BSM modeling in neutrino near detectors and the SBND experience

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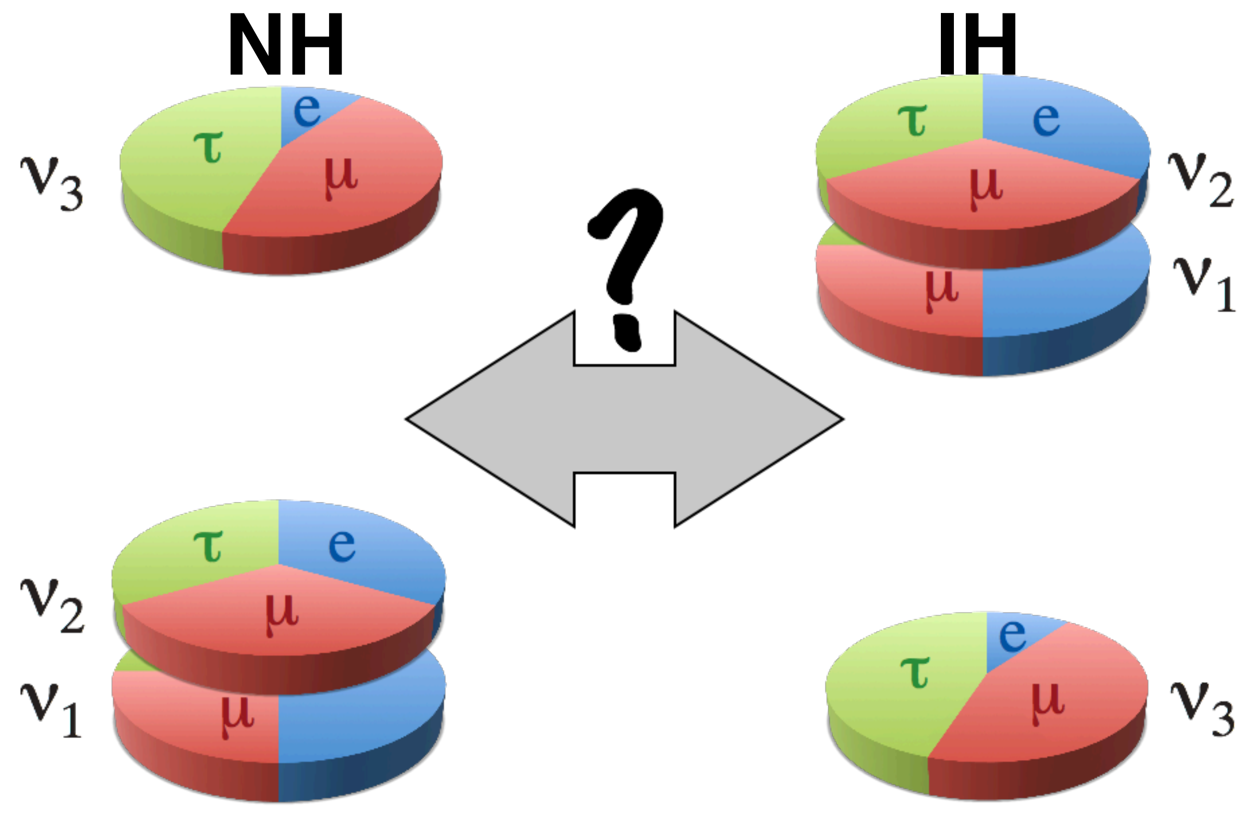
University of Texas at Arlington
December 14, 2022

PITT PACC Workshop: Nu Tools for BSM at Neutrino Beam Facilities
Dec 14-16, 2022

Unanswered questions in neutrino physics

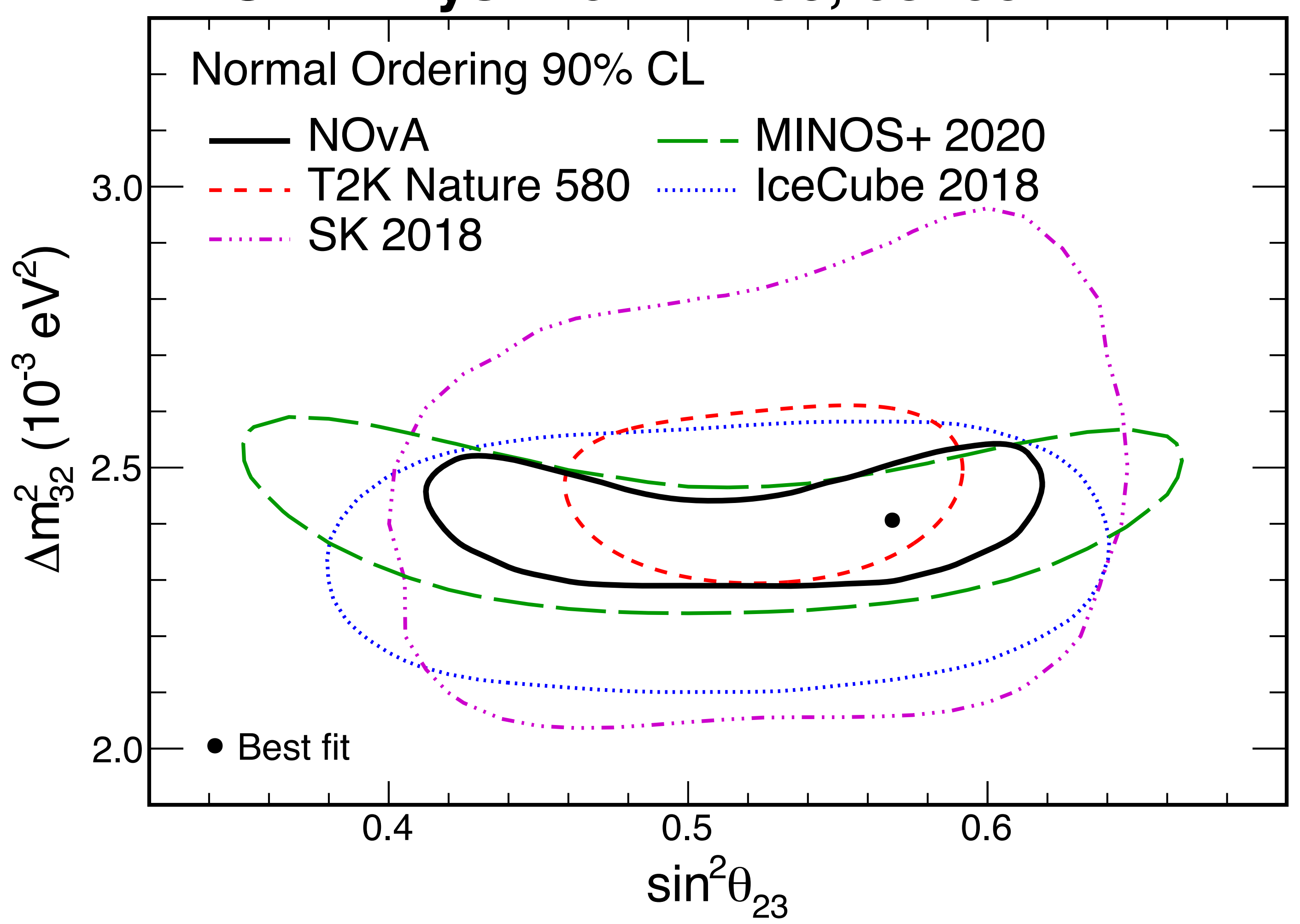


Is the neutrino mass hierarchy normal or inverted?

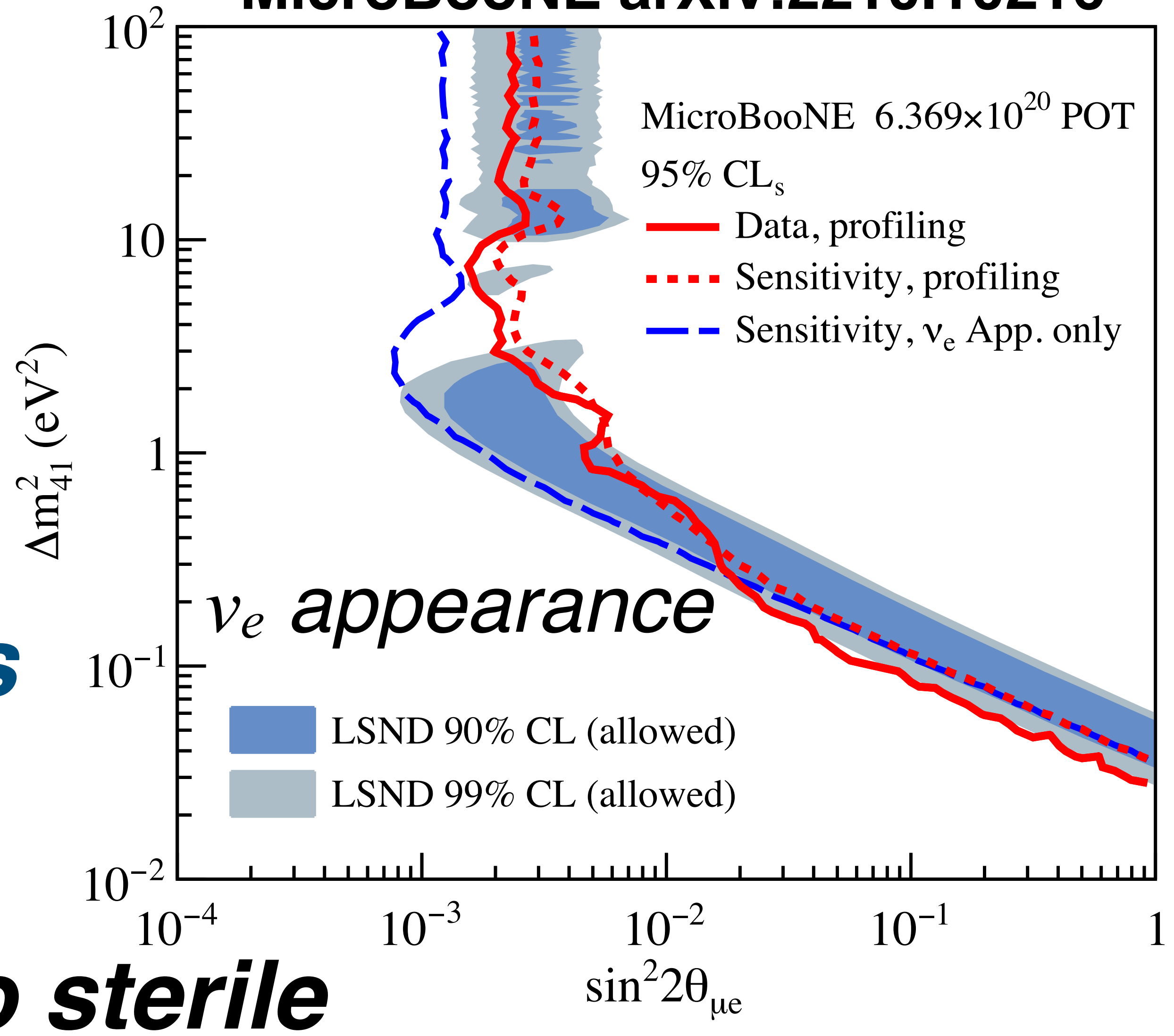
Is there a symmetry governing the ν_μ / ν_τ mixing into the mass states?

Is there a direct violation of CP symmetry by leptons ($\Delta P_{\nu\bar{\nu}} \sim \sin\delta_{CP}$) ?

NOvA Phys. Rev. D 106, 032004



MicroBooNE arXiv:2210.10216



Sterile neutrino(s)? *Various hints of anomalous electron-flavour appearance and disappearance may indicate new neutrinos participating in oscillations*

Long and short baseline neutrino experiments are working to address these questions

In the context of this talk, BSM will be physics beyond the light neutrino sterile

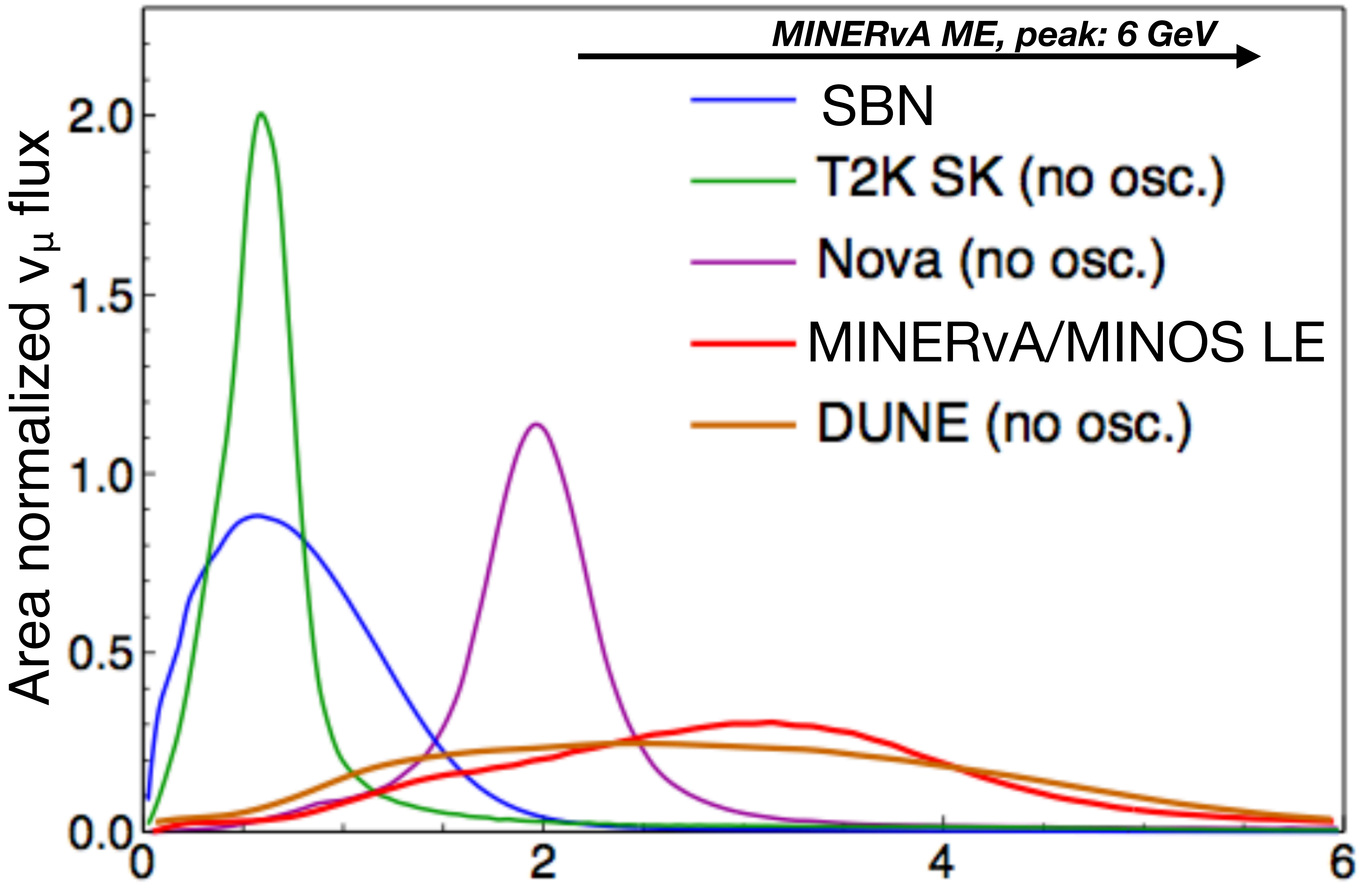
Neutrino fluxes

» Not monochromatic: wide-band.

» Beamline modeling (Geant4-based)

- Simulation starts from the **primary proton beam** interactions through the following **hadronic cascade** that **produces neutrinos**
- The theory of hadron production at these energies is not yet completed and **models disagree**
- **The hadron production (HP) model is constrained** with external measurements (NA49, HARP, etc).

» The **uncertainty** based on these external measurements results in **~ 8 -10%**.

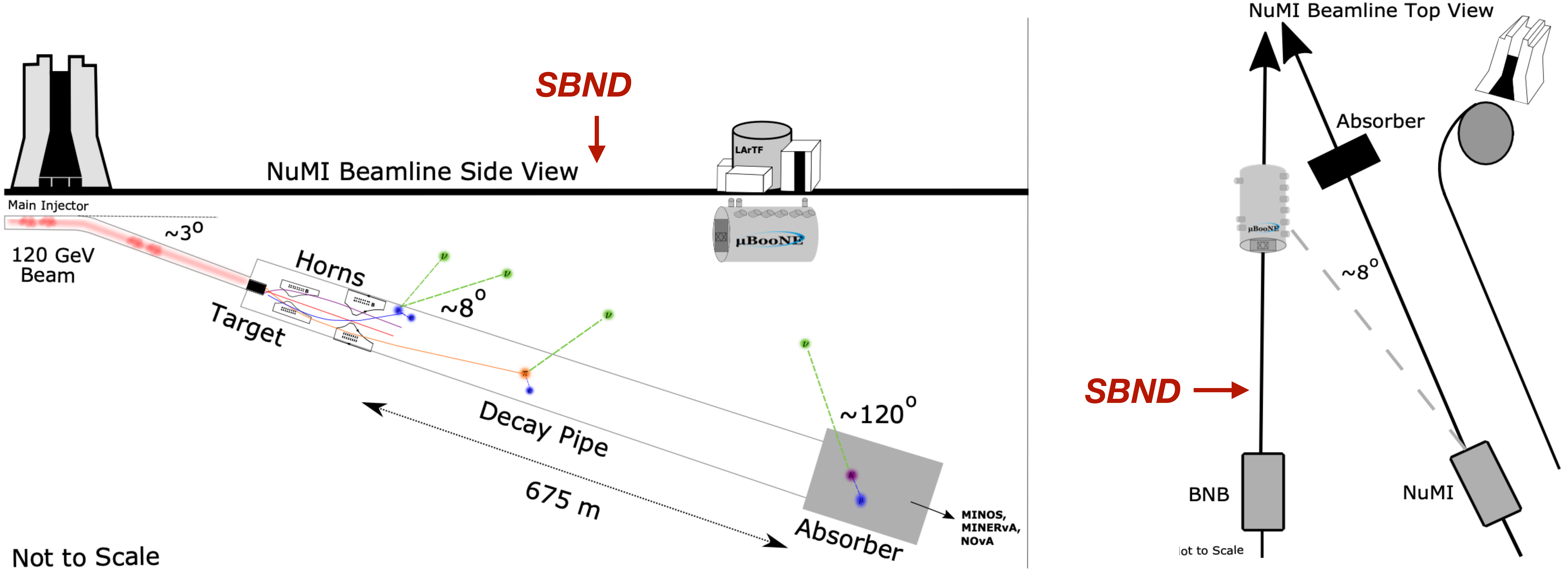


Fermilab JETP Seminar, Phil Rodrigues 2015

» Uncertainties on the beam alignment are sub-dominant at the peak

NuMI + BNB

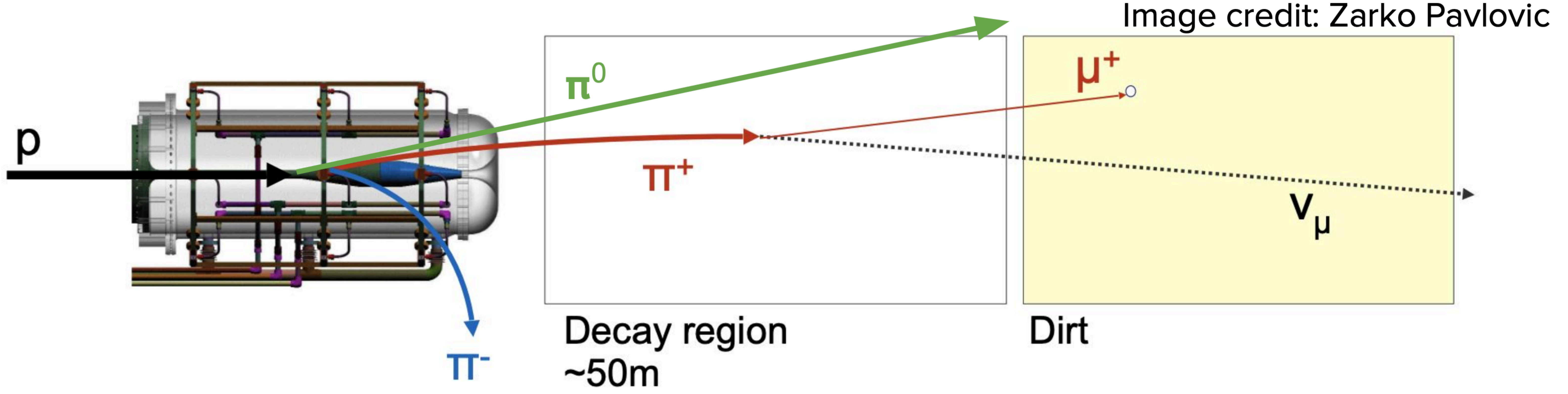
Illustration taken from MicroBooNE: Phys. Rev. D 104, 052002



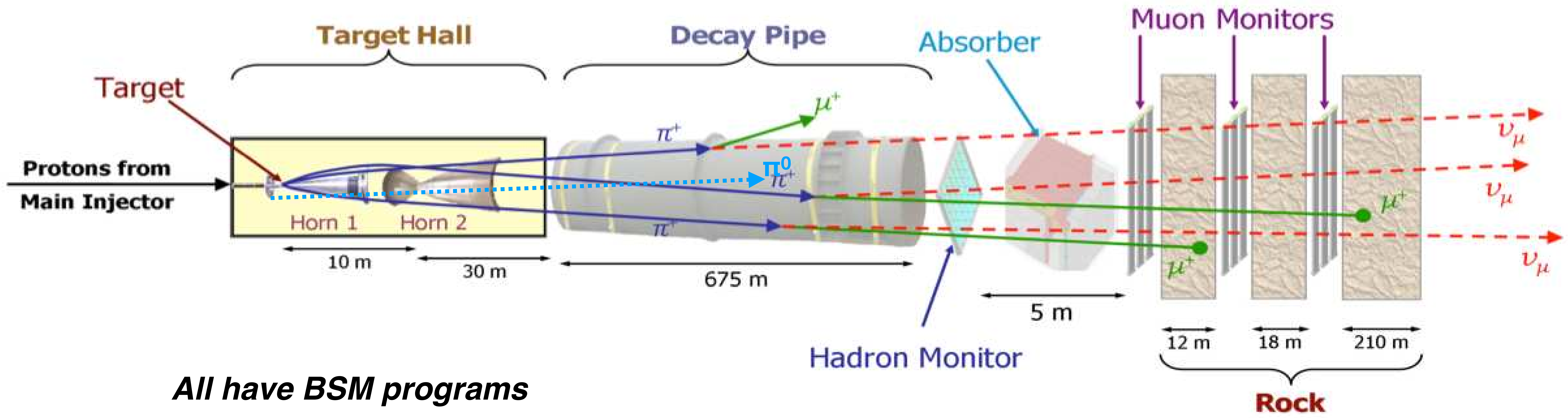
» BNB experiments some fraction of NuMI neutrinos at large angles
- Low energy neutrinos produced in the beamline
- Neutrinos coming from pion and kaon decay at rest from the absorber

Booster Neutrino Beam (BNB)

- » **8 GeV protons** from the Booster
- » Beryllium **target**
- » 1 Magnetic **horn**
- » **Decay Pipe**: 50 m
- » 25m steel **absorber**



Neutrinos at the Main Injector (NuMI)



All have BSM programs

~1Km from target: NOvA ND, MINOS ND, MINERvA and ArgoNeuT

- » **120 GeV protons** from Main Injector
- » Graphite **target**: 1.2 m
- » 2 Magnetic **horns**
- » **Decay Pipe**: 675 m filled with He
- » 5m steel **absorber**

See Ornella's talk on ArgoNeuT →

NOvA	ν oscillations	14 mrad off-axis
MINERvA	ν-A cross sections	On-axis
ArgoNeuT	ν-Ar interactions	On-axis
MINOS	ν oscillations	On-axis

All of them have also BSM searches

Commissioning | Legacy | Running | Analysis

Neutrino fluxes

» Muon neutrino enhanced beam when focused pion plus

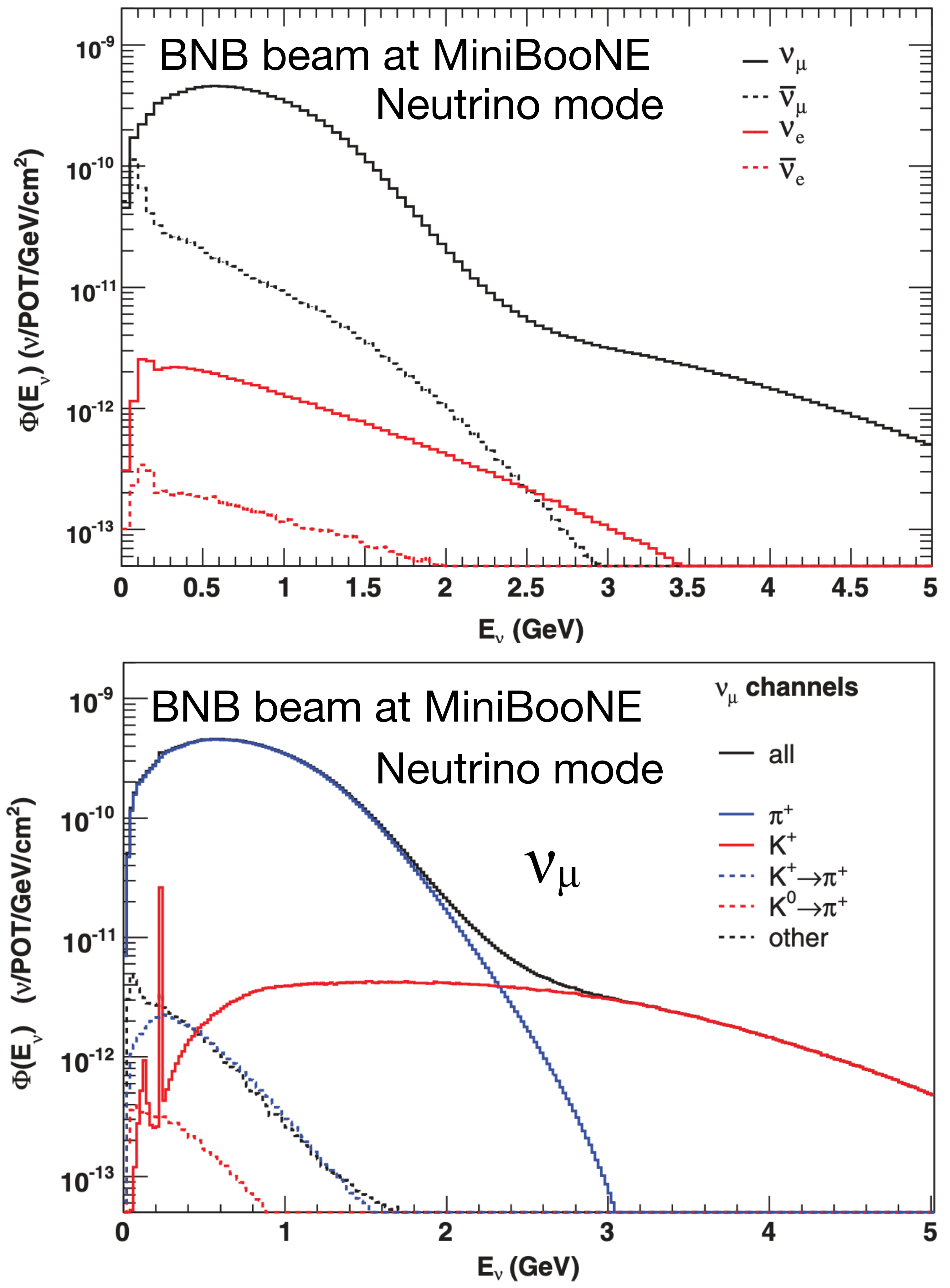
$$\pi^+ \rightarrow \nu_\mu + \mu^+$$
$$K^+ \rightarrow \nu_\mu + \mu^+$$

