Fermilab

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

Marco Del Tutto, for the SBND collaboration

In collaboration with Pedro Machado, Kevin Kelly, and Roni Harnik

APS April Meeting 2021

FERMILAB-SLIDES-21-018-ND

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

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) at Fermilab

Goals of the SBN program:

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

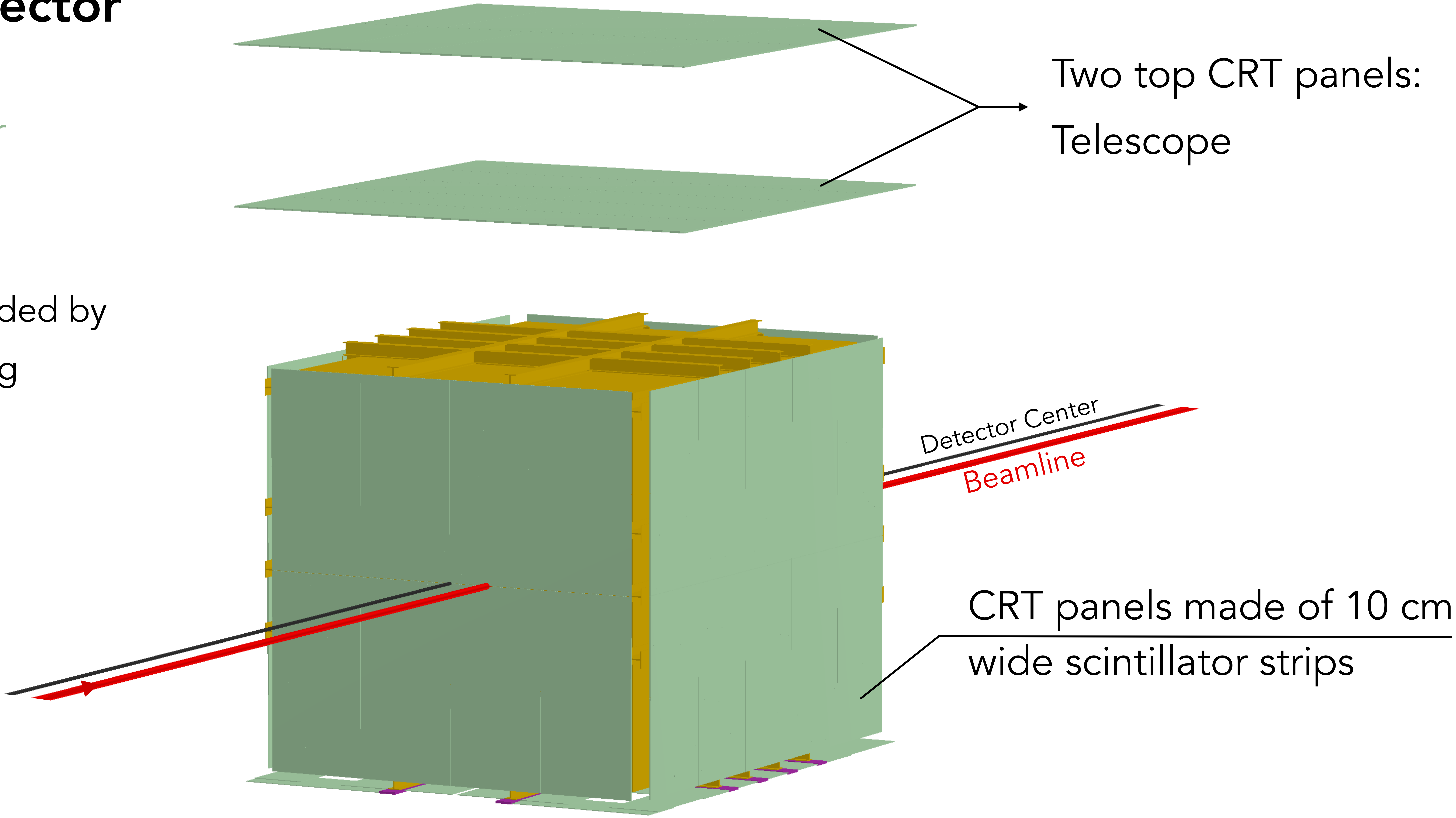
A Slightly Off-Axis Detector

The SBND detector

Cosmic Ray Tagger

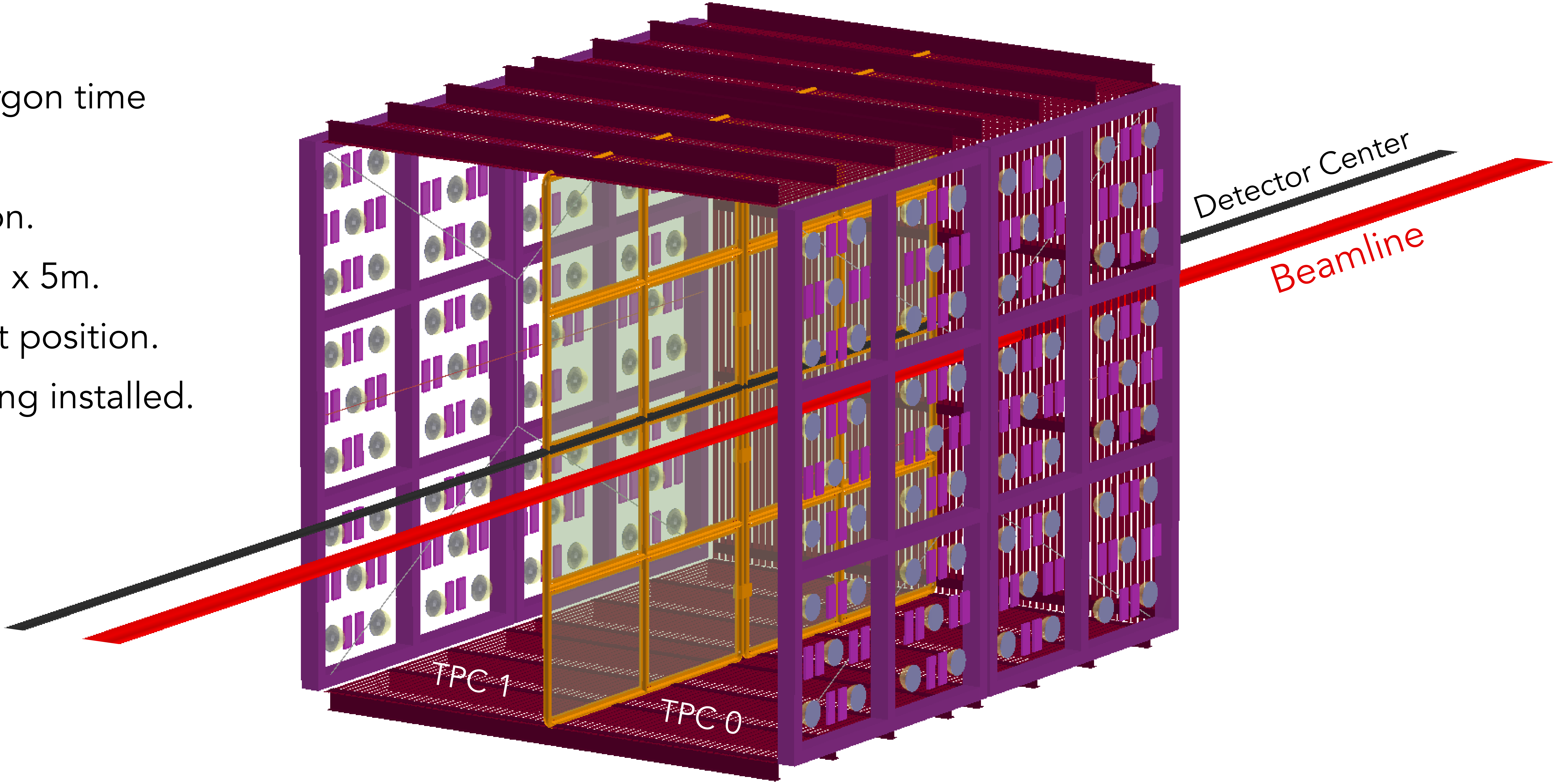
CRT

