Fermilab

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

Marco Del Tutto

Rising Stars Symposium

University of Chicago

22nd September 2021

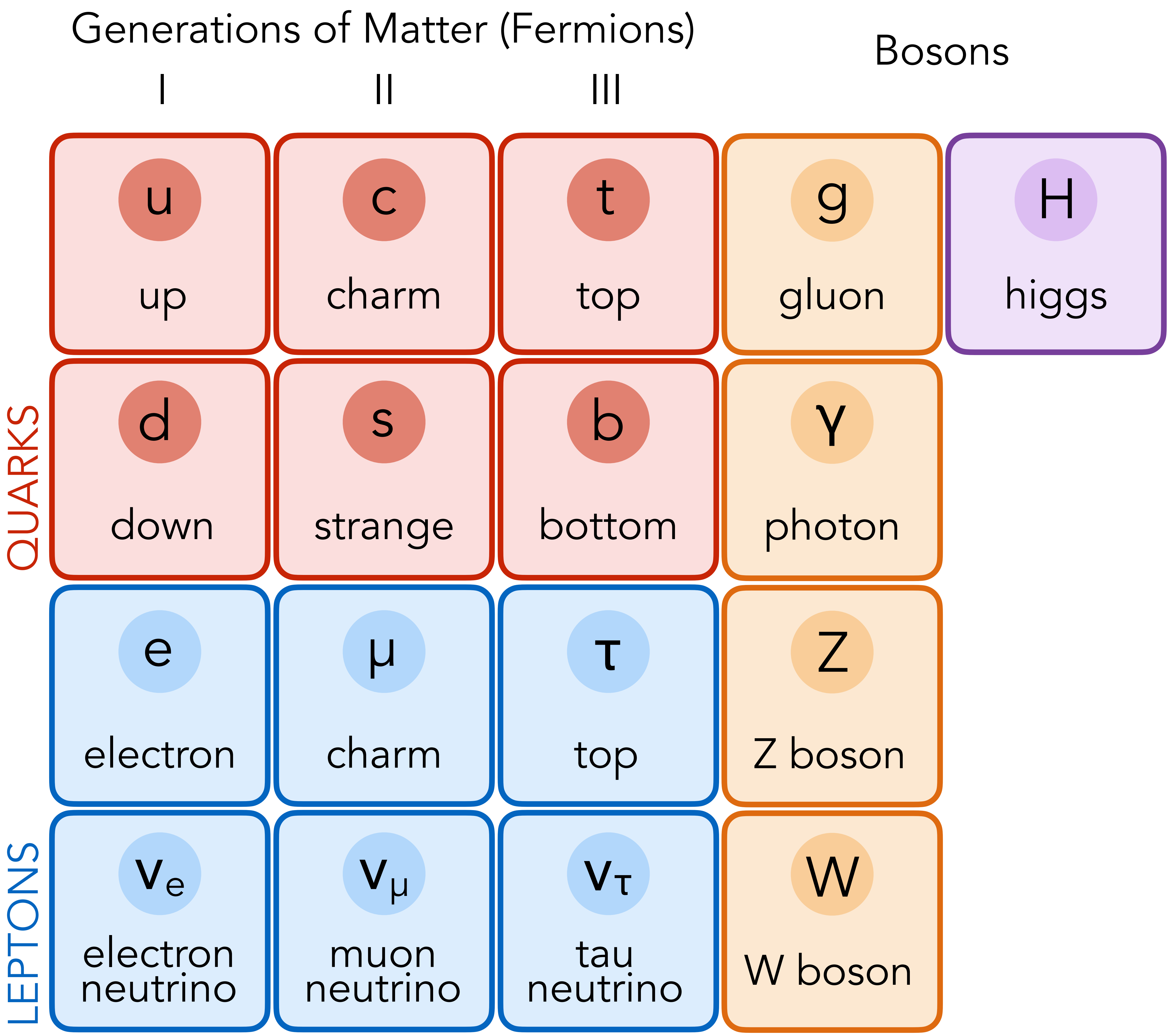
The Standard Model of Particle Physics

	Generations of Matter (Fermions) I	II	III	Bosons	
QUARKS	u up	c charm	t top	g gluon	H higgs
QUARKS	d down	s strange	b bottom	γ photon	
LEPTONS	e electron	μ charm	τ top	Z Z boson	
LEPTONS	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	

The Standard Model of Particle Physics is one of the most successful theories that humankind ever produced

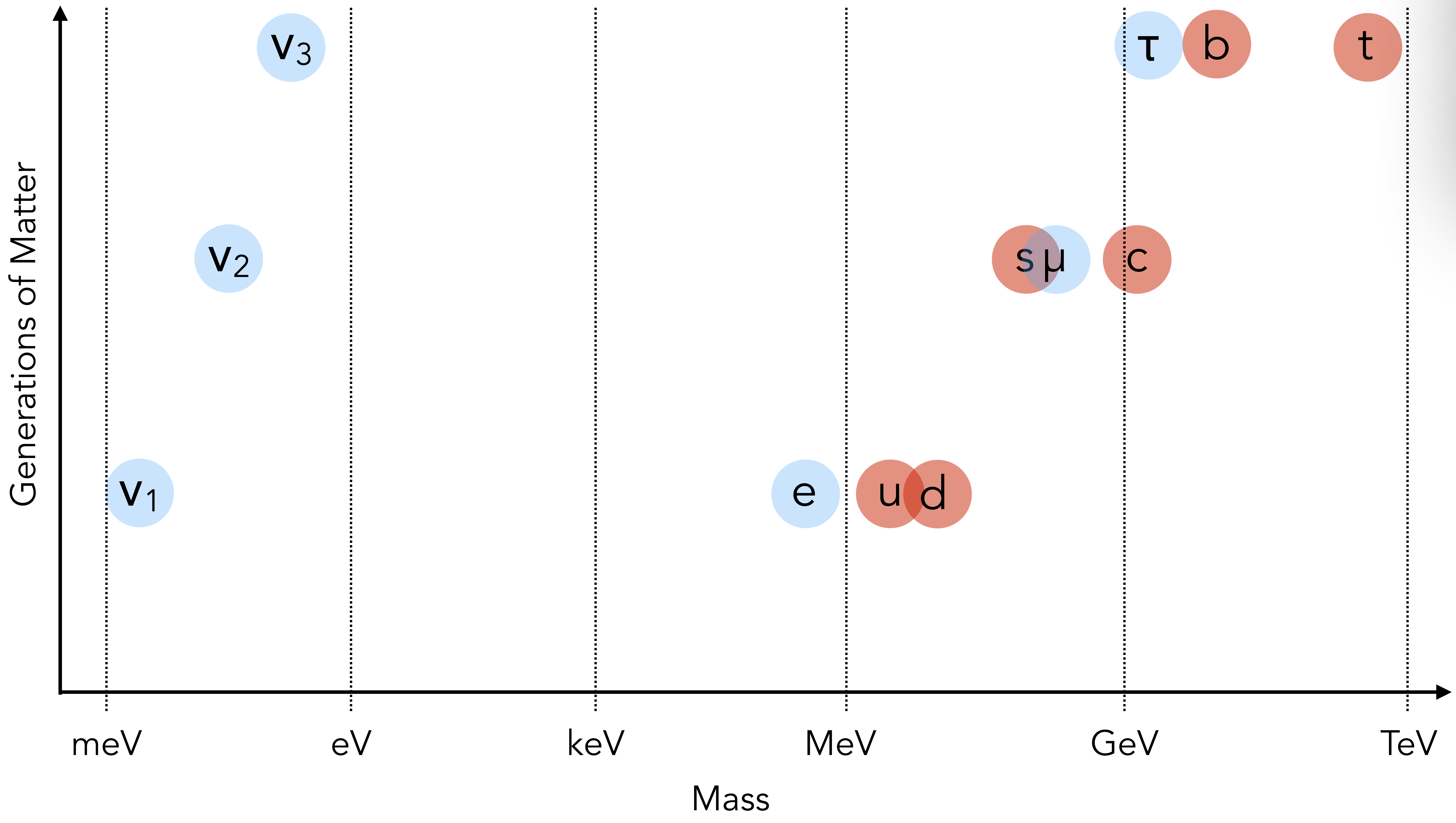
Despite its success, it is far from being the theory of everything and several outstanding questions remain unanswered

Open Questions in Particle Physics



- What is the Origin of the Hierarchy of Fermion Masses?
- Why Are There Three Generations of Fermions?
- Why is the Universe Made Wholly of Matter? (CP Violation)
- What is the Nature of the Higgs Boson?
- Can the Forces Be Unified?
- Does Supersymmetry Exist?
- What is Dark Matter?

Open Questions in Particle Physics



What is the Origin of the Hierarchy of Fermion Masses?

Why Are There Three Generations of Fermions?

Why is the Universe Made Wholly of Matter? (CP Violation)

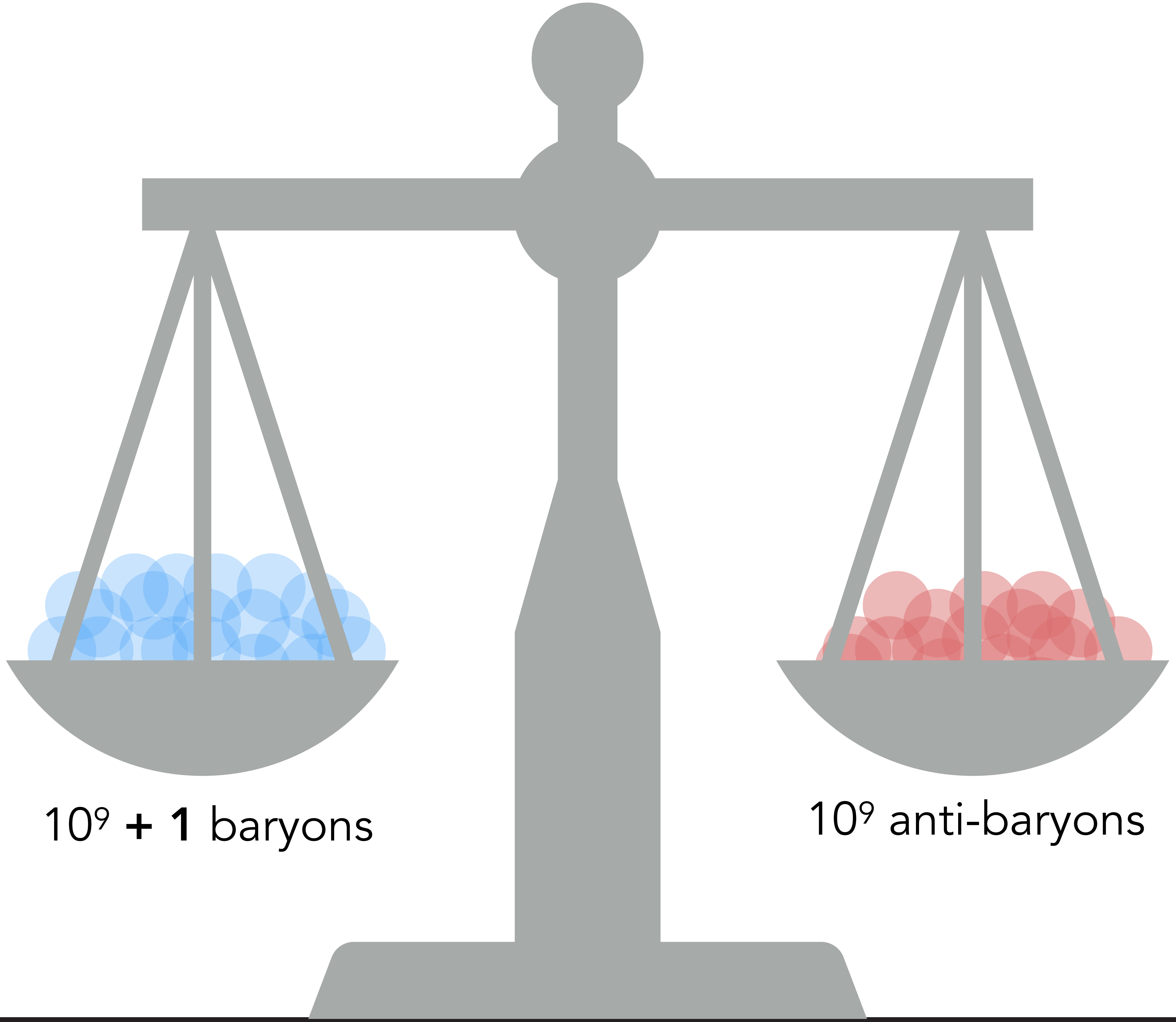
What is the Nature of the Higgs Boson?

Can the Forces Be Unified?

Does Supersymmetry Exist?

What is Dark Matter?

Open Questions in Particle Physics



What is the Origin of the Hierarchy of Fermion Masses?

Why Are There Three Generations of Fermions?

Why is the Universe Made Wholly of Matter? (CP Violation)

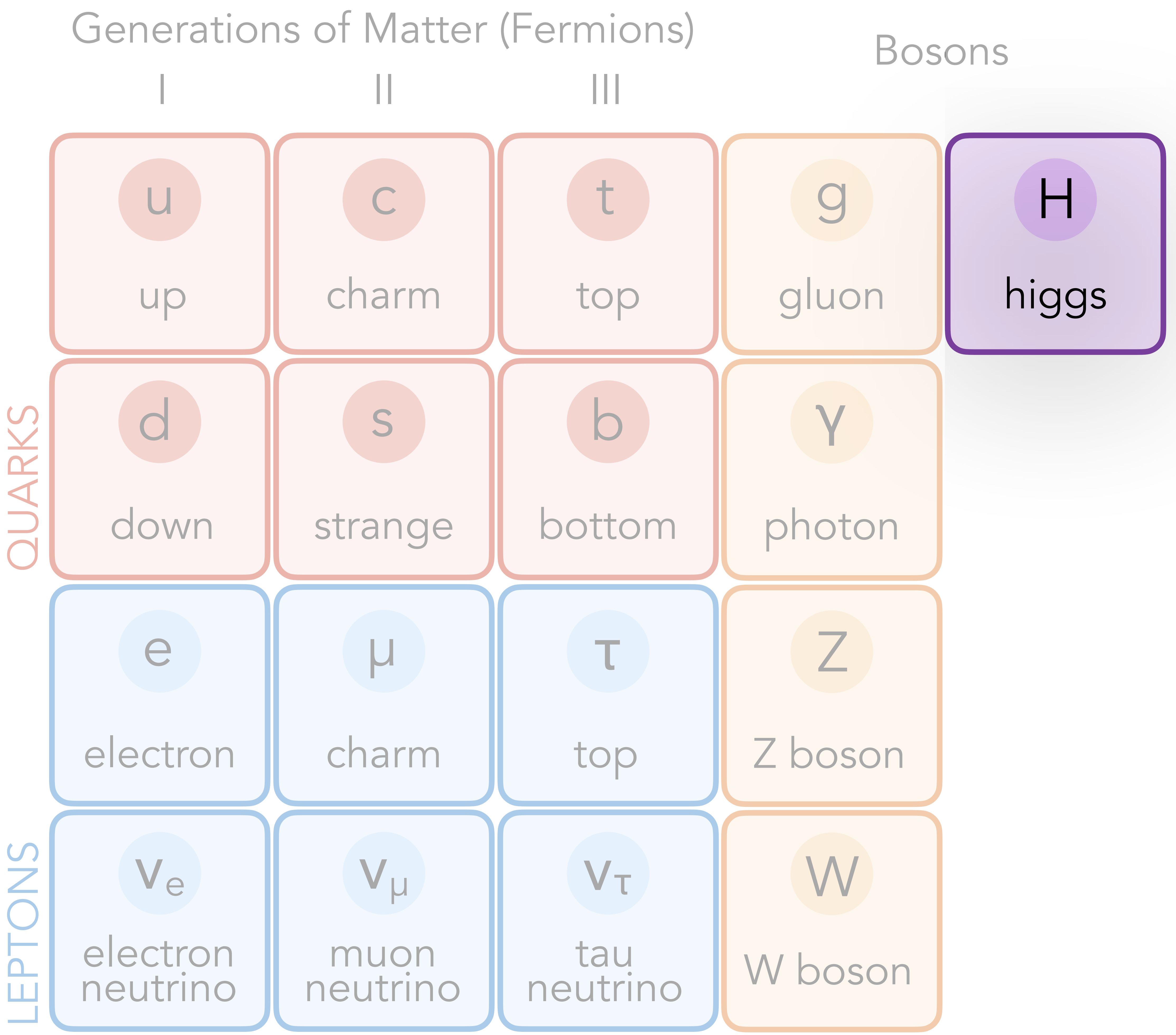
What is the Nature of the Higgs Boson?

Can the Forces Be Unified?

Does Supersymmetry Exist?

What is Dark Matter?

Open Questions in Particle Physics



What is the Origin of the Hierarchy of Fermion Masses?

Why Are There Three Generations of Fermions?

Why is the Universe Made Wholly of Matter? (CP Violation)

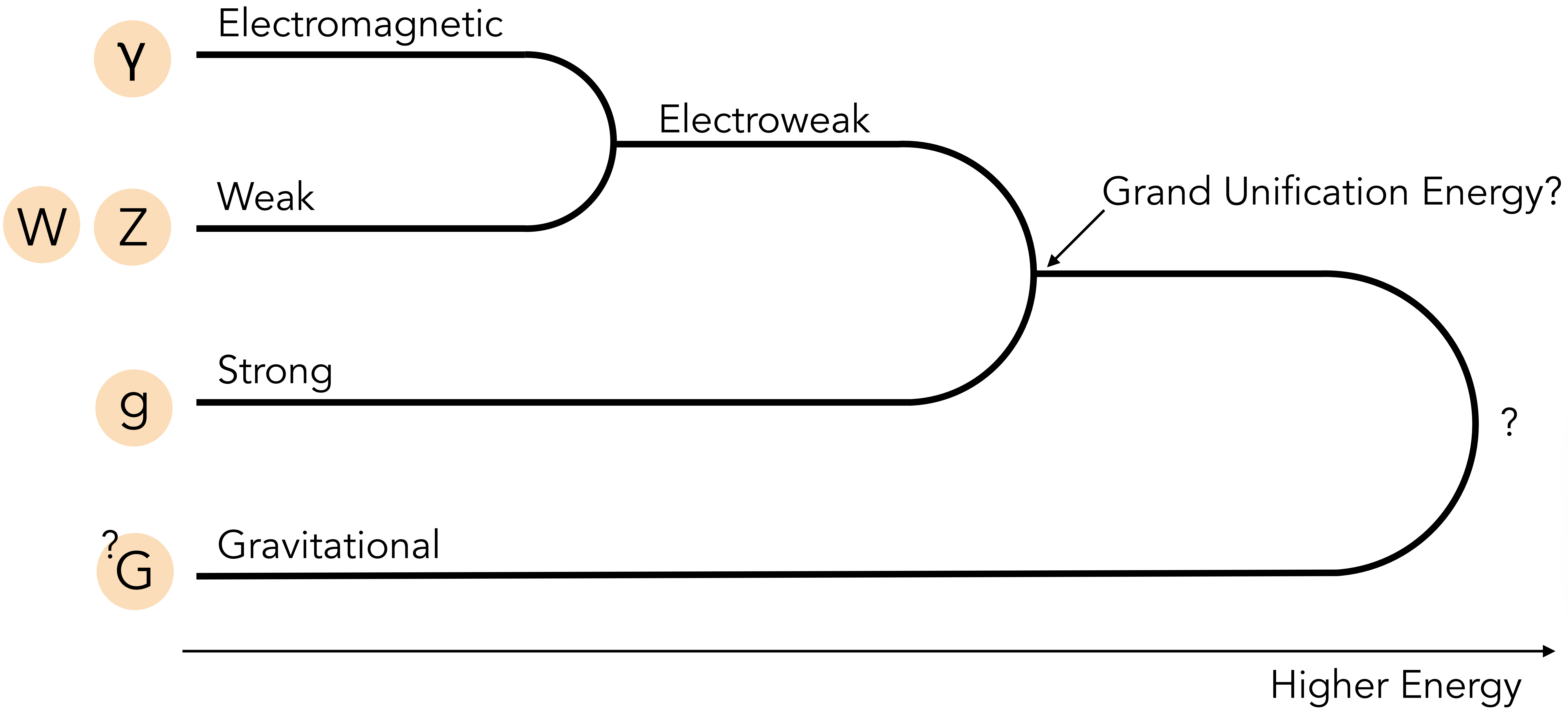
What is the Nature of the Higgs Boson?

Can the Forces Be Unified?

Does Supersymmetry Exist?

