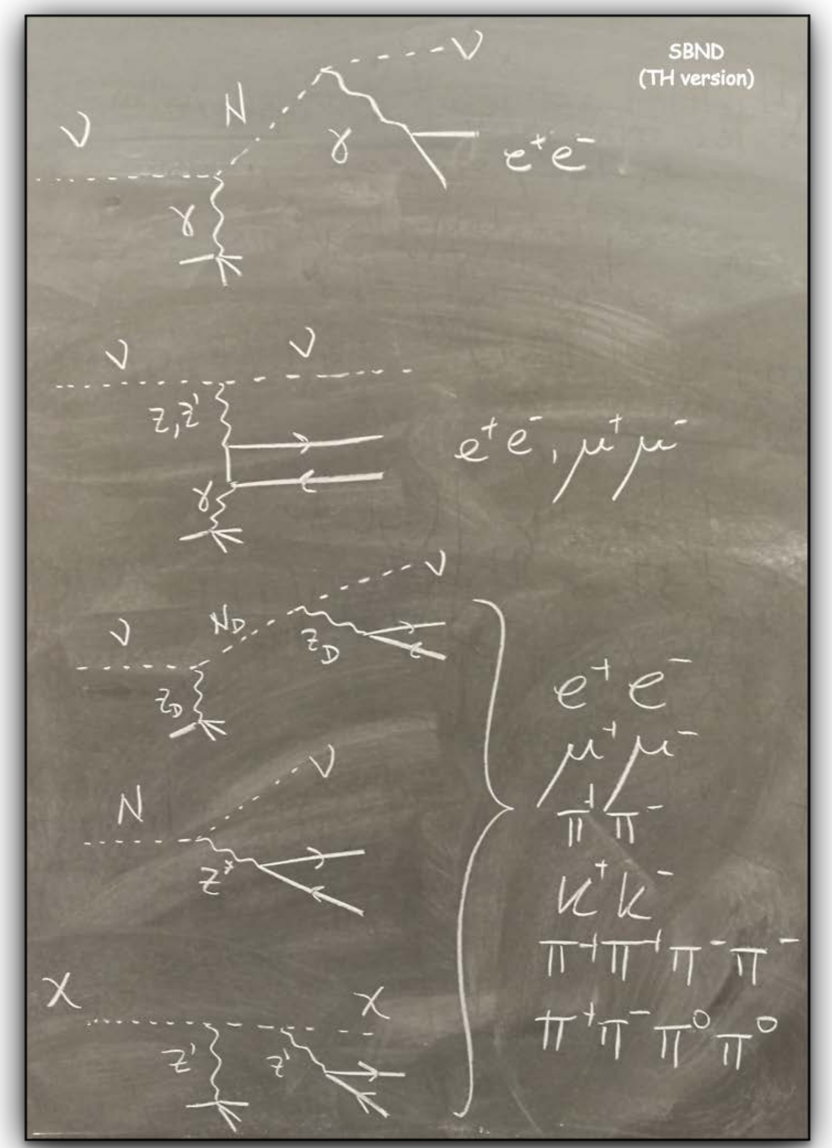
Neutrino-argon interactions: with **an order of magnitude more data** than is currently available.



We have expanded the physics program!

New physics scenarios: study alternative explanations of the short-baseline anomalies and other Beyond Standard Model scenarios.

Many ideas for new searches emerging from collaboration with theory colleagues.



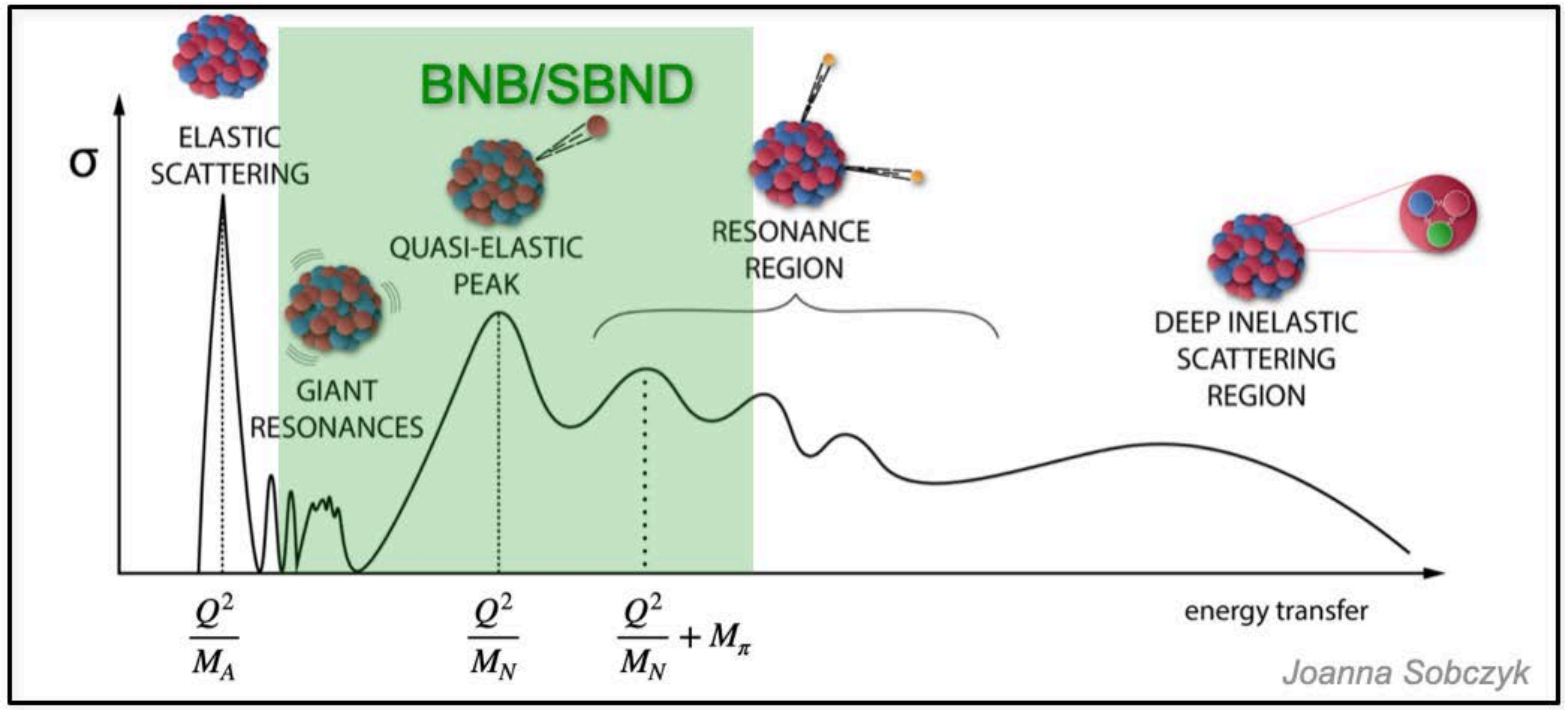
Courtesy of P. Machado

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

Large volumes of LAr data will enable further developments of powerful reconstruction and analysis techniques.

NEUTRINO-ARGON INTERACTIONS

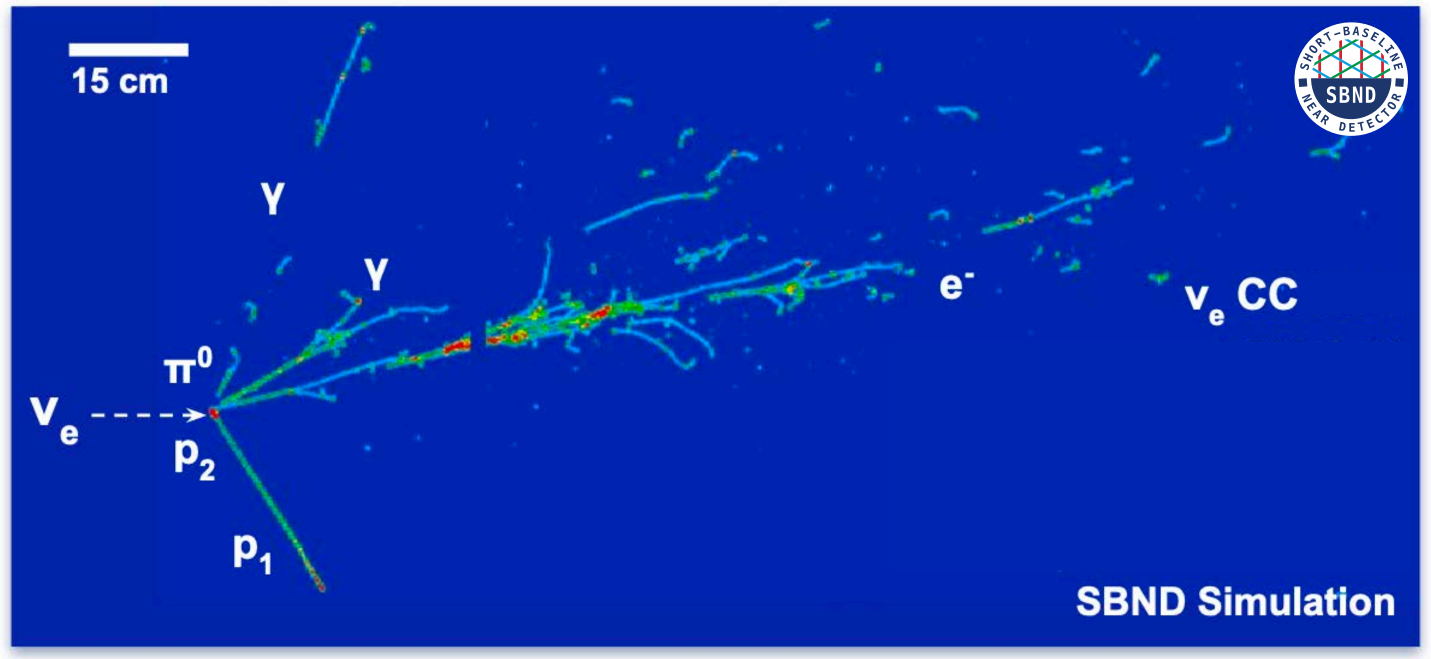
- Any discovery in the neutrino sector requires detailed understanding of neutrino interactions with the target detector material.
- A substantial **neutrino-argon cross-section physics program** is critical!

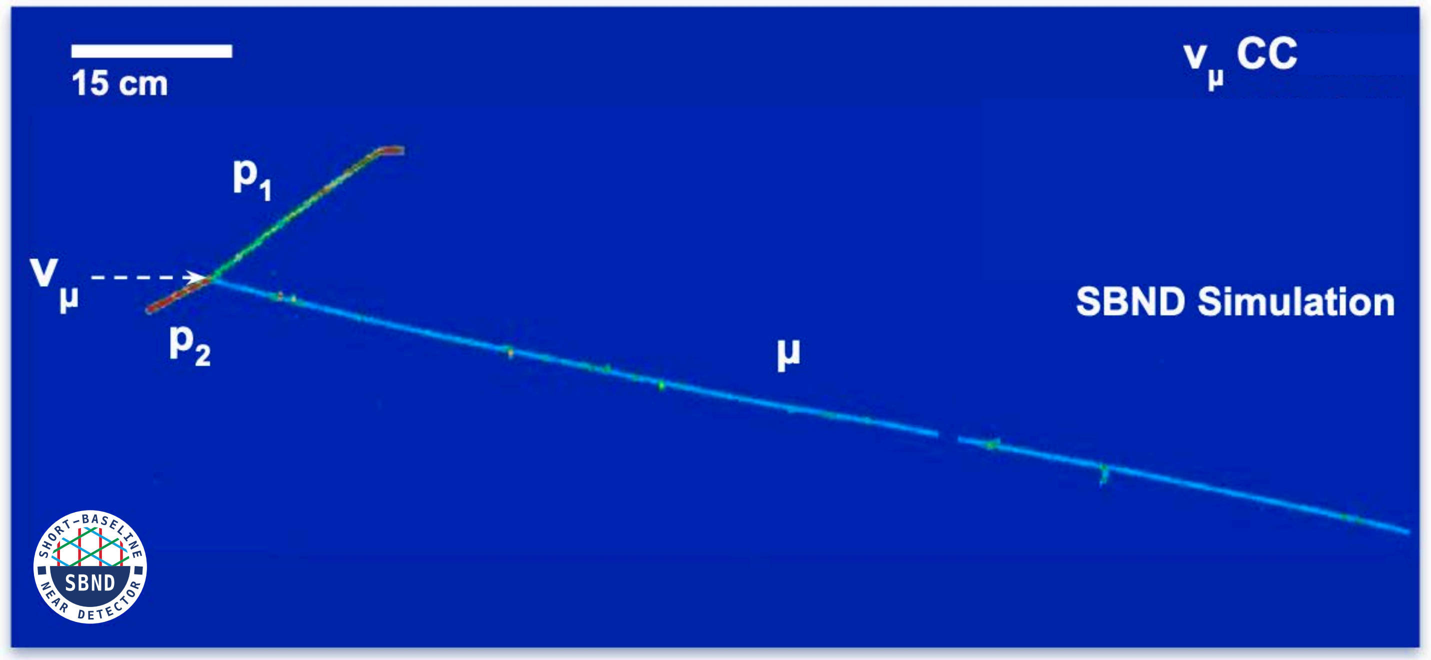


- MicroBooNE is already making several interesting measurements.
- SBND will enable a **generational advance in the study of neutrino-argon interactions** in the GeV energy range
  - Unprecedented statistics combined with **LArTPC detector's capabilities**.
  - **Unique detector capabilities** (large photon detector coverage, ns timing, ...)
  - **Multiple correlated fluxes** (PRISM)

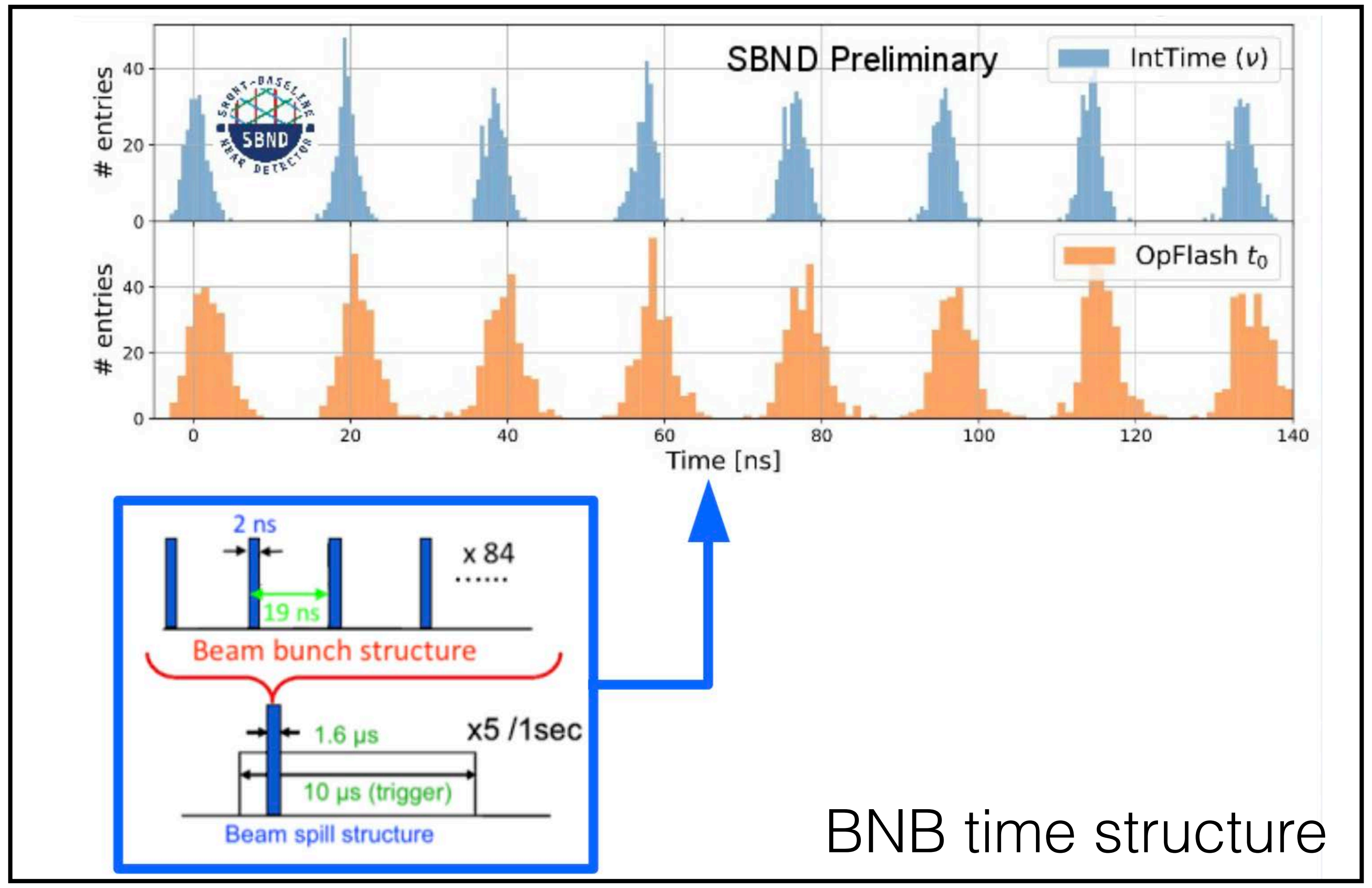
NEUTRINO INTERACTIONS IN SBND: LARTPC CAPABILITIES

- SBND has **3mm wire spacing**
  - Complex final states can be disentangled ⟹can **measure various exclusive final-states including rare channel** (e.g. production of hyperons).
  - **Isolated energy deposits** may be identified down to O(100 keV)⟹opportunity to study MeV-scale activity.



