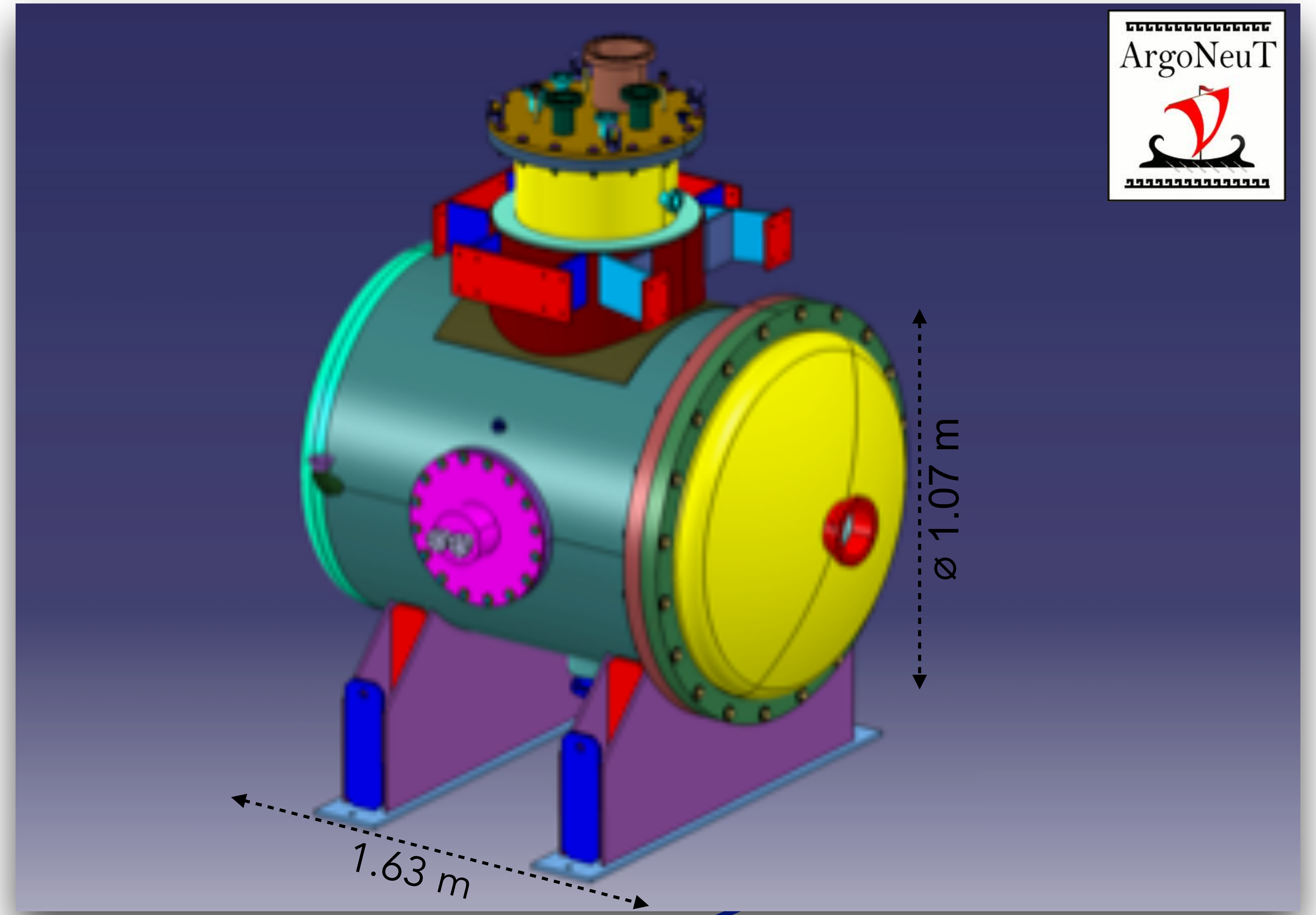


BSM Searches at ArgoNeuT

Good Things come in Small Packages!

PITT PACC Workshop: Nu Tools for BSM at Neutrino Beam Facilities

Pittsburg, December 15th 2022

Ornella Palamara

Fermilab & Yale University

Outline

Beyond the Standard Model (BSM) with Neutrinos:
why Short-Baseline Neutrino Liquid Argon Time Projection Chamber Experiments?

The ArgoNeuT experiment

Joint Experiment+Theory projects: Constraints on new physics in unexplored parameter space regions from ArgoNeuT data

Where to study New Physics?

We know there needs to be **physics beyond the standard model**. We have **no idea** of what and where that is.

A reach science program to explore the unknown!

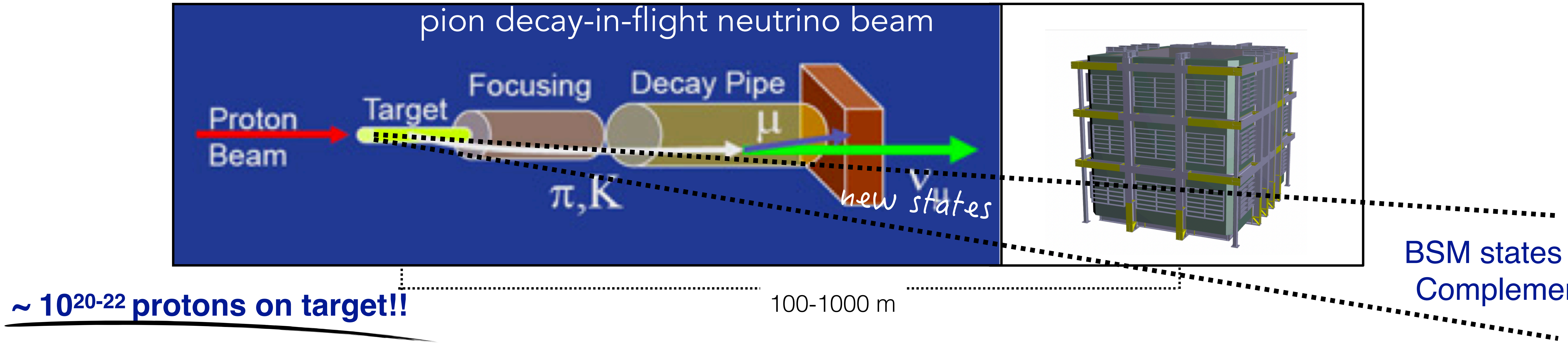
For a given experiment, search in many diverse signal regions for new models.

New physics searches have been the domain of high-energy colliders for decades.

Increasing interest for similar/complementary opportunities to be explored in neutrino experiments!

The BSM models accessible are specific to the neutrino source and the detector technology used.

Why BSM in Short-baseline LAr TPC Neutrino Experiments?



BSM states can be produced. Complementary to colliders.

The combination of

- **High-intensity proton beams (high intensity neutrino beams)** coupled with
- **Large mass LAr TPC detectors** close to the beam target, with
  - Event imaging
  - Fine granularity calorimetry and particle identification
  - Good timing resolution
  - Low energy threshold

opens up unprecedented opportunities to probe signatures for

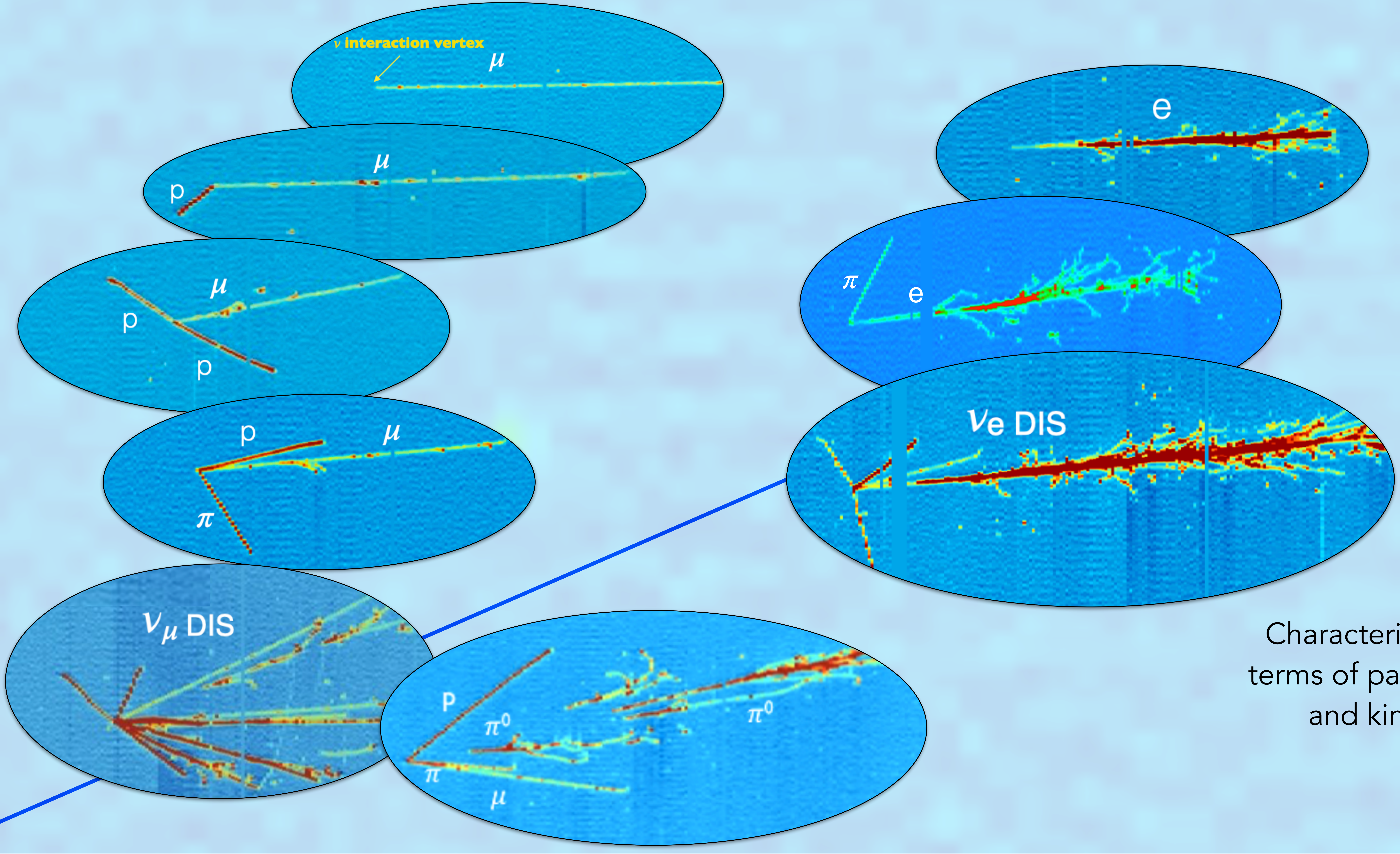
New Physics scenarios in the neutrino sector and beyond

Several targets of opportunity to complement the neutrino program.

Modifications to the neutrino oscillation paradigm
(effects of BSM physics on neutrino oscillation)

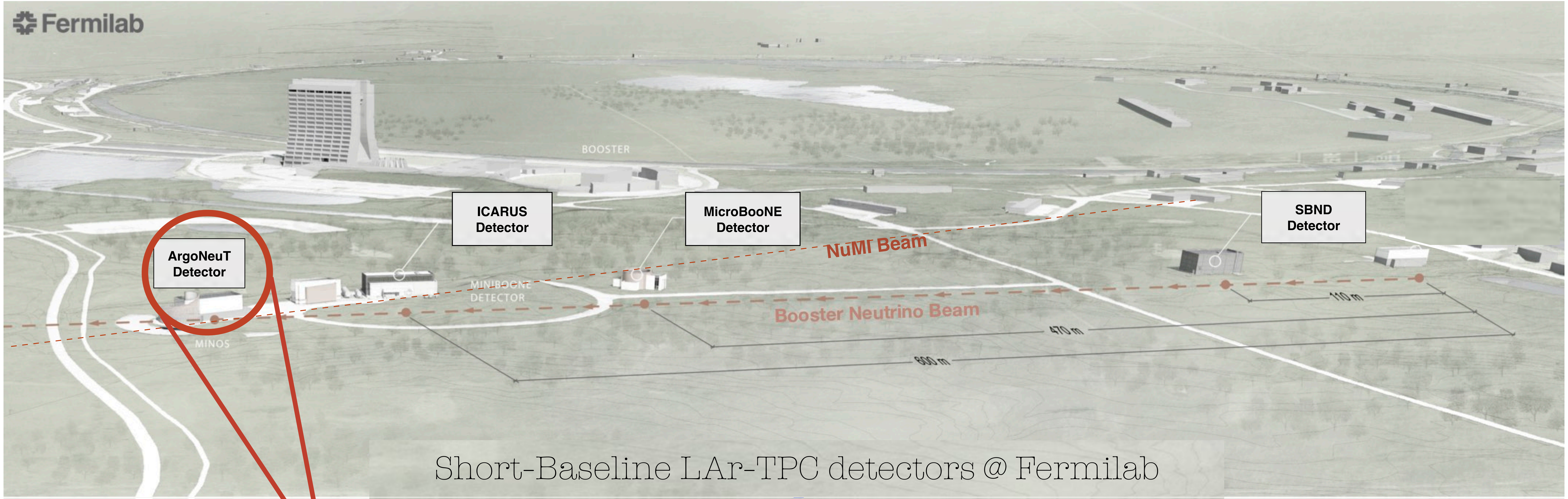
Novel experimental signatures
produced in the beam target

From "easy" to progressively more complicated topologies…

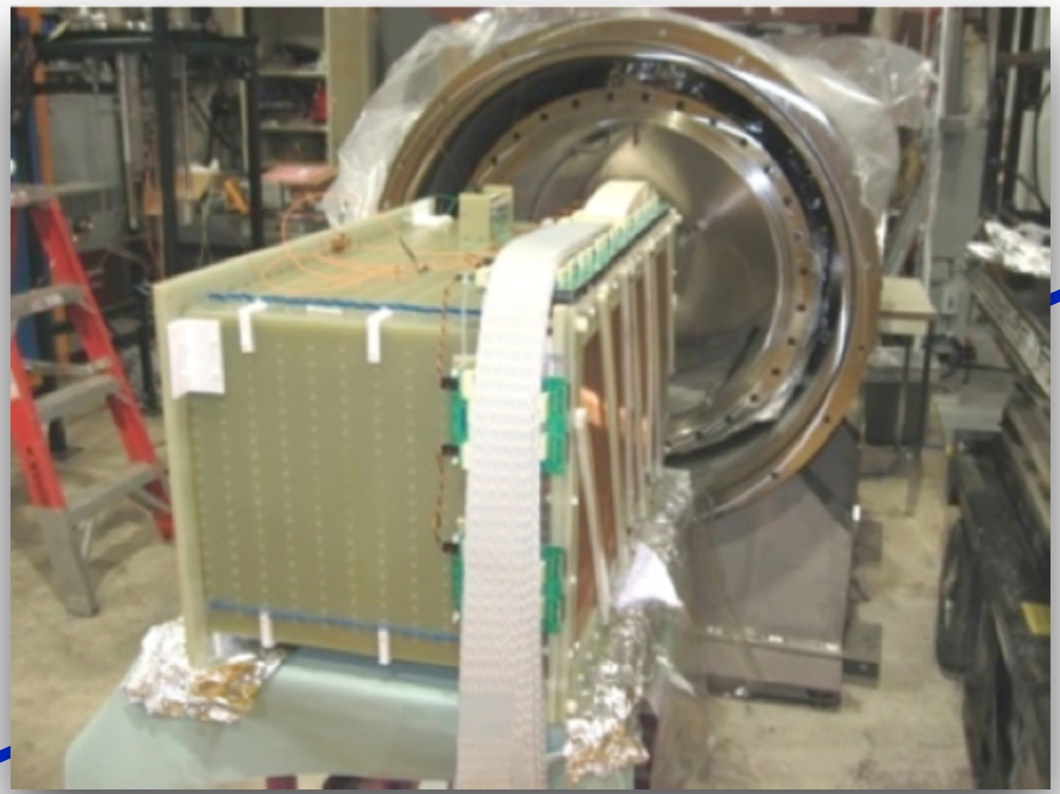


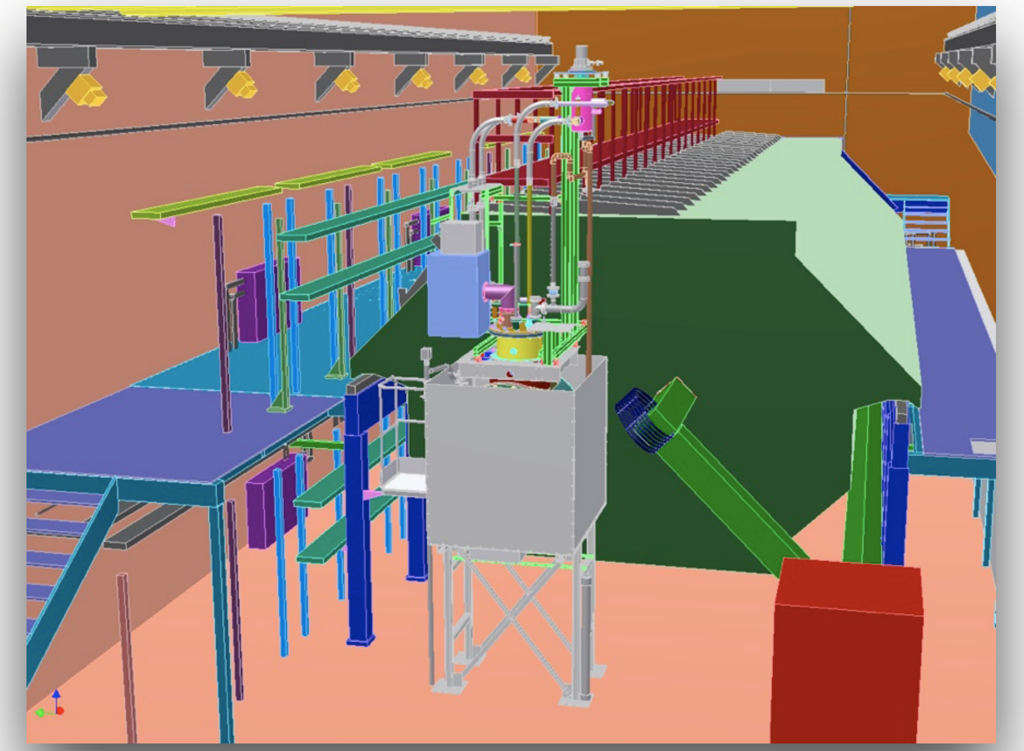
Characterize events in terms of particle content and kinematics.

Short-Baseline LAr TPC detectors at Fermilab: ArgoNeuT



First LAr TPC detector at FNAL
5 months data collected in 2009-2010

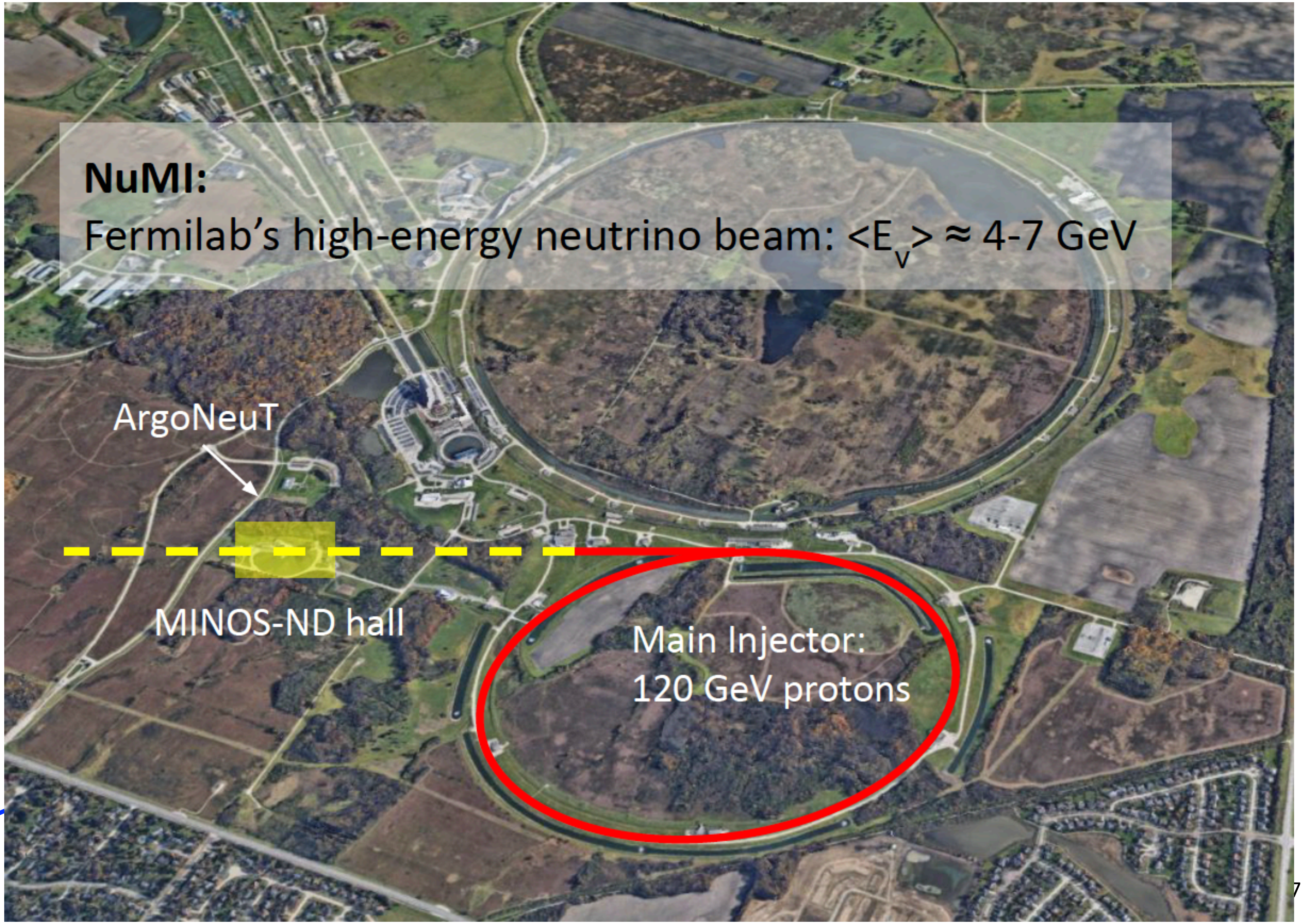




On-axis on NuMI beam, ~ 1 Km from the target

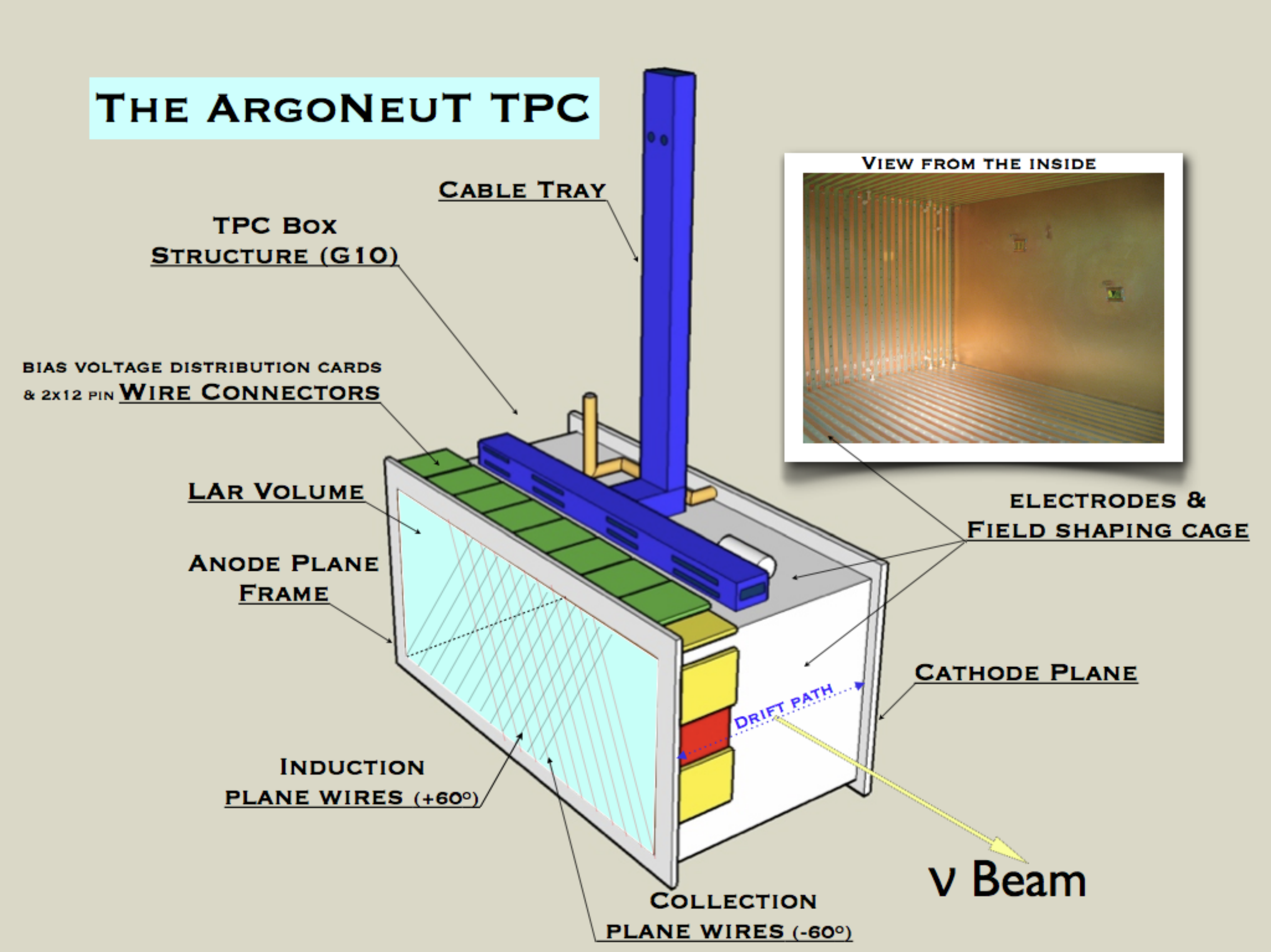
100 m underground, upstream of the MINOS ND