» Muon antineutrino from defocused pion minus

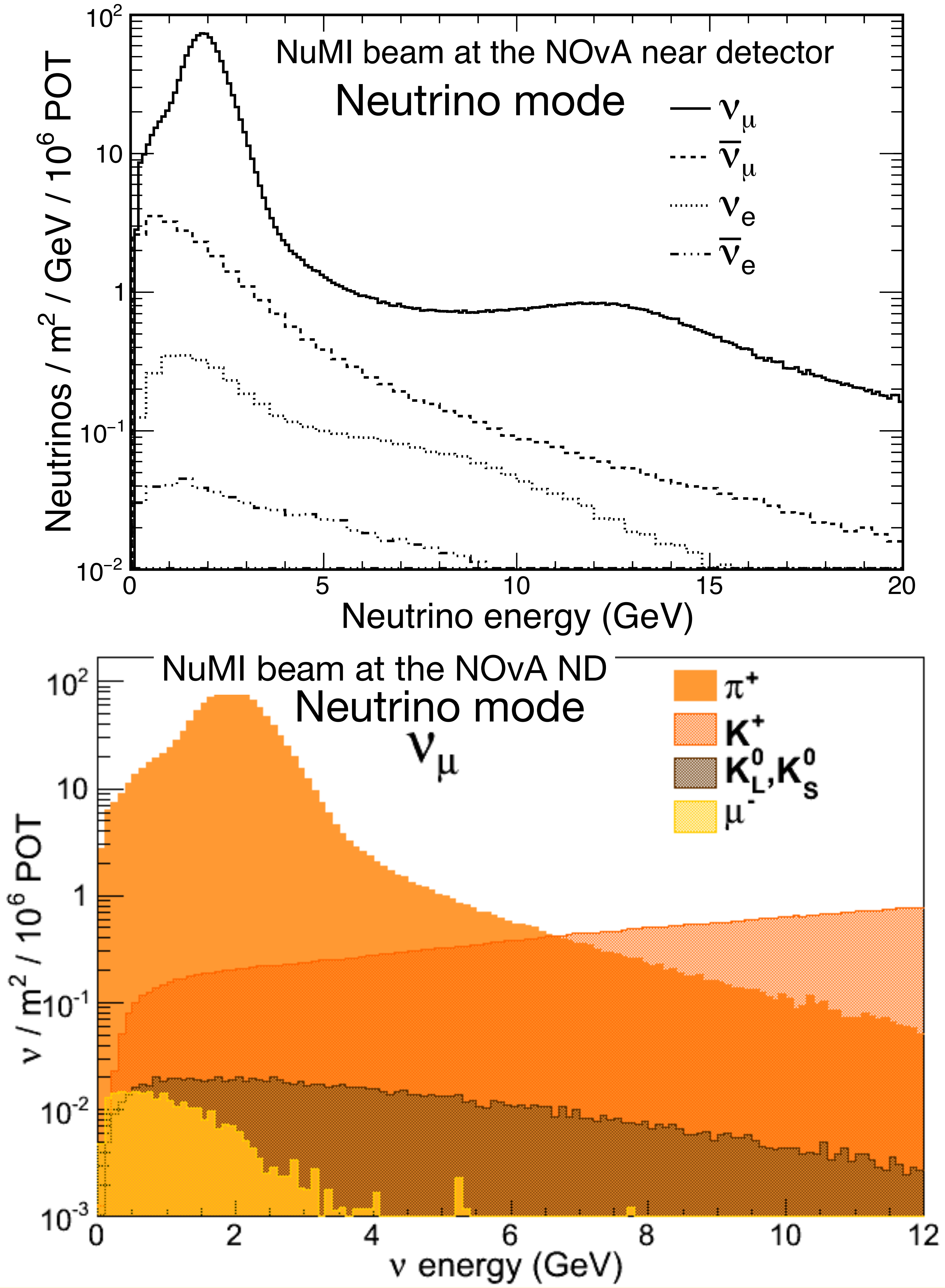
» Electron neutrino and antineutrino

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

Phys. Rev. D79, 072002 (2009)



arXiv:2109.12220 NOvA Simulation



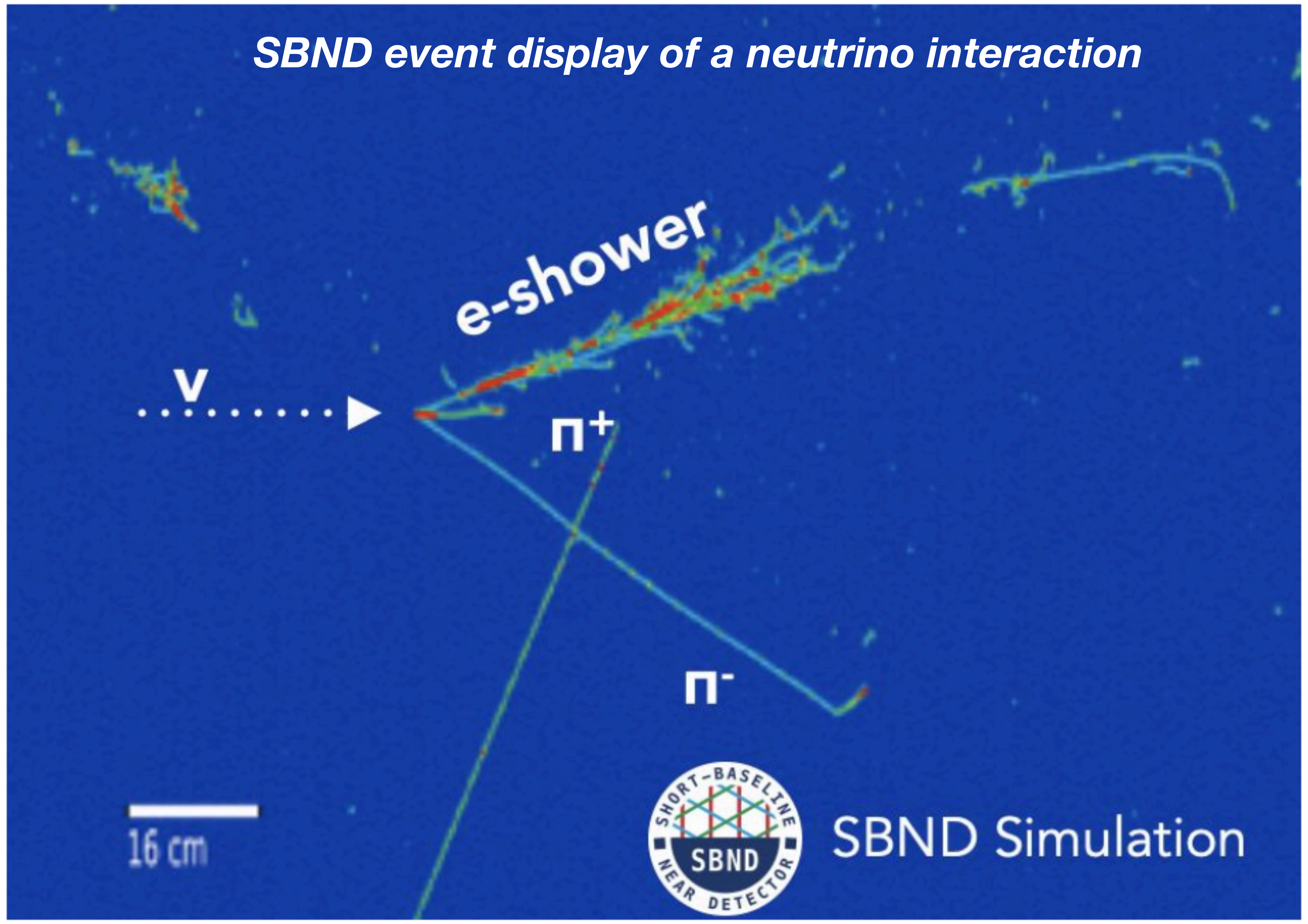
BSM at neutrino experiments

» There are numerous papers proposing Dark Sector/Hidden sector models that can be seen in neutrino experiments

» Learning from past and current efforts: MiniBooNE, ArgoNeuT, MicroBooNE

» Novel physics produced in the beam: dark matter, heavy neutral leptons, etc

» Some modifications to the neutrino oscillation paradigm may explain the short-baseline anomalies



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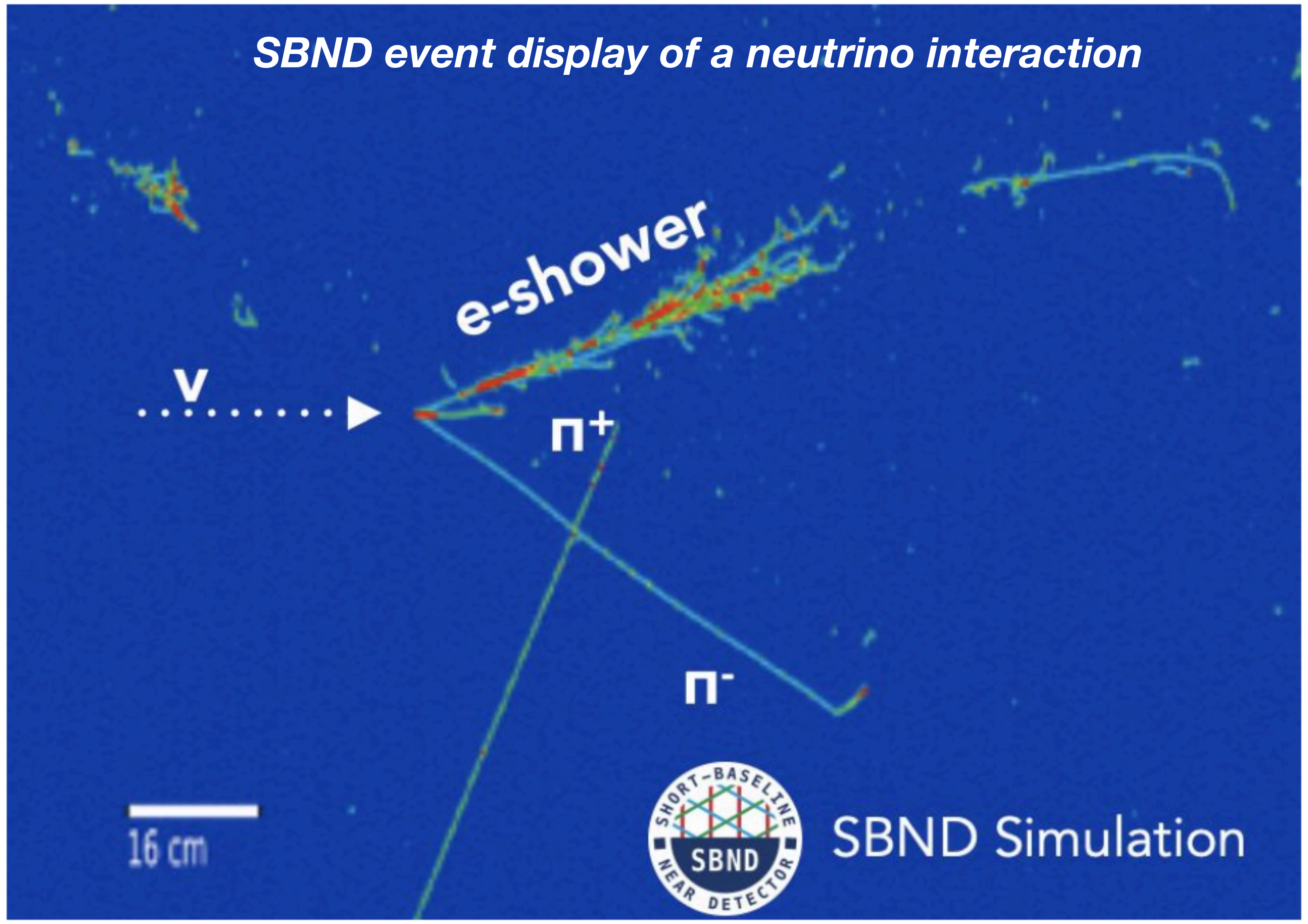


BSM experimental signatures produced in the beamline:

Challenging and new topologies

Heavier DS particles will arrive later than neutrinos

DS particles may deposit lower energies

DS particles may be produced in neutral meson decays (unfocused): different angular distribution

BSM opportunities at neutrino experiments

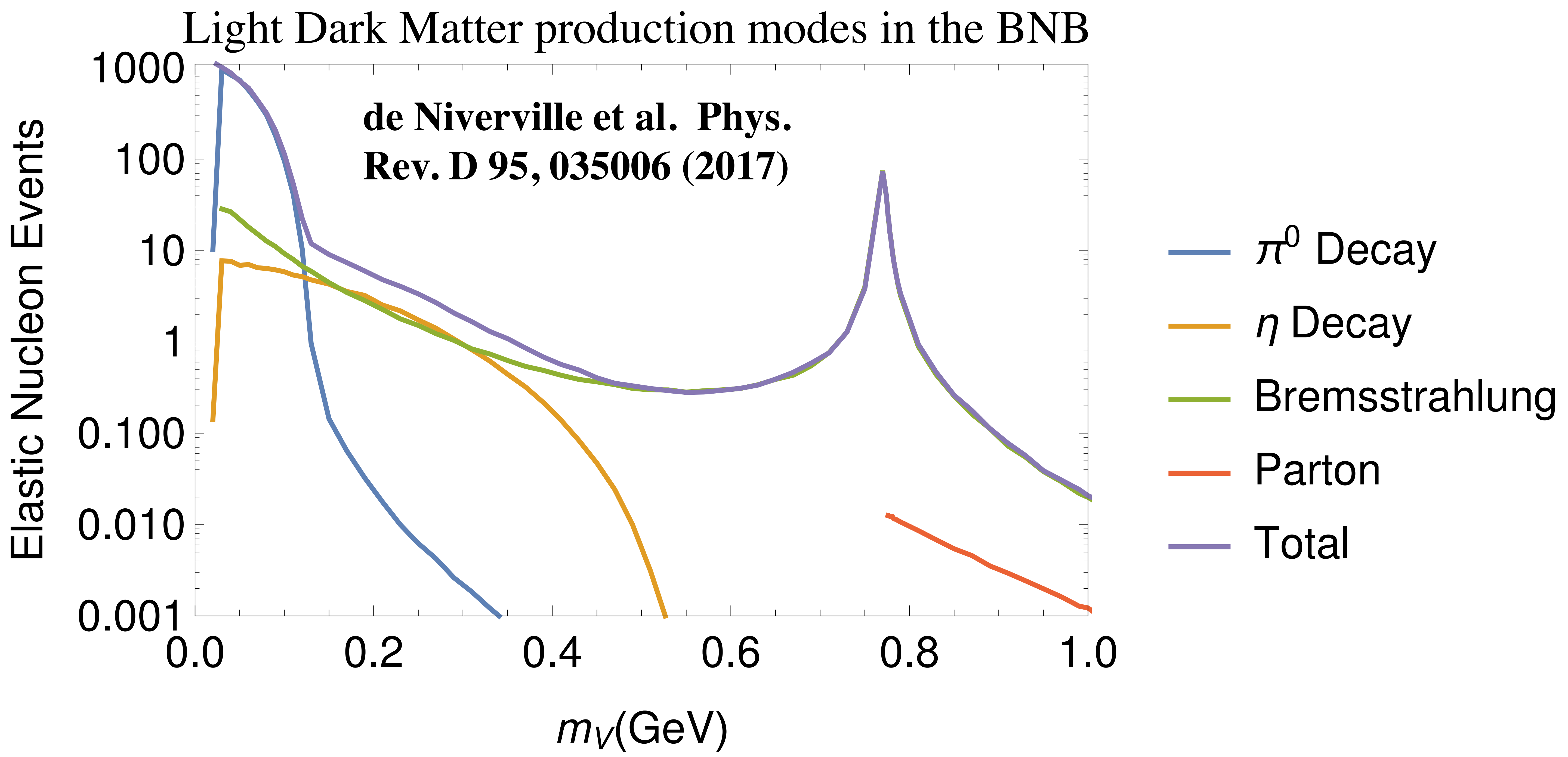
Unprecedented opportunities with a combination of:

a high-intensity proton beam

large mass detectors close to the beam target

A good timing resolution and low energy threshold

A good event imaging, fine granularity calorimetry and particle identification



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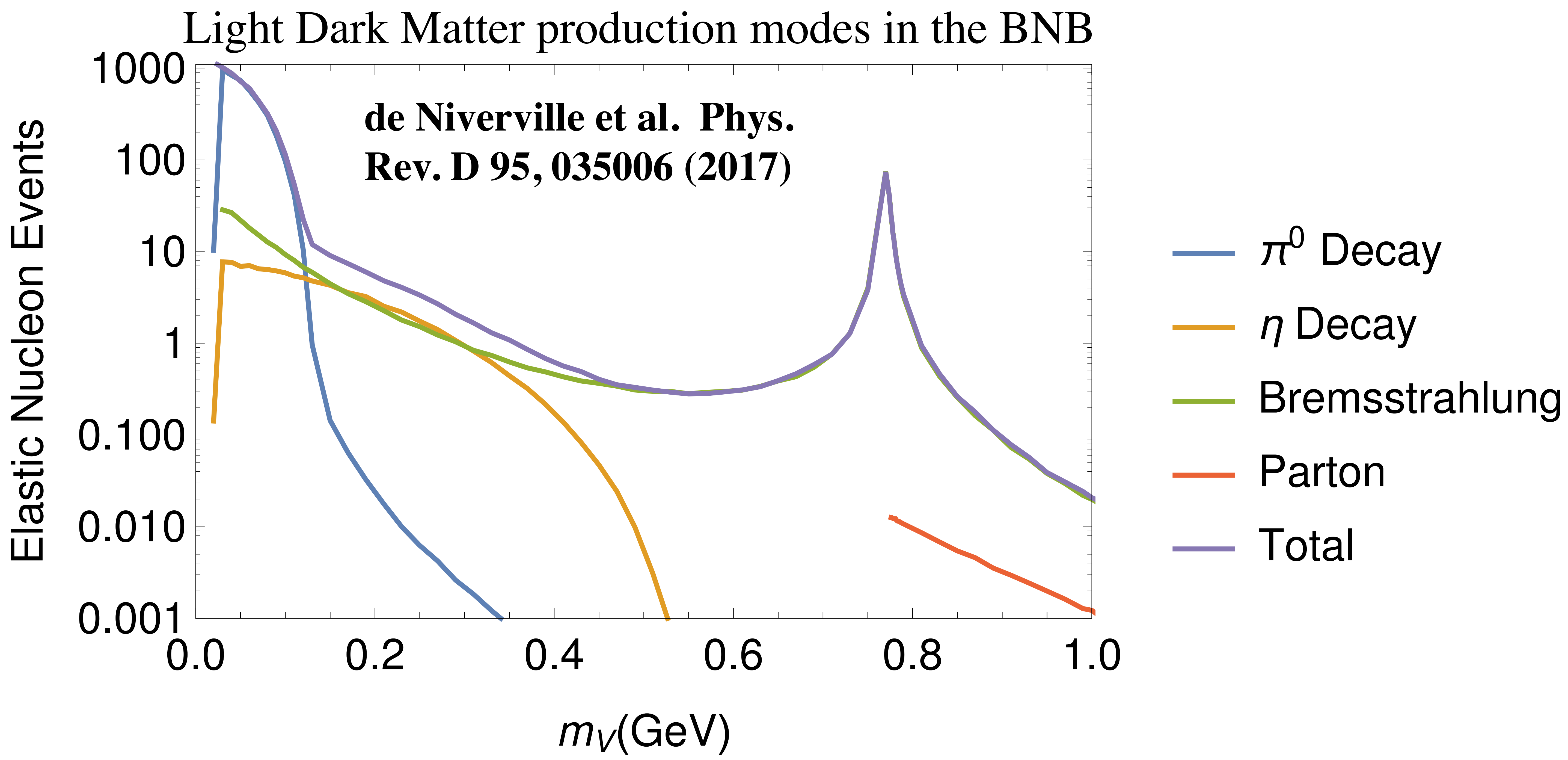


Neutrino interactions are background for some BSM signatures:

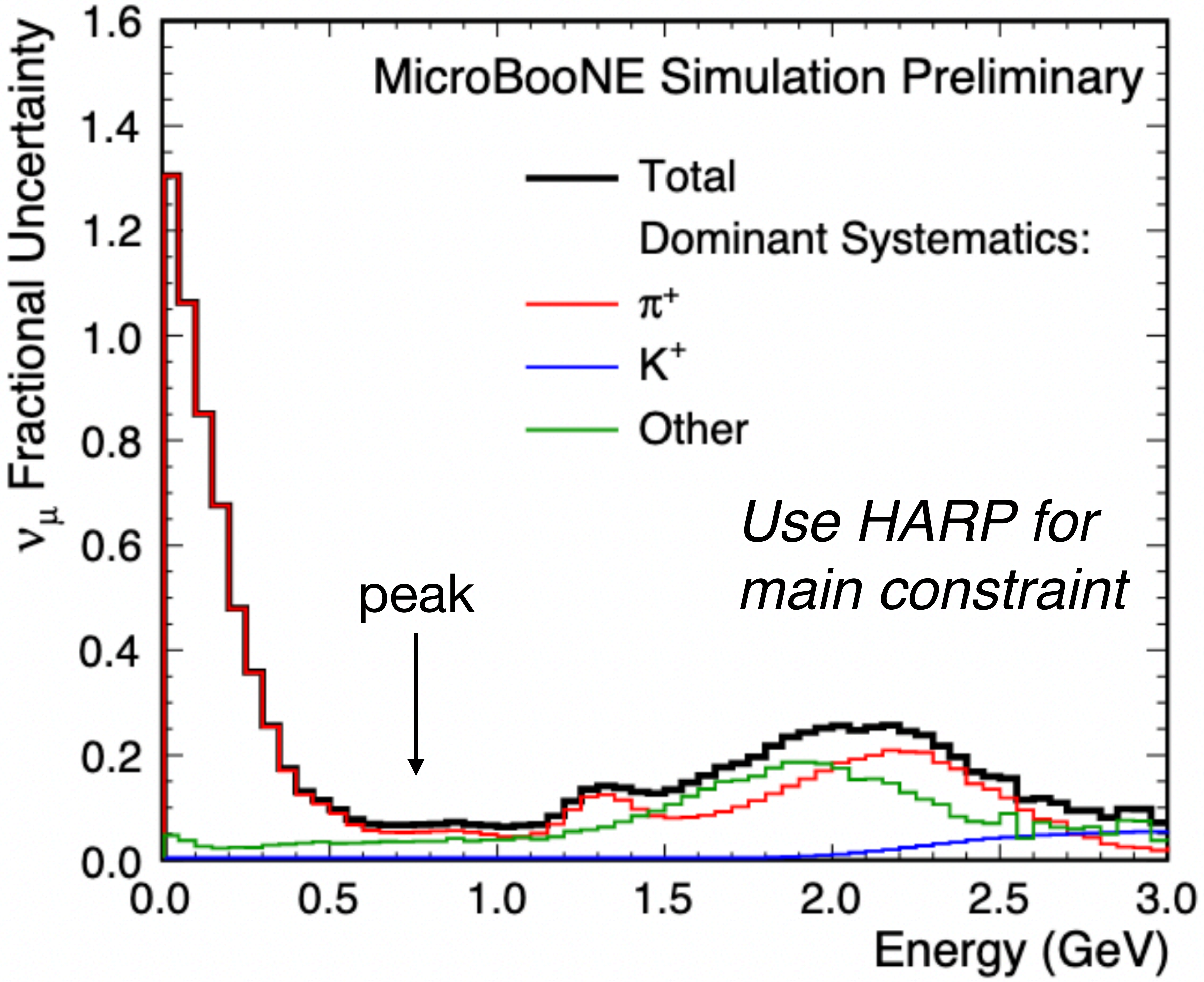
» The neutrino flux uncertainty is large!

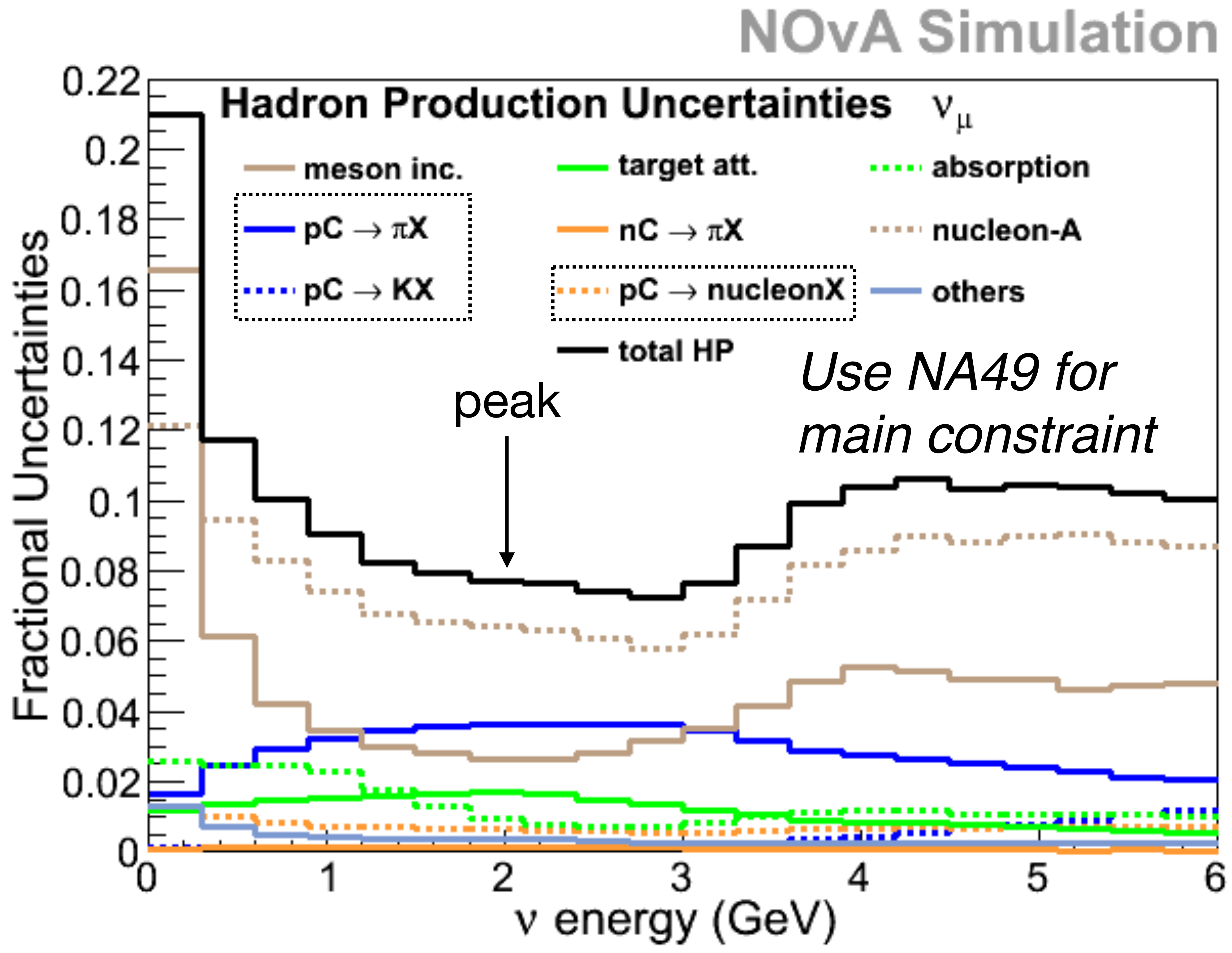
» Scattering off of nuclei will depend on nuclear effects!

» Any corrections coming from simulations: purity, efficiency, energy reconstruction rely in the Xsec model

Neutrino flux uncertainties

» Uncertainties coming from constraining the hadron production model with external data



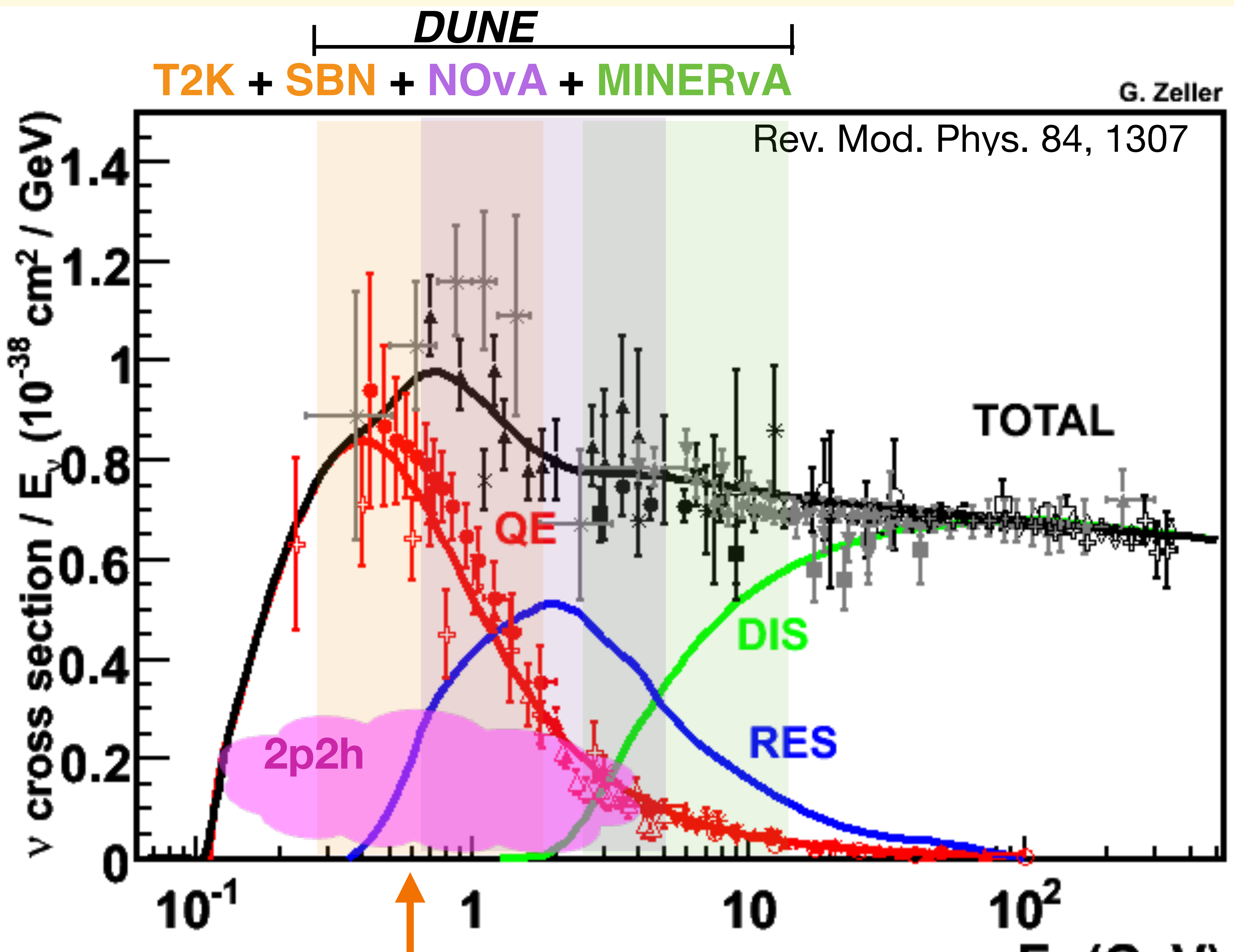


Interactions in dashed boxes use HP data directly

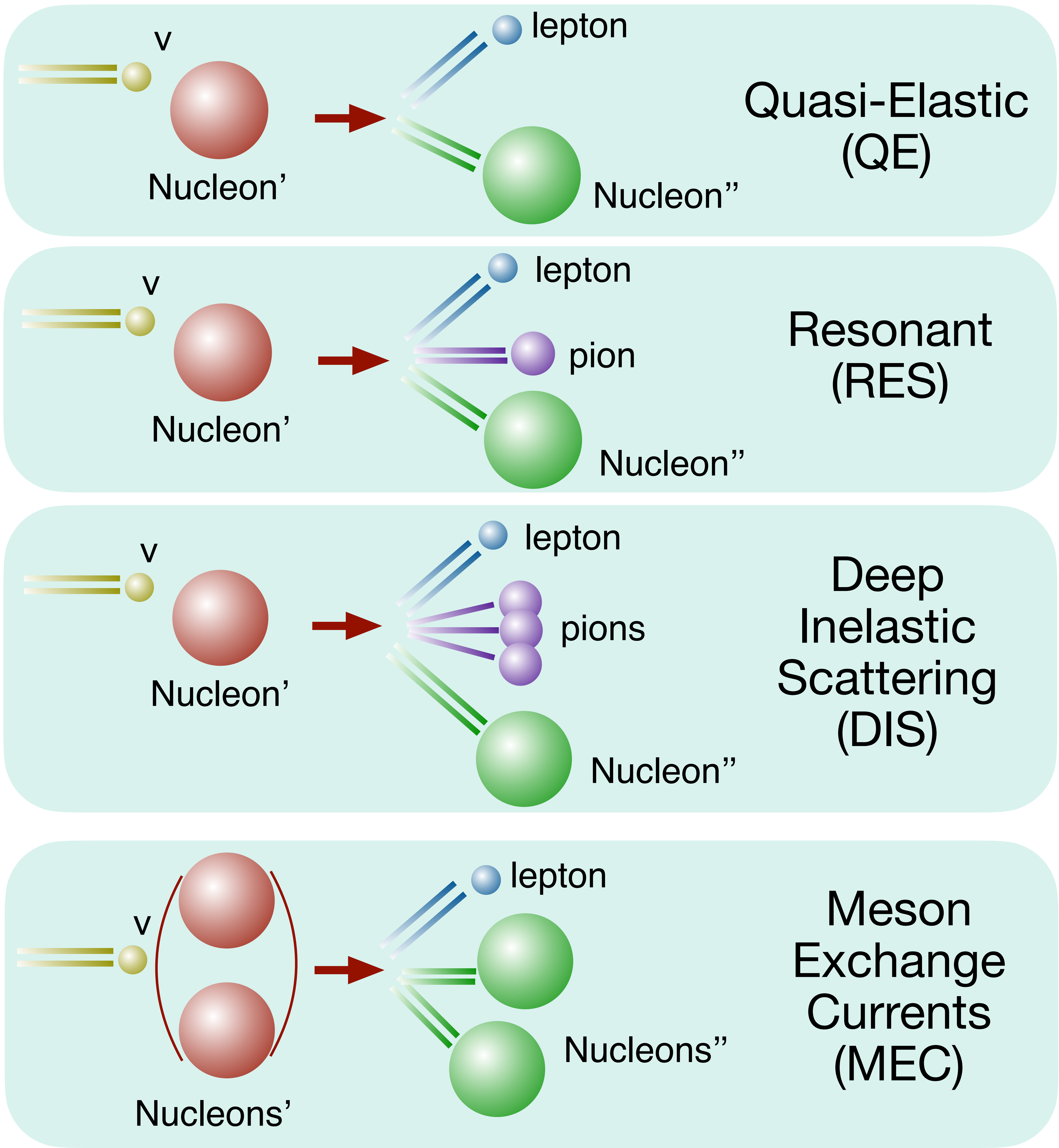
» Experiments such as MINERvA are using in-situ measurements to applied an additional constraint to the flux

» Uncertainty reduction is expected when more HP data is measured: NA61 (CERN) and EMPHATIC (FNAL)

Neutrino interactions



SBN flux peaks at 0.6-0.8 GeV

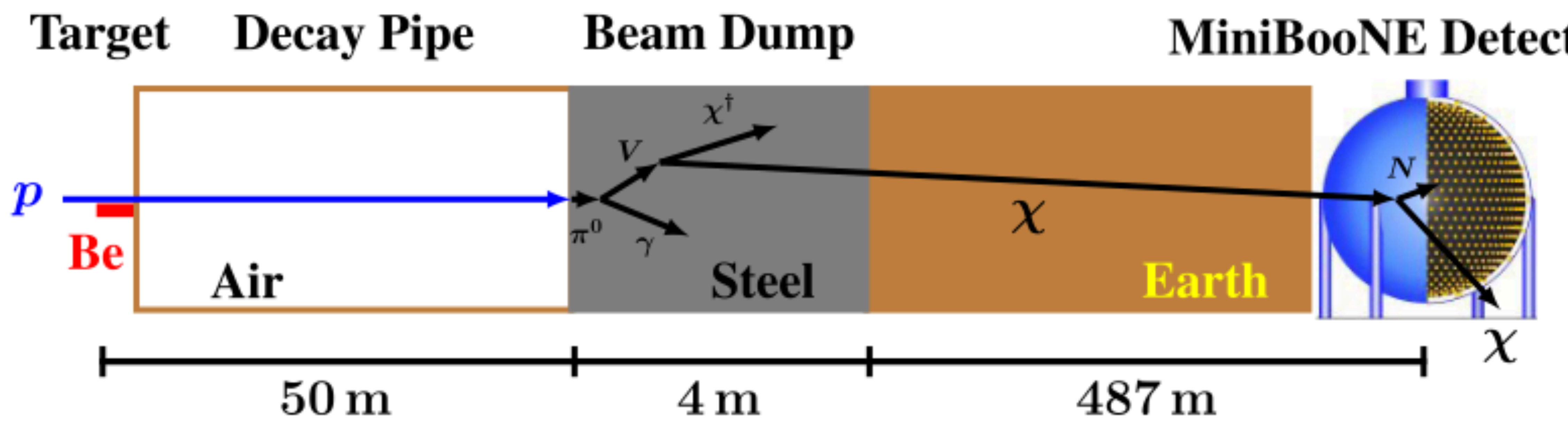


These interactions happen inside the nuclear media.