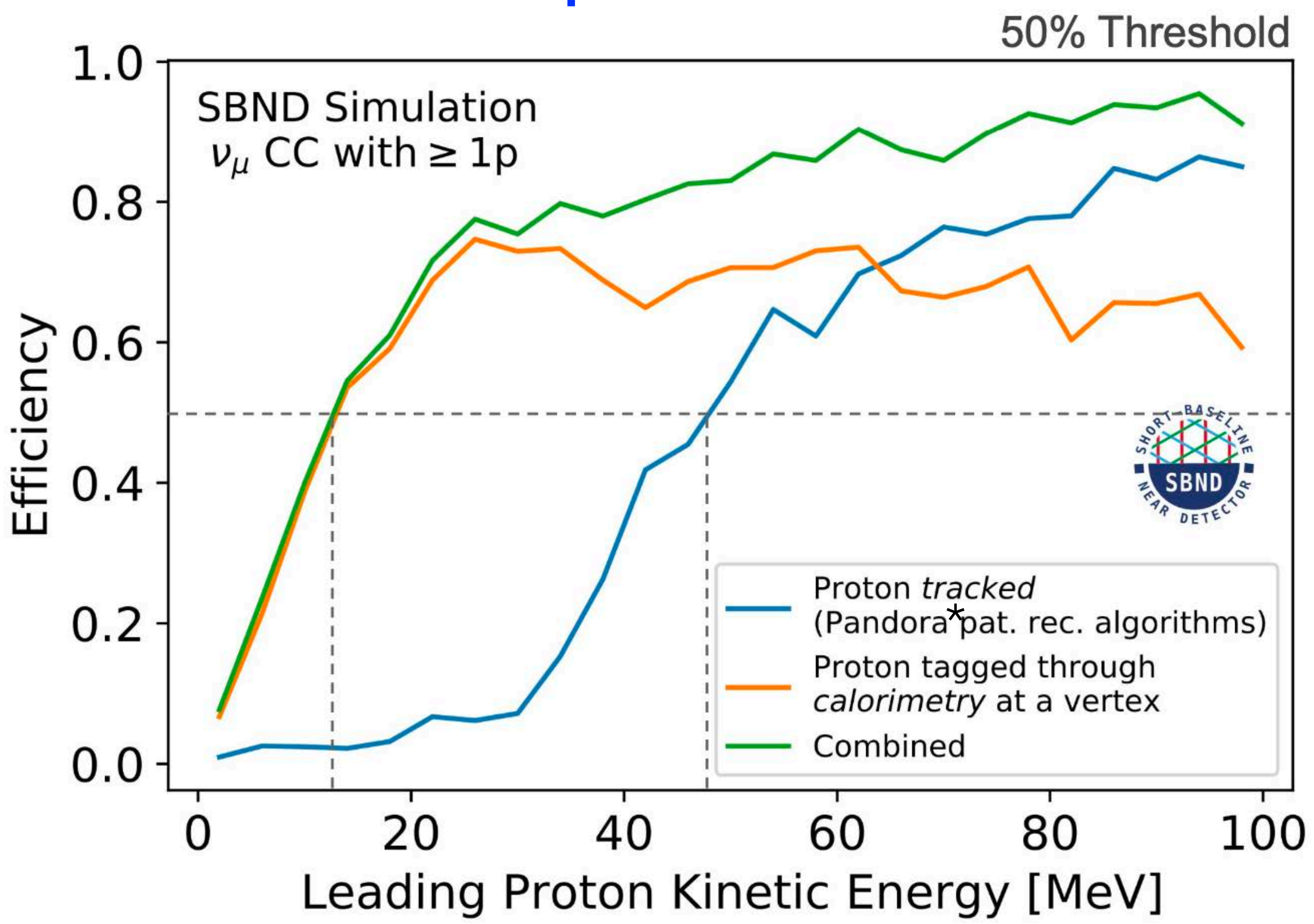


- **ns timing resolution**, facilitates:
  - **Cosmic rejection** in neutrino beam studies.
  - Rejection of neutrino interactions in rare and exotic searches (in between bunches searches).



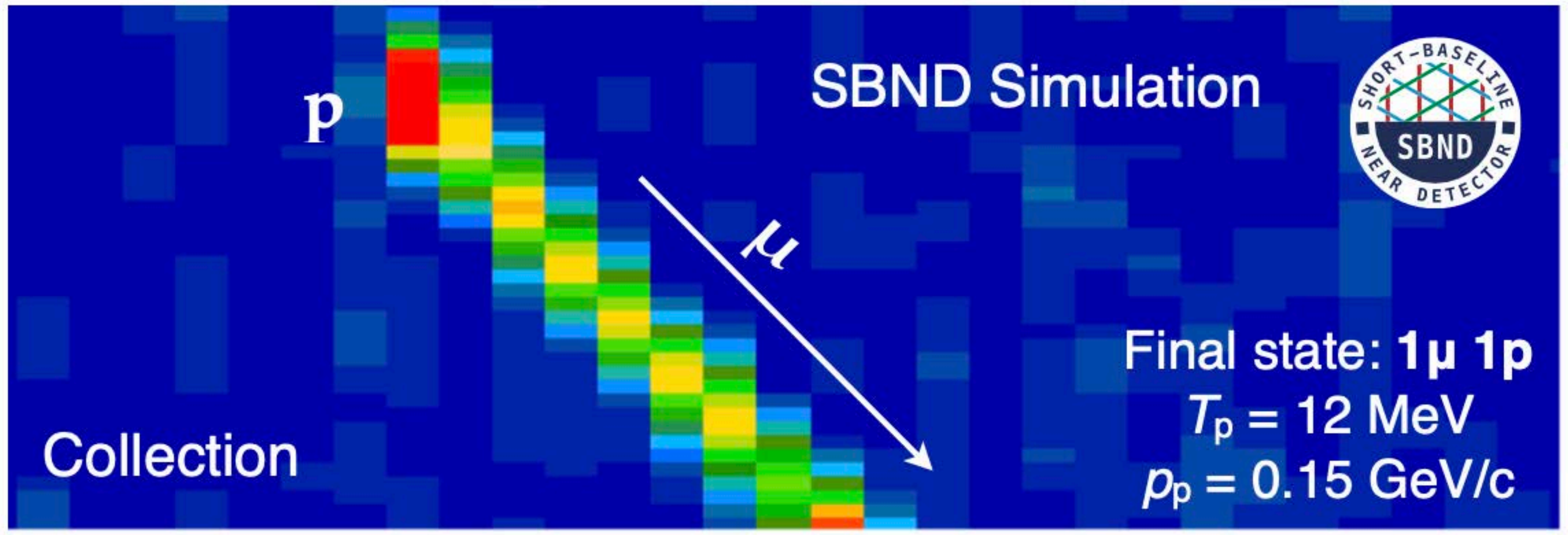
Hadron Reconstruction

A key challenge in reconstruction of neutrino interactions is the **proton reconstruction threshold**

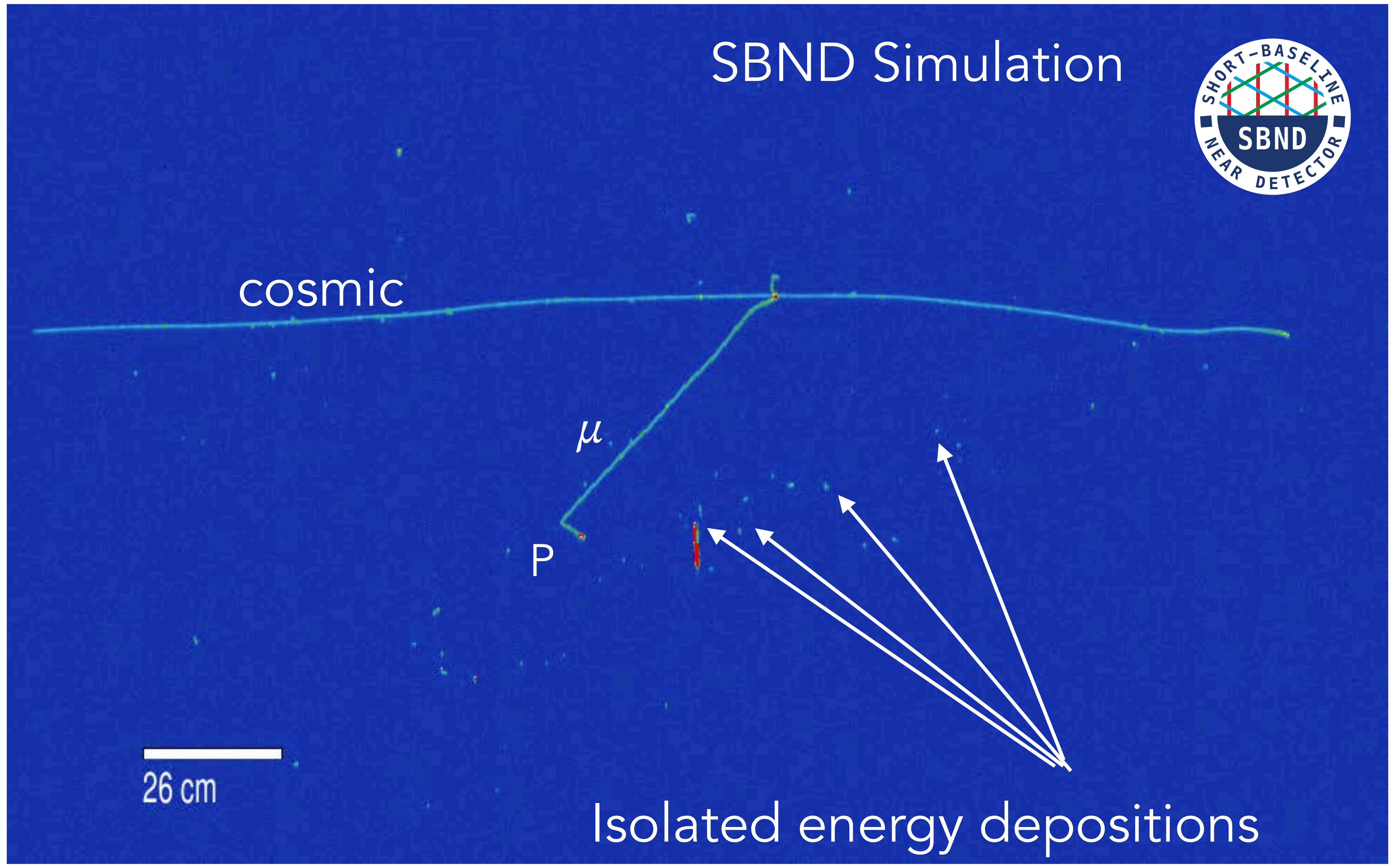


Proton identification threshold can be pushed below **15 MeV** (**green** curve)

**Pandora is the pattern recognition package used in LArTPC experiments: Eur. Phys. J. C 78, 82 (2018)*

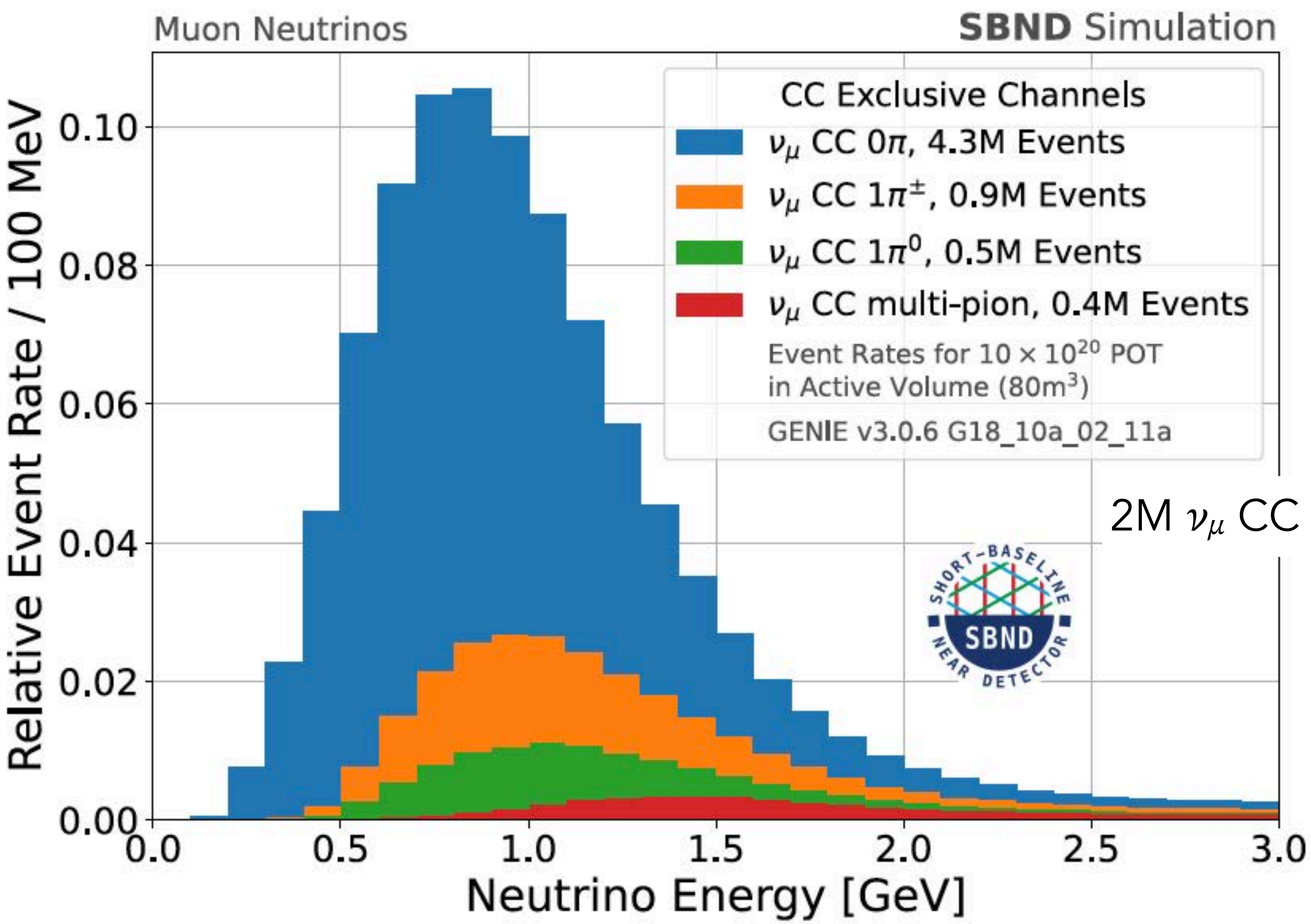


Neutron reconstruction - isolated energy depositions - e.g. can be exploited in neutrino energy reconstruction

