SBND-PRISM: Sampling Multiple Off-Axis Fluxes with the Same Detector

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On behalf of the SBND Collaboration

NuFACT 2022 Conference

4th August 2022

The Short-Baseline Near Detector (SBND)

SBND is the near detector in the Short-Baseline Neutrino (SBN) program at Fermilab

Three Liquid Argon Time Projection Chamber (LArTPC) detectors located along the Booster Neutrino Beamline (BNB)

SBND Talks at NuFACT:

SBND Status by M. Nebot-Guinot

SBND Trigger Status by G. Vitti Stenico

BSM in SBND by S. Balasubramanian

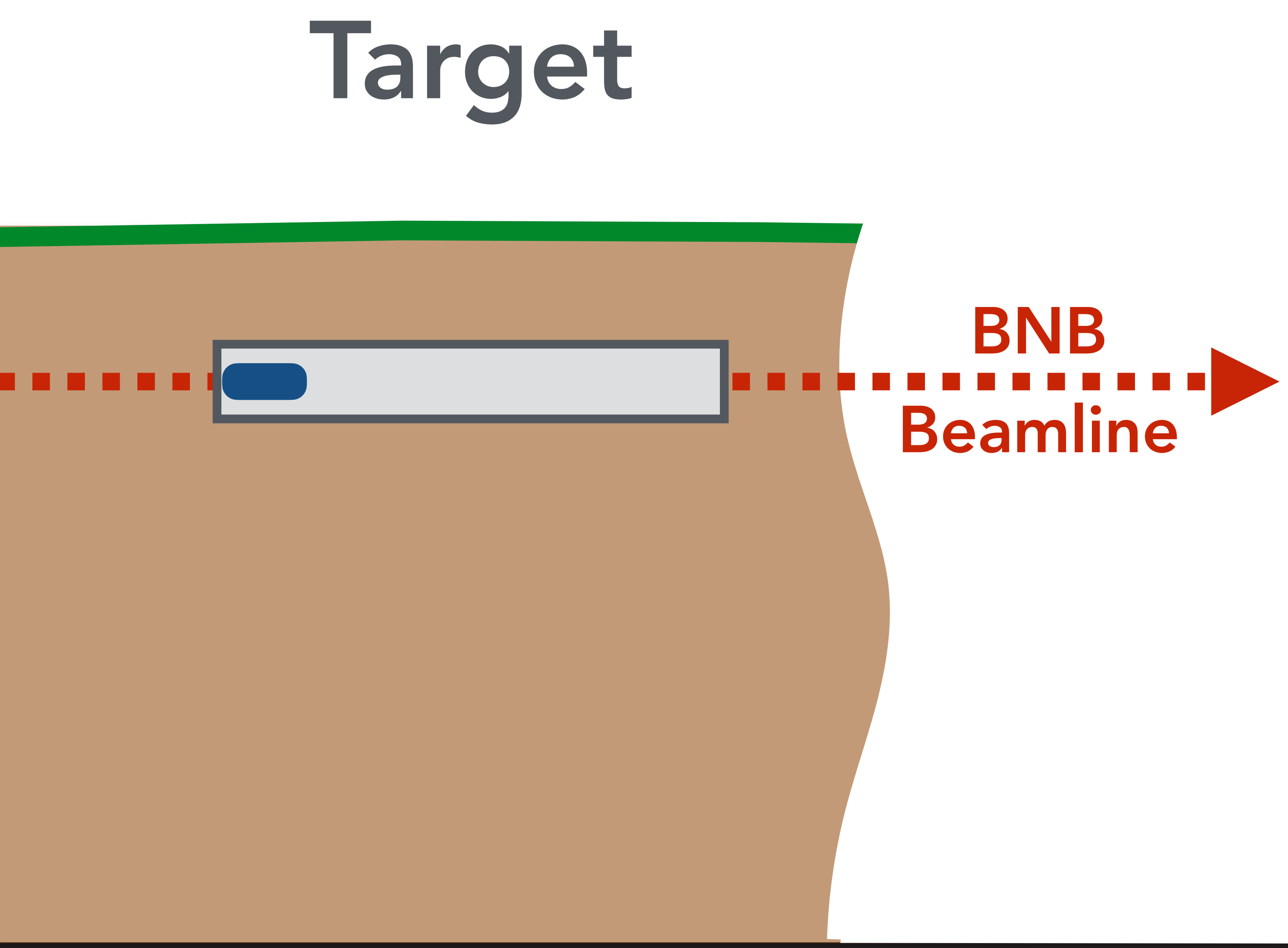
Goals of the SBND:

Search for eV mass-scale sterile neutrinos oscillations

Study of neutrino-argon interactions at the GeV energy scale

Search for new/rare physics processes in the neutrino sector and beyond

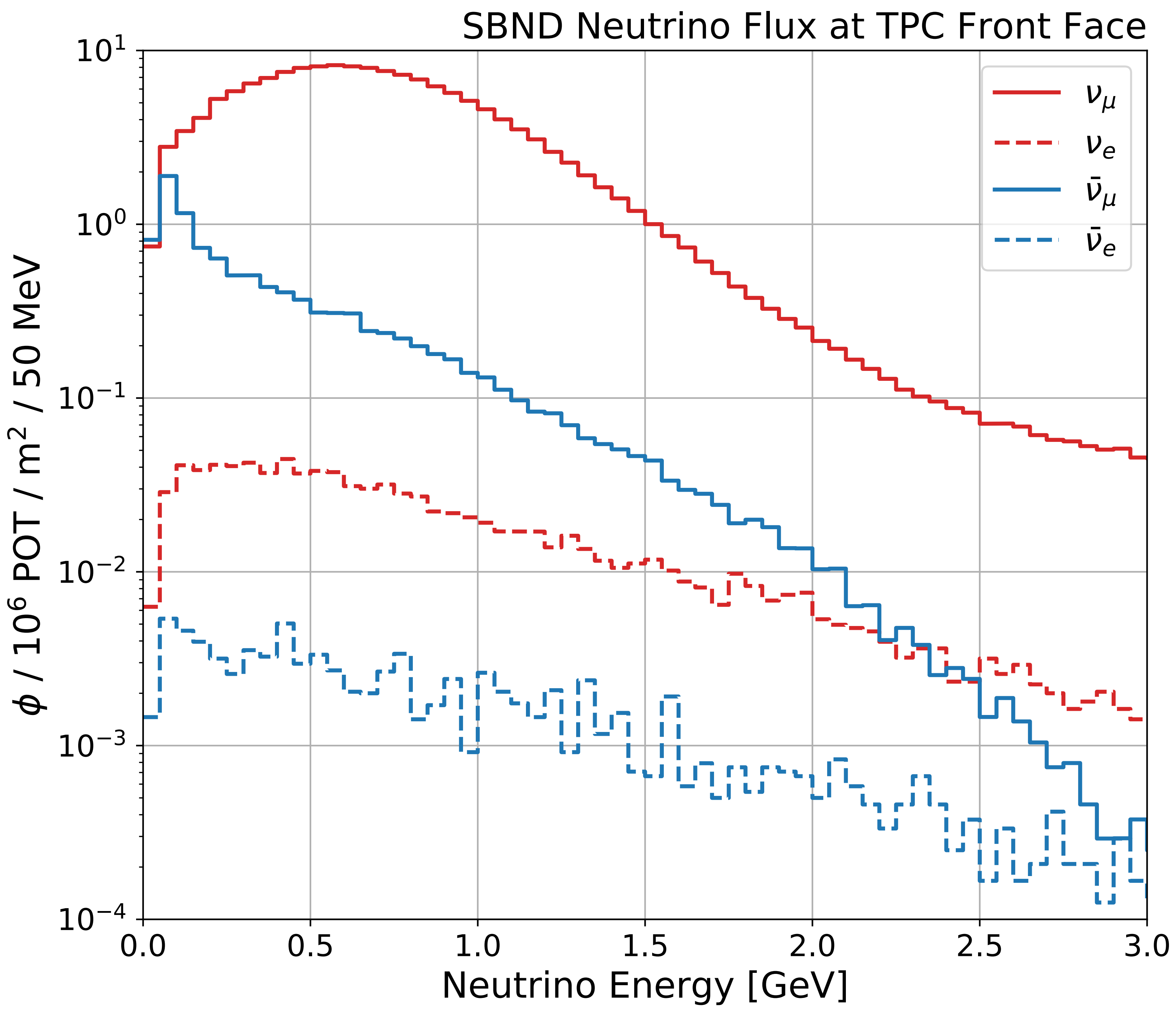
Booster Neutrino Beam



Booster Neutrino Beam

More on the Booster Neutrino Beam: https://arxiv.org/abs/0806.1449

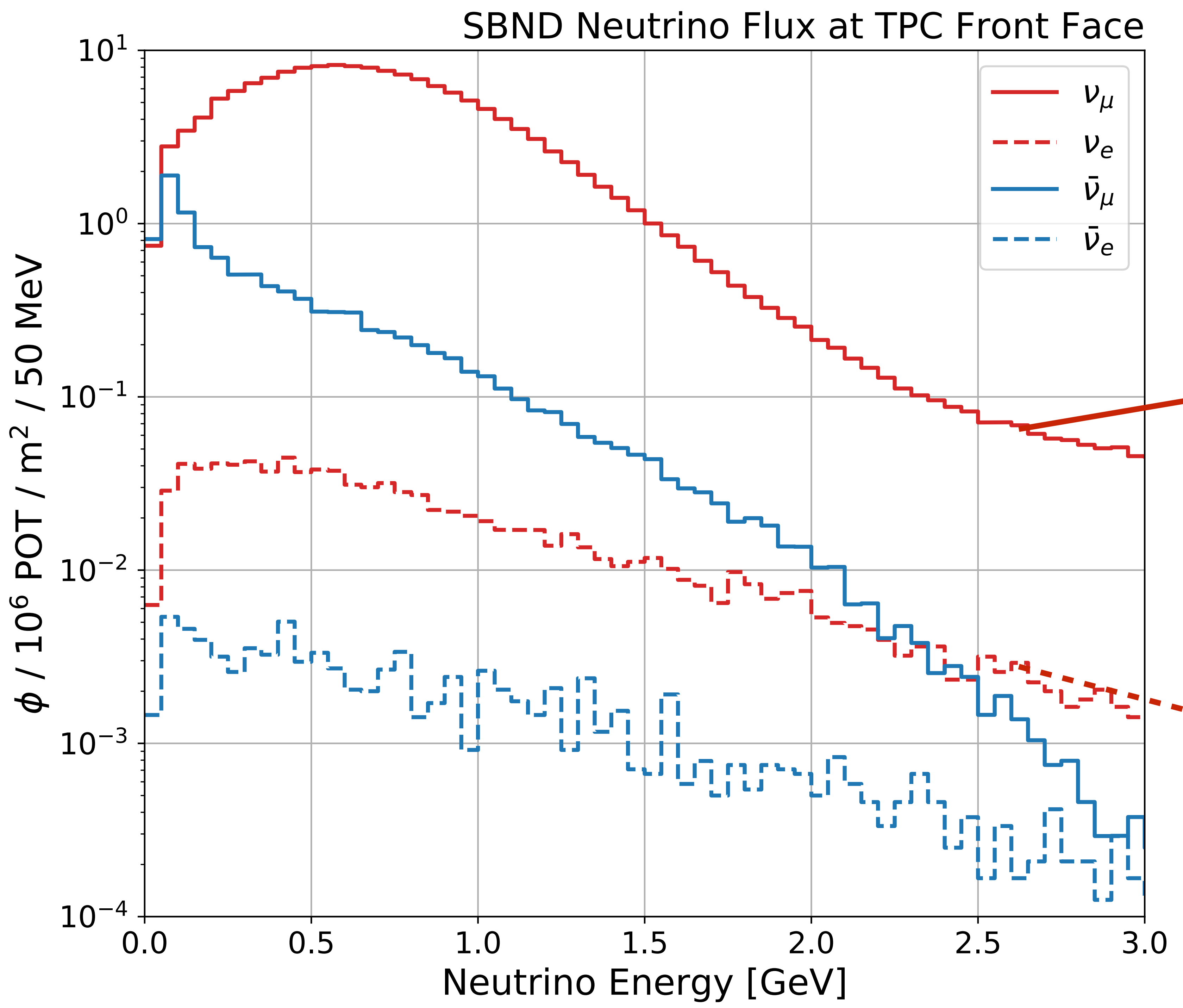
Neutrino Flux at SBND



Neutrino flux at the SBND front face

ν_μ (93.6%), $\bar{\nu}_\mu$ (5.9%), ν_e+$\bar{\nu}_e$ (0.5%)

Neutrino Flux at SBND



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ν_μ (93.6%), $\bar{\nu}_\mu$ (5.9%), ν_e+$\bar{\nu}_e$ (0.5%)

ν_μ Flux

$$\pi^+ \to \nu_\mu + \mu^+$$
$$K^+ \to \nu_\mu + \mu^+$$

Two-body decays

ν_e Flux

$$\mu^+ \to \nu_e + \bar{\nu}_\mu + e^+$$
$$K^+ \to \nu_e + e^+ + \pi^0$$
$$K_L^0 \to \nu_e + \pi^- + e^+$$

Three-body decays

Different kinematics: two-body vs three body decay.

The flux of ν_e has a larger angular spread than that of ν_μ (at the same parent energy)

SBND

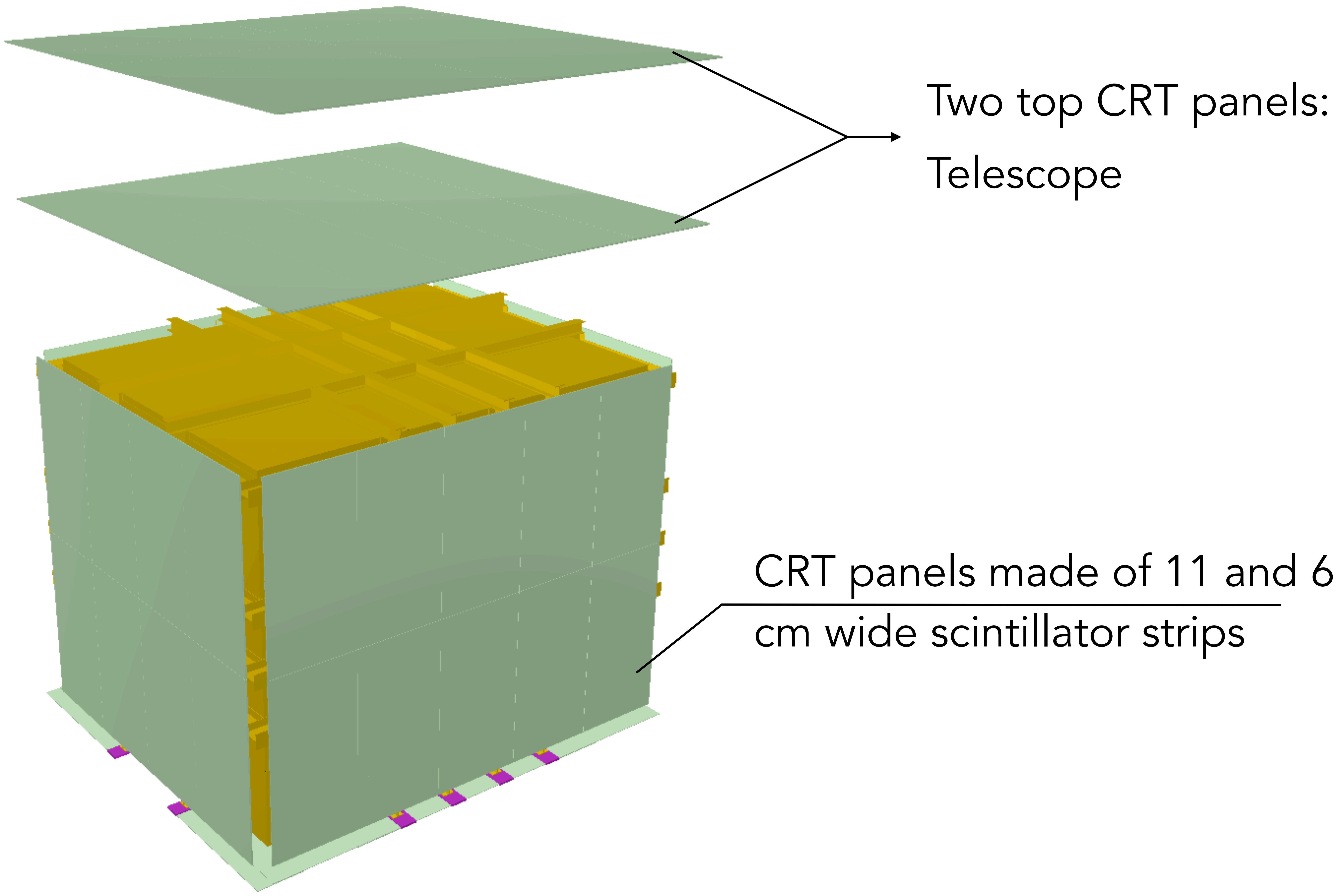
Target
SBND
MicroBooNE
ICARUS
BNB
Beamline
Argon mass: 112 ton
Argon mass: 86.6 ton
Argon mass: 476 ton
0
110 m
470 m
600 m
(Not to scale)