ArgoNeuT in the NuMI beam



ArgoNeuT experiment

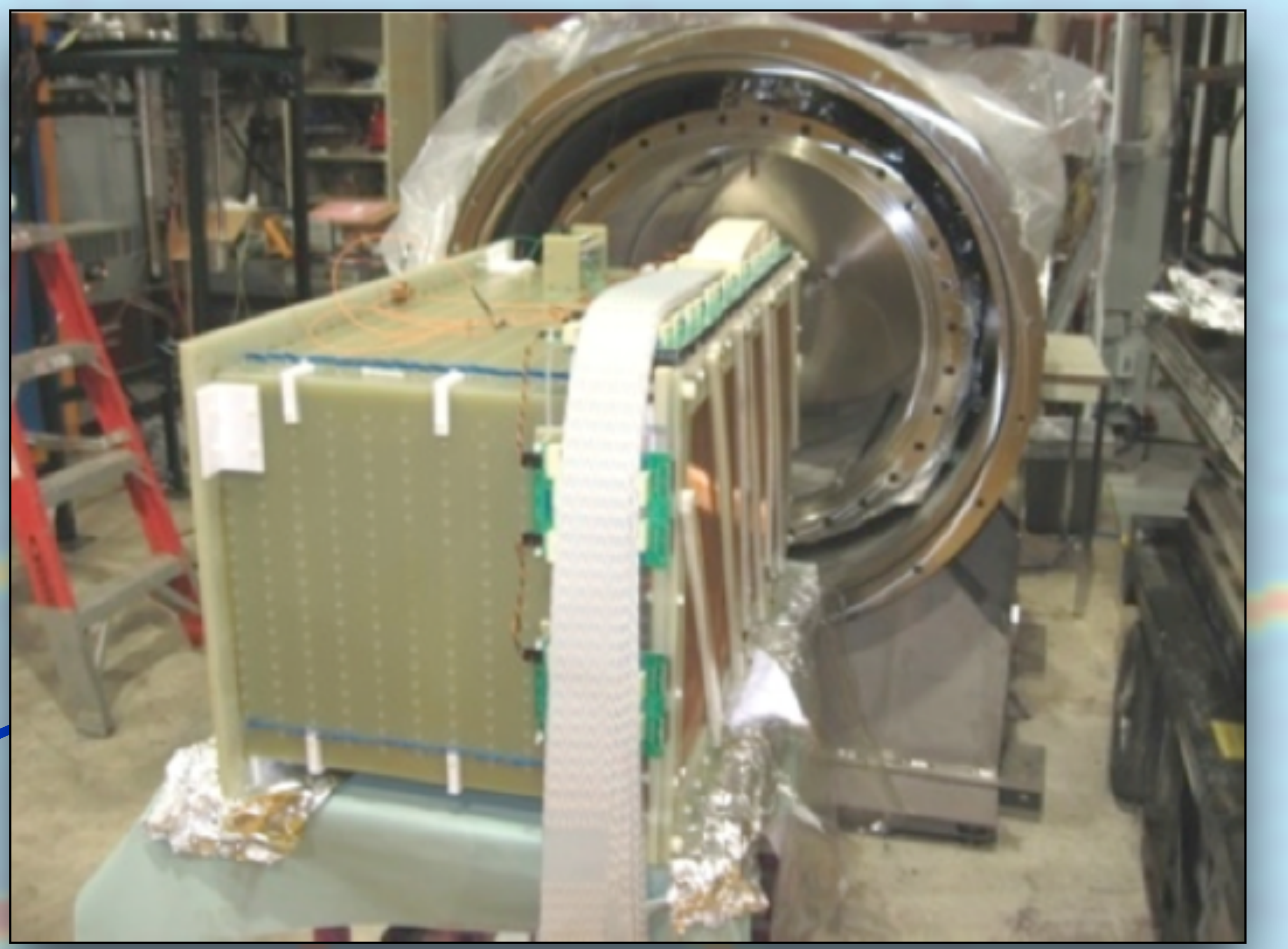
First LAr TPC in a neutrino beam in the US



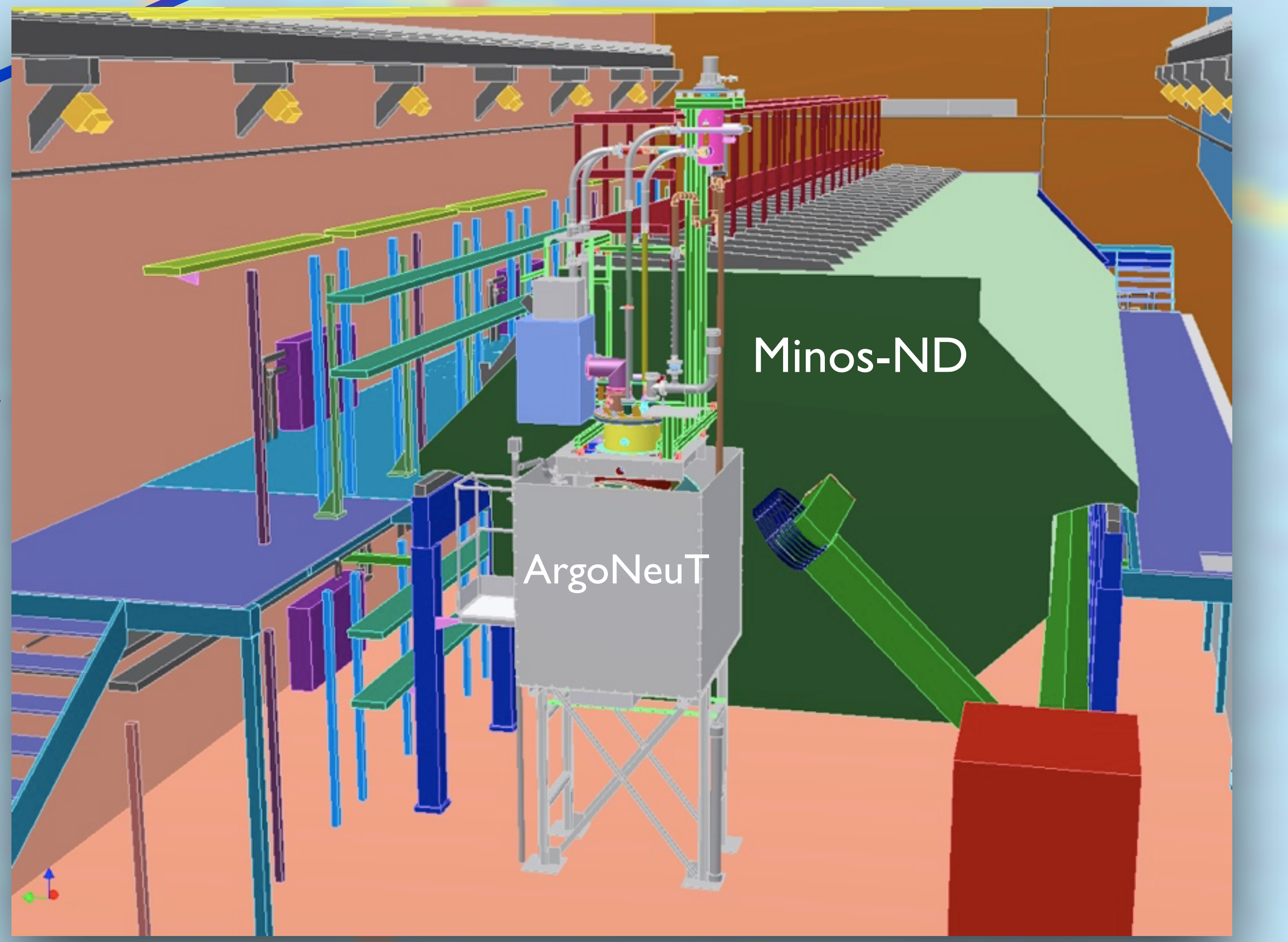
0.24 tons active volume
Liquid Argon Time
Projection Chamber

47(h)×40(w)×90(l) cm^3
2 readout planes
480 wires, 4 mm spacing
No light detection system

ArgoNeuT Collaboration, JINST 7 (2012) P10019



100 m underground
MINOS ND as muon spectrometer
for ArgoNeuT events

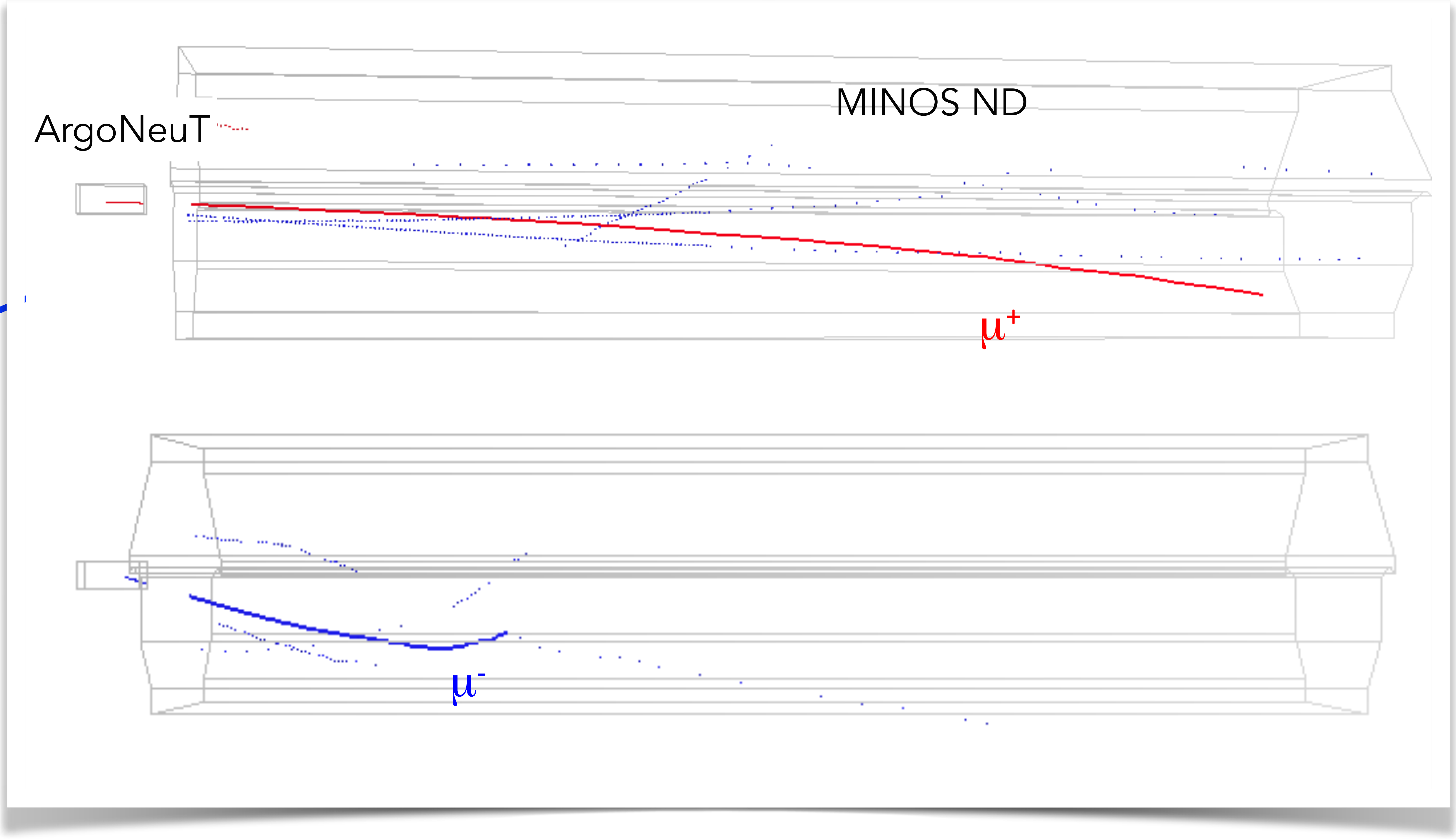


MINOS ND: large magnetized steel
and scintillator strip spectrometer

Advantages of ArgoNeuT

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

ArgoNeuT on the NuMI beam

Acquired 1.35×10^{20} POT, mainly in $\bar{\nu}_\mu$ mode (4.5 months run in **2009-2010**) on the NuMI beam at FNAL

~7000 neutrino events collected

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

First to demonstrate electron-gamma separation in LAr TPC

Developed LAr TPC calibration techniques

Several first ν-Ar cross sections measurements

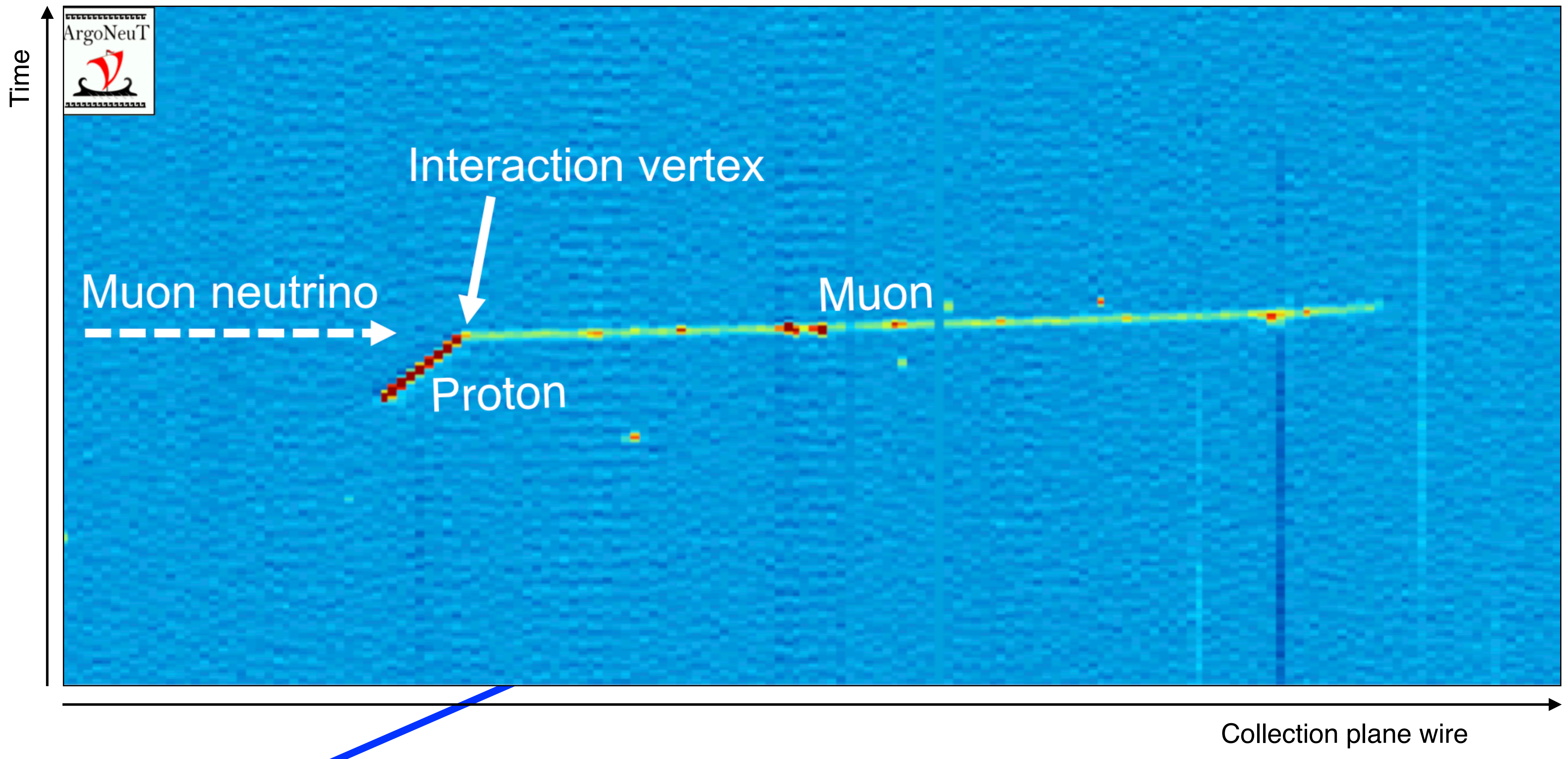
Studied of nuclear effects in ν-argon interactions

Demonstrated MeV-scale physics in LAr TPC

and…see next

The low energy frontier in LAr TPCs

A study from ArgoNeuT data has demonstrated the capability of LAr TPC to be able to detect and reconstruct (sub-)MeV energy depositions