The theory to describe this process is not well understood and uncertainties are challenging

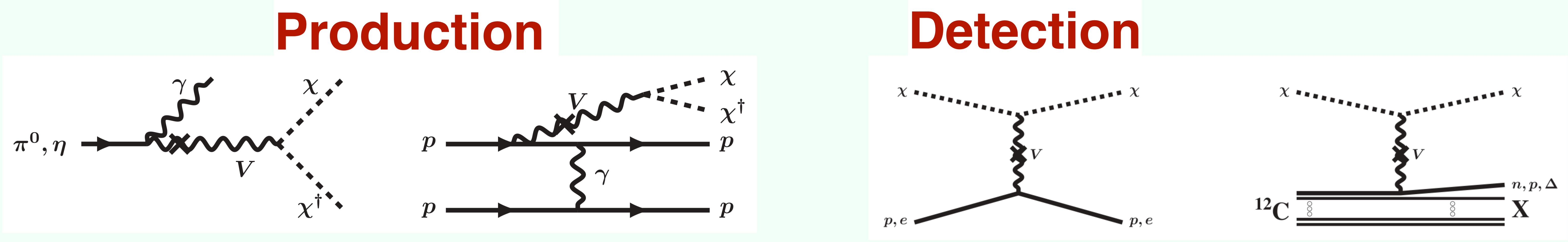
Nuclear targets at SBN experiments is Ar40

Previous DM Search



The MiniBooNE experiment performed Vector Portal Dark Matter search from proton beam dump

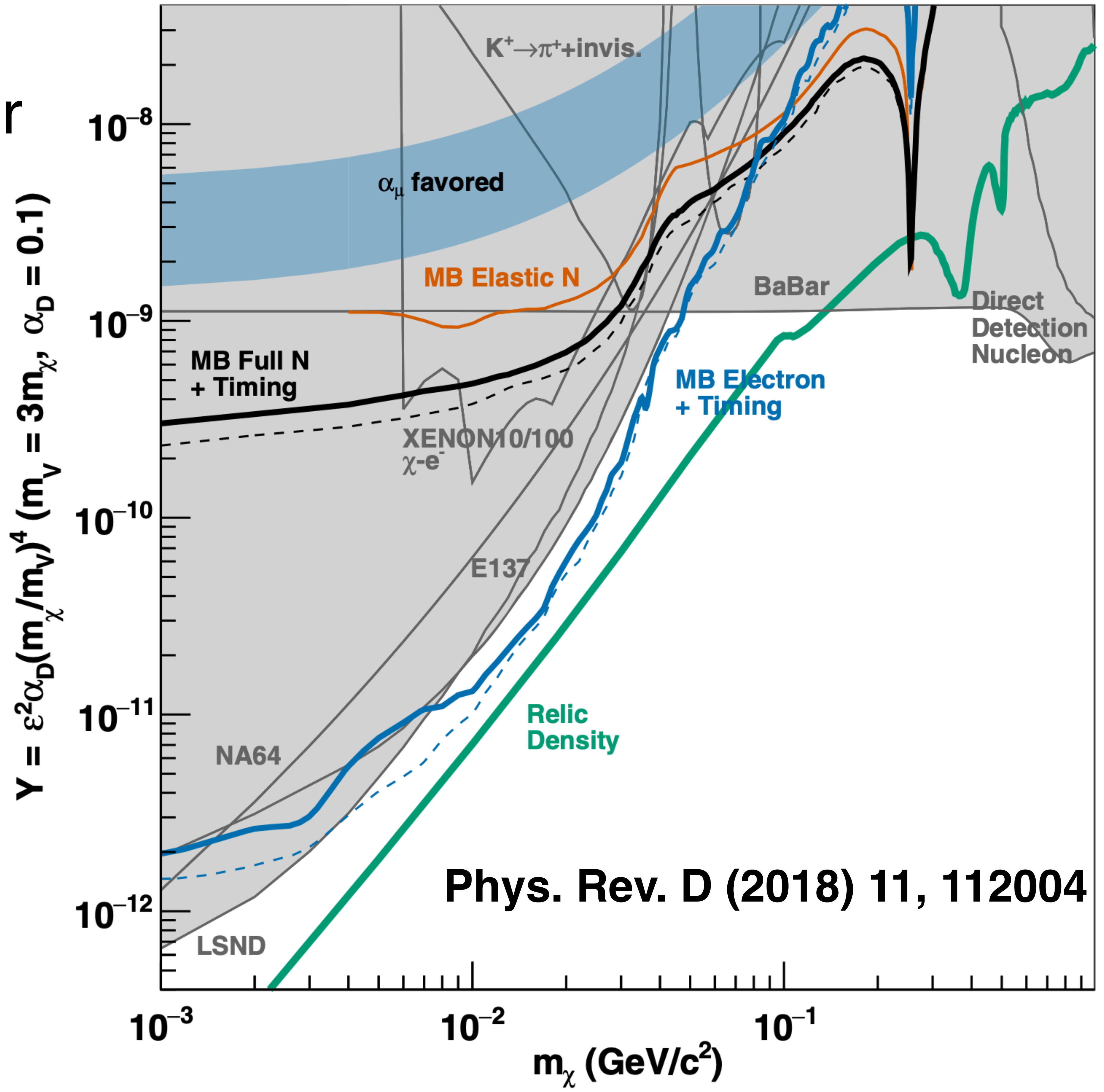
- Dedicated run with target off (1.9E20 POT)
- 8 GeV protons strike on the iron dump: 800 ton mineral oil detector
- Neutral meson (π^0, η) decays to DM particles



Put leading limits on low mass vector portal dark matter model

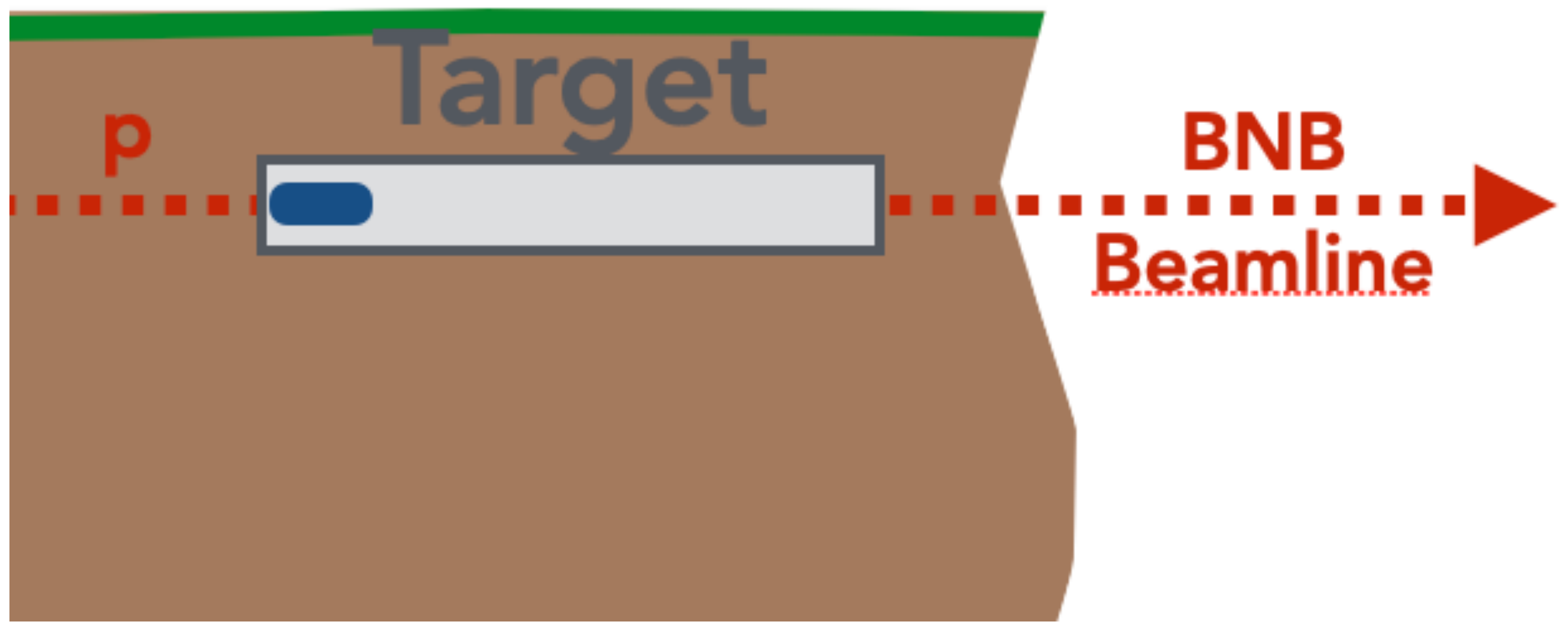
It showed that proton beam dump can be an effective approach for DM search

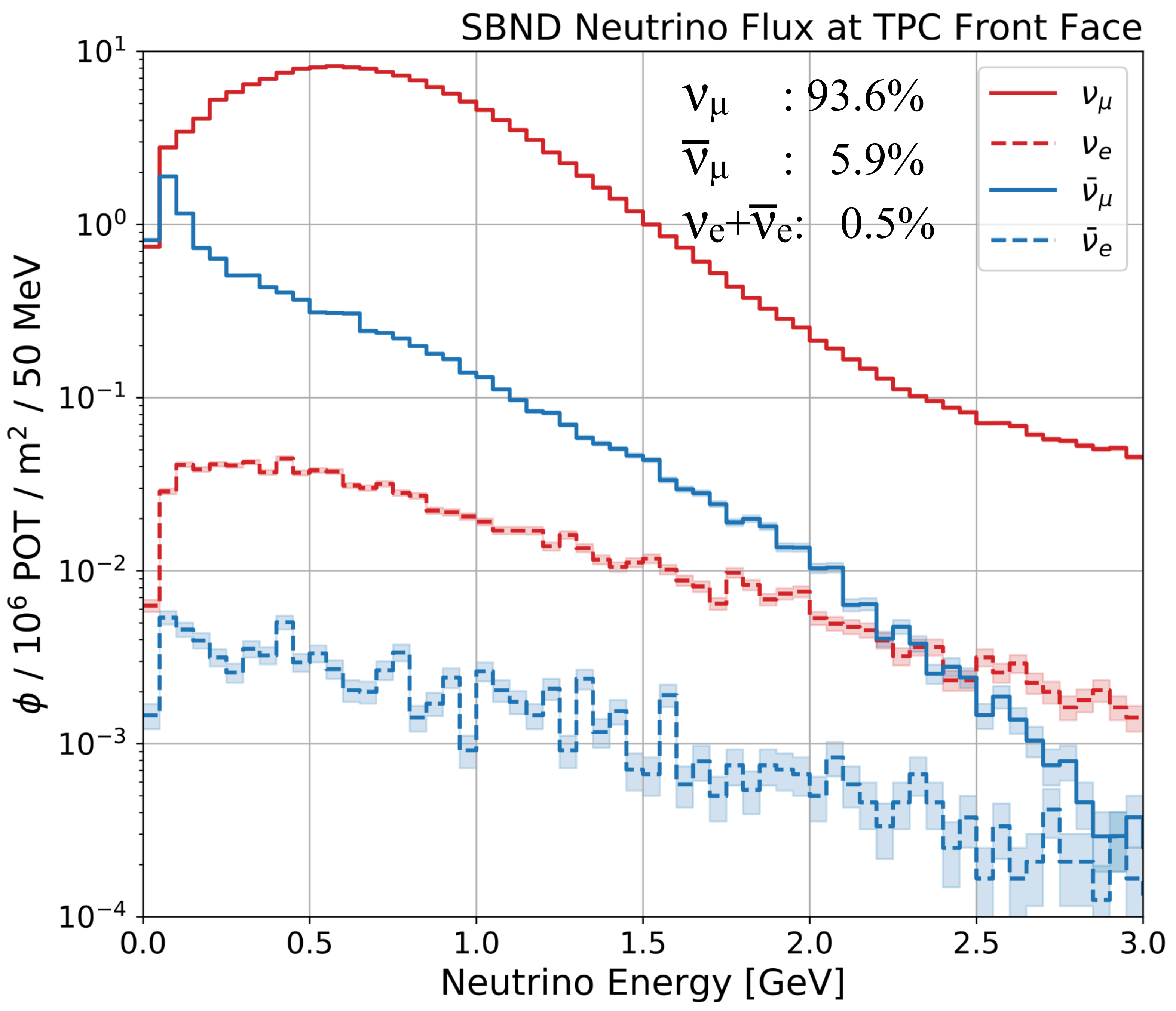
Can this first experience be done in current SBN experiments (SBND PRISM)?



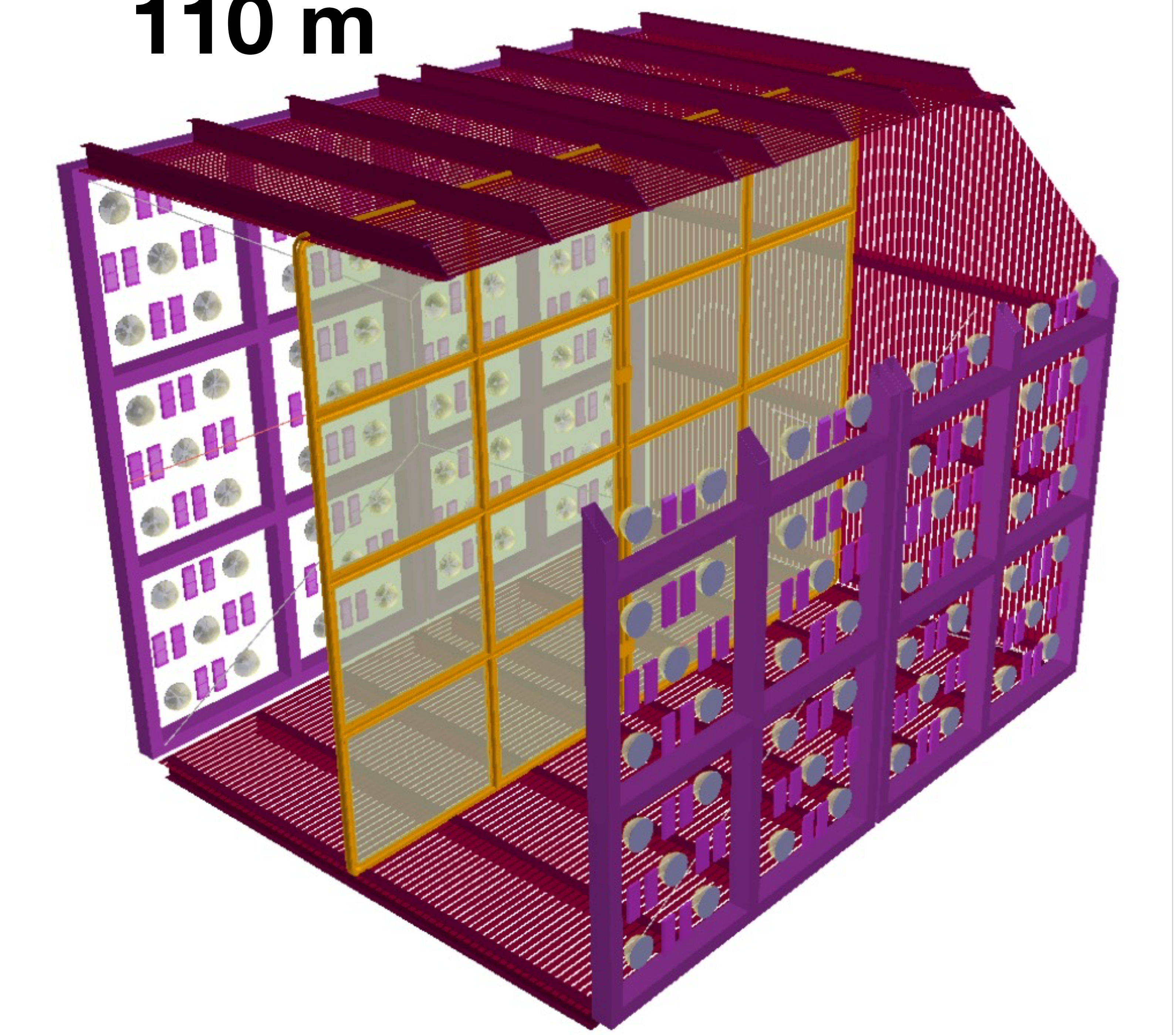
SBND

Short-Baseline Near Detector





110 m



Two-detector analyses for sterile neutrino analysis:

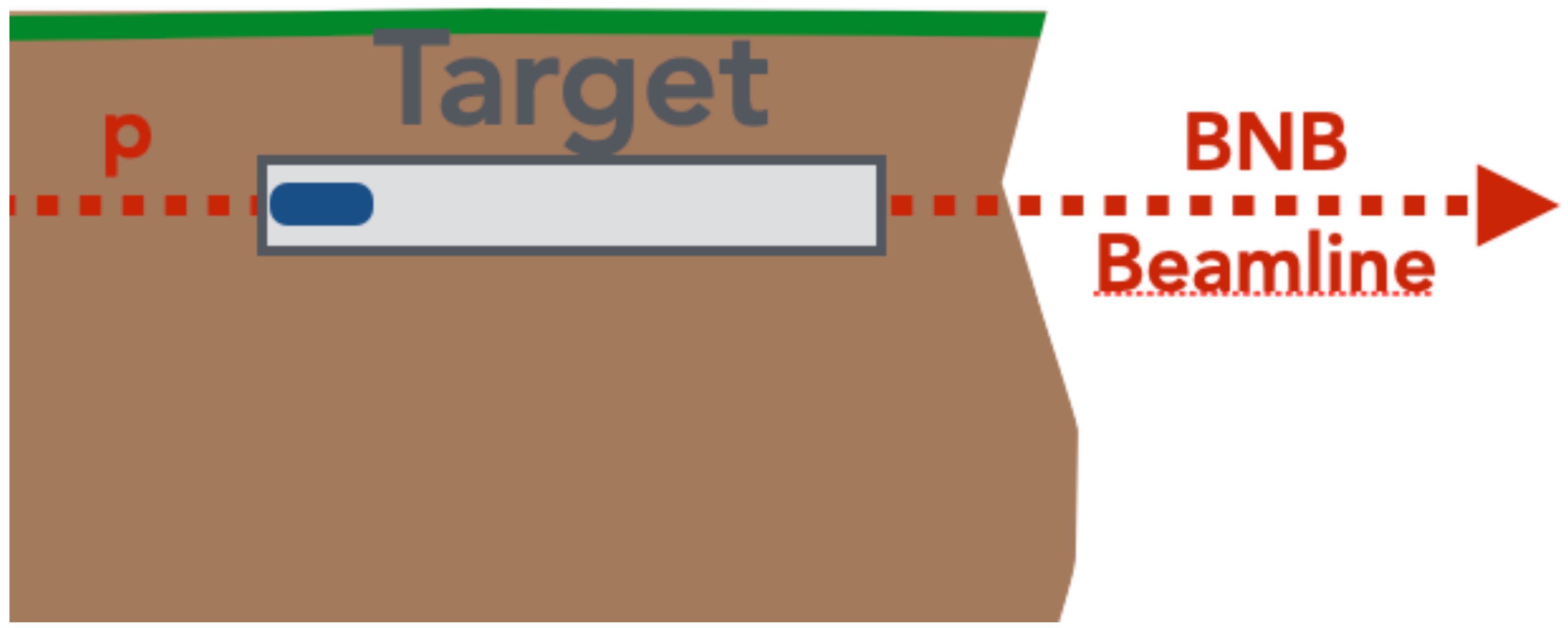
- » **Near Detector: SBND**
- » **Far Detector : ICARUS**

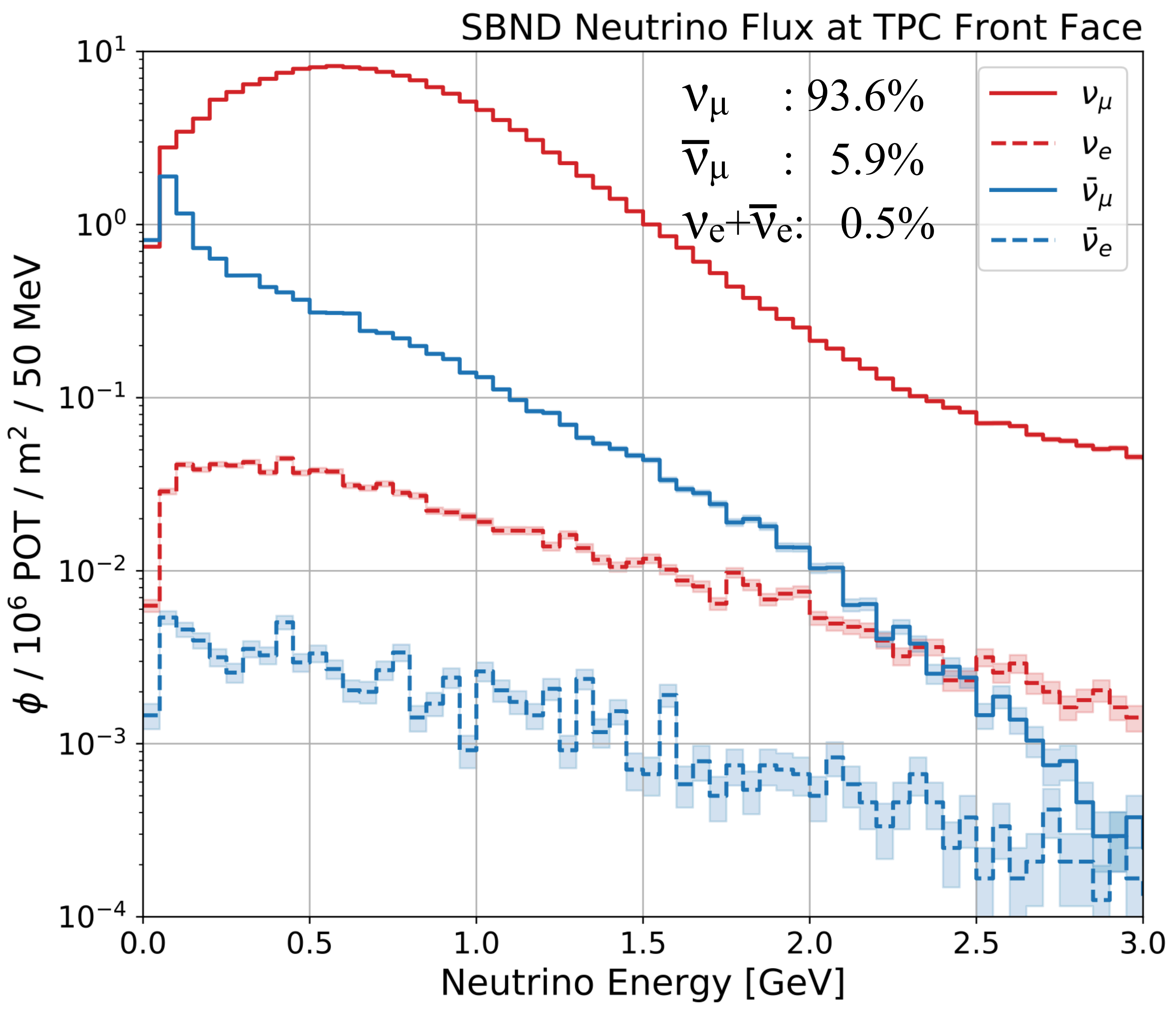
Same neutrino beam, nuclear target and detector technology (LAr TPC detectors) to reduce systematic uncertainties to the % level.