The SBND Detector

Cosmic Ray Tagger

CRT

SBND will be surrounded by scintillator strips to tag cosmic rays

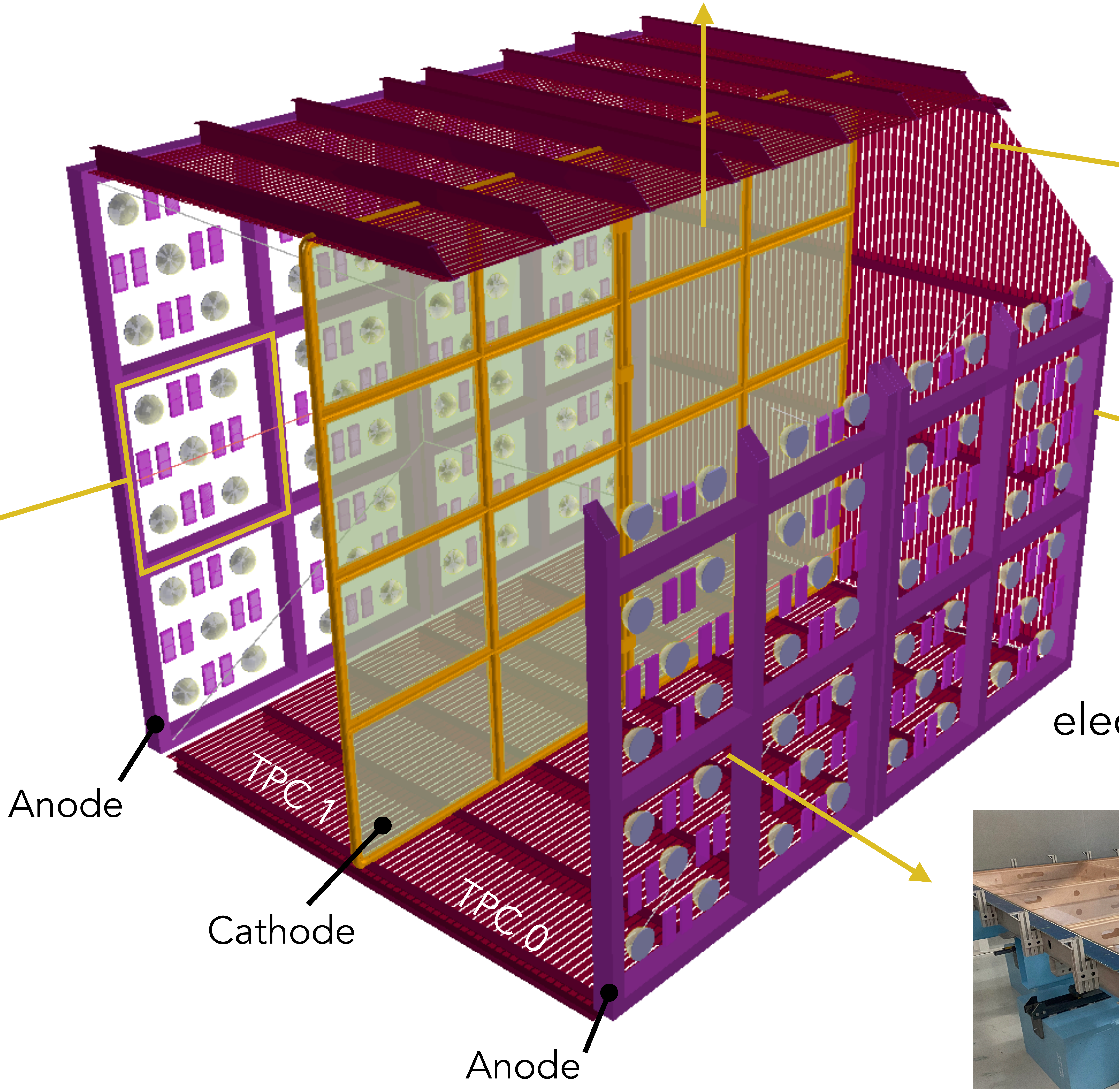


The SBND Detector

2 Time Projection Chambers

for a total of 4m x 4m x 5m

Cathode covered with TPB coated reflectors



Field Cage

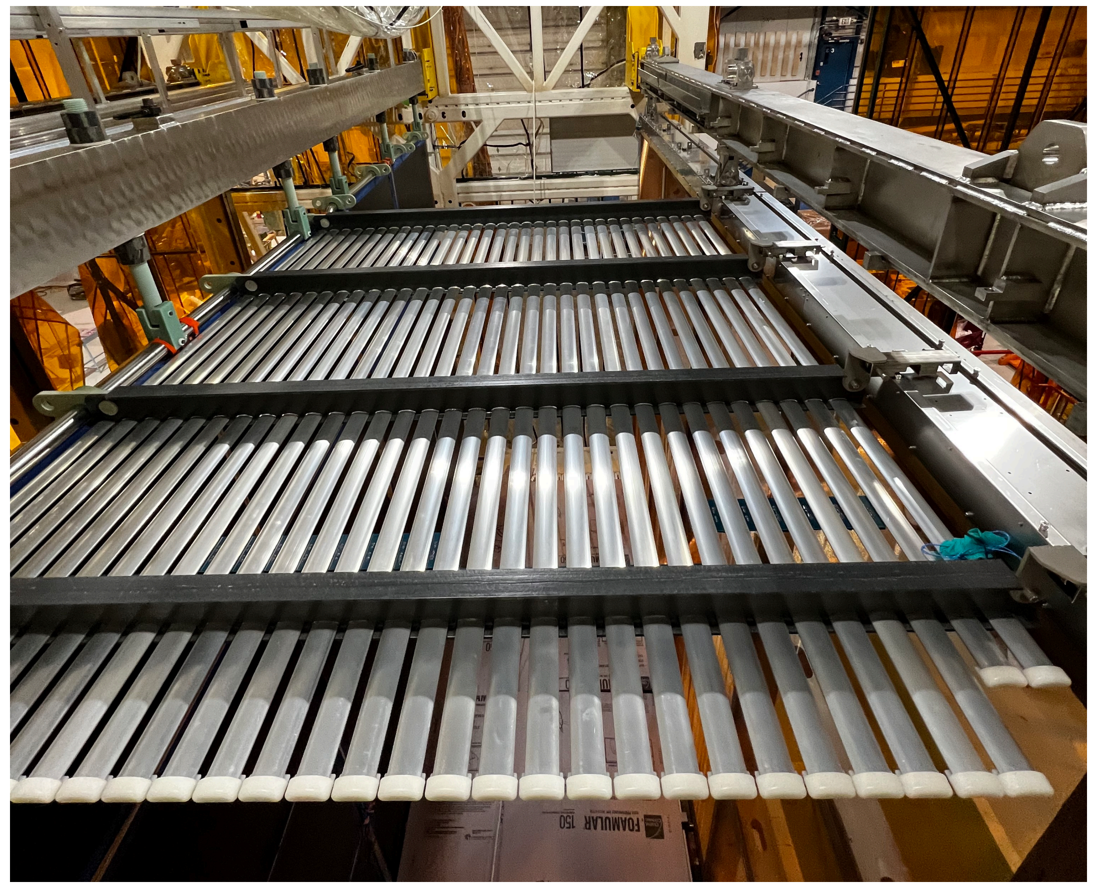
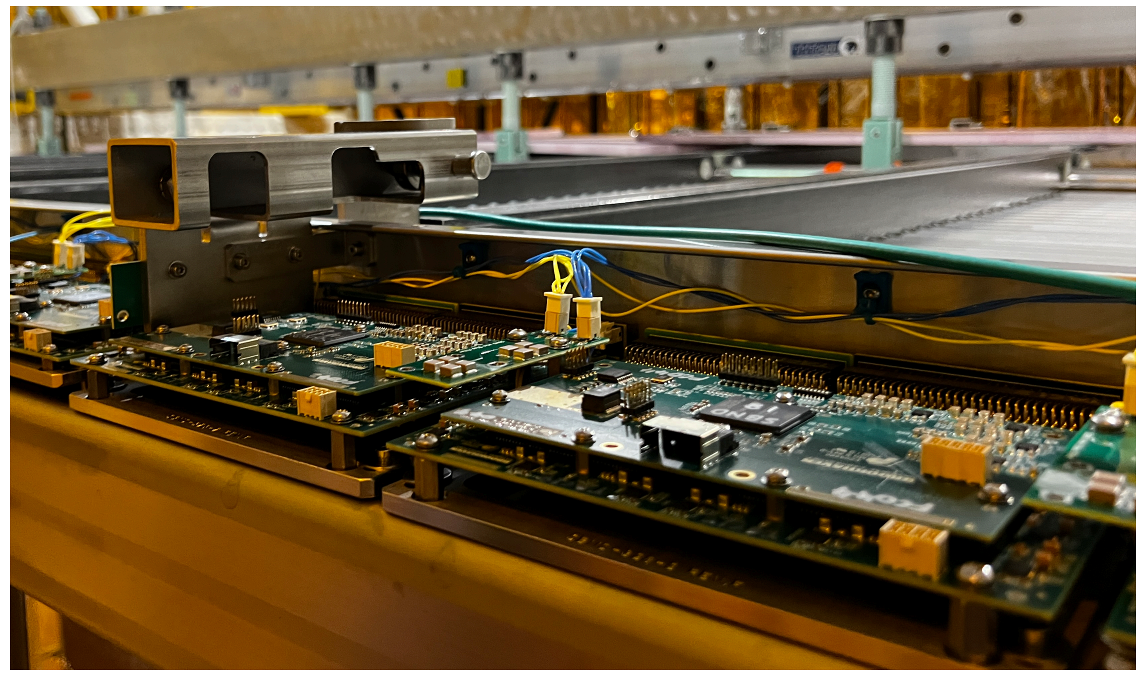


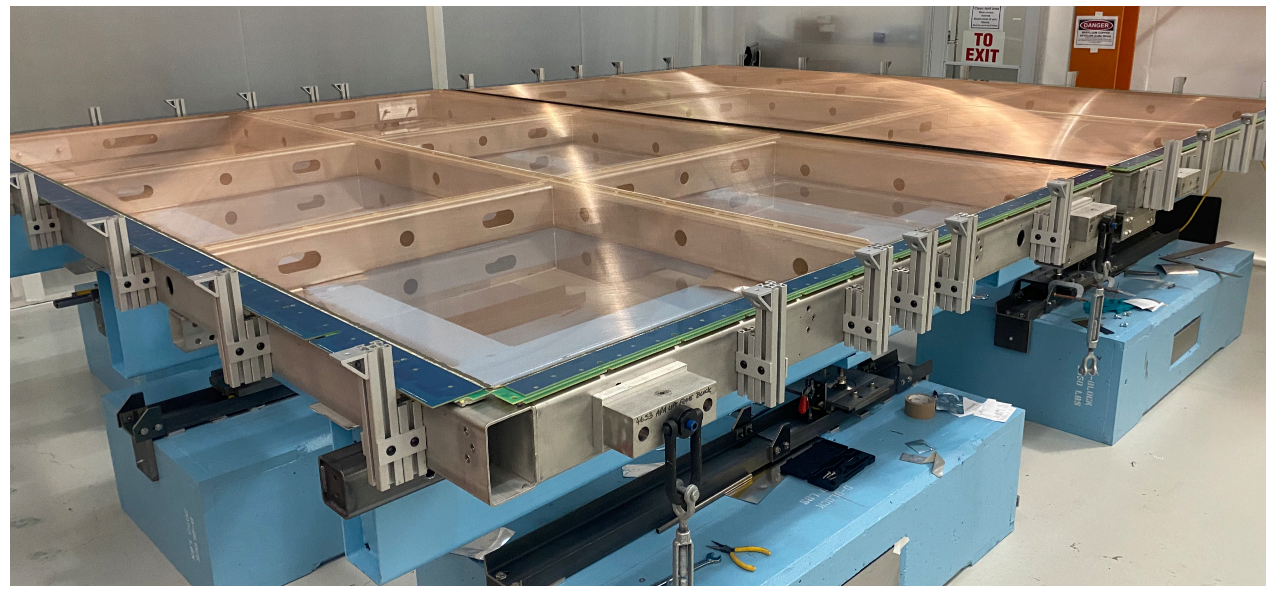
Photo Detection System:

120 PMTs

192 X-Arapucas

Cold electronics





Wire Plane

3 readout wire planes

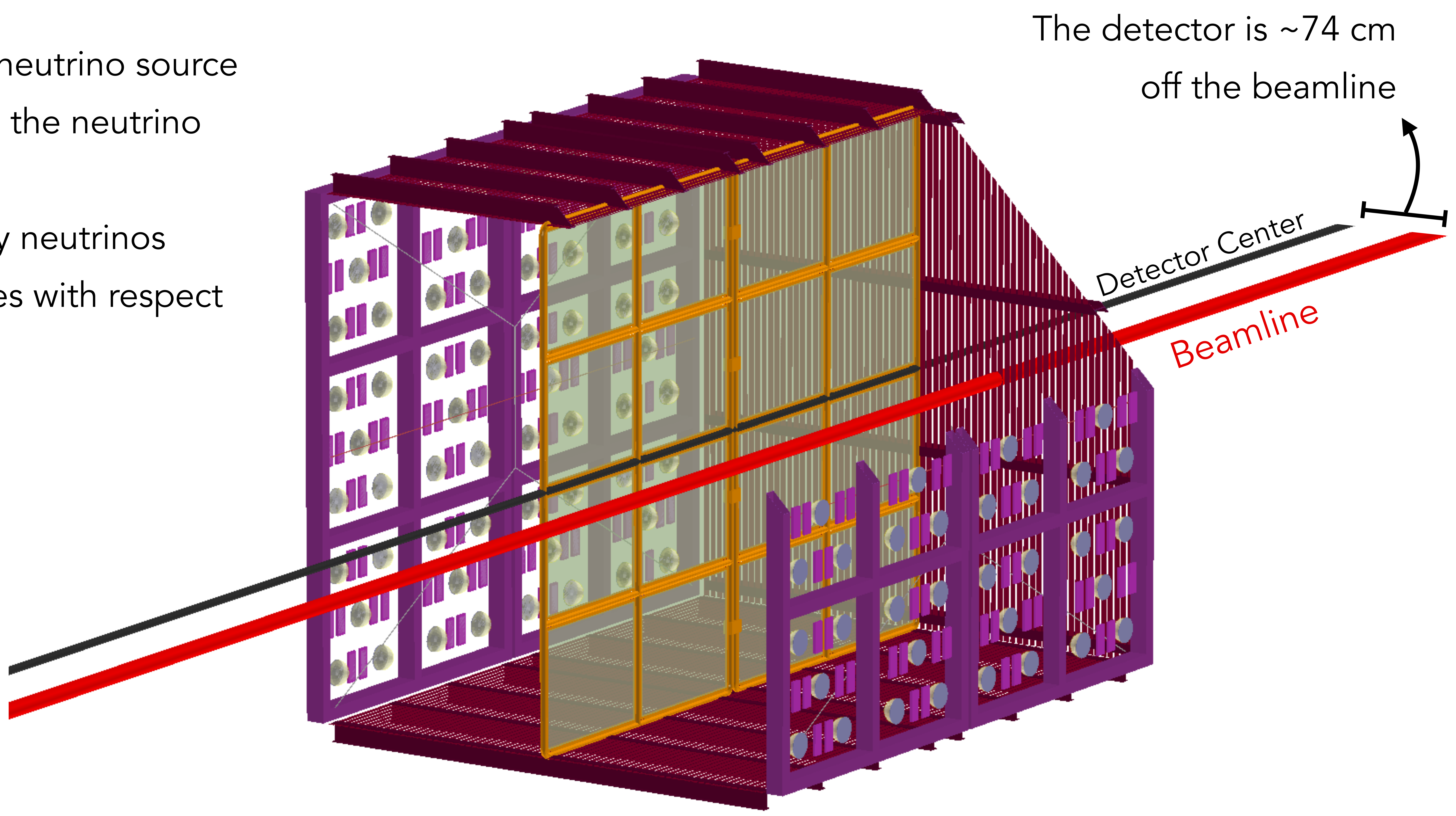
~11000 wires

A Slightly Off-Axis Detector

SBND is:

- very close (110 m) to the neutrino source
- not perfectly aligned with the neutrino beamline

The detector is traversed by neutrinos coming from different angles with respect to the beam axis.



