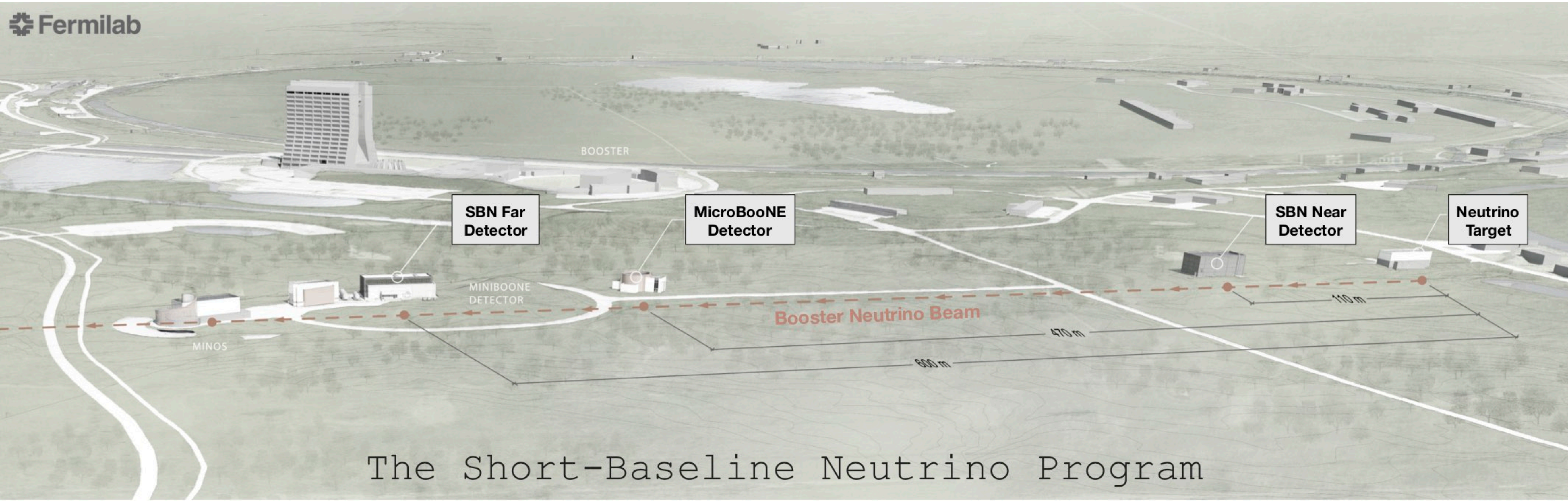


The Short-Baseline Neutrino Program at Fermilab

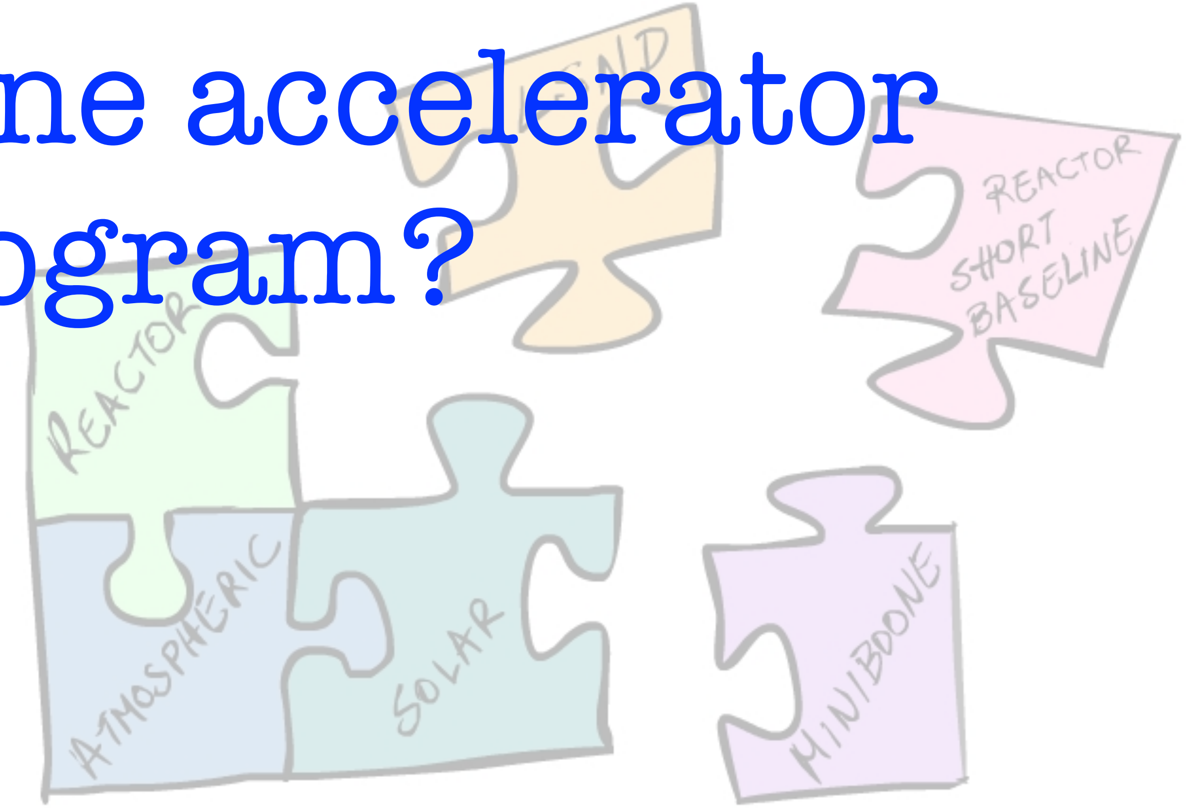
Hidden Sector Fixed Target experiments Symposium
September 4th 2019

Ornella Palamara
Fermilab & Yale University

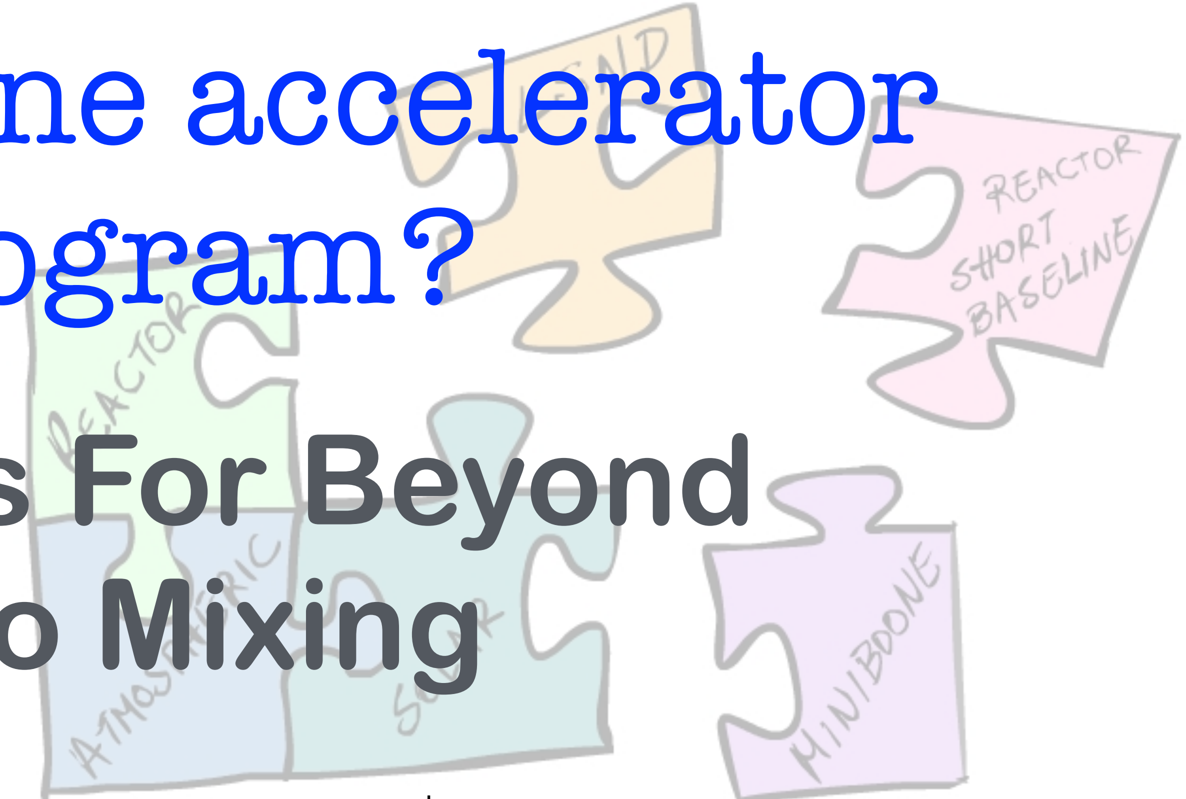
Outline

- Why a Short-Baseline Accelerator Neutrino program?
- Why LAr TPC?
- The Fermilab Short-Baseline Neutrino Program
  - Sterile Neutrino Sensitivity
  - Current Experimental Status
  - New Physics Opportunities

Why a Short-baseline accelerator neutrino program?

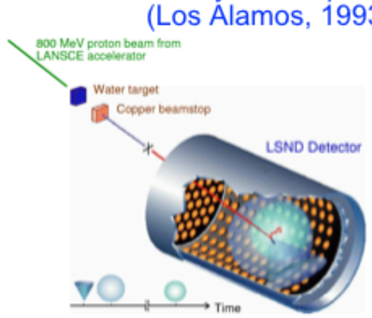


Why a Short-baseline accelerator neutrino program?



Experimental Hints For Beyond Three Neutrino Mixing

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



LSND

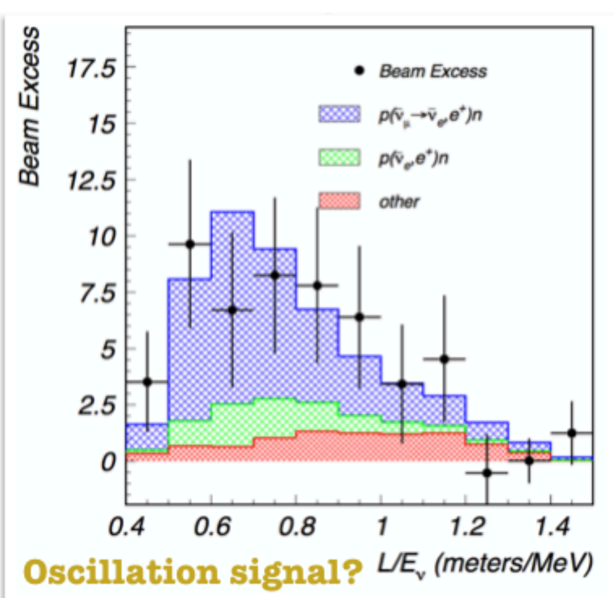
Baseline 30 m

E= [20 – 50] MeV

L/E ≈ 1 m/MeV

PRD 64 (2001) 112007

167 tons liquid scintillator



Decay in flight neutrino source (Booster Neutrino Beam - Fermilab)

L/E similar to LSND

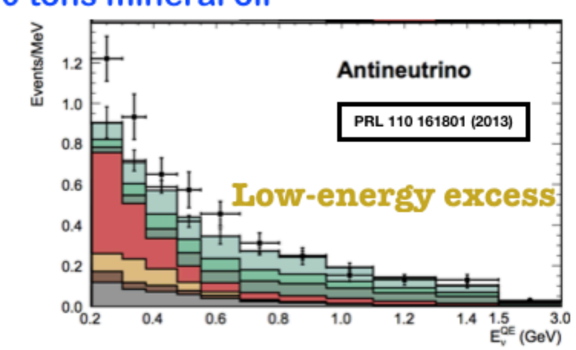
MiniBooNE

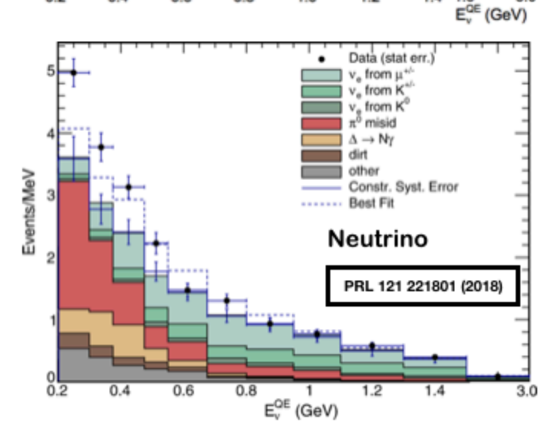
Baseline 540 m

E=[0 - 2] GeV

L/E ≈ 1 m/MeV

800 tons mineral oil

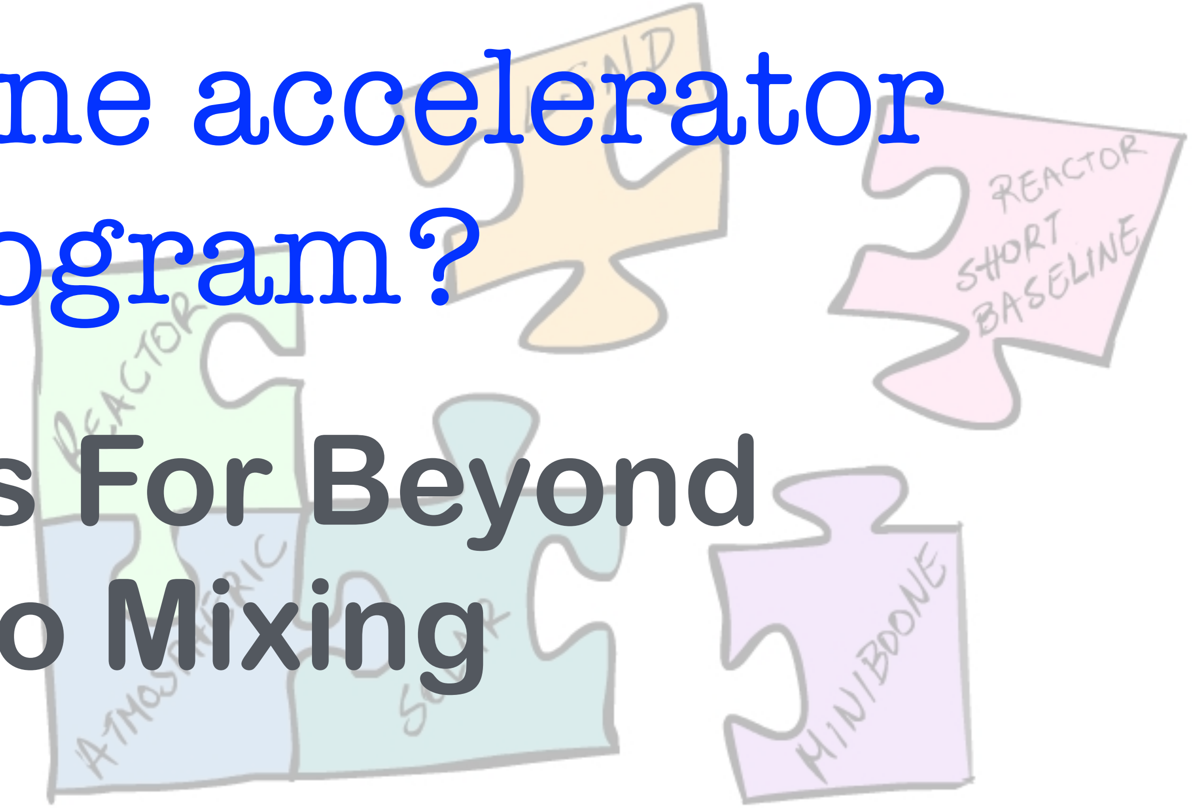




+

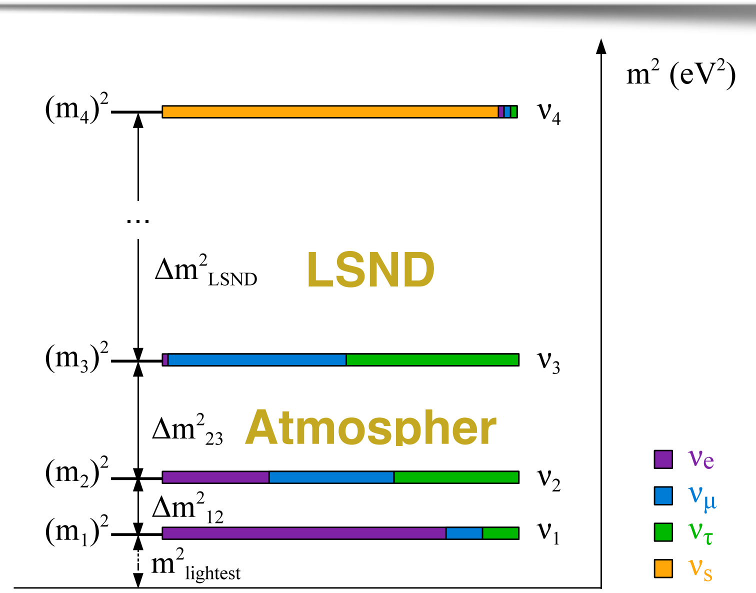
Reactor and Gallium “anomalies”

Why a Short-baseline accelerator neutrino program?



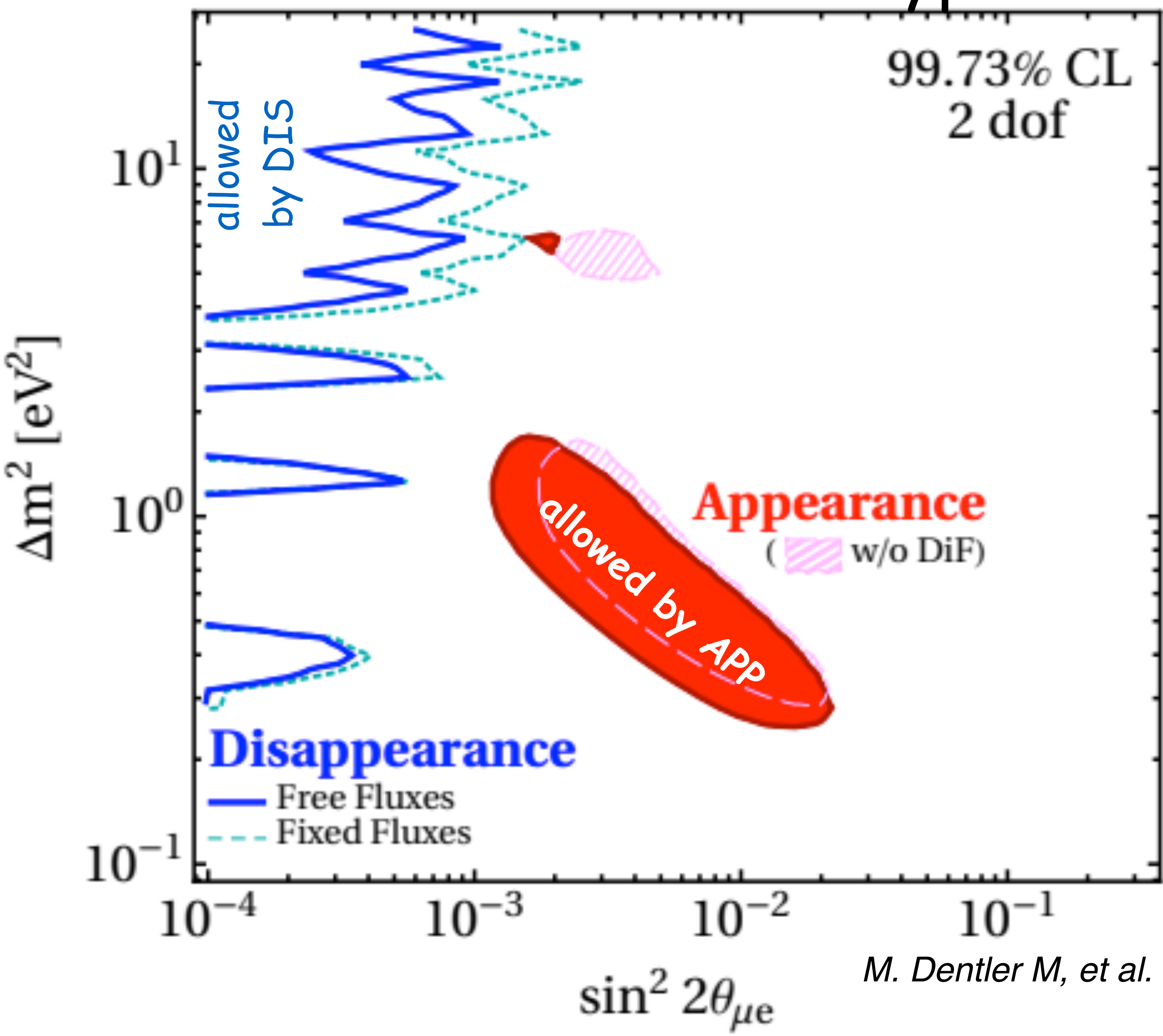
Experimental Hints For Beyond Three Neutrino Mixing

Could be pointing at **additional physics beyond the Standard Model** in the neutrino sector:
additional "sterile" neutrino states with larger mass-squared differences driving neutrino oscillation at small distances.



The Light Sterile Neutrino Experimental Landscape

The test of the sterile hypothesis

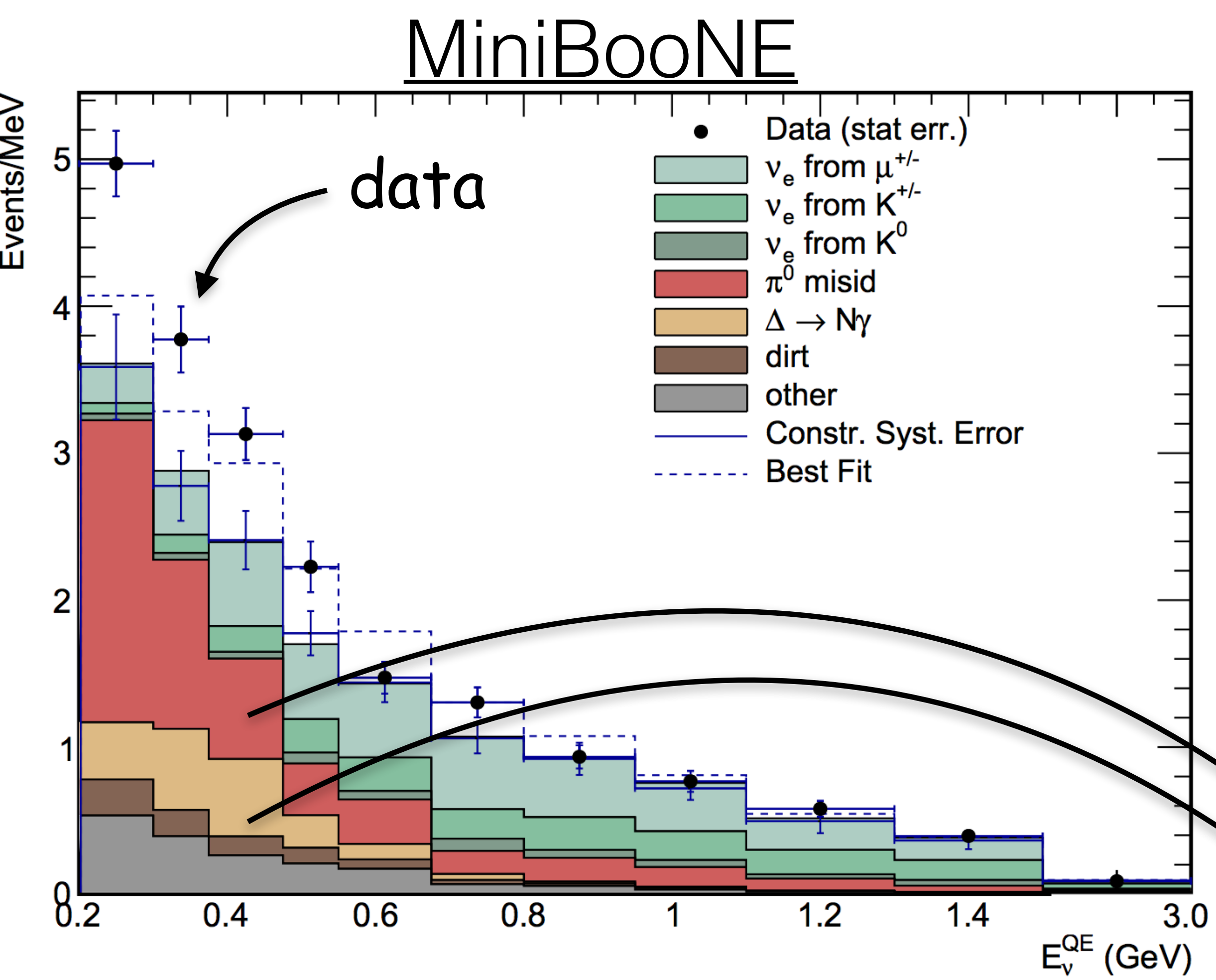


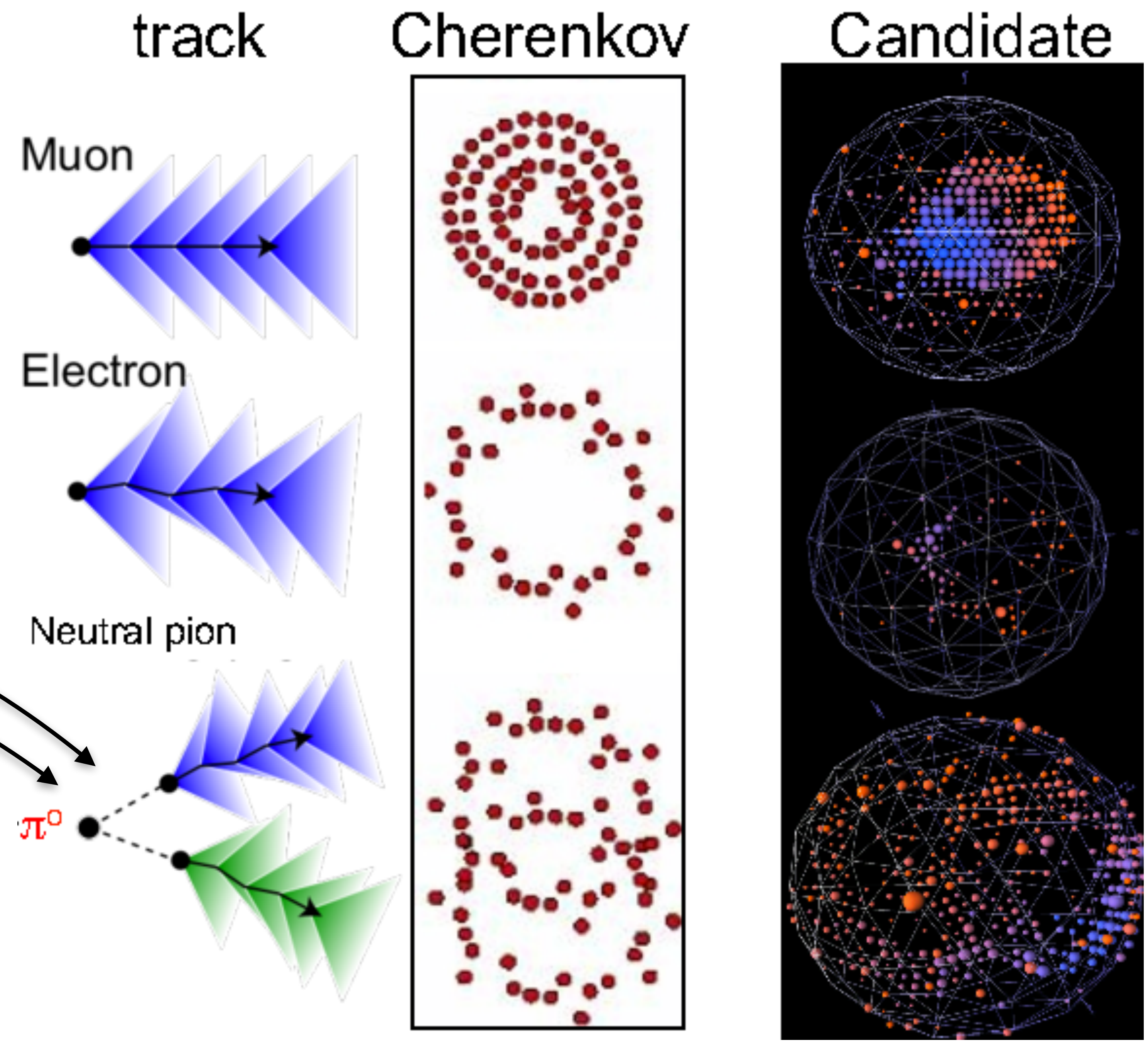
M. Dentler M, et al. JHEP 08:010 (2018)

Tension arises when combining ν_e appearance and ν_μ disappearance data sets.

Sterile Neutrinos

What is going on???



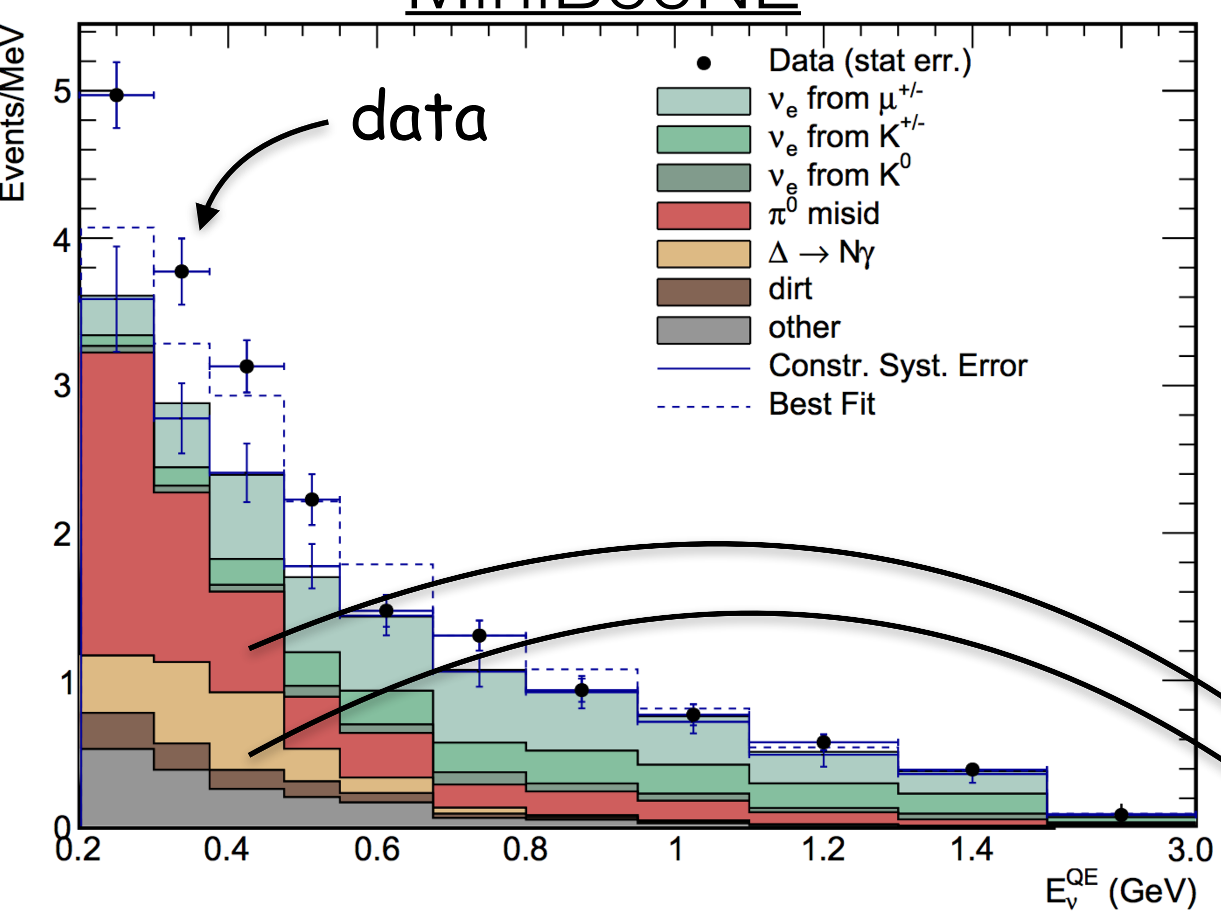


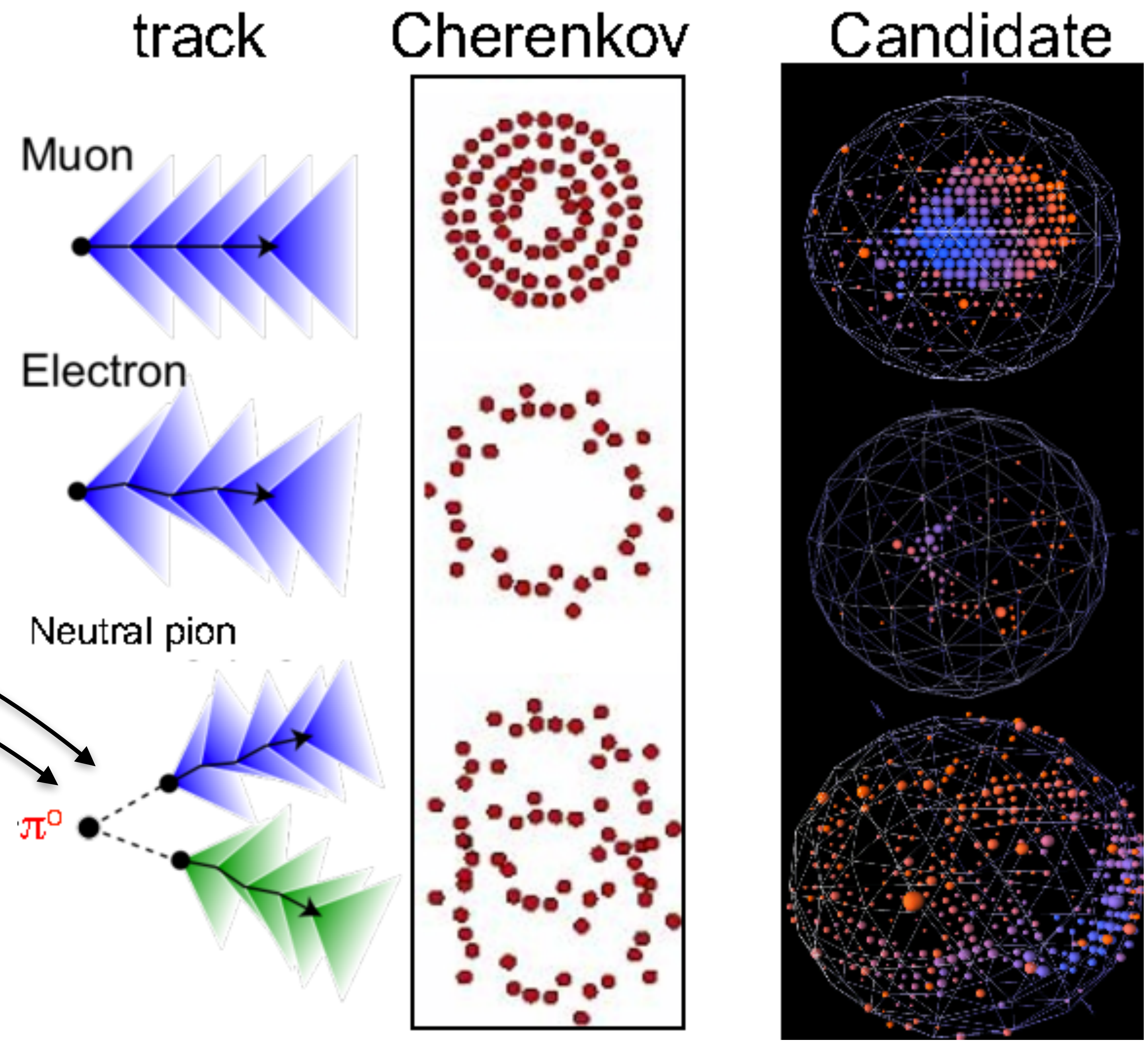
Photons? Electrons?