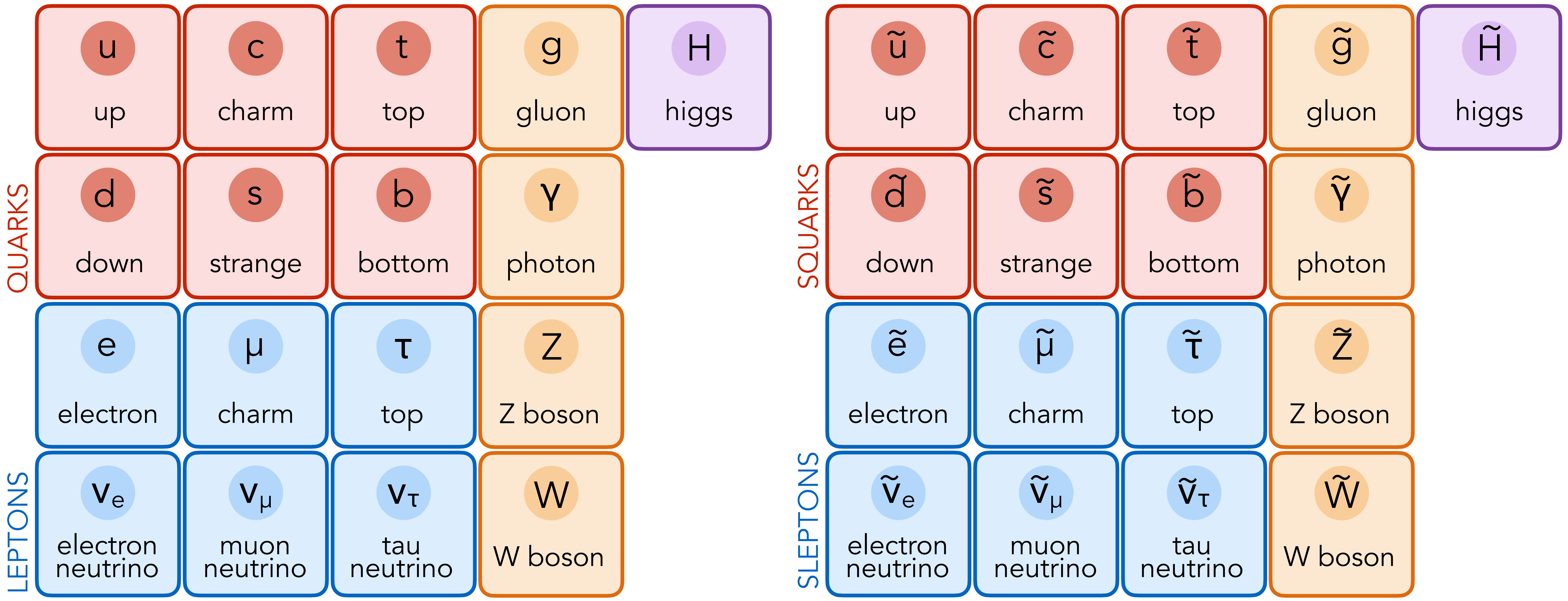
What is Dark Matter?

Open Questions in Particle Physics



- What is the Origin of the Hierarchy of Fermion Masses?
- Why Are There Three Generations of Fermions?
- Why is the Universe Made Wholly of Matter? (CP Violation)
- What is the Nature of the Higgs Boson?
- **Can the Forces Be Unified?**
- Does Supersymmetry Exist?
- What is Dark Matter?

Open Questions in Particle Physics



What is the Origin of the Hierarchy of Fermion Masses?

Why Are There Three Generations of Fermions?

Why is the Universe Made Wholly of Matter? (CP Violation)

What is the Nature of the Higgs Boson?

Can the Forces Be Unified?

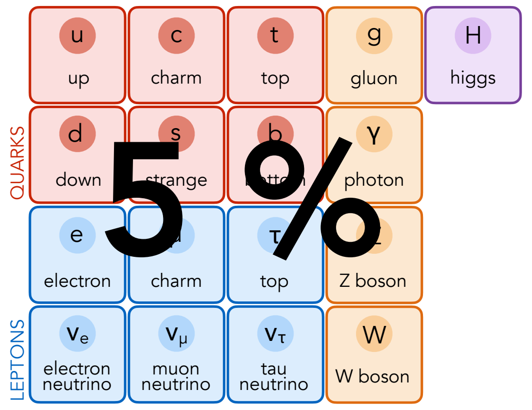
Does Supersymmetry Exist?

What is Dark Matter?

Open Questions in Particle Physics

Dark Matter: 27 %

Dark Energy: 68 %



5 %

What is the Origin of the Hierarchy of Fermion Masses?

Why Are There Three Generations of Fermions?

Why is the Universe Made Wholly of Matter? (CP Violation)

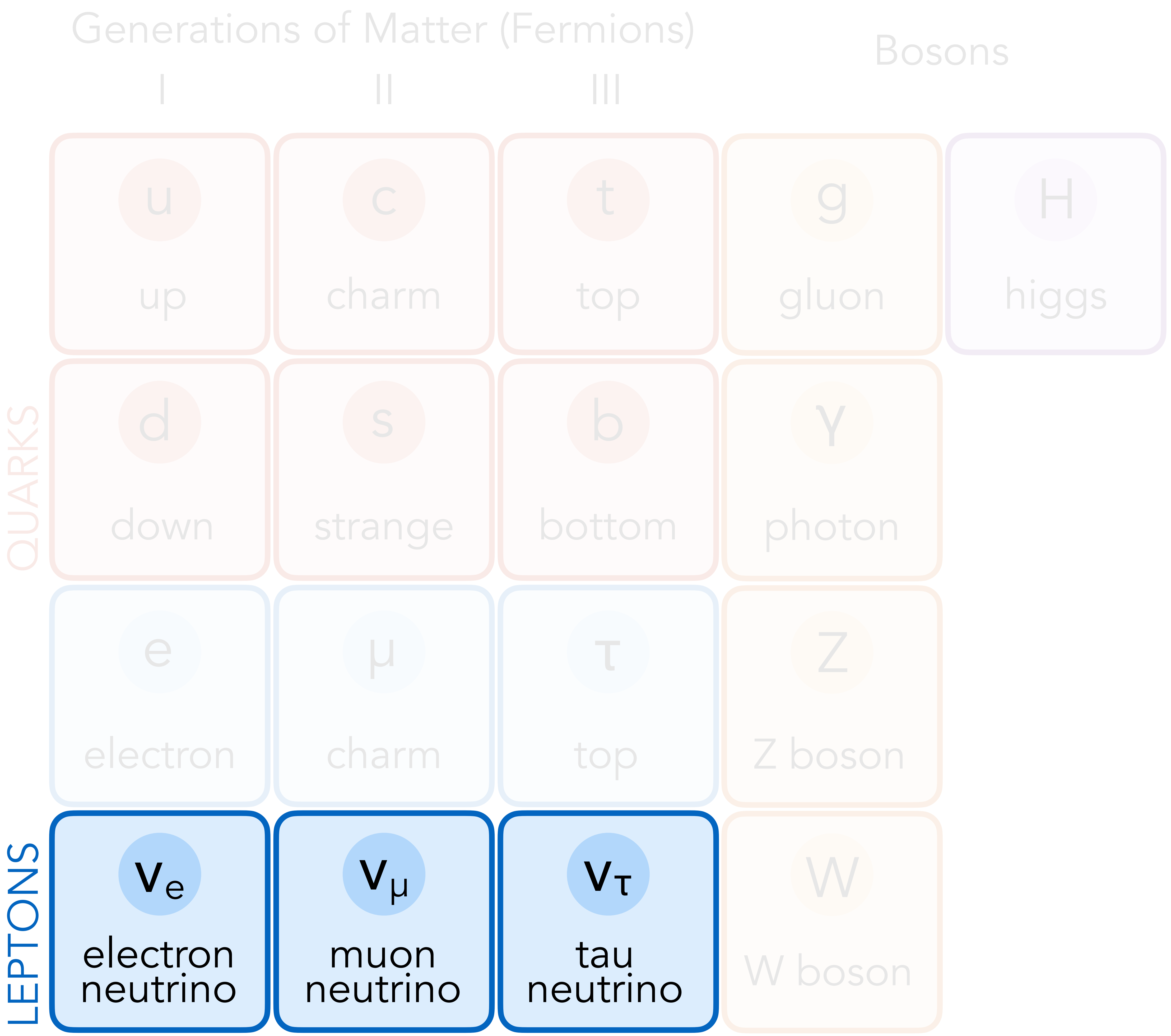
What is the Nature of the Higgs Boson?

Can the Forces Be Unified?

Does Supersymmetry Exist?

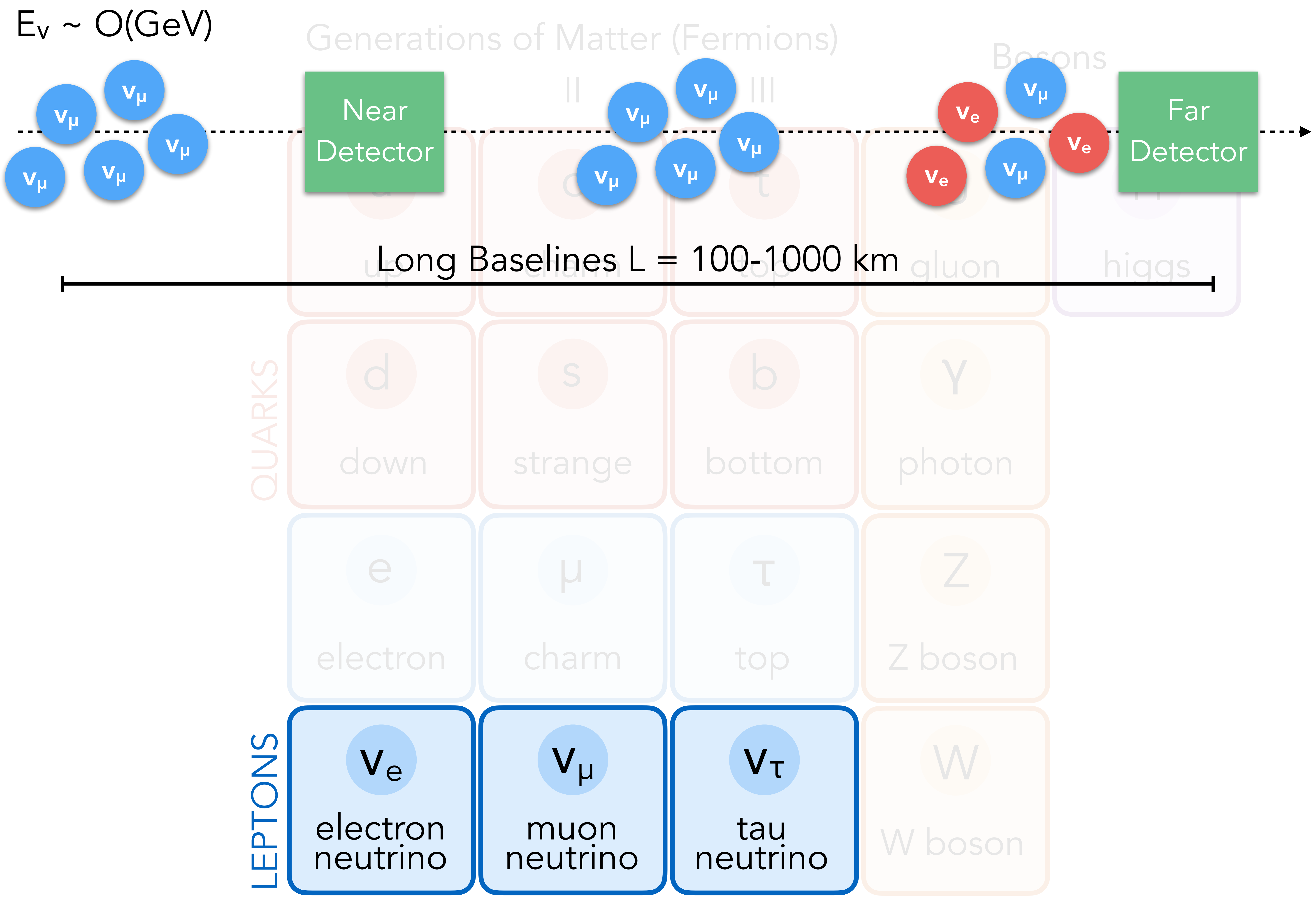
What is Dark Matter?

Neutrinos to Investigate Particles Physics Mysteries



Neutrinos are the least understood particles in the Standard Model

Neutrinos to Investigate Particles Physics Mysteries

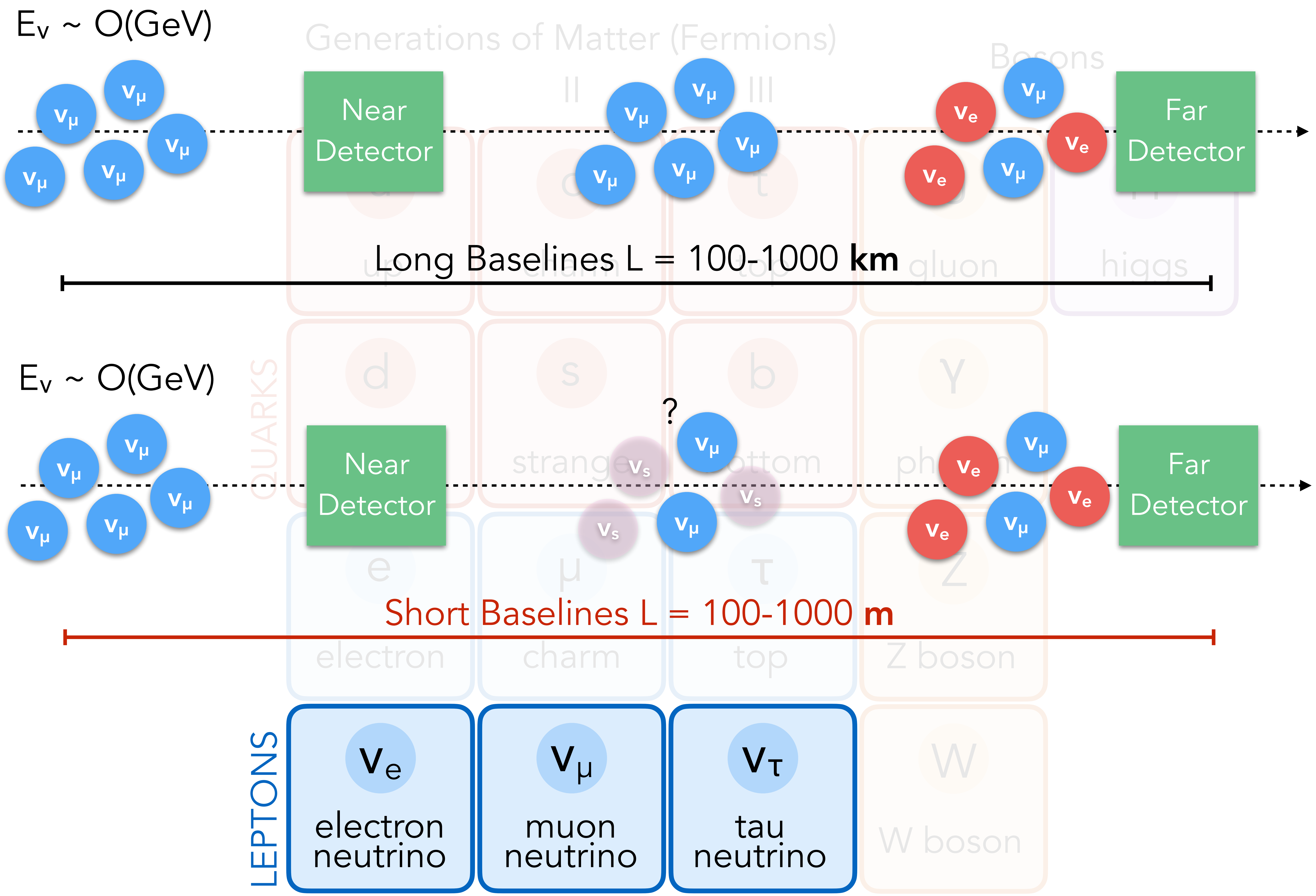


Neutrinos are the least understood particles in the Standard Model

Neutrinos oscillate
Implies that neutrinos have mass
This is an extension of the Standard Model

What are the masses of the neutrinos?
What is the ordering of the masses?

Neutrinos to Investigate Particles Physics Mysteries



Neutrinos are the least understood particles in the Standard Model

Neutrinos oscillate
Implies that neutrinos have mass
This is an extension of the Standard Model

What are the masses of the neutrinos?
What is the ordering of the masses?

Several **anomalies** in the neutrino sector hint for neutrino oscillations at **short baselines**

How many neutrinos exist?
Are there sterile neutrinos?

Short Baseline Neutrino Anomalies

$\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$

$\bar{\nu}_e \rightarrow \bar{\nu}_e$

$\nu_\mu \rightarrow \nu_\mu$

LSND

Reactor Anomaly

MiniBooNE

Gallium Anomaly

Short Baseline Neutrino Anomalies

$\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$

OBSERVED

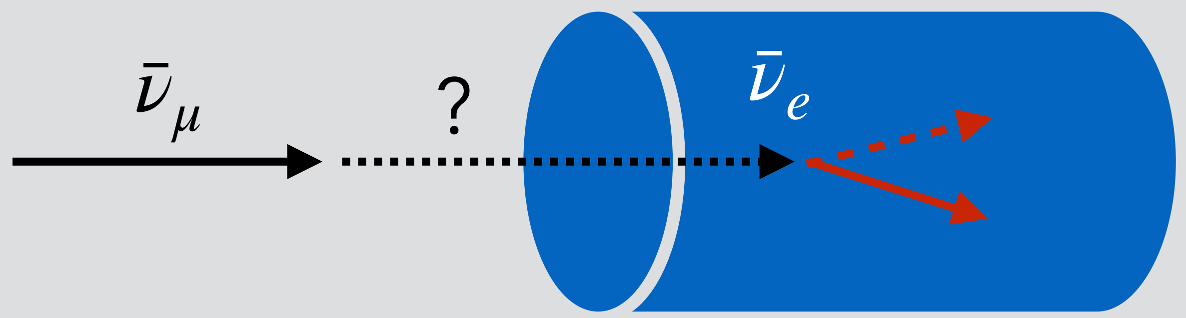
LSND

$\bar{\nu}_e \rightarrow \bar{\nu}_e$

$\nu_\mu \rightarrow \nu_\mu$

LSND

A 3.8 σ excess of events over backgrounds was observed, compatible with $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations with L/E ≈ 1 m/MeV



Reactor Anomaly

MiniBooNE

Gallium Anomaly

Short Baseline Neutrino Anomalies

$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$

OBSERVED

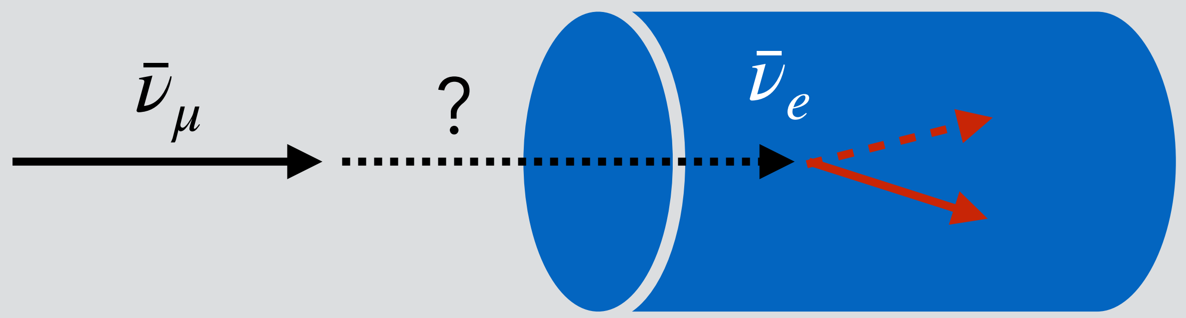
LSND, MiniBooNE

$\bar{\nu}_e \to \bar{\nu}_e$

$\nu_\mu \to \nu_\mu$

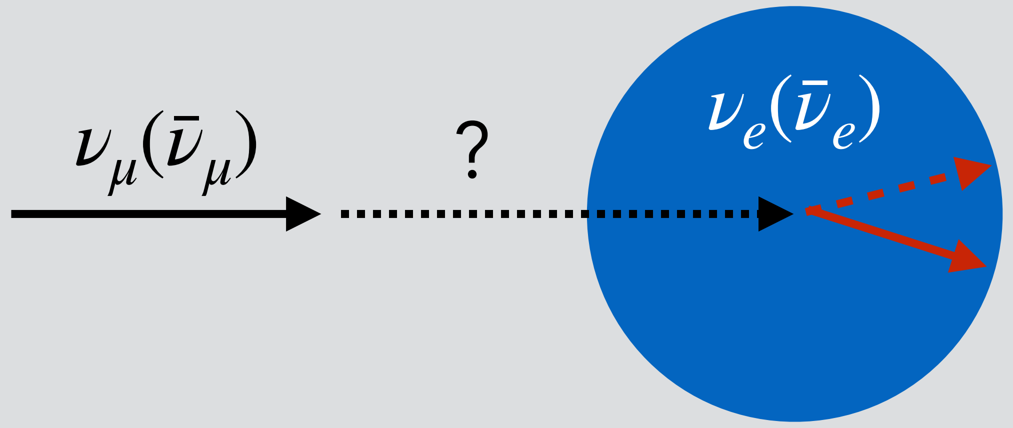
LSND

A 3.8 σ excess of events over backgrounds was observed, compatible with $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations with L/E ≈ 1 m/MeV



MiniBooNE

A 4.5 (2.8) σ excess of events observed with same L/E as LSND; excess compatible with LSND within a sterile neutrino framework