A Slightly Off-Axis Detector

SBND sees neutrinos from several off-axis angles (OAAs)

(Off-axis angle is calculated w.r.t. target position)

DUNE/SBND Comparison:

DUNE: 1° ≈ 10 m

SBND: 1° ≈ 2 m

A Slightly Off-Axis Detector

SBND sees neutrinos from several off-axis angles (OAAs)

(Off-axis angle is calculated w.r.t. target position)

The detector can be divided in several off-axis slices:

OAA ∈ [0.0°, 0.2°)

OAA ∈ [0.2°, 0.4°)

OAA ∈ [0.4°, 0.6°)

OAA ∈ [0.6°, 0.8°)

OAA ∈ [0.8°, 1.0°)

OAA ∈ [1.0°, 1.2°)

OAA ∈ [1.2°, 1.4°)

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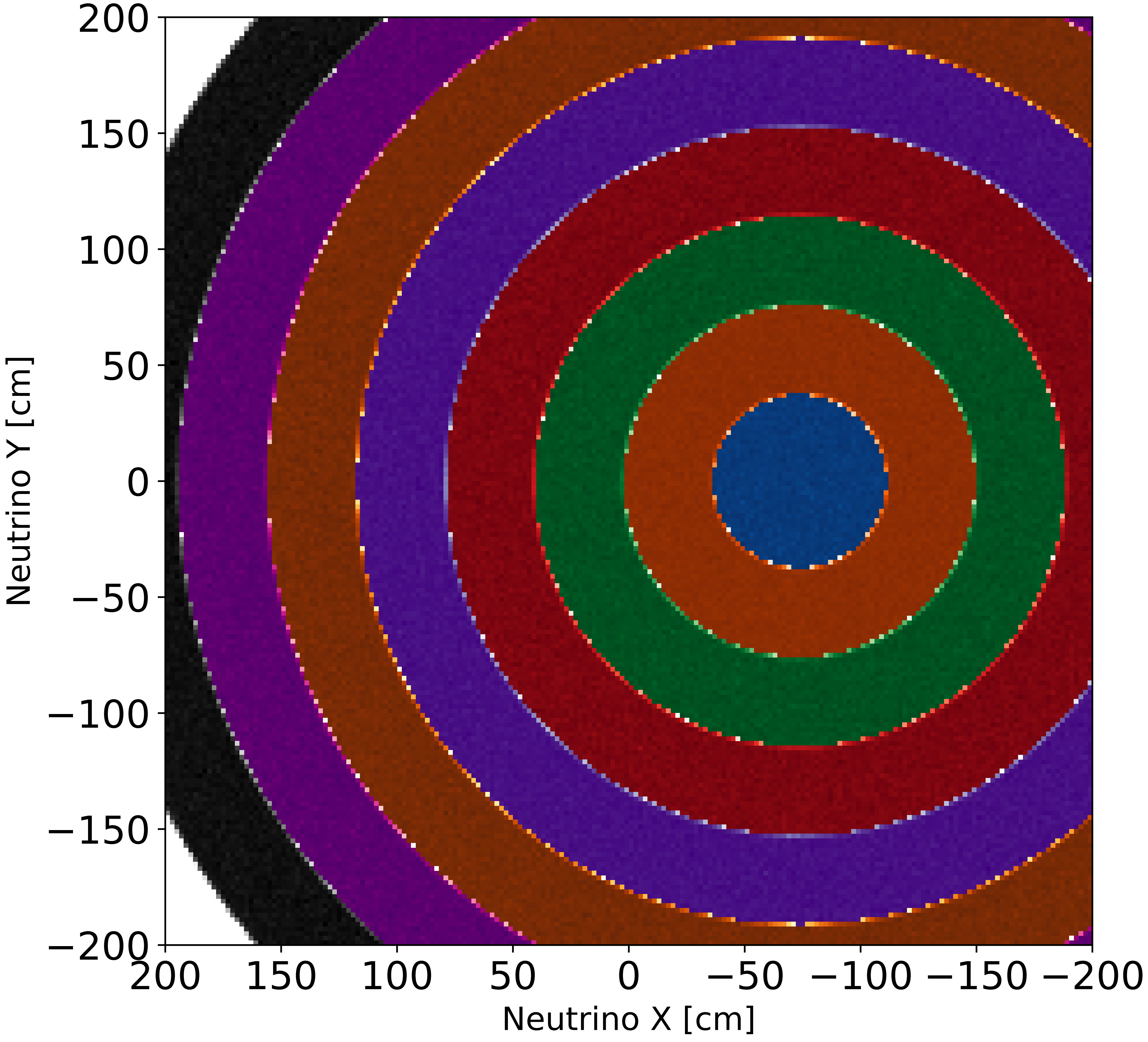
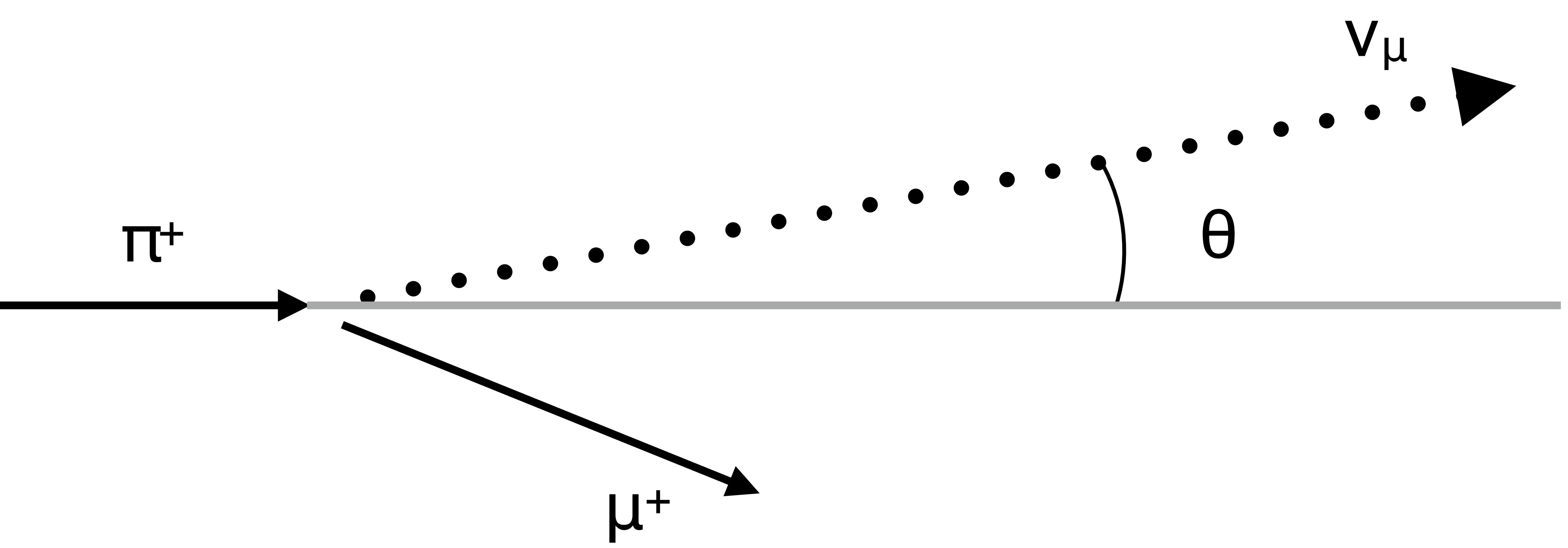
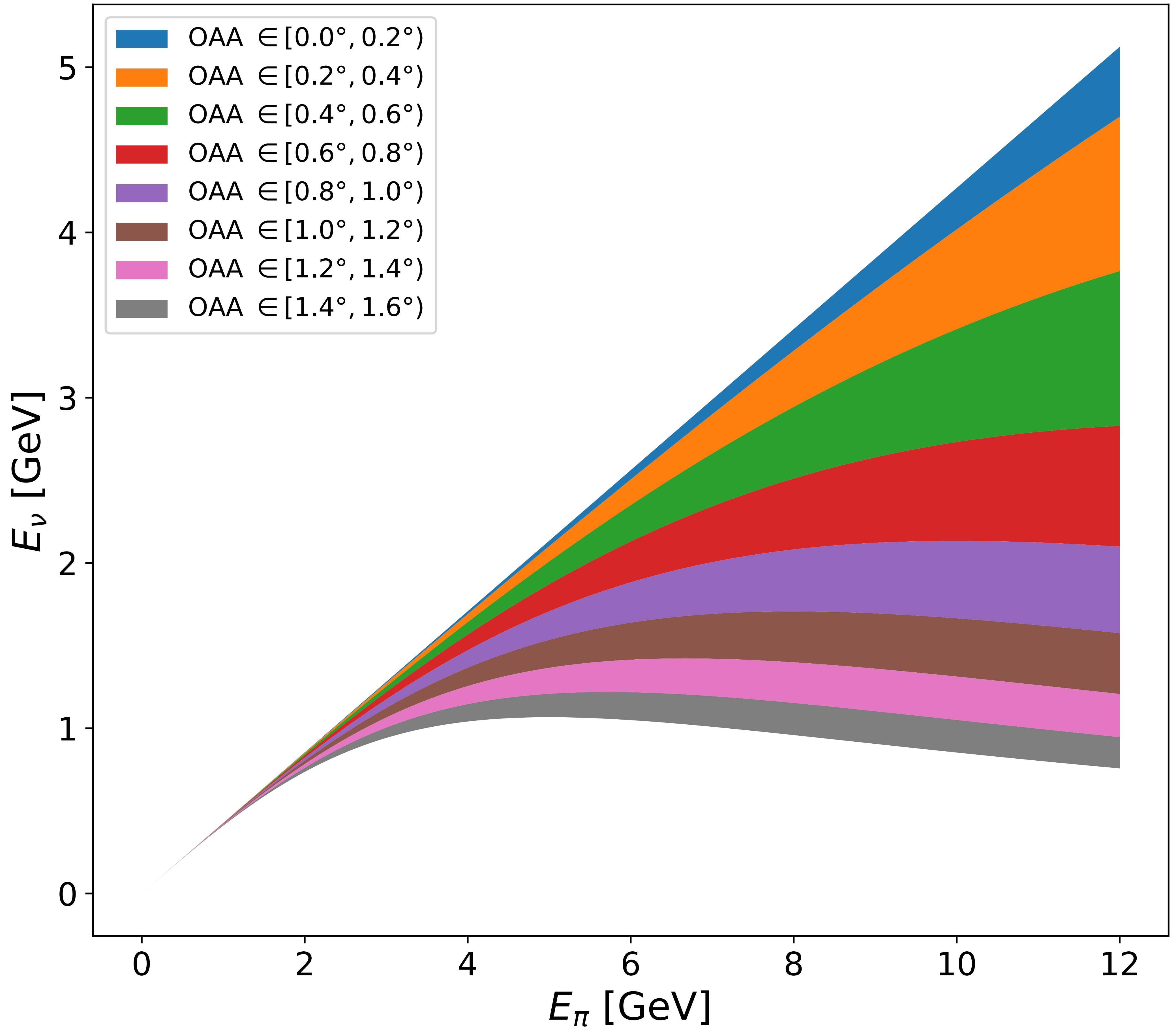


The Off-Axis Angle (OAA)

We can select lower neutrino energies, and a more mono-chromatic beam, by going off-axis.



Neutrino Energy vs Pion Energy for different decay angles



The plot assumes the pion is perfectly collinear with the beamline (perfect focusing)

A Slightly Off-Axis Detector

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

The ν_μ energy distribution is affected by the off-axis position

Neutrino events are divided based on the off-axis angle (OAA) region they fall in:

- OAA ∈ [0.0°, 0.2°)
- OAA ∈ [0.2°, 0.4°)
- OAA ∈ [0.4°, 0.6°)
- OAA ∈ [0.6°, 0.8°)
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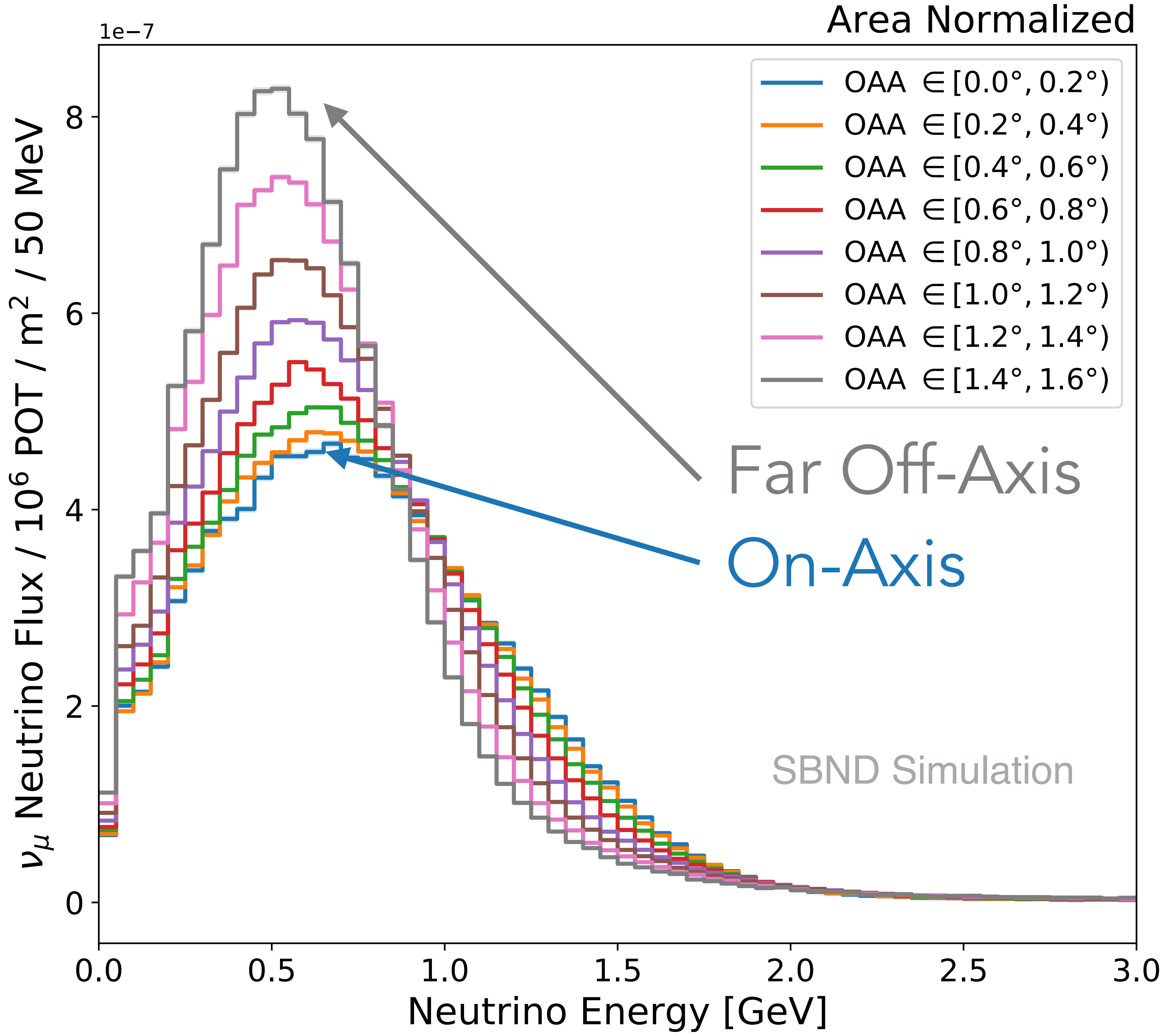
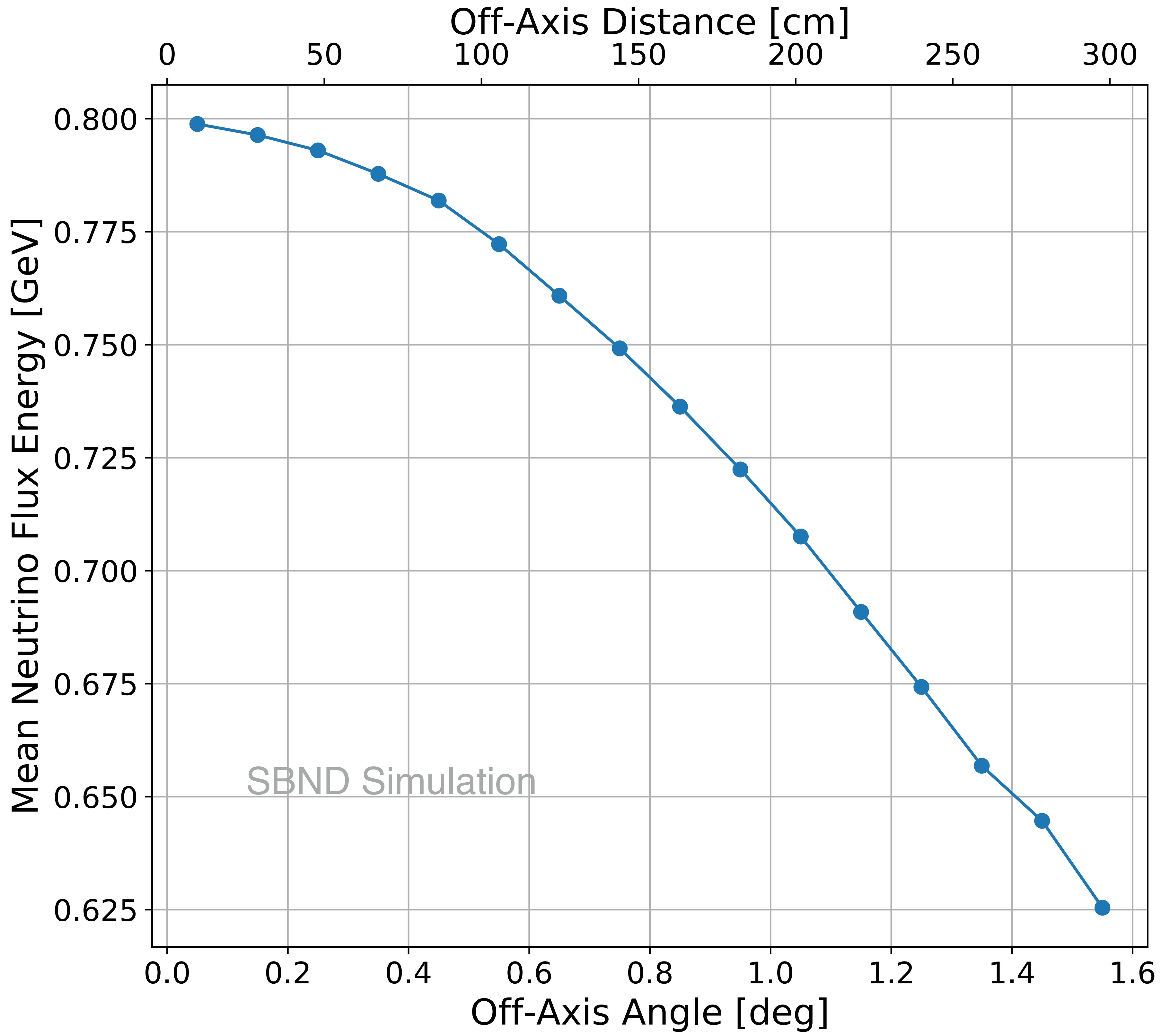
Muon neutrino flux in each of the OAA regions



Mean neutrino energy



(*) nuPRISM https://arxiv.org/abs/1412.3086

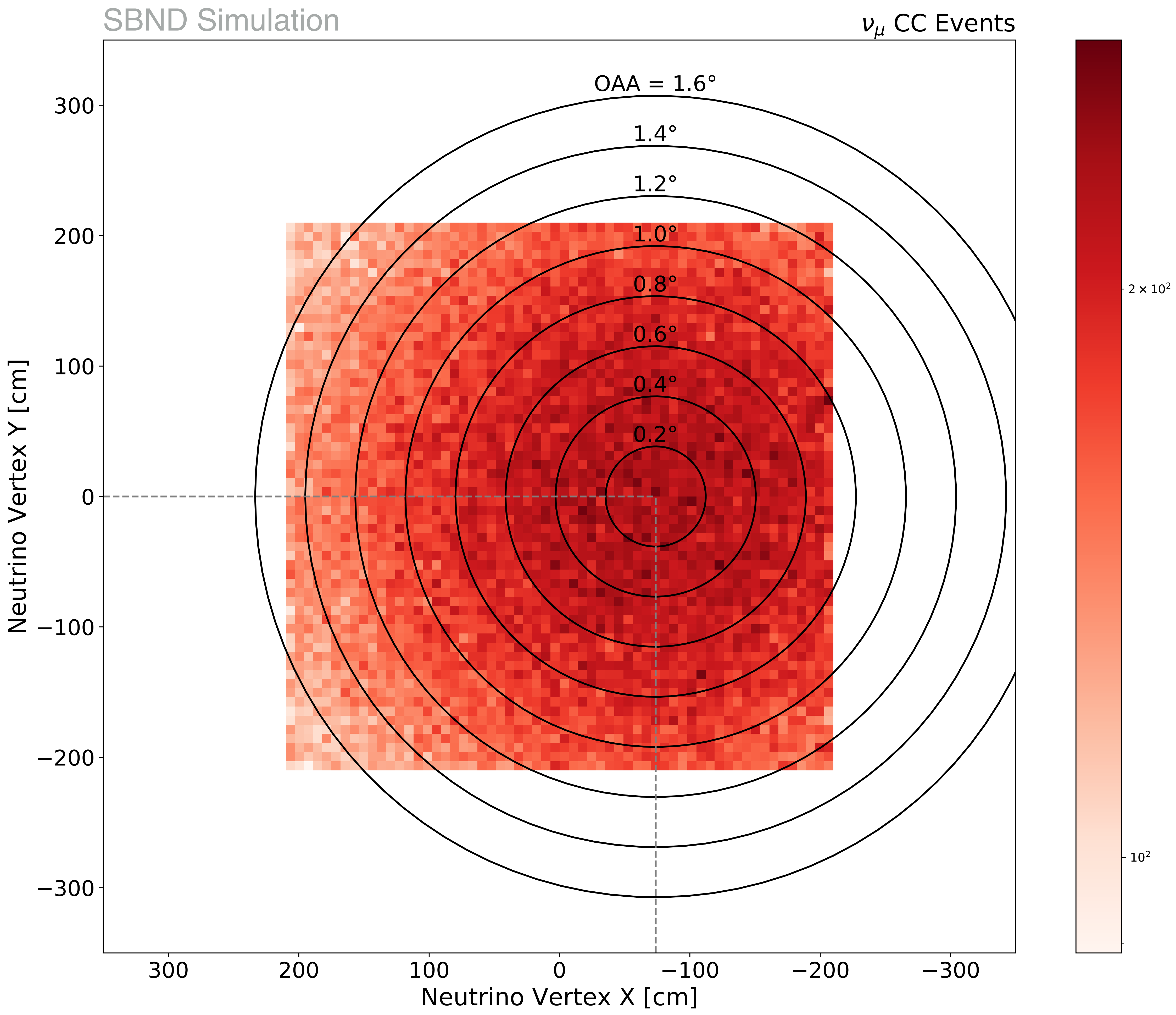
SBND-PRISM - Flux

Neutrinos come from charged mesons, focused by the magnetic horns in the beamline.

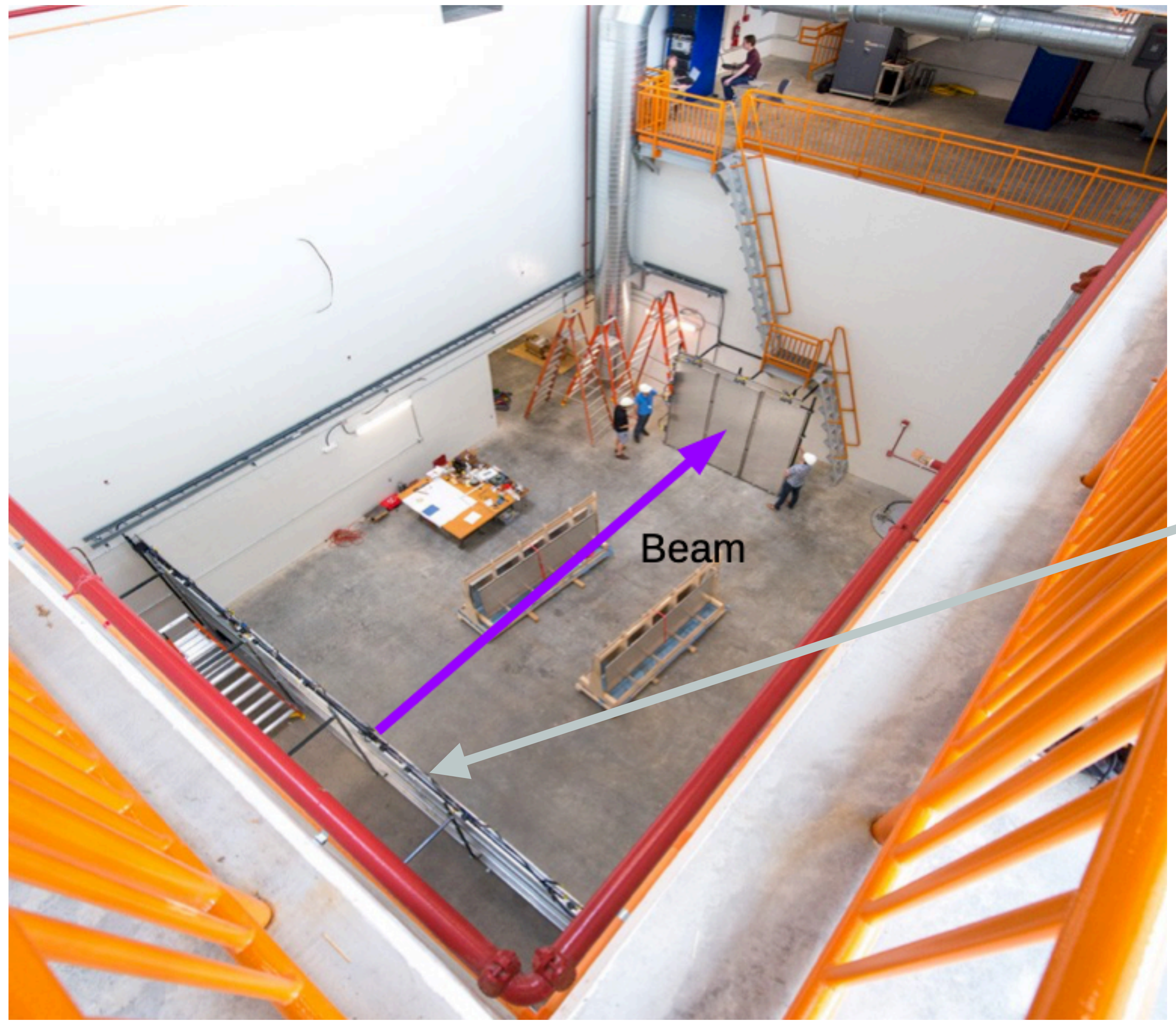
The flux is maximal on axis, and decreases moving away from the beam center.