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

In addition to the sterile and cross-section programs, the SBND large detector mass and proximity to intense beams enable a broad physics program

Short-**B**aseline **N**ear **D**etector





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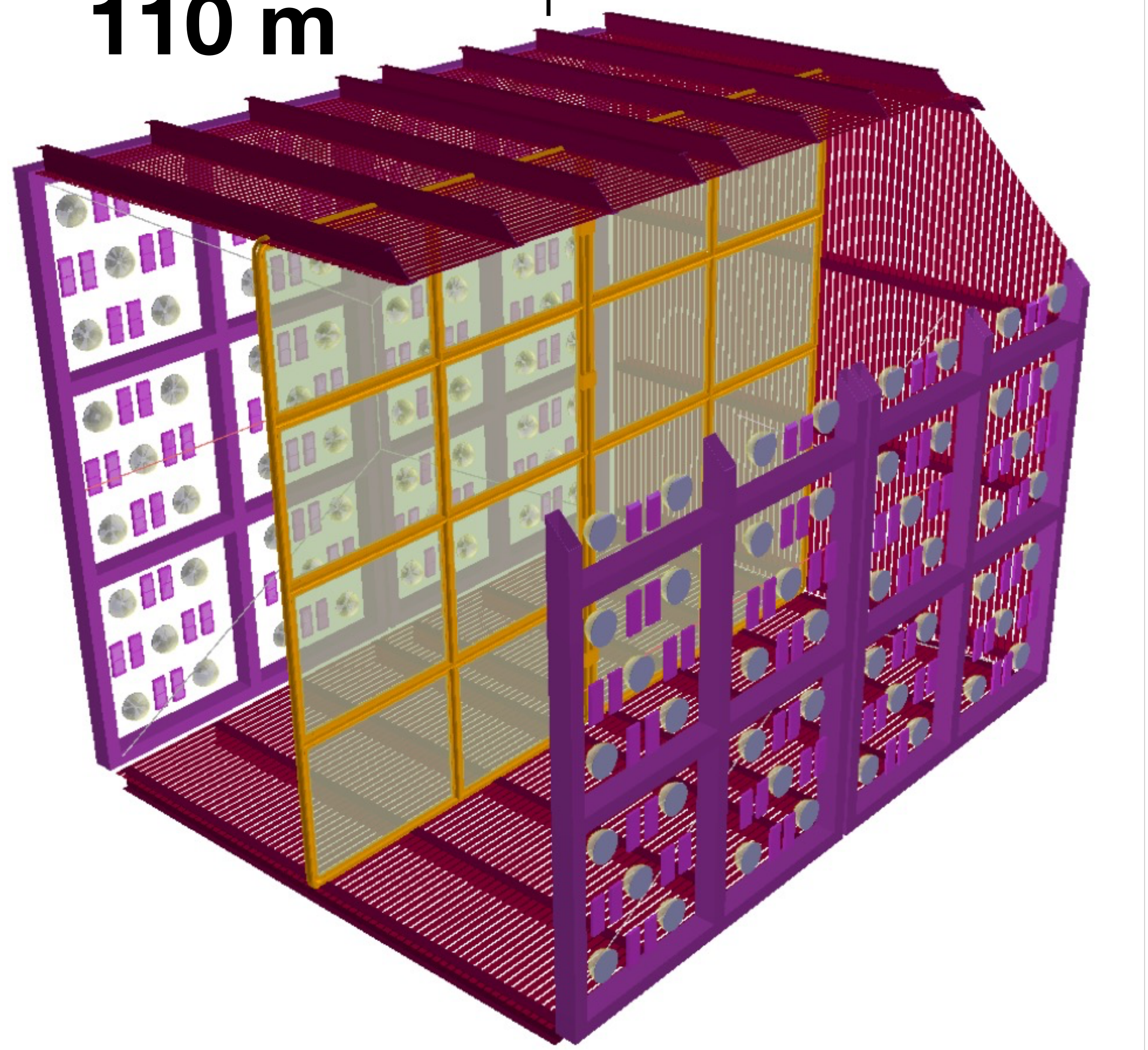
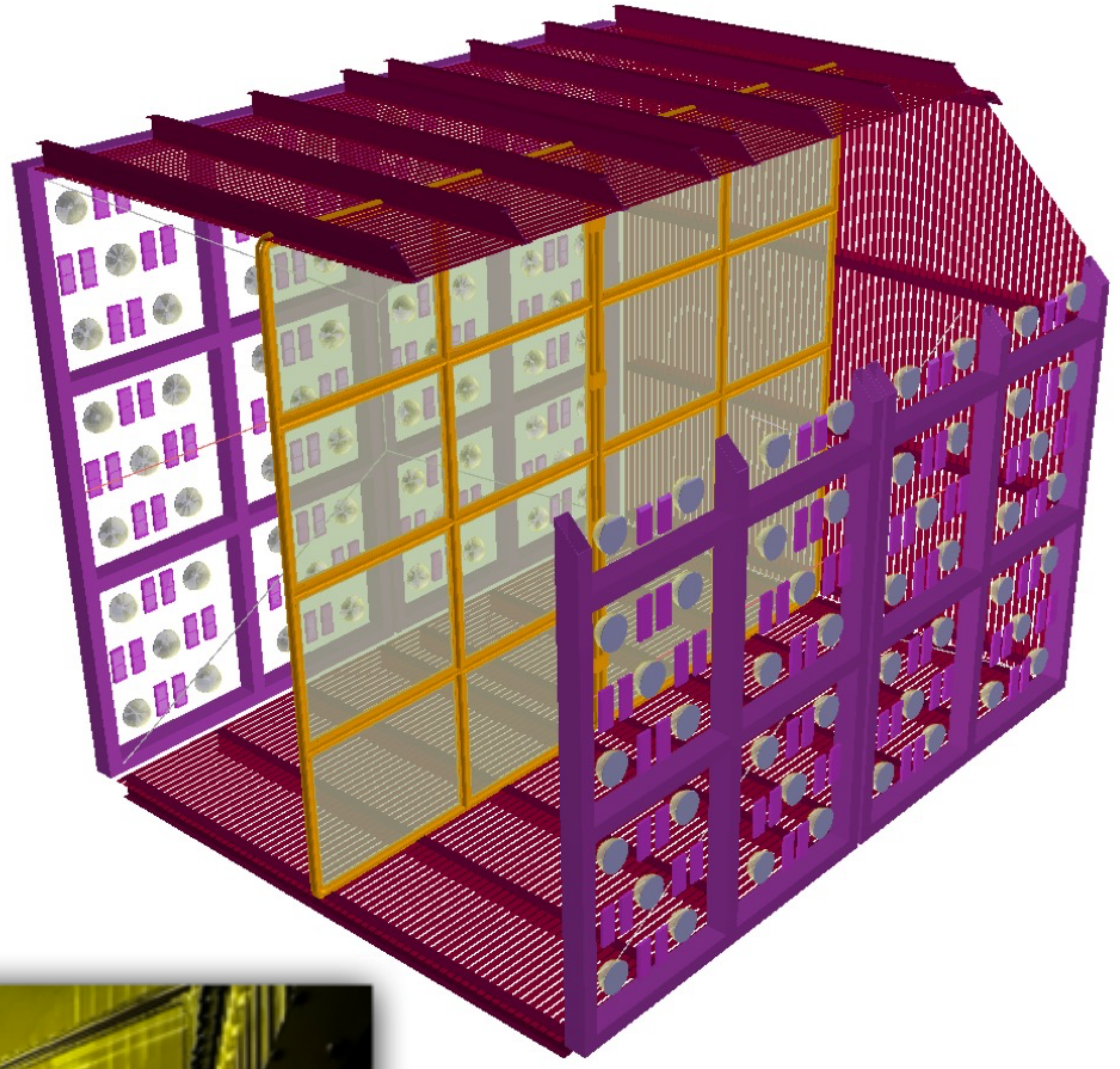


New physics scenarios: BSM physics program is an evolving landscape, with many new search ideas emerging from collaboration with theory colleagues

The detector has been built and moved to its final location.
Expected begin operation in 2023

Short-**B**aseline **N**ear **D**etector

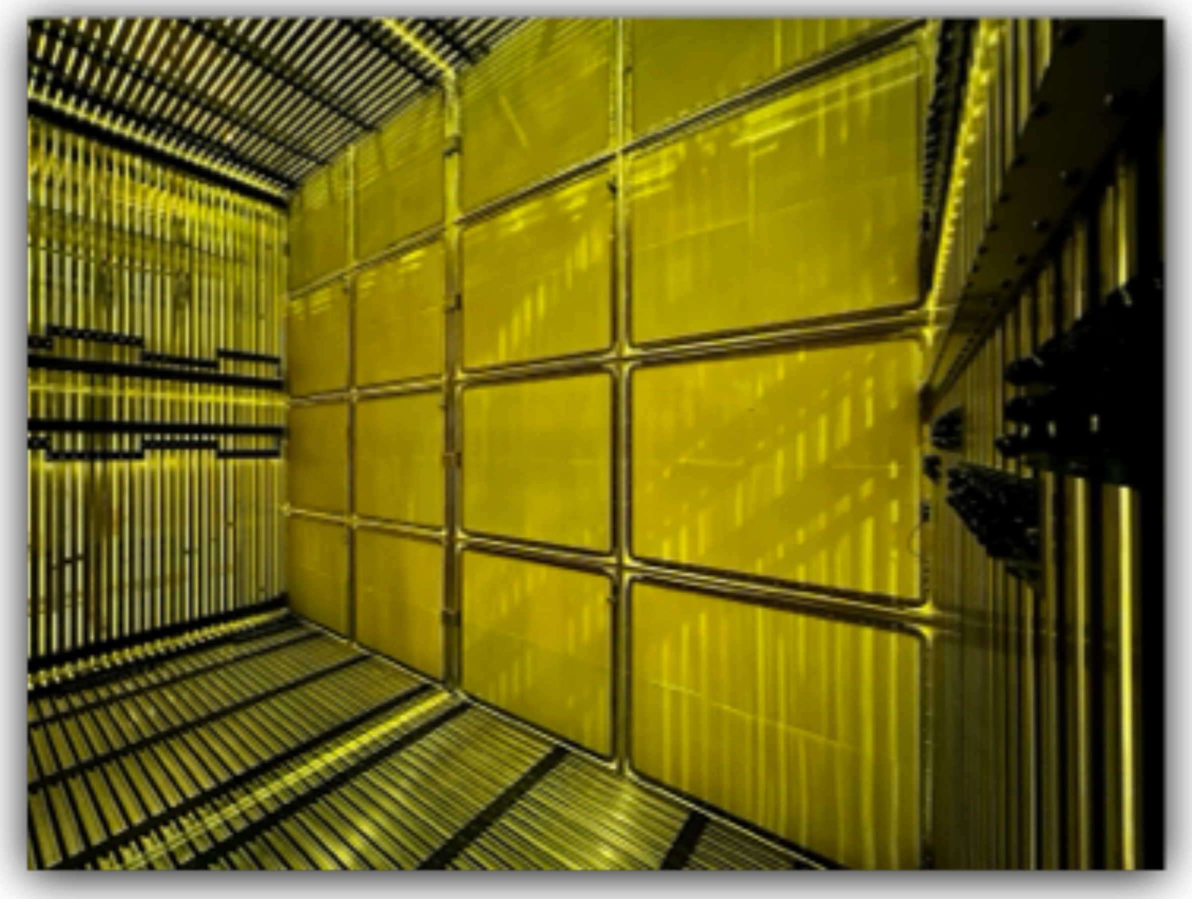


Large-mass Liquid Argon Time Projection Chamber (LArTPC)

- » *3D reconstruction with a mm position resolution*
- » *Fine-granularity calorimetry*
- » *Excellent particle identification with dE/dx information*
- » *Low energy thresholds: few MeV*

Photon Detection System (PDS)

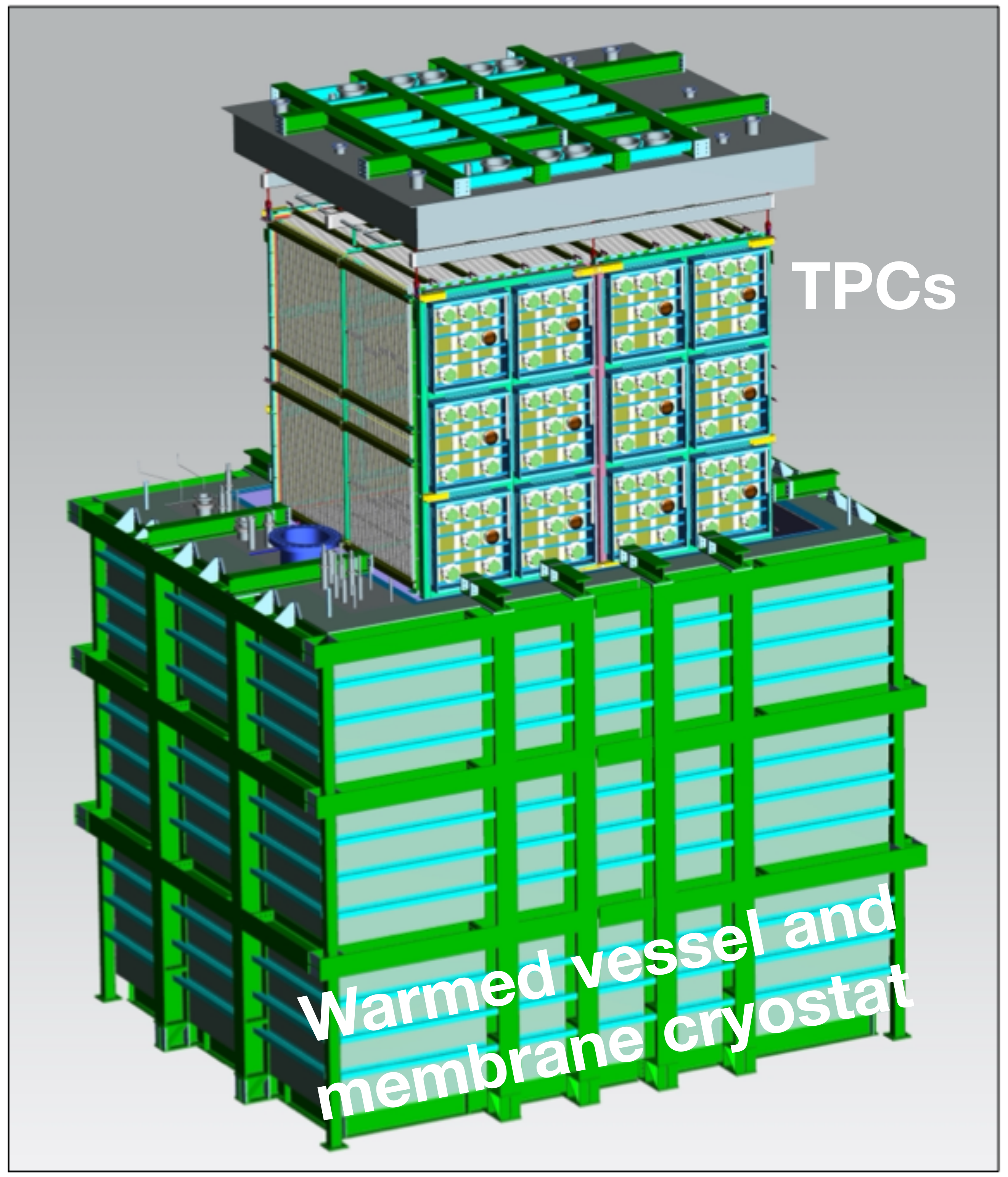
- » *Novel technology of PMTs and X-Arapucas.*
- » *Scintillation & reflected light => high and uniform light yield and excellent timing resolution*

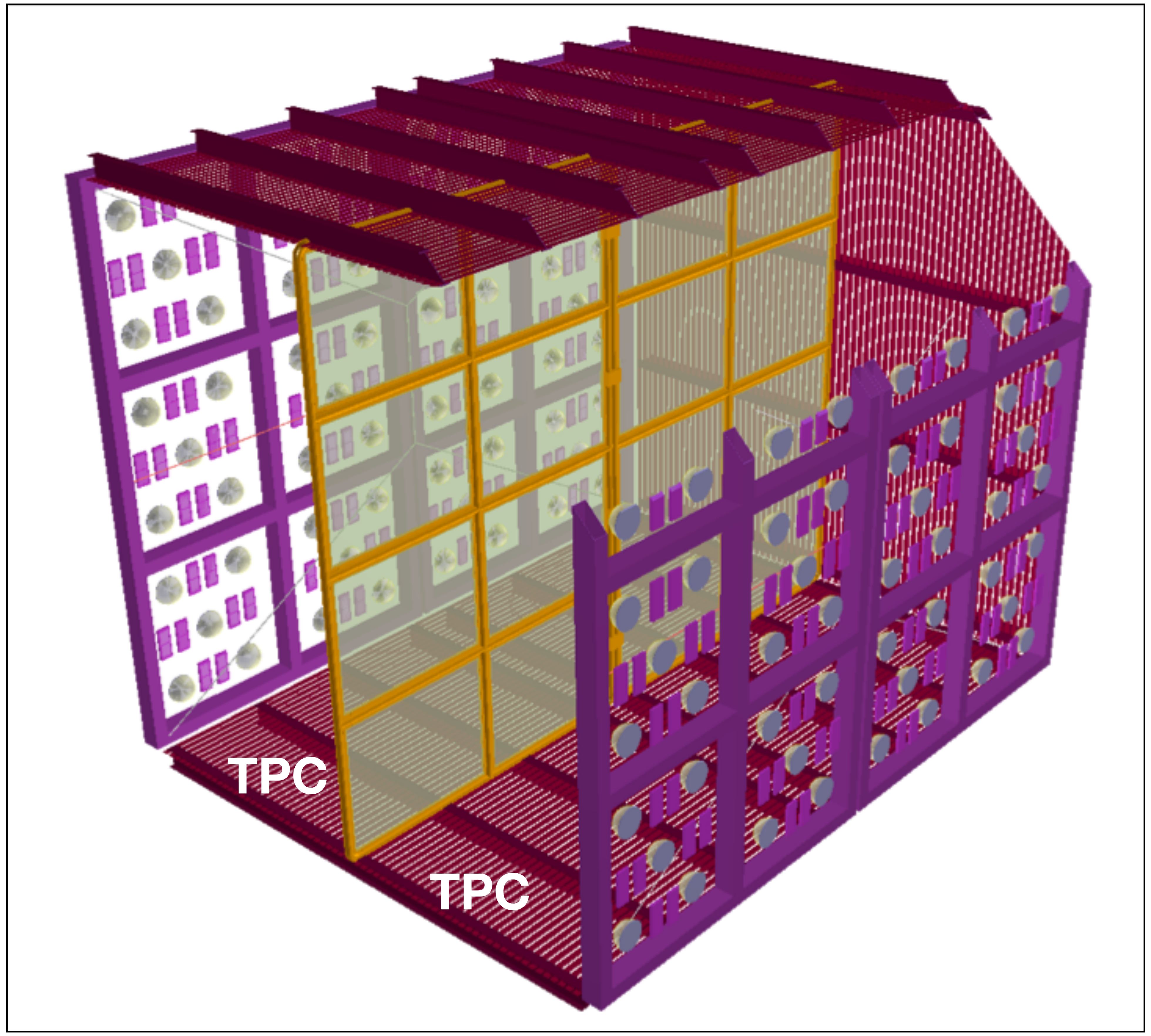


Cosmic Ray Tagger (CRT)

- » *Timing and position resolution allows for triggering on entering/exiting particles*

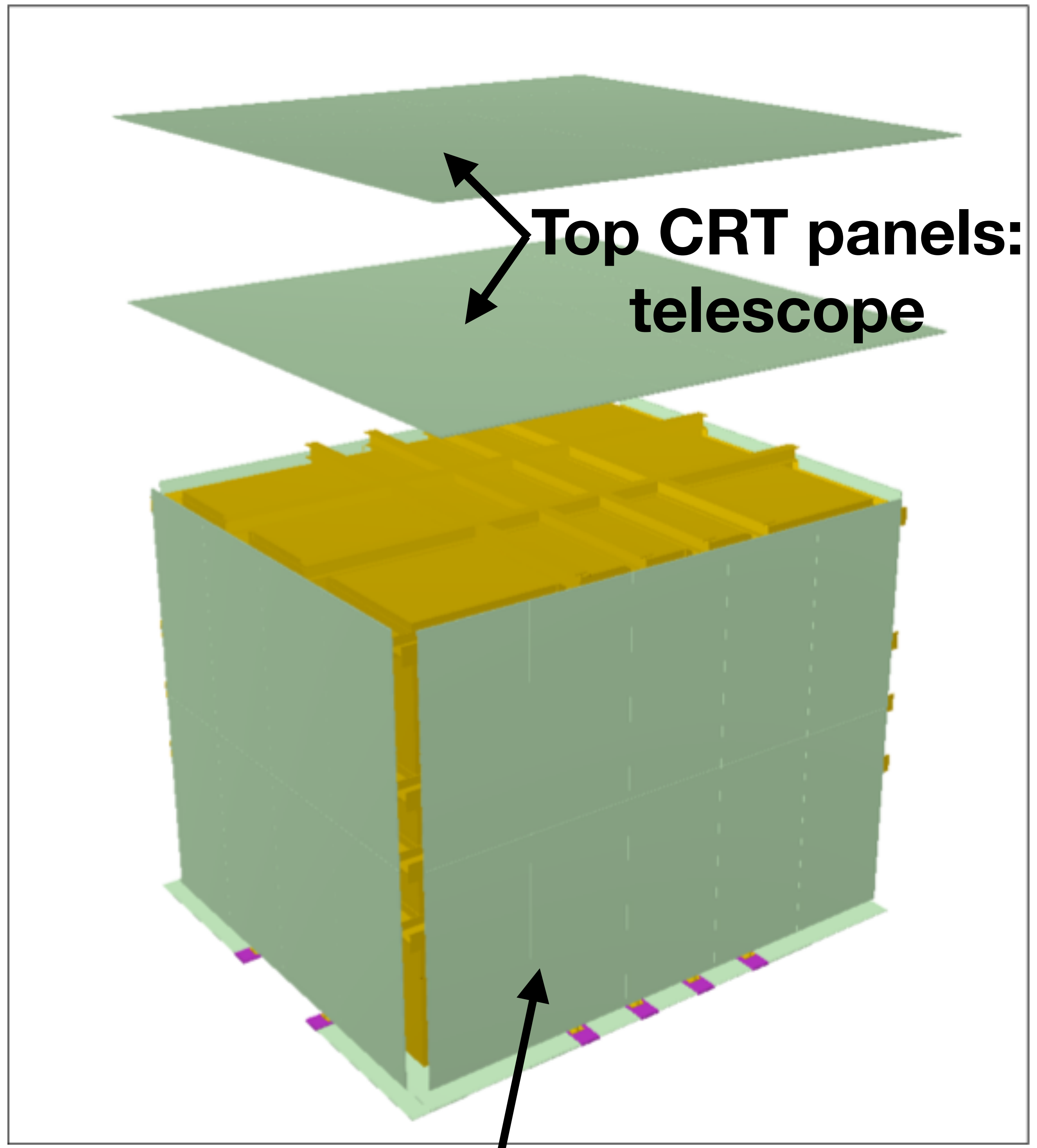
SBND Detector





Two Time Projection Chambers

Cryostat surrounded by a Cosmic Ray Tagger system

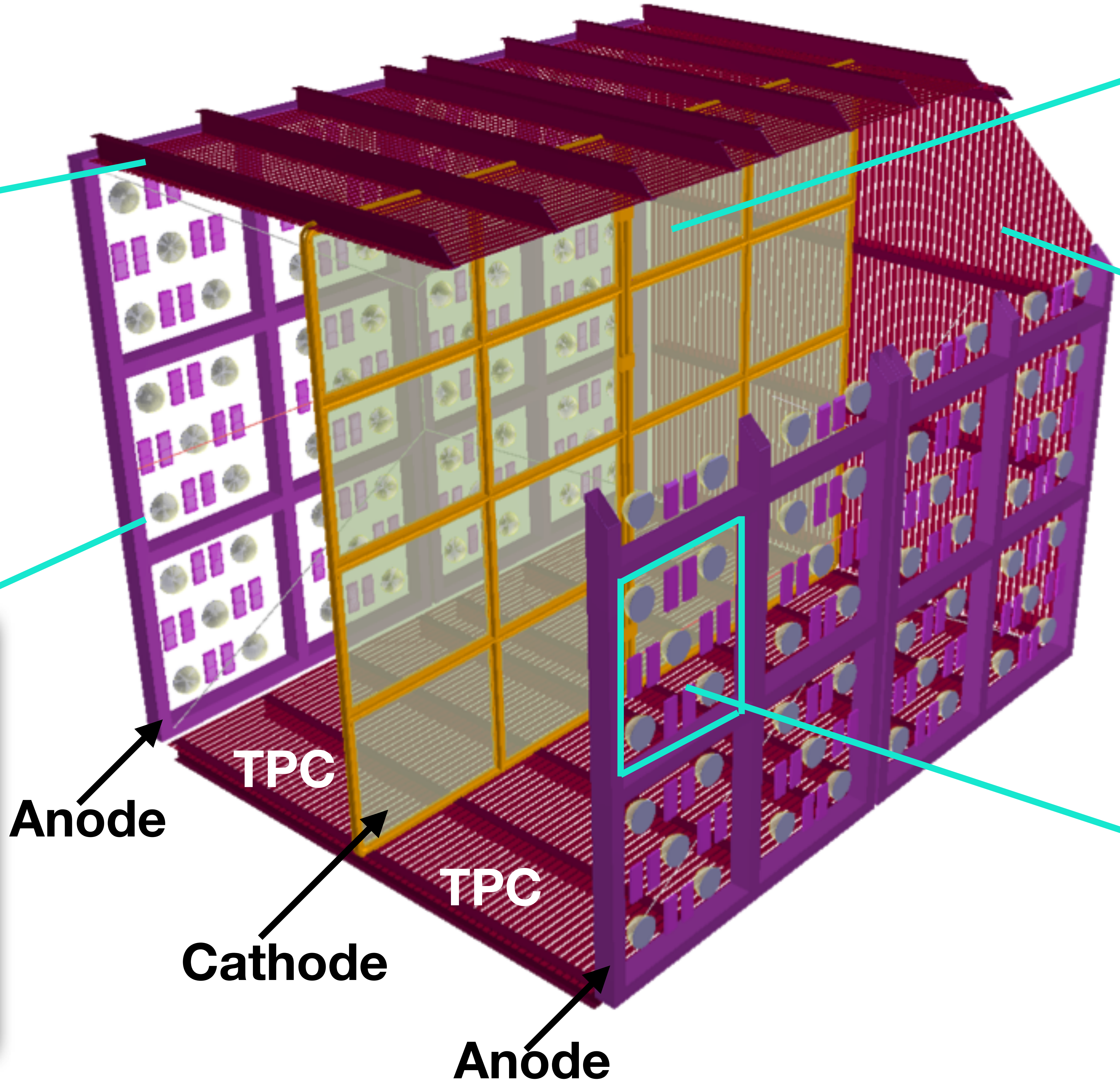


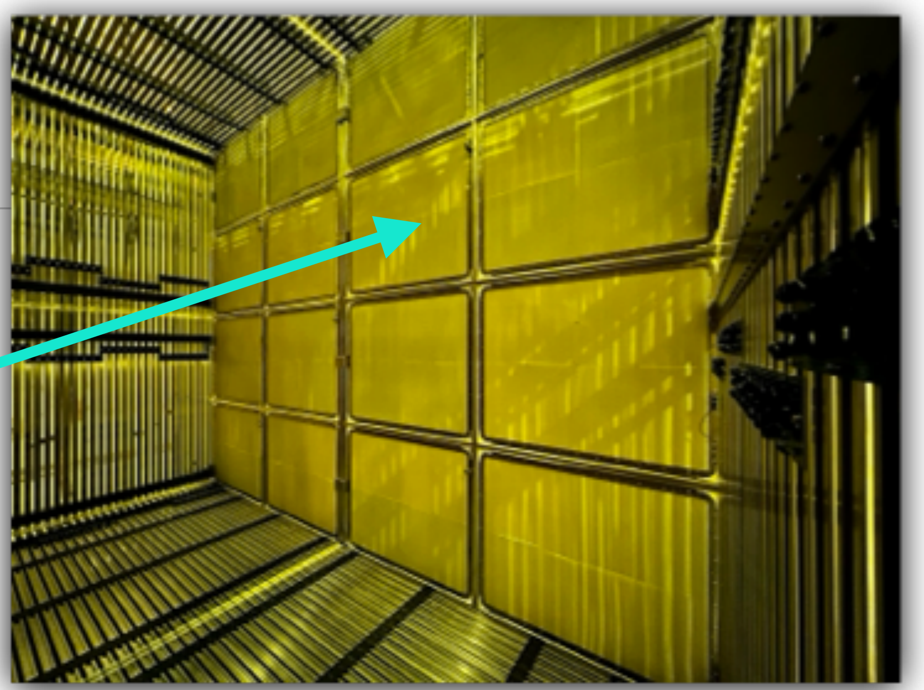
CRT panels made of scintillator strips

SBND Detector: TPC and PDS

TPC Cold electronics

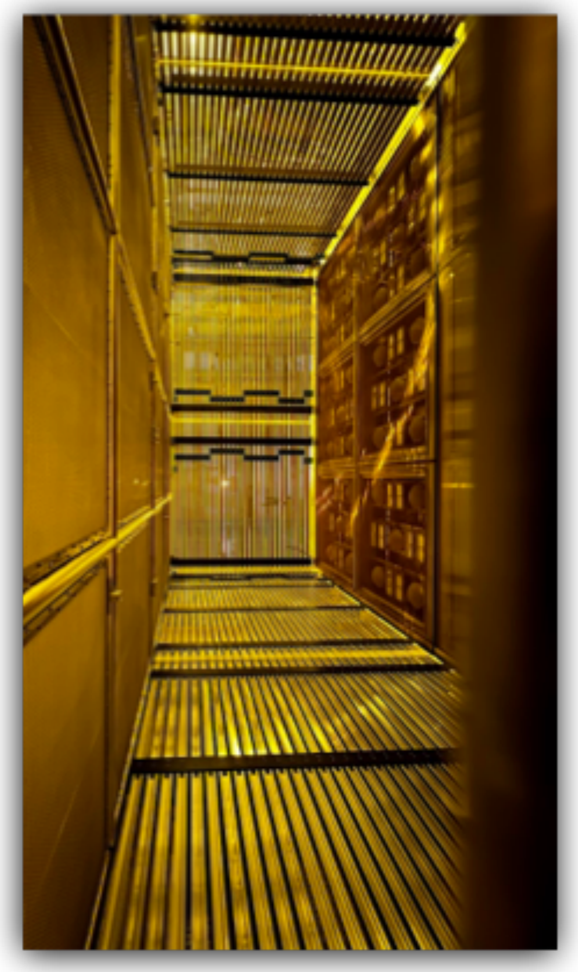
2 Time Projection Chambers
total dimension: 4m x 4m x 5m