The low energy frontier in LAr TPCs

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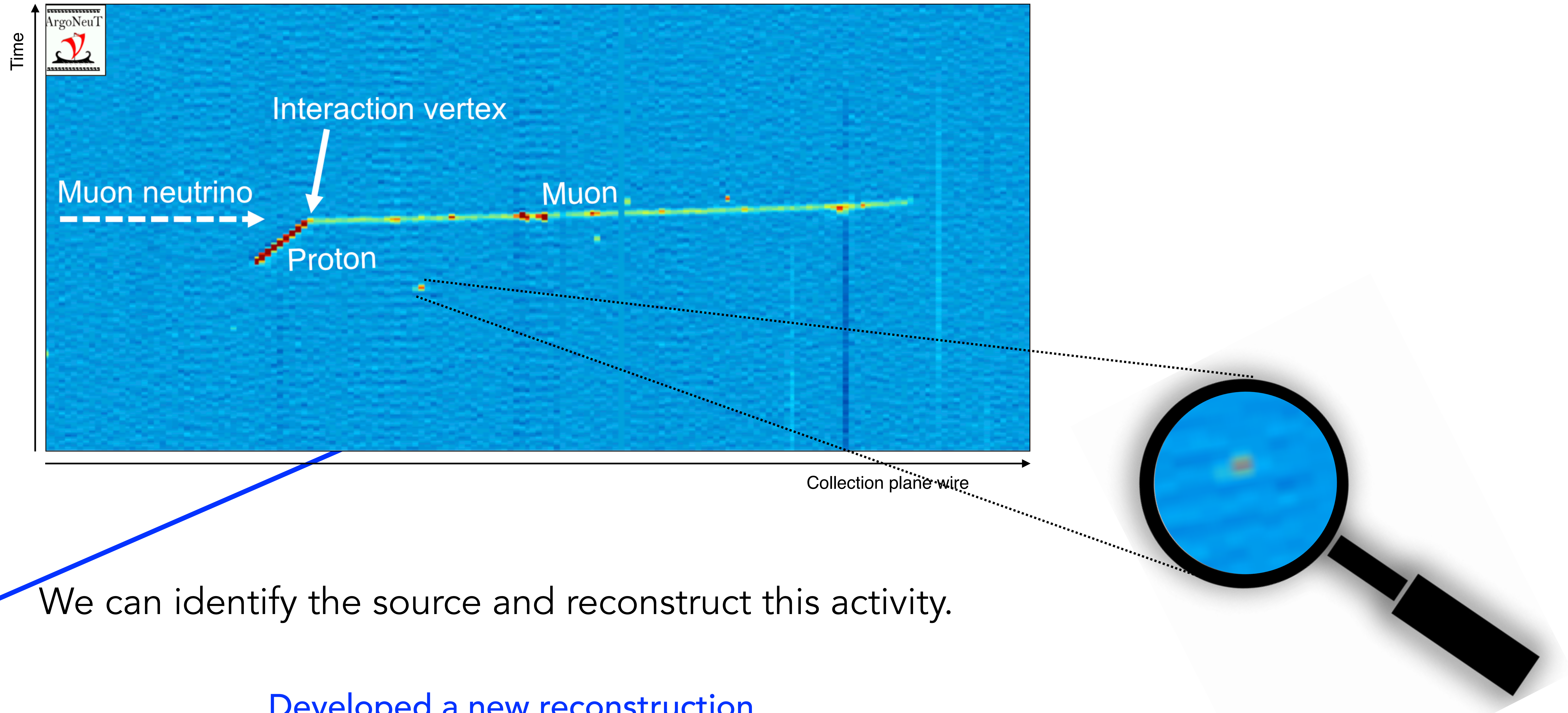
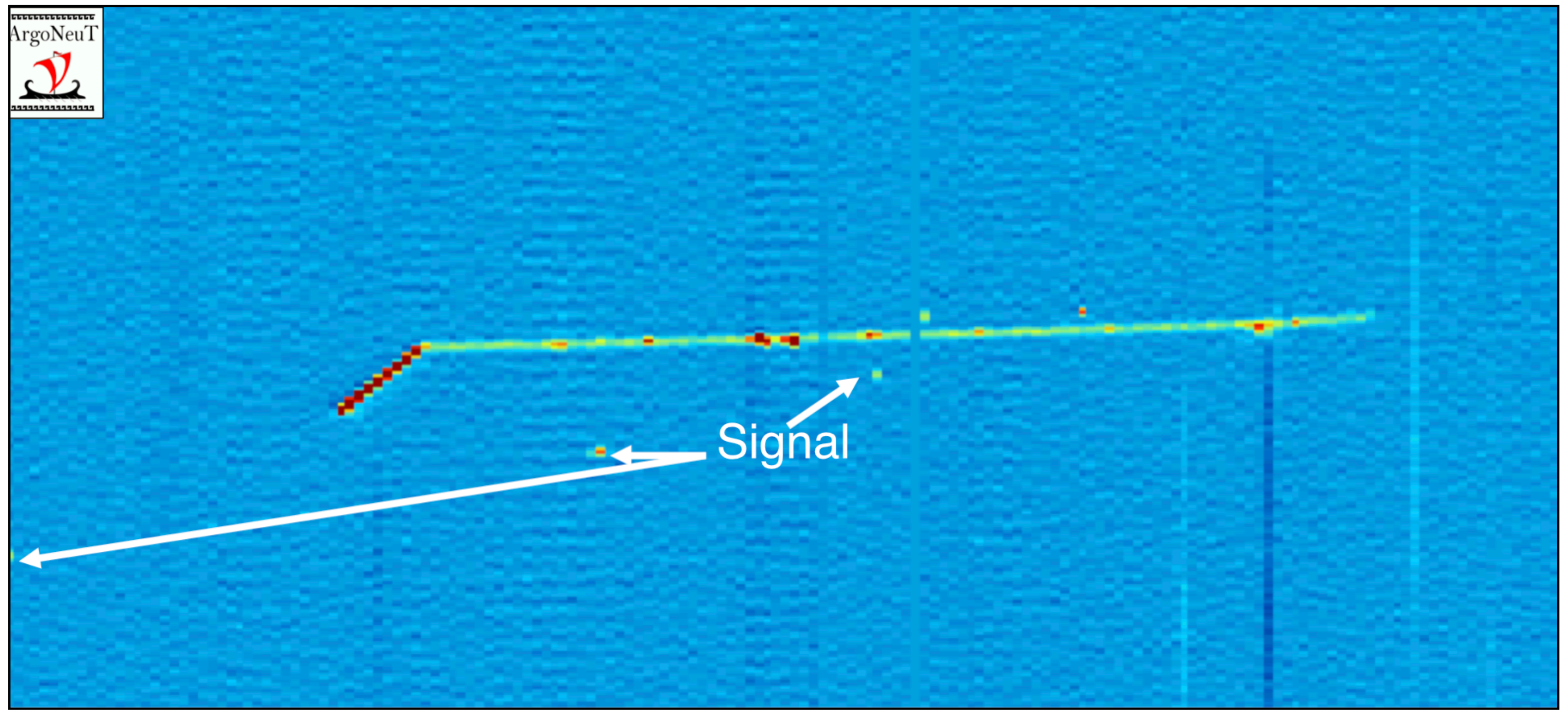


We can identify the source and reconstruct this activity.

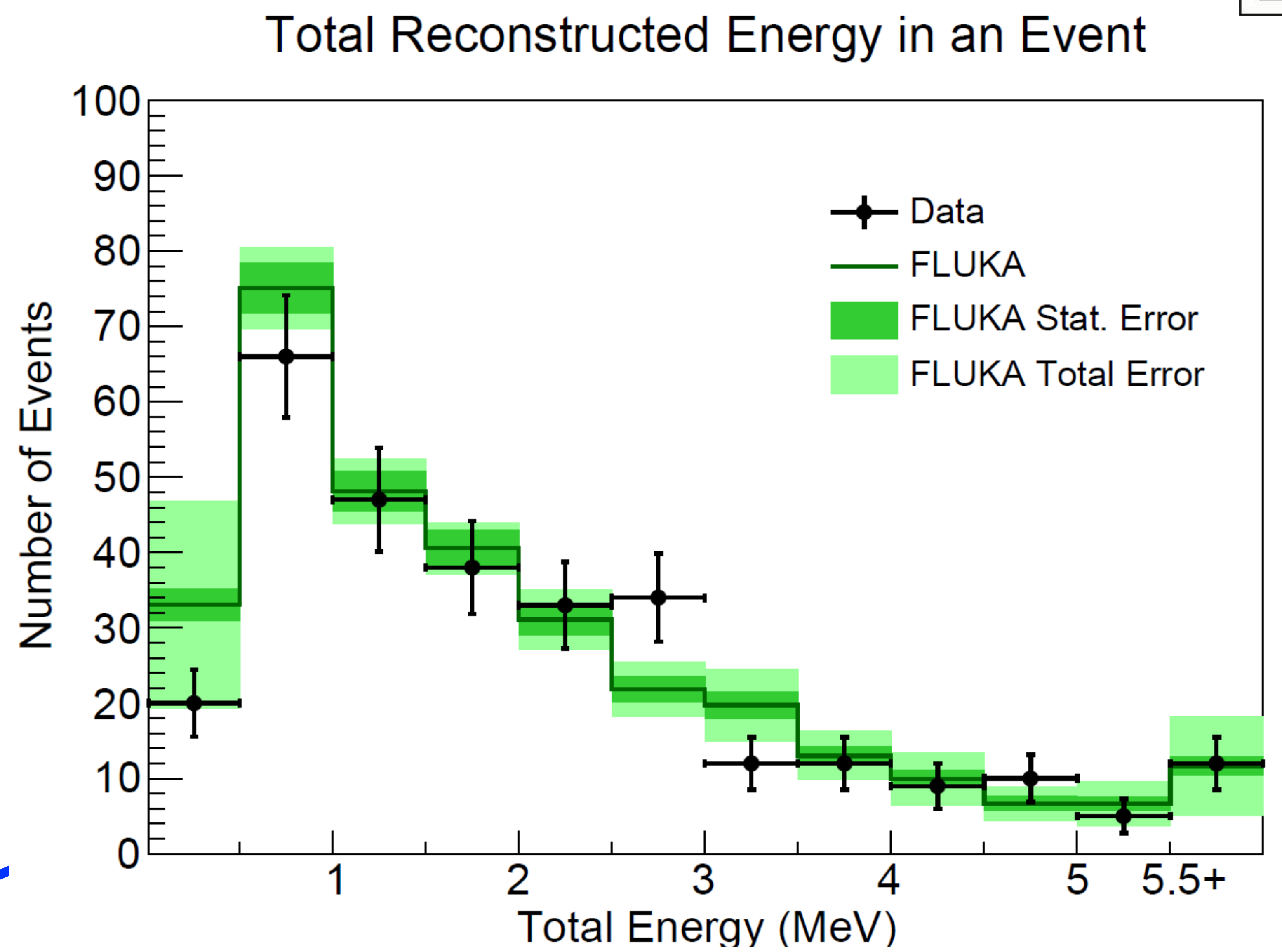
Developed a new reconstruction technique.

The low energy frontier in LAr TPCs



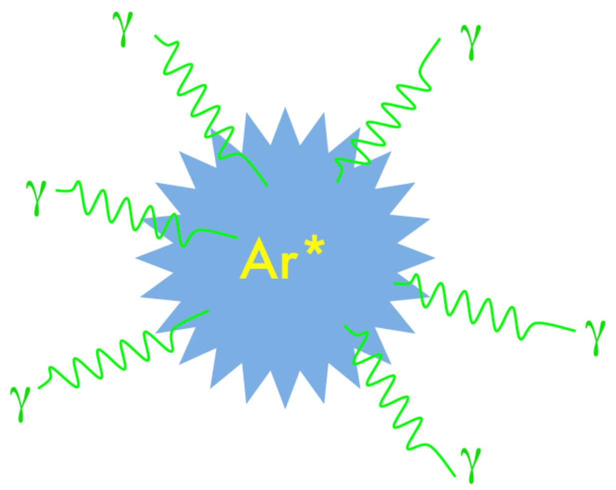
300 KeV threshold
In ArgoNeuT

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 (DUNE)
- Study new physics scenarios.

Joint Experiment+Theory meetings

Informal meetings (slides+backboard!!) - since 2018

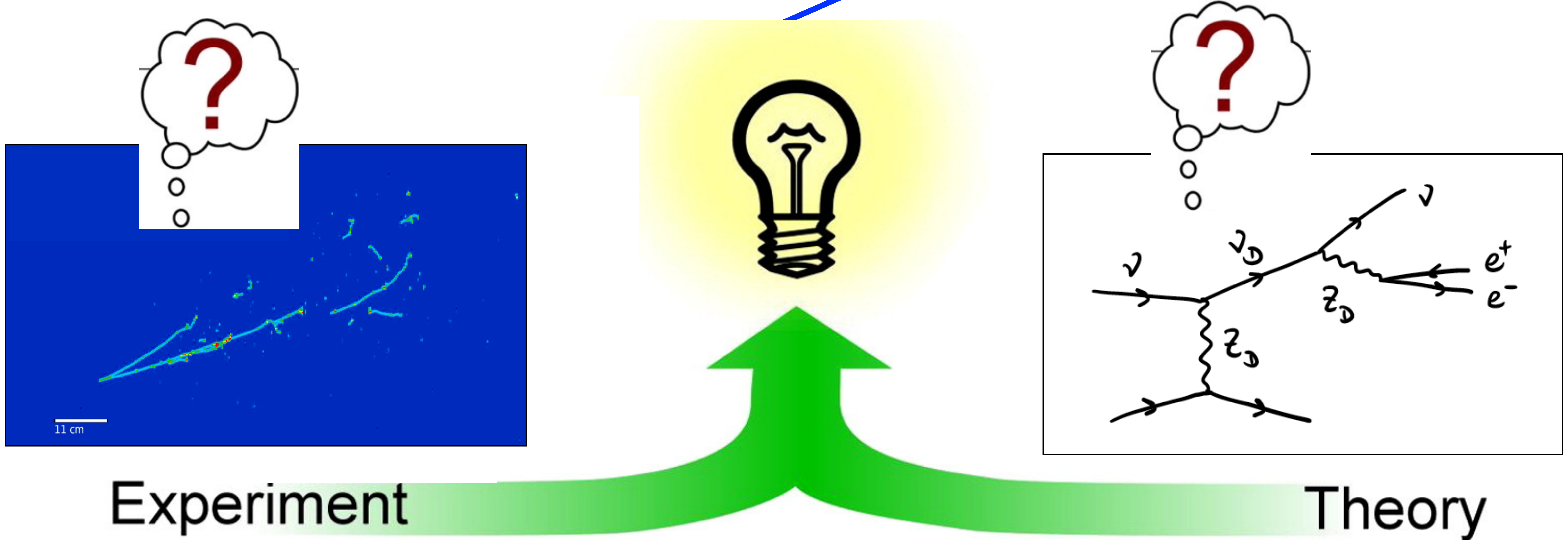
Discuss experimental capabilities of LAr TPC detectors, current status of event reconstruction, thresholds and resolution.

Discuss models for New Physics to be studied in LAr TPC neutrino experiments.

Theorists to better know how the LAr TPC technology works and experimentalists to better know what to look for.

Work **side-by-side** on various projects, understanding signal and background.

Organizer: Pedro Machado



Joint Experiment+Theory project:
Search for Millicharged Particles (mCPs)

Motivated by the LAr TPC's demonstrated ability to detect and reconstruct (sub-)MeV energy depositions,

we started a common project, which evolved into two papers:

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

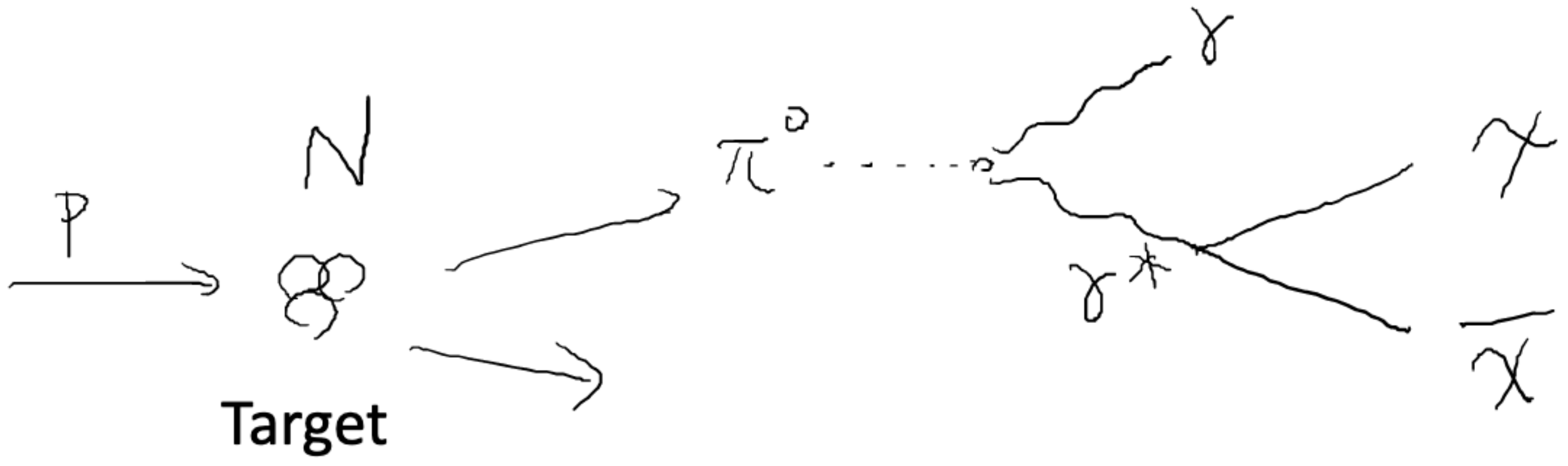
Theory paper

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

Experimental paper

mCP search - Production

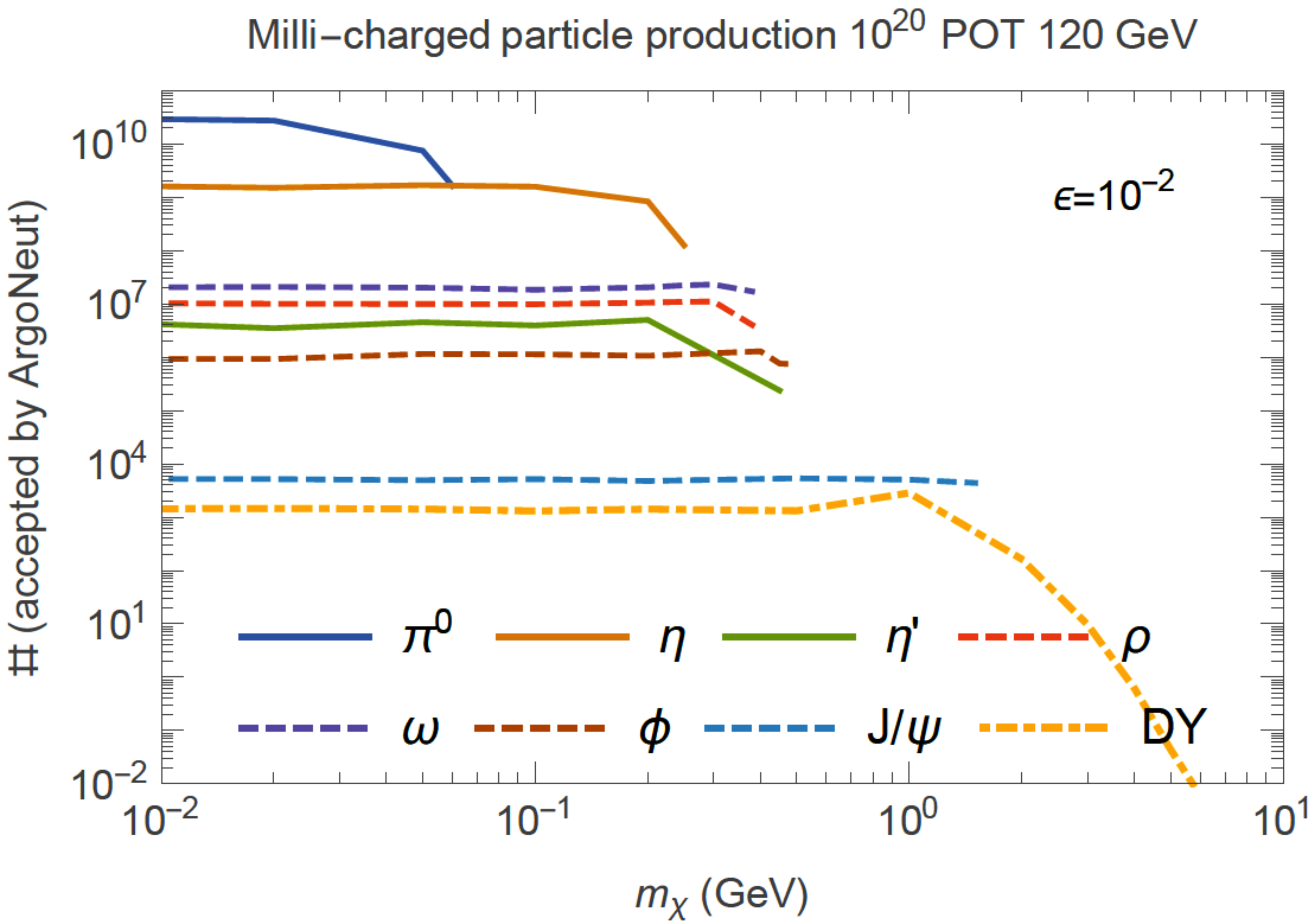
mCP have an electric charge $Q=\epsilon \cdot e$ ($\epsilon \ll 1$) and could be produced in neutrino beams



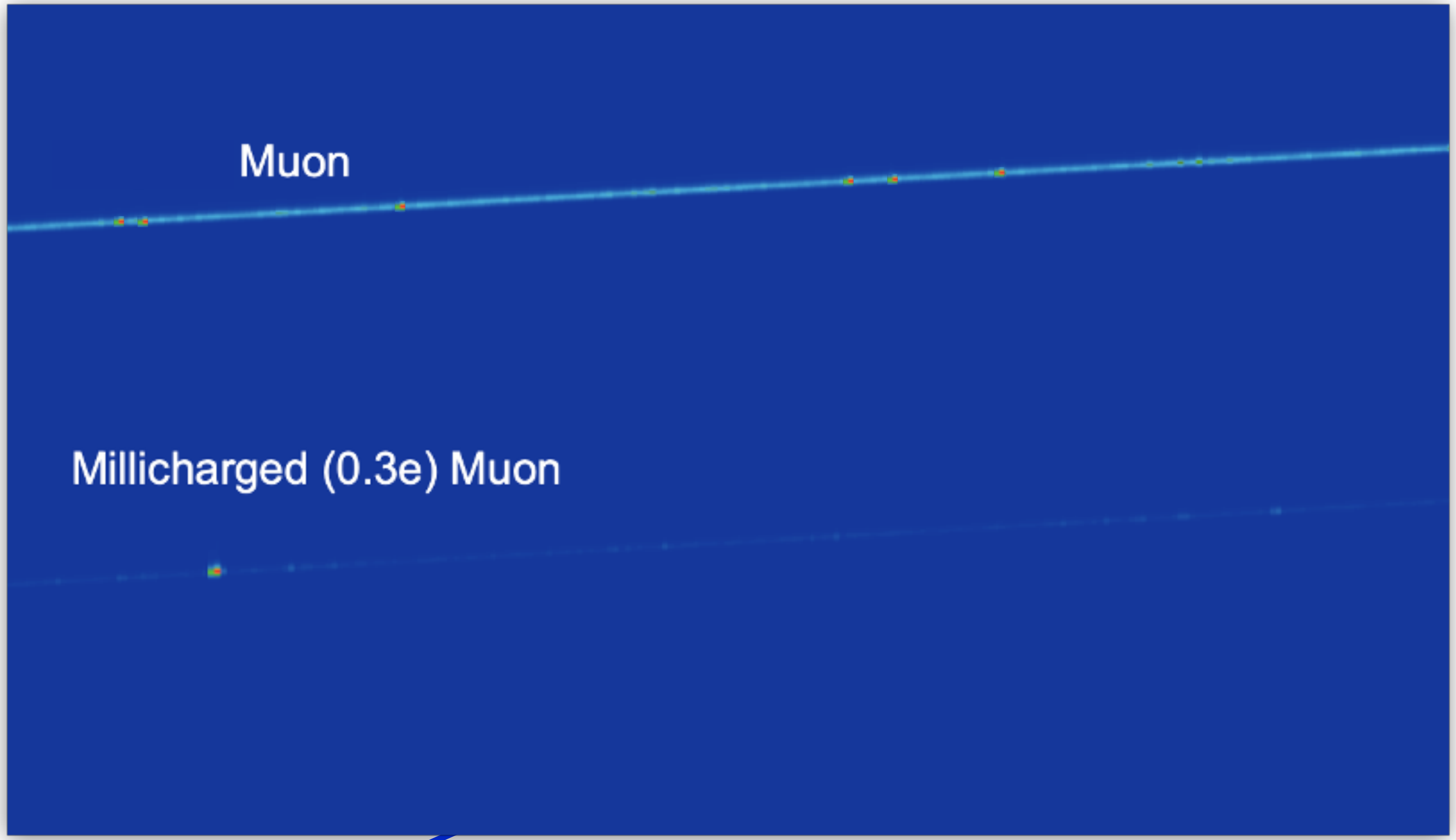
- production: meson decays

mCPs produced boosted, w/ energy ~ 5- 50 GeV

Many mCPs produced inside the target!



mCP search - How do we detect a particle with a tiny charge in LAr?



muon track

mCP "track"

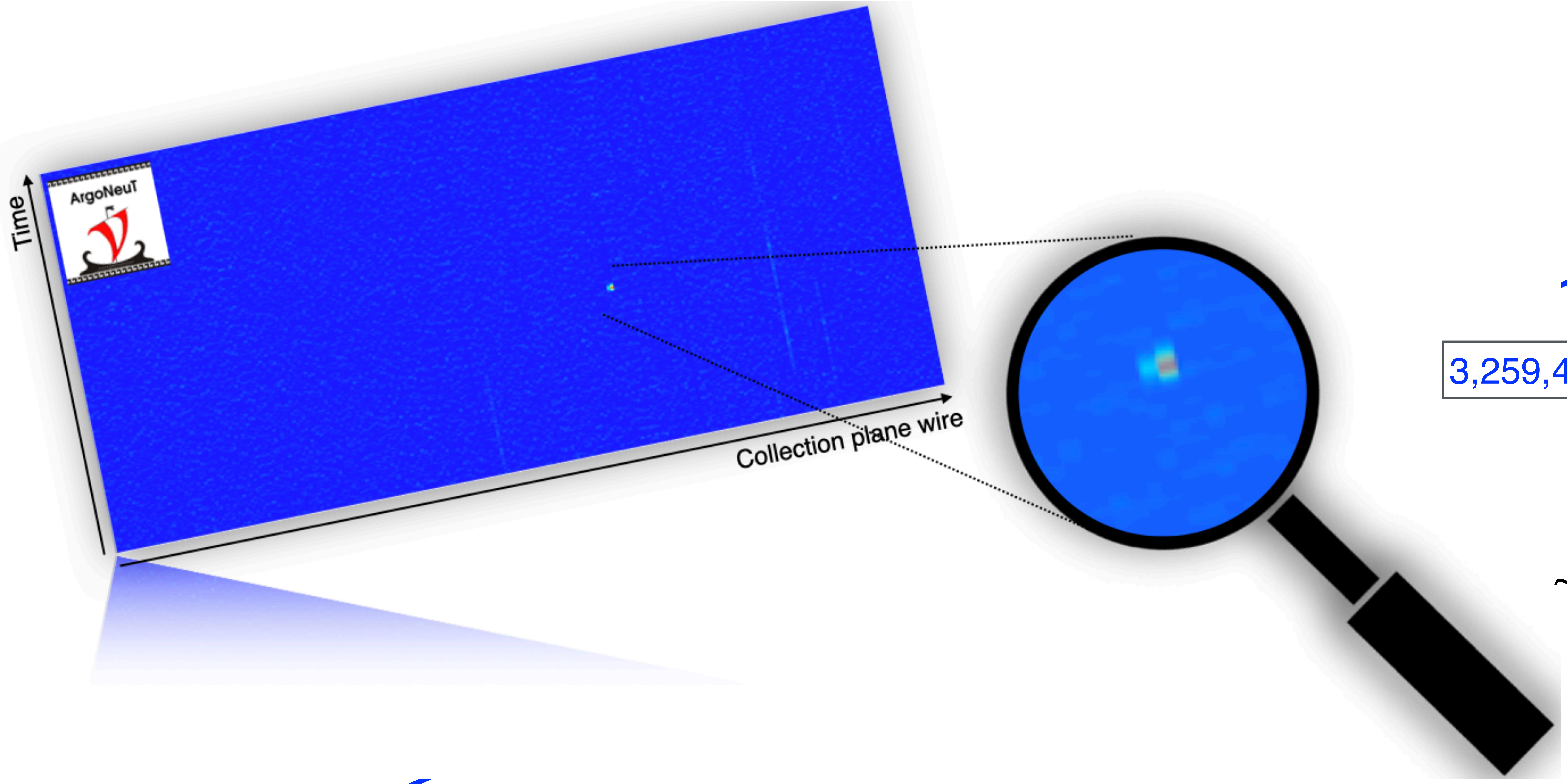
Soft hits dominate

mCP ionization track is undetectable except when knock-on electrons energetic enough to themselves produce a visible signal are emitted.

mCP signal consists of one or more soft hits (electron recoils above the detection threshold) within the detector volume.