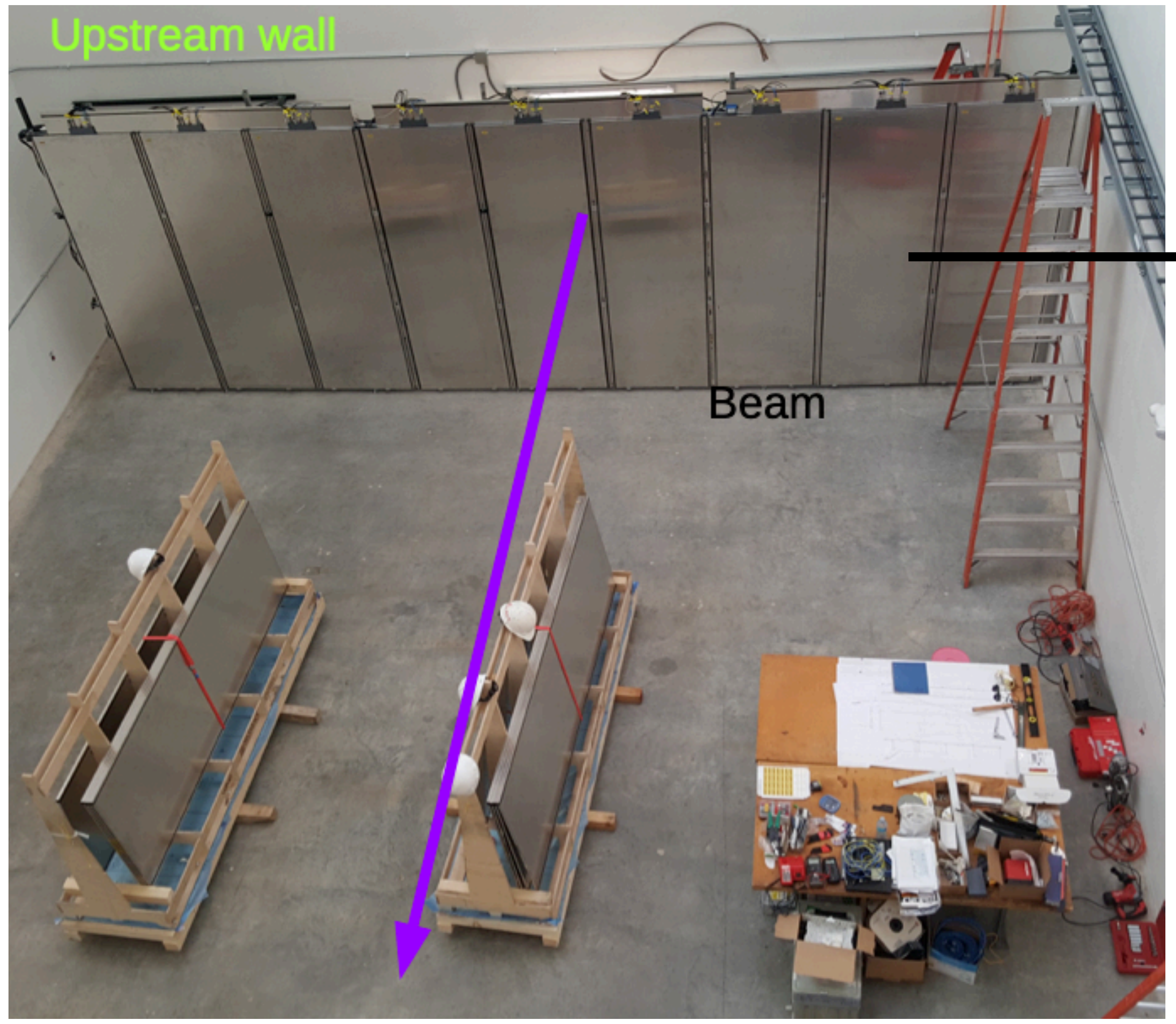
Muon-neutrinos CC Events

peak coincident with the on-axis position



Cosmic Ray Tagger Data

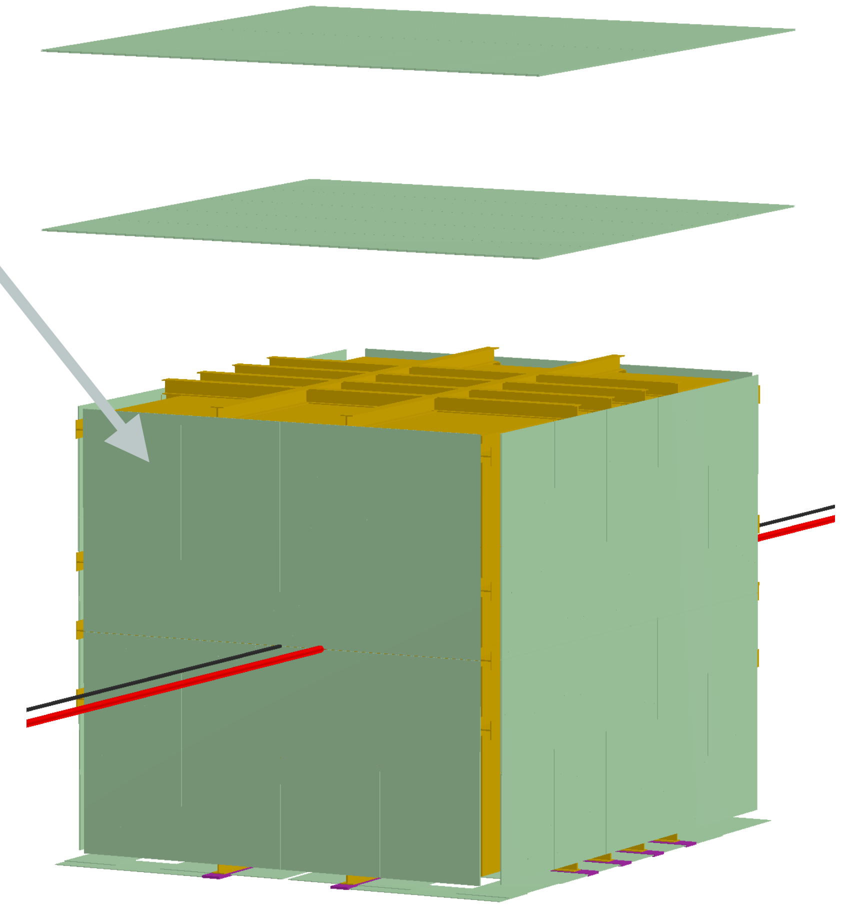


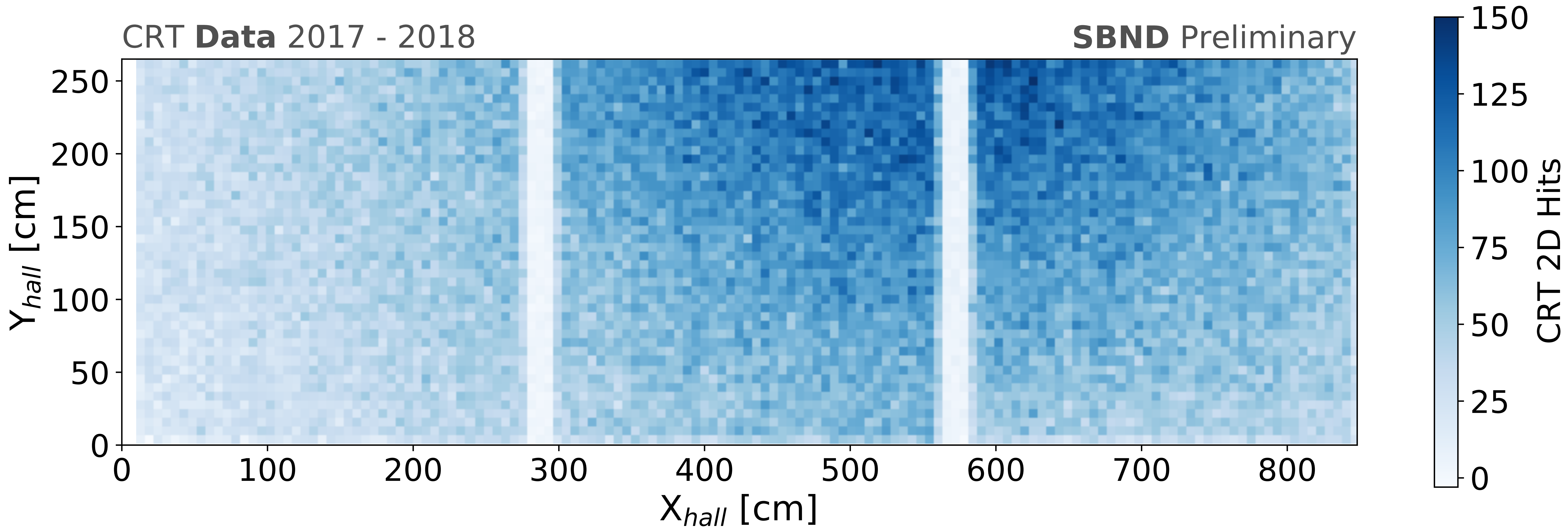


SBND will be surrounded by a cosmic ray tagger to identify cosmic rays

Part of the SBND cosmic ray tagger system was temporary installed in the detector hall

Real data showing muons from muon-neutrino interactions: beam intensity decreases moving away from the beam center





SBND-PRISM - Applications

Benefits of SBND-PRISM:

- Interaction Model Constraint
- Neutrino Oscillations
- Dark Matter Searches
- Study Energy Dependance of Cross Section
- Muon-to-Electron Neutrino Cross Section
- Study Neutrino Energy / Lepton Kinematics
- and more…

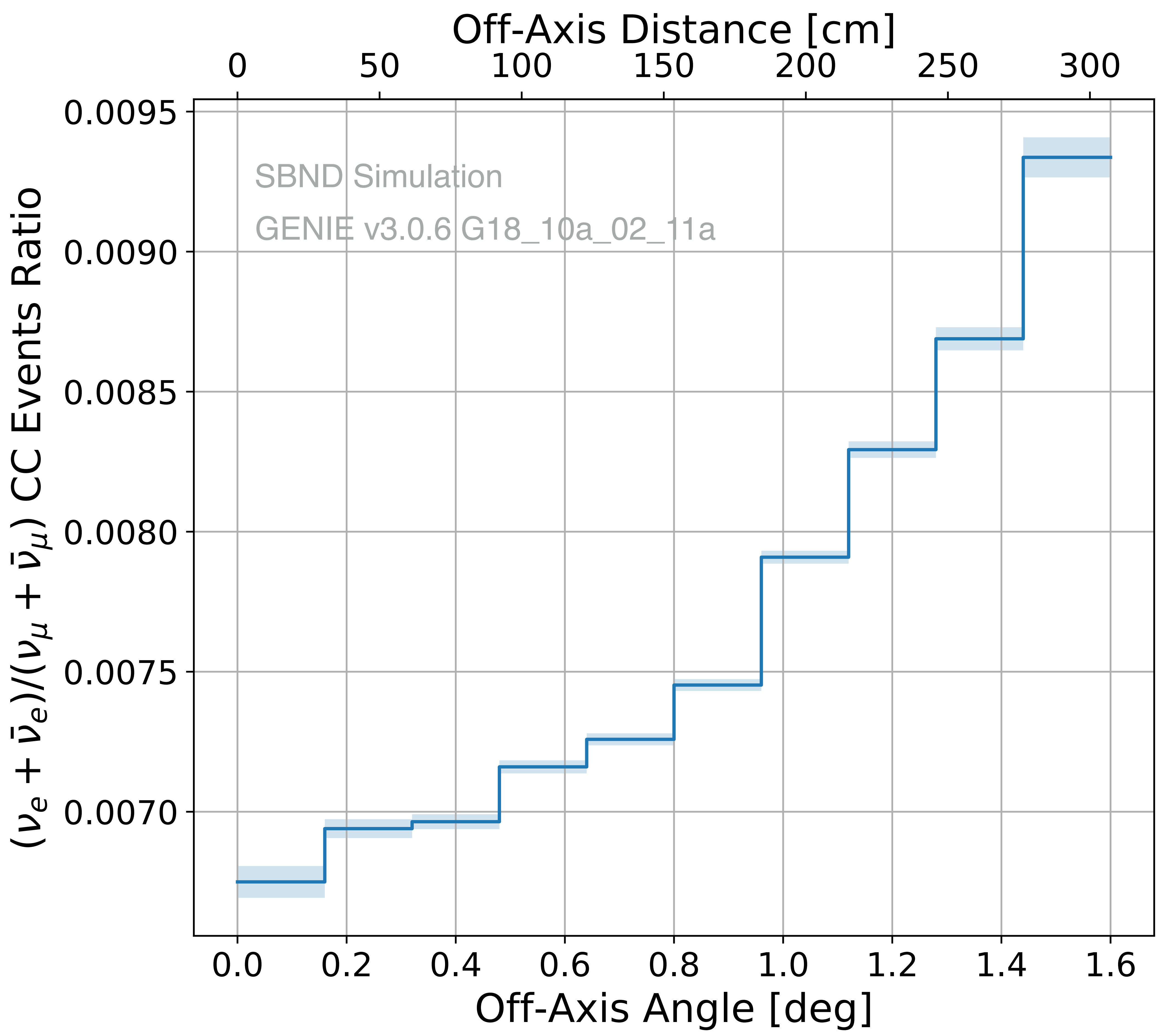
SBND-PRISM - Interaction Model Constraint

The PRISM feature of SBND opens up new analyses:

- Can make **neutrino cross-section measurements** over a peak/mean energy that spans over ~200 MeV energy difference (test of models/generators).

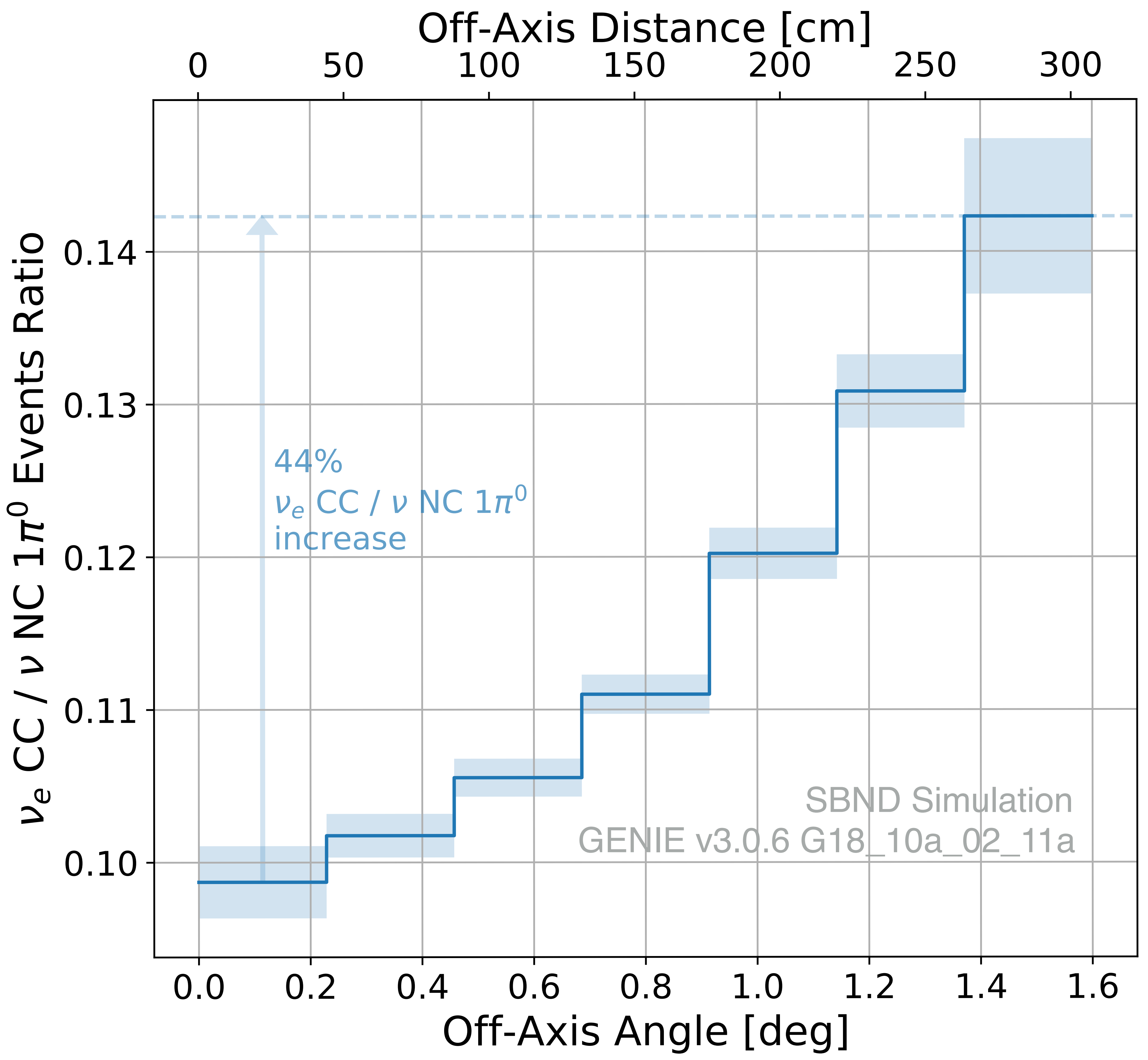
- ν_μ **to** ν_e **cross-section ratio**: going off-axis, the increase in ν_e to ν_μ flux ratio combined with a choice of kinematics where ν_e to ν_μ differences are prominent should allow us to measure the ν_e/ν_μ cross section (can study lepton mass effects).

ν-Ar CC Events



SBND-PRISM - Interaction Model Constraint

- Neutral Current events with π^0 in the final state can mimic a ν_e interaction.
- These events are a background for many physics analyses.
- PRISM provides a natural way to reduce background by moving off-axis.
- Note that we expect high event statistics in all off-axis regions.



SBND-PRISM - Sterile Neutrino Oscillations

Goal of the SBN program is to search for eV mass-scale sterile neutrino oscillations

$$\frac{N_{FD}}{N_{ND}} = \frac{\propto \phi_{FD} \otimes \sigma \otimes P_{osc}}{\propto \phi_{ND} \otimes \sigma}$$

Can SBND-PRISM improve the sensitivity to sterile-neutrino oscillations?

SBND-PRISM - Sterile Neutrino Oscillations

SBND-PRISM can potentially improve the SBN sensitivities to sterile neutrino oscillations

Two possibilities to use the PRISM technique:

1

Instead of treating SBND as a single detector, we can treat it as multiple detectors at different off-axis positions and include those in the **SBN oscillation fit**. Since the the energy spectra are different the neutrino interaction model will be over constrained.

2

Can **linearly combine** the measurements the different off-axis positions to reproduce a given choice of incident neutrino flux. Can match the ICARUS (far detector) oscillated spectrum in SBND (near detector).

