

SIGNATURES FOR NEW PHYSICS IN SHORT-BASELINE LIQUID ARGON NEUTRINO EXPERIMENTS

ASPEN WINTER CONFERENCE
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FERMILAB & YALE UNIVERSITY

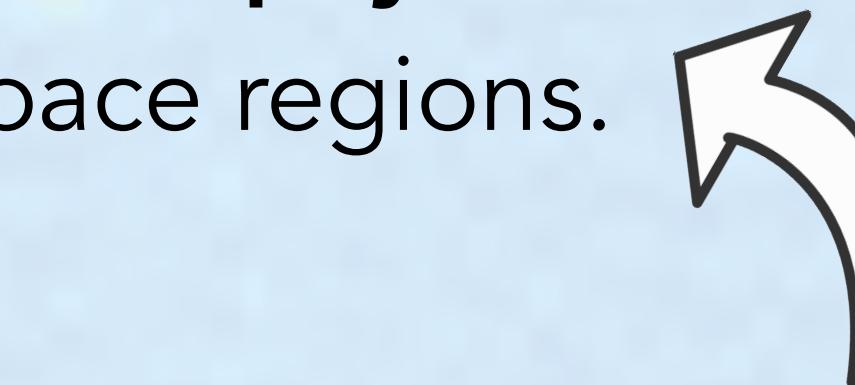
OUTLINE

Why Short-Baseline Neutrino Experiments?

Why Liquid Argon Neutrino Detectors?

Short-Baseline Neutrino program: **eV-scale sterile neutrinos & other BSM explorations.**

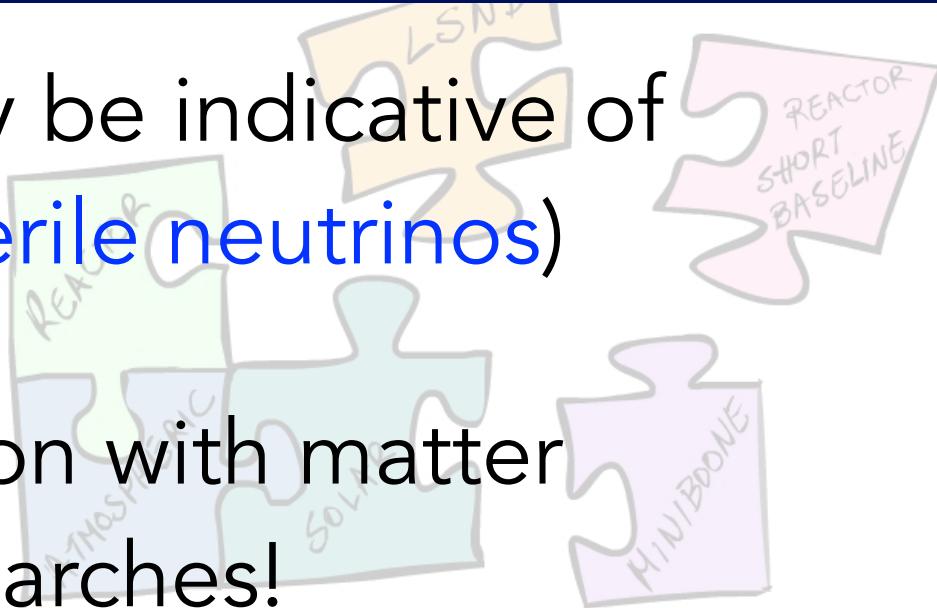
ArgoNeuT: constraints on **new physics** in unexplored parameter space regions.



Joint Experiment+Theory projects

WHY SHORT-BASELINE* NEUTRINO EXPERIMENTS?

Mainly - Various hints of anomalous electron-flavour appearance and disappearance may be indicative of new neutrinos participating in oscillations (beyond three-neutrino mixing, eV-scale sterile neutrinos)

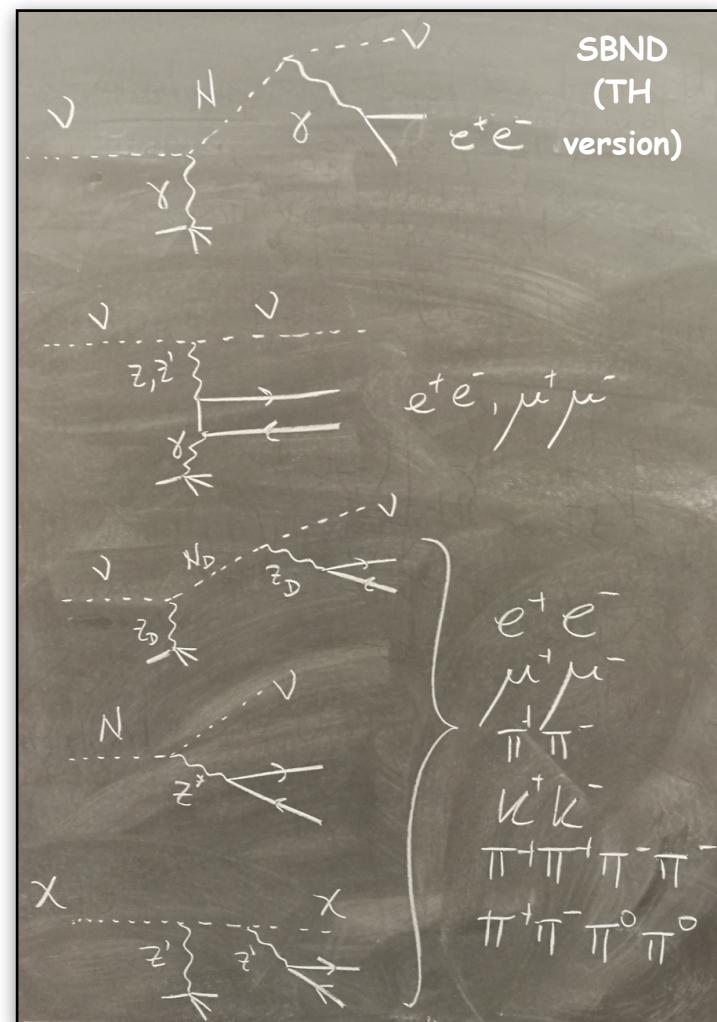


and also - **Neutrino cross sections** measurements for understanding neutrino interaction with matter and informing oscillation measurements. Neutrinos are background for BSM searches!

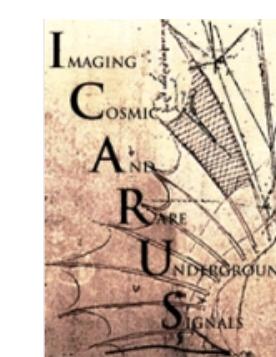
But it is an **evolving landscape** - Alternative explanations of the short-baseline anomalies and other Beyond Standard Model scenarios.

Many ideas for new searches emerging from collaboration with theory colleagues.

We have expanded the physics program!



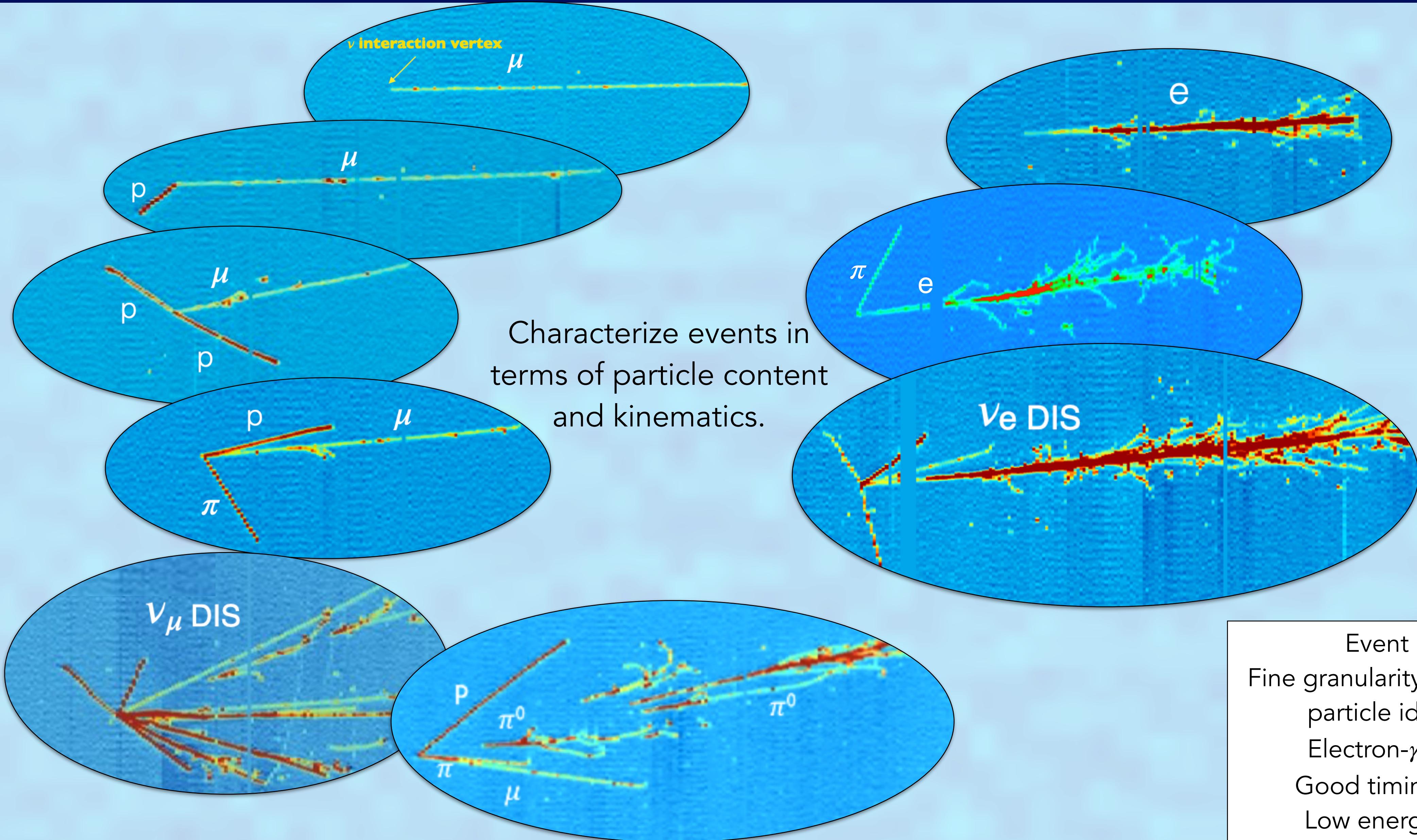
Here we will focus on accelerator-based (decay-in-flight) **Liquid Argon** neutrino experiments:
Short-baseline Neutrino program and **ArgoNeuT** experiment at Fermilab.



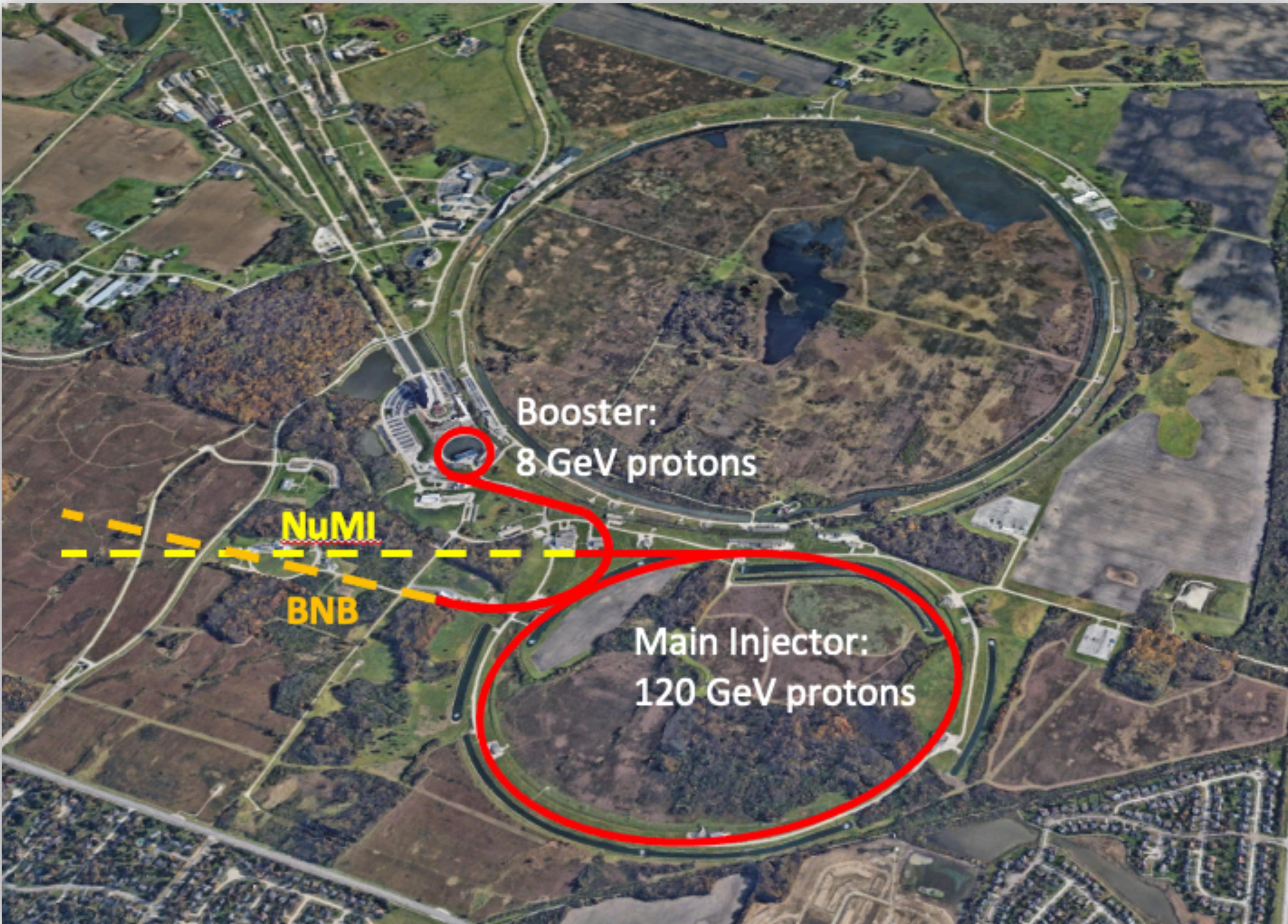
@  **Fermilab**

* Short-Baseline: $L \sim 100\text{-}1000\text{ m}$, $\Delta m^2 \sim 1\text{ eV}^2$
cfr.: Long-Baseline: $L \sim 100\text{-}1000\text{ km}$, $\Delta m^2 \sim 10^{-3}\text{ eV}^2$

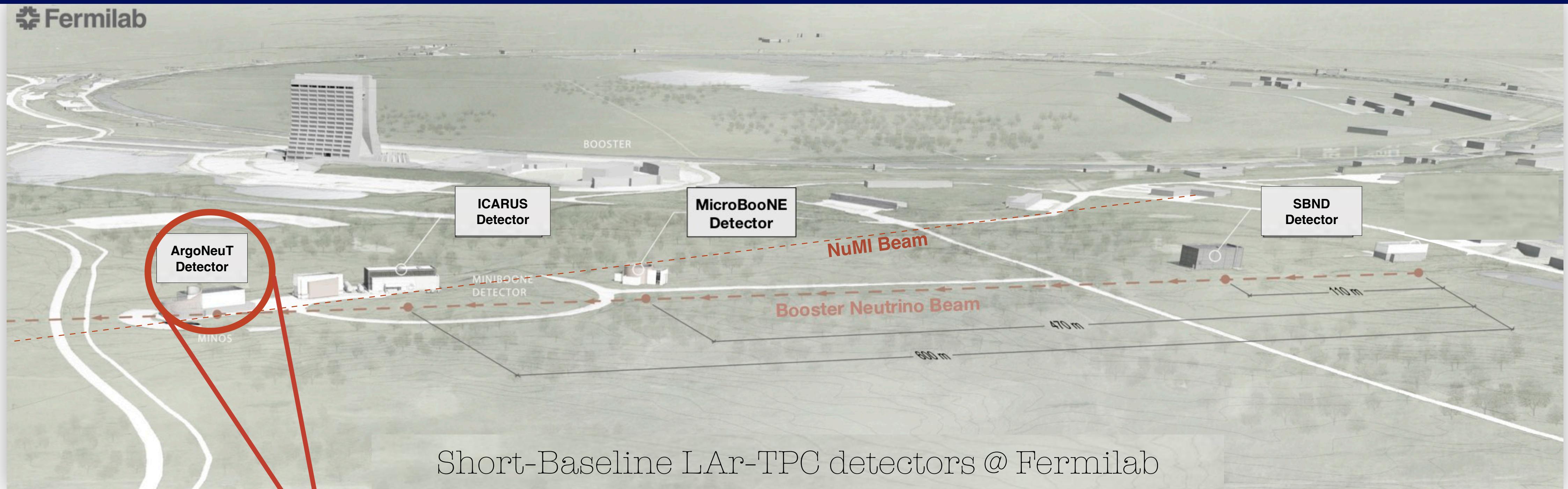
WHY LIQUID ARGON NEUTRINO DETECTORS?



FERMILAB - NEUTRINO BEAMS



SHORT-BASELINE LAr DETECTORS AT FERMILAB: ARGONeUT



First LAr TPC detector at Fermilab. 5 months neutrino data collected in 2009-2010

On-axis on NuMI
 $\langle E_\nu \rangle \approx 4 \text{ GeV}$

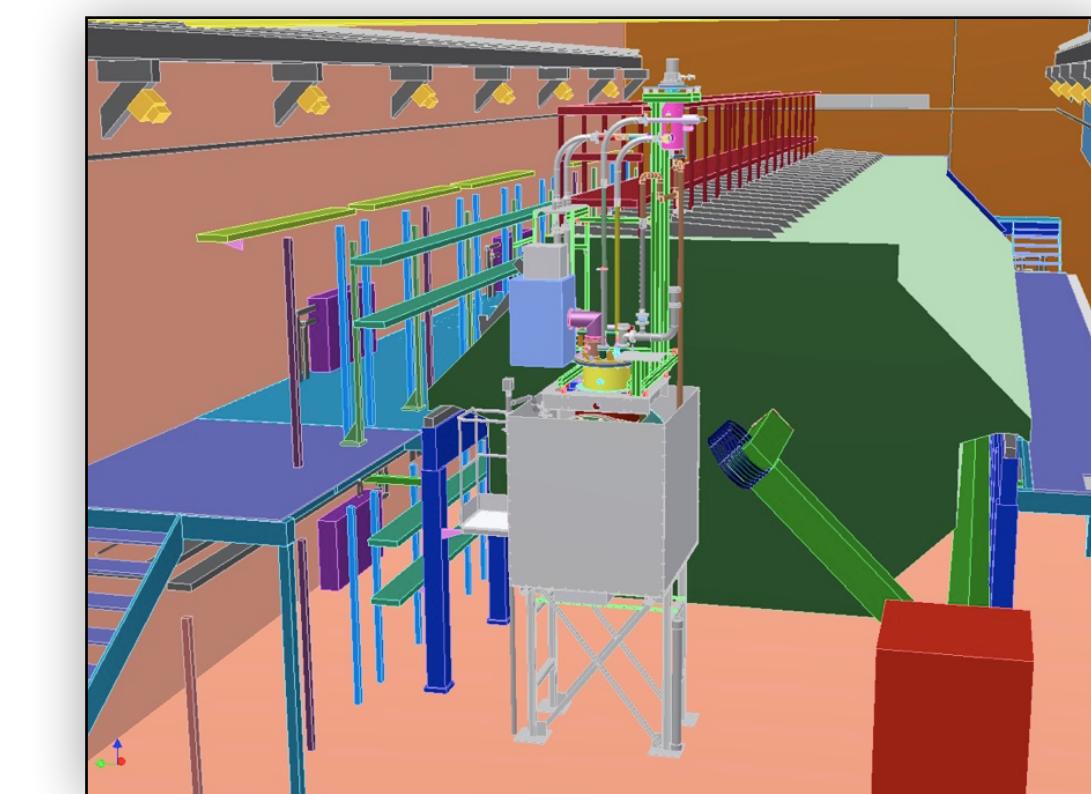
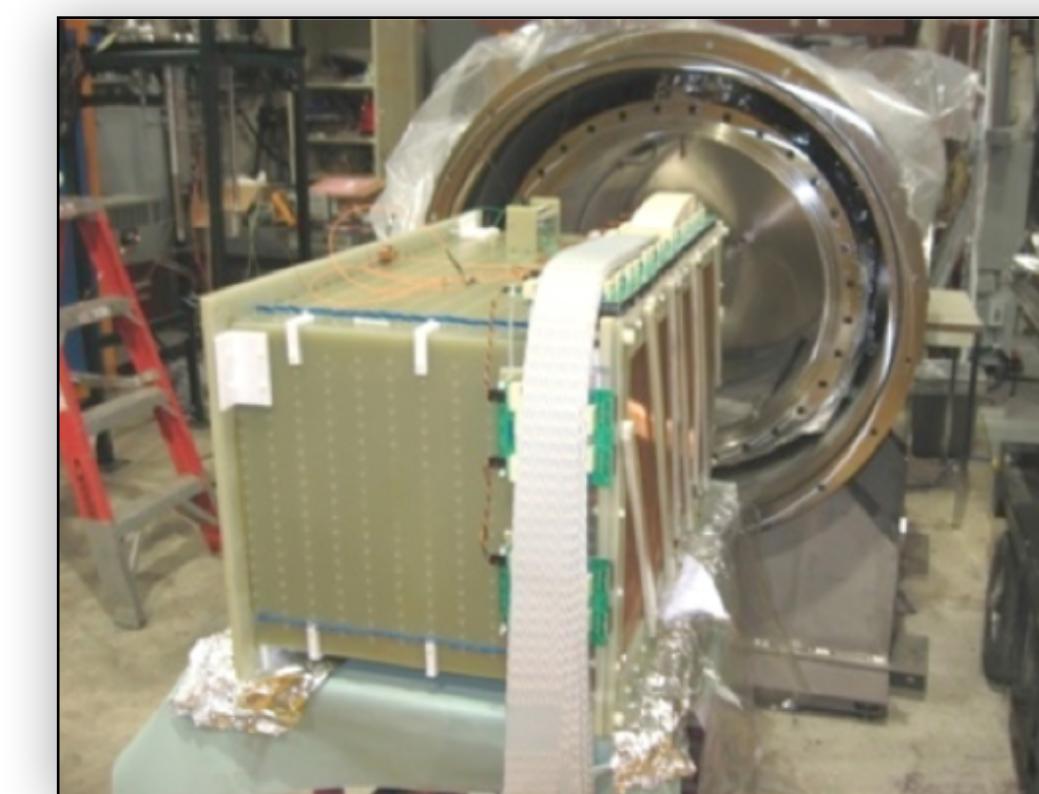
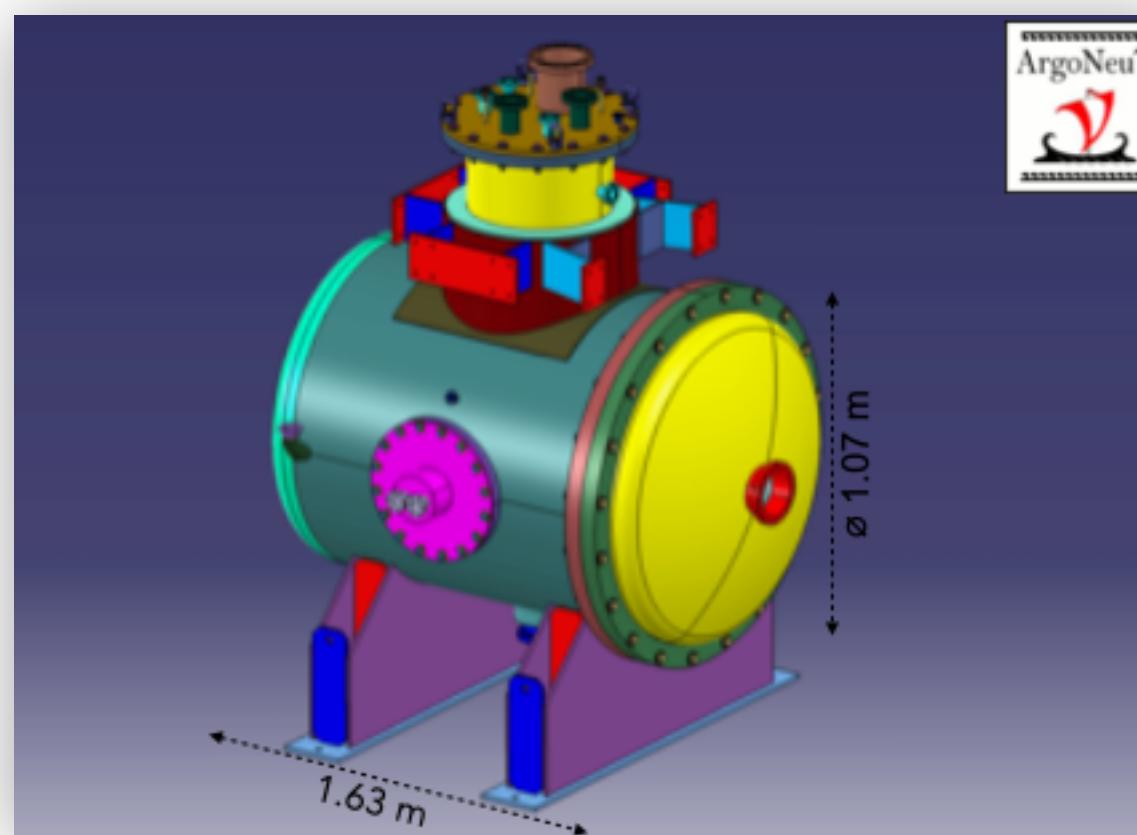


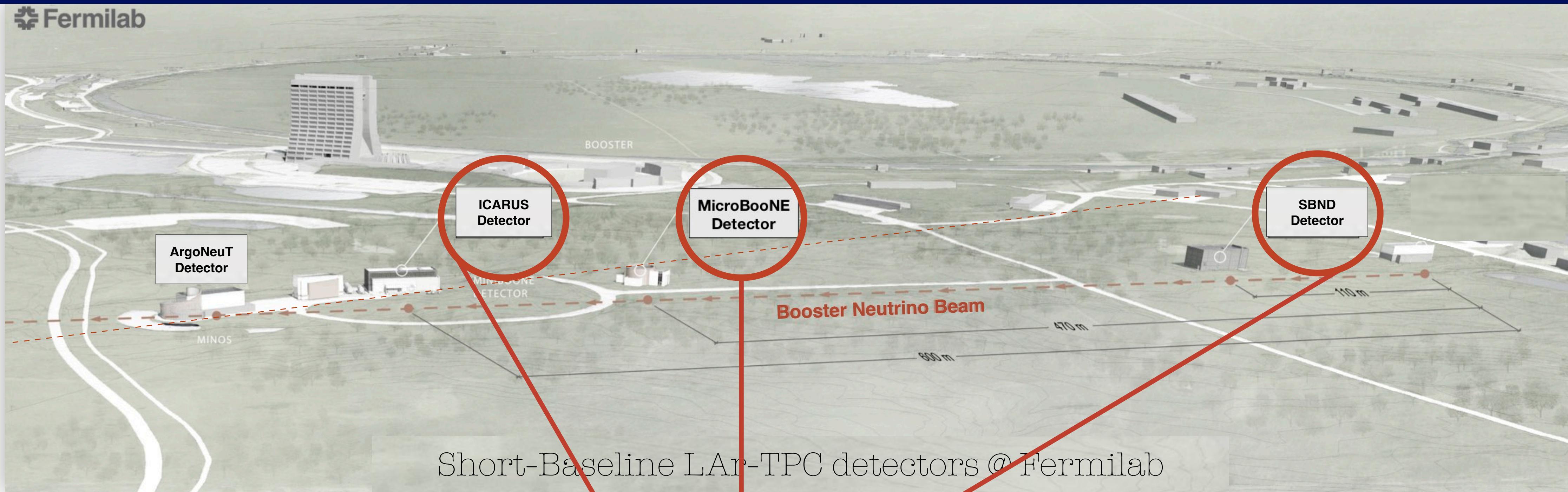
Table-top size, built as a test experiment...
but still producing physics results!

ArgoNeut Collaboration, JINST 7 (2012) P10019

0.24 tons active volume LAr TPC

100 m underground, in front of the MINOS ND, ~ 1km from target

SHORT-BASELINE LAr DETECTORS AT FERMILAB: SBN DETECTORS



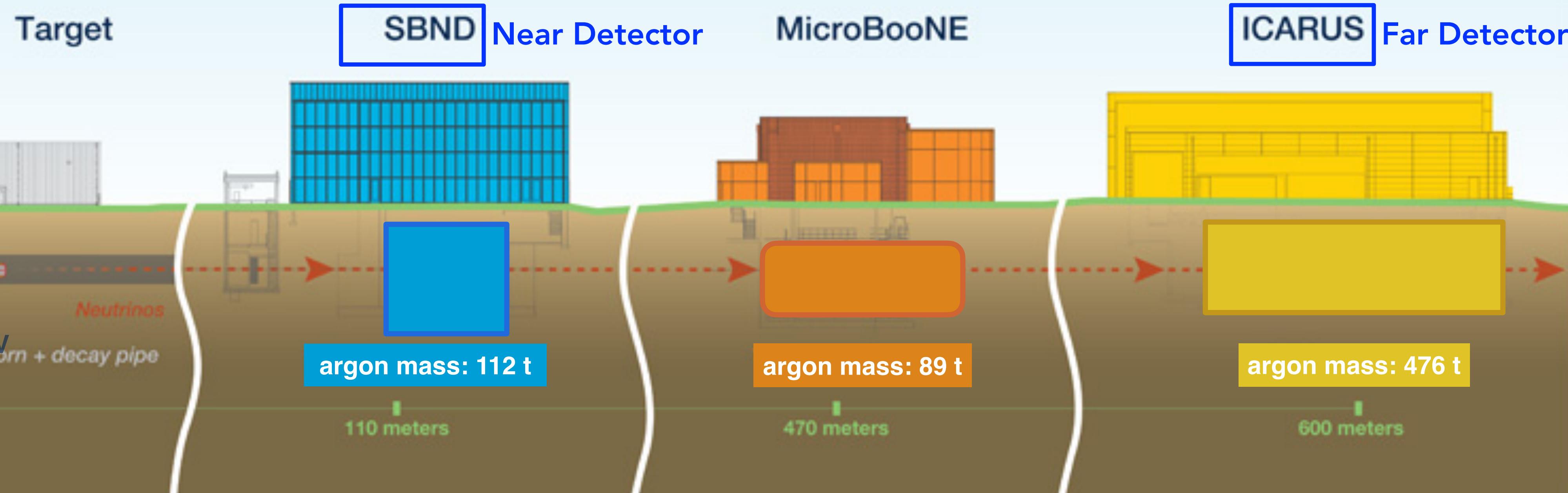
Short-Baseline LAr-TPC detectors @ Fermilab

Multiple LAr detectors on-axis on the Booster Neutrino Beam

SHORT BASELINE NEUTRINO PROGRAM

arXiv:1503.01520, January 2015

Short-Baseline Neutrino Program at Fermilab



Booster Neutrino Beam
Mean ν_μ energy:
~0.8 GeV
Beam composition:
 ν_μ (93.6%)
 $\bar{\nu}_\mu$ (5.9%)
 $\nu_e + \bar{\nu}_e$ (0.5%)

A program designed for **Sterile Neutrino** searches: same **neutrino beam**, **nuclear target** and **detector technology** to reduce systematic uncertainties to the % level.

But large mass LAr detectors and proximity to intense beams enables a **broad physics program**.

P.Machado, O.P., D. Schmitz, Annu. Rev. Nucl. Part. Sci. 69 363-387 (2019)

SBN FAR DETECTOR: ICARUS

From Gran Sasso Laboratory to Fermilab via CERN

August 2018

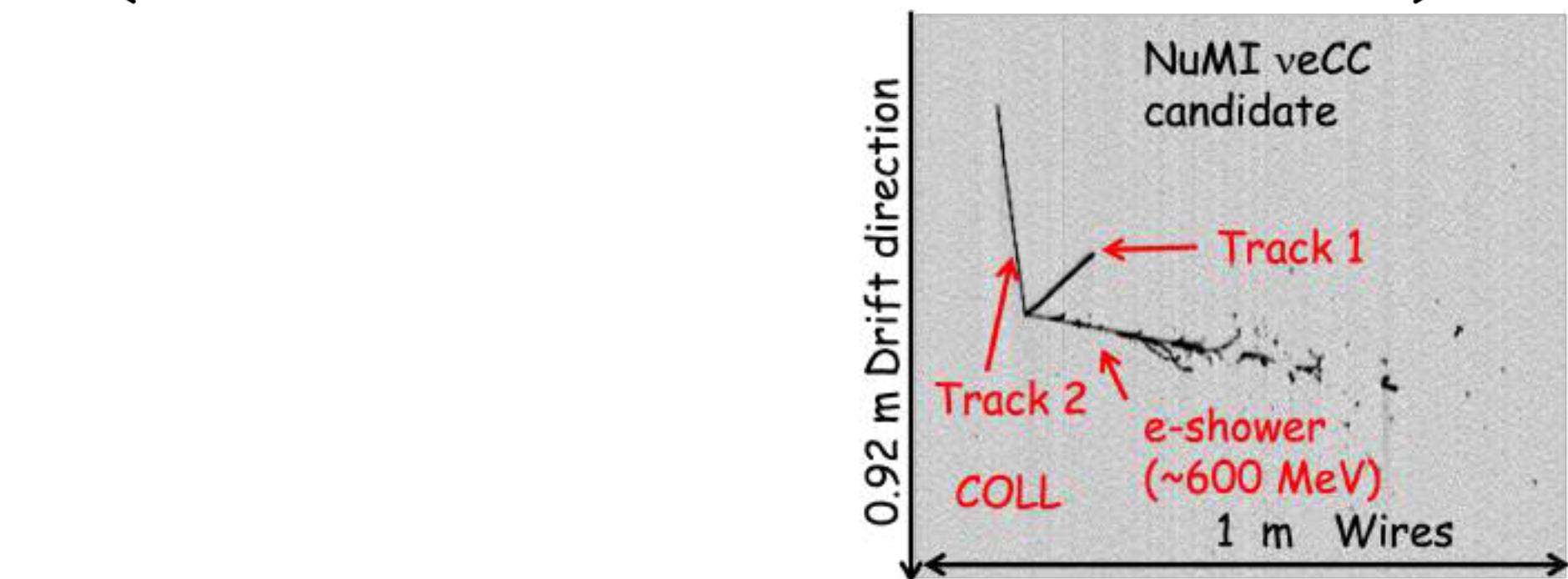
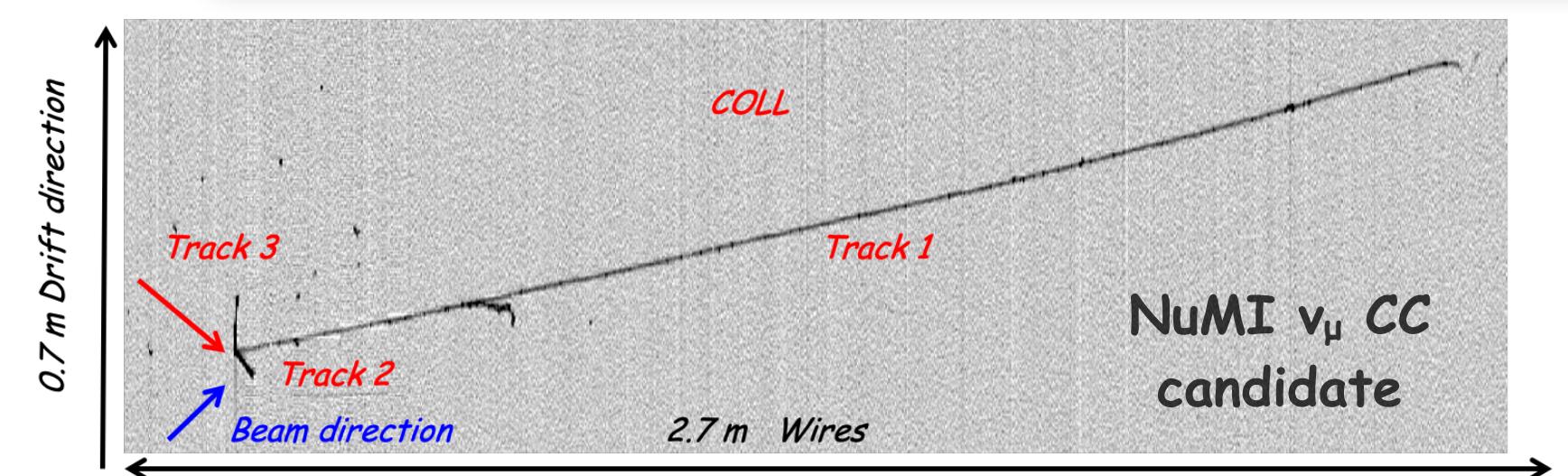
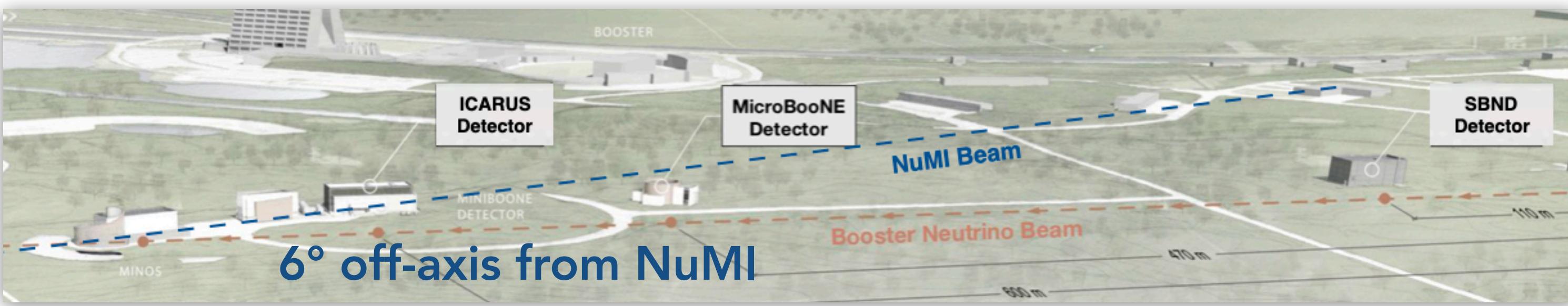


Four Time Projection Chambers
in two modules
Each module dimension:
3m x 4m x 18m

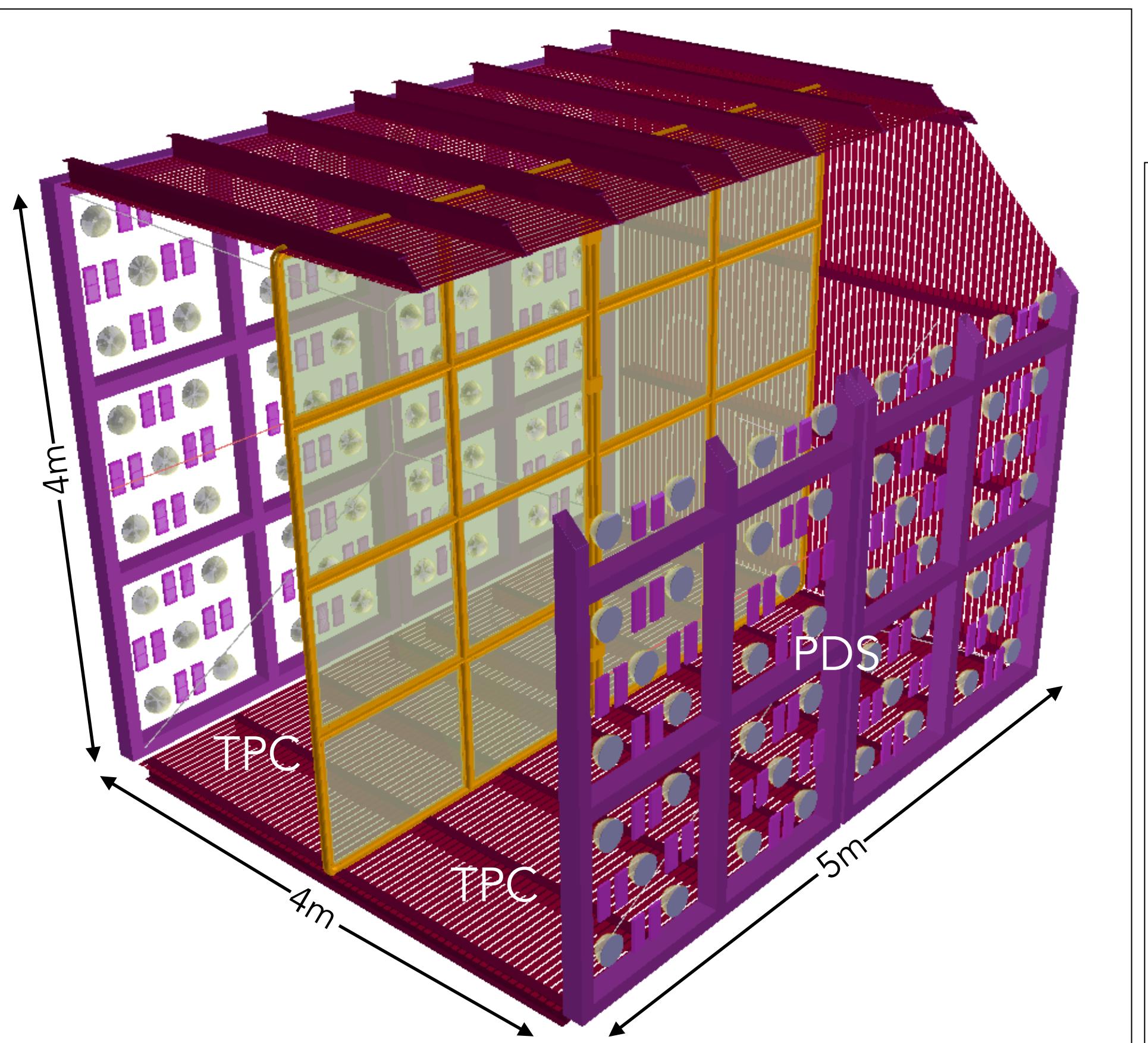
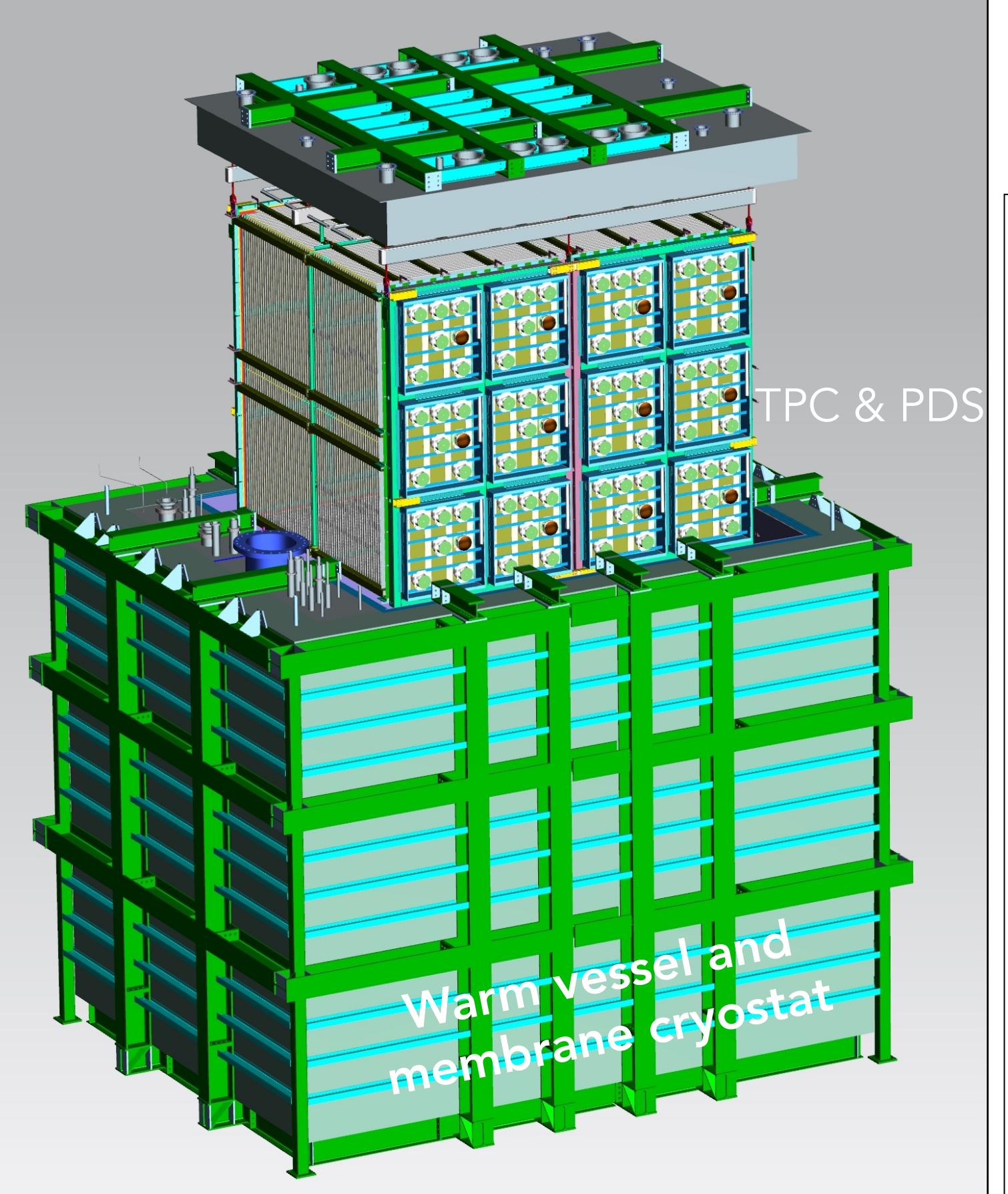
Installation of
ICARUS cryostats