Sterile Neutrinos

What is going on???

MiniBooNE

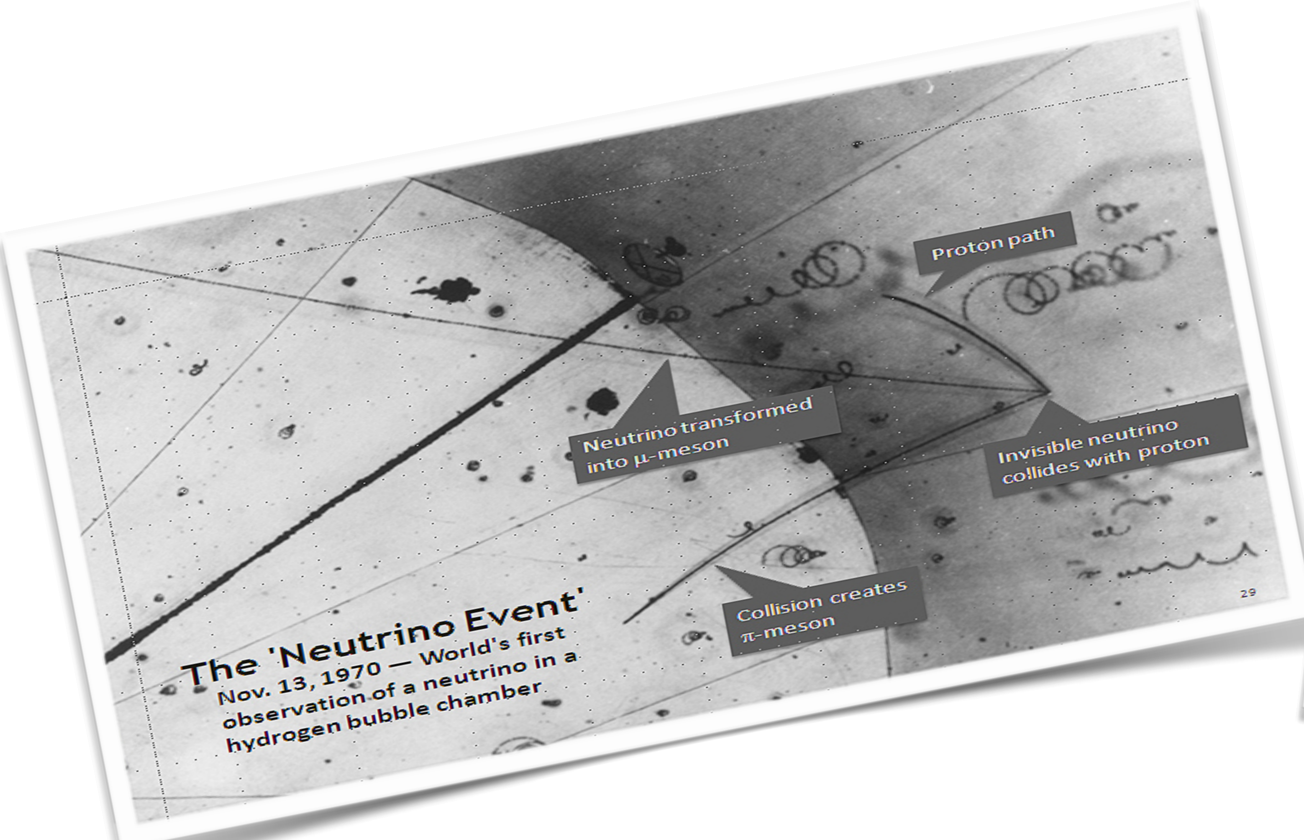


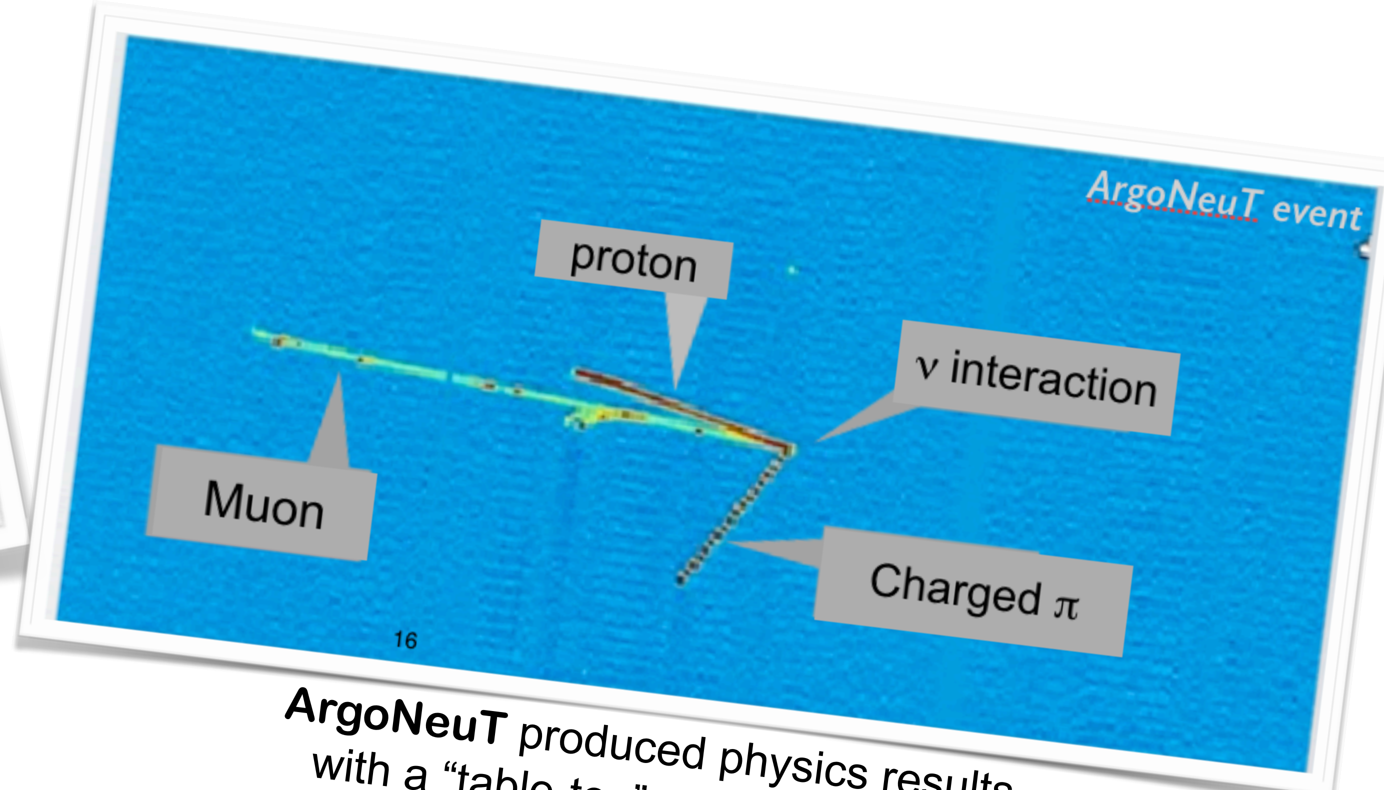


Photons? Electrons?

SBN program at FNAL (LAr TPC)

Why **Liquid Argon Time Projection Chamber**?



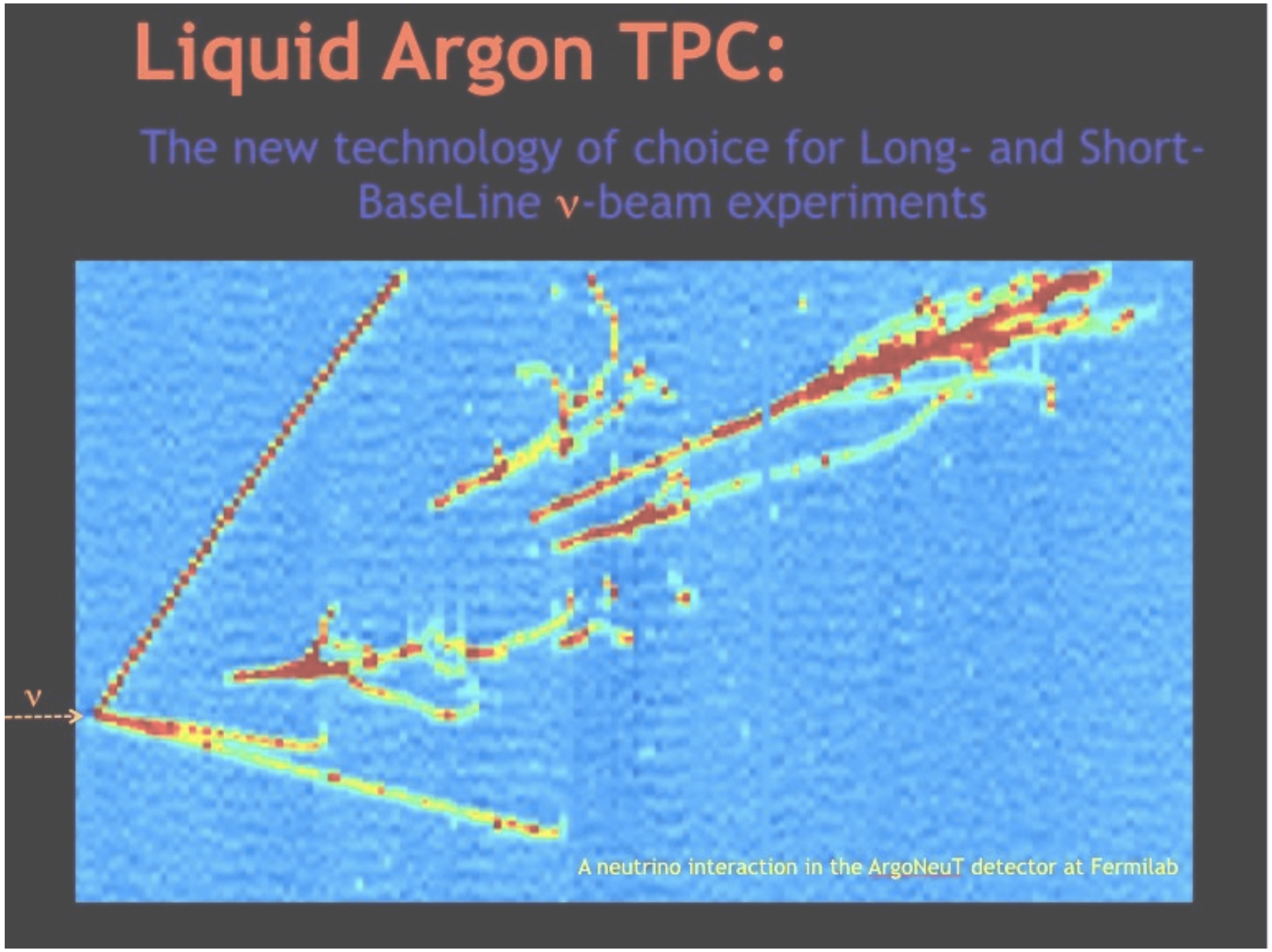


ArgoNeuT produced physics results with a "table-top" size experiment [240 Kg LArTPC]

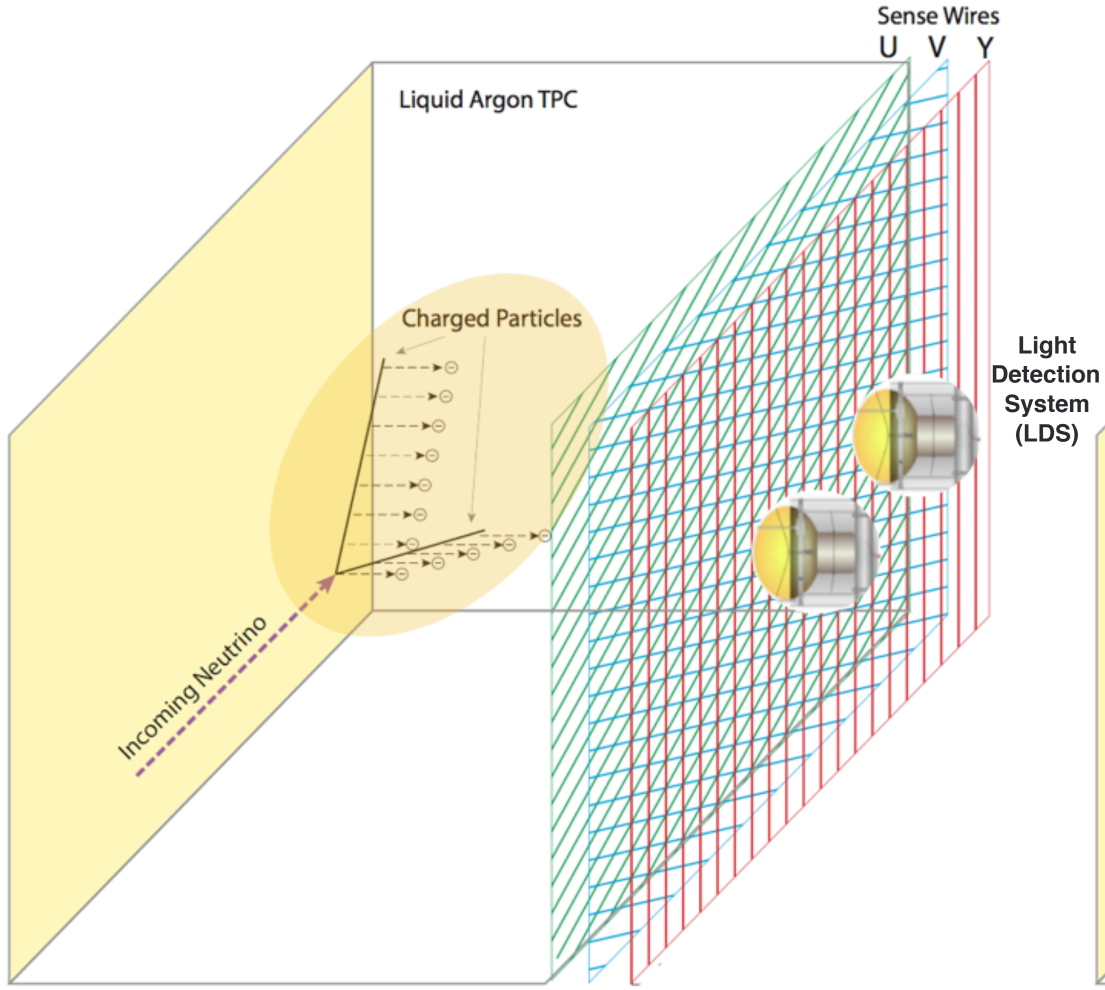
LAr TPC: Bubble chamber quality of data with added calorimetry

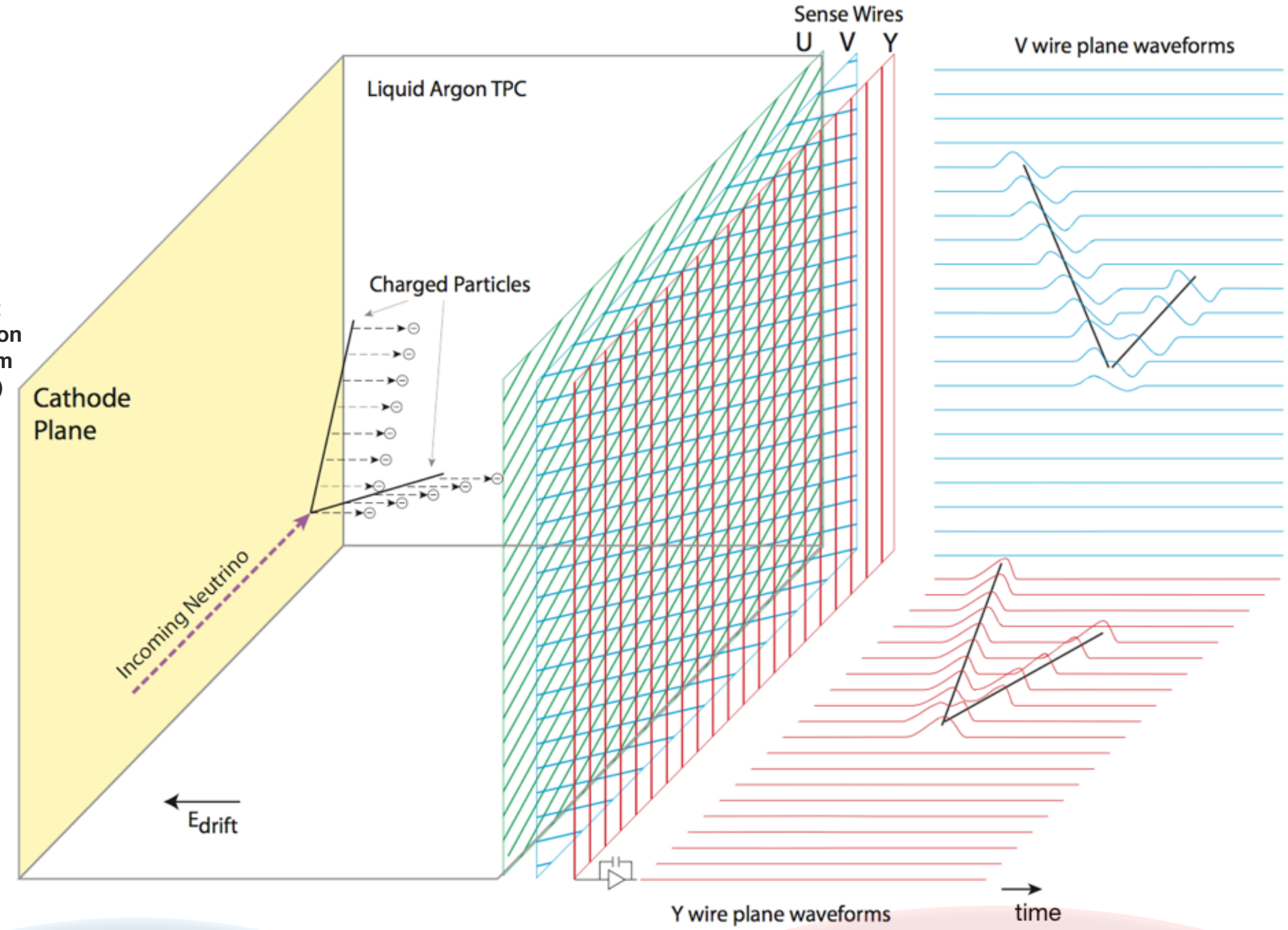
The LAr TPC Technology

- **LArTPC** technology offers the ability to measure interactions of neutrinos **in real time with (sub)-millimeter position resolution**, far beyond that offered by any other neutrino detection method.
- The U.S. accelerator neutrino program is based on the **LArTPC** technology (short- and long- baseline programs).
- LArTPC has unprecedented sensitivity in the **region of energy depositions from sub-MeV to few GeV**.



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]

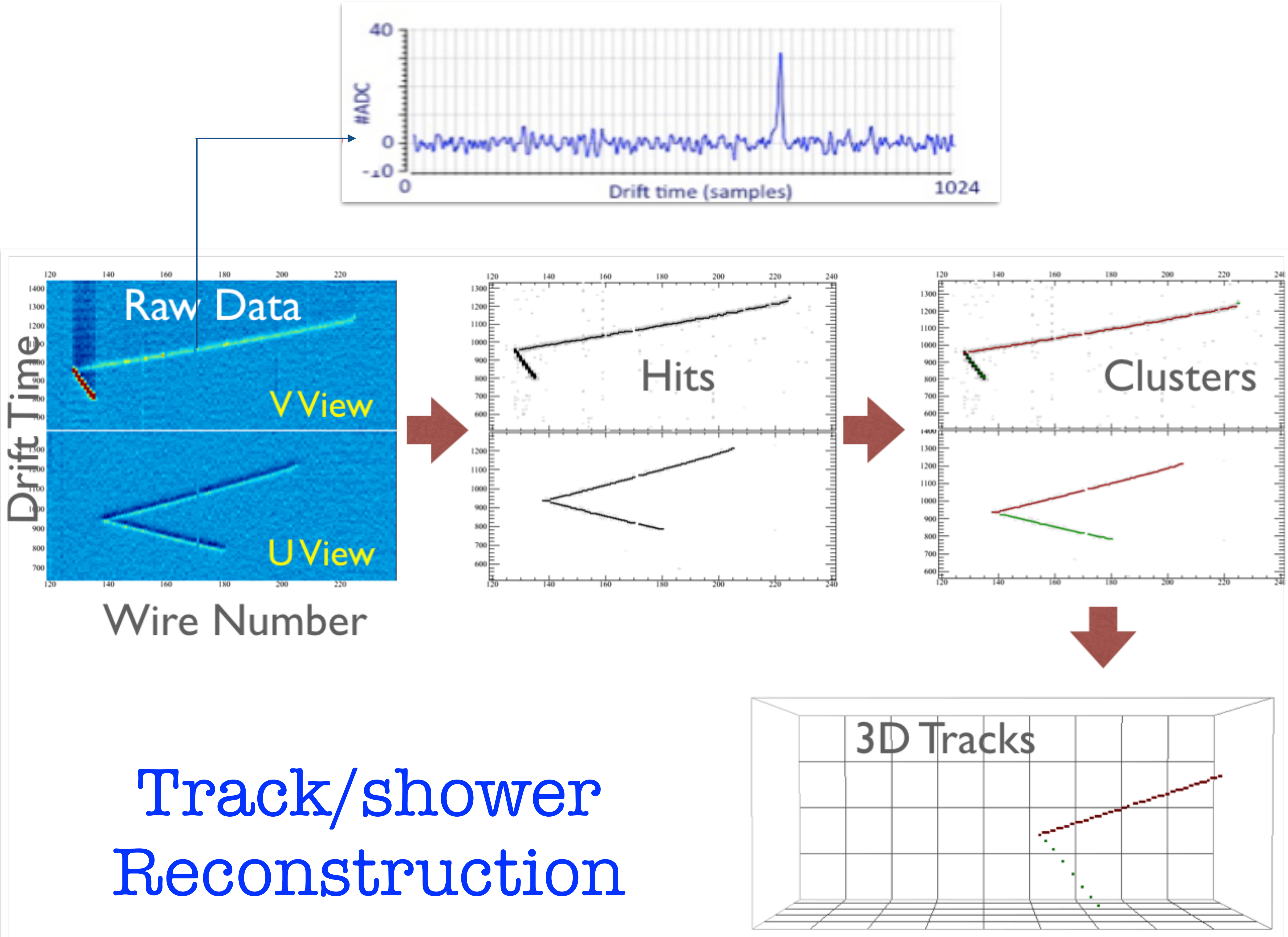
m.i.p. at 500 V/cm: ~ 60,000 e/cm
~ 50,000 photons/cm

Electron drift time ~ ms

VUV photons propagate and are shifted into VIS photons

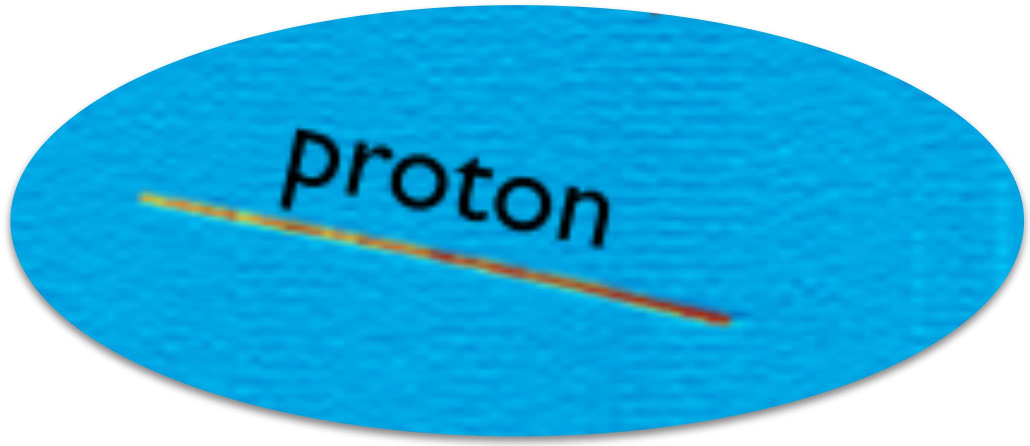
Scintillation light **fast** signals from LDSs give event timing