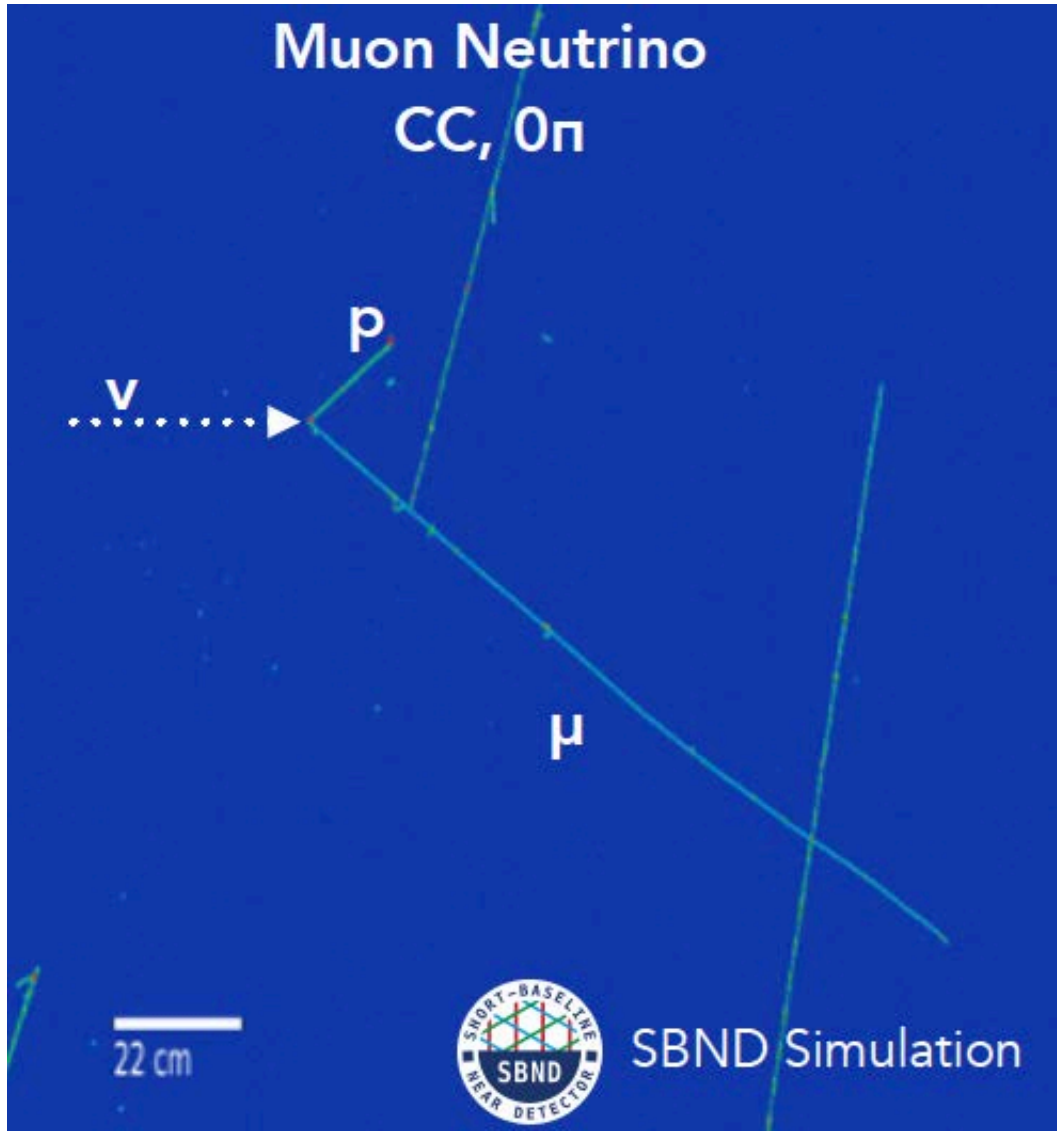


NEUTRINO-ARGON INTERACTIONS IN SBND: EVENT STATISTICS

With its proximity to the neutrino source, **SBND** expects **2 million ν_μ Charged Current (CC) events per year**



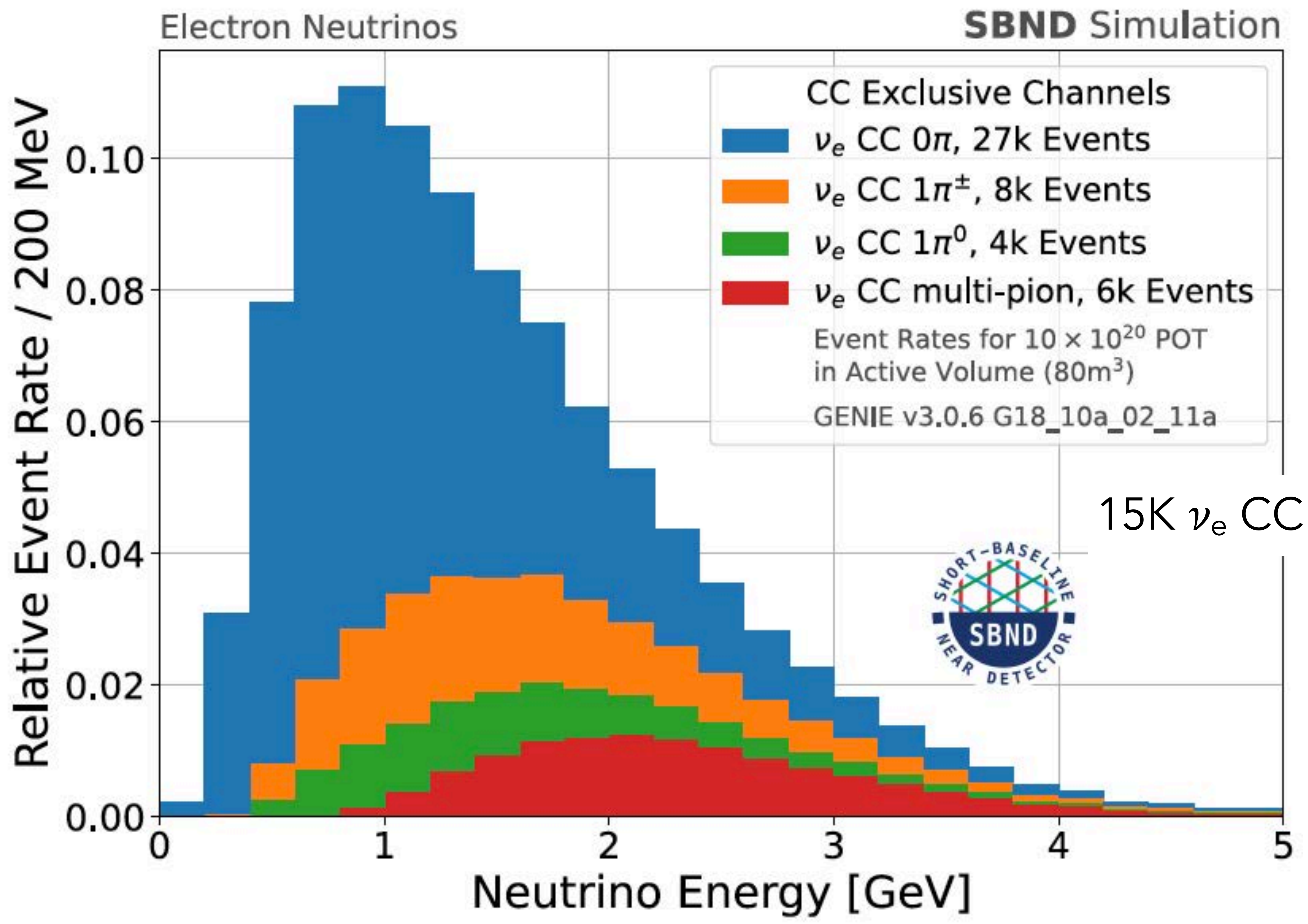
2M ν_μ CC events in 1 year



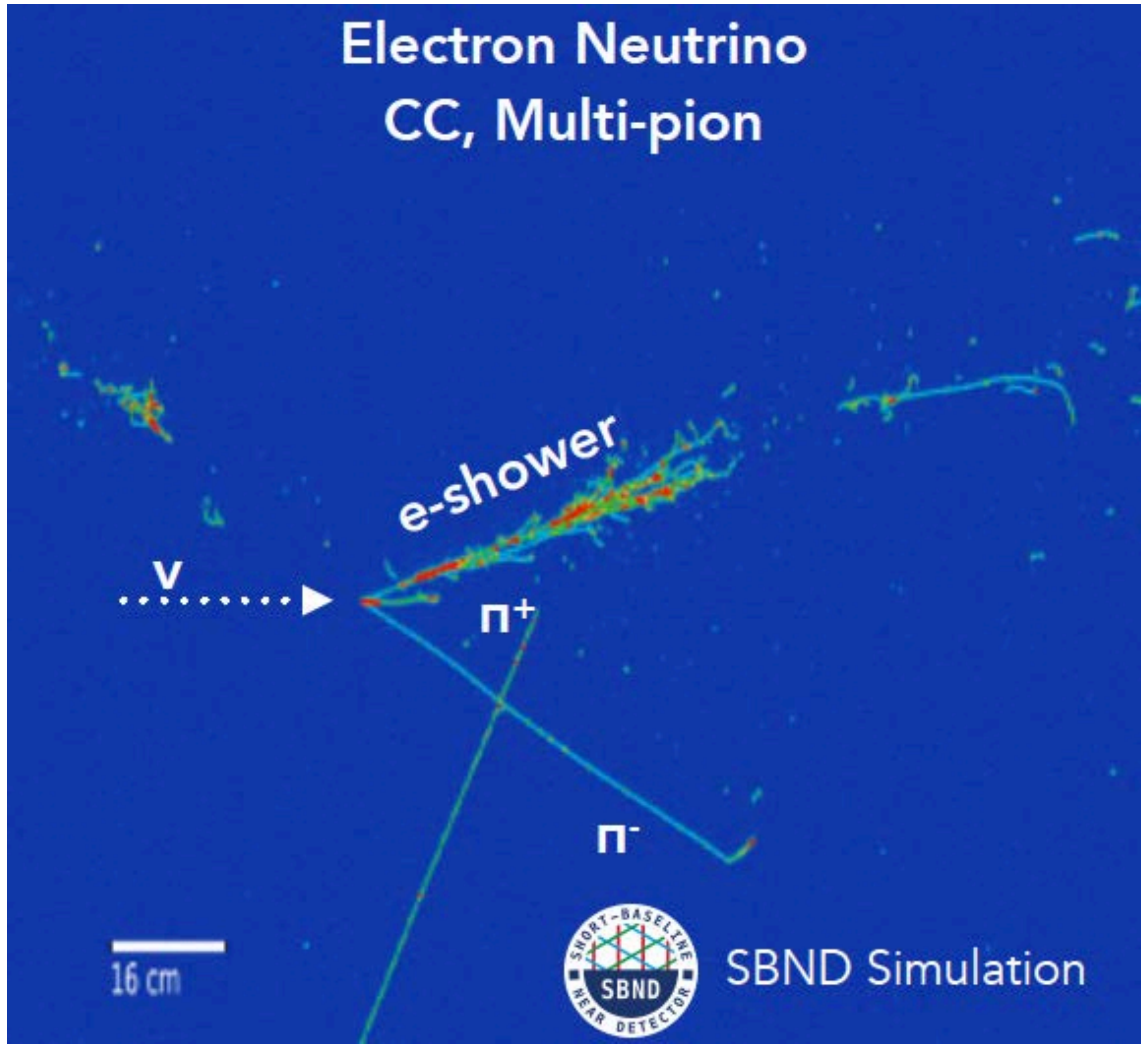
NEUTRINO-ARGON INTERACTIONS IN SBND: EVENT STATISTICS

With its proximity to the neutrino source, **SBND** expects **2 million ν_μ Charged Current (CC) events per year**

and **15 thousand ν_e CC interactions per year**



15K ν_e CC events in 1 year



NEUTRINO-ARGON INTERACTIONS IN SBND: EVENT STATISTICS

7000 ν neutrino events/per day in SBND!

Total (10×10^{20} POT exposure):
10 million neutrino events (CC+NC),
including around **50,000 ν_e CC events**

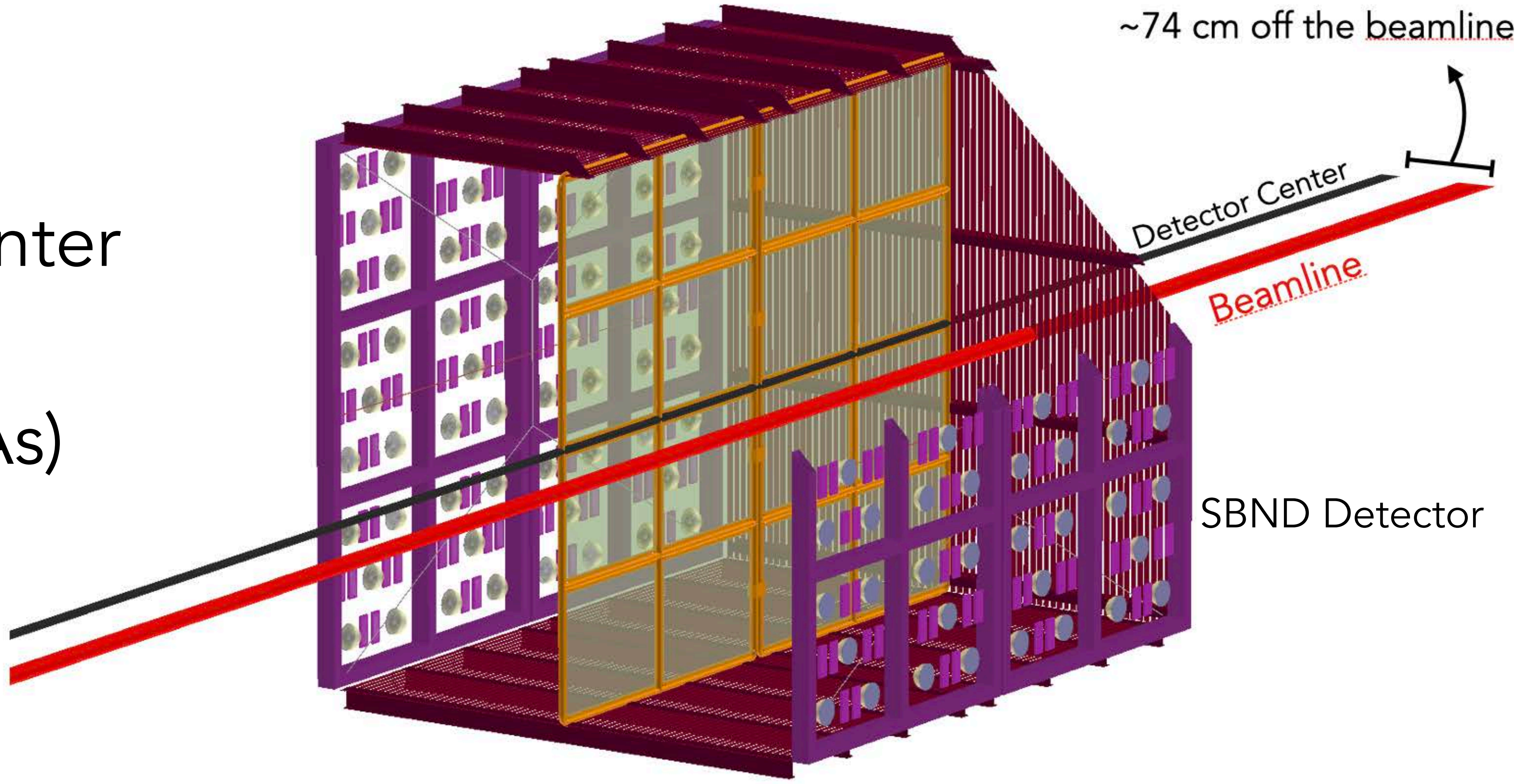
SBND will record **20-30x more neutrino-argon interactions** than is currently available.