Collecting data in final configuration
since **June 2022**

ICARUS receives two neutrino beams: it also sits 6° off-axis from the NuMI beam

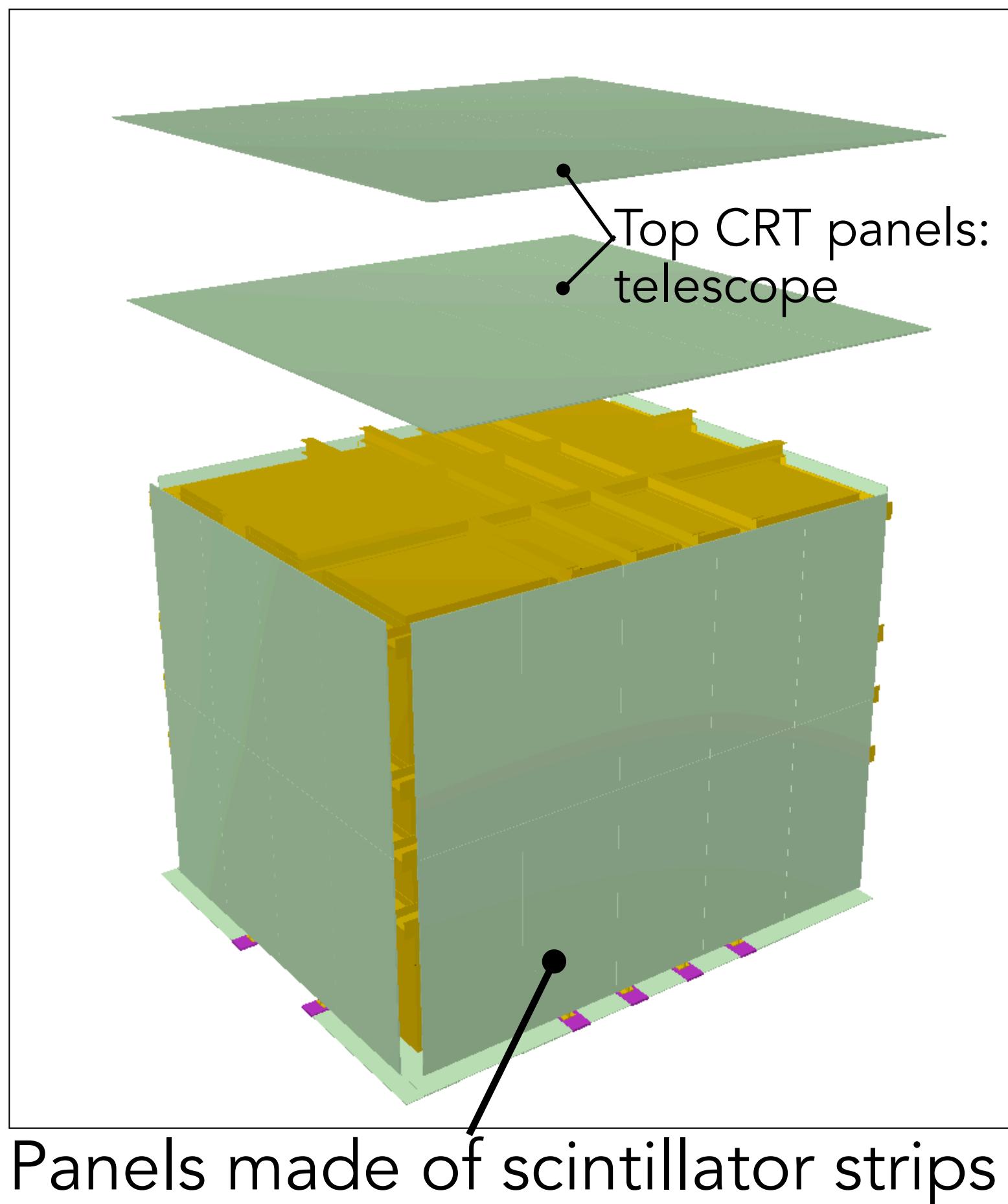


SBN NEAR DETECTOR: SBND



Two Time Projection Chambers
and Photon Detection systems

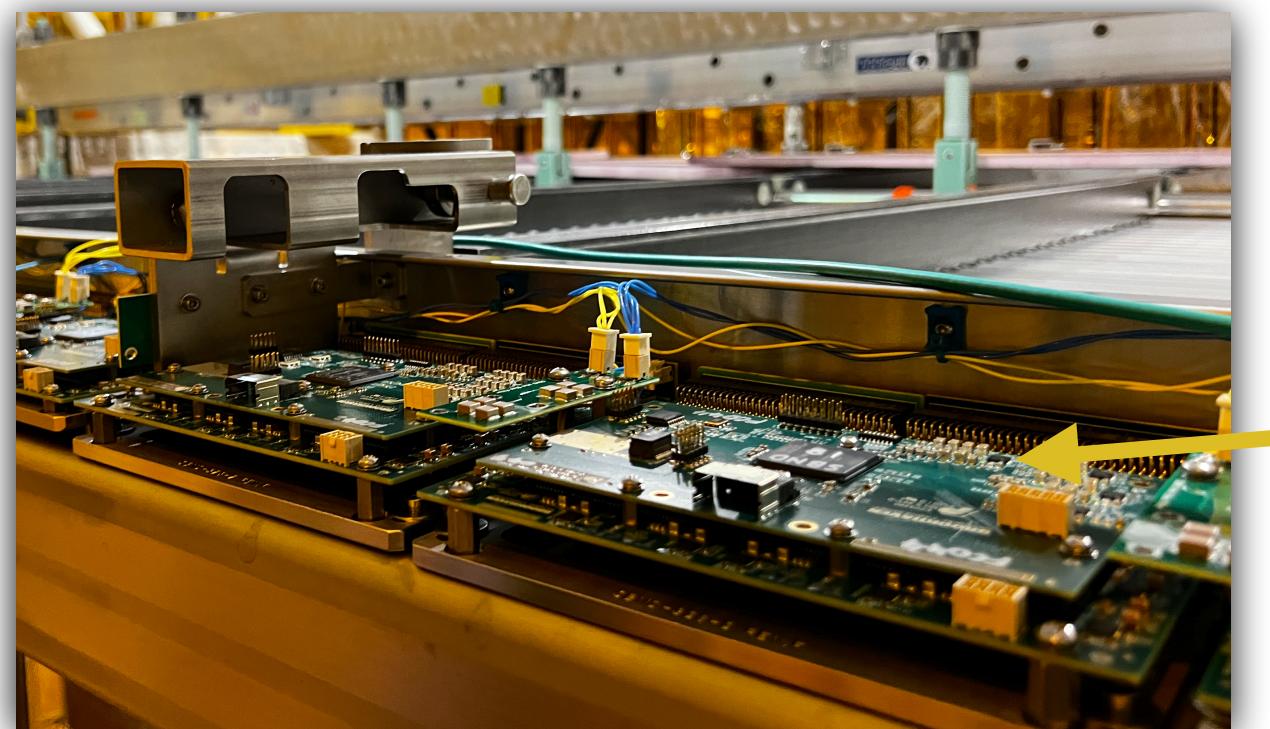
Cryostat surrounded by a
Cosmic Ray Tagger system
for cosmic ray rejection



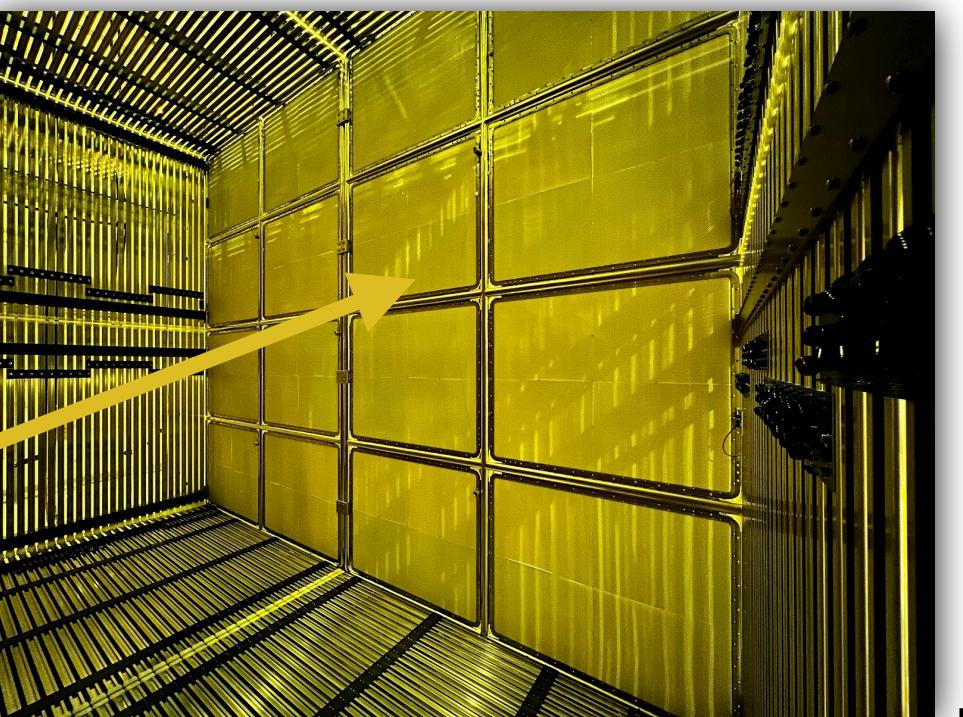
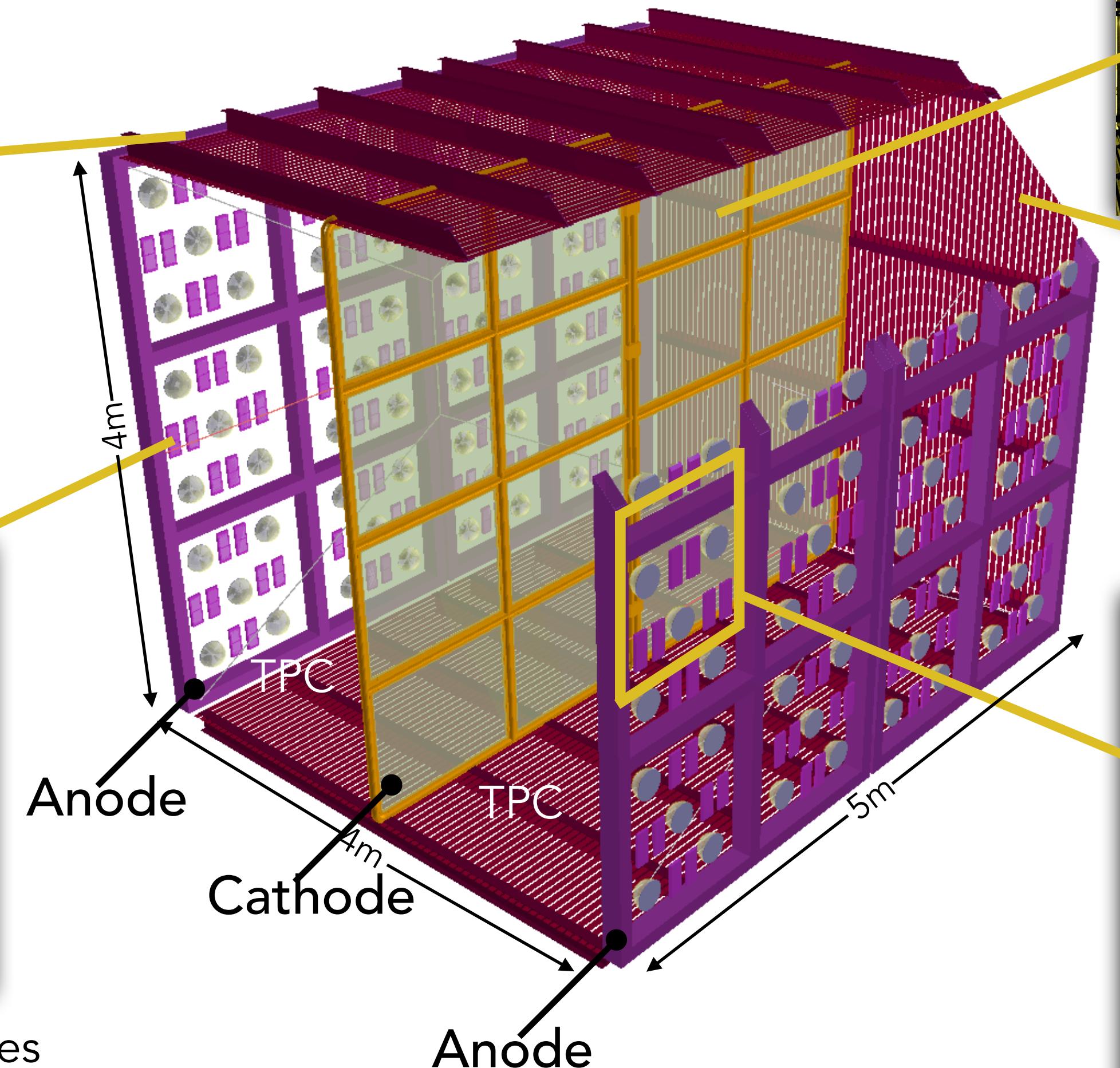
SBND DETECTOR: TPC AND PDS

The design of the SBND TPC is largely based on the design of the TPC for the DUNE Far Detector 1 (FD1)

TPC Cold electronics

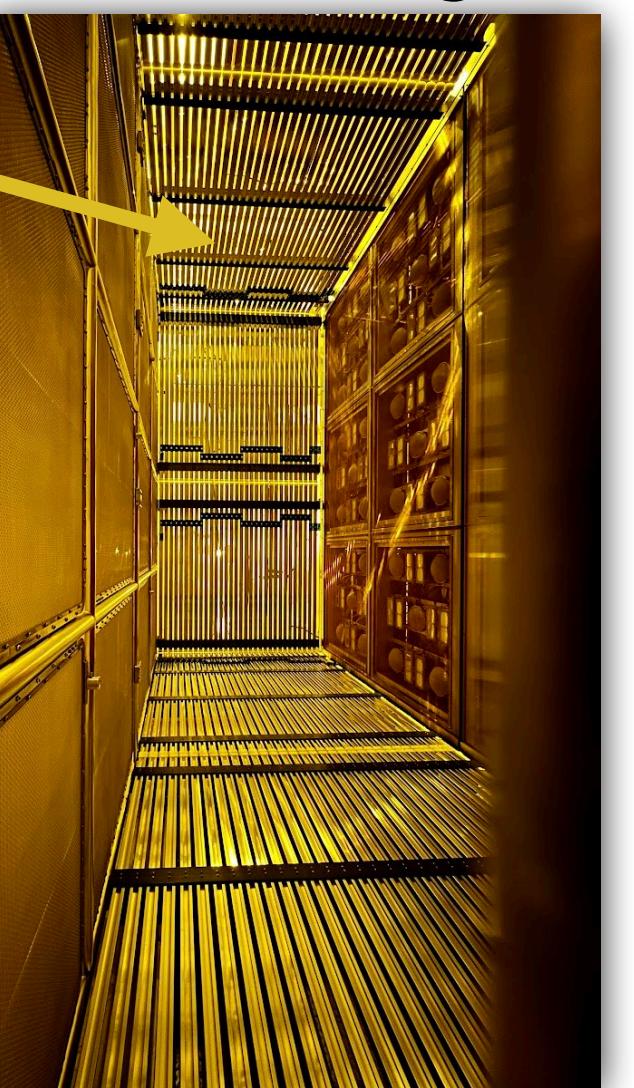


Two Time Projection Chambers
Total dimension: 4m x 4m x 5m

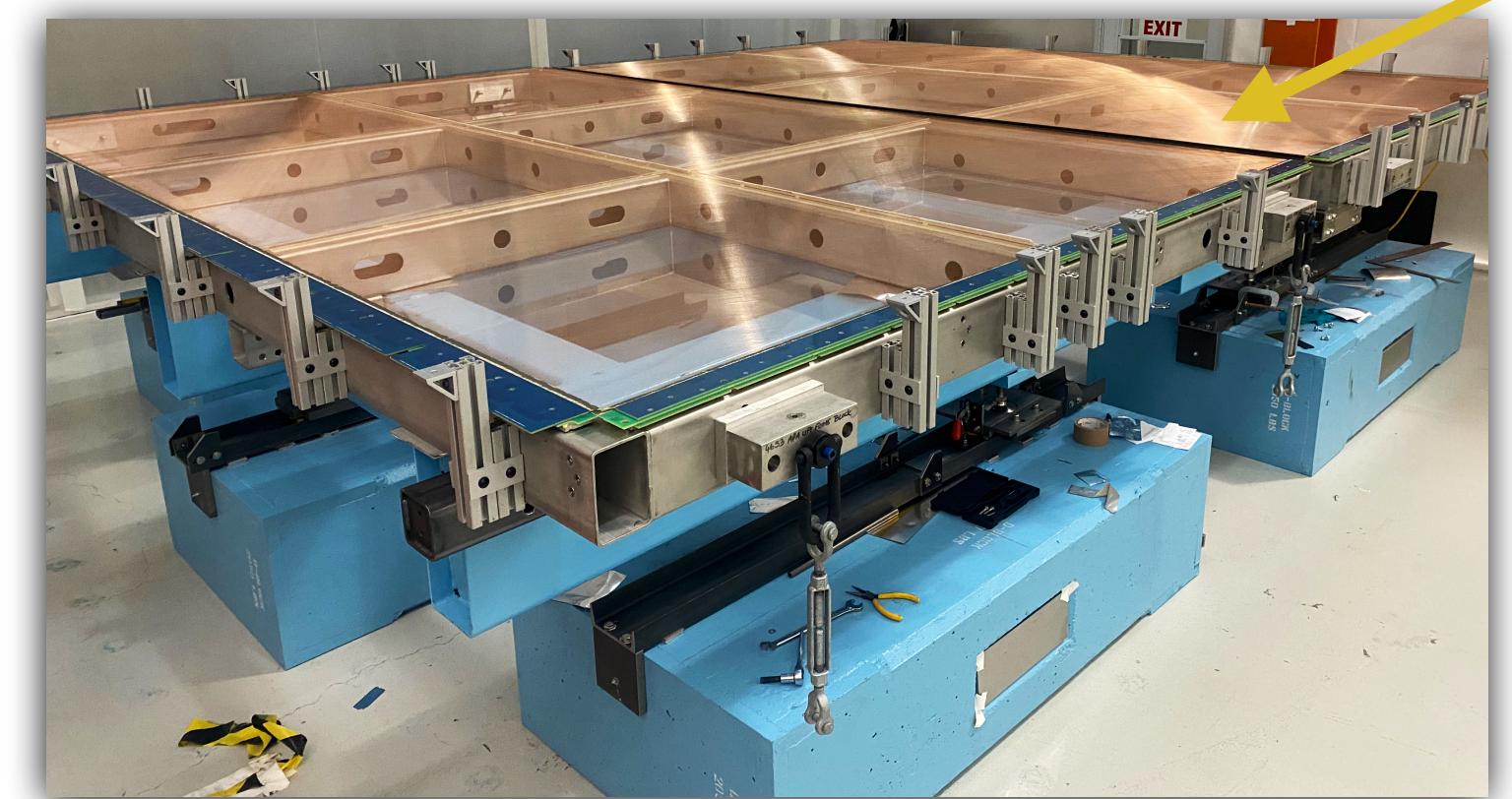


CPA-Cathode
covered with TPB
coated reflectors

Field Cage

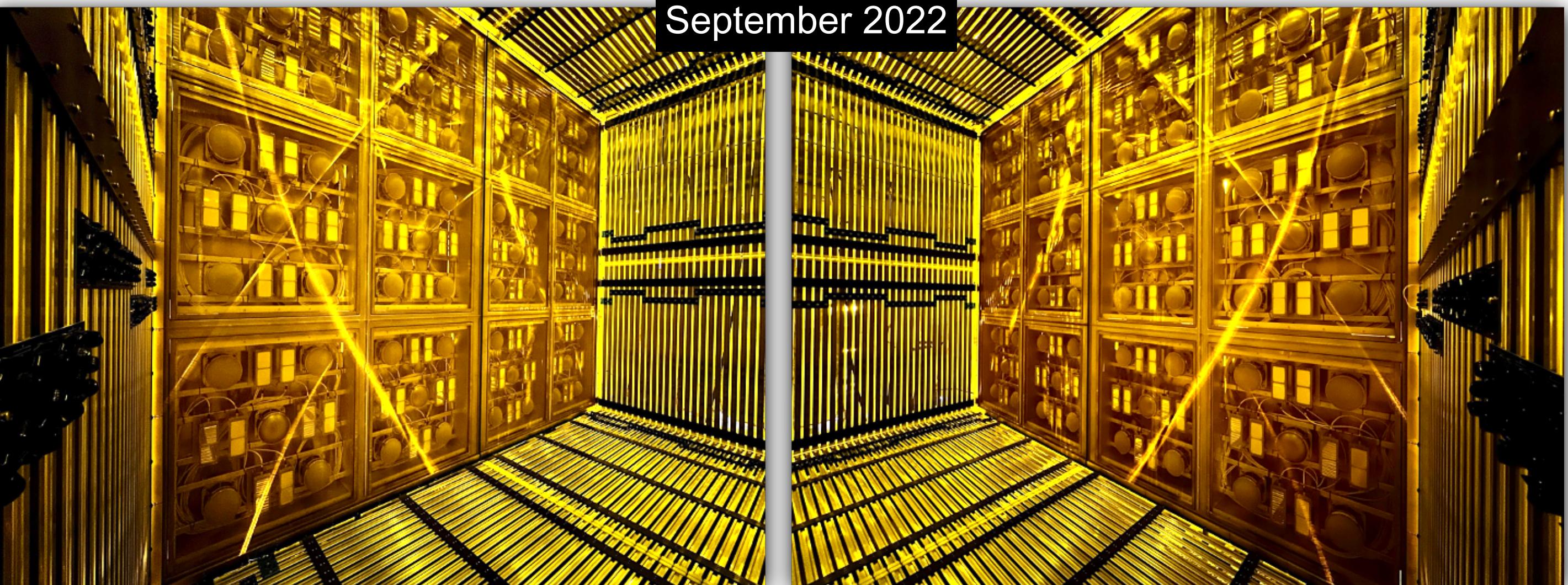


Photon Detection
Systems: 120 PMTs,
192 X-Arapucas

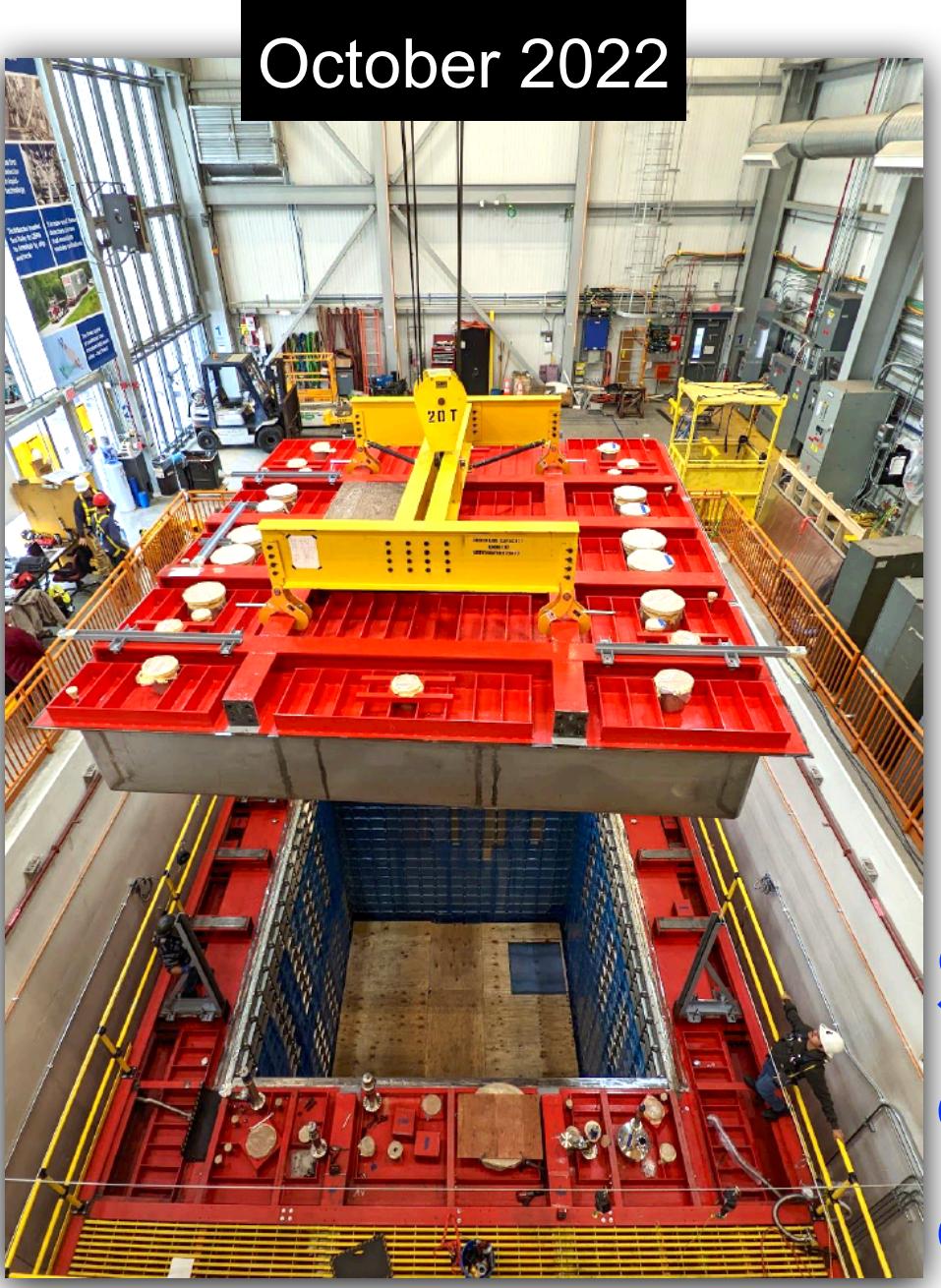


APA-Wire Planes- 3 planes, ~11000 wires

SBND STATUS



**SBND
detector
completed**



Membrane
cryostat as in
DUNE FD1 and
FD2

**SBND
cryostat
completed**

On **December 1, 2022** the assembled SBND TPC + photon detector systems was successfully moved across the Fermilab site from DAB to the SBND Detector hall



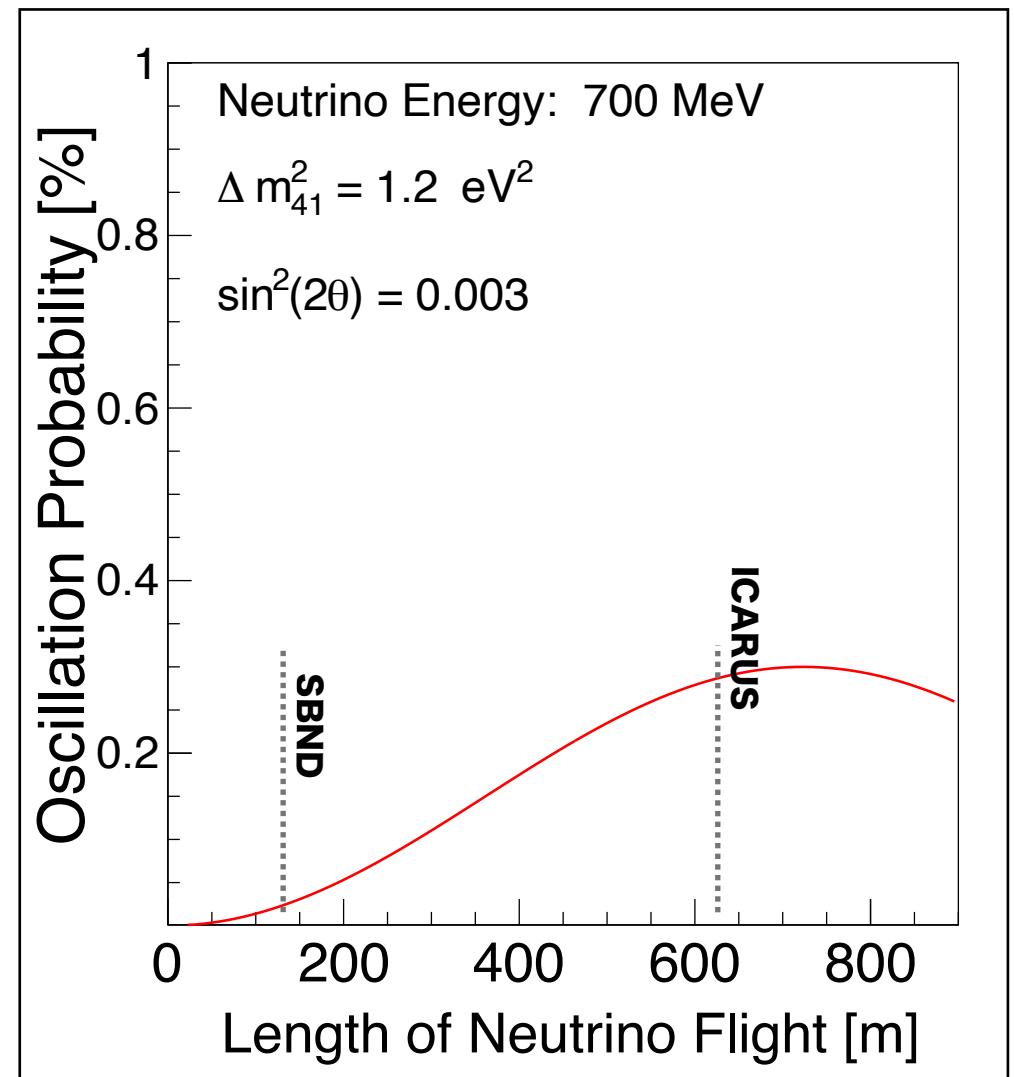
A newsworthy day



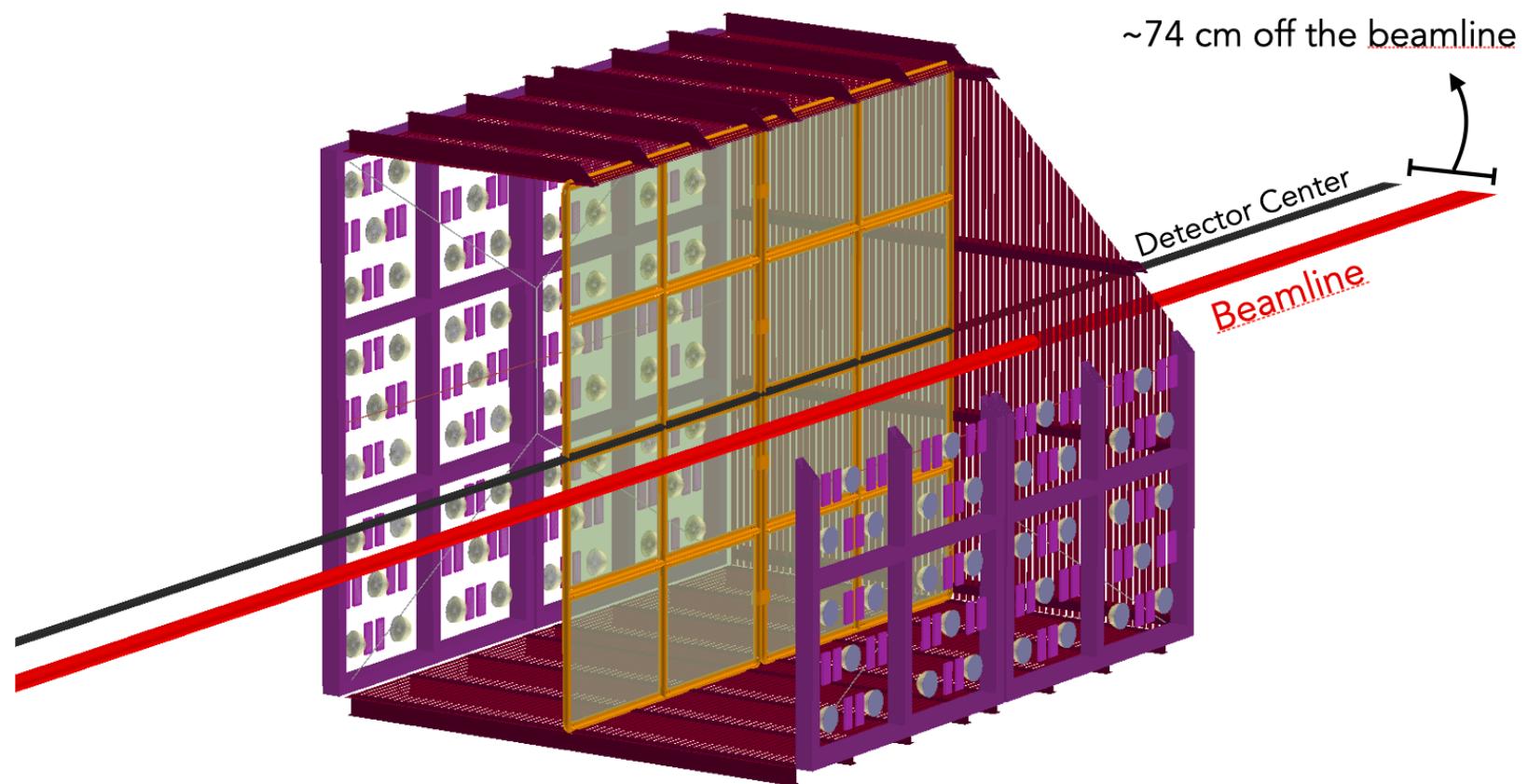
Expected to begin
operation in **Fall 2023**

WHAT MAKES THE SBN PROGRAM UNIQUE?

LAr Technology



SBND is close (110 m) to the neutrino source and intentionally positioned offset relative to the beam center.



Near detector **SBND**

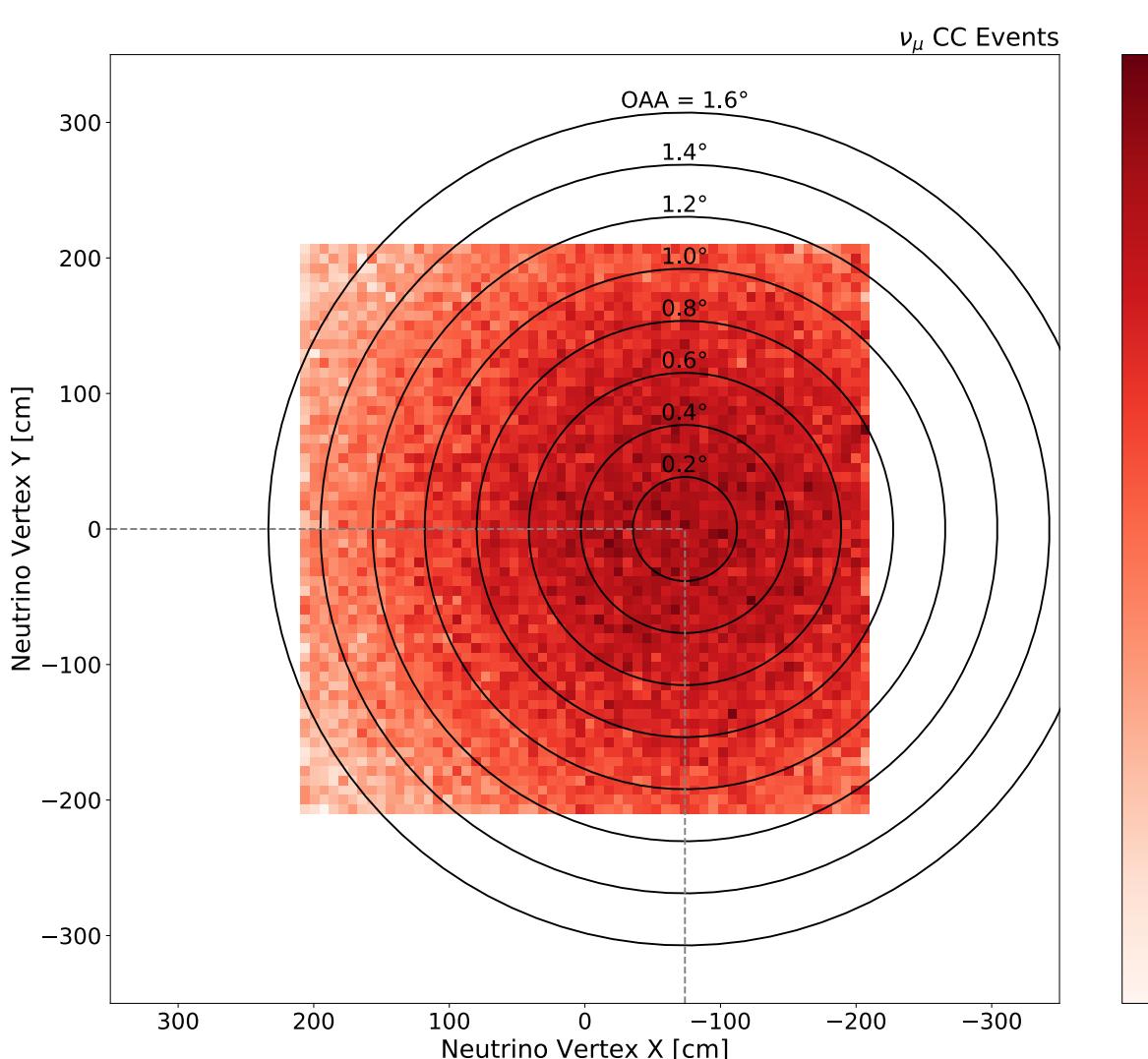
Crucial for oscillation searches.