LArTPC at work: imagining and energy

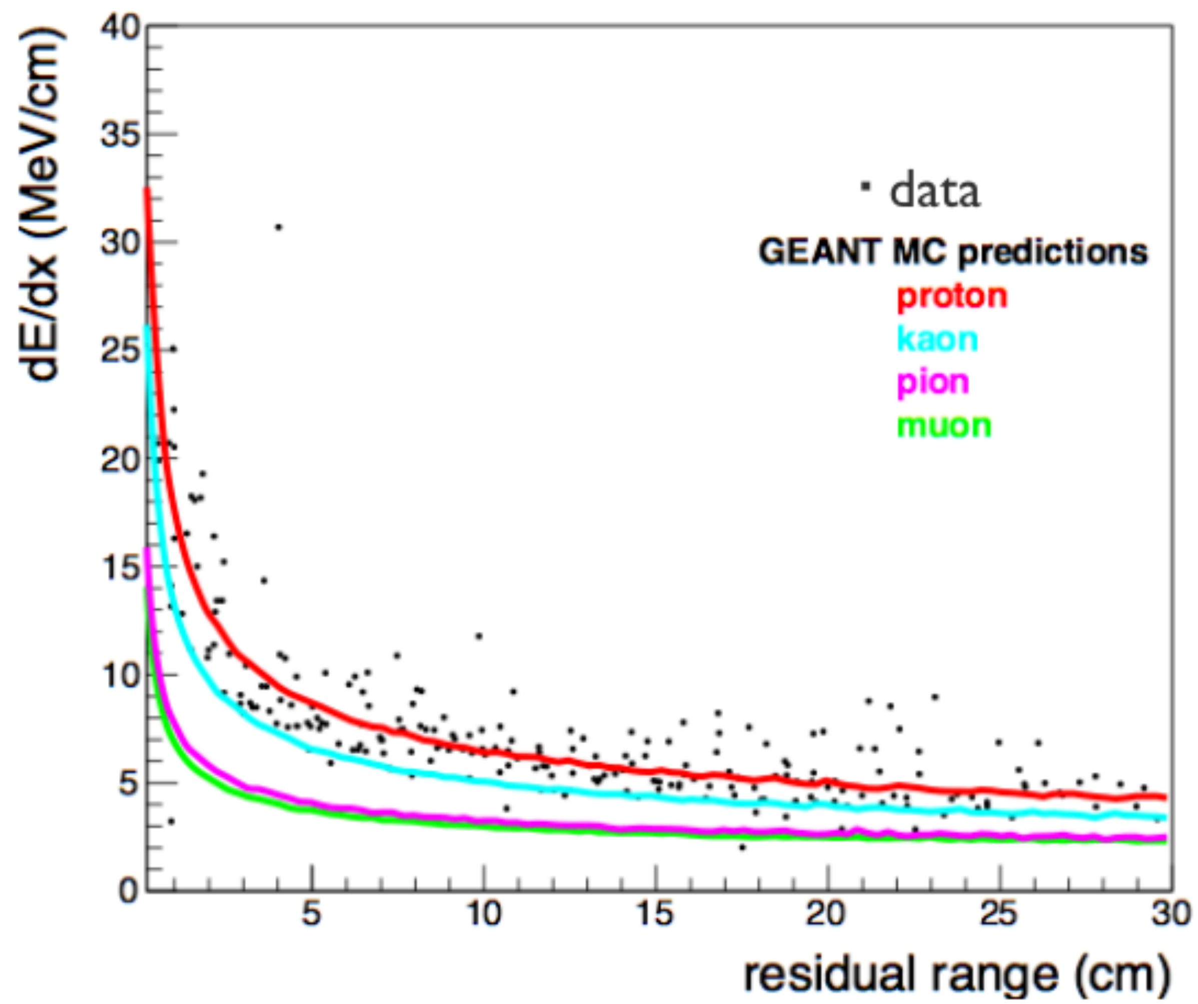


Track/shower Reconstruction

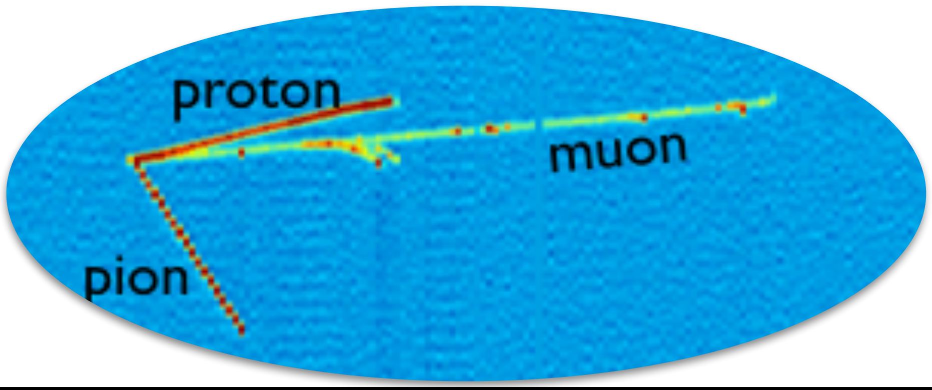
LArTPC at work: imagining and energy

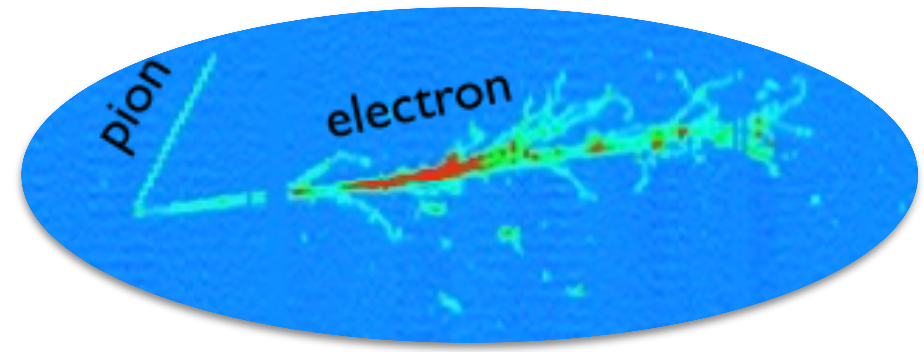


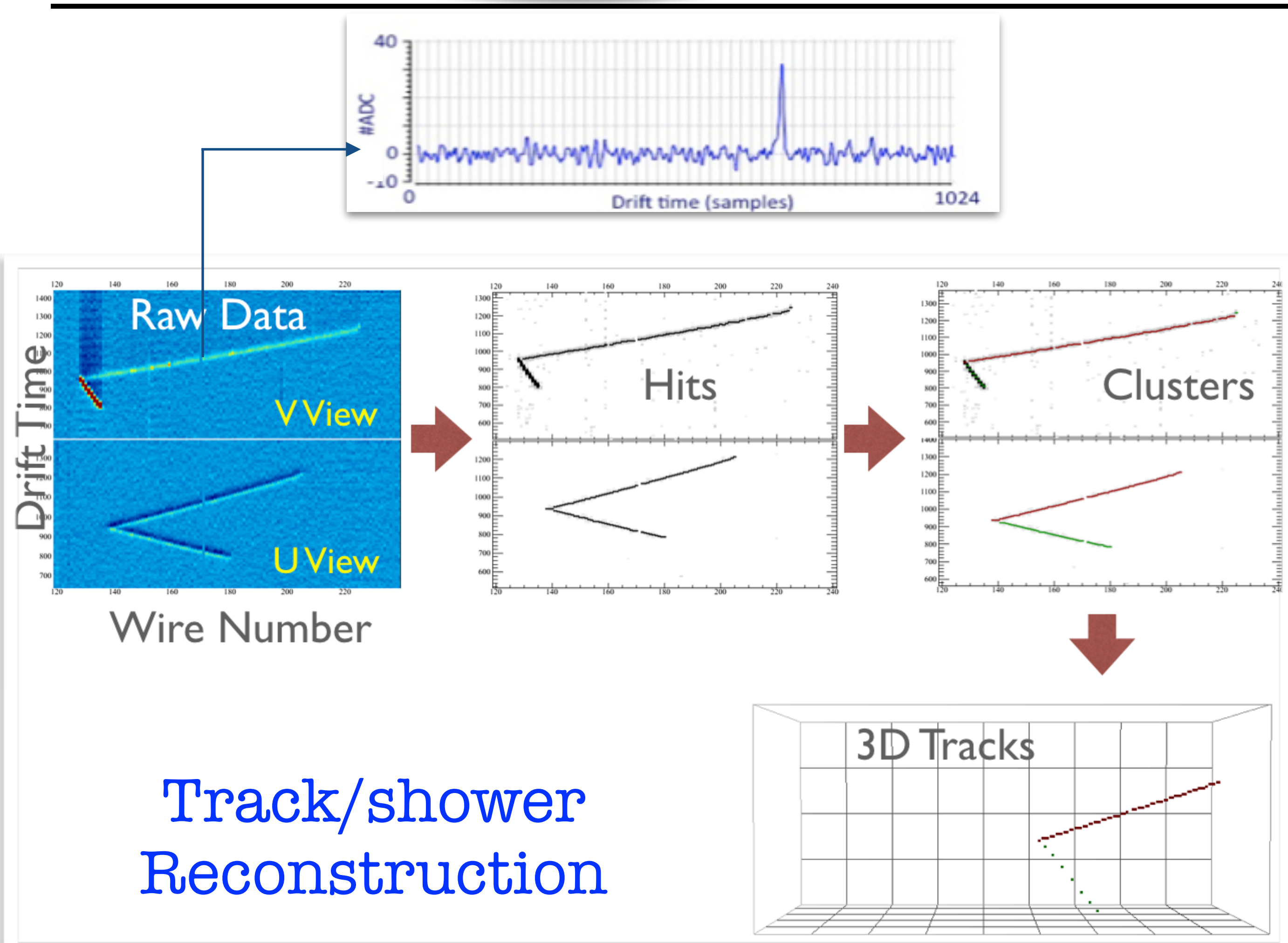
Calorimetry & Particle Identification

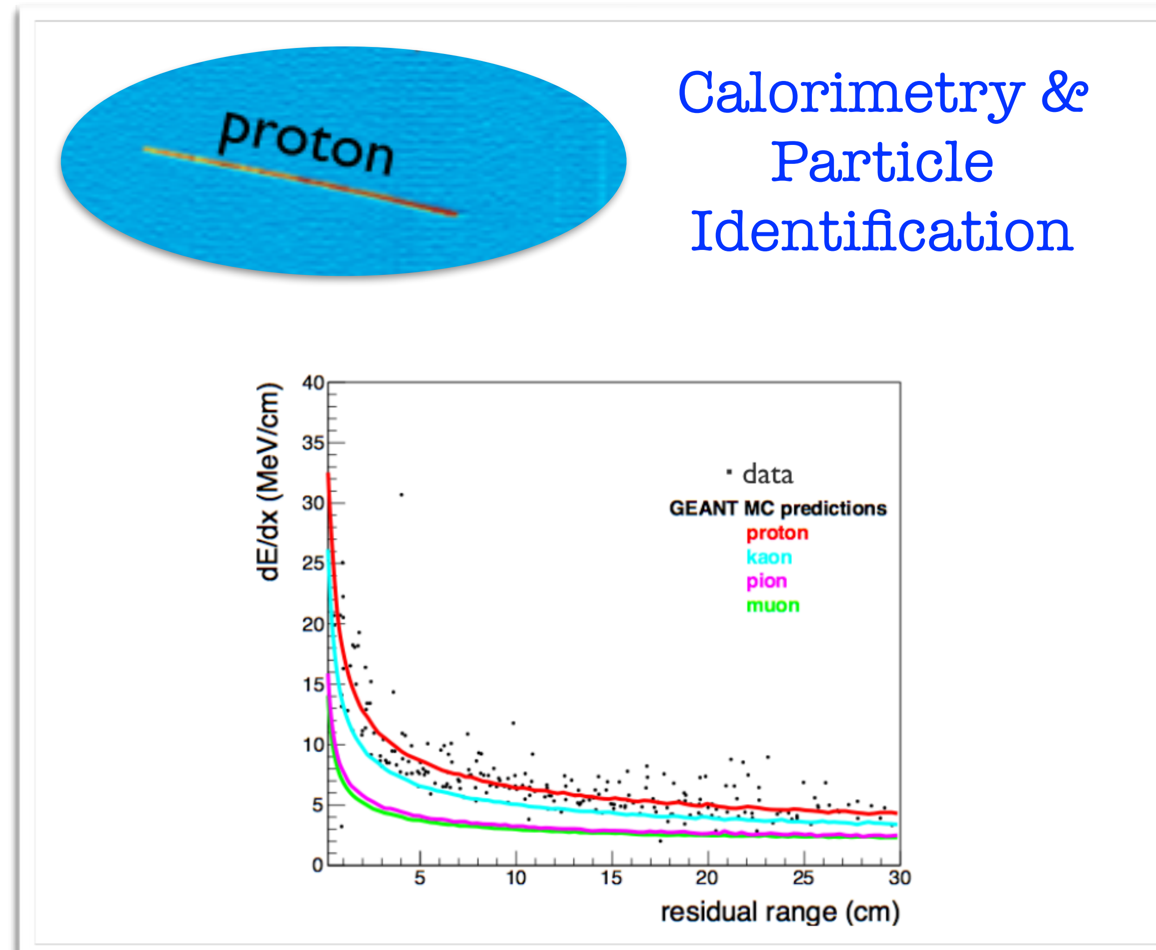


LArTPC at work: imagining and energy



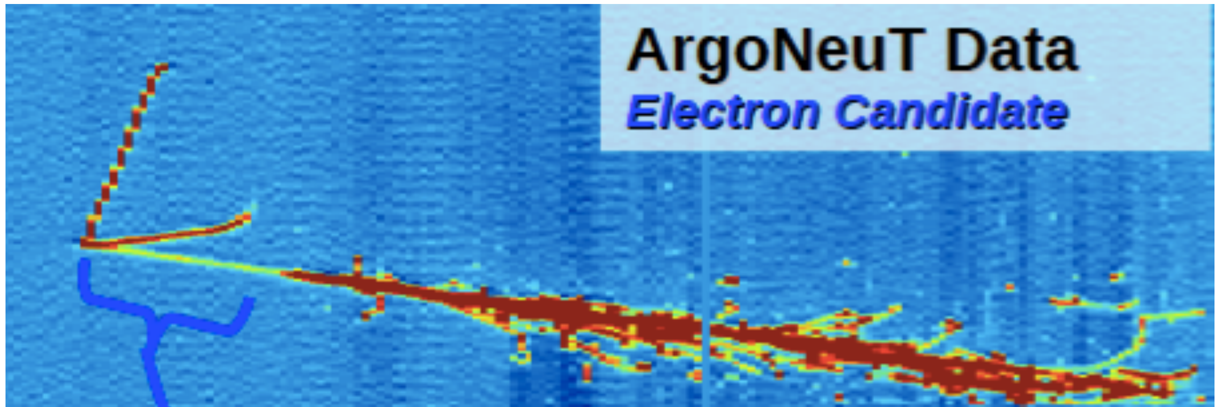


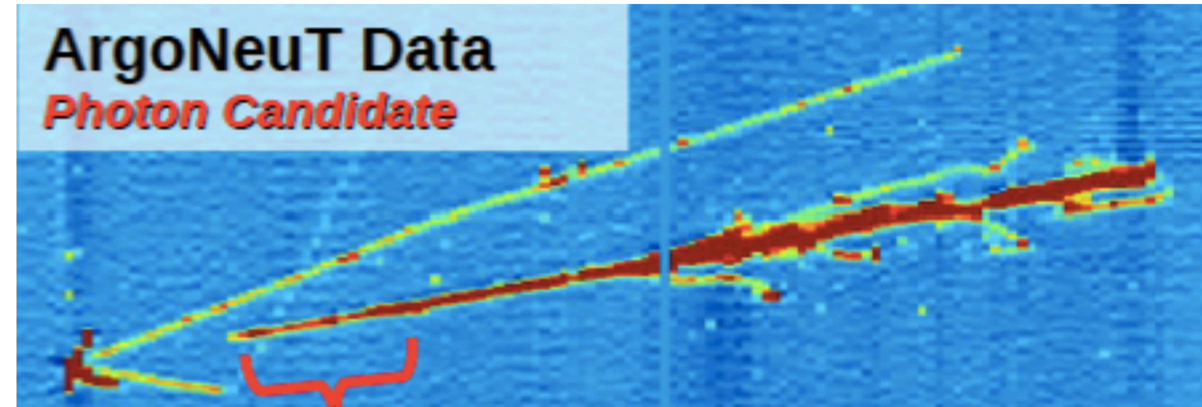


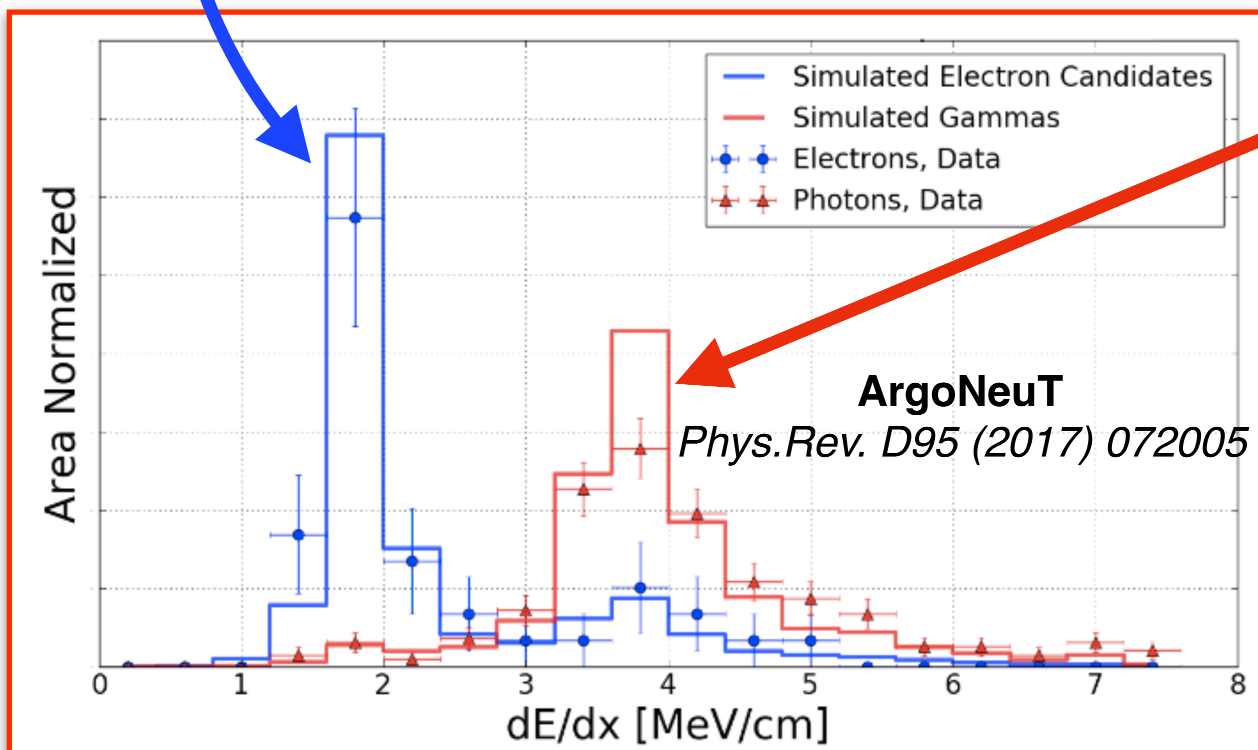


- Multiple 2D and the 3D reconstruction of charged particles tracks $\Rightarrow$ **Imaging**
- Total charge proportional to the deposited Energy $\Rightarrow$ **Calorimetry**
- dE/dx along the track $\Rightarrow$ **Particle Identification**

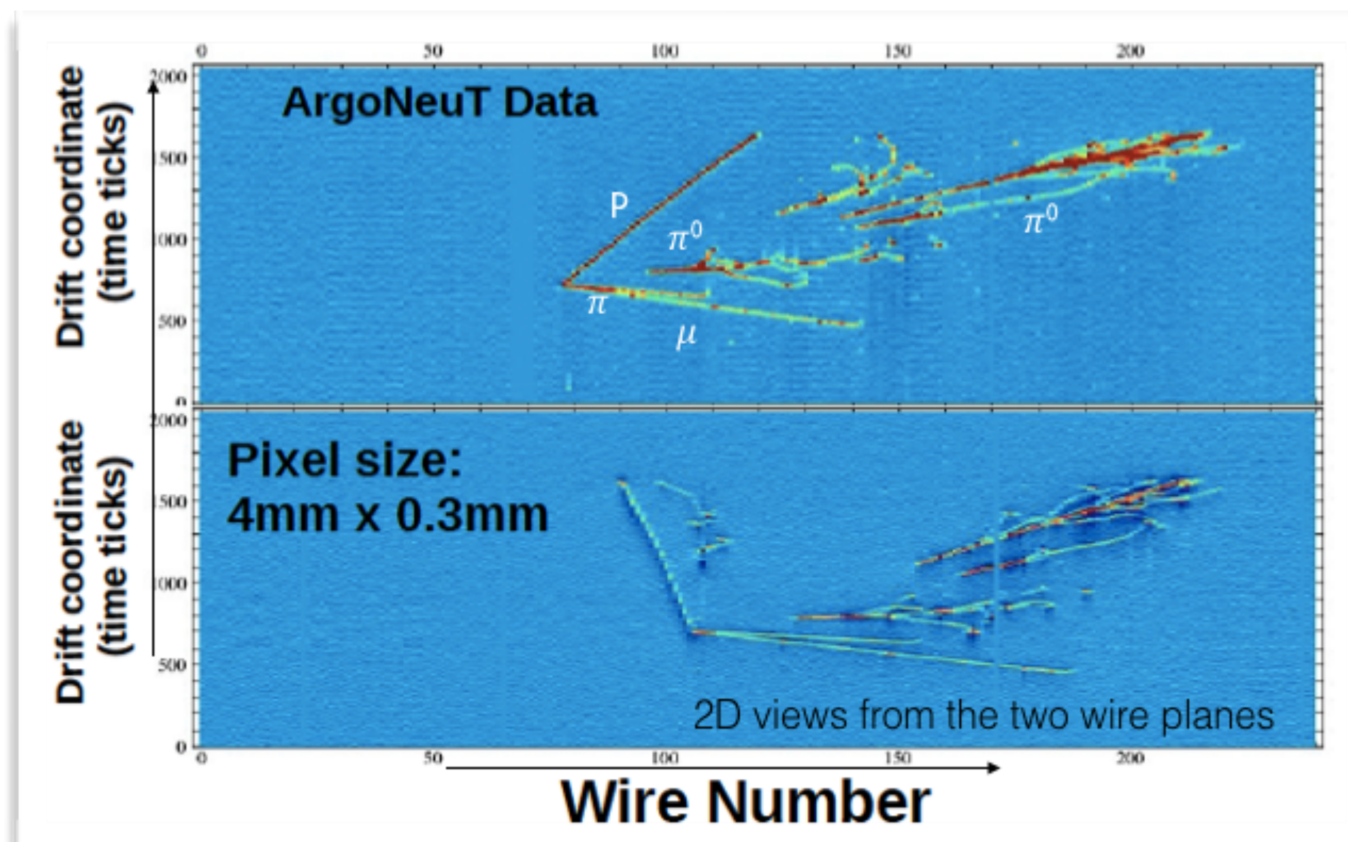
Electron-γ discrimination in LAr



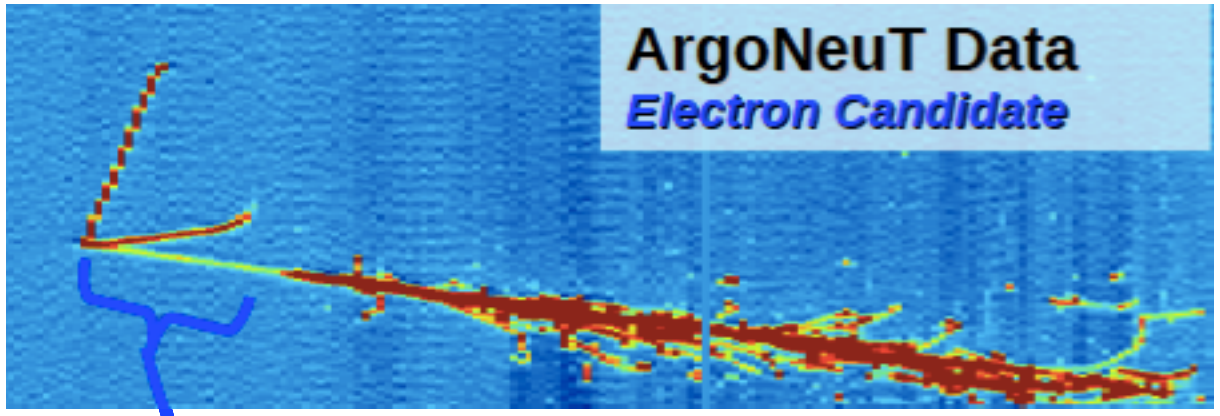


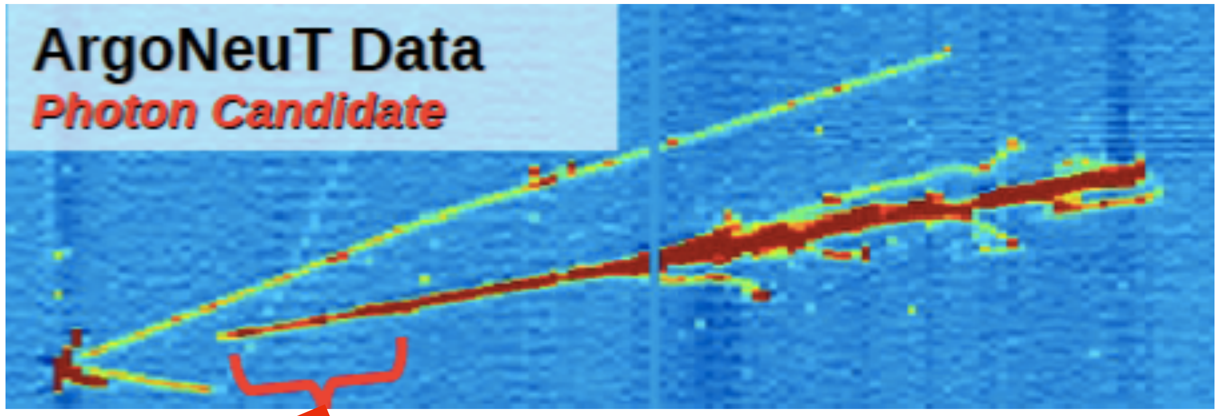


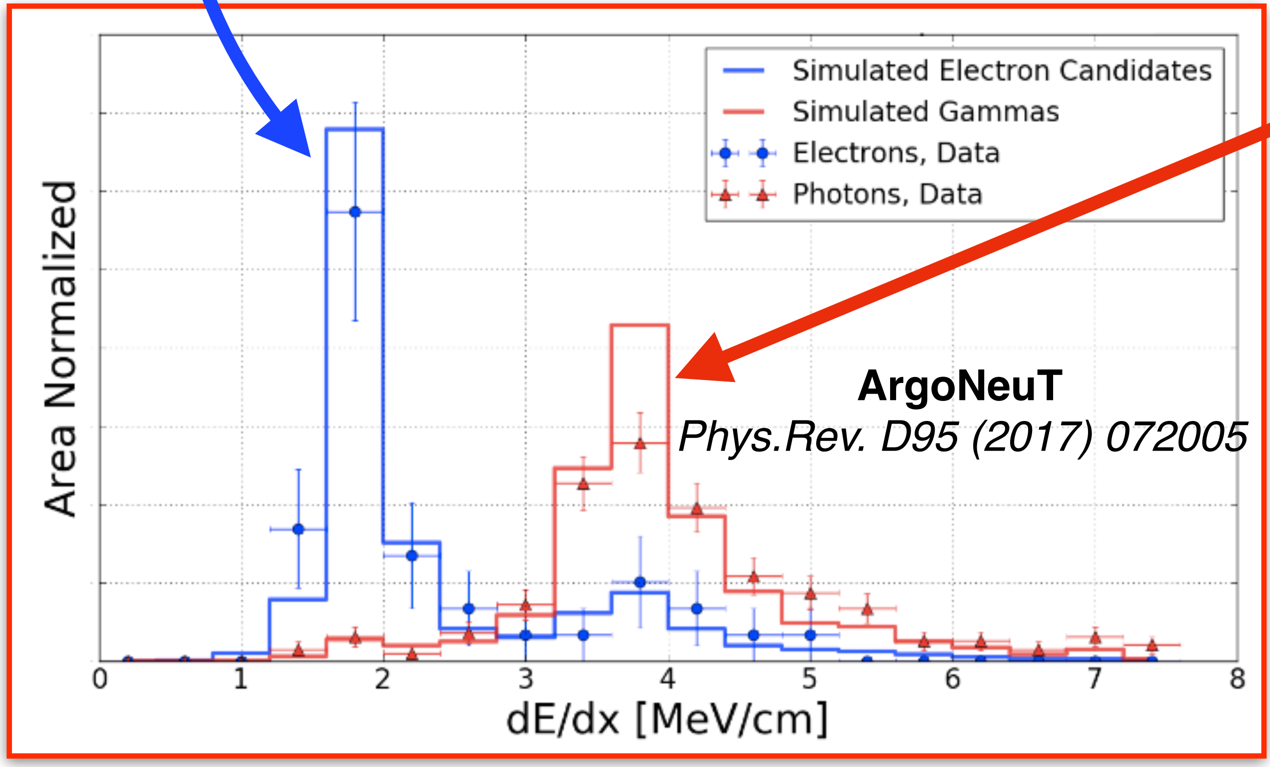
Analyzing topology and dE/dx



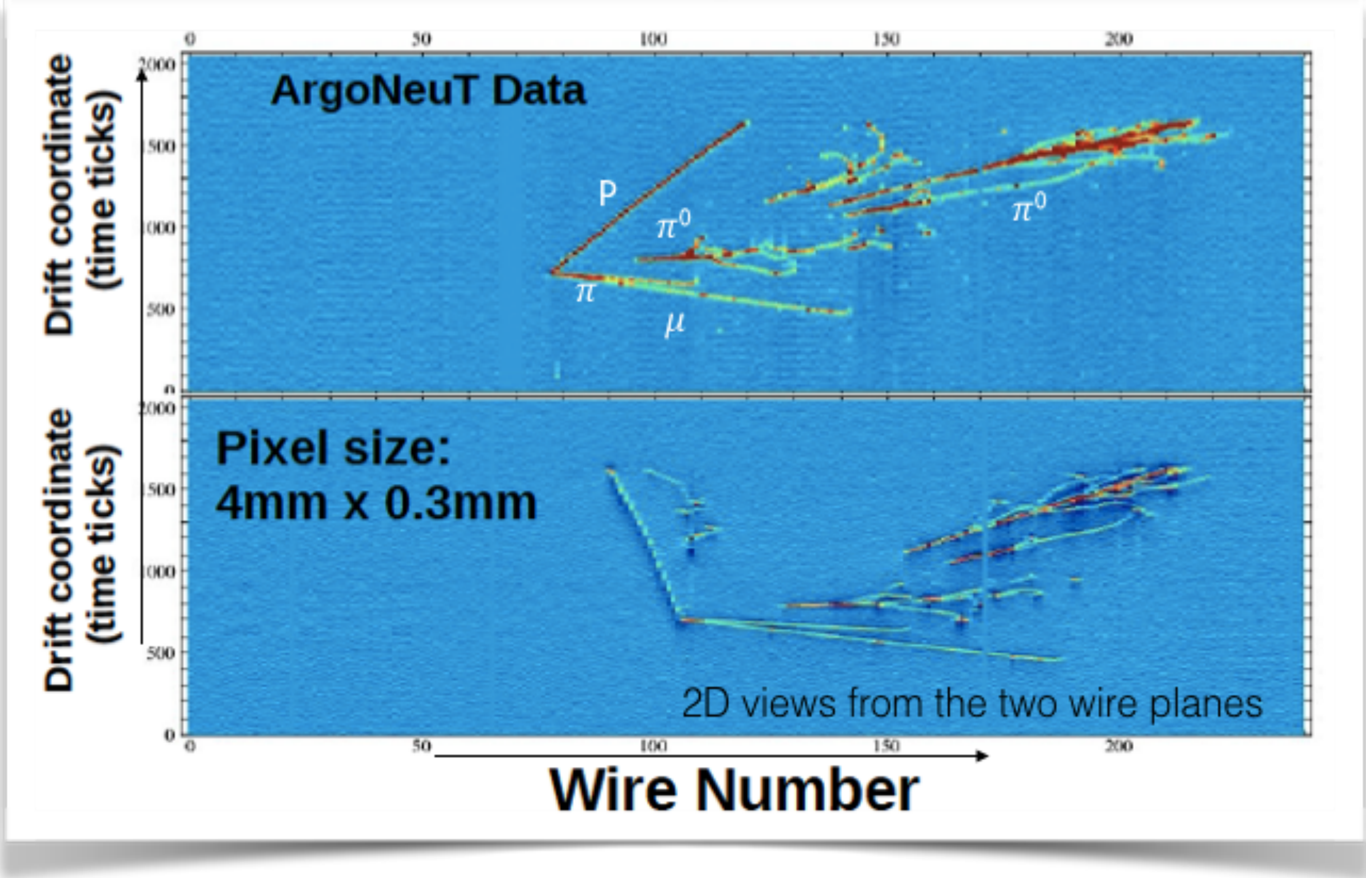
Electron-γ discrimination in LAr







Analyzing topology and dE/dx

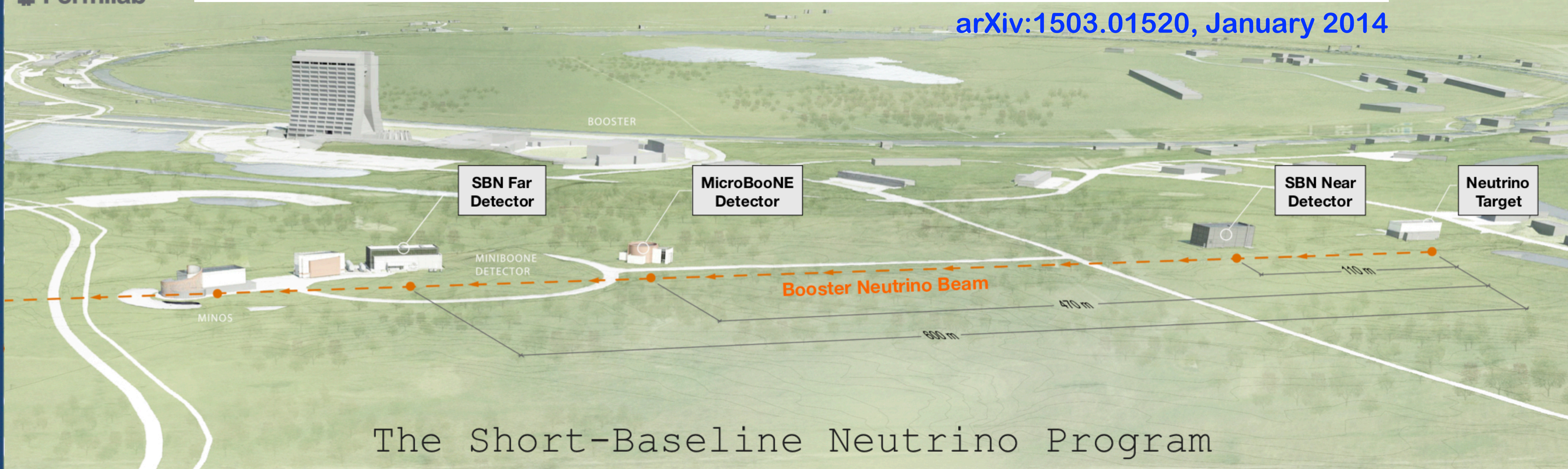


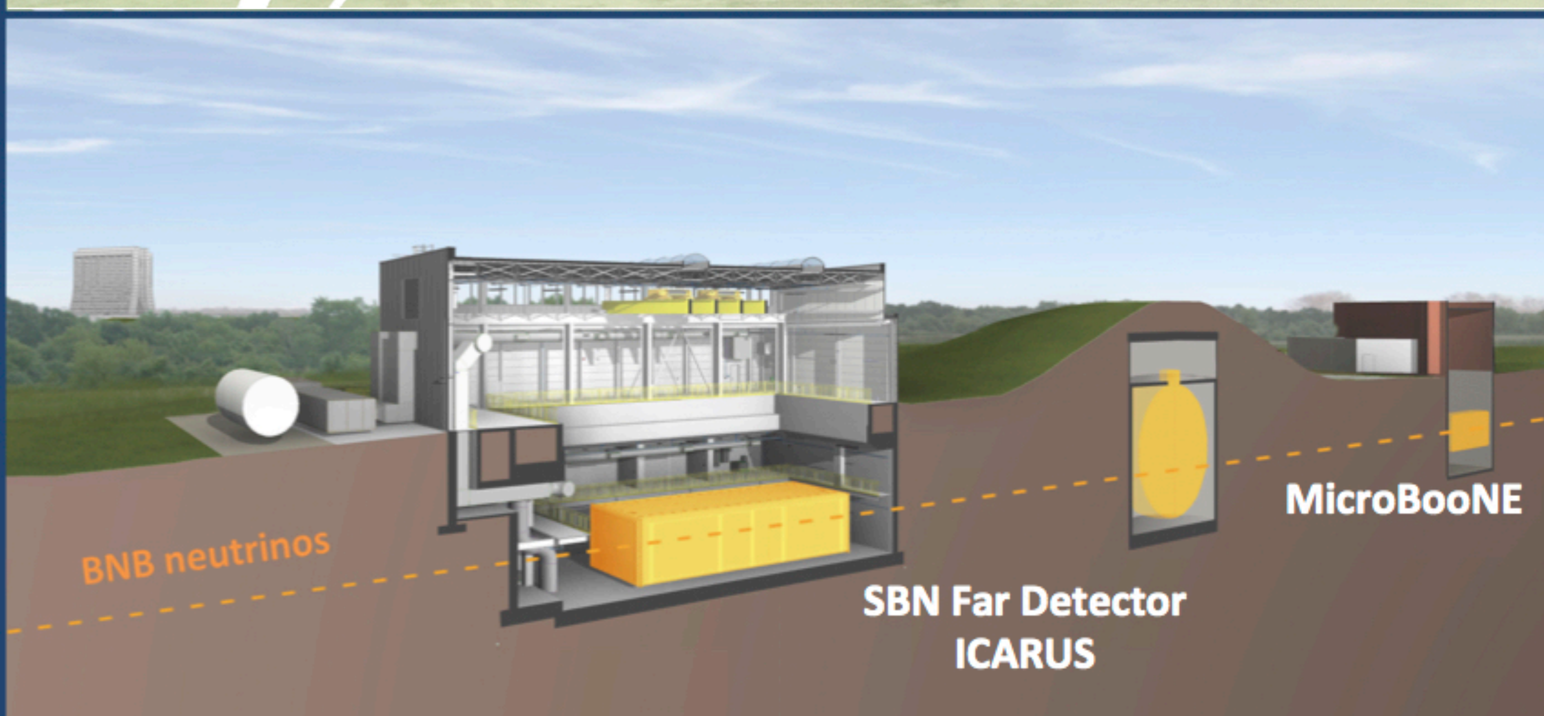
e-γ discrimination capability of LAr is crucial to understand the signal/background nature of the ν_e-like events observed by MiniBooNE

FNAL Short Baseline Neutrino program

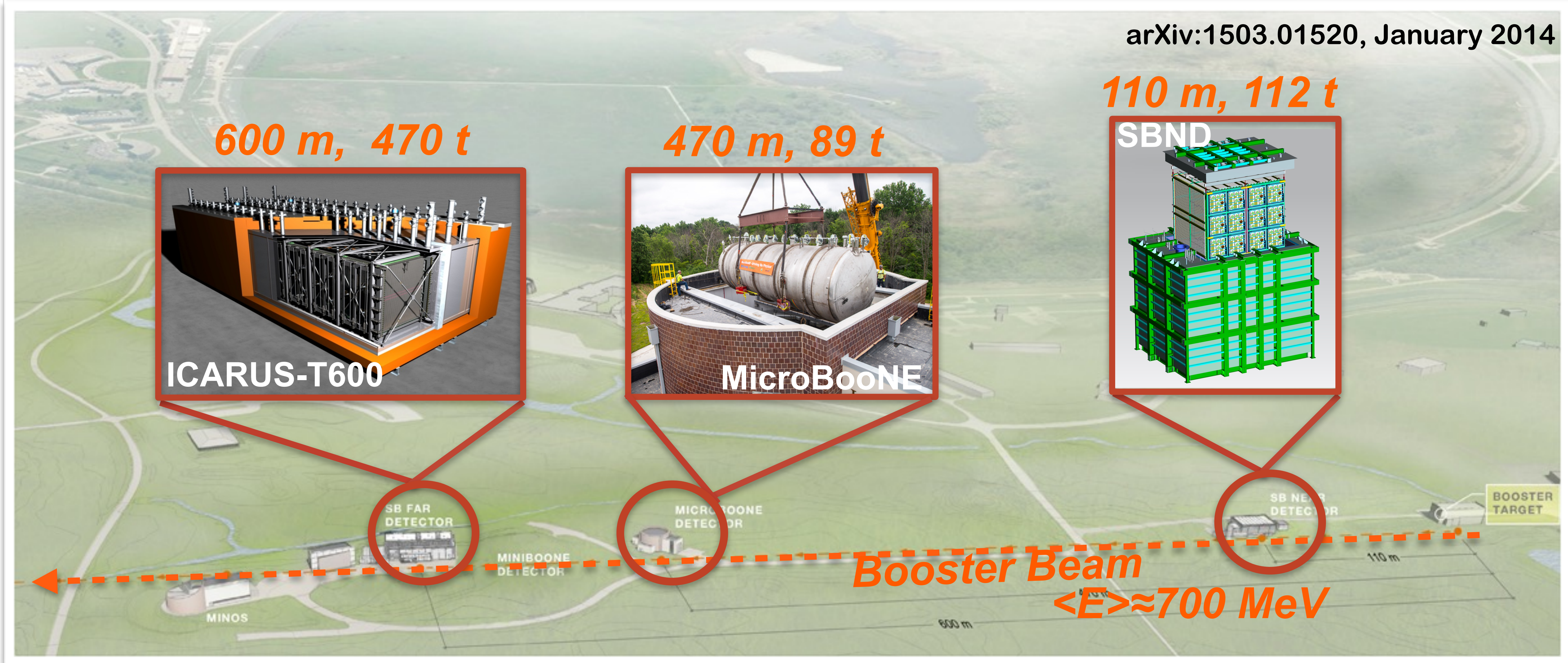
A multi-detector – LAr TPC based –
facility on the Booster Neutrino Beam at Fermilab

arXiv:1503.01520, January 2014





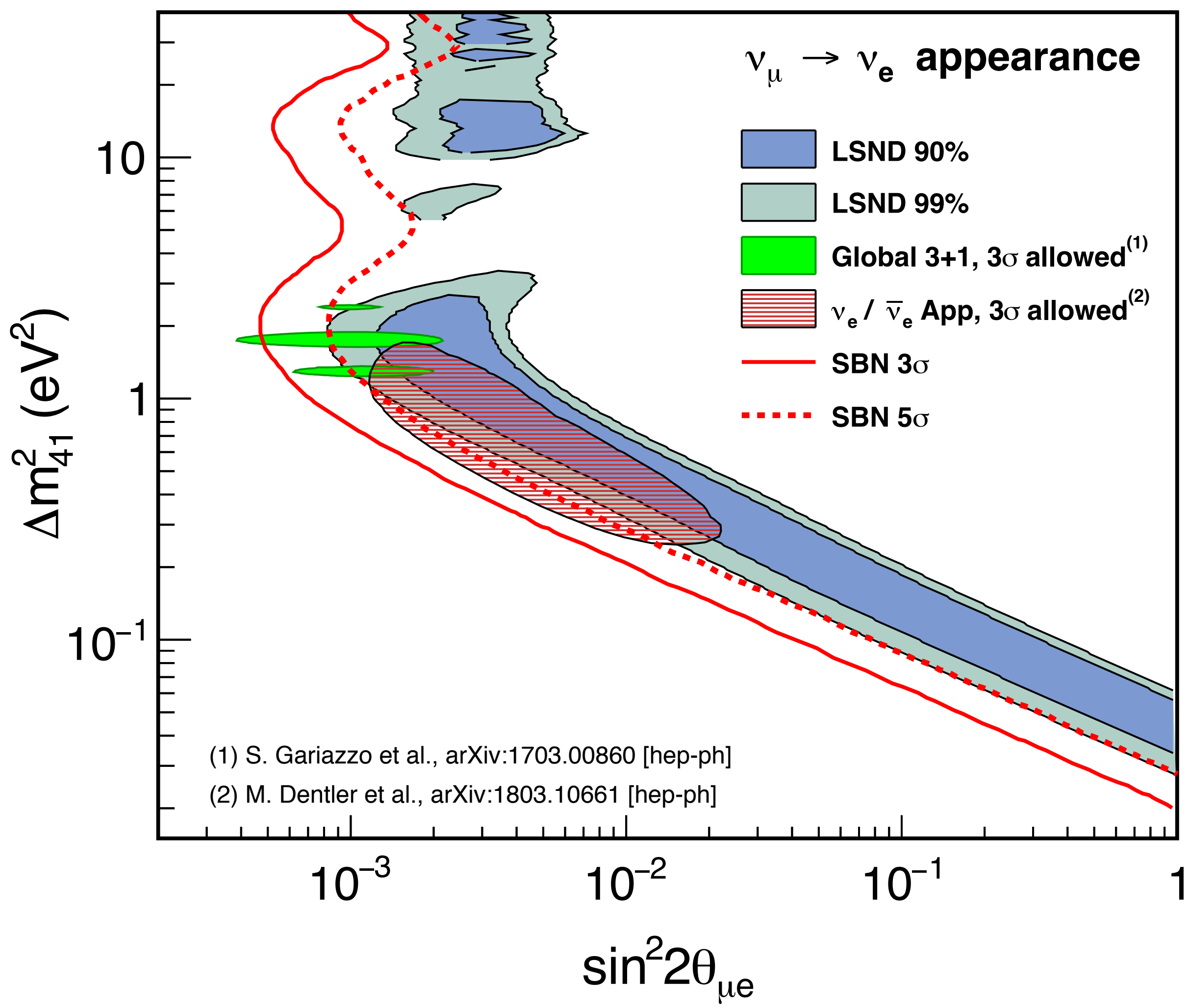
FNAL Short Baseline Neutrino program



Same neutrino beam, nuclear target, detector technology: reducing systematic uncertainties to the % level.