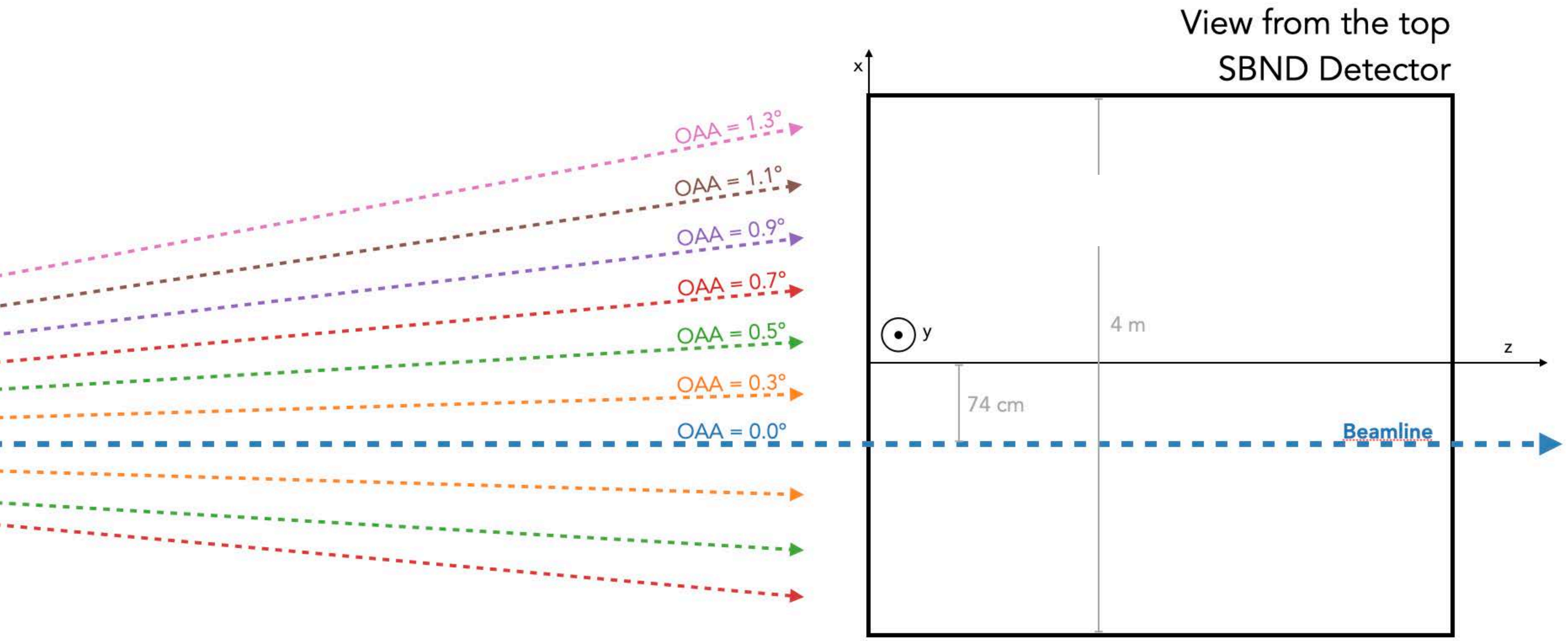
Largest neutrino-argon data set in the world (for several years to come)!

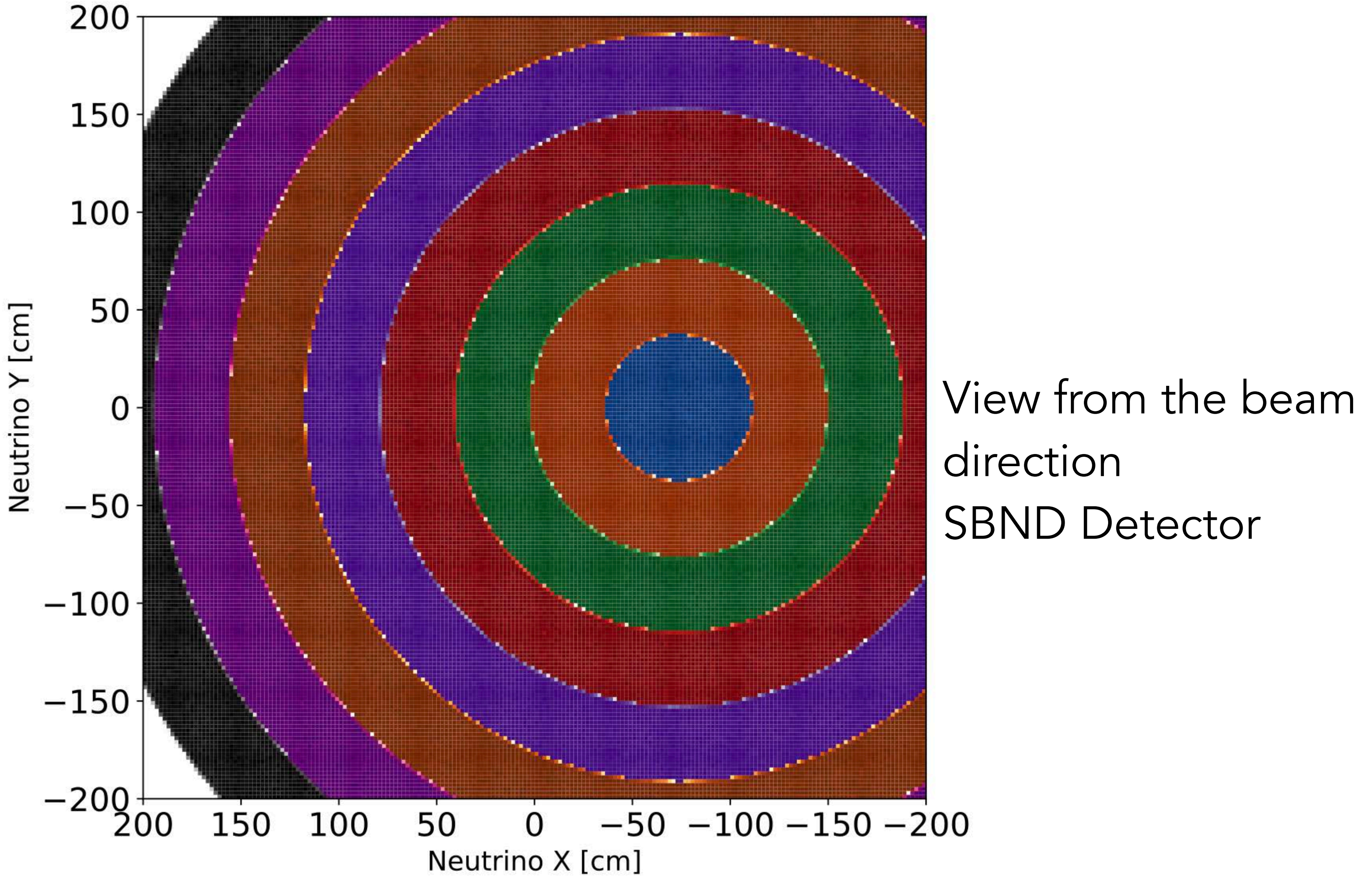
Every ~3 months, SBND will collect a dataset equivalent to the full MicroBooNE BNB five-year run

Being
- close (110 m) to the neutrino source
- intentionally positioned offset relative to the beam center

SBND sees neutrinos from a range of off-axis angles (OAAs)
- off-axis angles are calculated with respect to the BNB target position





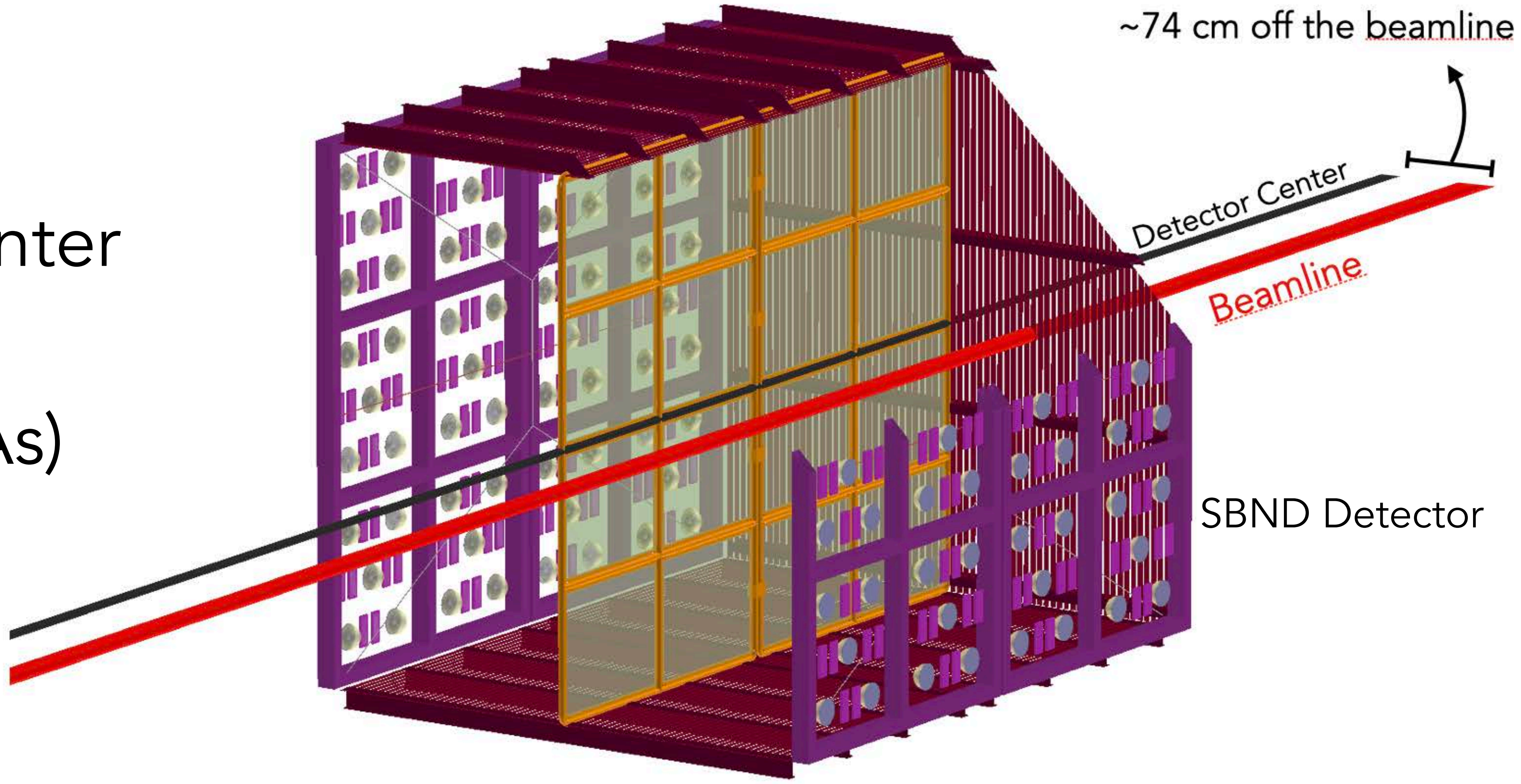


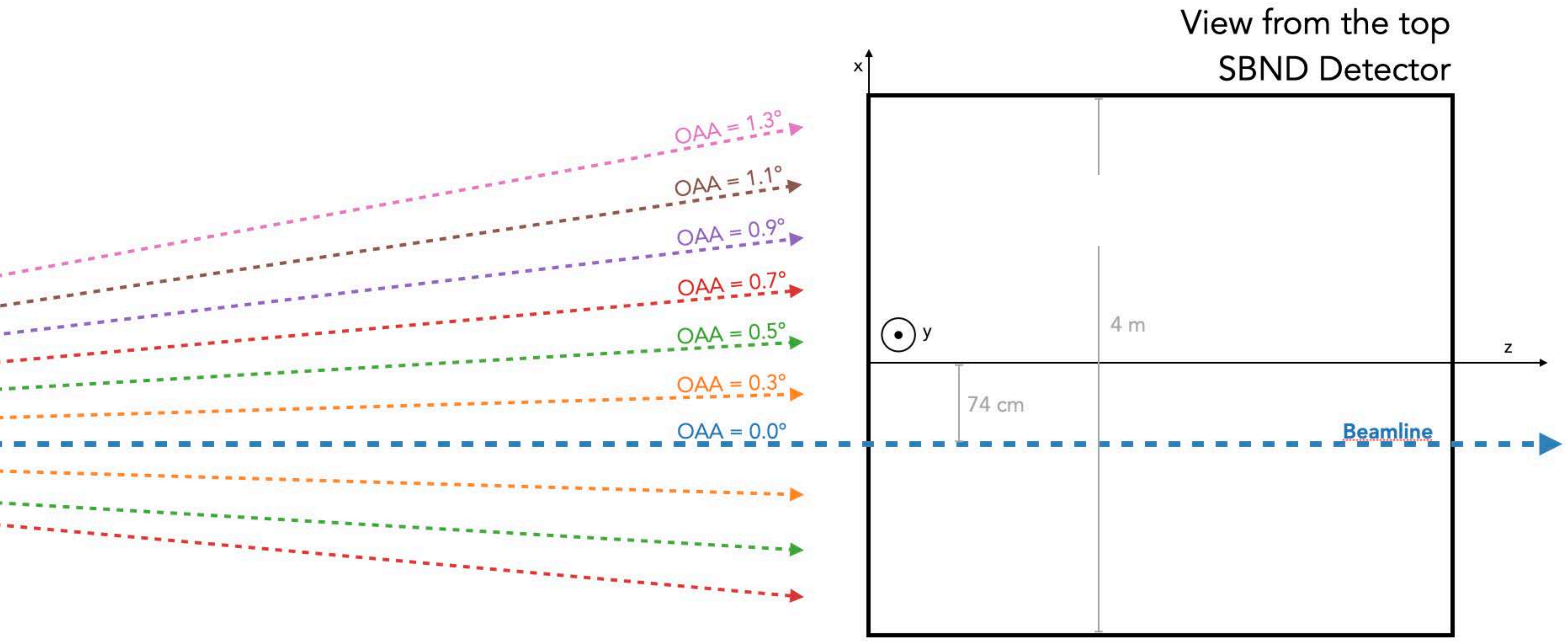
*Similar to the nu-PRISM and DUNE-PRISM concepts, but with a fixed detector.

