

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

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Fermilab 2021 Summer Student School

3rd August 2021

The Short Baseline Near Detector (SBND)

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

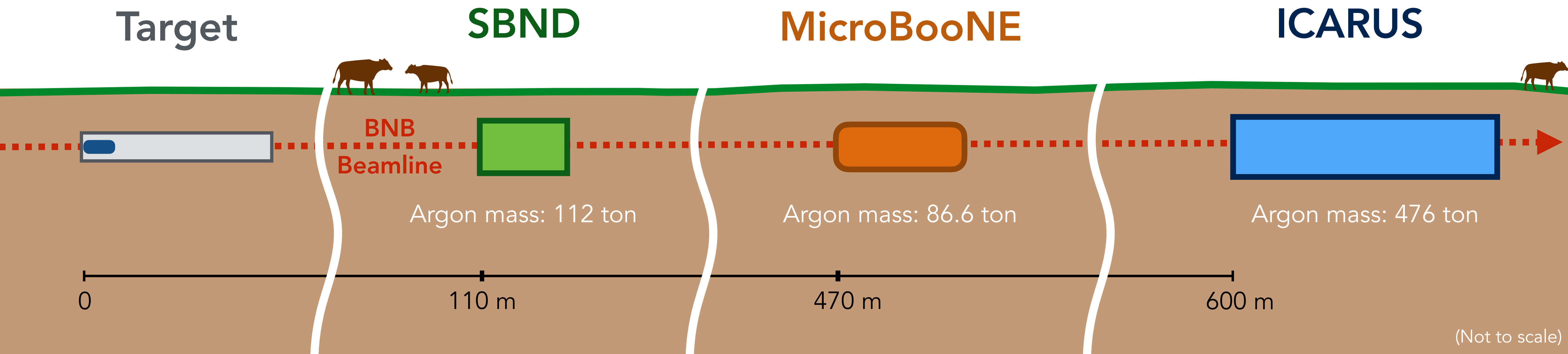
Three Liquid Argon Time Projection Chamber (LArTPC) detectors
located along the Booster Neutrino Beamline (BNB) at Fermilab

Goals of the SBN program:

Search for eV mass-scale sterile neutrinos oscillations

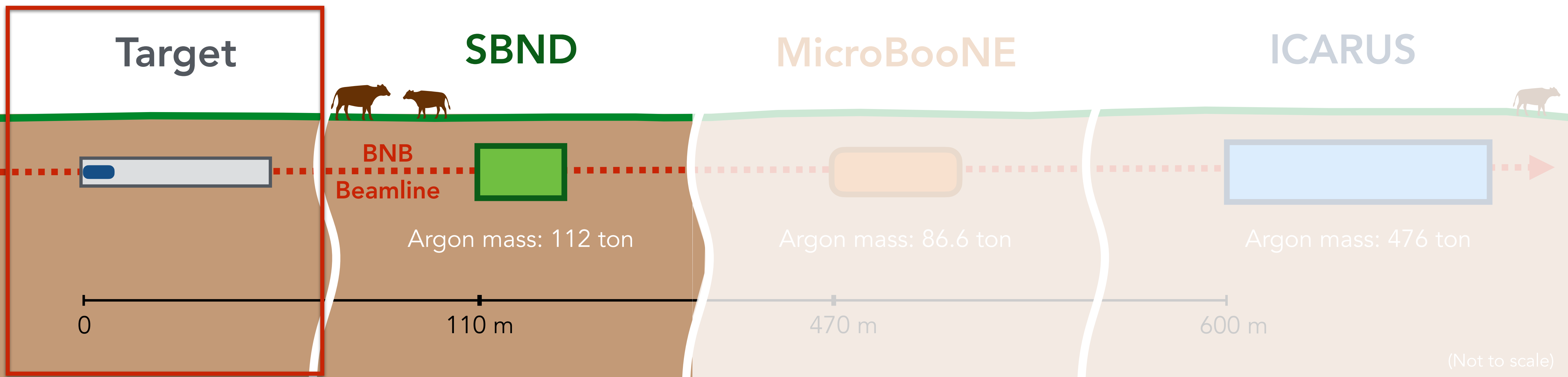
Study of neutrino-argon interactions at the GeV energy scale

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

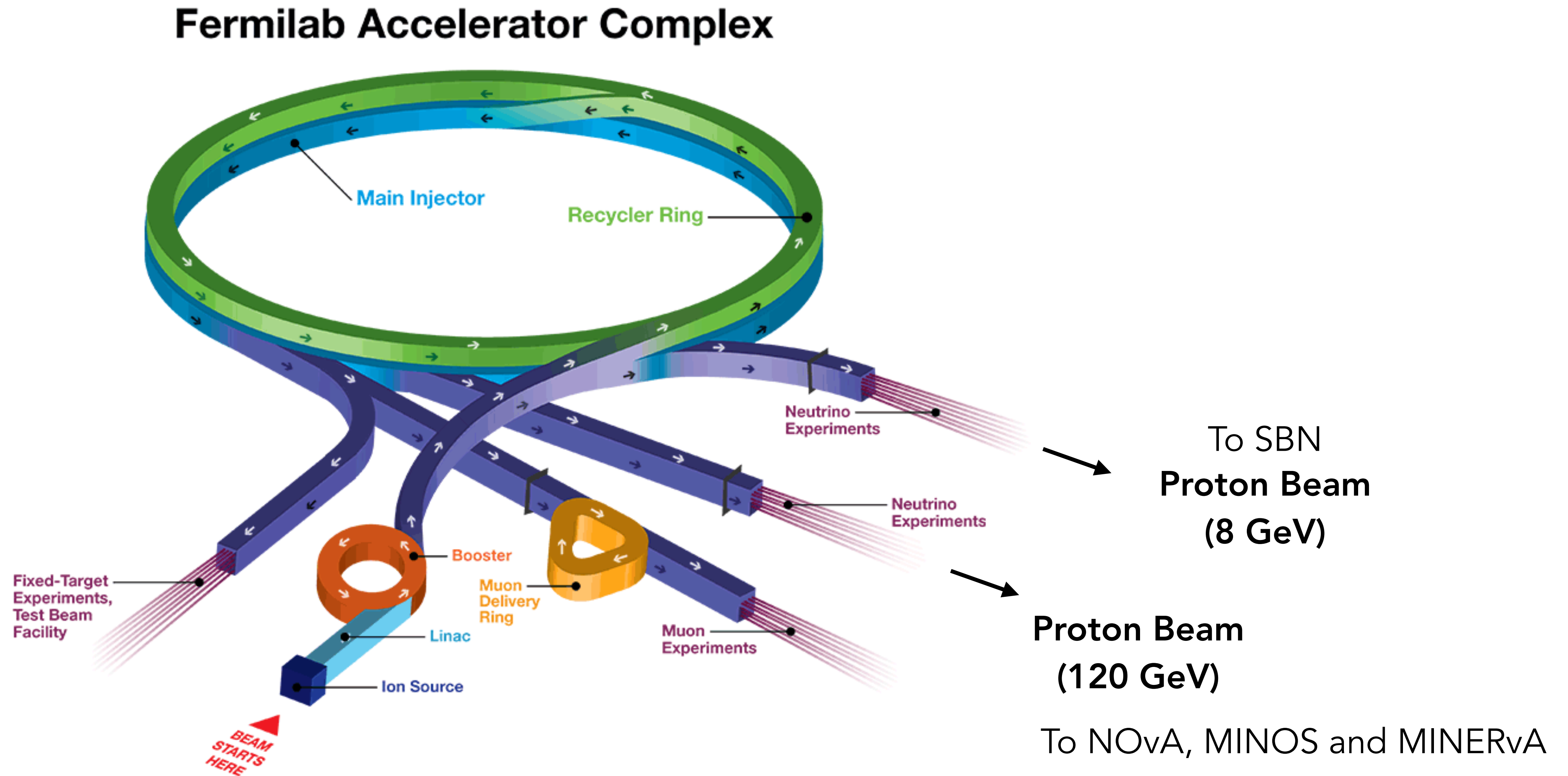


The Short Baseline Near Detector (SBND)

Brief introduction of how the neutrino beam is made



Neutrino Beamline

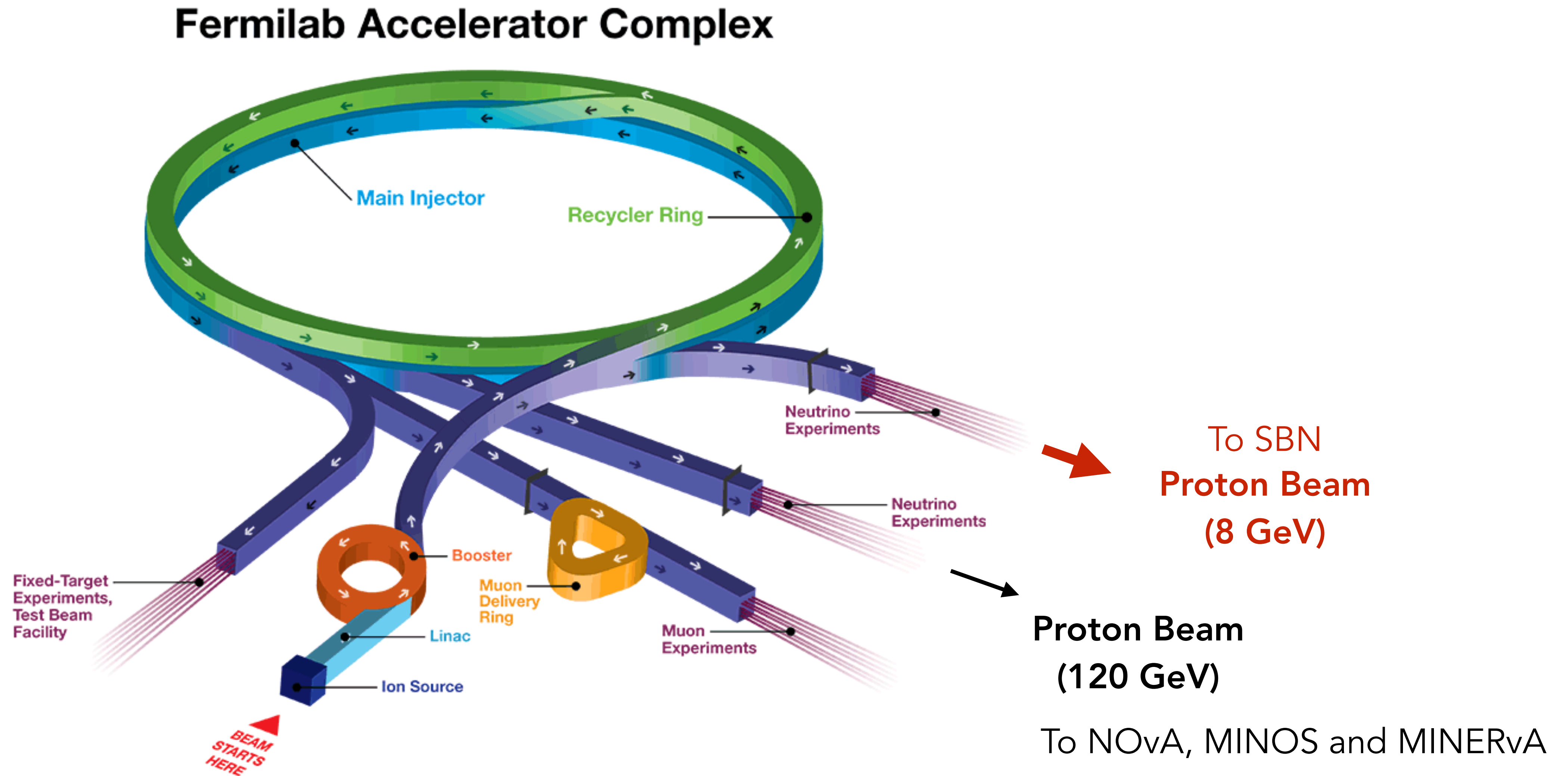


Neutrino Beamline

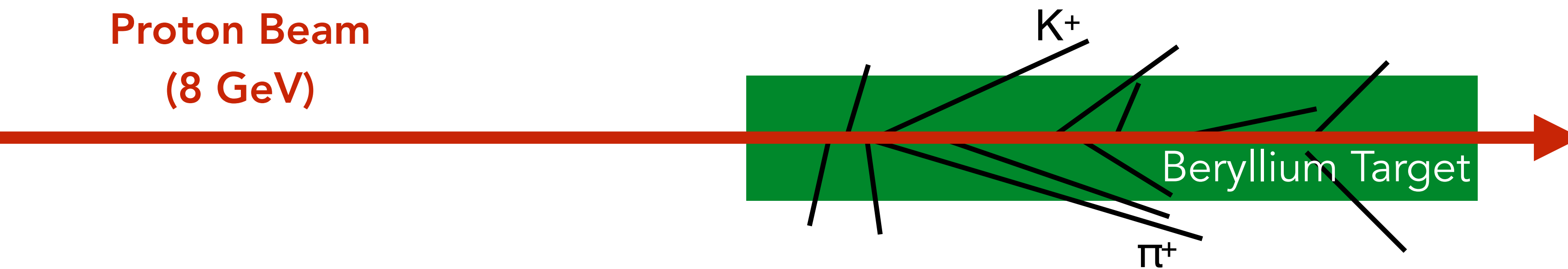
ICARUS
MicroBooNE
SBND



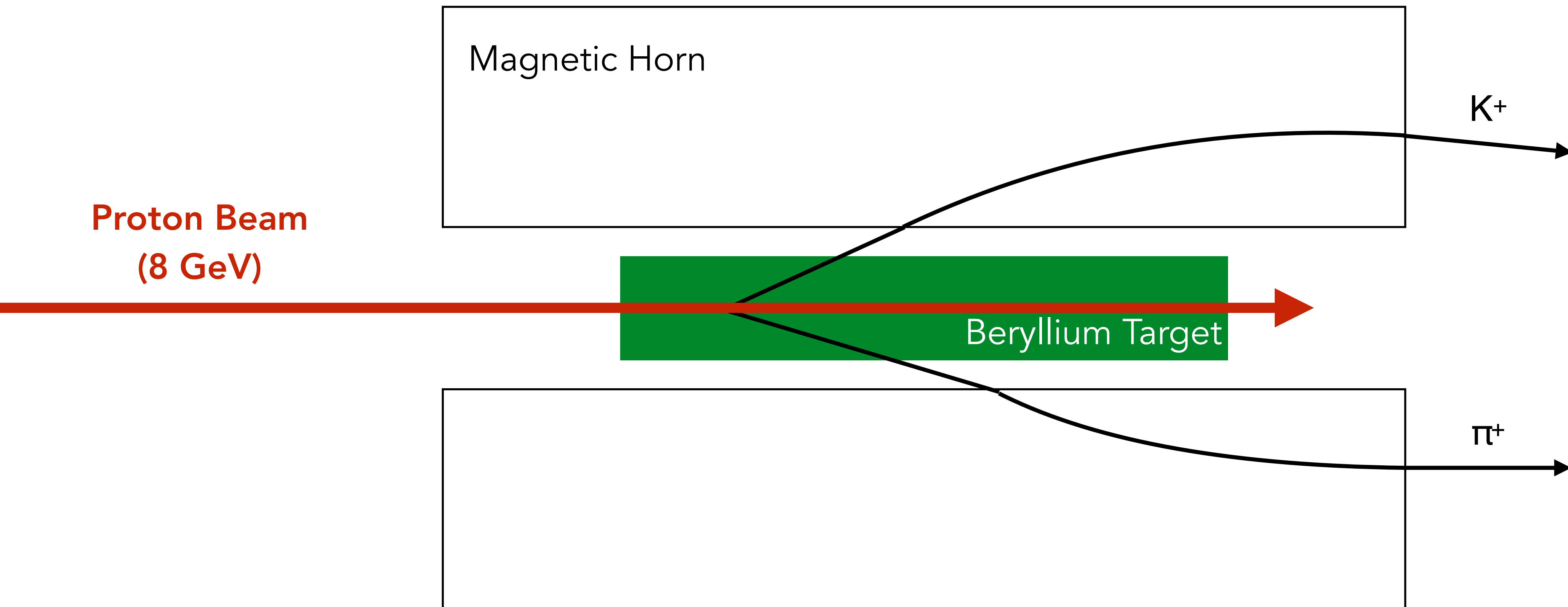
Neutrino Beamline



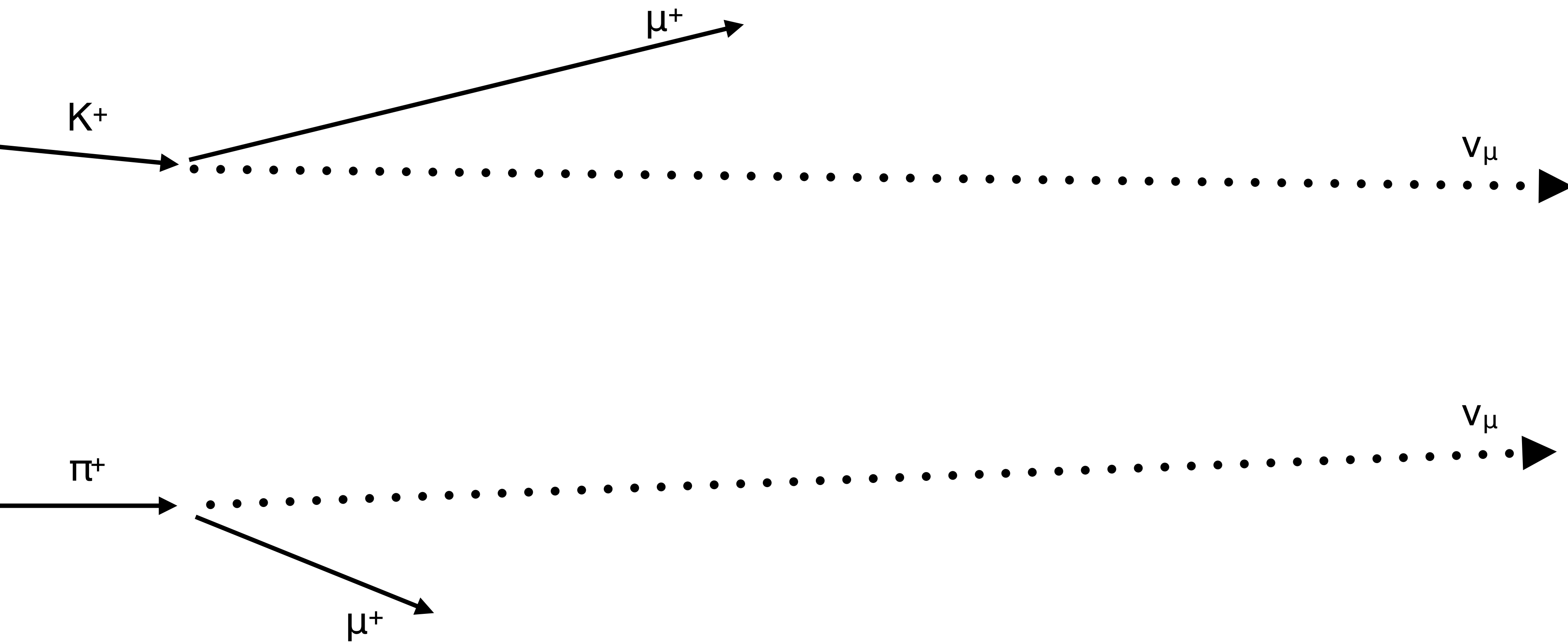
Neutrino Beamline



Neutrino Beamline



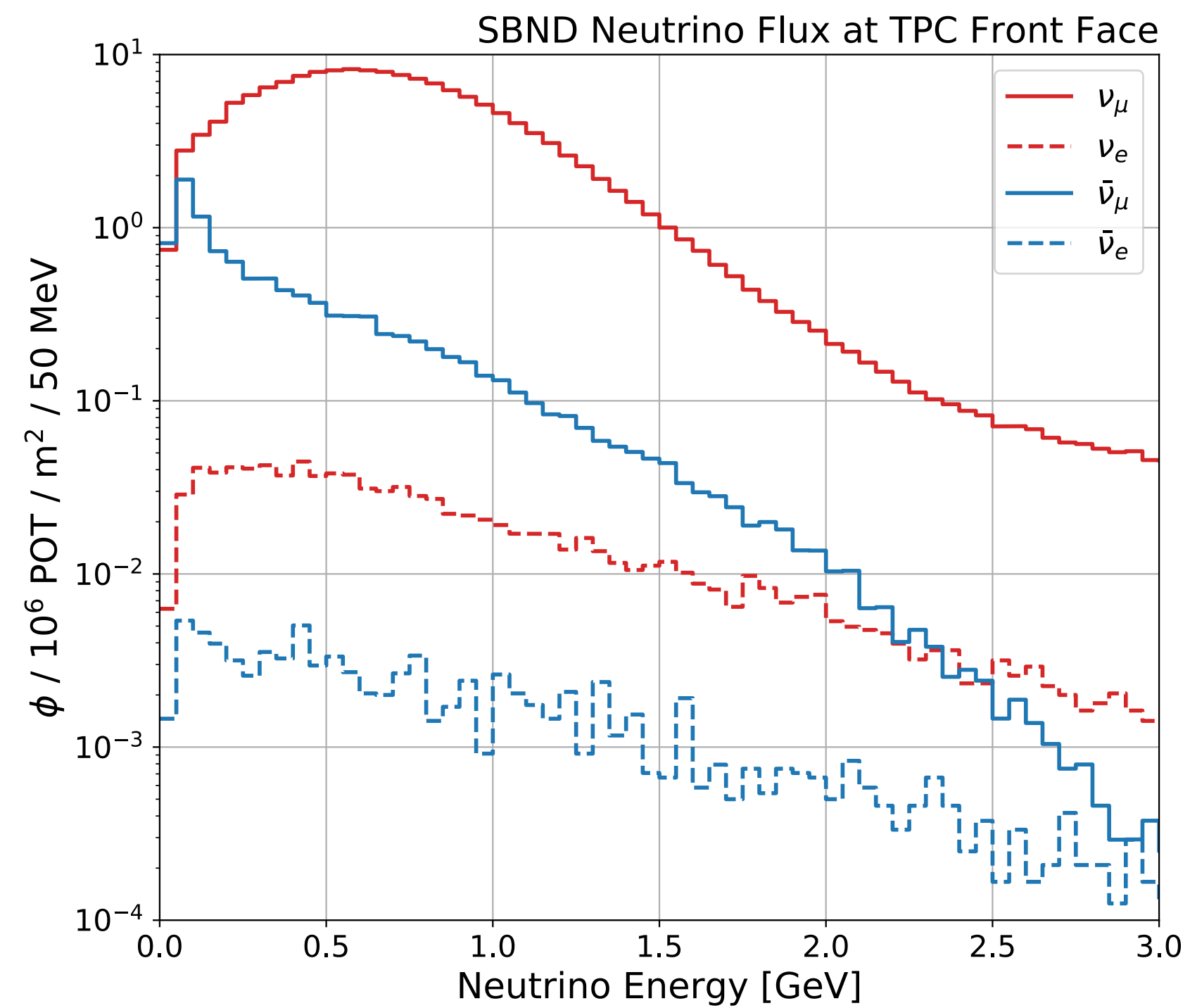
Neutrino Beamline



Neutrino Beam!


To SBN

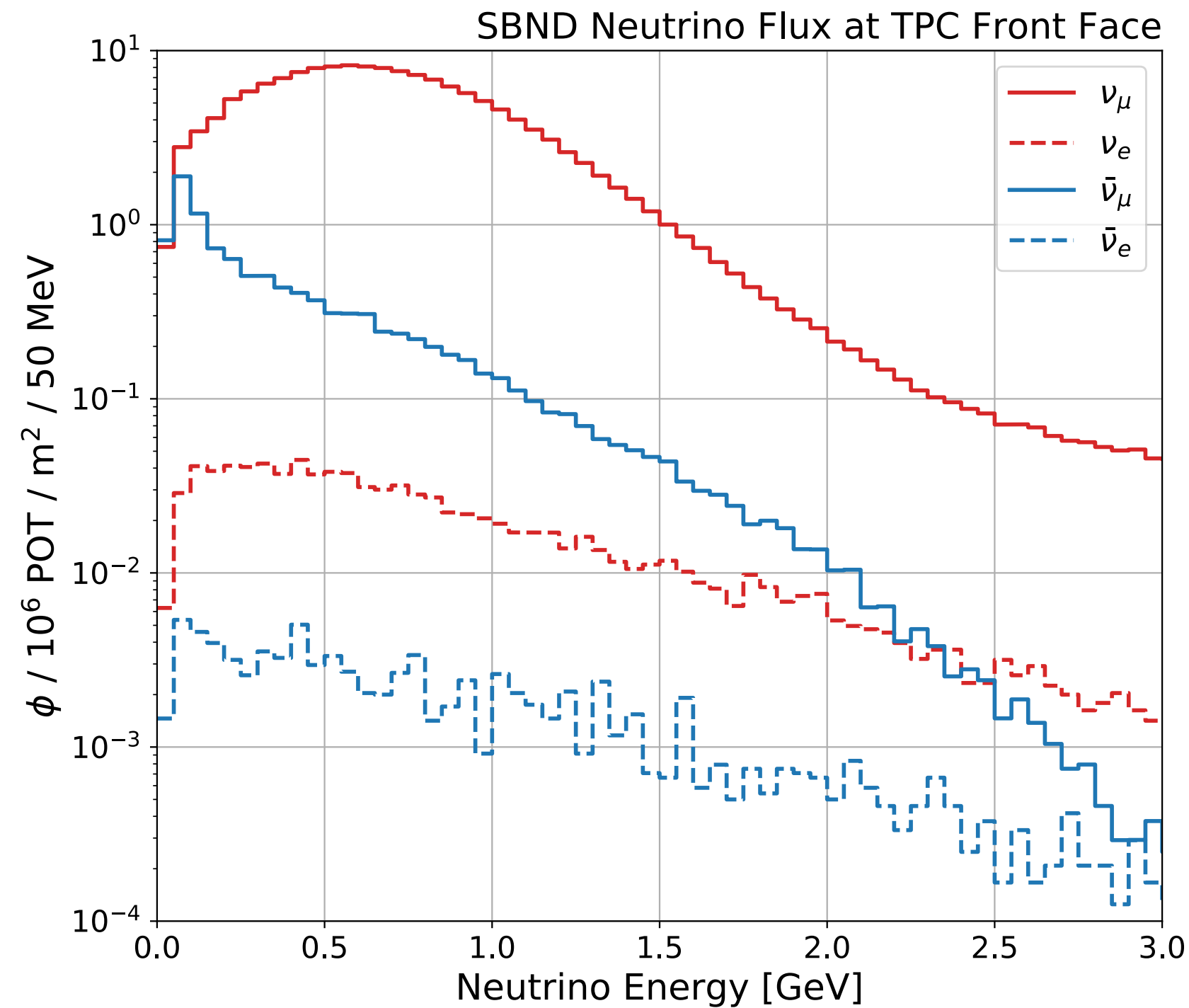
Neutrino Flux at SBND



Neutrino flux at the SBND
front face.