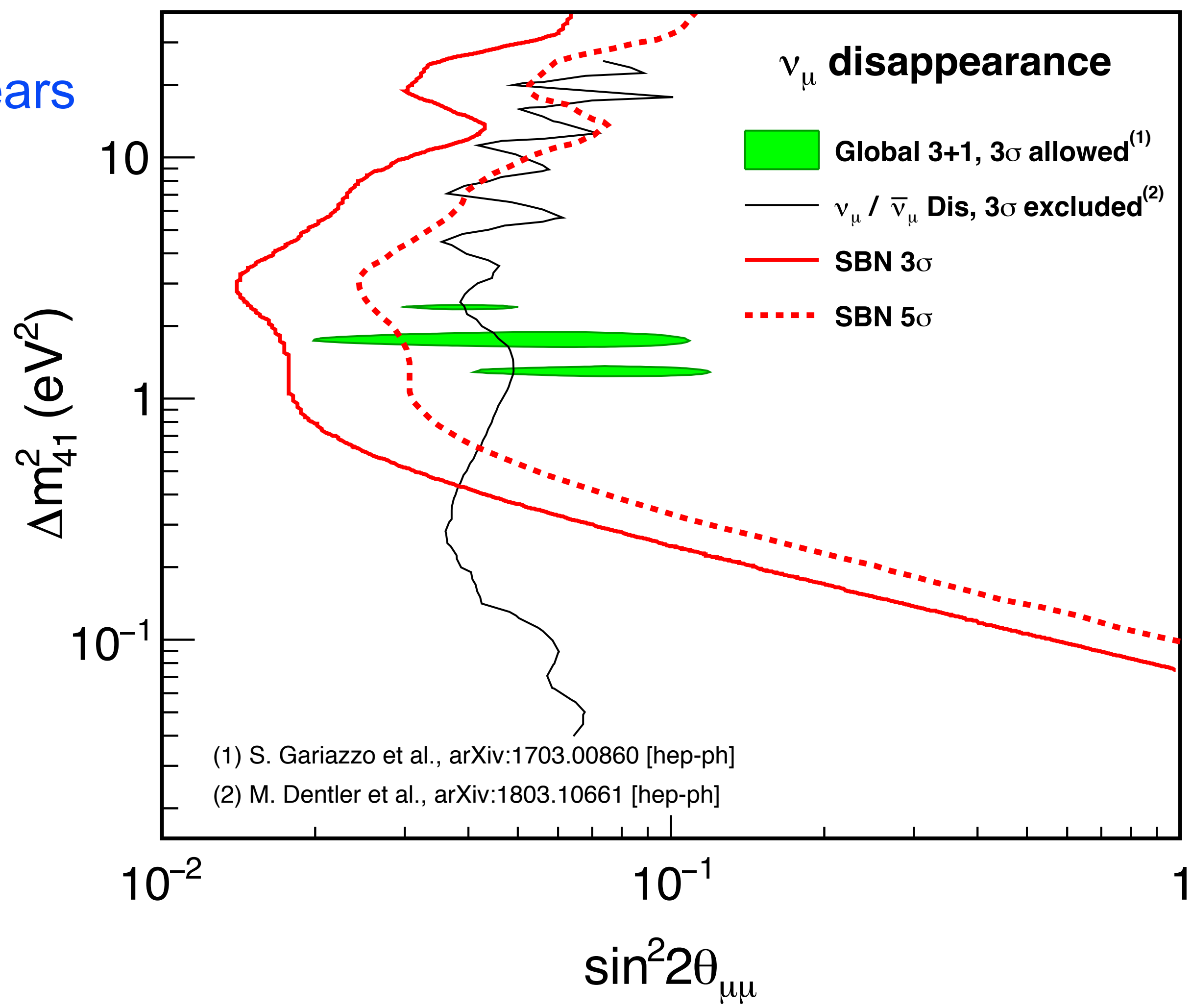
Sterile Neutrino Sensitivity

$\nu_\mu \rightarrow \nu_e$ Appearance sensitivity



~3 years

$\nu_\mu \rightarrow \nu_x$ Disappearance sensitivity



SBN can cover the parameters allowed by past anomalies at ≥ 5σ significance

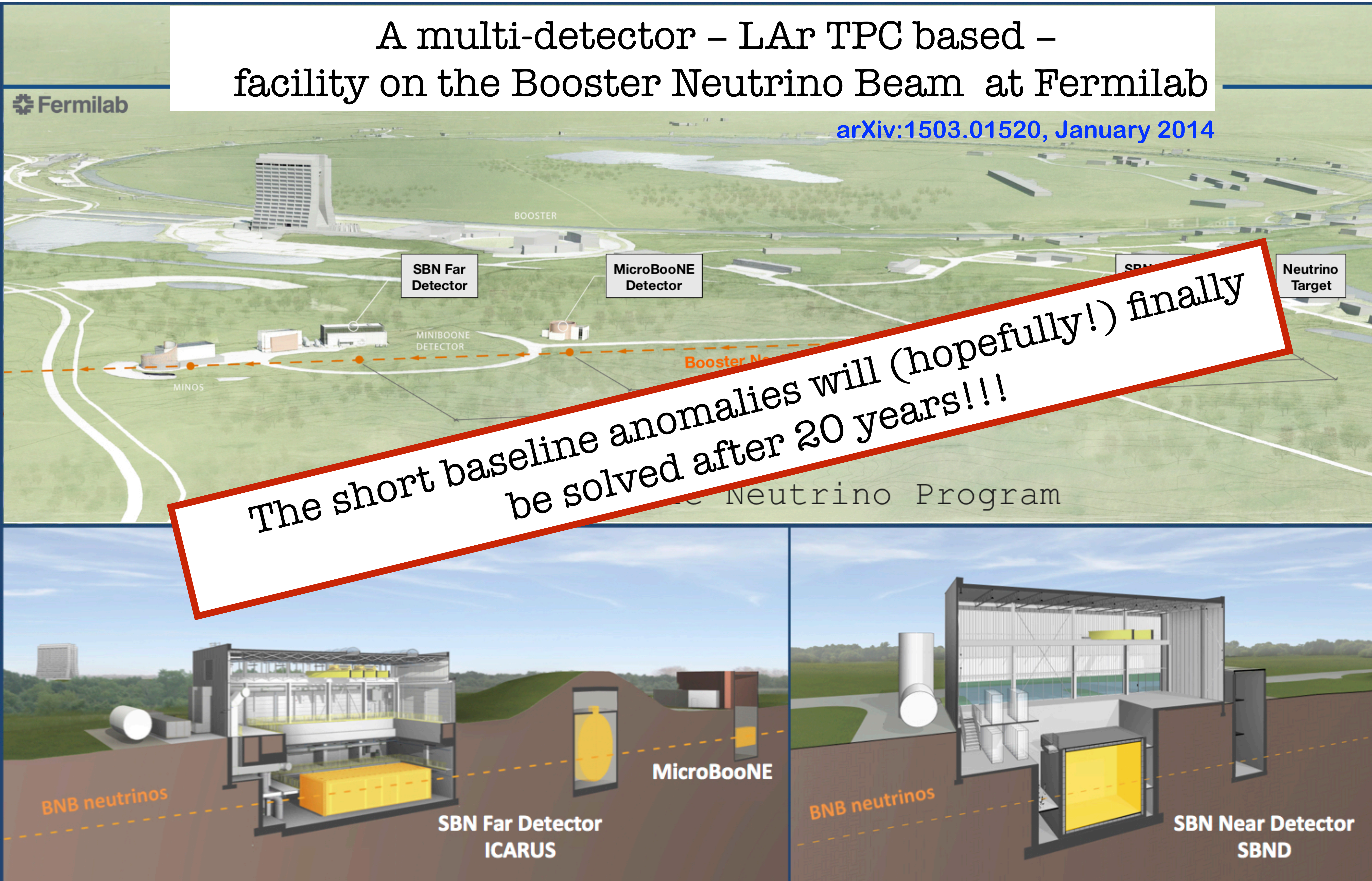
SBN also has sensitivity to ν_μ disappearance

The observation of ν_μ disappearance would be essential to the interpretation of any electron neutrino excess as being due to the existence of sterile neutrinos

FNAL Short Baseline Neutrino program

A multi-detector – LAr TPC based –
facility on the Booster Neutrino Beam at Fermilab

arXiv:1503.01520, January 2014



The short baseline anomalies will (hopefully!) finally be solved after 20 years!!!

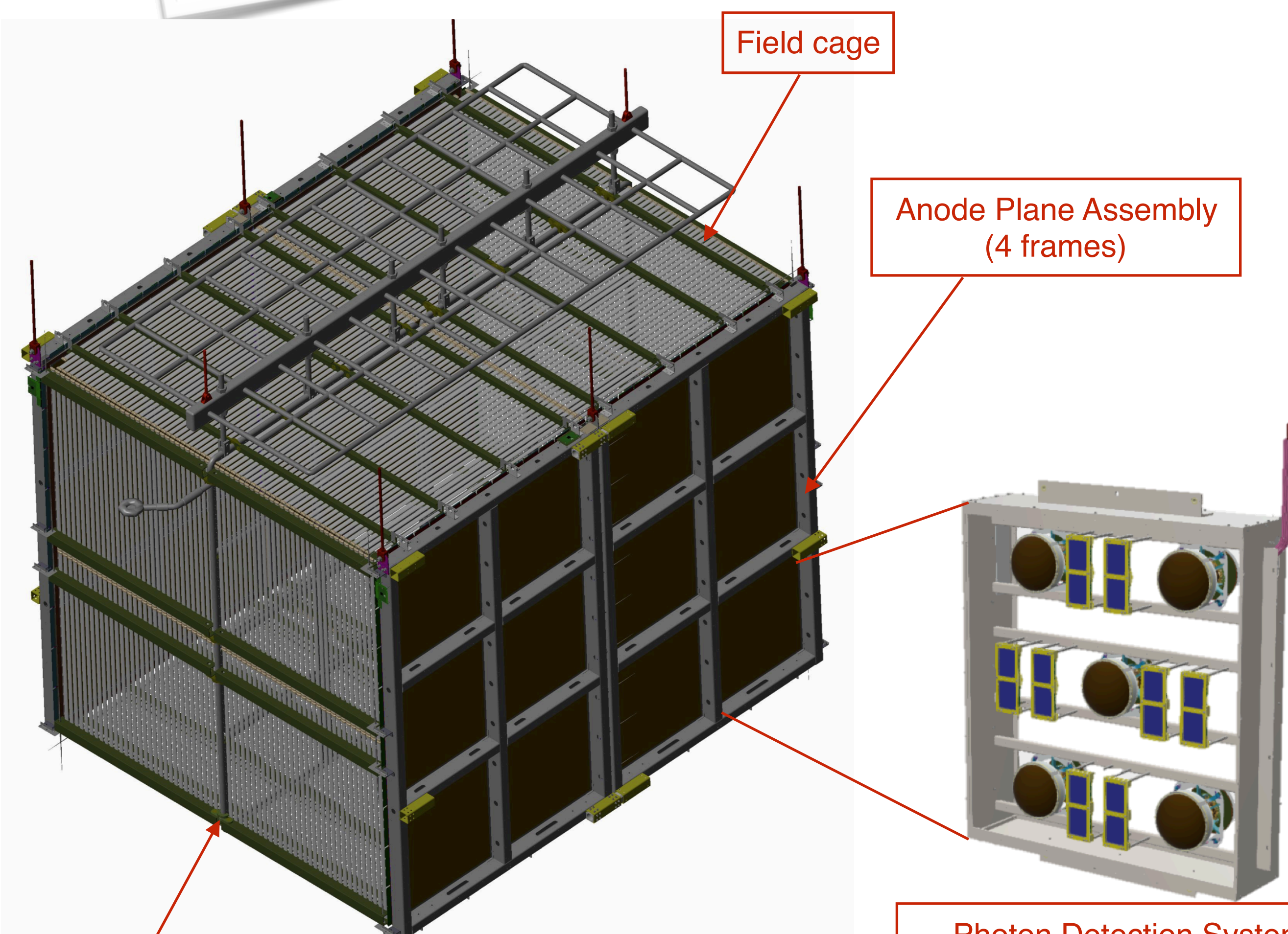
ICARUS-T600

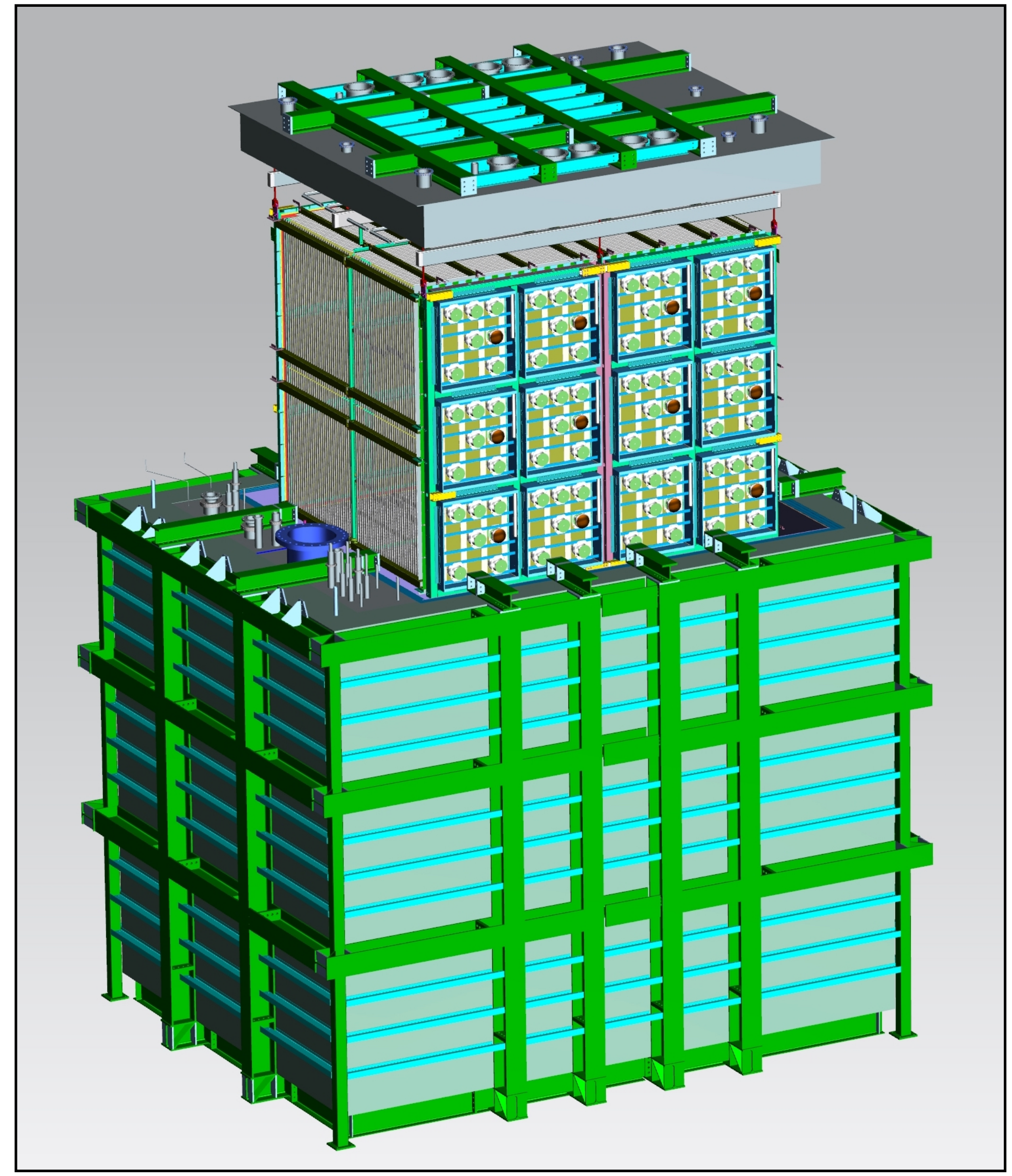
ICARUS-T600
commissioning
by the end of 2019

TPC Active volume
470 t of LAr
[6m x 3.2m x 18m]

Short-Baseline Near Detector: SBND

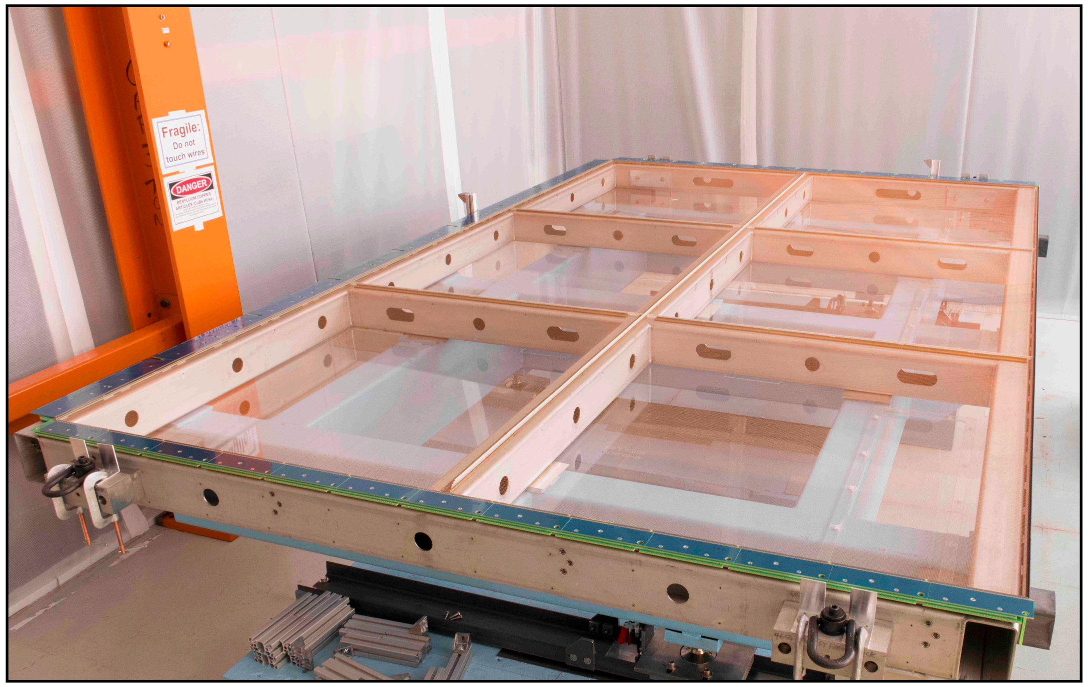
Overall, the design philosophy of the SBND detector is similar to the DUNE detector



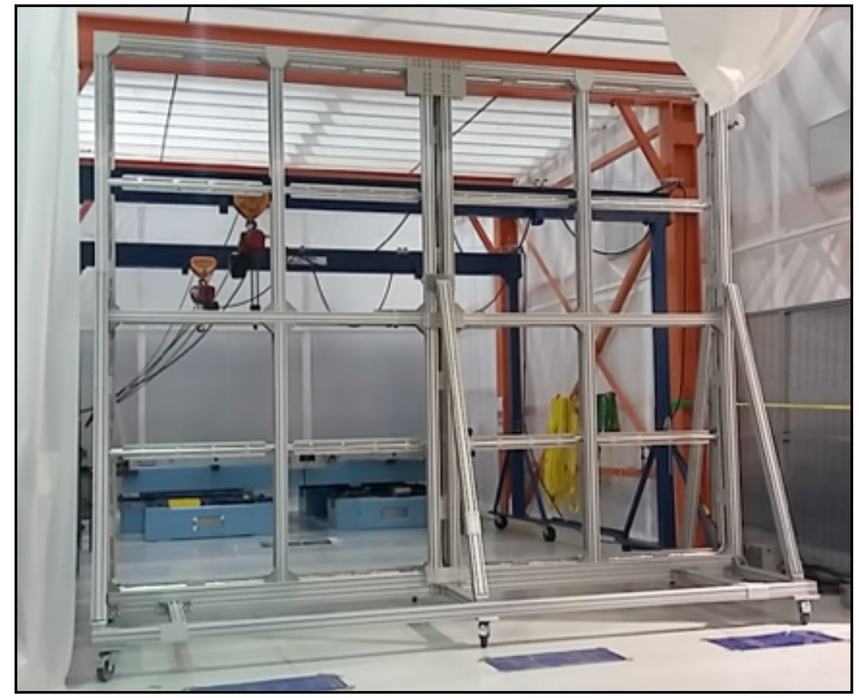


TPC Active volume
112 t of LAr
[4m x 4m x 5m]

SBND: Detector Construction



Anode plane (APA)



Cathode plane (APA)

Assembly Transportation Frame

SBND commissioning
by the end of 2020

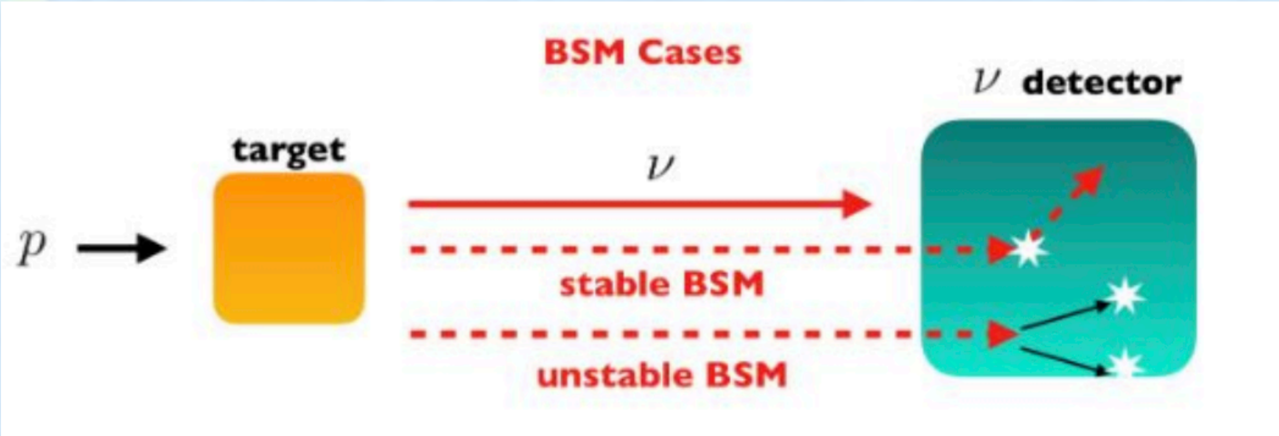
Warm cryostat structure construction at Cern

Cryogenic installations in the building

New Physics Opportunities

- The proximity to the beam target and large detector mass make SBN LAr TPC detectors [*precise tracking, energy measurement and particle identification, low energy threshold and good time resolution from Light Detection Systems (few ns)*] well suited for the exploration of a range of
  - **New physics scenarios in the neutrino sector** (effects of BSM physics on neutrino oscillation) as well as
  - **New states** (dark matter, heavy neutrinos…) **produced in the proton beam target**

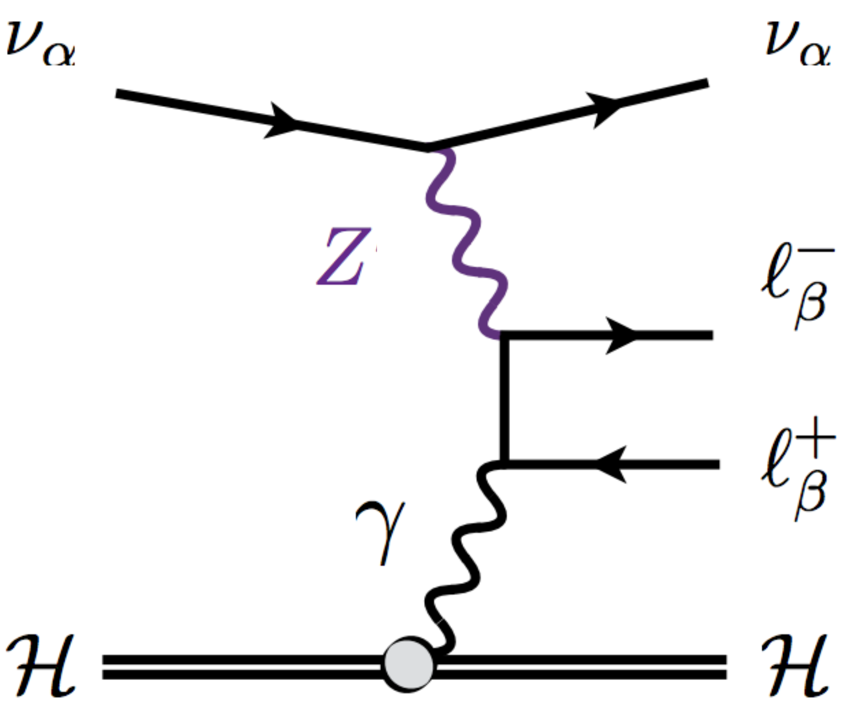
Sterile neutrinos
Neutrino tridents
Light dark matter
Millicharged particles
Heavy Neutral Leptons
…



P. Machado, O.P., D. Schmitz: arXiv:1903.04608

Neutrino Tridents

Neutrino tridents are standard model processes



Very rare events

- Only $\mu^+\mu^-$ was observed experimentally
- e^+e^-, μ^+e^-, μ^-e^+ are more difficult

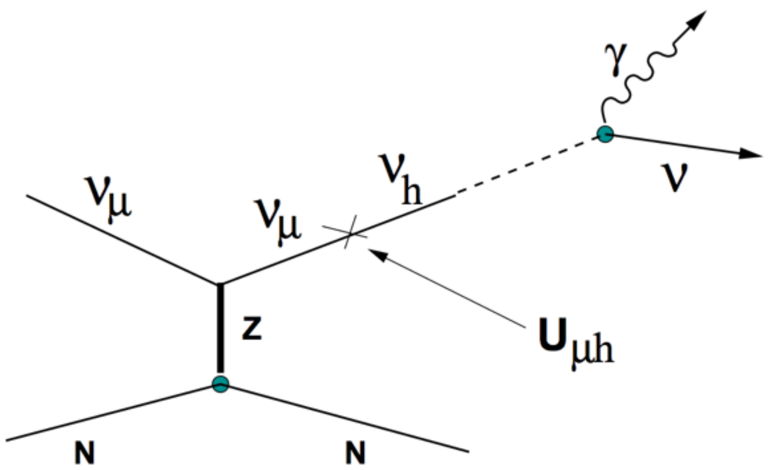
Several BSM scenarios can give rise to trident signatures

Courtesy of P. Machado

Courtesy of P. Machado

Neutrino Tridents

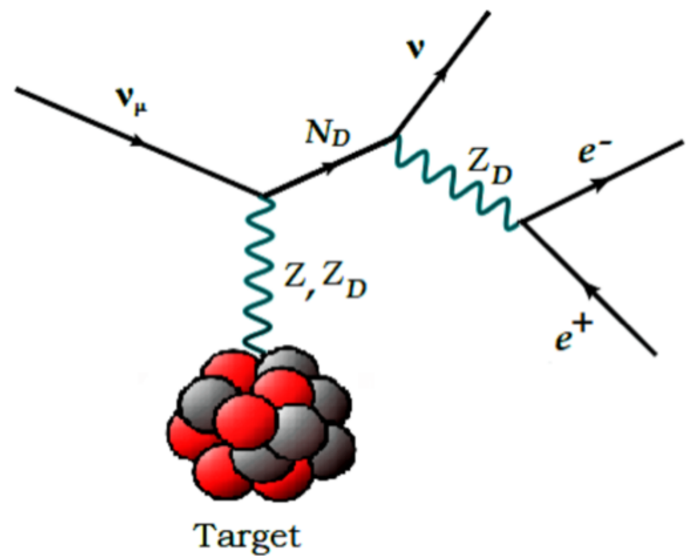
ν magnetic moment



Explains MiniBooNE

Gninenko 0902.3802

Dark neutrinos



Explains MiniBooNE

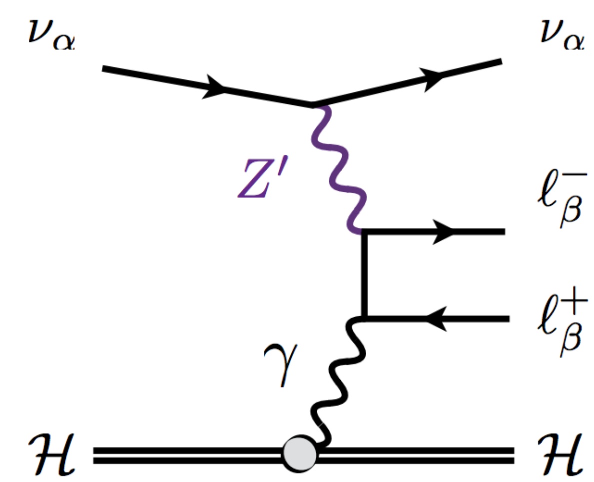
Explains m_ν

Bertuzzo et al 1807.09877, 1807.02500

Ballett et al 1808.02915

Arguelles et al 1812.08768

New gauge bosons (e.g. L_μ-L_τ)



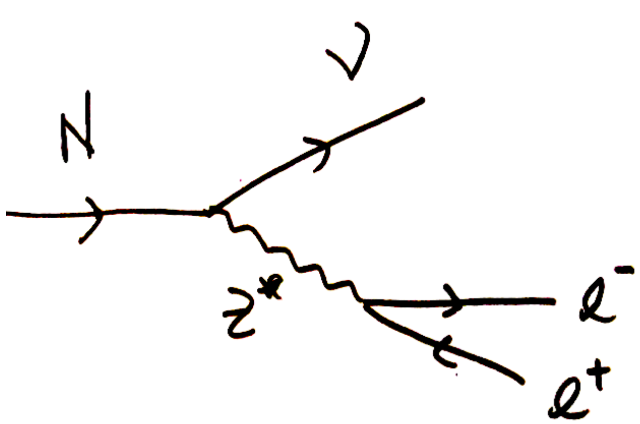
Explains $(g-2)_\mu$

Altmannshofer et al 1406.2332

Ballet et al 1902.08579

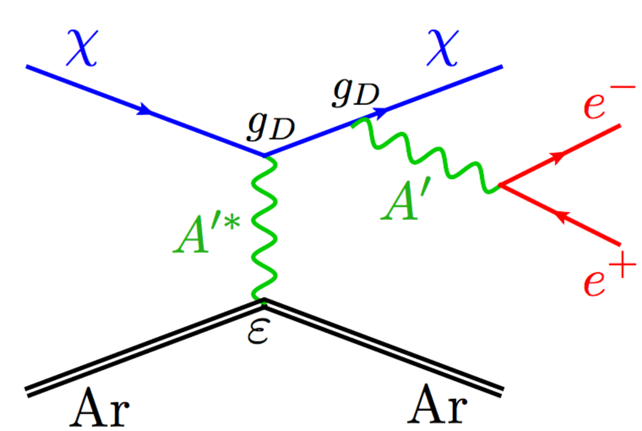
de Gouvêa et al 1809.06388

Heavy neutrinos



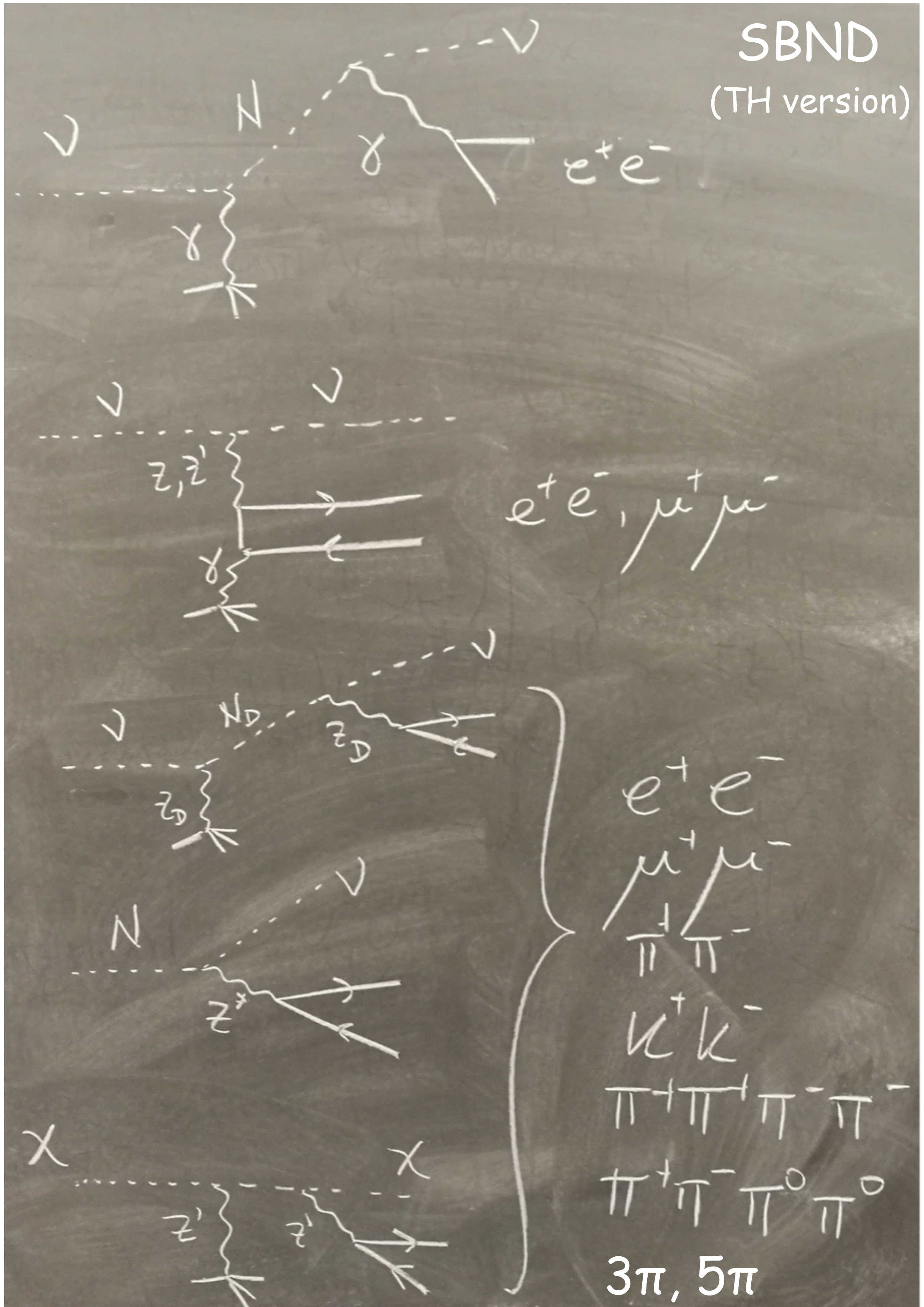
Explains m_ν

Dark tridents



Explains DM

Neutrino Tridents



Transition magnetic moment

Standard tridents, light Z′ (B-L, L_μ-L_τ, ...)