A SLIGHTLY OFF-AXIS DETECTOR: SBND-PRISM

Being
- close (110 m) to the neutrino source
- intentionally positioned offset relative to the beam center

SBND sees neutrinos from a range of off-axis angles (OAAs)
- off-axis angles are calculated with respect to the BNB target position





This "PRISM"* feature of SBND allows **sampling multiple neutrino fluxes in the detector**

SBND-PRISM provides unique constraints of systematic uncertainties, helps mitigate backgrounds, and expands the SBN(D) physics potentials

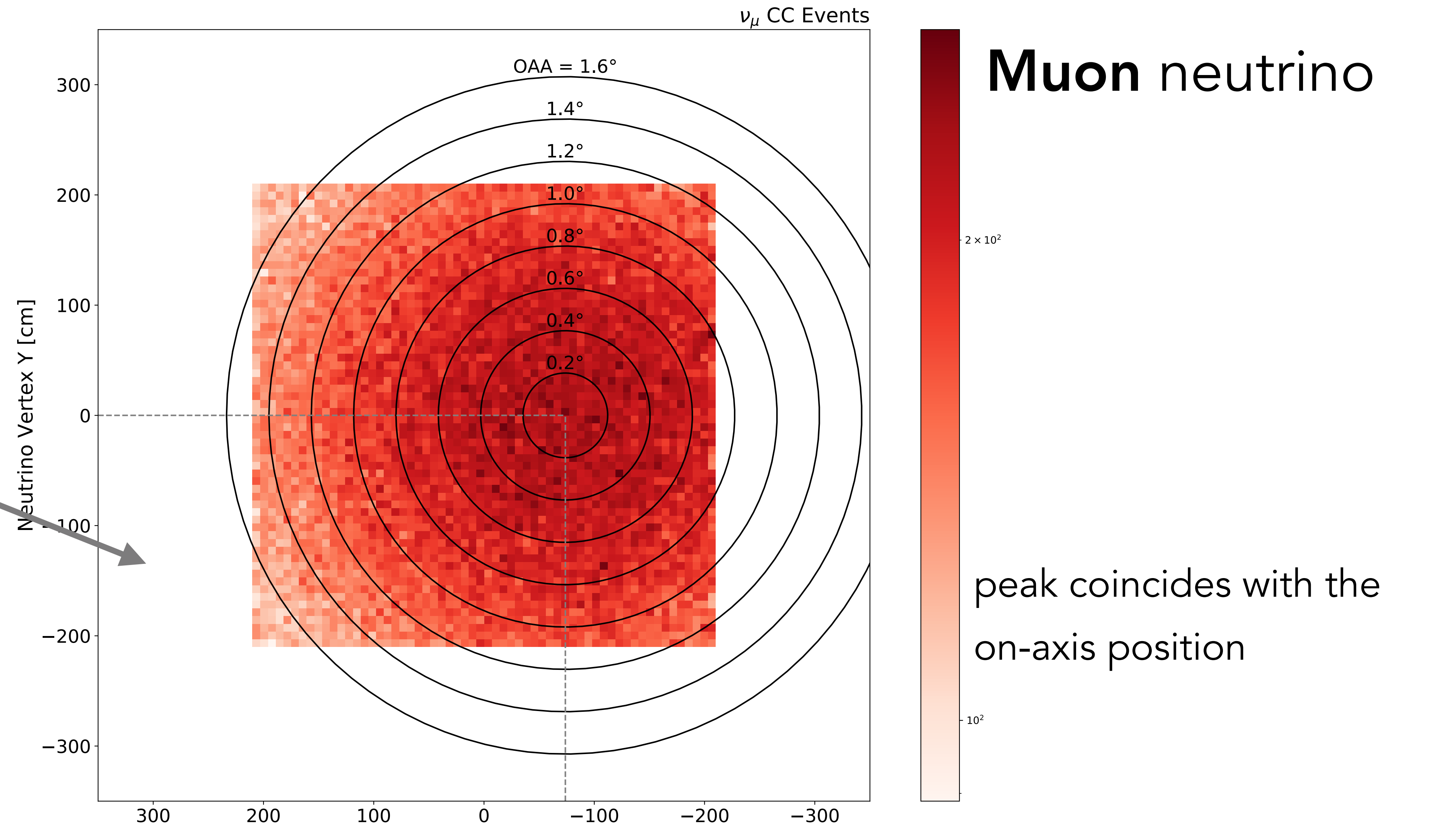
*Similar to the nu-PRISM and DUNE-PRISM concepts, but with a fixed detector

SBND-PRISM - Neutrino Events in OAA regions

ν_μ come predominantly from two-body decay

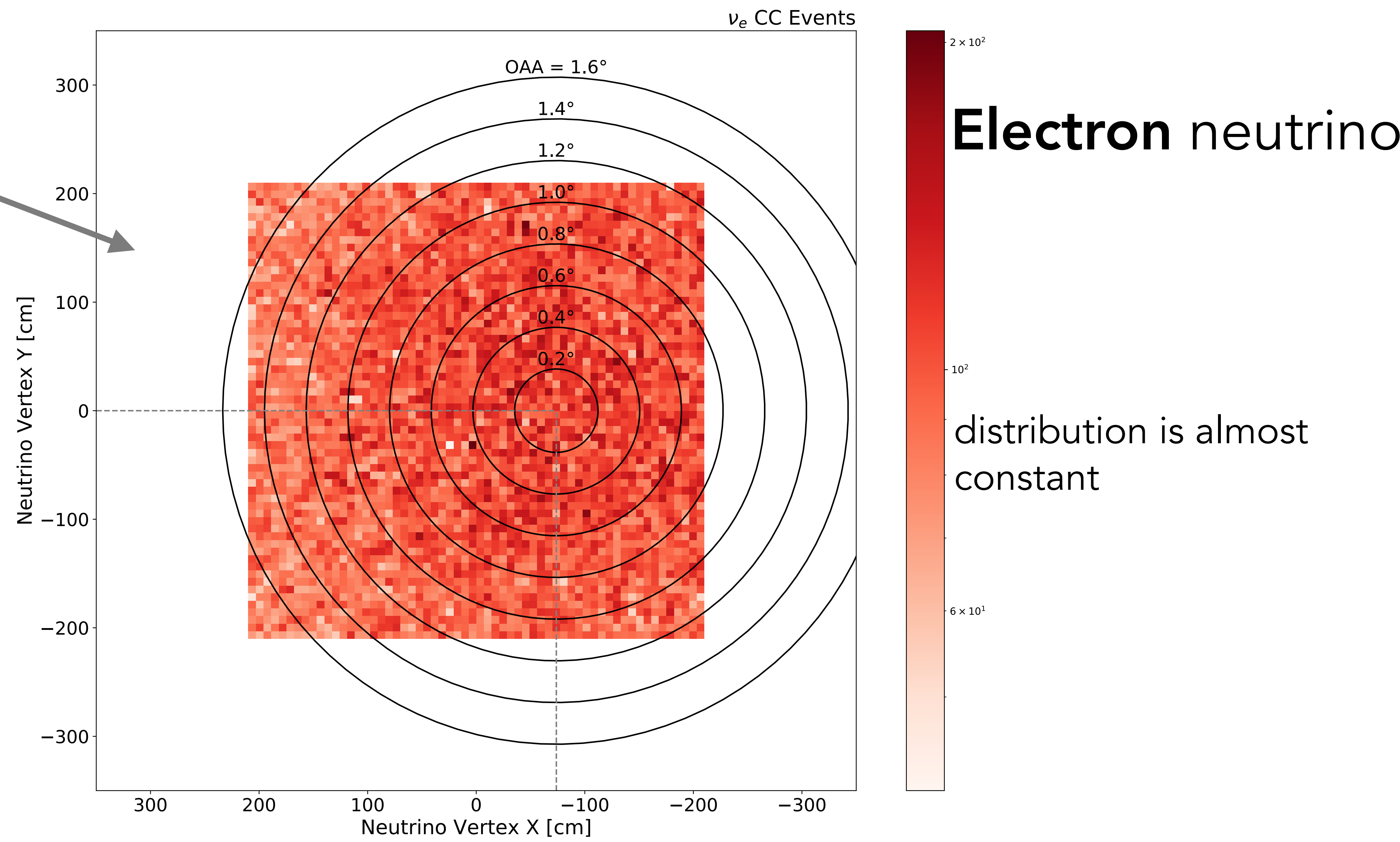
The **muon** neutrino distribution is affected by the off-axis position.

Larger off-axis angle → less ν_μ



ν_e come from three-body decay → larger angular spread than ν_μ

The **electron** neutrino distribution also change, but is less affected by off-axis position.

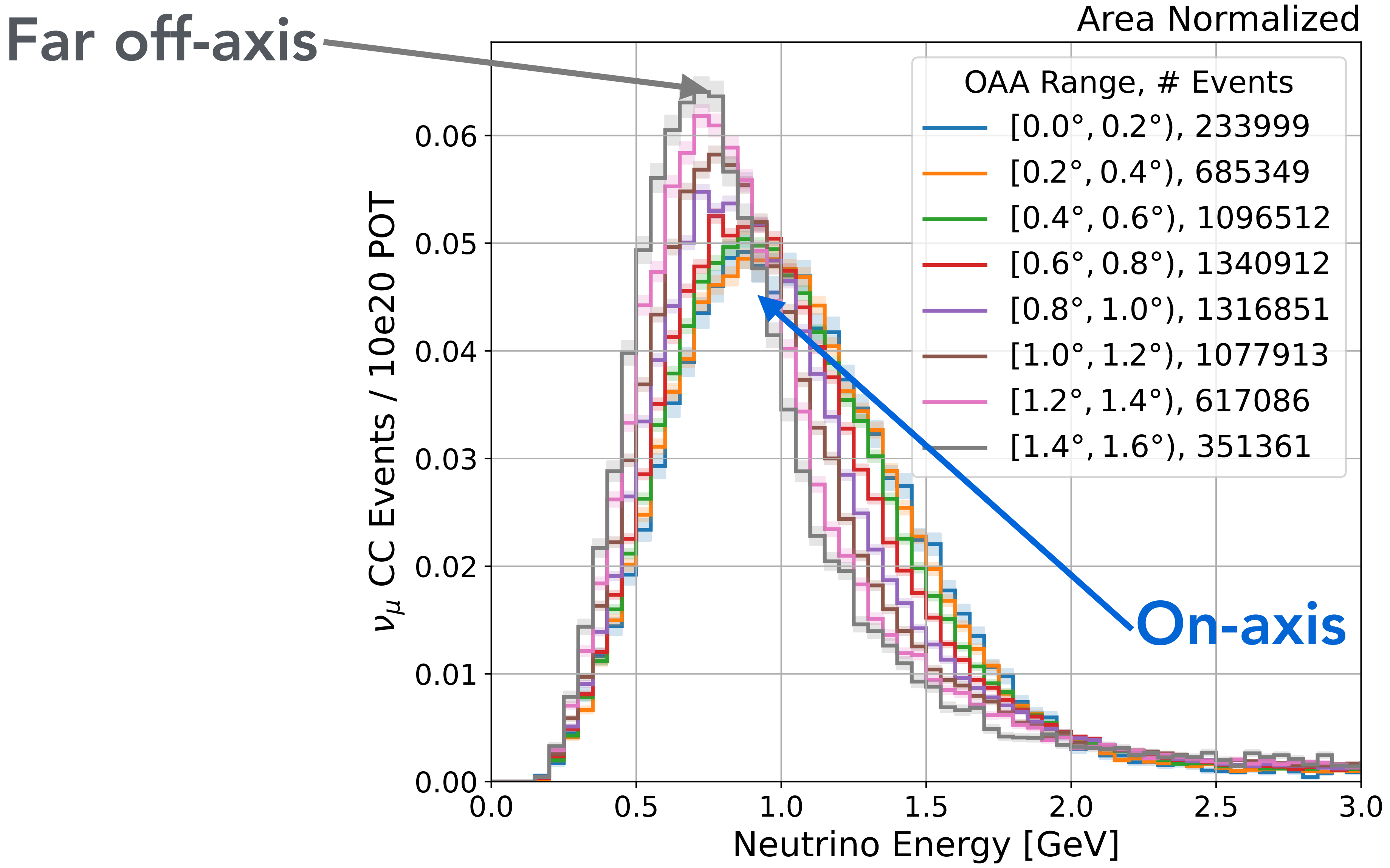


Note high event statistics in all off-axis regions.

ν_μ energy distributions are affected by the off-axis position

Larger off-axis angle → lower mean energy

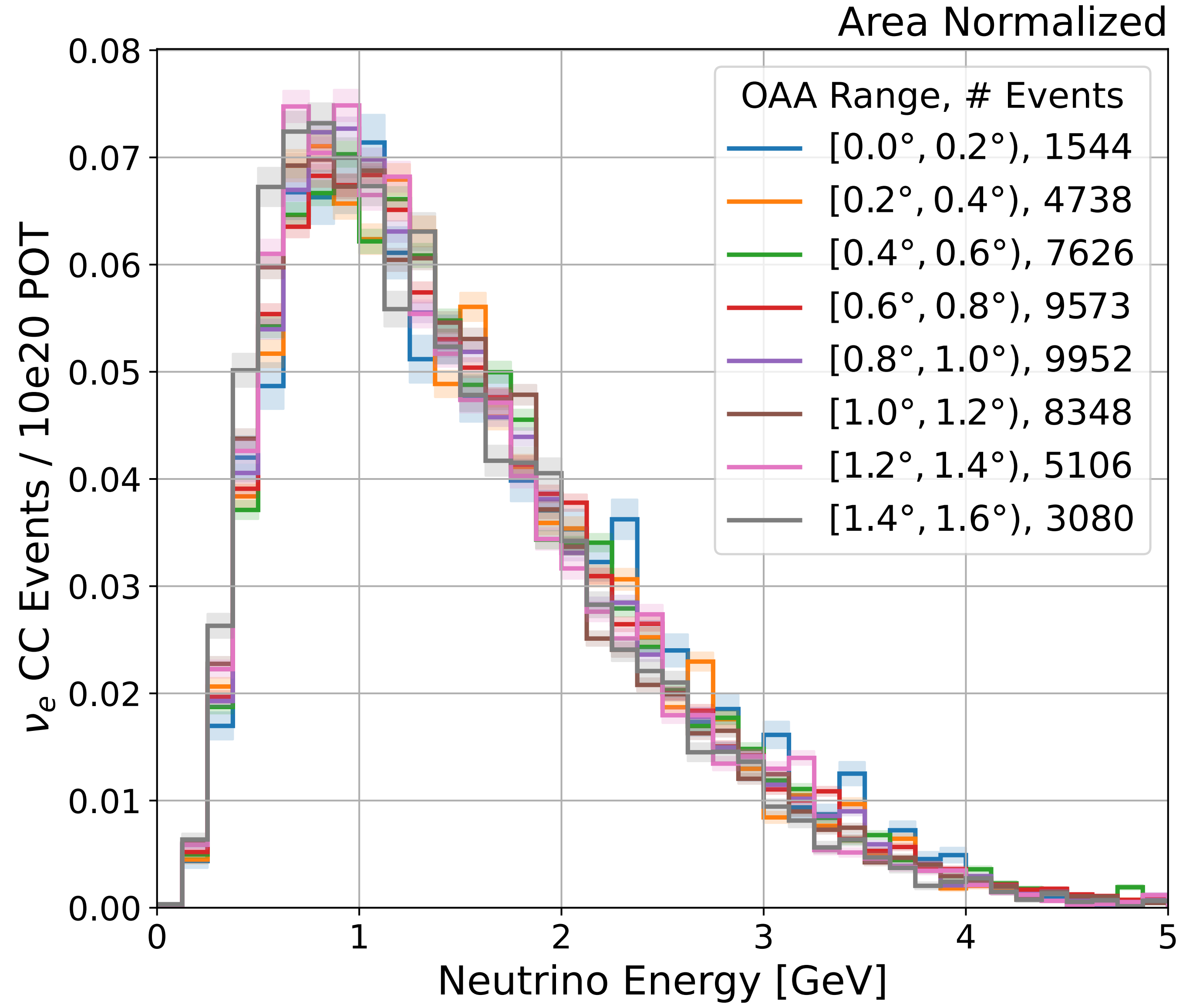
Neutrino Events in Off-Axis Angle (OAA) regions



Muon neutrino

With the OAA, the observed neutrino energy spectrum narrows and peaks at a lower energy.

ν_e energy distributions also change, but they are less affected by off-axis position



Electron neutrino

Muon and electron neutrino spectra change in a different way.

Note high event statistics in all off-axis regions.