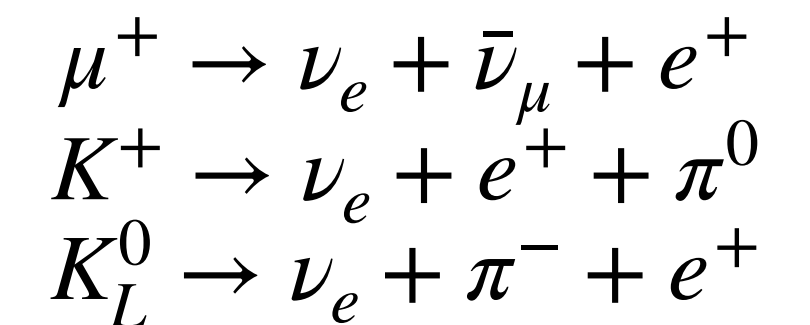
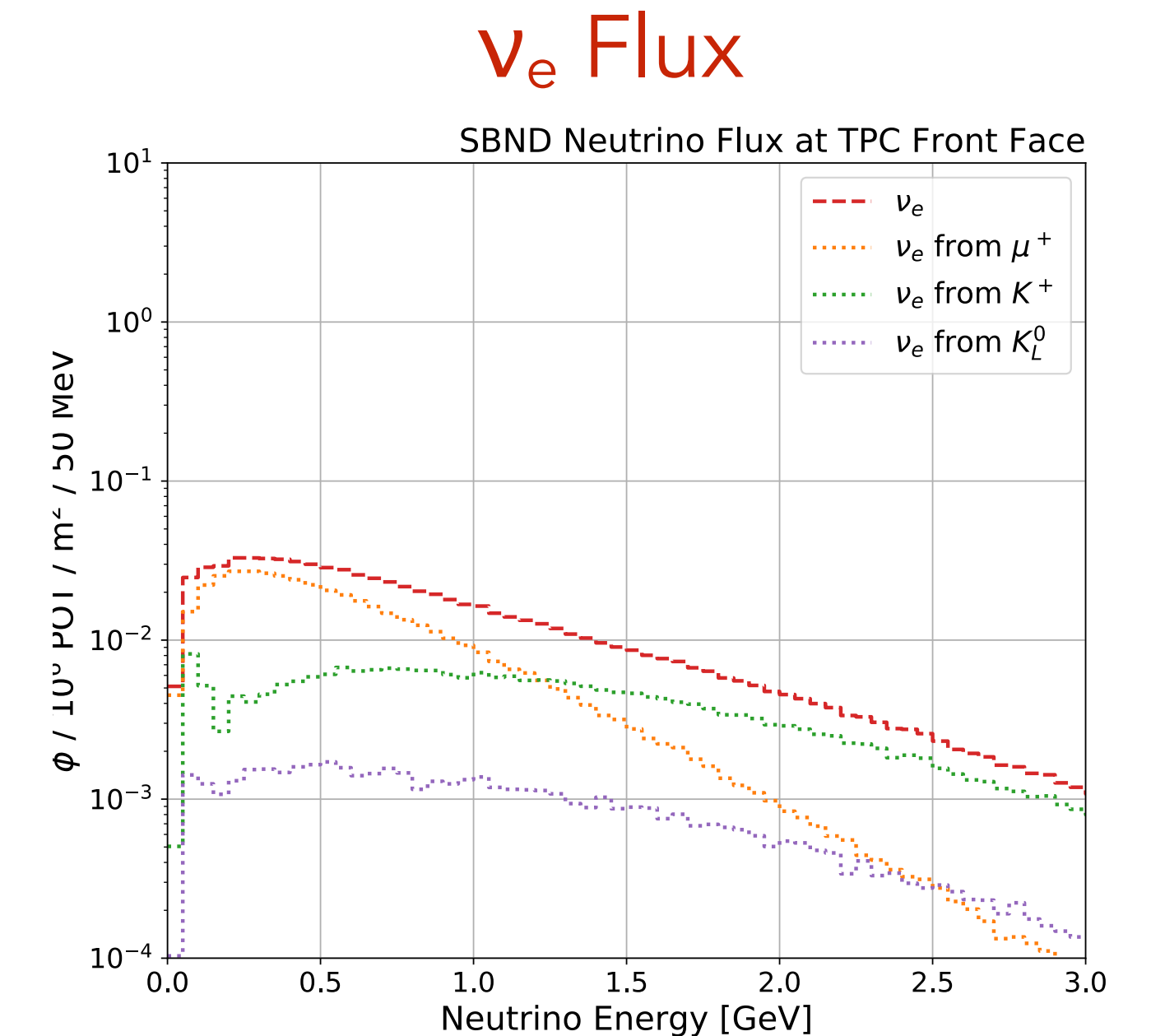
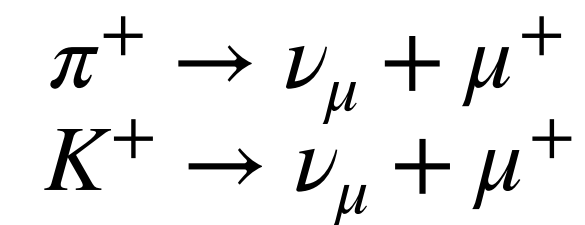
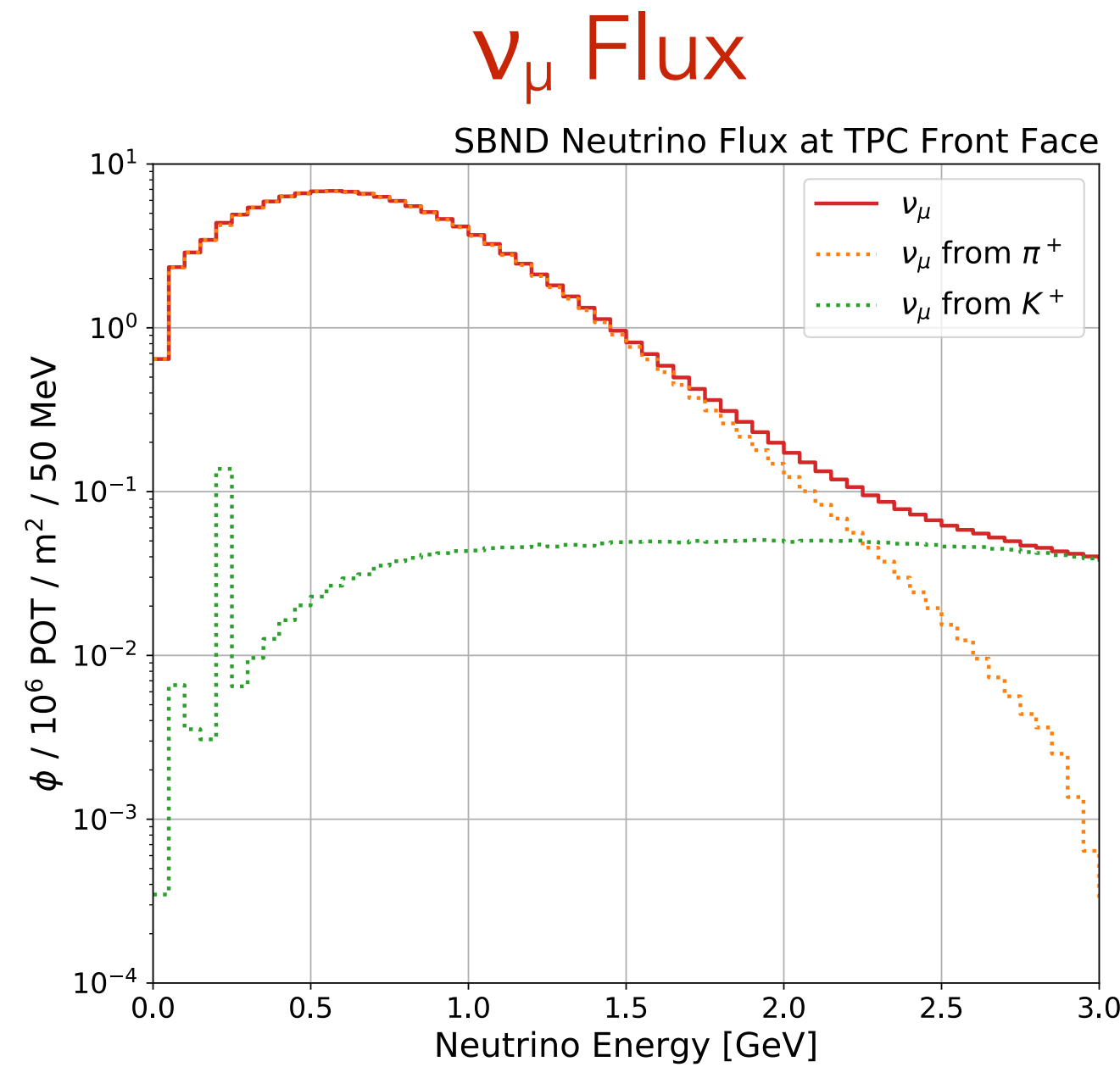
ν_μ (93.6%), $\bar{\nu}_\mu$ (5.9%), $\nu_e + \bar{\nu}_e$ (0.5%)

Neutrino Flux at SBND



Neutrino flux at the SBND
front face.

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

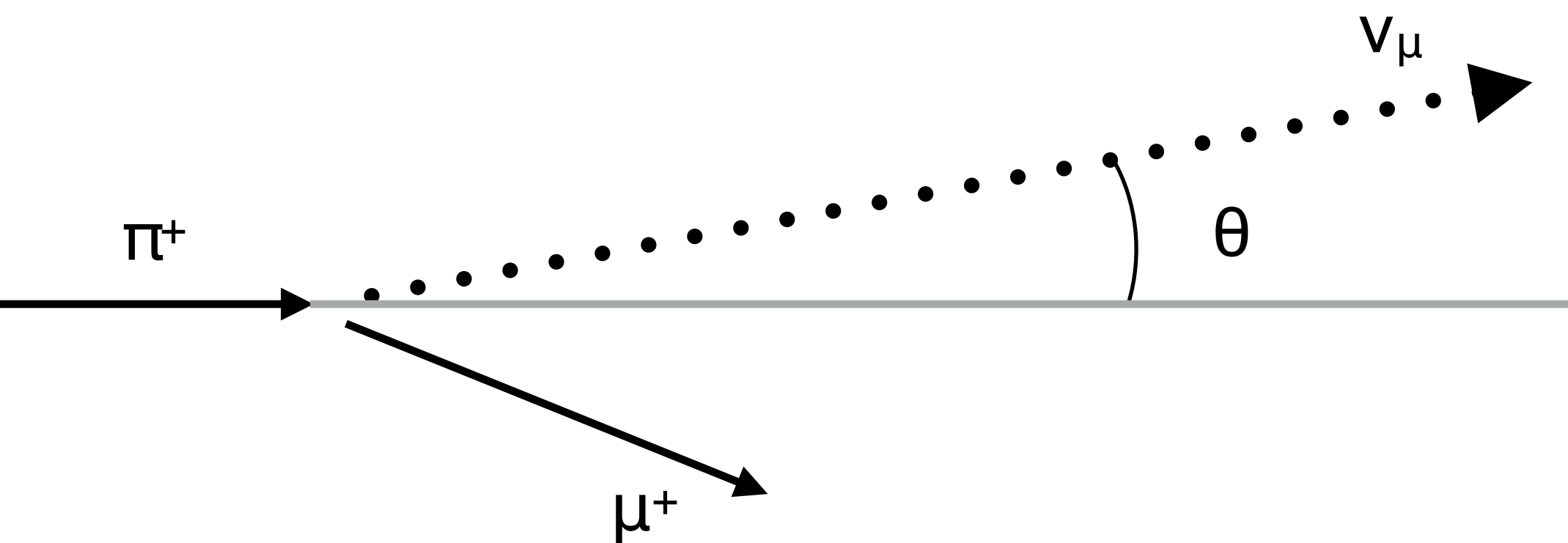


The ν_μ come predominantly from two-body decays while the ν_e come from three-body decays: the flux of ν_e has a larger angular spread than that of ν_μ (at the same parent energy): the ν_e to ν_μ flux ratio changes as we move off-axis.

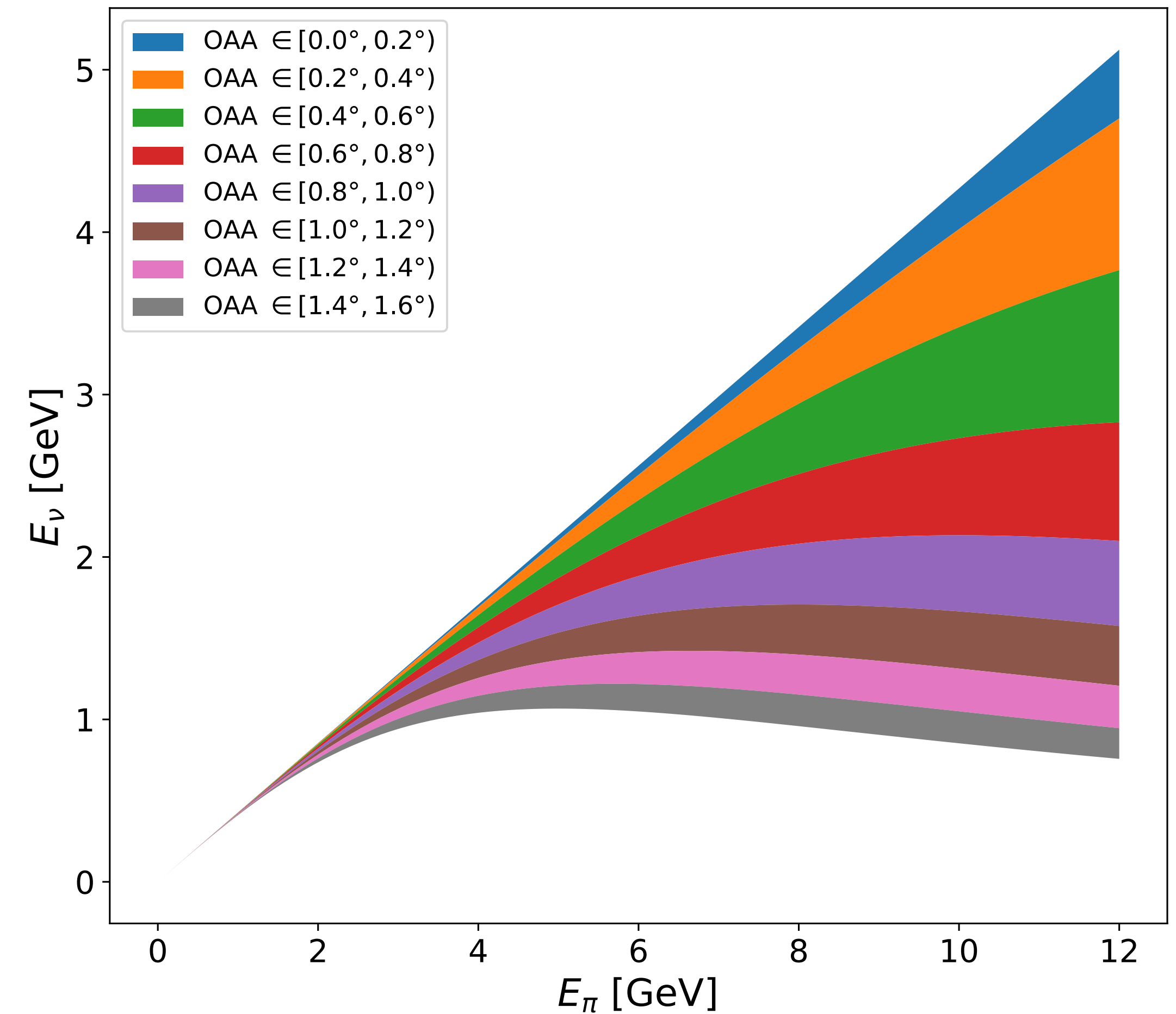
The Off-Axis Angle (OAA)

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

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

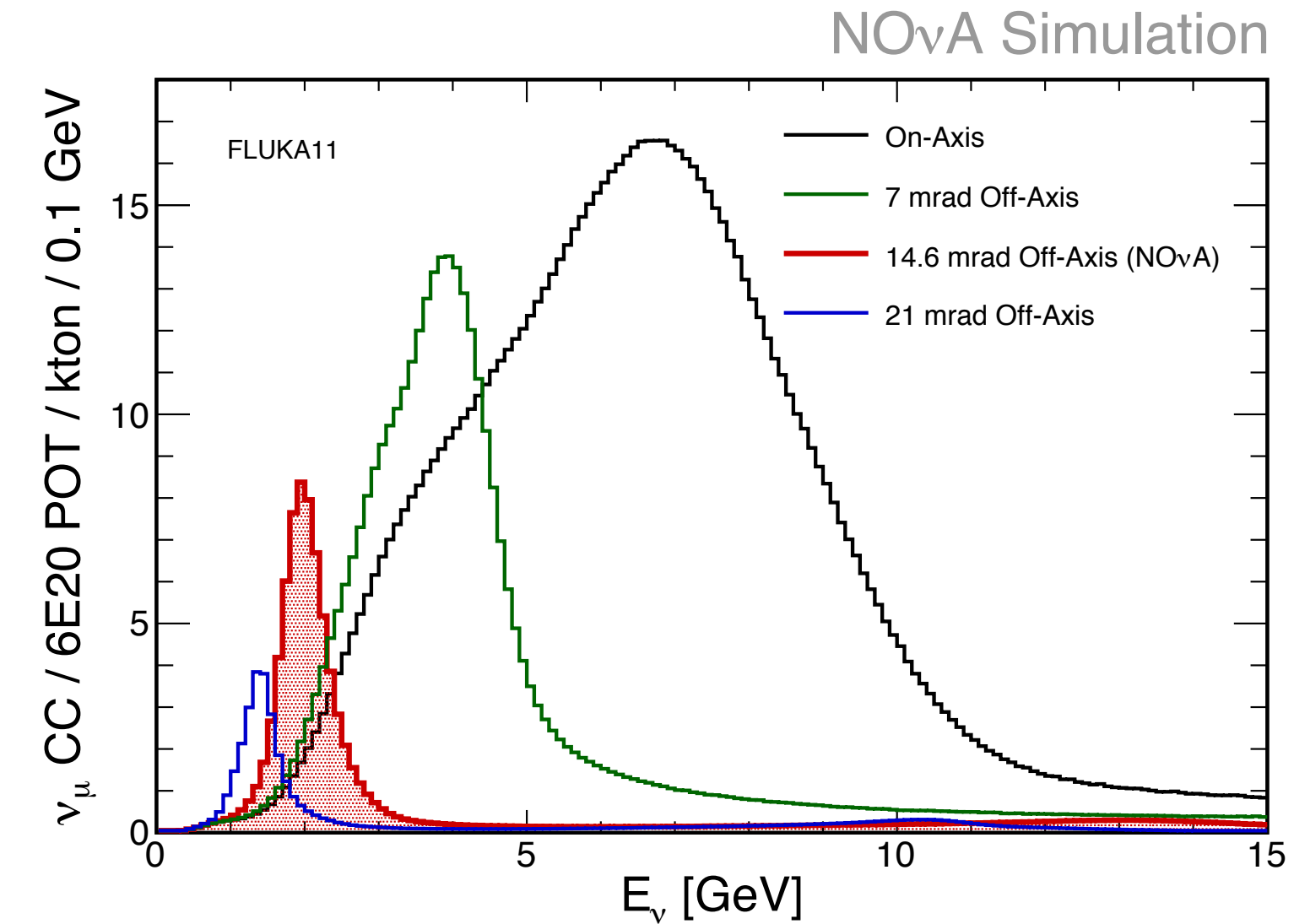


Neutrino Energy vs Pion Energy,
for different decay angles

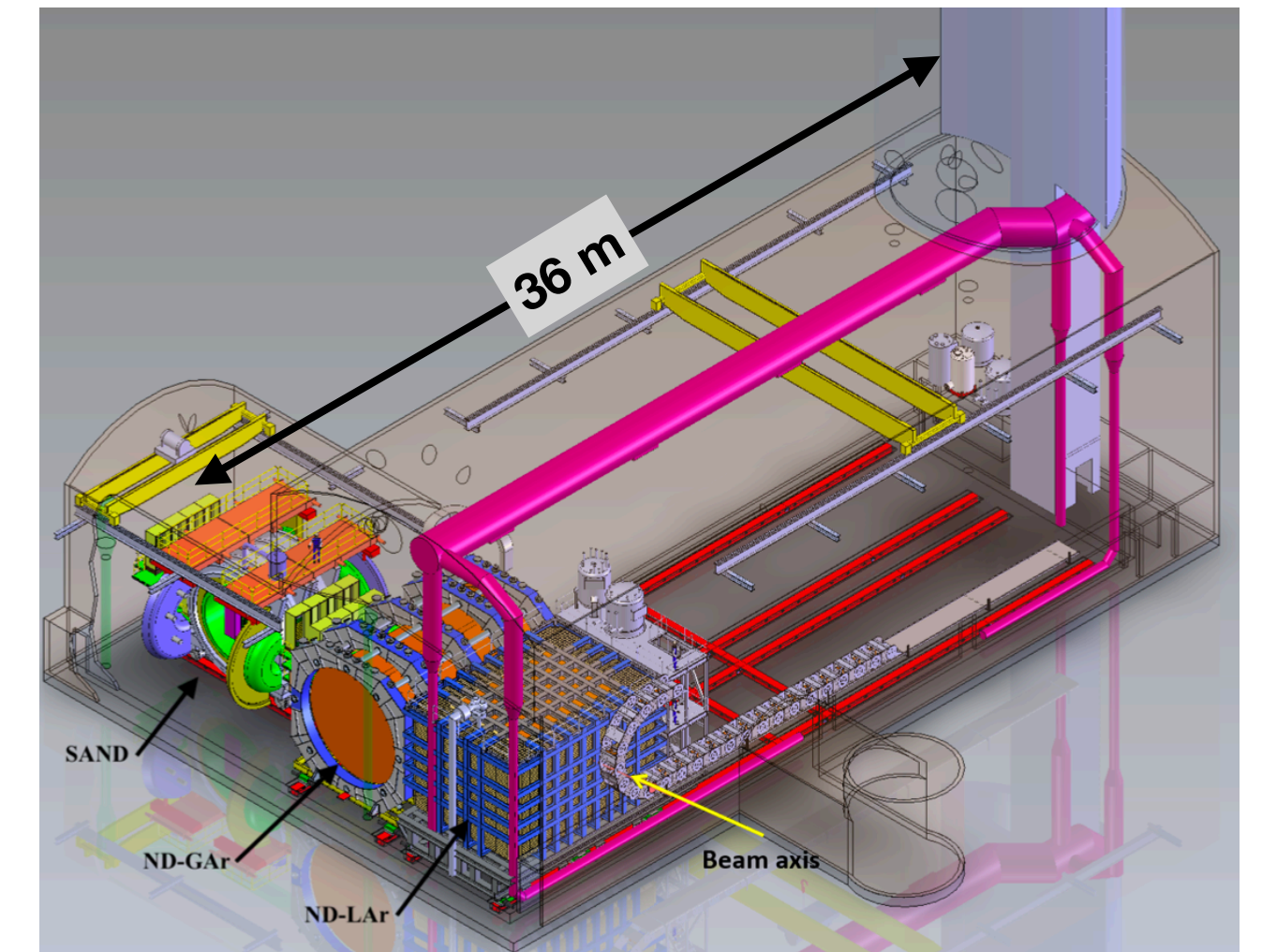
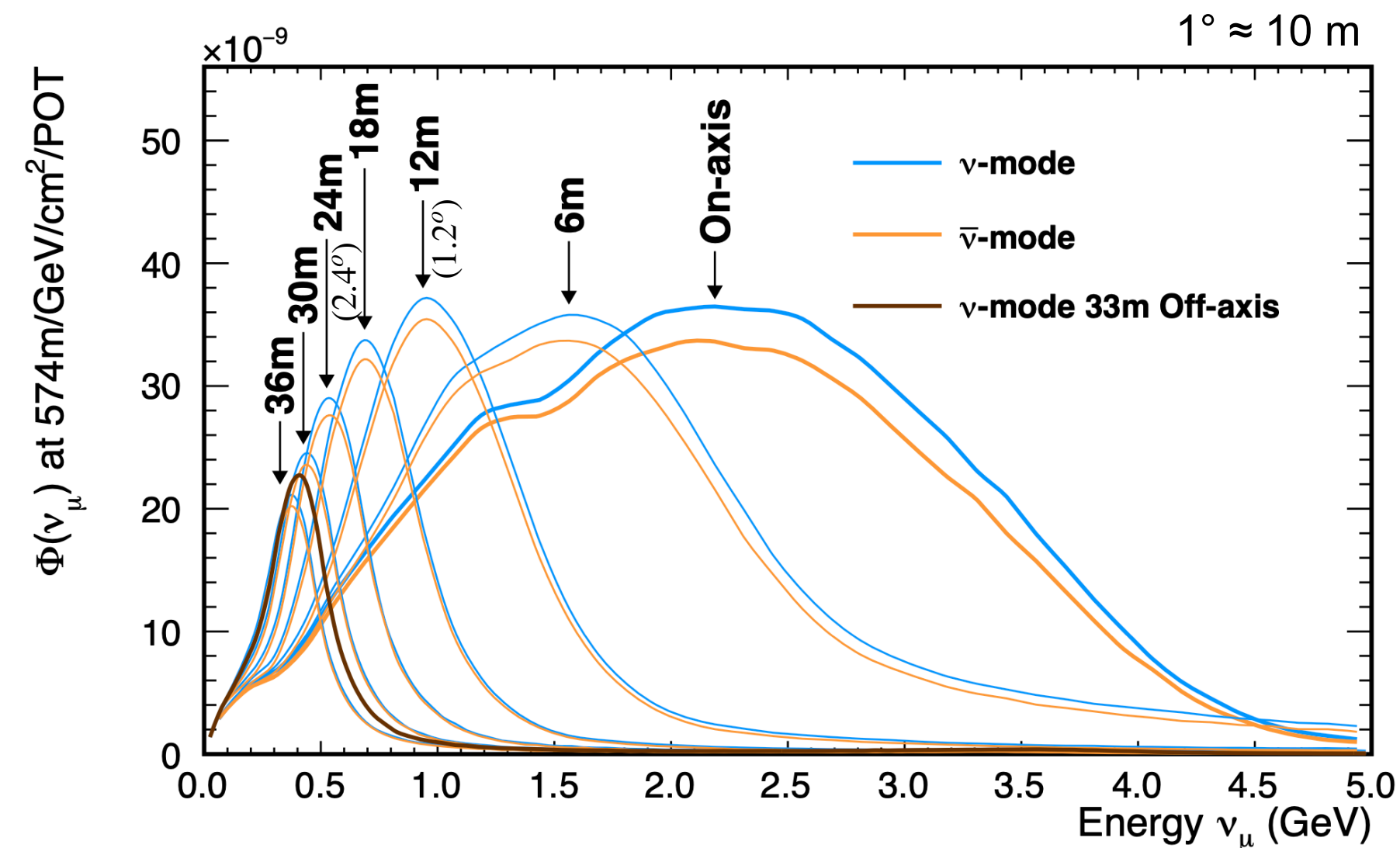