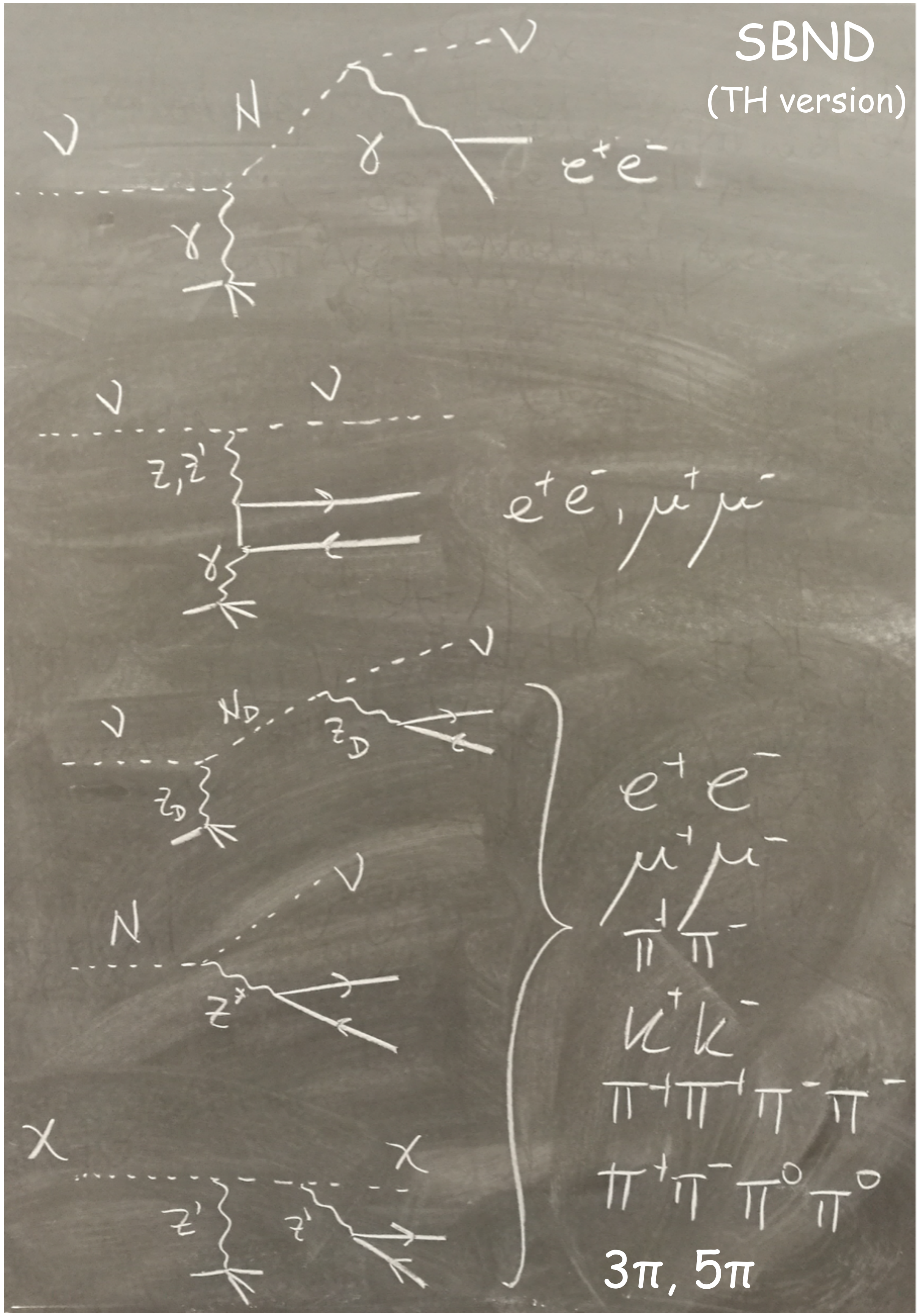
Dark neutrinos

Heavy neutral lepton

Dark matter

Courtesy of P. Machado

Neutrino Tridents



Challenges

Some of these signatures are *"clearer"*, like the $\mu^+\mu^-$ trident.

Others are more challenging, specially due to backgrounds.

In several detectors, photons and electrons are indistinguishable

In others, an electron or a photon is indistinguishable from e^+e^-

Interesting features

Signatures depend on mass spectrum

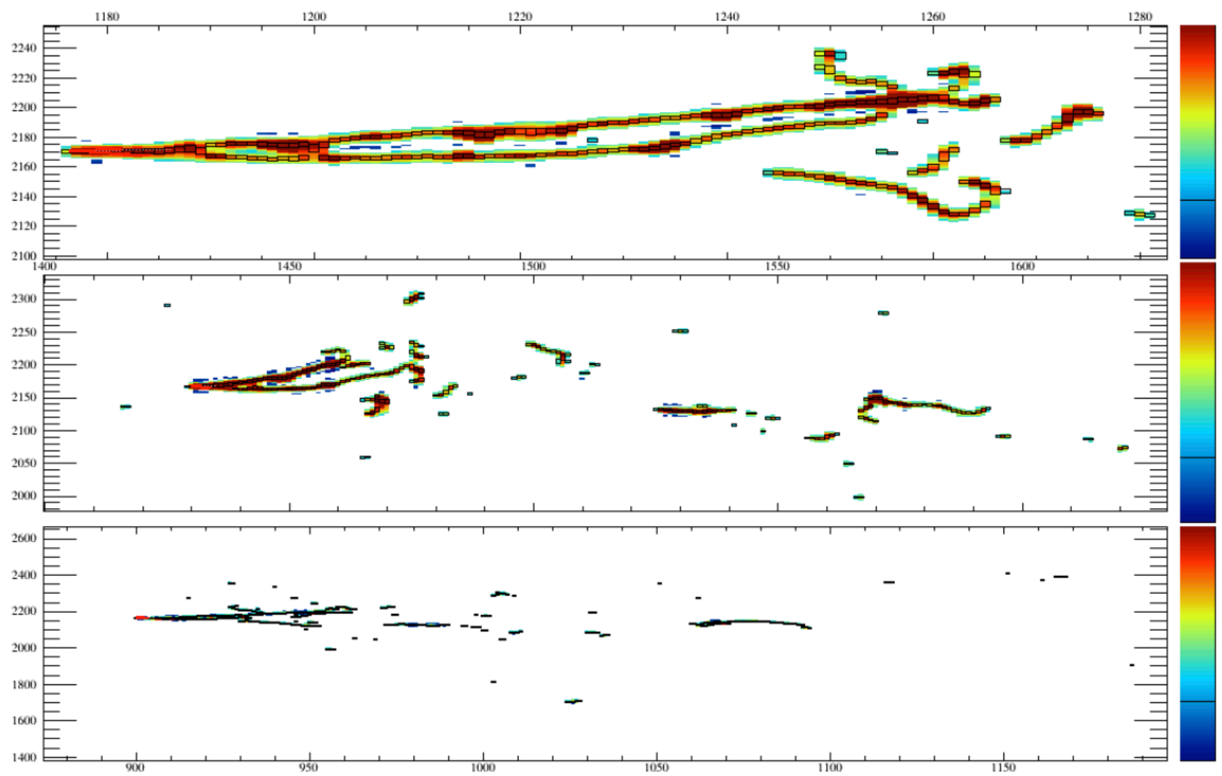
Invariant masses

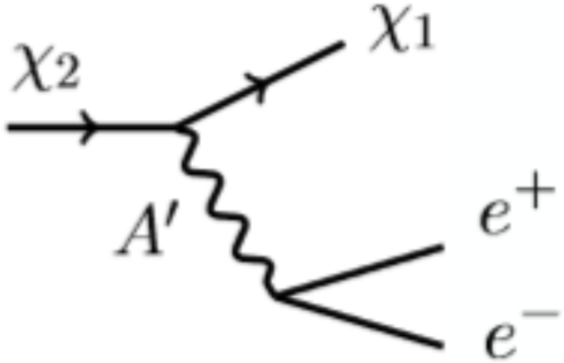
Angular distributions

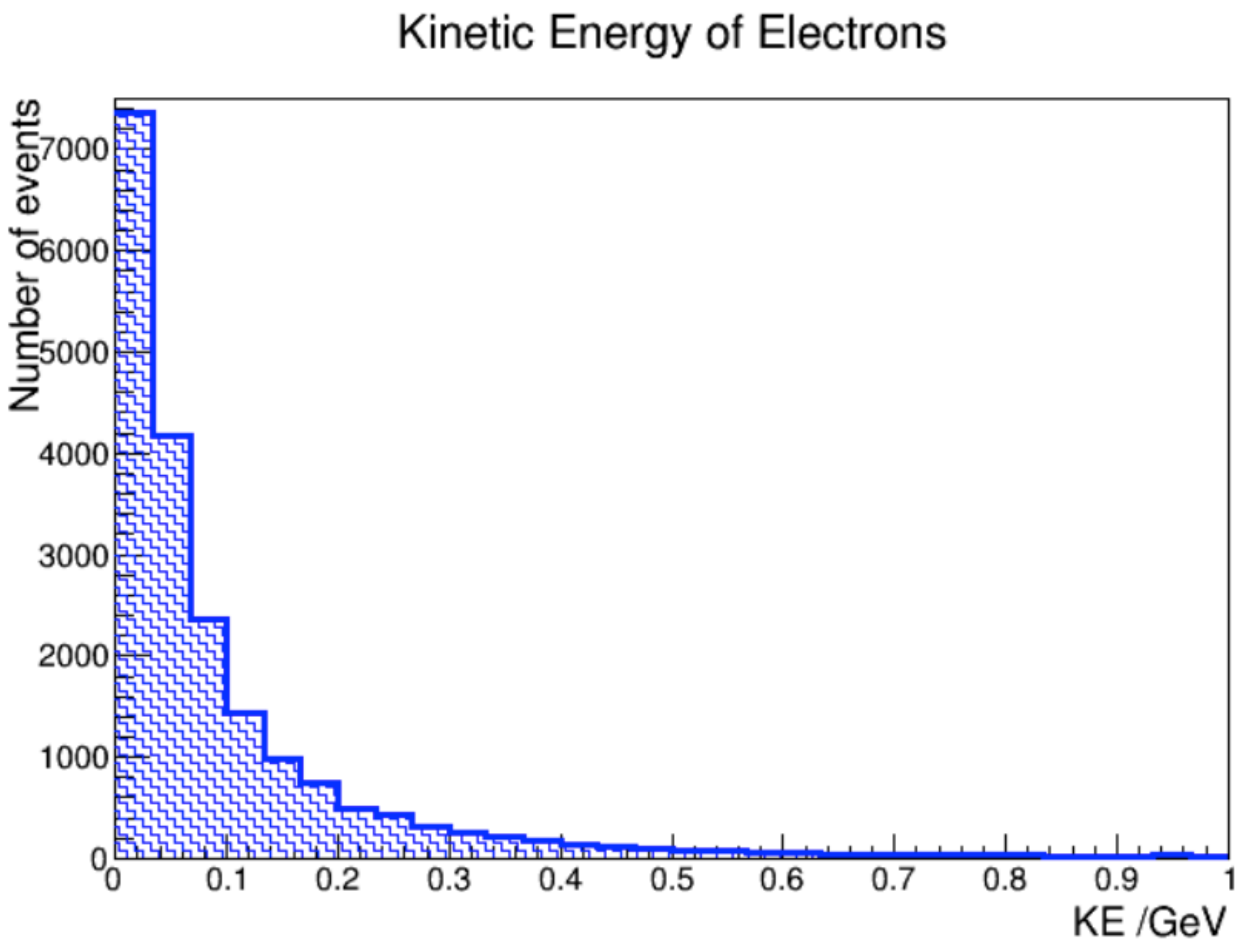
dE/dx

Courtesy of P. Machado

DM decay into an electron-positron pair in the SBND detector (MC simulation)



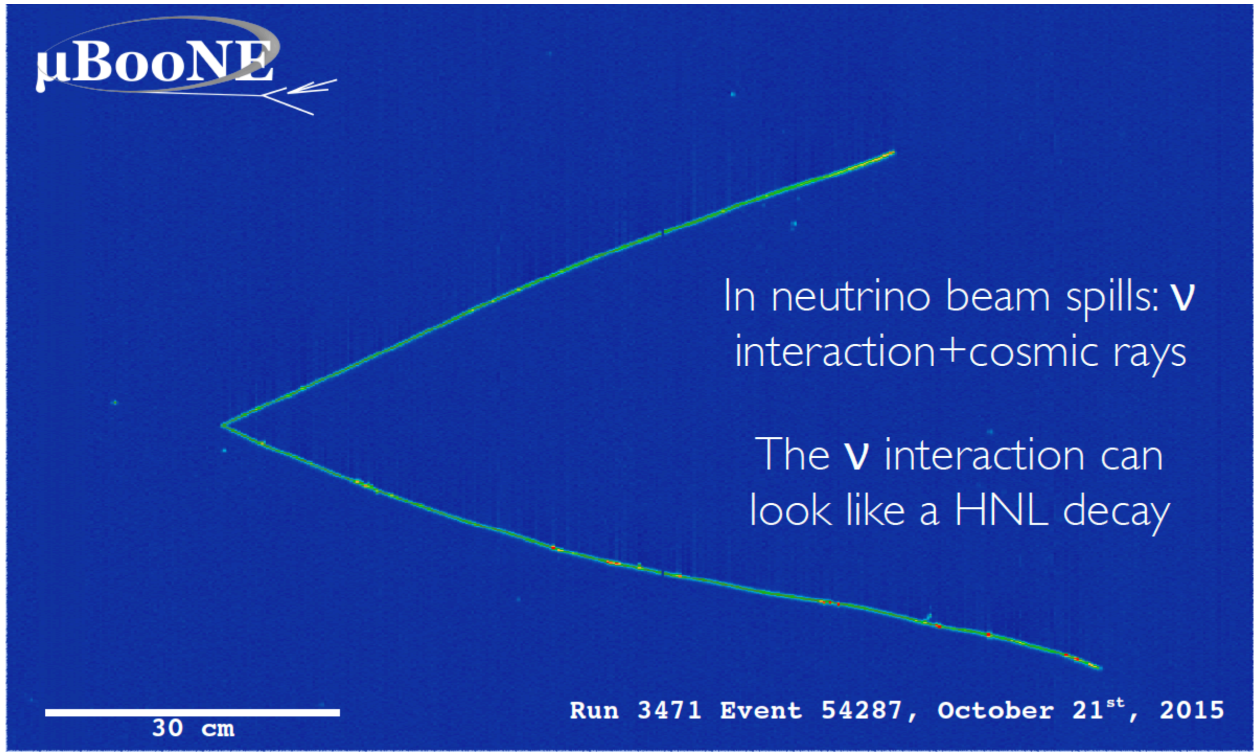


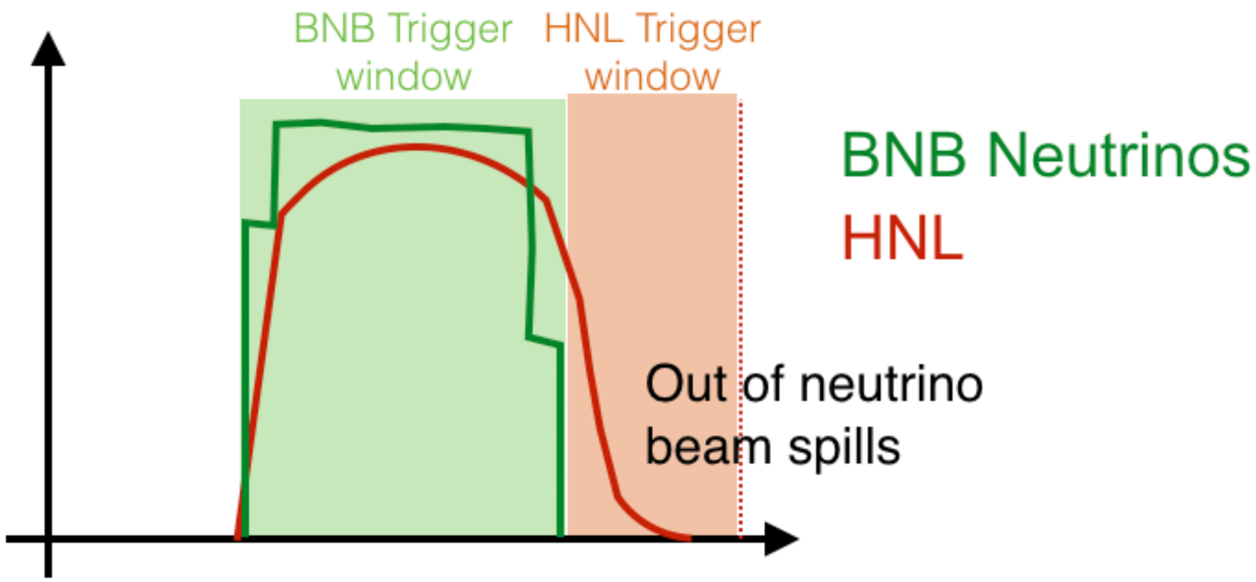


Background: single photon converting in e^+e^-

Search for Heavy Neutral leptons at MicroBooNE

Focus on N→$\mu^{\pm}\pi^{\mp}$ decay channel
in a **delayed time window**



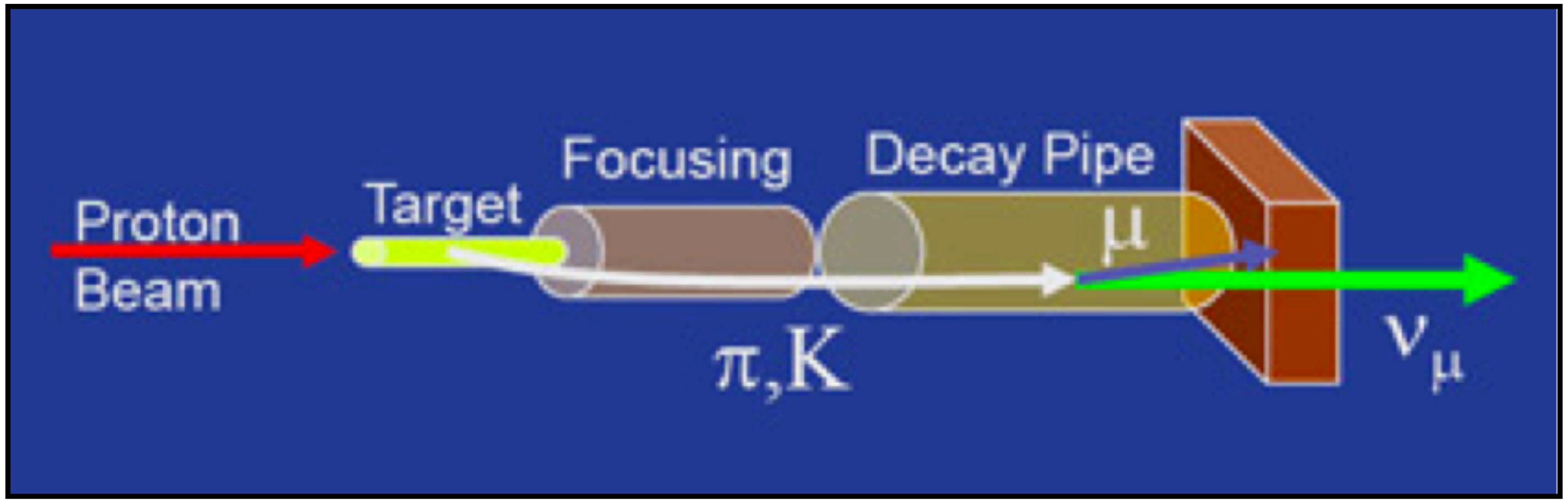


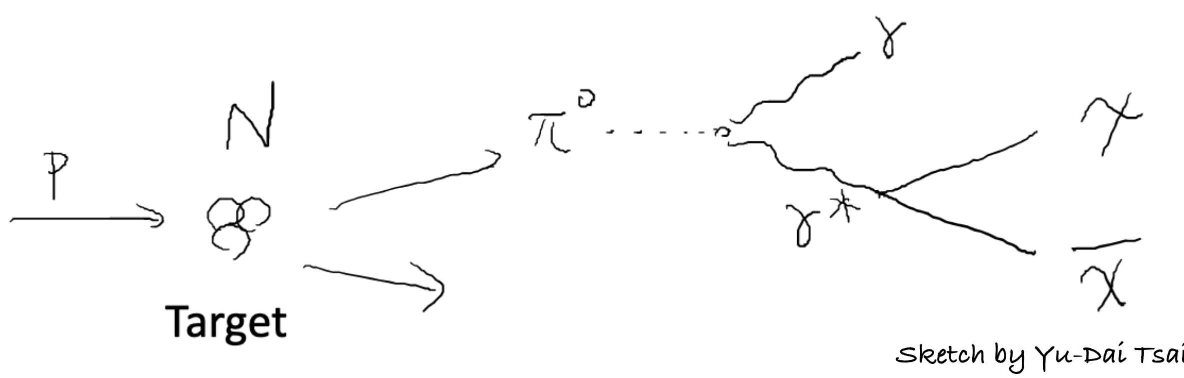
- A fraction of HNLs with masses in the several hundred MeV range will arrive after the beam spill
- No SM neutrino background in the out of neutrino beam spills

Results with ~2x10^{20} POT coming soon!

Millicharged Particles (production)

mCP would be produced in the target by e.g. π^0 decays





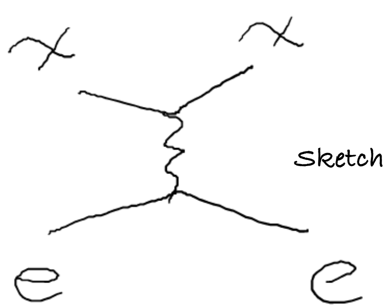
- ❑ production:
  meson decays

Neutrino detectors may be exposed to a **large flux of mCPs**

Millicharged Particles (detection)

When traveling through matter mCPs loose energy by atomic excitation and ionization like regular charged particles, **but with a rate reduced by ϵ^2**

mCPs are detected via electron recoils (elastic scattering with electrons)



Sketch by Yu-Dai Tsai

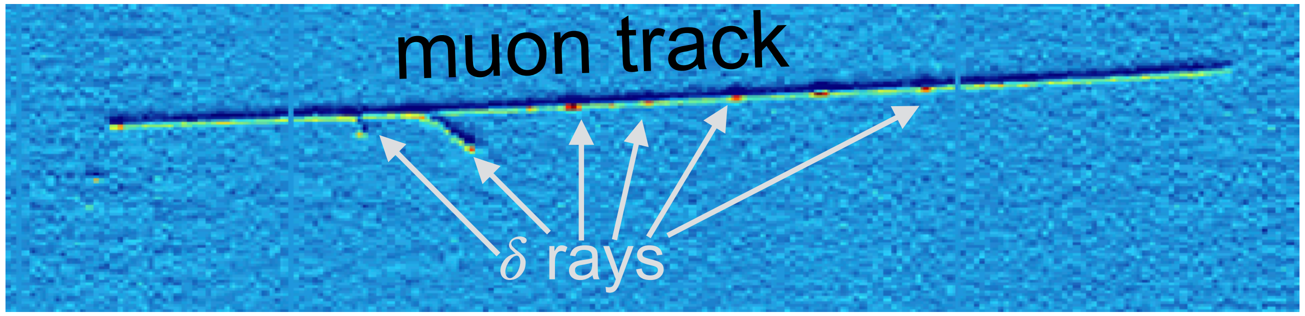
- detection: scattering electron

Tend to scatter at low recoil $\frac{\partial \sigma}{\partial E_r} \propto E_r^{-2}$

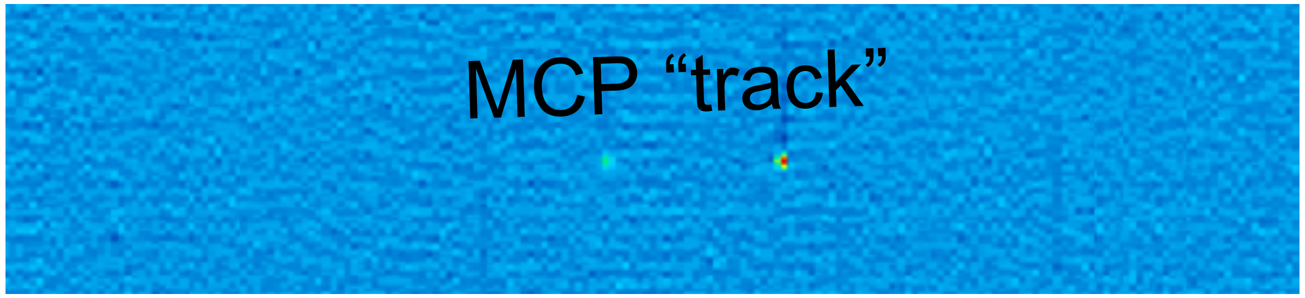
with small angular deflection $\Longrightarrow$ **mCP point back to the target**

Due to the softness of typical collisions
low energy threshold is key for detection

How do we detect a particle with a tiny charge?



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

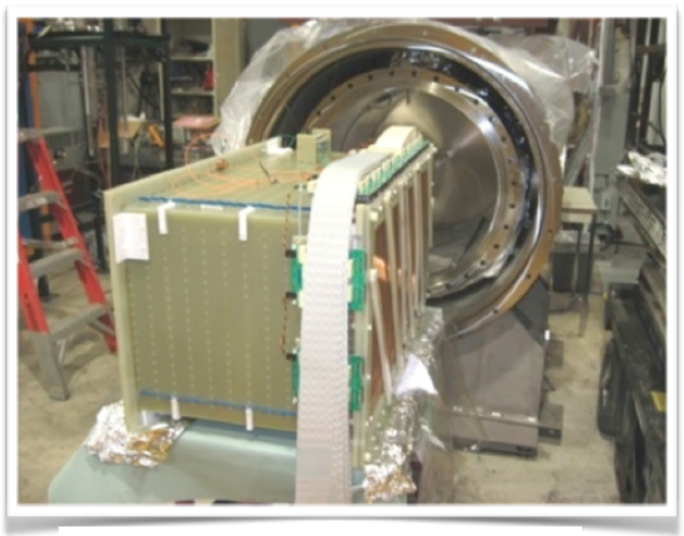


The low energy frontier

A recent study by the ArgoNeuT collaboration has demonstrated the capability of LAr TPC to detect (sub-)MeV-scale electron recoils.

PHYSICAL REVIEW D 99, 012002 (2019)

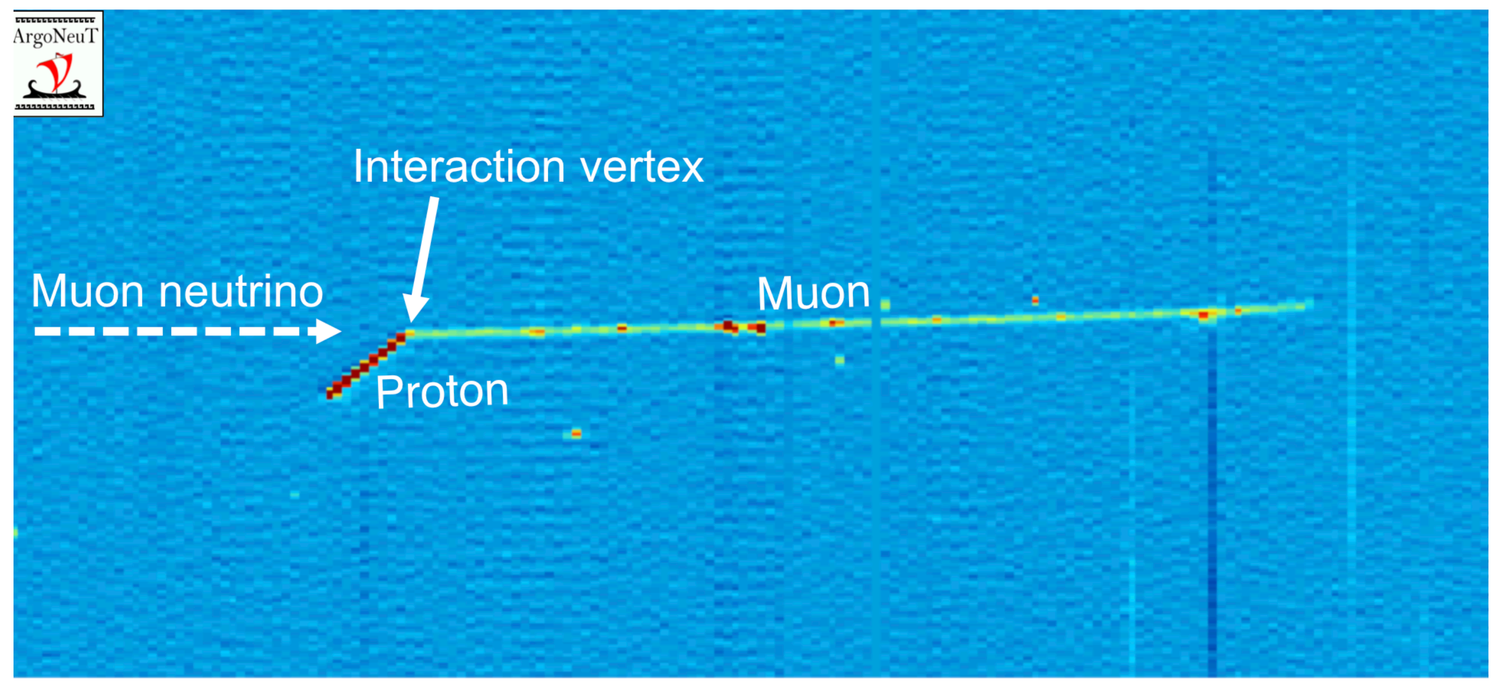
"*Demonstration of MeV-scale physics in liquid argon time projection chambers using ArgoNeuT*"

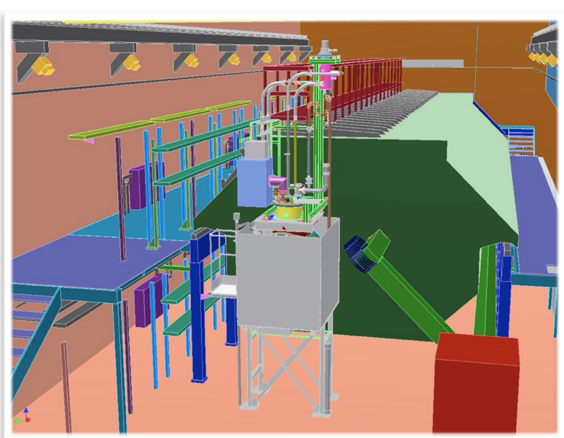


0.24 tons active volume

LAr TPC

47×40×90 cm^3, 2 readout planes,
480 wires, 4 mm spacing,
no light detection system





NuMI neutrino beam
$\langle E_\nu \rangle \simeq 4$ GeV

100 m underground
in front of the MINOS ND

The low energy frontier

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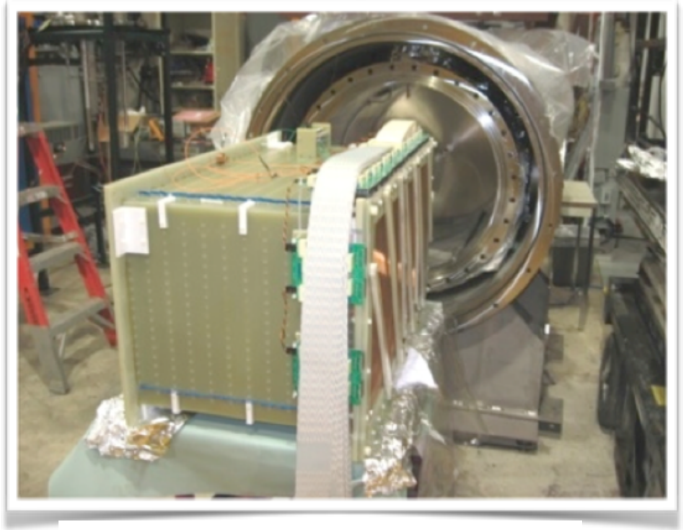

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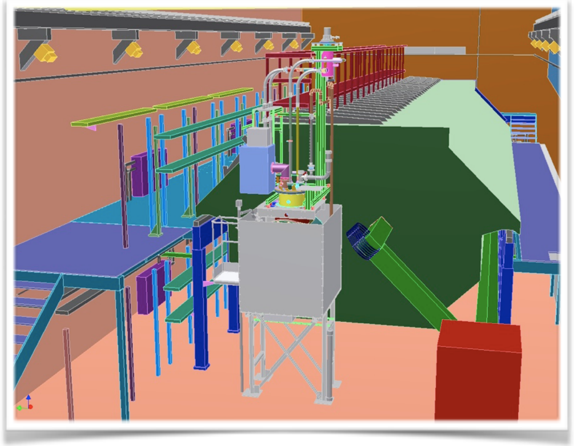
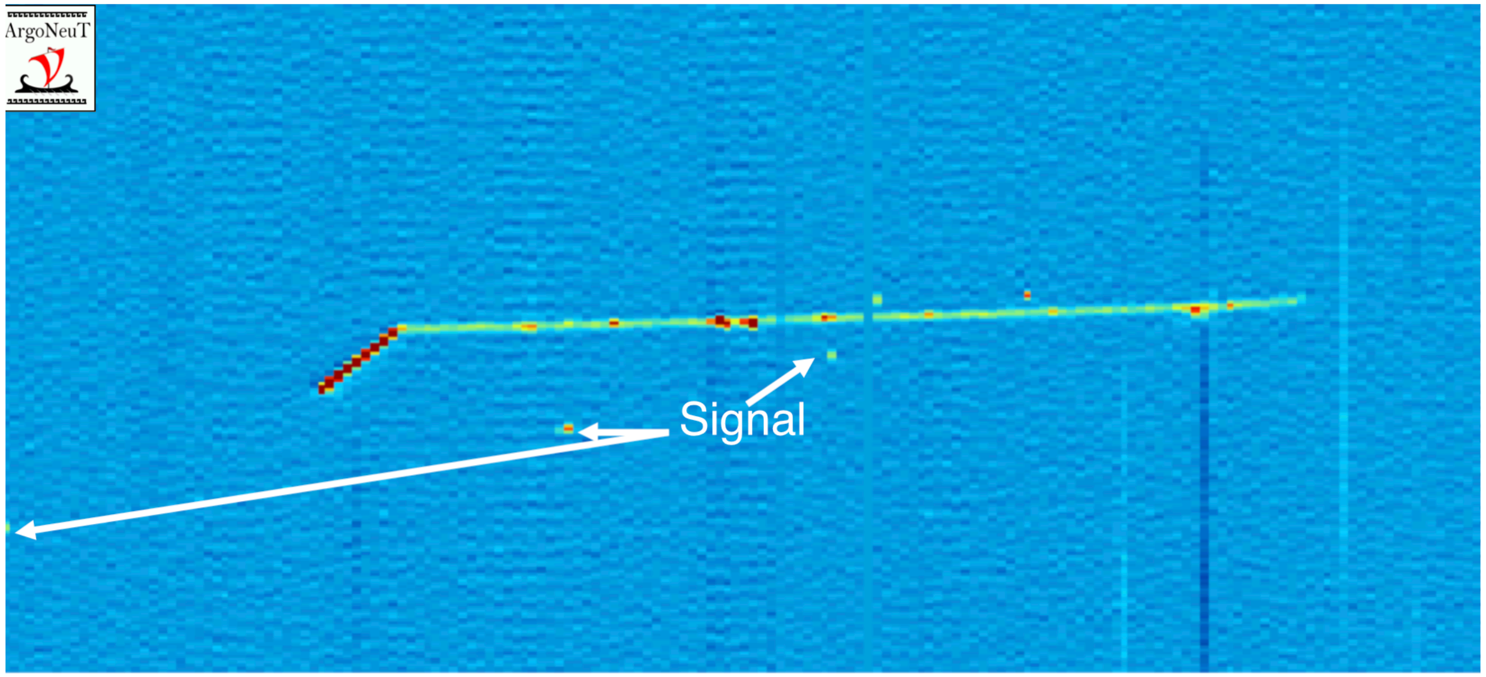
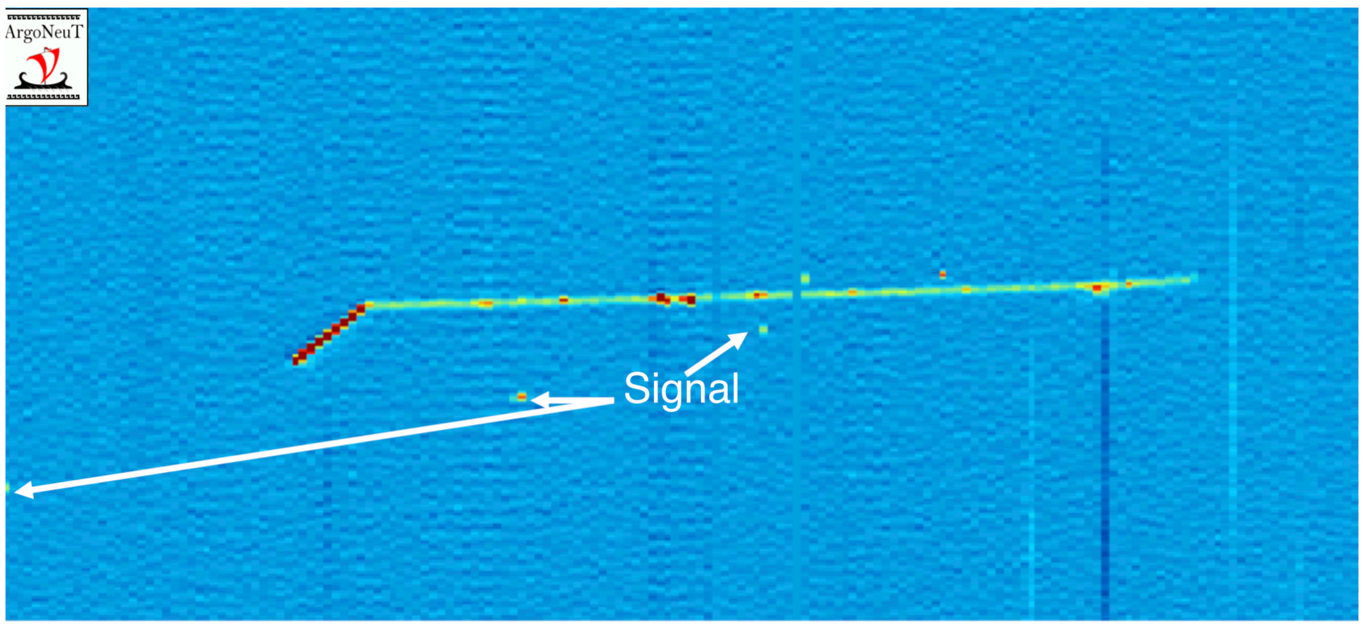