Energy Dependence:

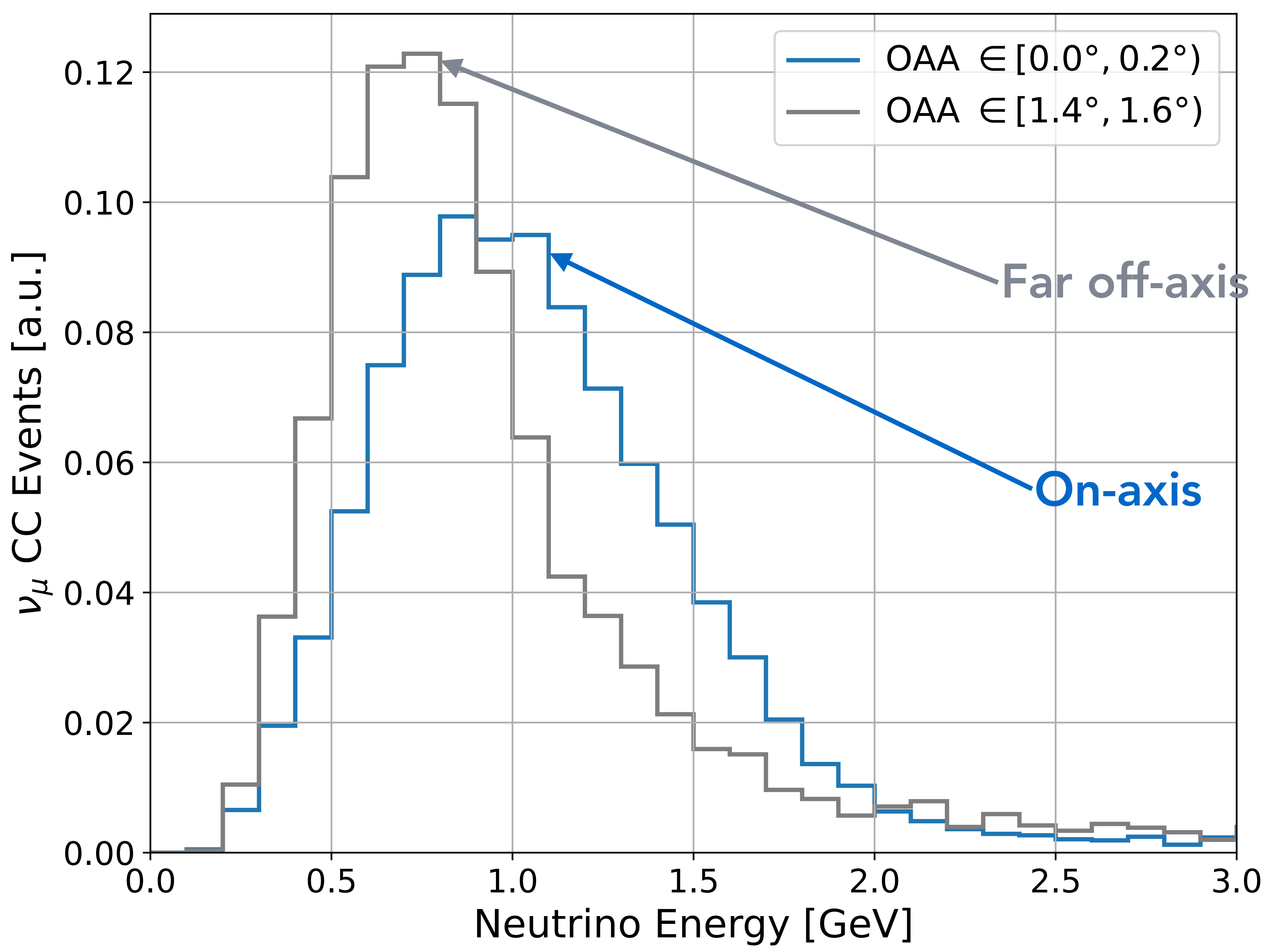
- Up to ~200 MeV difference in ν_μ mean energy
- By measuring neutrino interactions **at different OAA**, we can infer the **energy dependence of the cross section** (and various nuclear effects).
- Study the relationship between neutrino energy, and lepton and hadron kinematics by measuring differential cross-section in lepton and hadron kinematics at different OAA.

Disentangling nuclear physics for a given interaction:

- By combining OAA fluxes we can potentially isolate samples of specific interactions (QE, 2p-2h…), and study nuclear effects that affect that interaction.

Muon neutrino

Neutrino Events in Off-Axis Angle (OAA) regions

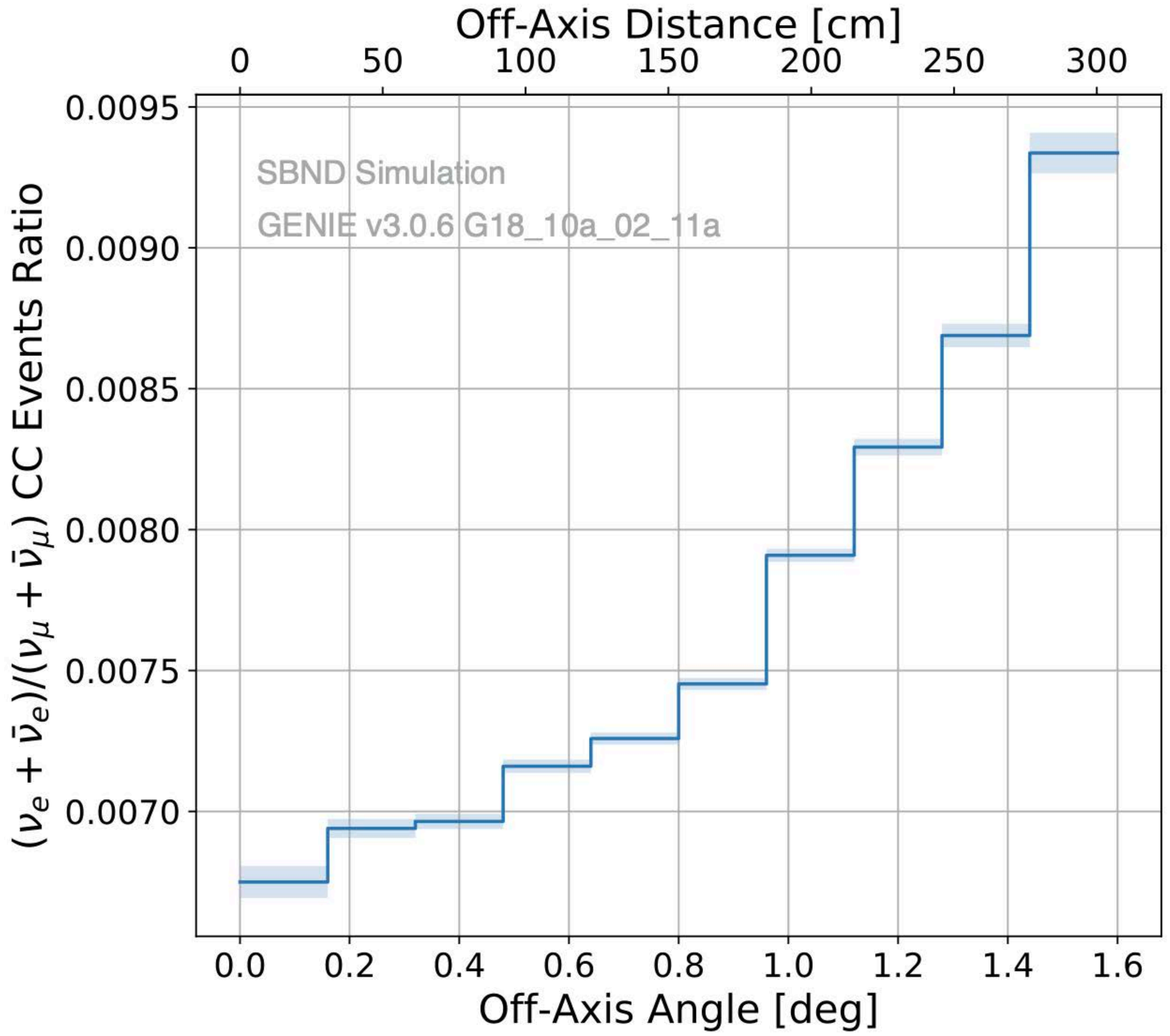


With the OAA, the observed neutrino energy spectrum narrows and peaks at a lower energy.

Allows stringent tests of theoretical models and event generators

ν_μ to ν_e cross sections:

- Going off-axis, the increase in ν_e to ν_μ flux ratio combined with a choice of kinematics where ν_e to ν_μ differences are expected to be prominent should allow us to measure the ν_e/ν_μ cross section.
- This would allow us to study **lepton mass effects**, and **test Lepton Flavor Universality**.



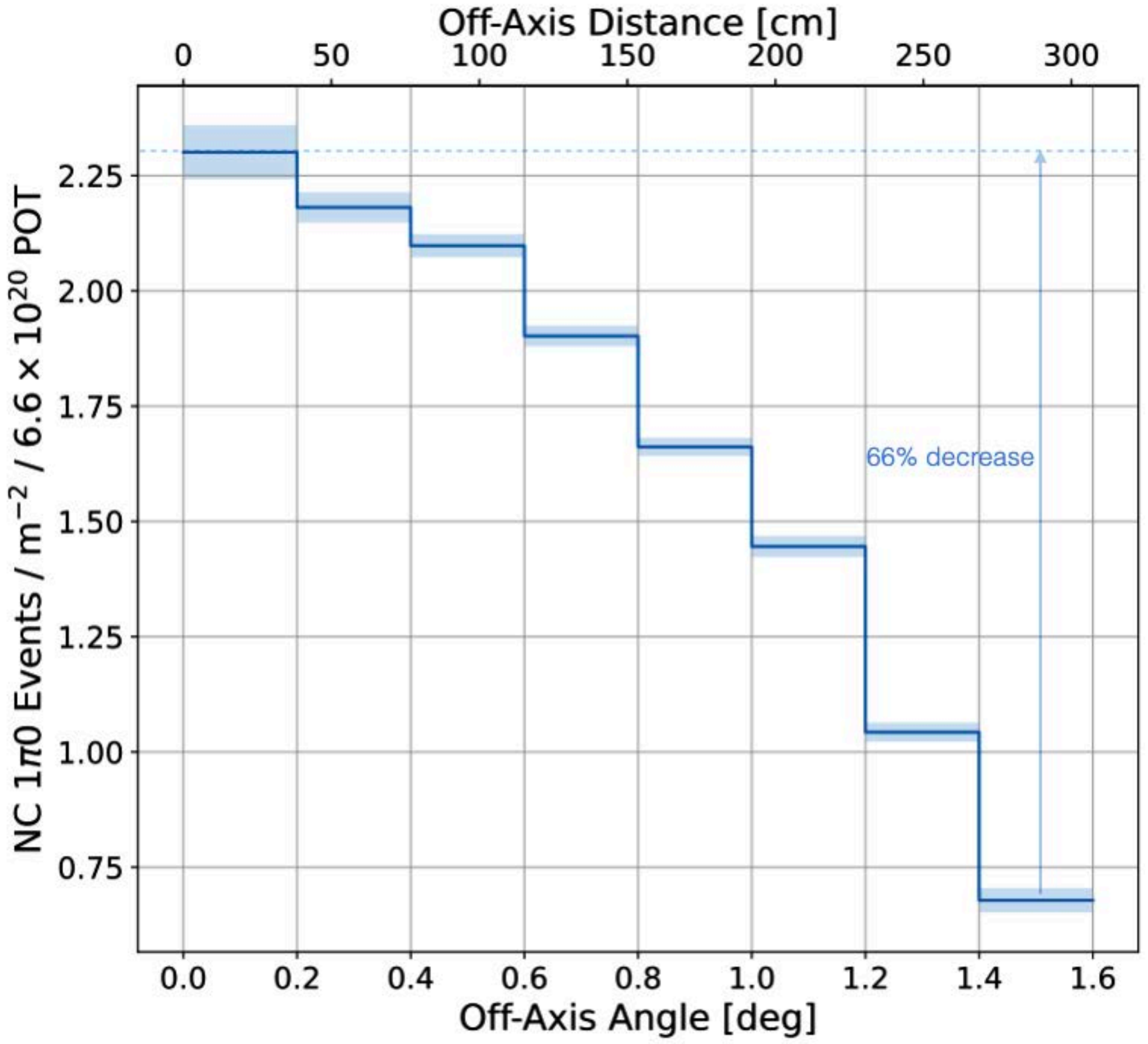
ν_e to ν_μ ratio changes moving off-axis

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

The **"higher energy" tail** of the ν_μ flux **shrinks as a function of the OAA**.

An example: electron neutrino measurements

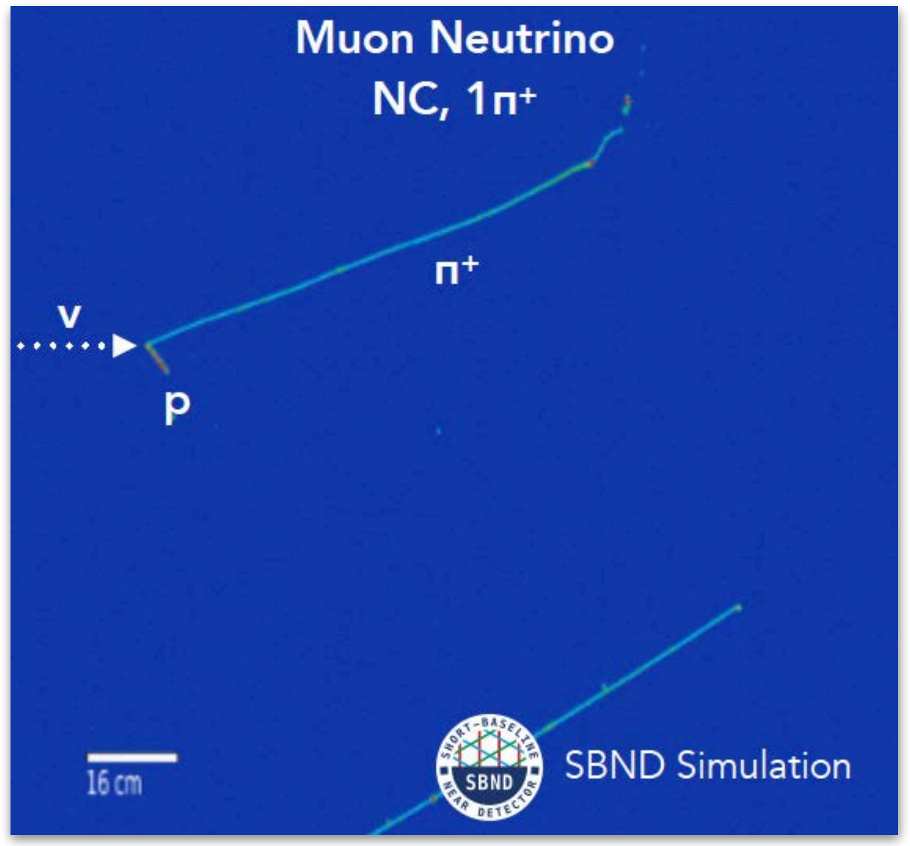
Main background for electron neutrino: NC $1\pi^0$ events.