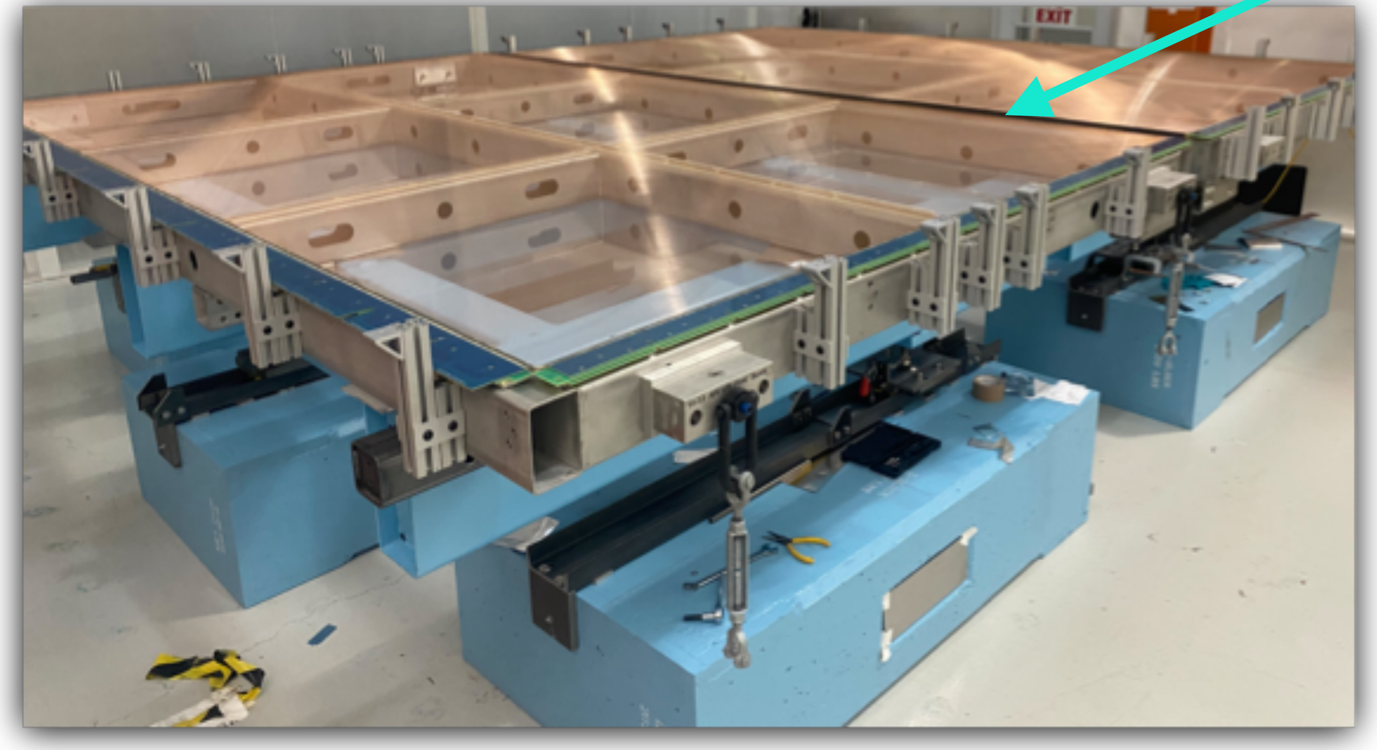




Cathode
covered with TPB
coated reflectors

Field Cage

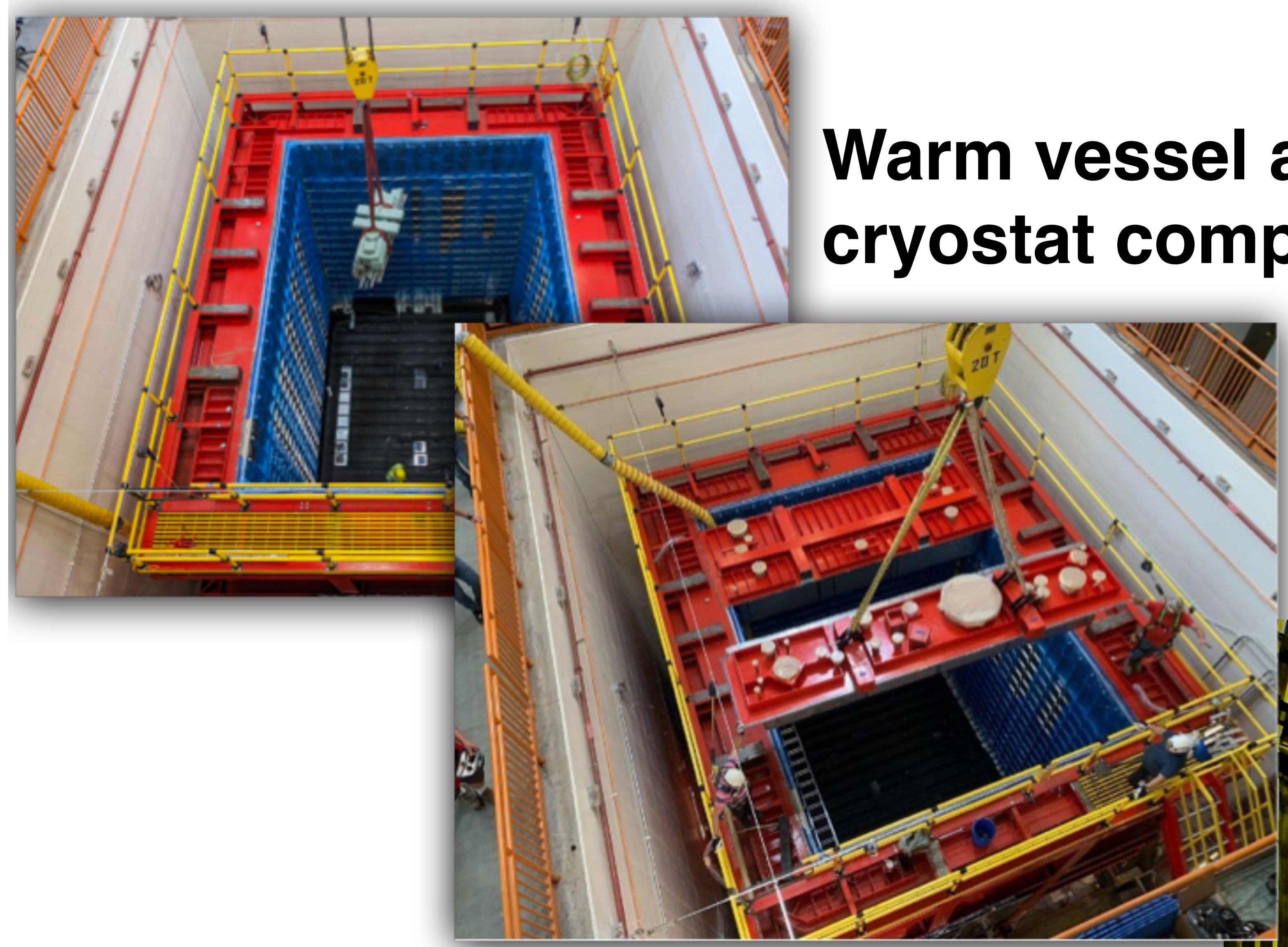




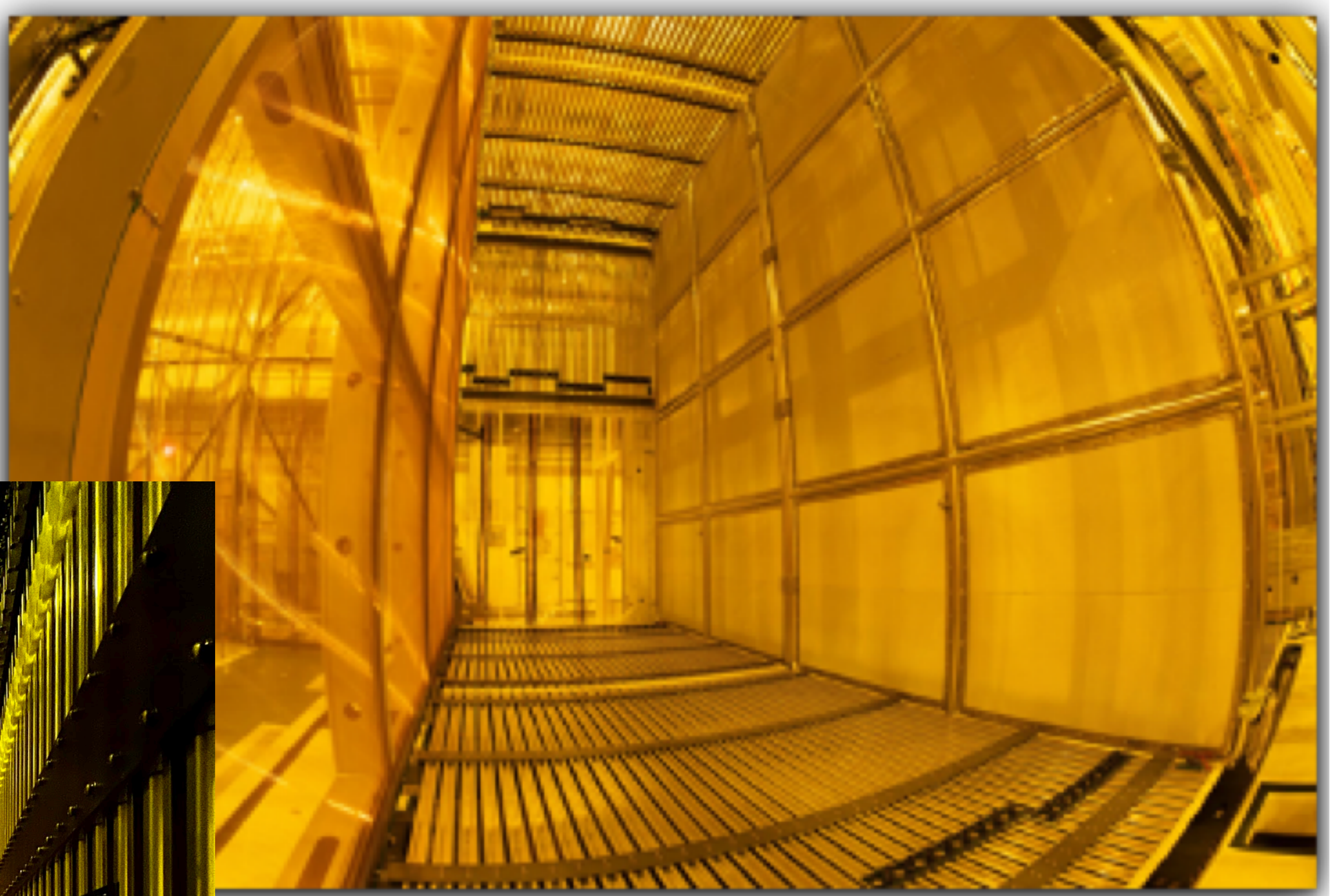
Wire Plane: 3 readout planes, ~11000 wires

Photo Detection System
120 PMTs, 192 X-Arapucas

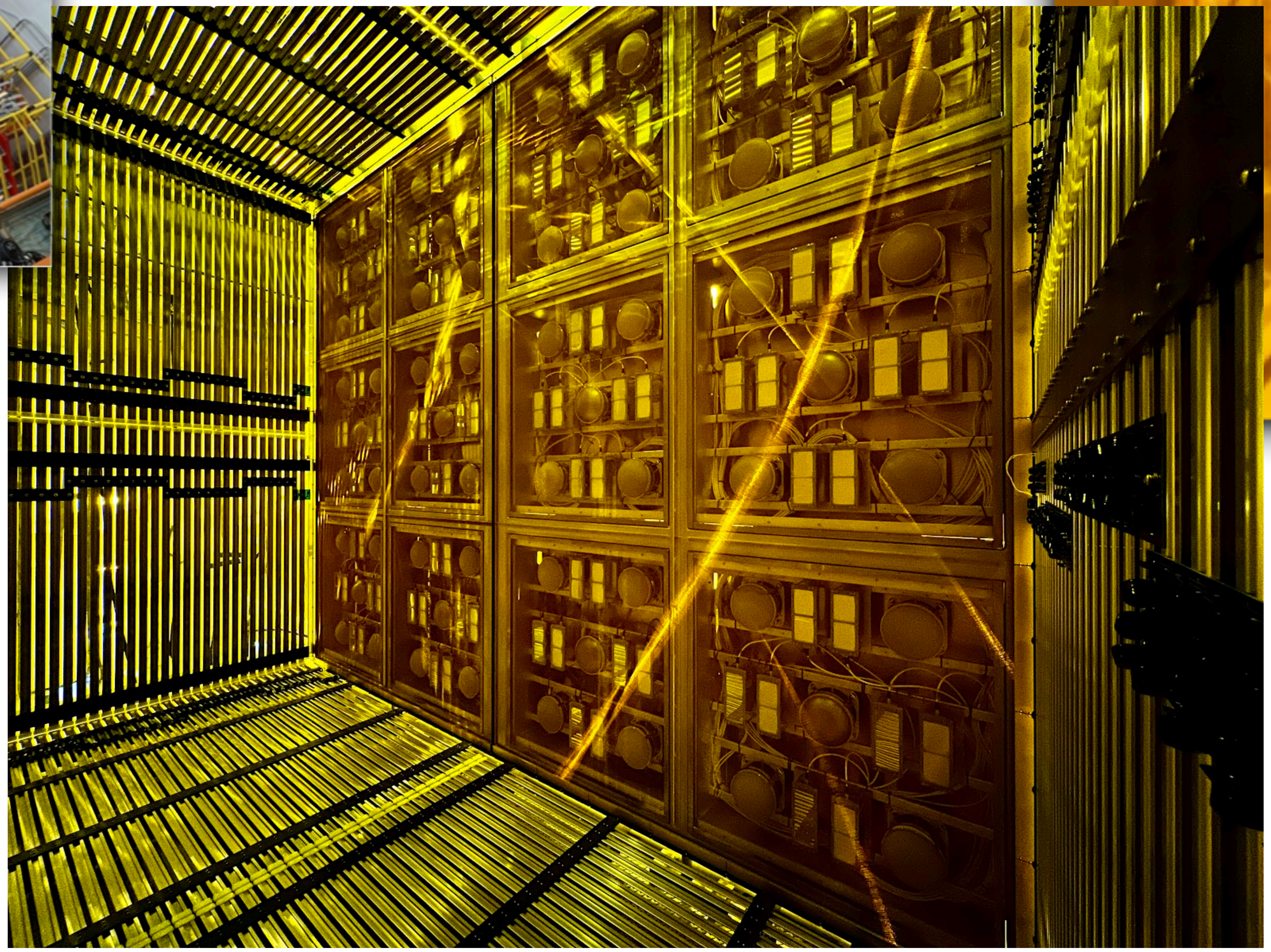
SBND Construction



Warm vessel and membrane cryostat completed

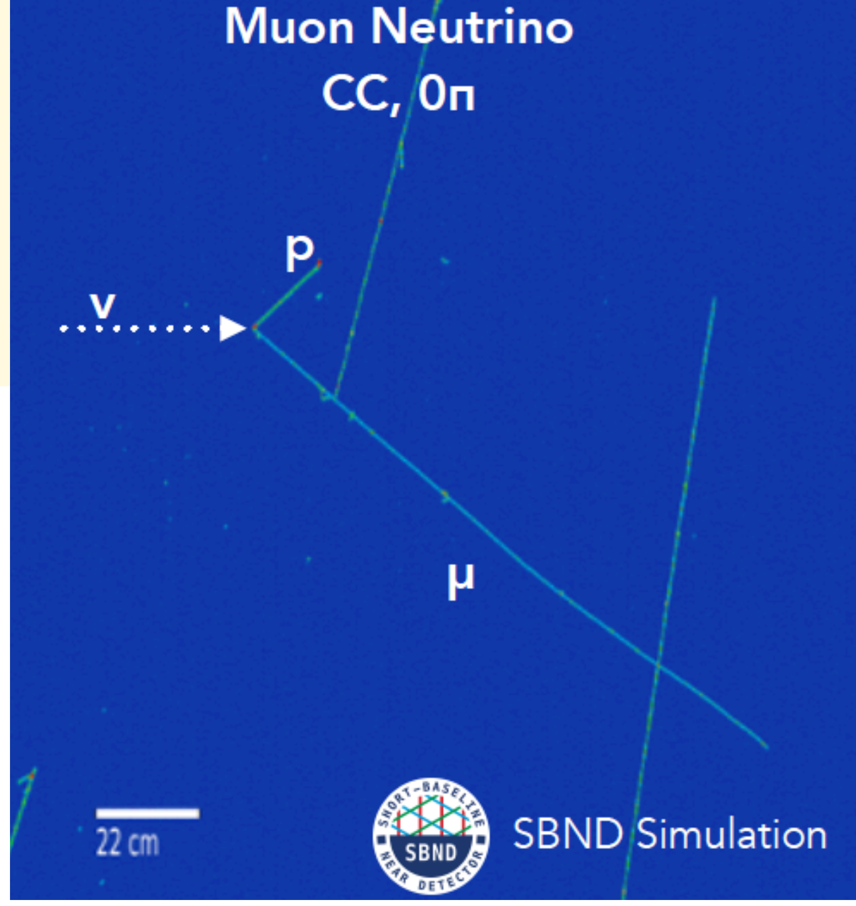


Detector assembly completed



Cryogenics installation in progress
Cold commissioning - Summer 2023

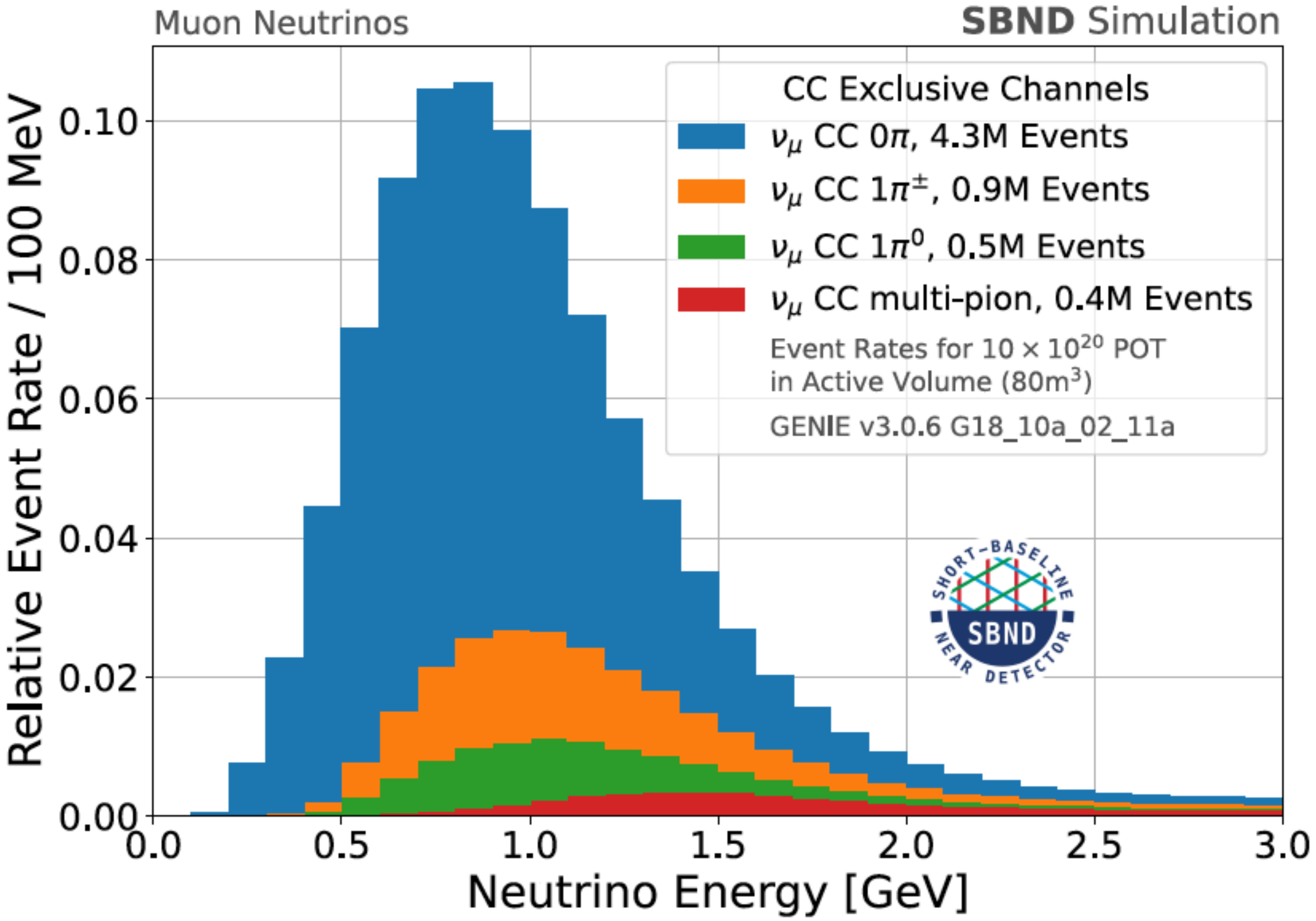
Neutrino Interactions in SBND

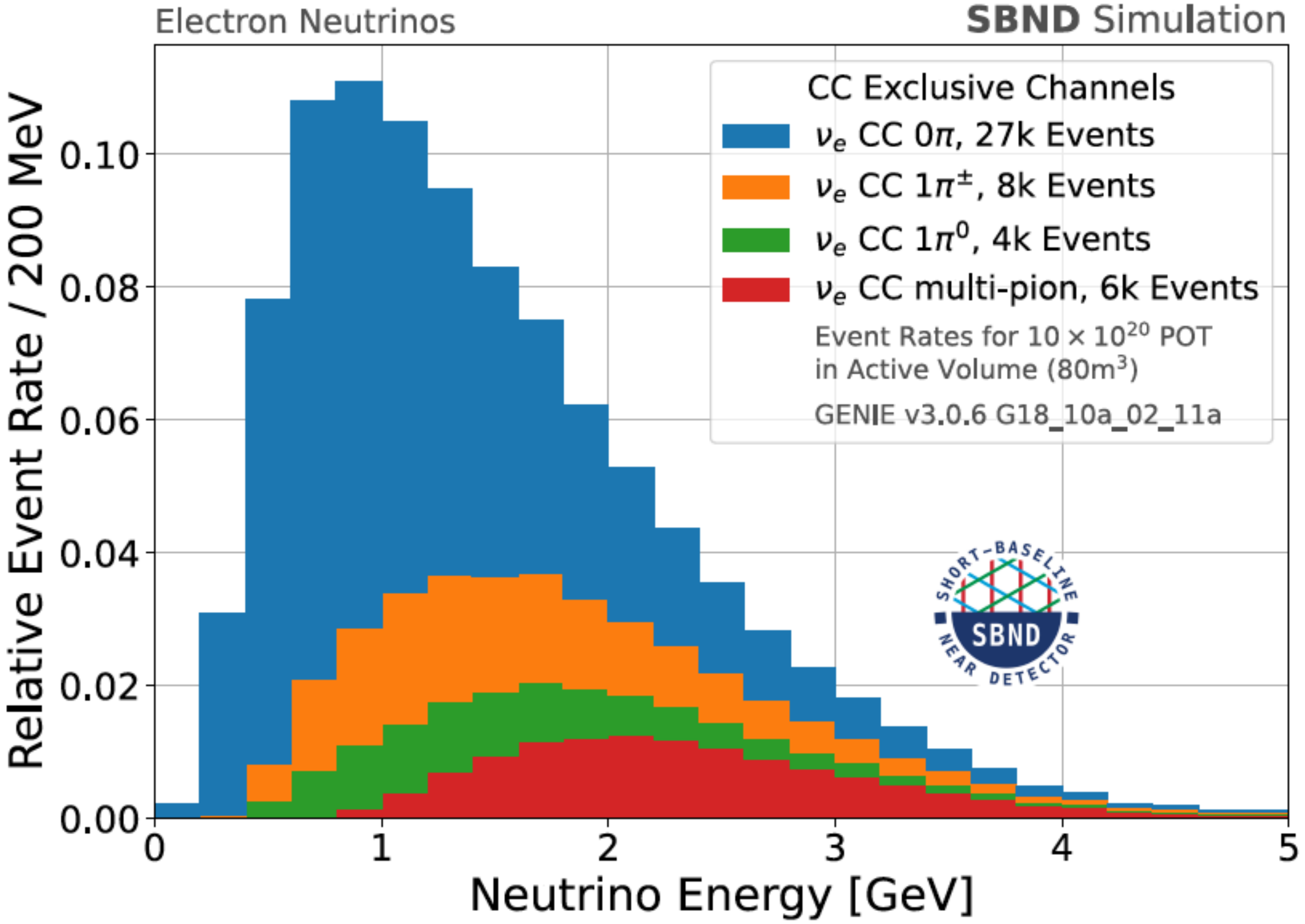


Precision Studies of ν -Ar interactions:

- *Unprecedented high event rate : **5000 ν events/per day** in SBND!*
- *Excellent reconstruction capabilities allowed by the LarTPC technology*

will enable a generational advance in the study of ν -Ar interactions in the GeV energy range.





SBND PRISM

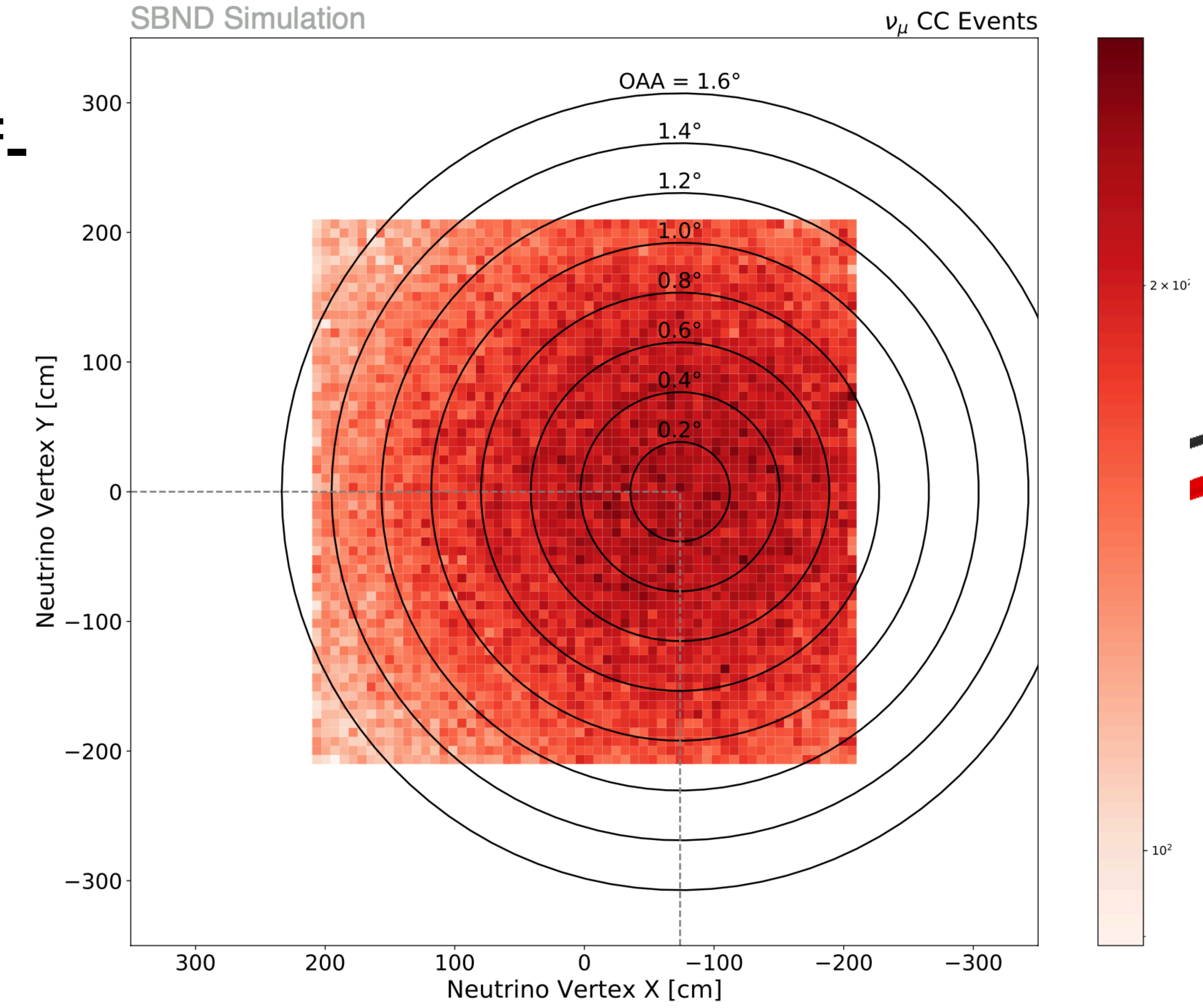
***P**recision **R**eaction **I**ndependent **S**pectrum **M**easurement*

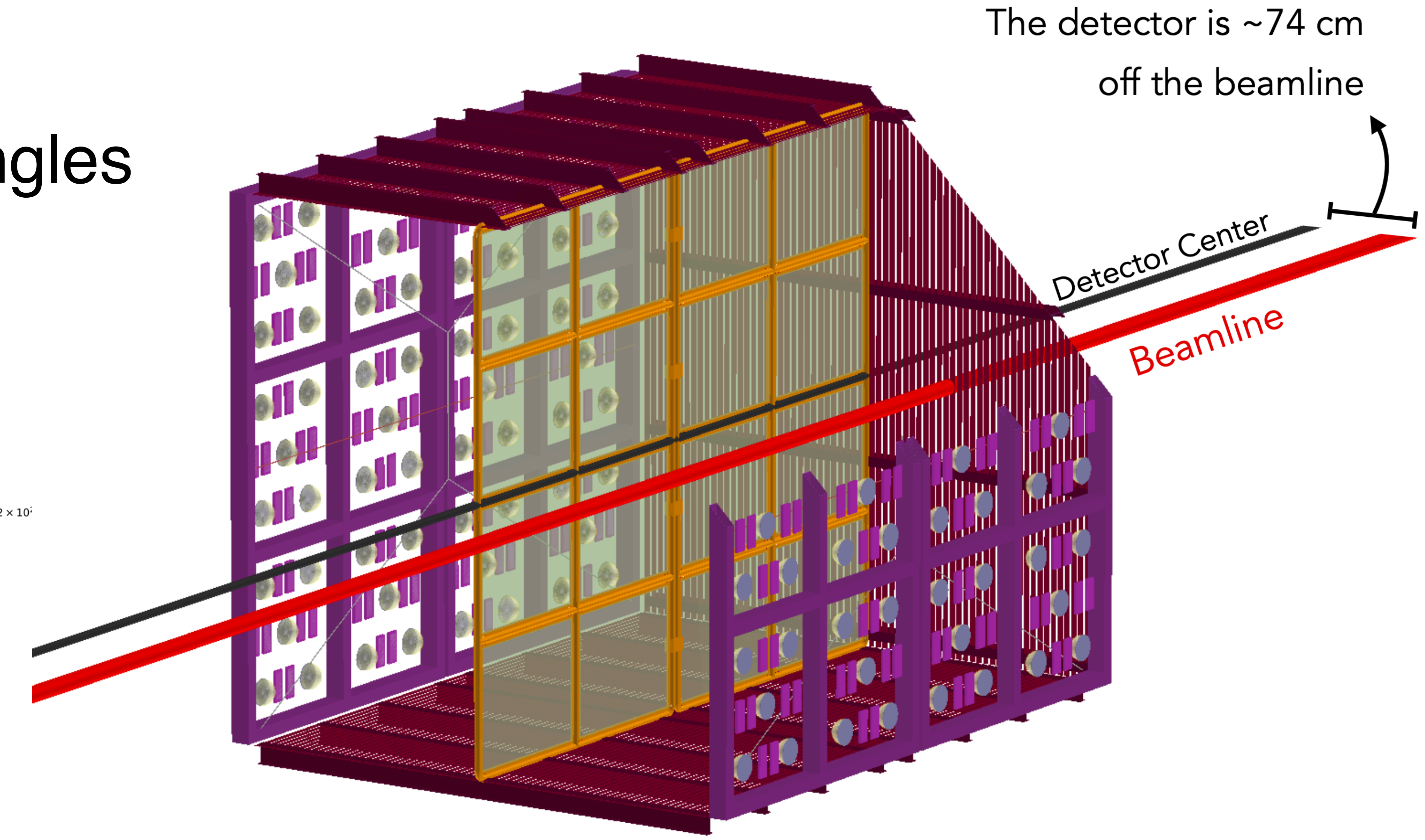
SBND detector is traversed by neutrinos coming from different angles with respect to the beam axis.