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)



5 months of ArgoNeuT data

3,259,427 events in 1.0 $\cdot 10^{20}$ protons on target (POT)

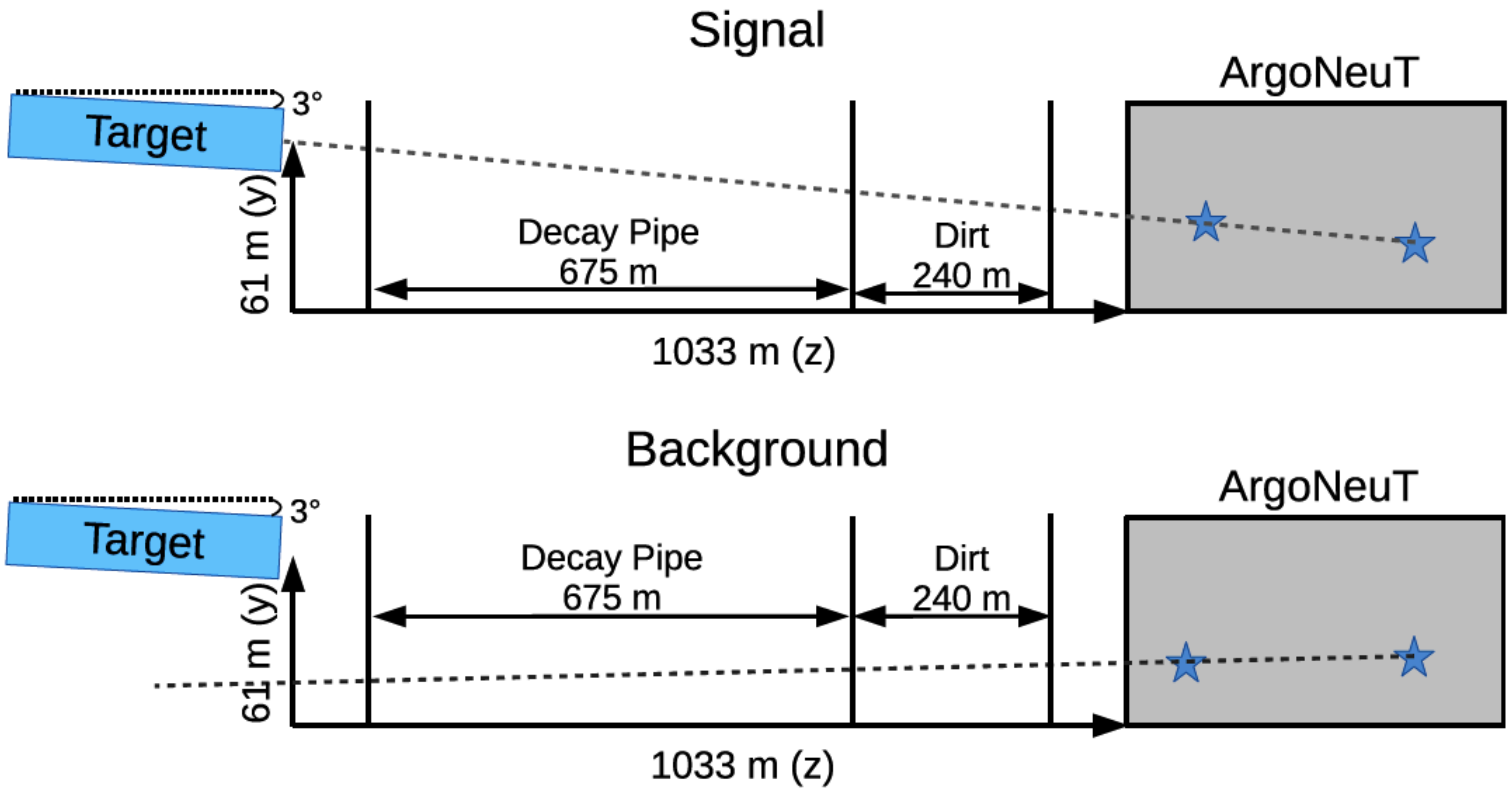
⇩

~88% have 0 clusters, ~2% have 2 clusters

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

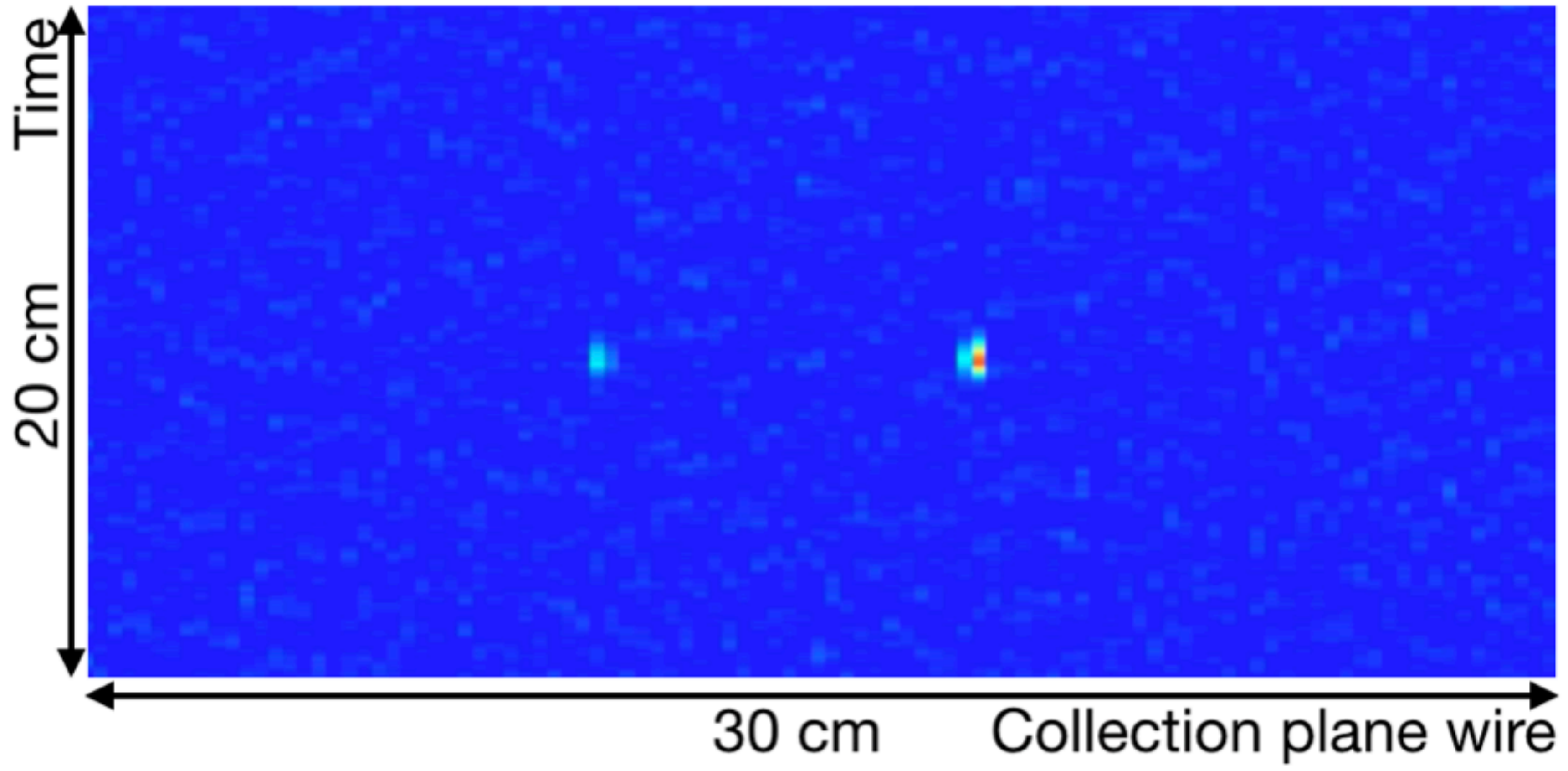
A background double-hit event doesn't point to the target

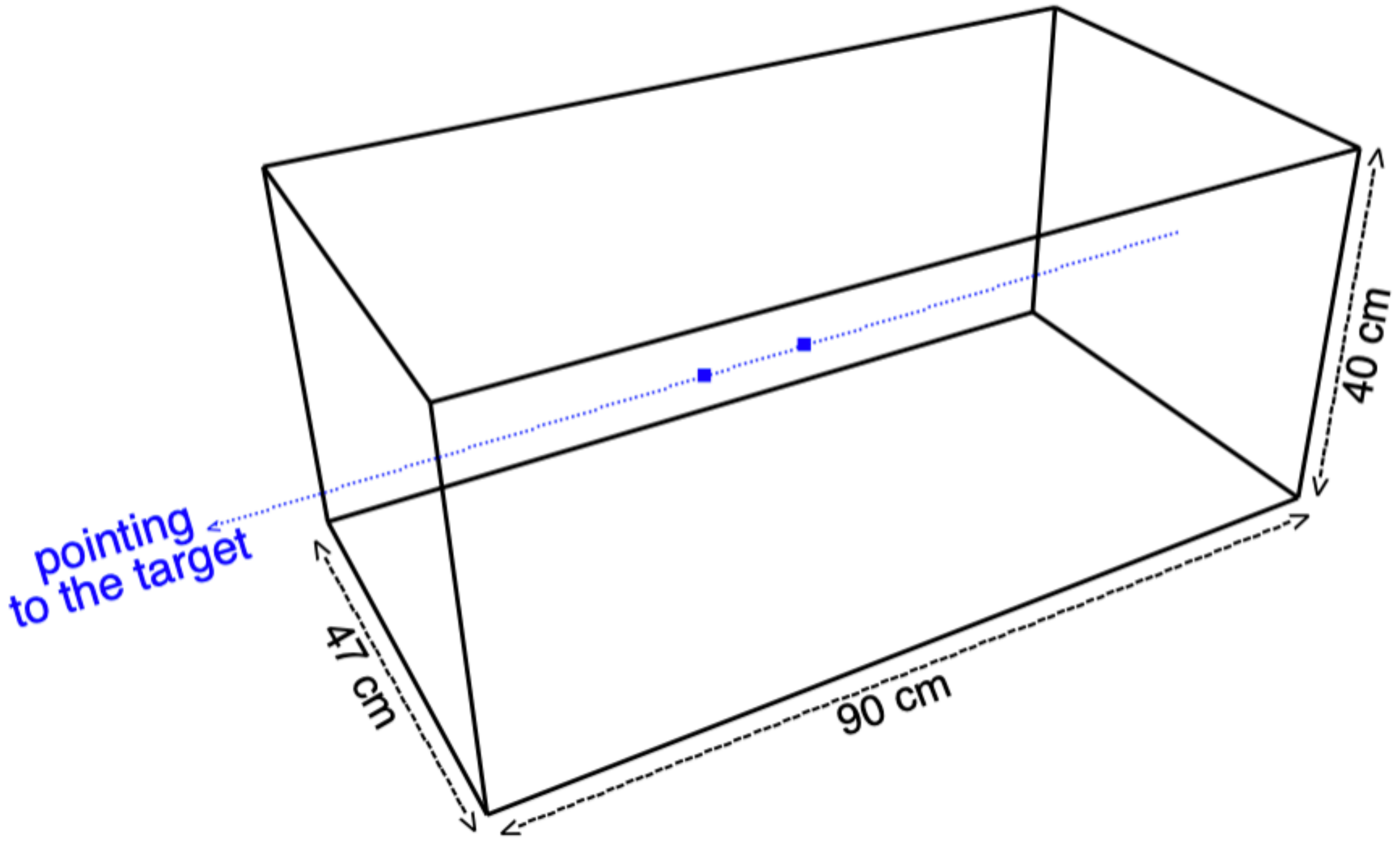
To reduce background:
search for double hits events aligned with the target

Joint Experiment+Theory project:
First Search for millicharged particles in LAr TPC

one mCP Signal Candidate Event observed

[compatible with the expected background]

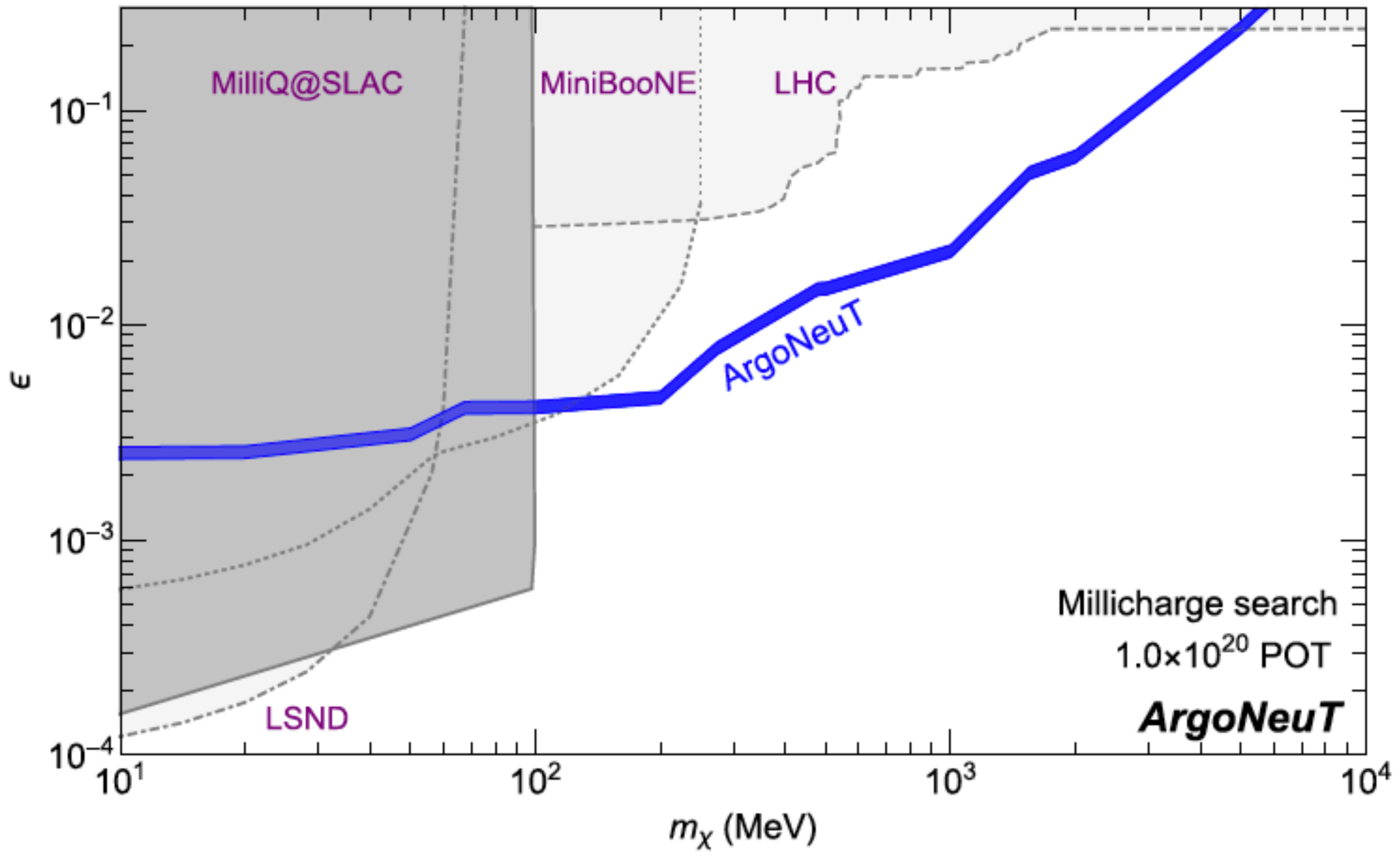




Low energy threshold (300 KeV) is the key!

ArgoNeuT Collaboration + 2 theorists (R. Harnik and Z. Liu)

R. Acciarri et al., PRL124 131801 (2020)

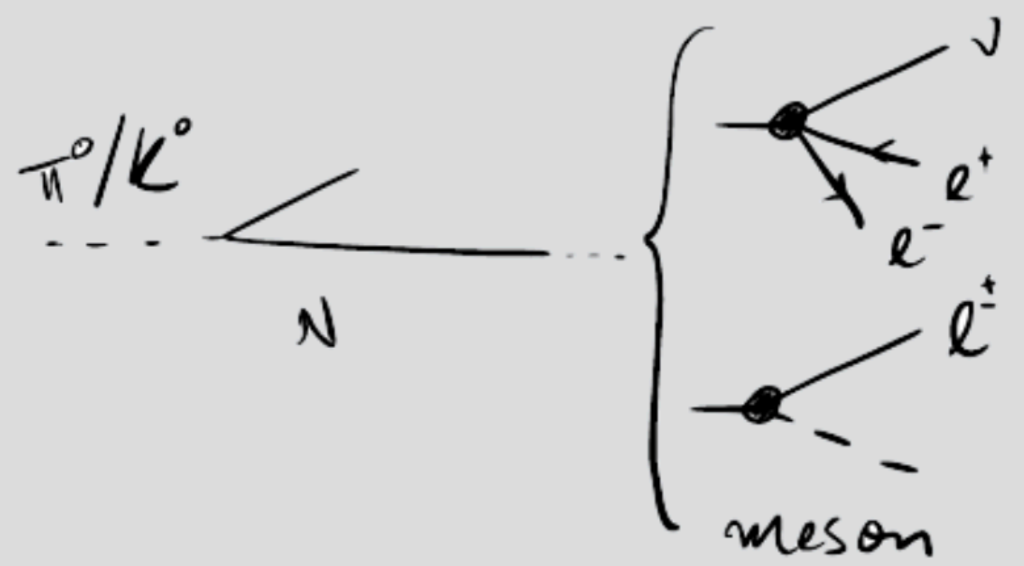


Leading constraints in unexplored parameter region!

Joint Experiment+Theory project:
Search for Heavy Neutral Leptons (HNL)

The 120 GeV protons at NuMI enables production of HNL with masses up to approximately 1 GeV and their decays can be searched for in ArgoNeuT.