Sitting close to the neutrino source, SBND plays a **unique role**. It sits before oscillations turn on @eV-scale → it characterizes the beam and **addresses the dominant systematic uncertainties**

Far detector **ICARUS**

Given its far location and large mass provides big exposure to oscillated neutrinos, allowing for a **high sensitivity oscillation search**

SBND-PRISM



This “PRISM”* feature of SBND allows **sampling multiple neutrino fluxes in the detector**

SBND-PRISM provides unique constraints of systematic uncertainties, helps mitigate backgrounds, and expands the SBN(D) physics potentials

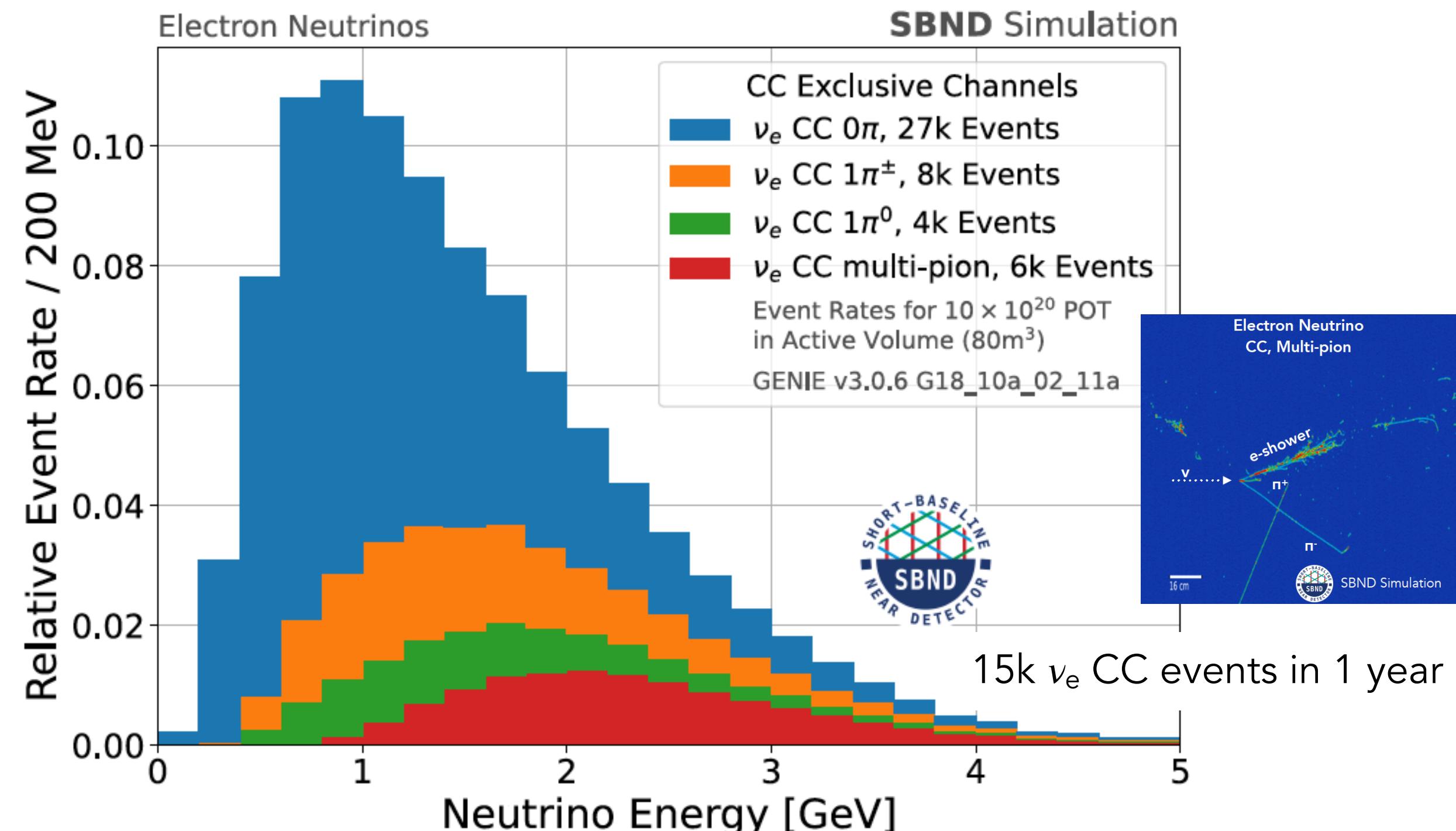
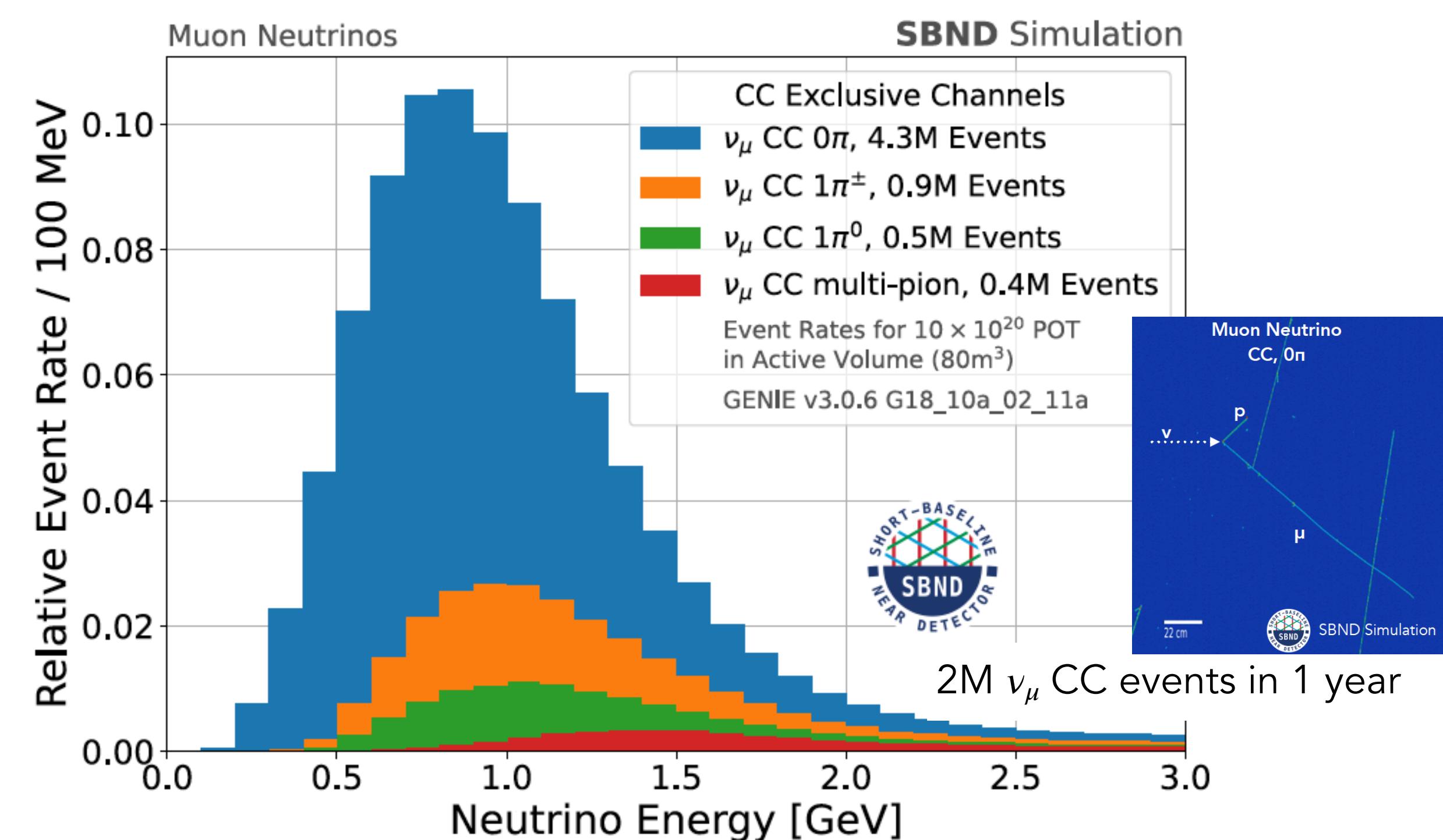
*Similar to the nu-PRISM and DUNE-PRISM concepts, but with a fixed detector.

PRECISION STUDIES OF NEUTRINO-ARGON INTERACTIONS IN SBND



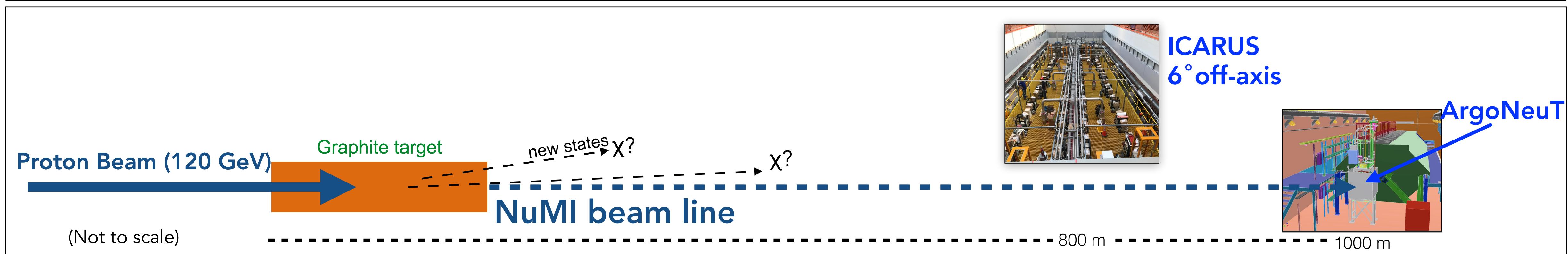
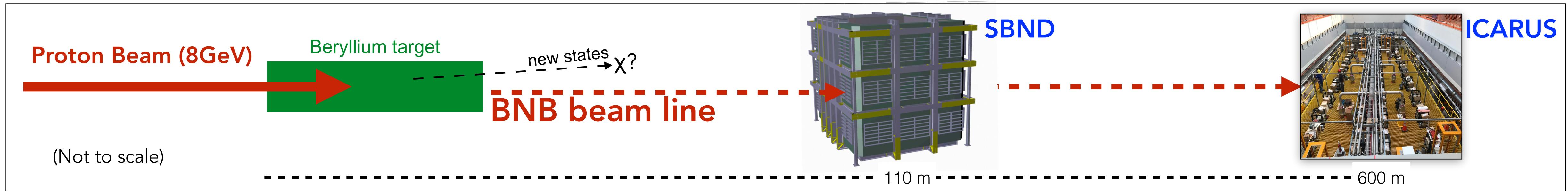
With its proximity to the neutrino source, **SBND** will compile neutrino data with unprecedented high event rate and will enable a generational advance in the study of neutrino-argon interactions in the GeV energy range.

Up to 7000 ν events/per day in SBND!



SBND will record **20-30x more neutrino-argon interactions** than is currently available
(10 million total events (CC+NC), including around 50,000 ν_μ CC events above 2 GeV, and 50,000 ν_e CC events).

SIGNATURES FOR NEW PHYSICS IN SBN AND ARGO NEUTRINO EXPERIMENTS



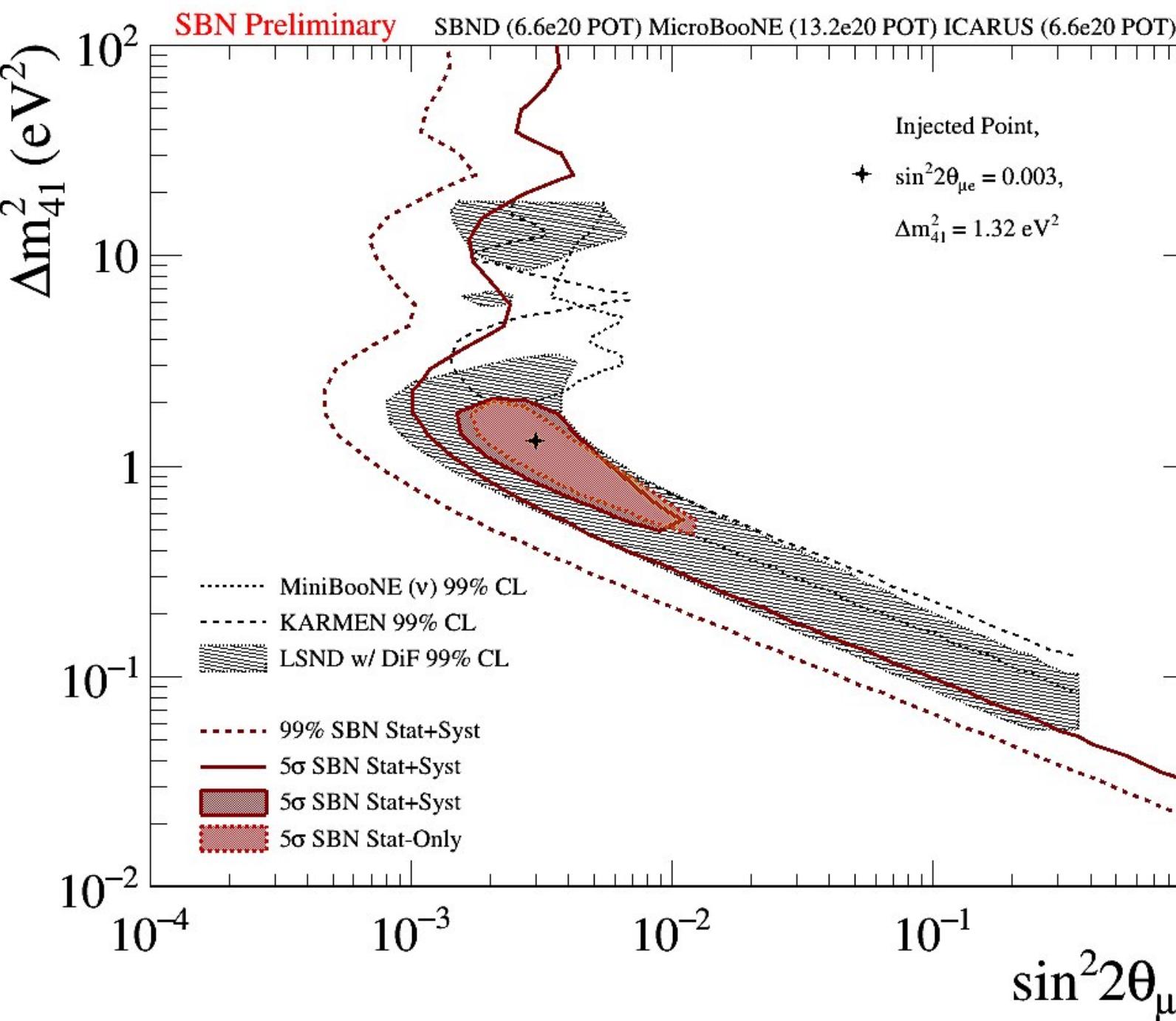
High-intensity proton beams
(high-intensity neutrino beams)

(Large mass) LAr detectors
close to the beam target

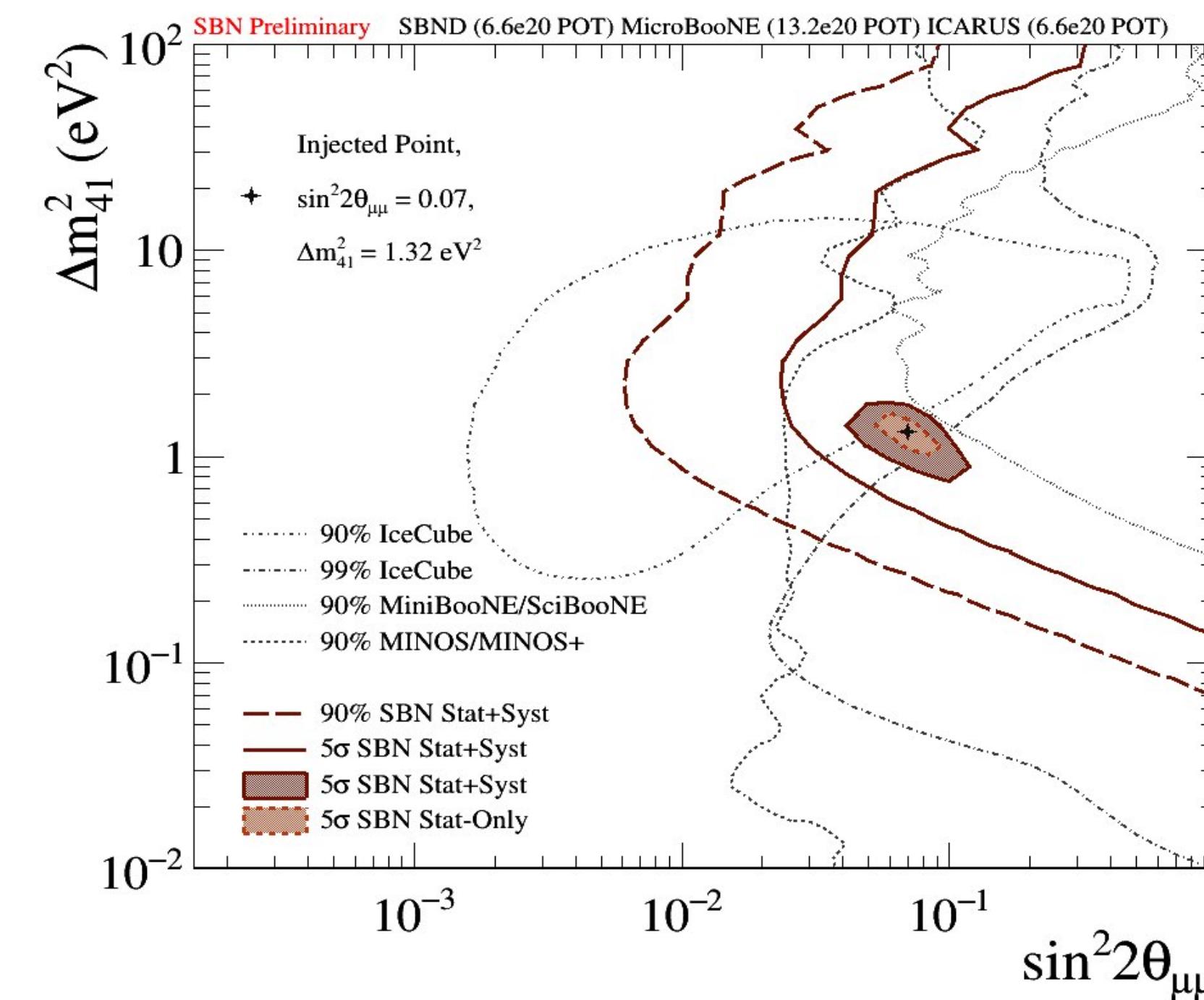
Opportunities to **probe signatures** for **new physics scenarios**
in the **neutrino sector** (modifications to the neutrino oscillation paradigm) and
beyond (novel experimental signatures produced in the beam target)

SBN STERILE NEUTRINO SENSITIVITIES

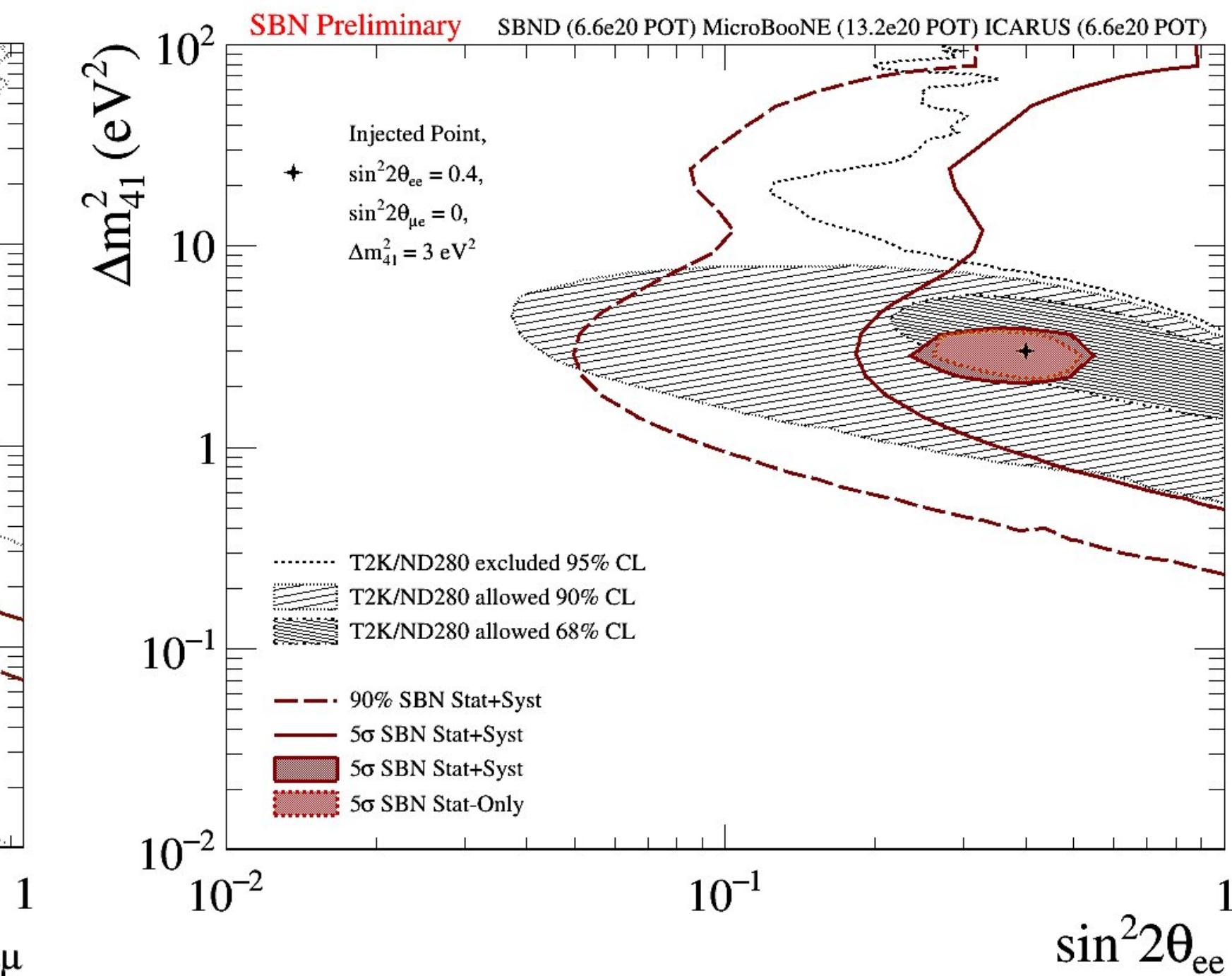
ν_e Appearance



ν_μ Disappearance



ν_e Disappearance



The SBN program tests the sterile neutrino hypothesis by covering the parameter regions allowed by past anomalies at **5σ significance**.

Complementary measurements in different modes:
important for interpretation in terms of **sterile neutrino oscillation**.

EVOLVING LANDSCAPE...

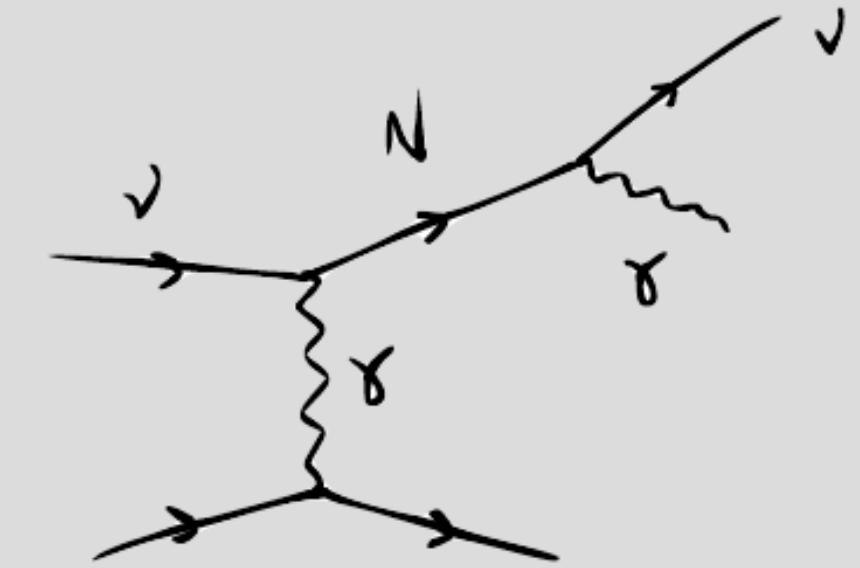
Alternative explanations
of the MiniBooNE excess
and other Beyond
Standard Model scenarios.

Dark Neutrinos



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

Transition Magnetic Moment



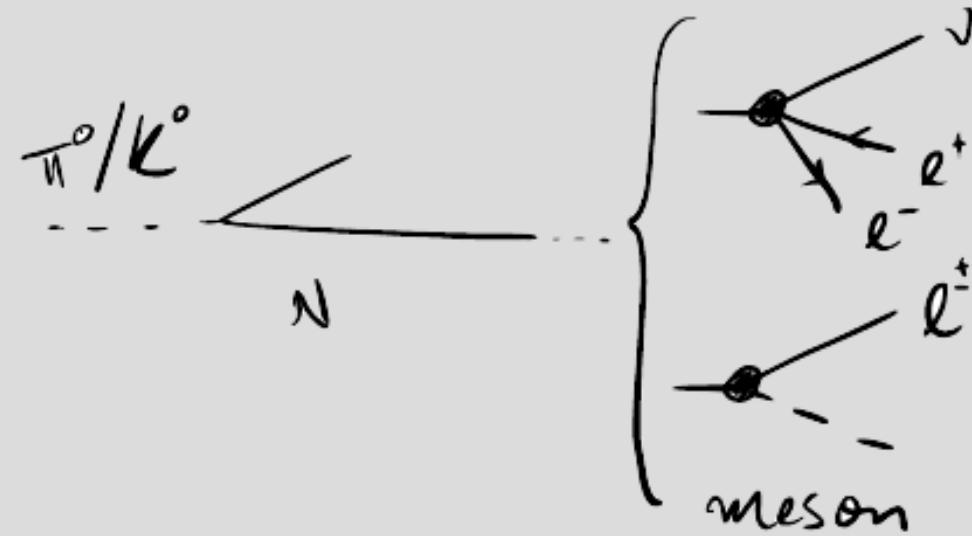
Gninenko PRL 2009
Coloma Machado Soler Shoemaker PRL 2017
Atkinson et al 2021 Vergani et al 2021

Axion-like Particles



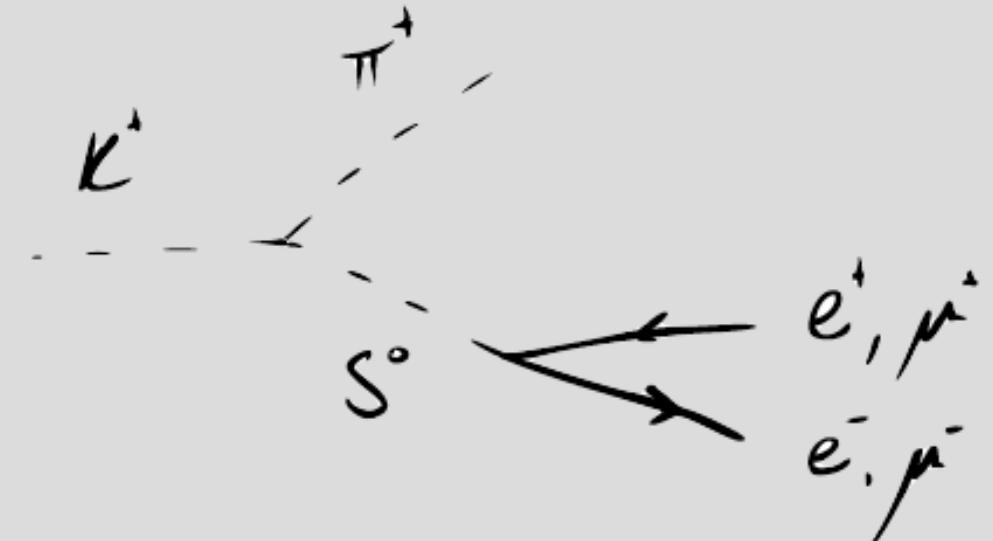
Kelly Kumar Liu PRD 2021
Brdar et al PRL 2021

Heavy Neutral Leptons



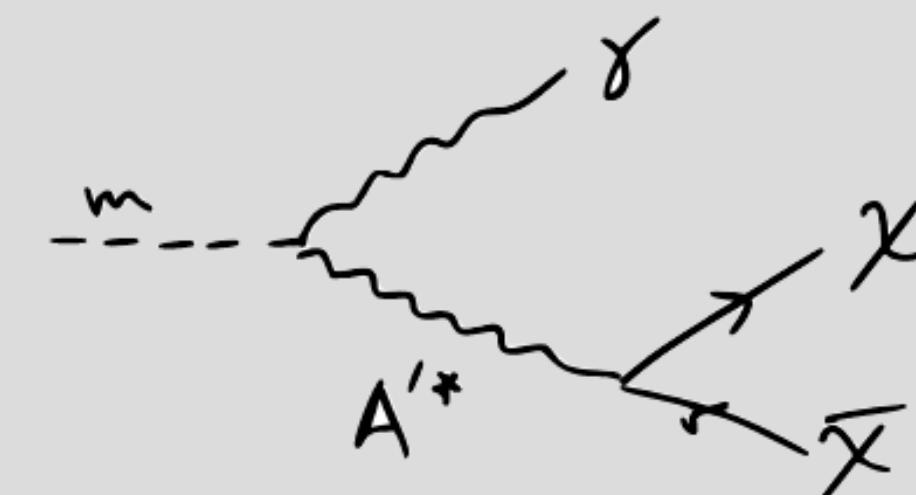
Ballett Pascoli Ross-Lonergan JHEP 2017
Kelly Machado PRD 2021

Higgs Portal Scalar



Pat Wilczek 2006
Battell Berger Ismail PRD 2019
MicroBooNE 2021

Light Dark Matter



Romeri Kelley Machado PRD 2019

Millicharged Particles



Magill, Plestid, Pospelov, Tsai, PRL 2019
Harnik Liu Palamara, JHEP 2019

Note: not an exhaustive list!

EVOLVING LANDSCAPE...

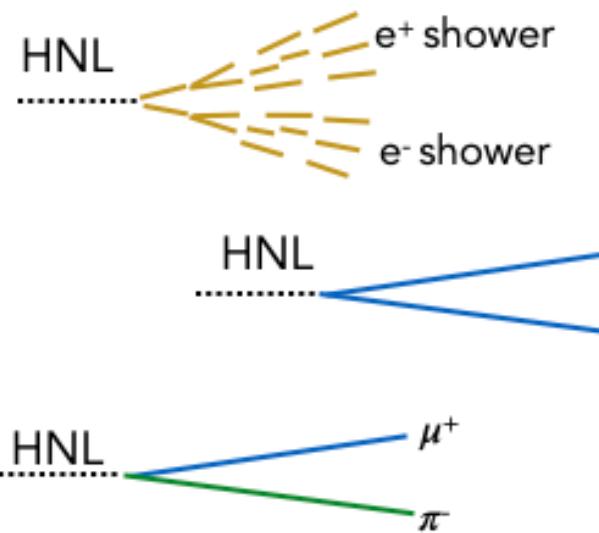
Final state experimental signature:

single photon, single electron,
"trident" with di-leptons - overlapping
and/or highly asymmetric,
with different levels of hadronic activity.

Exploit capabilities of LAr technology:

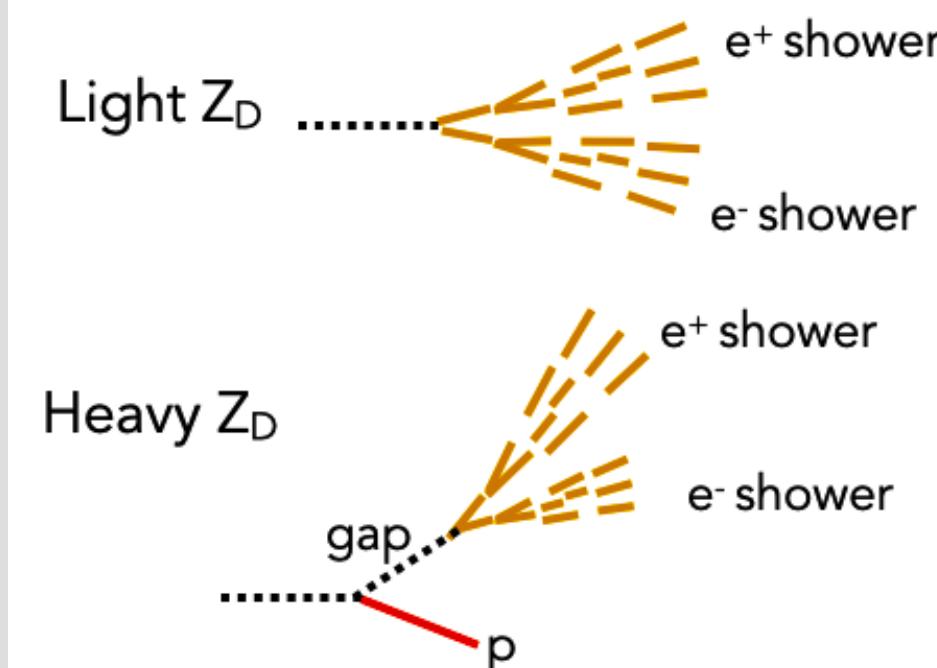
- Characterize events in term of final state particle content and kinematics.
- Recognize the presence hadronic activity.
- ns timing (delayed signals)

Heavy Neutral Leptons



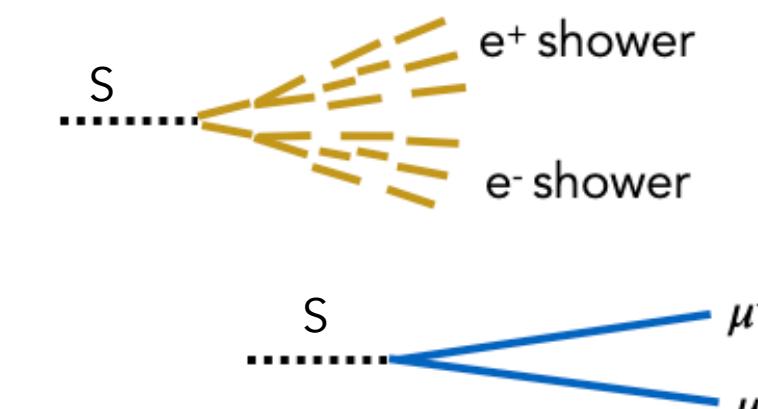
e^+e^- , $\mu^+\mu^-$, or $\mu^\pm\pi^\mp$ pair, no hadronic activity

Dark Neutrinos



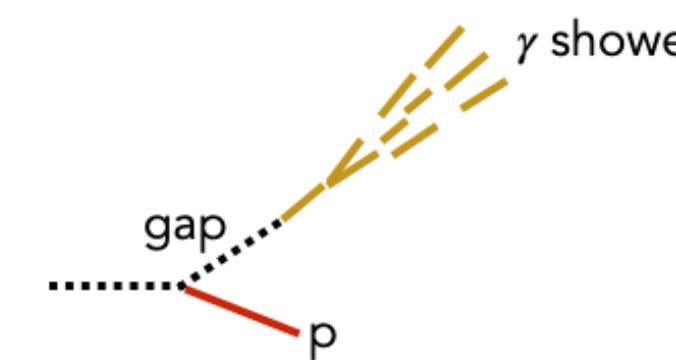
e^+e^- pair with or without hadronic activity

Higgs Portal Scalar



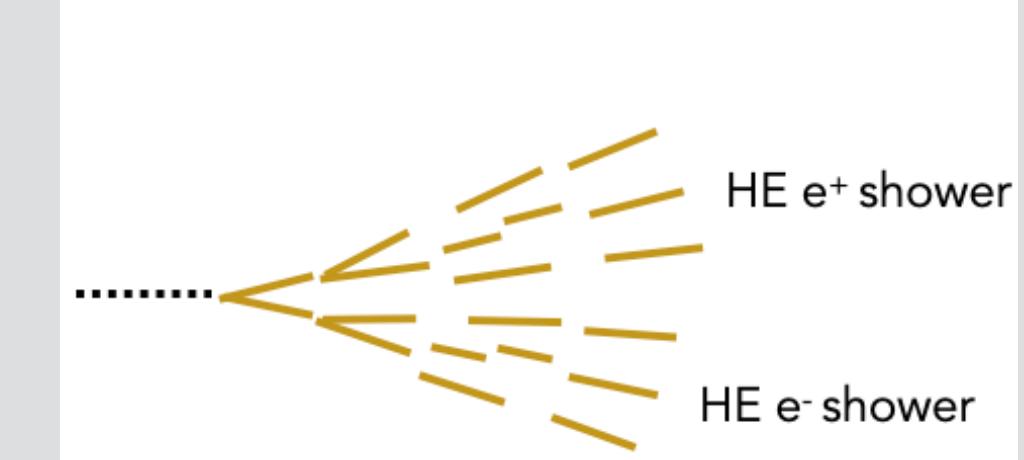
e^+e^- or $\mu^+\mu^-$ pair, no hadronic activity

Transition Magnetic Moment



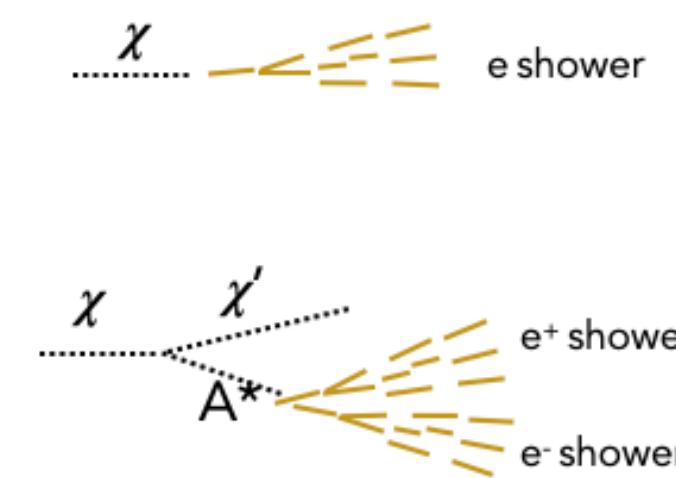
single photon and hadronic activity

Axion-like Particles



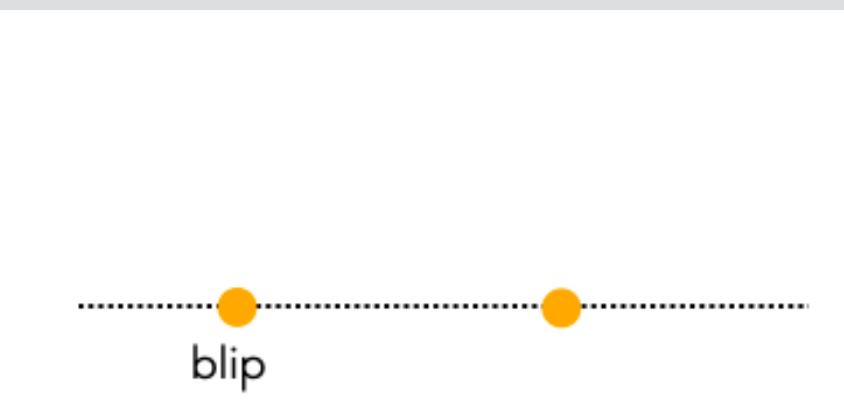
high-energy e^+e^- pair

Light Dark Matter



single e^- or e^+e^- pair, no hadronic activity

Millicharged Particles

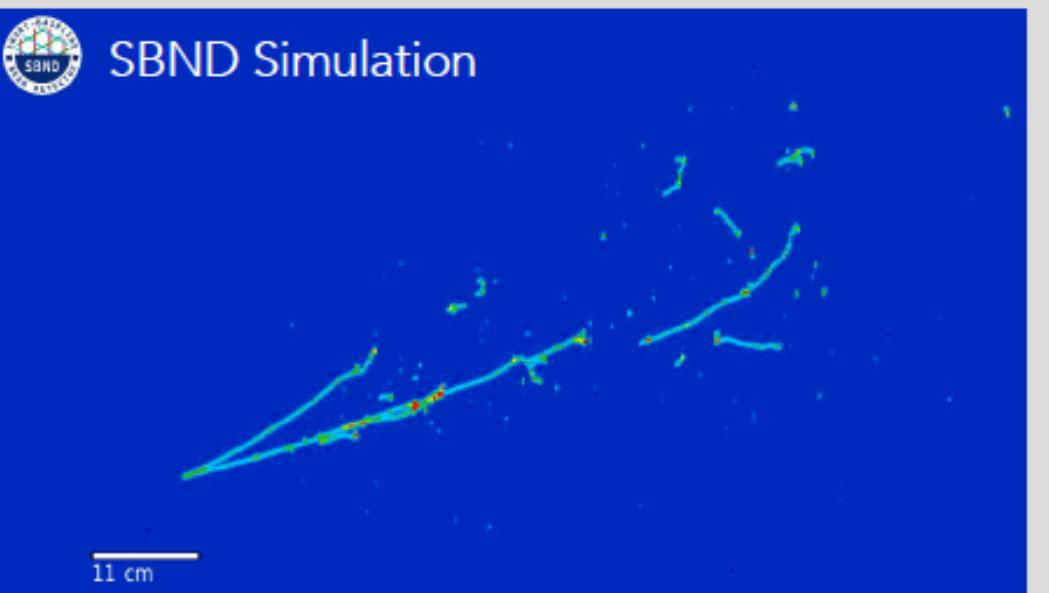


blips or faint tracks

SIGNATURES FOR NEW PHYSICS IN SBND

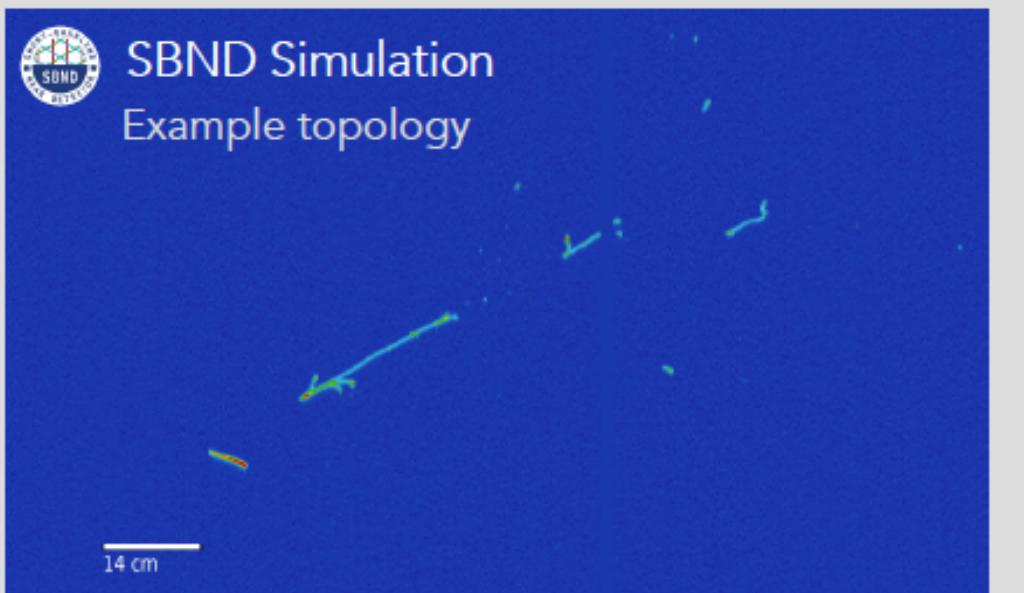
Collaboration between experimentalists and theorists is crucial for these searches.