Off-Axis Angle Experiments

Some neutrino detectors are intentionally placed off-axis, to select a narrower neutrino energy spectrum, ex NOvA and T2K



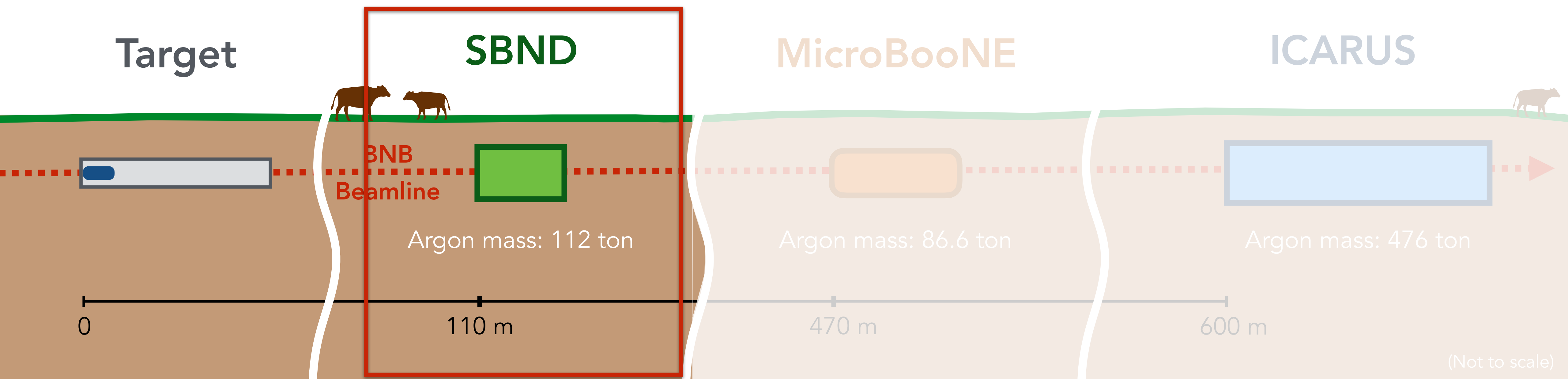
nuPRISM and DUNE-PRISM idea is to physically move the detector to select different off-axis angles



[DUNE Collaboration], arXiv:2103.13910 [physics.ins-det]

The Short Baseline Near Detector (SBND)

The SBND detector and SBND-PRISM

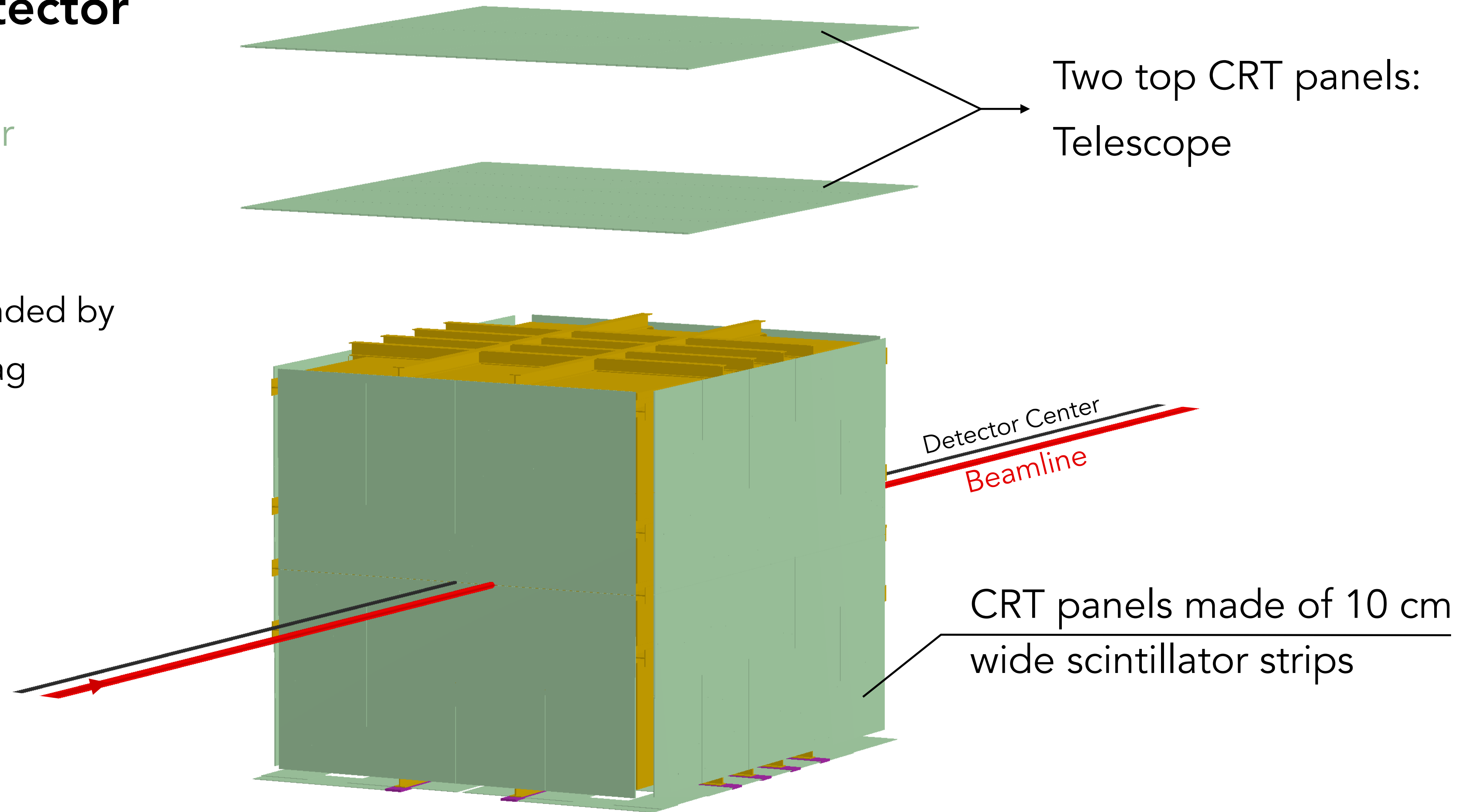


A Slightly Off-Axis Detector

The SBND detector

Cosmic Ray Tagger
CRT

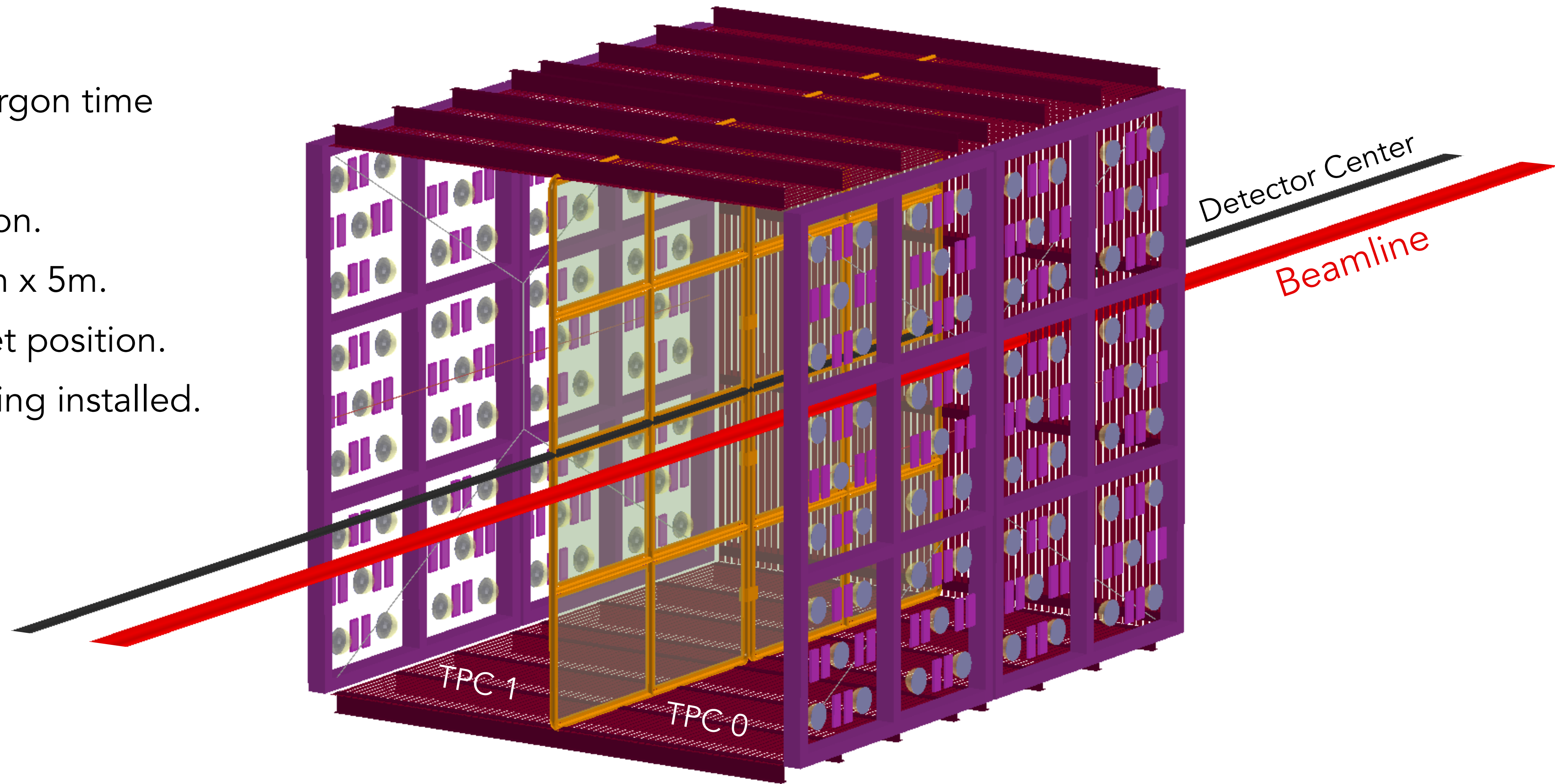
SBND will be surrounded by
scintillator strips to tag
cosmic rays



A Slightly Off-Axis Detector

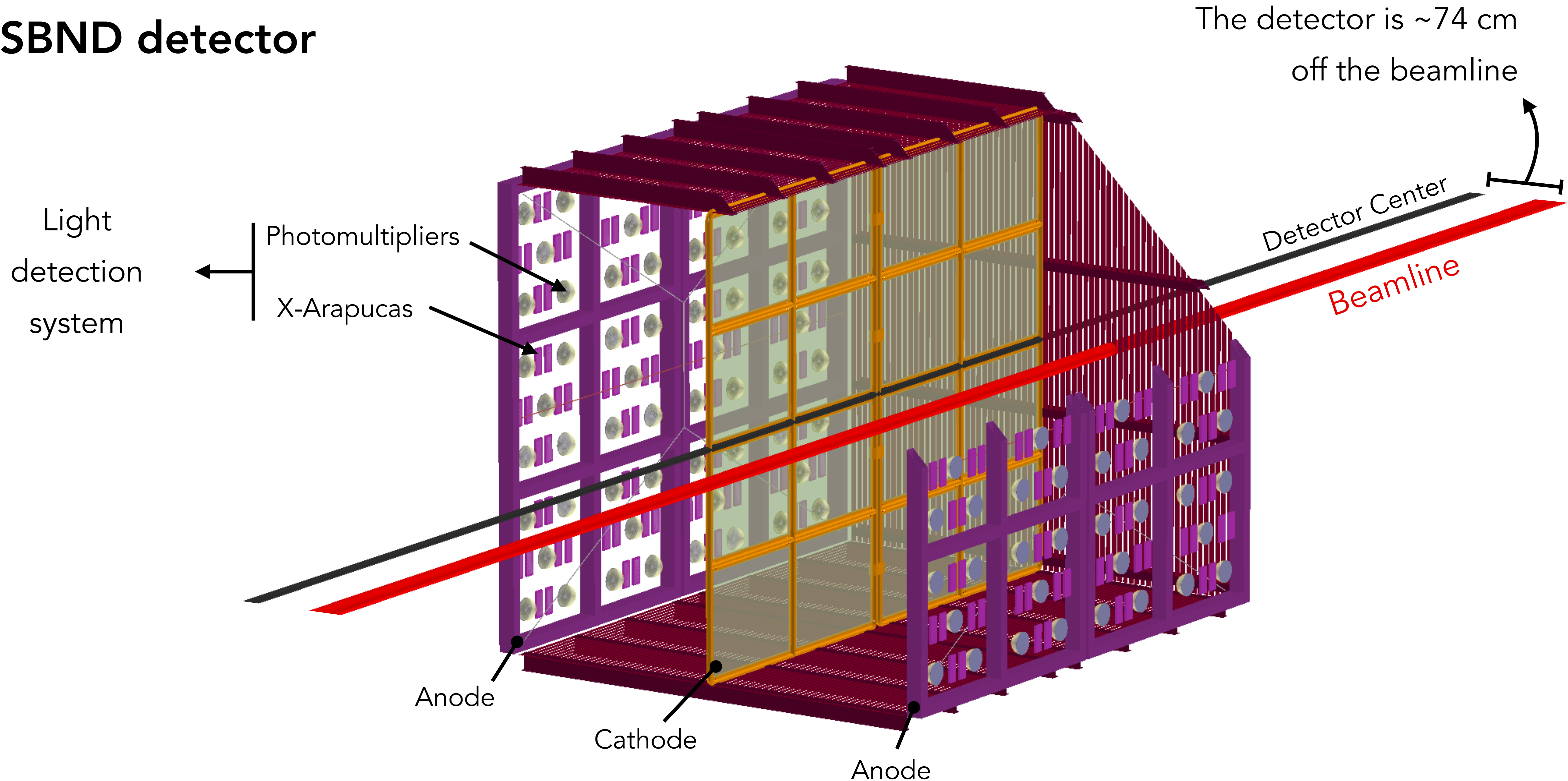
The SBND detector

- 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

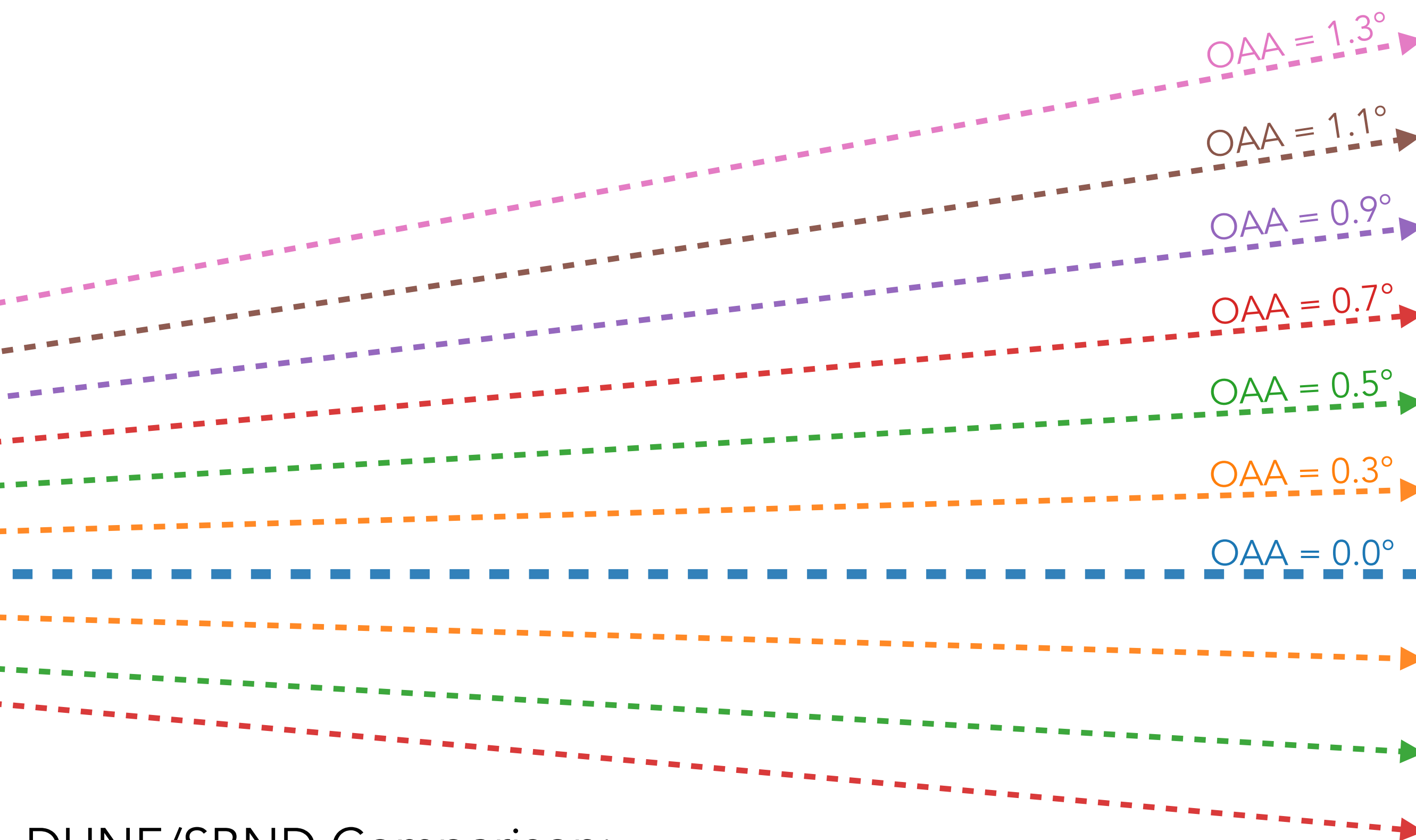
The SBND detector



A Slightly Off-Axis Detector

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

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

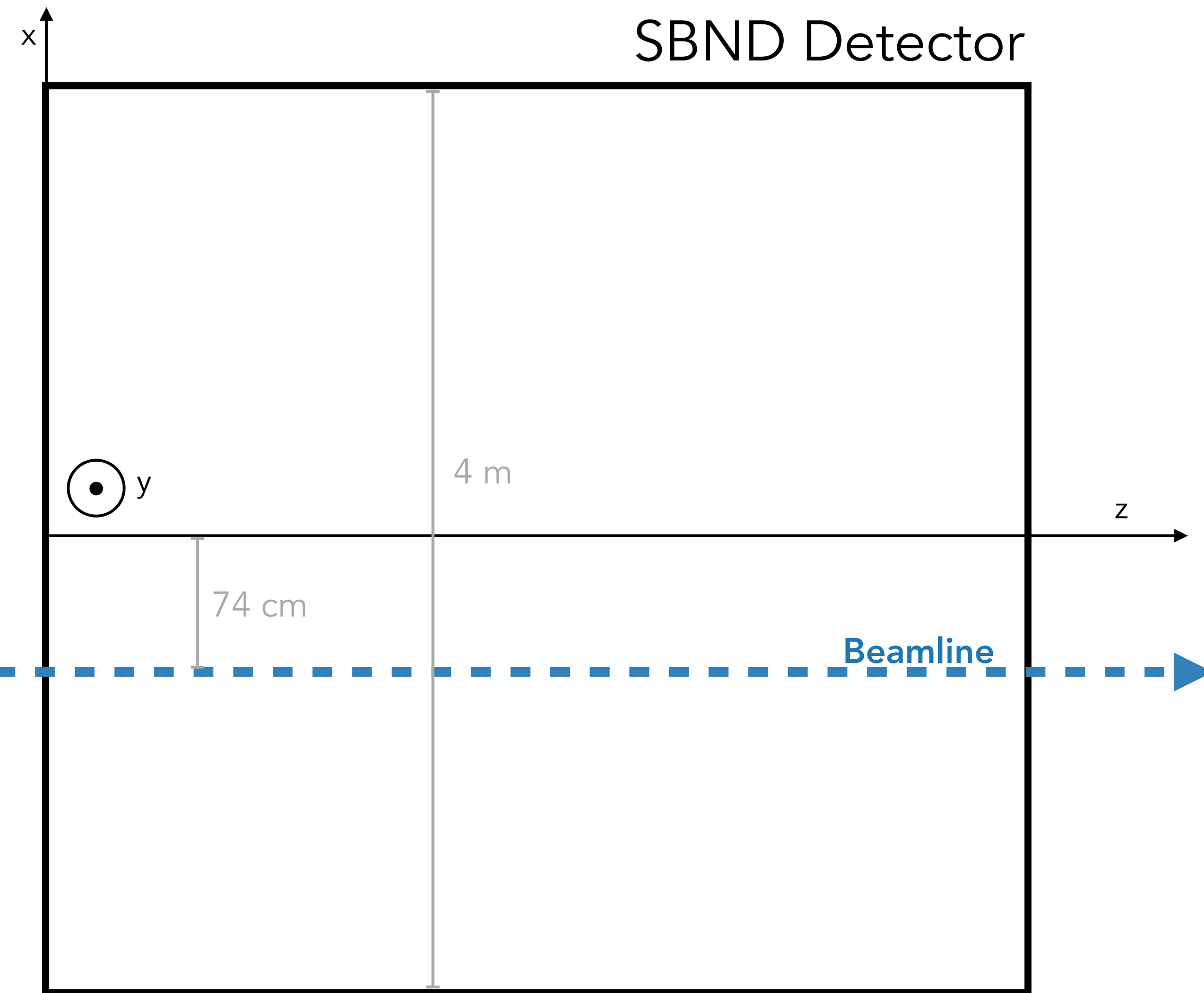


DUNE/SBND Comparison:

DUNE: $1^\circ \approx 10$ m

SBND: $1^\circ \approx 2$ m

View from the top
SBND Detector



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:

$OAA \in [0.0^\circ, 0.2^\circ)$

$OAA \in [0.2^\circ, 0.4^\circ)$

$OAA \in [0.4^\circ, 0.6^\circ)$

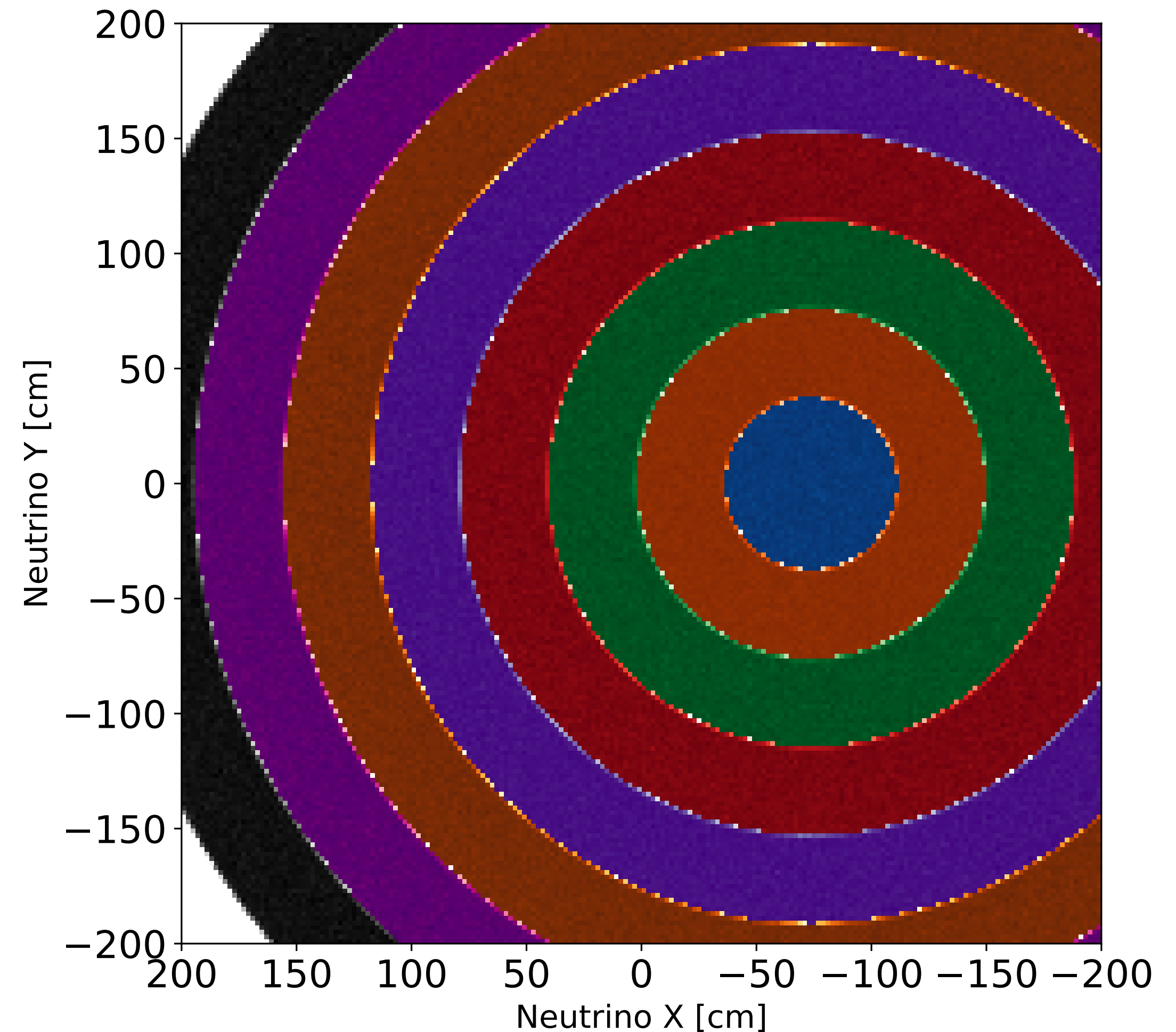
$OAA \in [0.6^\circ, 0.8^\circ)$

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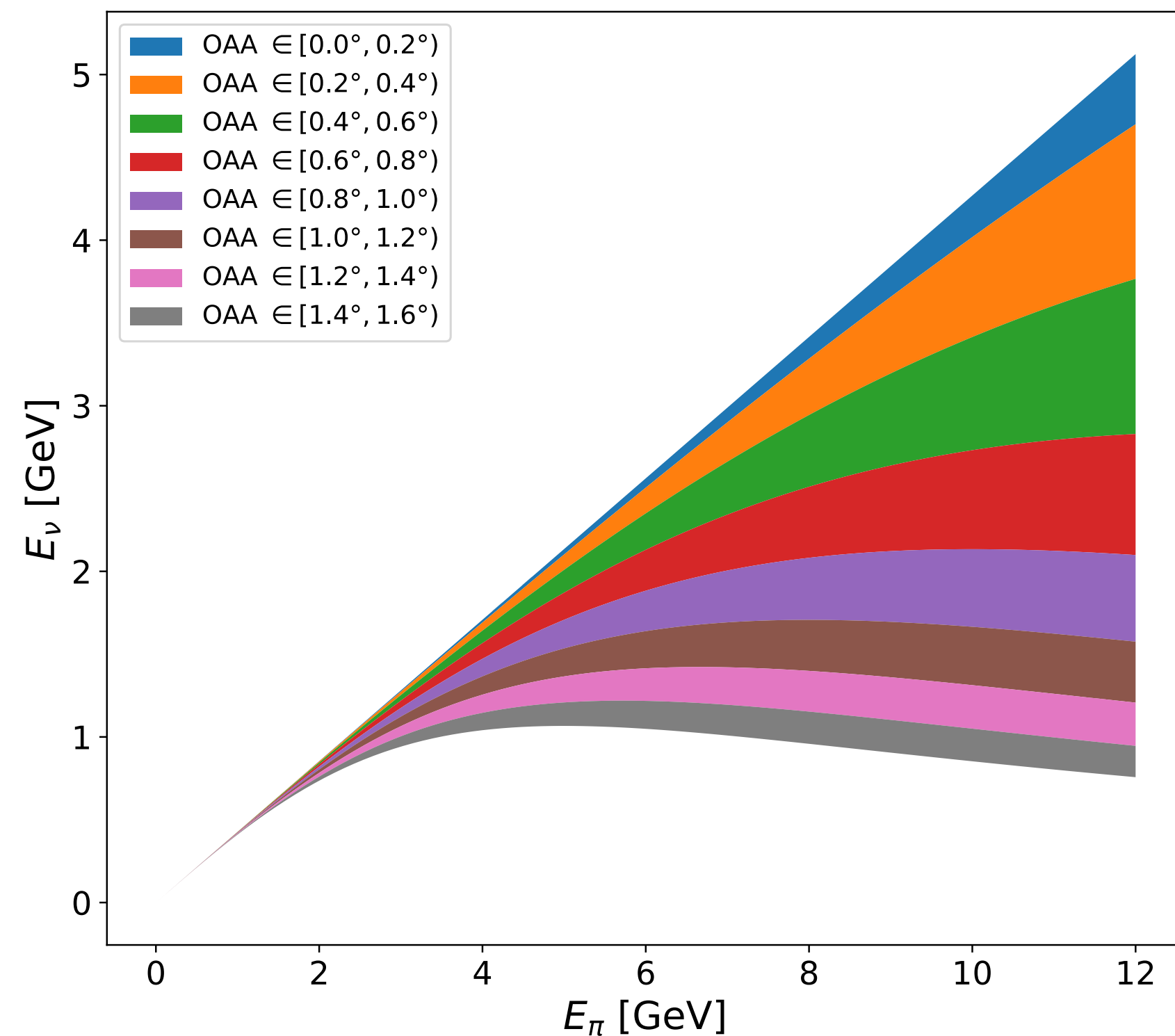


SBND-PRISM

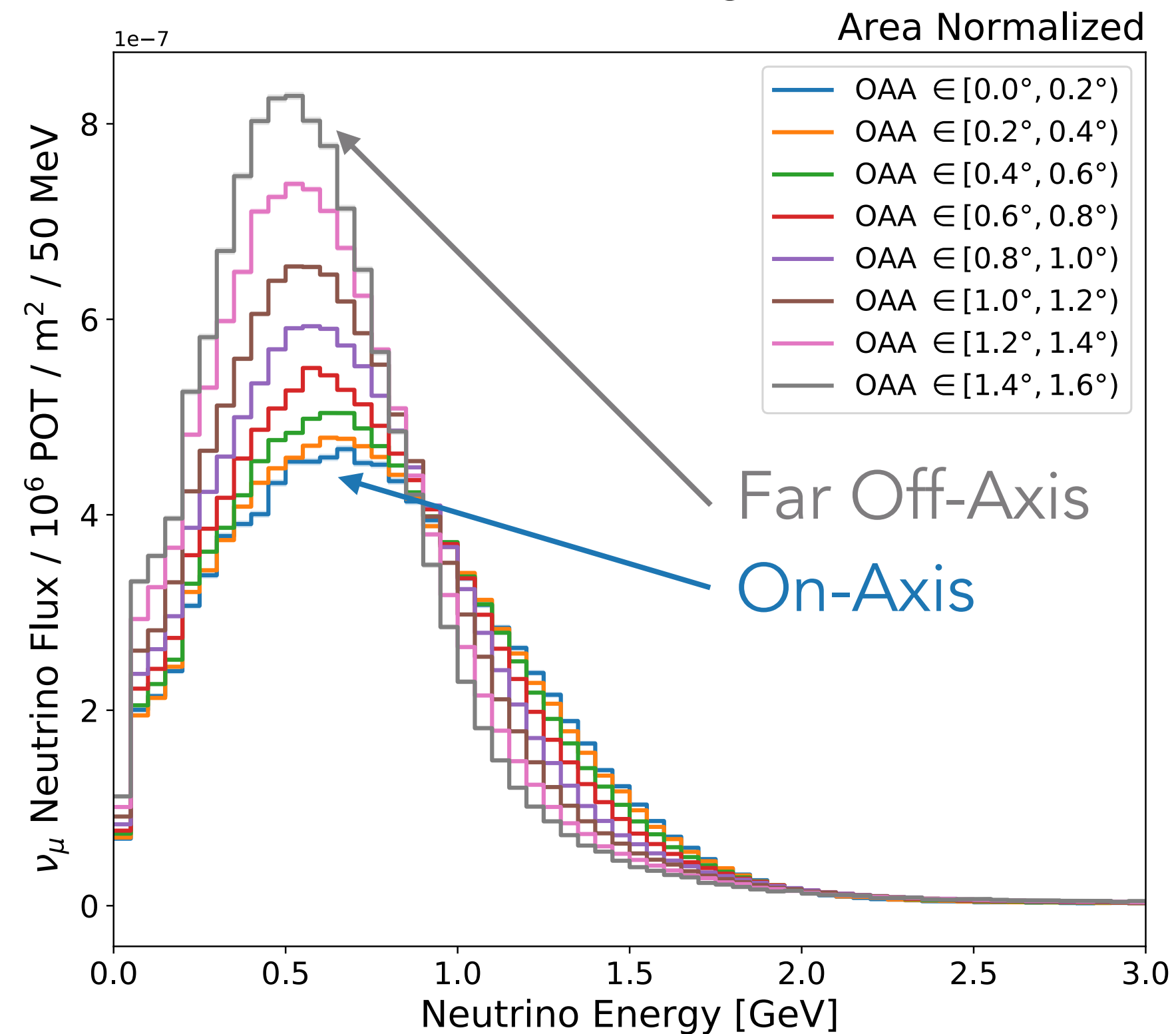
Precision Reaction Independent Spectrum Measurement (*)

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 $\in [0.0^\circ, 0.2^\circ]$

OAA $\in [0.2^\circ, 0.4^\circ]$

OAA $\in [0.4^\circ, 0.6^\circ]$

OAA $\in [0.6^\circ, 0.8^\circ]$

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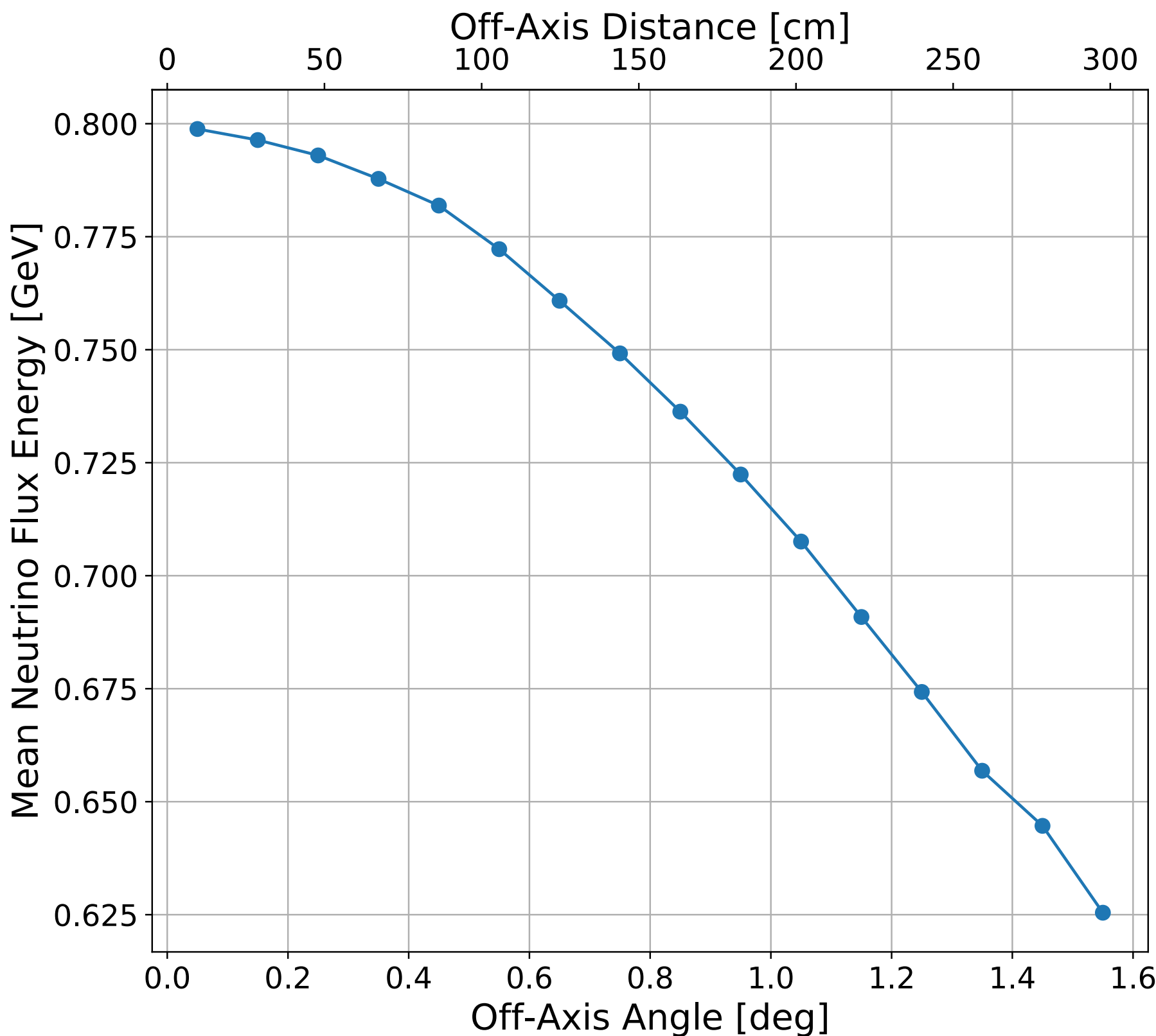
(*) nuPRISM <https://arxiv.org/abs/1412.3086>

SBND-PRISM

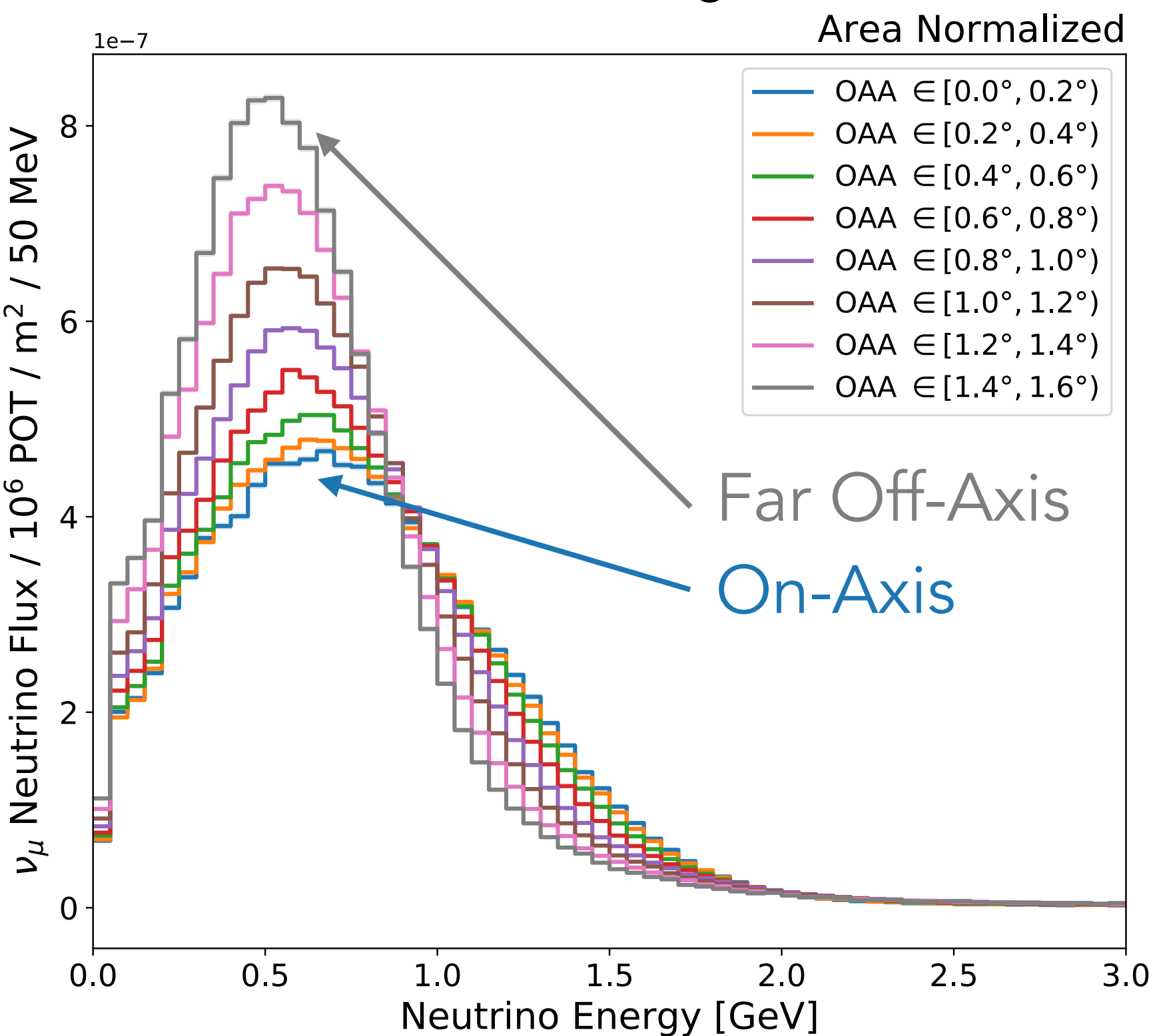
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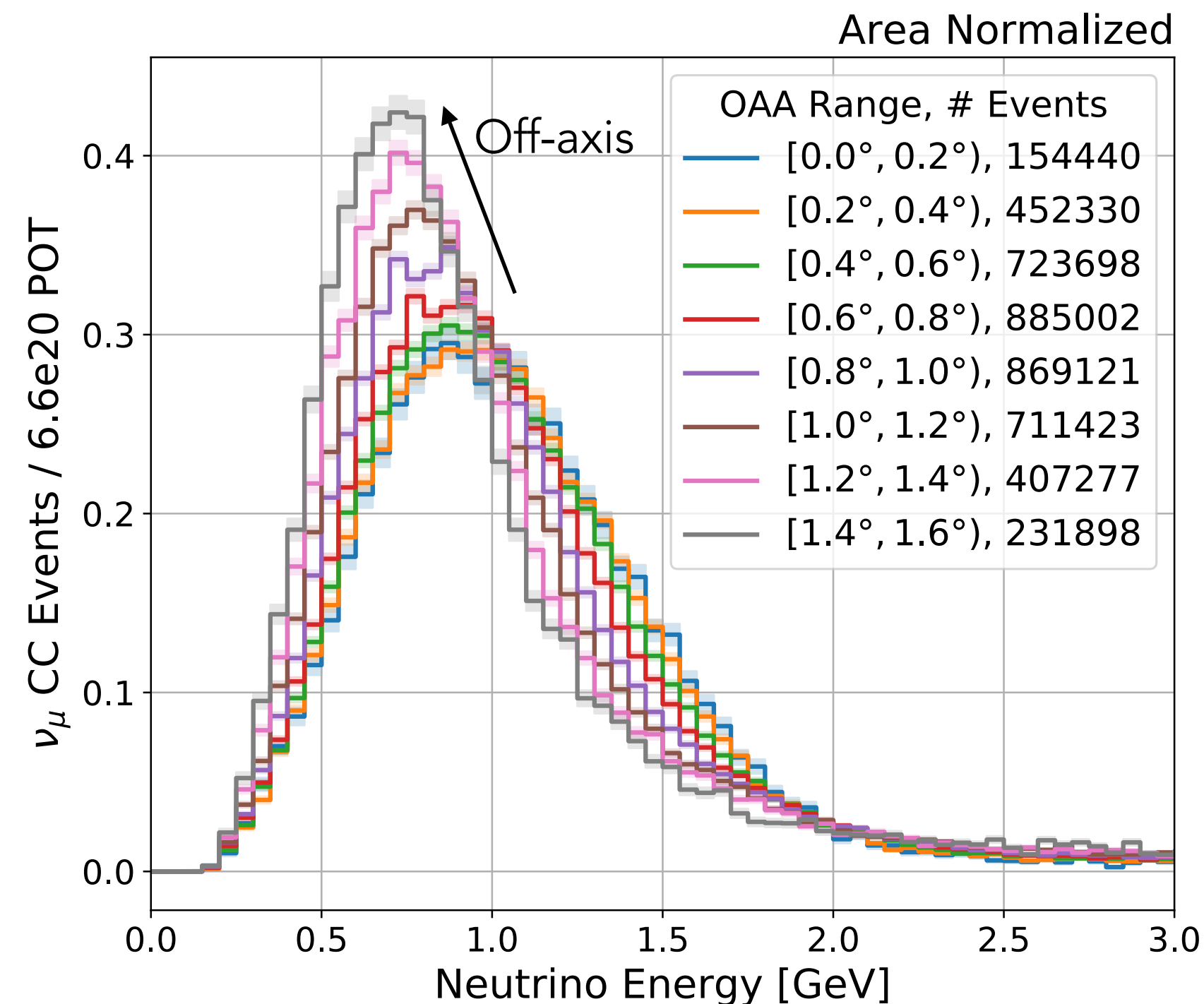
(*) nuPRISM <https://arxiv.org/abs/1412.3086>

SBND-PRISM - ν_μ / ν_e Differences 1/2

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

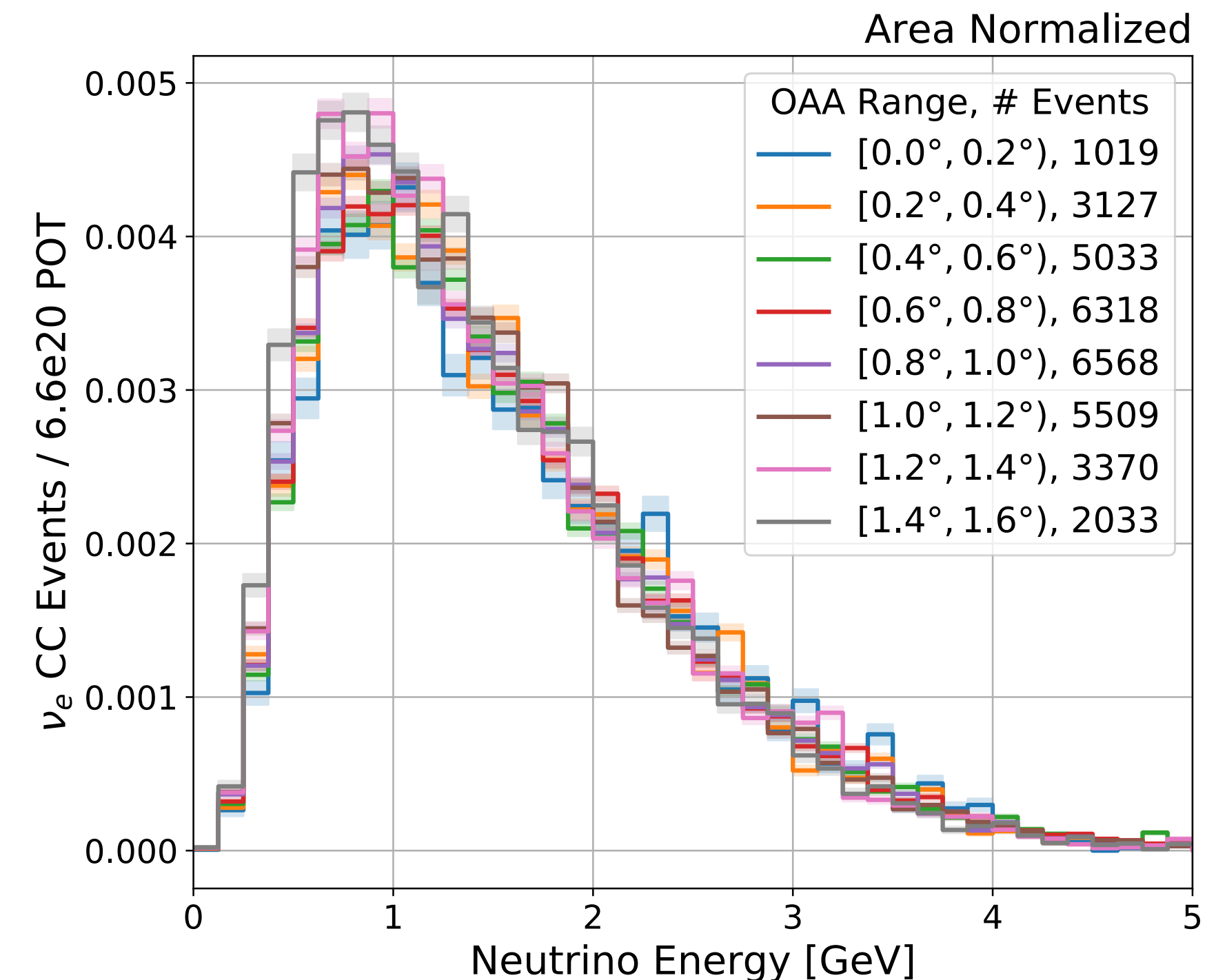
Muon-neutrino CC Events

higher off-axis angle \rightarrow lower mean energy



Electron-neutrino CC Events

higher off-axis angle \rightarrow ~same mean energy



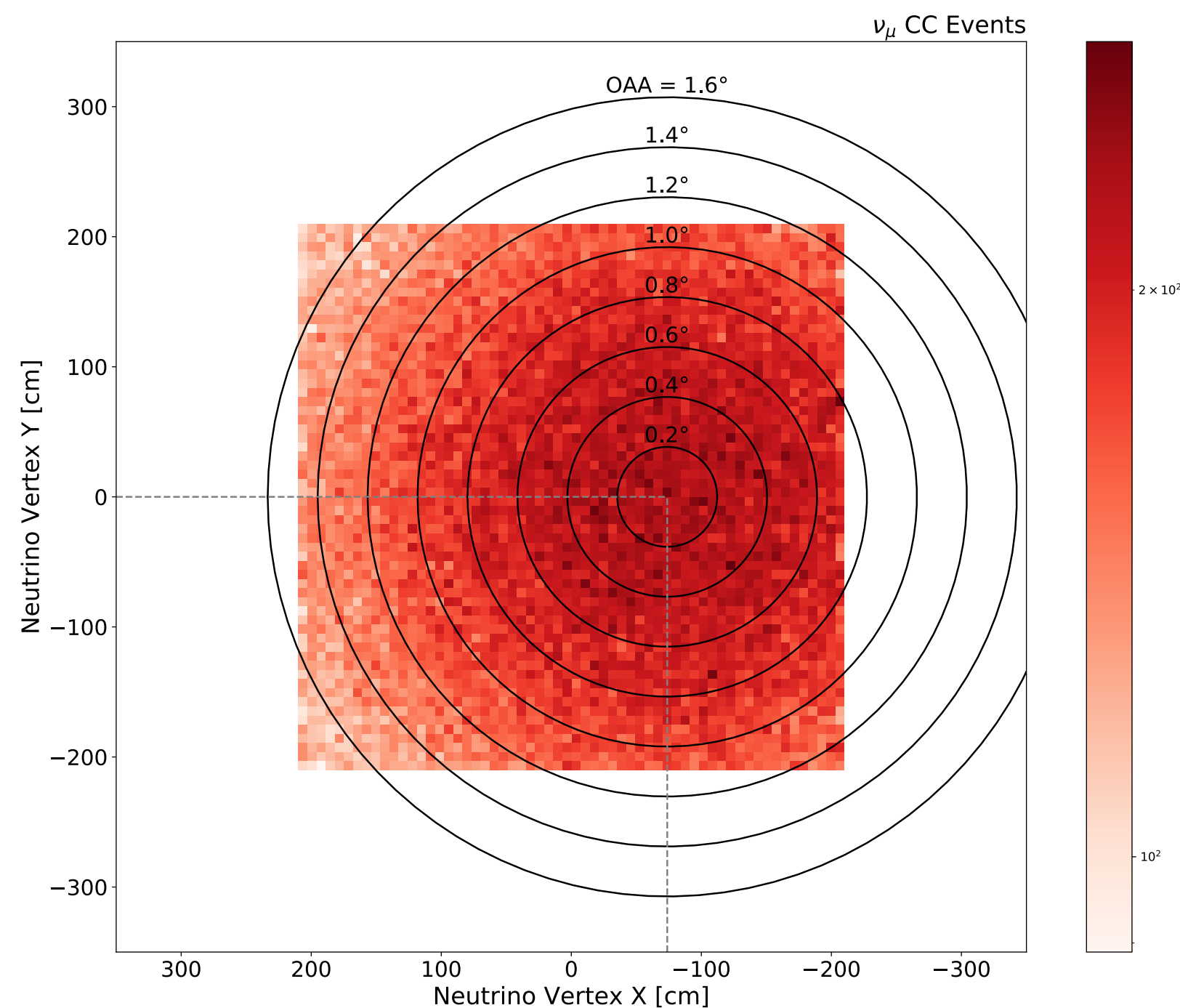
High event statistics in all off-axis regions

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.