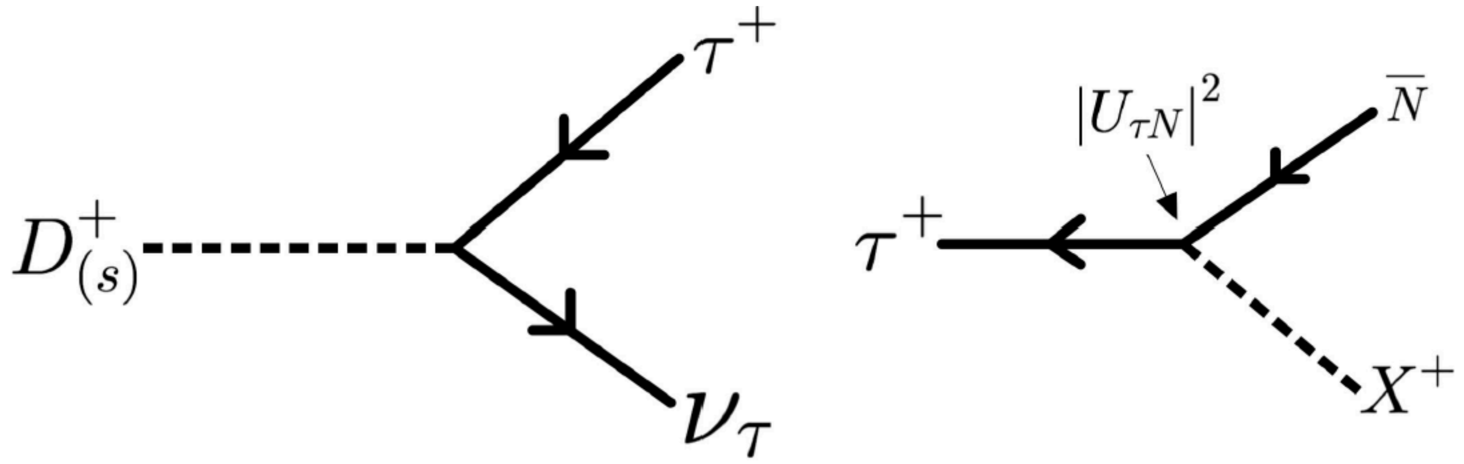
Heavy Neutral Leptons



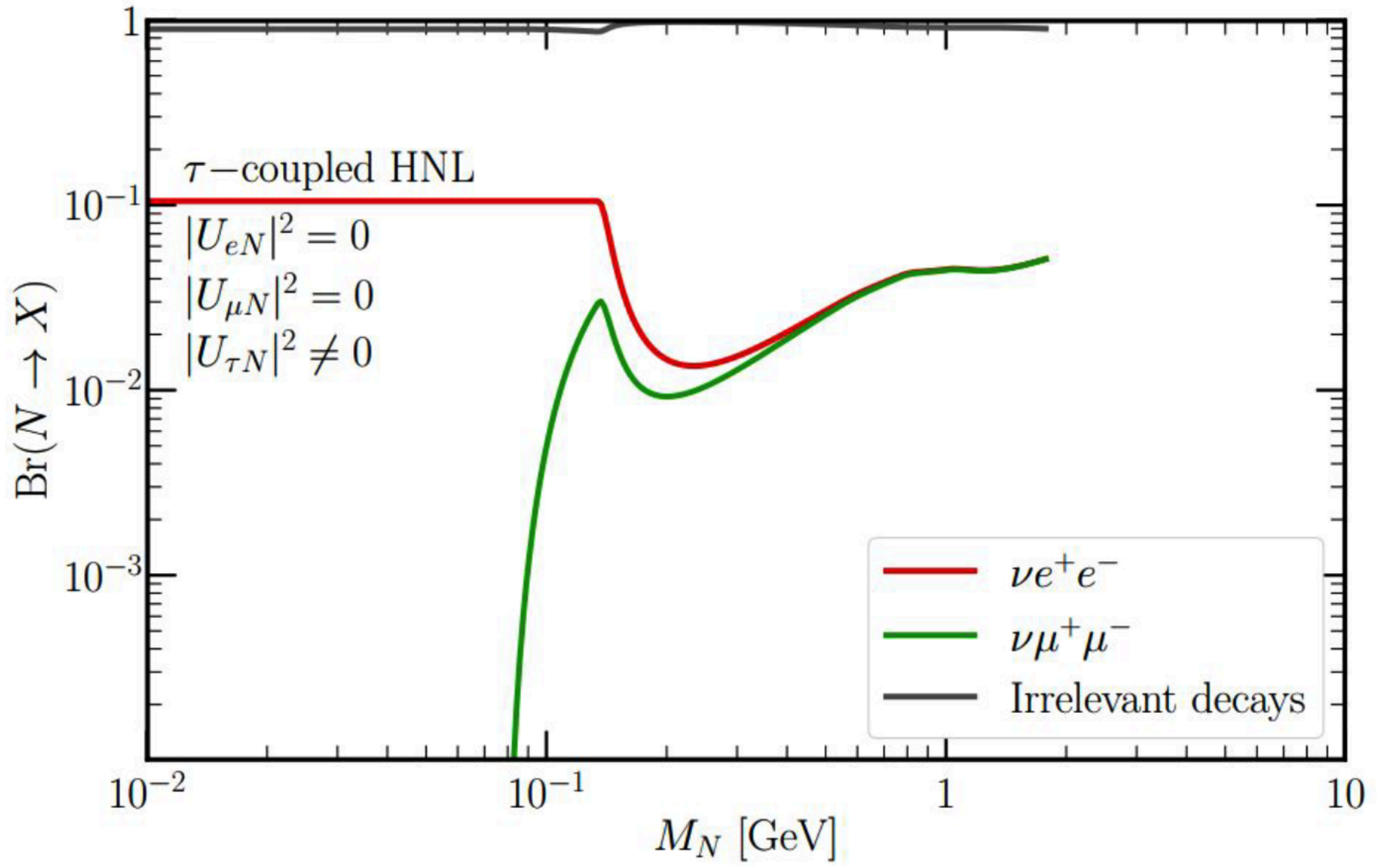
Ballett Pascoli Ross-Lonergan JHEP 2017
Kelly Machado PRD 2021

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 $\tau^\pm$ 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. $\pi^\pm$)



$$M_N \lesssim m_\tau$$

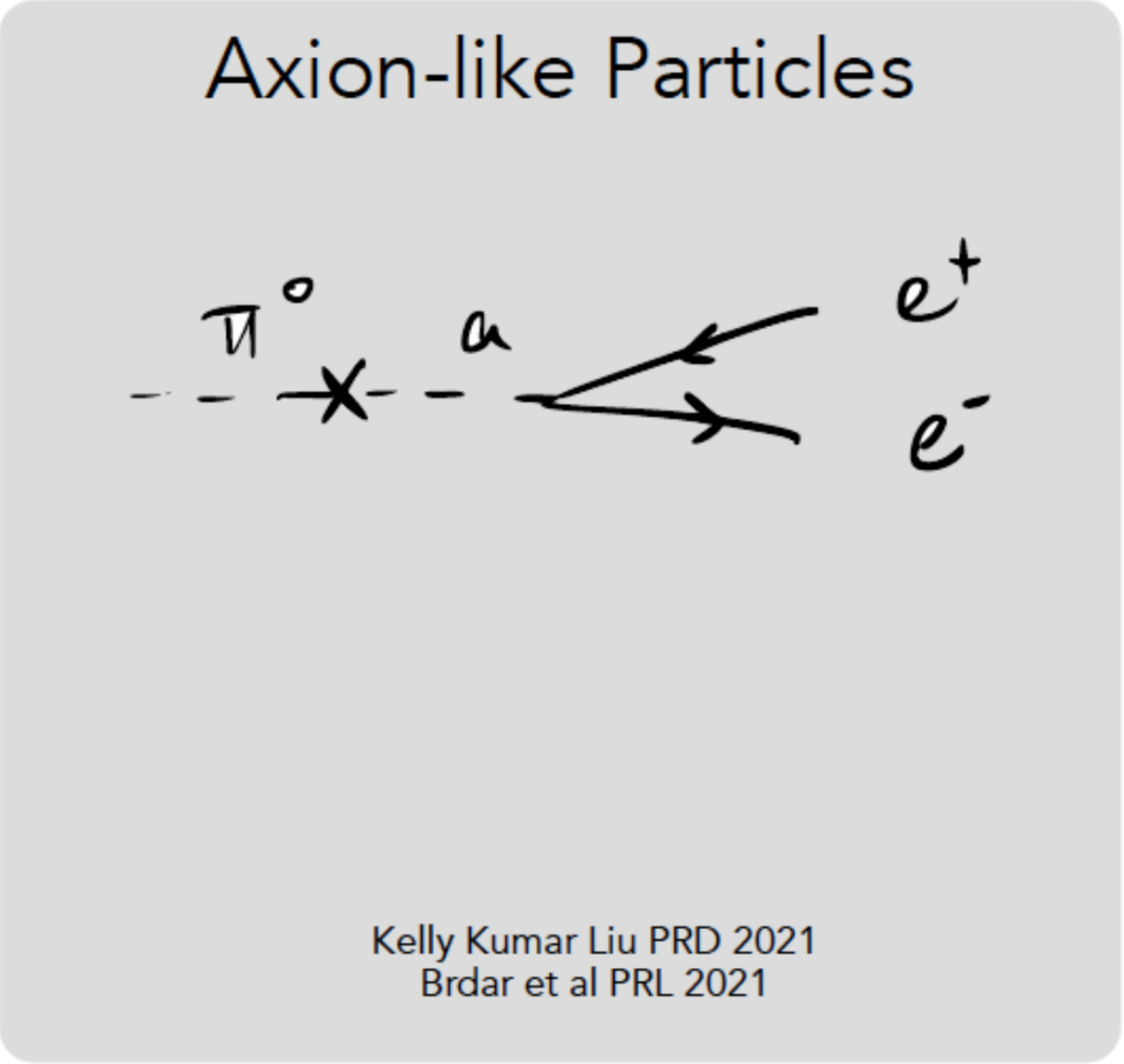


τ-coupled HNL: νee, ν**μμ** decay modes

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

Joint Experiment+Theory project: Search for Heavy QCD Axions

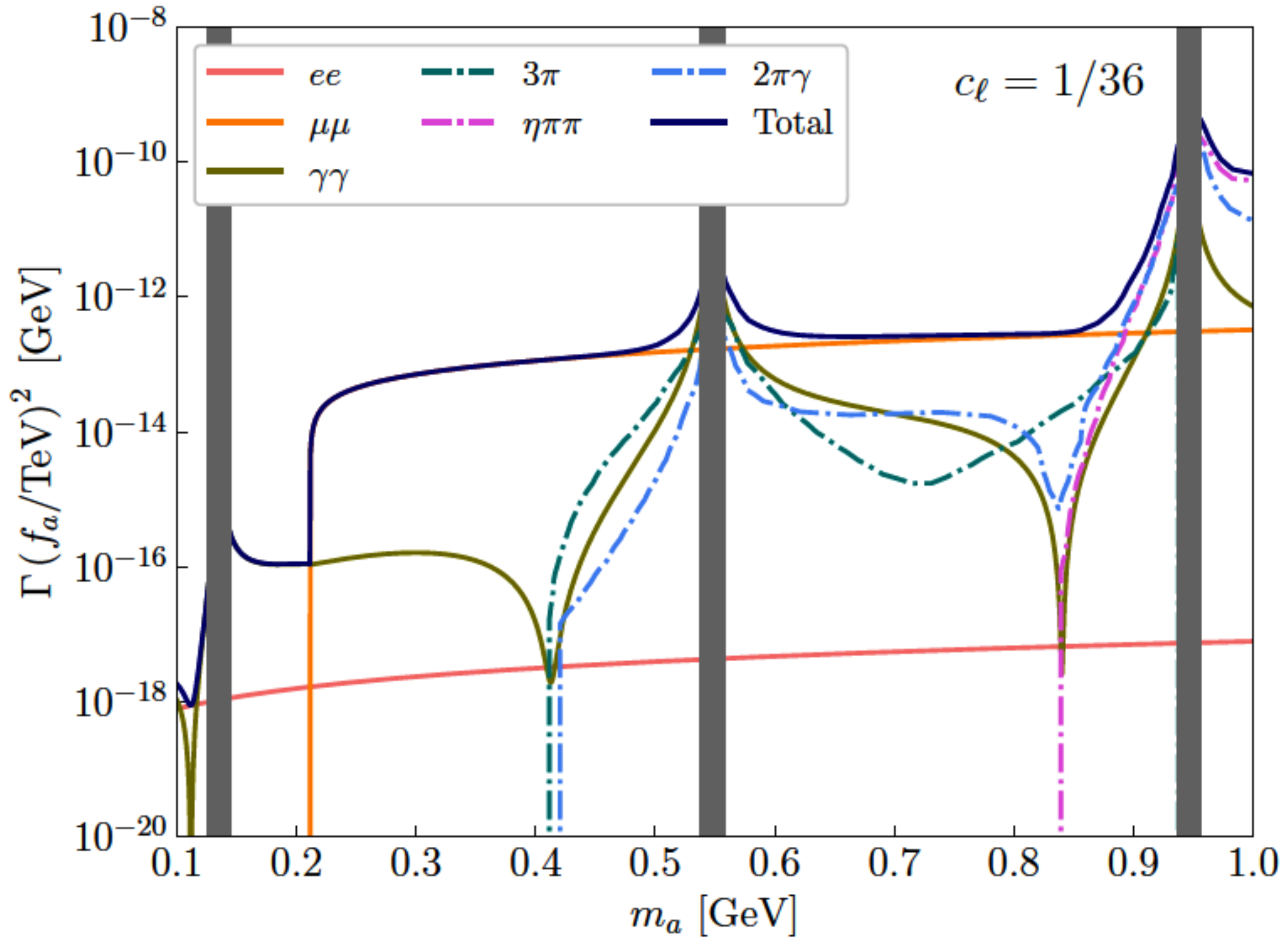
The 120 GeV protons at NuMI enables production of Heavy QCD axions with masses up to approximately 1 GeV and their decays can be searched for in ArgoNeuT.



Heavy QCD axions production from π^0, η and η' mesons.*

Heavy QCD axions decay: ee, **μμ**, γγ + hadronic modes.

Contributions depend on axion-lepton coupling, cl: two benchmark scenarios cl = 1/36 and cl = 1/100.



The gray-shaded band indicates a region with increased theoretical uncertainty around the π^0, η and η′ poles.

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

Highly Forward-going di-muon Signatures

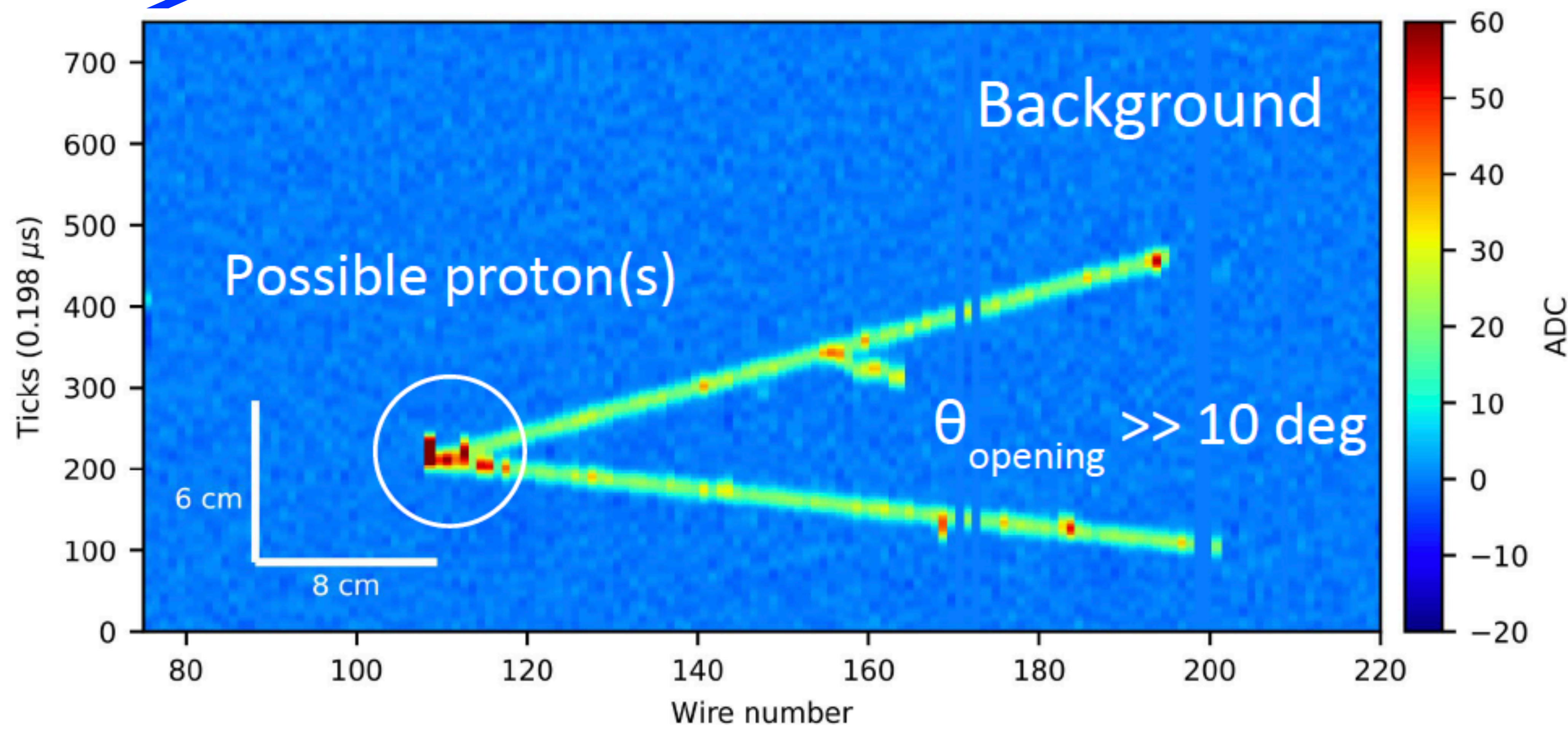
HNL and Heavy QCD axions are very different models… but can produce similar decay signatures in ArgoNeuT.

HNLs decaying to muon pair N ➝ ν μ+ μ-
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 ➝ μ+ μ-
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 (*see G.Putman presentation*)