Dark Neutrinos



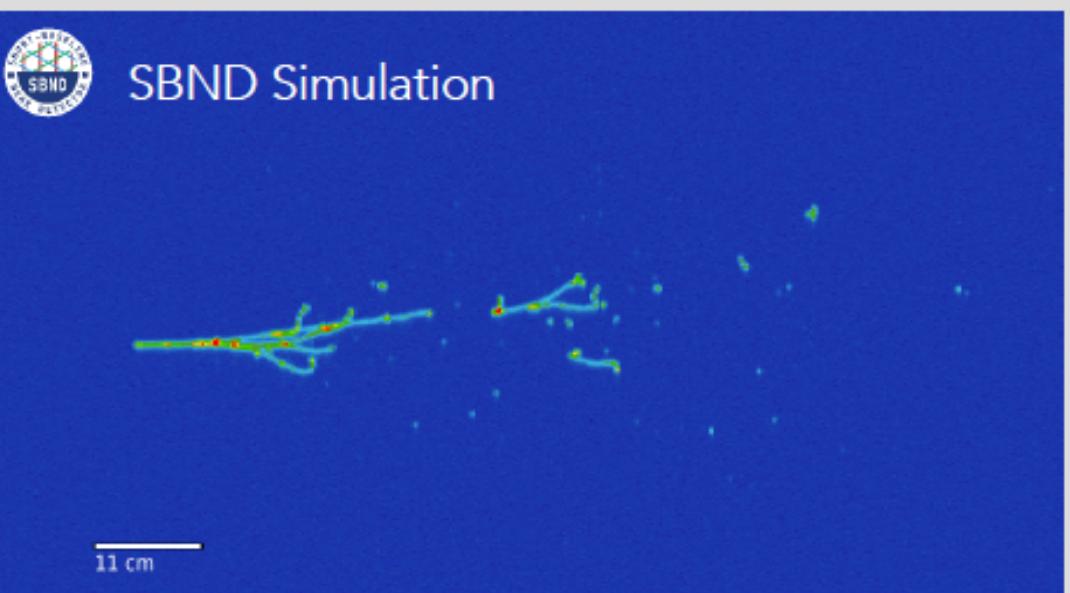
e^+e^- pair w/ or w/o hadronic activity

Transition Magnetic Moment



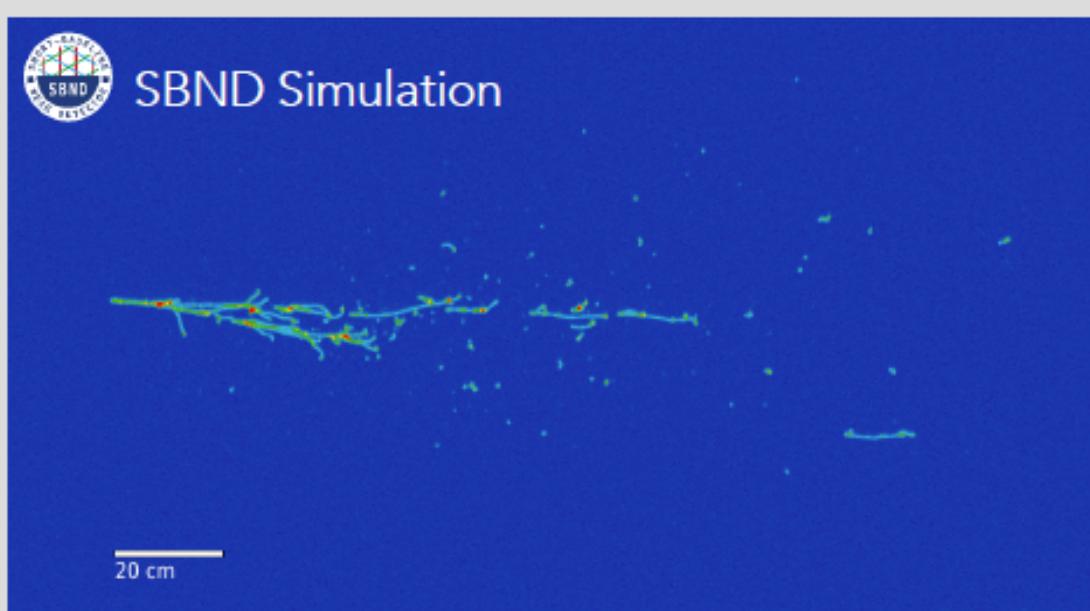
photon shower and hadronic activity

Axion-like Particles



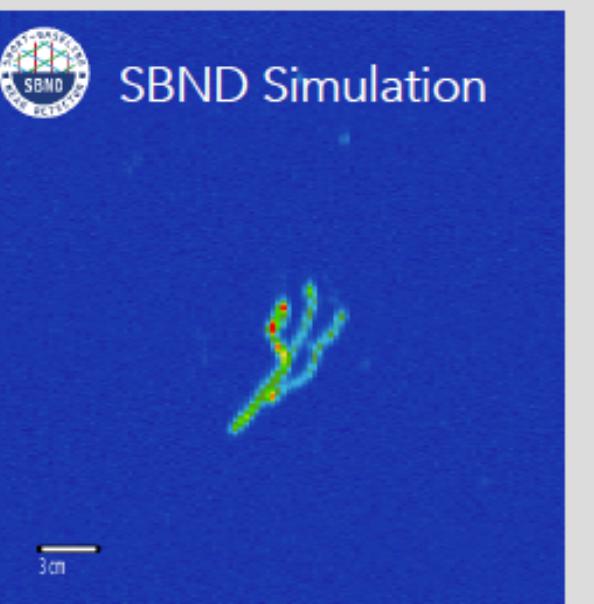
high-energy e^+e^- , $\mu^+\mu^-$

Heavy Neutral Leptons



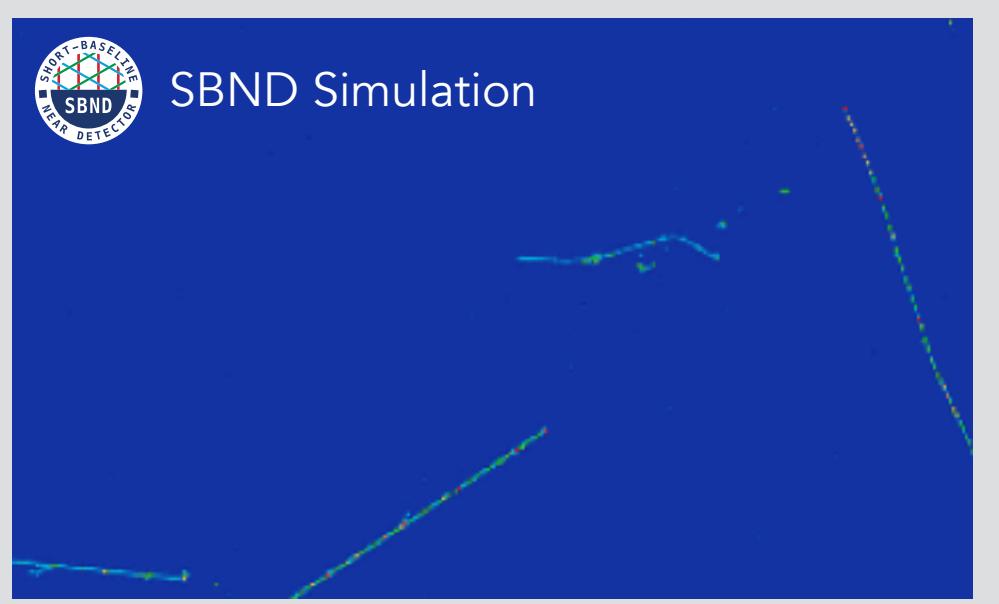
e^+e^- , $\mu^+\mu^-$, $\mu\pi$

Higgs Portal Scalar



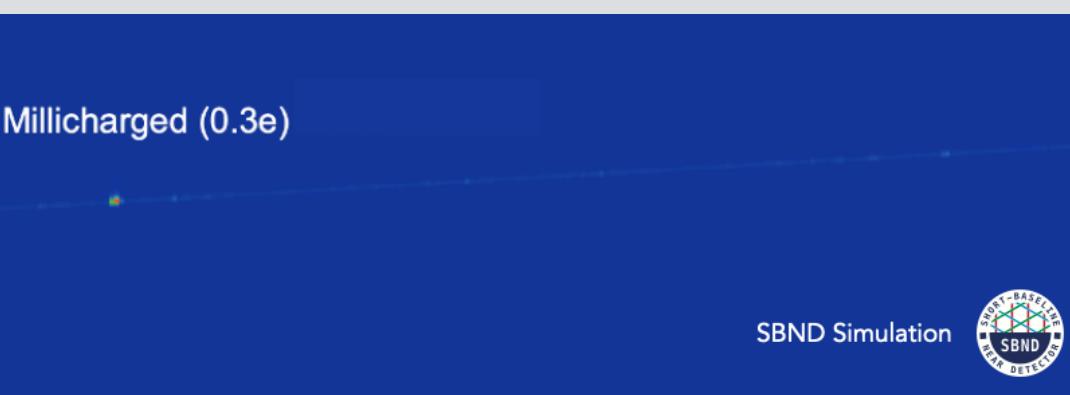
e^+e^- , $\mu^+\mu^-$, no hadronic activity

Light Dark Matter



electron scattering

Millicharged Particles

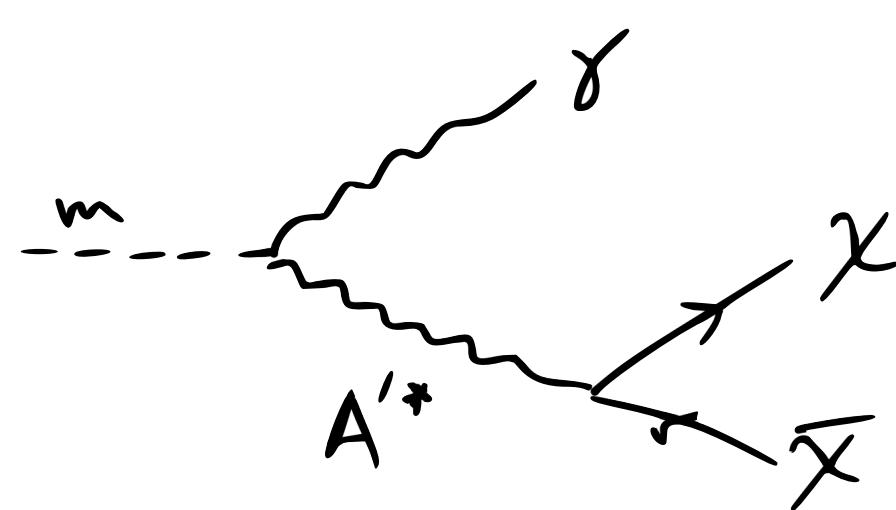


Millicharged (0.3e)

blips/faint tracks

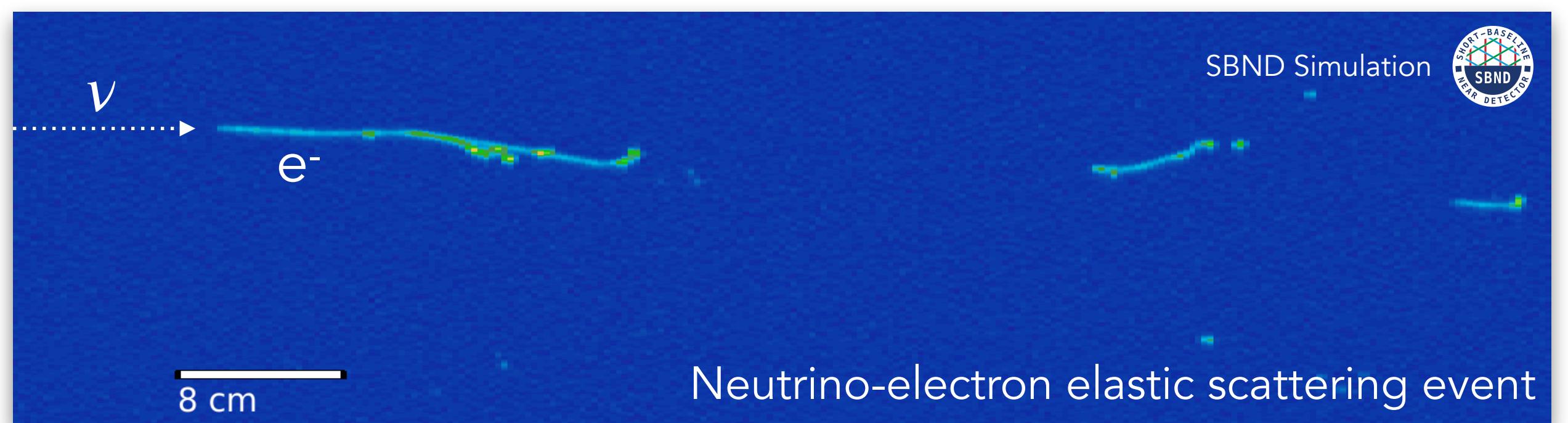
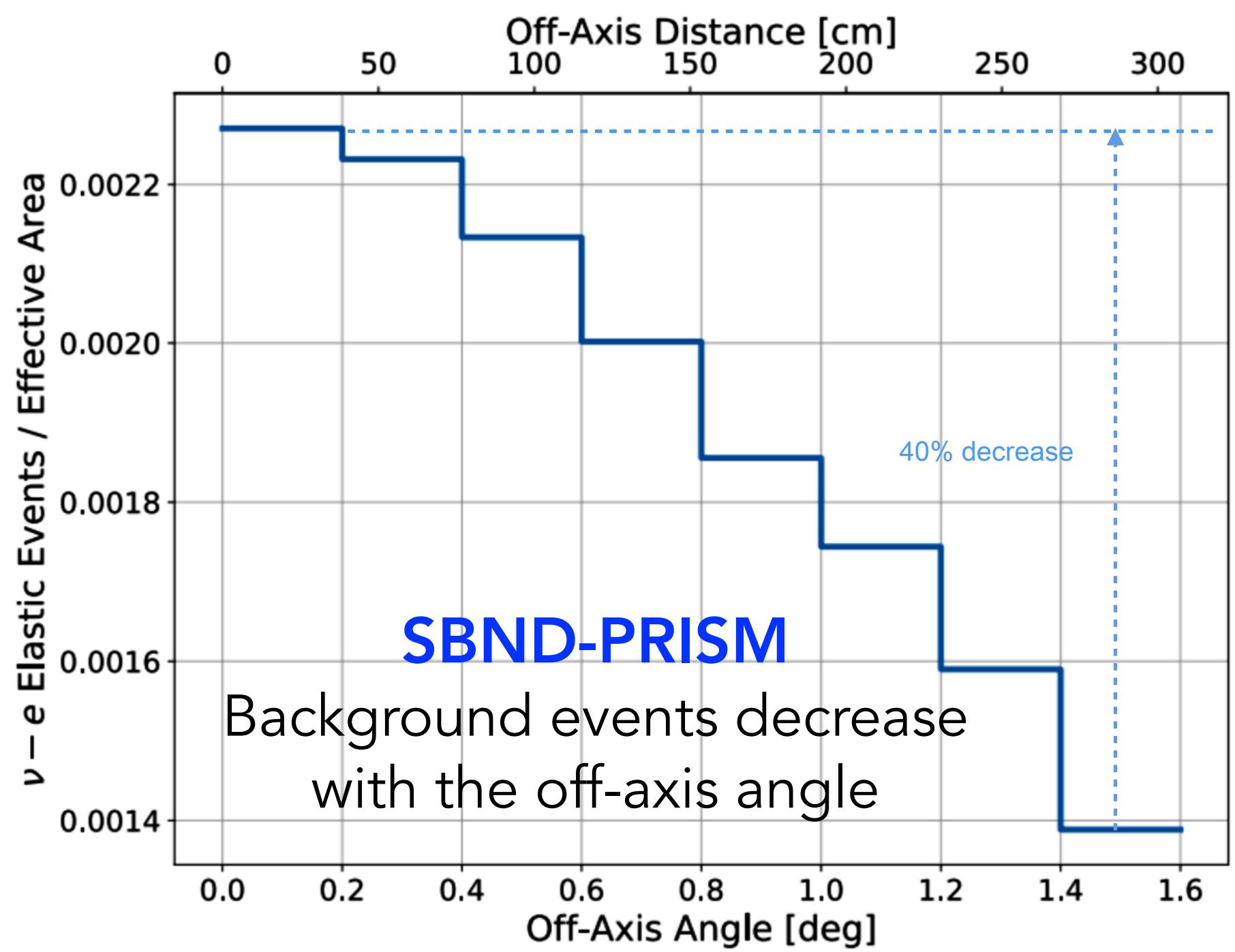
Note: not an exhaustive list!

SEARCHES FOR LIGHT DARK MATTER IN SBND



An example: **light (sub-GeV) dark matter**, coupled to the Standard Model via a dark photon. Dark photons can be produced by the decay of neutral meson (pions, etas) in the target, and decay into dark matter.

The dark matter, through the dark photon, **scatter off electrons** in the detector.



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

SEARCH FOR MILlichARGED PARTICLES IN SBND

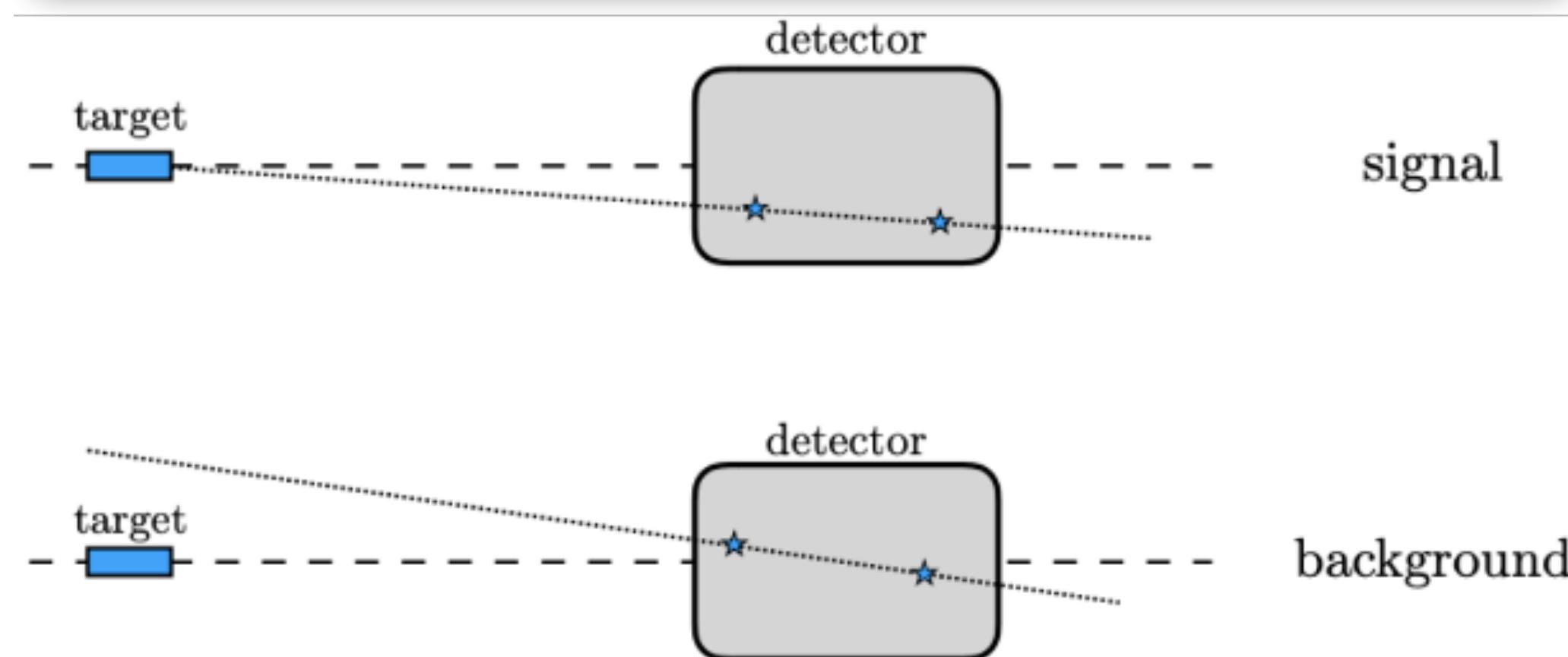
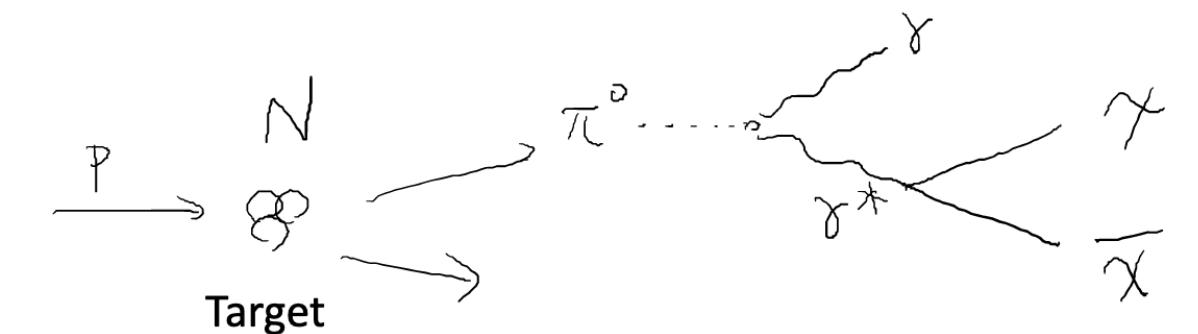


Image credit: ArgoNeuT, PRL124 131801 (2020)

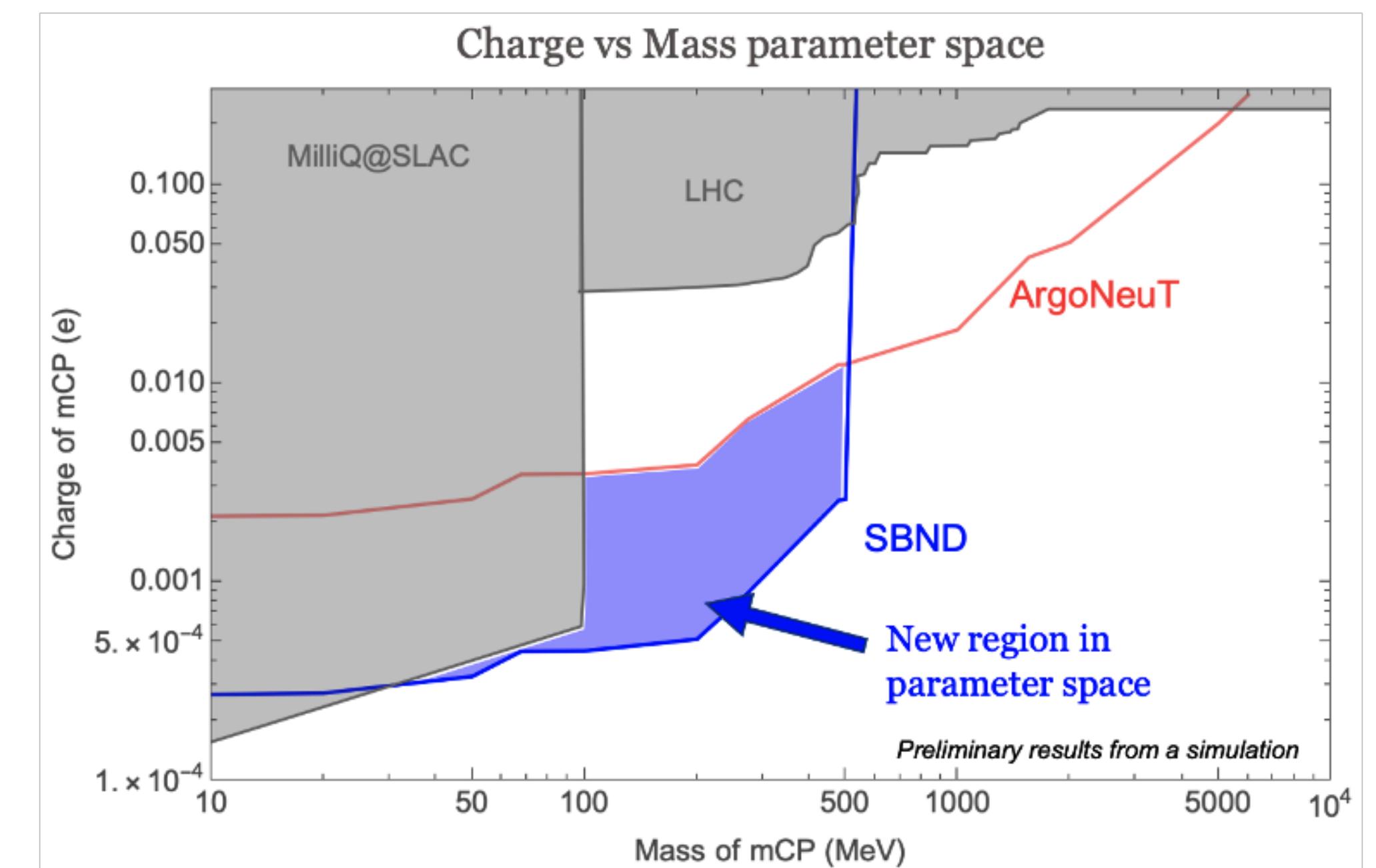
To reduce background:
search for double hits events aligned with the target

mCP have an electric charge $Q=\epsilon \cdot e$ ($\epsilon \ll 1$)



□ production:
meson decays

Millicharged particles would appear in SBND as **blips** or **faint tracks** pointing back to the target.



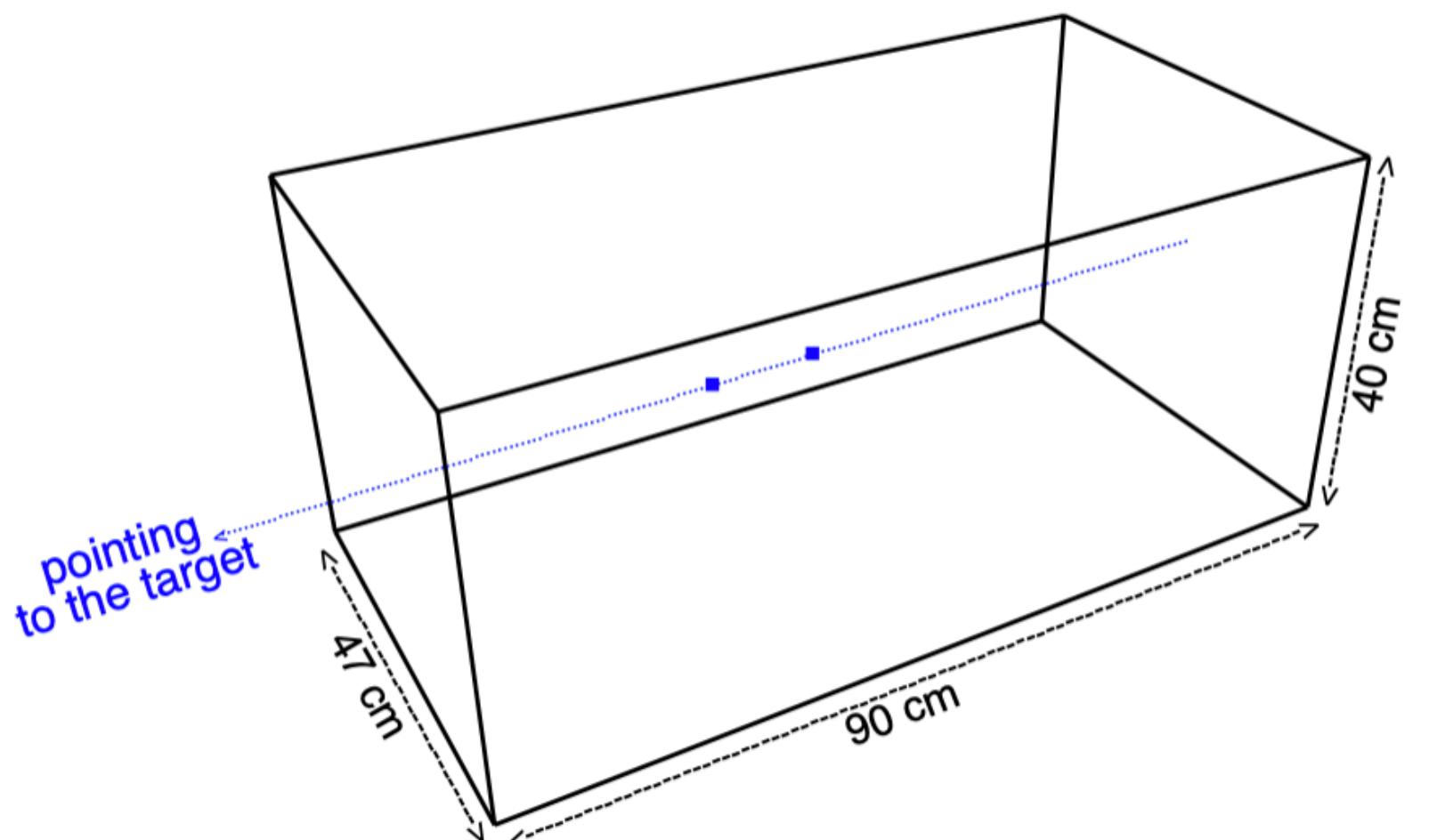
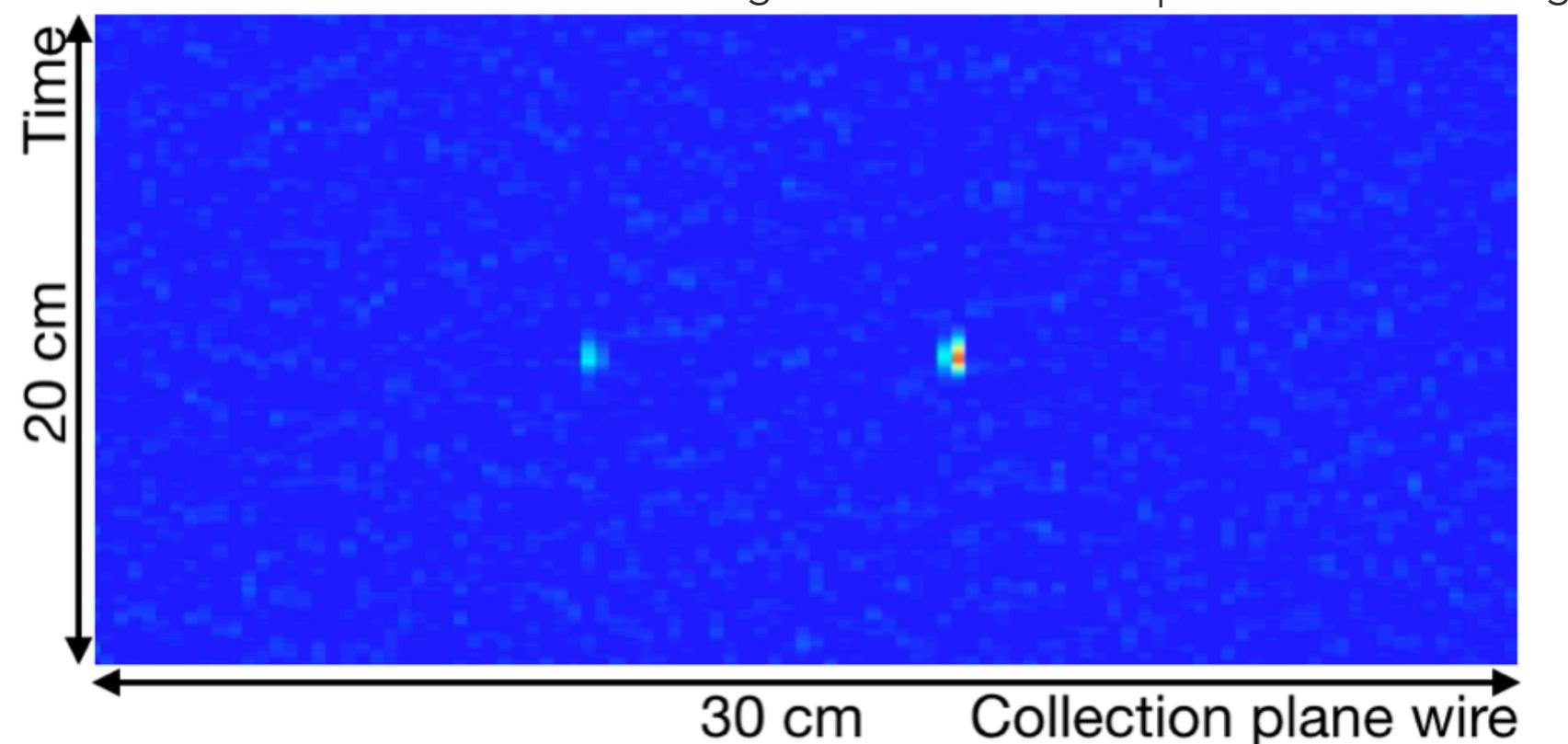
Projected SBND threshold: 50 keV

SIGNATURES FOR NEW PHYSICS IN ARGONeUT

First search for Millicharged Particles in LAr TPC

one mCP Signal Candidate Event observed

[compatible with the expected background]
1.46 background events which point back to the target expected

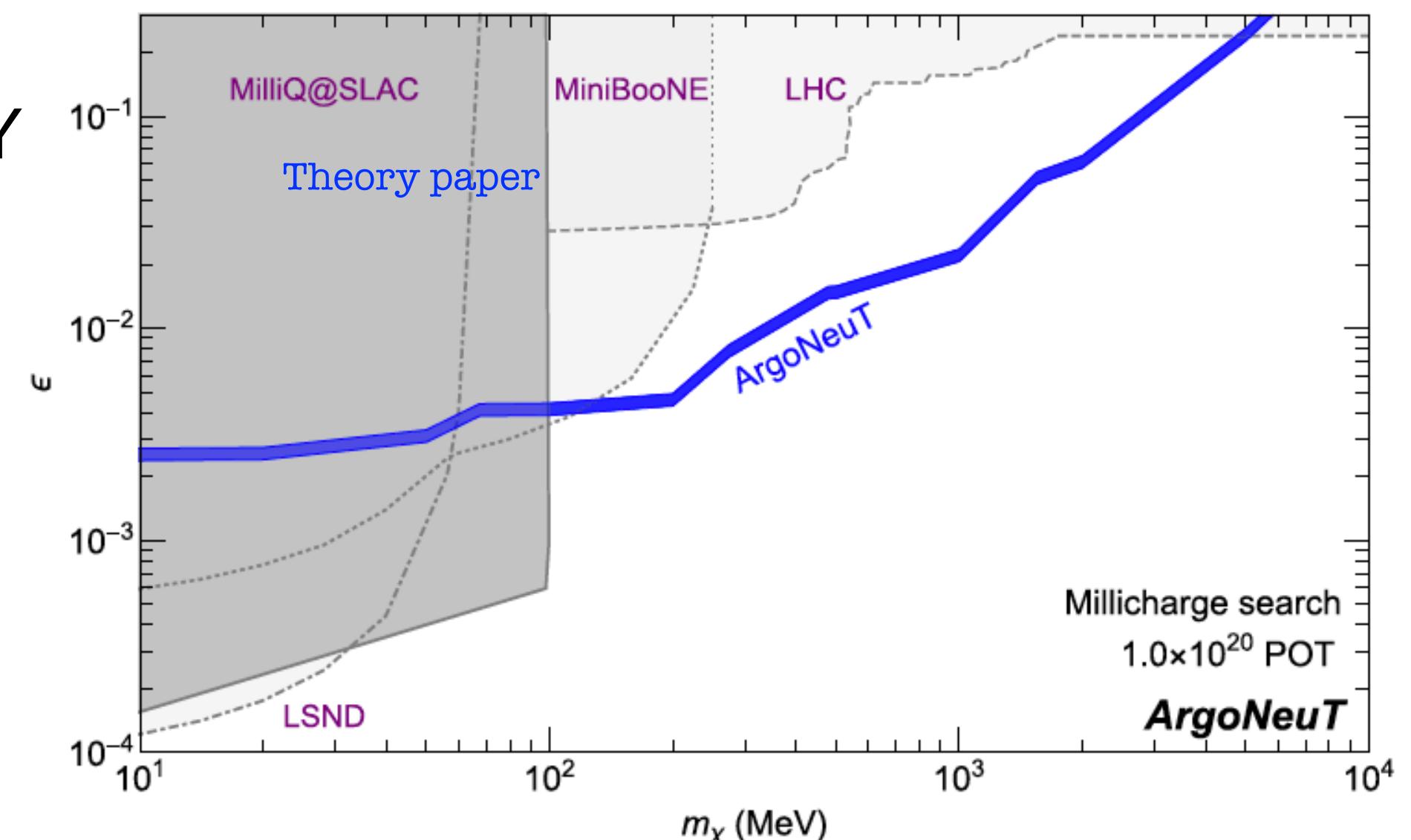


Low energy threshold (300 KeV) is the key!

JOINT
EXPERIMENT+THEORY
PROJECT

Roni Harnik, Zhen Liu, and O. P., "Millicharged particles in liquid argon neutrino experiments", JHEP 07, 170 (2019)

ArgoNeuT Collaboration + 2 theorists (R. Harnik and Z. Liu)
R. Acciari et al., PRL124 131801 (2020)



Leading constraints in unexplored parameter region!

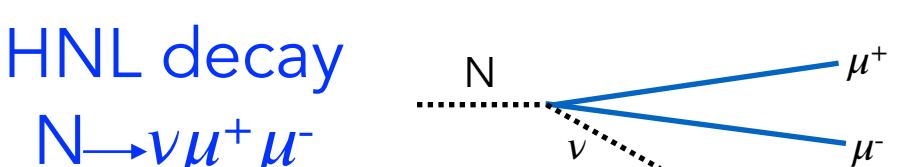
SIGNATURES FOR NEW PHYSICS IN ARGONeUT

First search for Heavy neutral Leptons $N \rightarrow \nu \mu^+ \mu^-$ in LAr TPC

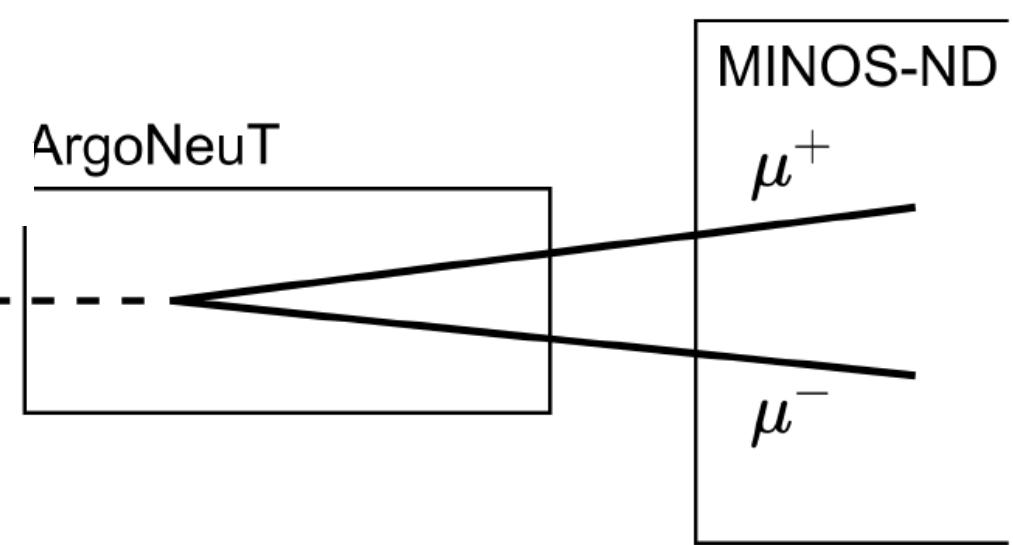
Consider **tau-coupled scenario**, i.e. $|U_{\tau N}|^2 \neq 0$ and $|U_{eN}|^2 = |U_{\mu N}|^2 = 0$

Assuming HNL production predominately from τ^\pm decay*:

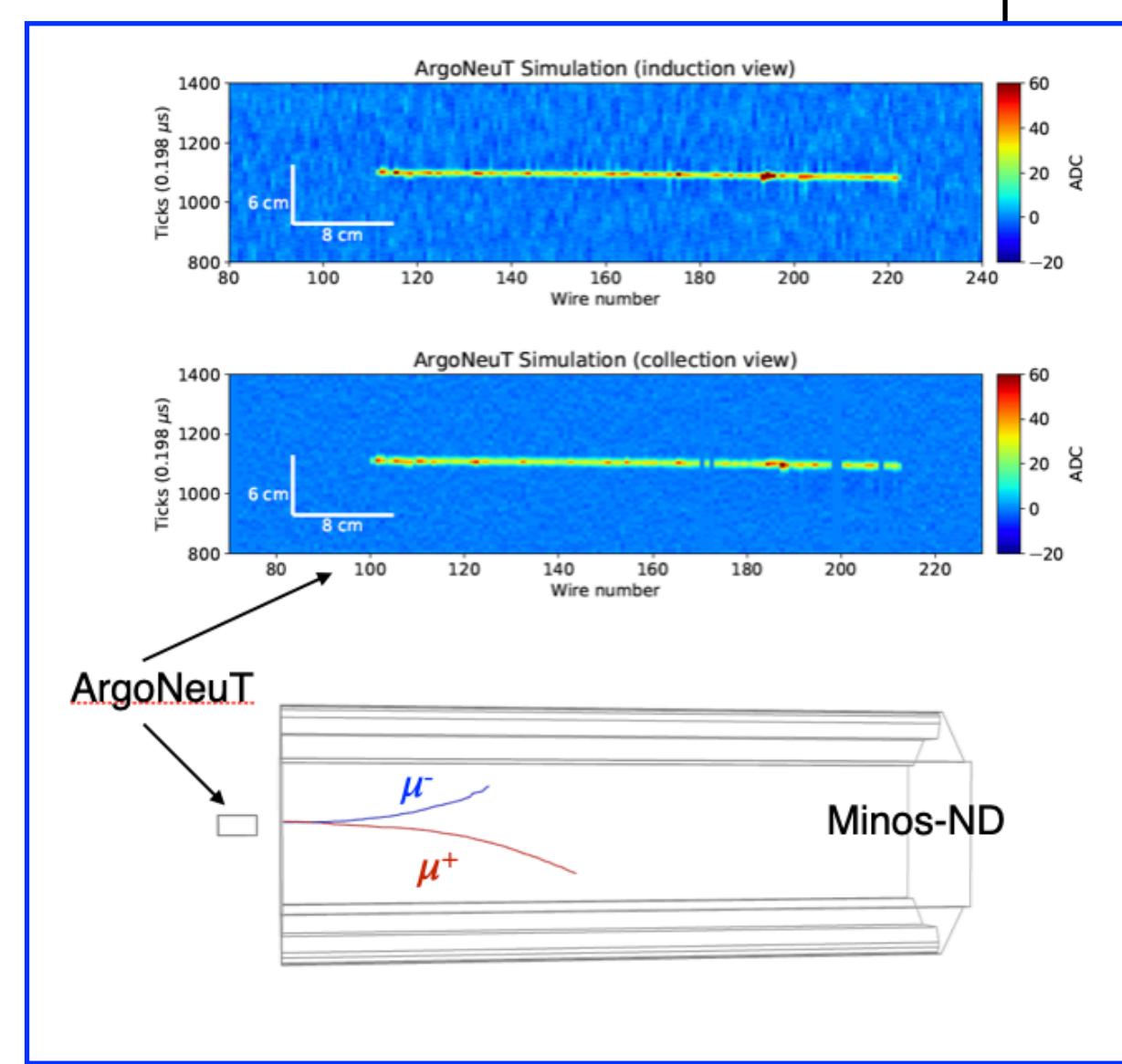
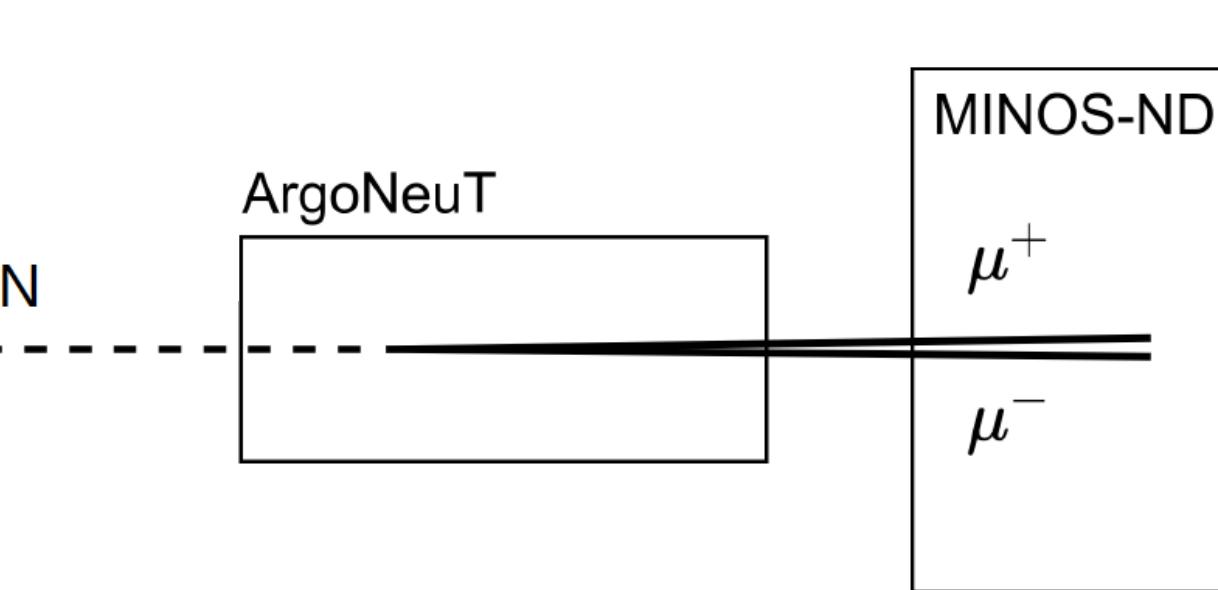
D/D_s decay to τ , that subsequently decay to HNLs
 $\tau^\pm \rightarrow N X^\pm$ (X^\pm is a SM particle e.g. π^\pm)



Two-track Event



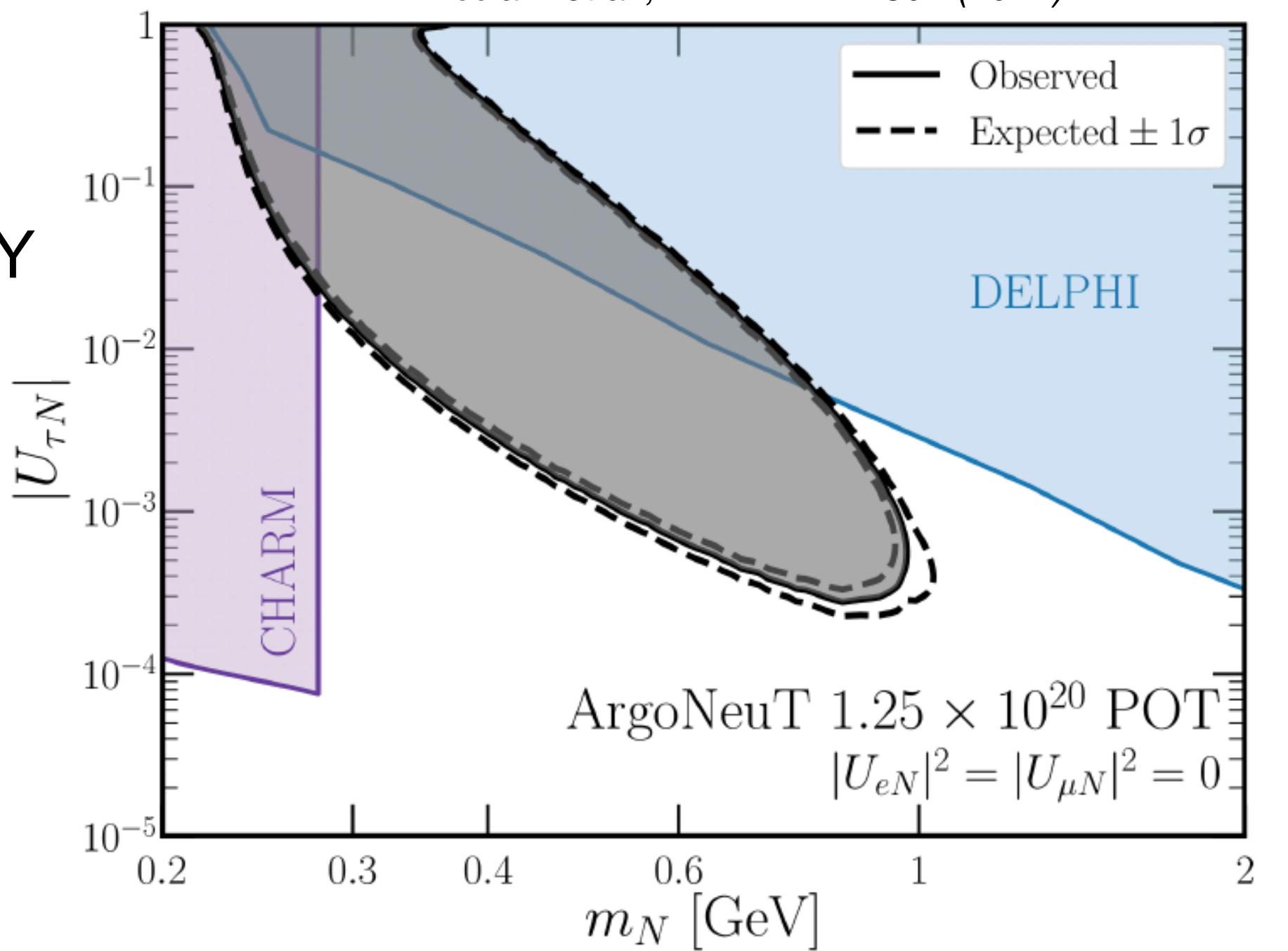
Double-MIP Event



JOINT
 EXPERIMENT+THEORY
 PROJECT

0 events observed in the data, consistent with background expectation of 0.4 ± 0.2 event

ArgoNeuT Collaboration + 2 theorists (K. Kelly and A. de Gouvêa)
 R. Acciarri et al., PRL 127 121801 (2021)



**Significant increase in the parameter space exclusion region!
 New exclusion limits for tau-coupled HNLs with $m_N=280-970$ MeV.**

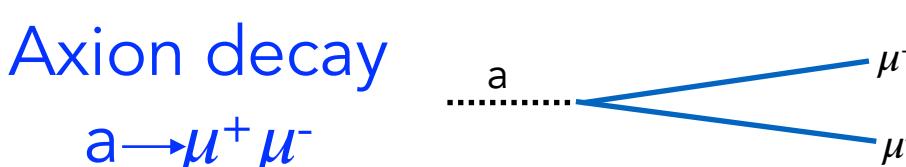
*For details see: P. Coloma et al. Eur. Phys. J. C, 81(1):78, 2021

SIGNATURES FOR NEW PHYSICS IN ARGONeUT

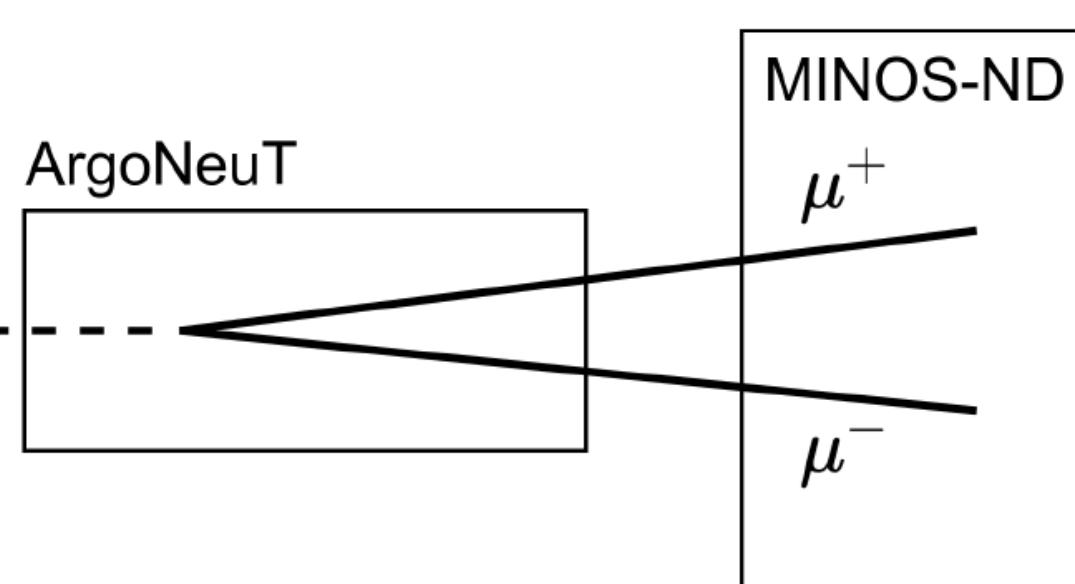
First search for Heavy QCD Axions in LAr TPC

Heavy QCD axions production from π^0 , η and η' mesons* and decay to ee, $\mu\mu$, $\gamma\gamma$ + hadronic modes.