Reactor Anomaly

Gallium Anomaly

Short Baseline Neutrino Anomalies

$\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$

OBSERVED

LSND, MiniBooNE

$\bar{\nu}_e \rightarrow \bar{\nu}_e$

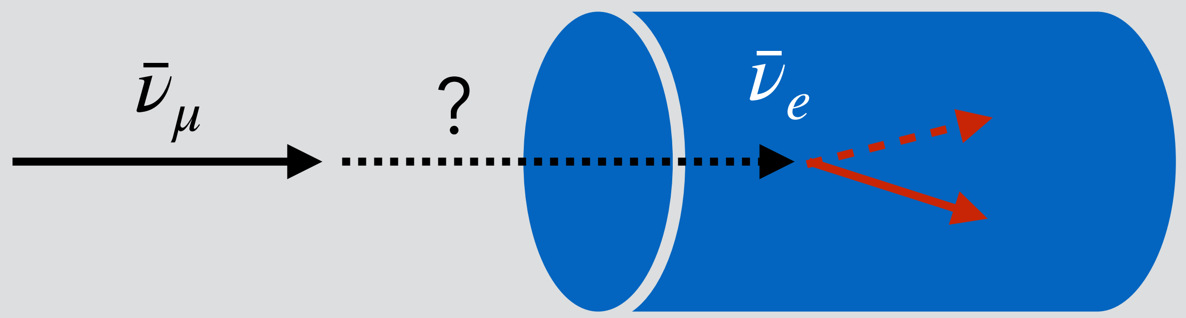
OBSERVED

Reactor anomaly

$\nu_\mu \rightarrow \nu_\mu$

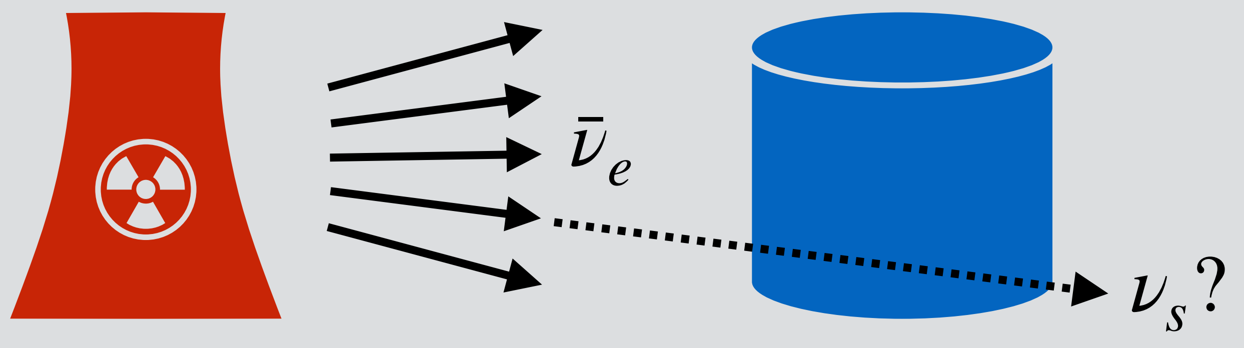
LSND

A 3.8 σ excess of events over backgrounds was observed, compatible with $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations with L/E ≈ 1 m/MeV



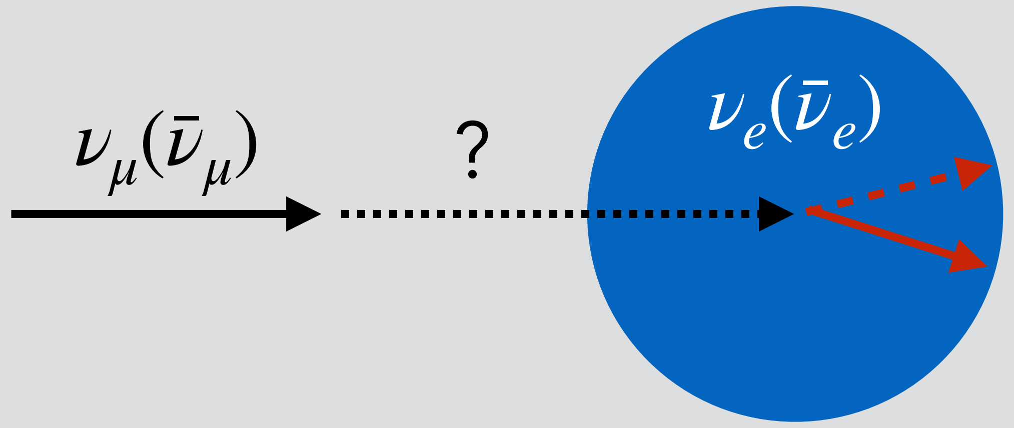
Reactor Anomaly

A 3 σ deficit in the detected $\bar{\nu}_e$ flux was seen in past reactor experiments when compared to theory calculations



MiniBooNE

A 4.5 (2.8) σ excess of events observed with same L/E as LSND; excess compatible with LSND within a sterile neutrino framework



Gallium Anomaly

Short Baseline Neutrino Anomalies

$\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$

OBSERVED

LSND, MiniBooNE

$\bar{\nu}_e \rightarrow \bar{\nu}_e$

OBSERVED

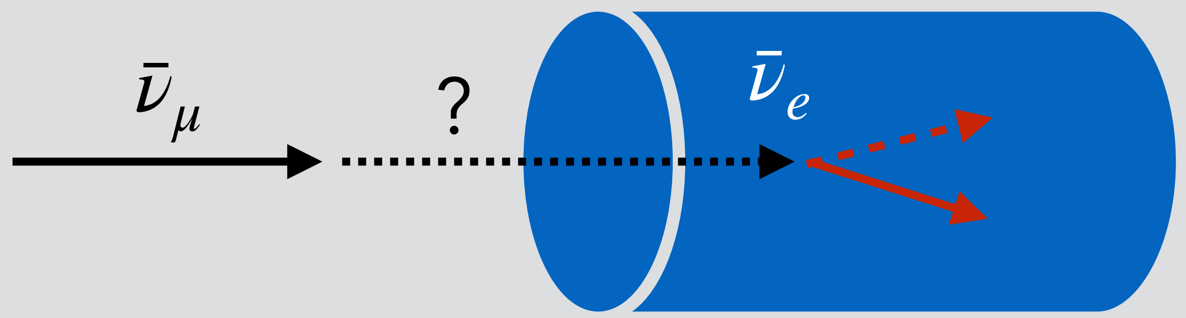
Reactor, Gallium anomalies

$\nu_\mu \rightarrow \nu_\mu$

NOT OBSERVED

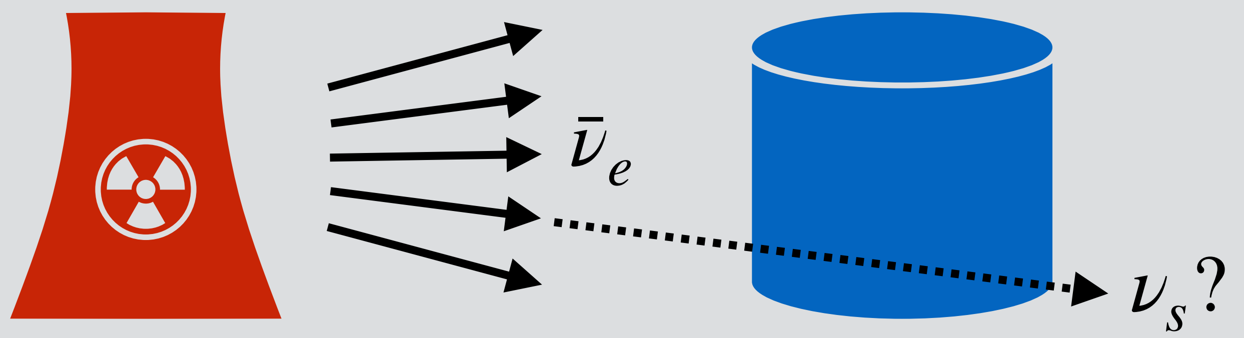
LSND

A 3.8 σ excess of events over backgrounds was observed, compatible with $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations with L/E ≈ 1 m/MeV



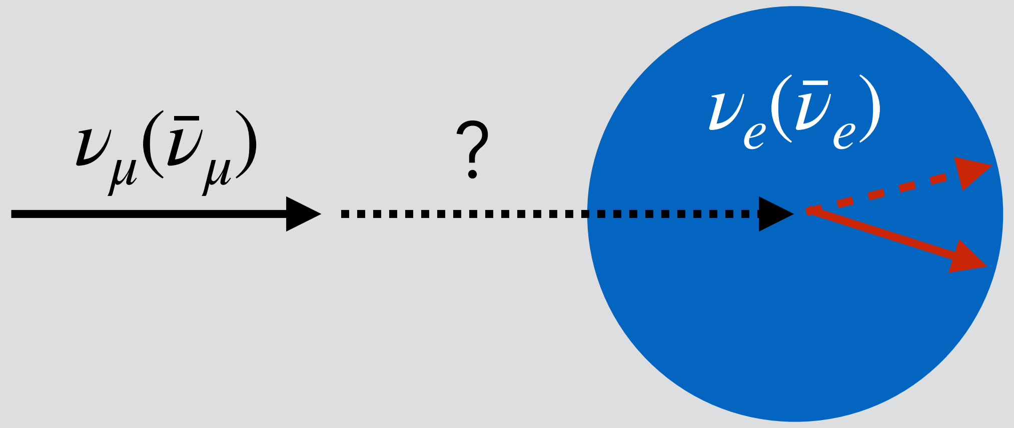
Reactor Anomaly

A 3 σ deficit in the detected $\bar{\nu}_e$ flux was seen in past reactor experiments when compared to theory calculations



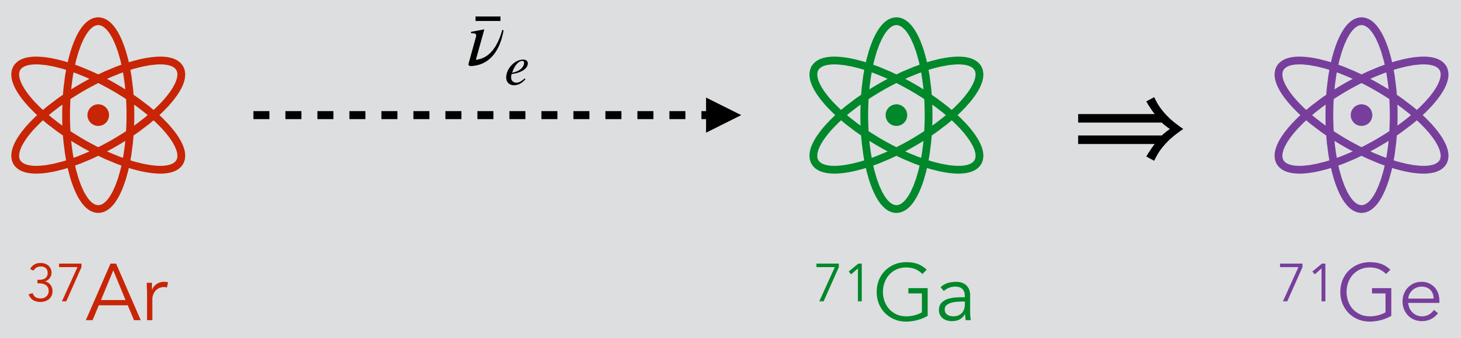
MiniBooNE

A 4.5 (2.8) σ excess of events observed with same L/E as LSND; excess compatible with LSND within a sterile neutrino framework



Gallium Anomaly

A 3 σ deficit in the detected ν_e flux was seen as seen during calibration runs of solar neutrino experiments



Marco Del Tutto
University of Chicago - Rising Stars Symposium

The Short Baseline Neutrino Program

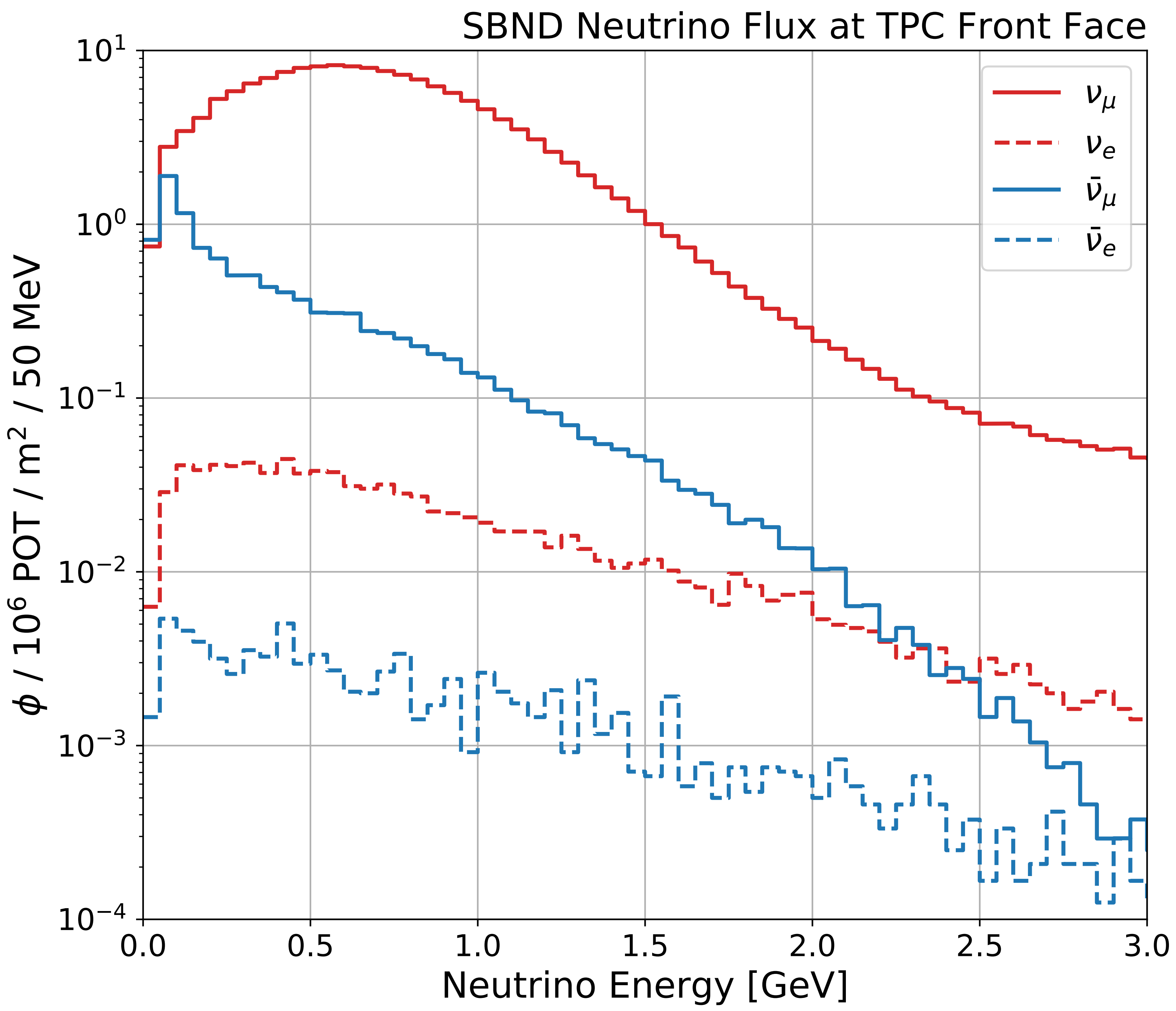
The Short Baseline Neutrino (SBN) program has been designed specifically to address the sterile neutrino interpretation of the experimental anomalies

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

Booster Neutrino Beam

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

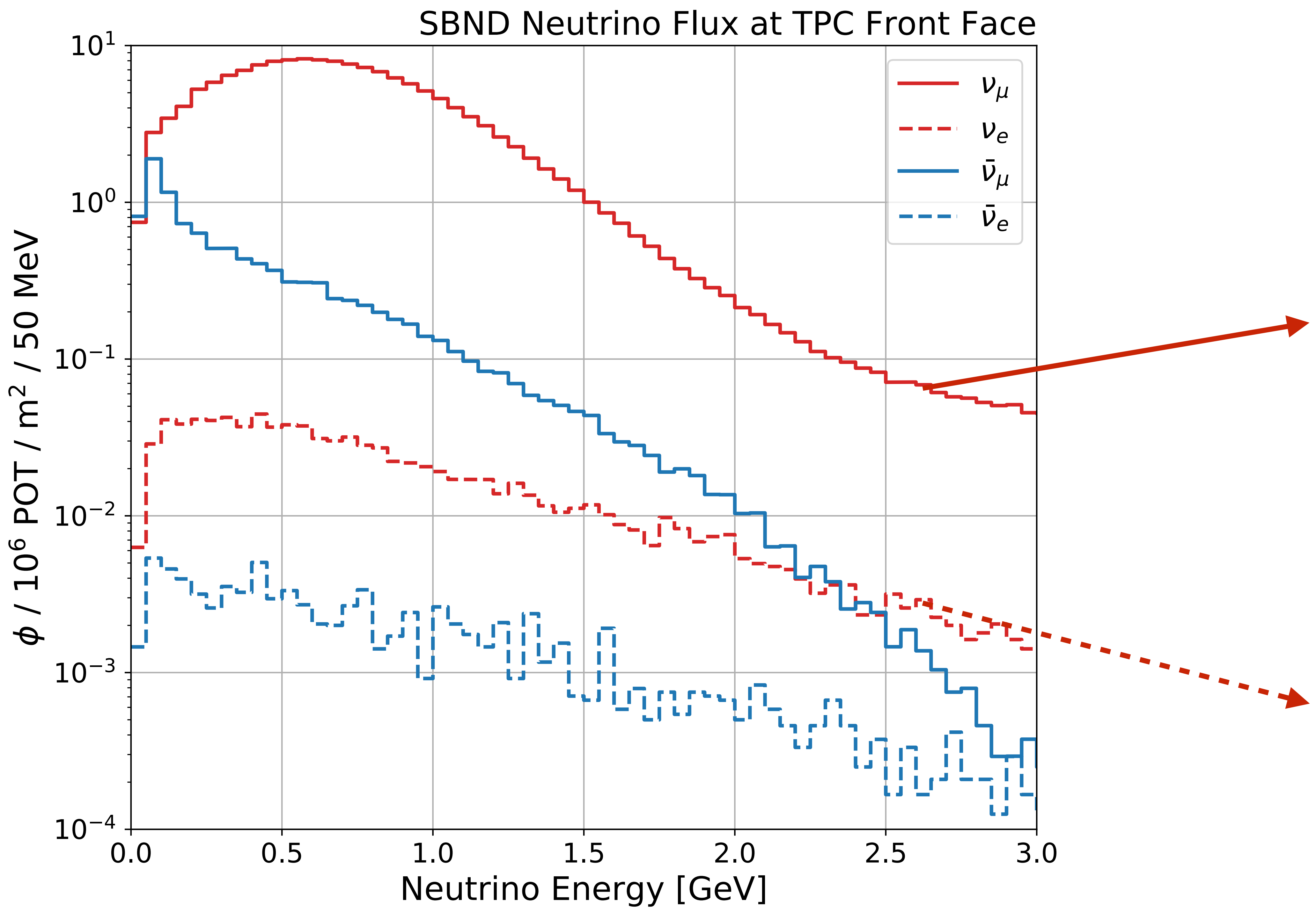
Neutrino Flux at SBND



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



Neutrino flux at the SBND front face

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

ν_μ Flux

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

Two-body decays

ν_e Flux

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

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)

Goals of the SBN Program

Search for eV mass-scale sterile neutrino oscillations

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

Measure Events: $N_{ND} \propto \phi_{ND} \otimes \sigma$ $N_{FD} \propto \phi_{FD} \otimes \sigma \otimes P_{osc}$