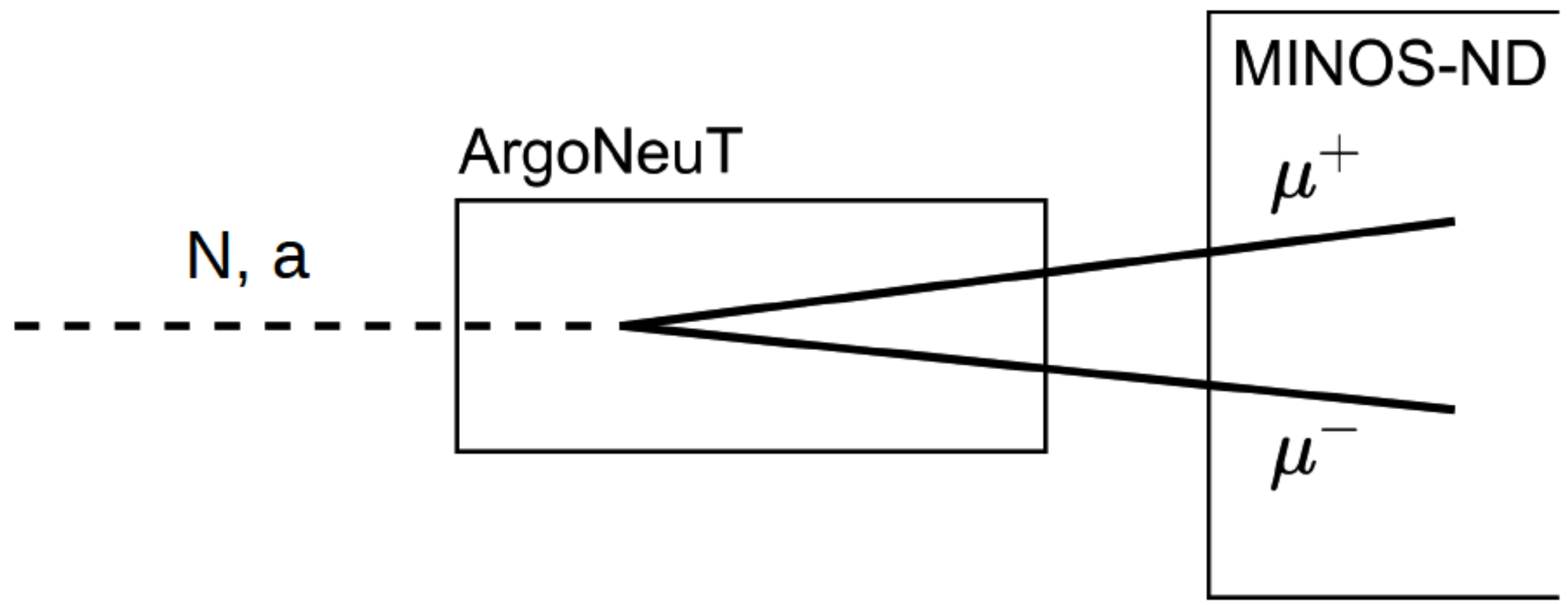
di-muon Signatures in ArgoNeuT

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

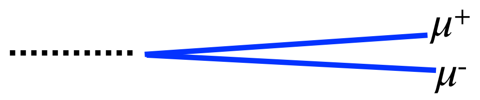
Two-track Event

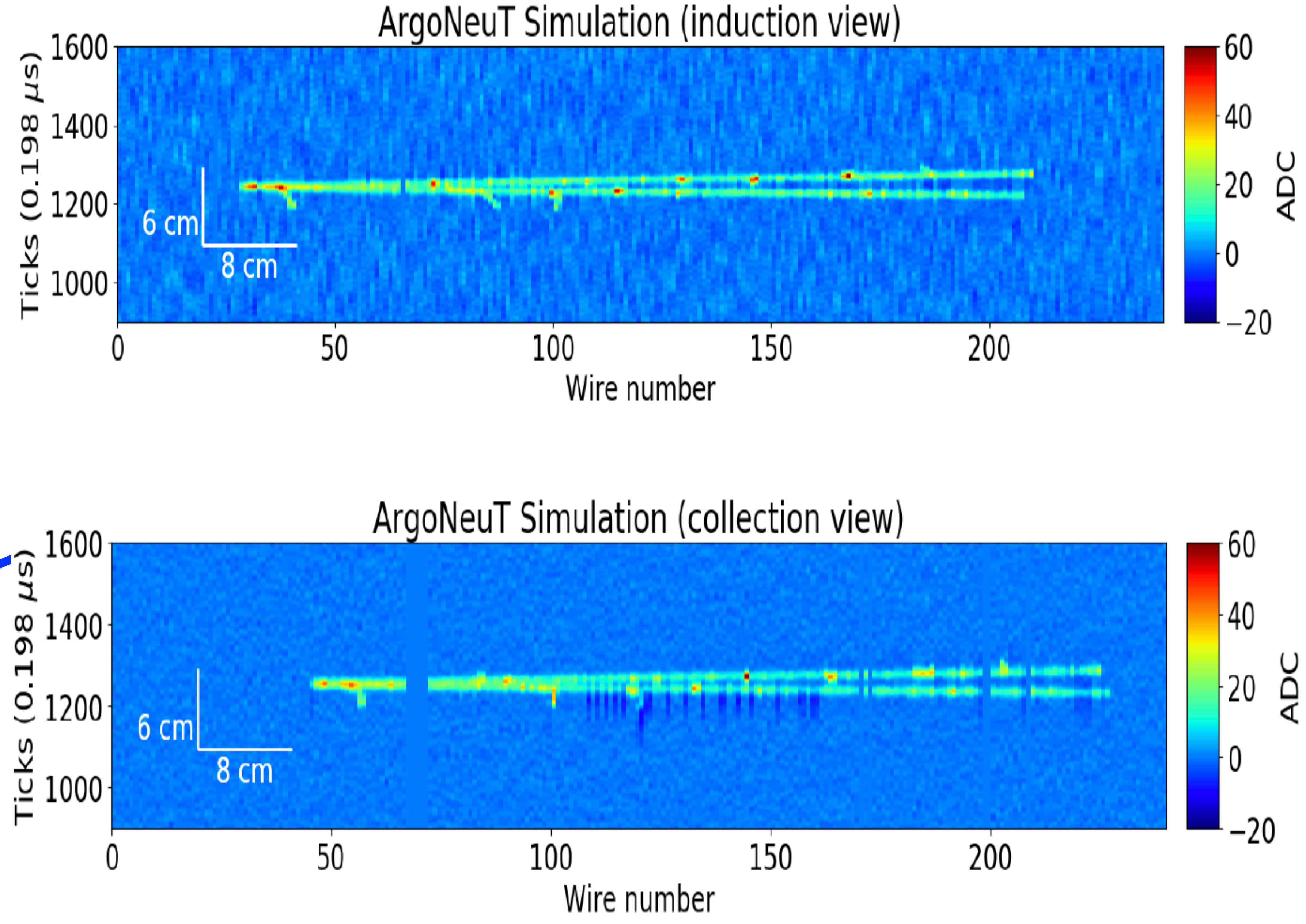


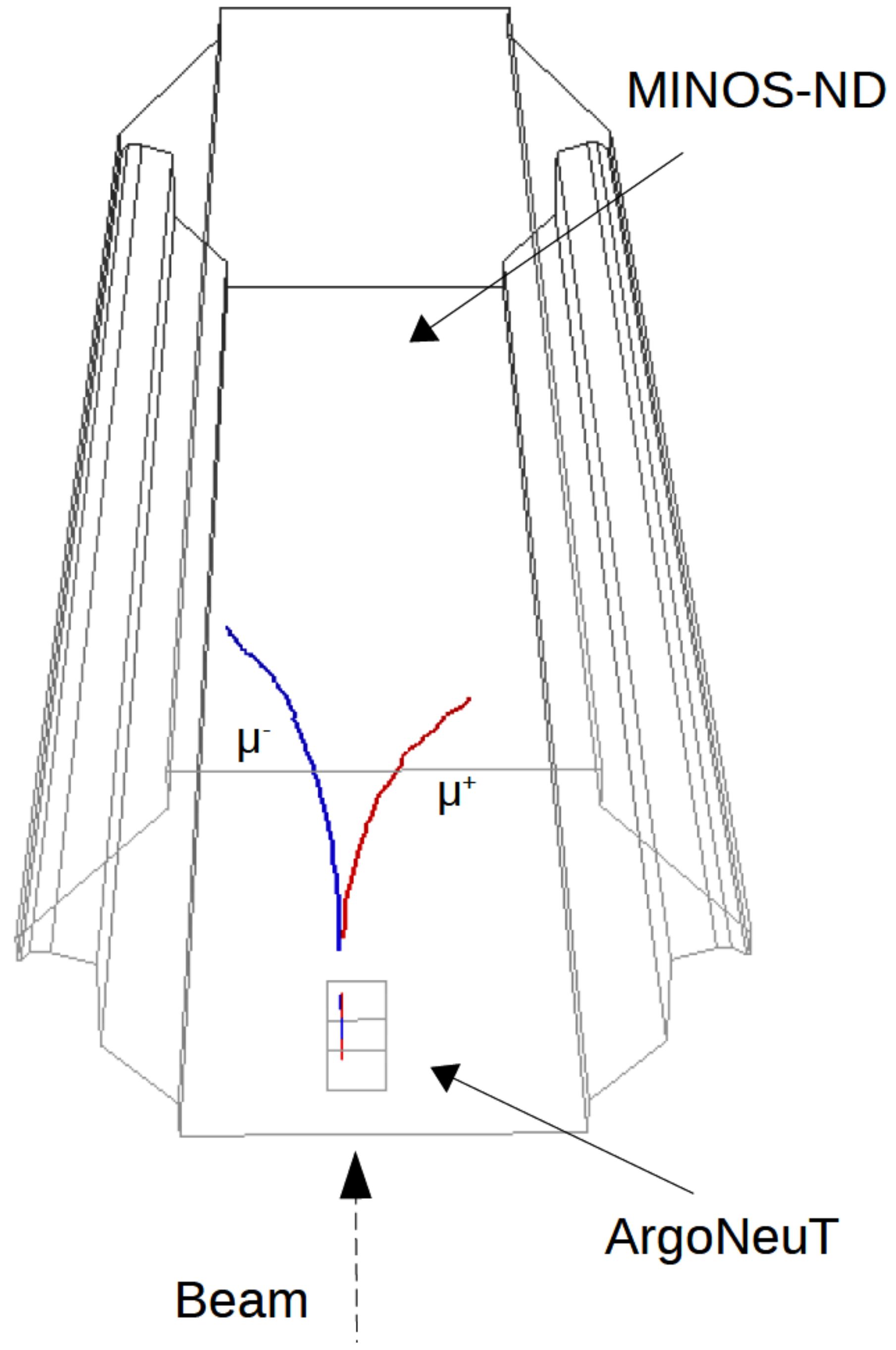
Signature 1

HNL decay (MC)

$N \rightarrow \nu\mu^+\mu^-$







Di-muon Signatures in ArgoNeuT

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

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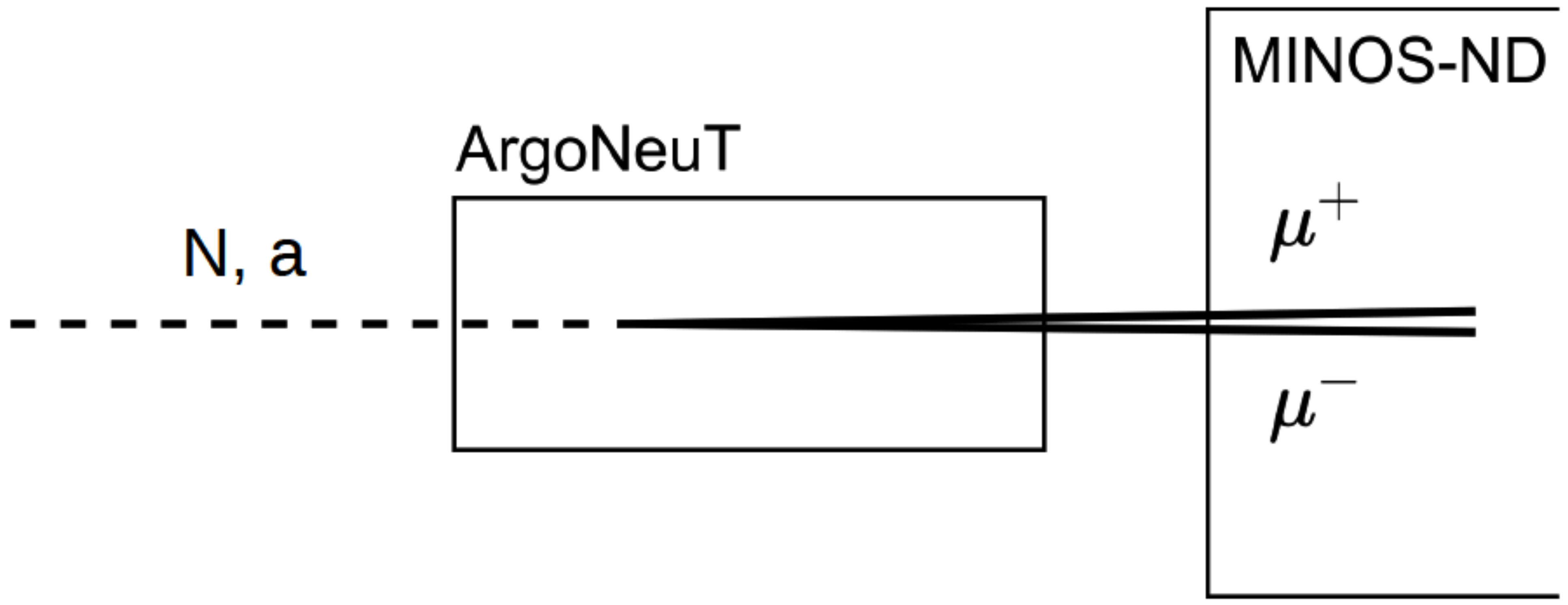
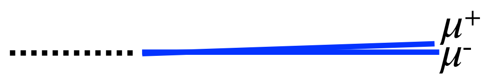
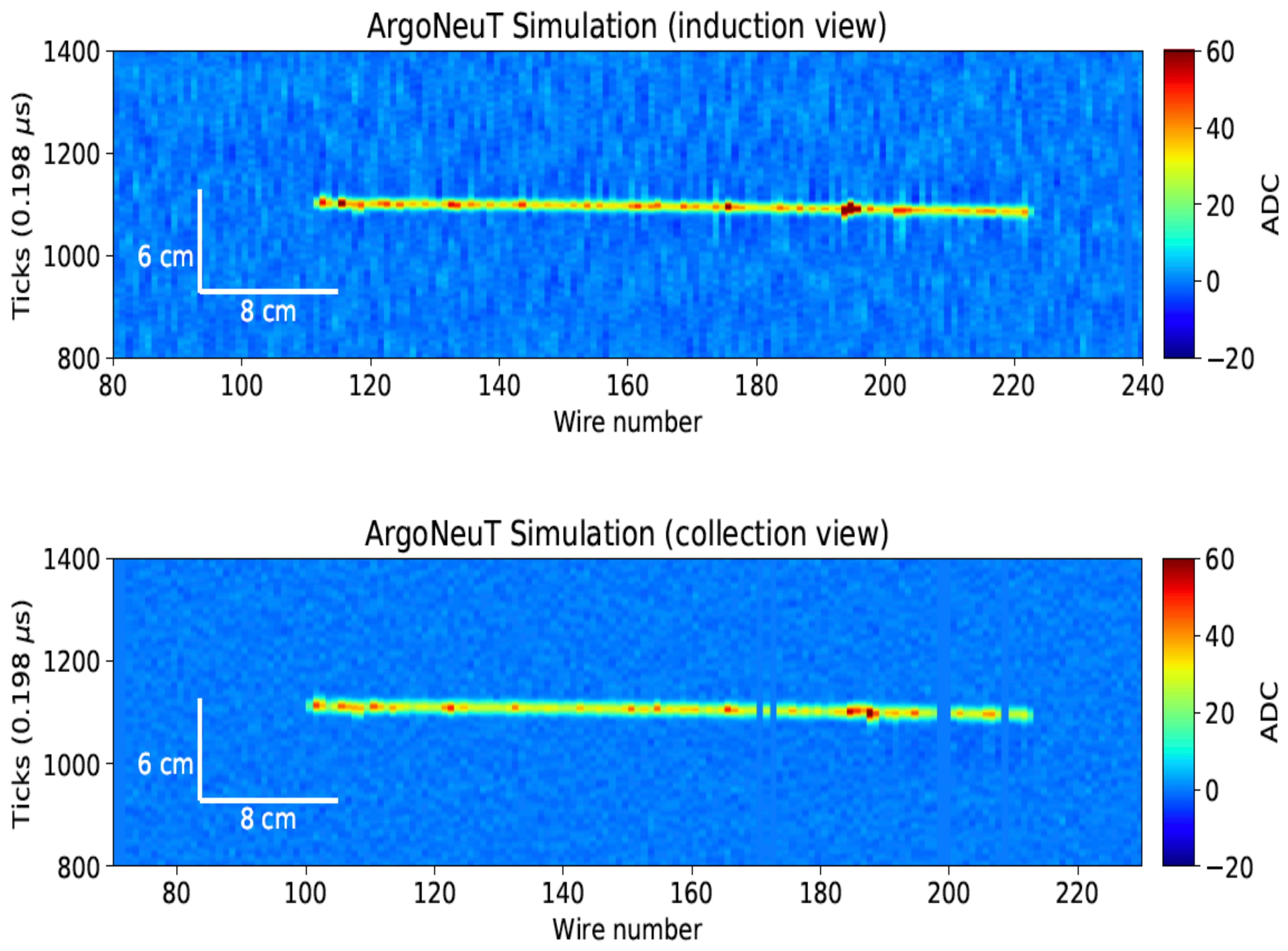
Double-MIP Event

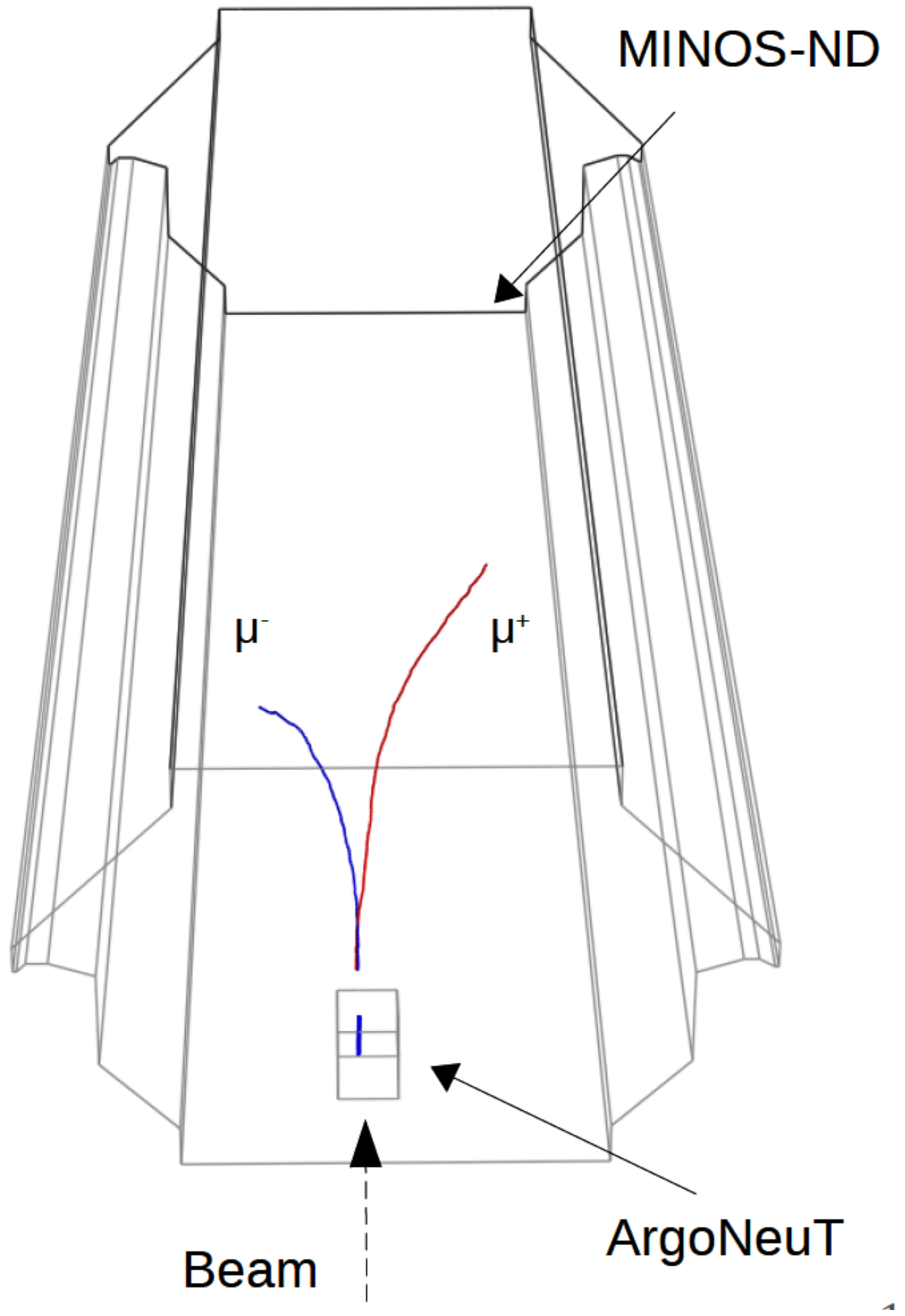


Signature 2

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







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

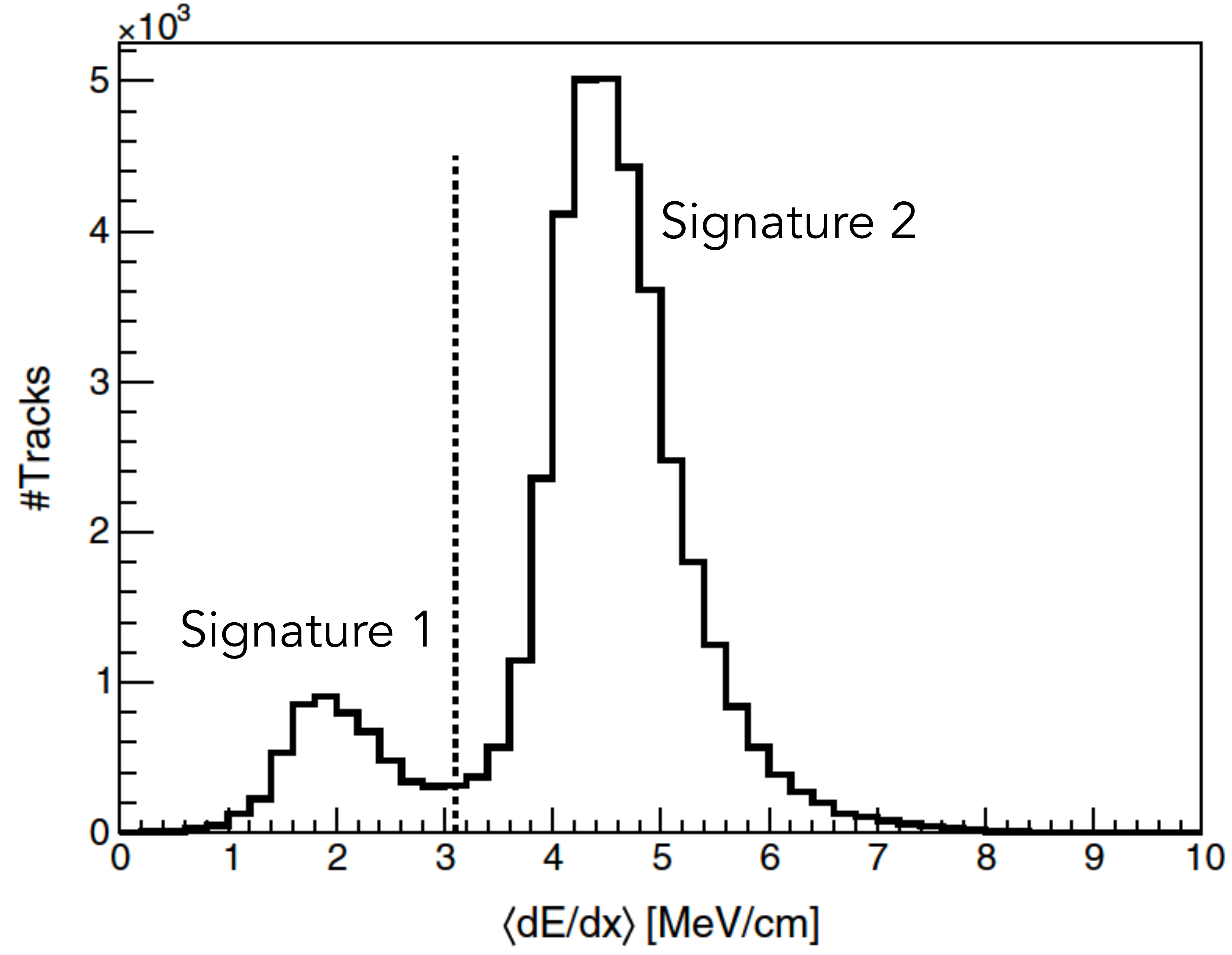
Di-muon Signatures in ArgoNeuT

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.

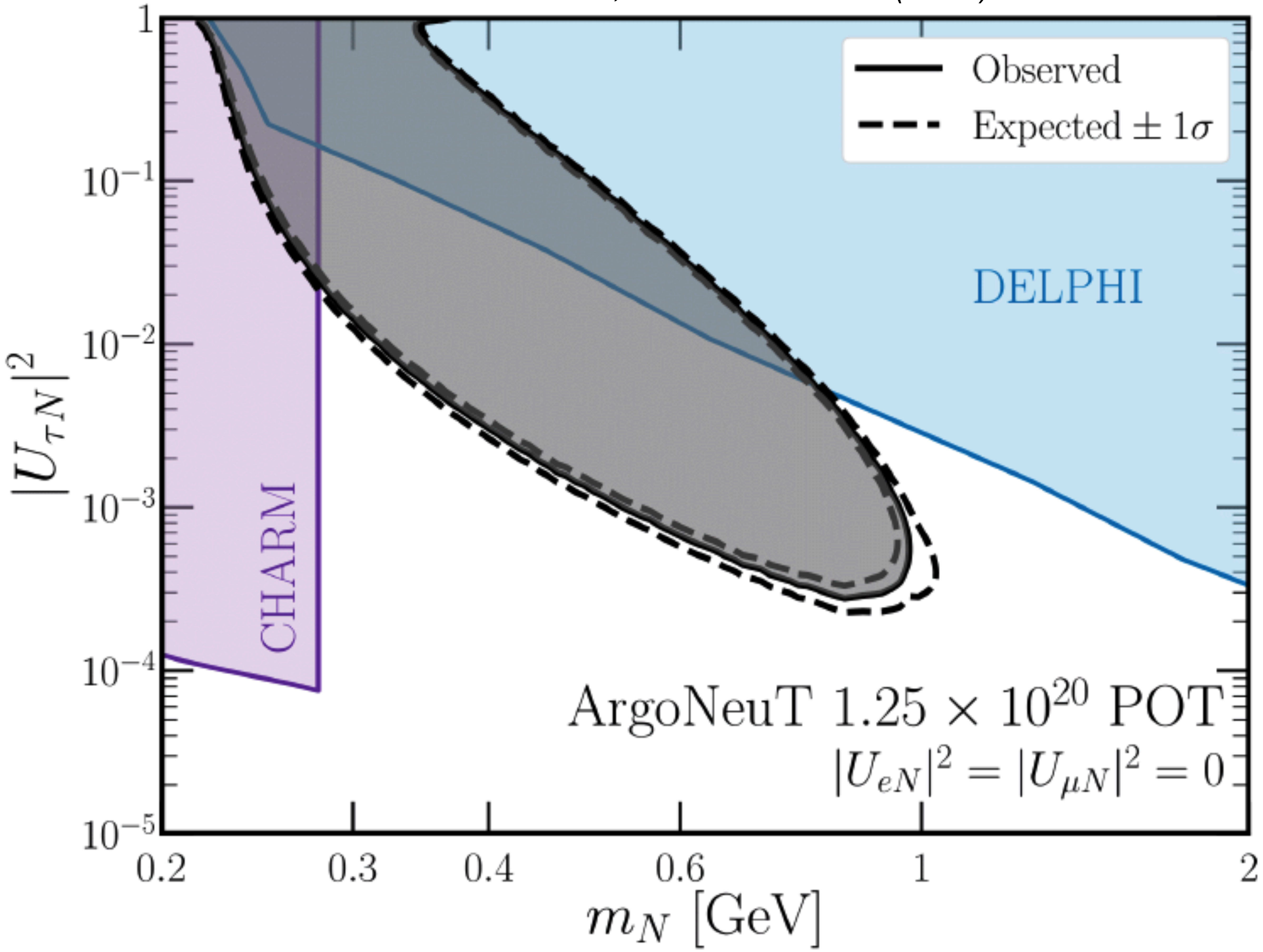


Identifying overlapping muon pairs:

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

Joint Experiment+Theory project:
First search for Heavy Neutral Leptons N $\rightarrow \nu\mu^+\mu^-$ in LAr TPC

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



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

Significant increase in the parameter space exclusion region!