SBND will be surrounded by scintillator strips to tag cosmic rays



The SBND detector

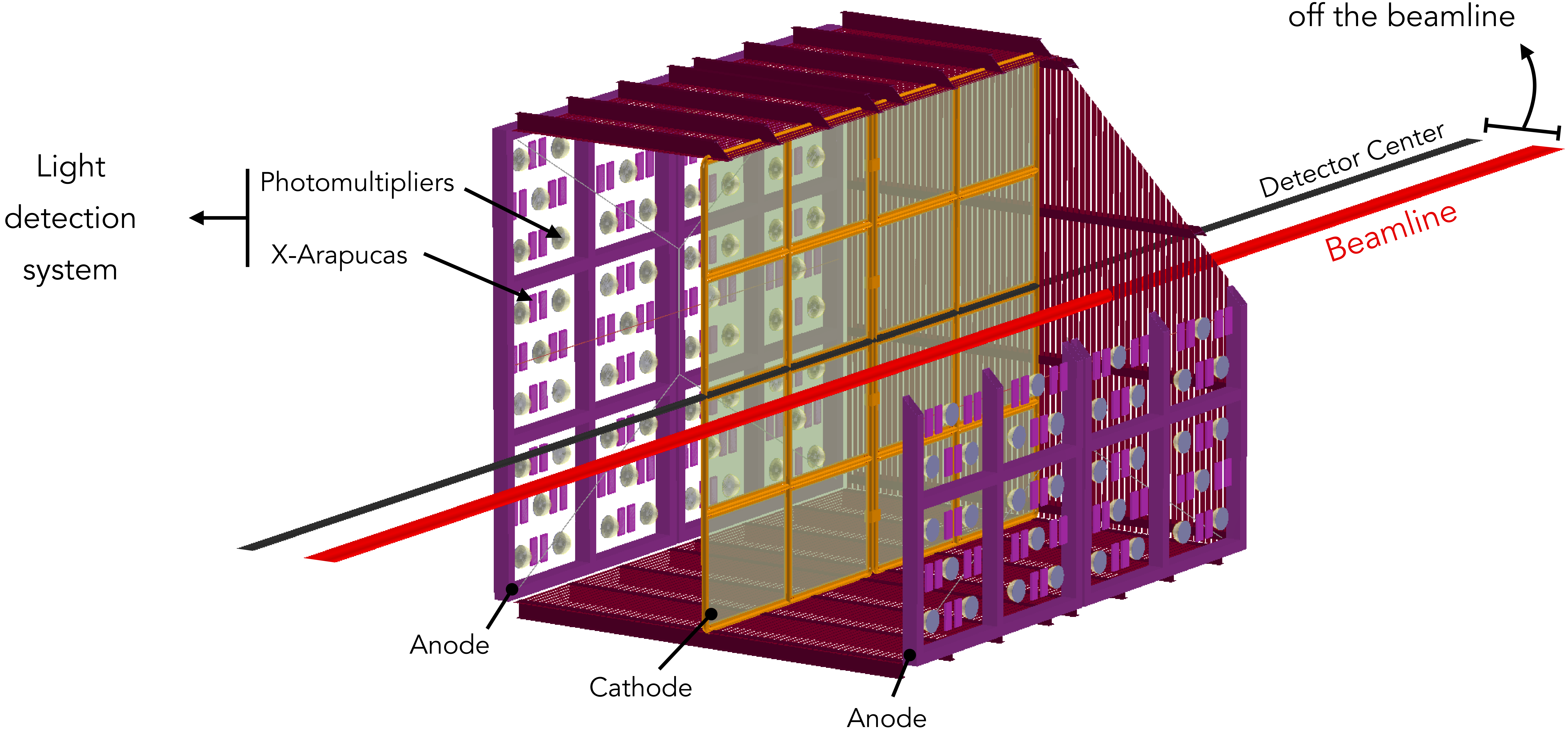
- Made of two liquid argon time projection chambers.
- 112 ton of liquid argon.
- Dimensions: 4m x 4m x 5m.
- 110 m from the target position.
- SBND is currently being installed.



A Slightly Off-Axis Detector

The SBND detector

The detector is ~74 cm off the beamline



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

(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°)

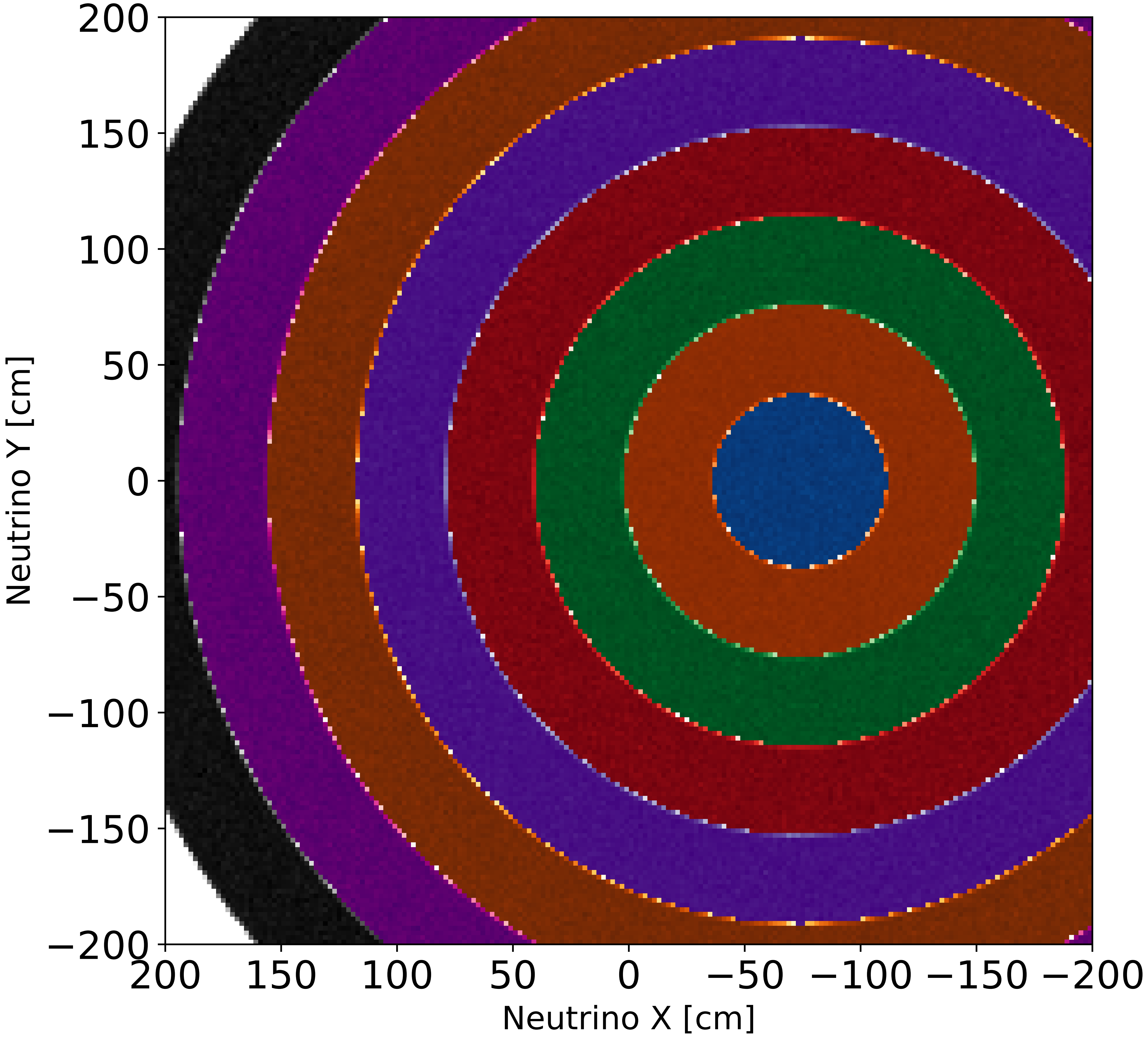
OAA ∈ [0.6°, 0.8°)

OAA ∈ [0.8°, 1.0°)

OAA ∈ [1.0°, 1.2°)

OAA ∈ [1.2°, 1.4°)

OAA ∈ [1.4°, 1.6°)