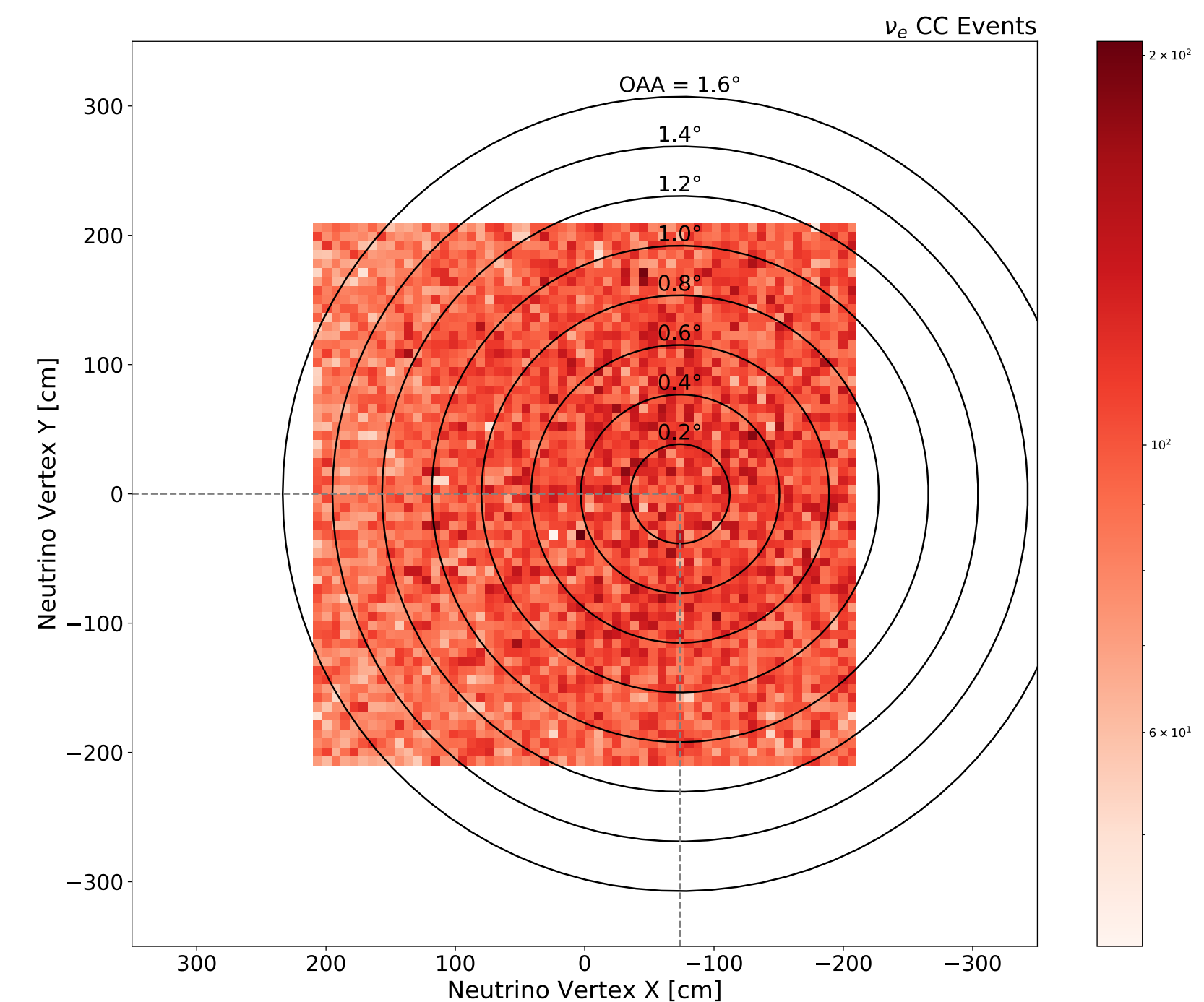
Muon-neutrinos CC Events

peak coincident with the on-axis position



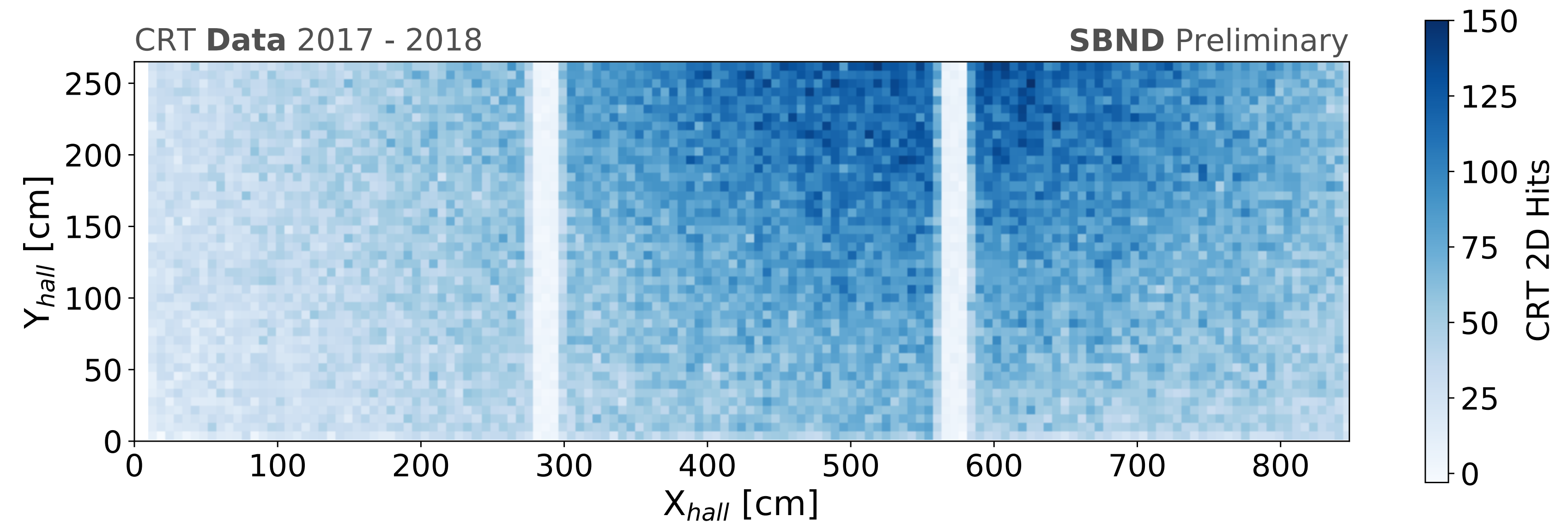
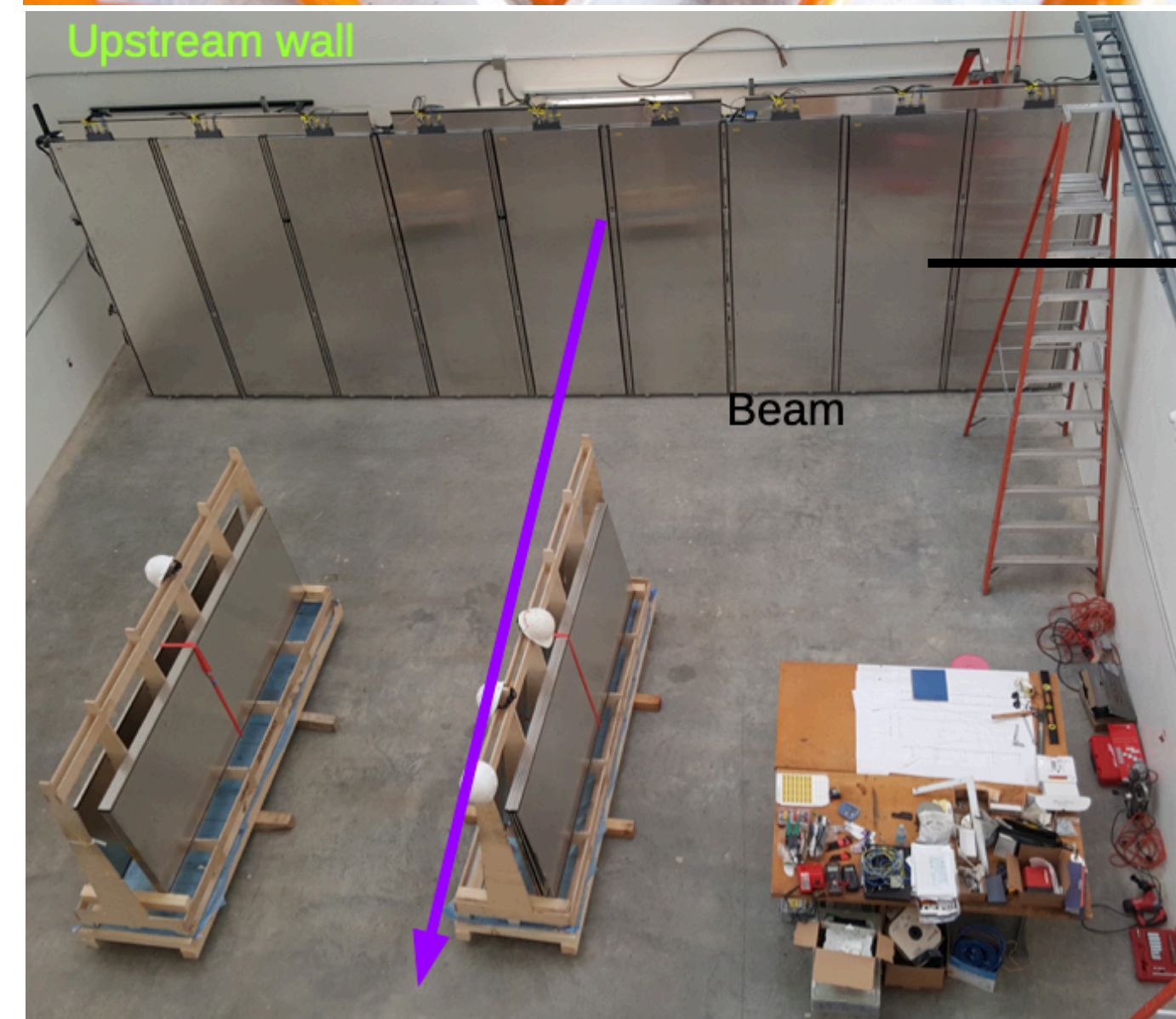
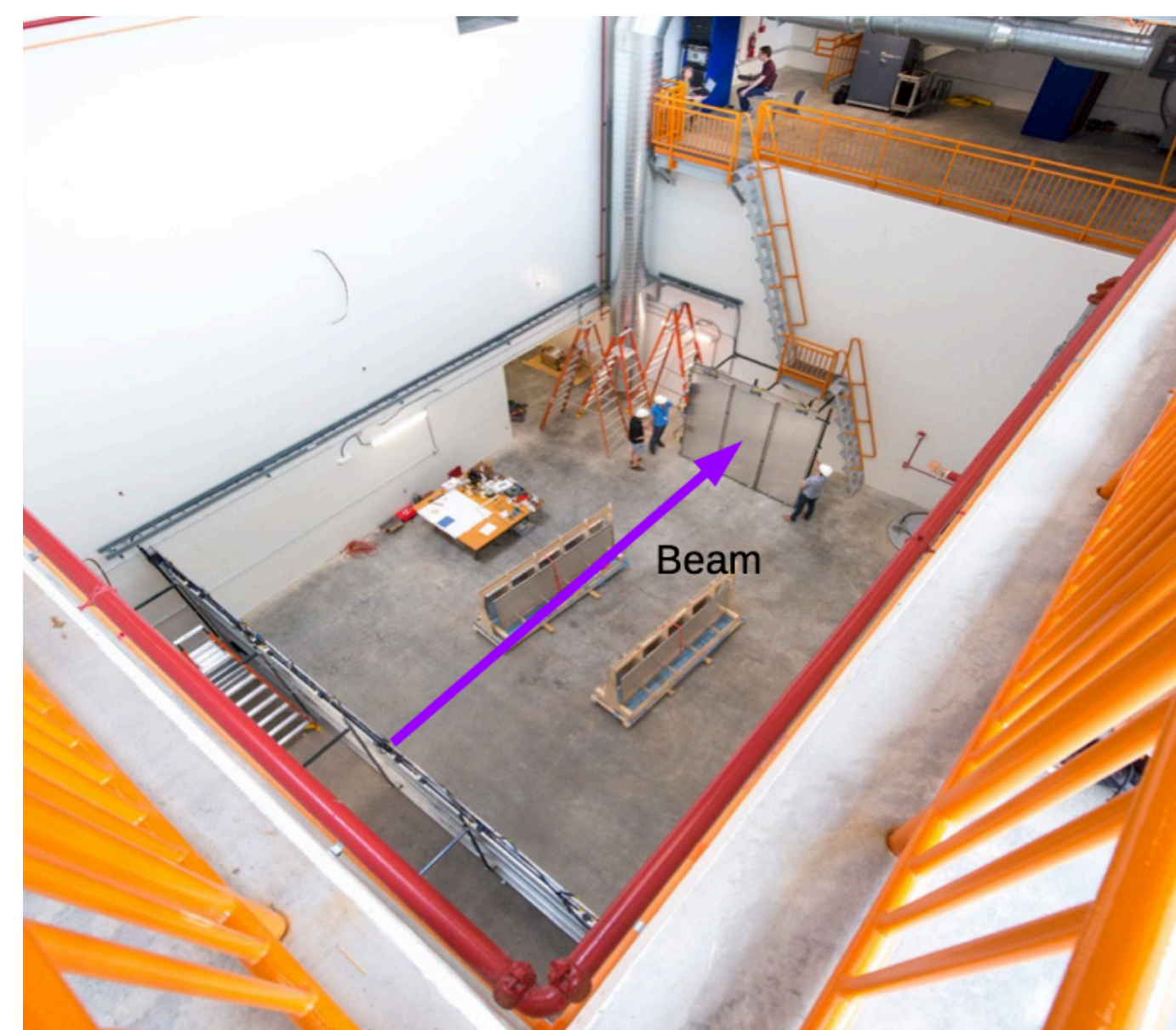
Electron-neutrinos CC Events

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.



Exploring Physics Potential of the SBND-PRISM

(Some ongoing studies, feedback/ideas welcome)

- Interaction Model Constraint
- Sterile Neutrino Oscillations
- SBND-Only Sterile Neutrino Oscillations
- Dark Matter Searches
- ...

Interaction Model Constraints

Interaction Model Constraint

Neutrino-Nucleus Interactions Physics

Energy dependence

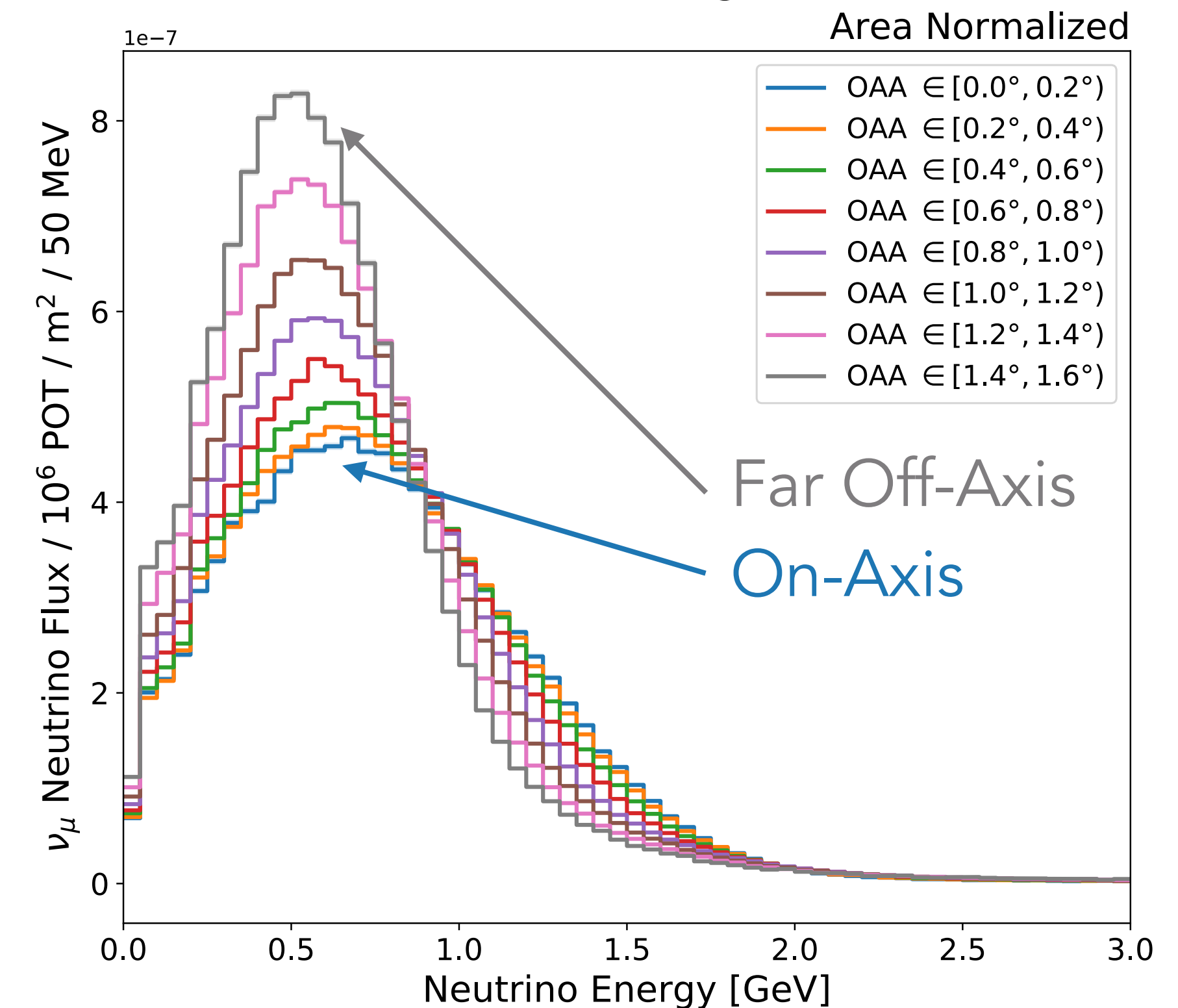
- By measuring neutrino interactions at different OAA, we can directly infer the energy dependence of the cross section (and various nuclear effects) spanning over nearly 200 MeV energy difference.
- Study the relationship between neutrino energy, and lepton (and hadron) kinematics, done by measuring differential cross-section in lepton (and hadron) kinematics at different OAA.

Disentangling nuclear physics at the “higher-energy” tail

- The “higher energy” tail of the ν_μ flux shrinks as a function of the OAA. This would potentially allow us to disentangle nuclear effects that start to dominate at ~ 1 GeV energy, e.g. non-QE contributions (2p-2h contribution, etc.).

Need realistic neutrino interaction model to study subtle effects across the ~ 200 MeV difference (before we have data).

Muon neutrino flux in each
of the OAA regions

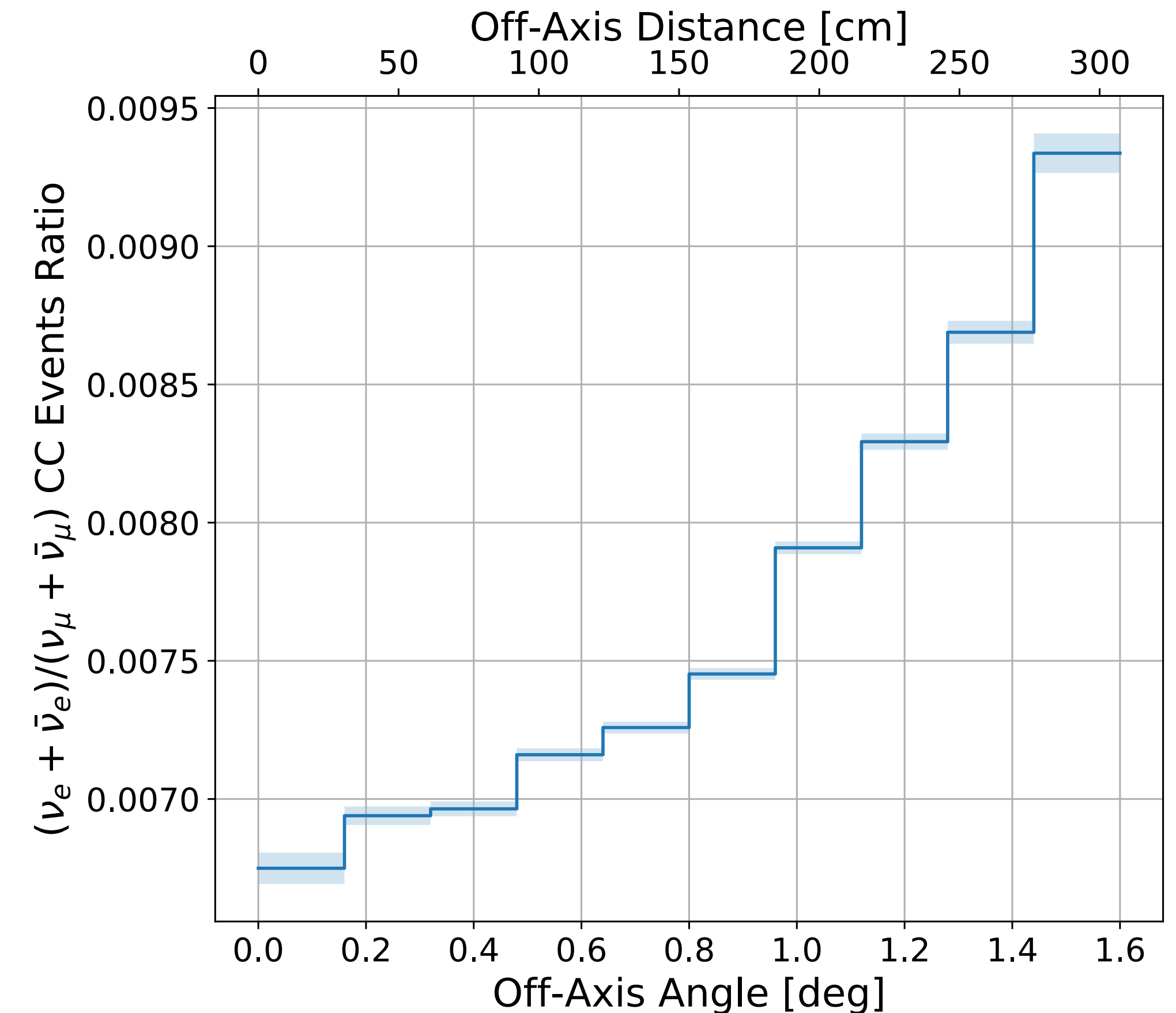


Interaction Model Constraint

Neutrino-Nucleus Interactions Physics

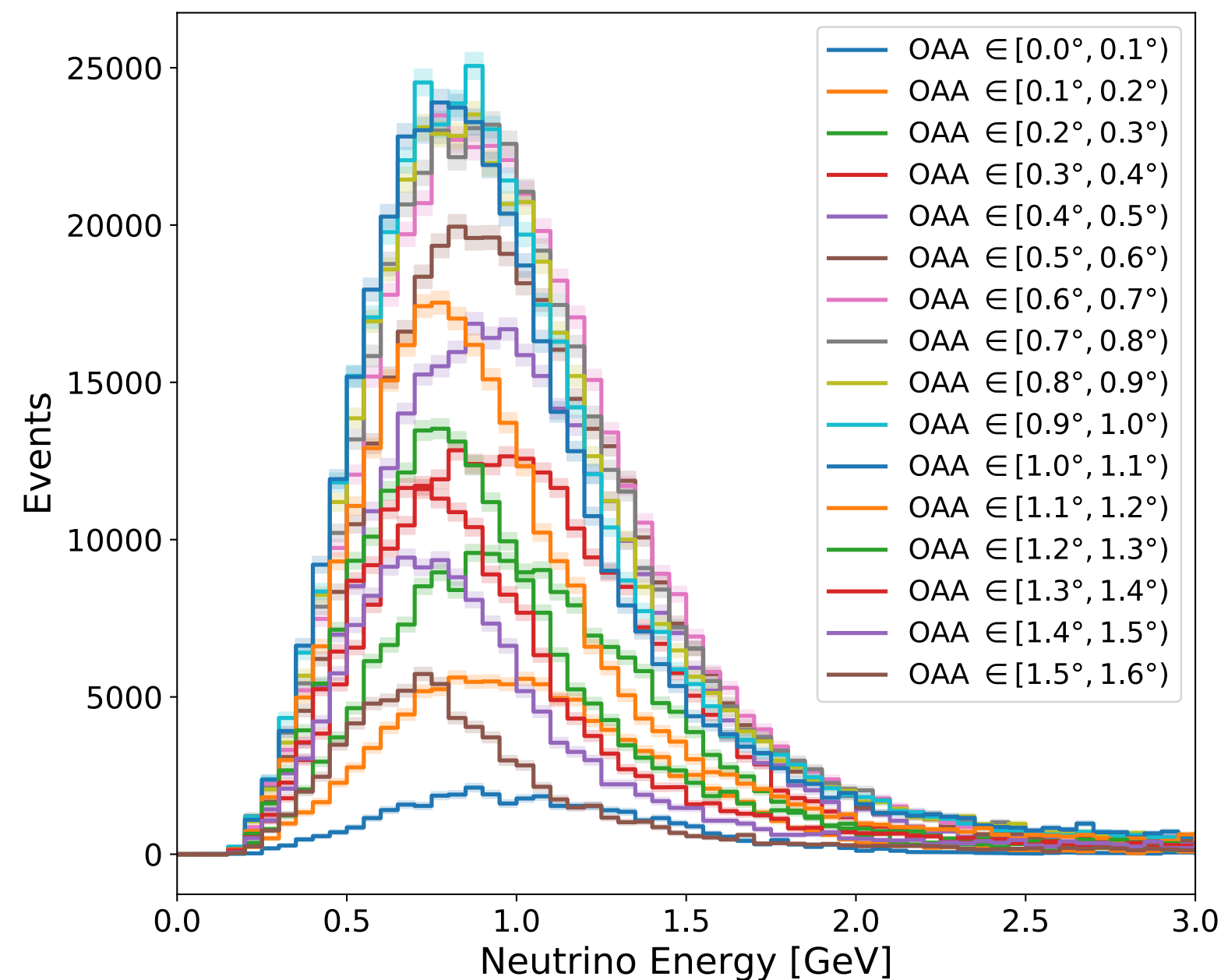
ν_μ to ν_e cross sections

- 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 prominent should allow us to measure the ν_e/ν_μ cross section (can study lepton mass effects).
- This would allow us to study lepton mass effects, and test Lepton Flavor Universality.
- Note that we expect high event statistics in all off- axis regions.