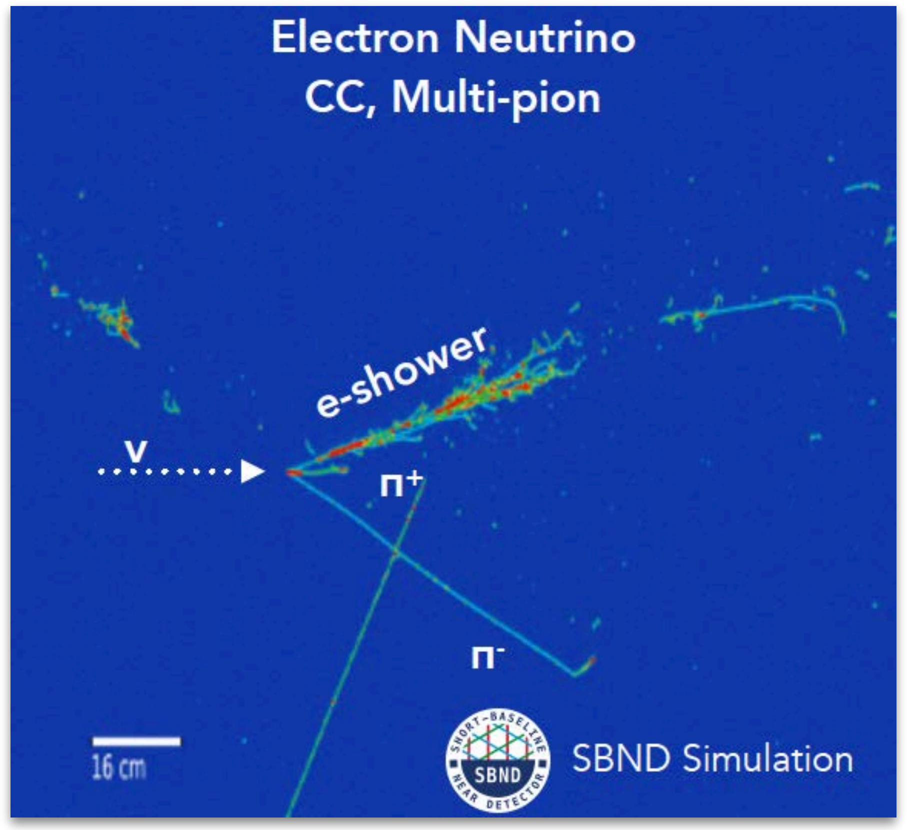


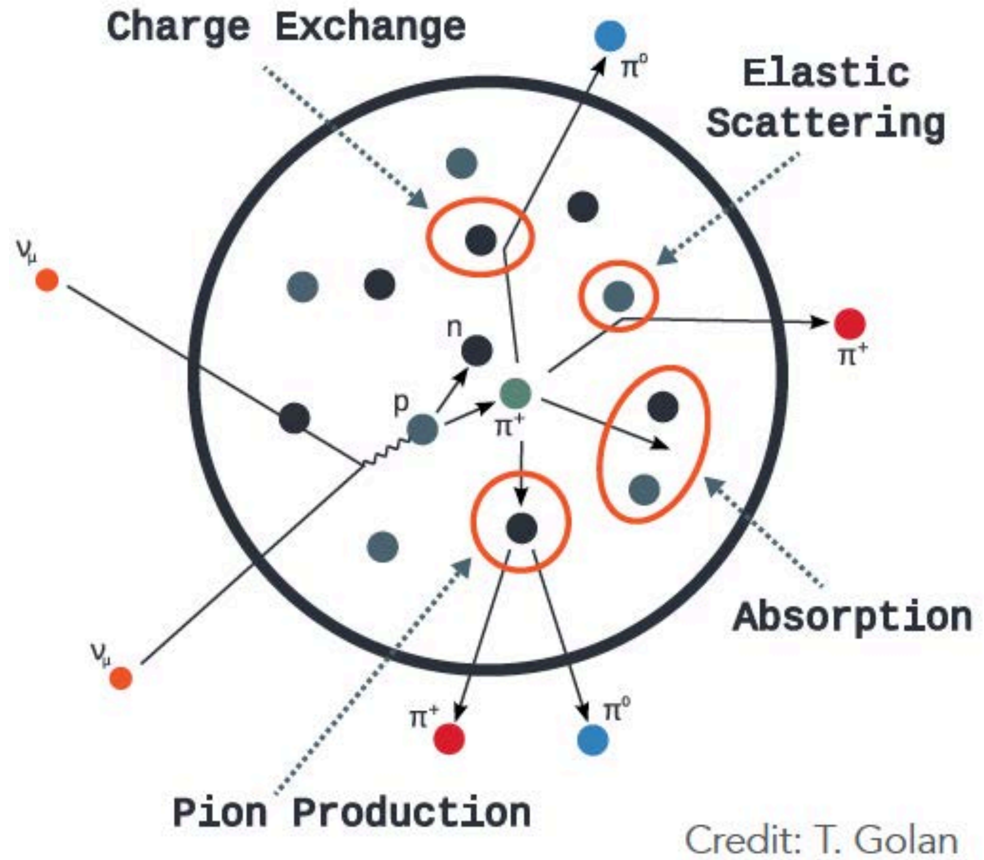
NC π^0 decreases moving off-axis

The capabilities of SBND provide ample opportunities

- High-statistics searches: SBND can perform **multi-dimensional analyses of many signatures** charactering events in terms of **particle content and kinematics,** and **exploiting SBND-PRISM**.
- These capabilities allow to **study nuclear effects in neutrino interactions** on argon nuclei with unprecedented high precision, providing the **testbed to assess and validate nuclear models and generator**, paving the way for **precision neutrino-argon scattering physics**.







Credit: T. Golan

Studies in the previous slides are from GENIE, but we started to also use GIBUU.

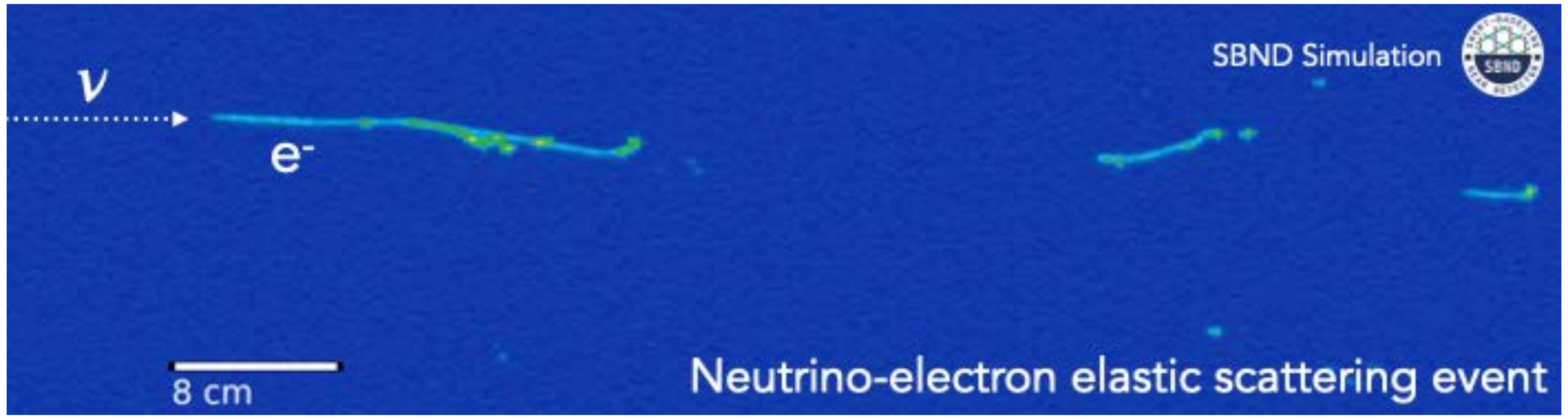
Our goal is to **design analyses capable of probing regions of greatest model discrimination power.**

Engagement from the theory community is highly encouraged to fully exploit the SBND neutrino interaction program!

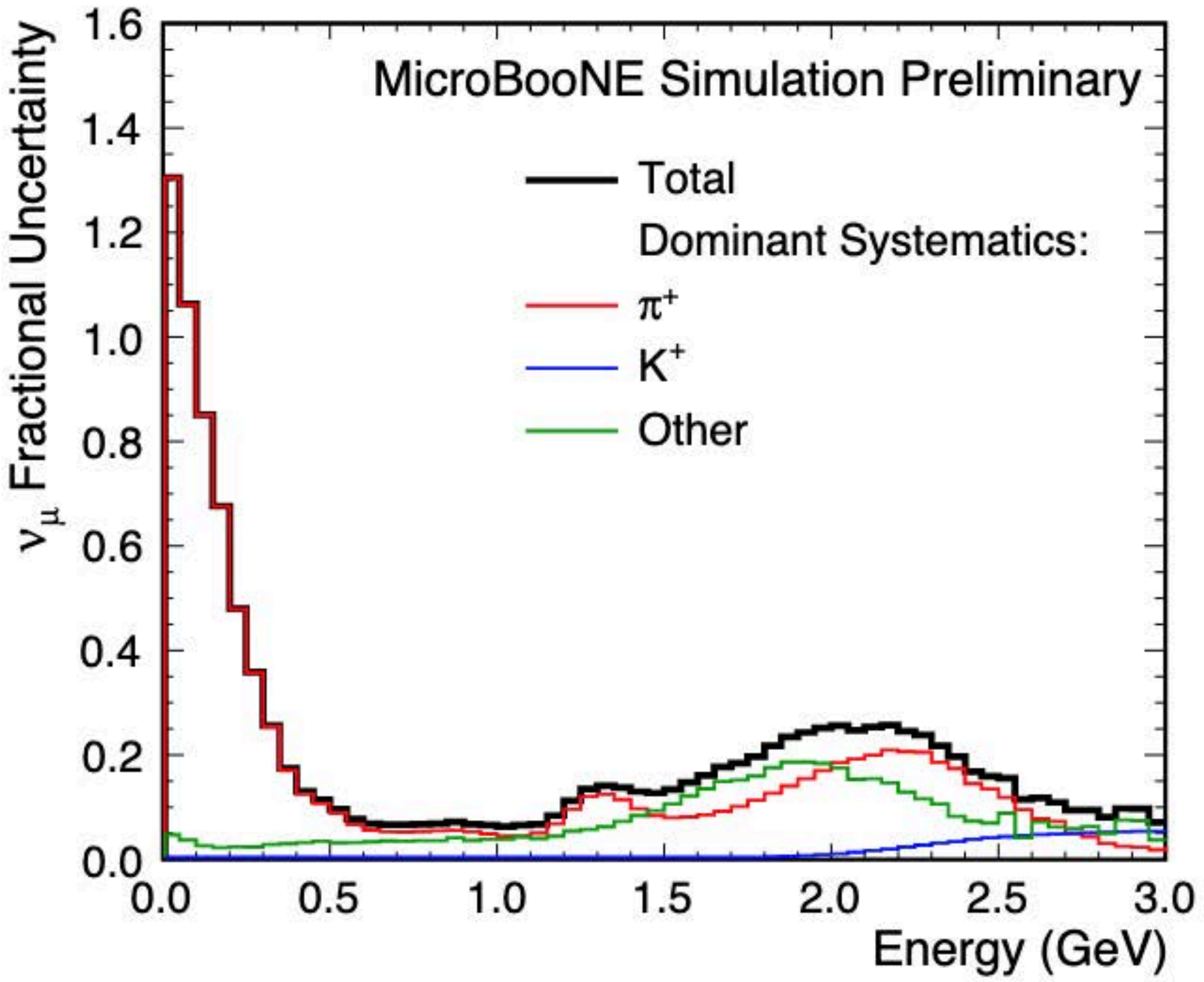
REDUCING FLUX UNCERTAINTIES

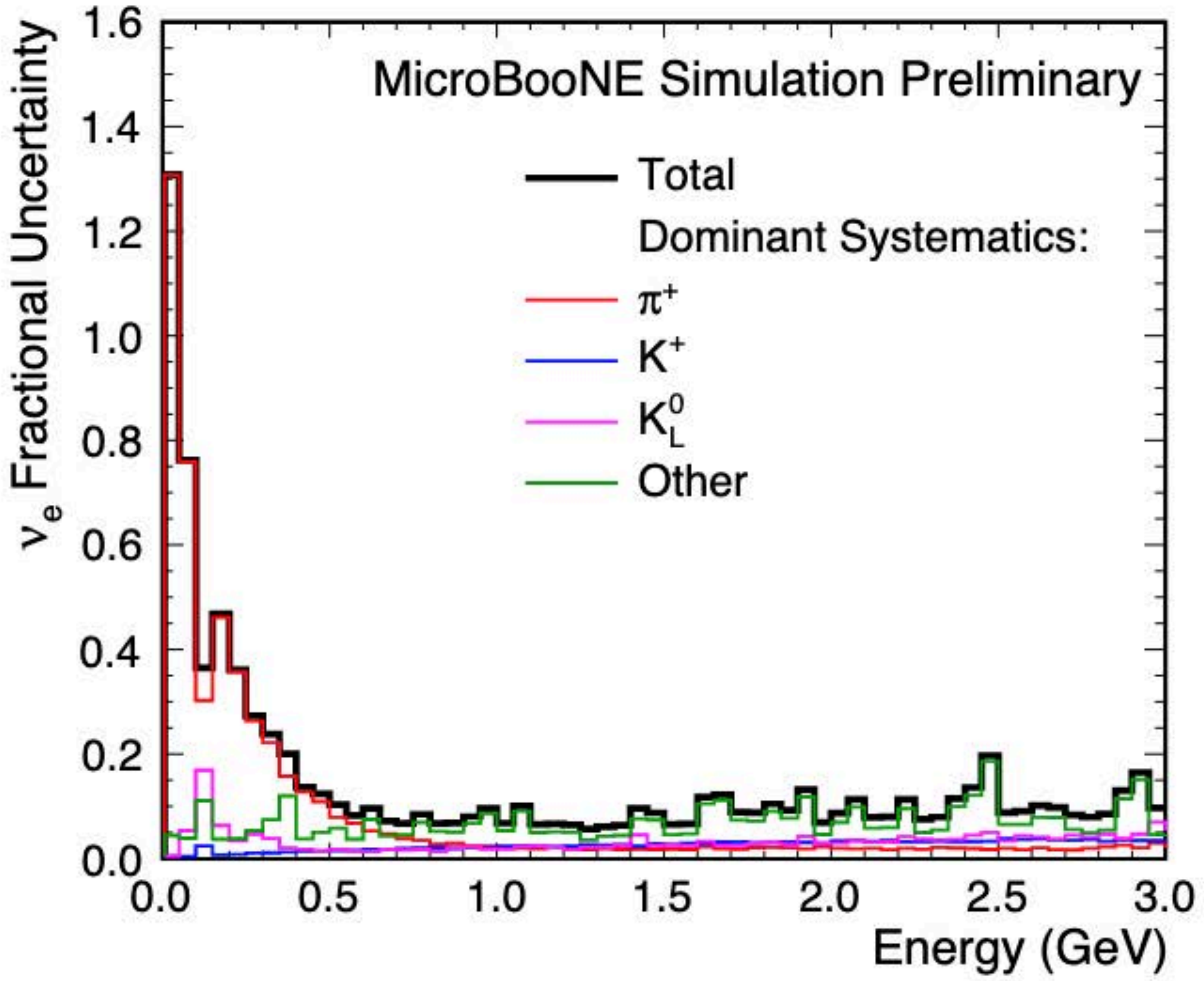
Dominant uncertainty is expected to be the neutrino flux

- To reduce these uncertainties:
  - **Neutrino-electron elastic scattering** (in-situ constraint) – O(500) events expected in SBND in 3 years