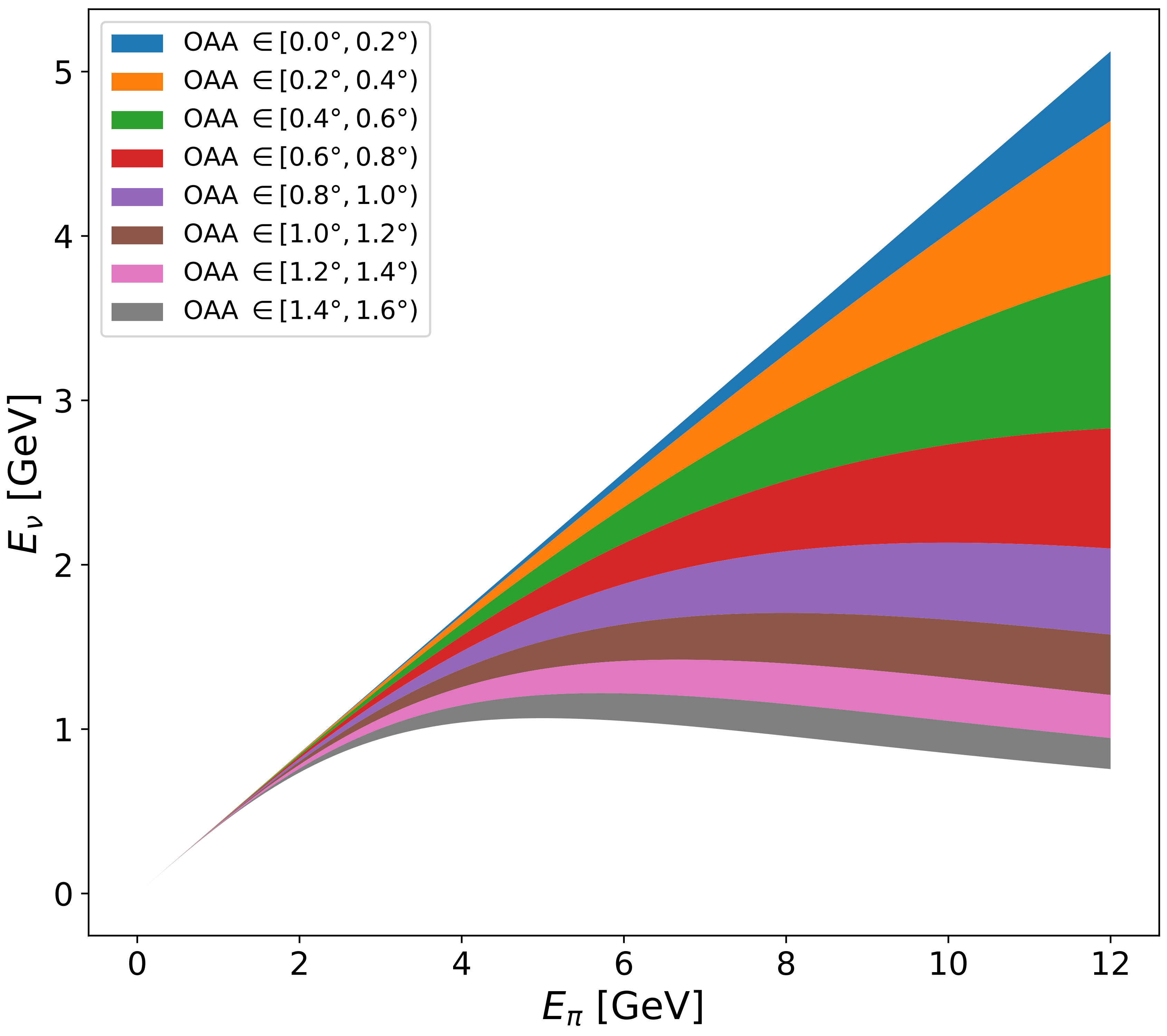


SBND-PRISM

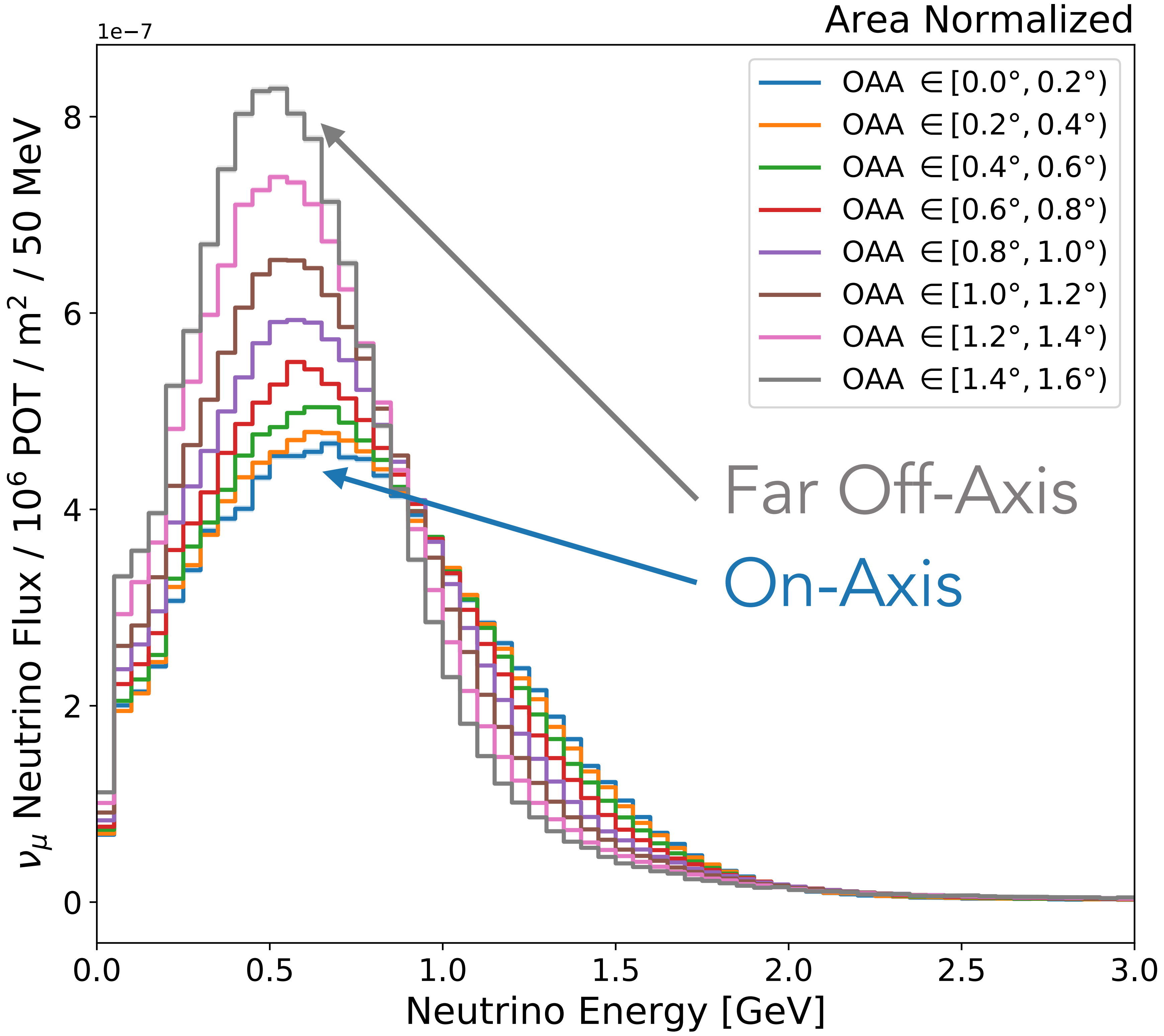
Precision **R**eaction **I**ndependent **S**pectrum **M**easurement (*)

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

Mean neutrino energy



Muon neutrino flux in each of the OAA regions



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°)
- OAA ∈ [0.8°, 1.0°)
- OAA ∈ [1.0°, 1.2°)
- OAA ∈ [1.2°, 1.4°)
- OAA ∈ [1.4°, 1.6°)

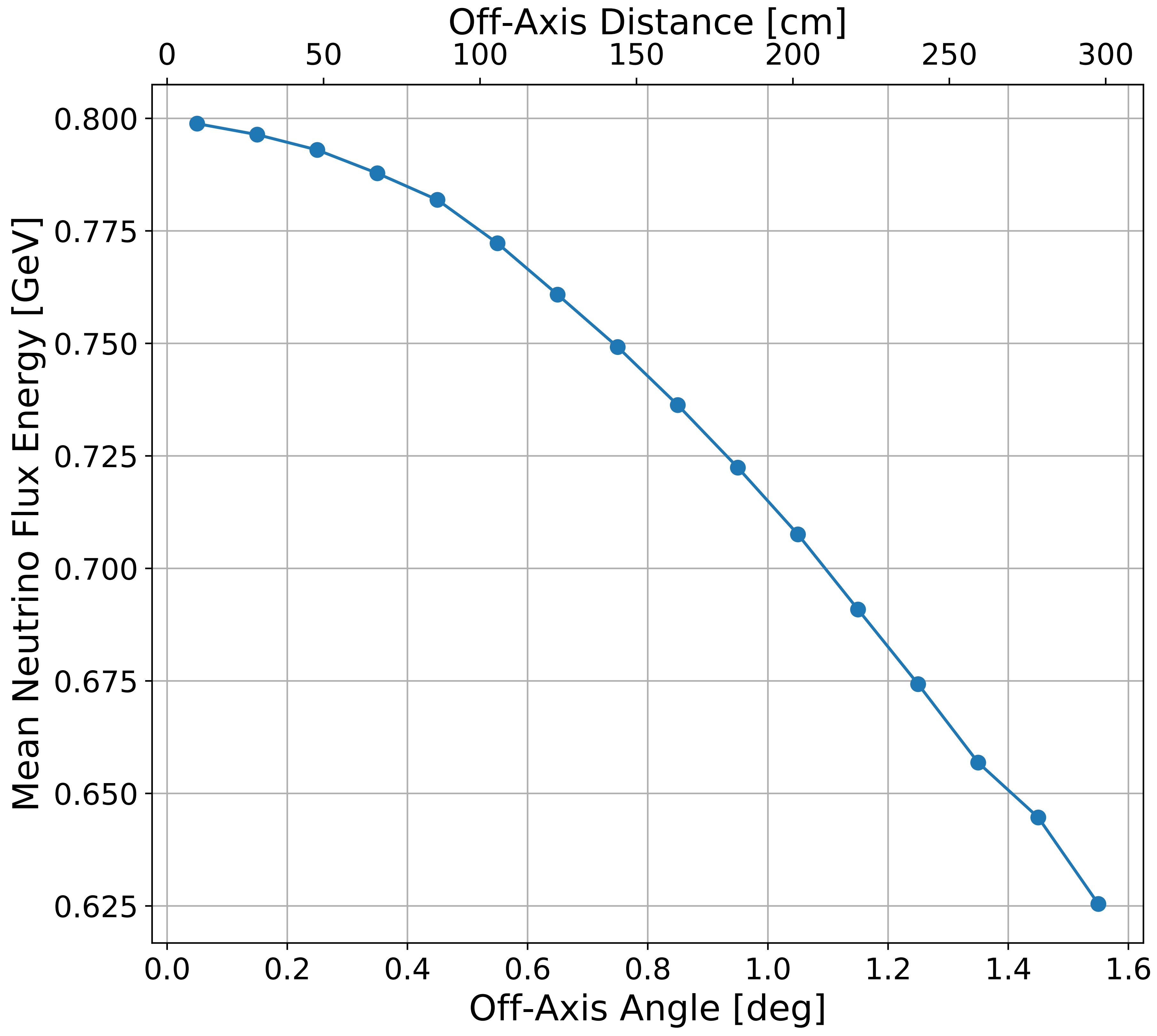
(*) nuPRISM https://arxiv.org/abs/1412.3086

SBND-PRISM

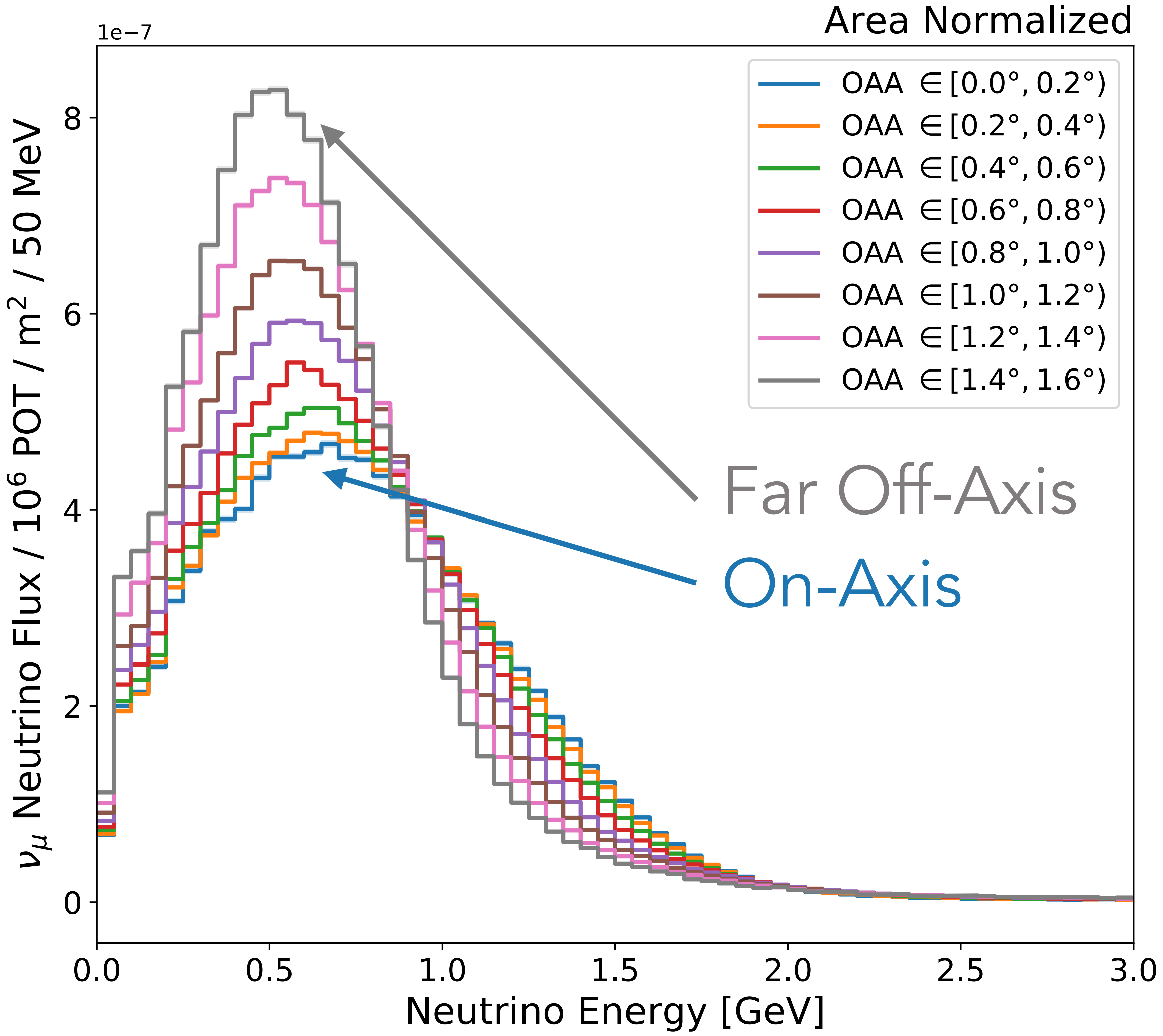
Precision **R**eaction **I**ndependent **S**pectrum **M**easurement (*)