Concept: sampling multiple off-axis fluxes using a fixed single detector : SBND

SBND unique features:

- *Being close to the neutrino source (110 m)*
- *It is not perfectly aligned with the neutrino beamline*



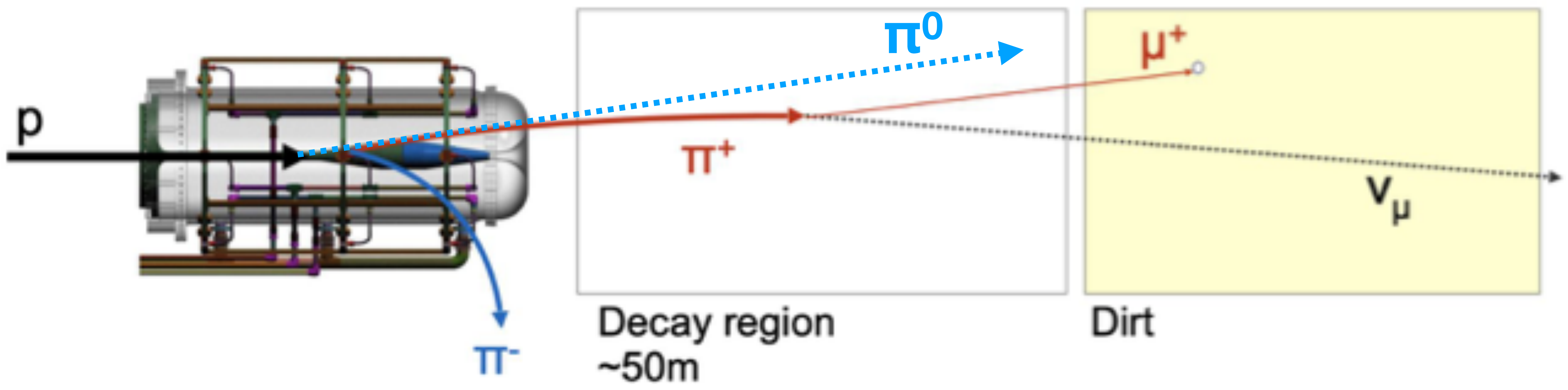


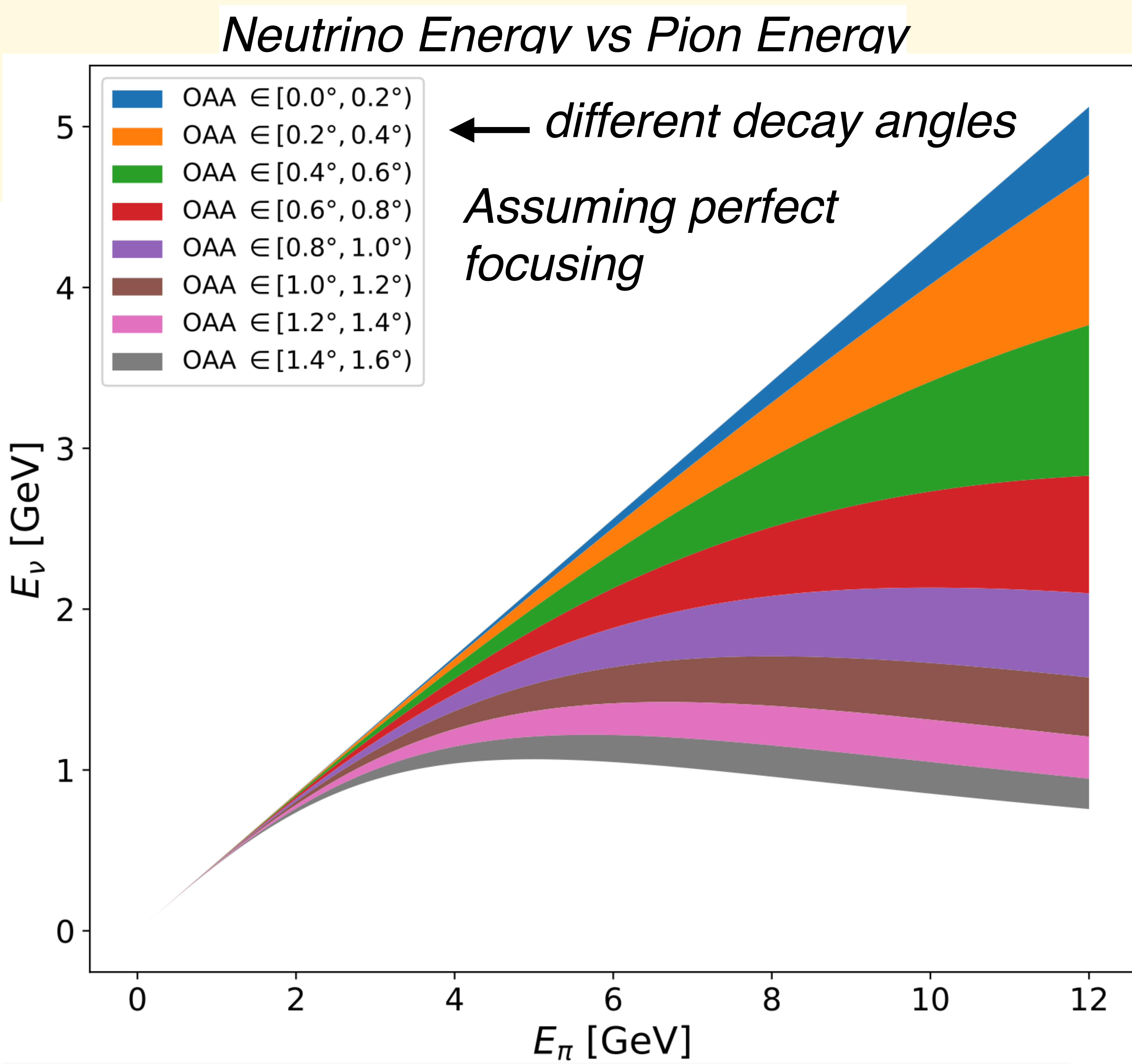
As reference:
DUNE: 1° ≈ 10 m
SBND: 1° ≈ 2 m

Original concept from nu-PRISM (T2K).

DUNE-PRISM and Hyper-K- IWCD are planned to perform measurements at different off-axis angles by moving the ND transverse to the neutrino beam

SBND PRISM





Charged mesons in the BNB are more focused

- produce SM neutrinos.

*The **muon neutrino** energy distributions are affected by the off-axis position.*

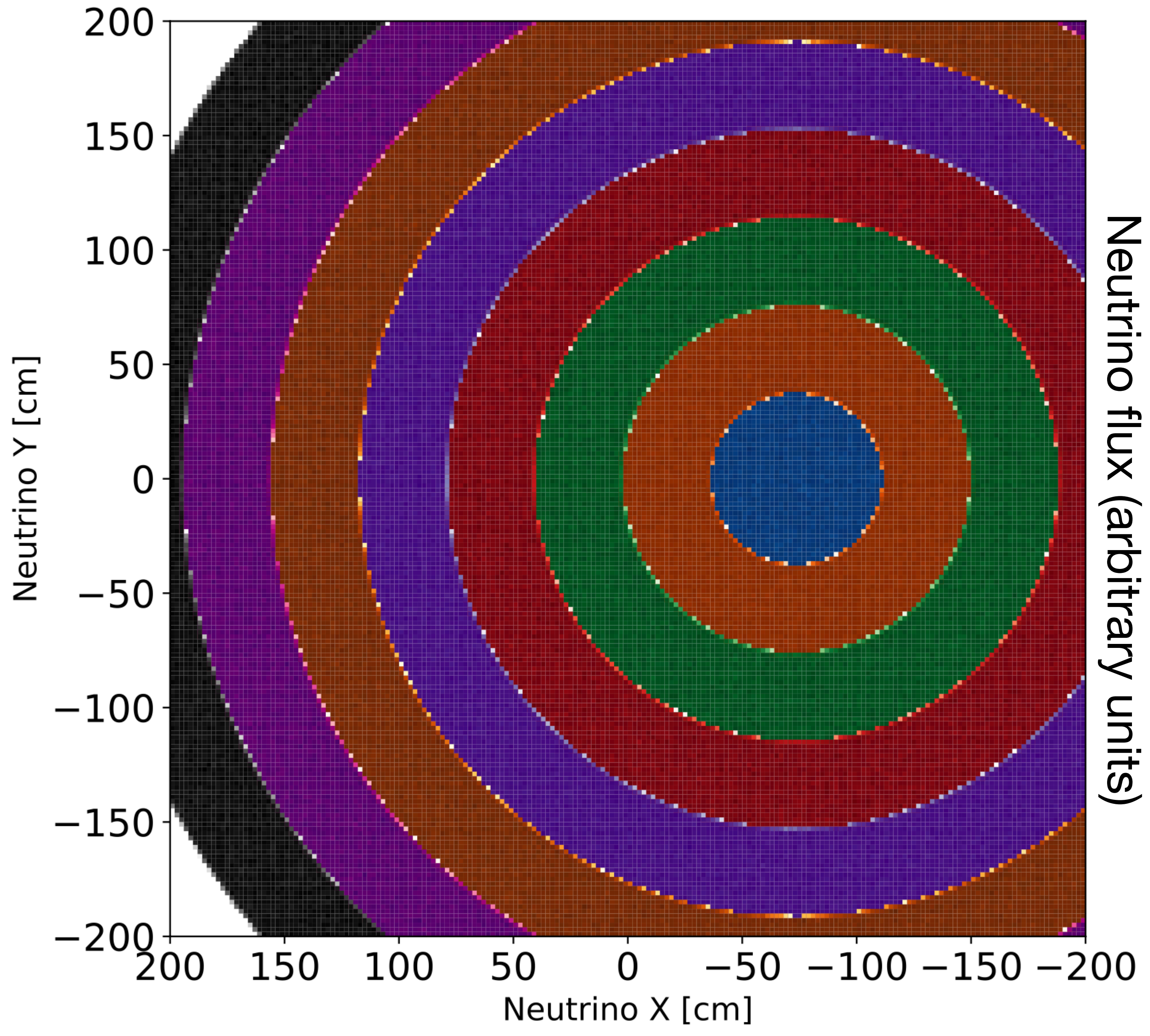
$$\pi^+ \rightarrow \nu_\mu + \mu^+$$
$$K^+ \rightarrow \nu_\mu + \mu^+$$

*The **electron neutrino** energy distributions also change, but they are less affected by off-axis position.*

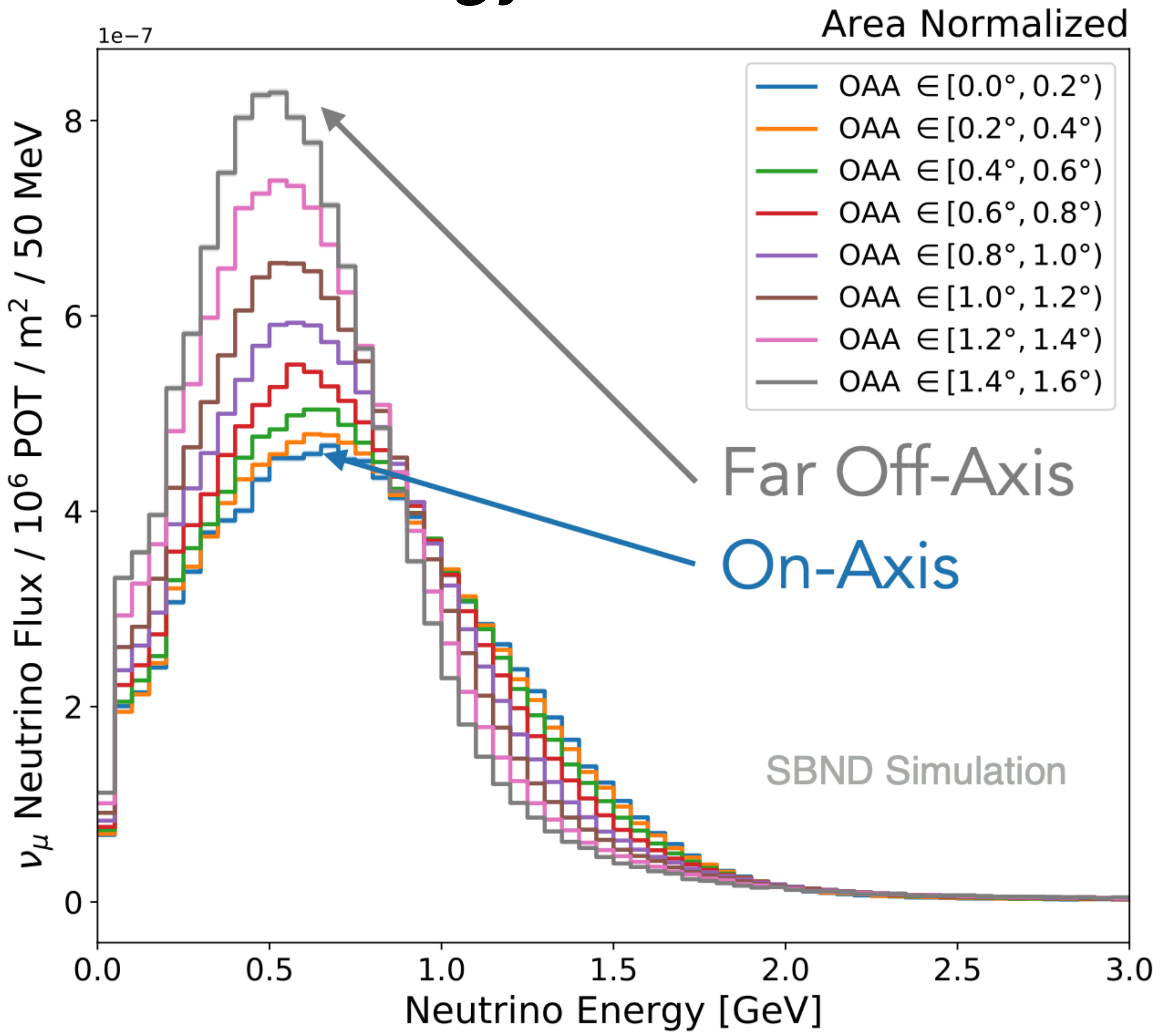
$$\mu^+ \rightarrow \nu_e + \bar{\nu}_\mu + e^+$$
$$K^+ \rightarrow \nu_e + e^+ + \pi^0$$
$$K_L^0 \rightarrow \nu_e + \pi^- + e^+$$

SBND PRISM

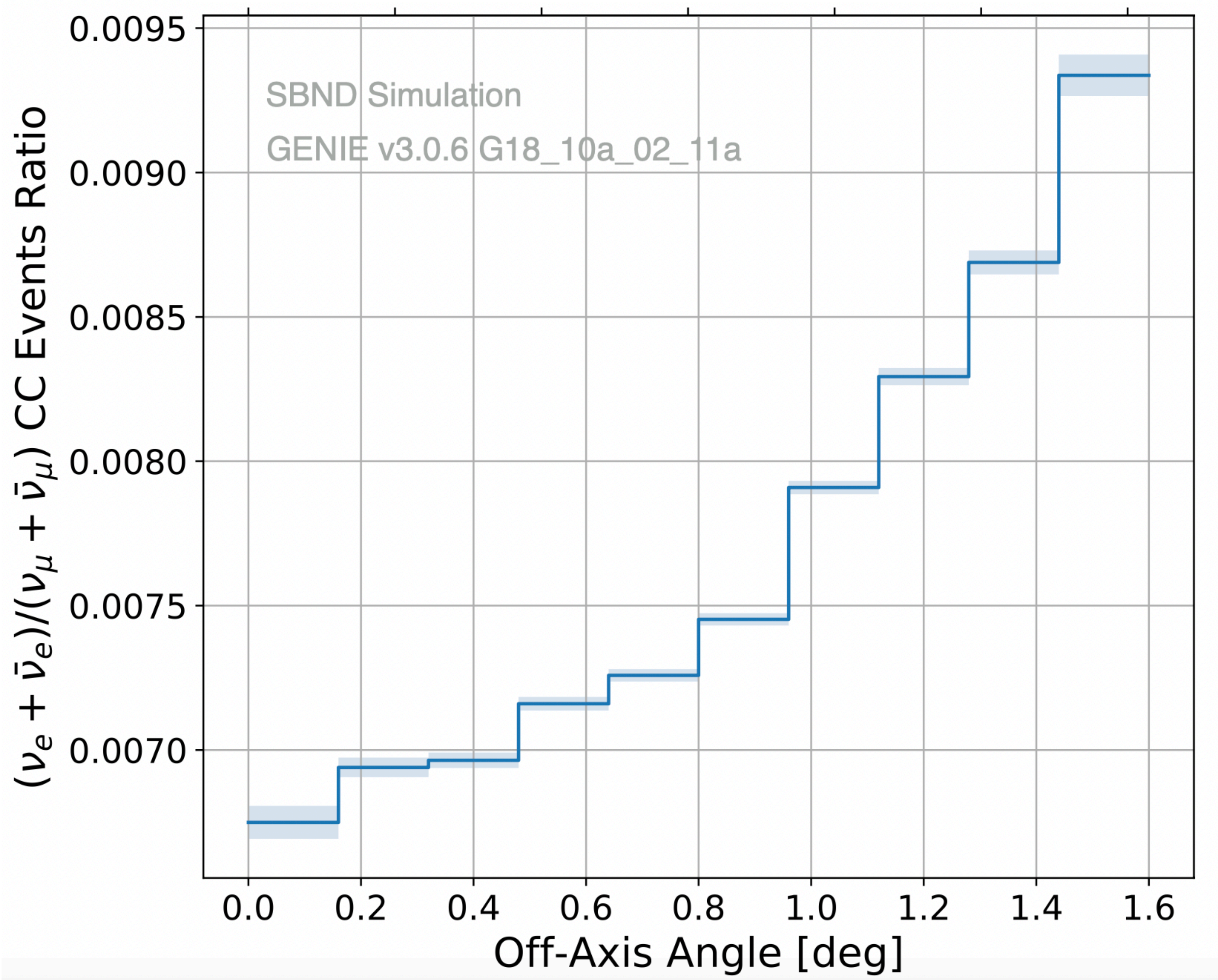
Slightly off-axis SBND allows to perform measurements with large off-axis angles



Larger off-axis angle produce narrower beams with lower mean energy



Going off-axis, ν_e/ν_μ the increases



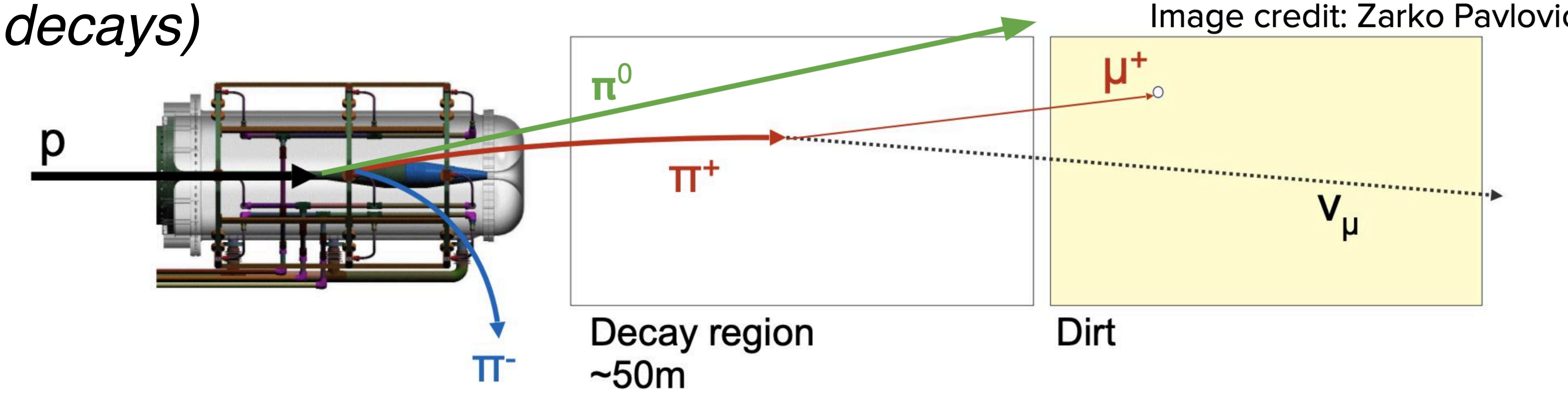
- SBND PRISM will allow improved the sensitivity on the sterile neutrino search and a better constraint of the neutrino flux and neutrino interaction cross sections
- ***It can be a very useful tool for the BSM program***

Production and Detection

» **Some DM particles are produced from neutral meson decay, mostly π^0 and η**

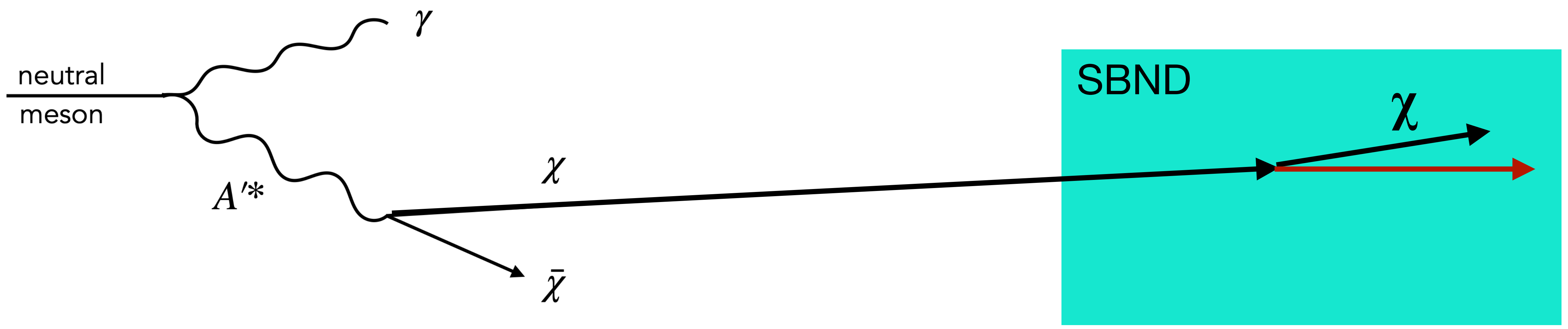
- *These particles are unfocused and their products* ***can span wider angles than the SM neutrinos*** *(from focused meson decays)*

Image credit: Zarko Pavlovic



» **Identifying a DM interaction have to handle the main background: neutrino interactions.**

- *The knowledge neutrino interactions is* ***limited by the models on the flux and the cross sections***



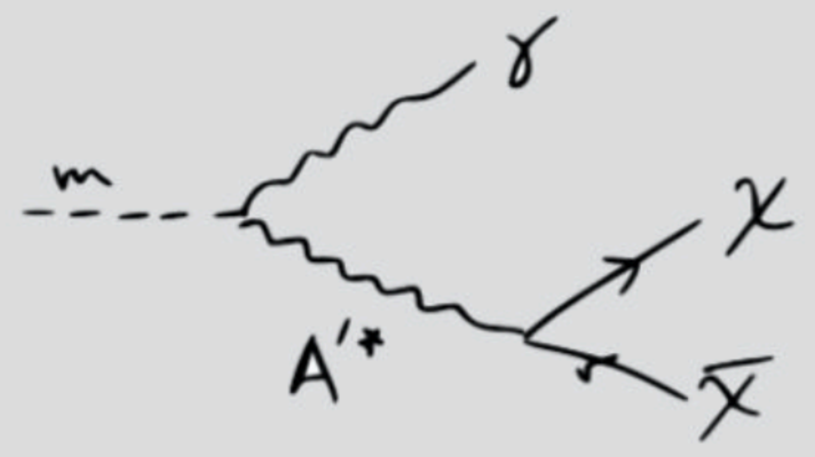
» **SBND PRISM is a key tool for BSM searches in SBND**

BSM Production in the BNB

A non-exhaustive list of BSM new physics produced in the BNB

It may provide alternative explanations of the MiniBooNE excess and other BSM scenarios

Light Dark Matter



Romeri Kelley Machado PRD 2019

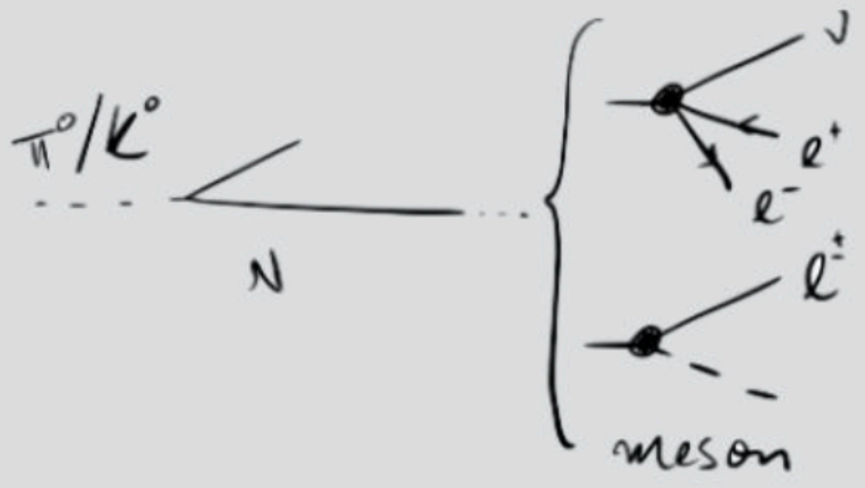
Dark Neutrinos

Bertuzzo Jana Machado Zukanovich PRL 2018, PLB 2019
Arguelles Hostert Tsai PRL 2019
Ballett Pascoli Ross-Lonergan PRD 2019
Ballet Hostert Pascoli PRD 2020

Millicharged Particles

Magill Plestid Pospelov Tsai PRL 2019
Harnik Liu Palamara JHEP 2019

Heavy Neutral Leptons

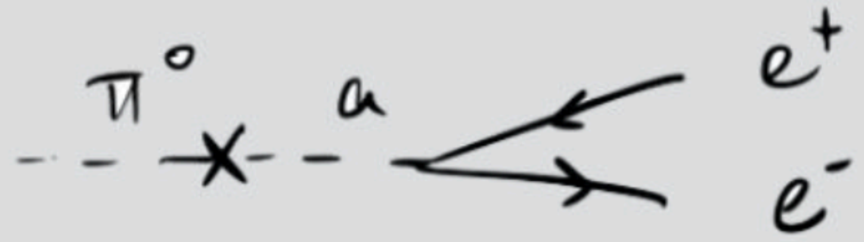


Ballett Pascoli Ross-Lonergan JHEP 2017
Kelly Machado PRD 2021

Higgs Portal Scalar

Pat Wilczek 2006
Batell Berger Ismail PRD 2019
MicroBooNE 2021

Axion-like Particles



Kelly Kumar Liu PRD 2021
Brdar et al PRL 2021

Signatures for New Physics in SBND

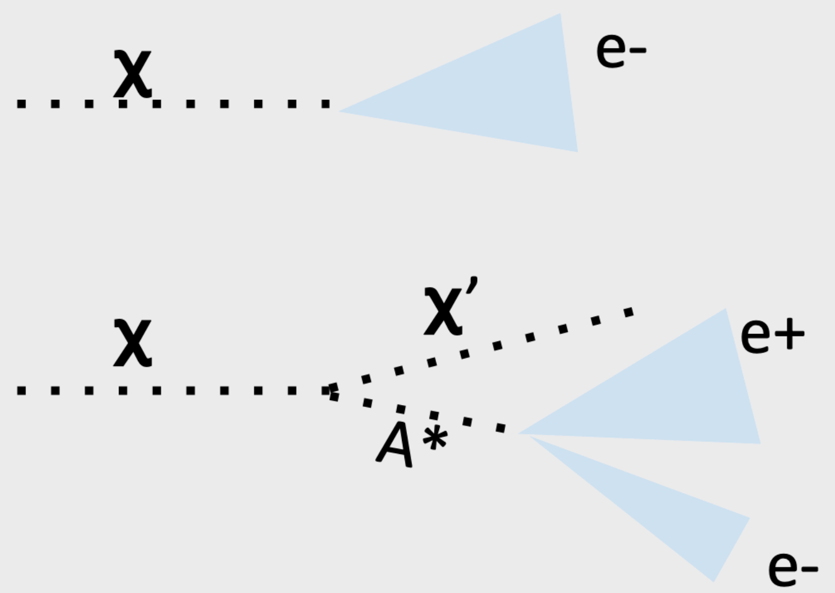
A non-exhaustive list of BSM new physics produced in the BNB

It may provide alternative explanations of the MiniBooNE excess and other BSM scenarios

Distinguishable final state experimental signature:

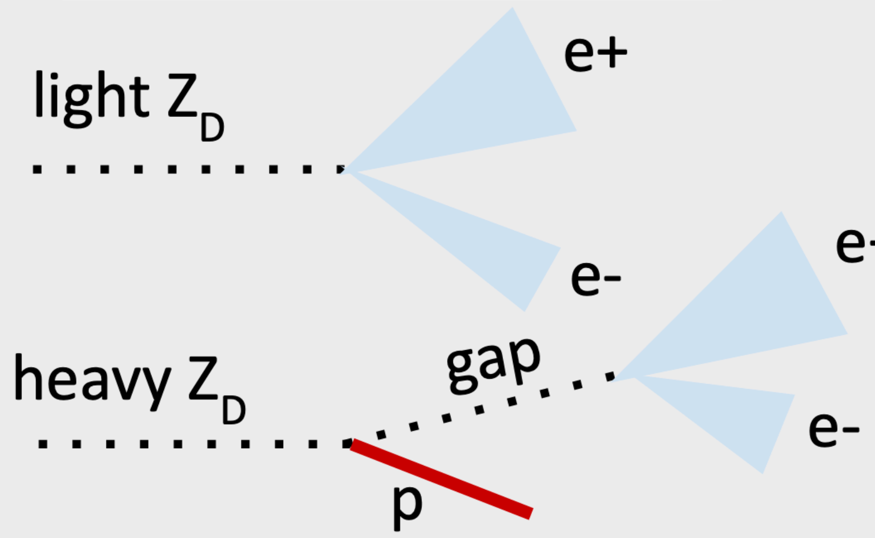
- single photon
- single electron
- “trident” with di-leptons overlapping and/or highly asymmetric
- different levels of hadronic activity