Interaction Model Constraint

Make linear combination of all the neutrino event distributions at different OAA angles, to reproduce a given target distribution.



Strategy:

- Detector divided into 0.1° OAA slices
- Energy spectrum is evaluated in each slice.
- The spectra are linearly combined to reproduce a target distribution.
- Here the target distribution is a Gaussian with a desired mean and sigma.

$$H_{Target}(E_\nu) = \sum_{i=0}^{N_{OAA}} c_i \cdot h_i(E_\nu)$$

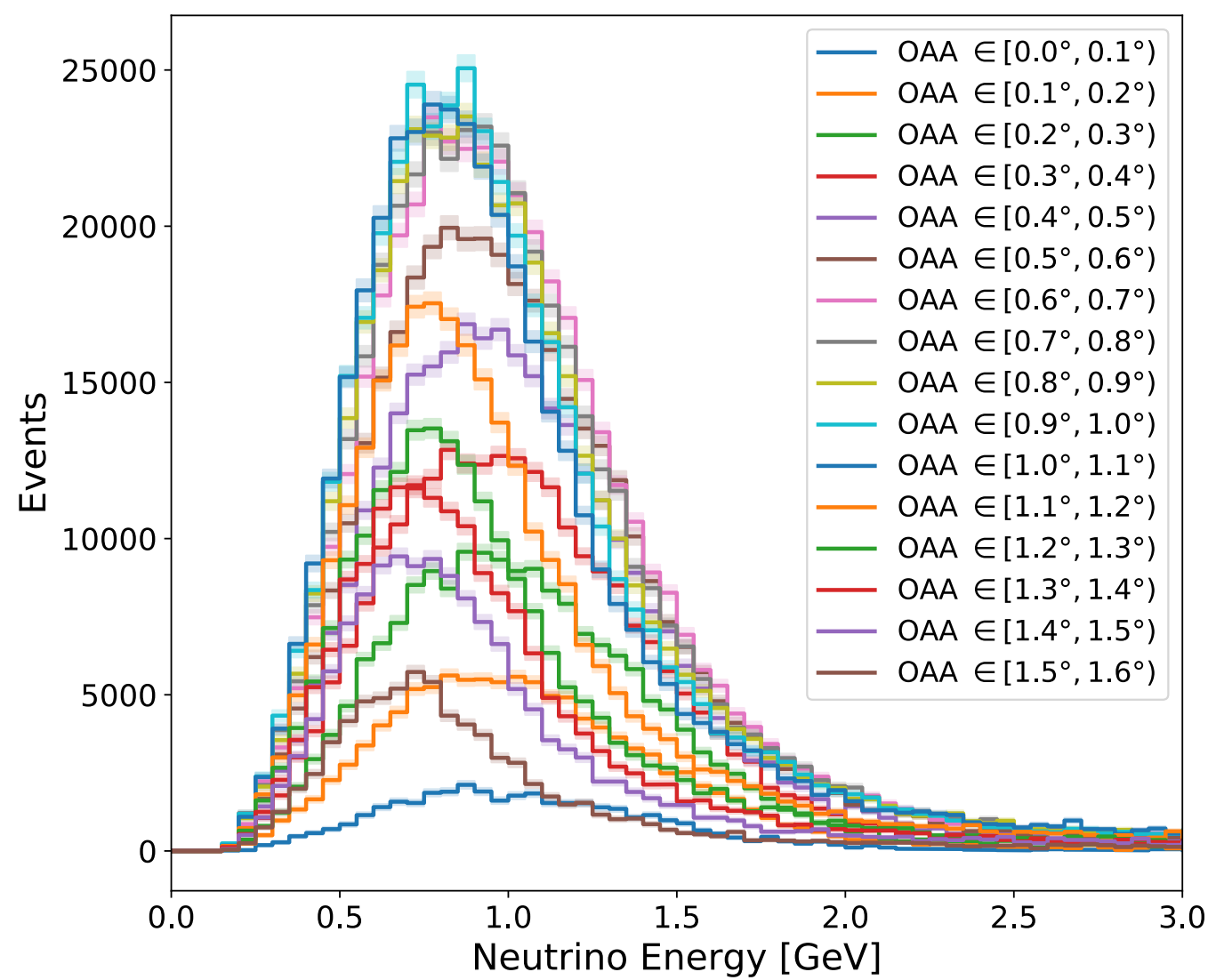
Target Distribution

Coefficients to be found

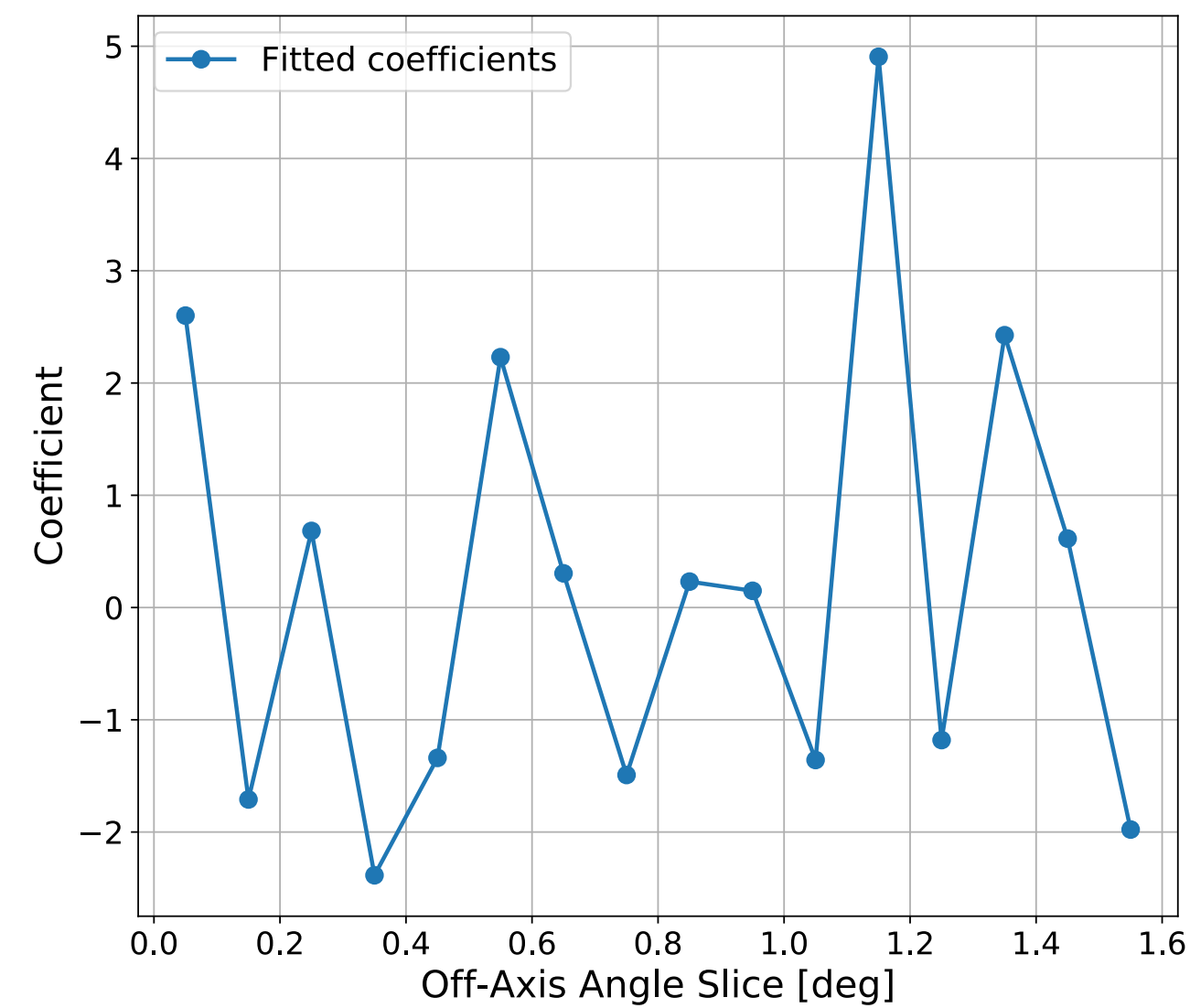
Event distribution in OAA slice i

Original idea from NuPRISM <https://arxiv.org/abs/1412.3086>:

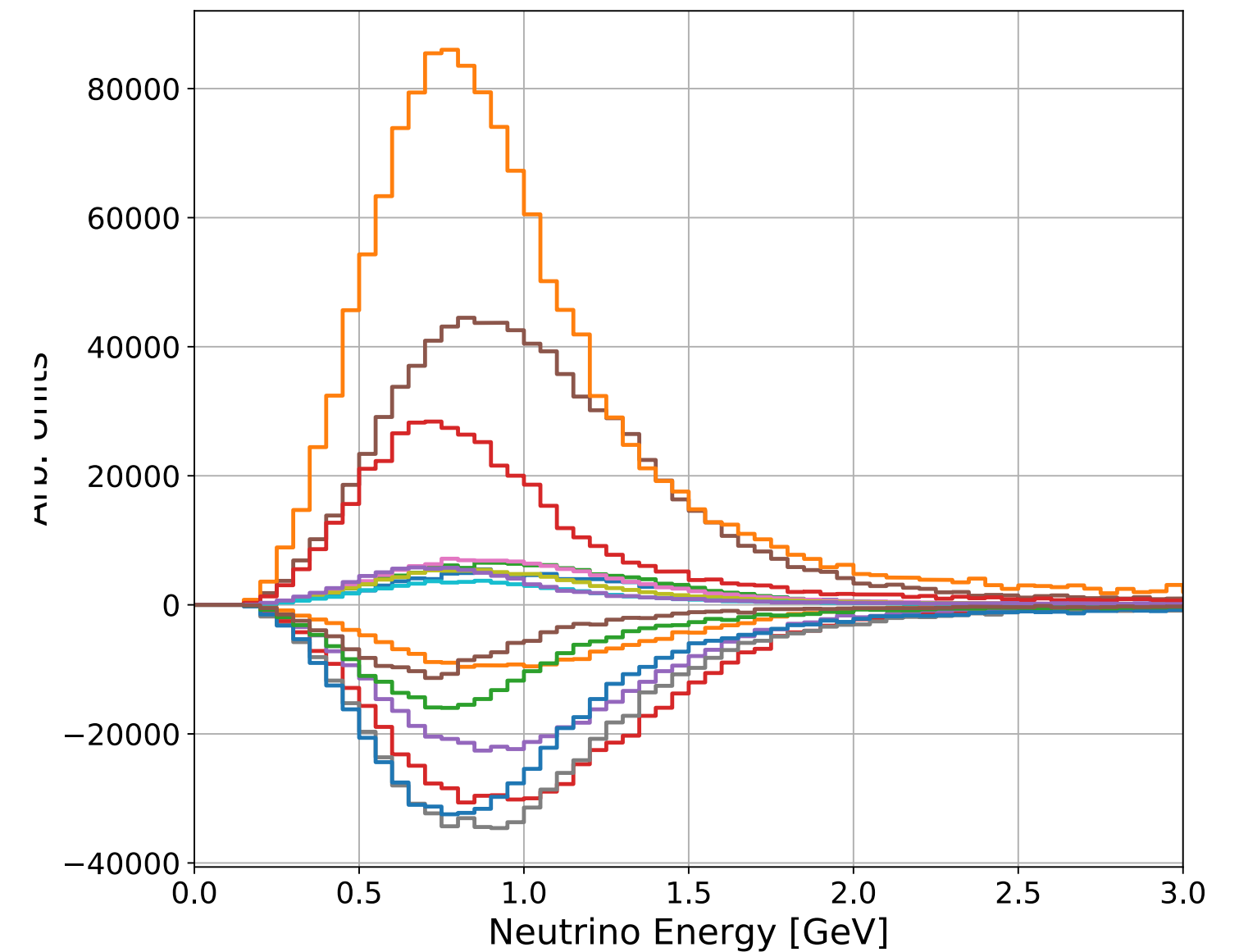
SBND-PRISM - Interaction Model Constraint



X



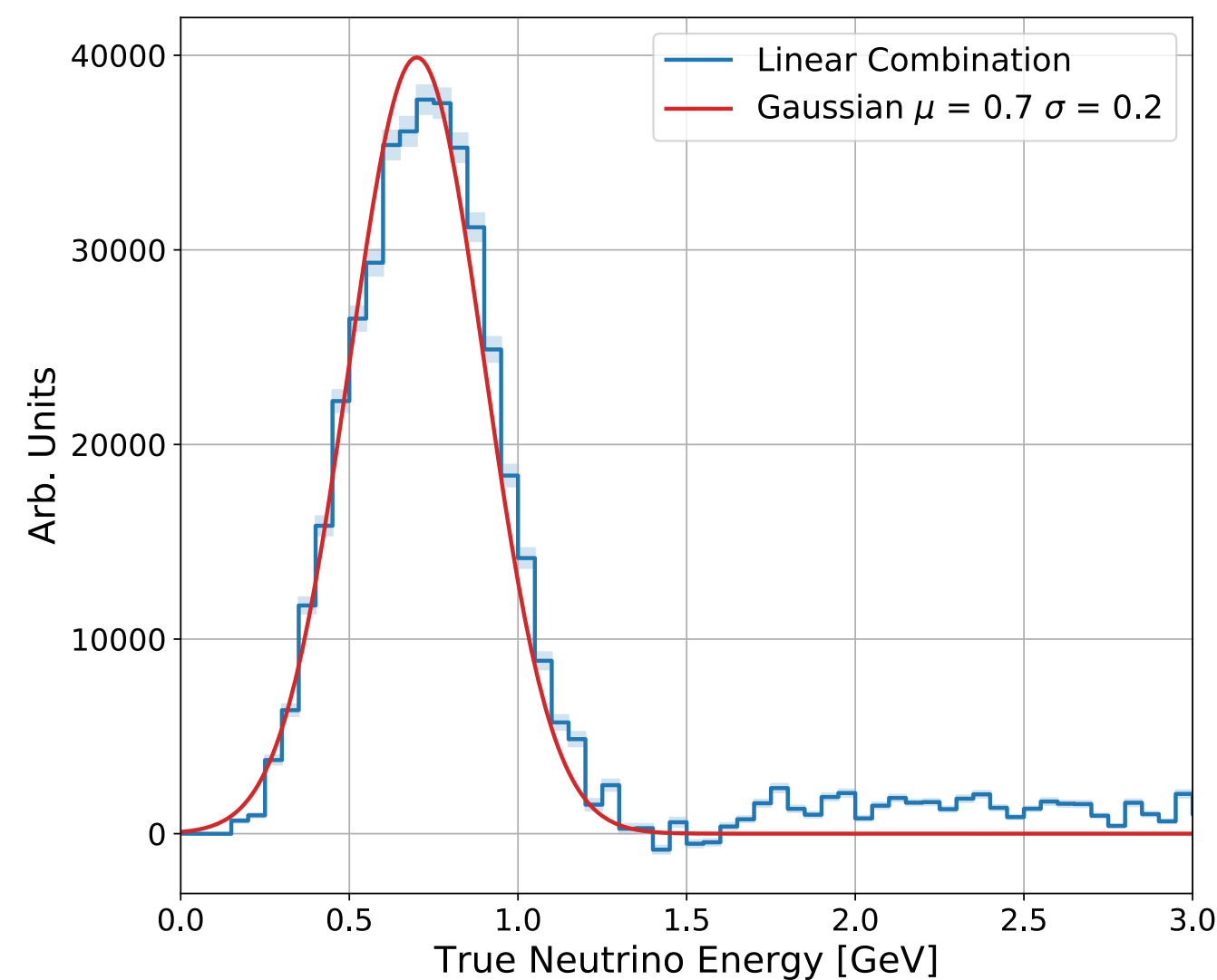
=



Target: gaussian with

$$\langle E_\nu \rangle = 0.7 \text{ GeV}$$

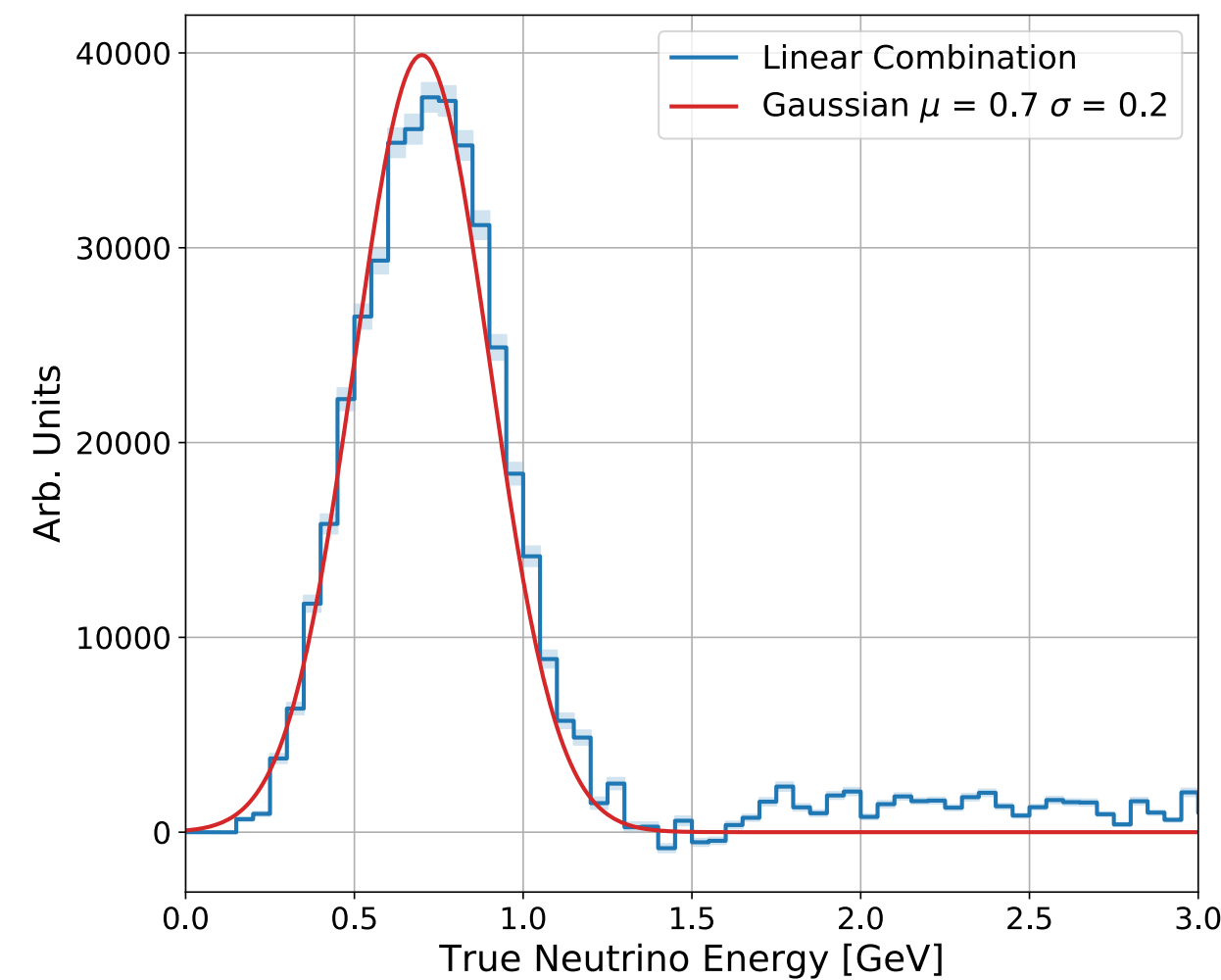
$$\sigma = 0.2 \text{ GeV}$$



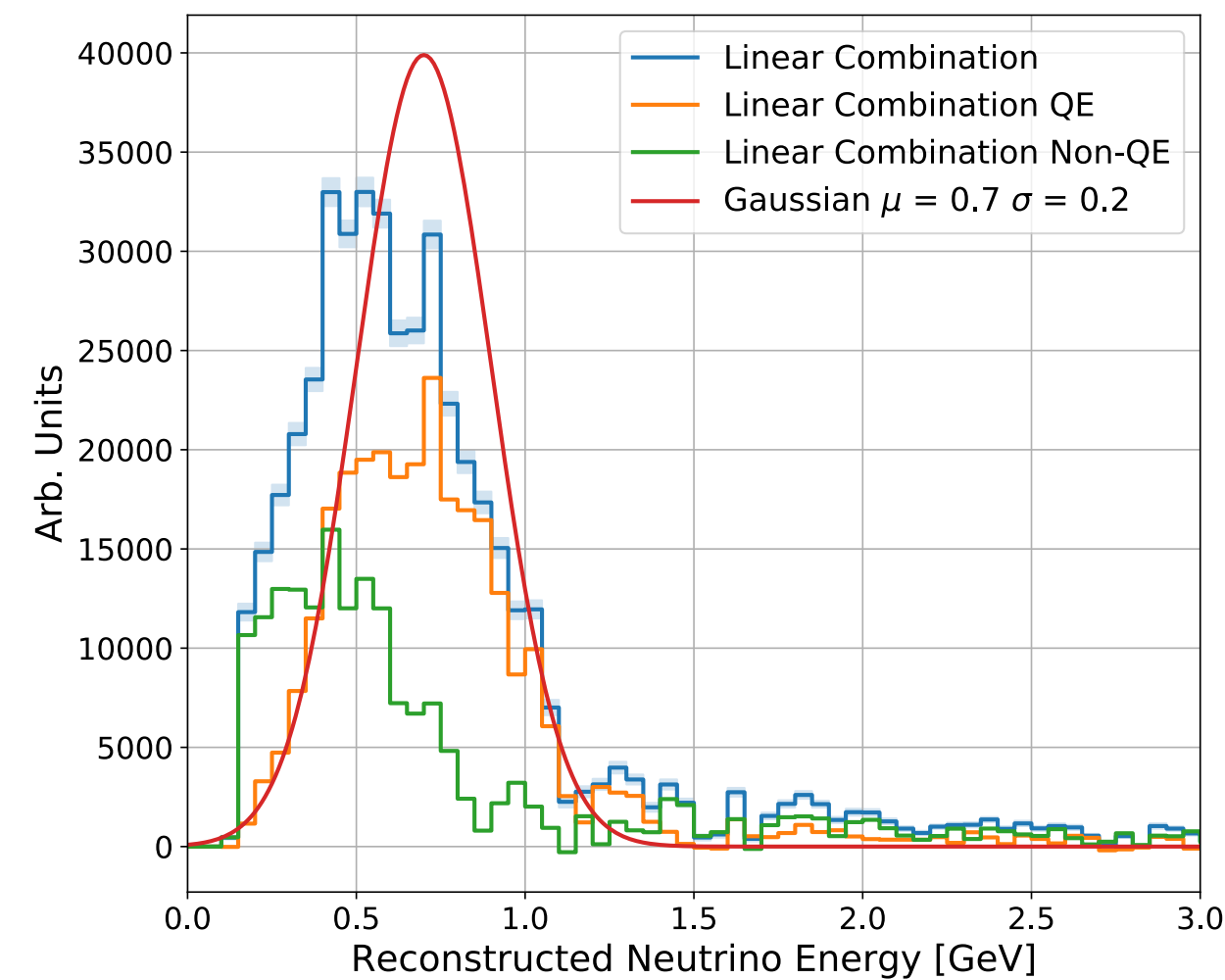
Summing up all these contributions gives our mono energetic spectrum