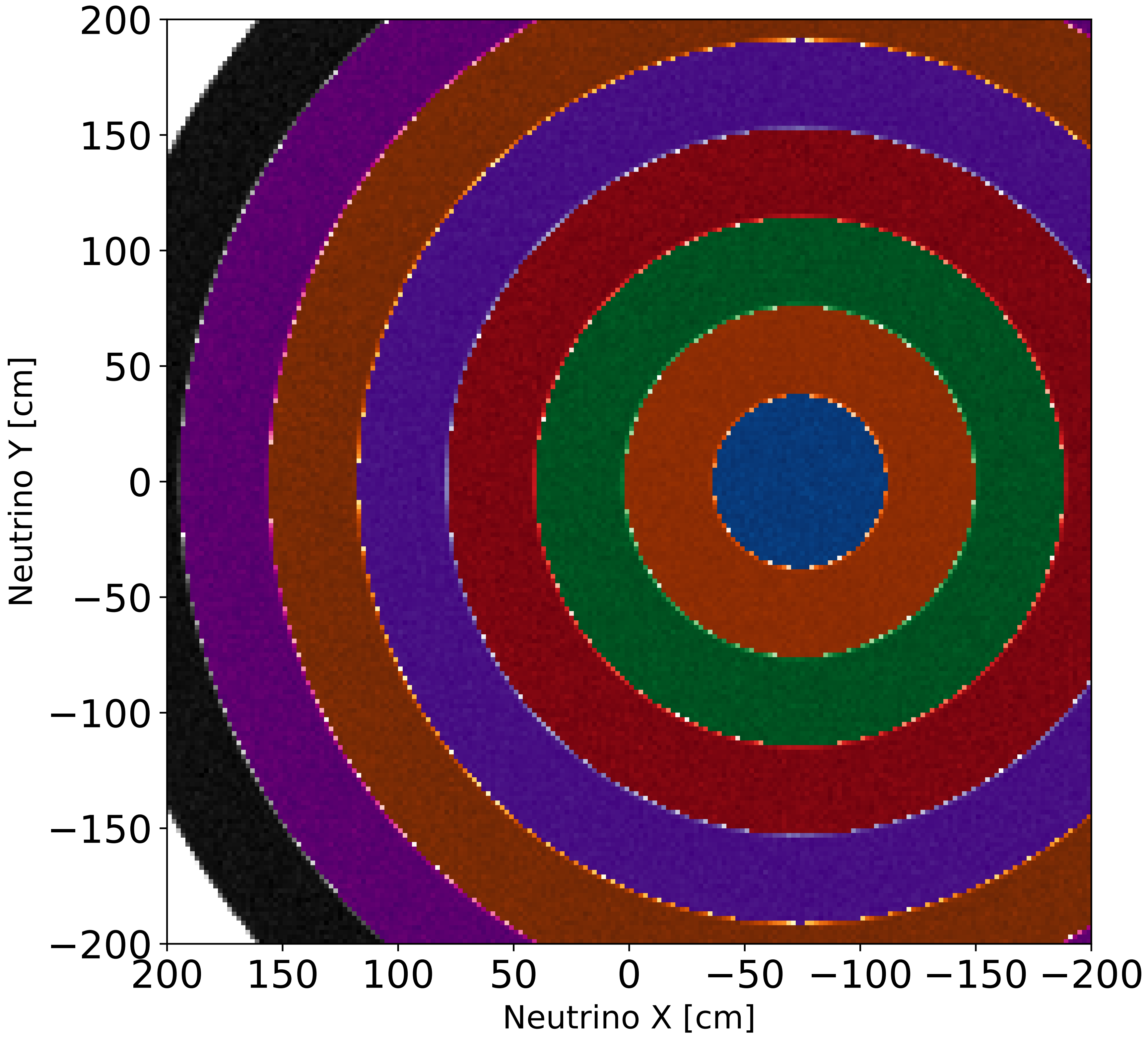
SBND-PRISM - Sterile Neutrino Oscillations - 1

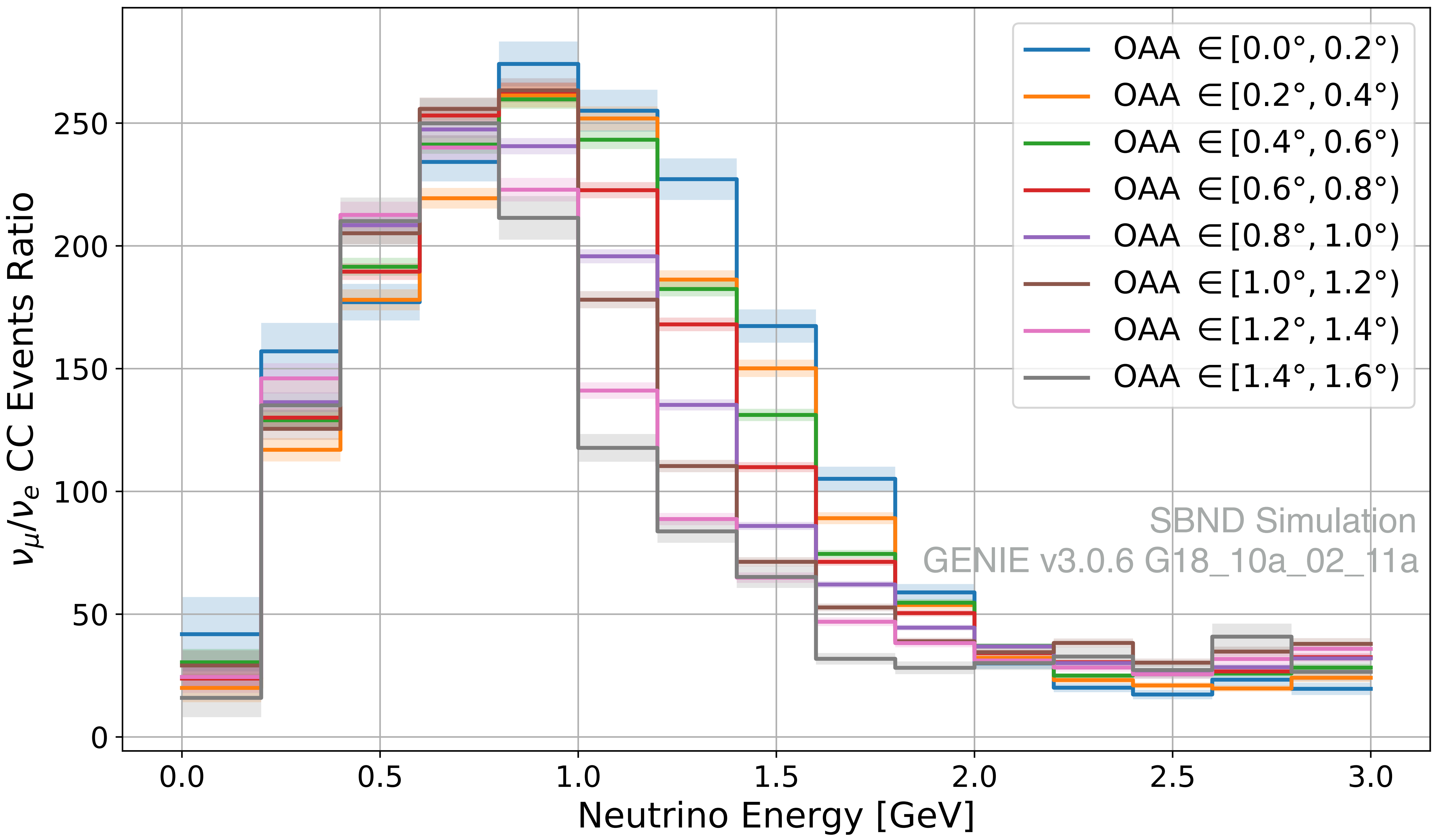
In a ν_e appearance search:

- the beam intrinsic ν_e are a background
- the signal ν_e come from oscillated ν_μ

The ν_μ and ν_e fluxes behave differently going off-axis, giving rise to different signal-to-background ratios which constrain systematics

The mismatch between ν_μ flux and ν_e contamination on different off-axis positions may be an opportunity to do physics





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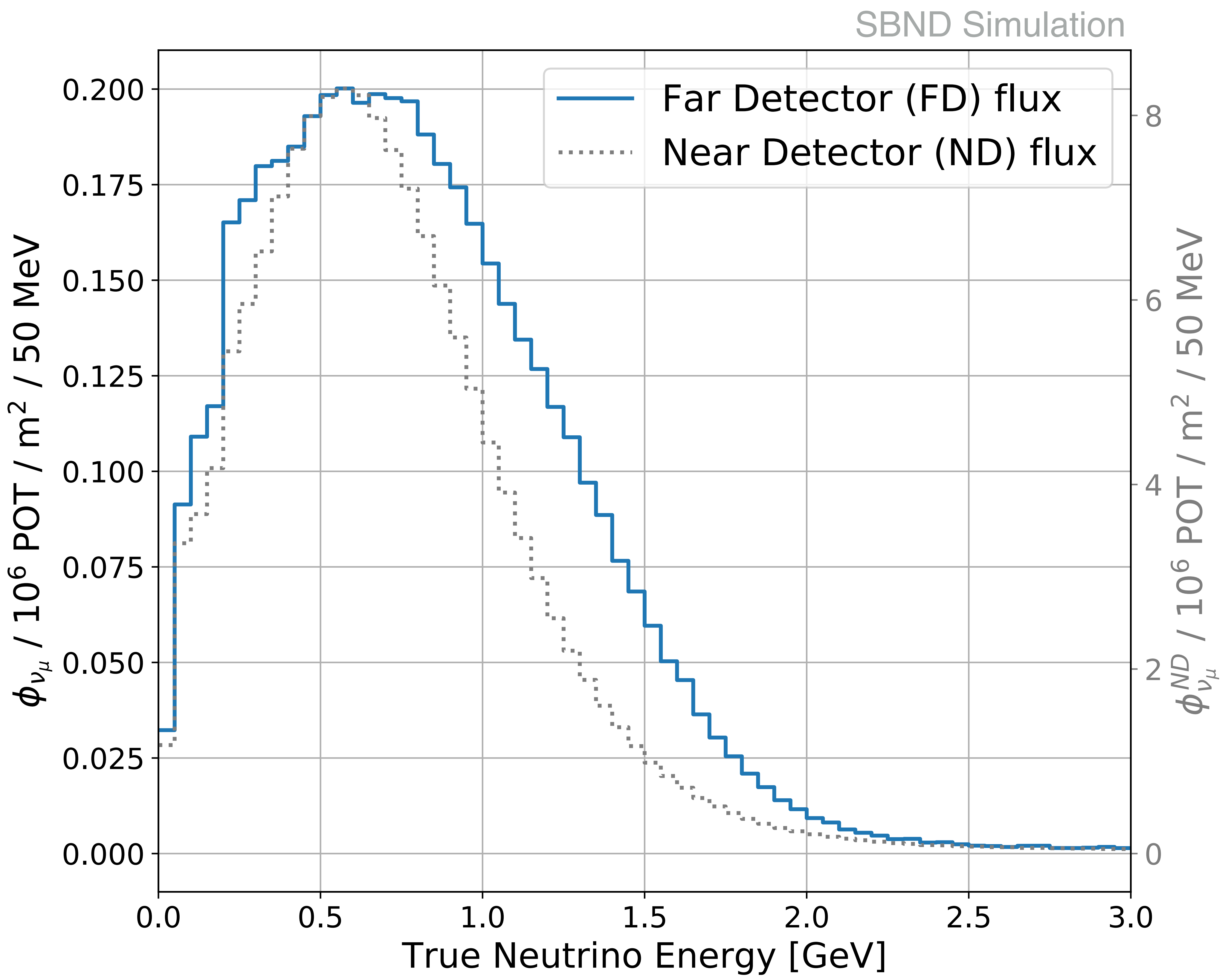
$$\frac{N_{FD}}{N_{ND}} = \frac{\propto \phi_{FD} \otimes \sigma \otimes P_{osc}}{\propto \phi_{ND} \otimes \sigma}$$

Can we make the two fluxes similar?