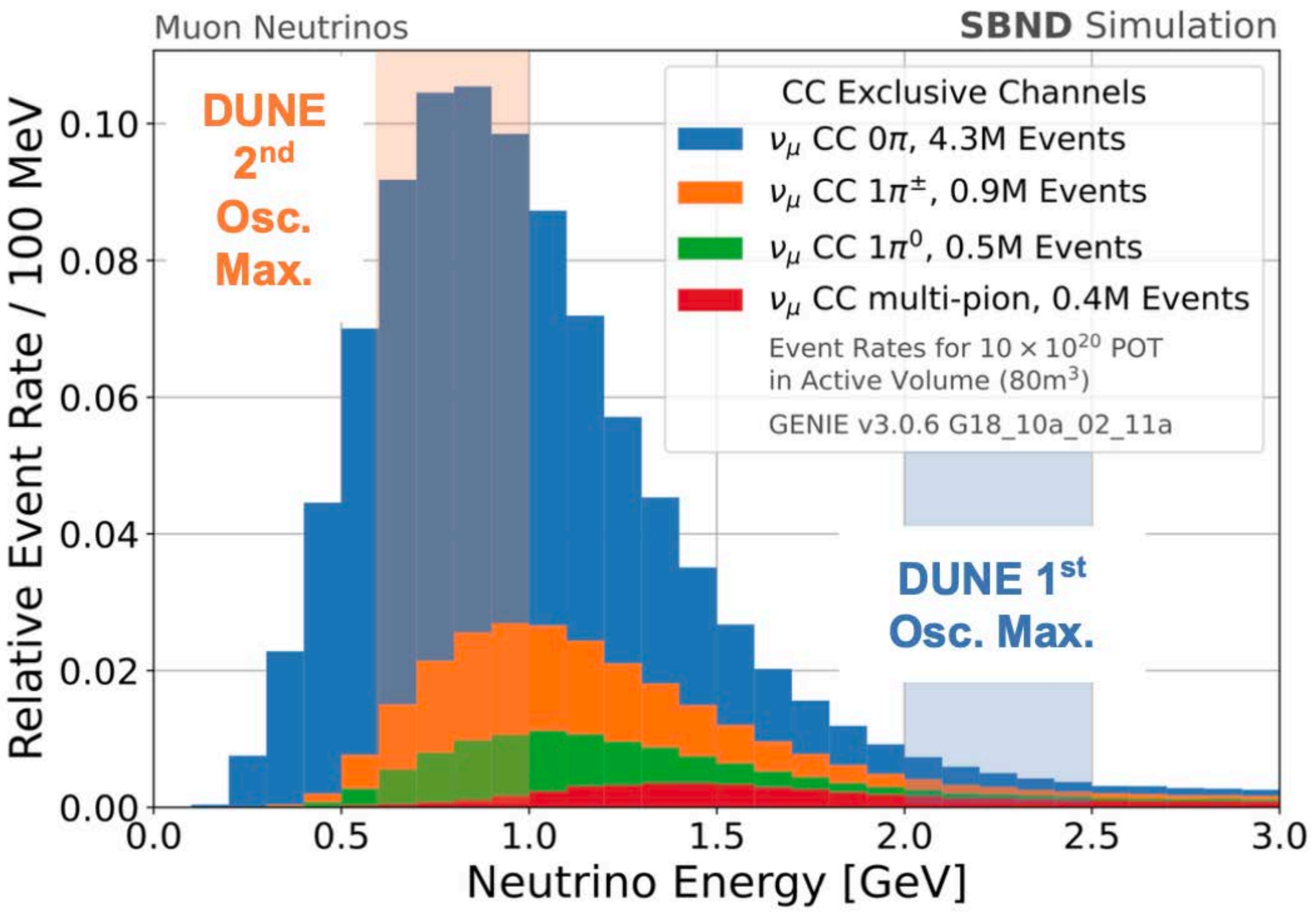


  - New hadron production measurements (external constraint) – **NA61/SHINE** and **EMPHATIC** data – p on Be target



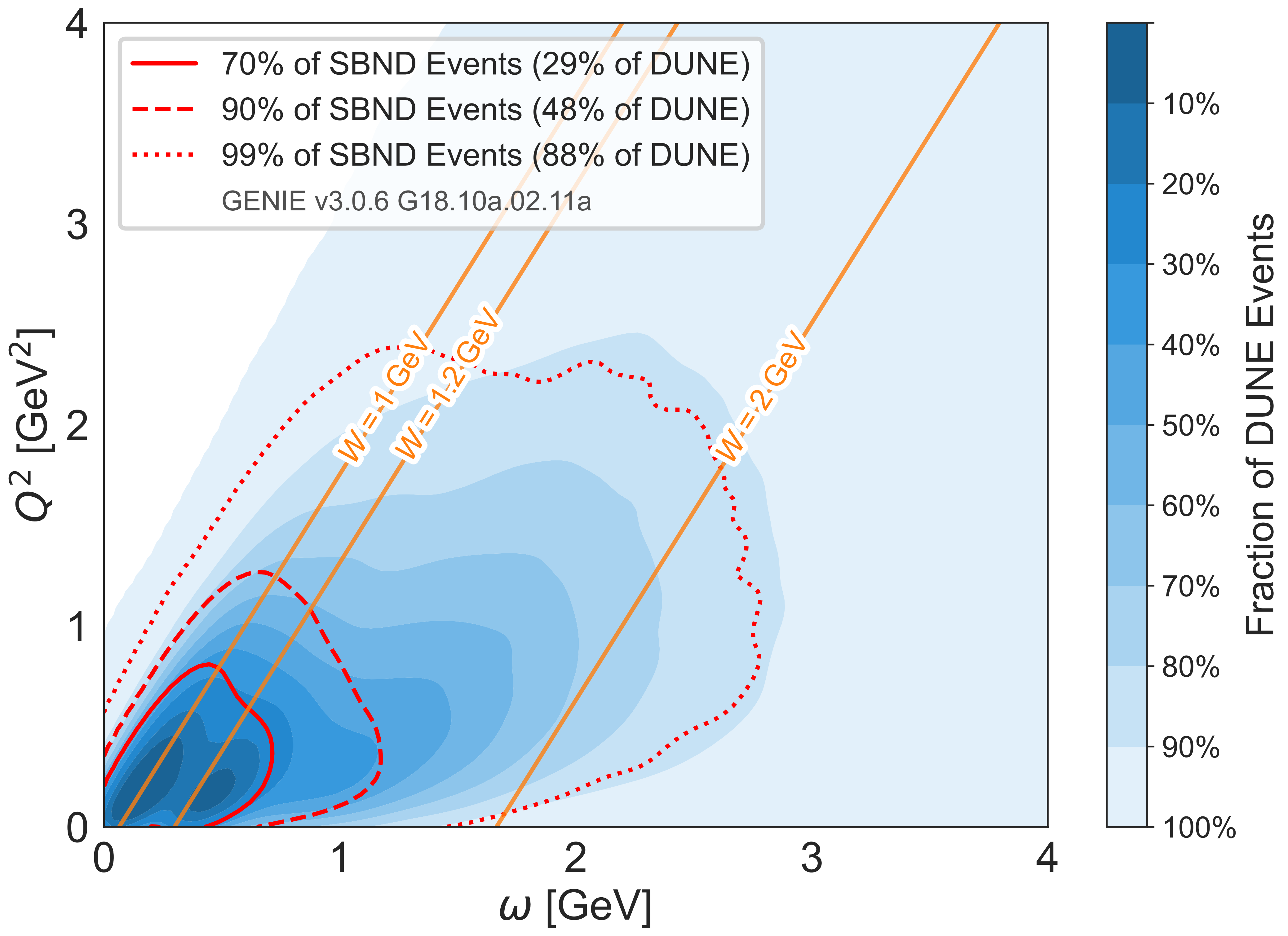


SBND interactions cover significant parts of kinematic phase space relevant for DUNE, including energy range spanning first and second oscillation maxima



SBND total: 10 million total events (CC+NC), including around **50,000 ν_μ CC events above 2 GeV**.

SBND has a **significant phase space overlap with DUNE** → SBND measurements can be used to constrain the same physics DUNE needs to know



DUNE kinematic coverage is represented with the blue 2D histogram. SBND kinematic coverage is shown with 3 contours, representing 70%, 90%, and 99% of all SBND data.

SBN STERILE NEUTRINO SENSITIVITIES

ν_e Appearance — ν_μ Disappearance — ν_e Disappearance

The SBN program tests the sterile neutrino hypothesis by covering the parameter regions favored by previous measurements at **5σ confidence level.**

eV-scale Sterile Neutrinos and New Physics Scenarios

SBN Sterile Neutrino Sensitivities

ν_e Appearance | ν_μ Disappearance | ν_e Disappearance

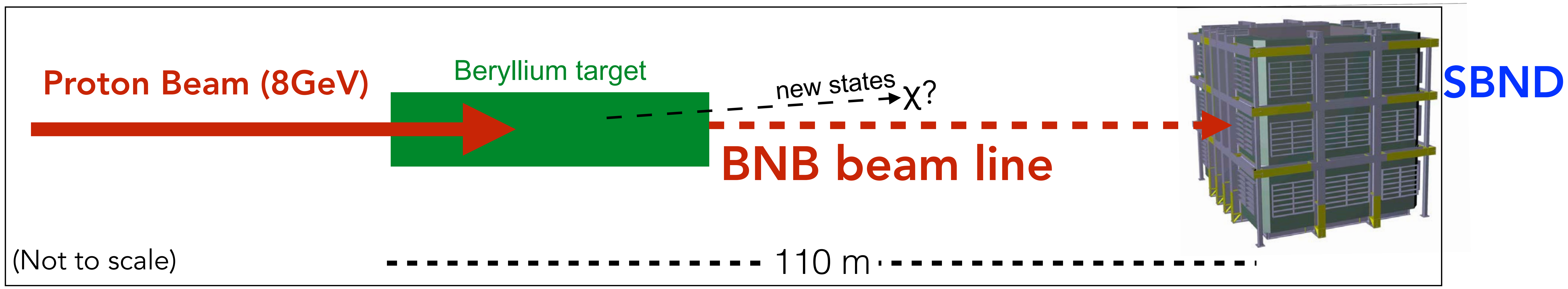
Near detector data is essential for performing a broad, definitive test of the light sterile neutrino hypothesis - both appearance and disappearance.

The SBN program tests the sterile neutrino hypothesis by covering the parameter regions favored by previous measurements at **5σ confidence level.**

Complementary measurements in different modes: important for interpretation in terms of **sterile neutrino oscillation**.

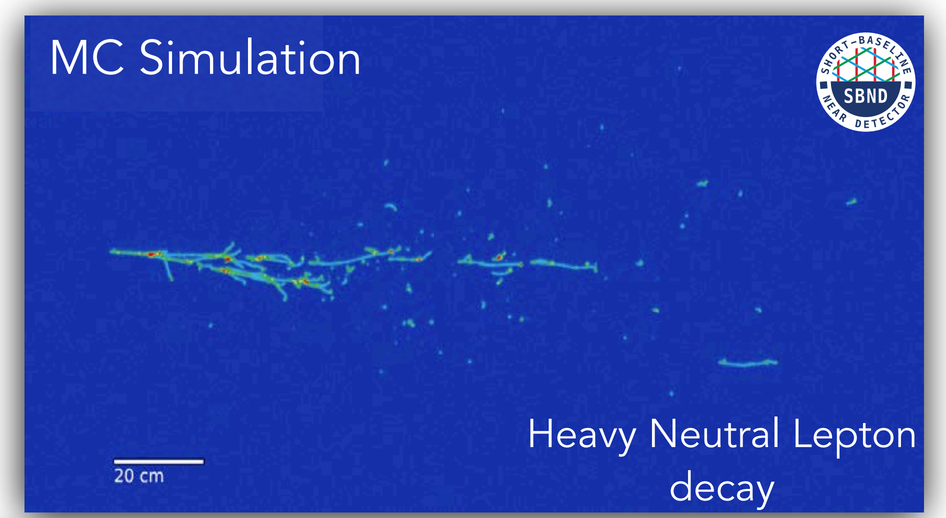
Directly addressing existing tensions observed when combining appearance and disappearance data.

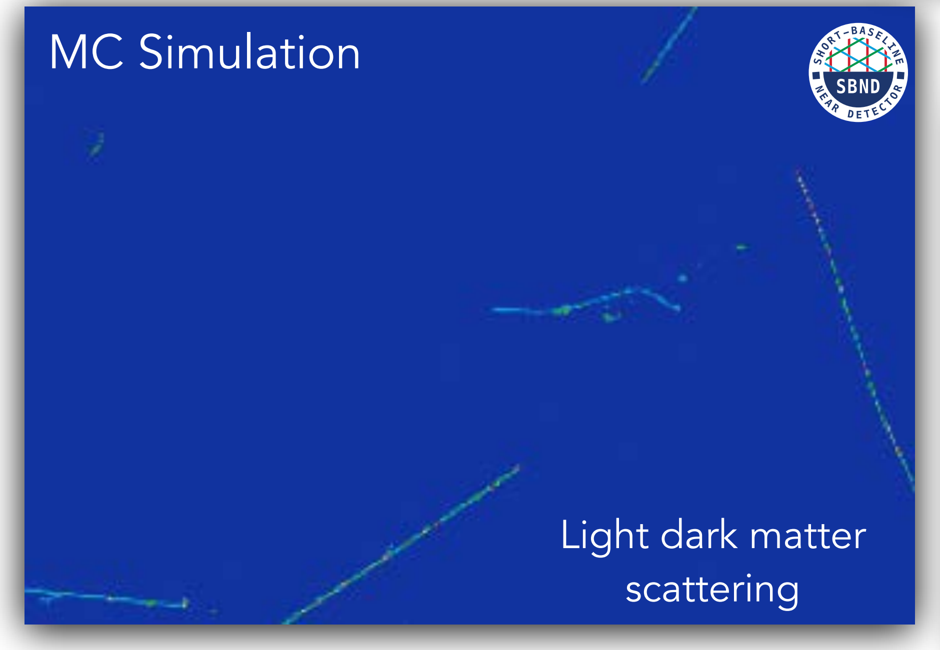
SIGNATURES FOR NEW PHYSICS IN SBND

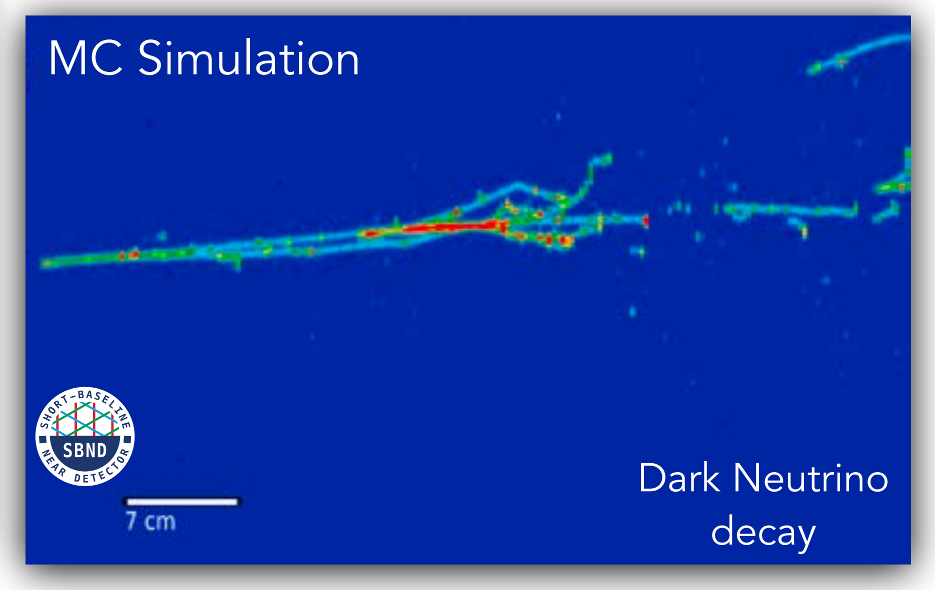


Large mass LAr detector close to the beam target

High-intensity proton beams (high-intensity neutrino beams)







Final state signatures: single photon, single electron, "trident" with di-leptons and different levels of hadronic activity

Opportunities to **probe signatures** for **new physics scenarios** in the **neutrino sector** and **beyond**

Summary

SBND experiment is wrapping up installation, preparing for commissioning, and is on track to **start operations early in 2024**!

SBND has a **broad science goal** as part of SBN program and on its own, and **SBND-PRISM** enhances the physics potential of SBND.

Neutrino interaction measurements are a key part of SBND's physics program, and will benefit other physics goals of the SBN program and beyond.

The highly-capable LArTPC detector technology combined with SBND's high statistics will enable a **wide variety of neutrino–argon interaction measurements** at the GeV scale, with sensitivities **beyond what has been possible before.**

SBND data will provide the testbed to assess and validate nuclear models and generator, and pave the way for **precision neutrino-argon scattering physics**.