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

Mean neutrino energy



Muon neutrino flux in each of the OAA regions



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

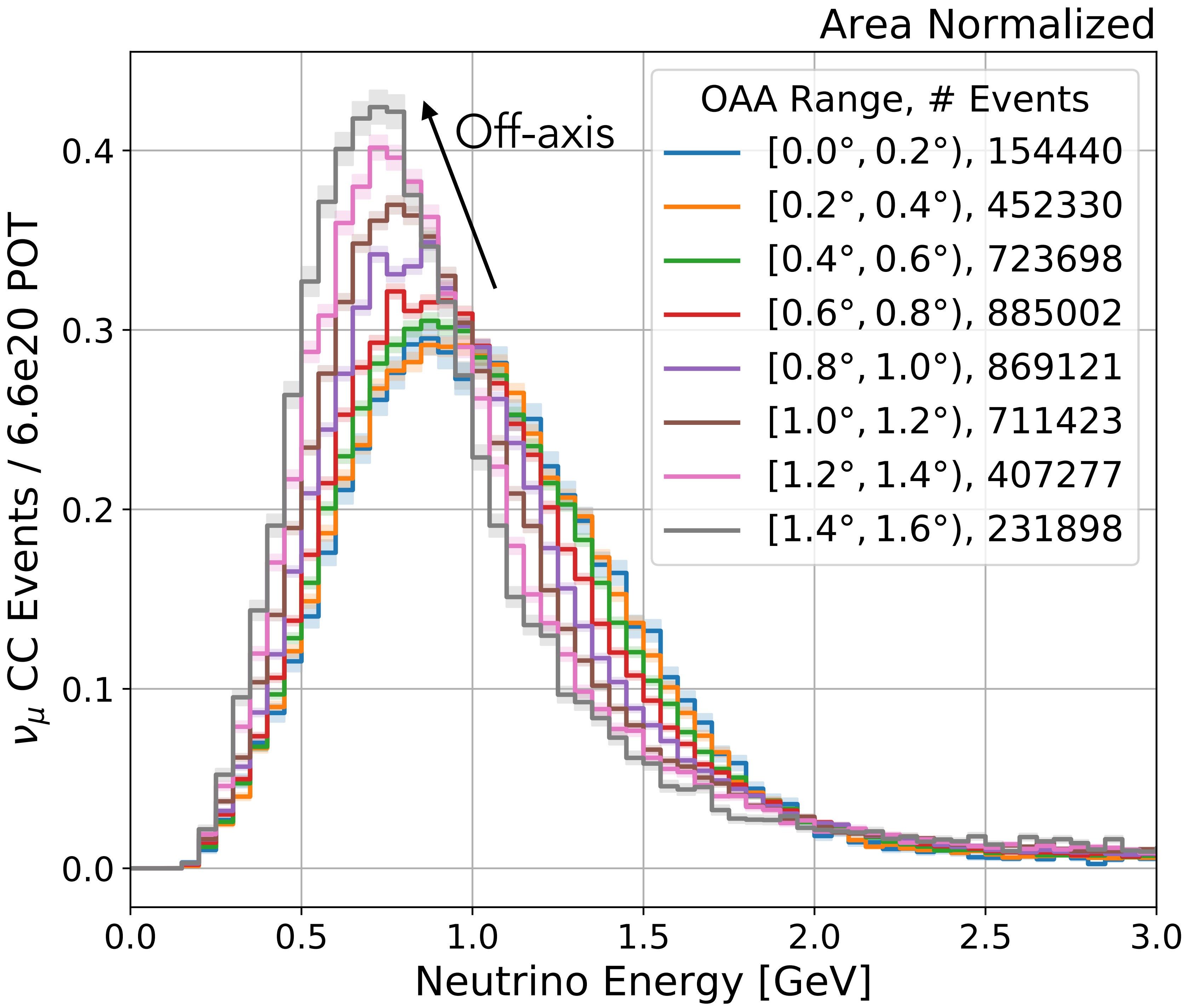
- OAA ∈ [0.0°, 0.2°)
- OAA ∈ [0.2°, 0.4°)
- OAA ∈ [0.4°, 0.6°)
- OAA ∈ [0.6°, 0.8°)
- OAA ∈ [0.8°, 1.0°)
- OAA ∈ [1.0°, 1.2°)
- OAA ∈ [1.2°, 1.4°)
- OAA ∈ [1.4°, 1.6°)

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

Muon neutrino energy spectrum changes with the off-axis angle, while the electron neutrino one stays almost the same