Near Detector

Far Detector

Goals of the SBN Program

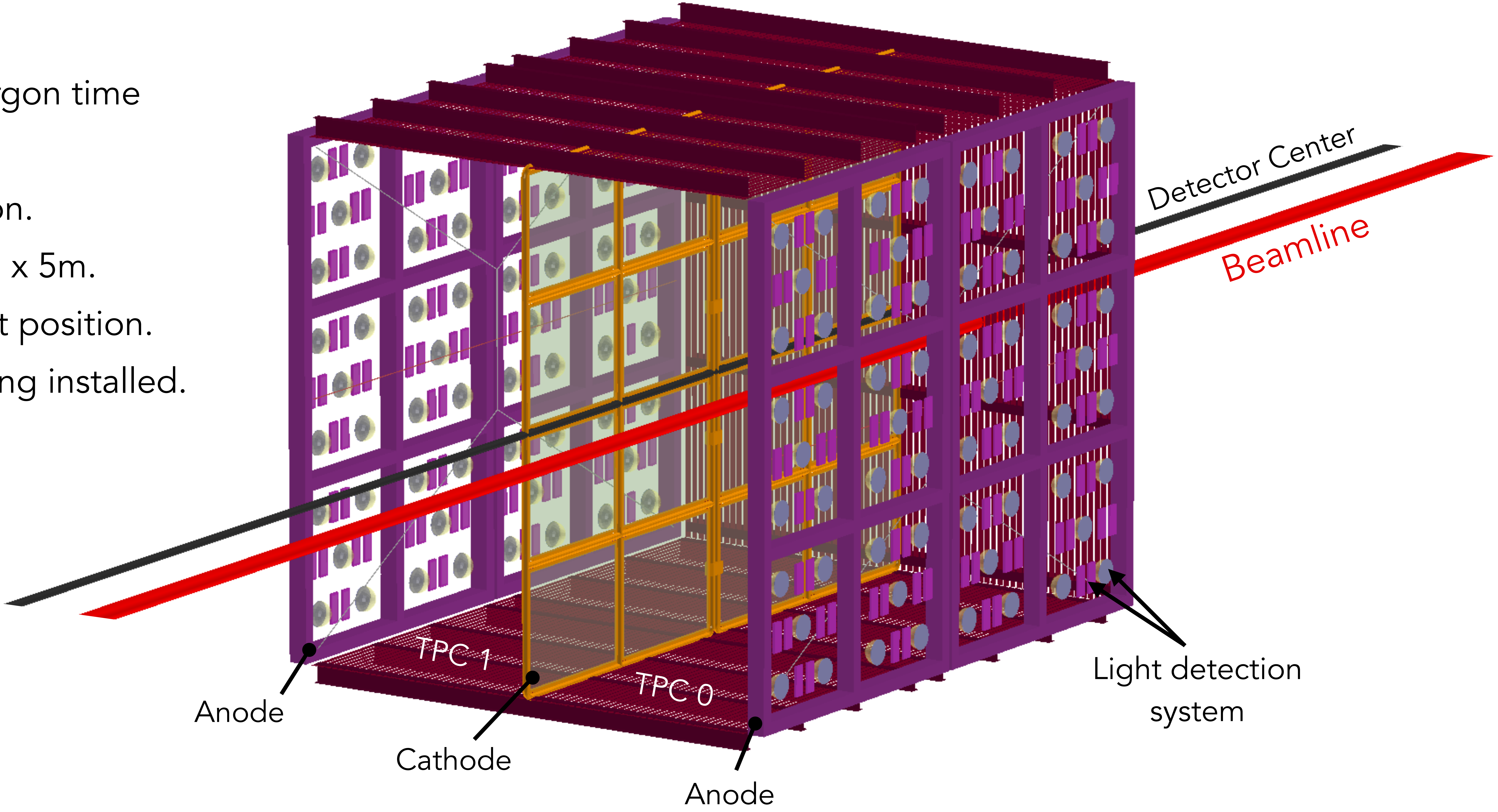
Neutrino-Nucleus Interactions	New Physics
Millions of Interactions per Year	Light Dark Matter
Precision Physics Studies	Millicharged Particles
Exclusive Cross-Section Measurements	Dark Neutrinos
Study of Nuclear Effects	Heavy Neutral Leptons
Measure Rare Interaction Channels	Neutrino Tridents

Marco Del Tutto
University of Chicago - Rising Stars Symposium

The Short Baseline Near Detector (SBND)

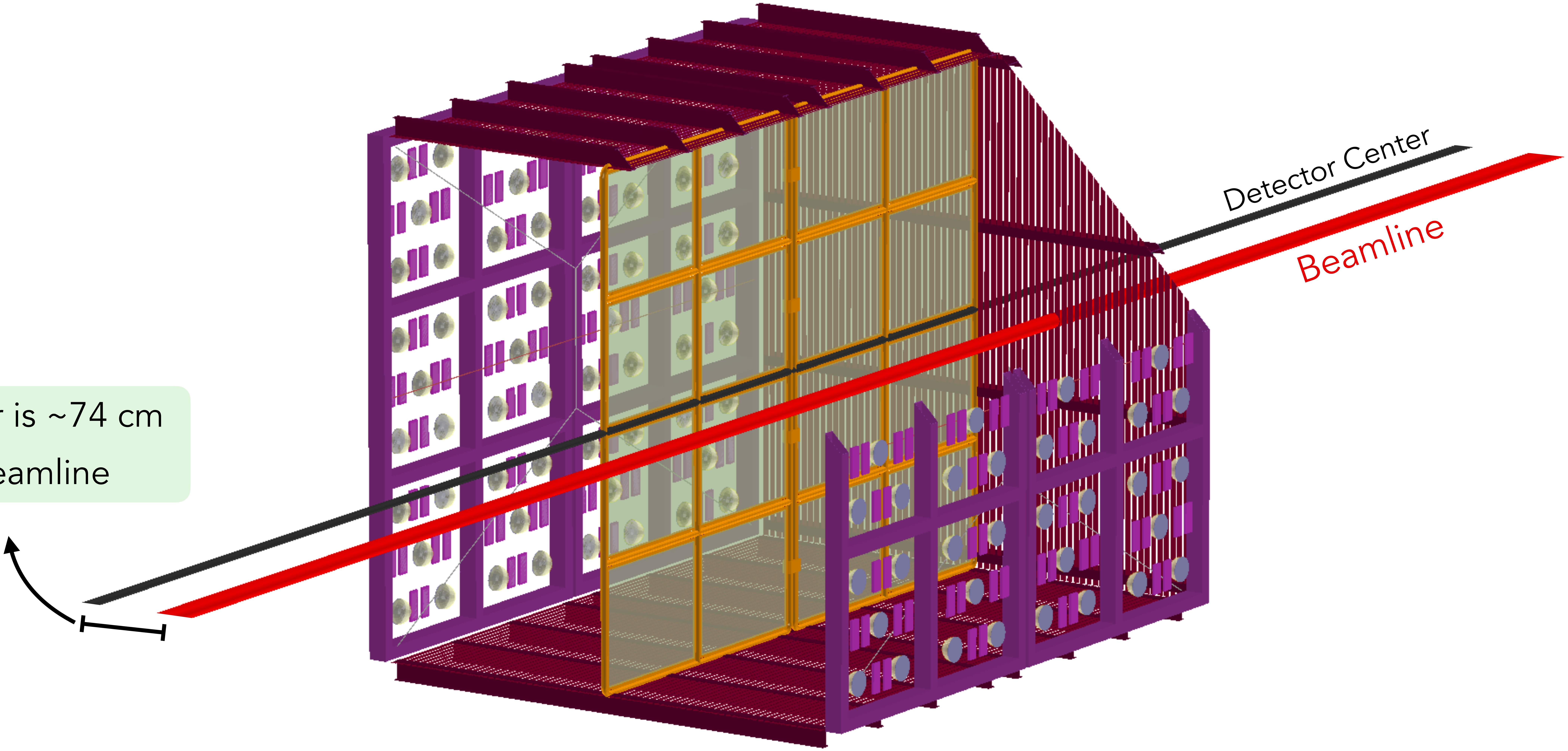
The SBND detector

- 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)

View from the top of the SBND Detector

Marco Del Tutto
University of Chicago - Rising Stars Symposium

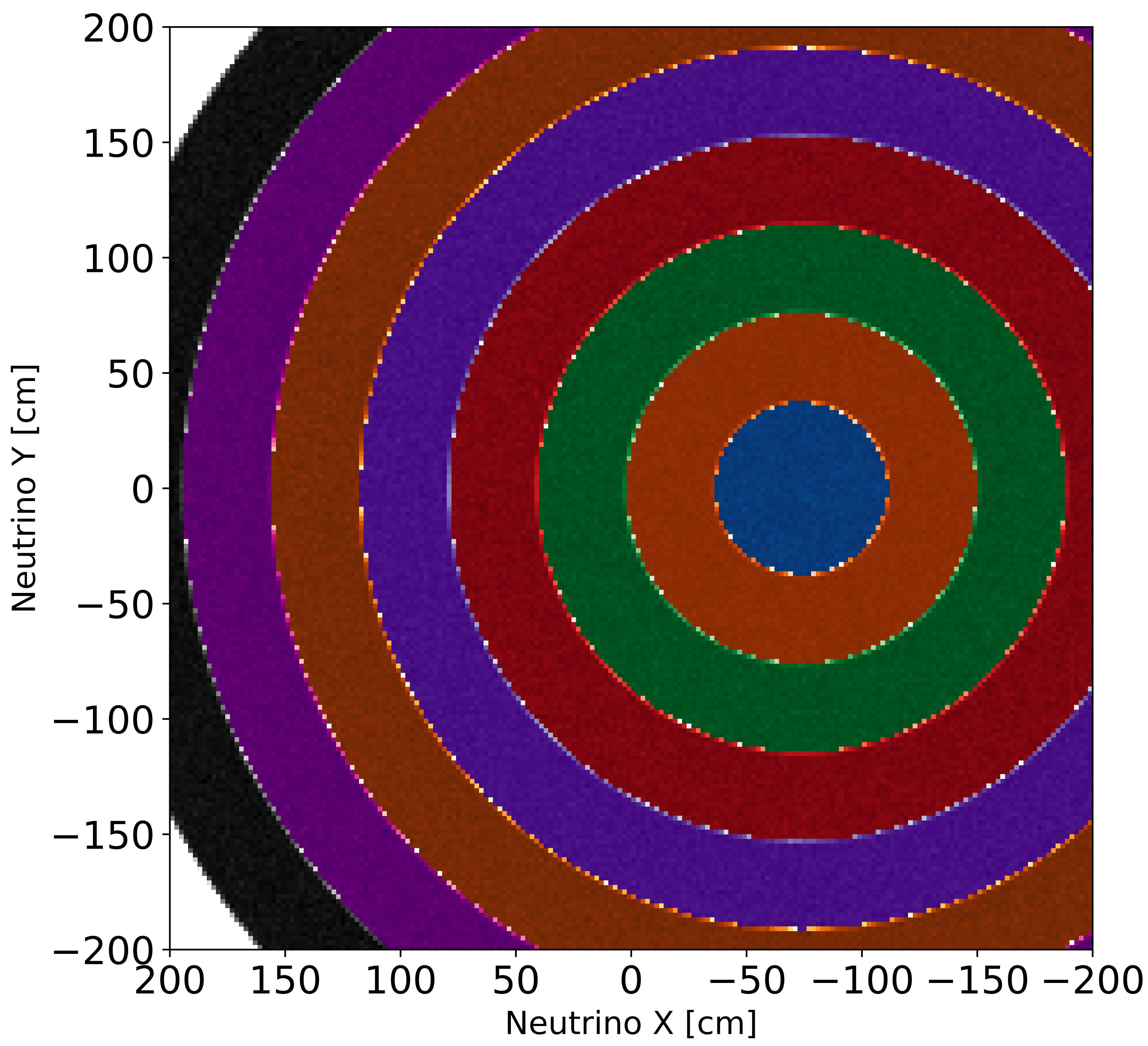
A Slightly Off-Axis Detector

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

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

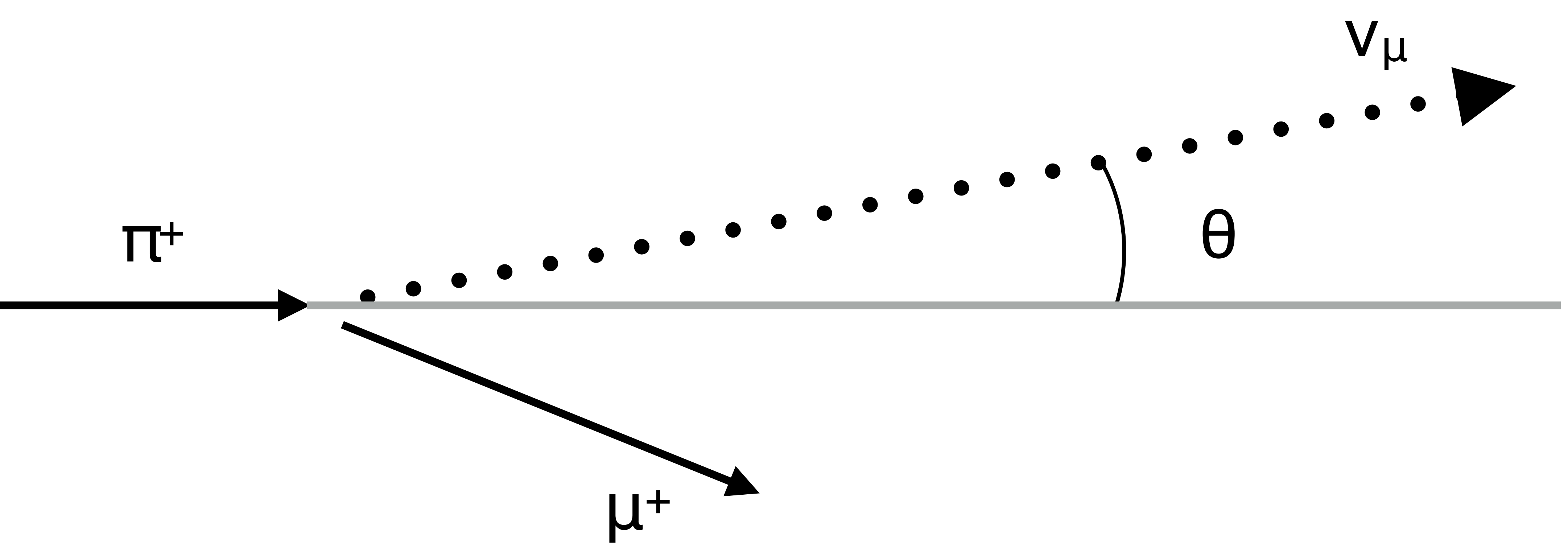
The detector can be divided in several off-axis slices:

- 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°)
- OAA ∈ [1.4°, 1.6°)

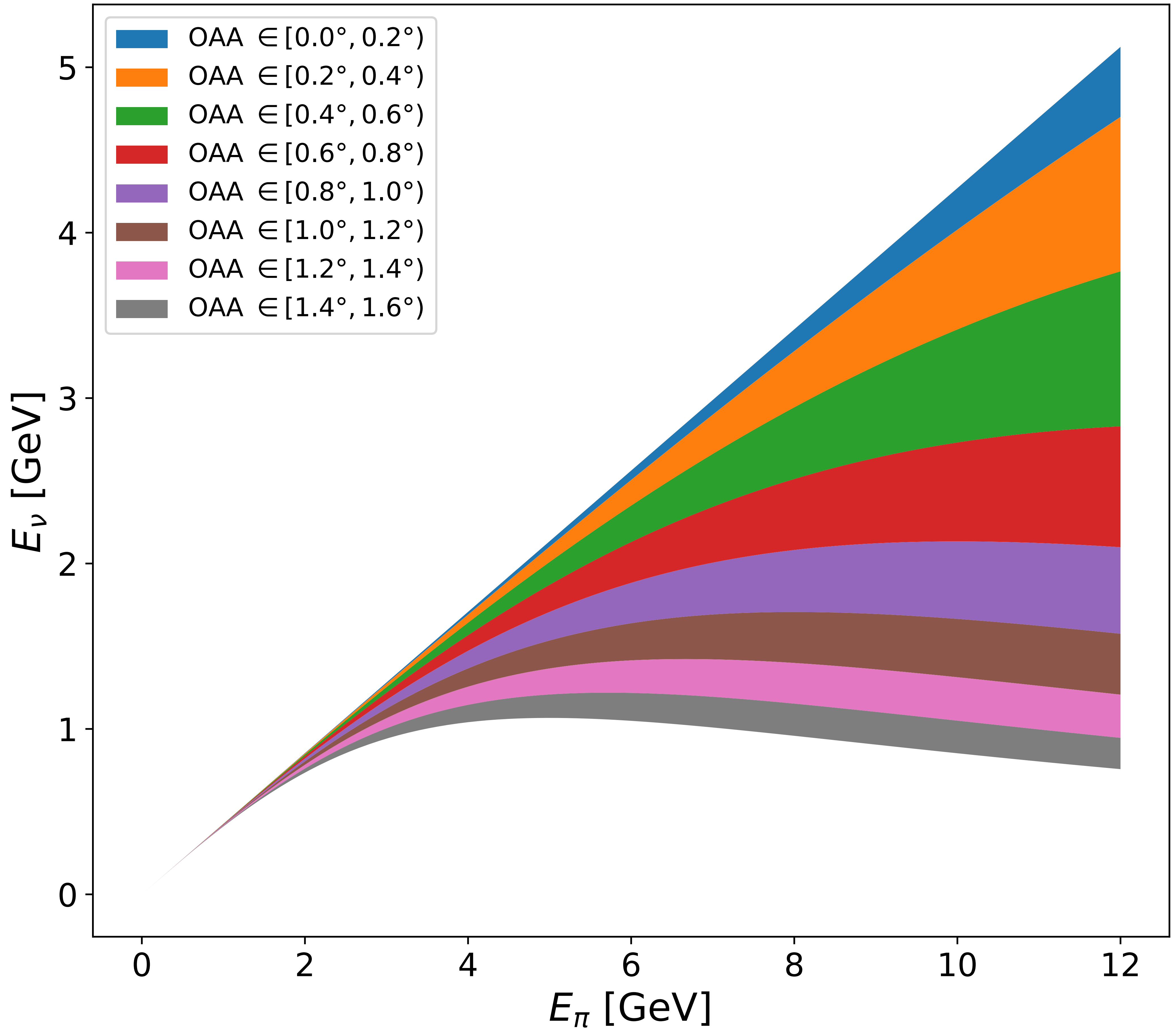


The Off-Axis Angle (OAA)

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)

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°)

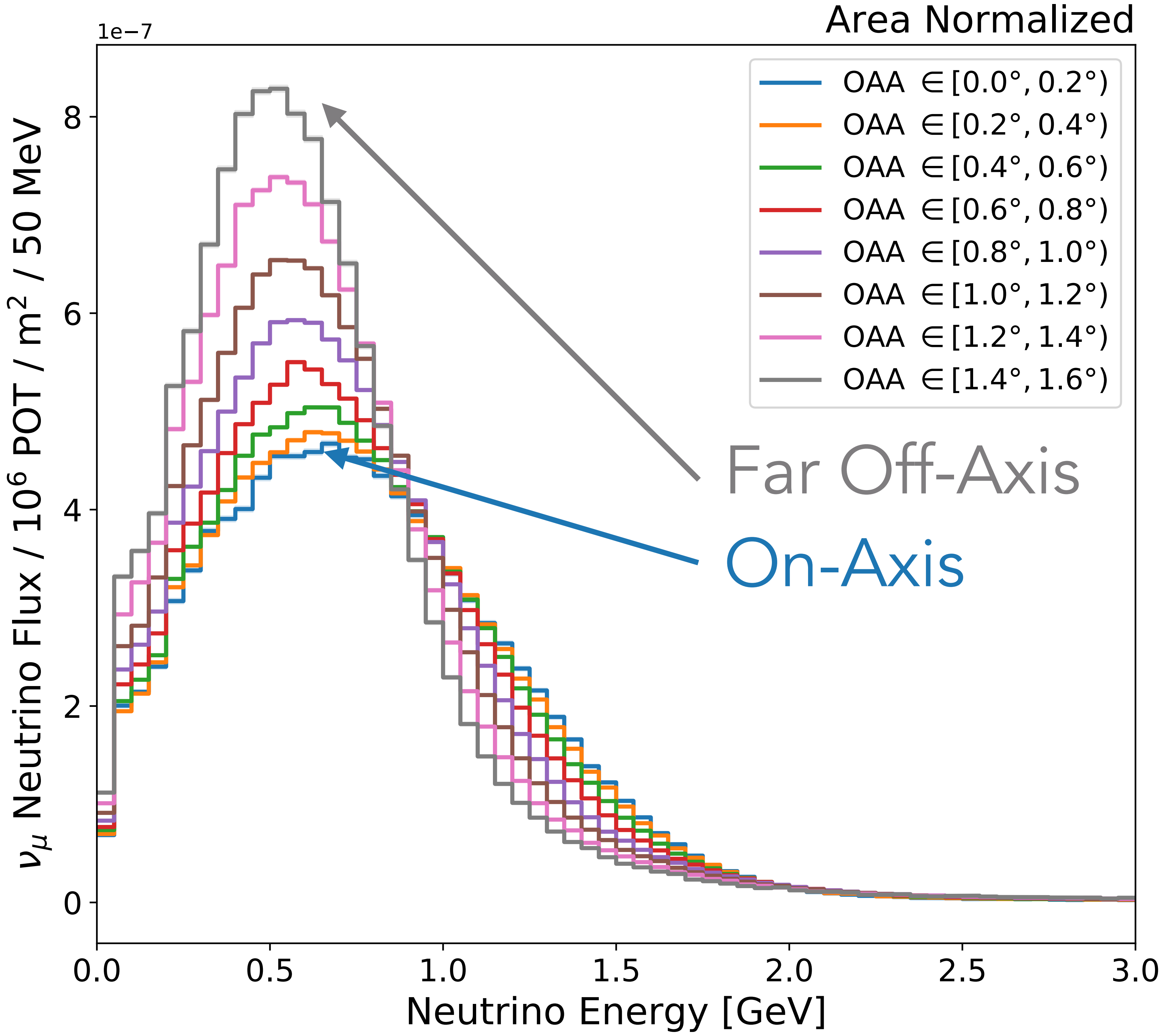
OAA ∈ [0.8°, 1.0°)

OAA ∈ [1.0°, 1.2°)