SBND-PRISM - Interaction Model Constraint

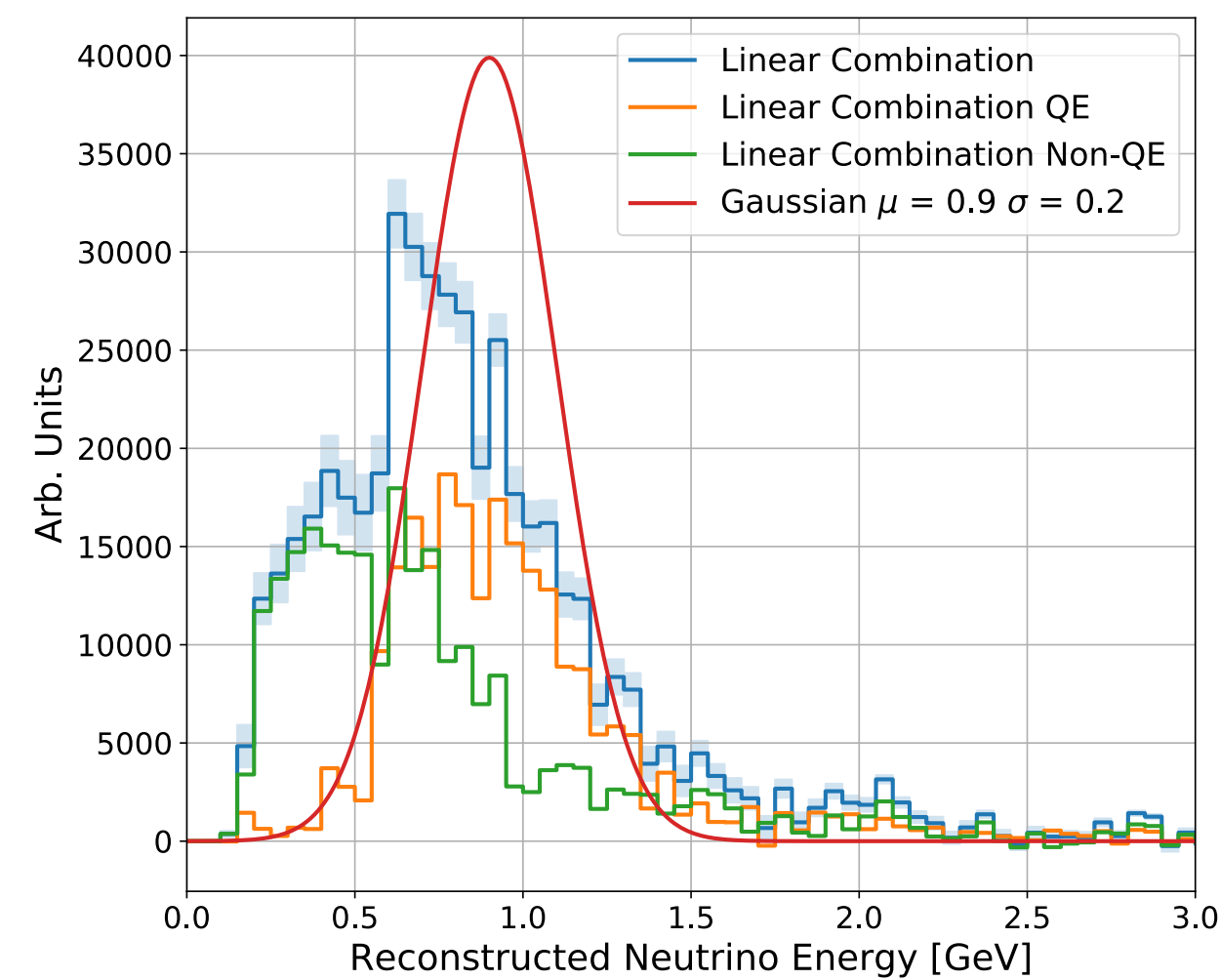
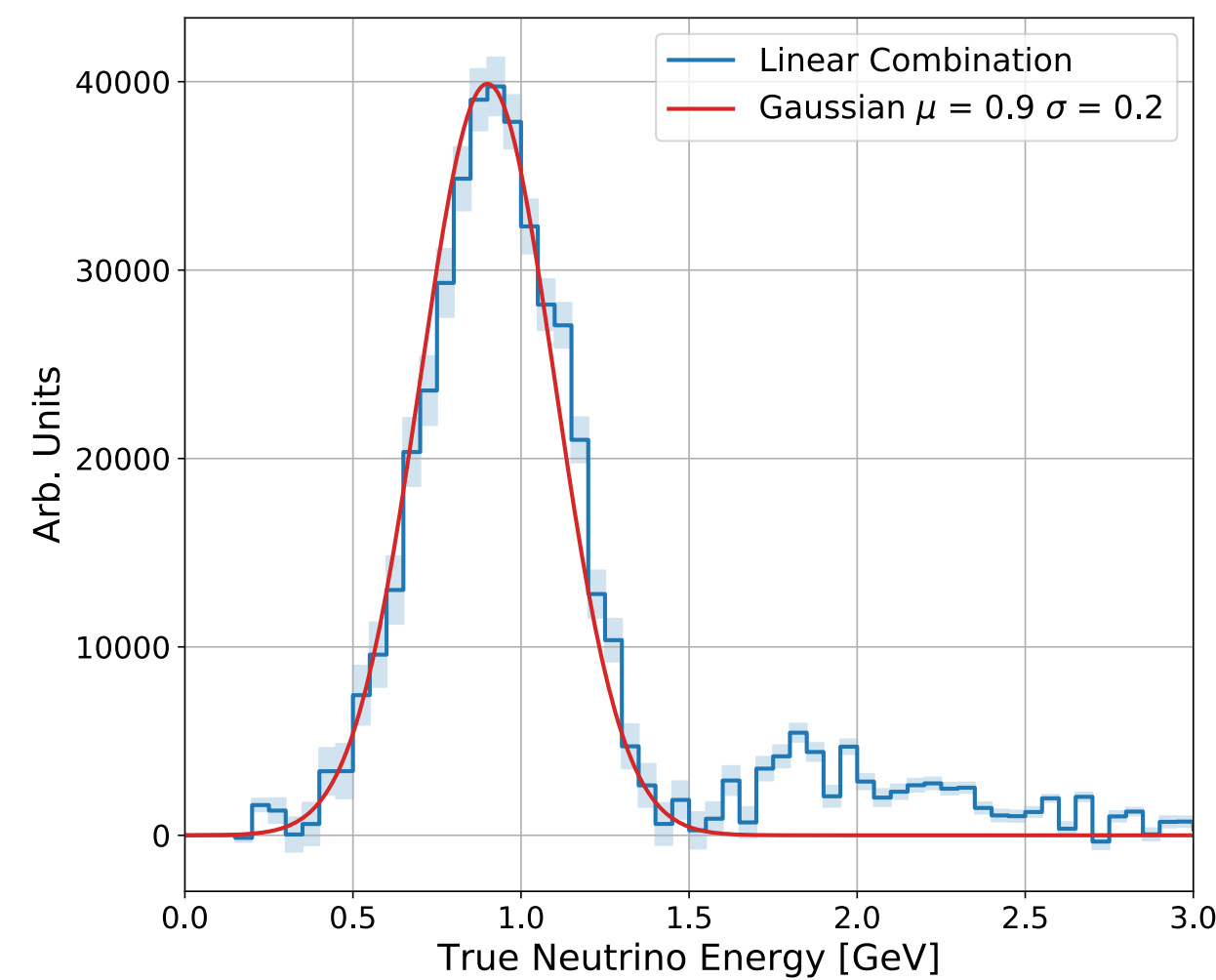
True Energy



Reconstructed Energy*



$$\langle E_\nu \rangle = 0.7 \text{ GeV}$$
$$\sigma = 0.2 \text{ GeV}$$



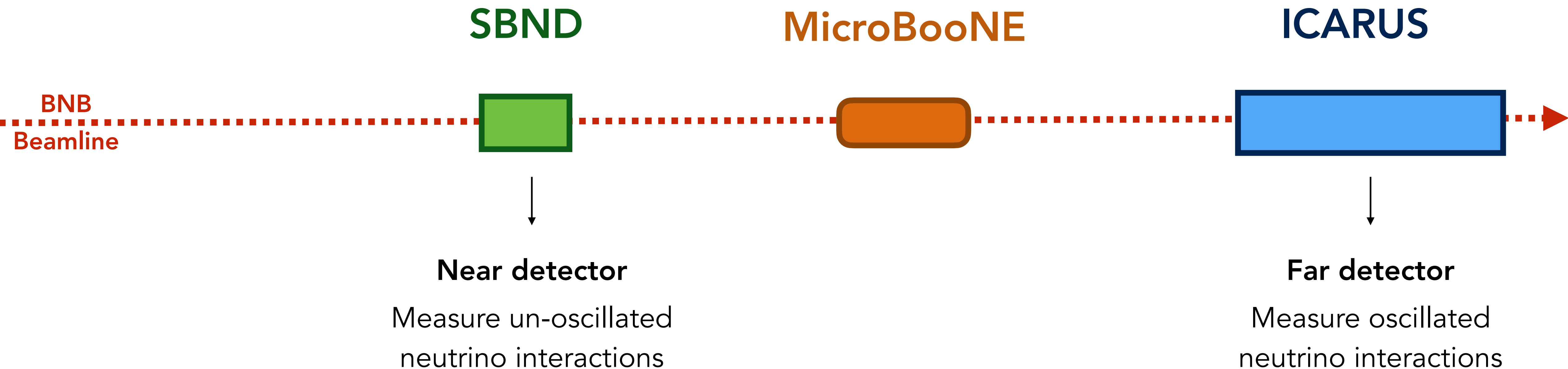
$$\langle E_\nu \rangle = 0.9 \text{ GeV}$$
$$\sigma = 0.2 \text{ GeV}$$

* only a proof of principle: reconstructed energy is estimated from truth under the QE hypothesis

Sterile Neutrino Searches

Sterile Neutrino Oscillations

Main goal of the SBN program is to search for eV mass-scale sterile neutrinos oscillations

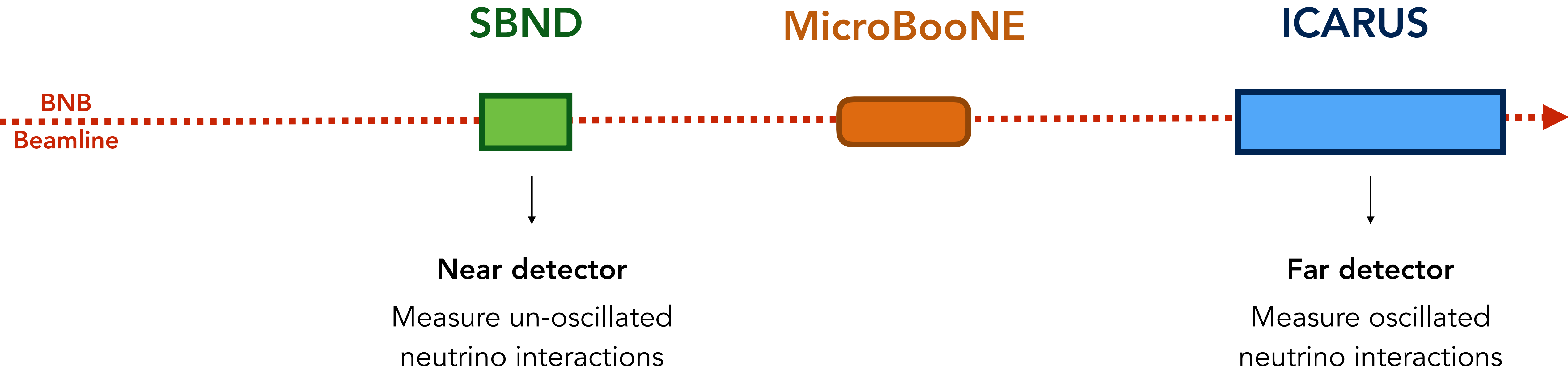


By comparing the number of interaction between the near and far detector, we can see neutrino oscillations

Sterile Neutrino Oscillations

Sterile neutrino:

Main goal of the SBN program is to search for eV mass-scale sterile neutrinos oscillations



We need to measure the interactions at the next detector (before oscillations happen) to constrain the neutrino flux.

The neutrino flux is hard to predict exactly!

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:

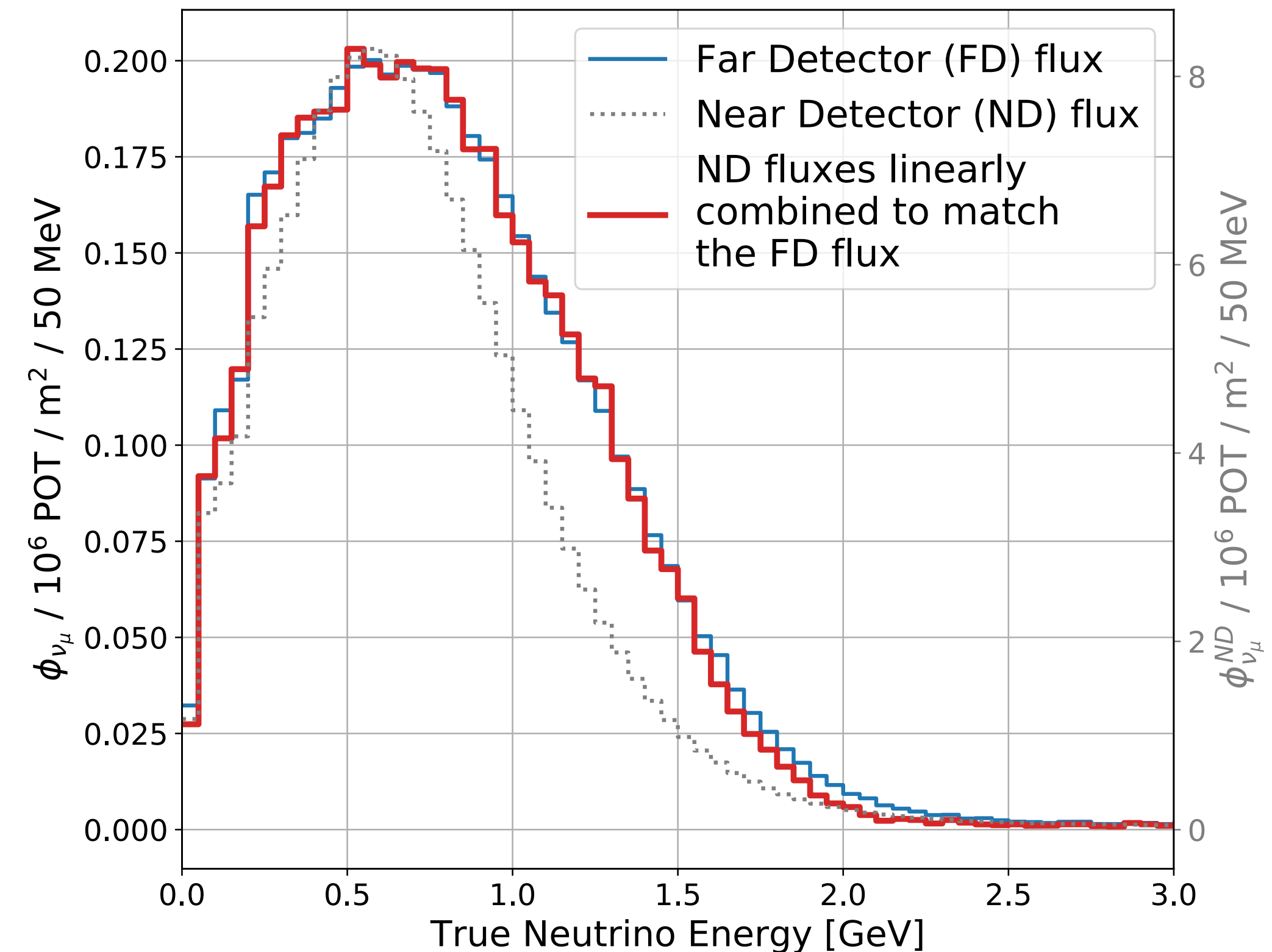
1. Instead of treating SBND as a single detector, we can treat it as multiple detectors at different off-axis positions and include those in the **SBN oscillation fit**. Since the the energy spectra are different the neutrino interaction model will be over constrained.

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-Only Sterile Neutrino Searches

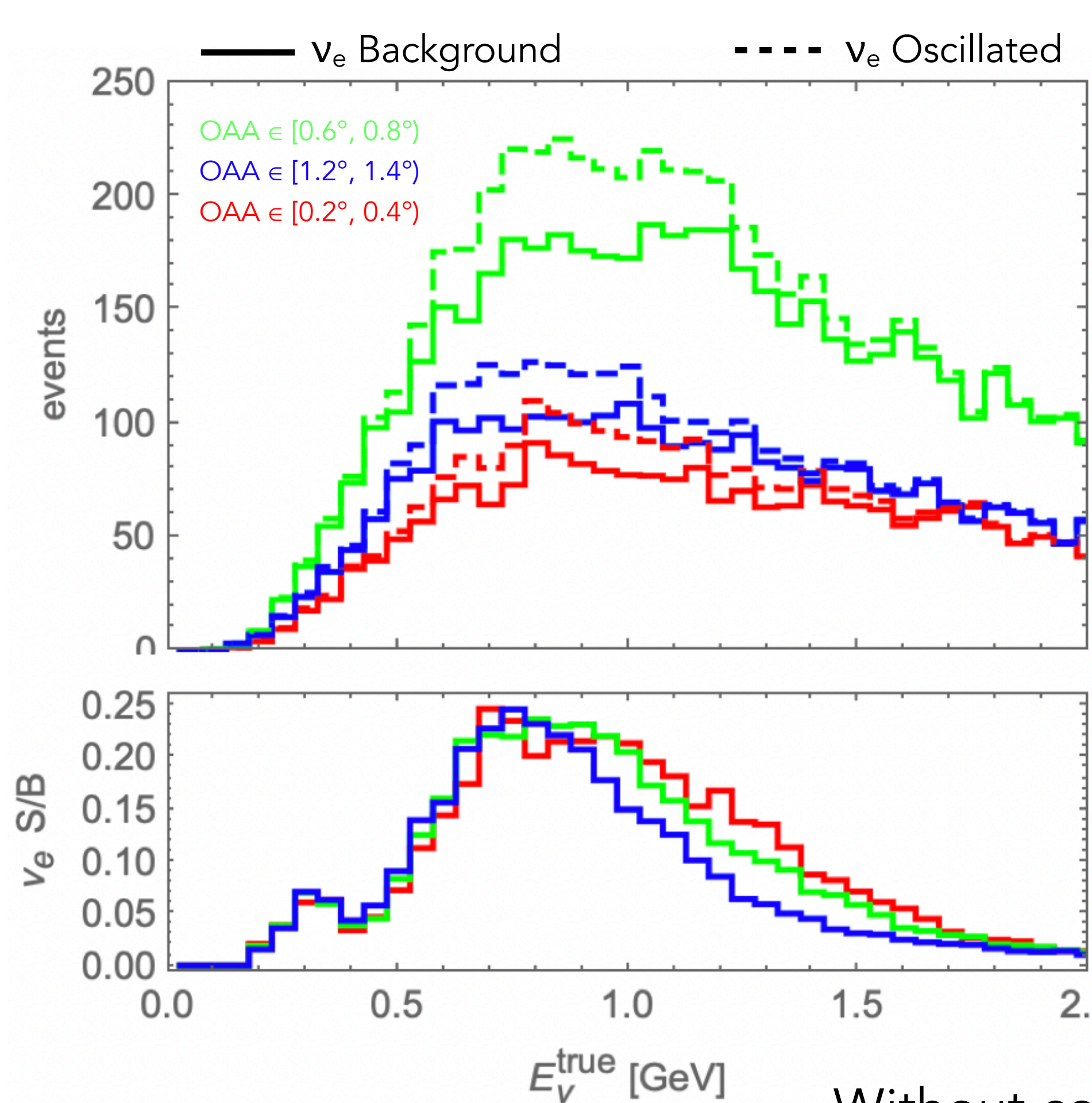
SBND-Only Sterile Neutrino Oscillations

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

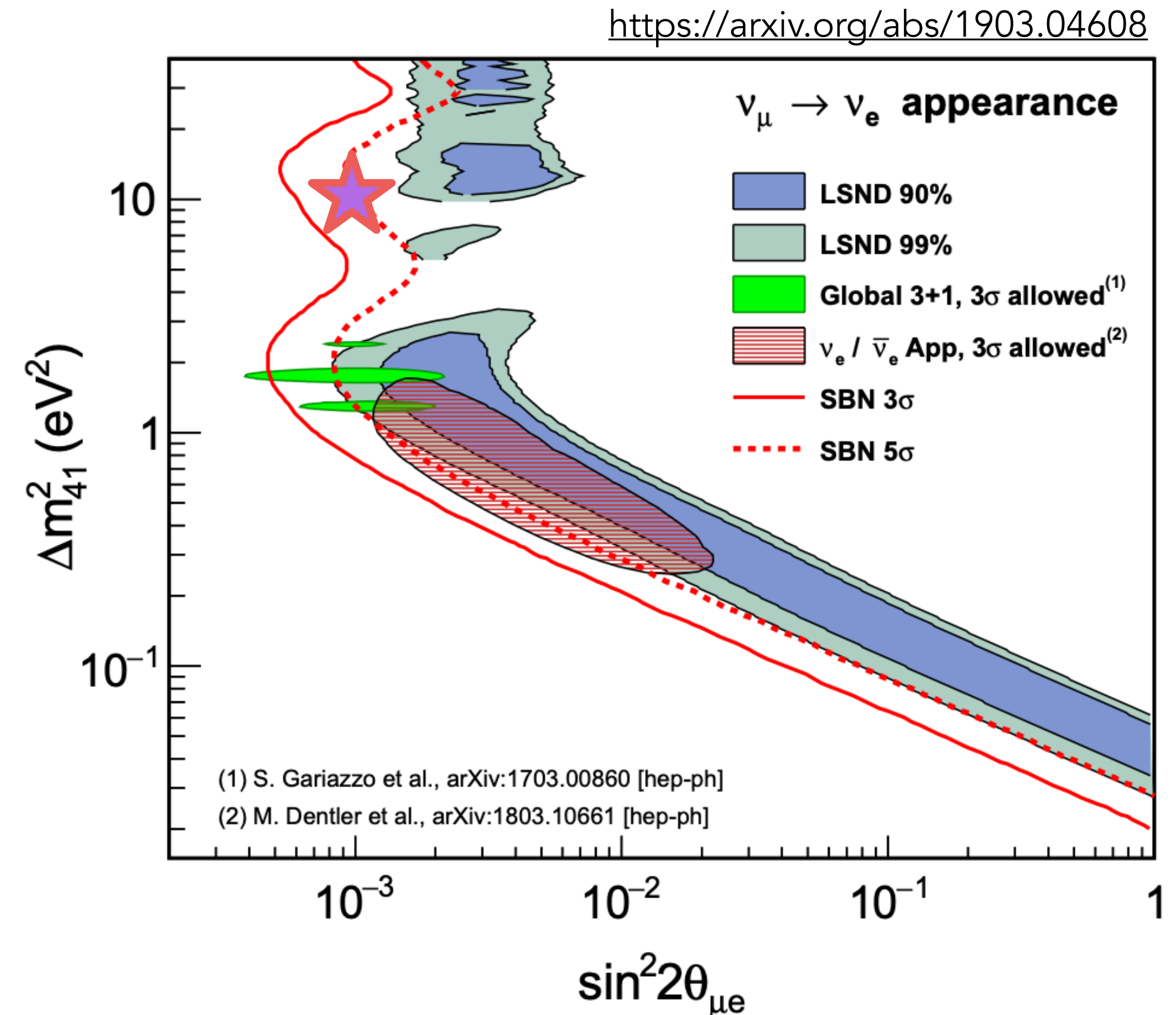
- Usually, two detectors (near and far) are needed to look for neutrino oscillations as they provide a way to constrain the neutrino flux.
- Treating SBND as multiple sub-detectors at different OAAs can help in constraining the flux, and it may be possible to do an oscillation analysis using SBND alone.
- SBND-PRISM potentially allows probing higher values of Δm^2 for sterile neutrino oscillation searches.

SBND-Only Oscillations - Appearance Mode

Can SBND beat all current limits on **appearance**? $\Delta m^2 = 10 \text{ eV}^2 \sin^2 2\theta_{\mu e} = 0.001$



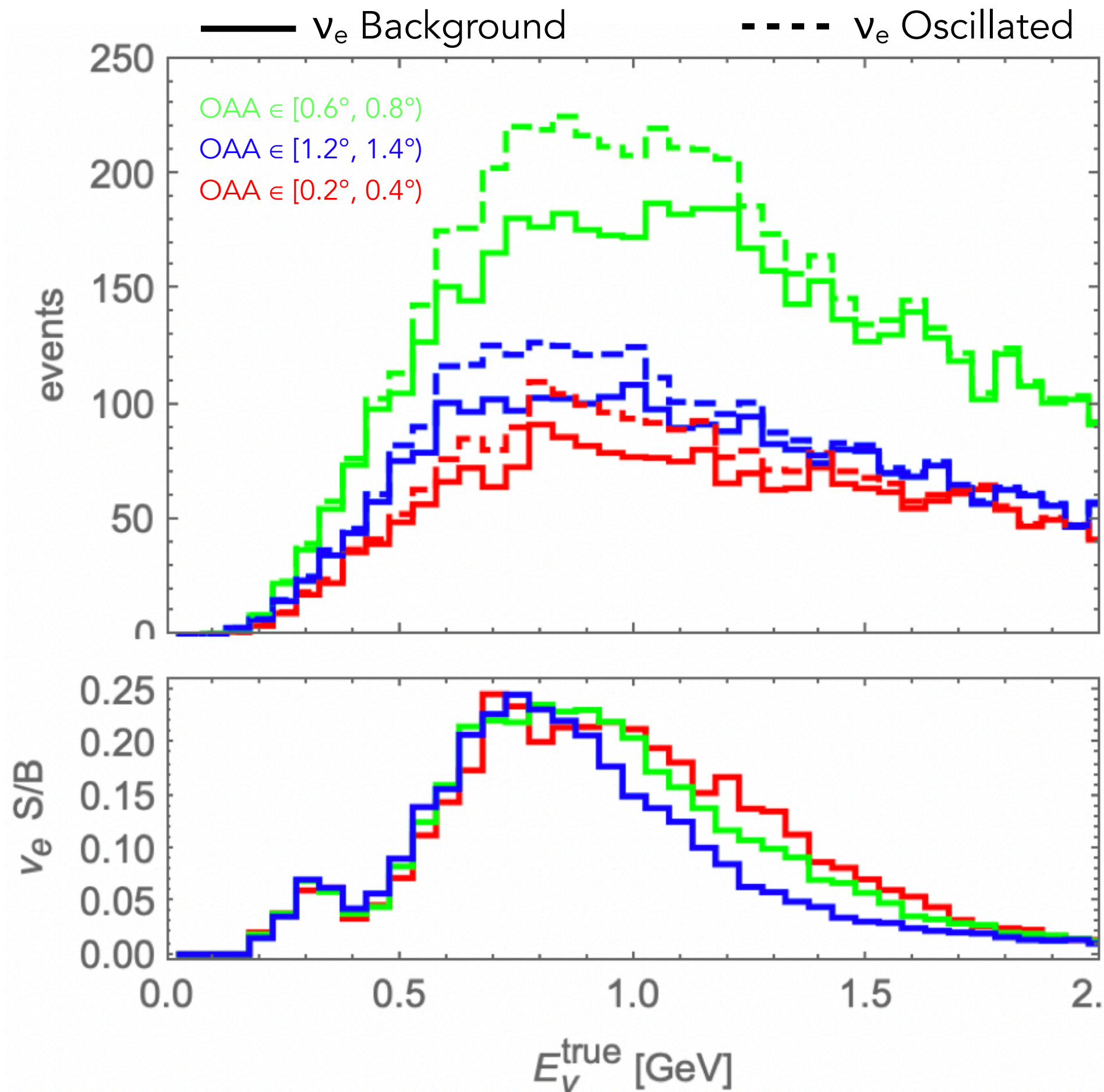
Without considering any other background source



SBND-Only Oscillations - Appearance Mode

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



$$\chi^2_{\text{syst}} = \sum_{i,j}^{\text{pos., bins}} \frac{(N_{ij} + \alpha T_{ij})^2}{N_{ij} + \sigma_{\text{bin}}^2 N_{ij}^2} + \left(\frac{\alpha - 1}{\sigma_{\text{corr}}} \right)^2 = \begin{matrix} 13 & \text{w/ PRISM} \\ 2 & \text{w/o PRISM} \end{matrix}$$

A χ^2 of 13 is promising! It may be possible for SBND to probe this parameter space of neutrino oscillations!