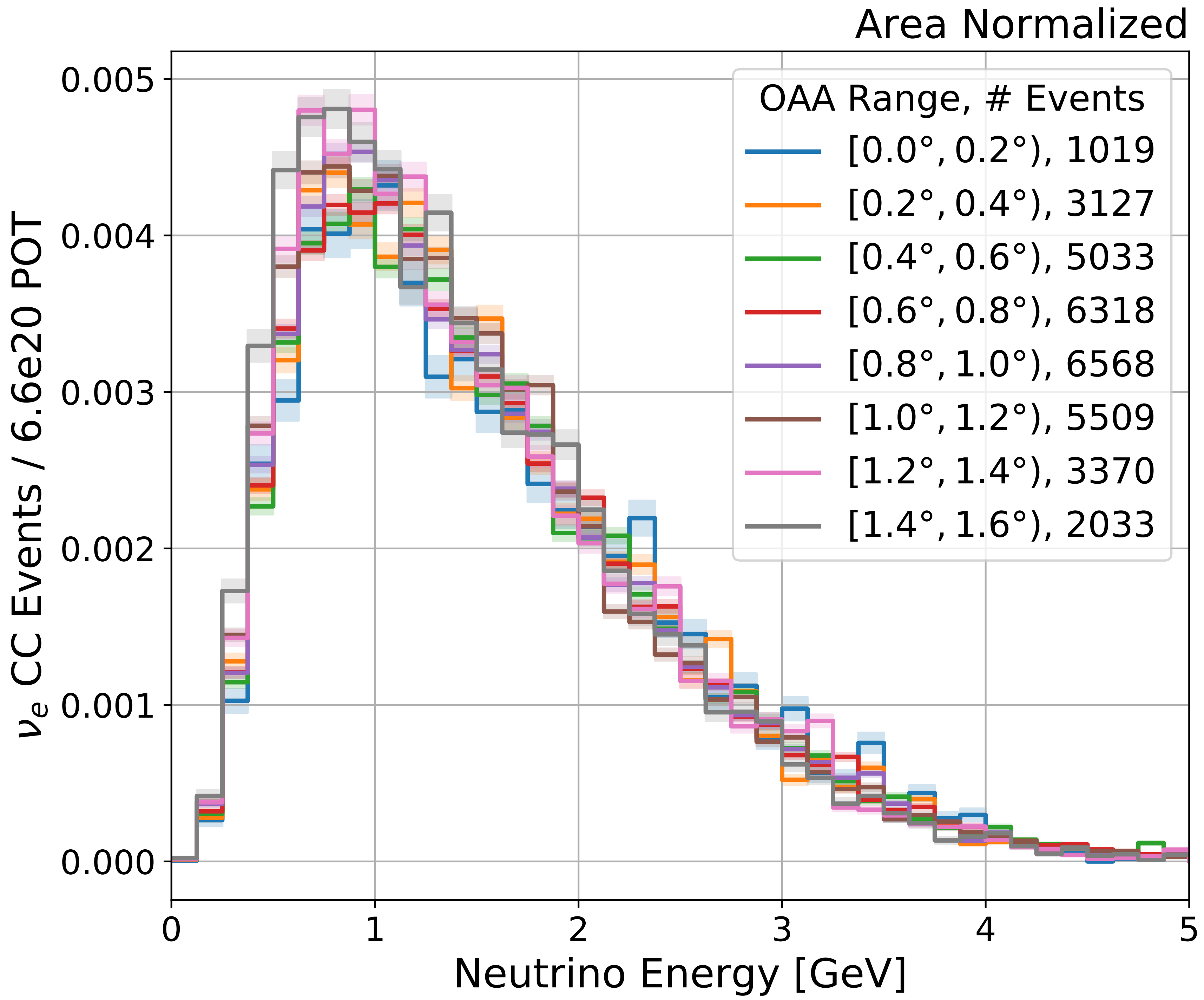
Muon-neutrino CC Events

higher off-axis angle → lower mean energy



Electron-neutrino CC Events

higher off-axis angle → ~same mean energy



High event statistics in all off-axis regions

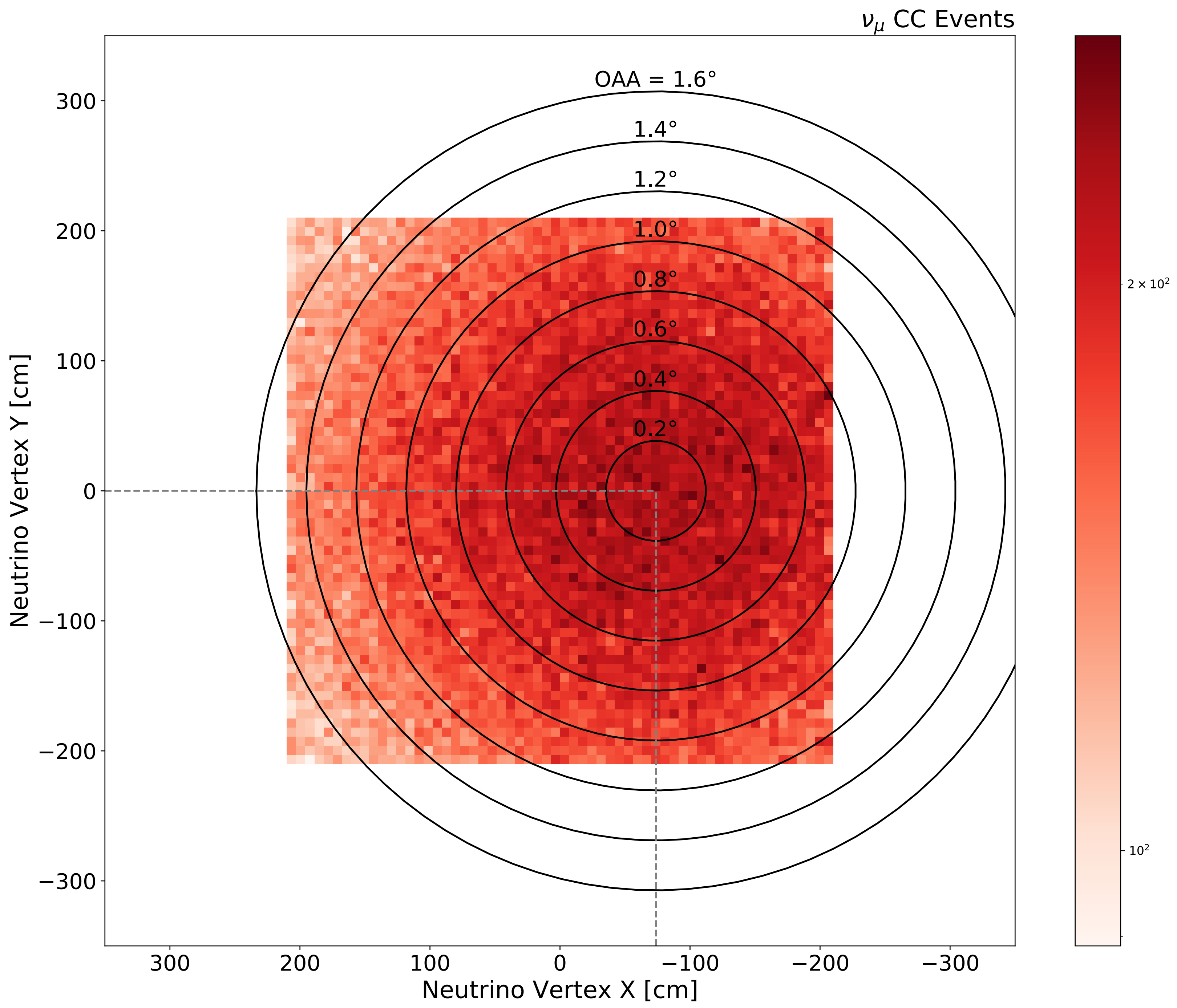
SBND-PRISM - ν_μ / ν_e Differences 2/2

Moving away from the beam-line axis, the number of ν_μ and ν_e interactions varies differently.

While the number of ν_e events stays almost constant, the number of ν_μ events decreases.