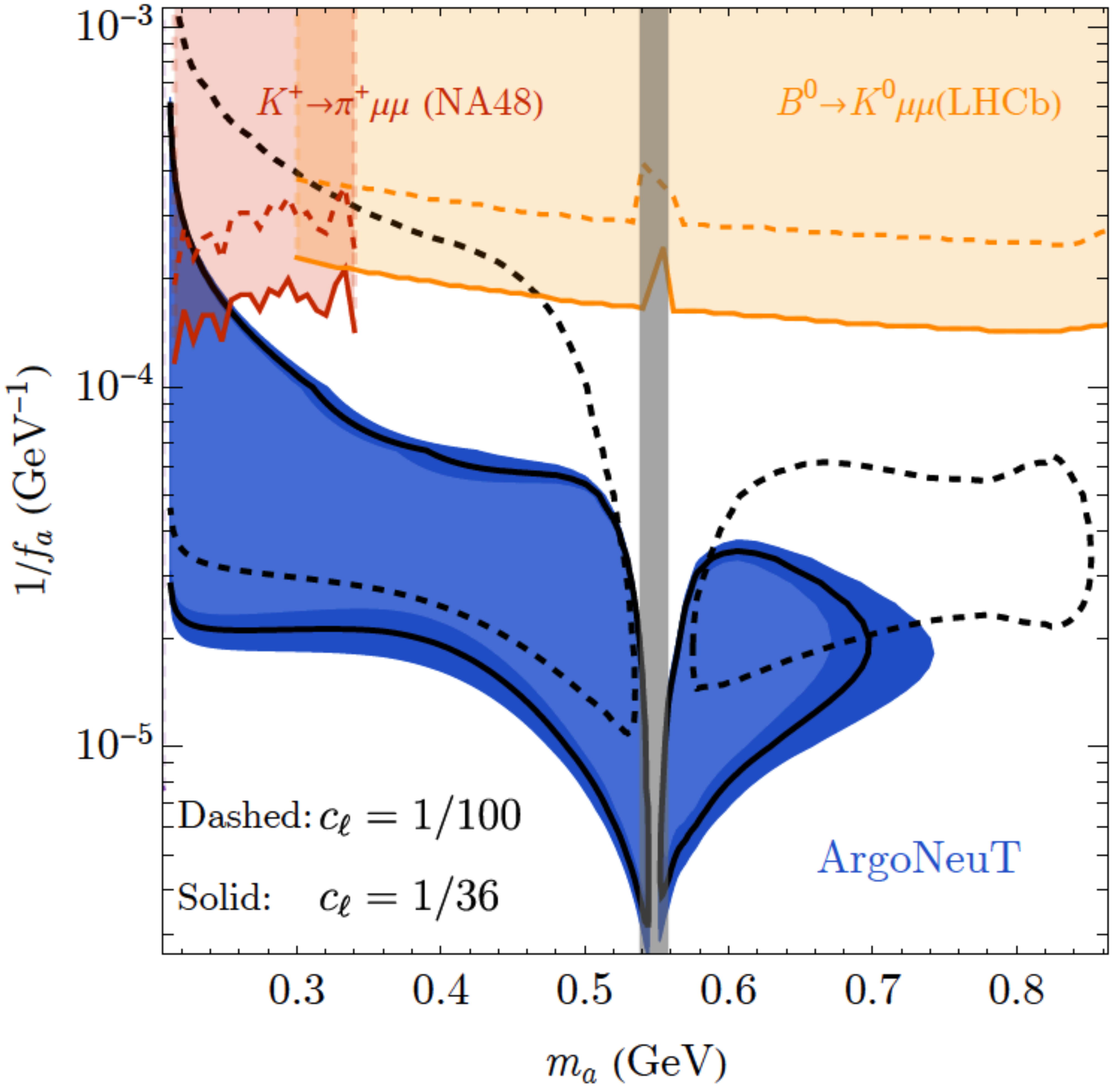
New exclusion limits for tau-coupled HNLs with m_N = 280 – 970 MeV.

Joint Experiment+Theory project:
First search for Heavy QCD Axions in LAr TPC

ArgoNeuT Collaboration + 6 theorists (R. Co, R. Harnik, K. Kelly, S. Kumar, Z. Liu. K Lyu)
R. Acciarri et al., https://arxiv.org/abs/2207.08448

Search for: $a \rightarrow \mu^+ + \mu^-$

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



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

The gray-shaded band indicates a region with increased theoretical uncertainty around the η pole.

Good Things Come in Small Packages!

ArgoNeuT, a small LAr TPC running for 5 months on the NuMI beam, produced **world leading BSM searches!**

Current and next- generation LAr TPC neutrino experiments are fantastic tools to look for New Physics in the neutrino sector and beyond.

Close/direct collaboration between experimentalists and theorists is the key to success!

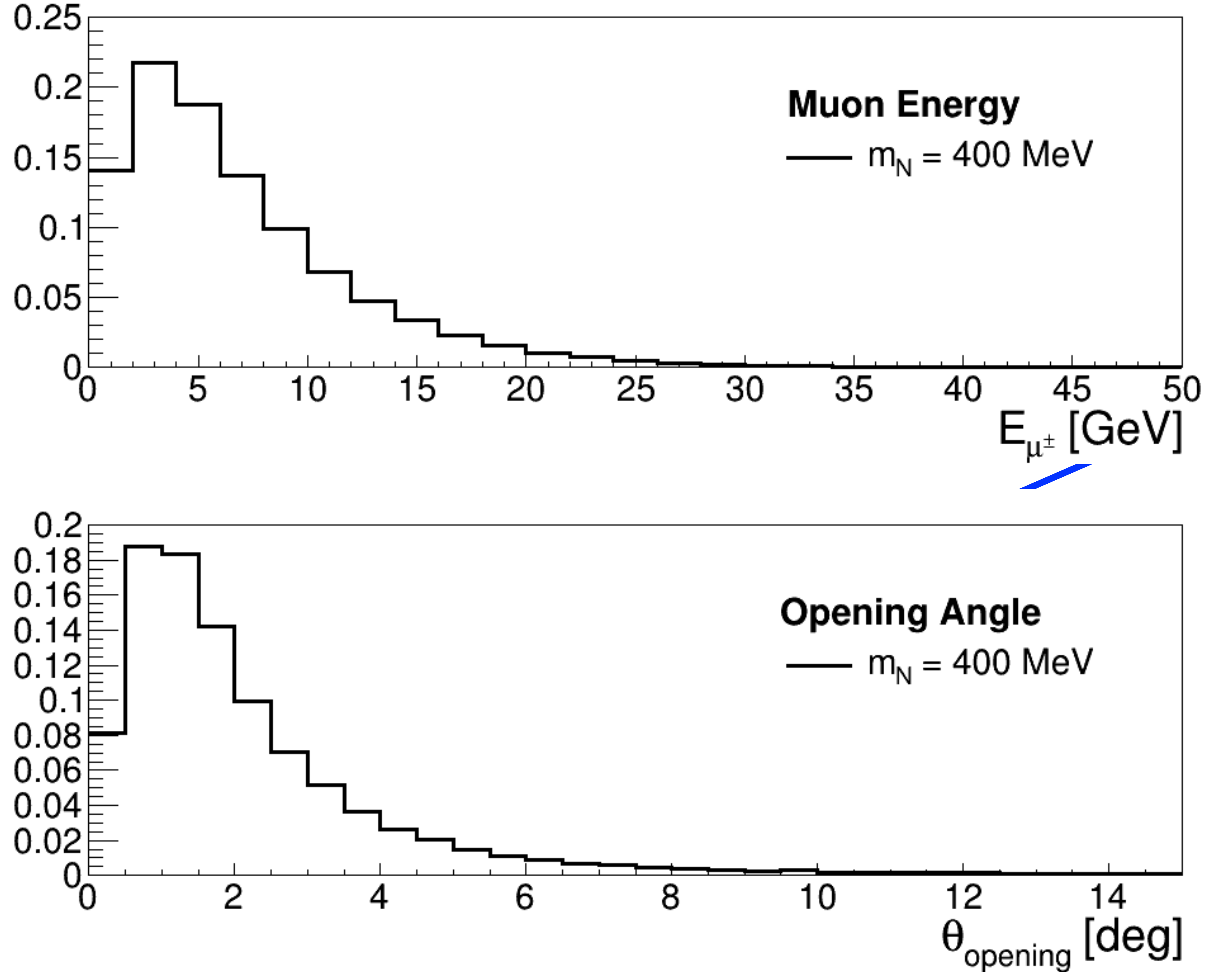
OVERFLOW

HNL and Axion simulation

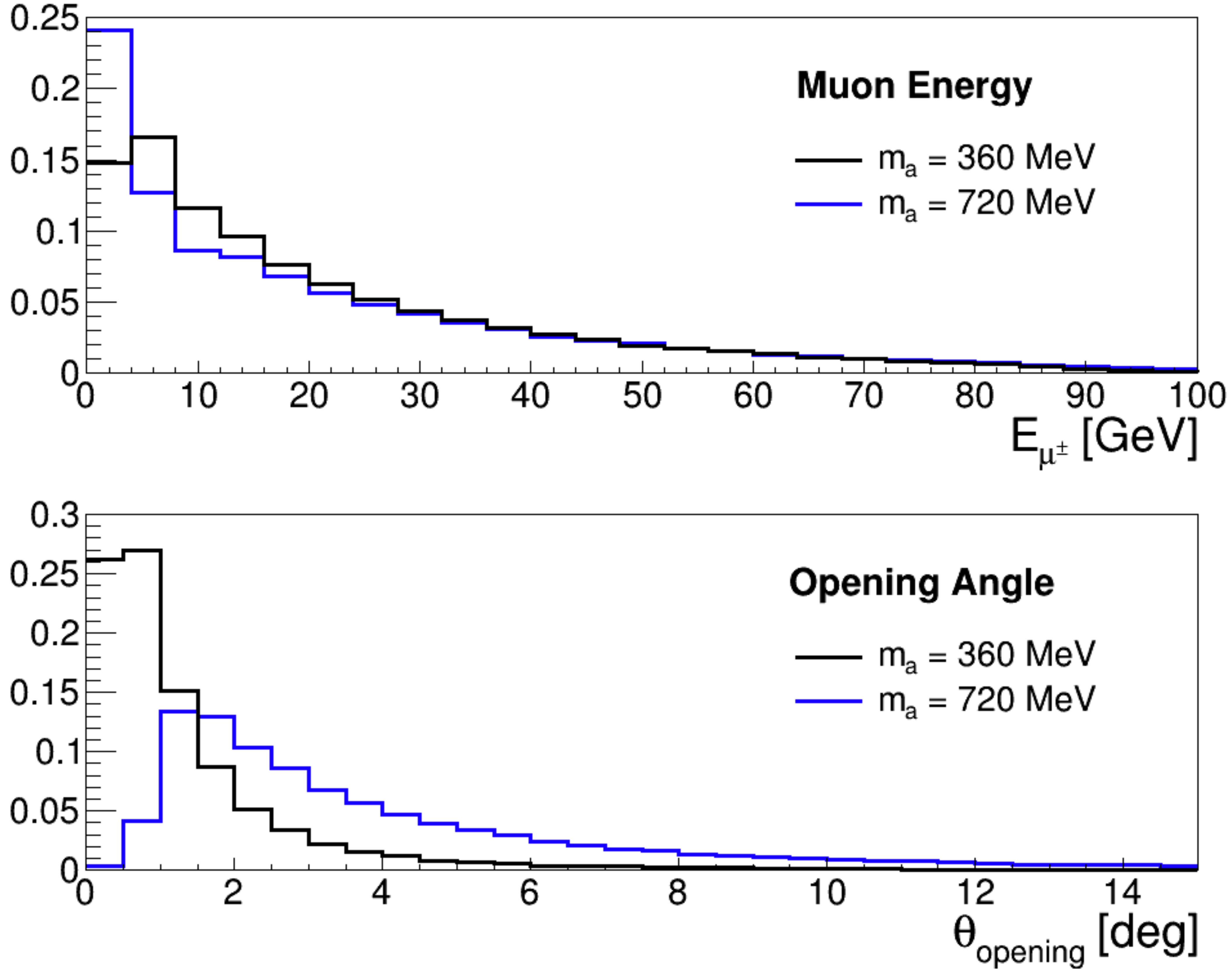
Dedicated simulations performed for both heavy neutral leptons and heavy QCD axions:

- Production using pythia8 + standard ArgoNeuT and MINOS simulation and reconstruction chains
- Resulting muons energetic and highly forward-going – may be reconstructed as overlapping in ArgoNeuT

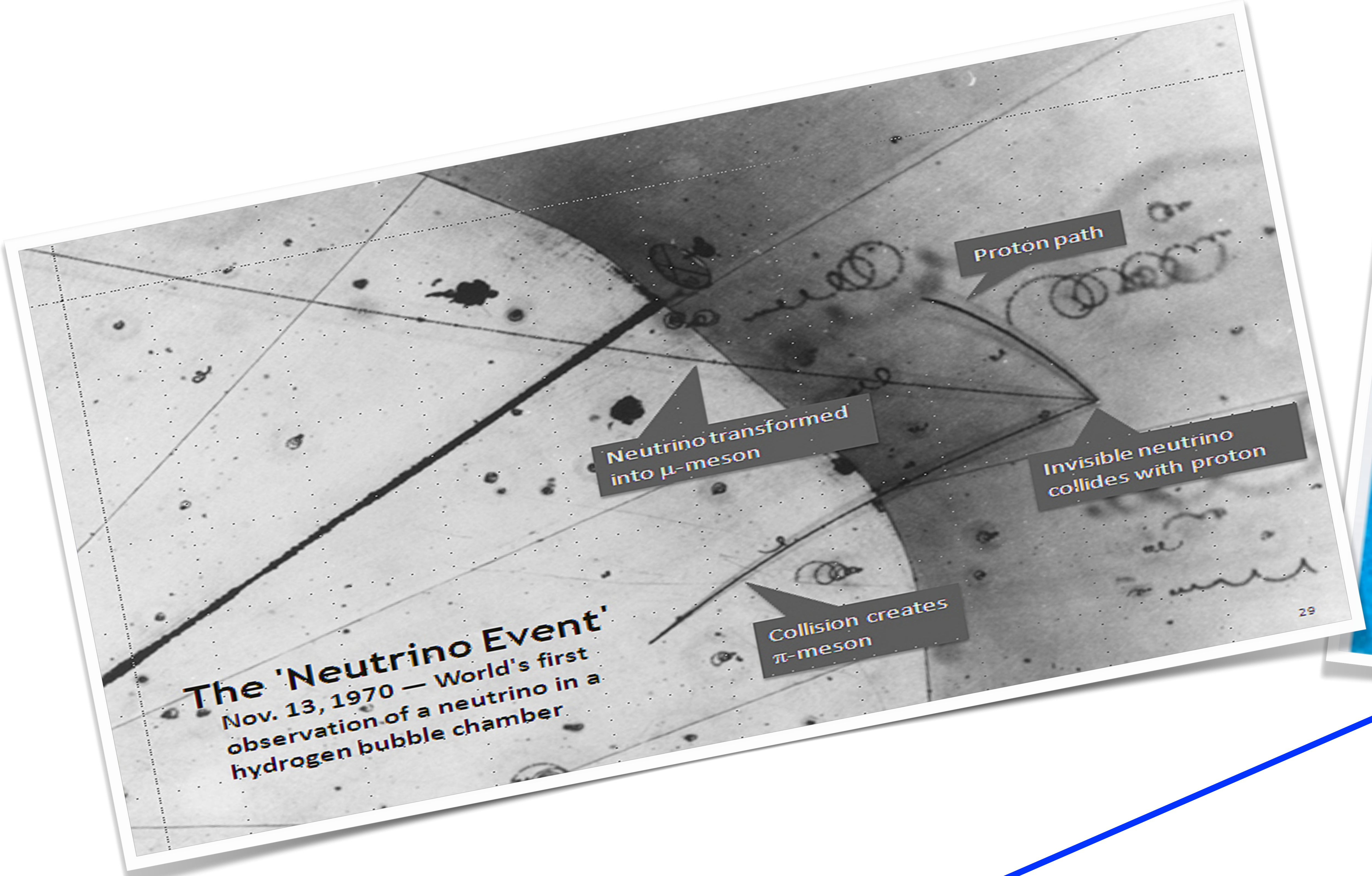
Heavy neutral leptons

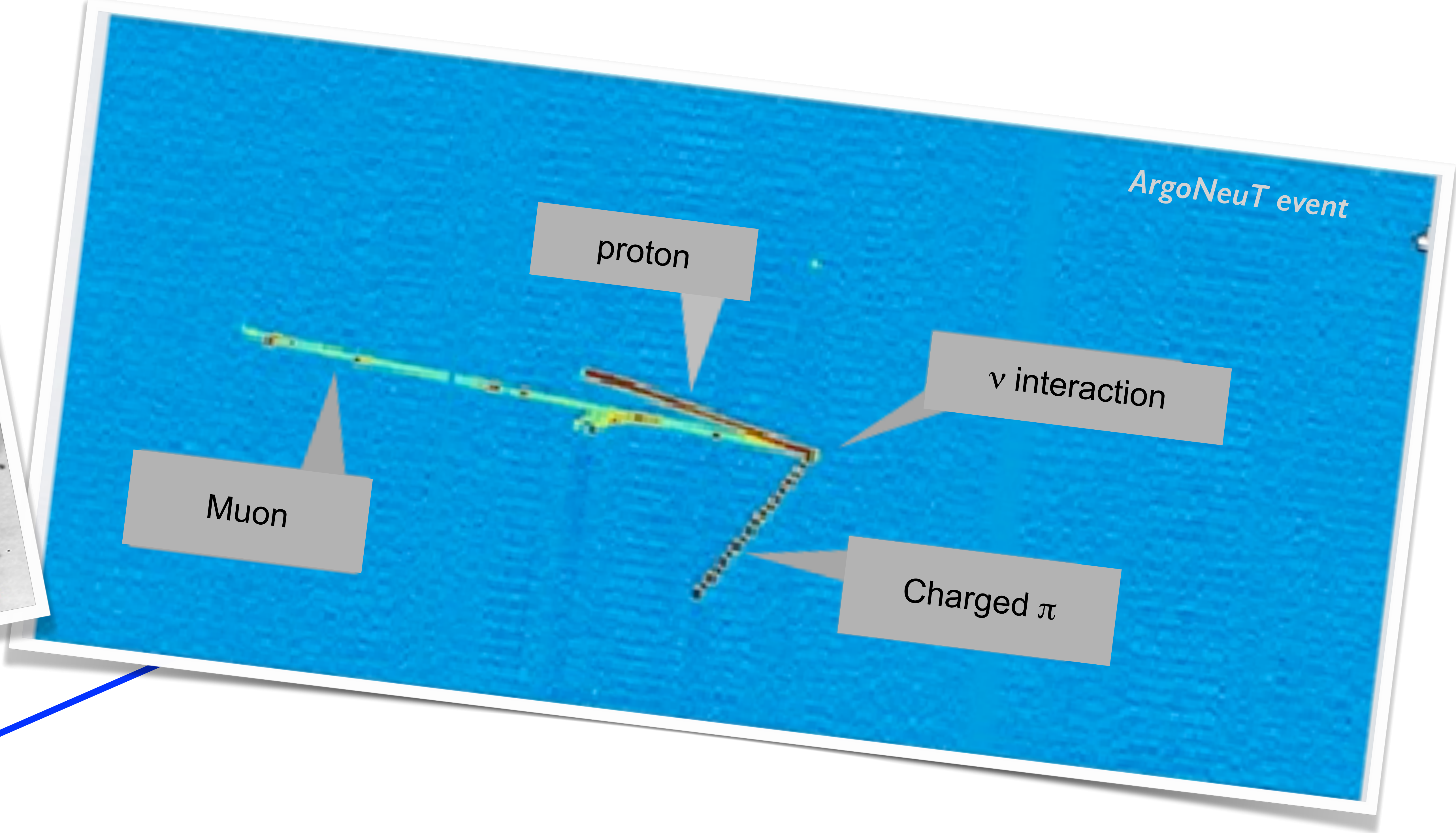


Heavy QCD Axions



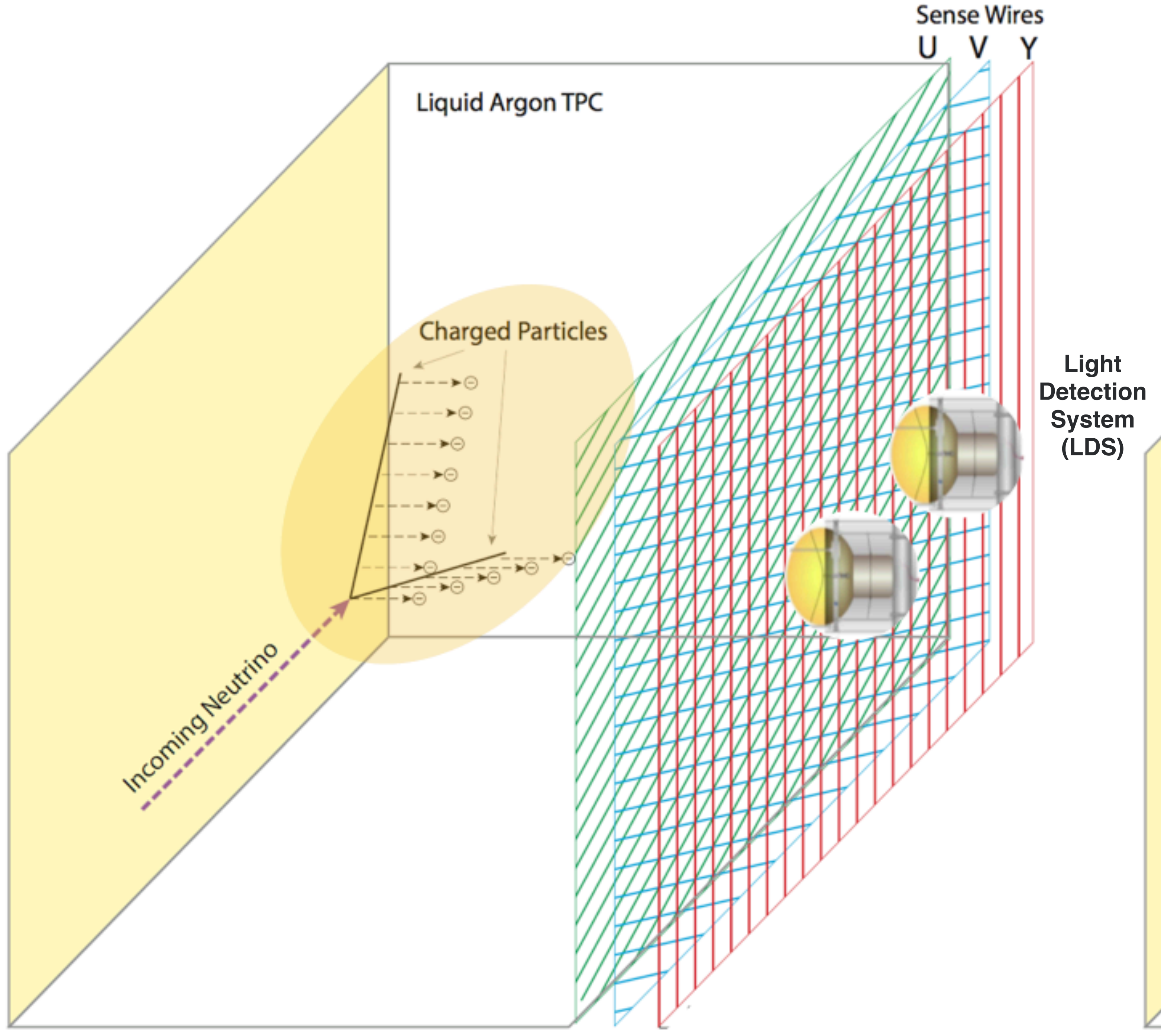
Why Liquid Argon Time Projection Chamber?