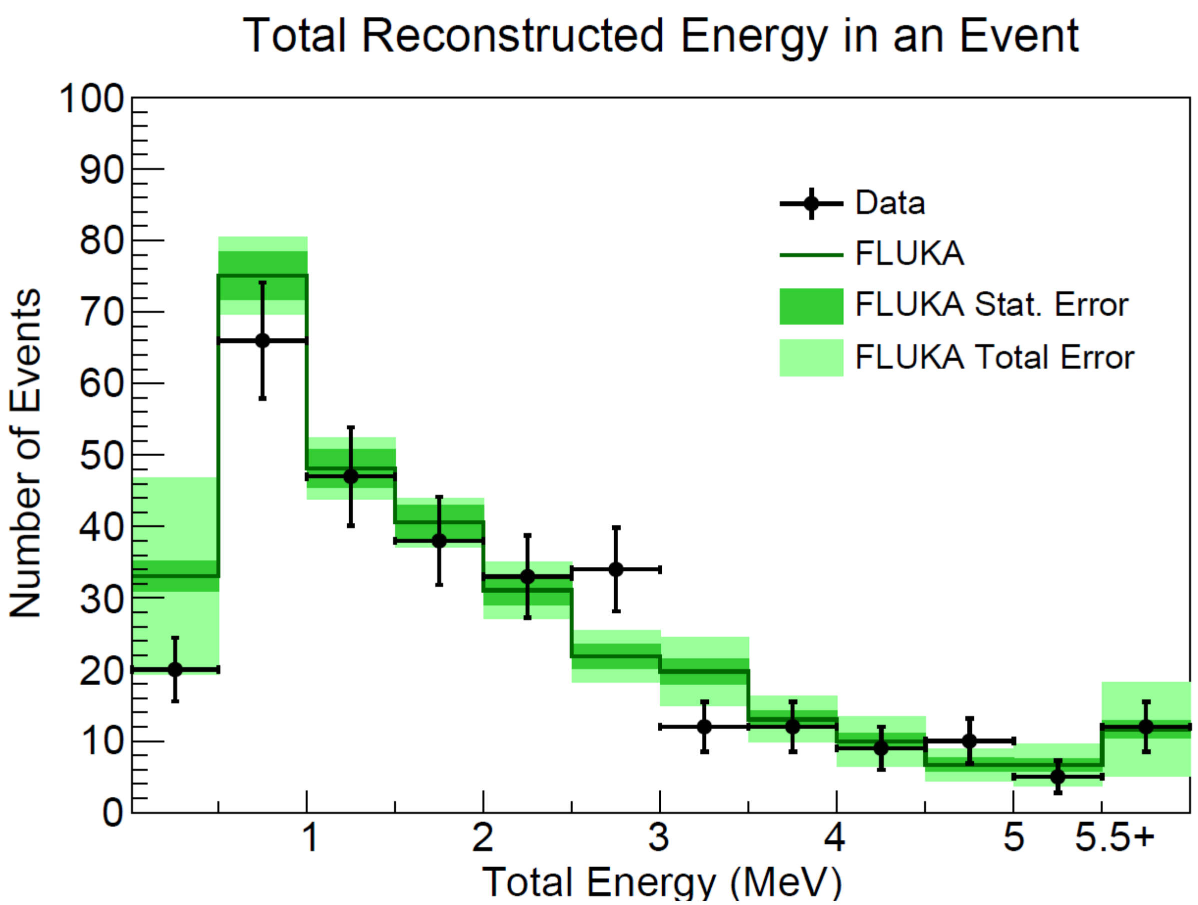
NuMI neutrino beam
<Eν>≃4 GeV

100 m underground
in front of the MINOS ND



MeV-scale physics in LAr TPC



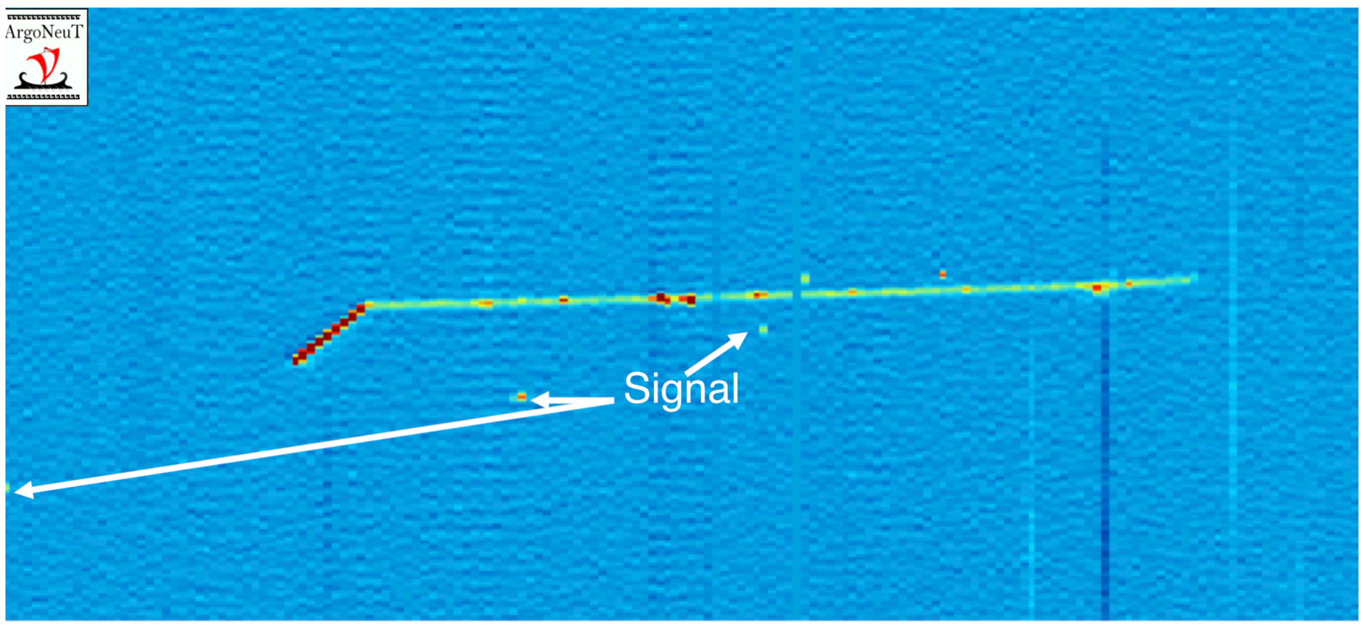


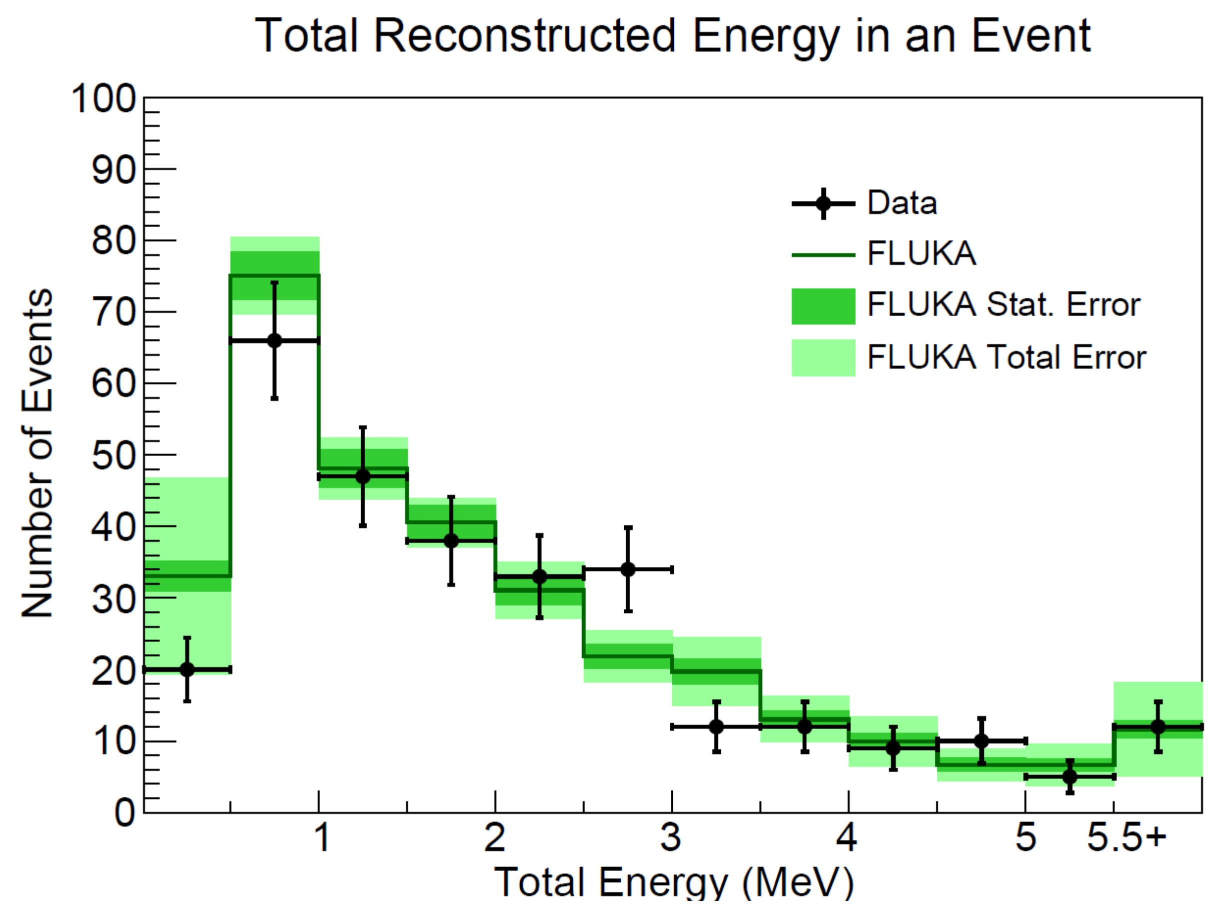
300 KeV threshold!

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

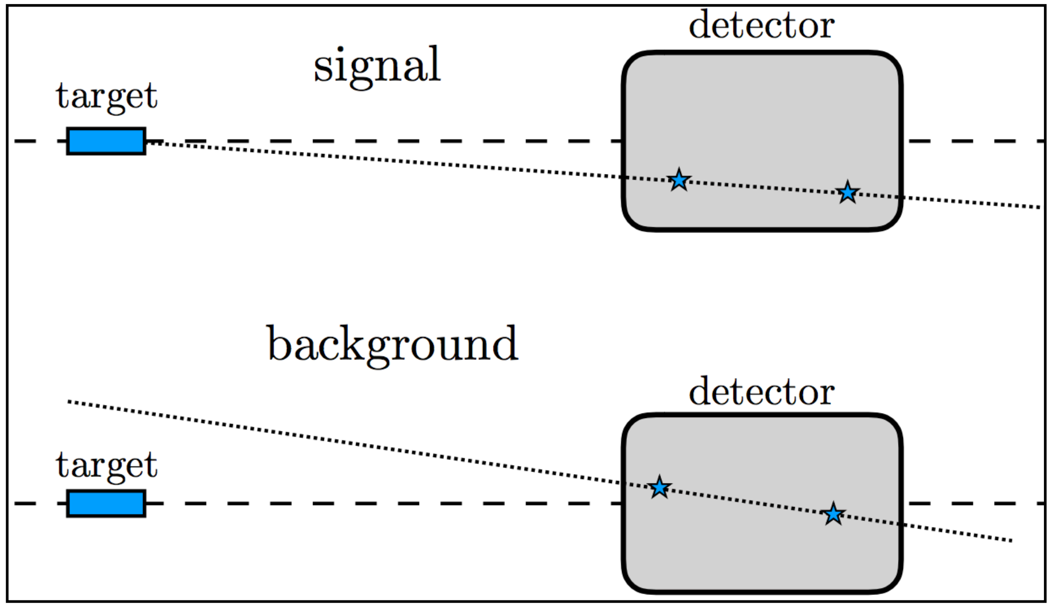
- de-excitation photons from the target nucleus and
- photon produced by neutron inelastic interactions

MeV-scale physics in LAr TPC



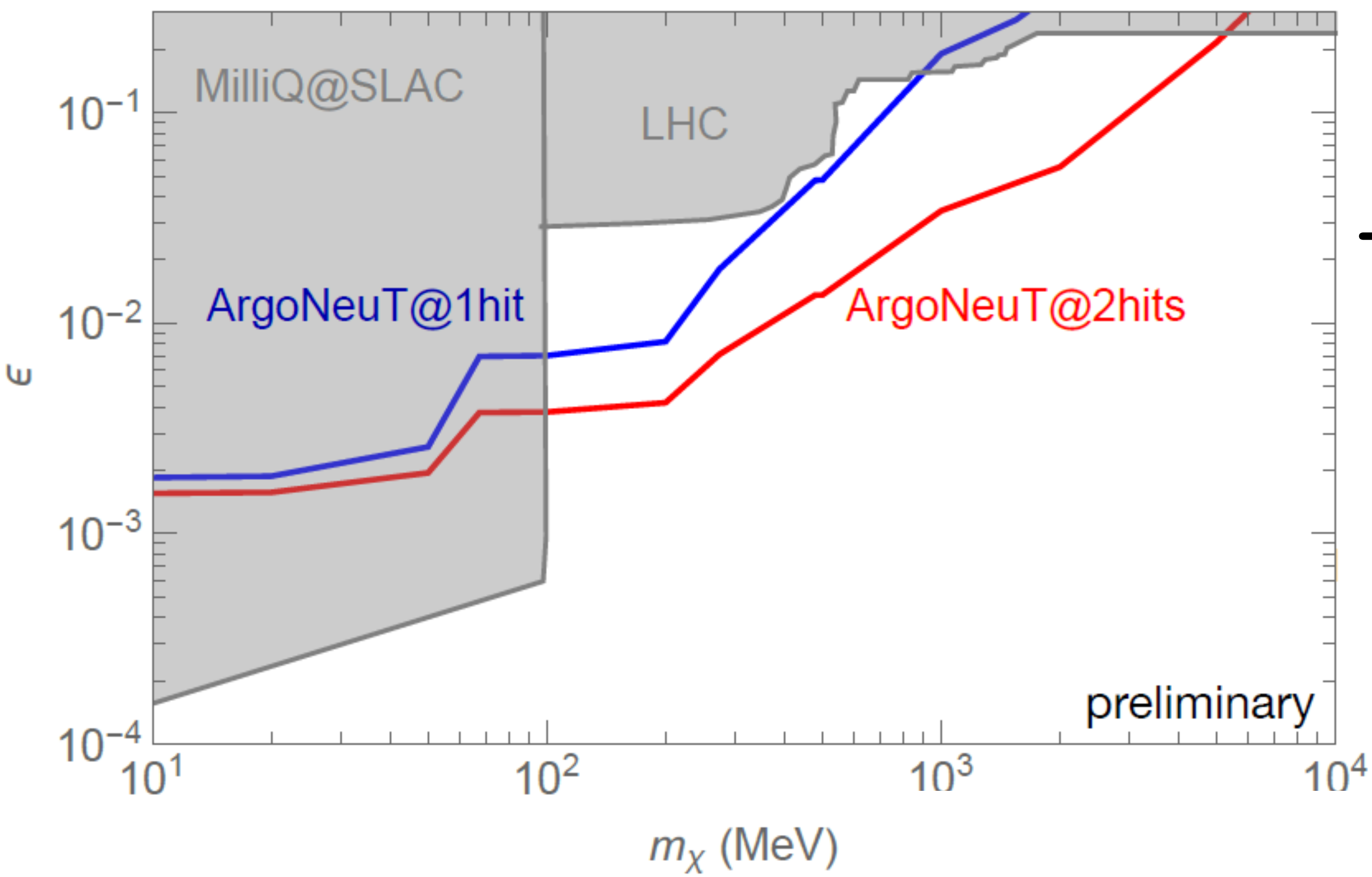


The capability to resolve the individual collisions down to a threshold of around MeV or less enables to search for **millicharged particles (mCPs)** in LAr TPC in neutrino beams.



R. Harnik, Zhen Liu, and O. Palamara, arXiv:1902.03246

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

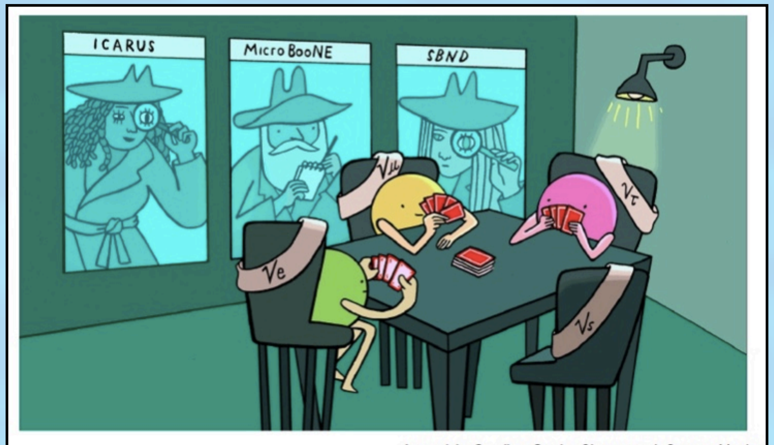


The "table-top" size ArgoneuT LArTPC detector can set a competitive limit on millicharged particles!

An ArgoNeuT data analysis is about to published (ArgoNeuT Collaboration + R. Harnik and Z. Liu)

SBN:
The search for a fourth type of neutrino

The three SBN detectors sitting on the Booster Neutrino Beam line at Fermilab will use the state-of-the-art **liquid-argon time projection technology** to perform a **world-leading** search for **eV-scale sterile neutrino**.



Artwork by Sandbox Studio, Chicago with Corinne Mucha

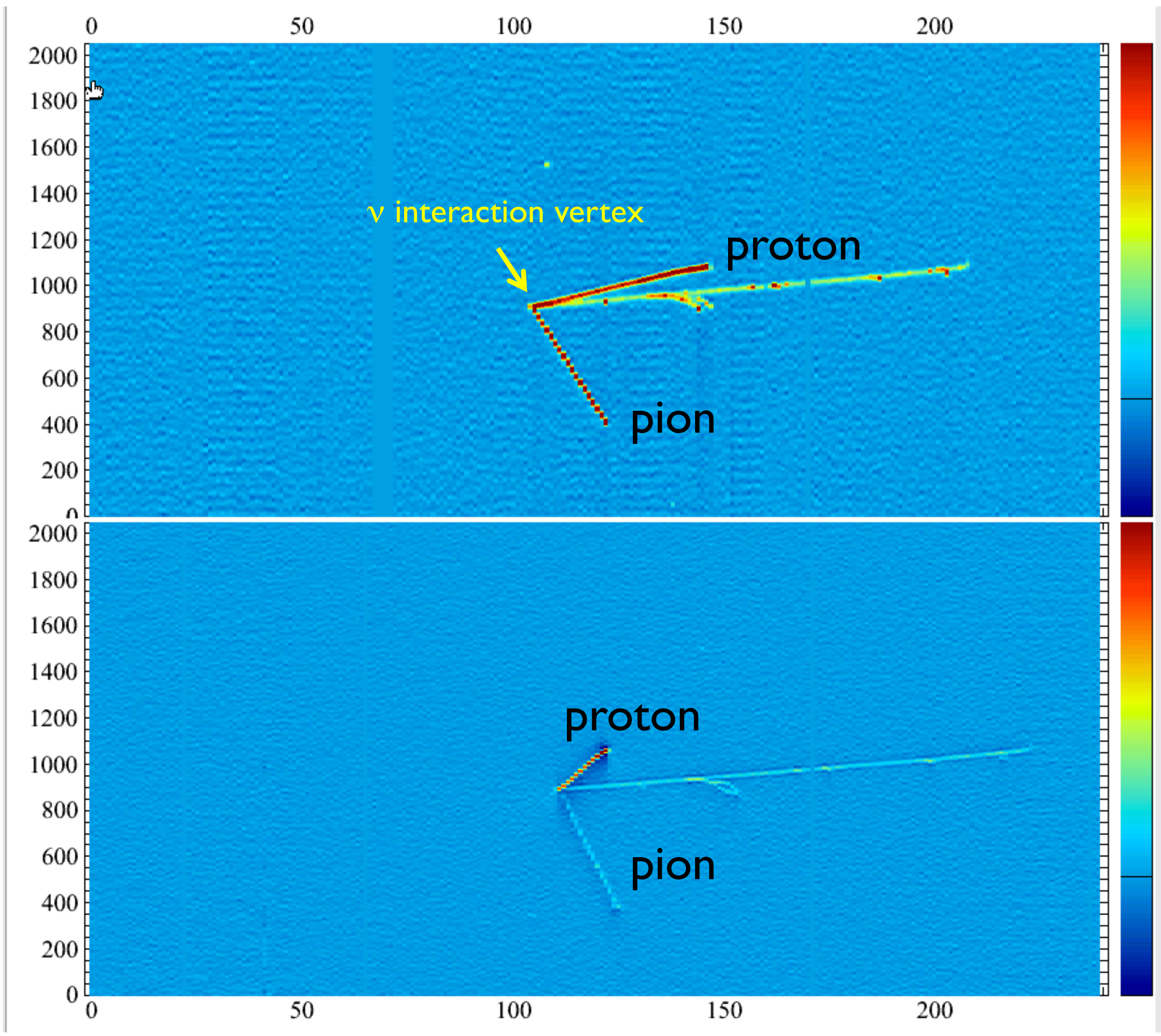
SBN:
Not only oscillation physics

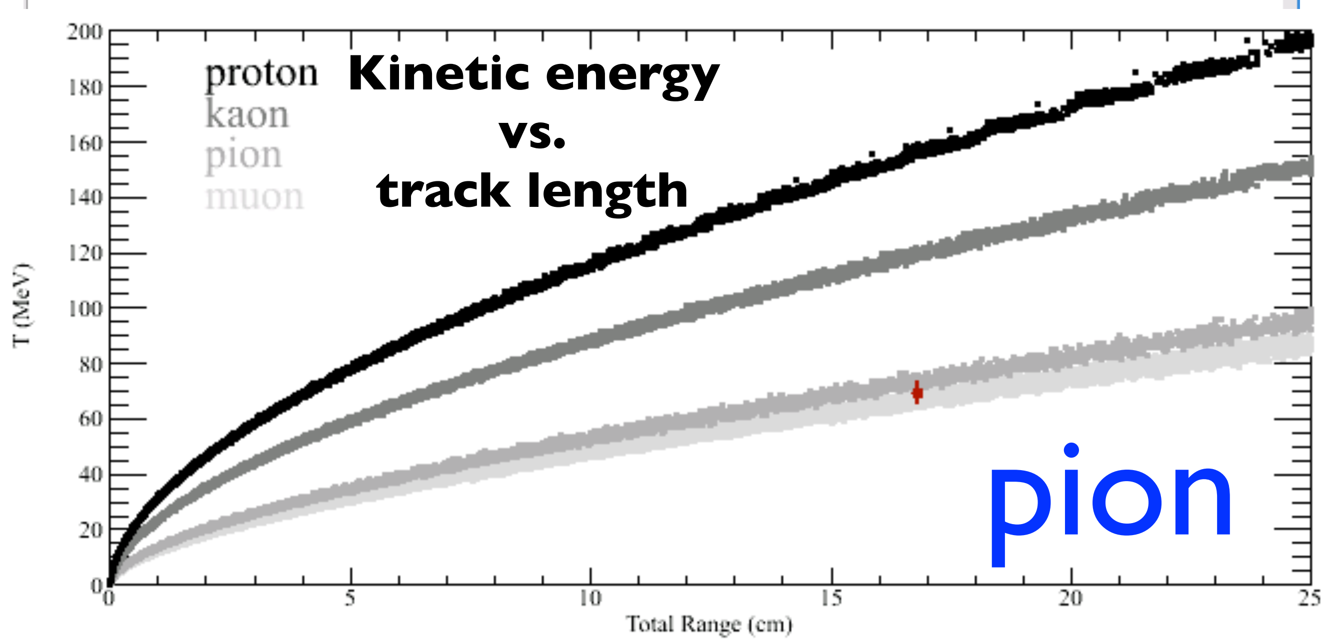
The SBN science program includes **high precision** studies of **neutrino-argon cross sections** at the GeV energy scale.

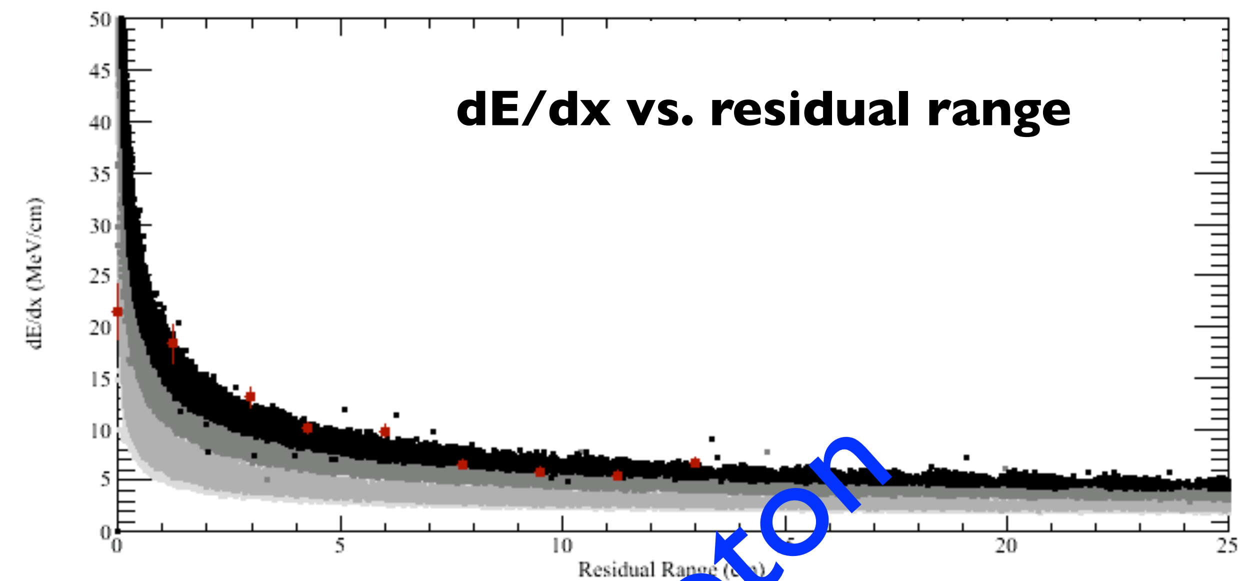
SBN LAr TPC detectors are fantastic tools to look for additional **new physics in the neutrino sector and beyond**!

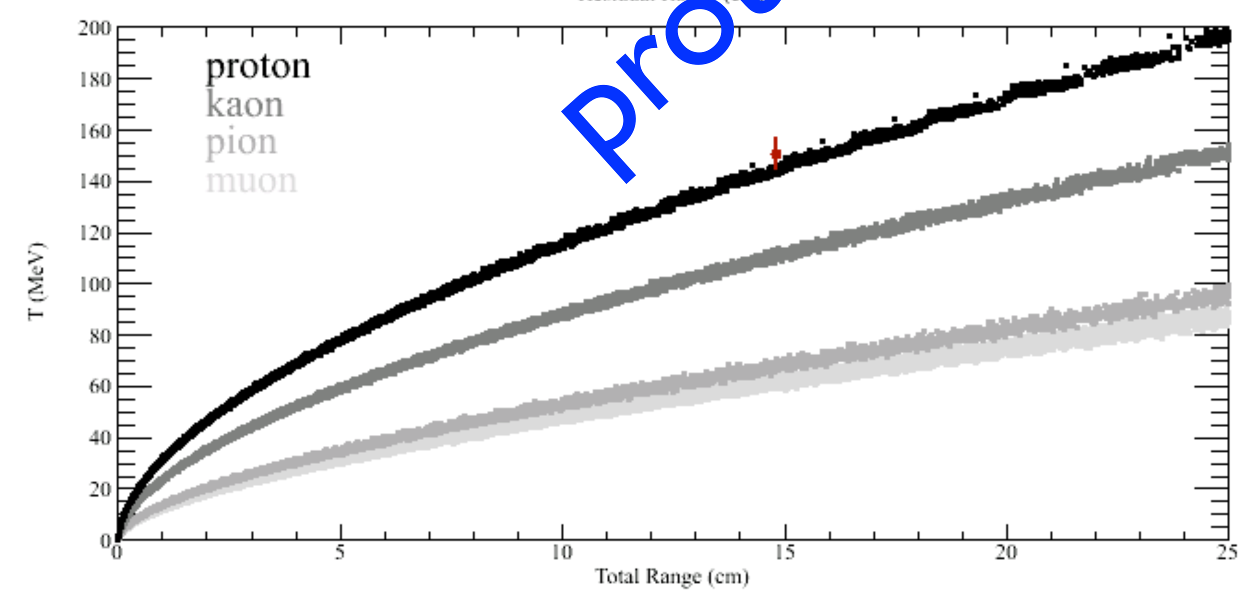
Overflow

Proton/$\pi^{\pm}$ identification

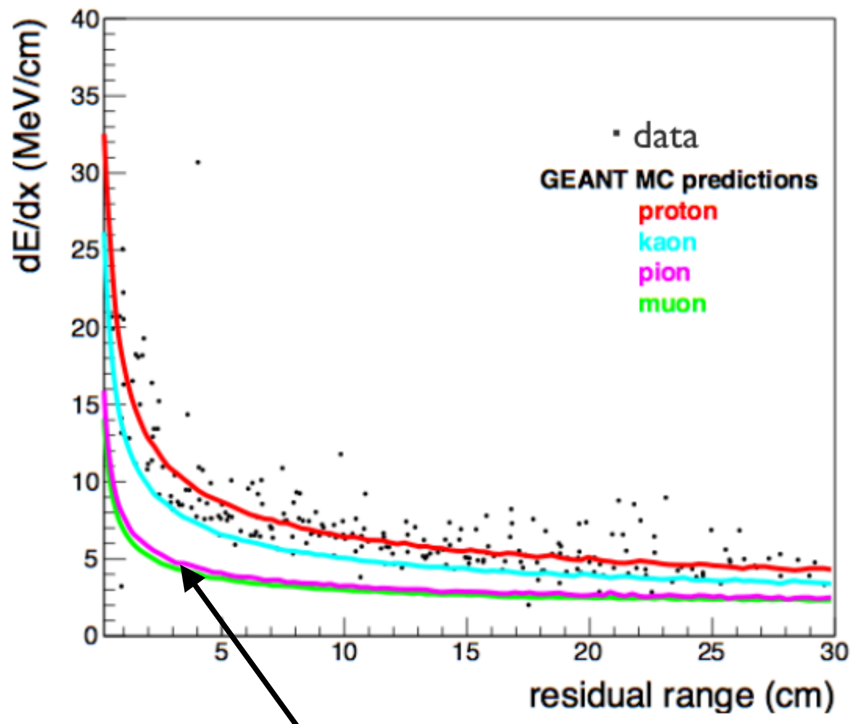






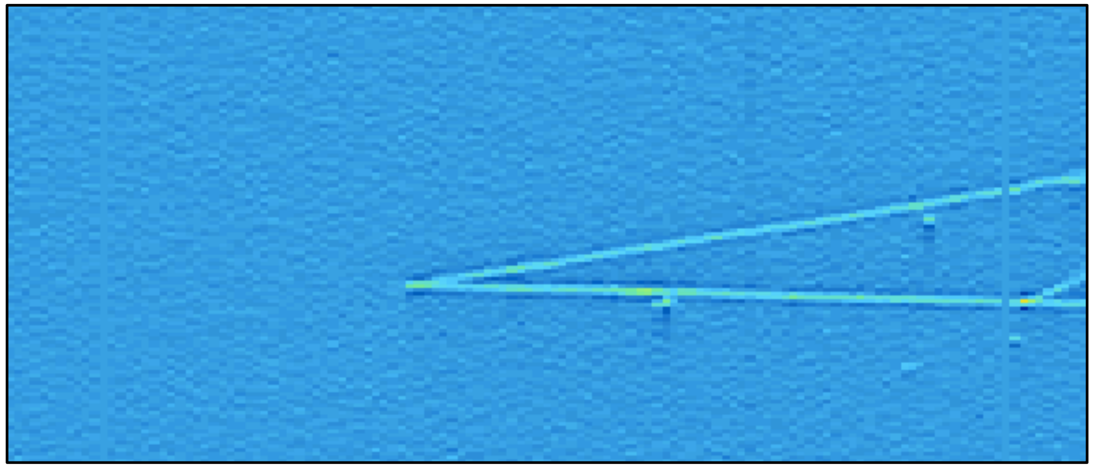


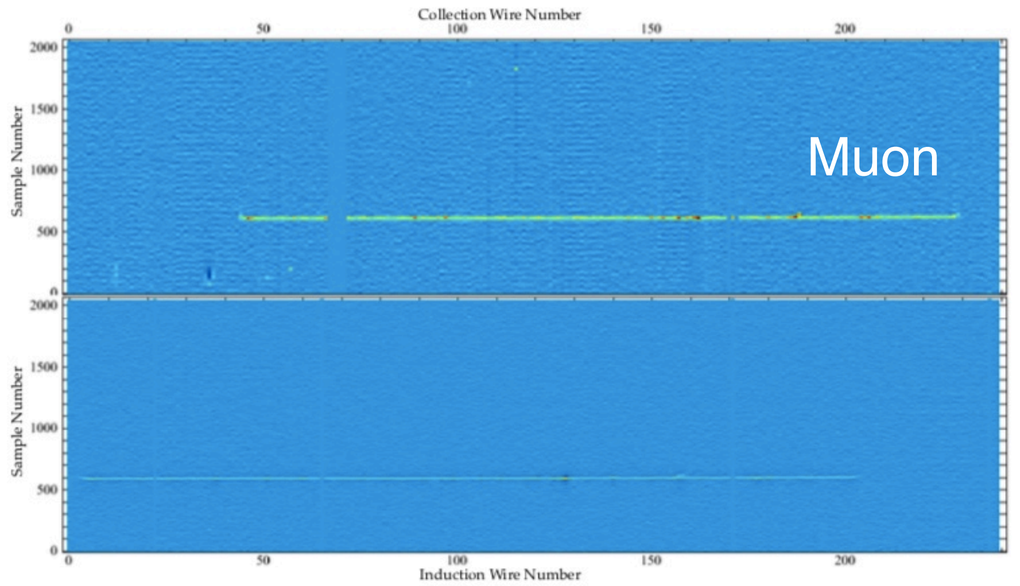
Muon/π± identification



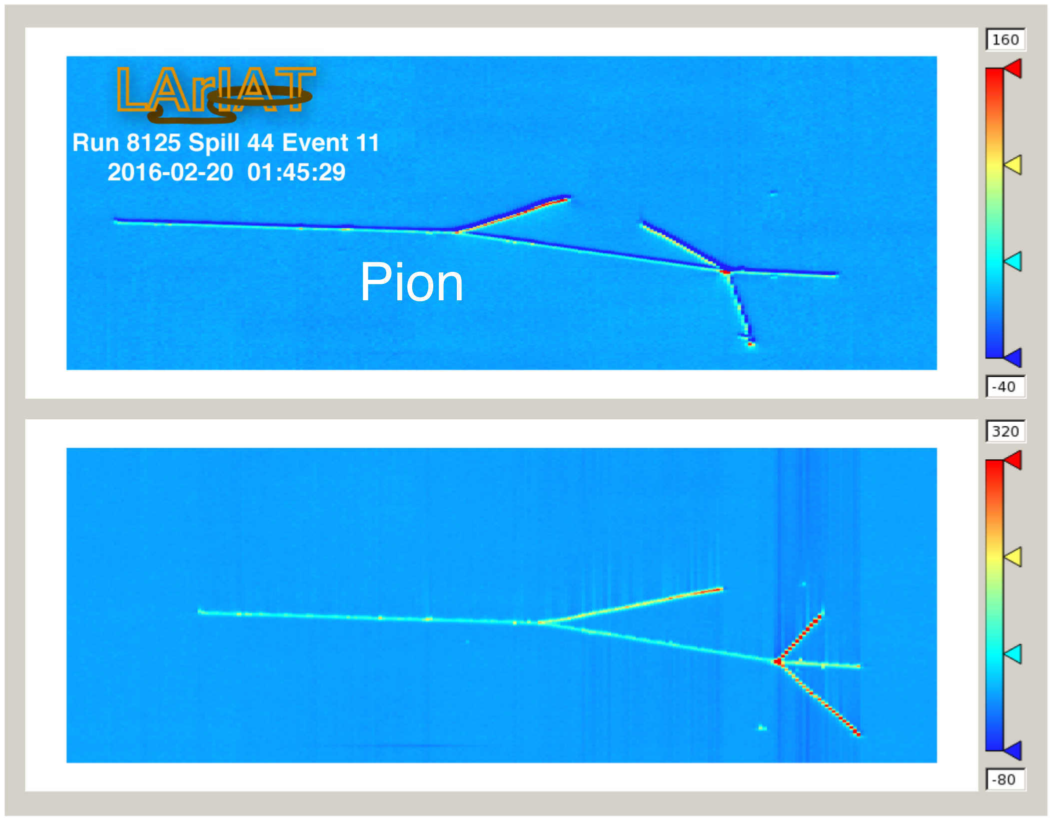
Muon/pion separation is a challenge!