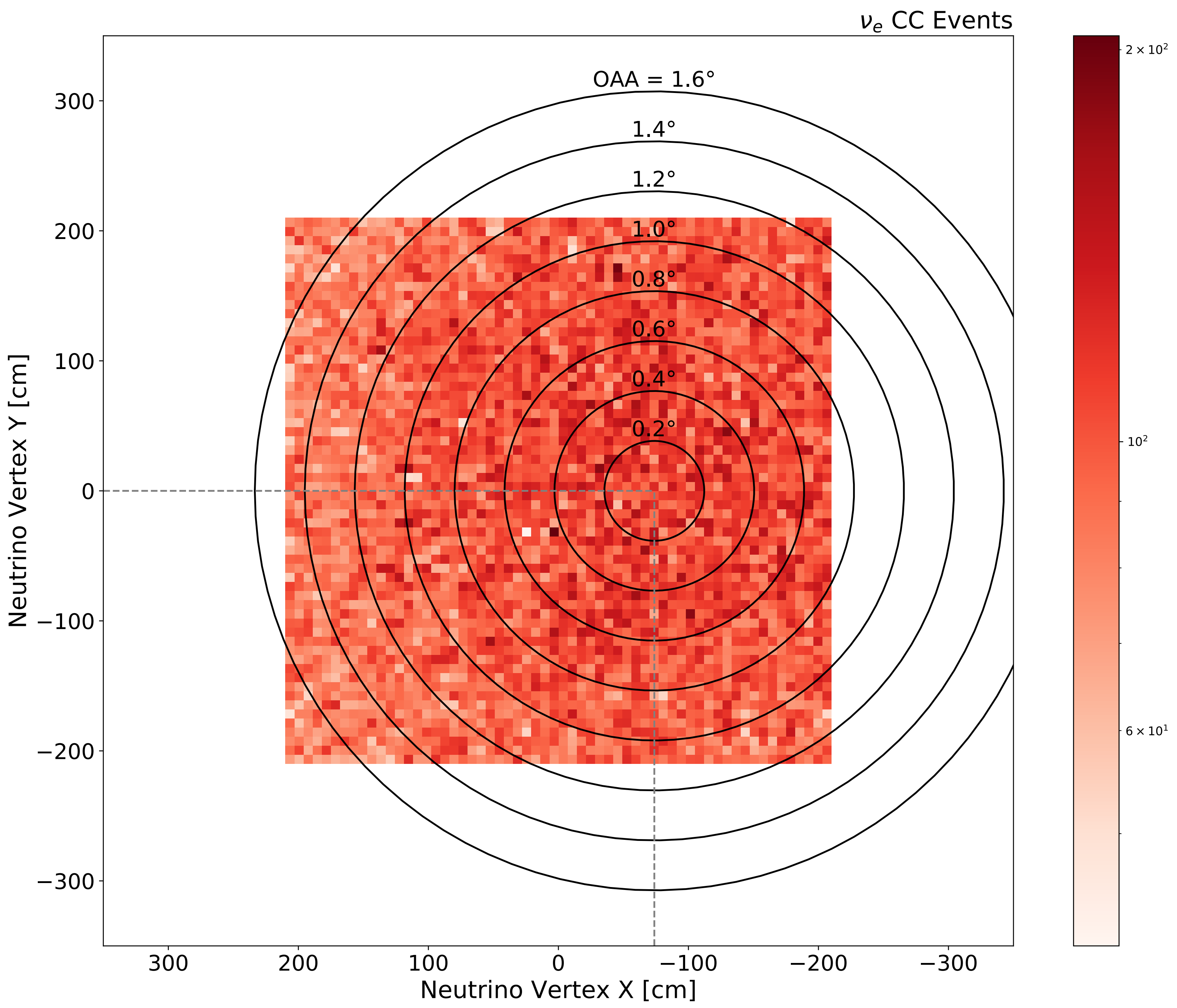
Muon-neutrinos CC Events

peak coincident with the on-axis position

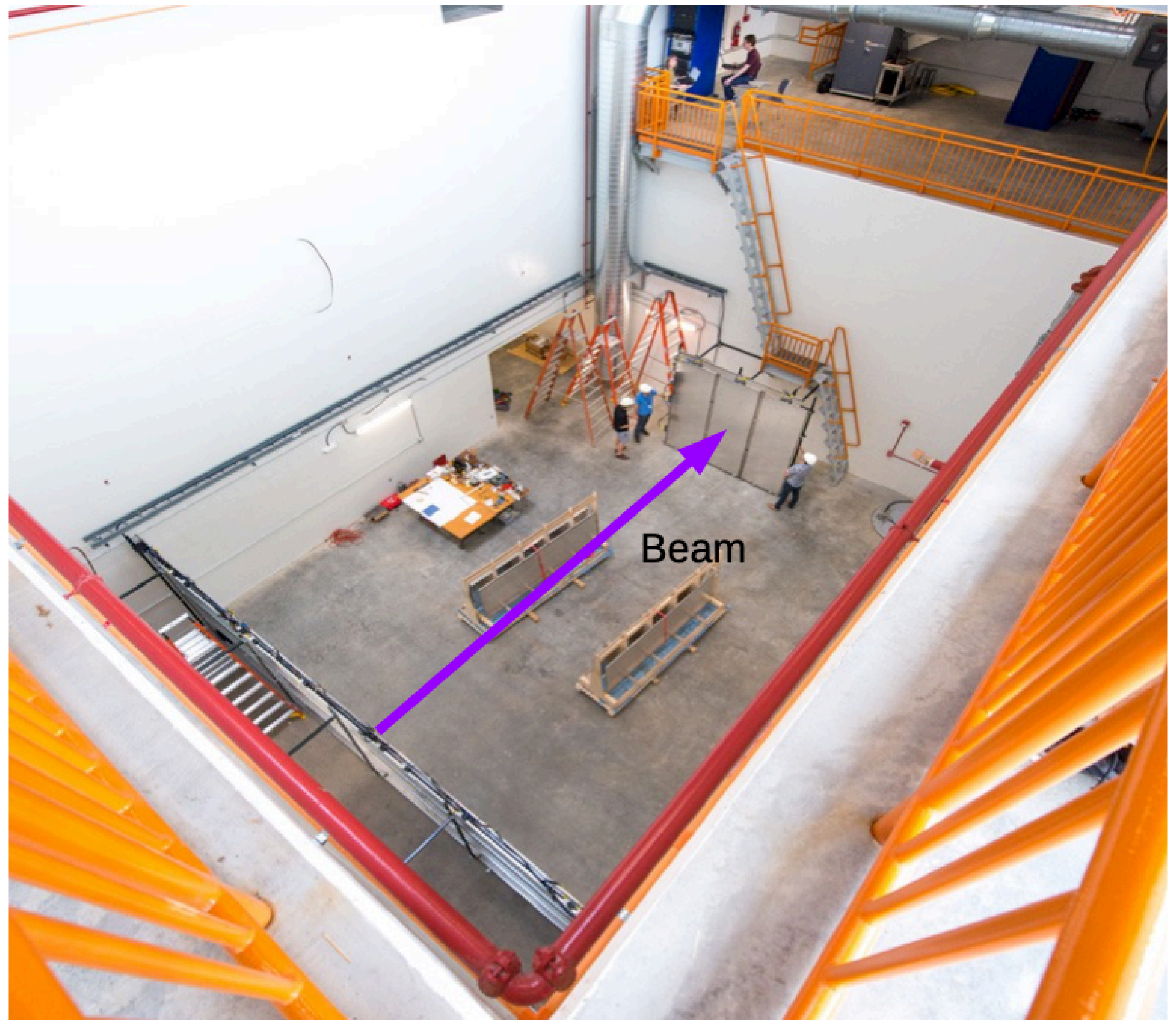


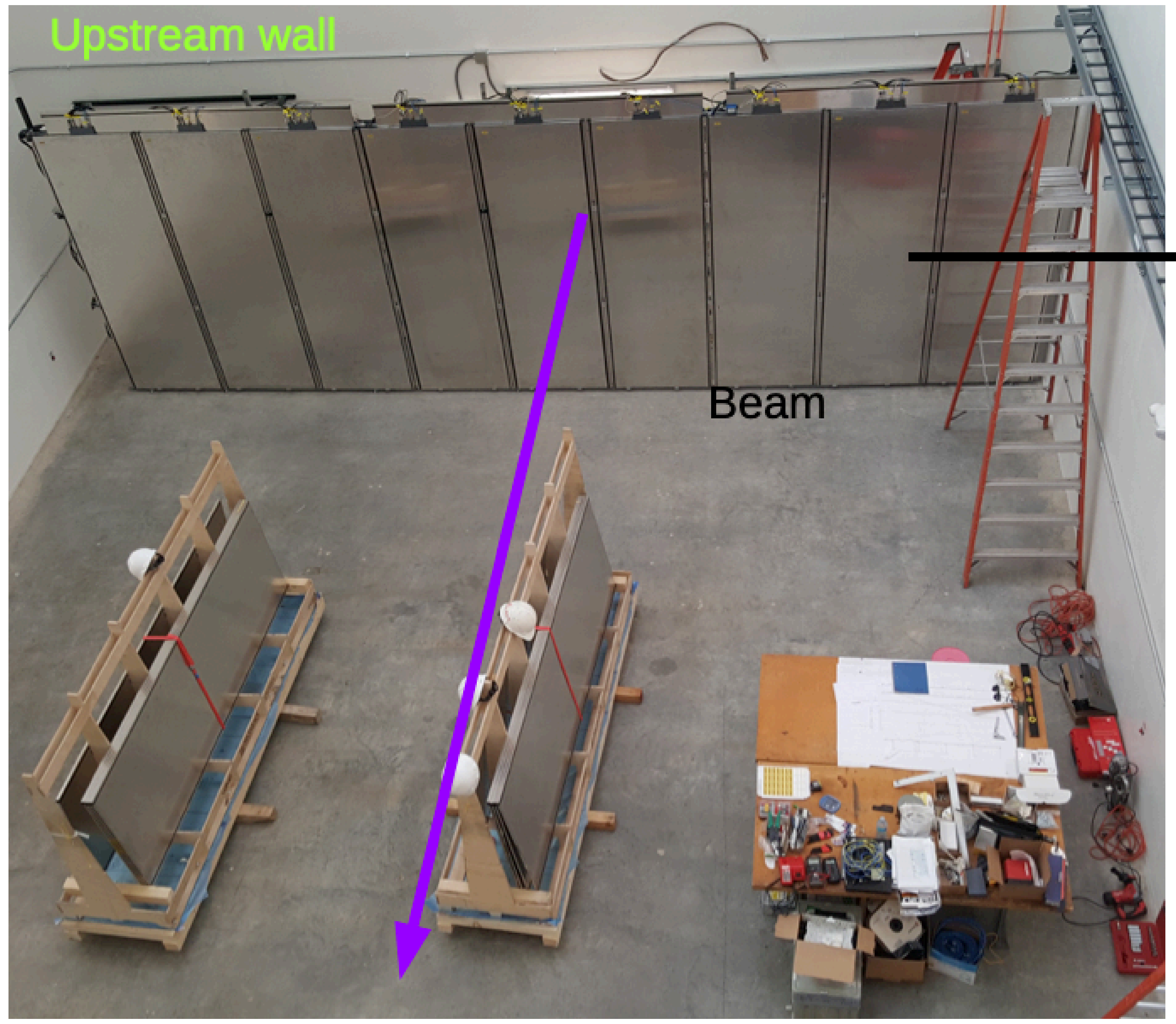
Electron-neutrinos CC Events

distribution is almost constant
(angular distribution of ν_e is wider due to three-body decay)

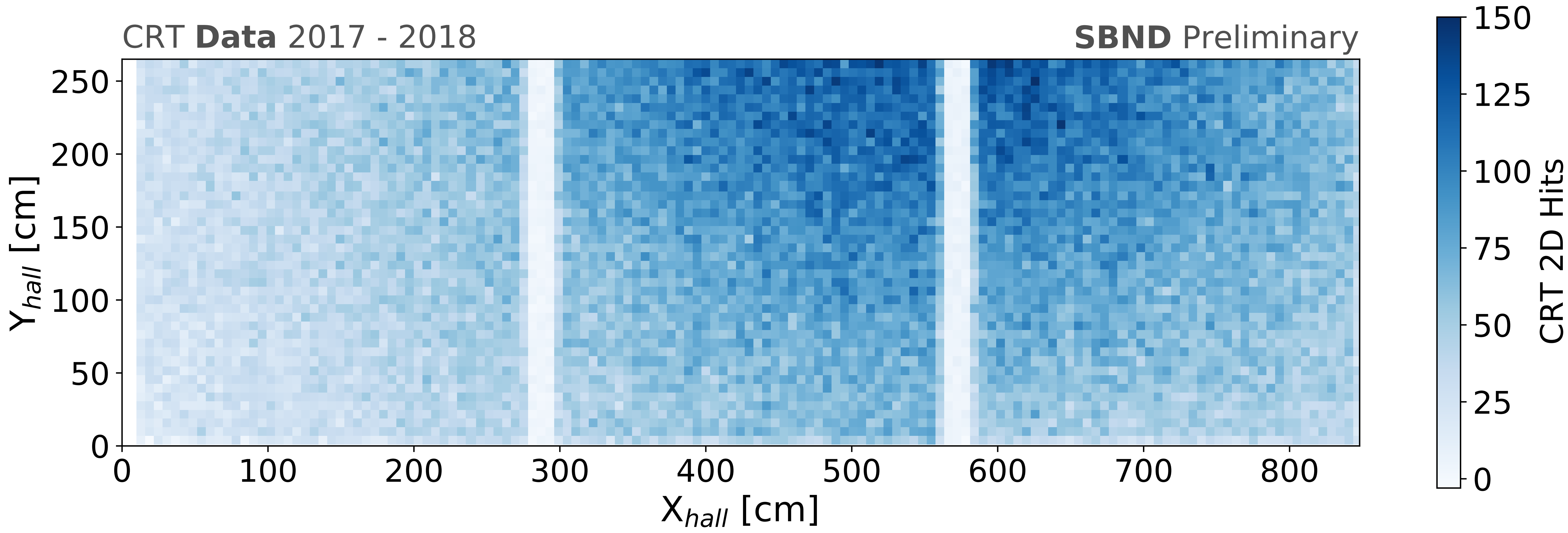


Cosmic Ray Tagger Data





- Part of the SBND cosmic ray tagger system was temporary installed in the detector hall.
- Below is a real data plot of **muons from neutrinos** interacting in the material upstream of the SBND detector hall (cosmic background subtracted).
- Data taken with the CRT shows the number of beam-induced muons decreases moving away from the beam center.