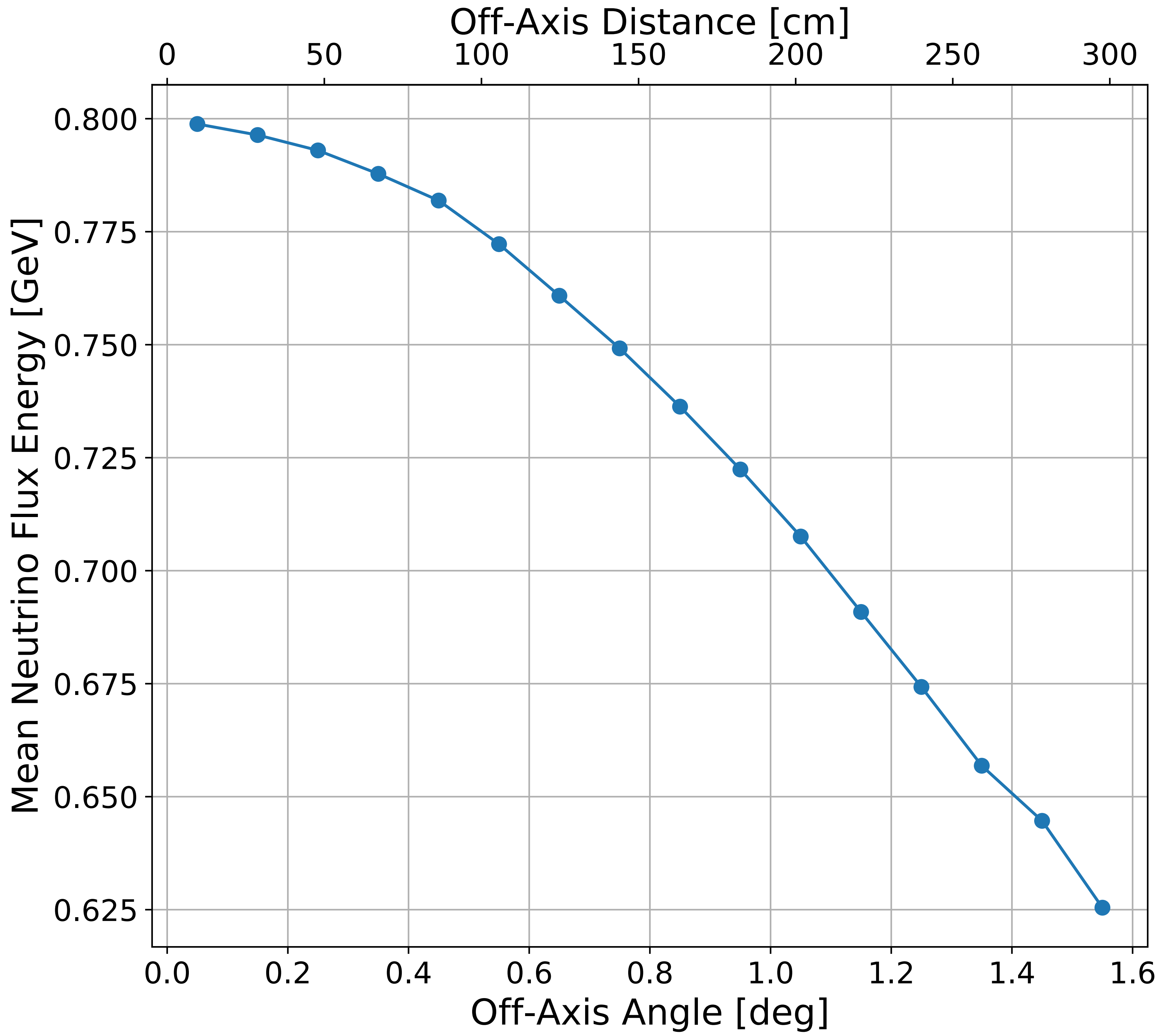
OAA ∈ [1.2°, 1.4°)

OAA ∈ [1.4°, 1.6°)

Muon neutrino flux in each of the OAA regions



Mean neutrino energy



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

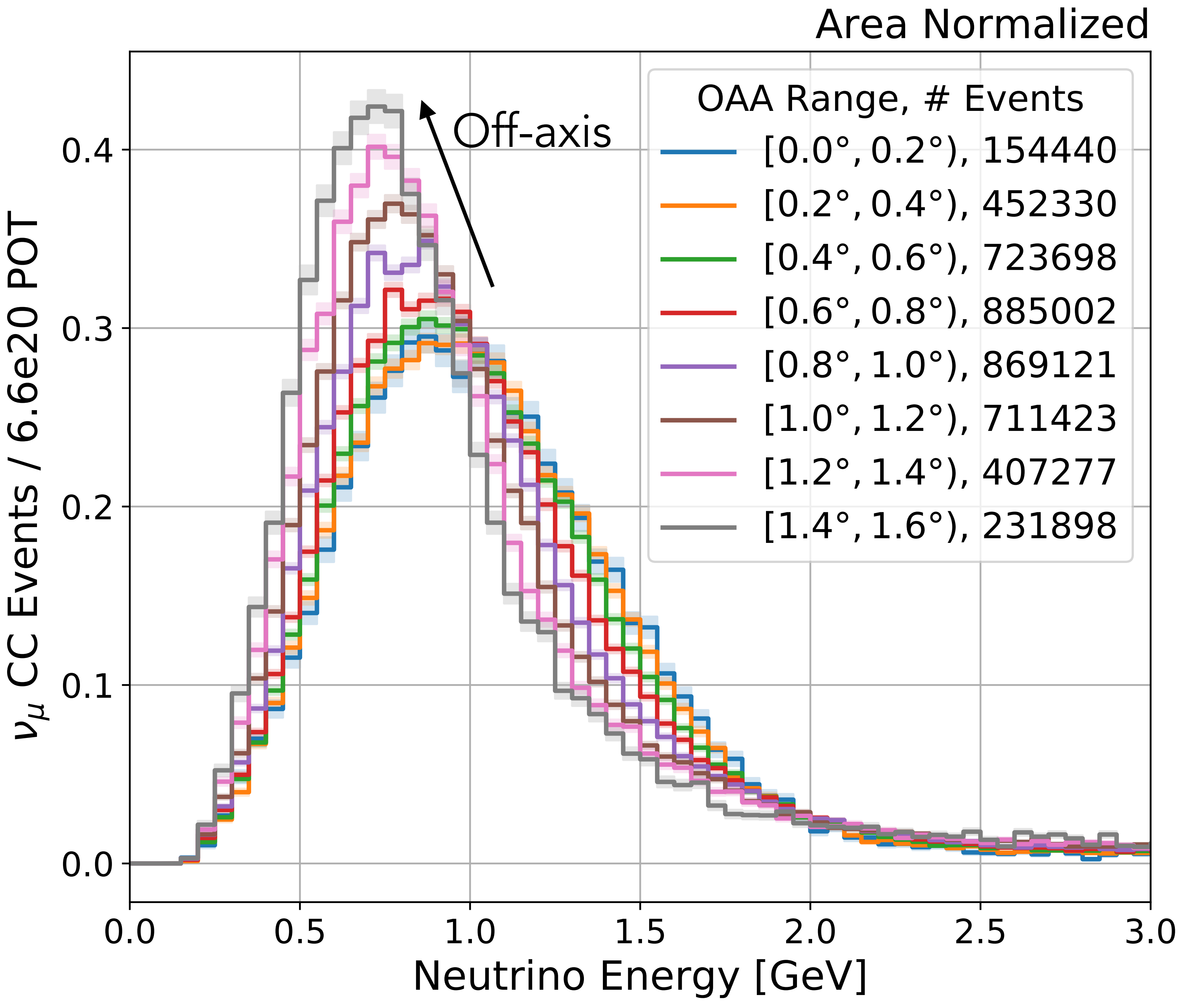
SBND-PRISM - ν_μ / ν_e Differences 1/2

Muon neutrino energy spectrum changes with the off-axis angle,

while the electron neutrino one stays almost the same

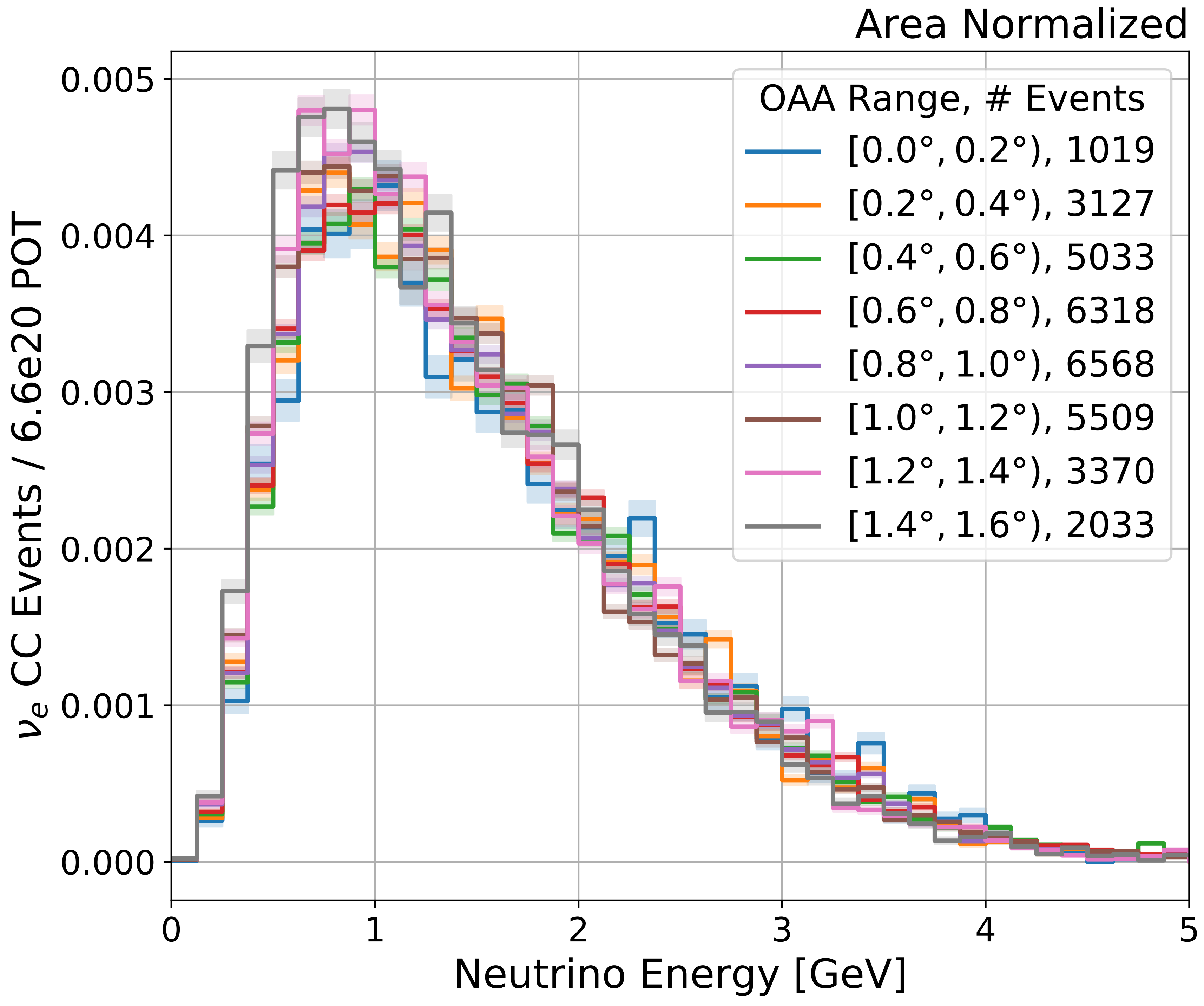
Muon-neutrino CC Events

higher off-axis angle → lower mean energy



Electron-neutrino CC Events

higher off-axis angle → ~same mean energy



High event statistics in all off-axis regions

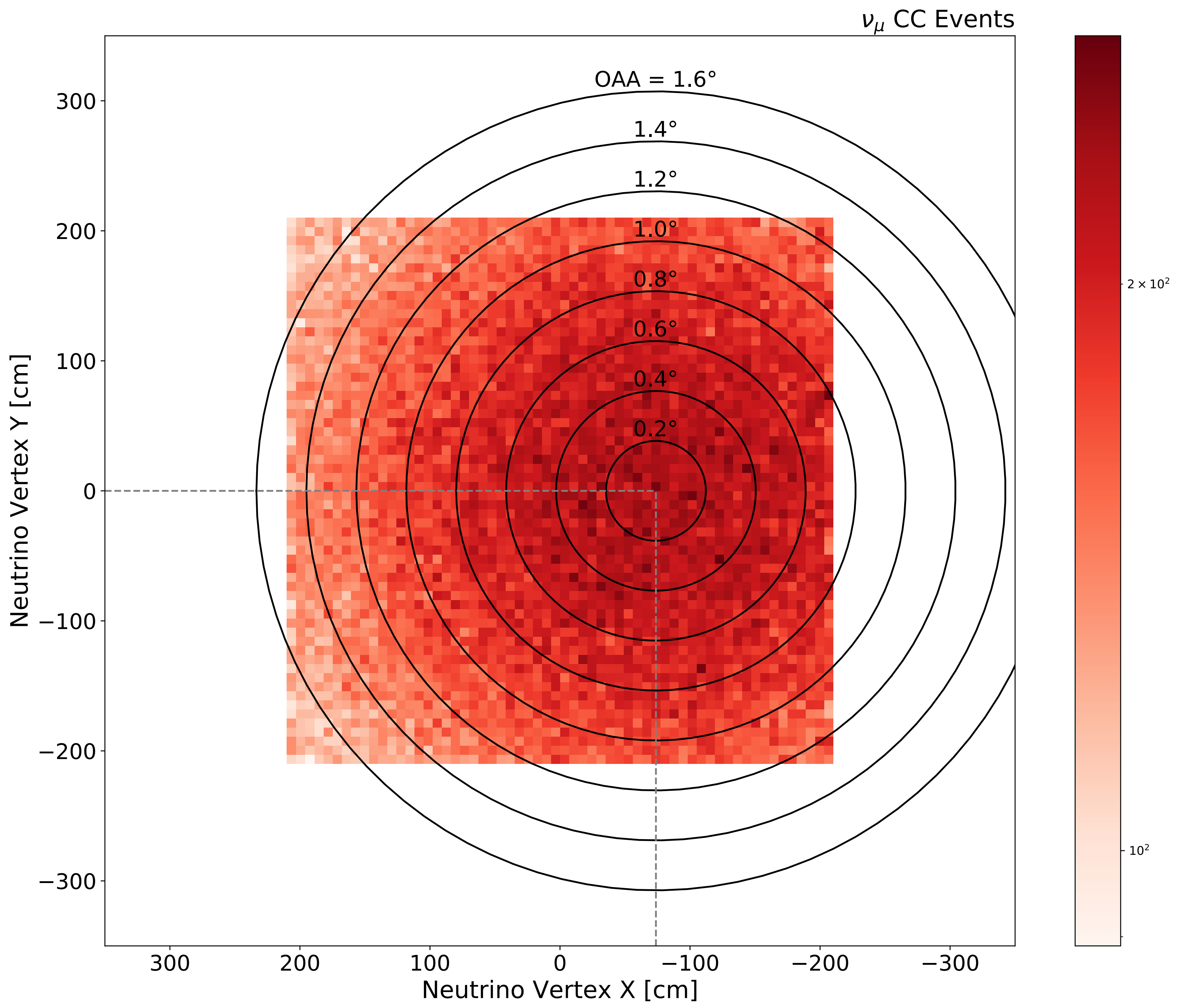
SBND-PRISM - ν_μ / ν_e Differences 2/2

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.