Light Dark Matter



electron scattering w/o hadronic activity

Dark Neutrinos

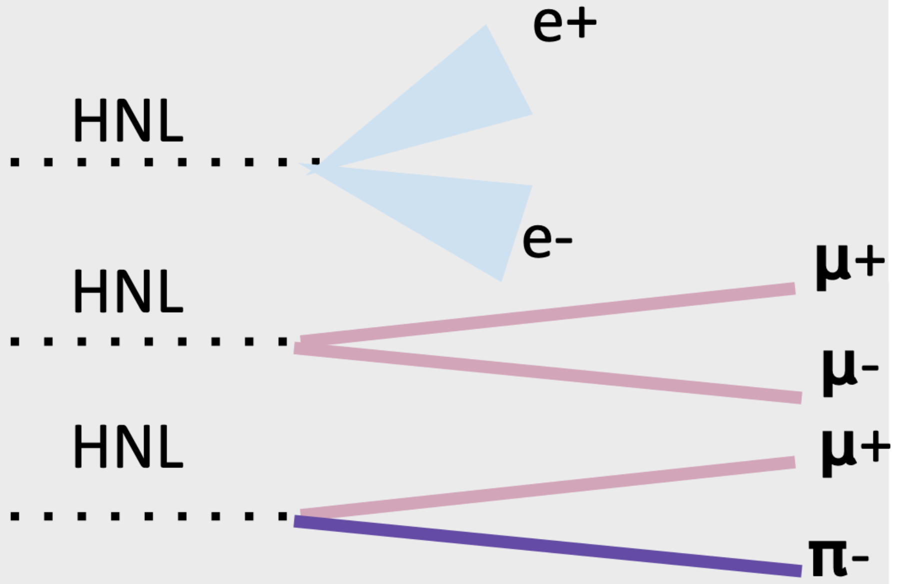


e^+e^- pair w/ or w/o hadronic activity

Millicharged Particles

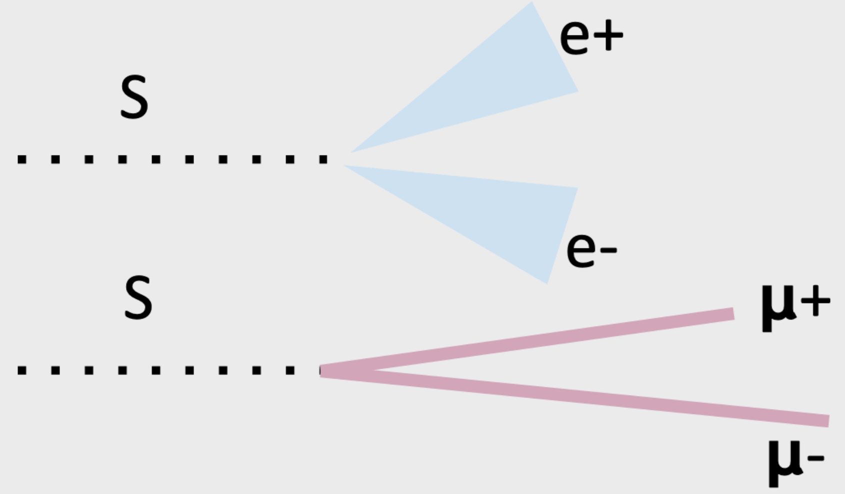
blips or faints tracks

Heavy Neutral Leptons



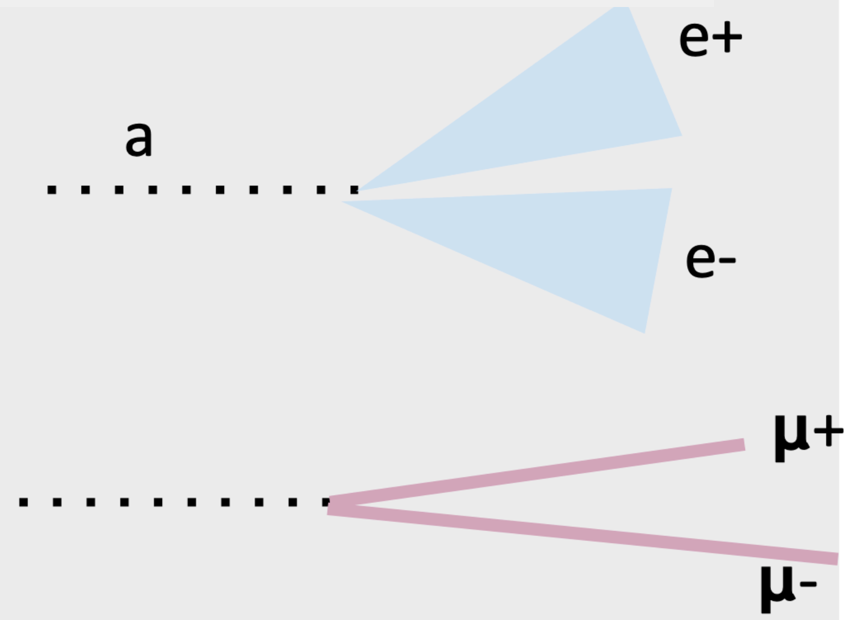
e^+e^-, $\mu^+\mu^-$, μπ w/o hadronic activity

Higgs Portal Scalar



e^+e^- or $\mu^+\mu^-$ w/o hadronic activity

Axion-like Particles



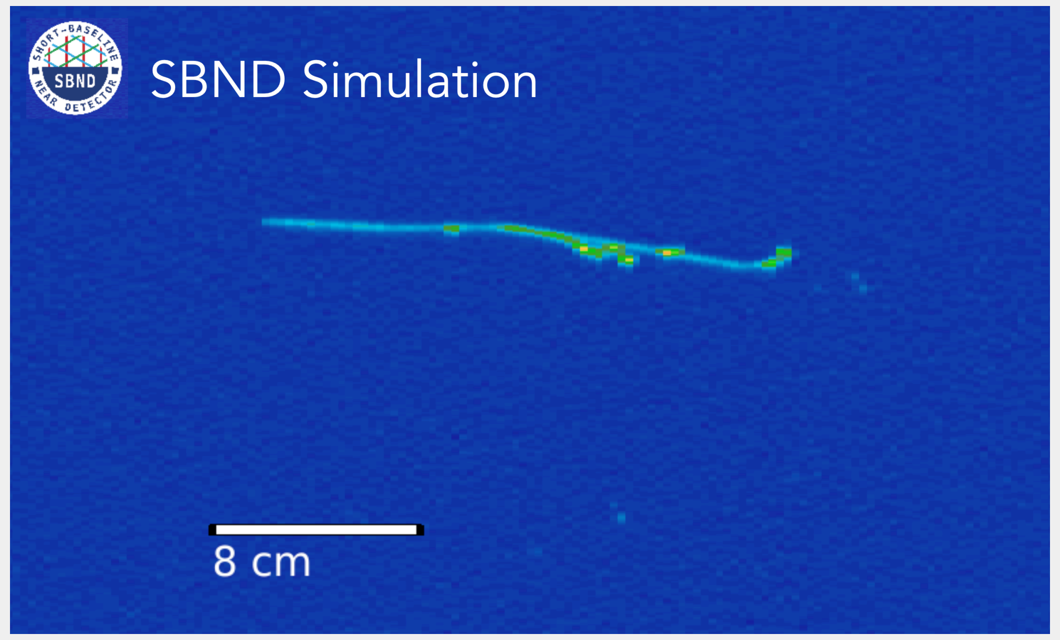
high-energy e^+e^- or $\mu^+\mu^-$ pair

Signatures for New Physics in SBND

Unique capabilities of the **LAr TPC technology**:

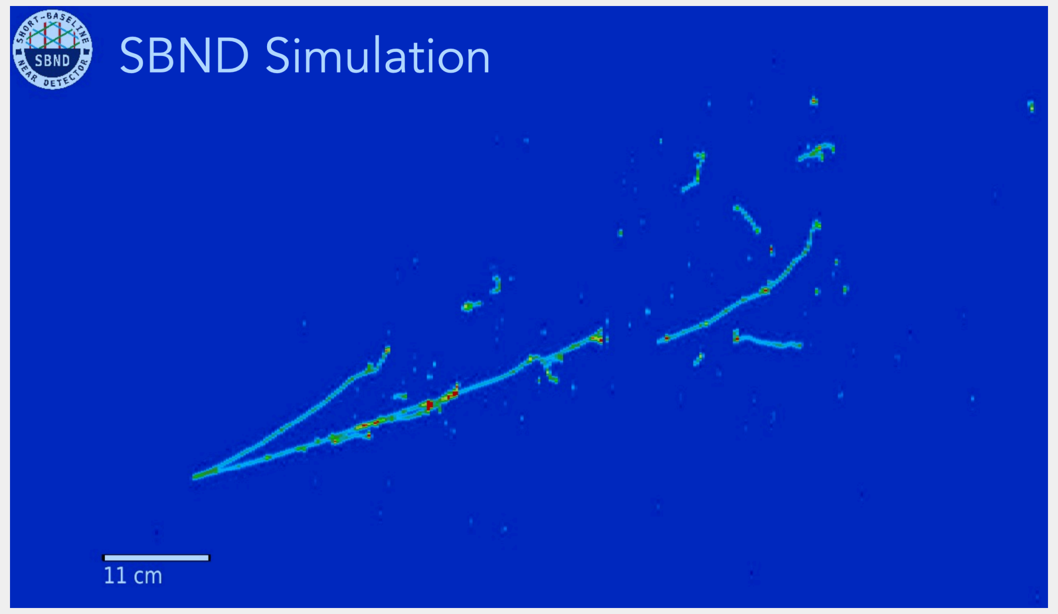
- **Better characterization of events:** identification of final state particle and reconstruction of their kinematics
- **Lower energy threshold** allows to recognize the presence of low hadronic activity

Light Dark Matter



electron scattering w/o hadronic activity

Dark Neutrinos

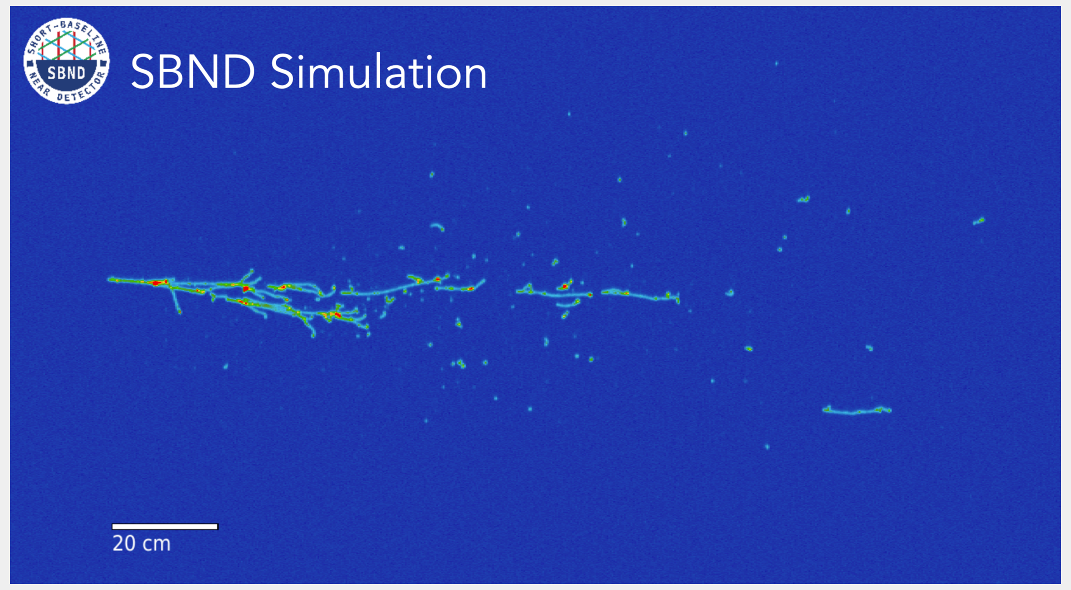


e^+e^- pair w/ or w/o hadronic activity

Millicharged Particles

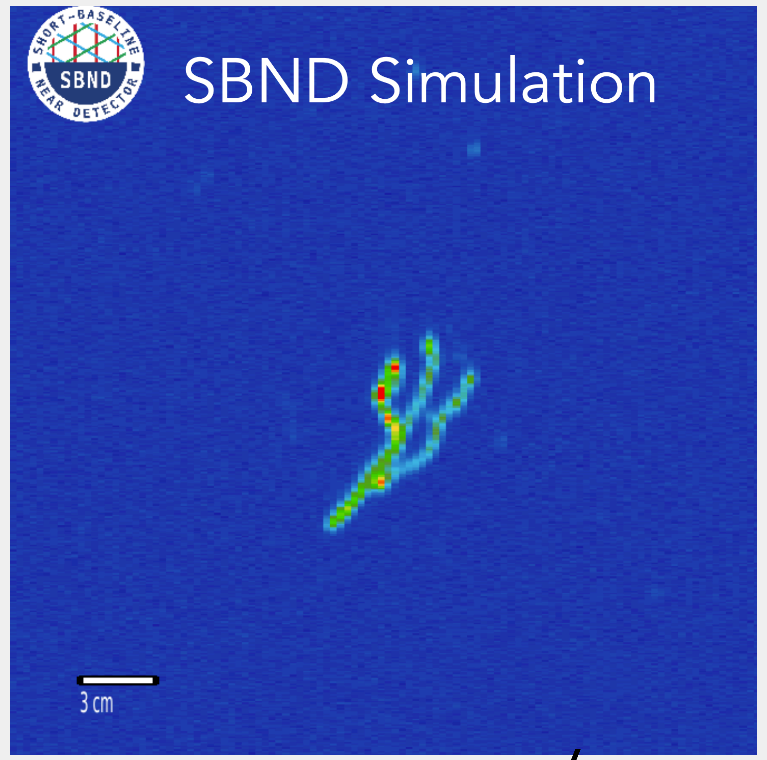
blips or faints tracks

Heavy Neutral Leptons



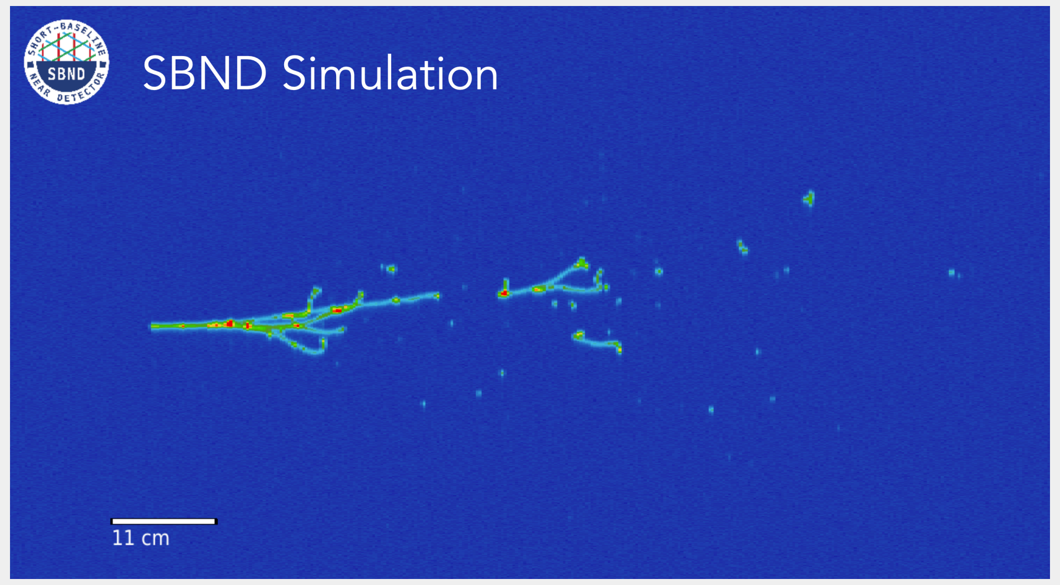
e^+e^-, $\mu^+\mu^-$, $\mu\pi$ w/o hadronic activity

Higgs Portal Scalar



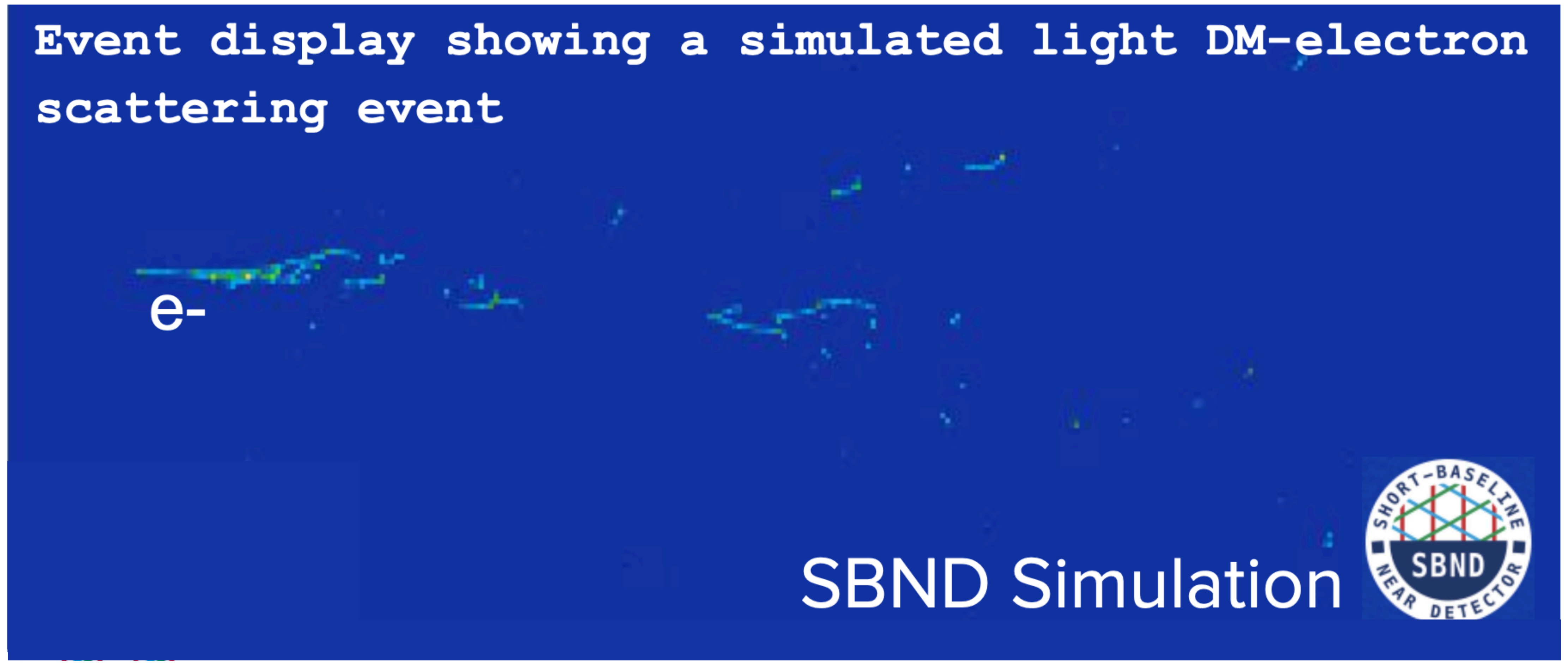
e^+e^- or $\mu^+\mu^-$ w/o hadronic activity

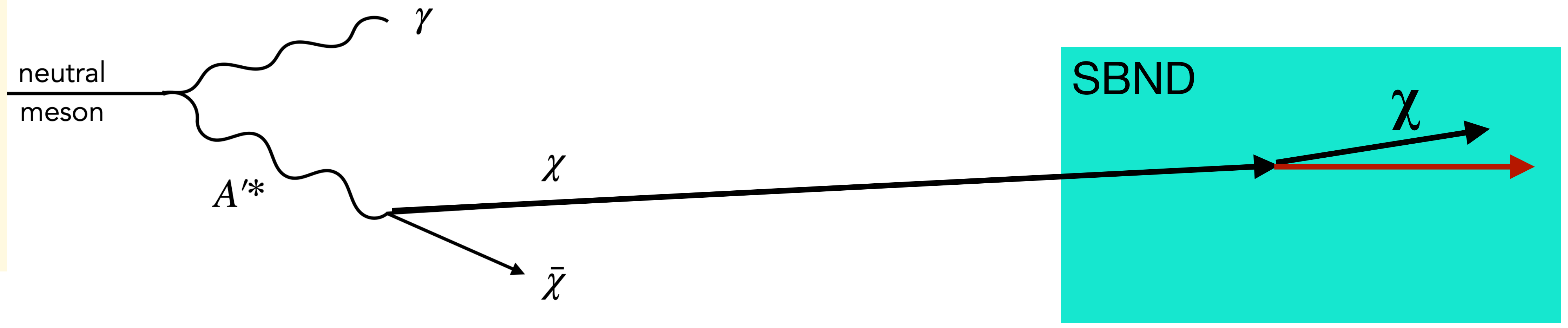
Axion-like Particles



high-energy e^+e^- or $\mu^+\mu^-$ pair

Light Dark Matter-e-





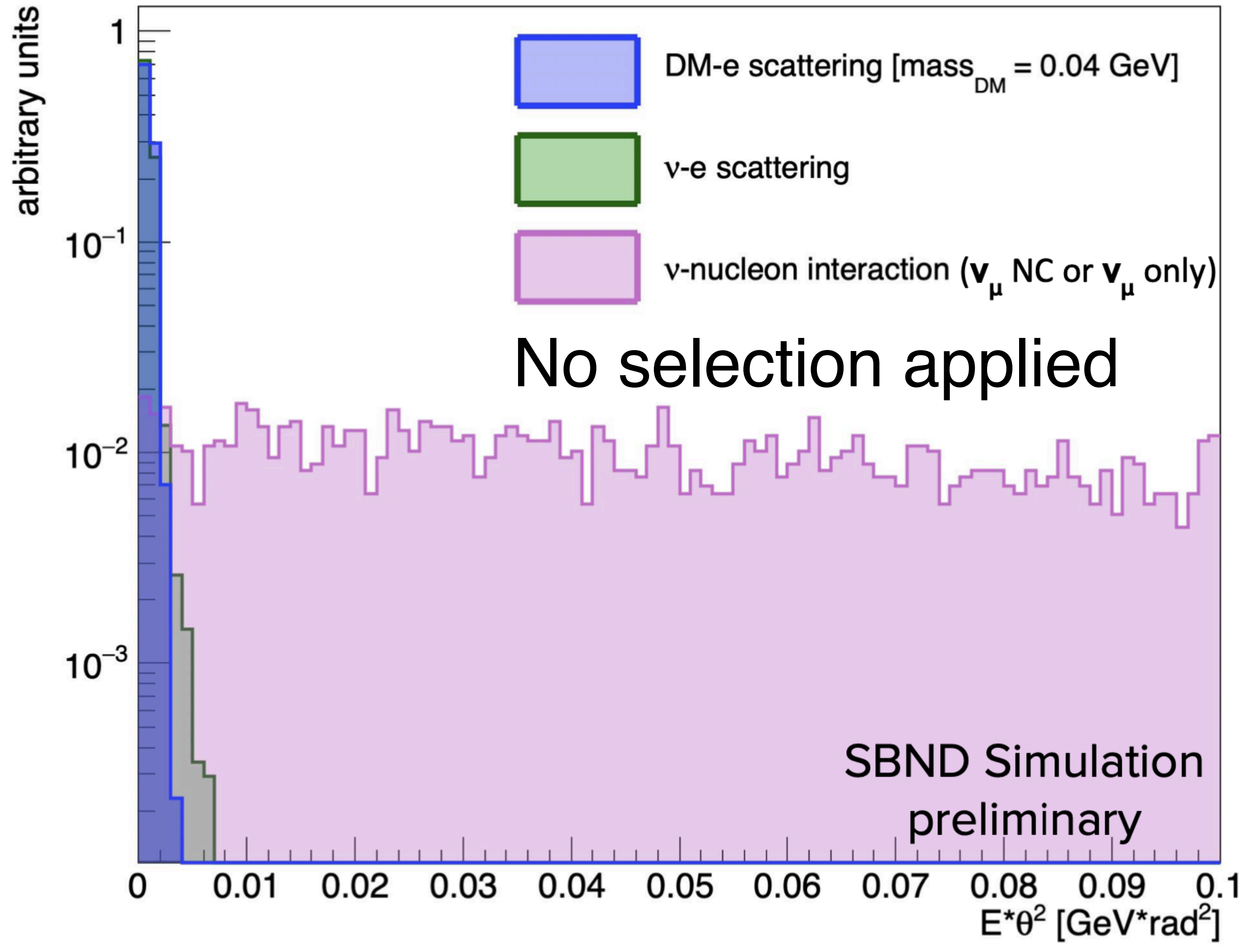
LDM produced by π^0 and η^0 decay

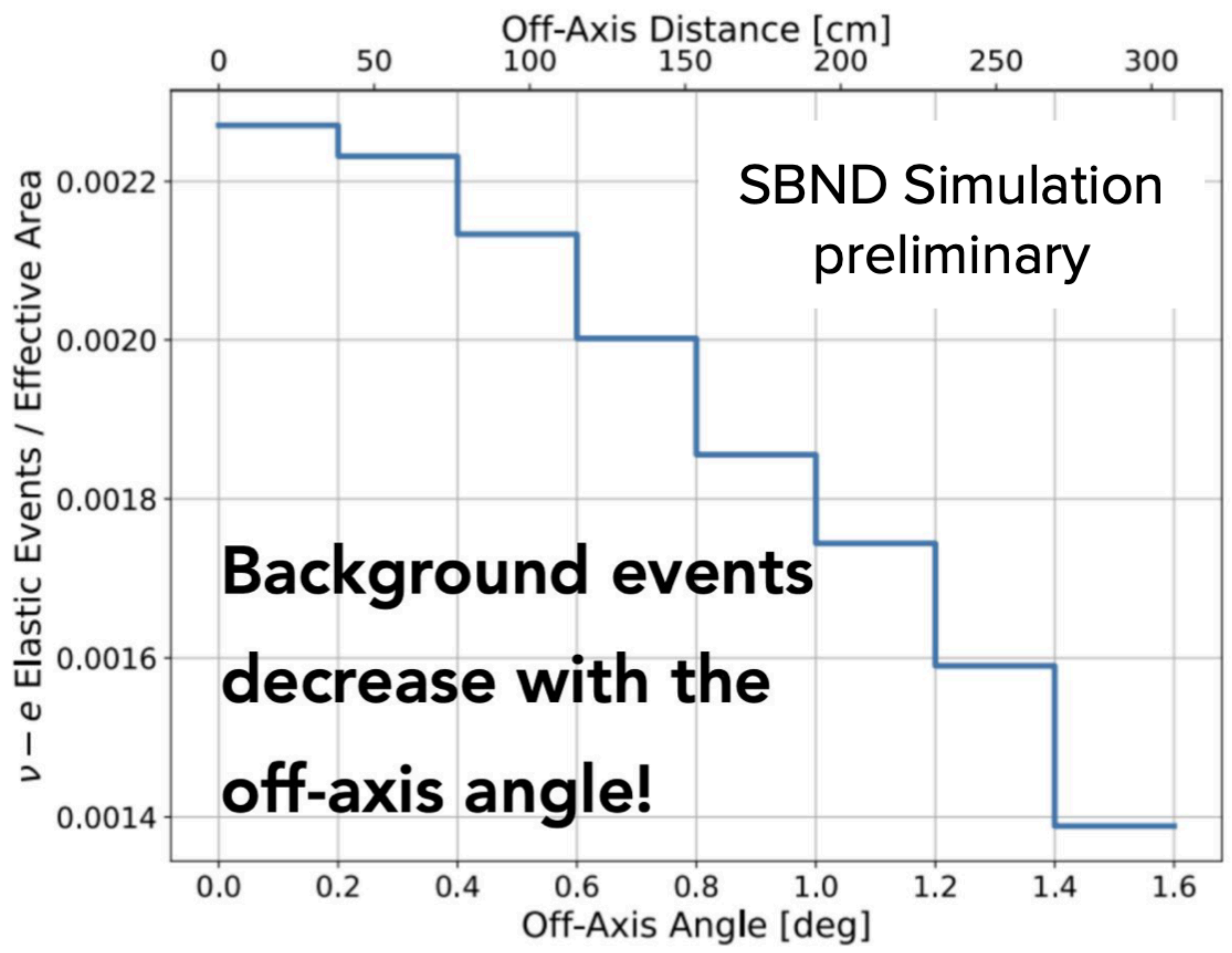
Signature: a single highly forward-going electron with no other hadronic activity.

Backgrounds: ***ν***-e scattering and ***ν***-nucleon NC interactions

SBND is working to develop:

- *An **improved low-energy electron shower** reconstruction*
- *An **improved proton identification** and **cosmic ray rejection***
- ***SBND PRISM to reduce ν-electron scattering backgrounds***

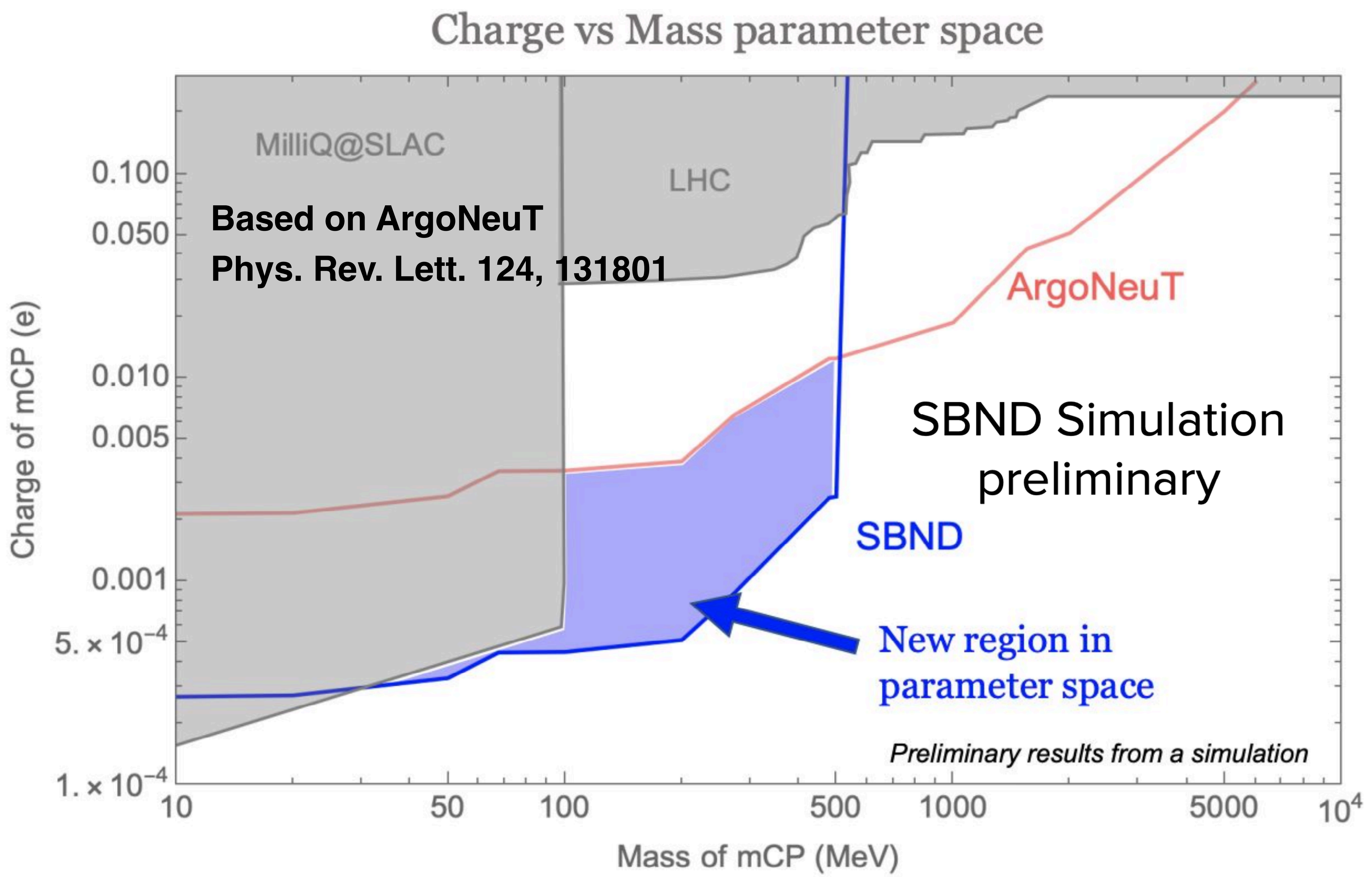




Millicharged particles

Hypothesized particles with fractional electronic charge, motivated by a cosmological anomaly (EDGES).