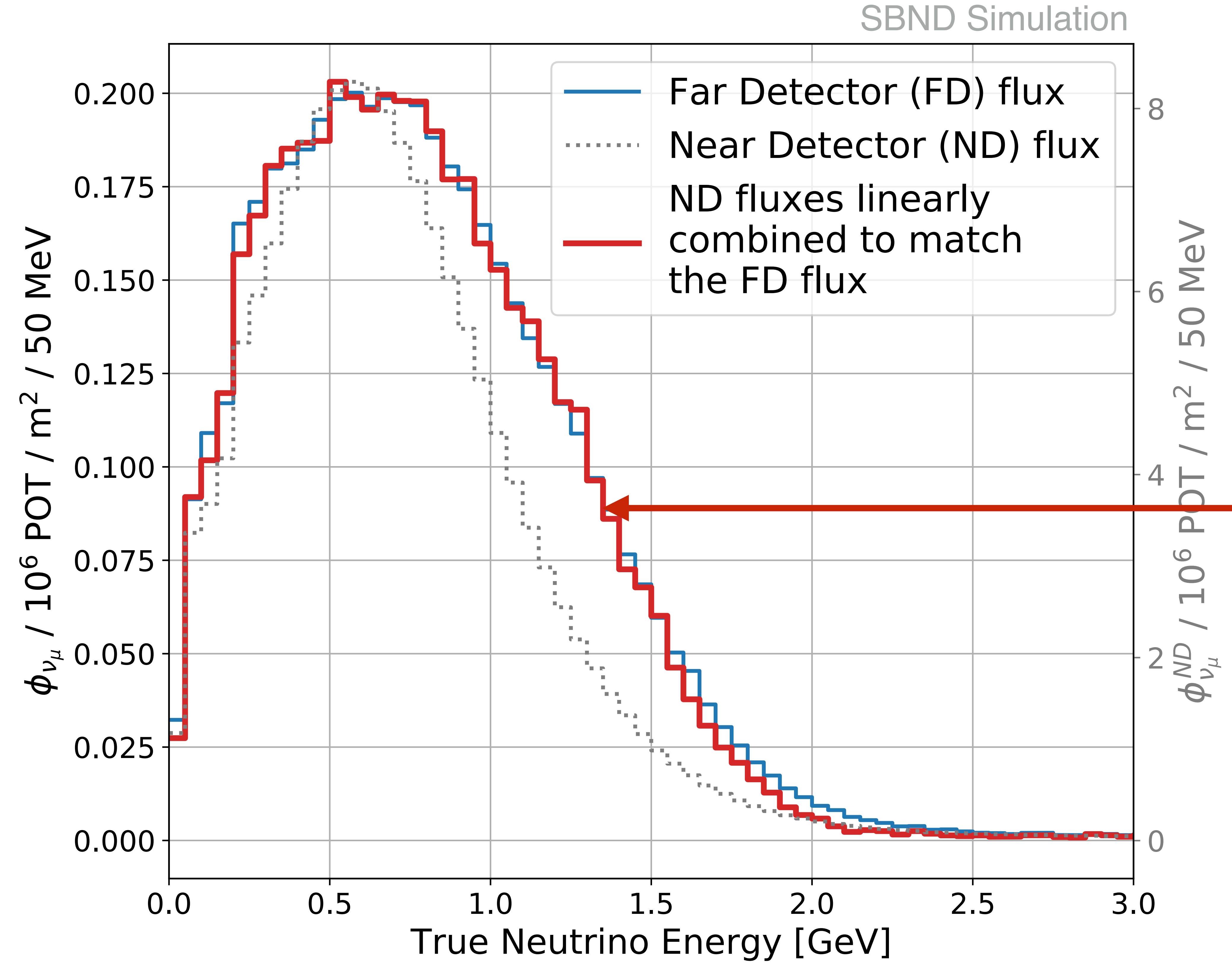


SBND-PRISM - Sterile Neutrino Oscillations - 2

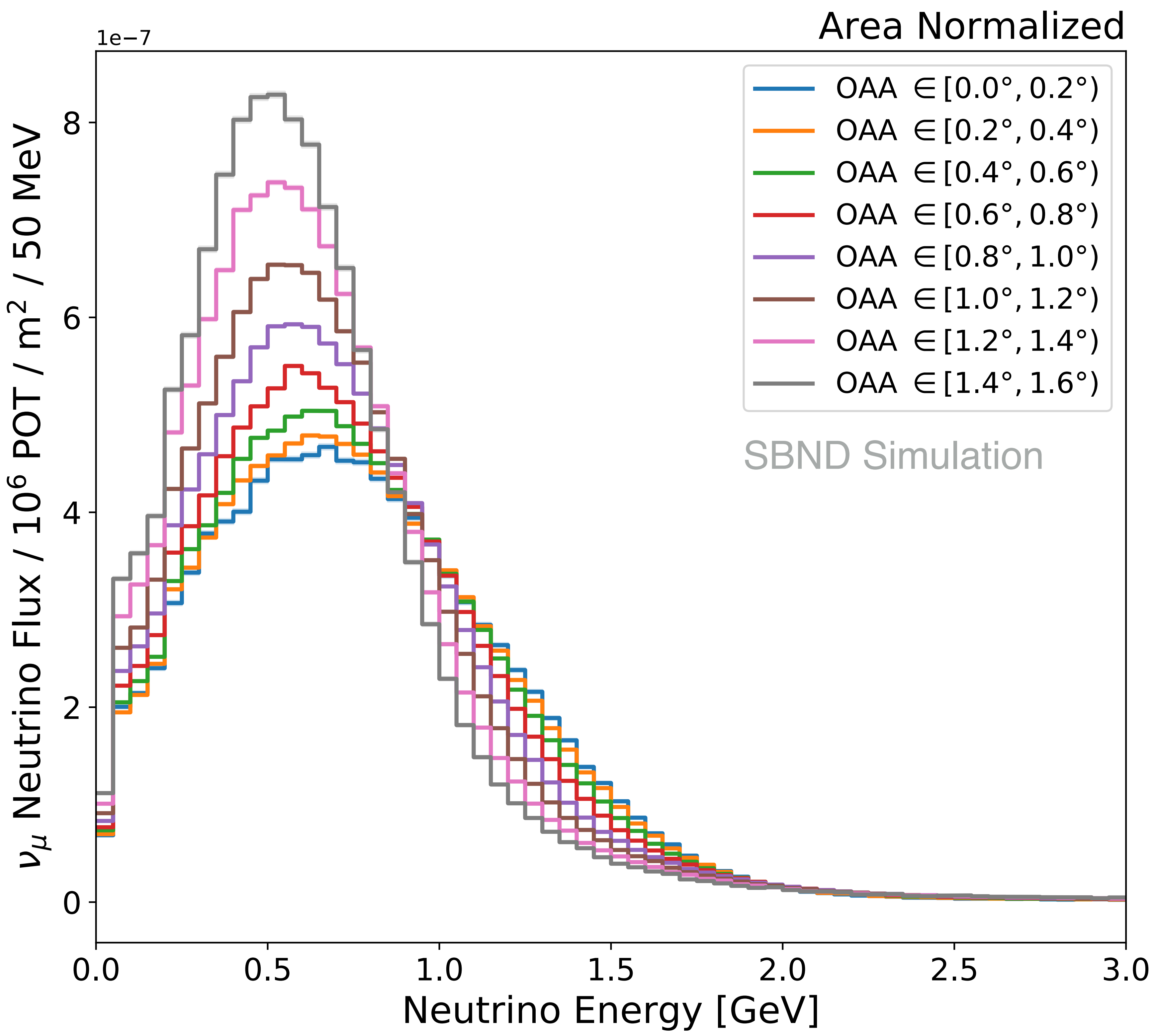
$$\frac{N_{FD}}{N_{ND}} = \frac{\propto \phi_{FD} \otimes \sigma \otimes P_{osc}}{\propto \phi_{ND} \otimes \sigma}$$

Can we make the two fluxes similar?

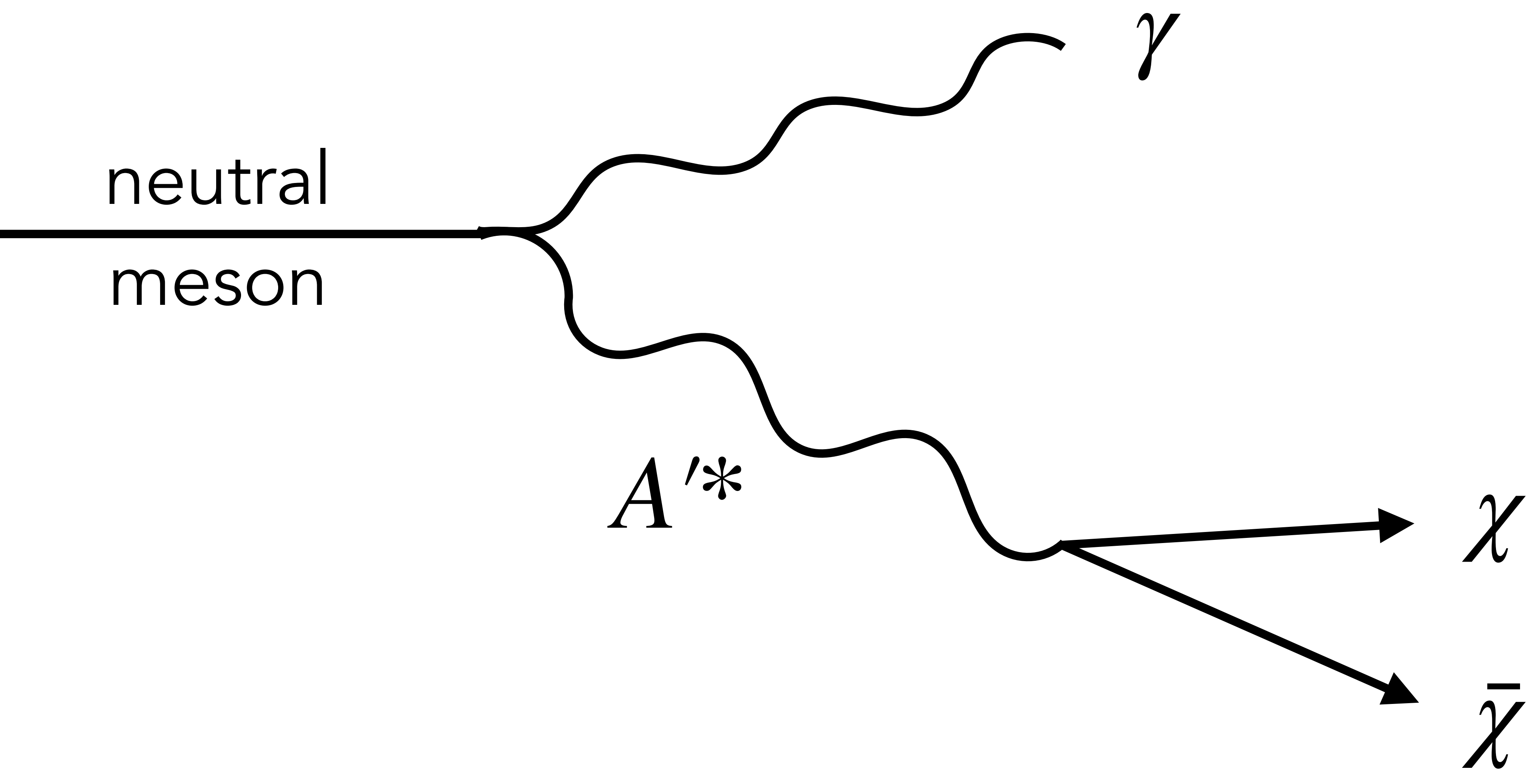
Yes!



Fit a **linear combination of the ND** fluxes to reproduce the FD flux at the ND



Dark Matter Searches with SBND-PRISM



Light dark matter (sub-GeV) that is coupled to the Standard Model via a dark photon. The dark photons can be produced by neutral meson decays (pions, etas) in the target, and then decay to the dark matter.

Phys.Rev.D 100 (2019) 9, 095010

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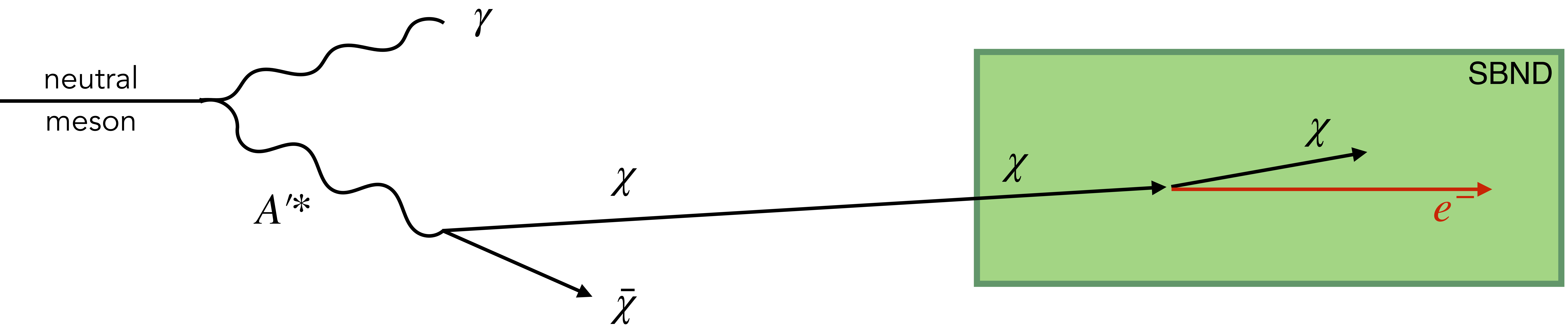

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The dark matter can then travel to SBND and, through the dark photon, **scatter off electrons in the detector**.

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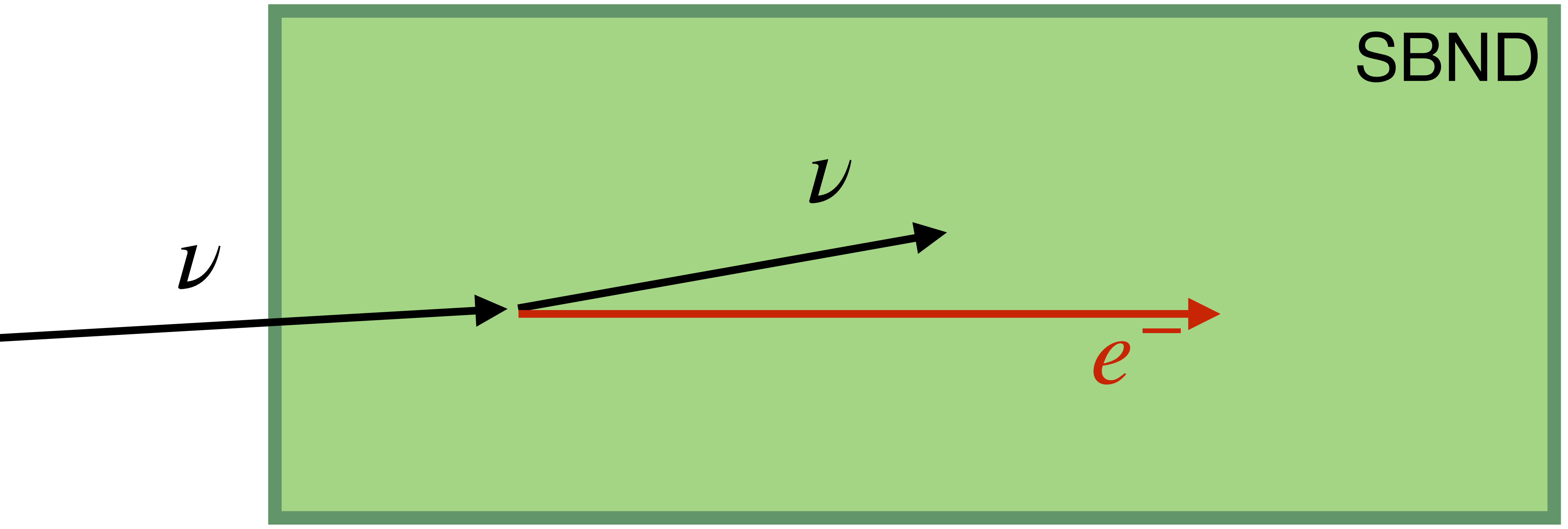

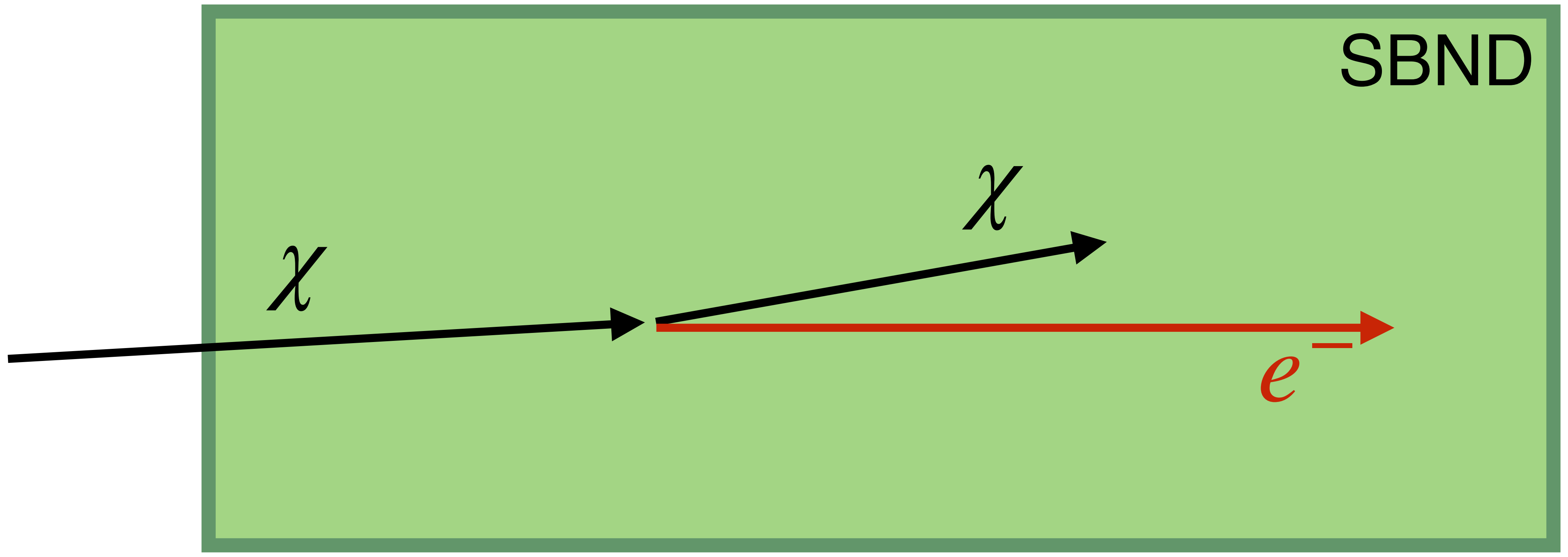

Background

Neutrino-electron elastic scattering. Neutrinos come from two-body decays of charged (focused) mesons.

Signal

Elastic scattering electron events. Dark matter comes from three-body decays of neutral (unfocused) mesons.