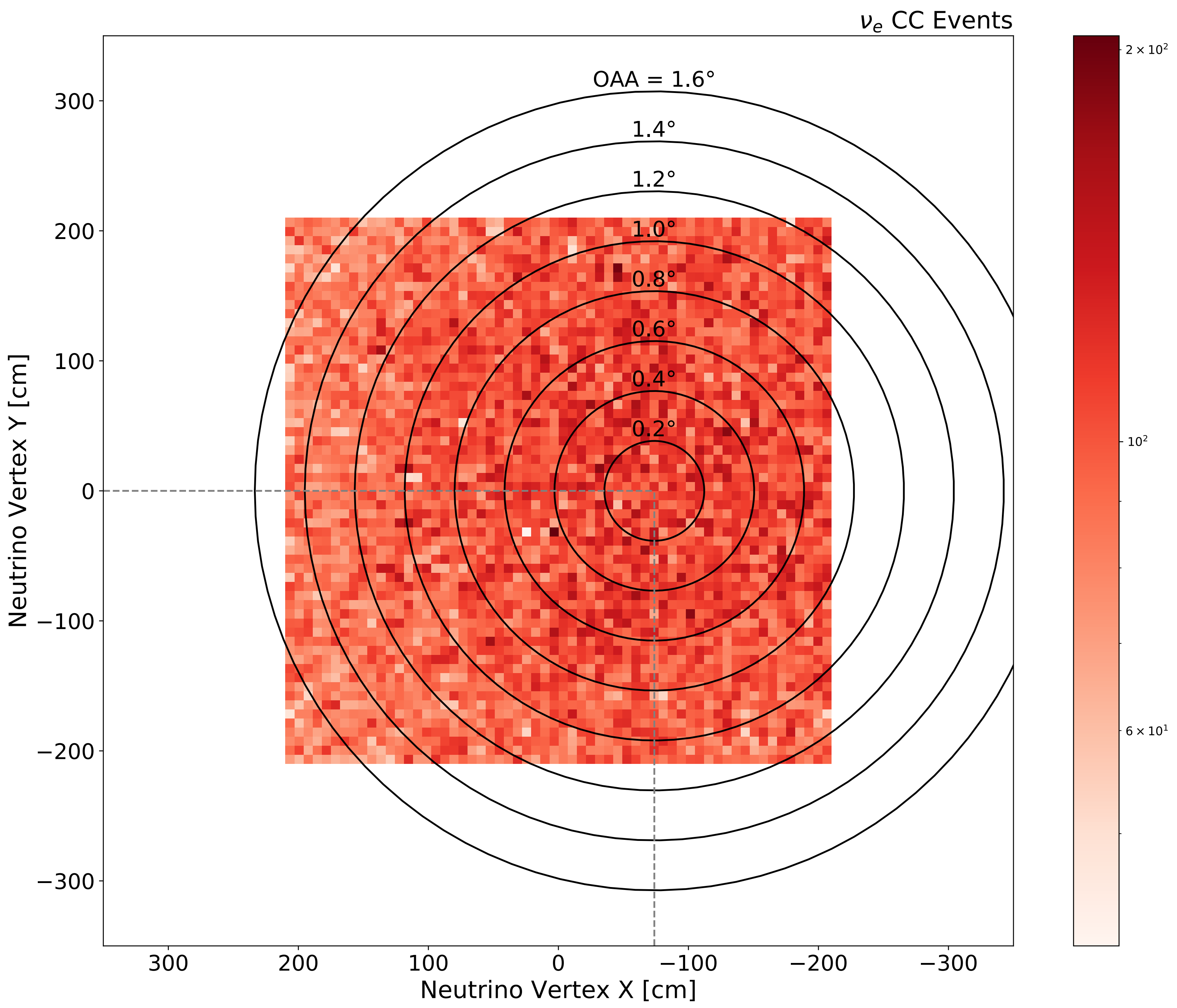
Muon-neutrinos CC Events

peak coincident with the on-axis position

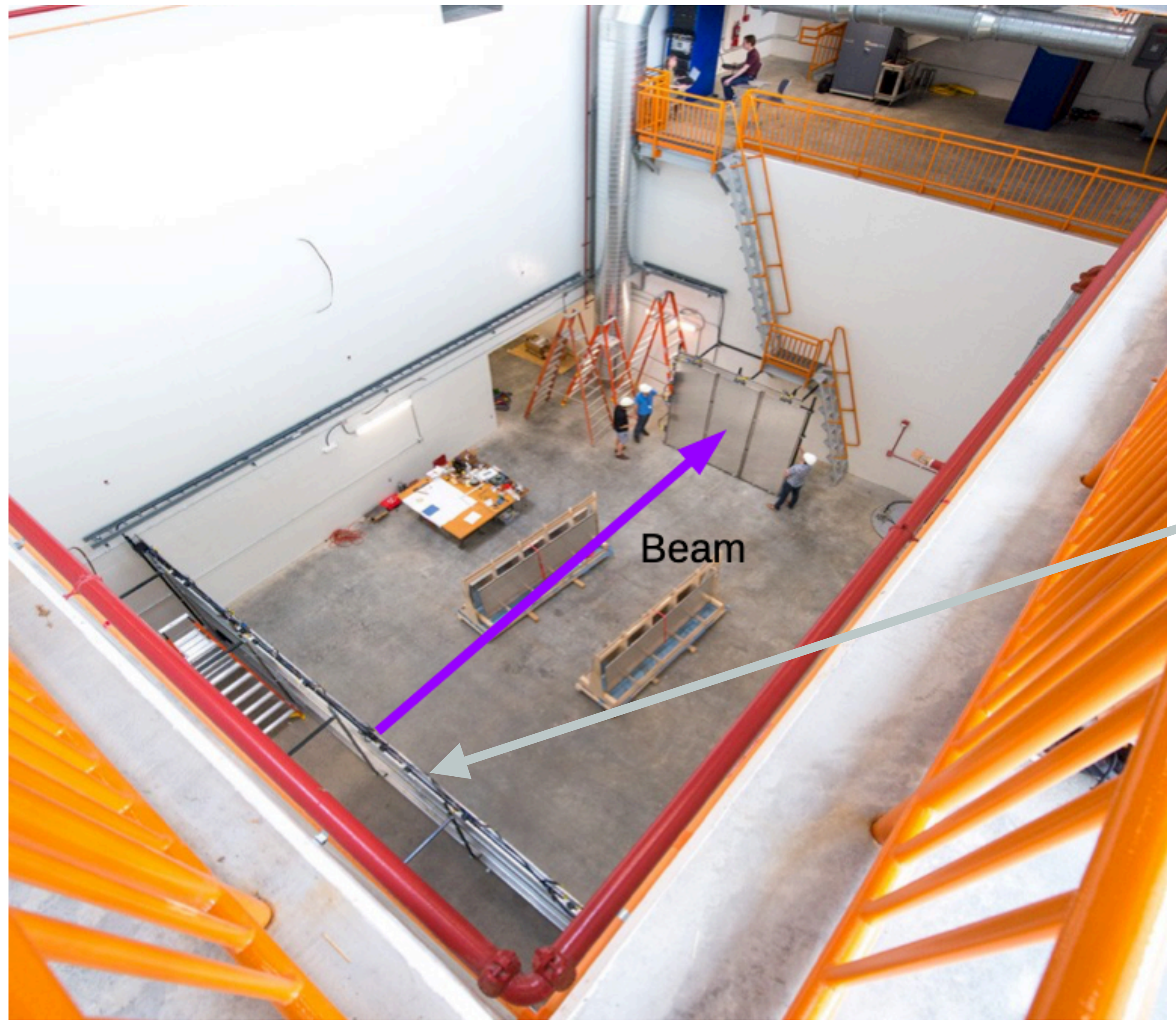


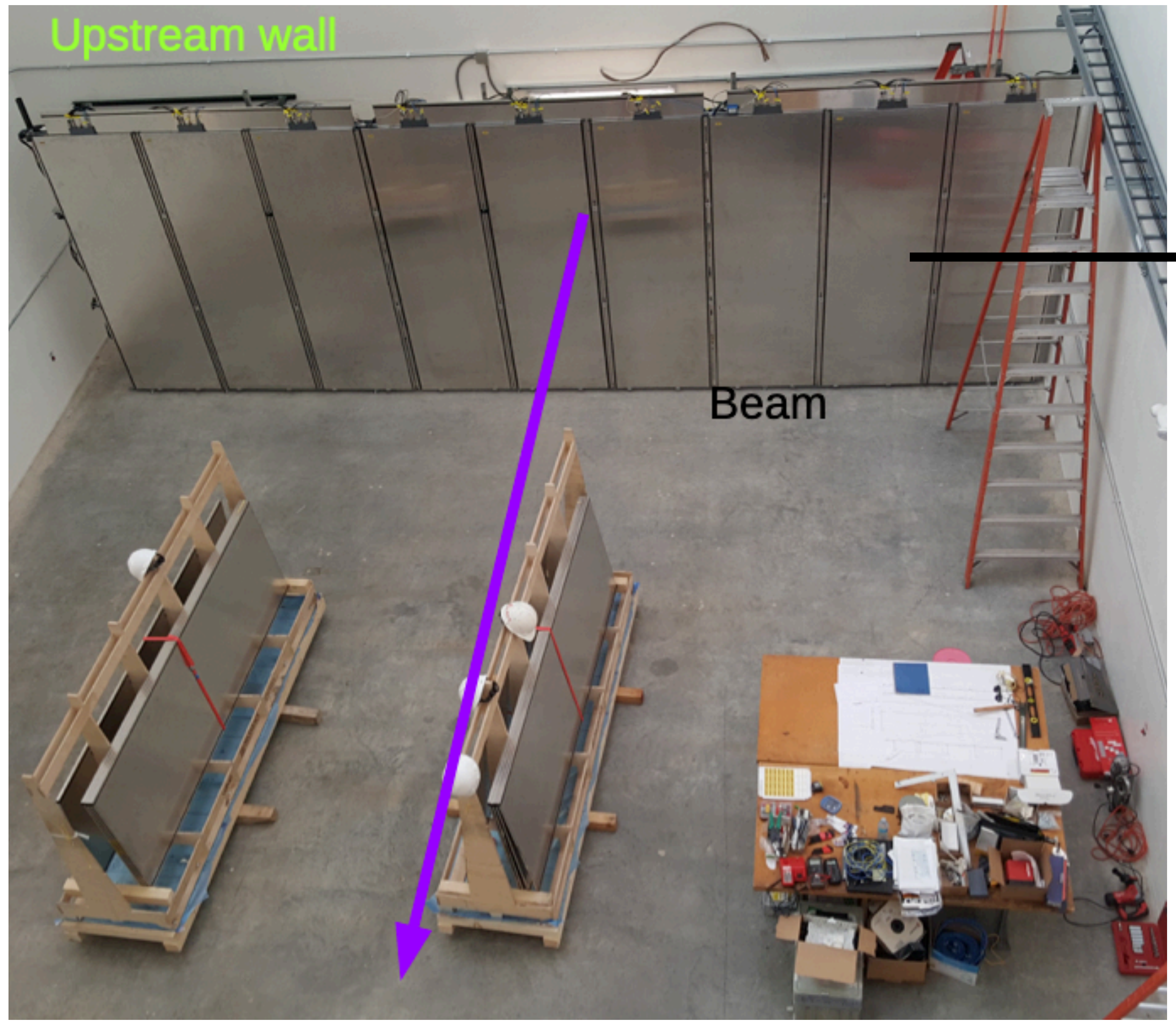
Electron-neutrinos CC Events

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



Cosmic Ray Tagger Data

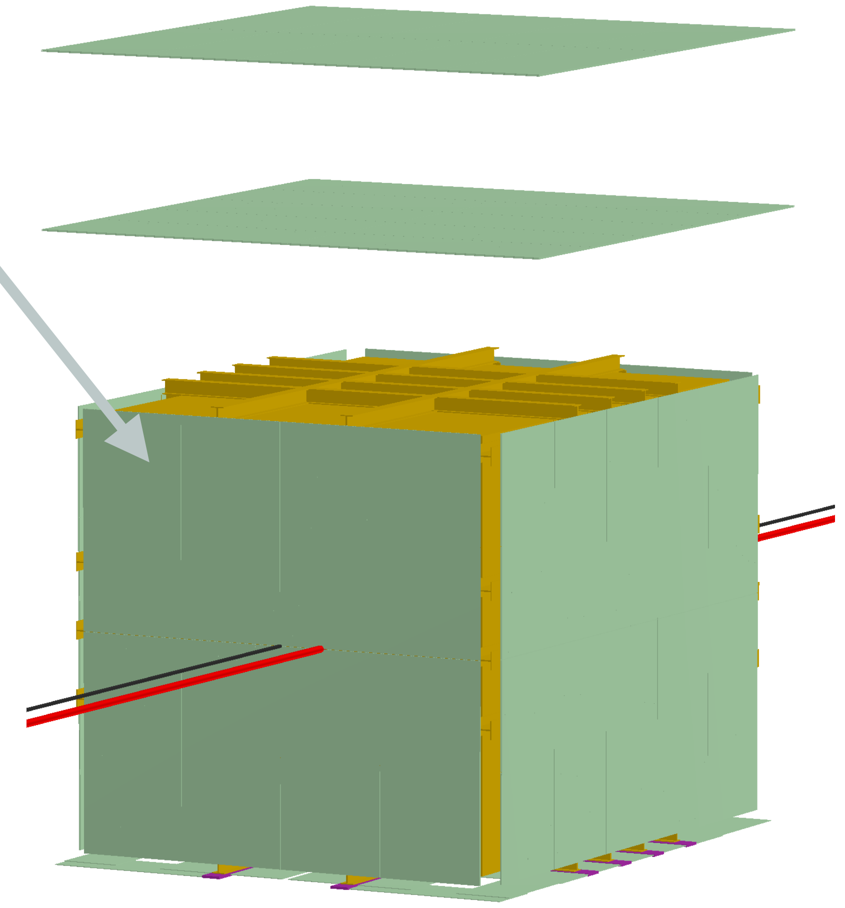


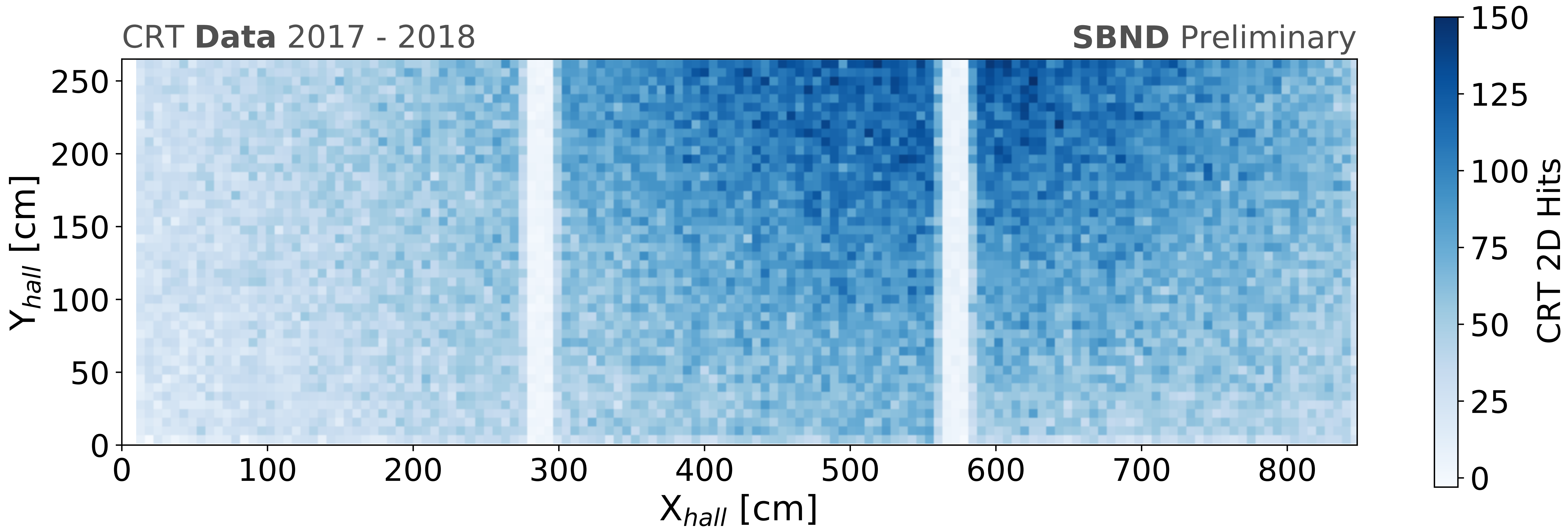


SBND will be surrounded by a cosmic ray tagger to identify cosmic rays

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





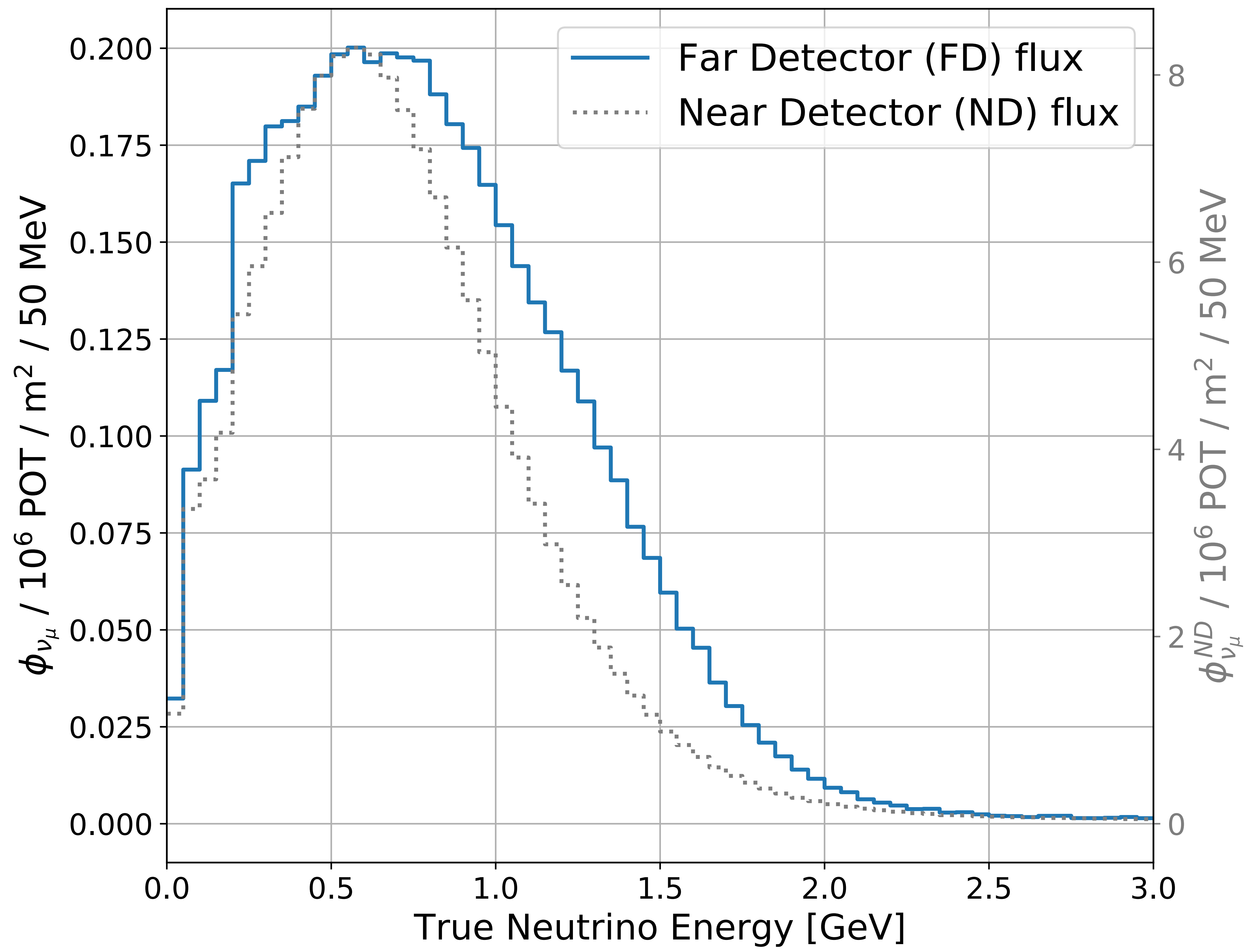
SBND-PRISM - Physics Opportunities

- Neutrino Oscillations
- SBND-Only Neutrino Oscillations
- Dark Matter Searches
- Study Energy Dependence of Cross-Section
- Interaction Model Contraints
- Muon-to-Electron Neutrino Cross-Section Ratio
- Study Neutrino Energy / Lepton Kinematics Relation

Sterile Neutrino Oscillations with SBND-PRISM

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

Can we make the two fluxes similar?

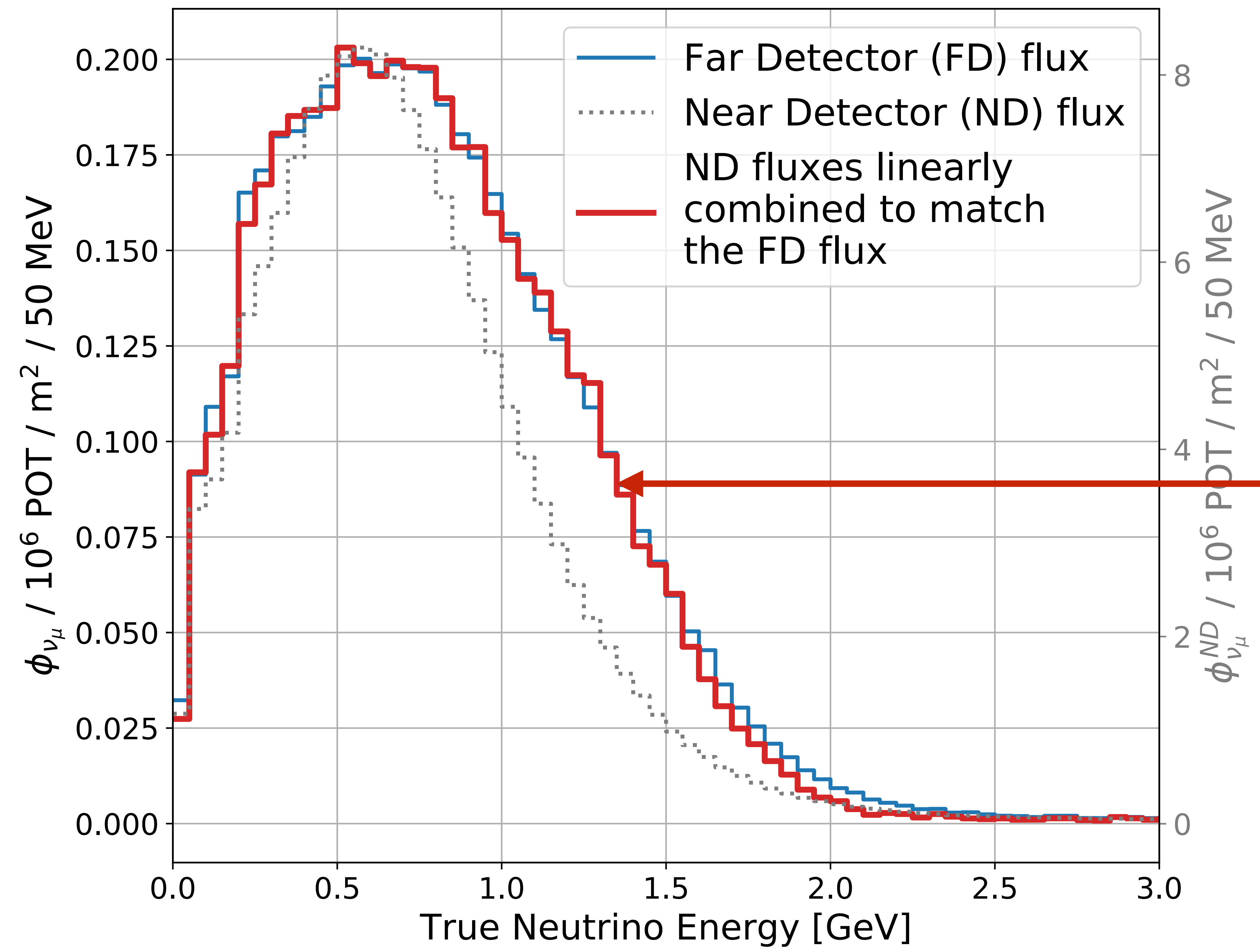


Sterile Neutrino Oscillations with SBND-PRISM

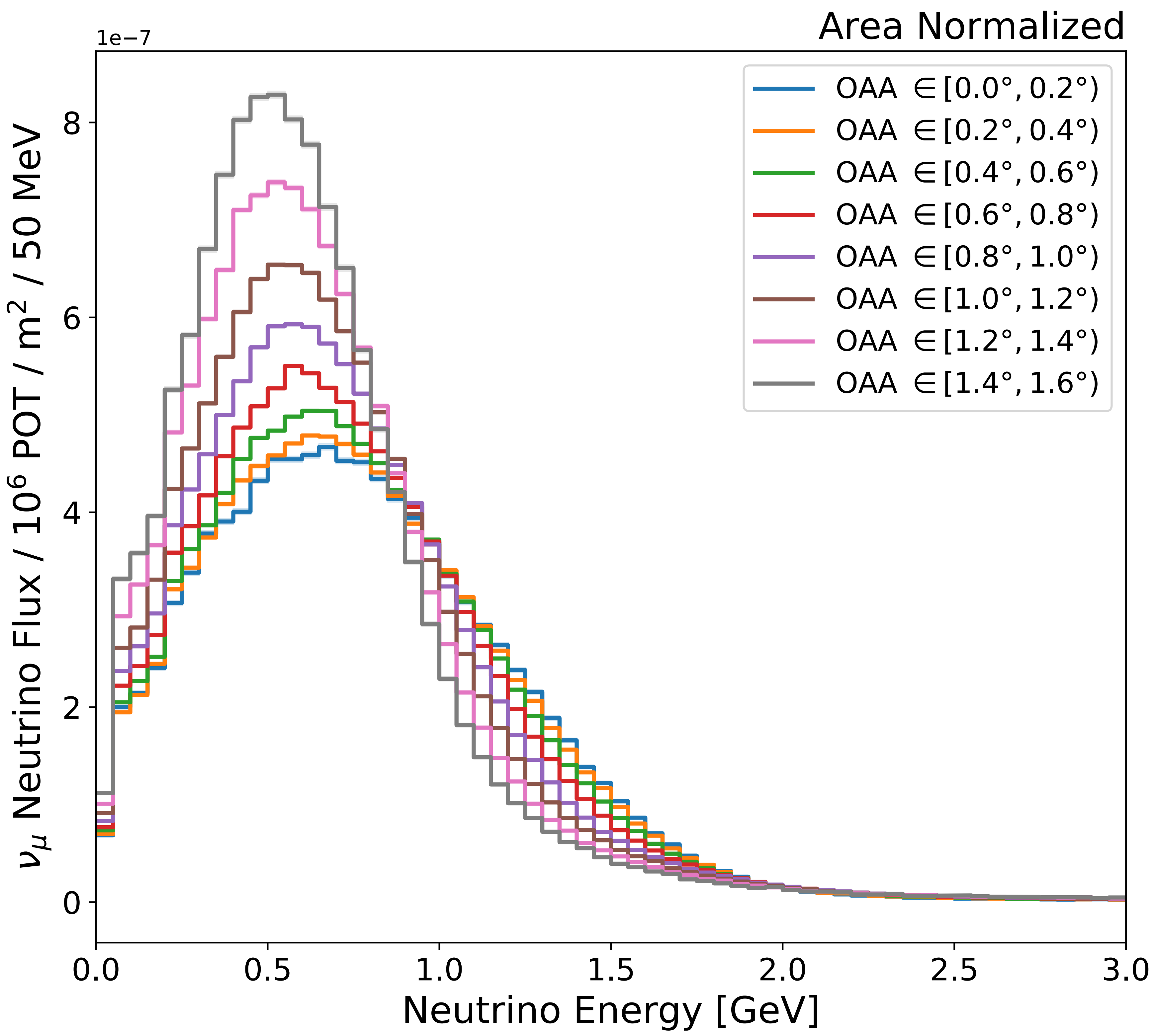
$$\frac{N_{FD}}{N_{ND}} = \frac{\propto \phi_{FD} \otimes \sigma \otimes P_{osc}}{\propto \phi_{ND} \otimes \sigma}$$

Can we make the two fluxes similar?