Is this a $\mu^+\mu^-$ event?



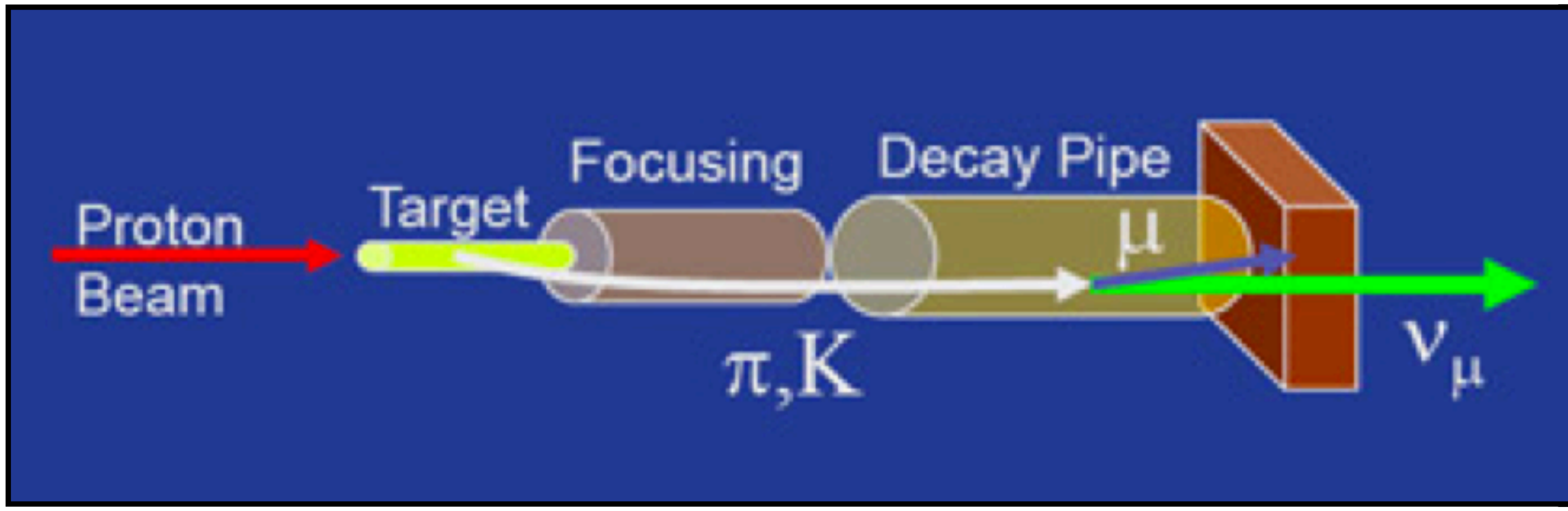


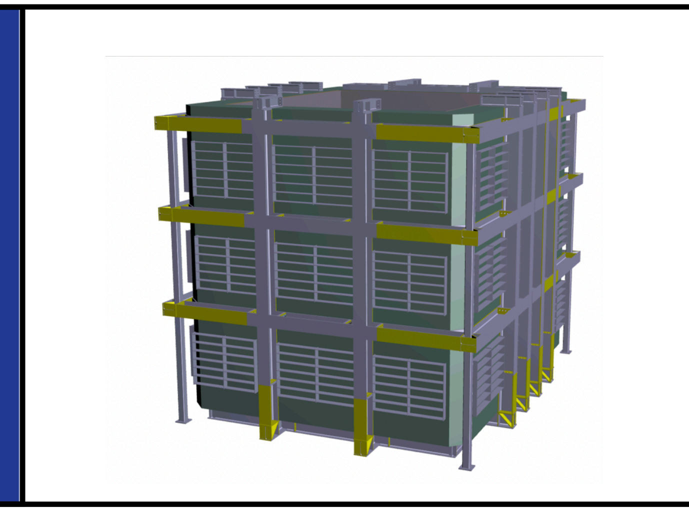
Muons penetrate further



Charged pions can have multiple interactions along their path

Why BSM in Accelerator Neutrino Experiments?



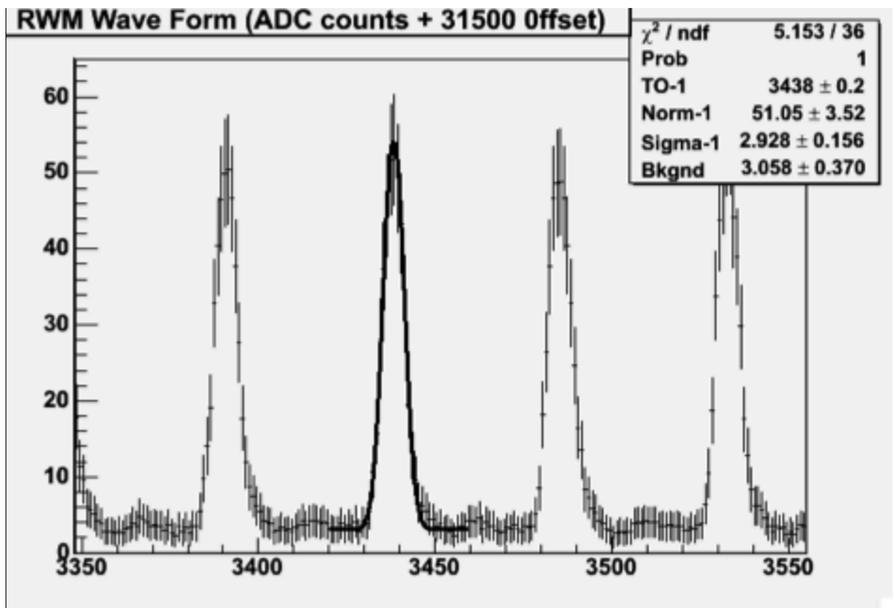


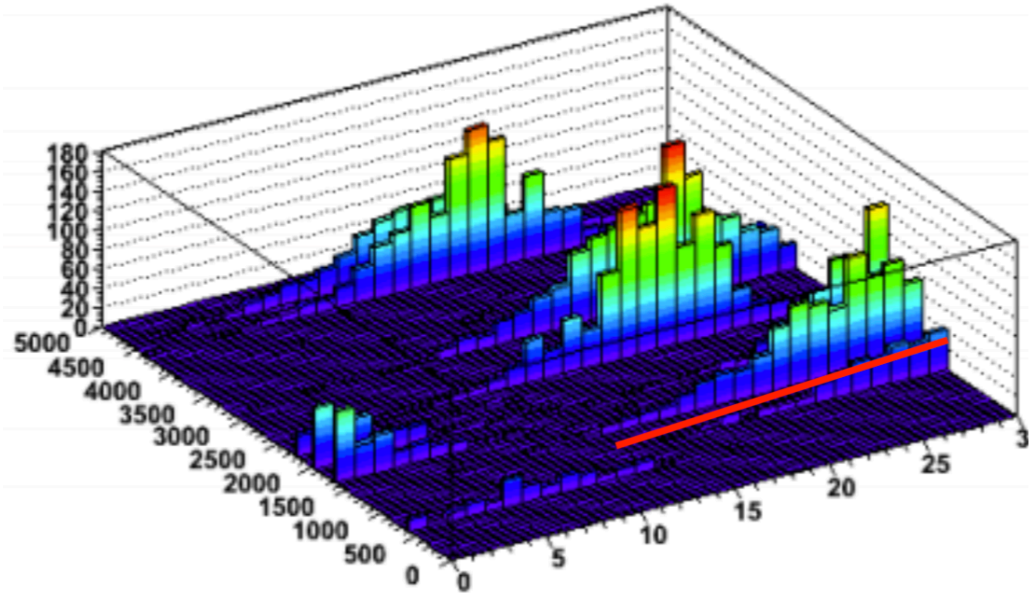
- The combination of:
  - **High-intensity proton beams (high intensity neutrino beams)** for neutrino precision measurements with
  - **Large mass detectors** with
    - Highly precise tracking and energy measurement
    - Excellent timing resolution and
    - Low energy threshold

Enable searches for New Physics scenarios/BSM phenomena

LArTPC PDS: timing, position & calorimetry

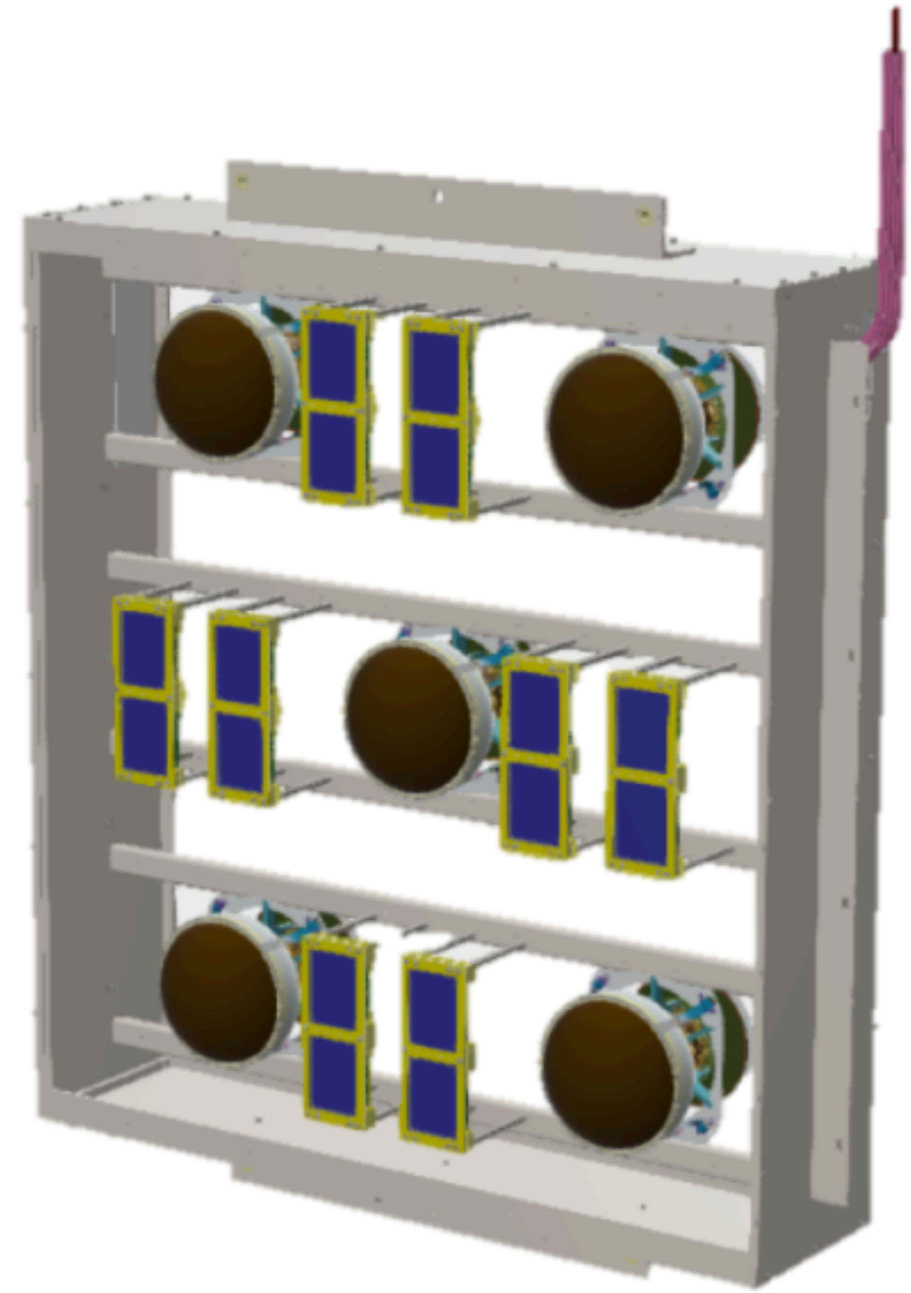
- Detection of scintillation light can provide:
  - Absolute time measurement of the event
  - Internal trigger
- Light signals (amplitude & shape) could also provide improvement of time and position resolution, energy and PID, and enable improved background rejection and access to additional physics topics.





SBND Photon Detection System

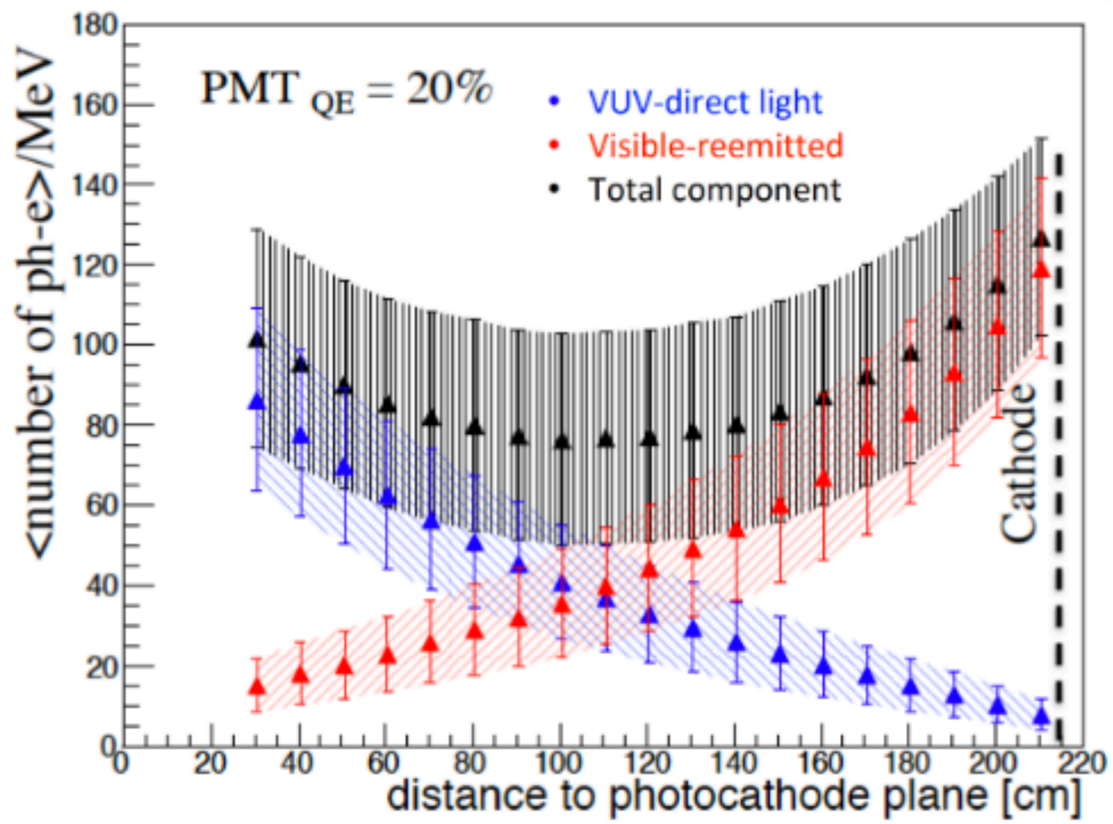
- PDS modules (24)
  - Photomultiplier tubes (120)
  - ARAPUCA (8)
  - X-ARAPUCA (168)
- Reflector foils mounted at cathode
  - ~2m away from PDS
  - Wavelength-shifter (TPB) coated reflective surface
- Light detection for
  - Primary scintillation light (VUV)
  - Reflected light (visible)



SBND PDS physics

- Combination of reflected light and primary scintillation light
  - Improved total light yield
  - More uniformity in light yield
  - Difference between VUV and visible light contributions can be used to determine position in drift direction at the time of the trigger

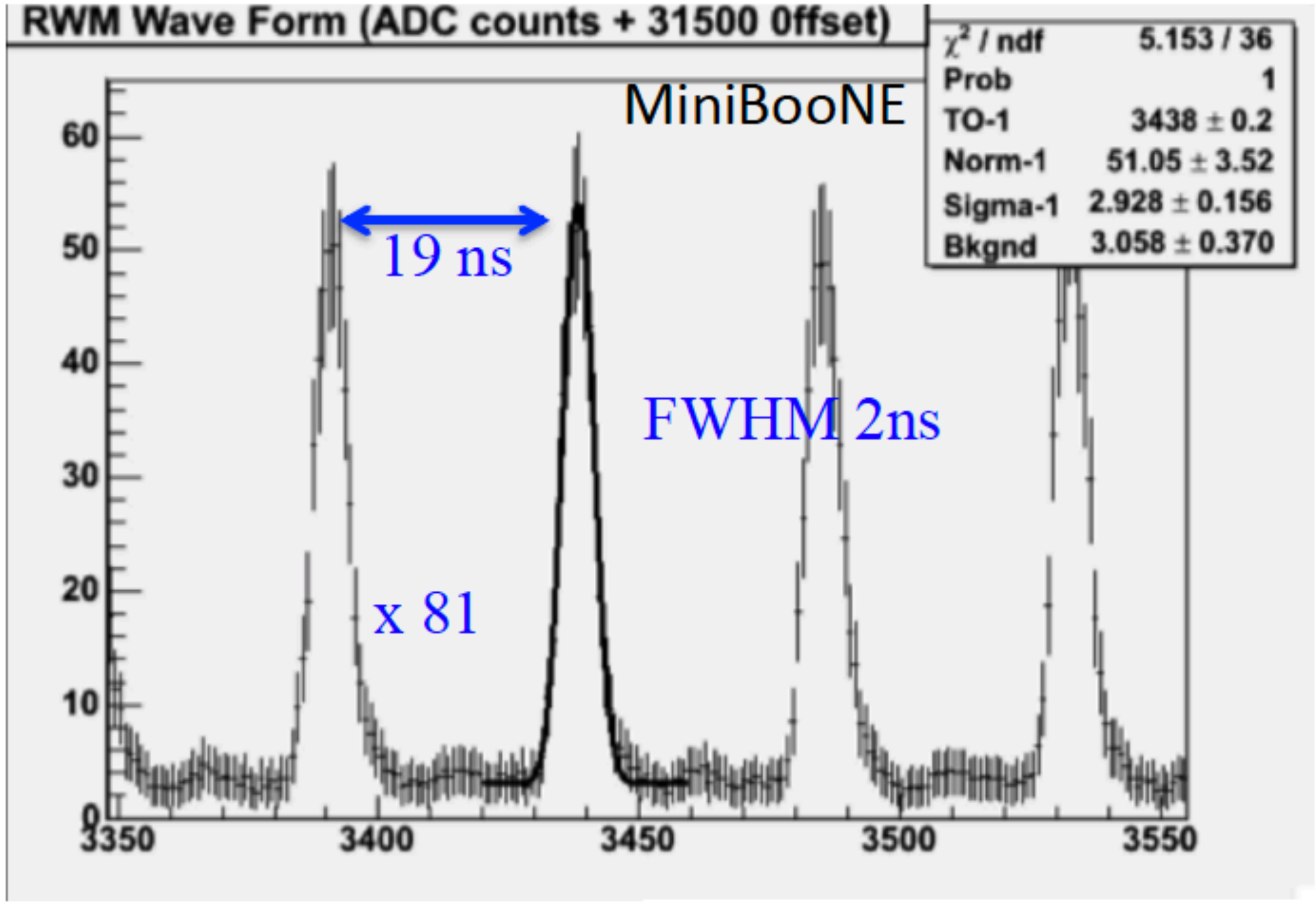
[D. Garcia-Gamez, Journal of Physics: Conf. Series 888 (2017) 012094]



- Importance of high coverage PDS to SBND physics
  - Calibration and particle identification
  - Improved cosmic rejection
    - Granularity allows improved matching of charge and light signals
    - Especially important for a surface detector
  - Trigger
    - Uniformity of light collection across detector allows trigger thresholds to be higher

Light time and “cosmics” removal

- LArTPCs are relatively slow detectors (1 frame is ~1 ms)
- Improving time resolution opens new physics possibilities for the light signals



- ❖ Few 100 ns resolution: tag events as being “in-spill”
- ❖ ~5 ns resolution (also for CRT): tag muons as *entering/exiting* → measuring sign(t_{TPC} - t_{CRT})
- ❖ 1-2 ns resolution : tag events as being “in-bucket” → x 5 background reduction

Not only oscillation physics: Neutrino Cross Sections at SBN

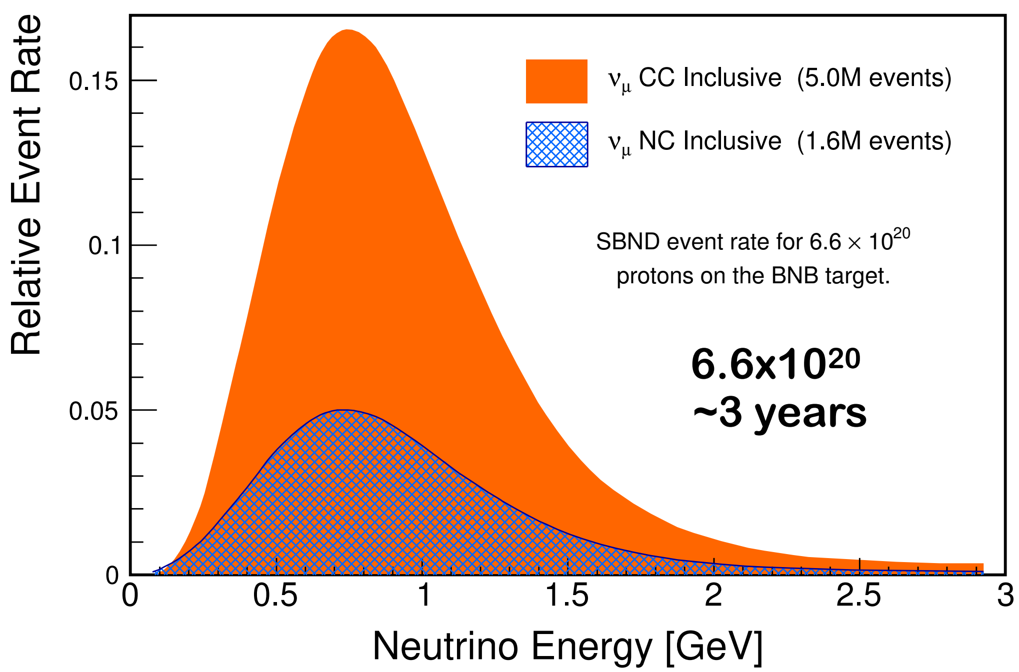
- A correct interpretation of the outcome of ν oscillation experiments requires precise understanding of **neutrino-nucleus interactions**.
- The SBN science program includes high precision studies of neutrino-argon cross sections at the GeV energy scale.
- SBND detector will provide an **enormous neutrino-argon event sample** from the BNB and will record **more than 2 million neutrino interactions per year**.
  - The BNB spectrum at SBND peaks near the neutrino energy of the second oscillation maximum for DUNE (0.8 GeV) and includes a substantial sample up to the first DUNE oscillation maximum (2.6 GeV).
- ICARUS-T600 will collect ~100k NuMI off-axis events per year.

A generational advance in neutrino-nucleus interaction studies!

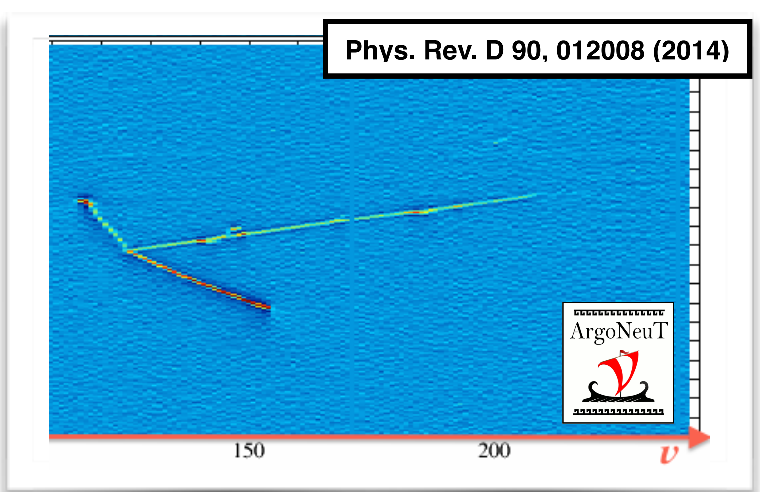
High neutrino event rate with excellent imaging capabilities

- SBND provides an ideal venue to conduct precision studies of neutrino-argon interactions in the GeV energy range and will make the **world's highest statistics** cross section measurements for many ν-Ar scattering processes.

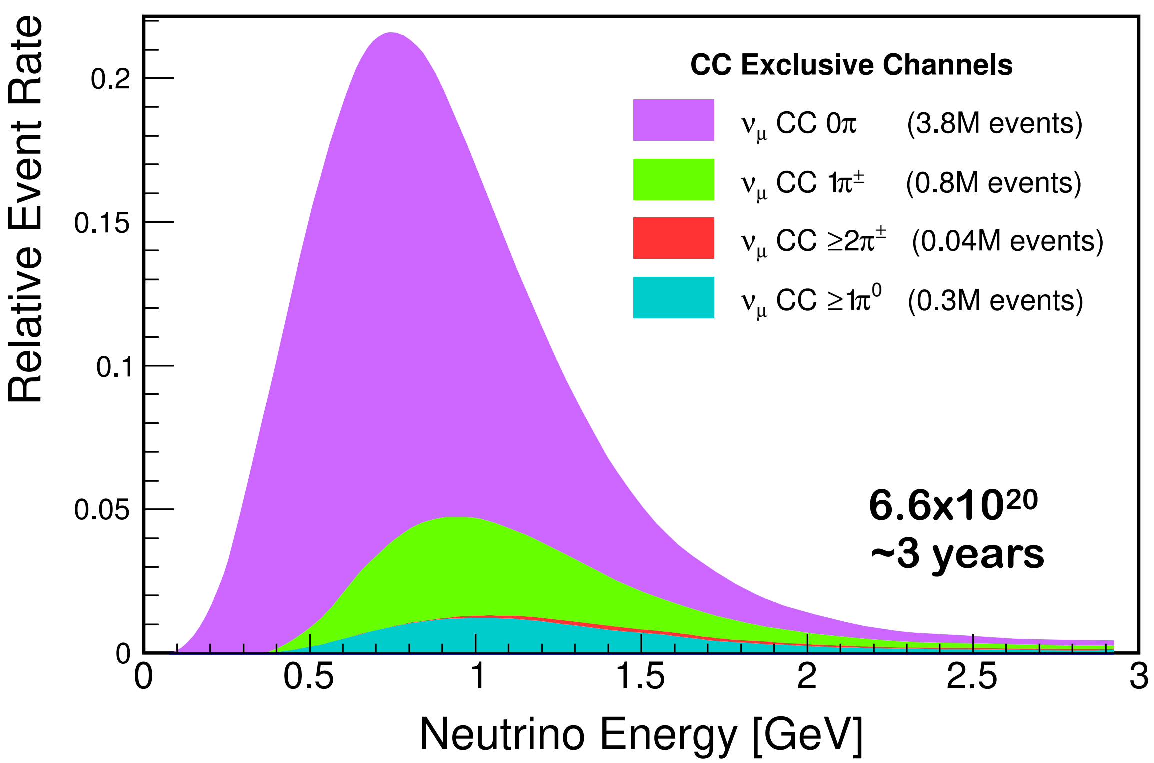
- SBND will collect **~1.5 million** ν_μ **Charged Current (CC)** and **~12,000** ν_e **CC** interactions per year.



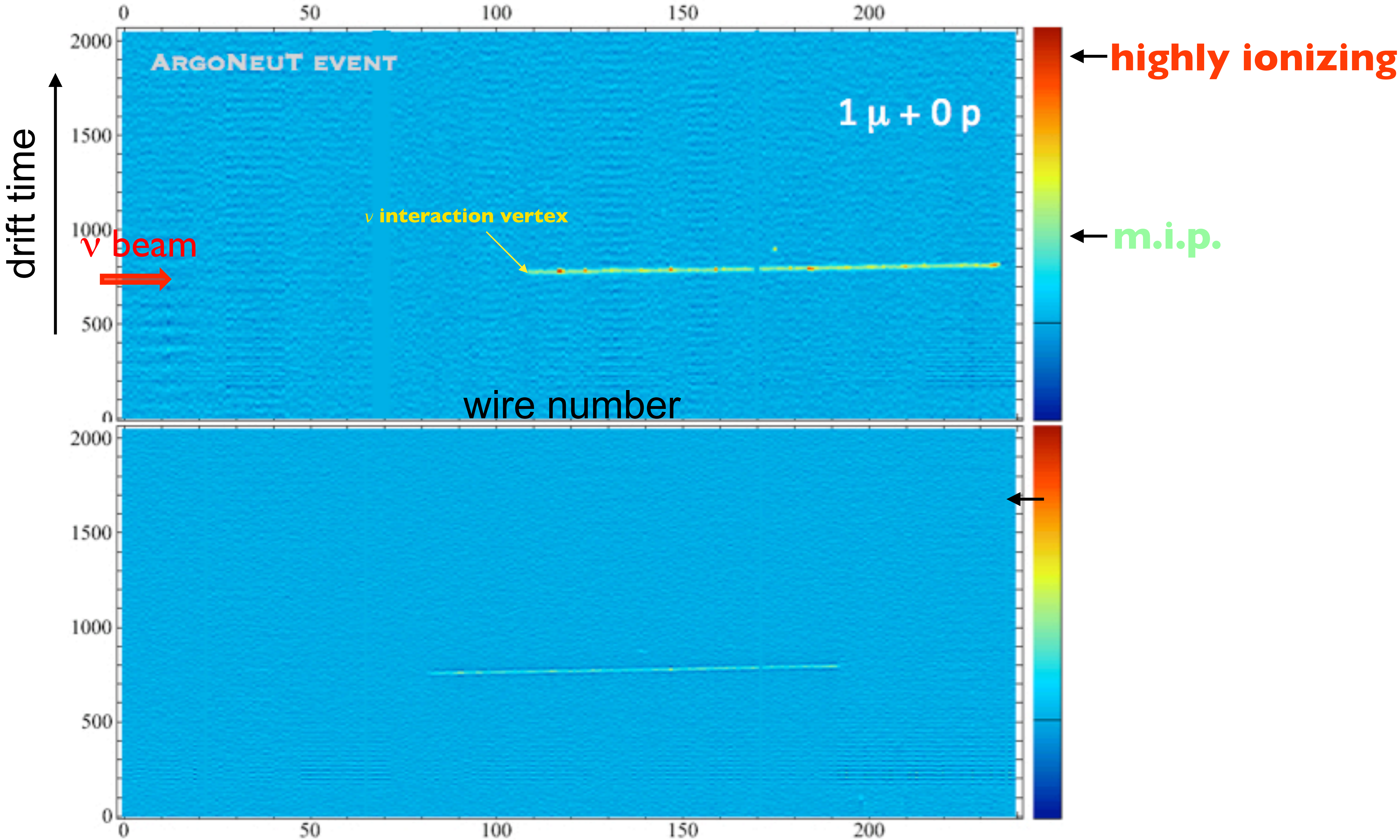
- SBND will perform many **exclusive measurements** of different final states for ν_μ and ν_e events with high precision, will measure nuclear effects and rare processes.



~360,000 ($1\mu + 2p$) events per year in SBND

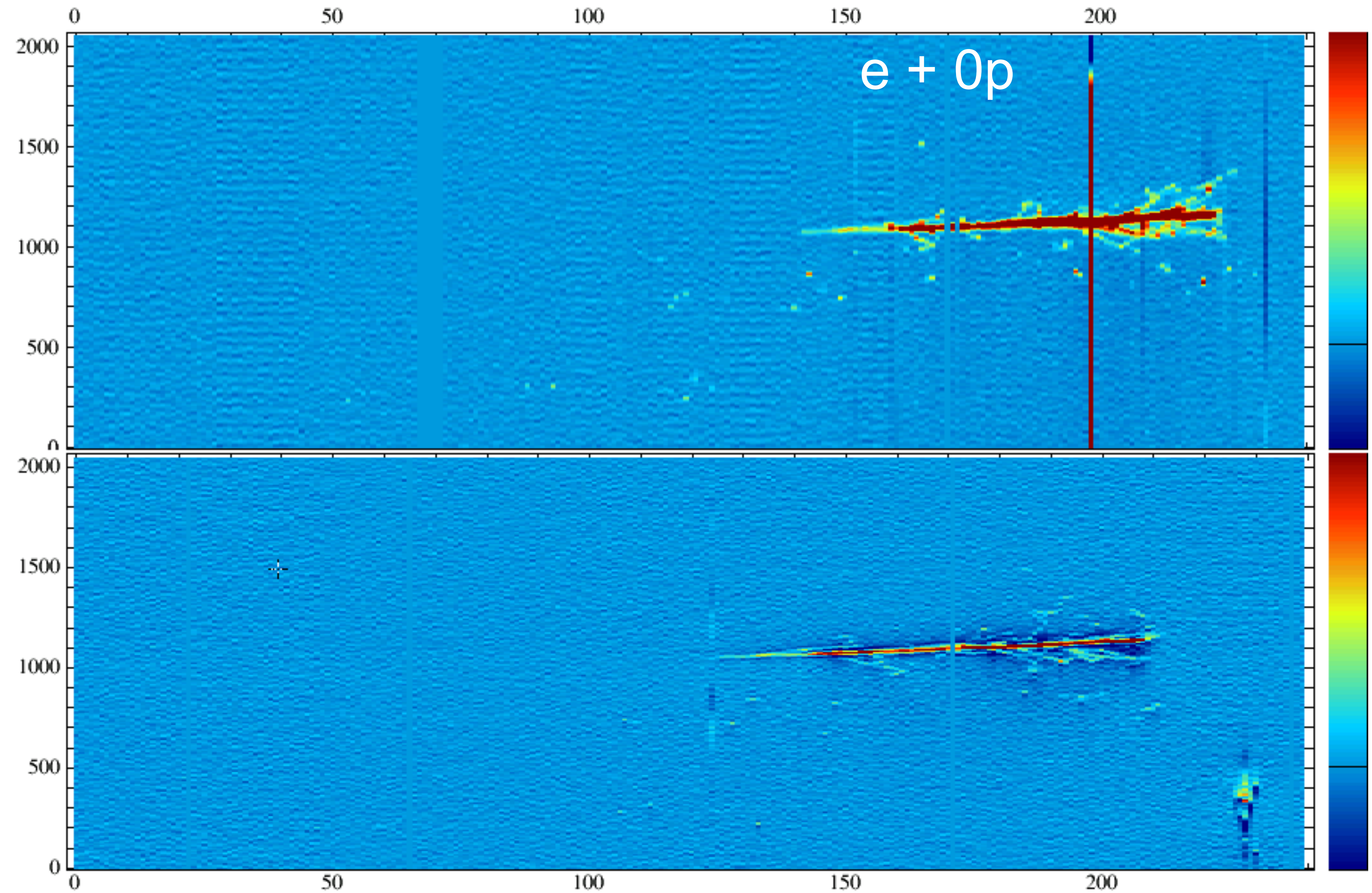


From "easy" to progressively more complicated topologies...