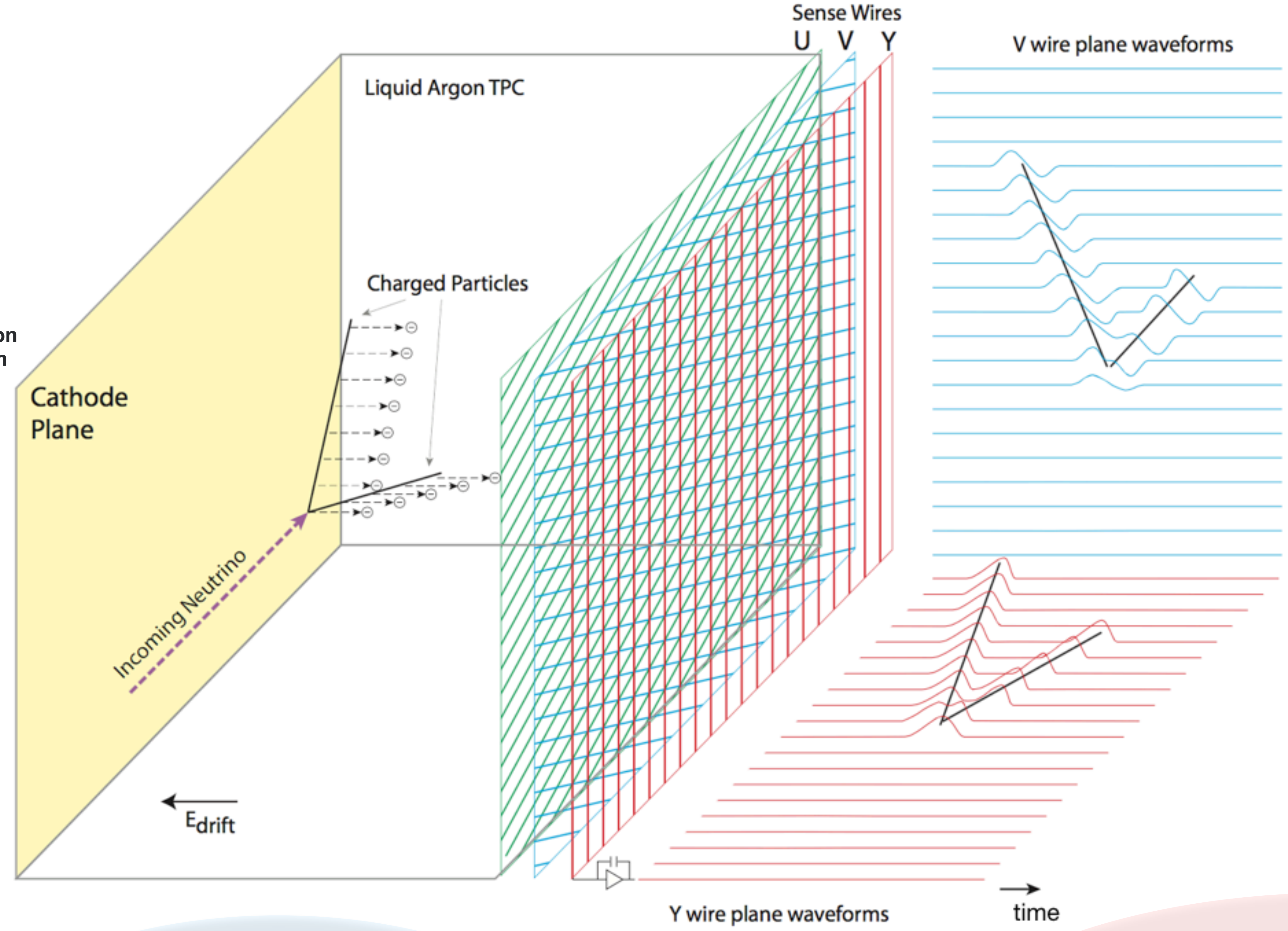




LAr TPC: Bubble chamber quality of data, with added calorimetry

LArTPC at work





Charged particles in LAr produce free ionization electrons and scintillation light

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

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*]

m.i.p. at 500 V/cm: ~ 60,000 e/cm
~ 50,000 photons/cm

Electron drift time ~ ms

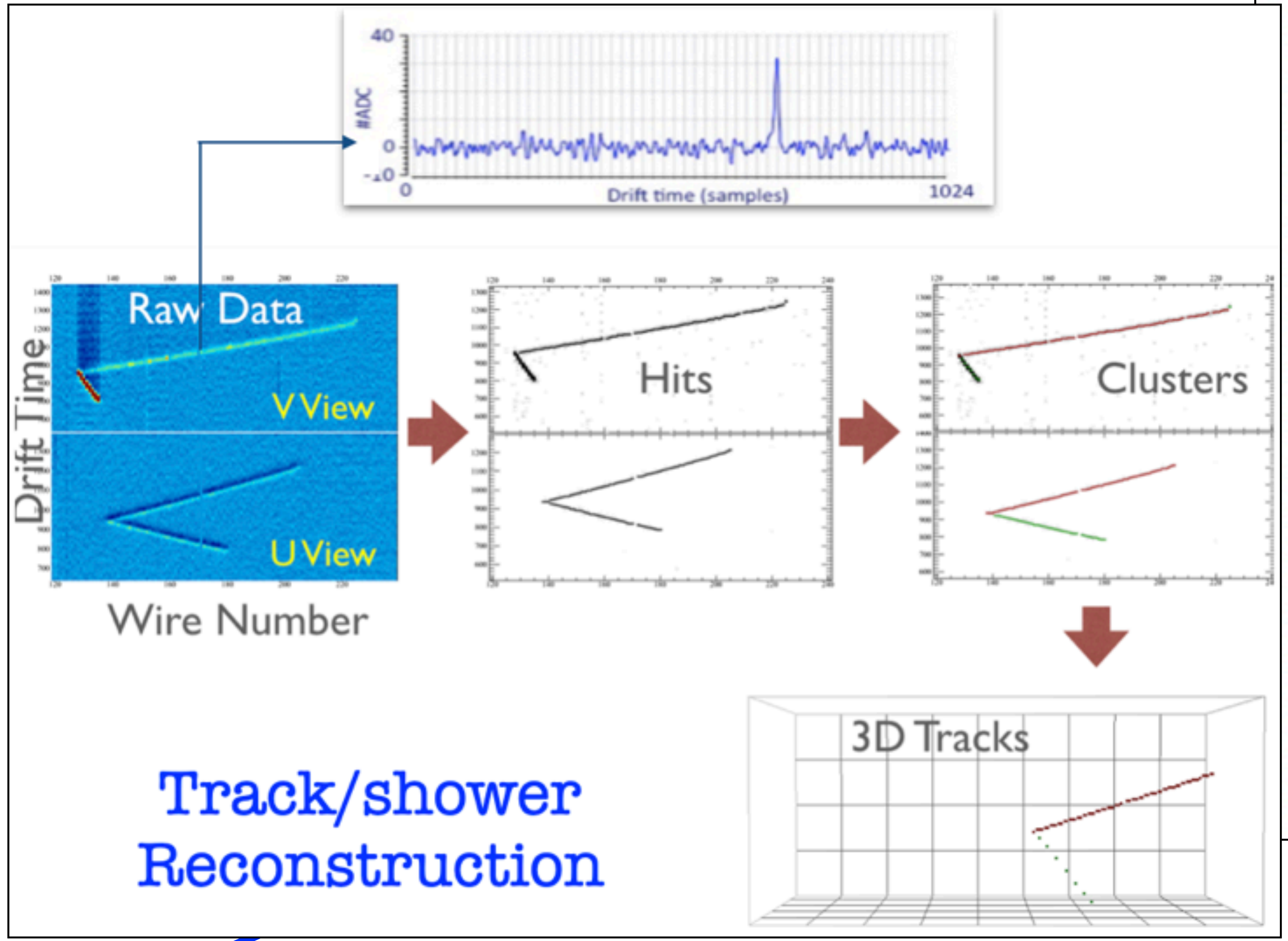
VUV photons propagate and are shifted into VIS photons

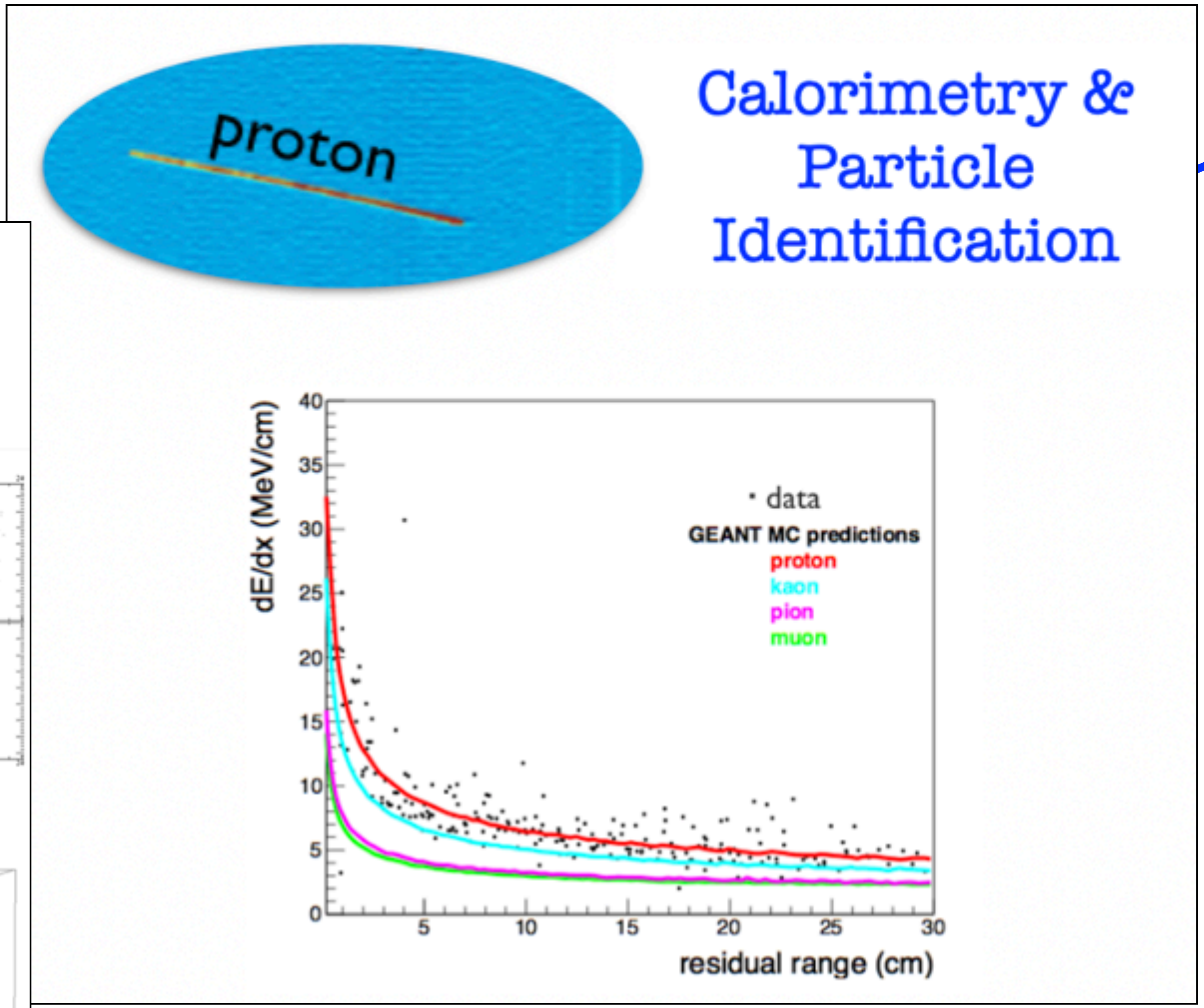
Scintillation light fast signals from LDSs give event timing

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

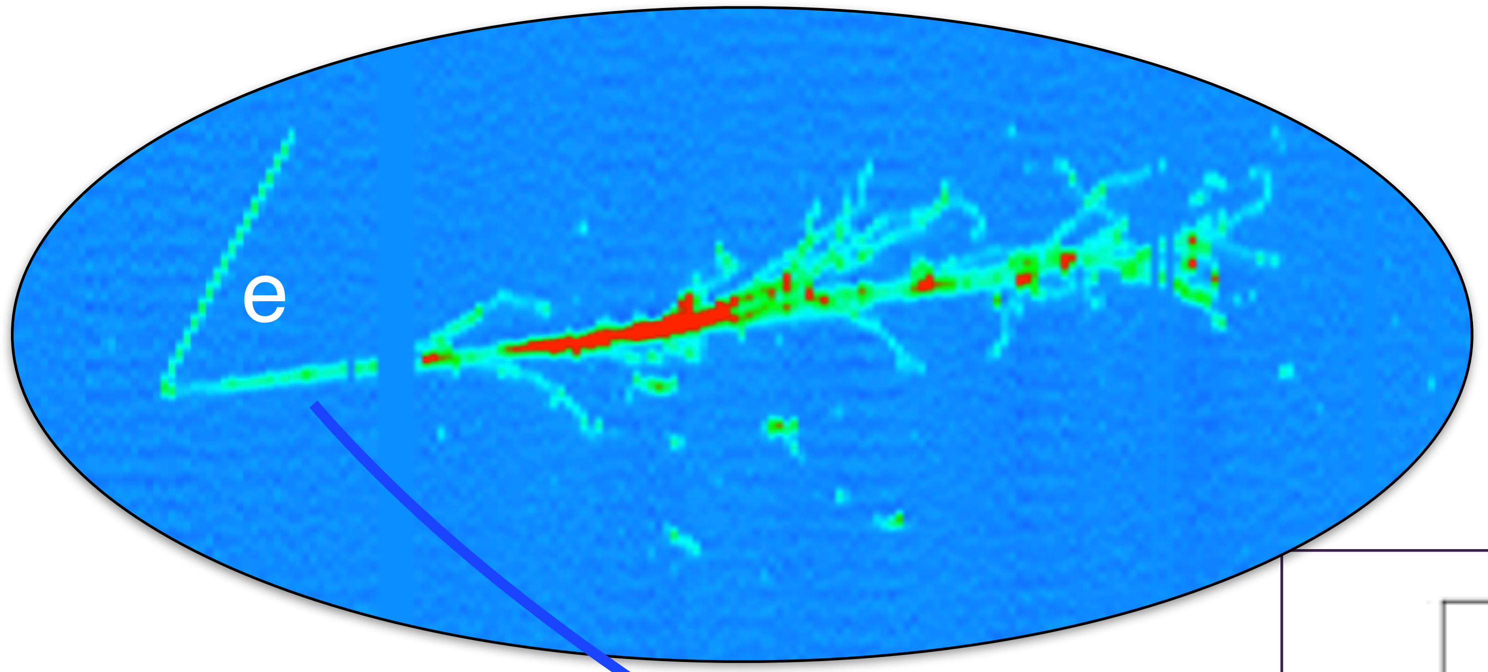


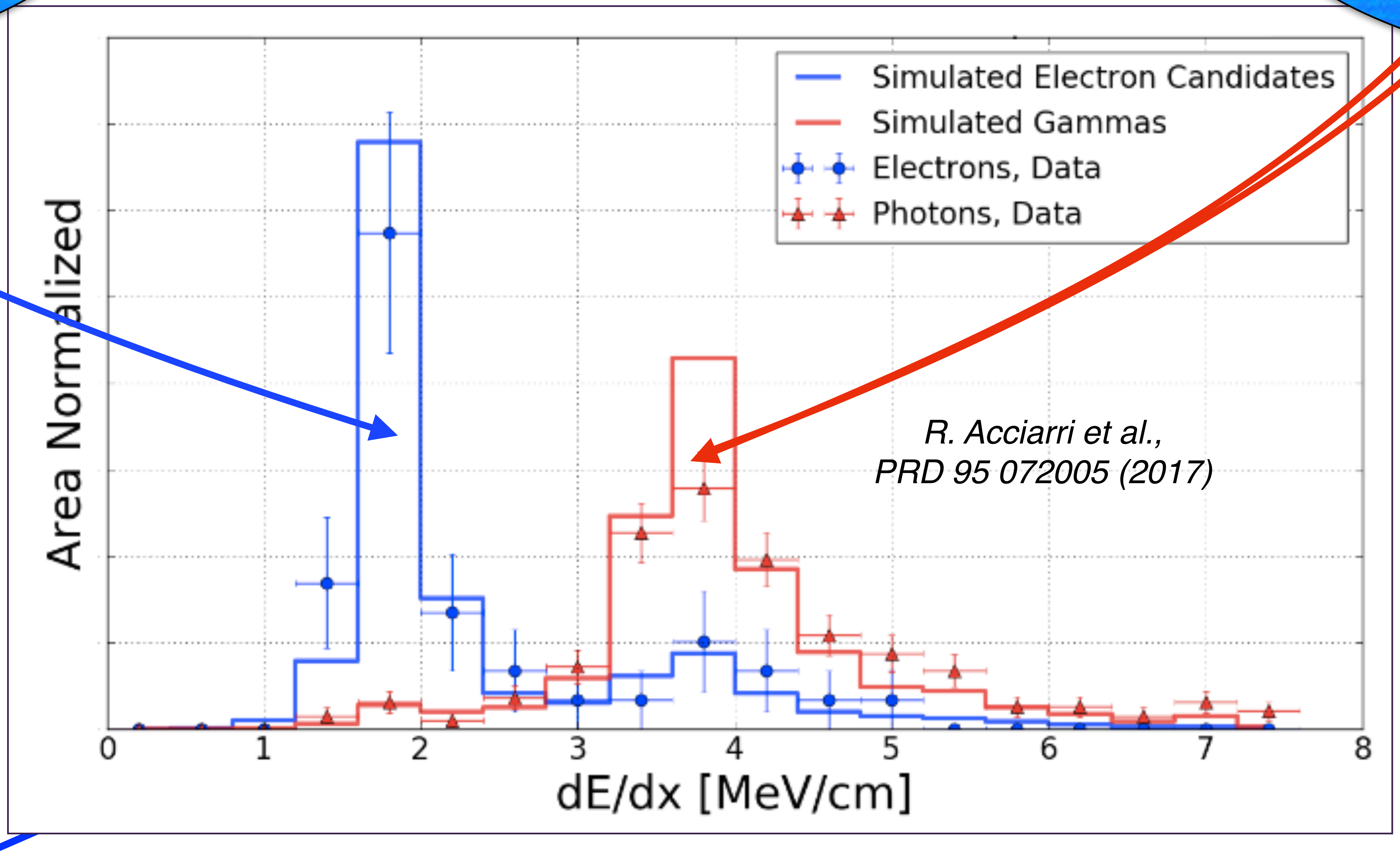


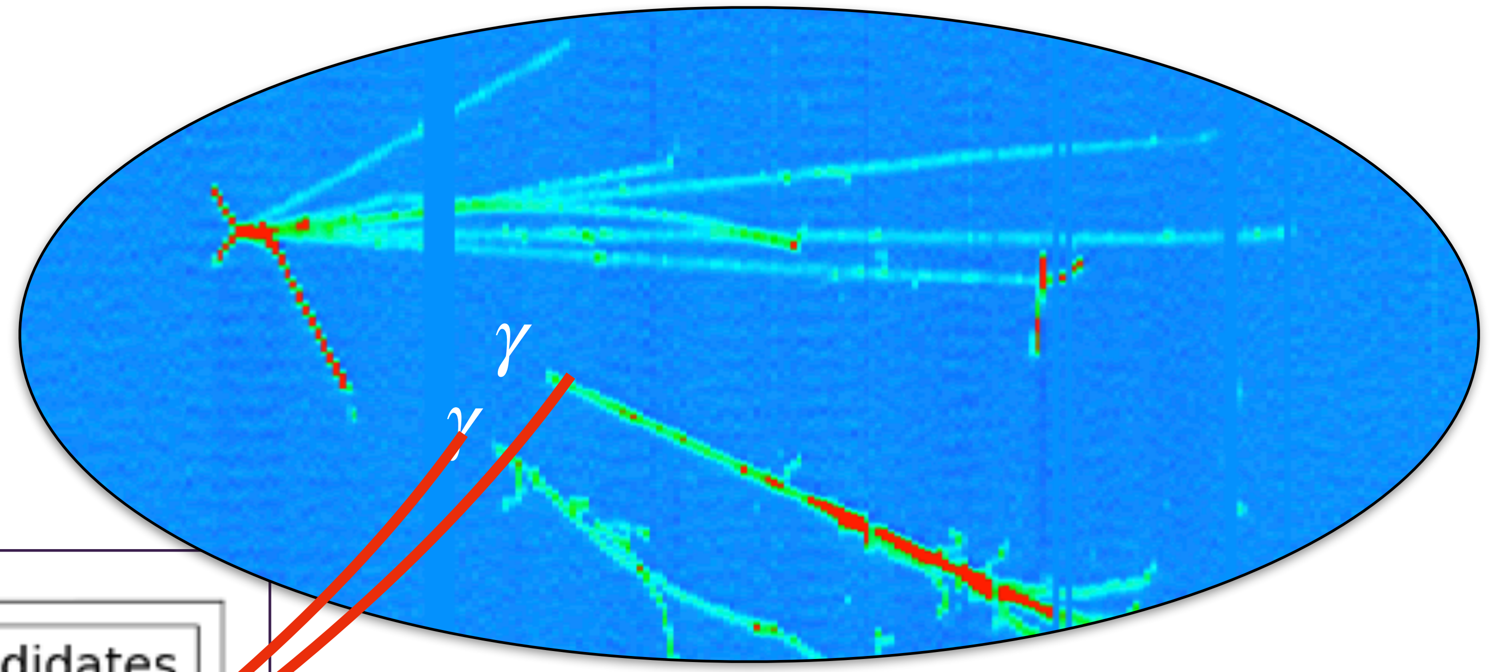
- Multiple 2D and the 3D reconstruction of charged particles ⇒ **Imaging**
- Total charge proportional to the deposited energy ⇒ **Calorimetry**
- dE/dx along the track ⇒ **Particle Identification**

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

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