Yes!



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



SBND-PRISM: SBND-Only Sterile Neutrino Oscillations

Can we use SBND-PRISM for **SBND-only** sterile neutrino searches (without a Far Detector)?

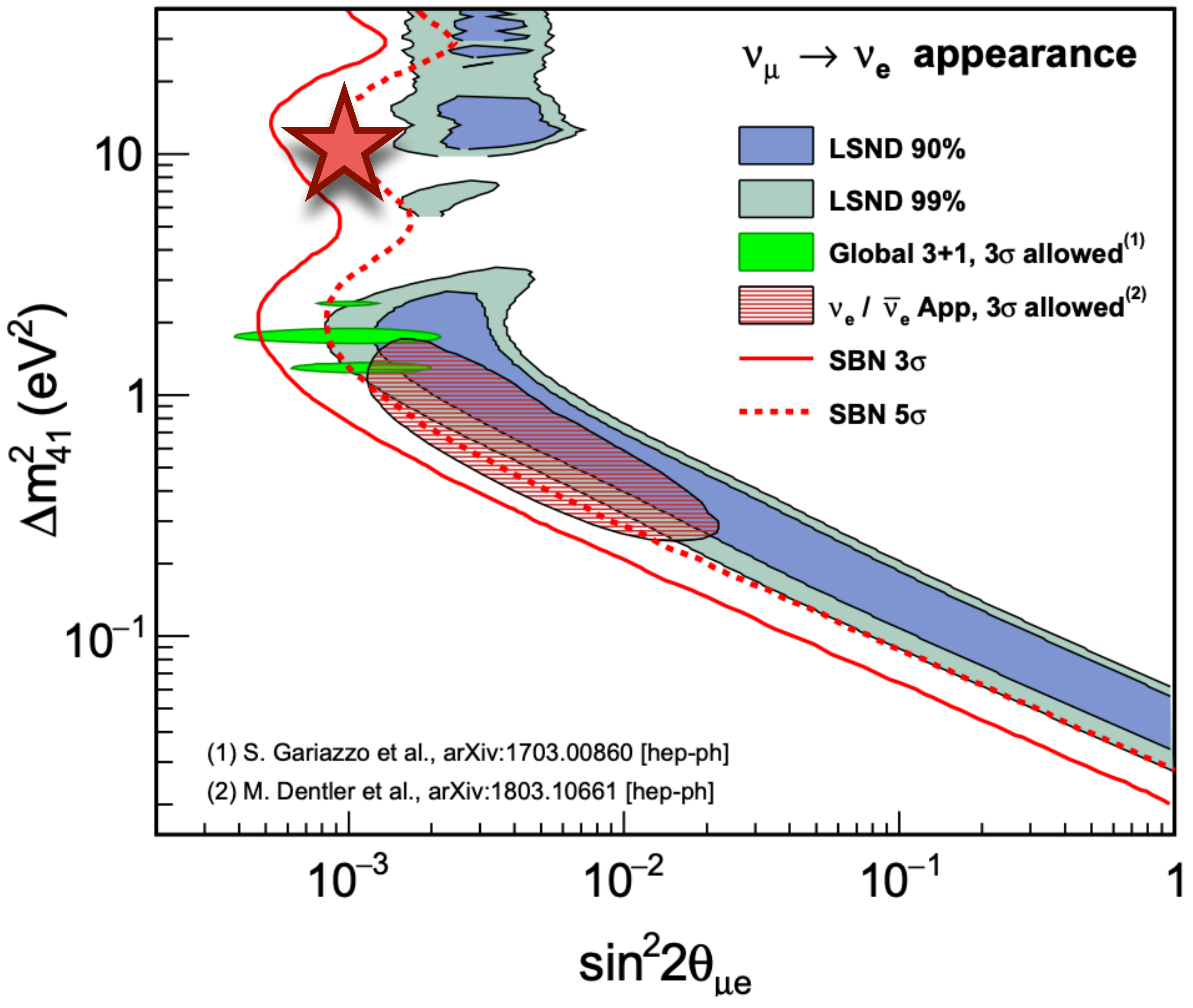
SBND-PRISM potentially allows probing **higher values of Δm^2** for sterile neutrino oscillation searches

SBND-PRISM: SBND-Only Sterile Neutrino Oscillations

Can we use SBND-PRISM for **SBND-only** sterile neutrino searches (without a Far Detector)?

SBND-PRISM potentially allows probing **higher values of Δm^2** for sterile neutrino oscillation searches

Annu. Rev. Nucl. Part. Sci. 69:363-387, 2019

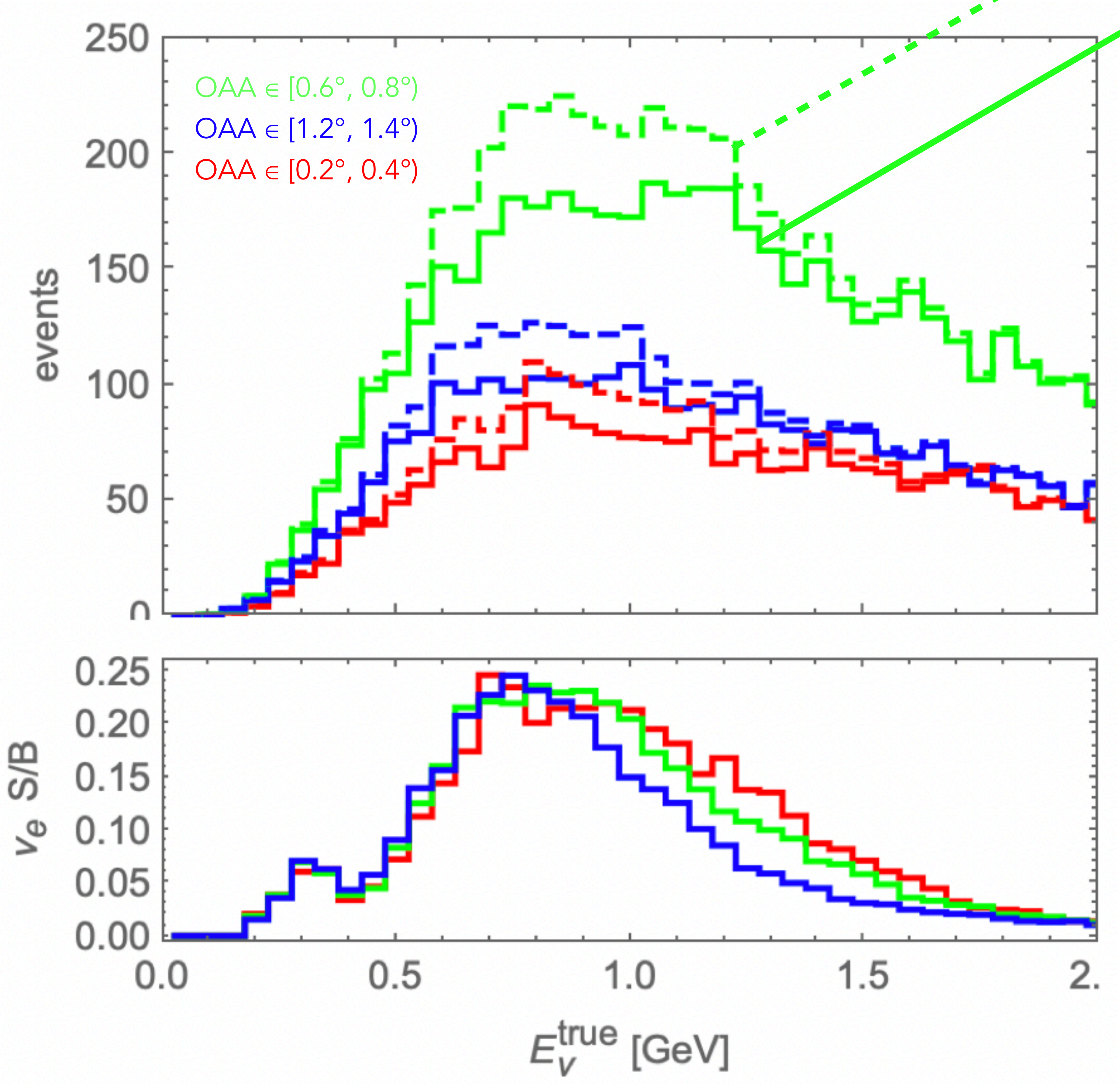


Testing sensitivity with:

- $\Delta m^2 = 10$ 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

SBND-PRISM: SBND-Only Sterile Neutrino Oscillations

Only showing 3 off-axis bins for clarity



ν_e coming from oscillation $\nu_\mu \rightarrow \nu_e$

ν_e intrinsic from the beam (background)

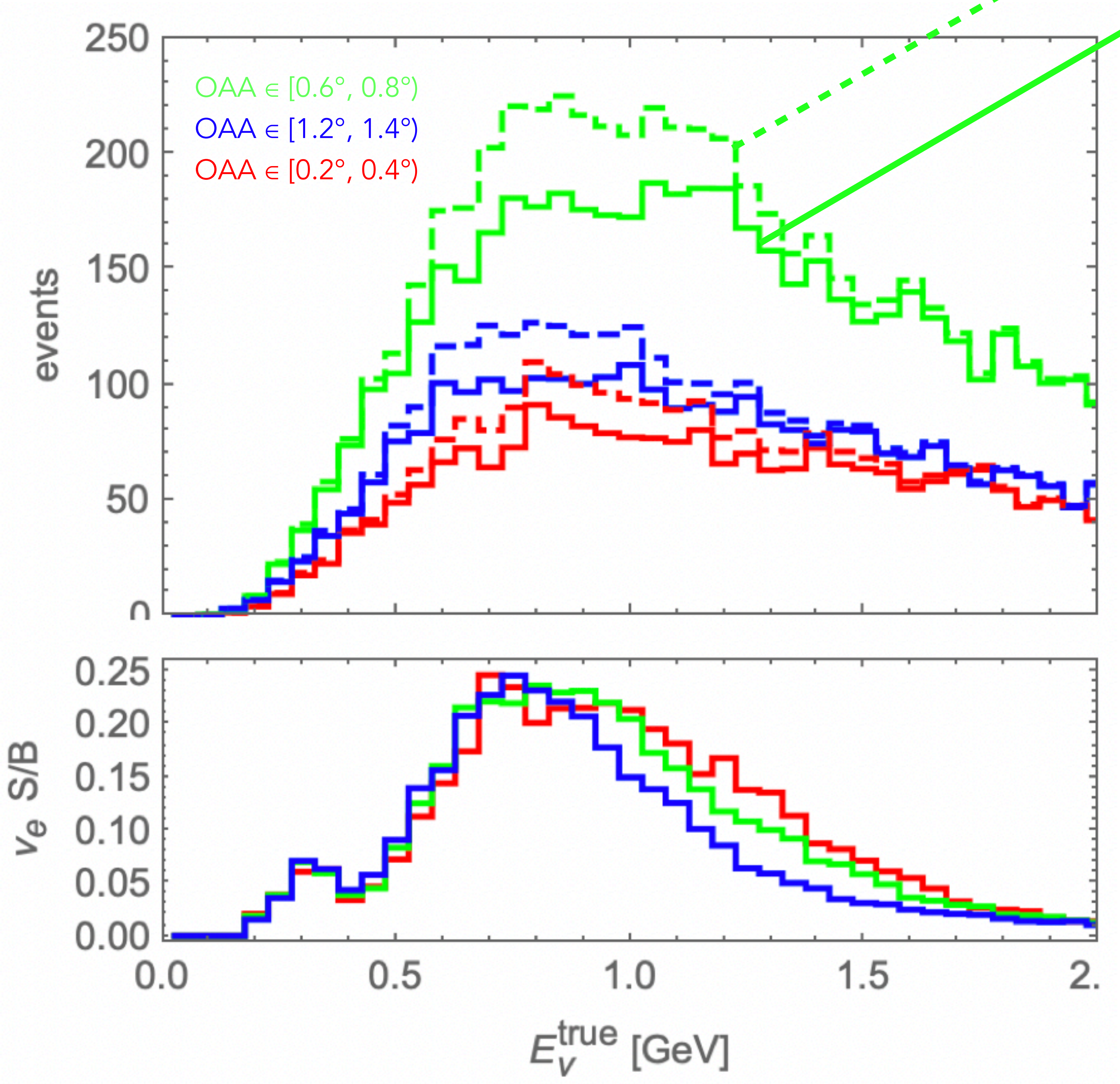
We run a X^2 test to understand if we are sensitive to these oscillations

w/o PRISM (treating SBND as a single detector)	$X^2 = 2$ background and signal are compatible we are **not** sensitive to oscillations
w/ PRISM (treating SBND as made of multiple off-axis sub-detectors)	$X^2 = 13$ background and signal are **not** compatible we are sensitive to oscillations

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

SBND-PRISM: SBND-Only Sterile Neutrino Oscillations

Only showing 3 off-axis bins for clarity



ν_e coming from oscillation $\nu_\mu \to \nu_e$

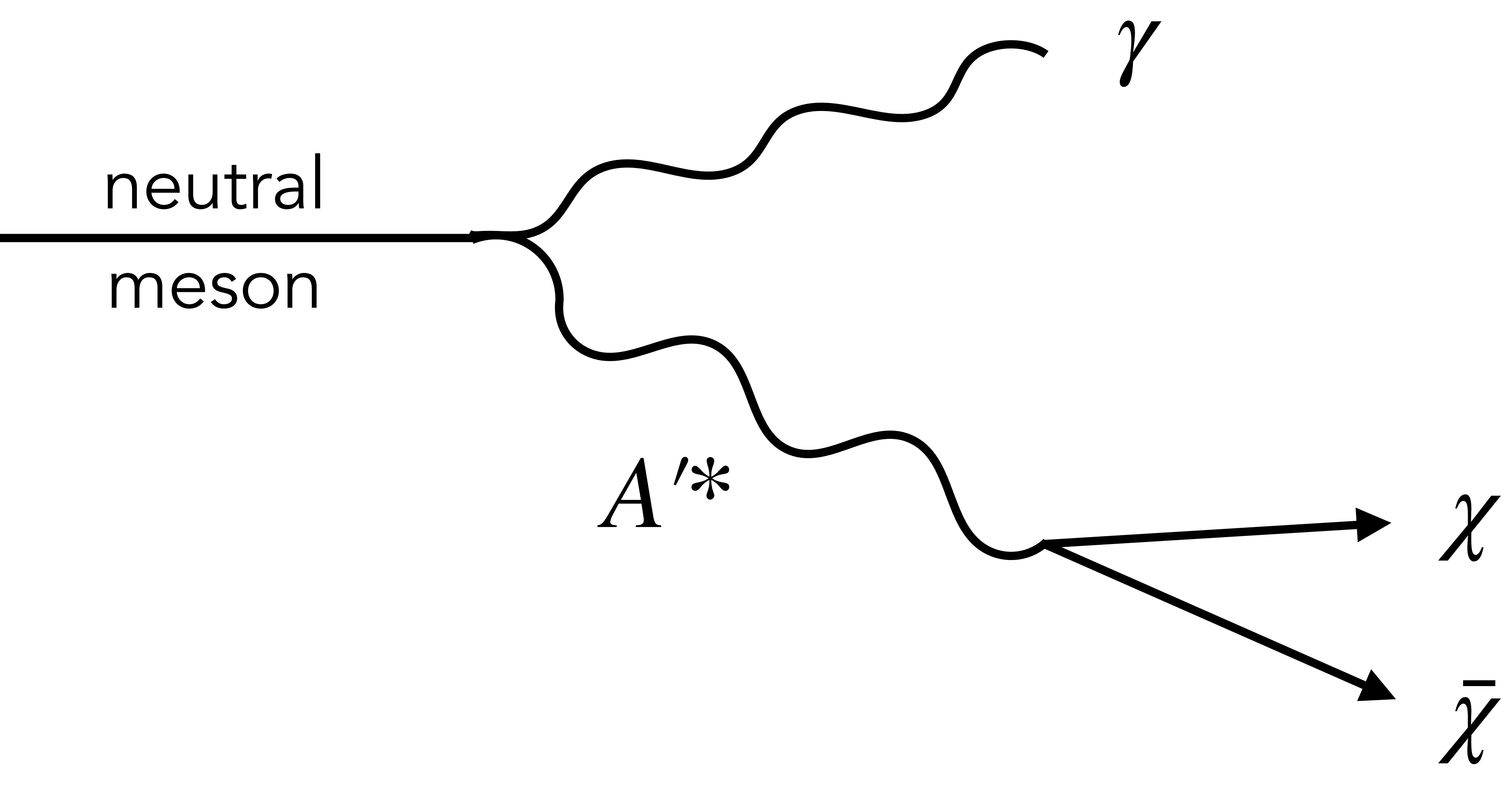
ν_e intrinsic from the beam (background)

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

w/ PRISM	$X^2 = 13$
(treating SBND as made of multiple off-axis sub-detectors)	background and signal are **not** compatible we are sensitive to oscillations

Can measure oscillations using SBND alone!