2D views from two wire planes

From "easy" to progressively more complicated topologies...



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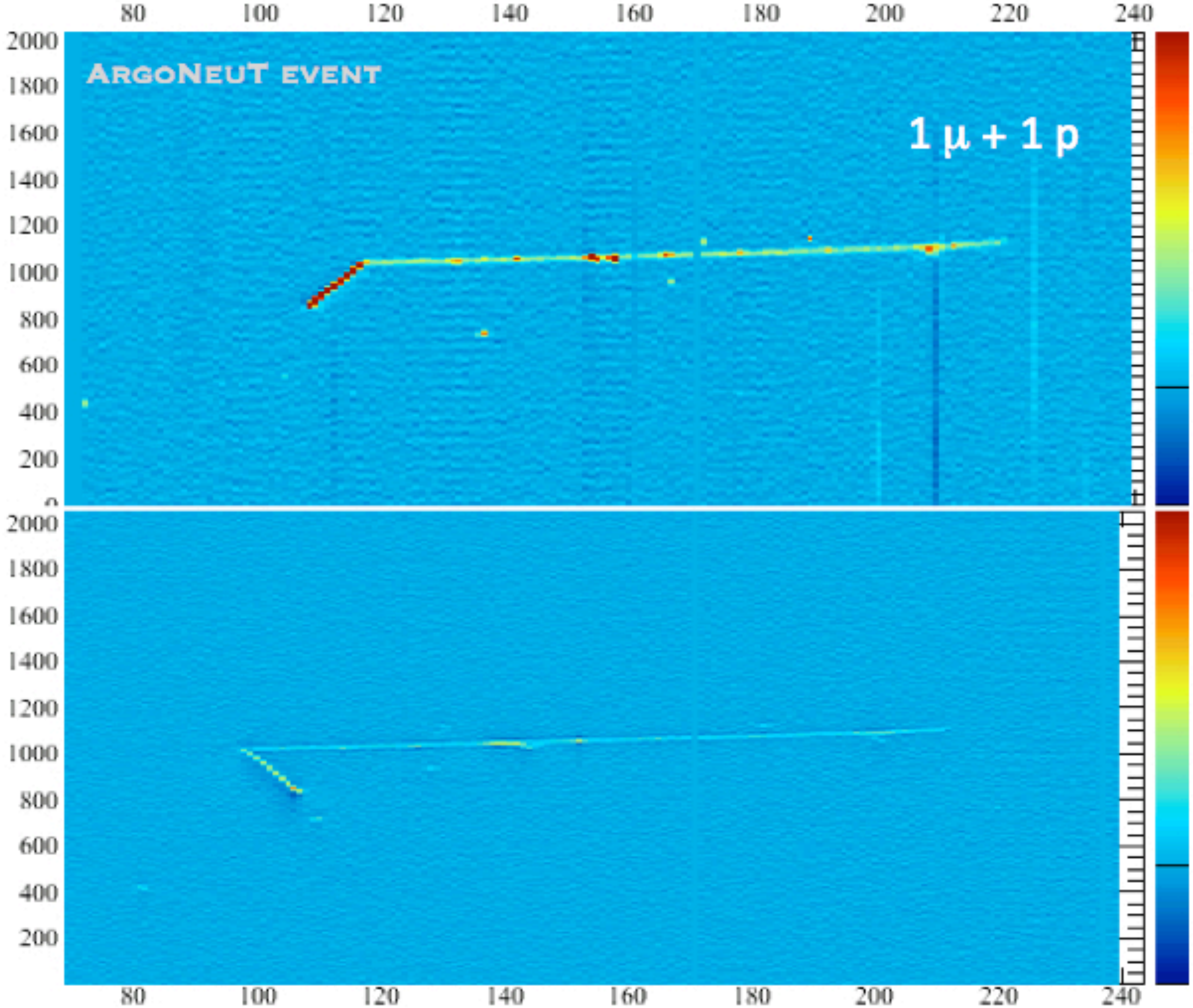

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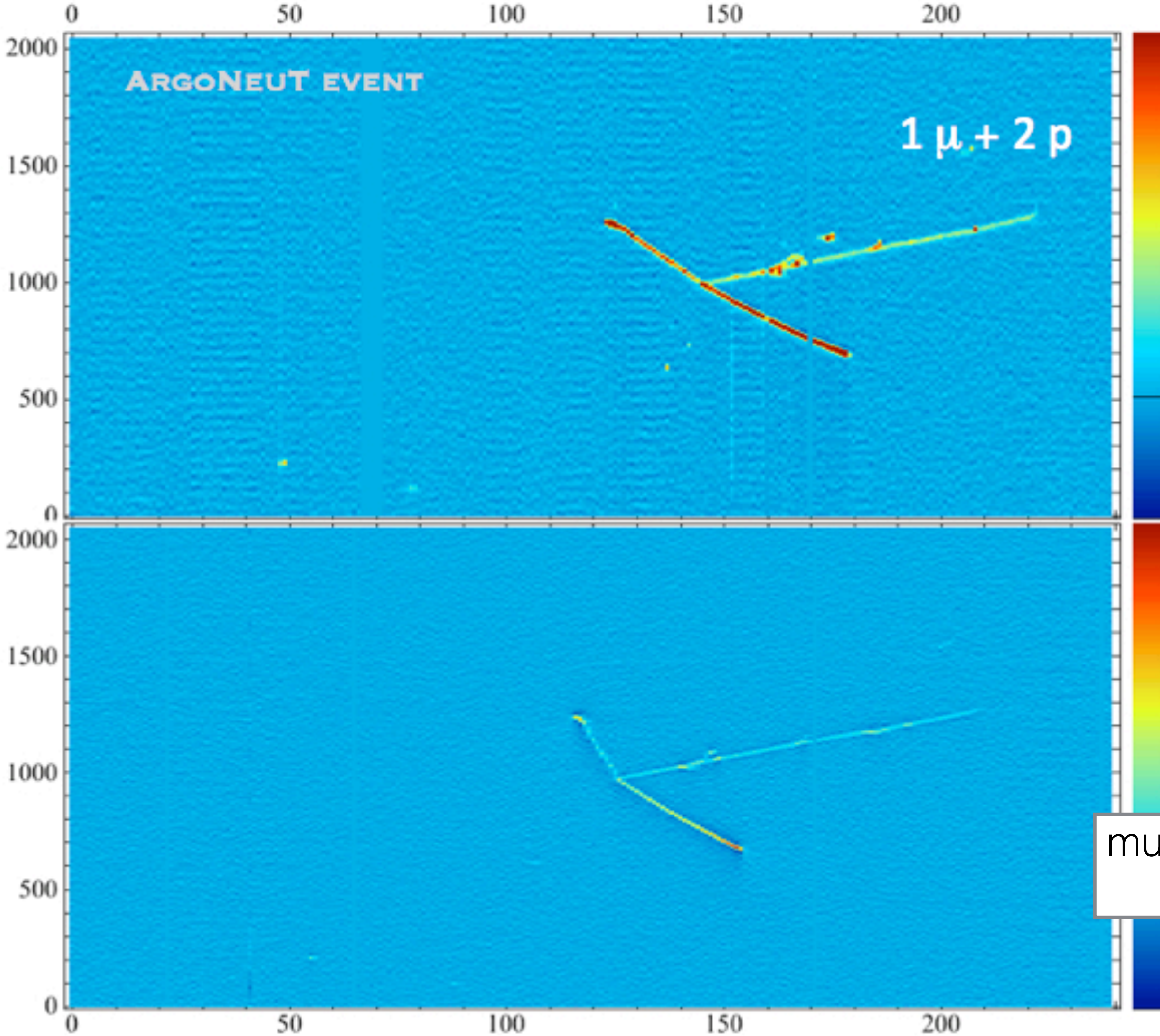
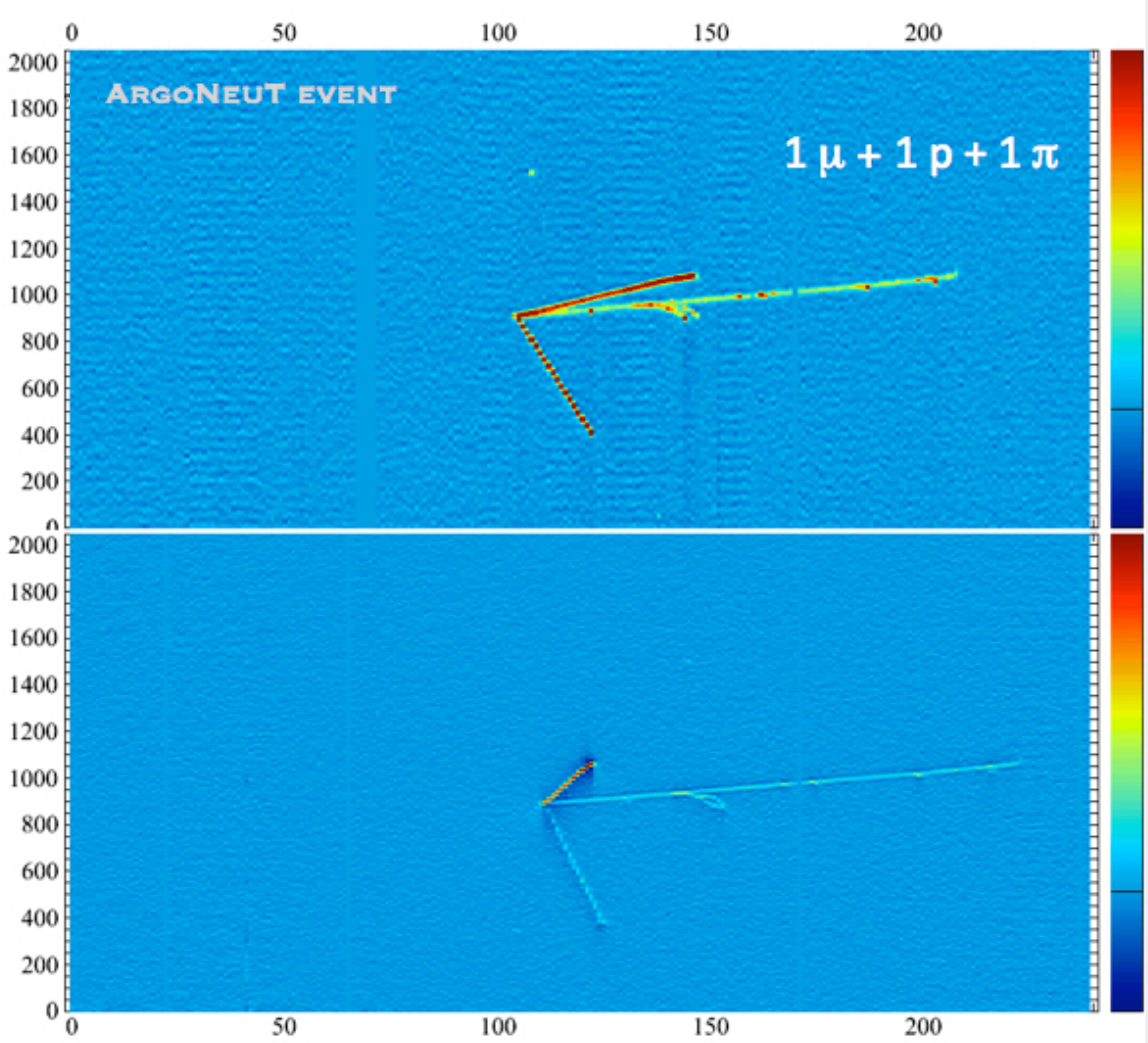


multi-p accompanying the leading muon

From "easy" to progressively more complicated topologies...



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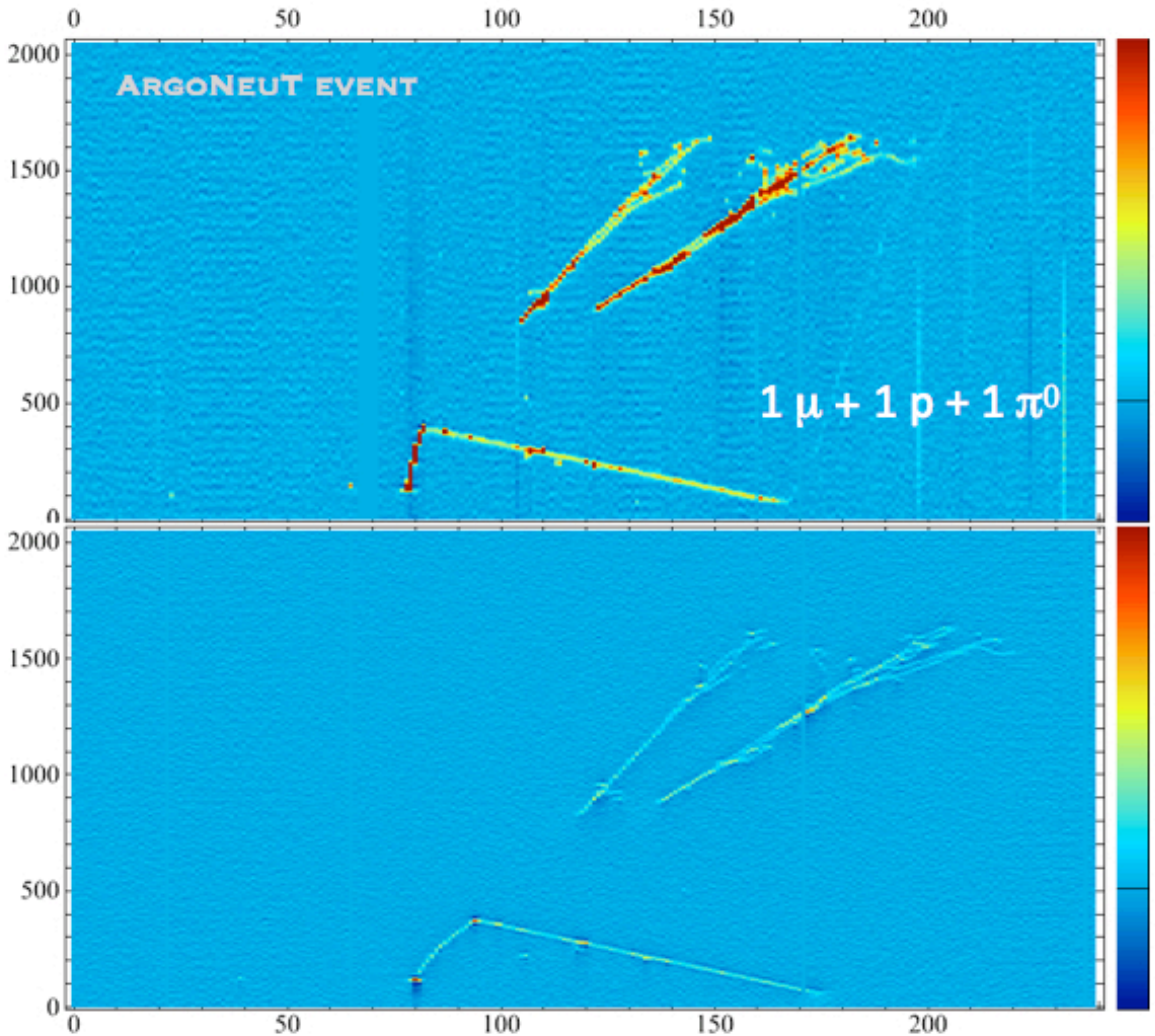

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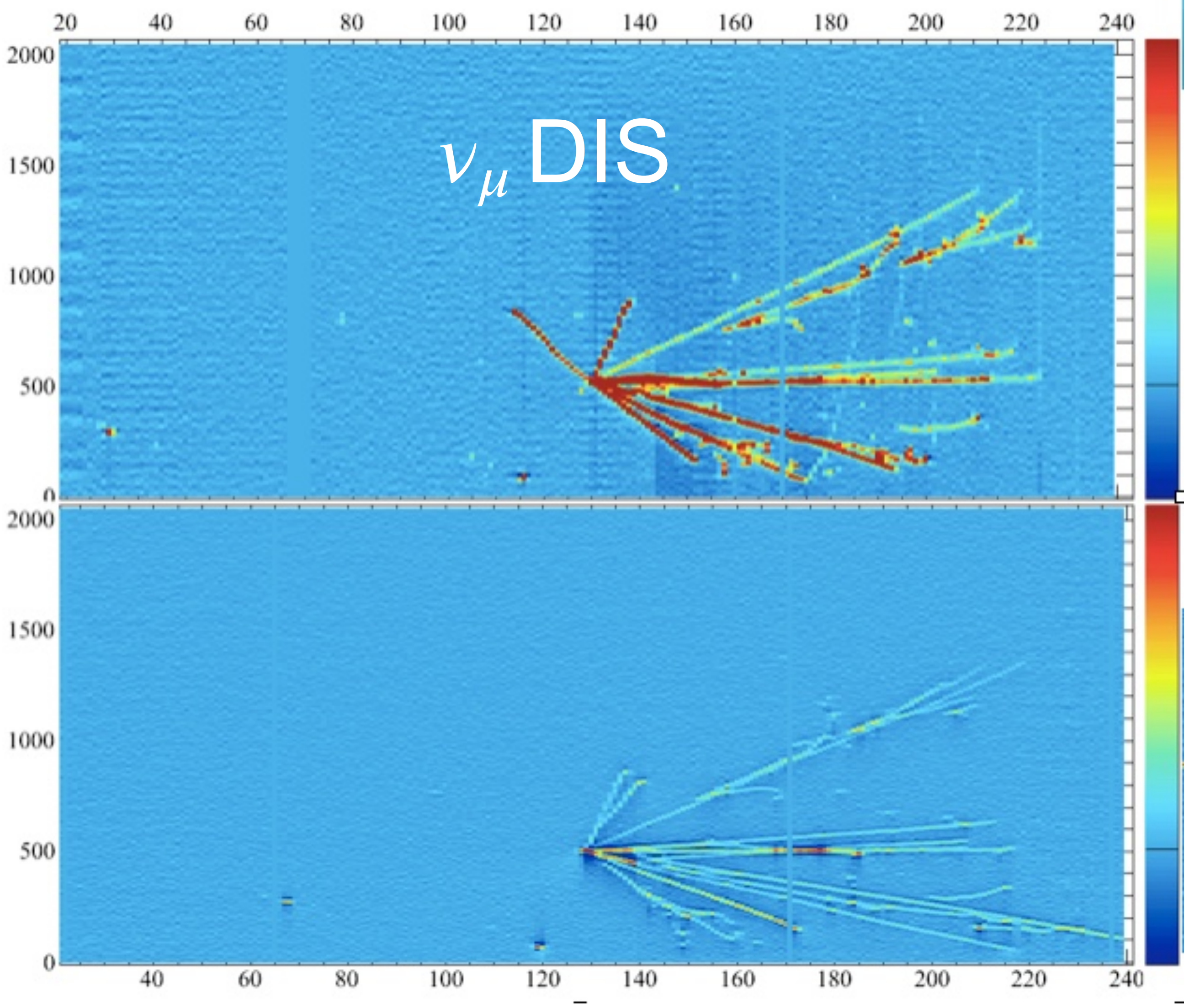
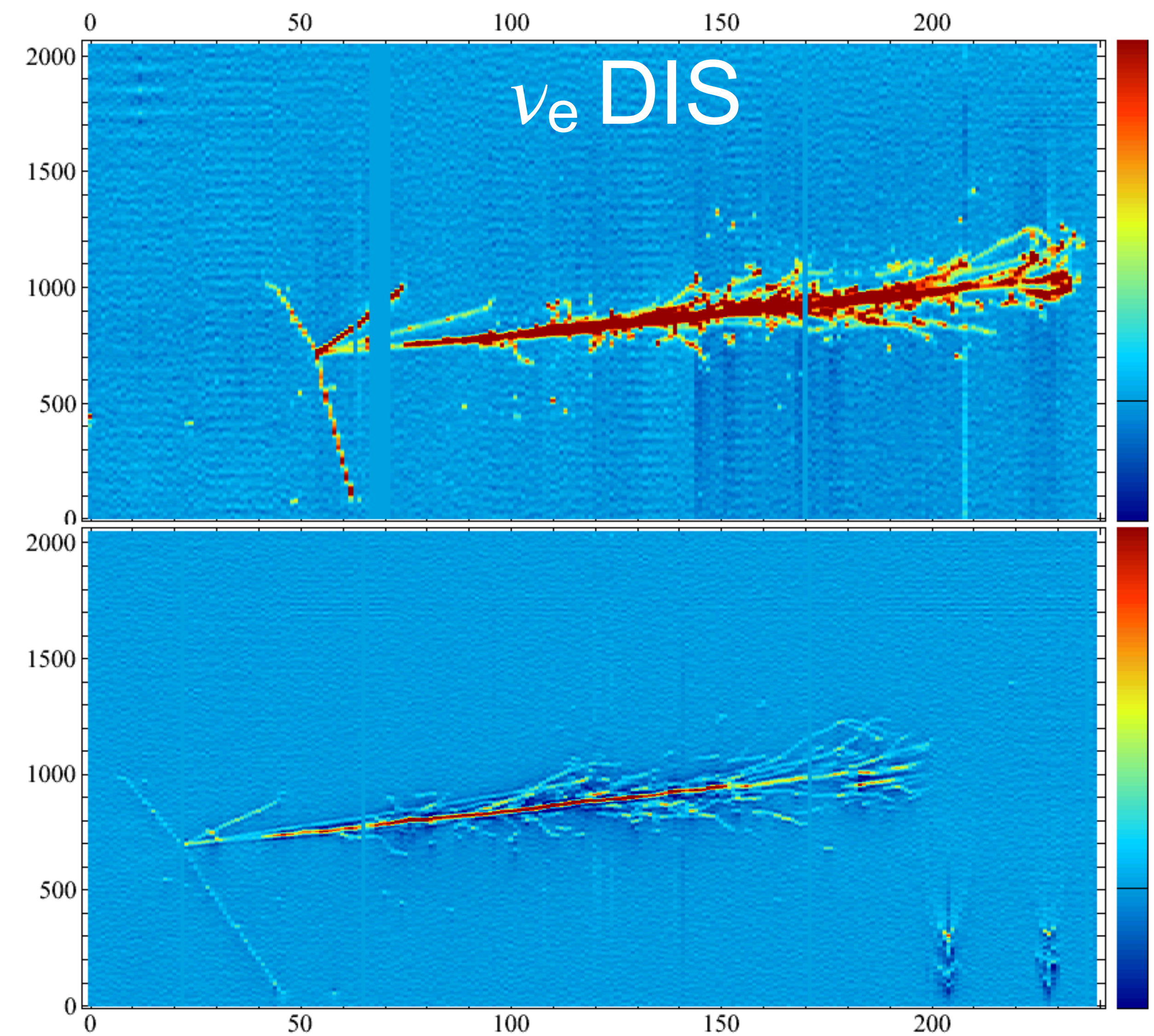
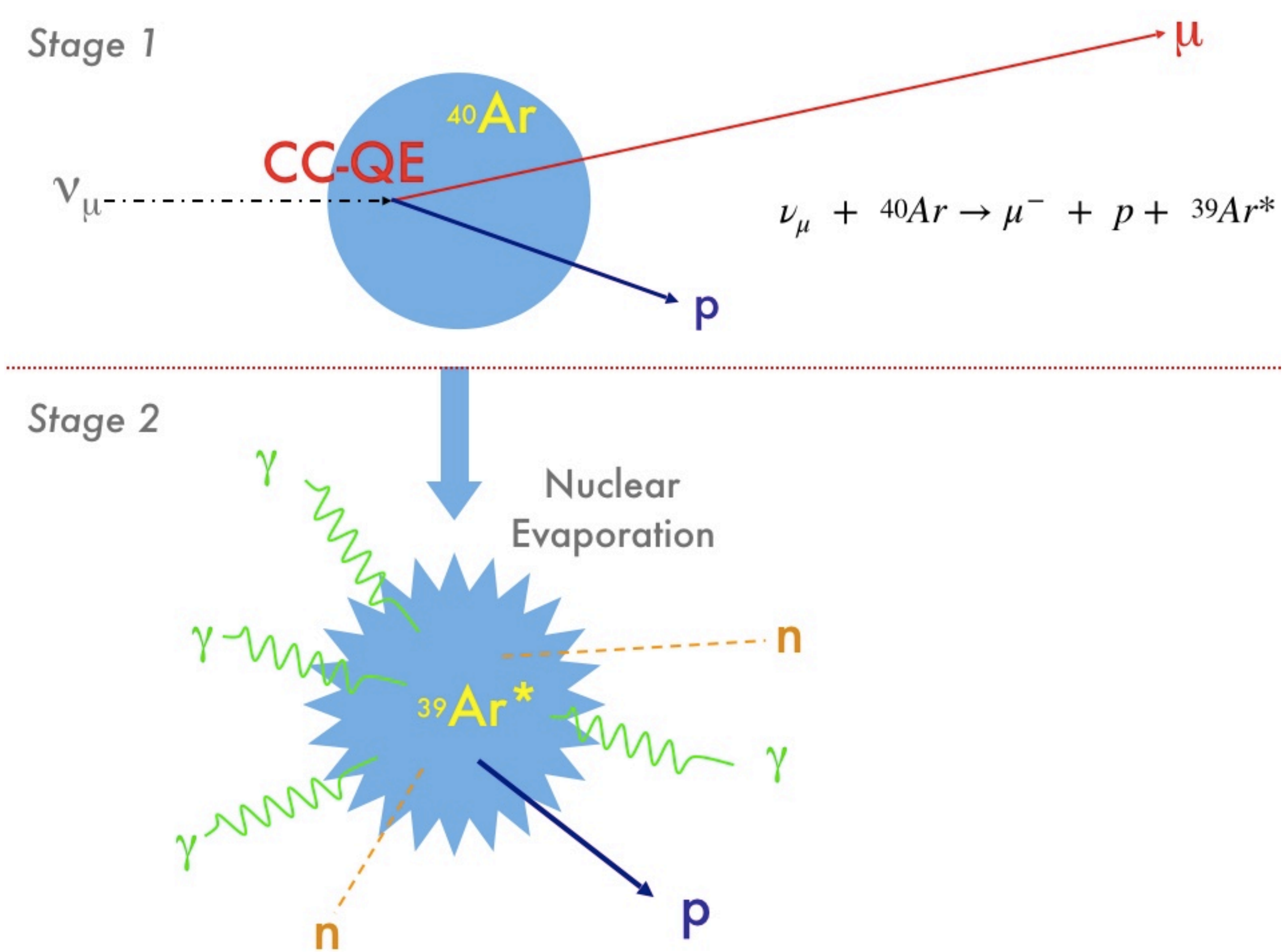




Low Energy Photon Production

Low Energy (MeV) Photons can be produced in GeV neutrino-argon interactions by two possible mechanisms:

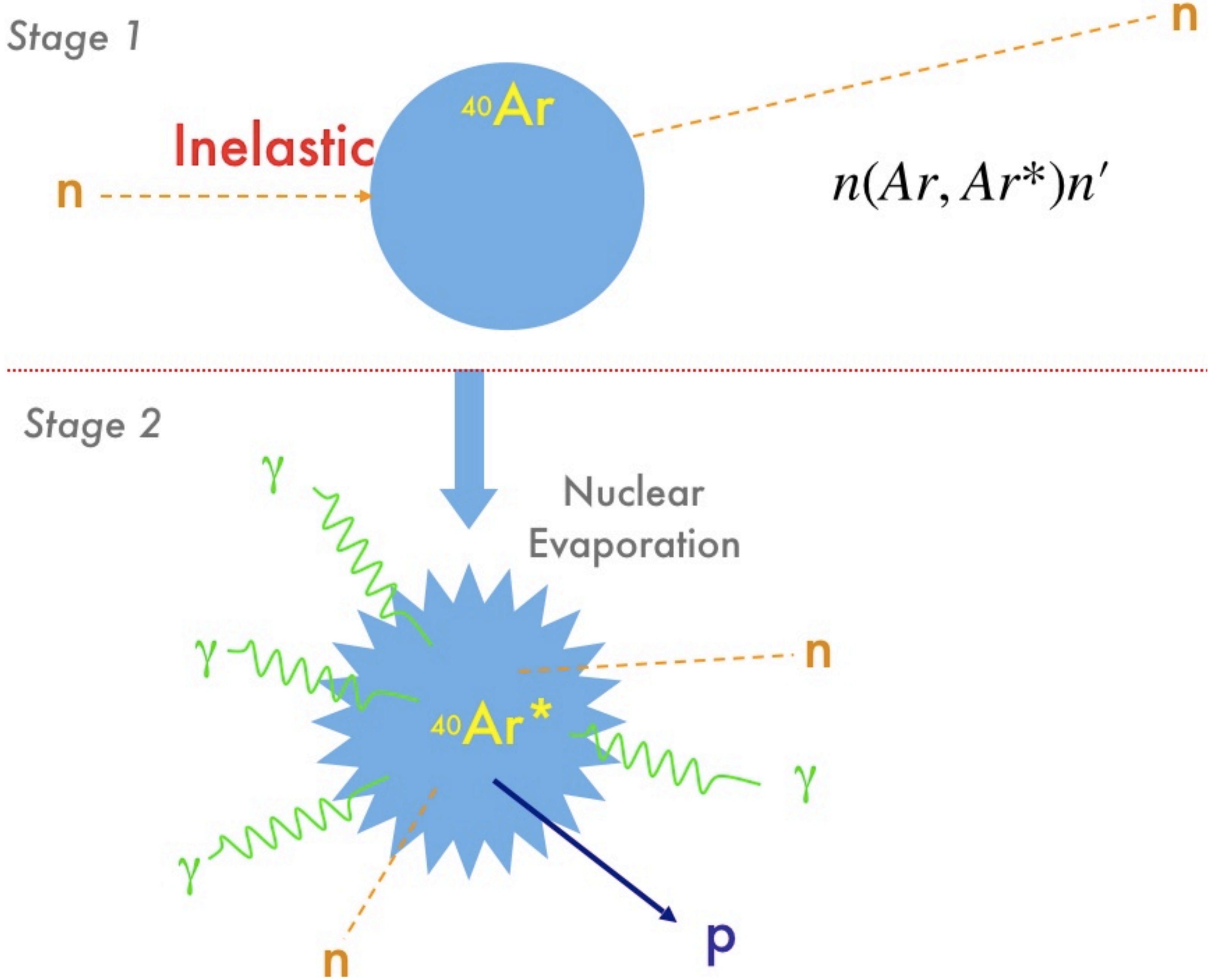
1. De-excitation of the target nucleus



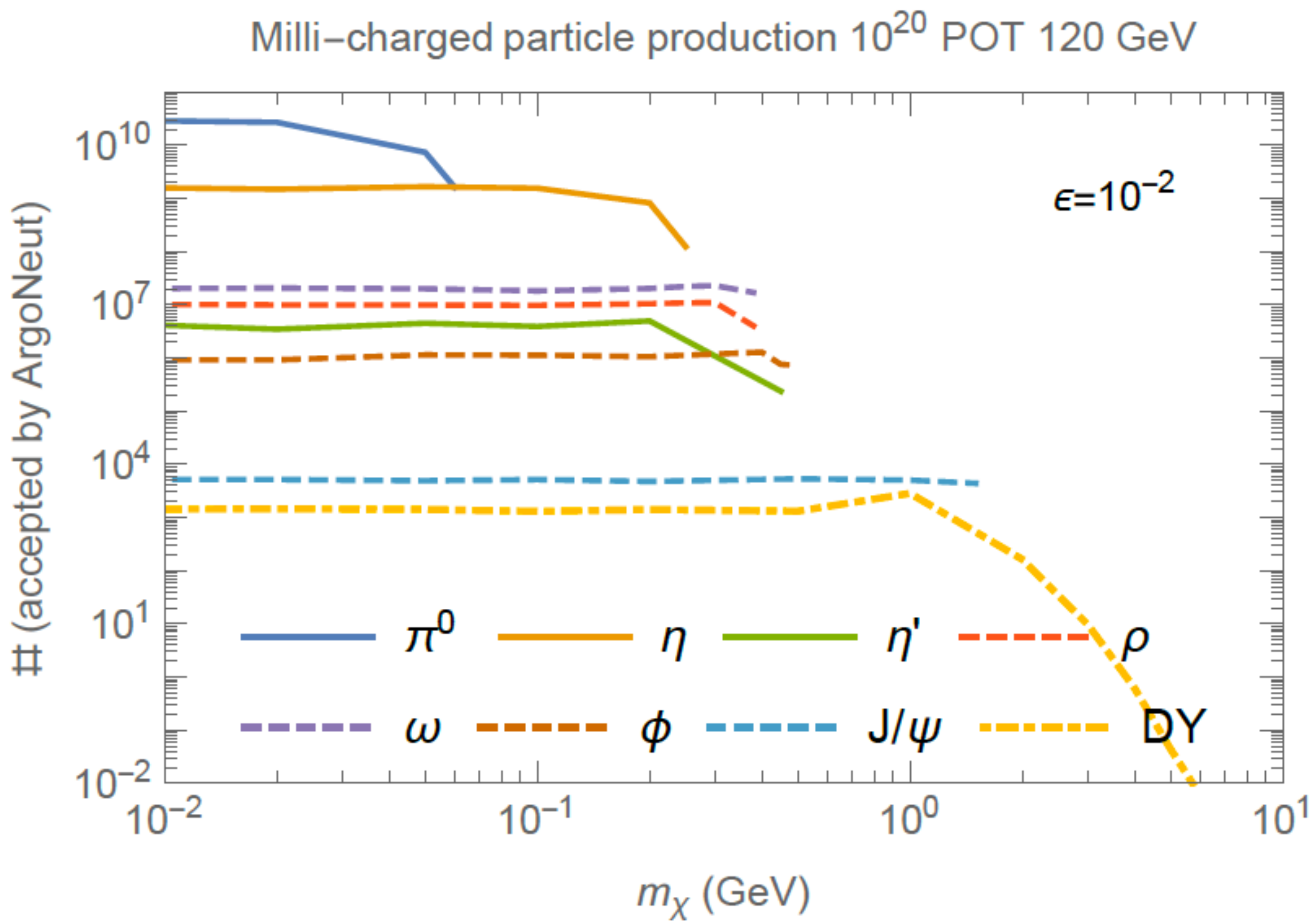
Low Energy Photon Production

Low Energy (MeV) Photons can be produced in GeV neutrino-argon interactions by two possible mechanisms:

1. De-excitation of the target nucleus
2. Inelastic scattering of neutrons



Millicharged production @ ArgoNeuT



R. Harnik, Zhen Liu, and O. Palamara, arXiv:1902.03246