Note that the result is not as good if we don't use PRISM (i.e. if we consider the detector as a whole)

SBND-Only Sterile Neutrino Oscillations

Free norm + 30% bin-by-bin systematics on bkg

$$\chi^2_{\text{syst}} = \sum_{i,j}^{\text{pos., bins}} \frac{(N_{ij} + \alpha T_{ij})^2}{N_{ij} + \sigma_{\text{bin}}^2 N_{ij}^2} + \left(\frac{\alpha - 1}{\sigma_{\text{corr}}} \right)^2 = \begin{matrix} 13 & \text{w/ PRISM} \\ 2 & \text{w/o PRISM} \end{matrix}$$

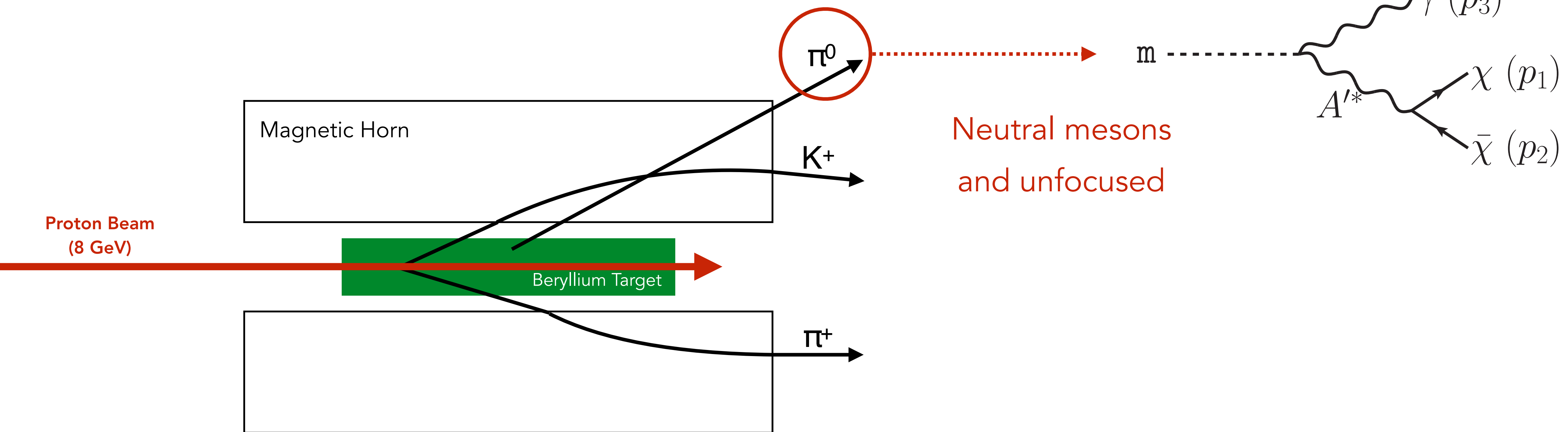
- Mismatch between ν_μ flux and ν_e contamination on different off-axis positions may be an opportunity to do physics.
- Statistics is large, which means systematics dominate
- Flux systematics, particularly correlations, are crucial to get realistic result, and needed before final conclusions can be made, but results look promising with current (conservative) systematic guess.

Dark Matter Searches

SBND-PRISM - Dark Matter Searches

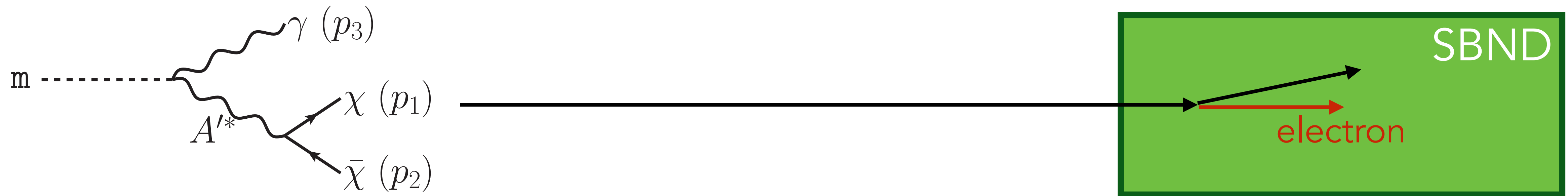
If dark matter is light (MeV-GeV) and can be produced in meson decays, we can search for it in SBND via electron scattering.

Dark photons with masses below ~ 1 GeV can be produced by neutral meson decays

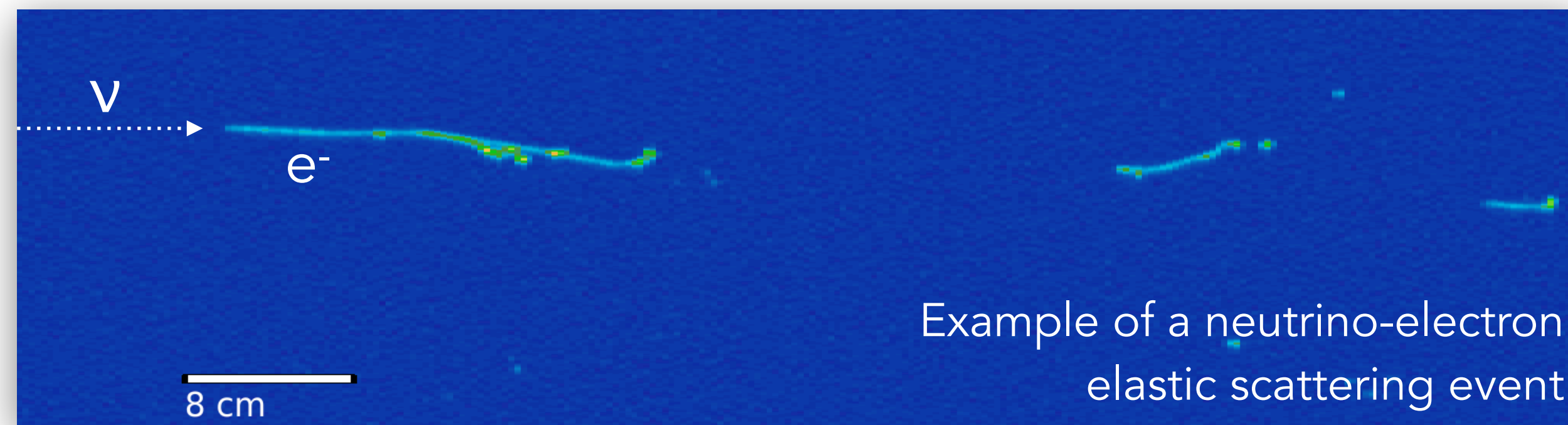


SBND-PRISM - Dark Matter Searches

Can search for dark matter in SBND via electron scattering

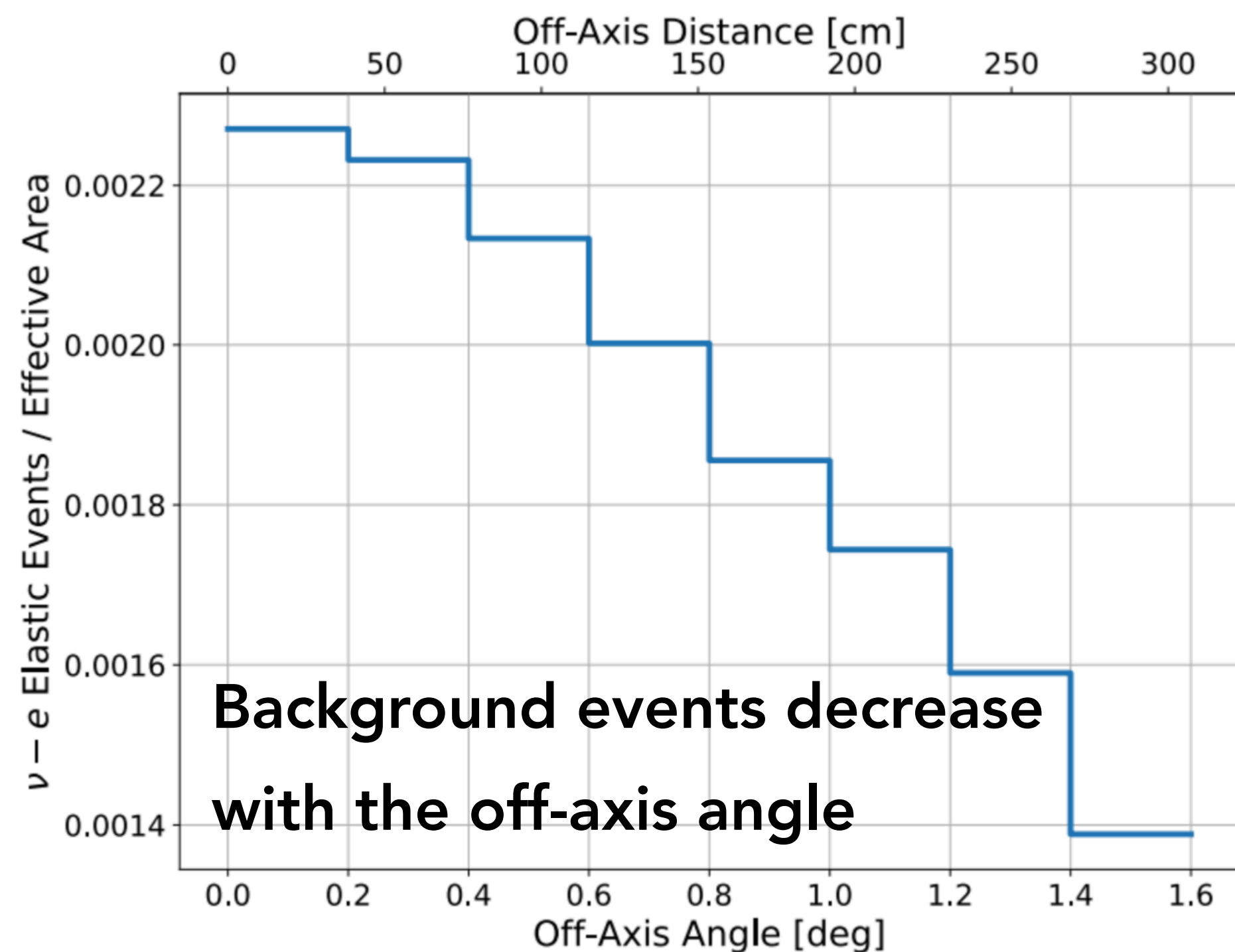
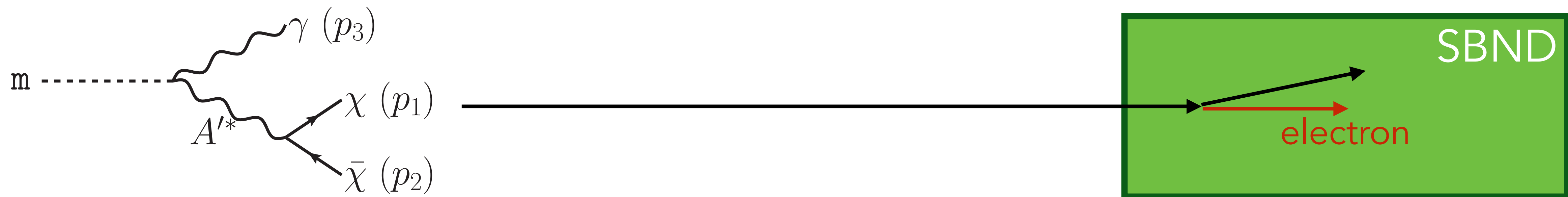


Example of electron scattering event in SBND



SBND-PRISM - Dark Matter Searches

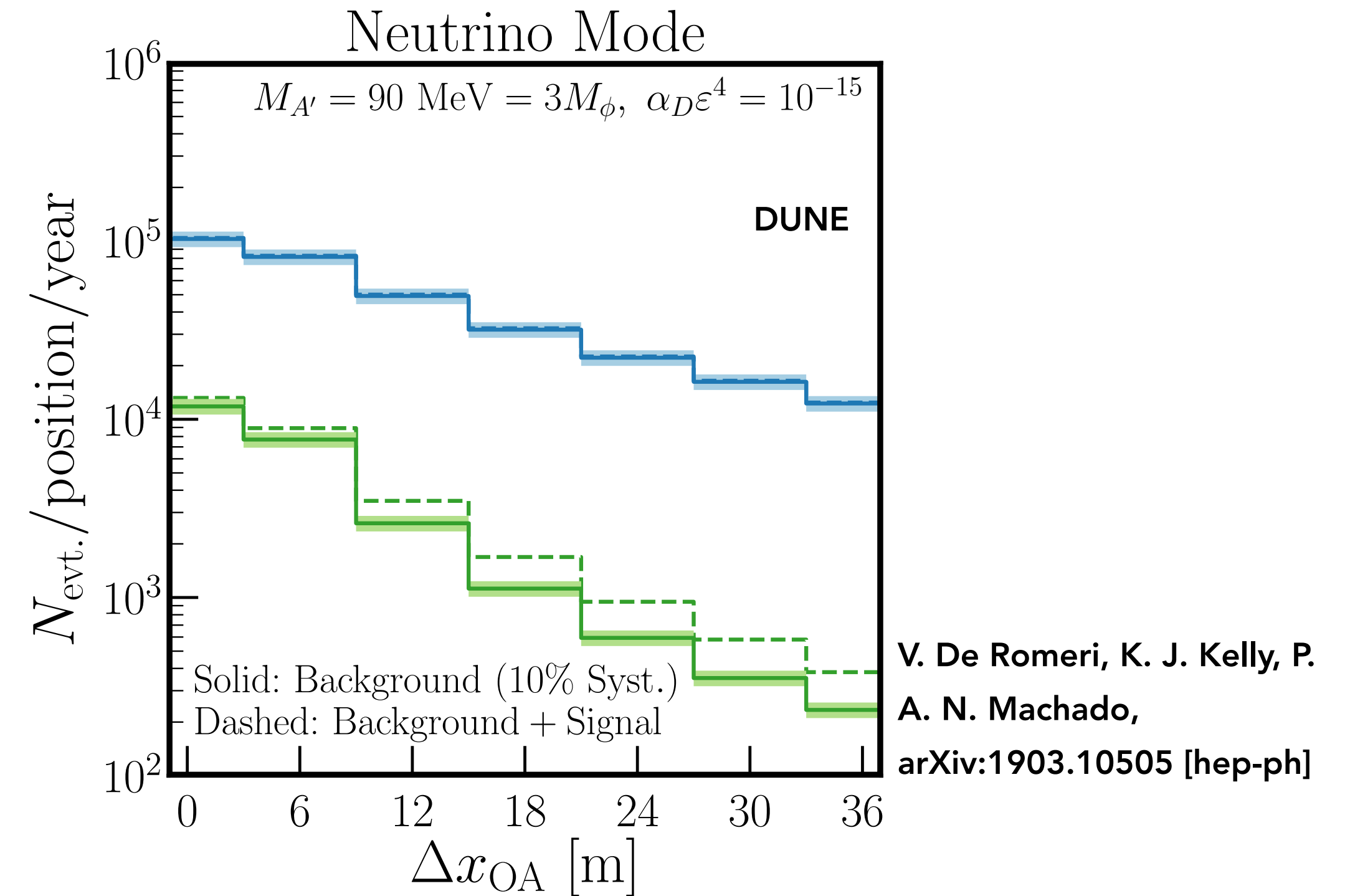
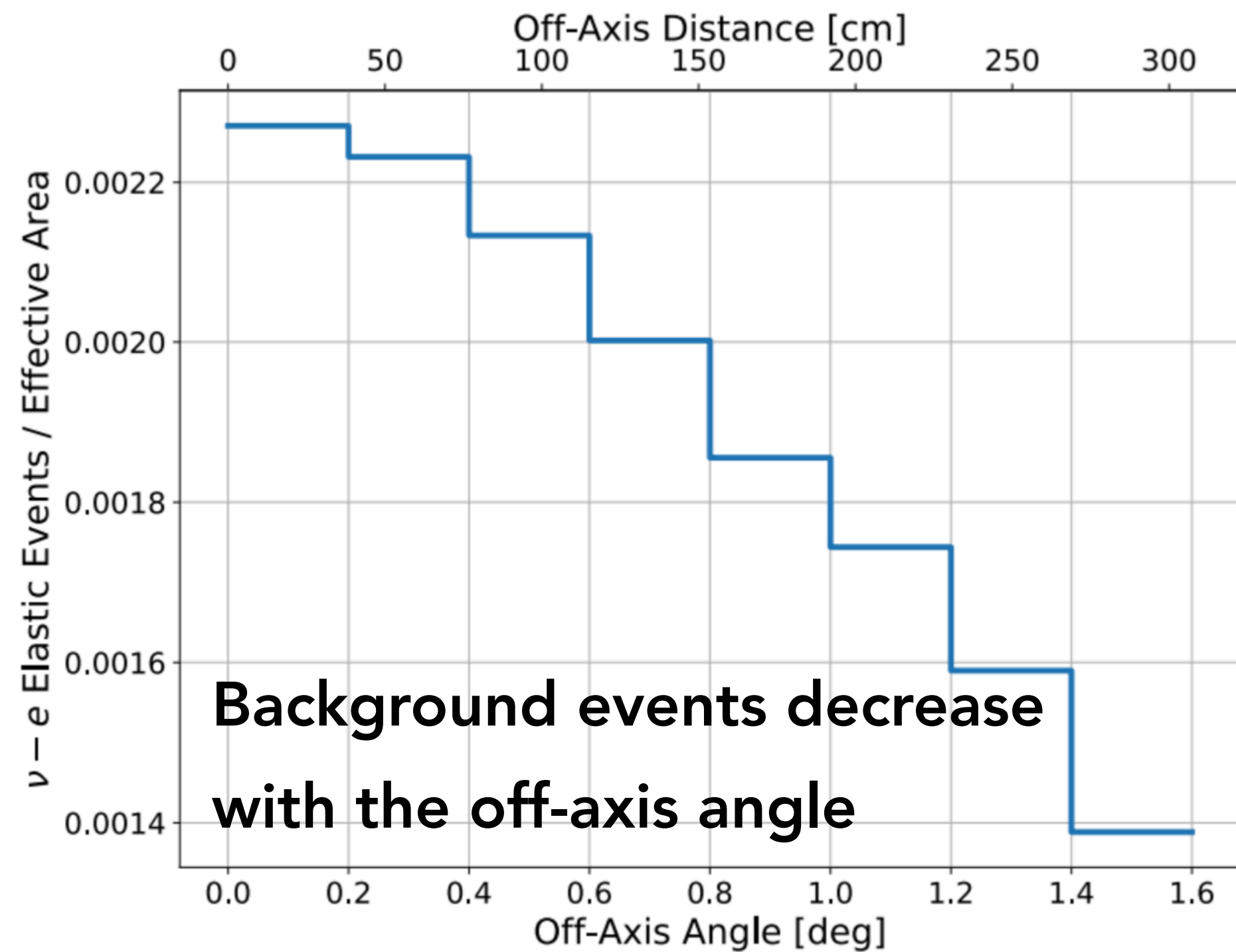
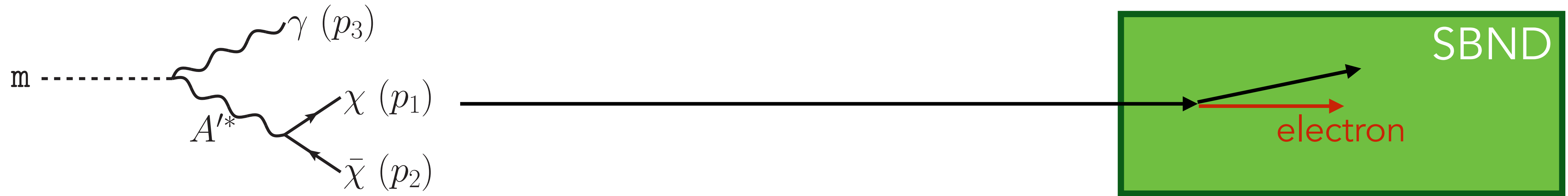
Can search for dark matter in SBND via electron scattering



- **Signal:** elastic scattering electron events. Dark matter comes from three-body decays of neutral (unfocused) mesons.
- **Background:** neutrino-electron elastic scattering. Neutrinos come from two-body decays of charged (focused) mesons.
- **Neutrino flux drops off more sharply as a function of radius!**

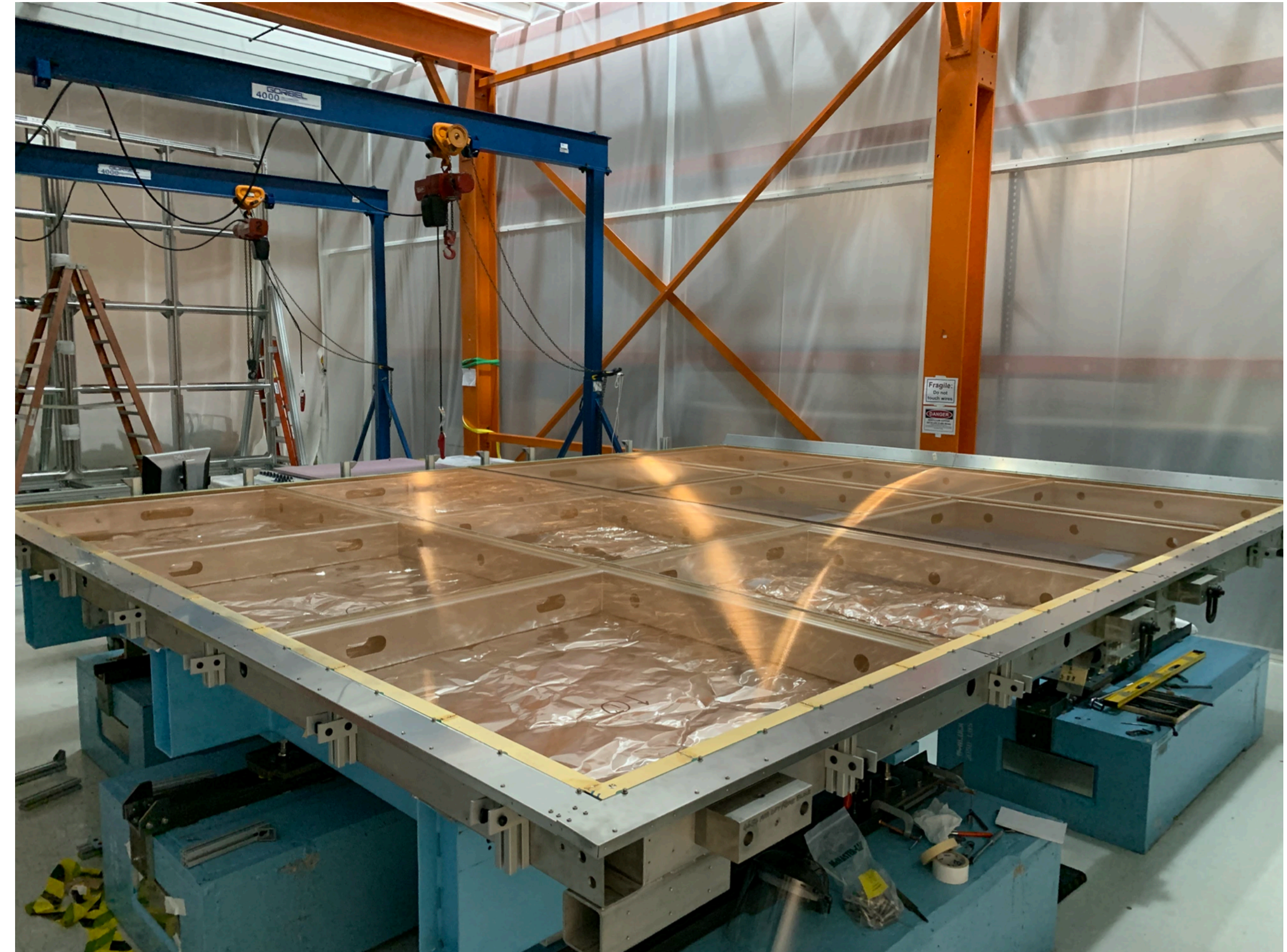
SBND-PRISM - Dark Matter Searches

Can search for dark matter in SBND via electron scattering



SBND - Current Status

SBND is currently being assembled and it will start taking data soon!



Conclusions

Thank You!