SBND-PRISM - Applications

Benefits of SBND-PRISM:

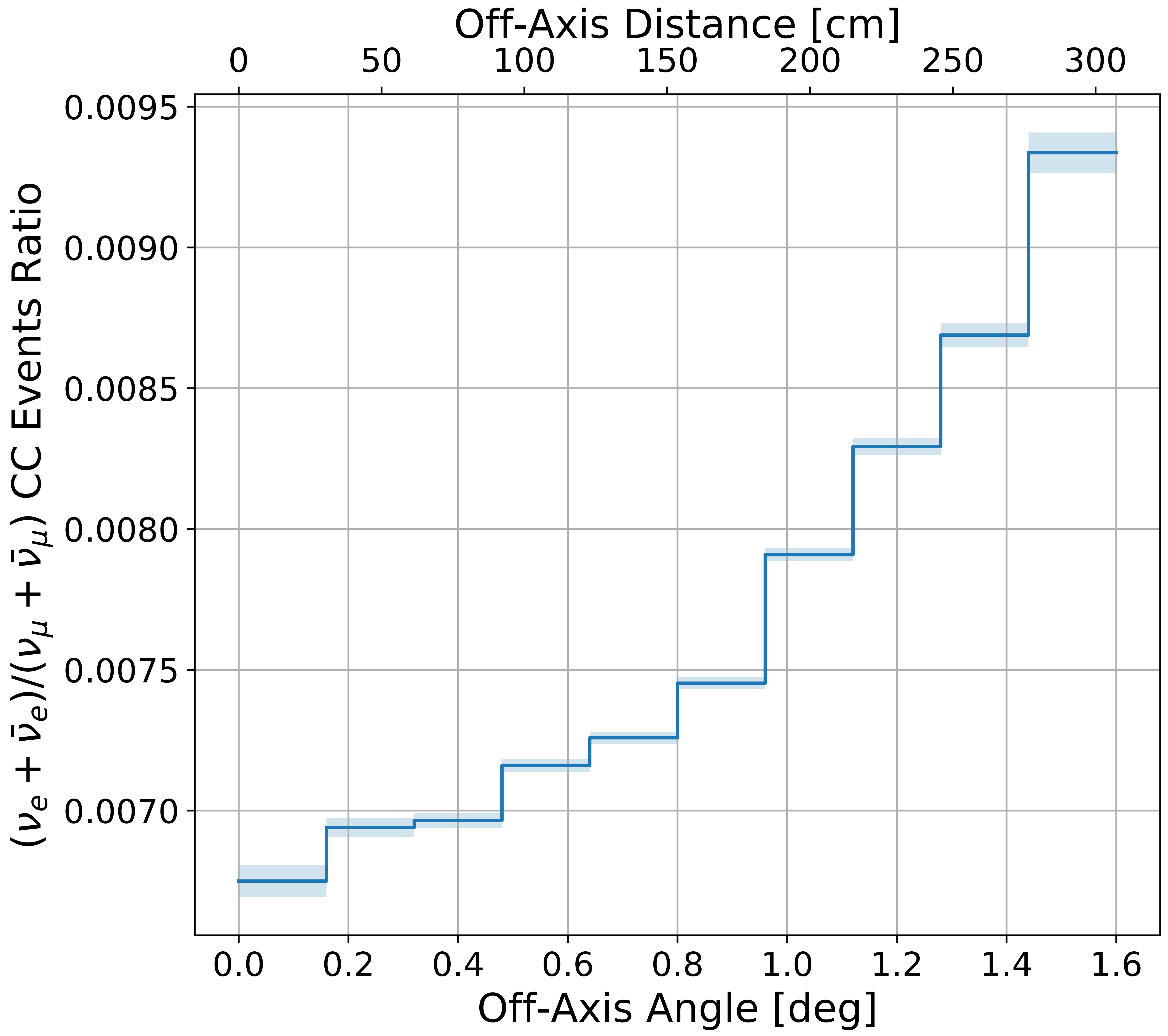
- Interaction Model Constraint
- Neutrino Oscillations
- Dark Matter Searches

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).
- Study the **relationship between neutrino energy and lepton (and hadron) kinematics**, done by measuring differential cross-section in lepton (and hadron) kinematics at different beam angles (= different neutrino energies).
- 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



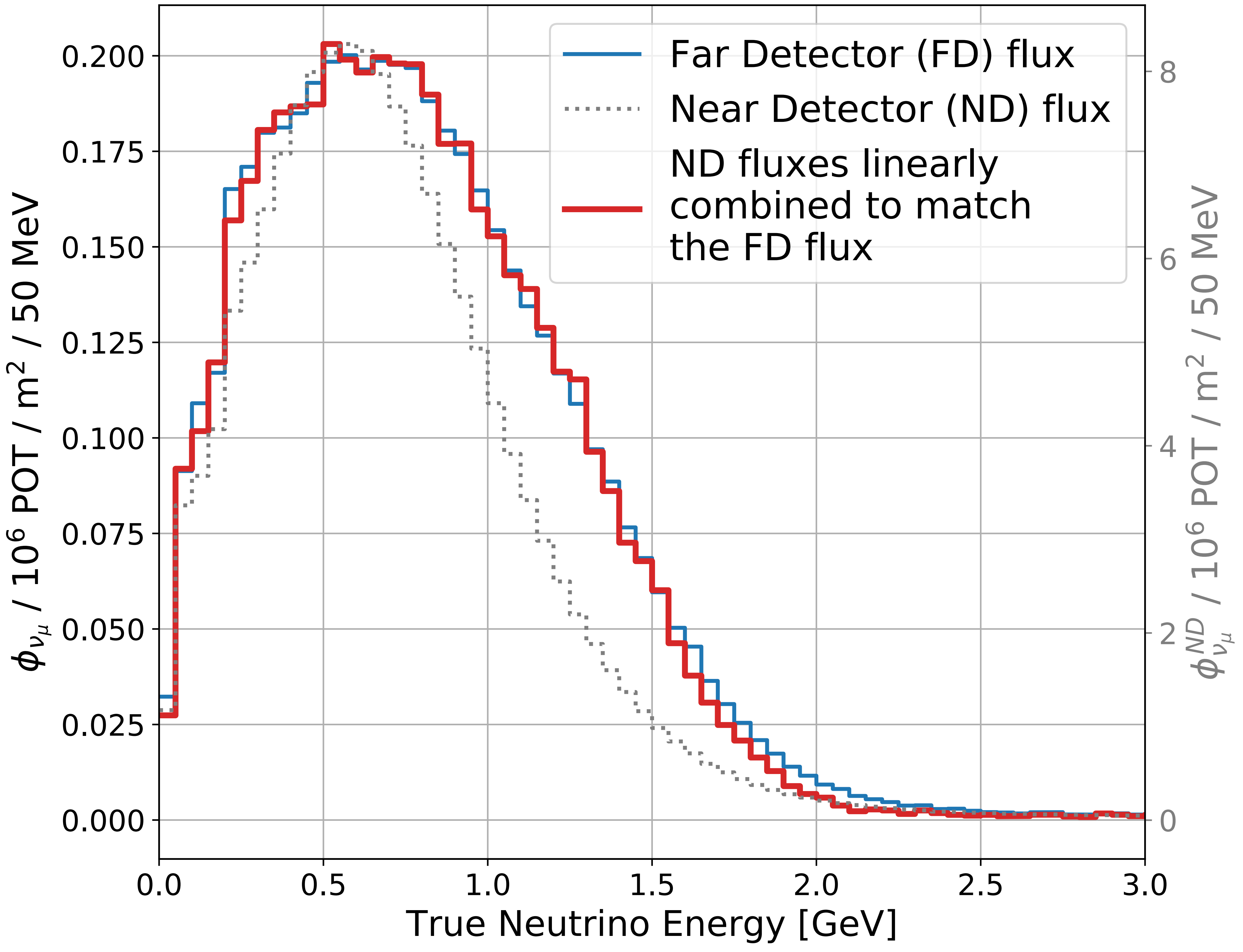
SBND-PRISM - Sterile Neutrino Oscillations

The PRISM feature of SBND can potentially improve the SBN sensitivities to sterile neutrino oscillations.

Two possibilities to use the PRISM feature:

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.

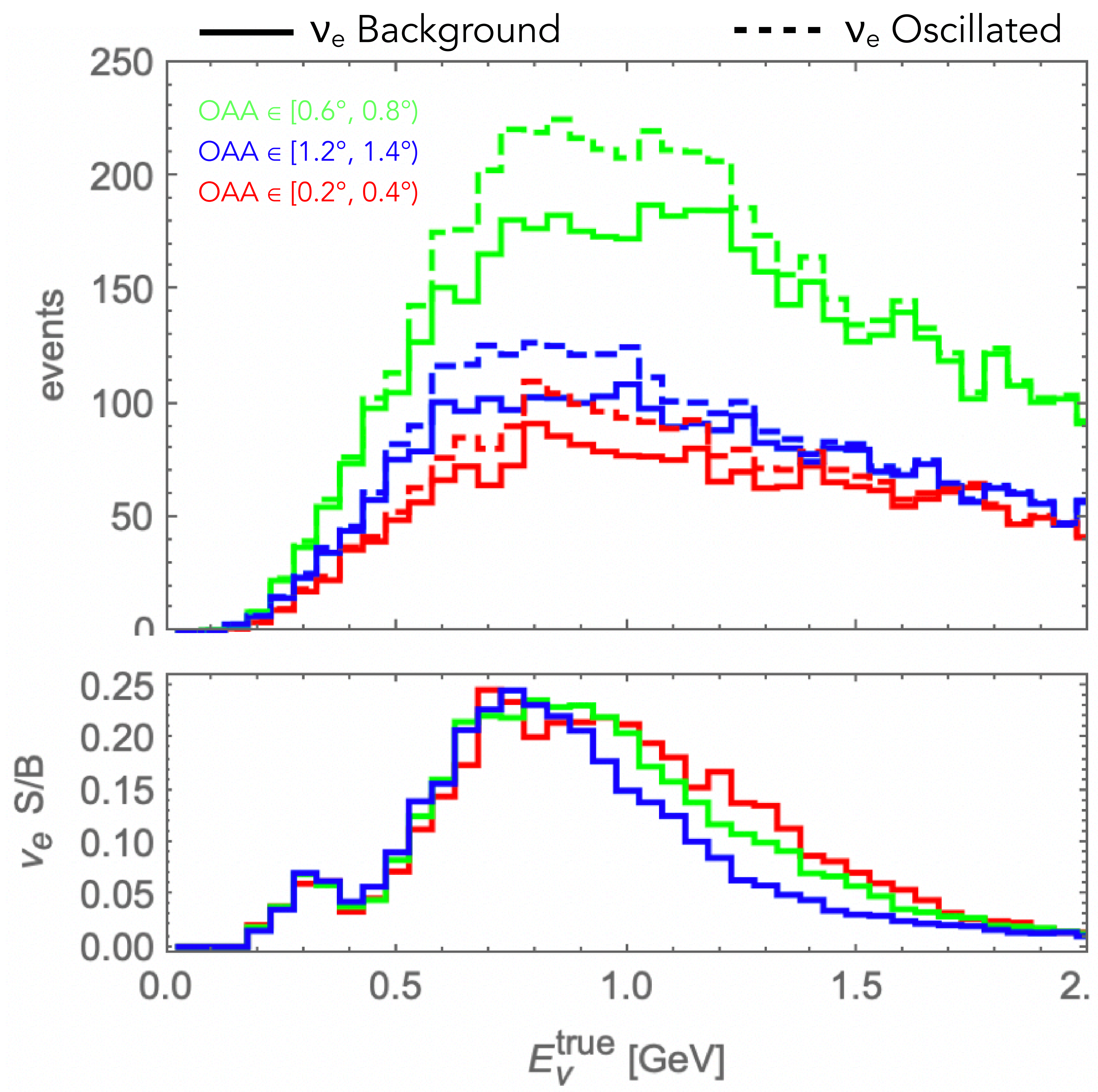
2. Can **linearly combine** the measurements the different off-axis positions to reproduce a given choice of incident neutrino flux. Can match the ICARUS (far detector) oscillated spectrum in SBND (near detector.)