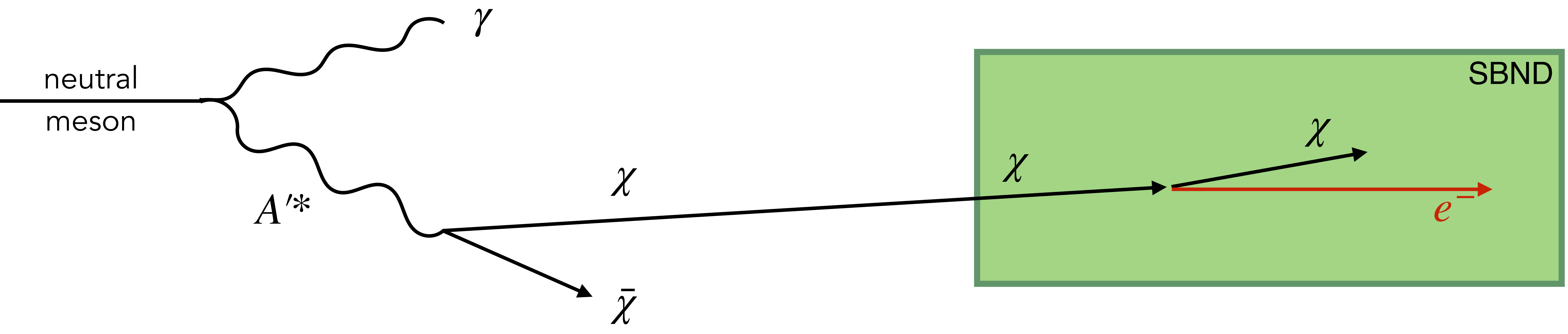
Dark Matter Searches with SBND-PRISM



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

Dark Matter Searches with SBND-PRISM

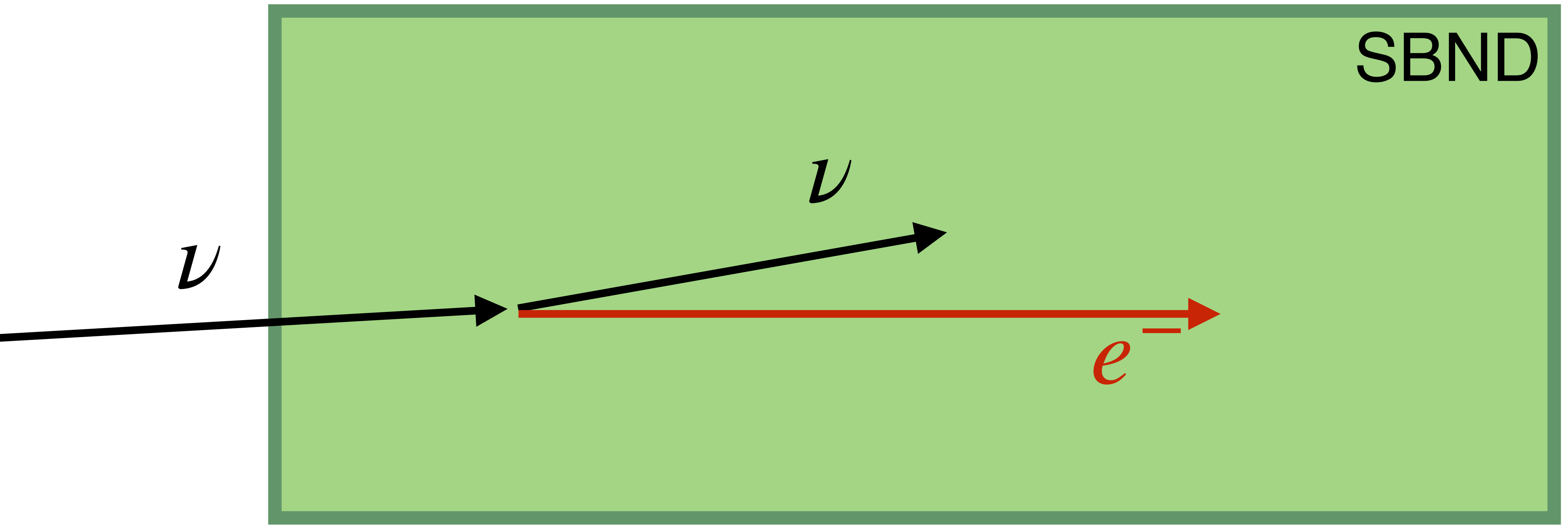


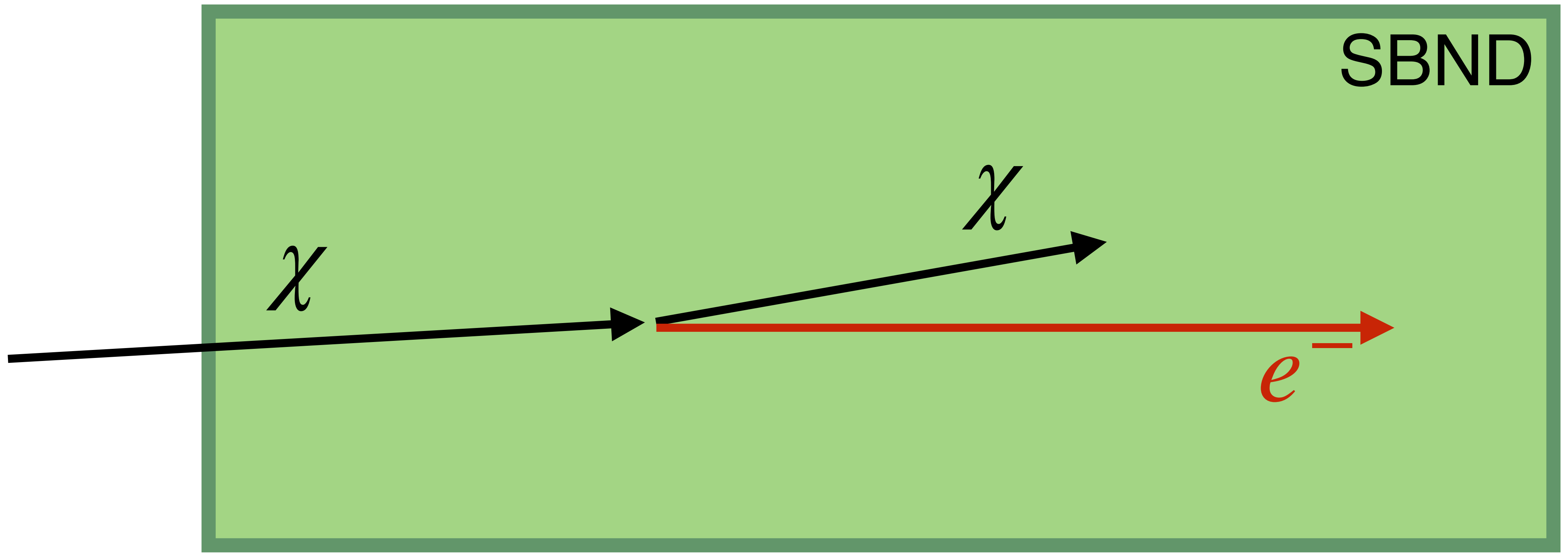
Light dark matter (sub-GeV) that is coupled to the Standard Model via a dark photon. The dark photons can be produced by neutral meson decays (pions, etas) in the target, and then decay to the dark matter.

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

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

Dark Matter Searches with SBND-PRISM





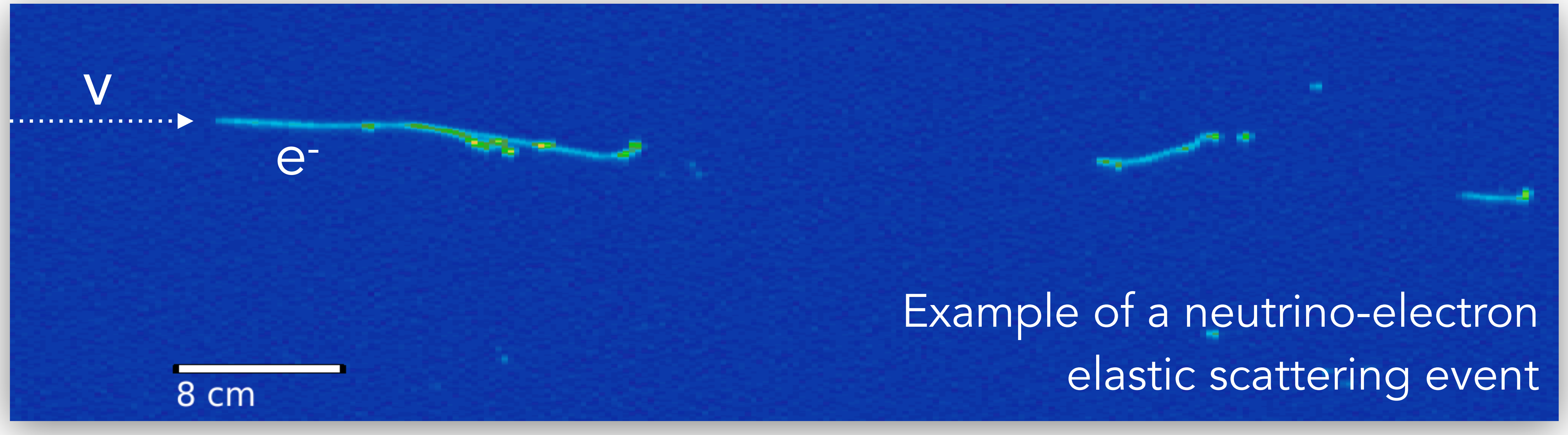
Background

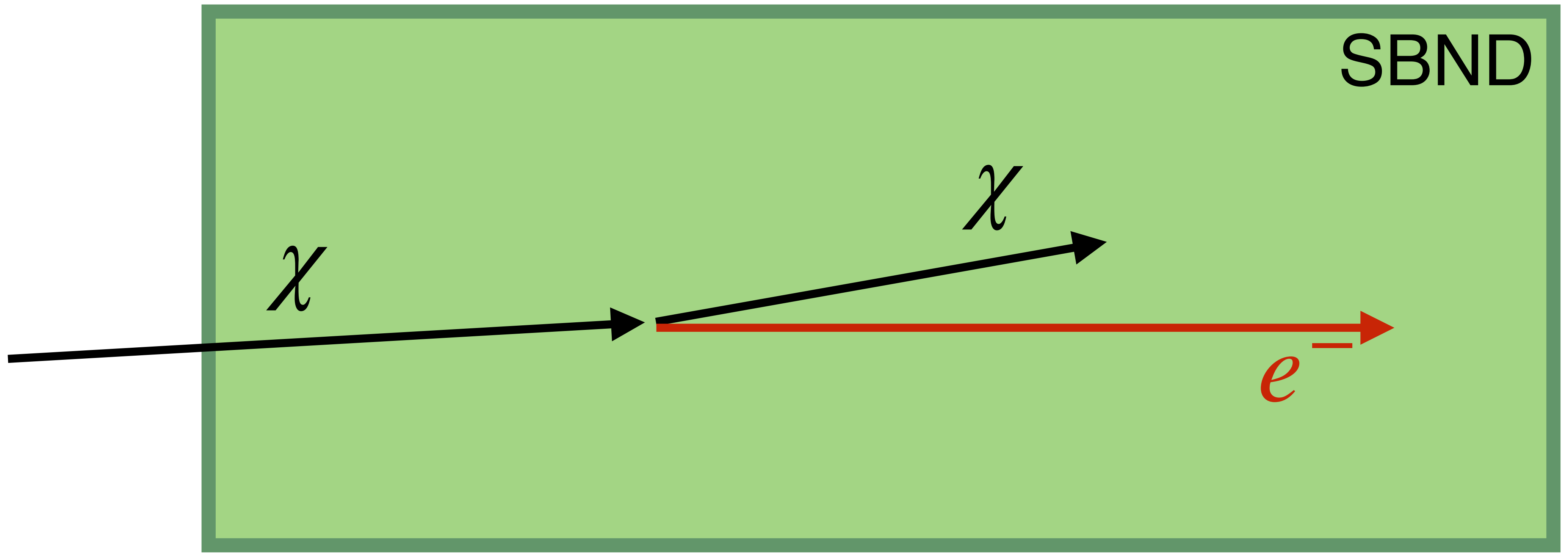
Neutrino-electron elastic scattering. Neutrinos come from two-body decays of charged (focused) mesons.

Signal

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

Dark Matter Searches with SBND-PRISM





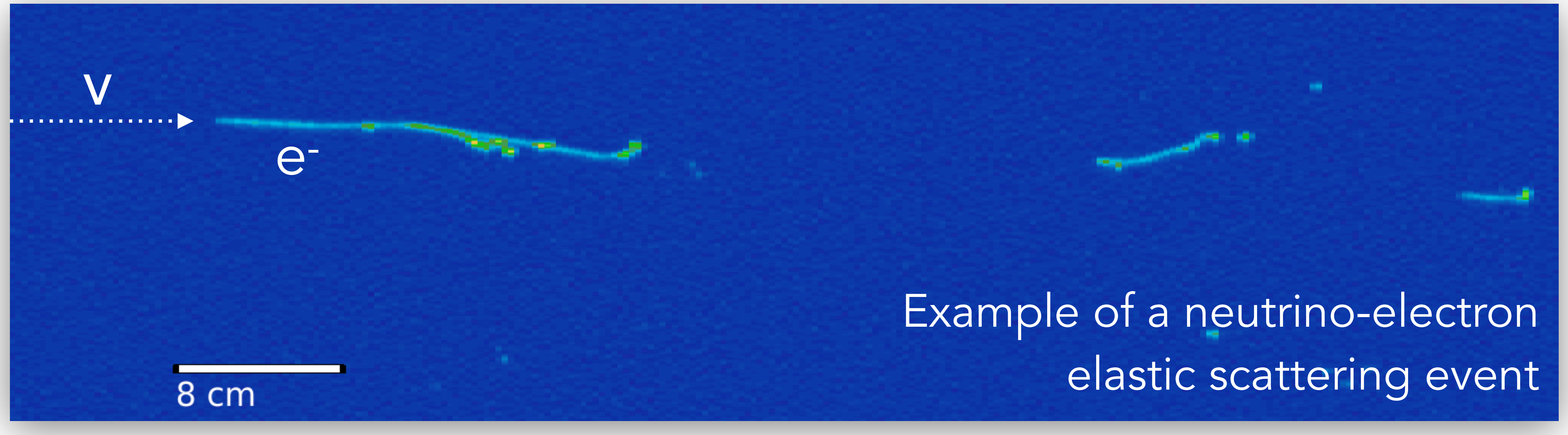
Background

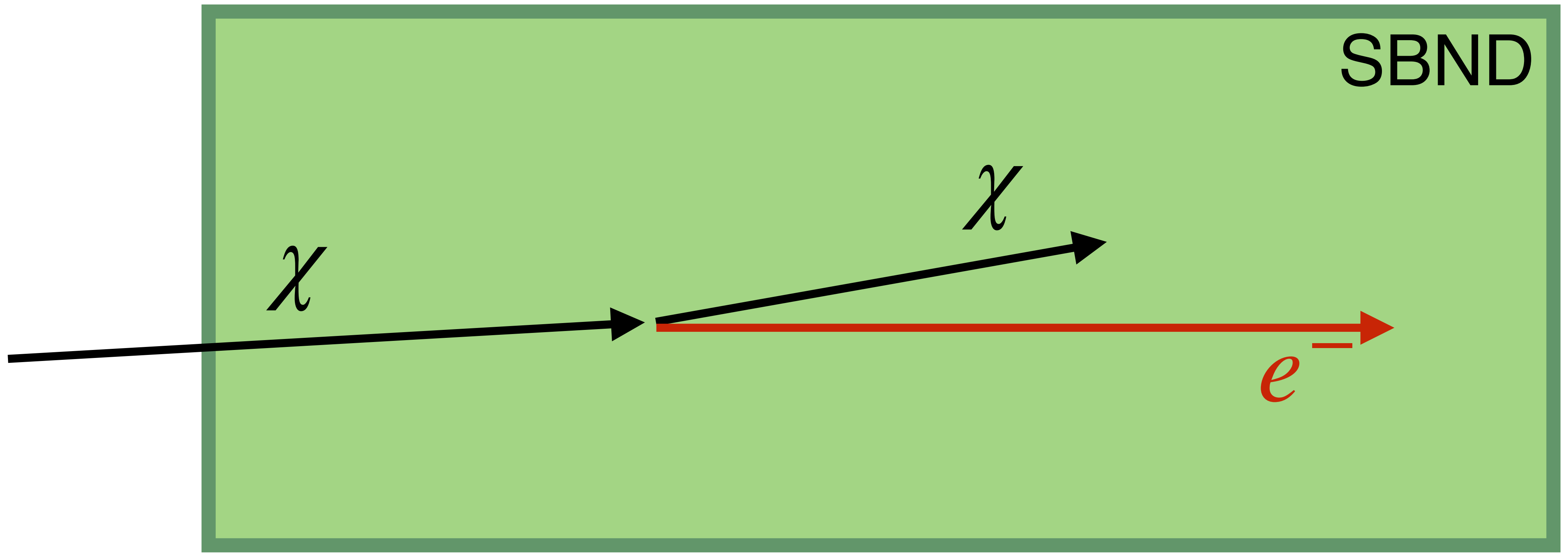
Neutrino-electron elastic scattering. Neutrinos come from two-body decays of charged (focused) mesons.

Signal

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

Dark Matter Searches with SBND-PRISM





Background

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

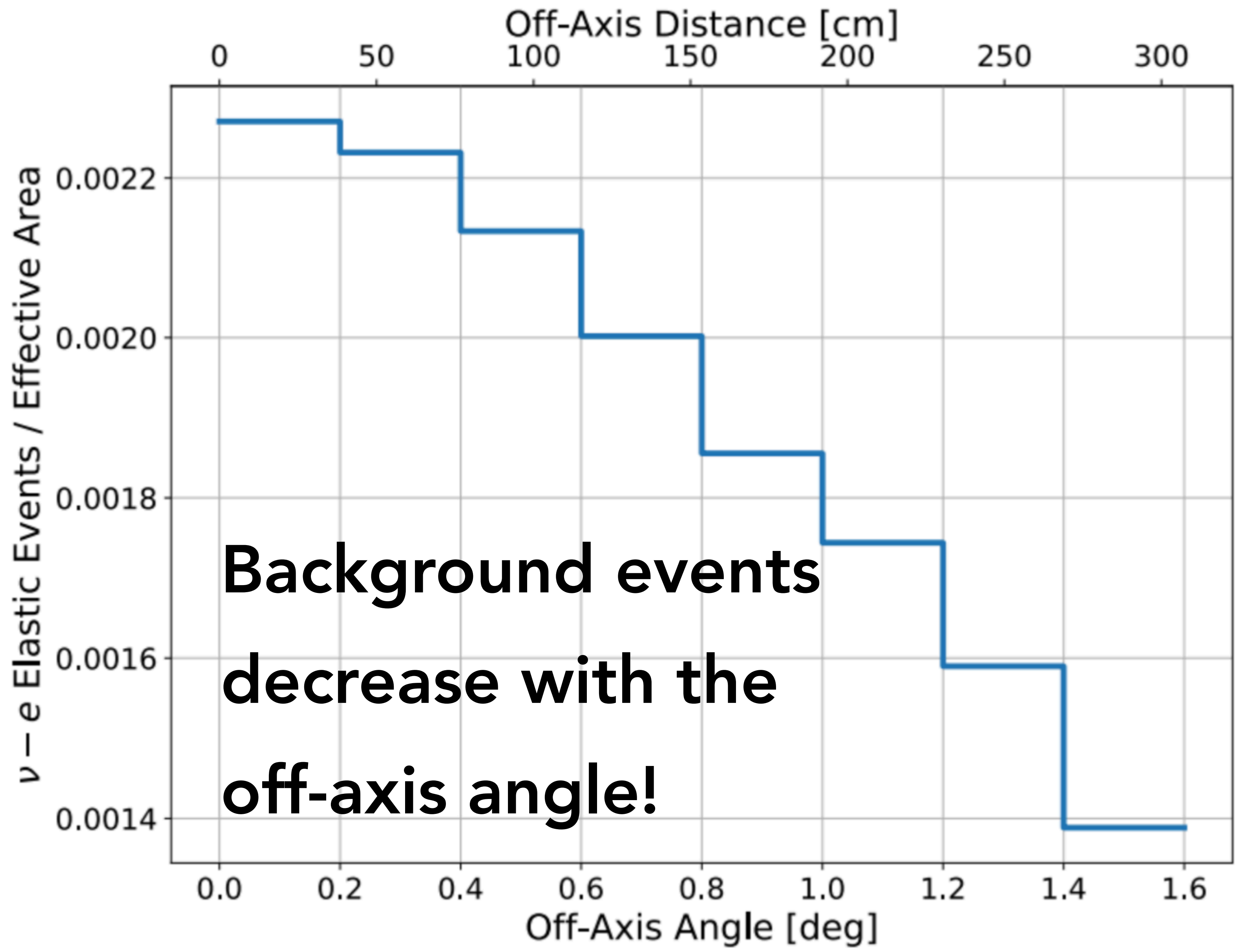
SBND-PRIMS: Neutrinos (background events) **decrease** with the off axis angle

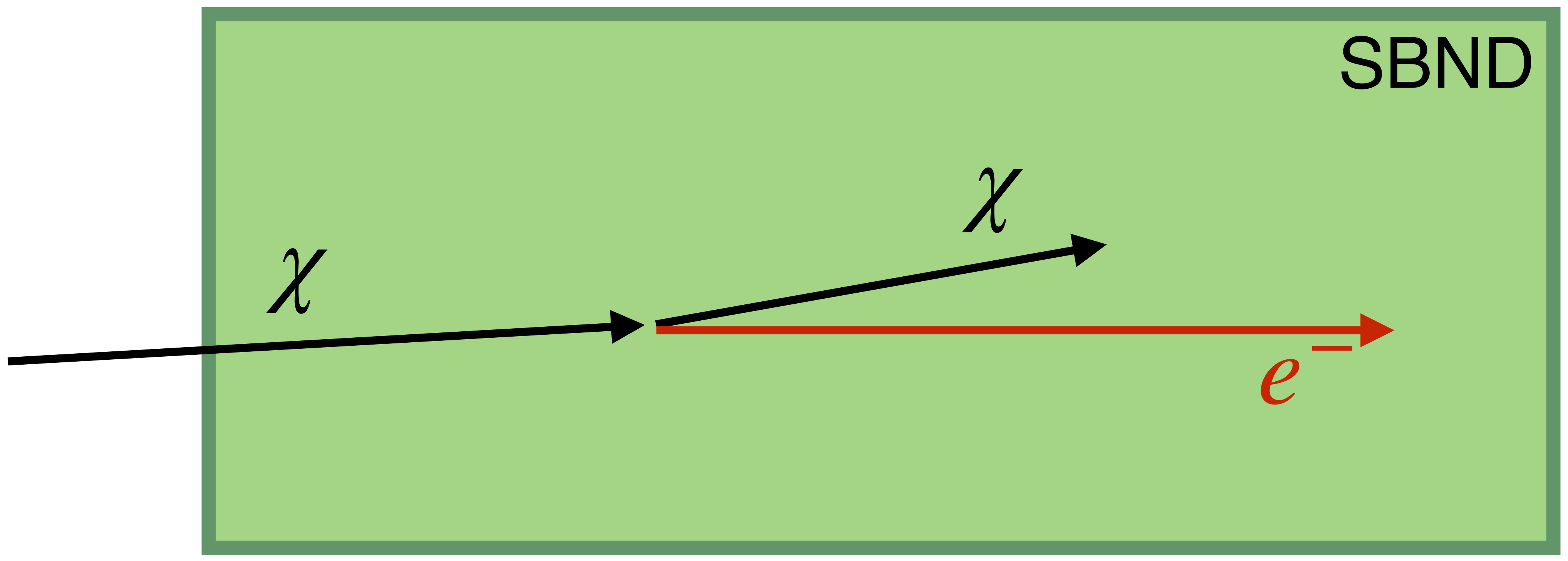
Signal

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

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

Dark Matter Searches with SBND-PRISM





Background

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

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

Signal

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

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

Conclusions

SBND-PRISM is a new innovative way to exploit important SBND features

- Closeness to the neutrino source
- Being slightly off-axis
- Abundance of statistics

SBND-PRISM largely expands the physics reach of SBND in multiple directions

- SBN neutrino oscillations
- SBND-only neutrino oscillations
- Dark matter searches
- Neutrino interaction modelling
- …

Thank You!