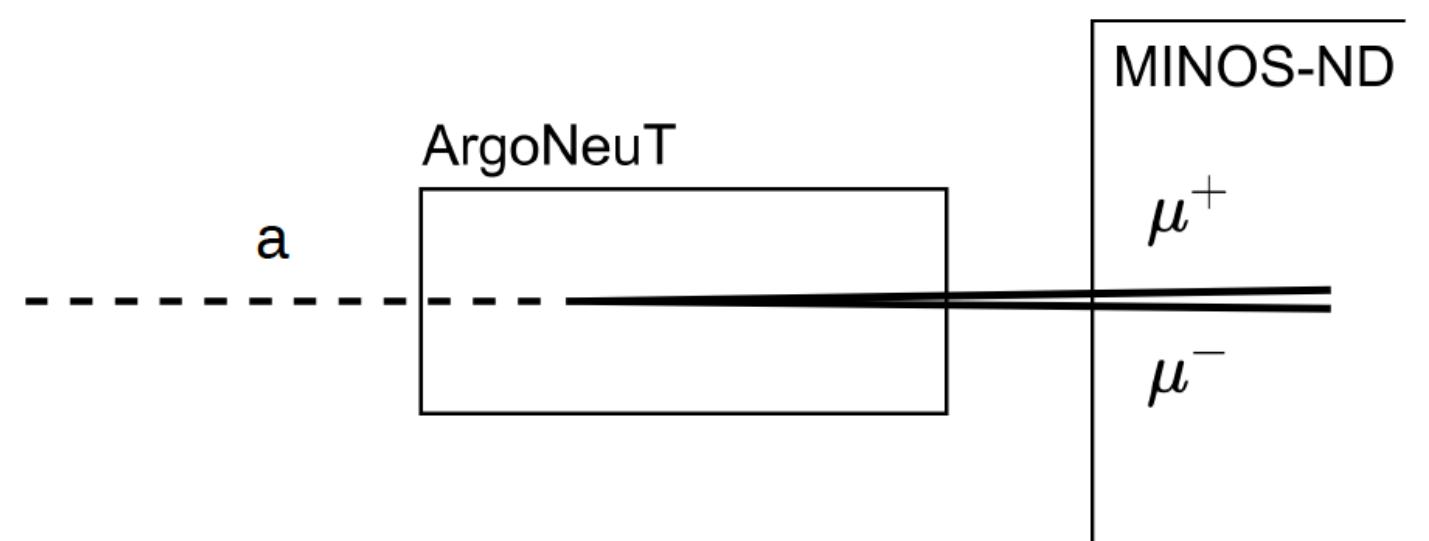
Contributions depend on axion-lepton coupling, c_ℓ : two benchmark scenarios $c_\ell = 1/36$ and $c_\ell = 1/100$.



Two-track Event



Double-MIP Event

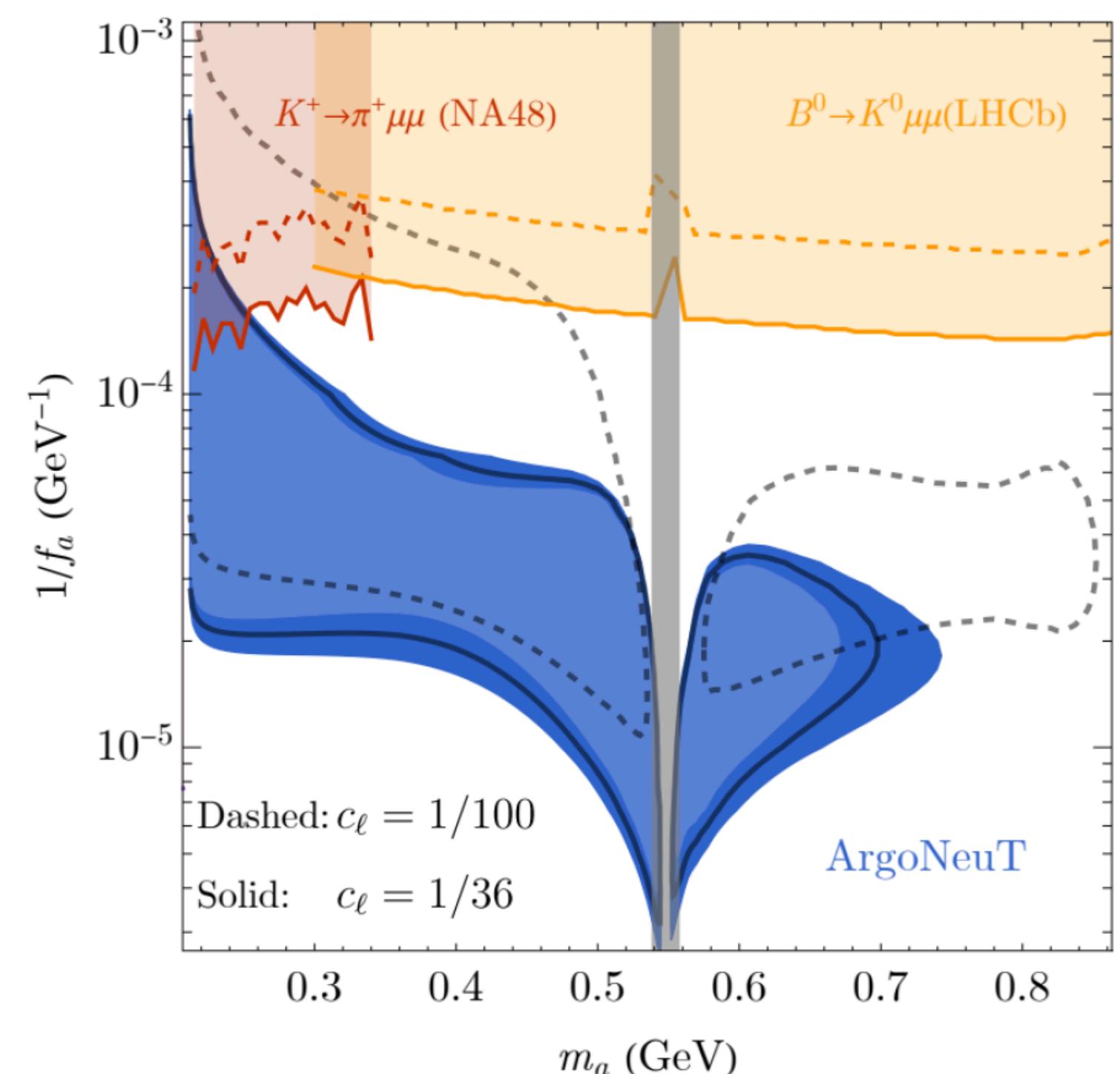


JOINT
EXPERIMENT+THEORY
PROJECT

0 events observed in the data, consistent with background expectation of 0.1 ± 0.1 event

ArgoNeuT Collaboration + 6 theorists (R. Co, R. Harnik, K. Kelly, S. Kumar, Z. Liu, K Lyu)

R. Acciari et al., <https://arxiv.org/abs/2207.08448>



New exclusion constraints for heavy QCD axions with $m_a \sim 0.2$ – 0.9 GeV and axion decay constant $f_a \sim 10$ TeV.

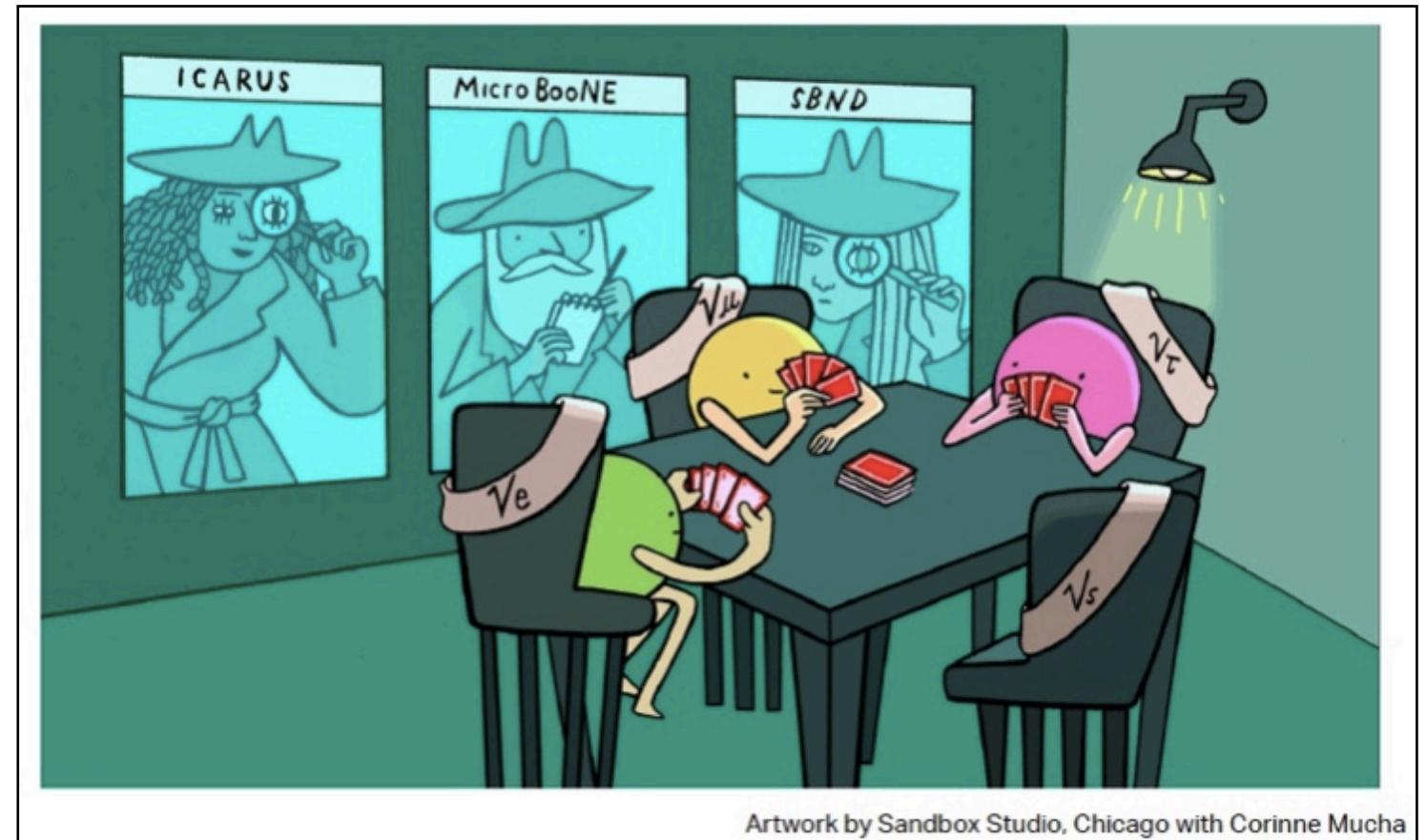
*For details see: K. Kelly, S. Kumar and Z. Liu Phys. Rev. D 103 (2021) 9, 095002

SUMMARY

LAr TPC neutrino detectors at Short-Baseline are fantastic tools to look for
 new physics in the neutrino sector and beyond!

ArgoNeuT, a small LAr-TPC provided **leading constraints** on millicharged particles, heavy neutral leptons and
 heavy QCD axions in unexplored parameter space regions.

The **Short-Baseline Neutrino (SBN)** program will
 perform a **world-leading** search for
 eV-scale sterile neutrinos.



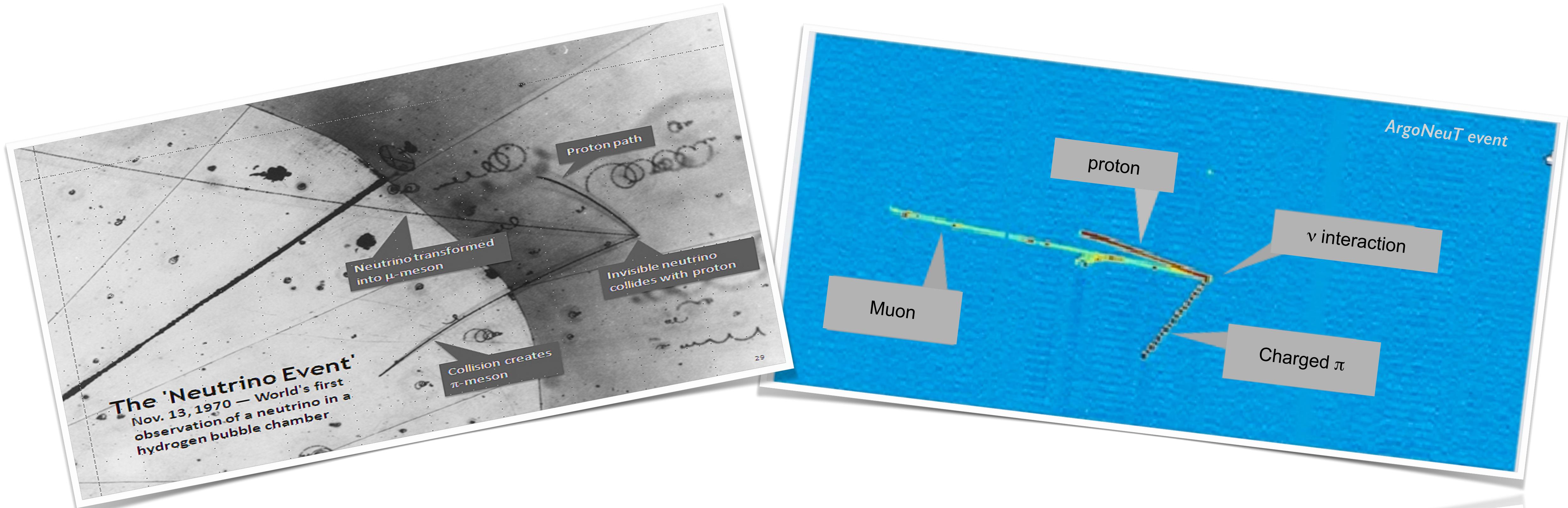
Beyond oscillation searches, SBN has a broad science goal, which
 addresses alternative explanations of the Short-Baseline anomalies and
 includes other **Beyond Standard Model explorations**.



Exciting times are ahead for the SBN Program. **ICARUS** is collecting data.
SBND completed the construction of the detector and will begin operations in the Fall.

EXTRAS

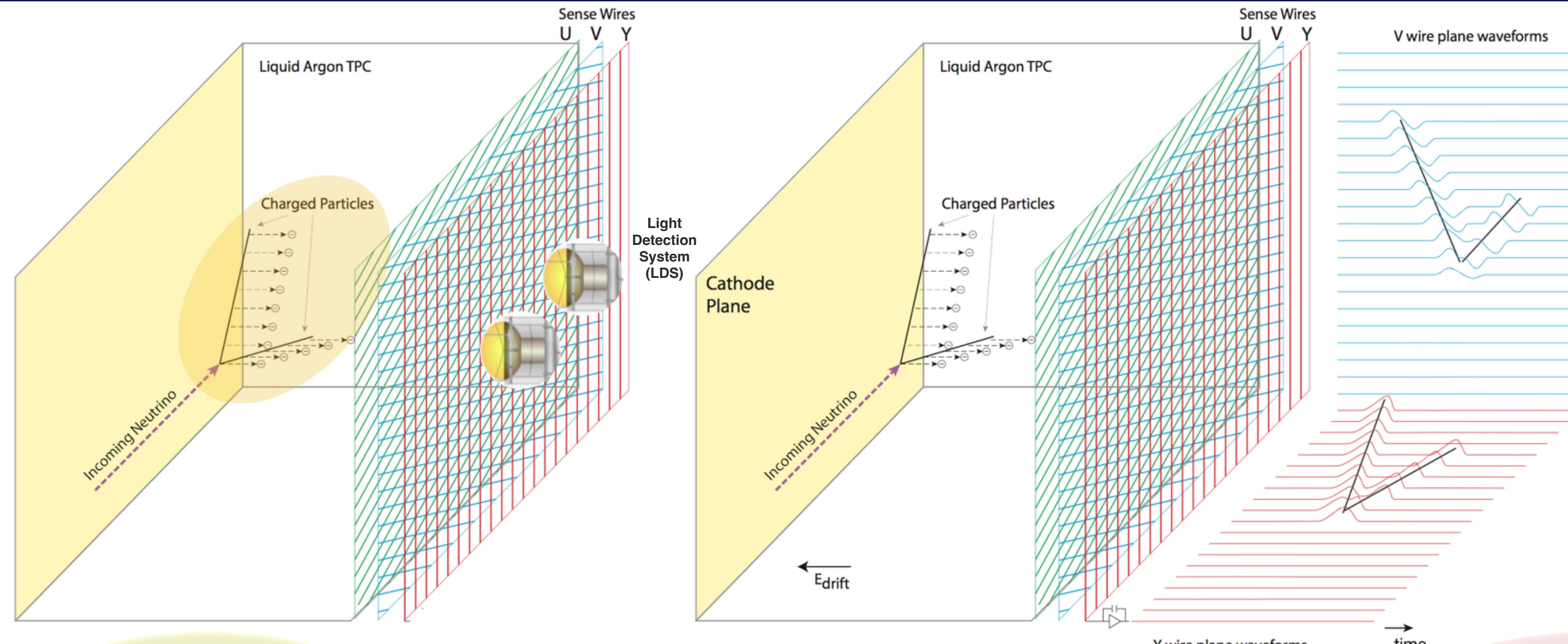
WHY LAr TIME PROJECTION CHAMBER?



LAr TPC: Bubble chamber quality of data with added calorimetry

Liquid argon is the technology of choice for precision neutrino physics. The Fermilab accelerator neutrino program is based on the LArTPC technology.

LAR TPC AT WORK



Charged particles in LAr produce free ionization electrons and scintillation light

m.i.p. at 500 V/cm: $\sim 60,000 \text{ e}/\text{cm}$
 $\sim 50,000 \text{ photons}/\text{cm}$

VUV photons propagate and are shifted into VIS photons

Ionization charge drifts in a uniform electric field towards the readout wire-planes

Electron drift time $\sim \text{ms}$

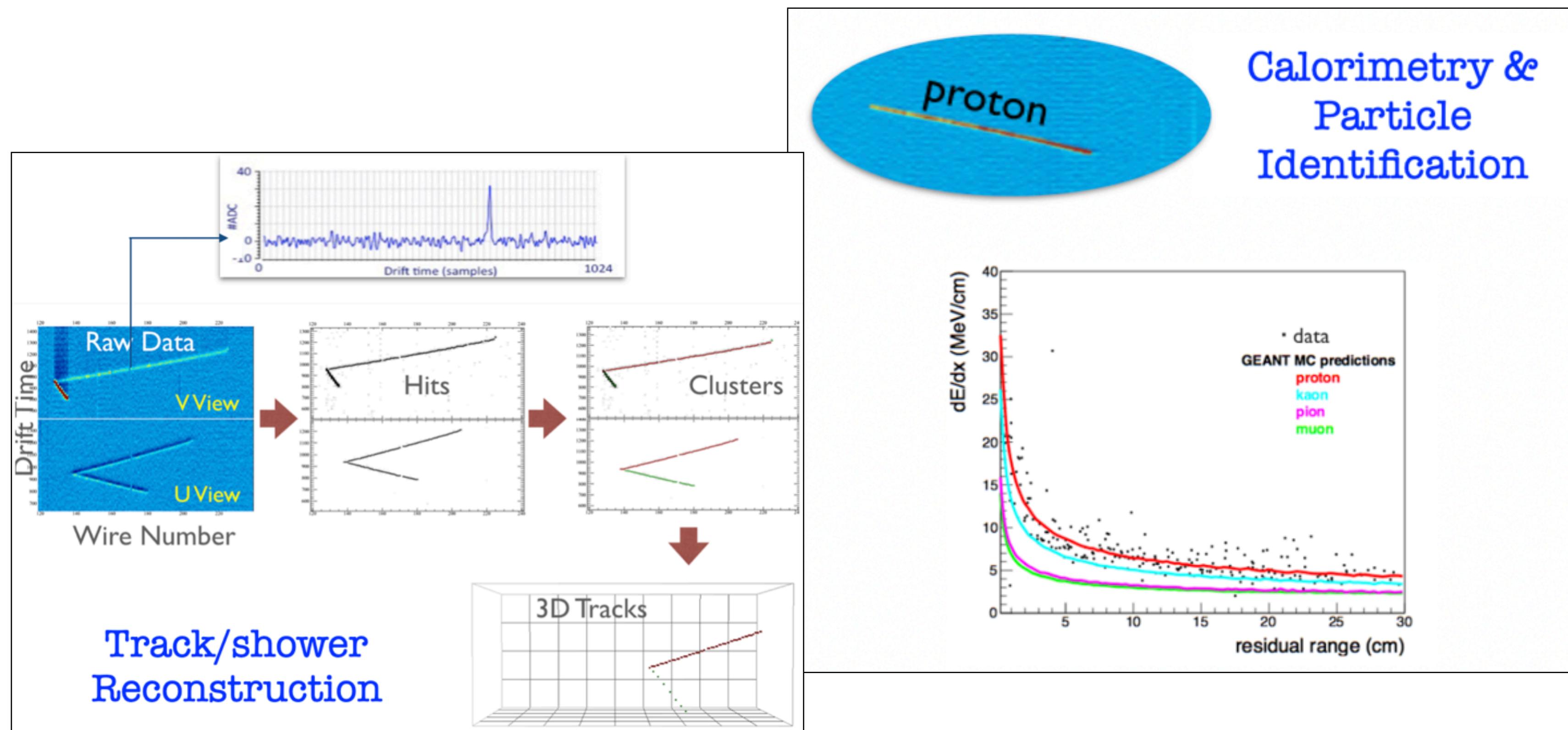
Scintillation light fast signals from LDSs give event timing

Digitized signals from the wires are collected [time of the wire pulses gives the drift coordinate of the track and amplitude gives the deposited charge]

THE LAr TPC TECHNOLOGY

Measure neutrino interactions **in real time** with millimeter position resolution.
Excellent capability for energy depositions **from sub-MeV to few GeV**,
far beyond that offered by any other neutrino detector.

LArTPC at work: imagining, energy and timing



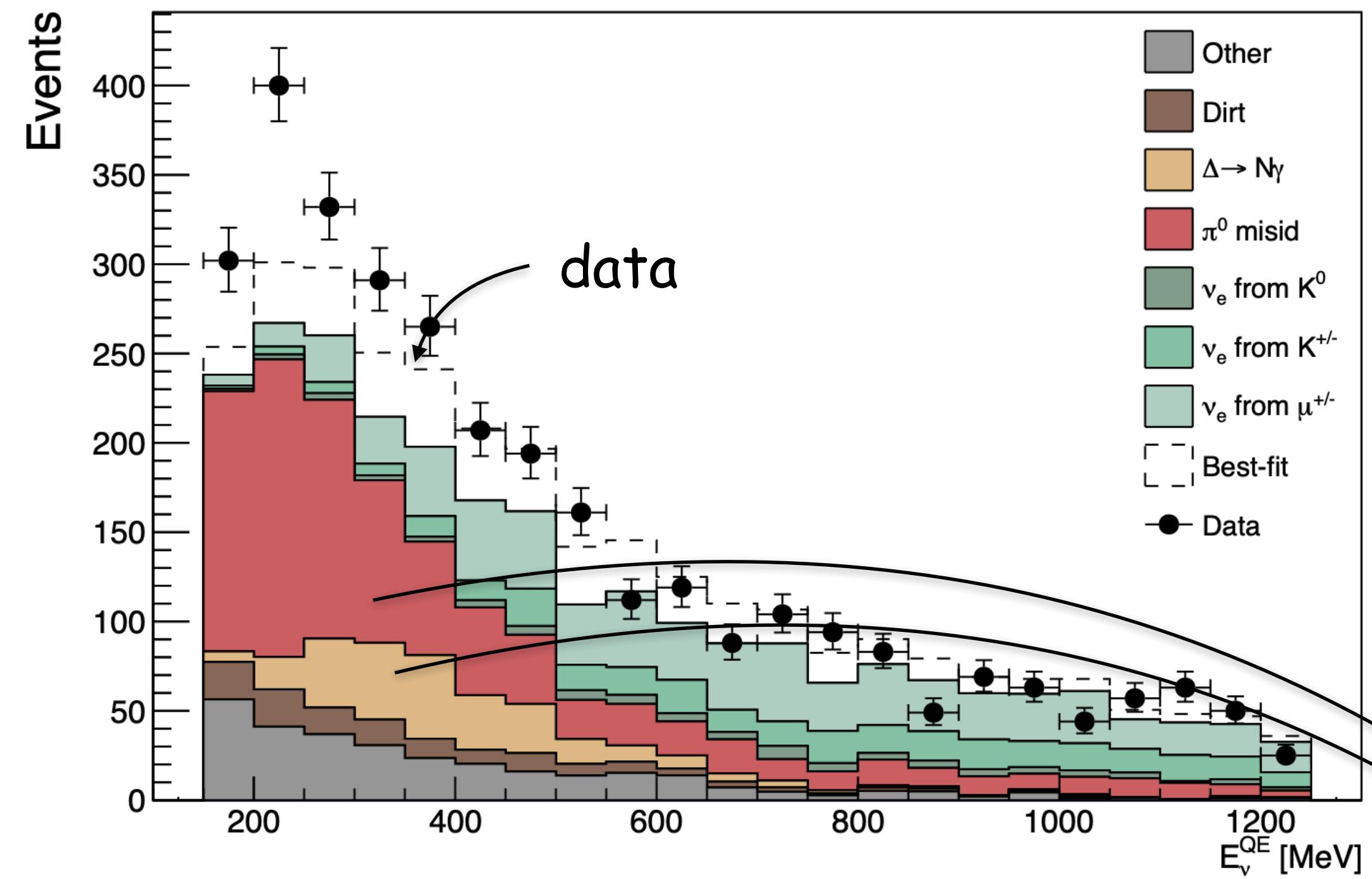
and few ns **timing** resolution from light detection system(s).

- Multiple 2D and the 3D reconstruction of charged particles ⇒ **Imaging**
- Total charge proportional to the deposited energy ⇒ **Calorimetry**
- dE/dx along the track ⇒ **Particle Identification**

ELECTRONS OR PHOTONS?

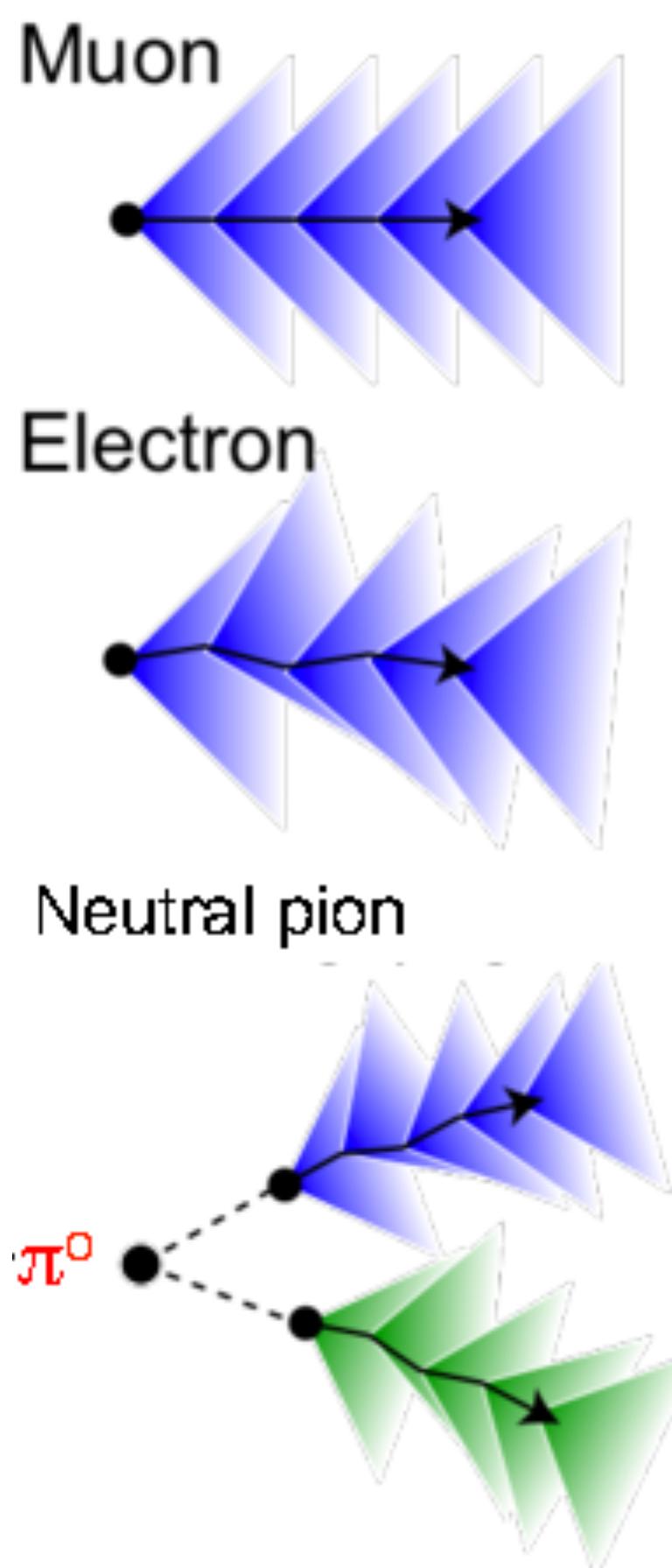
MiniBooNE

Phys. Rev. D 103, 052002 (2021)



**MiniBooNE electron-like
“Low Energy excess”...
Photons? Electrons?**

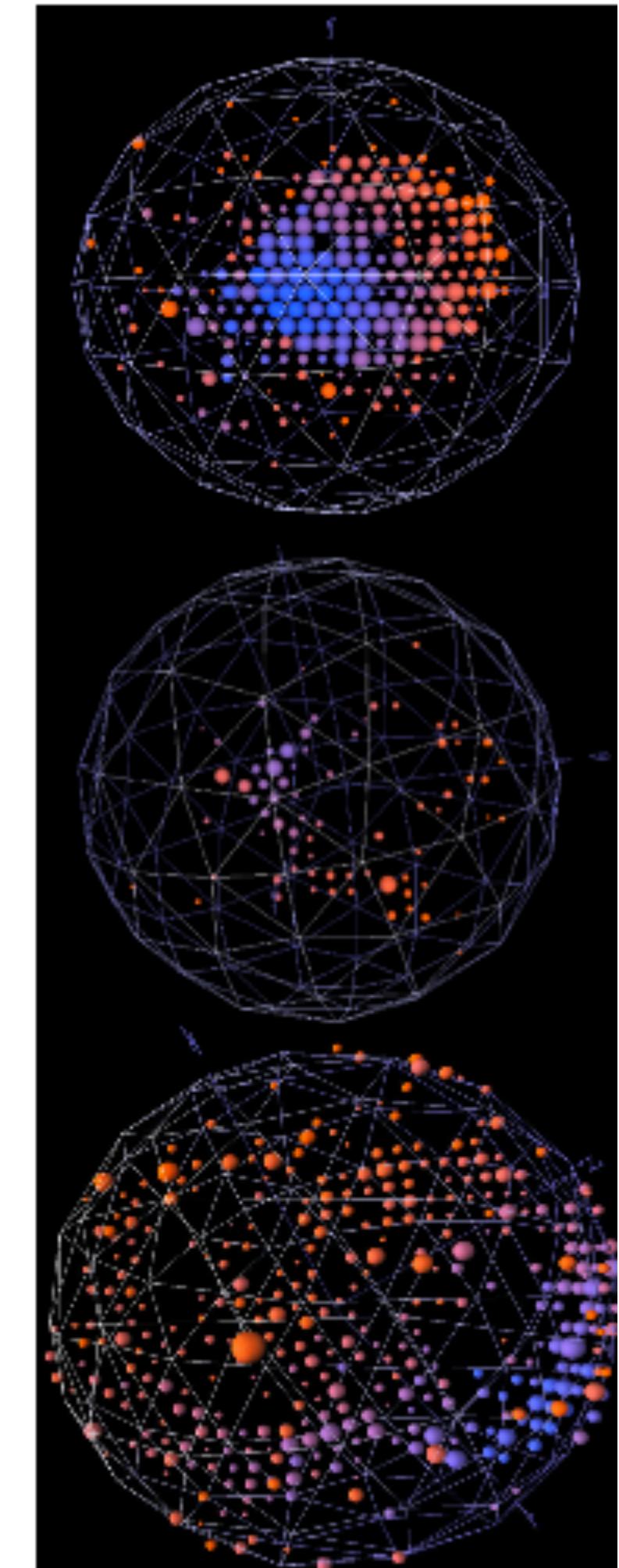
track



Cherenkov

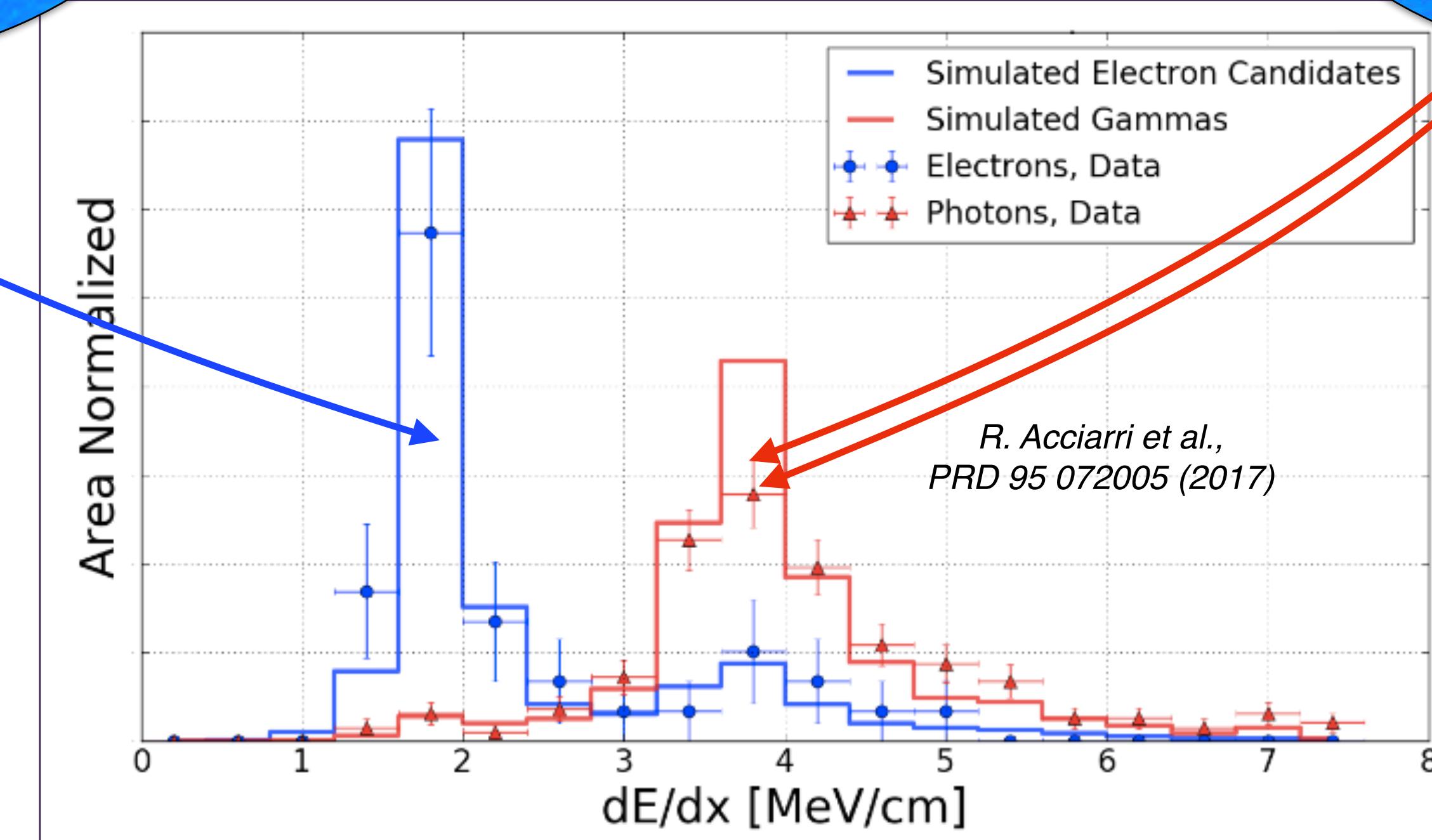
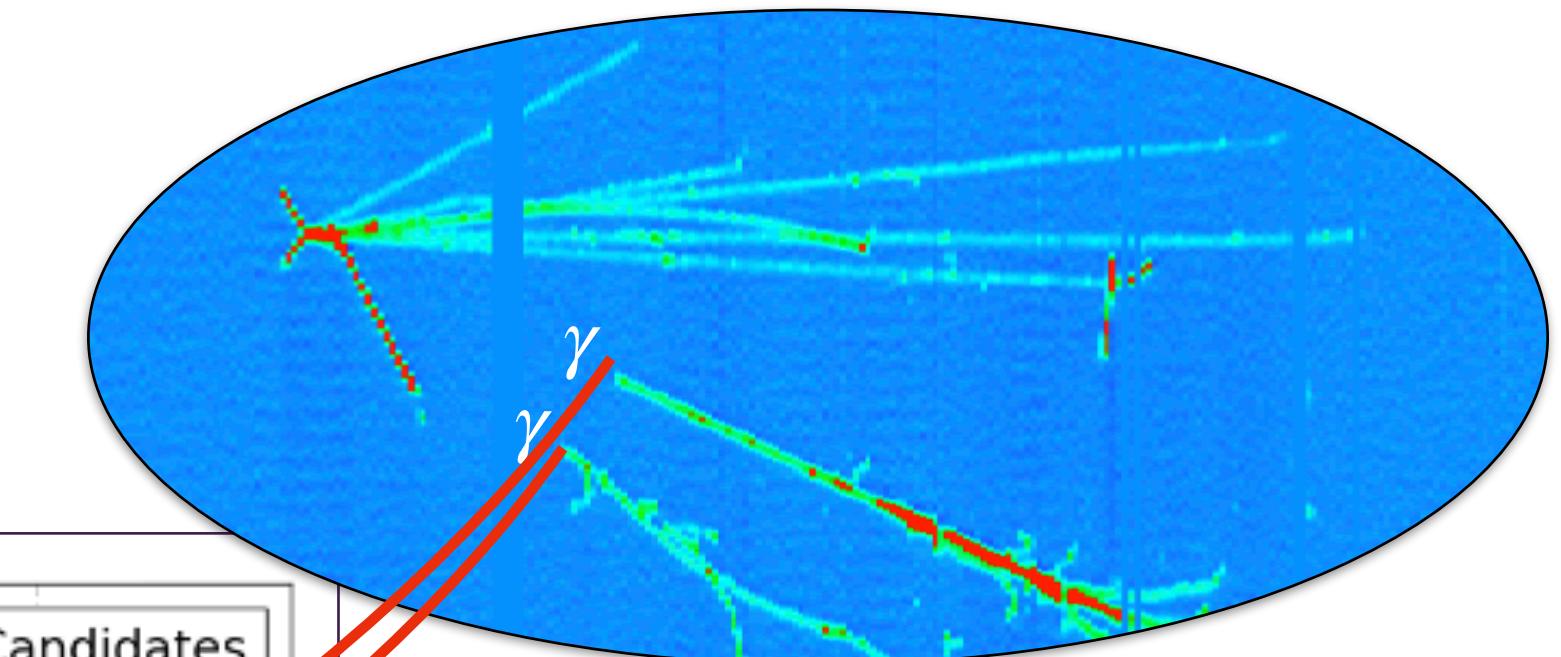
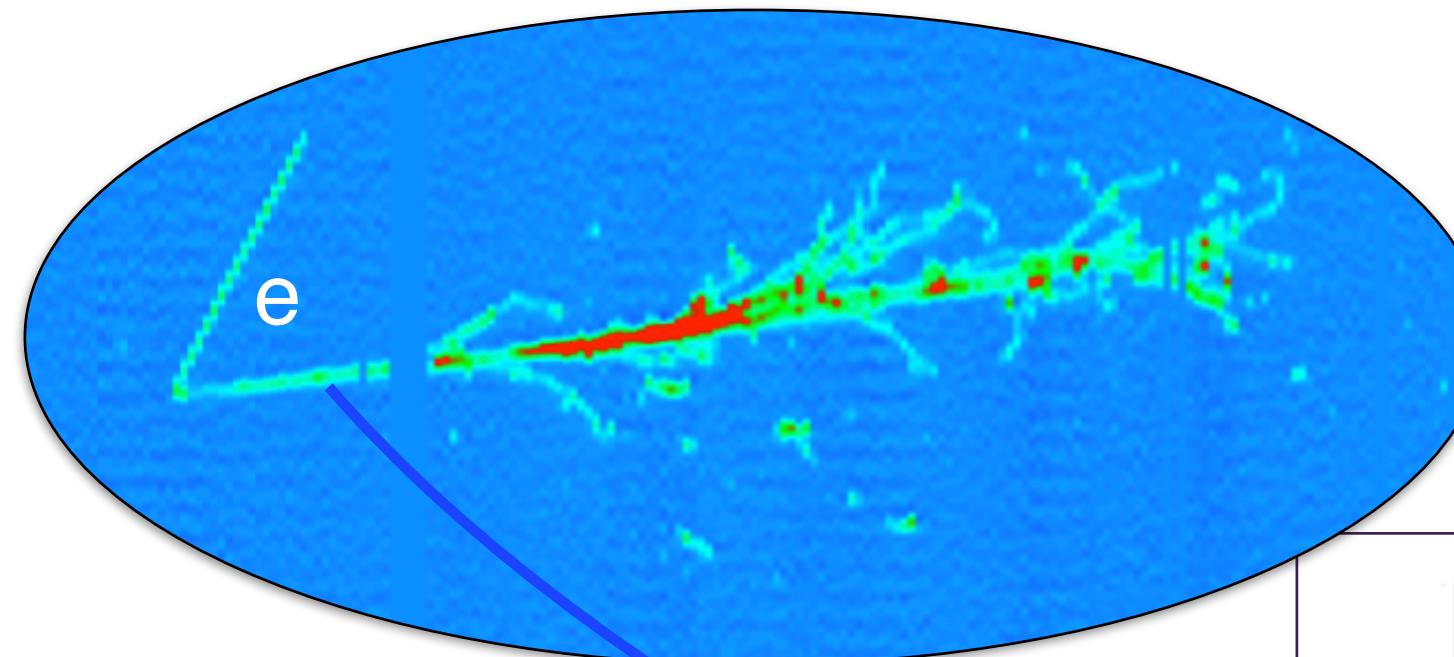