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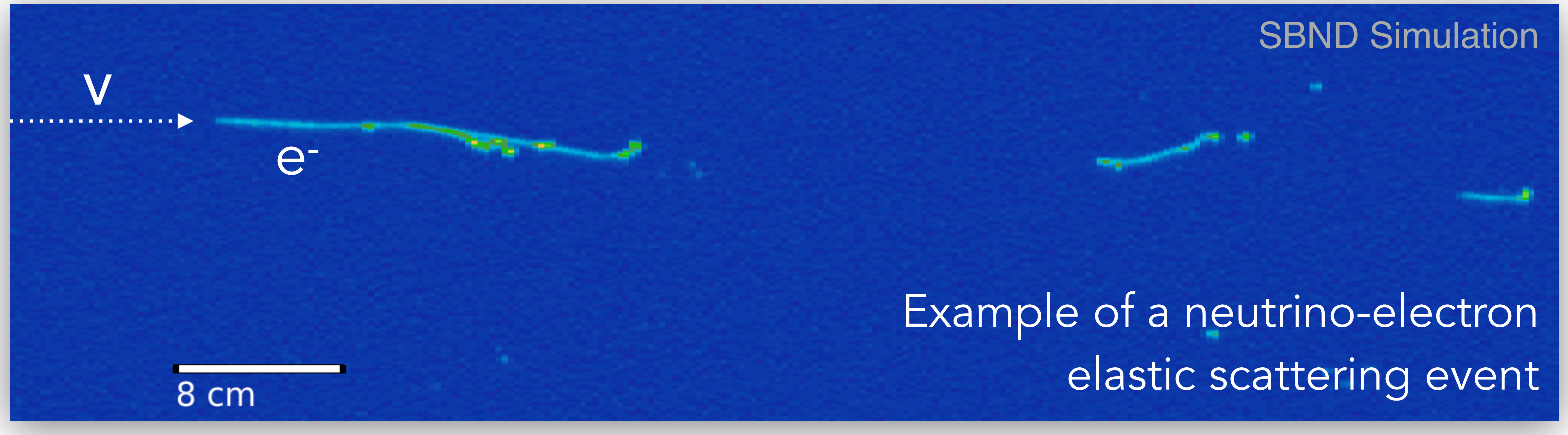

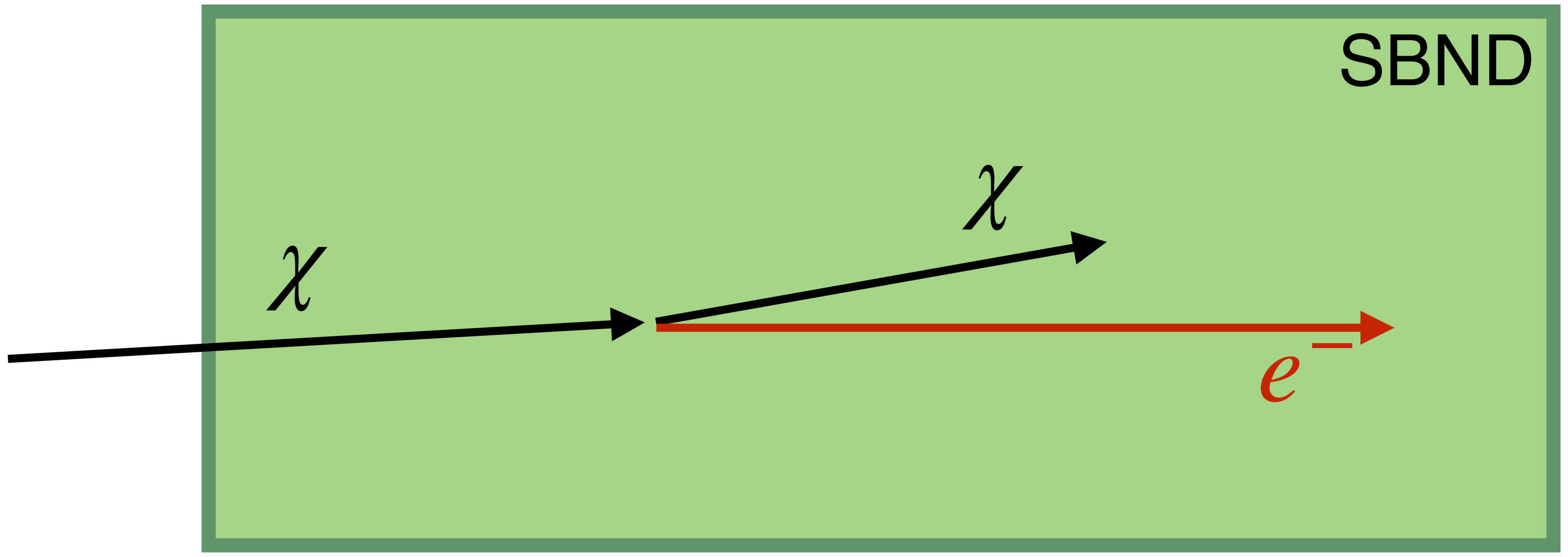

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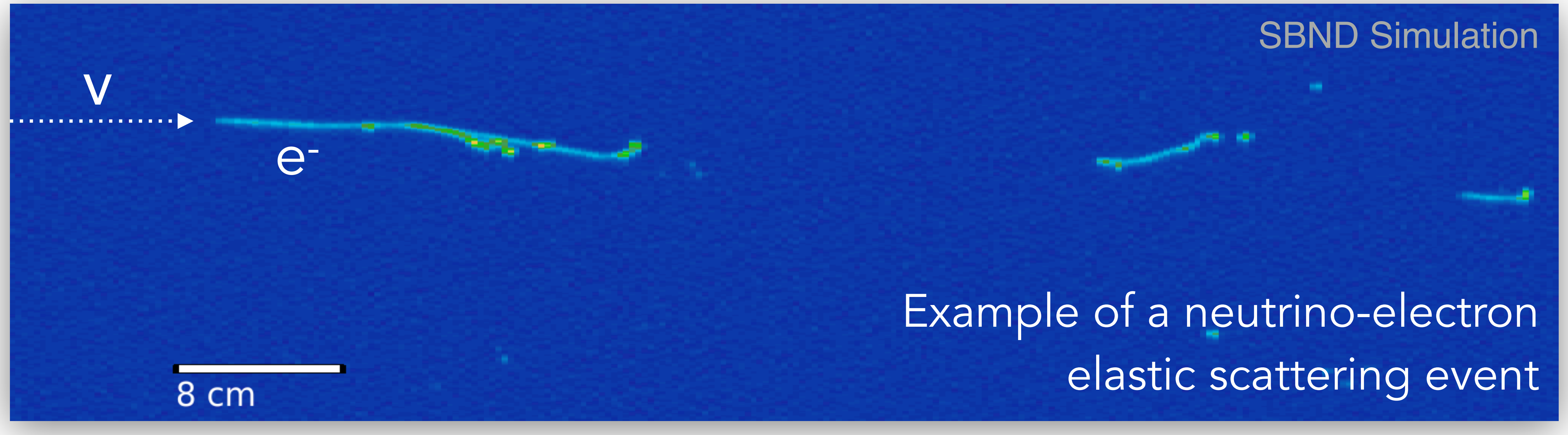

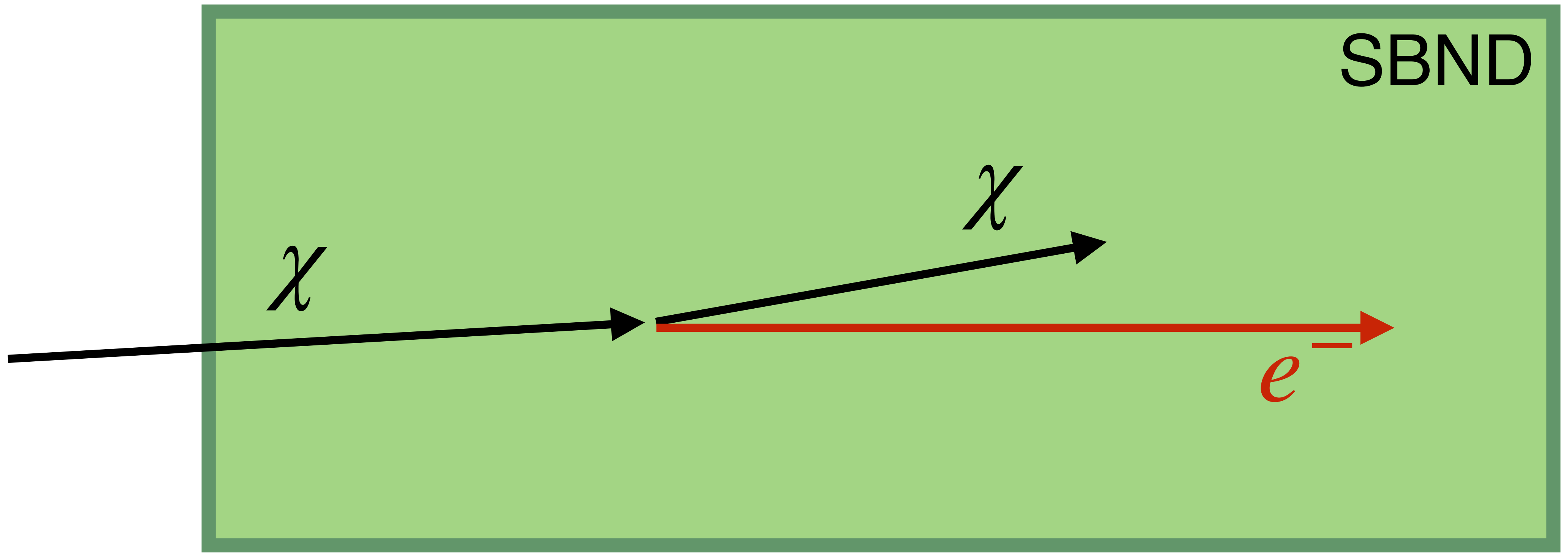

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SBND-PRIMS: Neutrinos (background events) **decrease** with the off axis angle

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Dark matter (signal) events come from **unfocused** neutral mesons

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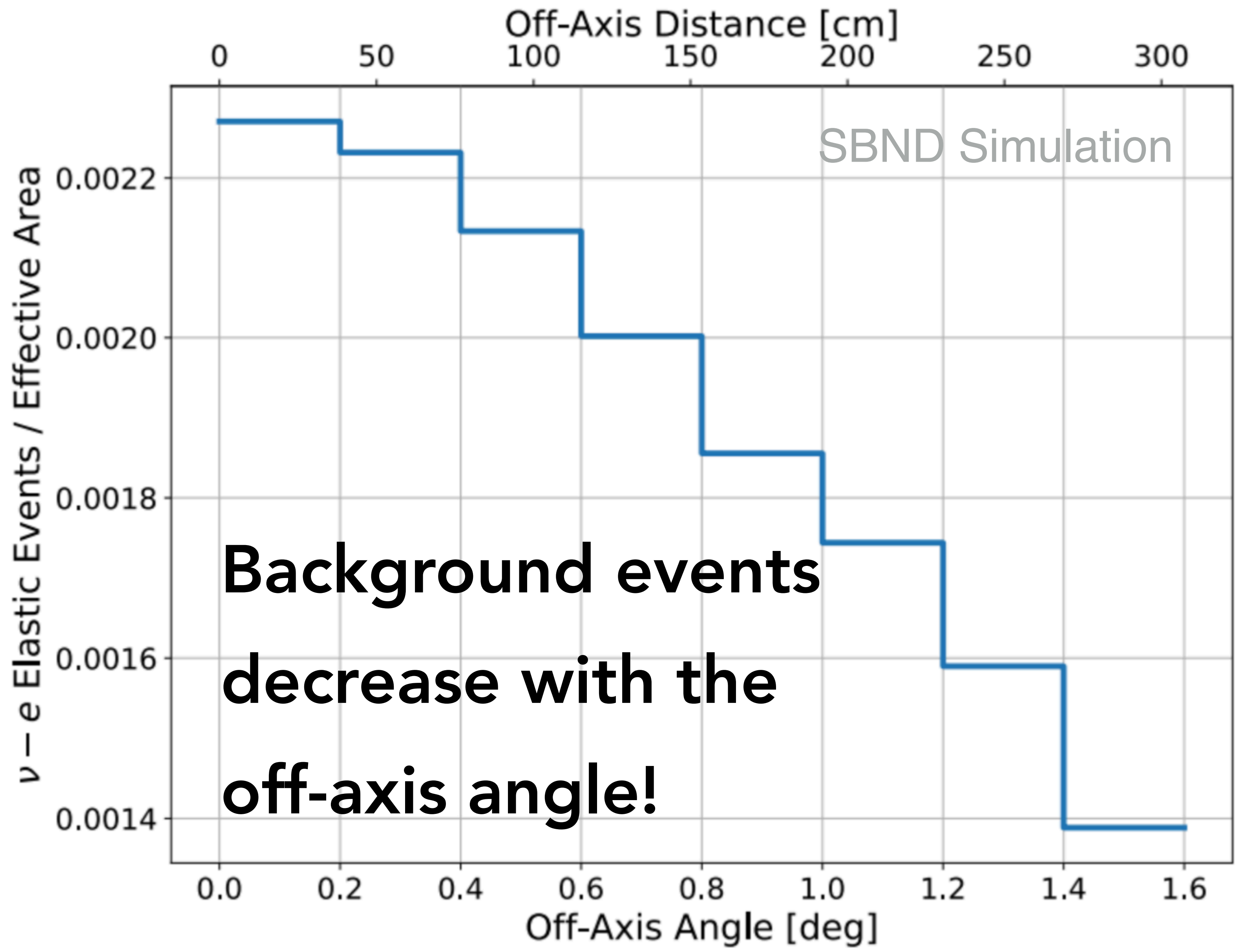

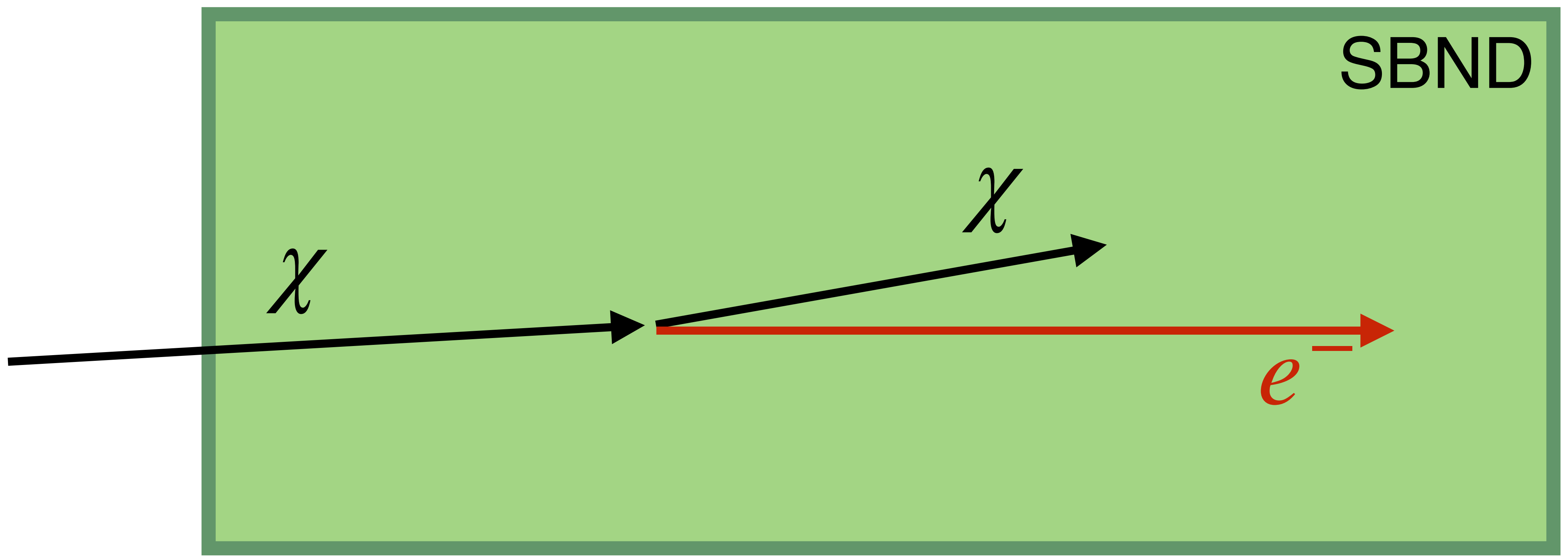

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Dark matter (signal) events come from **unfocused** neutral mesons

Conclusions

- The closeness of SBND to the neutrino source, combined with the abundance of statistics allows us to use this "free" PRISM feature.
- Contrary to DUNE-PRISM, SBND can take data on all the off-axis regions simultaneously, no need to move the detector.
- SBND-PRISM opens up new possibilities: can potentially constrain interaction modeling, improve oscillation fits, perform an SBND-only oscillation analysis and other BSM searches.

Conclusions

Thank You!