SBND-PRISM - SBND-Only Sterile Neutrino Oscillations

Can we use SBND-PRISM for **SBND-only** sterile neutrino searches?

SBND-PRISM potentially allows probing **higher values of Δm²** for sterile neutrino oscillation searches.



Testing sensitivity with:

- $\Delta m^2 = 10\ \text{eV}^2$, $\sin^2 2\theta_{\mu e} = 0.001$
- ν_e appearance mode
- very conservative systematics: free norm. + 30% bin-by-bin sys. on bkg

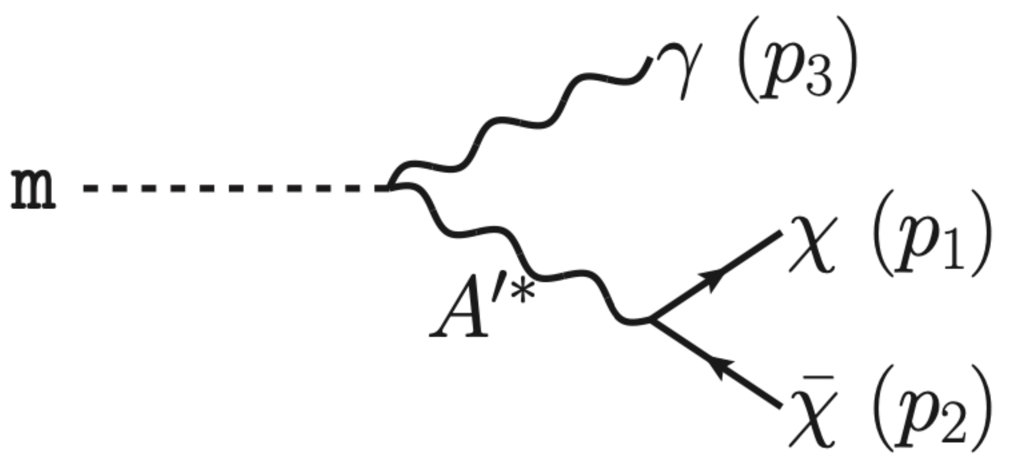
$$\chi^2 = \sum_{i,j}^{\text{pos., bins}} \frac{(N_{ij} + \alpha\, T_{ij})^2}{N_{ij} + \sigma_{\text{bin}}^2 N_{ij}^2}$$

w/ PRISM X^2: 13

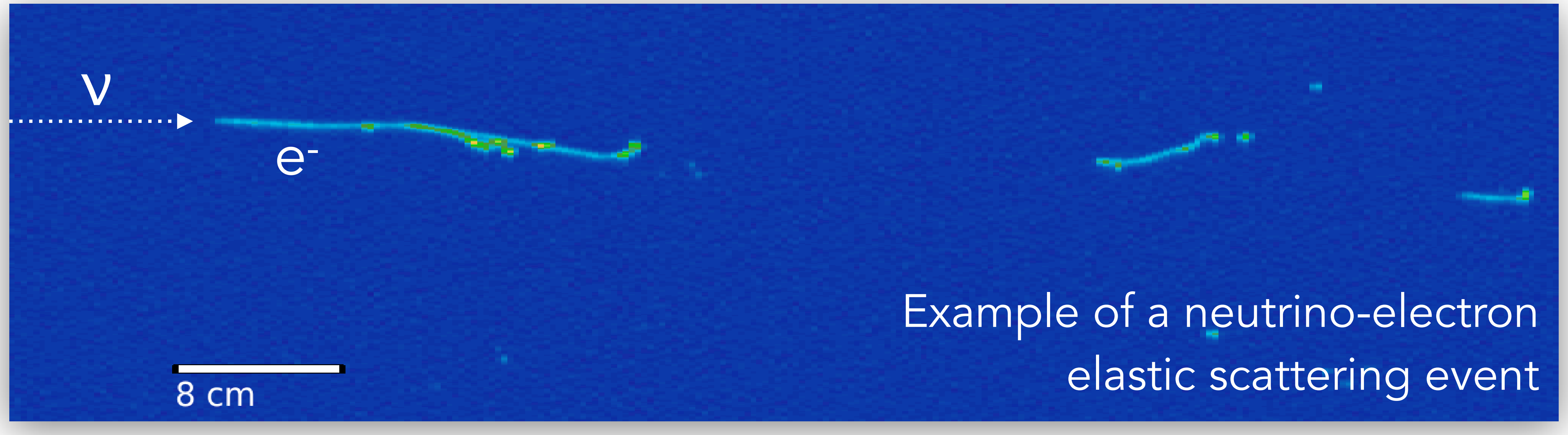
w/o PRISM X^2: 2

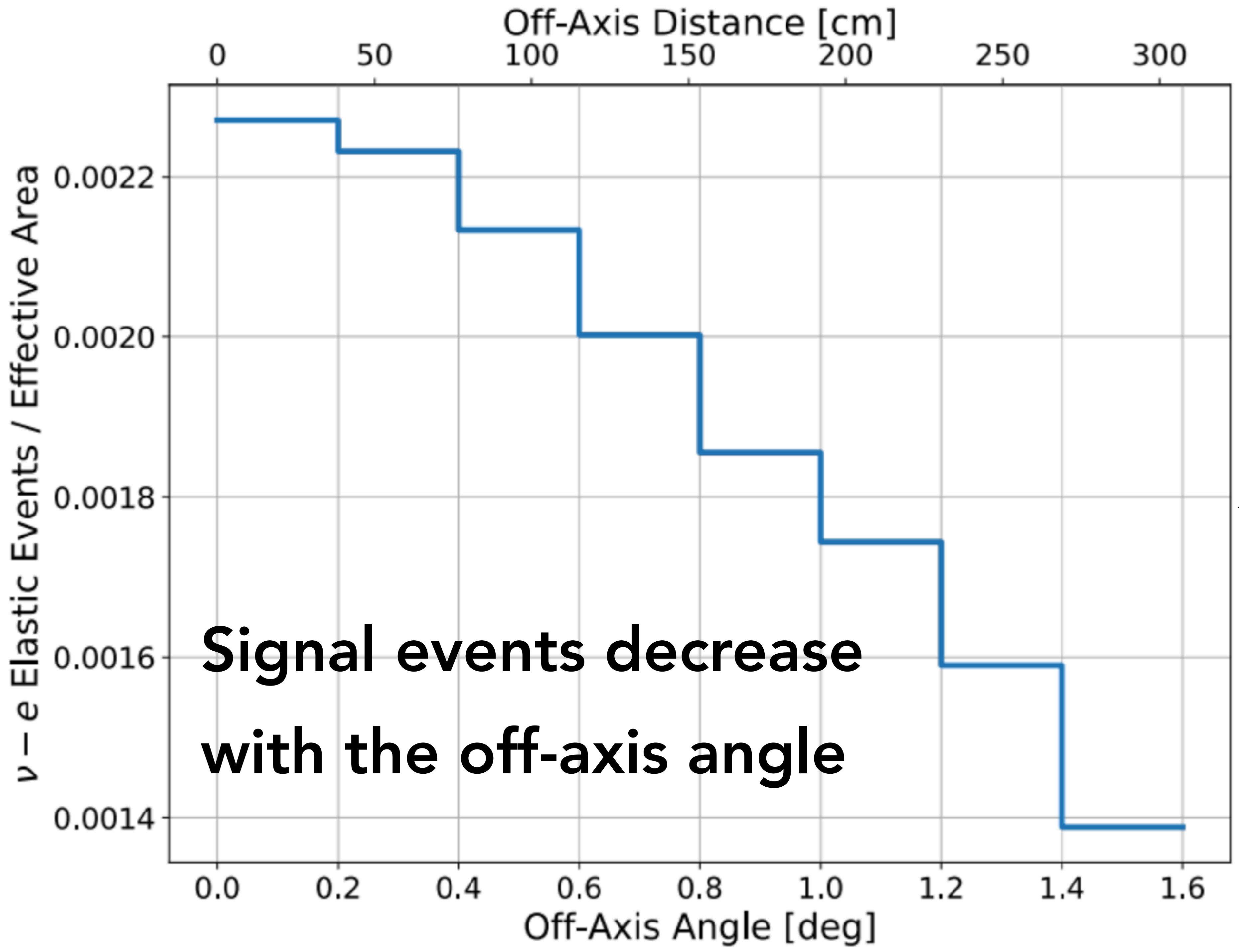
- Mismatch between ν_μ flux and ν_e contamination on different off-axis positions may be an opportunity to do physics.
- Proper estimation of systematics is needed before final conclusions can be made, but results look promising with current (conservative) systematic guess.

SBND-PRISM - Dark Matter Searches



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





- **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.
  - **Neutrino flux drops off more sharply as a function of radius!**

See also https://arxiv.org/abs/1903.10505

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 could constrain the relationship between true and reconstructed energy and potentially help disentangling the effects due to mismodeling of the neutrino flux, neutrino interaction cross-sections, and detector response
- SBND-PRISM opens up new possibilities: can potentially constrain interaction modeling, improve oscillation fits, allows for an SBND-only oscillation analysis, and other BSM searches.

Thank You!