Candidate



→ **LAr TPC!**

ELECTRON- γ DISCRIMINATION IN LAr TPC

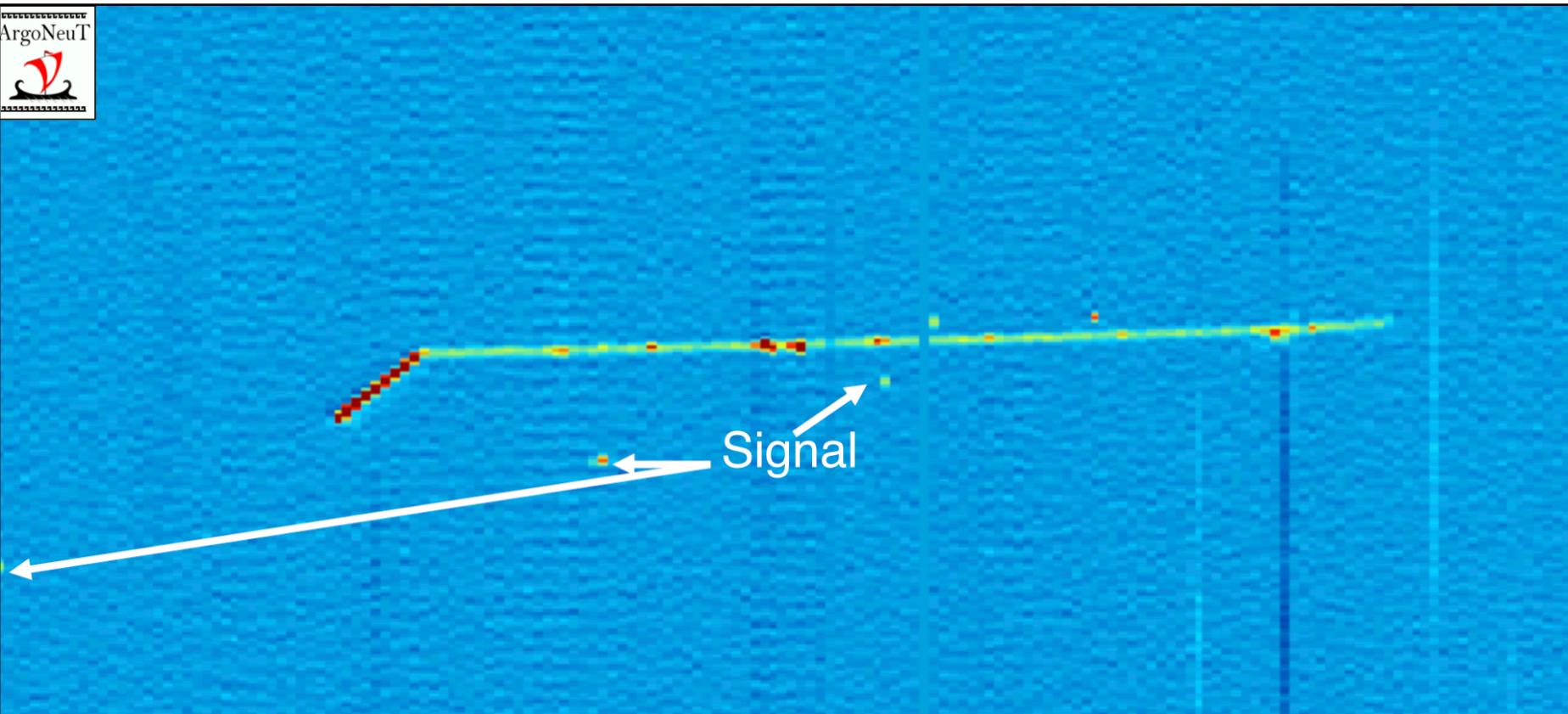


Analyzing topology
(gap from the vertex) and
 dE/dx

e- γ discrimination capability of LAr is crucial
to disentangle the signal/background nature
of the electron-like excess
observed by MiniBooNE

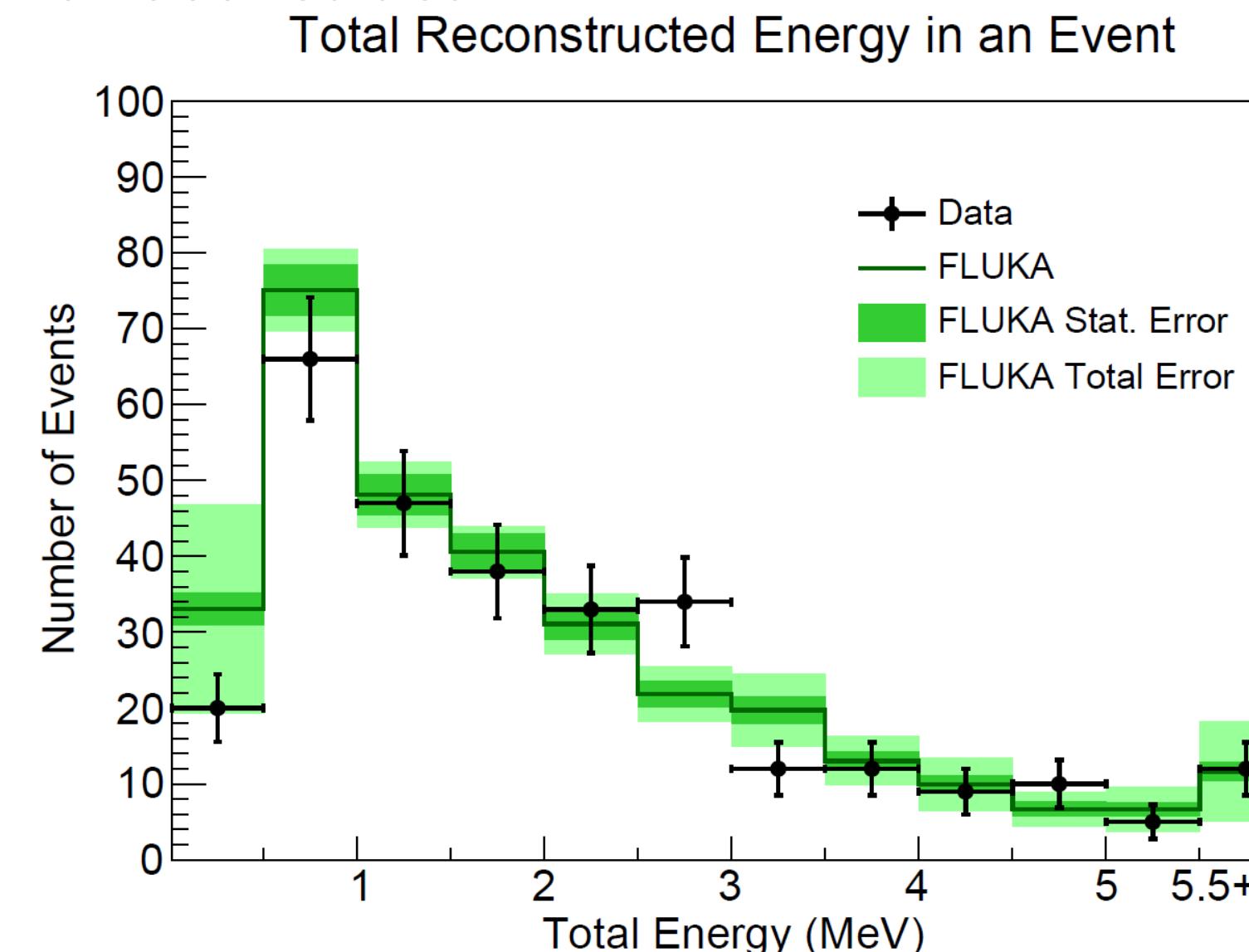
THE LOW ENERGY FRONTIER

LAr TPC's have demonstrated to be able to detect and reconstruct
(sub-)MeV energy depositions



**300 KeV threshold
In ArgoNeuT**

R. Acciarri et al., PRD 99, 012002 (2019)



Topologically separated low-energy depositions are identified as electrons produced by Compton scattering of

- de-excitation photons from the target nucleus and
- photon produced by neutron inelastic interactions

The capability to resolve individual collisions down to < MeV threshold is important for

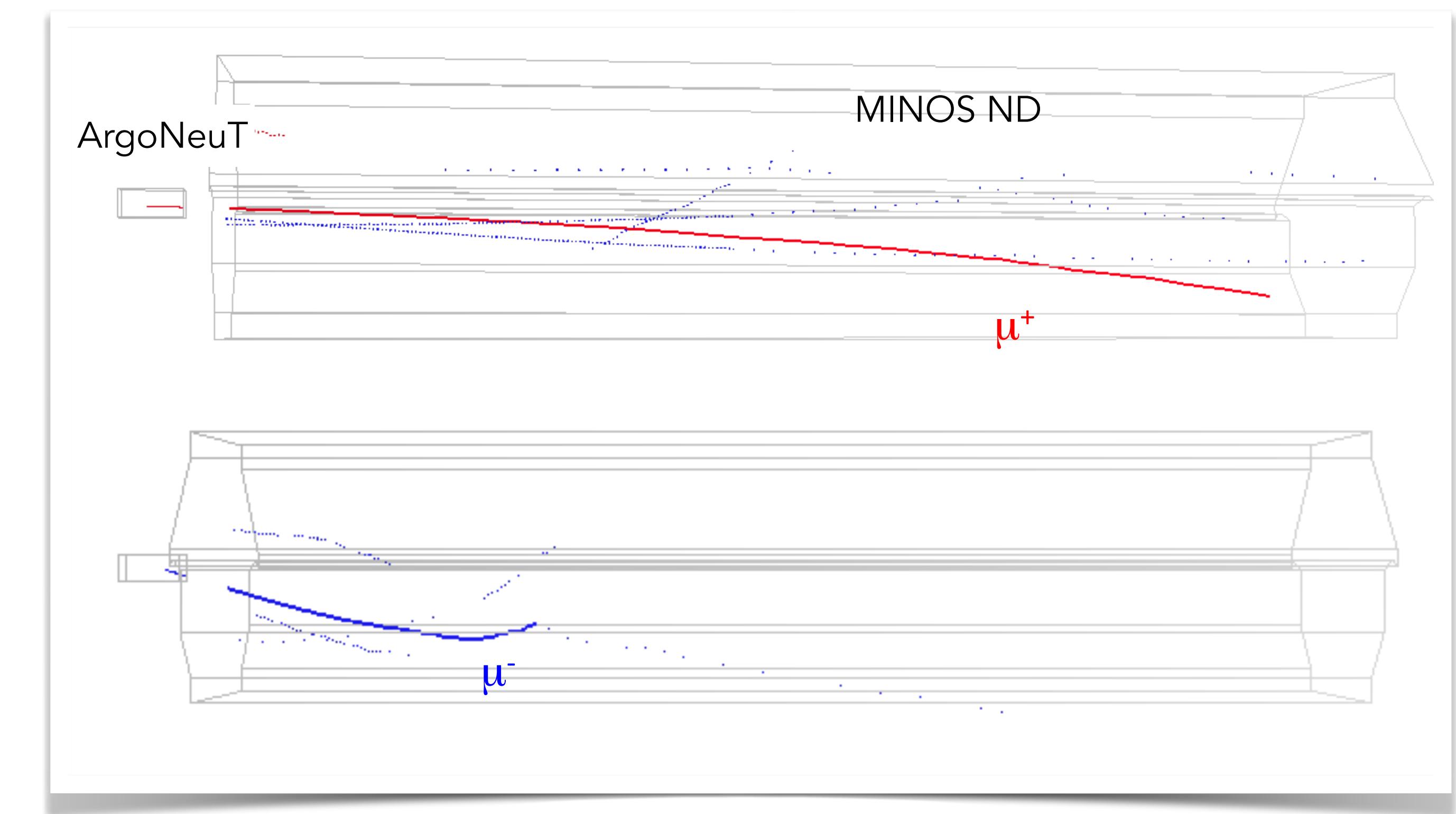
- Neutrino Energy reconstruction [A. Friedland and S. Weishi Li, PRD 99, 036009 (2019)]
- Detection and reconstruction of supernova neutrino interactions in large LArTPCs (ex. DUNE)
- Study new physics scenarios.

ADVANTAGES OF ARGO NEUT

Despite being a small LAr TPC and taking data for a short time, Argoneut has some advantages:

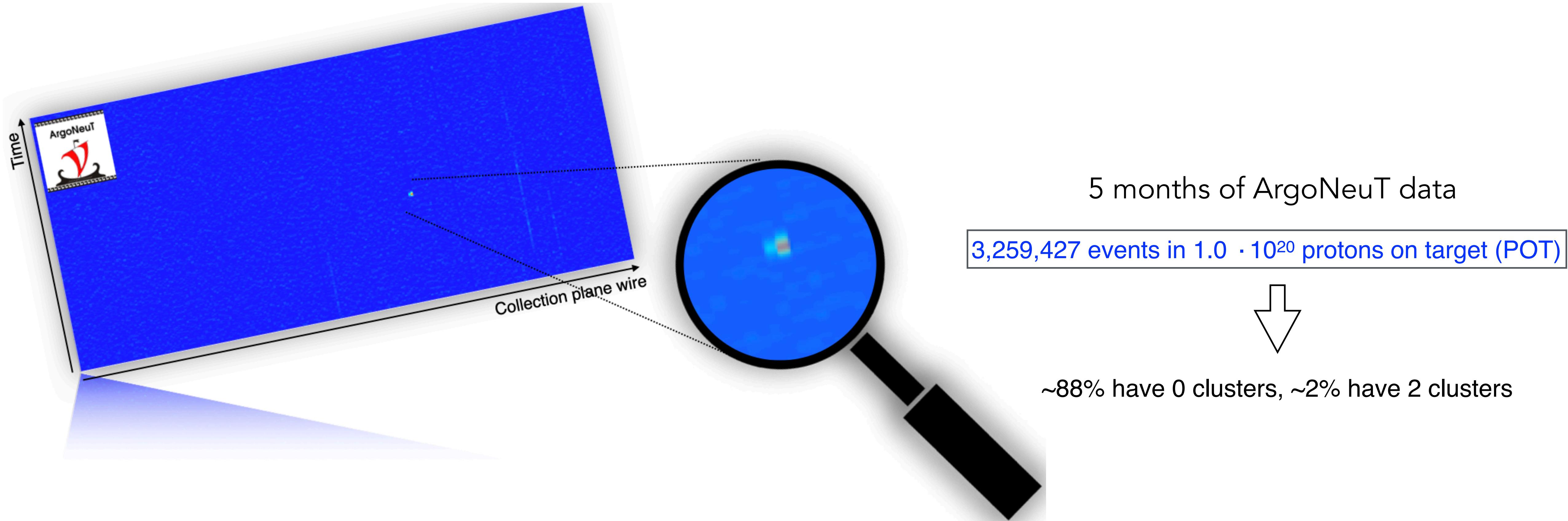
- 100 m underground → no cosmics
- Well understood/calibrated data set
- MINOS ND as spectrometer
 - Magnetic field allows muon momentum measurement and charge recognition
 - Allows to distinguish pion from muon, typically difficult in LAr TPCs

MINOS ND used to identify muons - tracks exiting ArgoNeuT are reconstructed in MINOS ND



JOINT EXPERIMENT+THEORY PROJECT: USE OF “EMPTY” EVENTS!

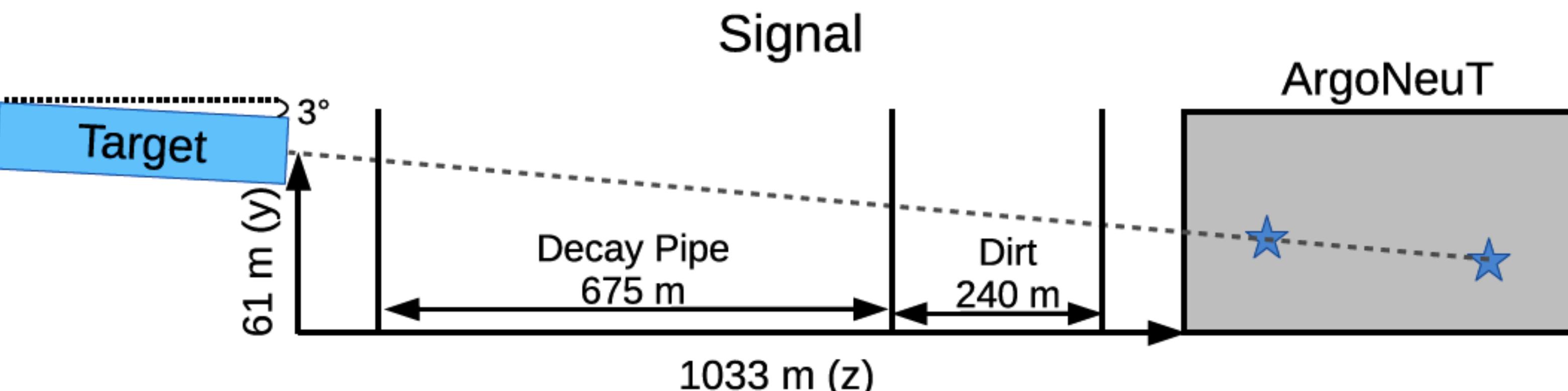
The vast majority of NuMI beam spills delivered did not produce a neutrino interaction within the TPC (due to the limited size of the detector)



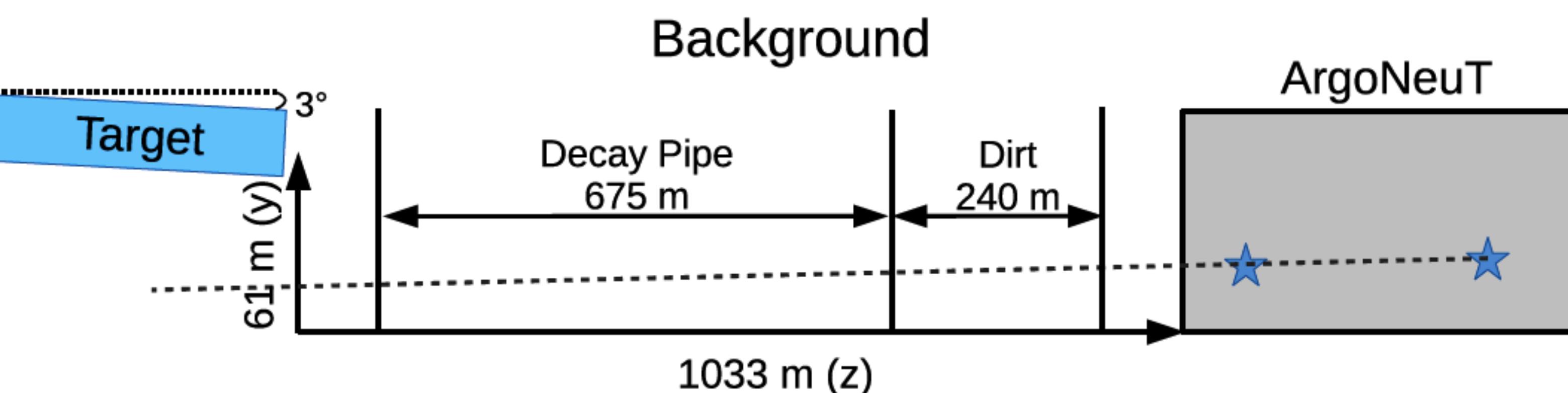
We searched for the possible presence of mCPs in these empty events.

MCP SEARCH - ARGONEUT ANALYSIS TECHNIQUE

En route to the detector, mCPs travel through hundreds of meters of dirt, energy loss is negligible and angular deflections are small → **mCPs point back to the target.**



Signal is a double-hit event
with a line defined by the two hits pointing
to the target



A background double-hit event
doesn't point to the target

**To reduce background:
search for double hits events aligned with the target**

HIGHLY FORWARD-GOING DI-MUON SIGNATURES

HNL and Heavy QCD axions are very different models... but can produce similar decay signatures in ArgoNeuT.

HNLs decaying to muon pair $N \rightarrow \nu \mu^+ \mu^-$

Muons highly boosted:

- average energy ~ 7 GeV
- average angle with respect to beam direction ~ 1.5 deg
- average opening angle ~ 3 deg

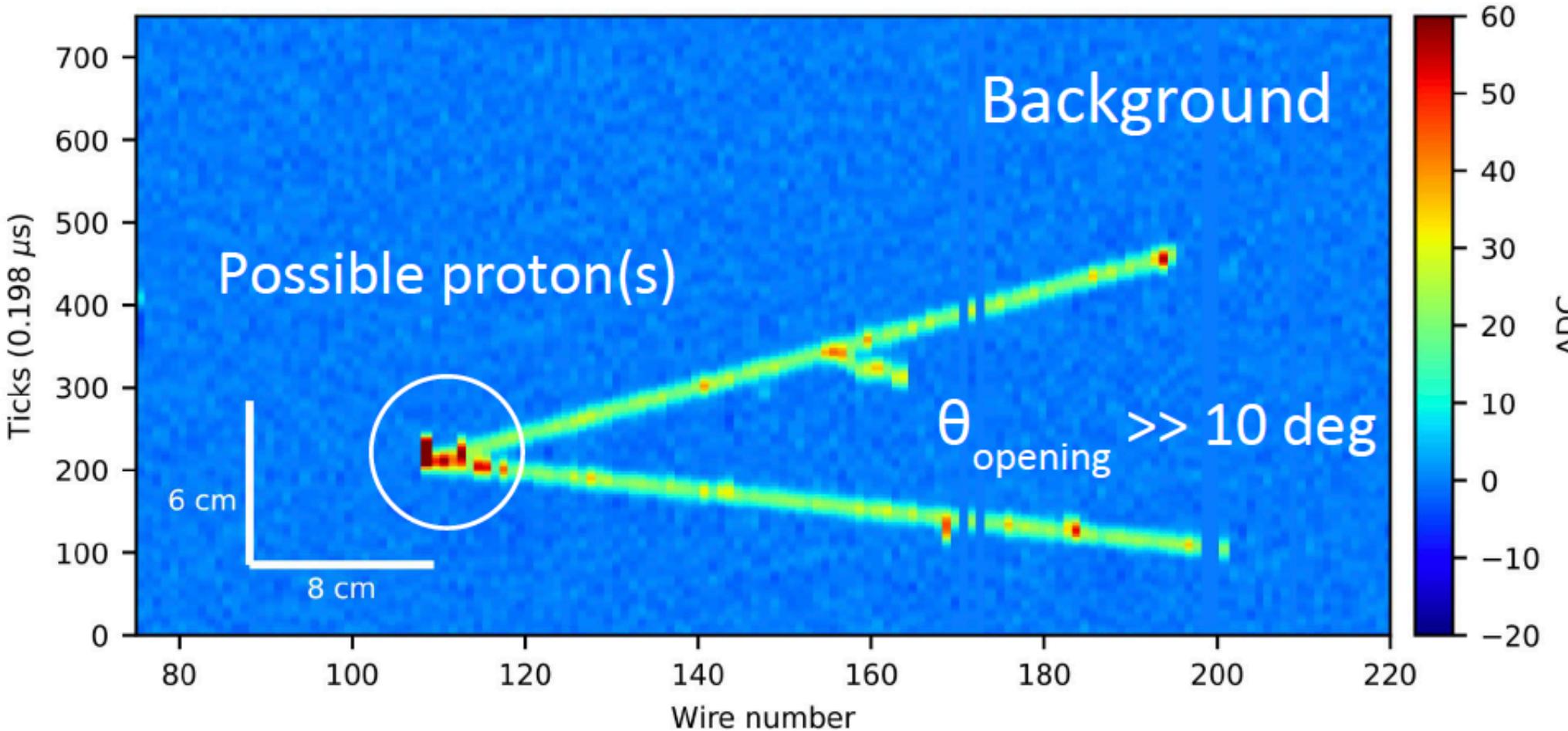
Axions decaying to muon pair $a \rightarrow \mu^+ \mu^-$

Muons highly boosted:

- average energy ~ 20 GeV
- average angle with respect to beam direction ~ 1.5 deg
- average opening angle ~ 2.5 deg

ArgoNeuT + MINOS ND, ideal to search for $\mu^+ \mu^-$ **signatures**

- ArgoNeuT LArTPC: vertex identification and reconstruction of low energy particles - allows identification of background
- MINOS ND: muon charge reconstruction and pion rejection



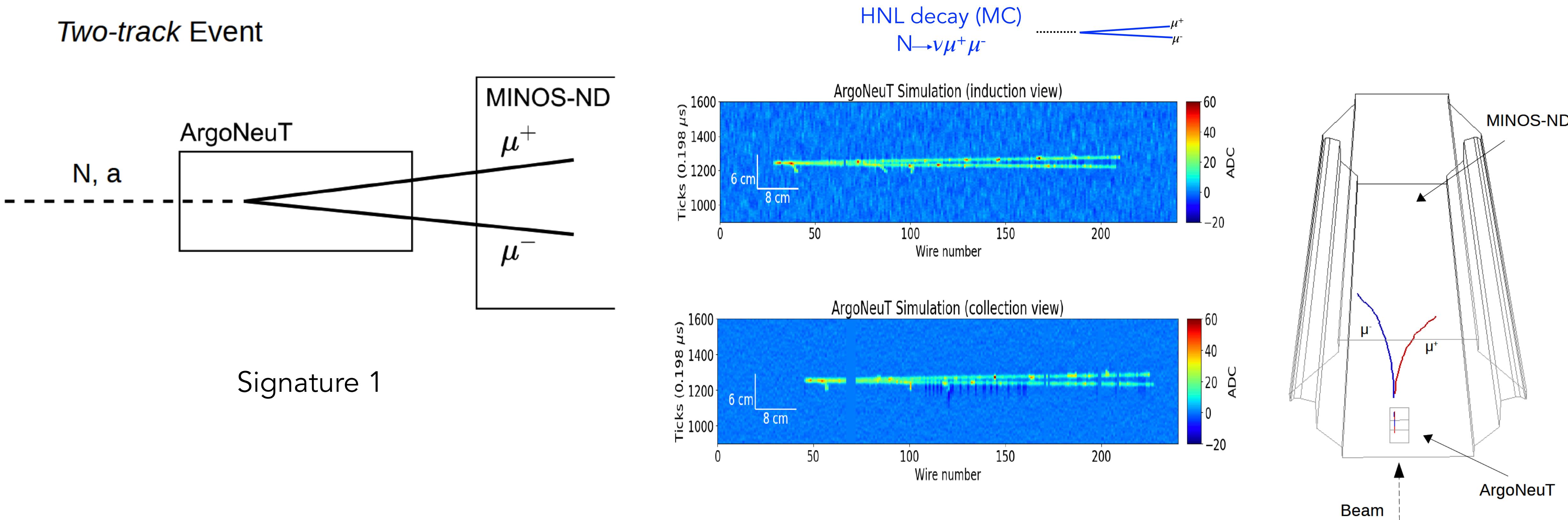
Identify the presence of hadronic activity at the vertex

DI-MUON SIGNATURES IN ARGONeUT

Two different signatures, depending on how forward going the muons are:

Signature 1: **two MIP tracks** in ArgoNeut, match to **two tracks** in MINOS-ND

Signature 2: single **double-MIP dE/dx** track in ArgoNeut, matches to **two tracks** in MINOS-ND



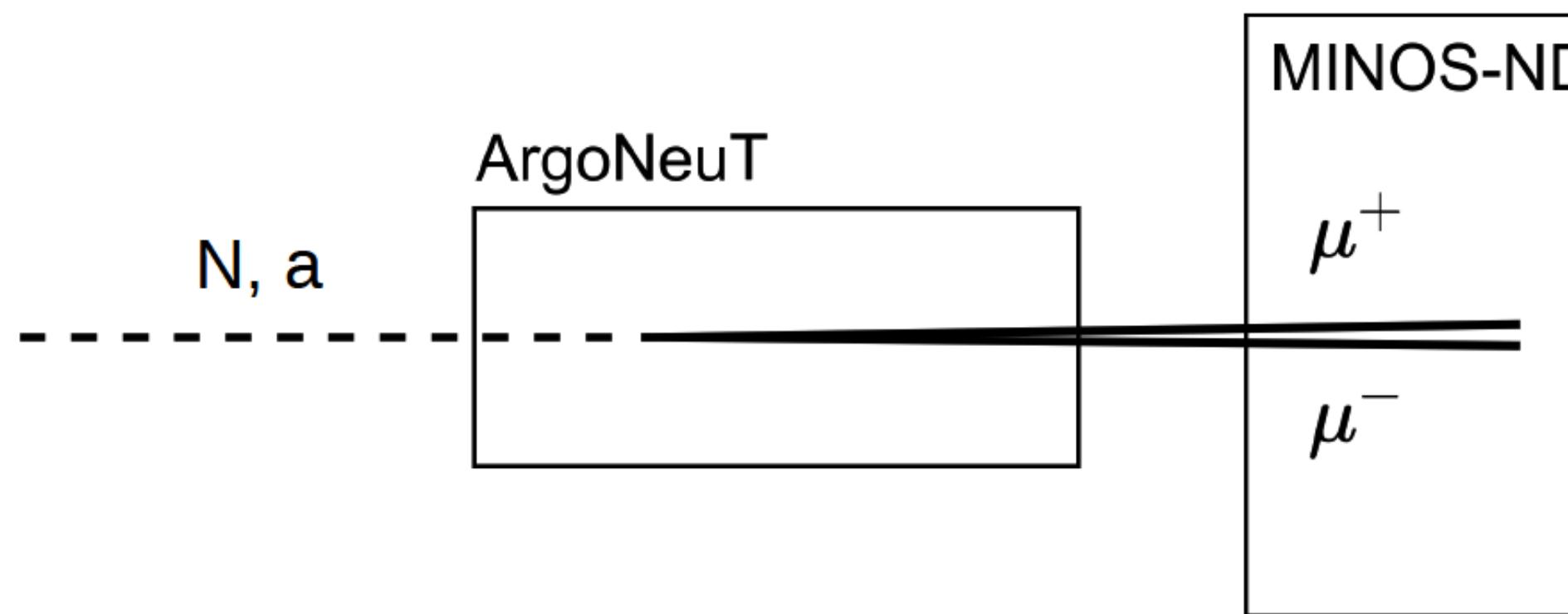
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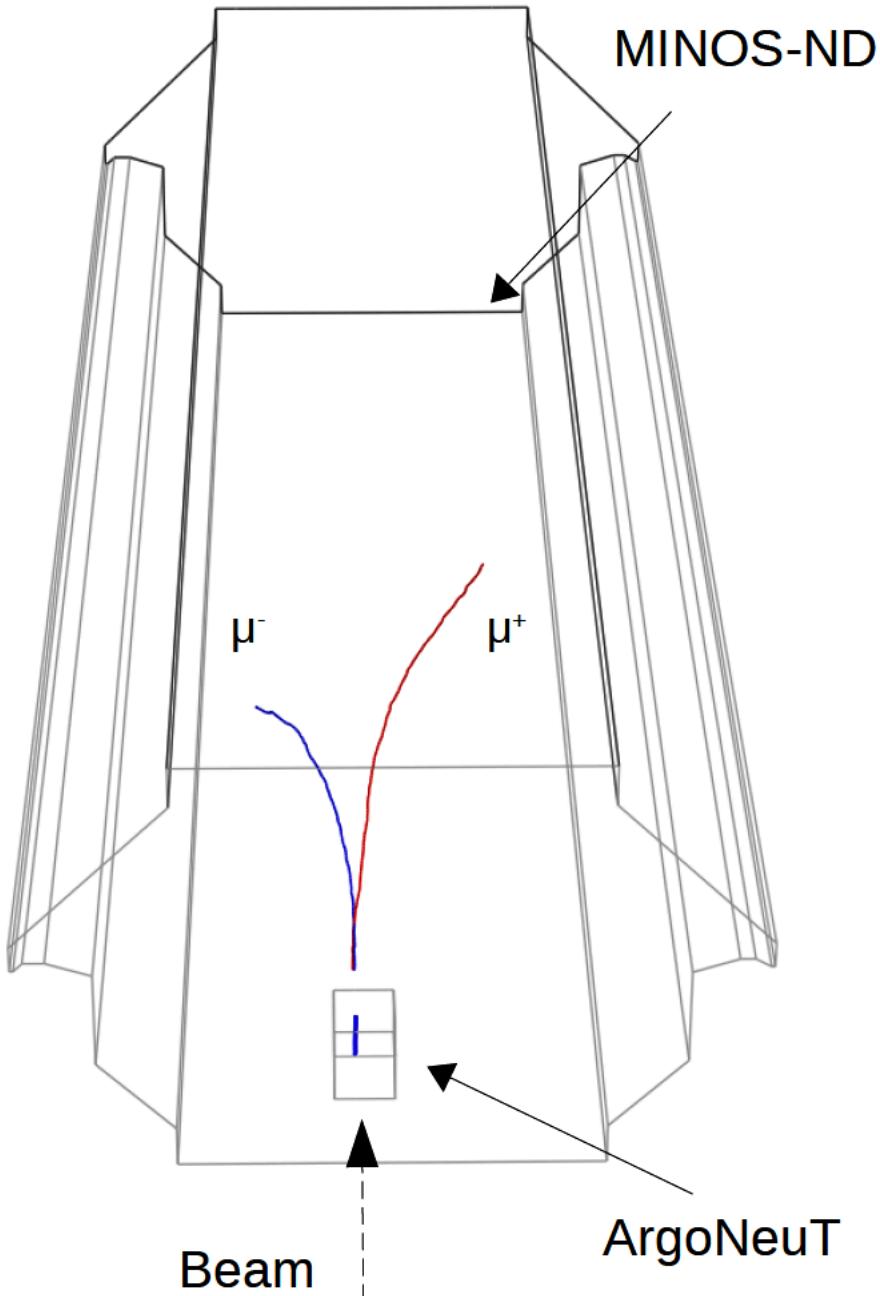
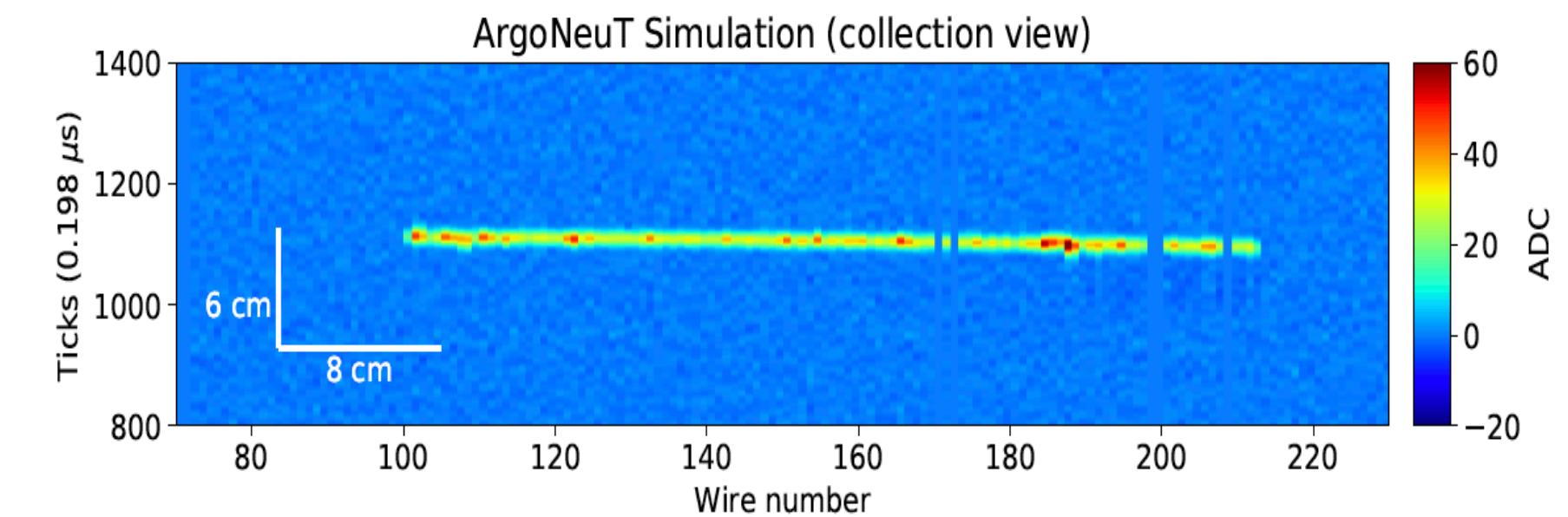
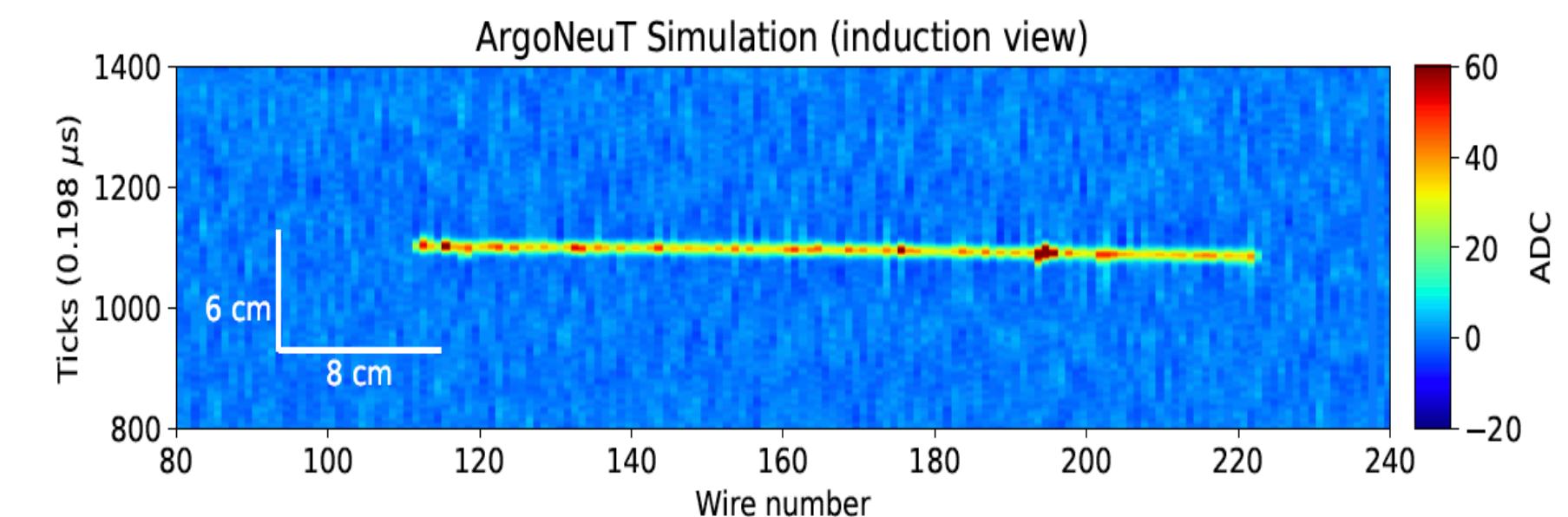
Signature 2: single **double-MIP dE/dx** track in ArgoNeut, matches to **two tracks** in MINOS-ND

Double-MIP Event



Signature 2

HNL decay (MC)
 $N \rightarrow \nu \mu^+ \mu^-$



In most forward-going cases, muon pair may be reconstructed as overlapping in ArgoNeut.