Could be a constituent of Dark Matter. Produced by neutral meson decay in the BNB.



They would appear as blips or faint tracks pointing back to the target in SBND.

Projected SBND threshold: 50 keV [MicroBooNE threshold: 100 keV]

See tomorrow's Ornella's talk on BSM searches at ArgoNeuT

Conclusions

» The neutrino experiments at few-GeV neutrino energy present an opportunity to efficiently probe the parameter space of proposing Dark Sector/Hidden sector models and BSM physics in general

» Previous experiences such as at MiniBooNE, ArgoNeuT and MicroBooNE demonstrate that these analyses are possible

» SBN experiments are actively working on these analysis

Grays' previous talk was focused at ICARUS

Yung Tse's tomorrow's talk on BSM at SBN focused at MicroBooNE

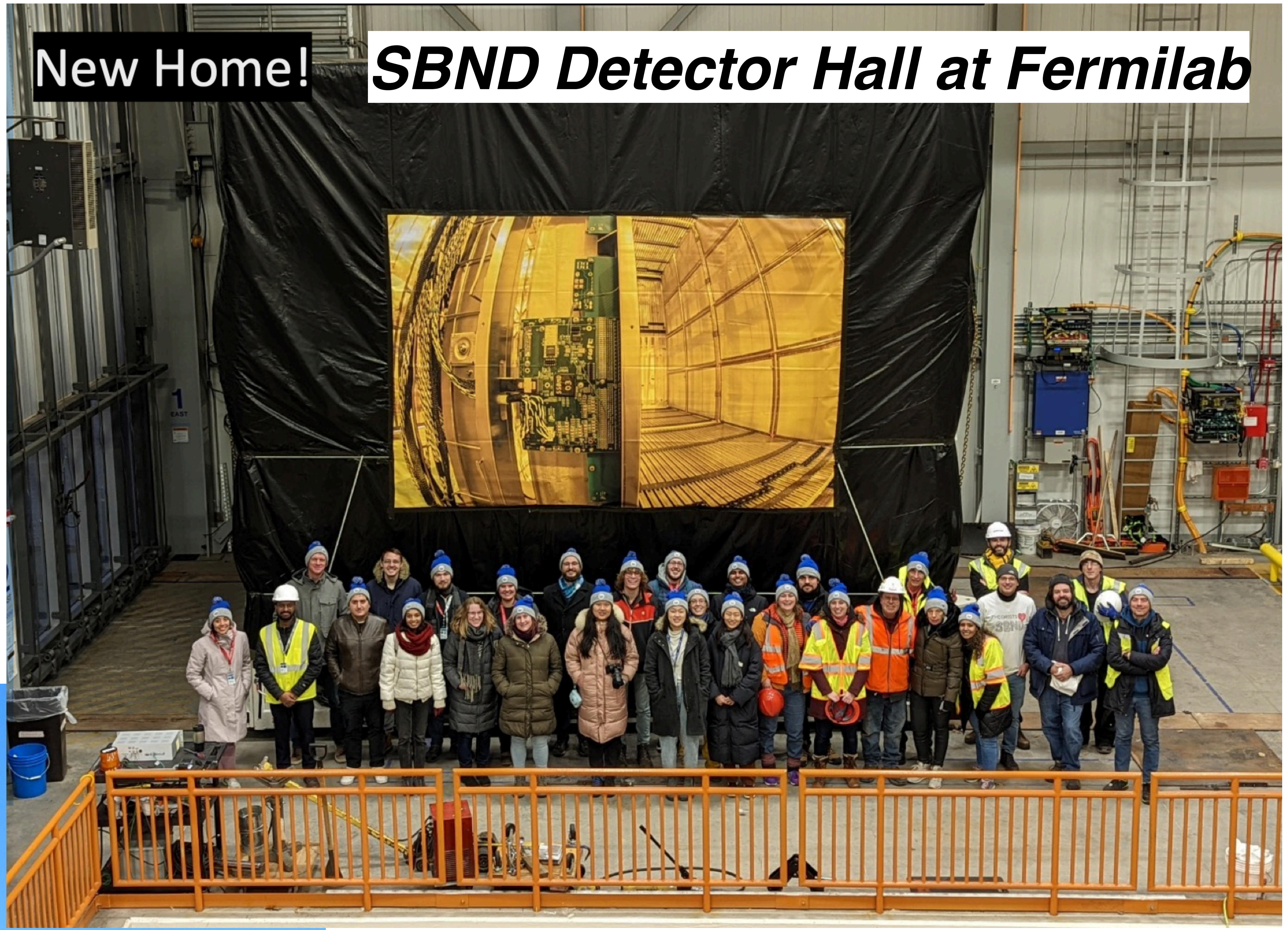
» **The SBND experiment will also carry out precision searches for new physics in neutrinos**

- and untangling the physics of neutrino-nucleus scattering at the GeV energy scale

» Some of these new physics searches could explain short-baseline anomalies by modifying the neutrino oscillation paradigm

Collaboration between experimentalists and theoreticians is key for these searches

We recently completed the installation of the Photon Detection System in the SBND TPC and moved the detector from D0 to the final location:



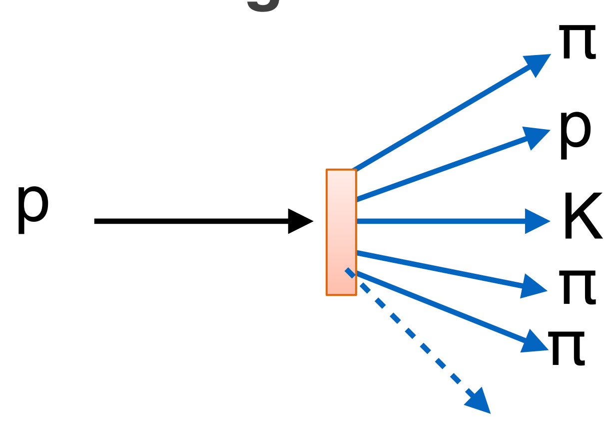
Thank you!

Backup

External Data of for NuMI Flux Prediction

- Hadron production data at the relevant energies for NuMI:

Thin Target Data



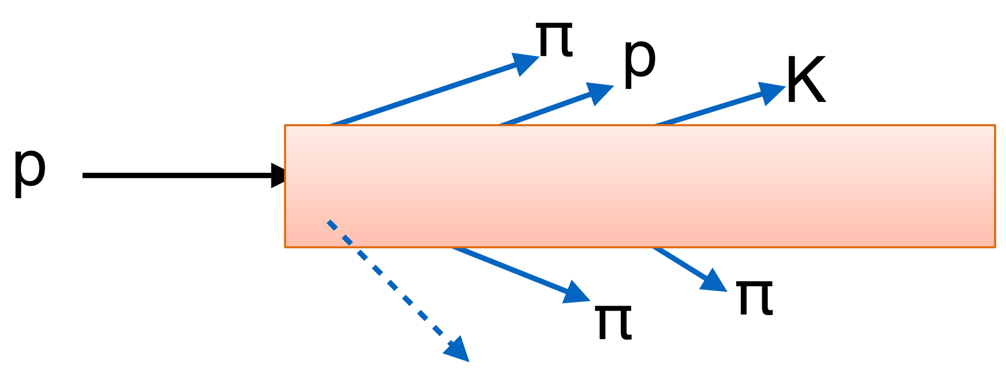
Inelastic/absoption cross section

- Belletinni, Denisov, etc. of p-C, π-C, π-Al etc. at different energies.
- NA61 and NA49 p-C at 31 and 158 GeV.

Hadron production

- NA49 π, K, p (x_F, p_T dependence) and n (x_F dependence) production @ 158 GeV and Barton π @100 GeV.
- NA61 π @ 31 GeV is used to validate scaling from NA49.
- MIPP π/K from pC @ 120 GeV for $P_Z > 20$ GeV.

Thick Target Data



MIPP: proton on a LE NuMI spare target @ 120 GeV

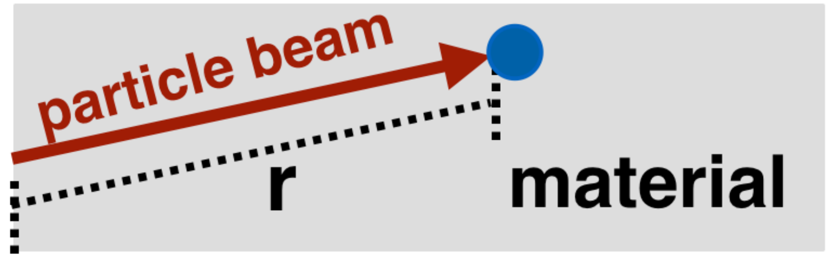
- π production up to 80 GeV/c.
- K/π for $P_Z > 20$ GeV/c.

We use this data to correct FTFP_BERT in geant4.9.2.p03.

How do We Use the Data to Correct the Models?

Two corrections are applied (data/MC):

1. Beam attenuation



interacting

$$correction(r) = \frac{\sigma_{Data}}{\sigma_{MC}} e^{-r\frac{N_A \rho (\sigma_{Data} - \sigma_{MC})}{A}}$$

N_A: Avogadro Number, ρ: density, A: mass number

2 scenarios, depending if the particle intact or passes without interacting in the volume

without interacting

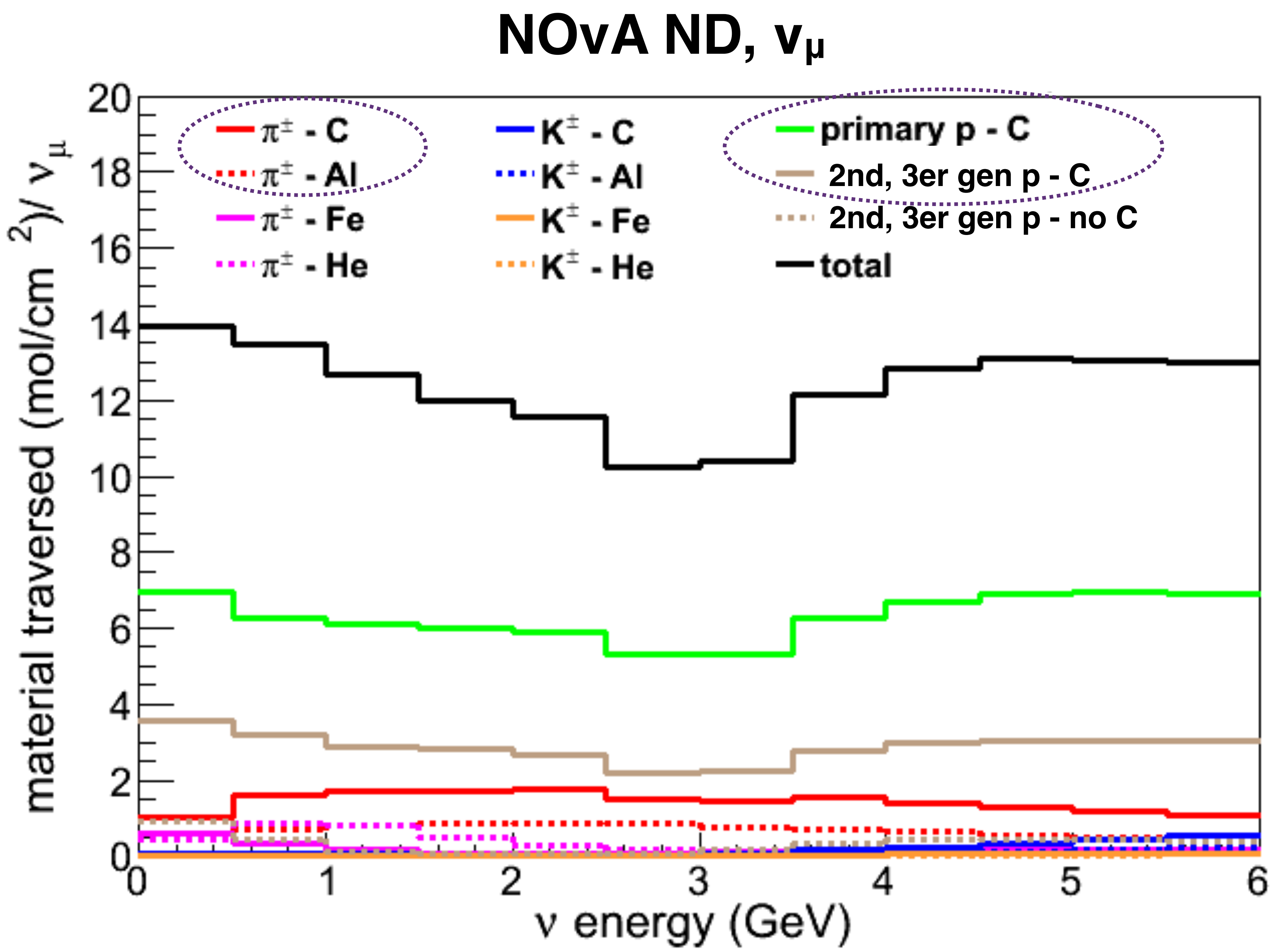
$$correction(r) = e^{-r\frac{N_A \rho (\sigma_{Data} - \sigma_{MC})}{A}}$$

Two variables are important here:

- The amount of material: $\mathbf{rN_A\rho/A}$ **.**
- The $\boldsymbol{\sigma_{Data}}$ and $\boldsymbol{\sigma_{MC}}$ disagreement .

Amount of Material Traversed

- Muon neutrino parent:

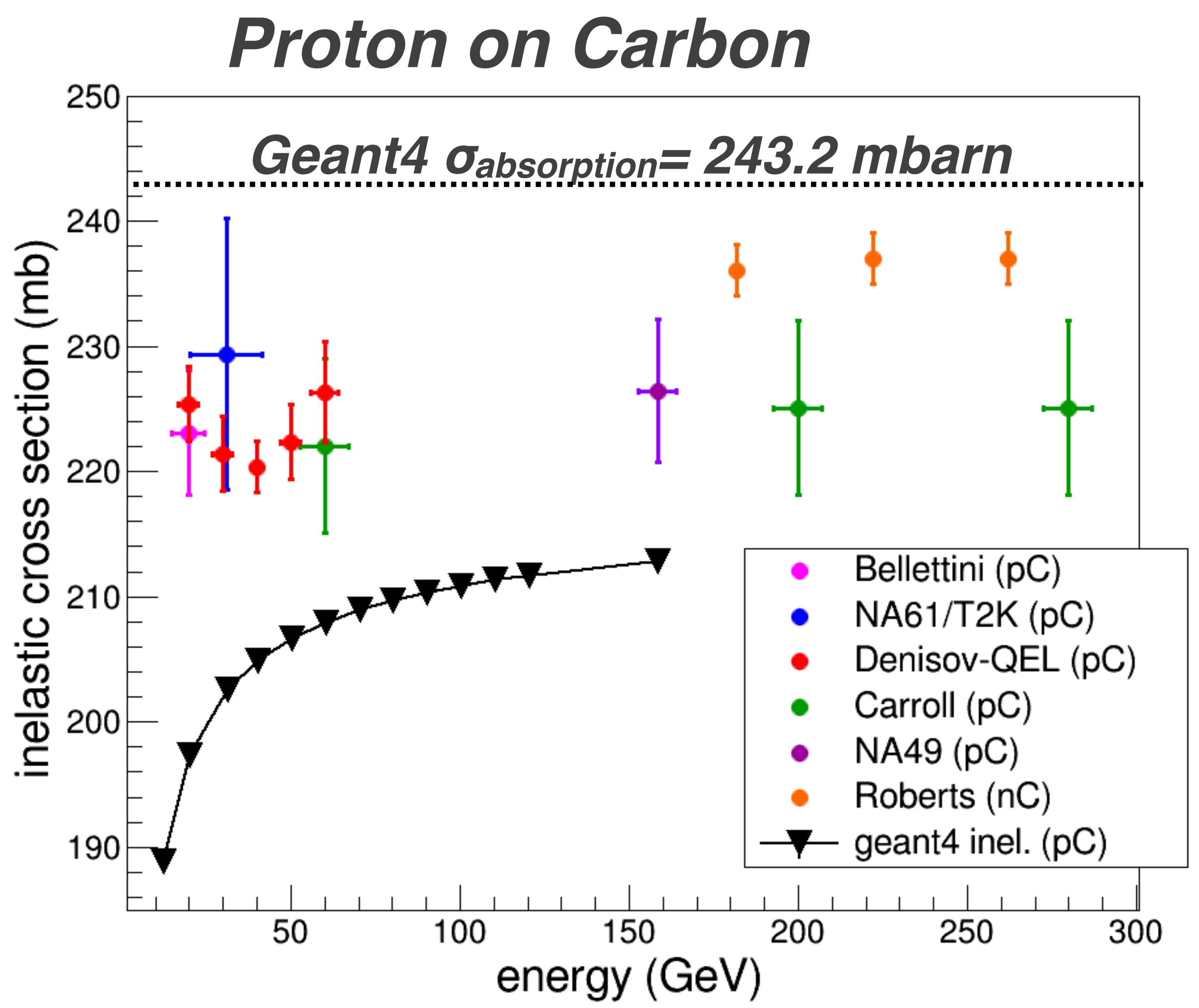


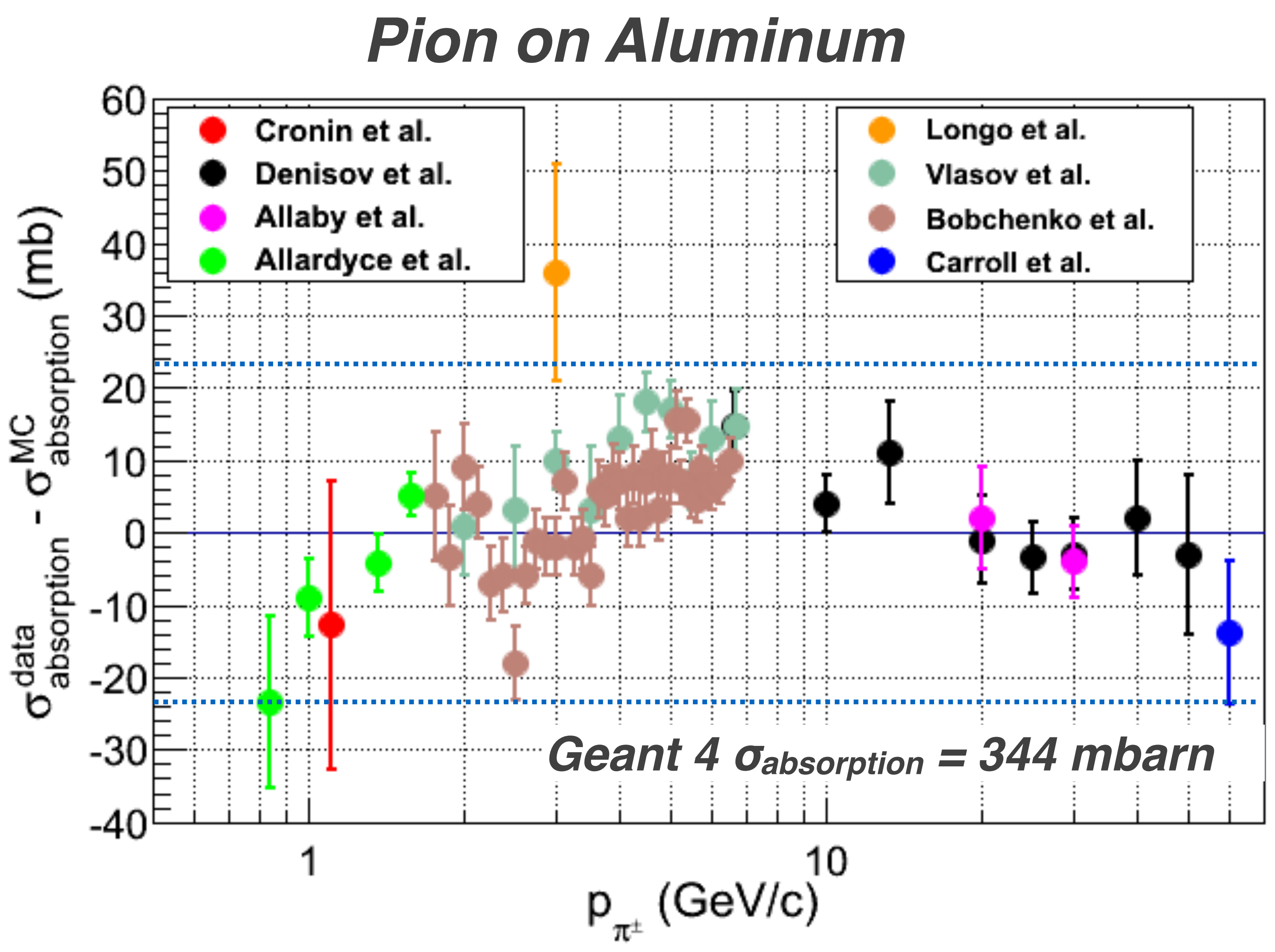
References:

- ***C: 6 mol/cm² ≈ 40 cm***
- ***Al: 1 mol/cm² ≈ 10 cm***
- ***He: 1 mol/cm² ≈ 500 m***

Data - MC Comparison

- Inelastic cross section
- Absorption cross section





We apply 23.8 mb uncertainty (~6.9%)

$$\sigma_{total} = \sigma_{elastic} + \underbrace{\sigma_{inelastic} + \sigma_{quasi-elastic}}_{\sigma_{absorption}}$$

How do We Use the Data to Correct the Models?

2. Hadron production.

For thin target data (NA49 for instance):

$$correction(x_F, p_T, E) = \frac{f_{Data}(x_F, p_T, E = 158GeV) \times scale(x_F, p_T, E)}{f_{MC}(x_F, p_T, E)}$$

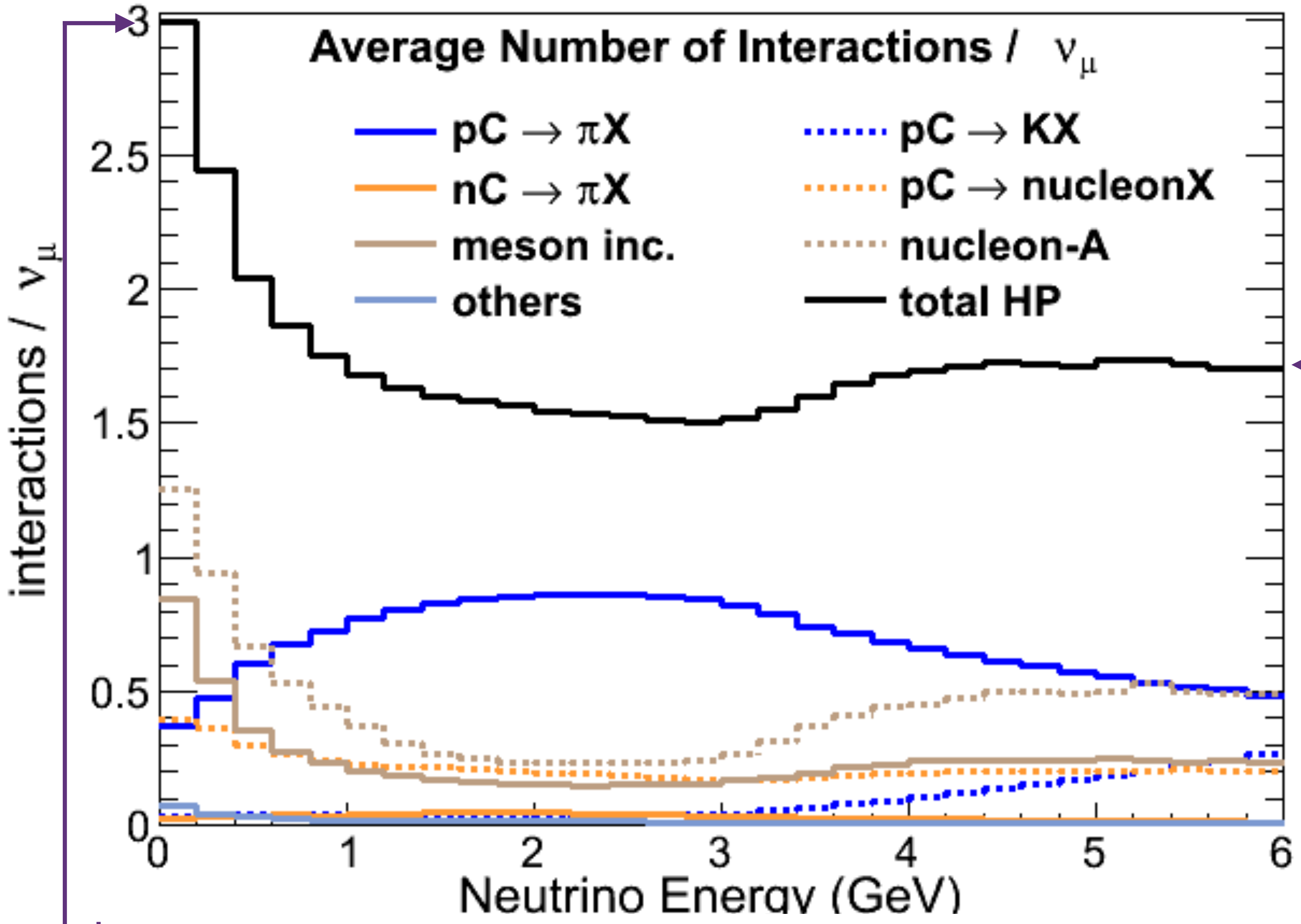
(**$f = Ed^3\sigma/dp^3$**: invariant production cross section)

- The **scale** allows us to use NA49 for proton on carbon in 12-120 GeV (calculated with FLUKA).
- It was checked by comparing with NA61 at 31 GeV.

Average Number of Interactions

Current NuMI prediction used in NOvA is based on thin target data

NOvA ND, ν_μ



~3.0 for low E_ν and ~1.5-1.6 for the rest

*π, **K** and **nucleons** productions from **pC** based on data (mainly NA49).*

We assume large uncertainties for meson incident: 40%

- **nucleon-A** (quasi-elastics, extension from carbon to other materials, production outside data coverage, etc).

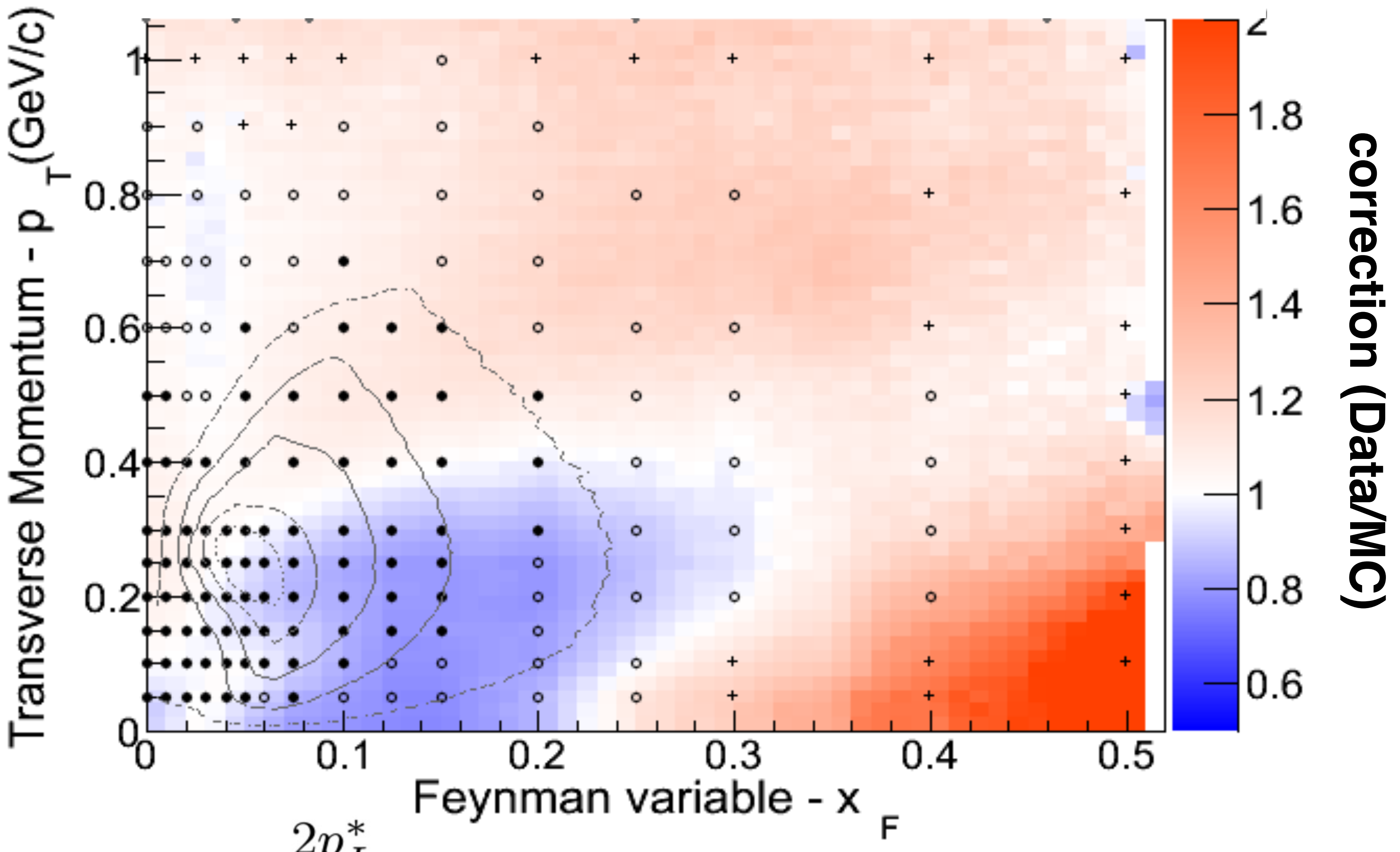
Example: NA49 Data/MC comparison (closed circles = statistical error < 2.5%, Open circles = statistical error 2.5-5.0%, Crosses > 5%).

NOvA ND, ν_μ

Contours: 2.5, 10, 25, 50 and 75 % of the pion yields.

- Systematics are highly correlated bin-to-bin (assumed 100%).

pC -> π⁺X



$$x_F = \frac{2p_L^*}{\sqrt{s}}$$

Systematic uncertainties = 3.8% (added in quadrature).