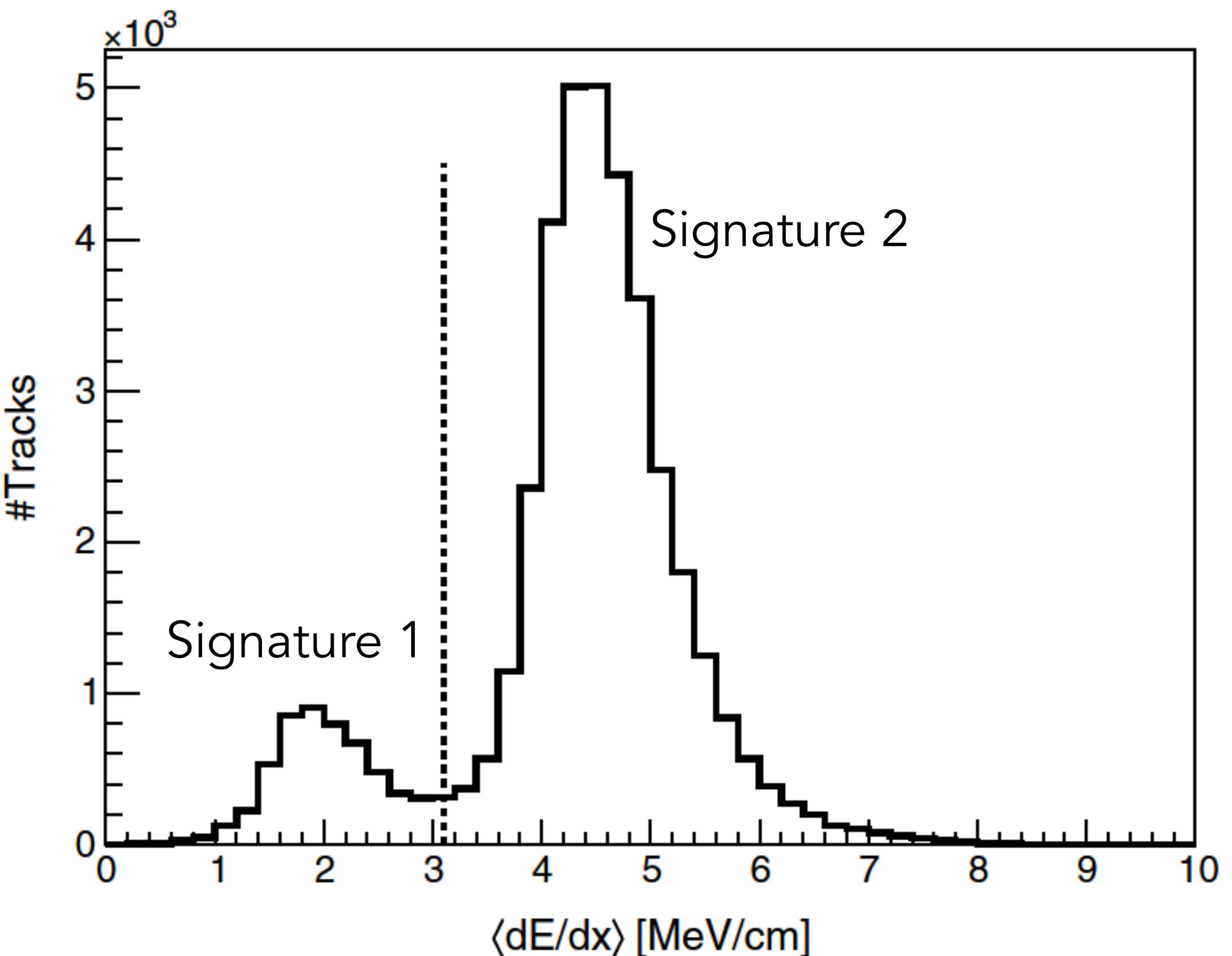
DI-MUON SIGNATURES IN ARGONeUT

Two different signatures, depending on how forward going the muons are:

Signature 1: **two MIP tracks** in ArgoNeut, match to **two tracks** in MINOS-ND

Signature 2: single **double-MIP dE/dx** track in ArgoNeut, matches to **two tracks** in MINOS-ND

Developed new techniques to identify highly-forward-going muon pairs, applicable to future searches in LArTPC detectors, e.g. the DUNE near detector.



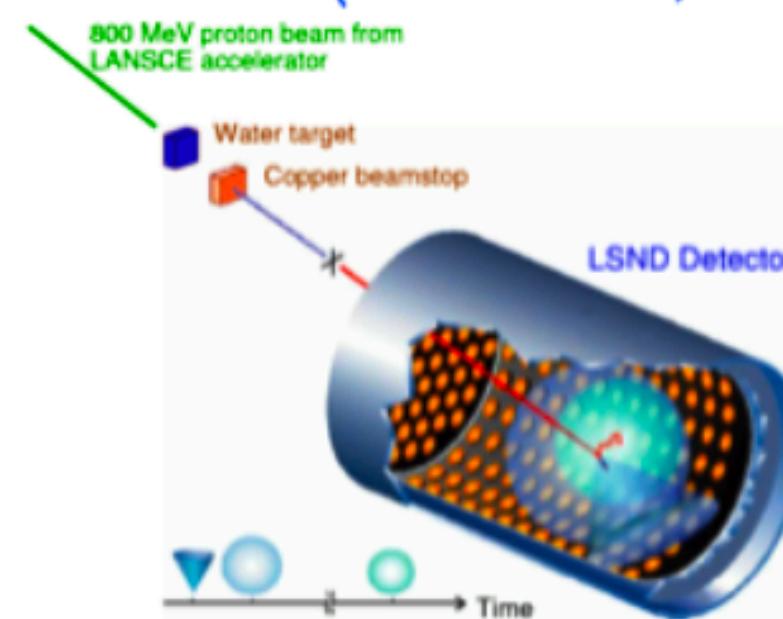
Identifying overlapping muon pairs:

Average reconstructed dE/dx over the first 5 cm of tracks resulting from simulated HNL decays.

EXPERIMENTAL HINTS FOR BEYOND THREE NEUTRINO MIXING

Sterile Neutrinos?

Low energy $\bar{\nu}_\mu$ beam from a decay-at-rest pion beam (Los Alamos, 1993-1998)



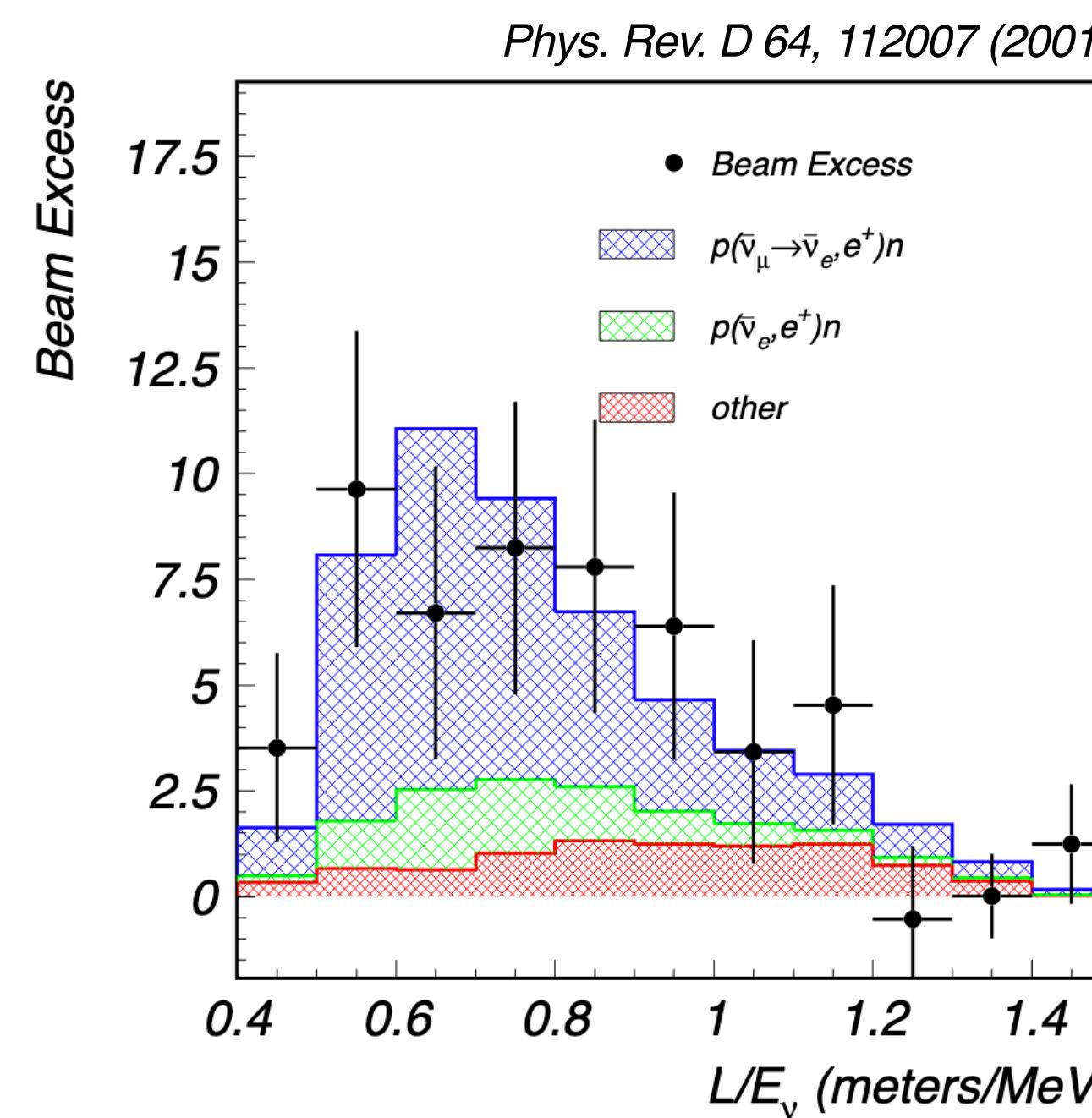
LSND

Baseline 30 m

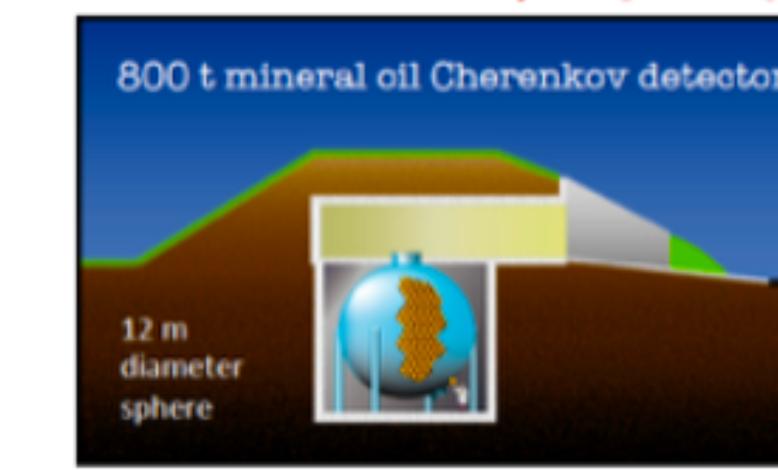
$E = [20 - 50] \text{ MeV}$

$L/E \approx 1 \text{ m/MeV}$

167 tons liquid scintillator



Decay in flight neutrino source
(Booster Neutrino Beam - Fermilab)
L/E similar to LSND

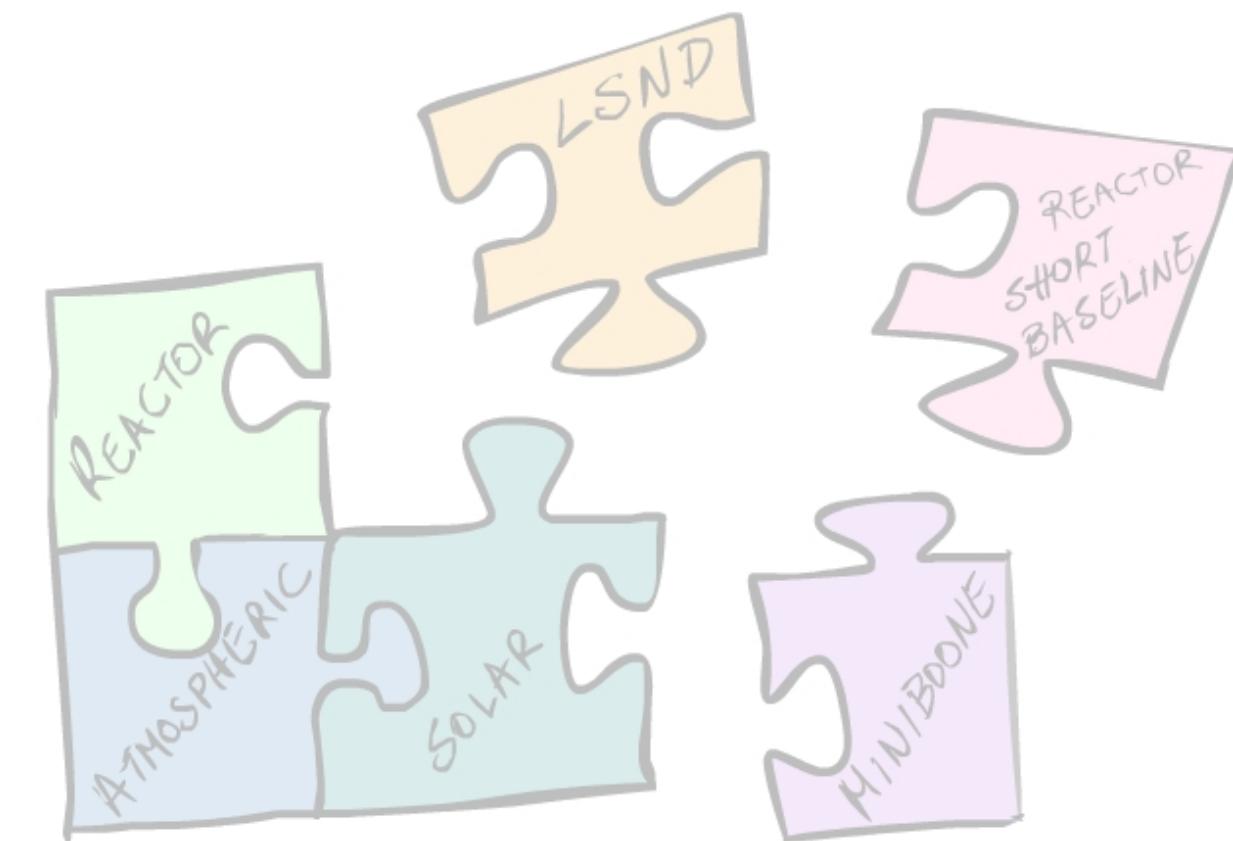


MiniBooNE

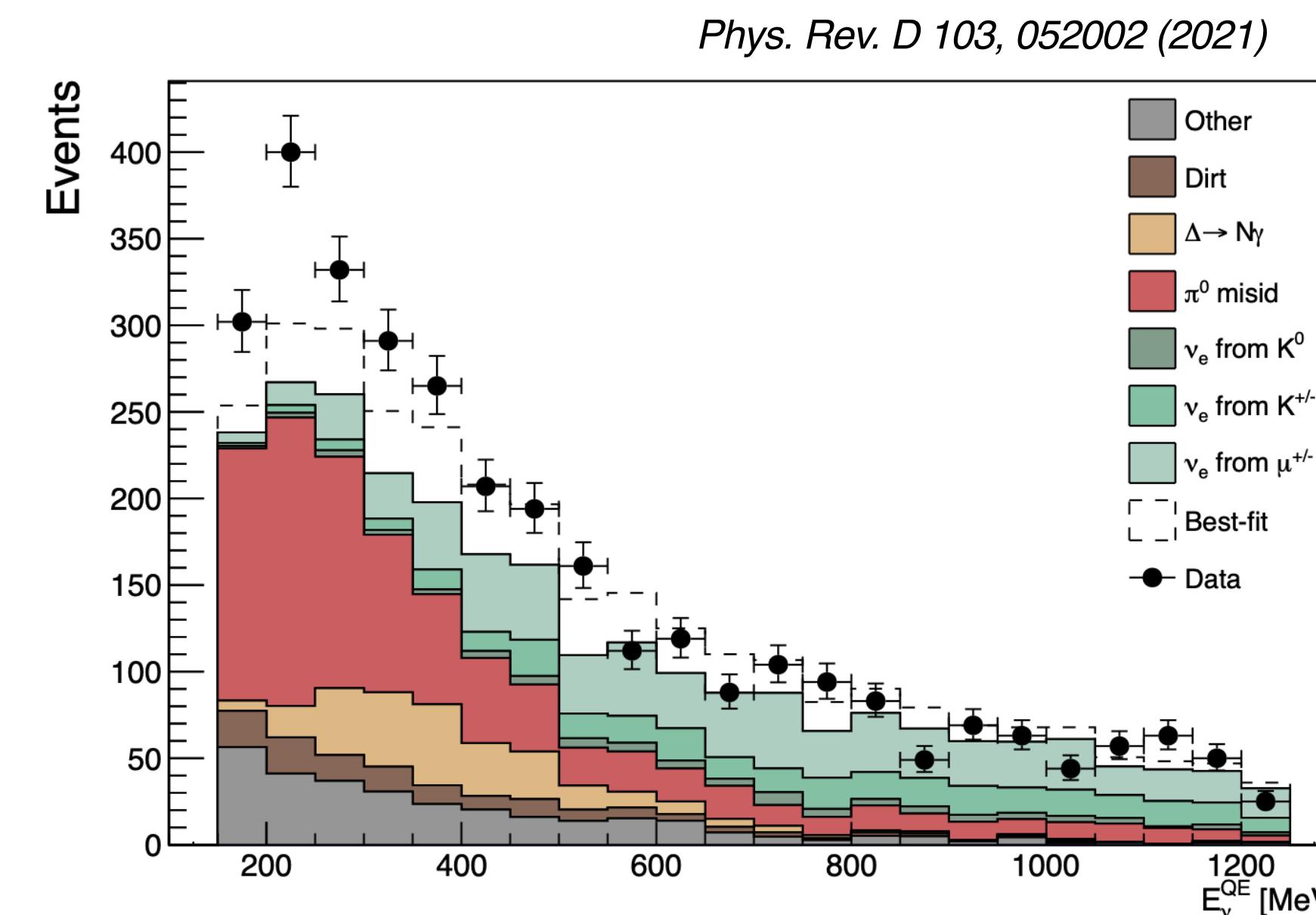
Baseline 540 m

$E=[0 - 2] \text{ GeV}$

$L/E \approx 1 \text{ m/MeV}$

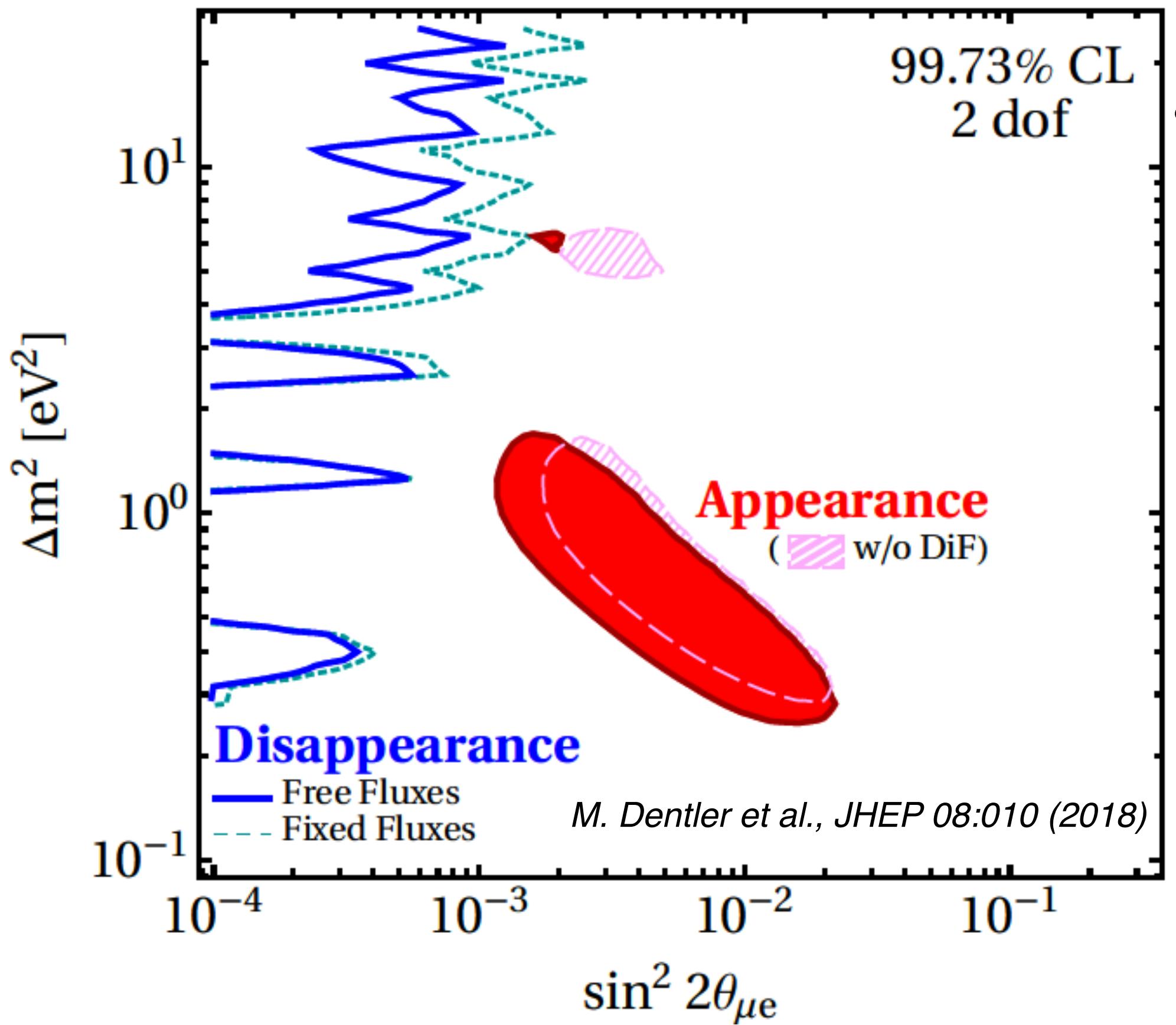


+
Reactor and
Gallium
“anomalies”



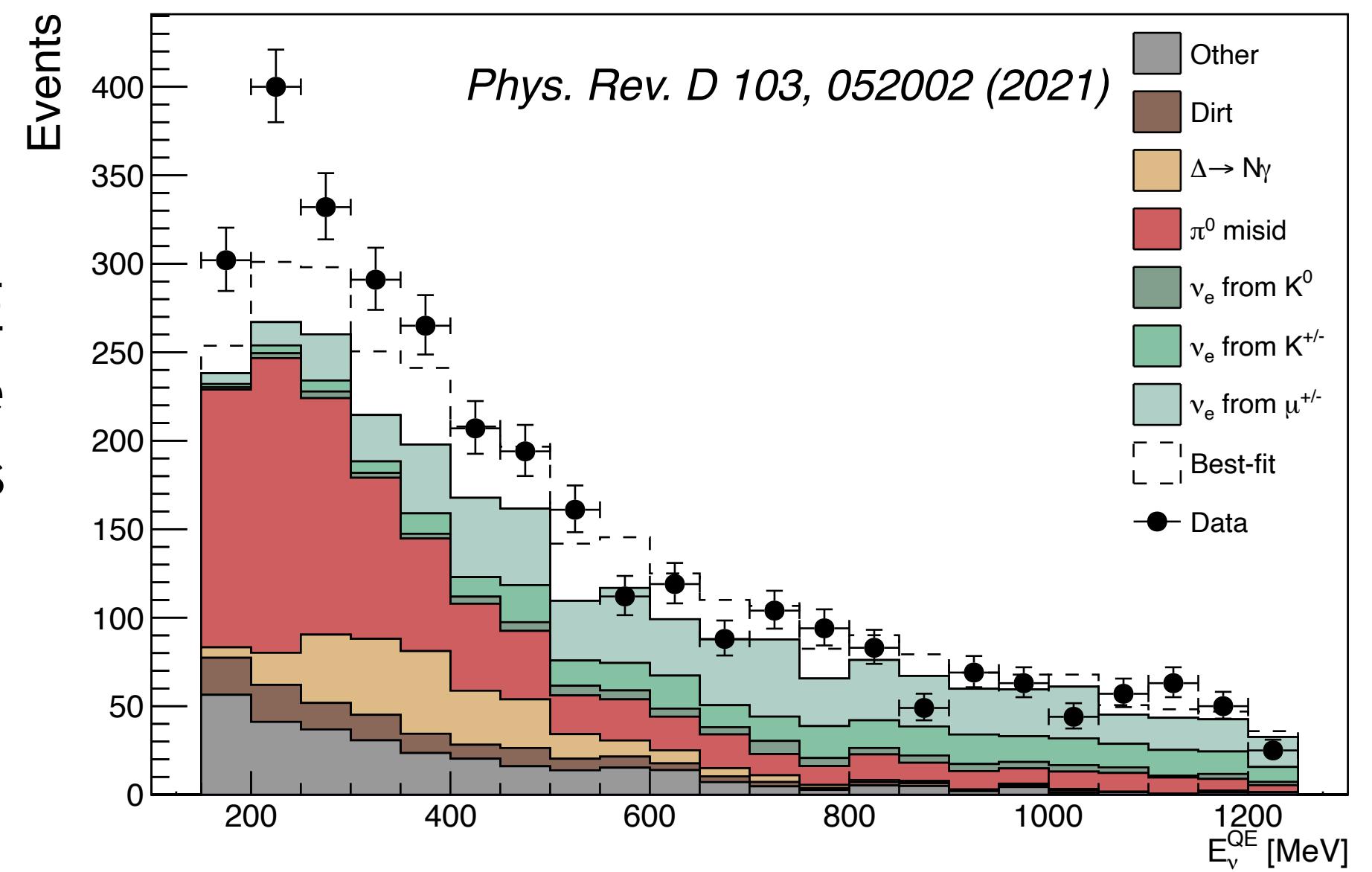
LIGHT STERILE NEUTRINO - EXPERIMENTAL LANDSCAPE

A 4.7σ tension arises when combining ν_e appearance and ν_μ disappearance data sets.



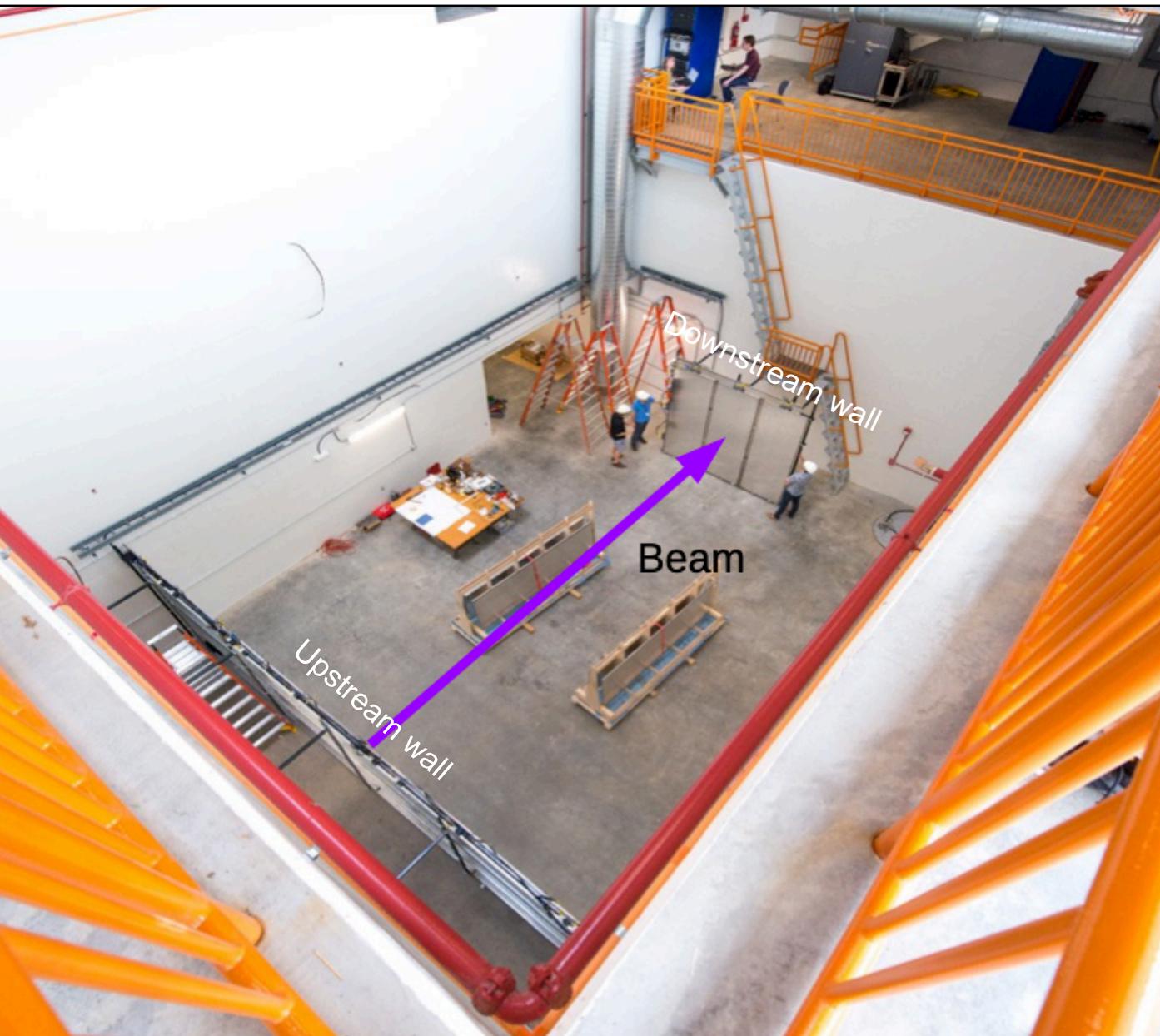
Limits from disappearance and appearance allowed region

MiniBooNE
electron-like
excess



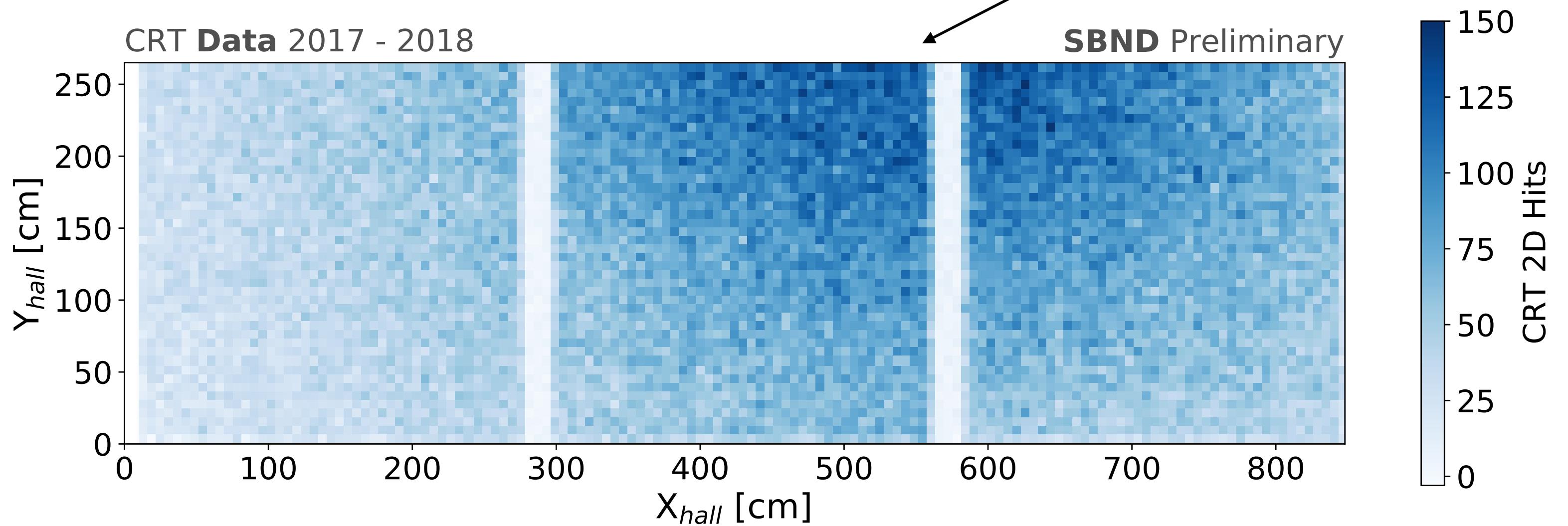
Alternative (Beyond Standard Model) explanations exist that could explain the MiniBooNE (and LSND) anomalies.

SBND COSMIC RAY TAGGER (CRT) DATA



Part of the SBND CRT system was temporary installed in the detector hall and took BNB data in 2017-2018

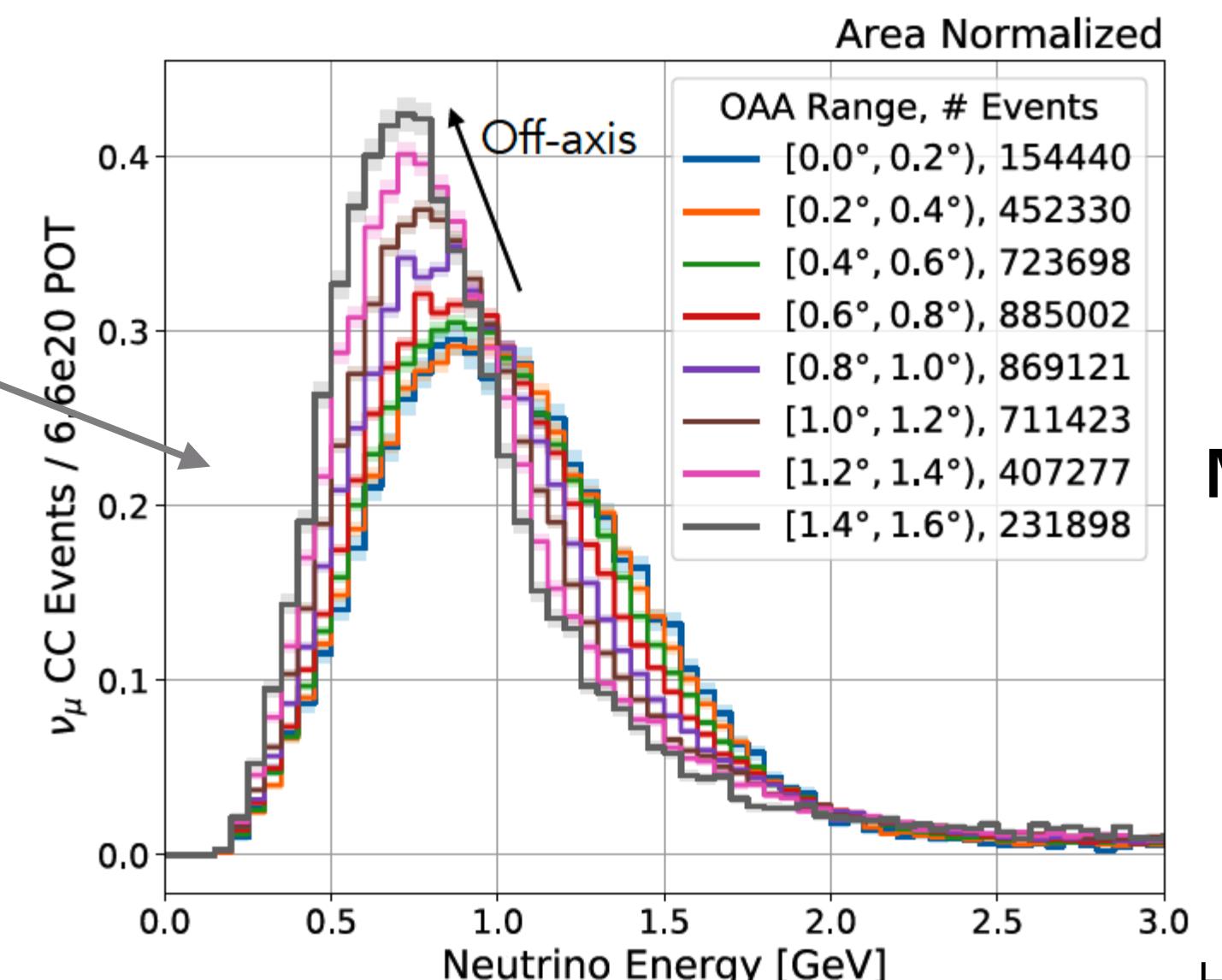
CRT data: **muons from neutrinos** that interacted in the material upstream of the SBND detector hall. The beam intensity decreases moving away from the beam center.



SBND-PRISM - NEUTRINO FLUXES

The **Muon** neutrino energy distributions are affected by the off-axis position [ν_μ come predominantly from two-body decay]. Larger off-axis angle \rightarrow lower mean energy.

Neutrino Fluxes in Off-Axis Angle (OAA) regions

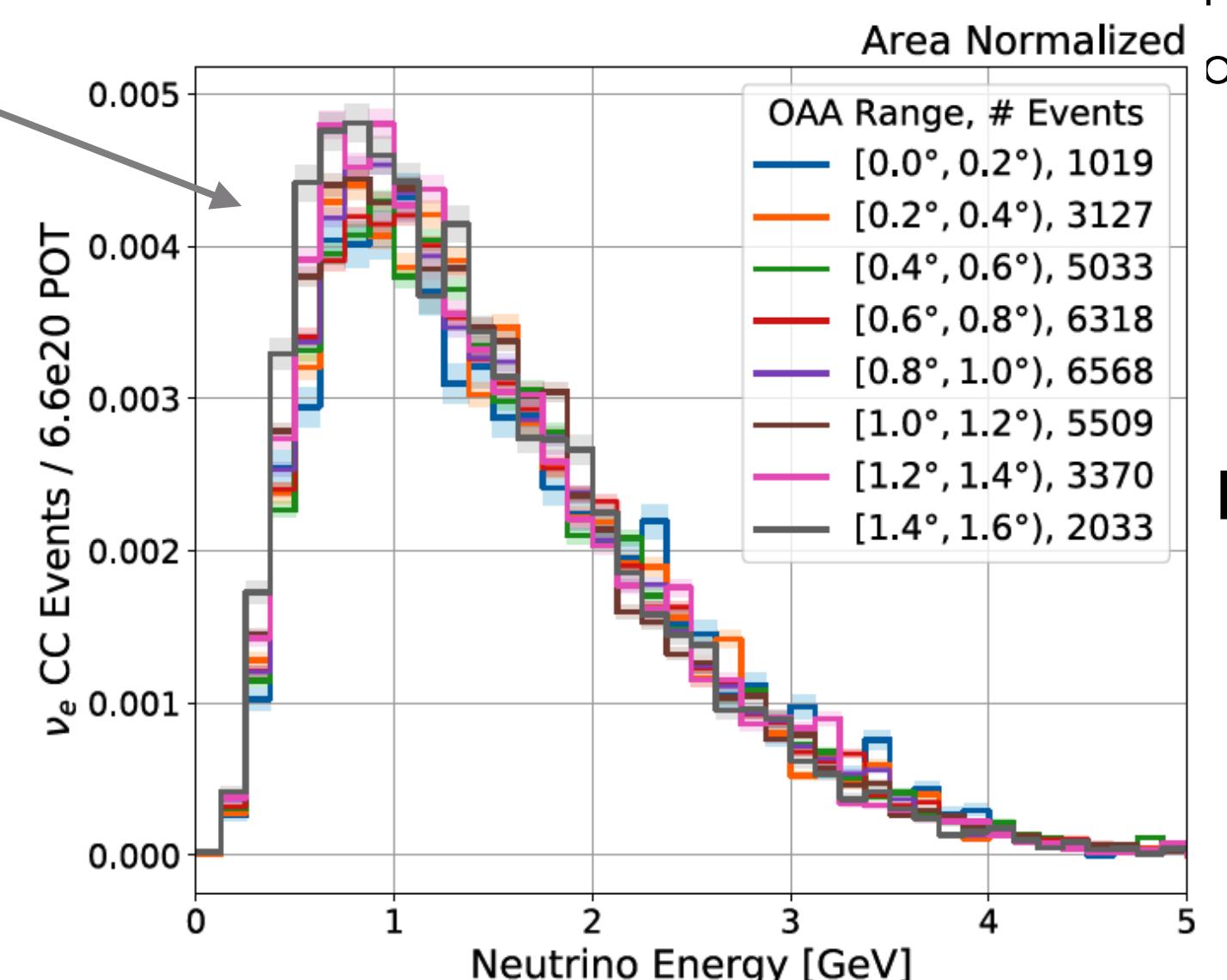


Muon neutrino

The **Electron** neutrino energy distributions also change, but they are less affected by off-axis position [ν_e come from three-body decay].

Muon and electron neutrino spectra change in a different way!

Leveraging the different behavior of muon and electron neutrinos in the OAA regions, we can improve sensitivity for sterile neutrino searches.



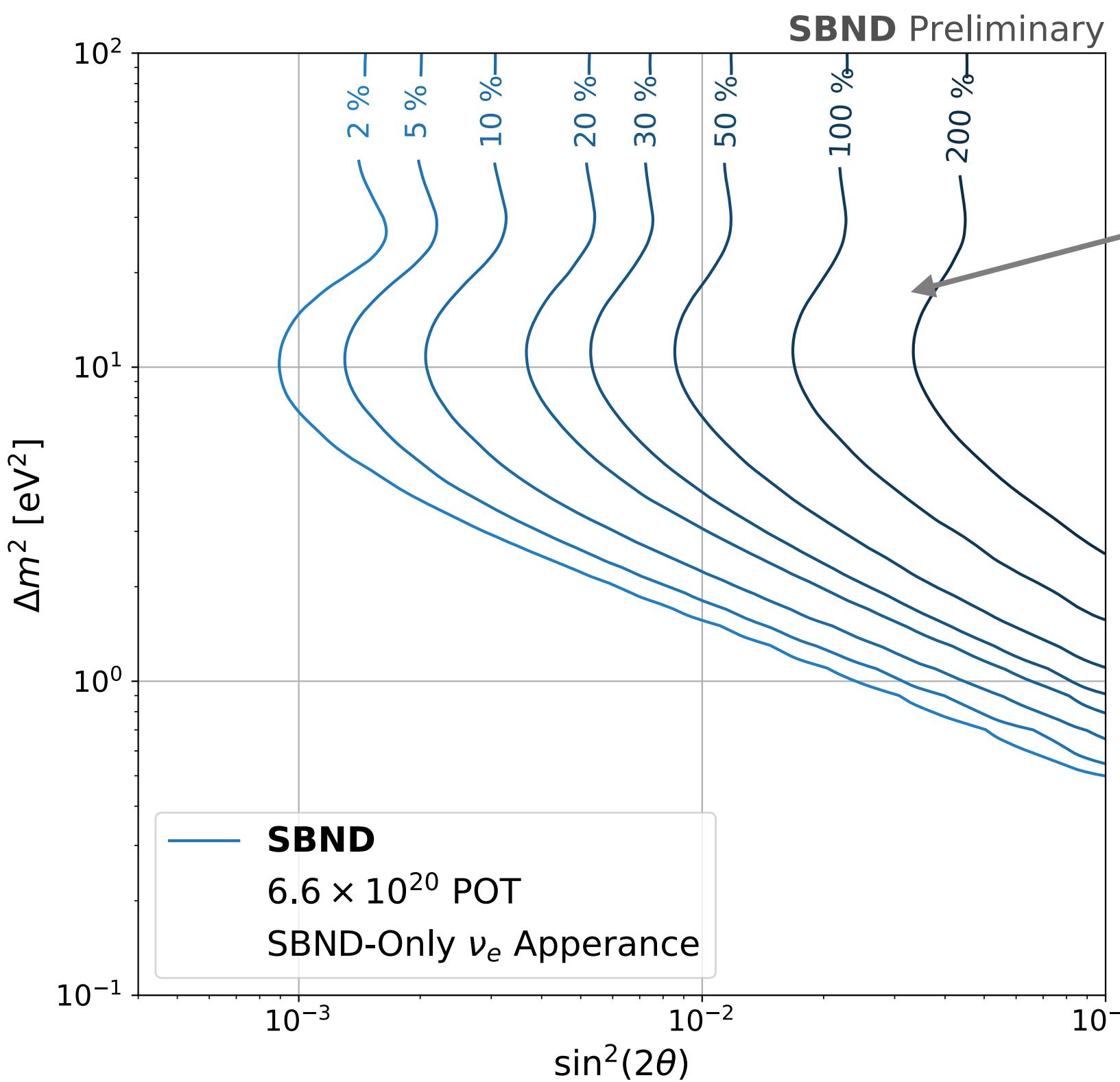
High event statistics in all off-axis regions.

Electron neutrino

EFFECT OF SBND-PRISM ON OSCILLATION ANALYSES

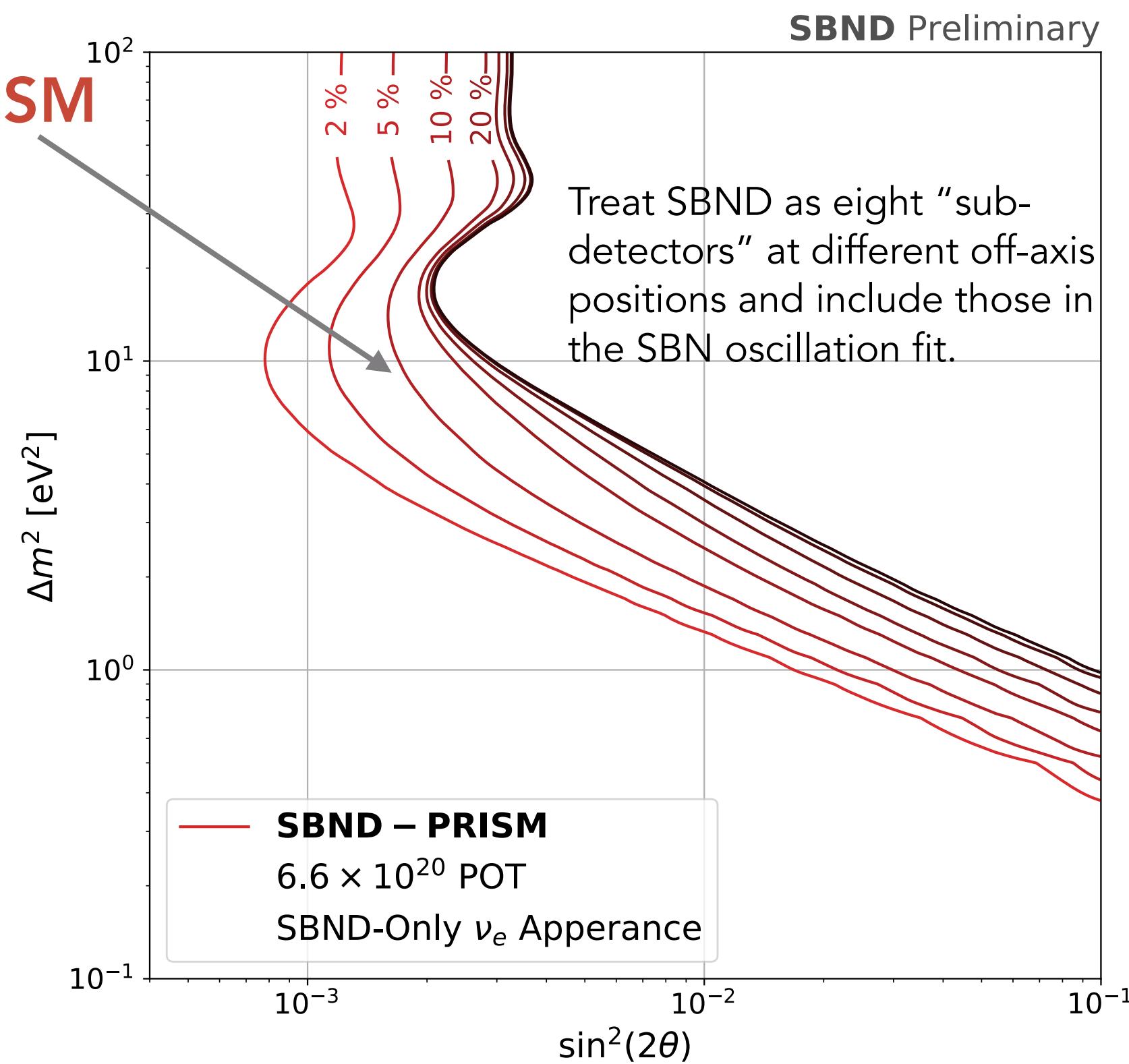


SBND-only - simplified Oscillation Analysis (ν_e Appearance)



SBND as a single detector vs SBND-PRISM

Curves include neutrino flux plus 2-to-200% systematics on total cross section.



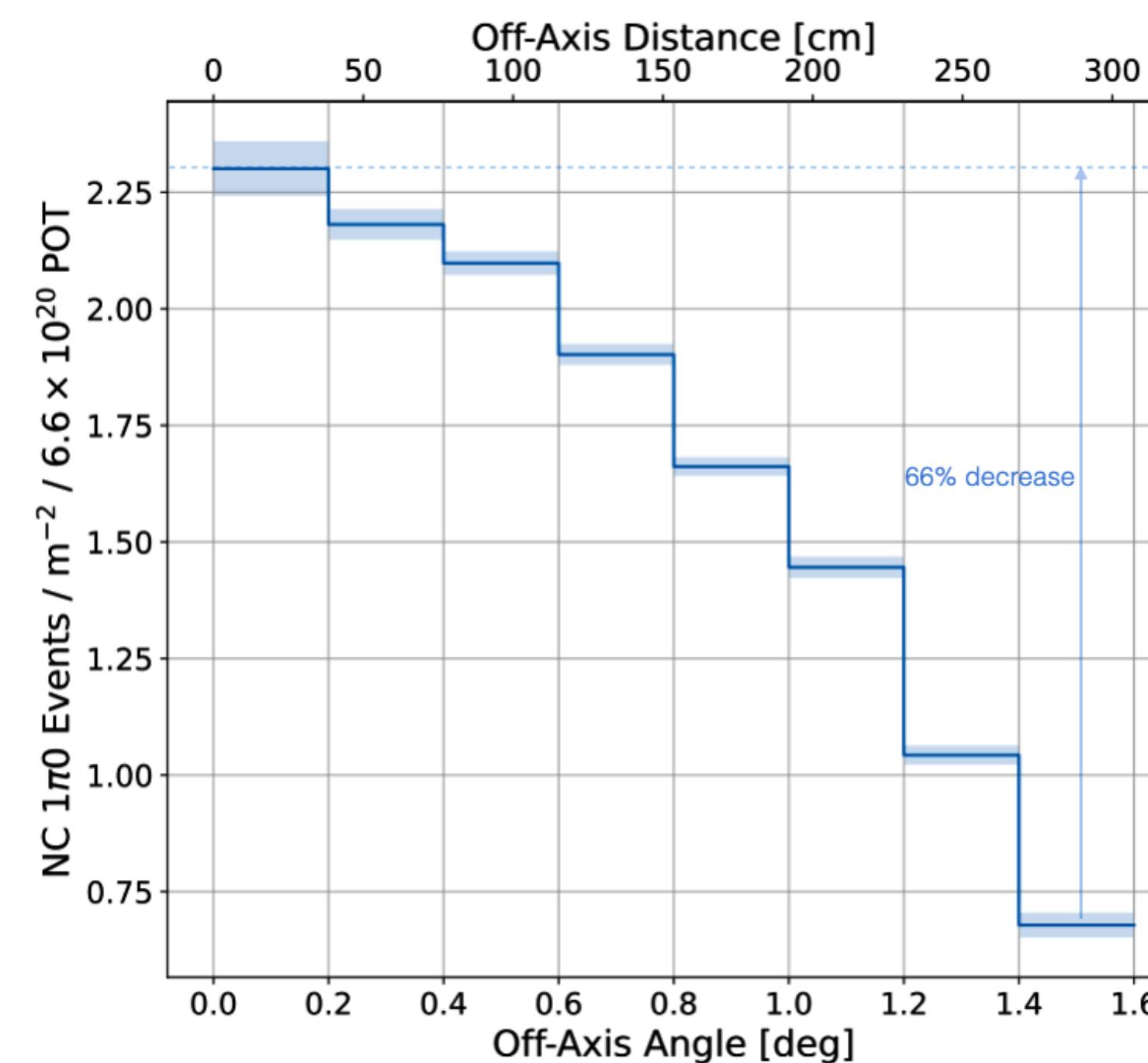
- Improvement in sensitivity by exploiting SBND-PRISM.
- Using the PRISM technique the neutrino interaction model is over-constrained, becoming ~ insensitive to cross section model uncertainties above 20%. Robust against large cross-section uncertainties.

Study of the effect of SBND-PRISM on SBN Sterile neutrino oscillation sensitivities is ongoing.

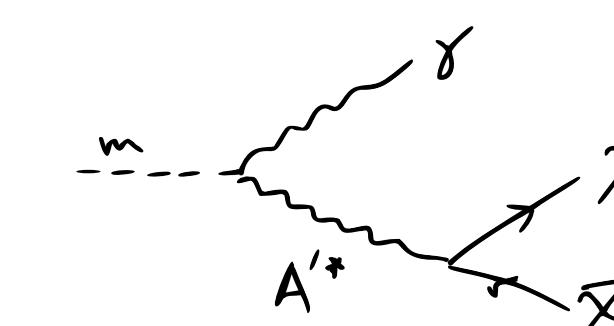
SBND-PRISM TO MITIGATE BACKGROUNDS

An example: electron neutrino measurements

Main background for electron neutrino:
NC 1 π^0 events.

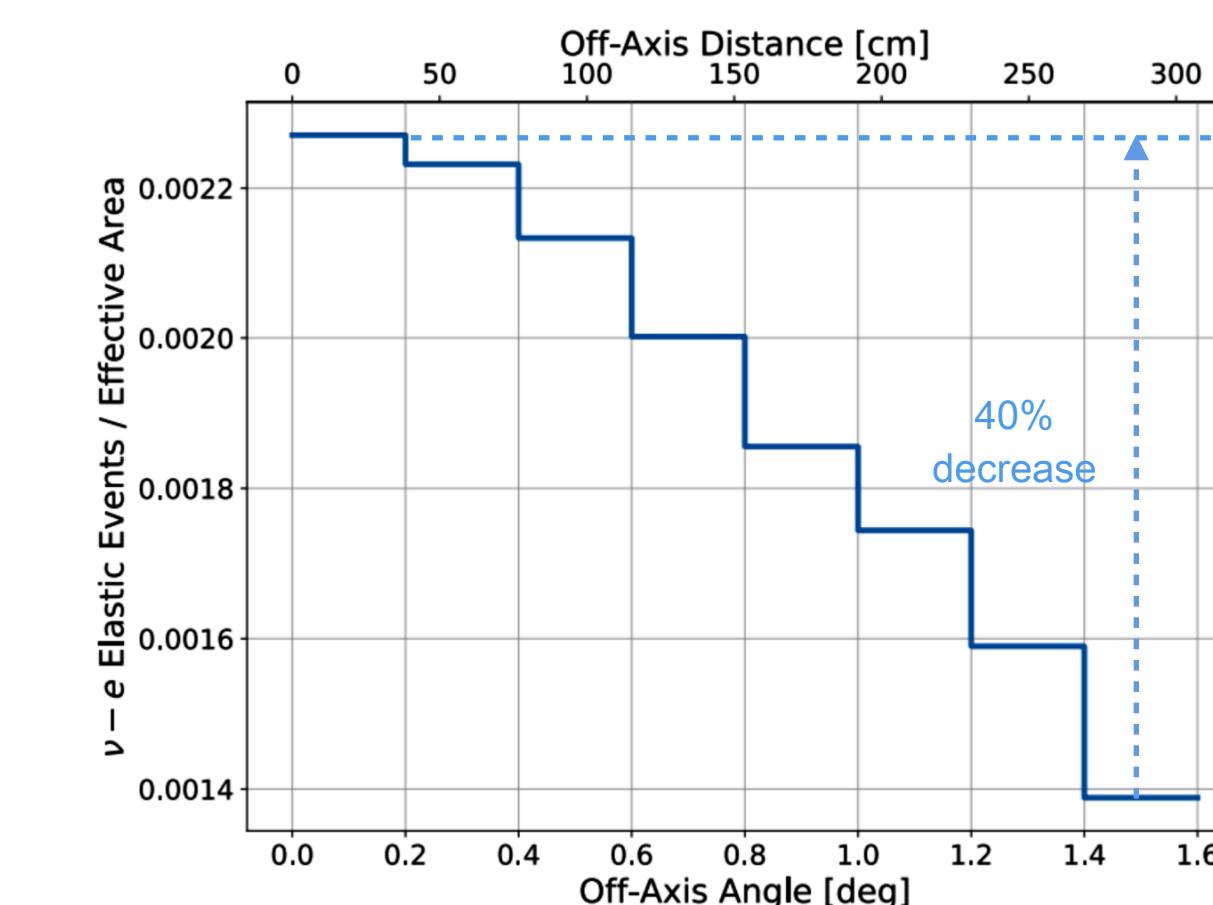


Another example: search for Light (sub-GeV) Dark Matter

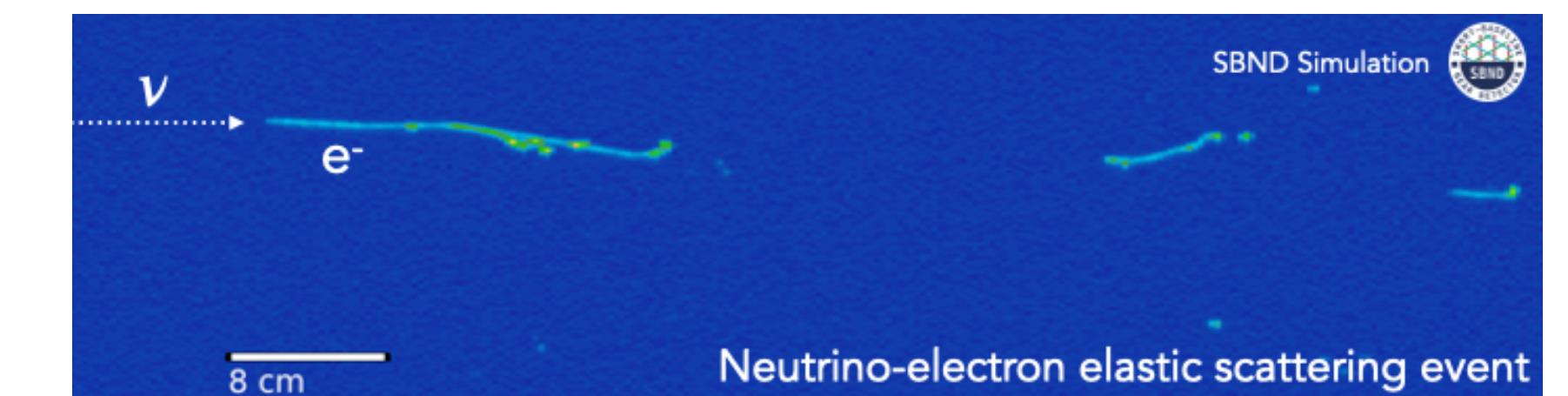


Dark photons, produced by the decay of neutral meson (pions, etas) in the target and decay into dark matter.

The dark matter, through the dark photon, **scatter off electrons in the detector**.

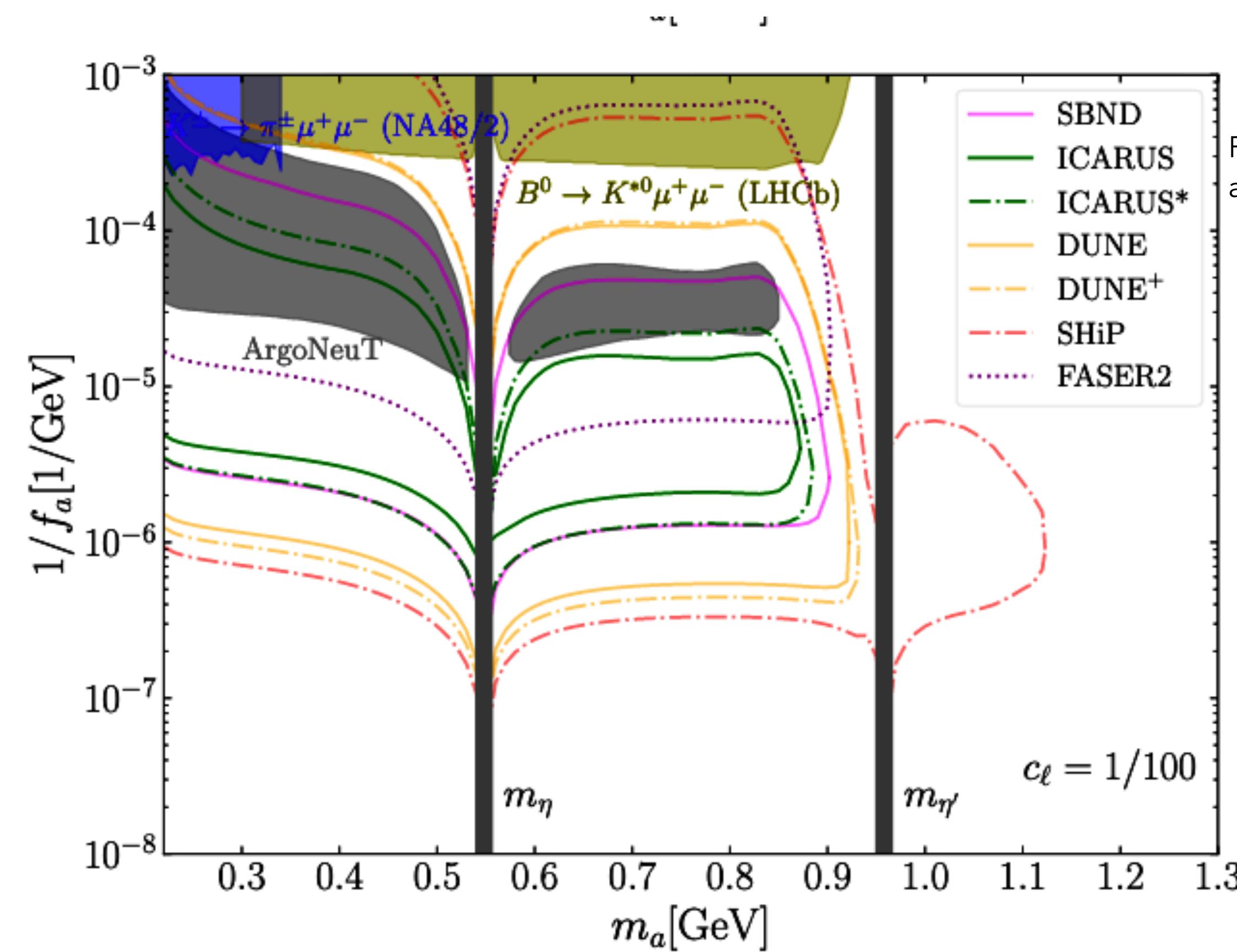


- **Signal:** DM elastic scattering electron events. DM comes from neutral (unfocused) mesons.
- **Background:** neutrino-electron elastic scattering. Neutrinos come from two-body decays of charged (focused) mesons.



SBND-PRISM provides a natural way to **reduce backgrounds by looking off-axis**.

HEAVY QCD AXIONS VIA DIMUON FINAL STATES



R. T. Co,^{1, 2}, S. Kumar, and Z. Liu
arXiv:2210.02462v1

FIG. 6. Constraints (shaded-regions) and projections (curves) for $c_\ell = 1/36$ (upper panel) and $c_\ell = 1/100$ (lower panel). The curve labeled DUNE⁺ denotes a scenario in which the axion can decay up to 30 m before the DUNE ND. The high-energy muons produced via these decays can still reach the detector. The curve labeled ICARUS* is for the reach ICARUS would have through the off-axis NuMI beam. See text for more details.

OTHER BSM SEARCHES AT SBL

MicroBooNE:

- **Heavy Neutral leptons** ($N \rightarrow \mu^\pm \pi^\mp$ decay channel in a delayed time window)

P. Abratenko et al., PRD 101 052001 (2020)

- **Higgs scalar portal** (e^+e^- final state from NuMi off-axis events)

P. Abratenko et al., PRL 127 151803 (2021)

Results recasted to constraint **Heavy Neutral Leptons**

K. Kelly and P. Machado, arXiv:2106.06548

DUNE(-ND) will also probe several BSM scenarios

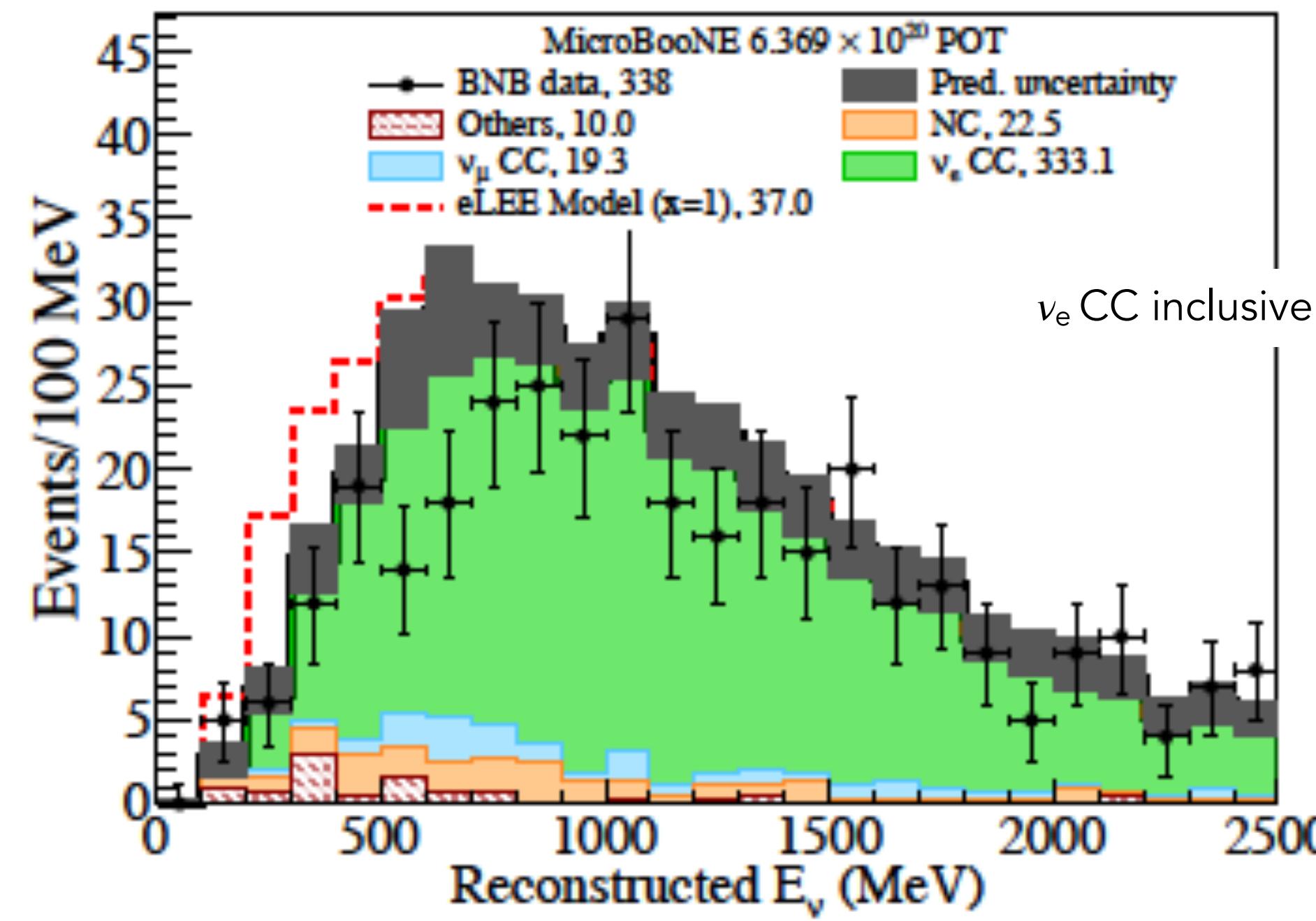
B. Abi et al, Eur. Phys. J. C (2021) 81

STERILE NEUTRINO SEARCHES BEYOND MicroBooNE

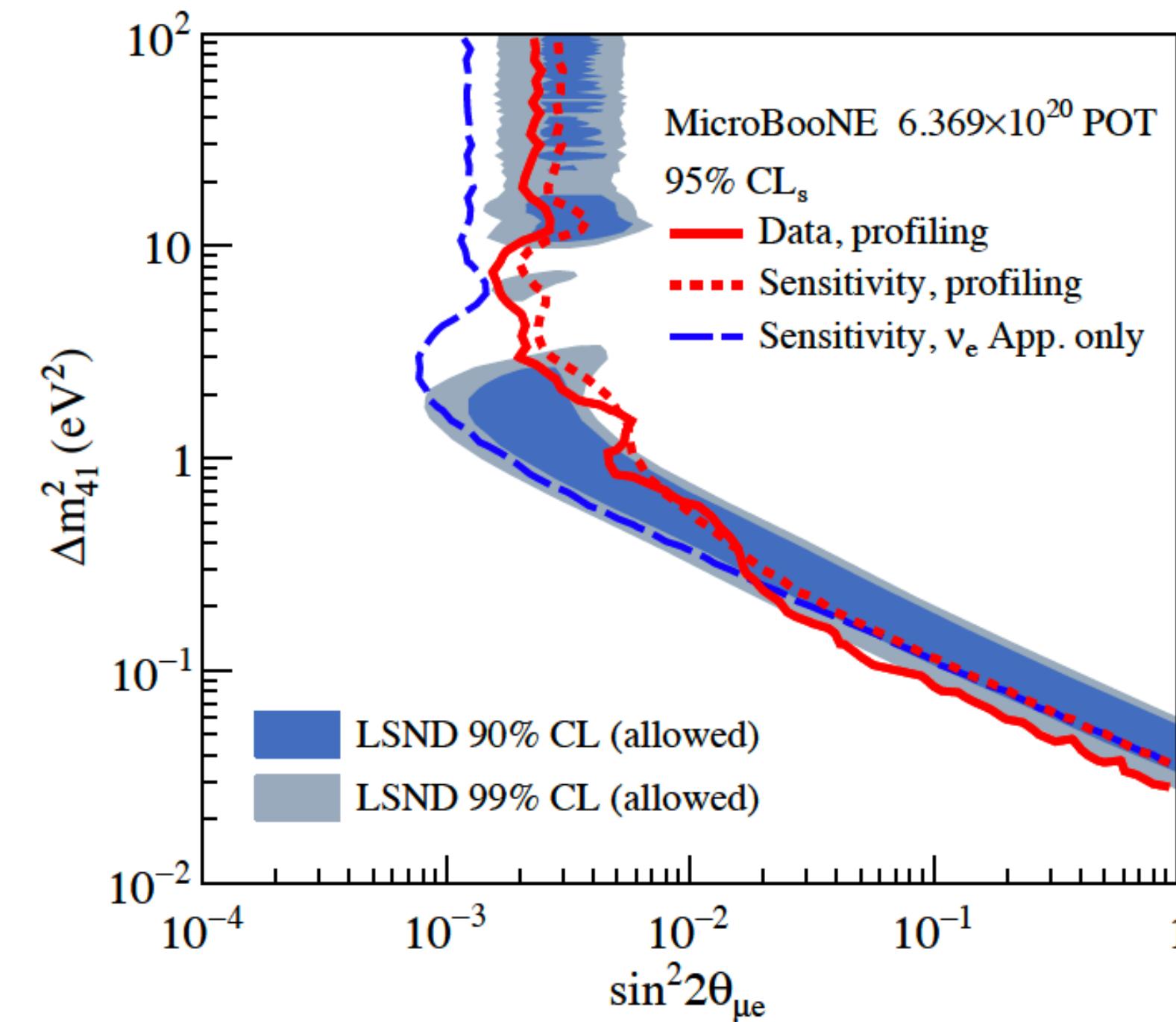
The MicroBooNE experiment presented very interesting results of first analyses searching for an excess of low-energy electromagnetic events:

no hints of an electromagnetic event excess, but results **do not rule out existence of sterile neutrinos.**

P. Abratenko et al., Phys. Rev. Lett. 128, 241801



P. Abratenko et al., <https://arxiv.org/abs/2210.10216>

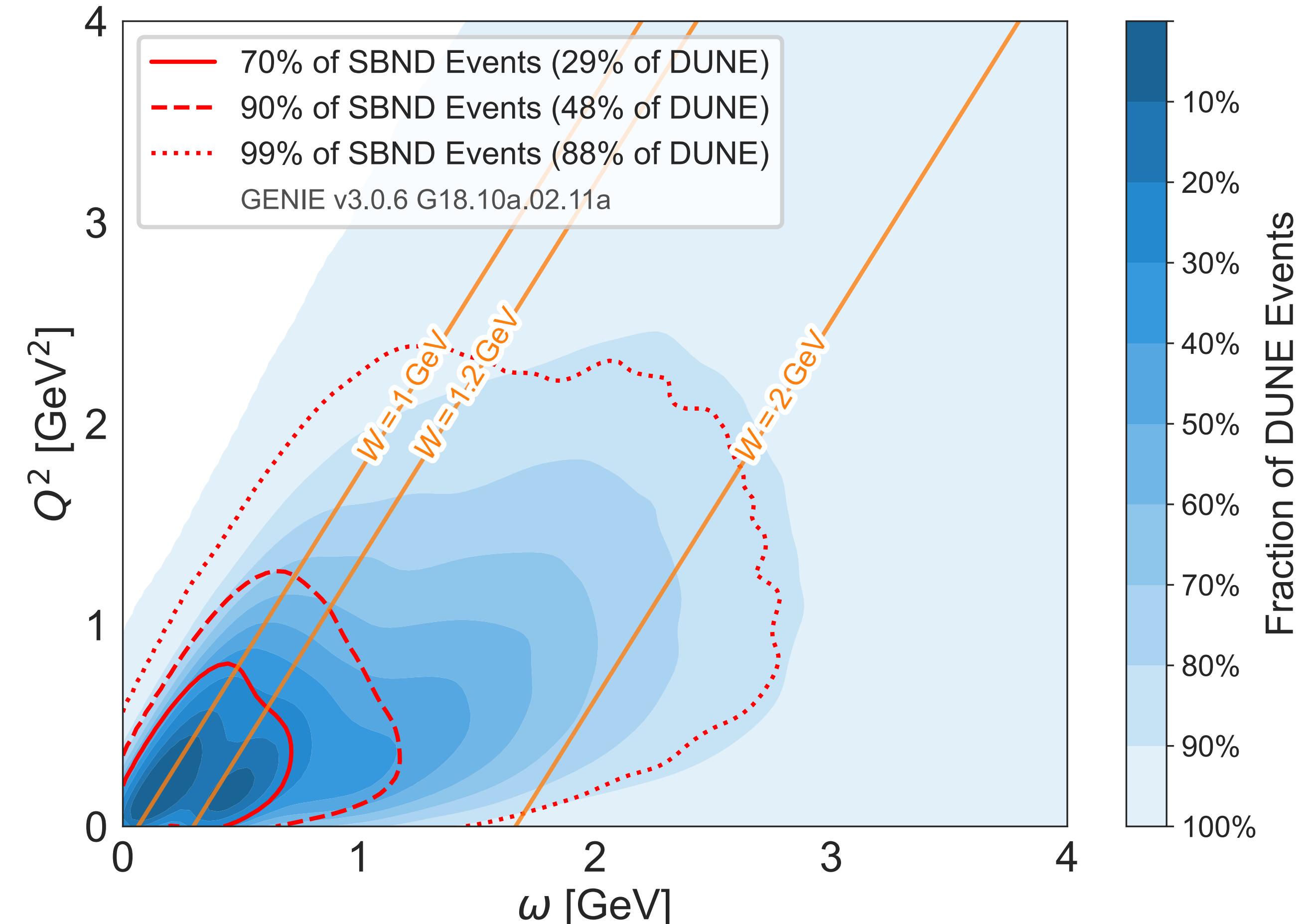


Entering the **next phase** now, with a **Near detector** and a **larger Far detector**.

SBND-DUNE KINEMATIC COVERAGE

DUNE kinematic coverage is represented with the blue 2D histogram.

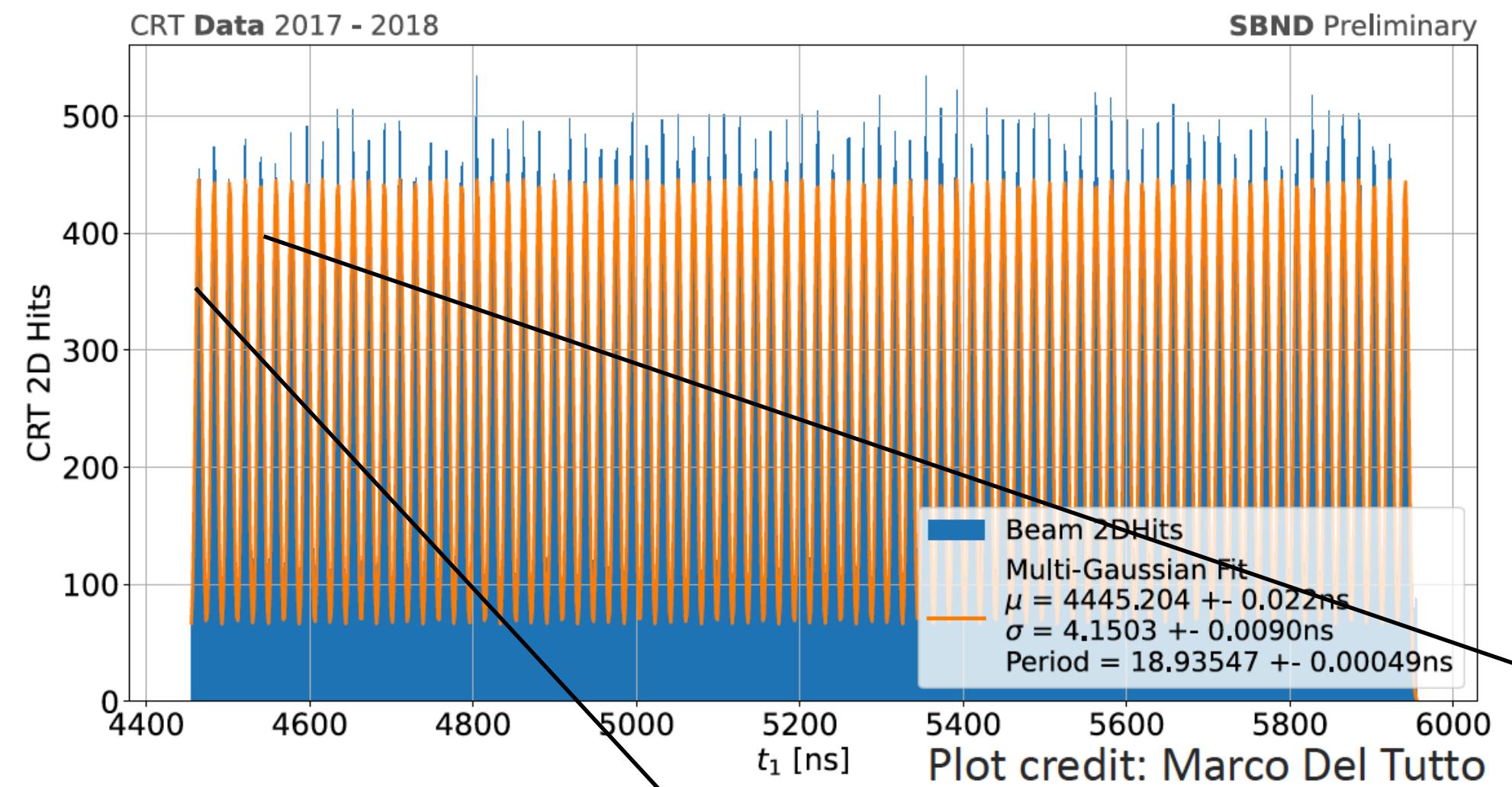
SBND kinematic coverage is shown with 3 contours, representing 70%, 90%, and 99% of all SBND data.



SBND has a **significant phase space overlap with DUNE** → SBND measurements can be used to constrain the same physics DUNE needs to know.

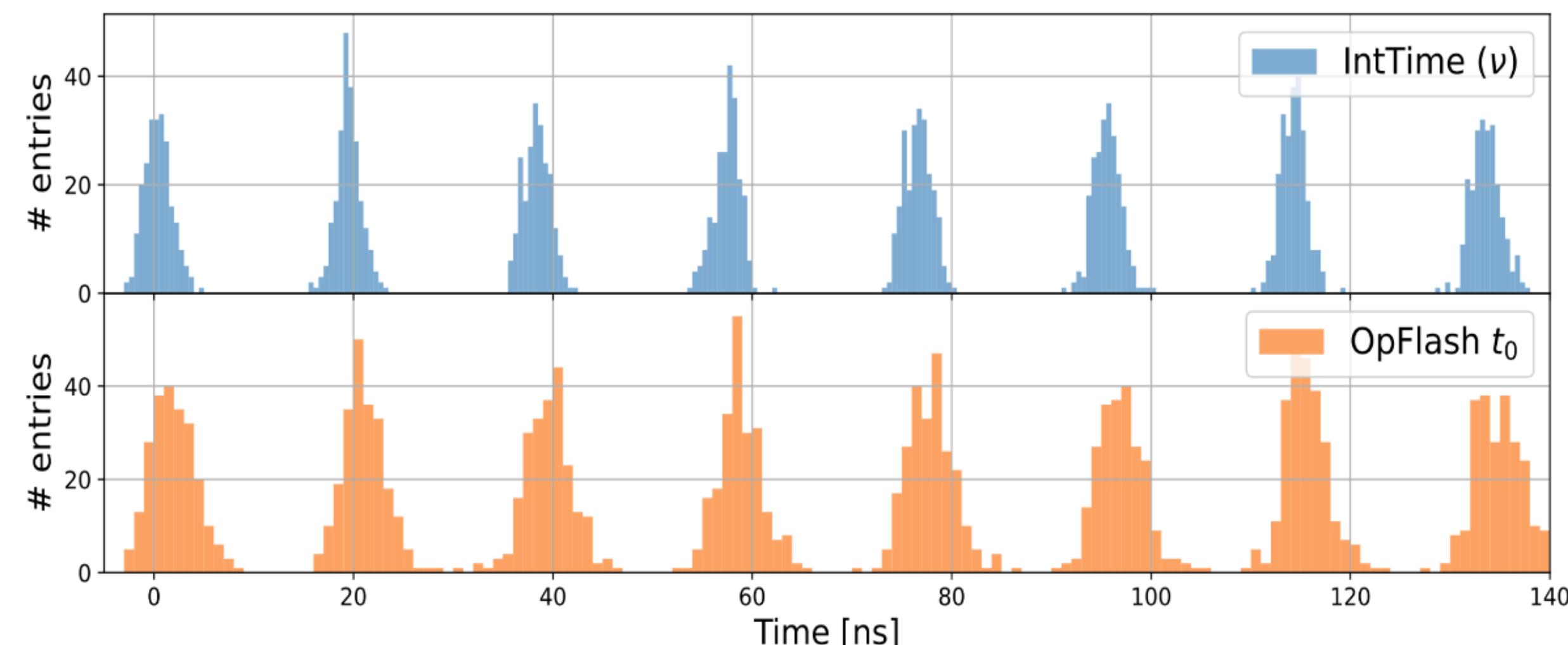
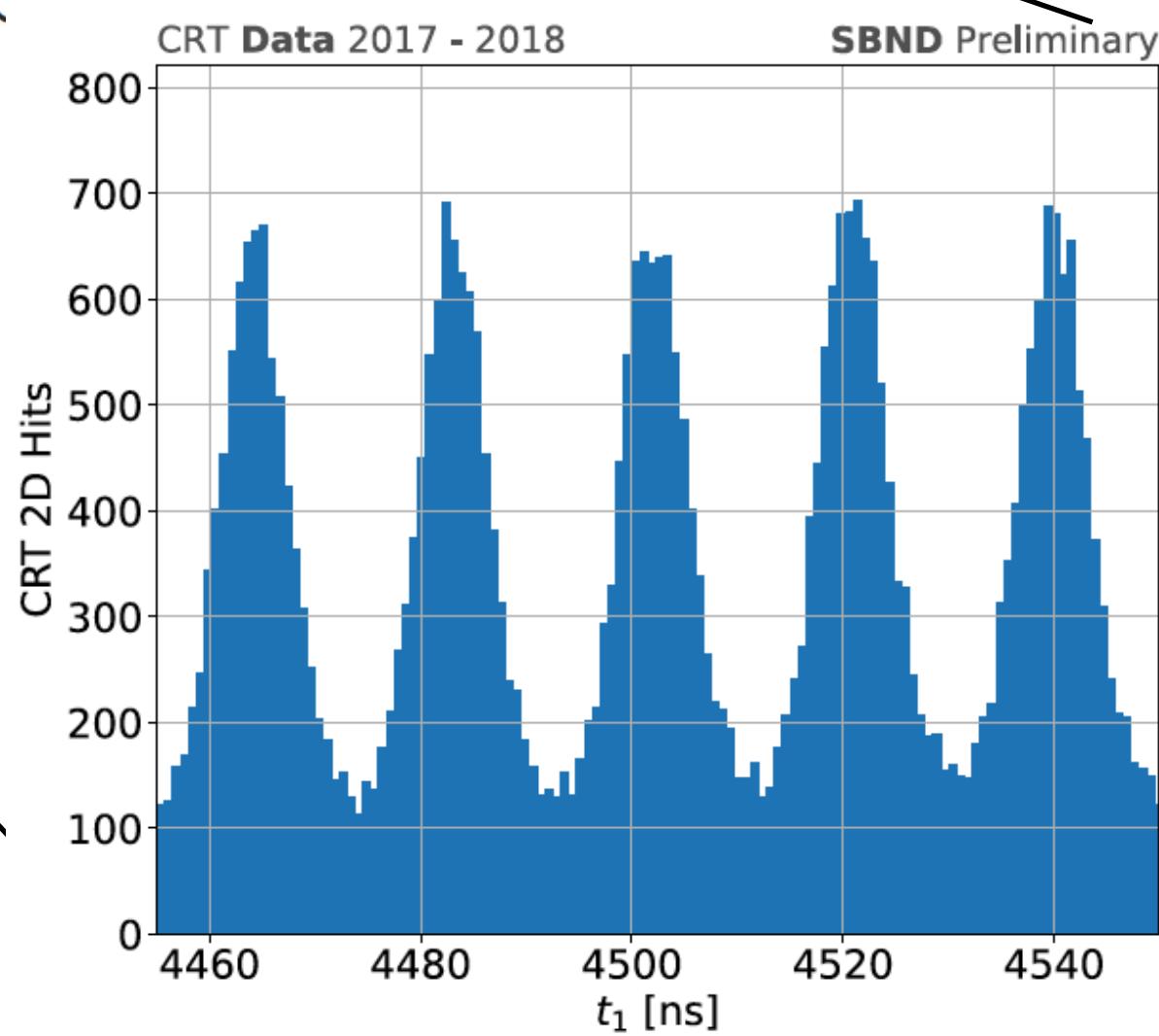
BNB TIME STRUCTURE

CRT Beam Telescope Run 2017-2018



Muons from neutrino interactions in the dirt up of the pit are detected by the telescope. The beam spill substructure can be seen

- 81 bunches with 19 ns spacing
- spill duration of $1.6 \mu\text{s}$



Simulated (top) and reconstructed (bottom) light flashes showing the neutrino beam structure.