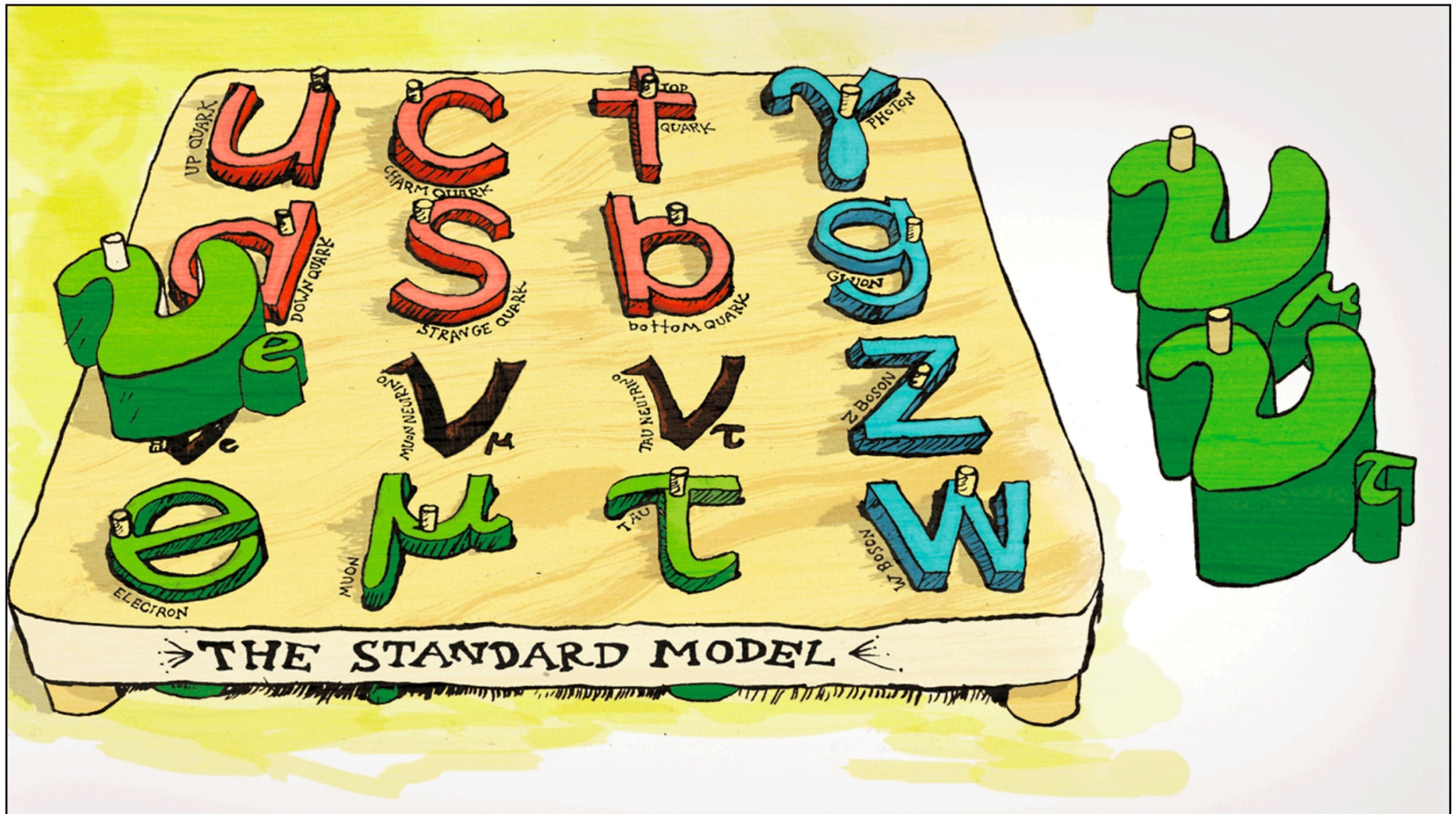

Illustration by Sandbox Studio, Chicago

Experimental searches for Beyond the Standard Model Physics with Neutrinos

12th International Neutrino Summer School

Fermilab, August 15th 2019

Ornella Palamara

Fermilab & Yale University

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Outline

- Why Beyond the Standard Model (BSM)?
- Why BSM with Neutrinos?
- The case of BSM Physics with **Liquid Argon Time Projection Chamber** detectors at **accelerator neutrino beam** facilities.
- Of the many accessible New Physics opportunities, this lecture covers three selected topics:
  - Sterile Neutrinos
  - Neutrino Trident
  - Millicharged Particles

Disclaimers

This lecture focuses on the experimental detection of BSM physics.
Other lectures covered the theory-phenomelogy*

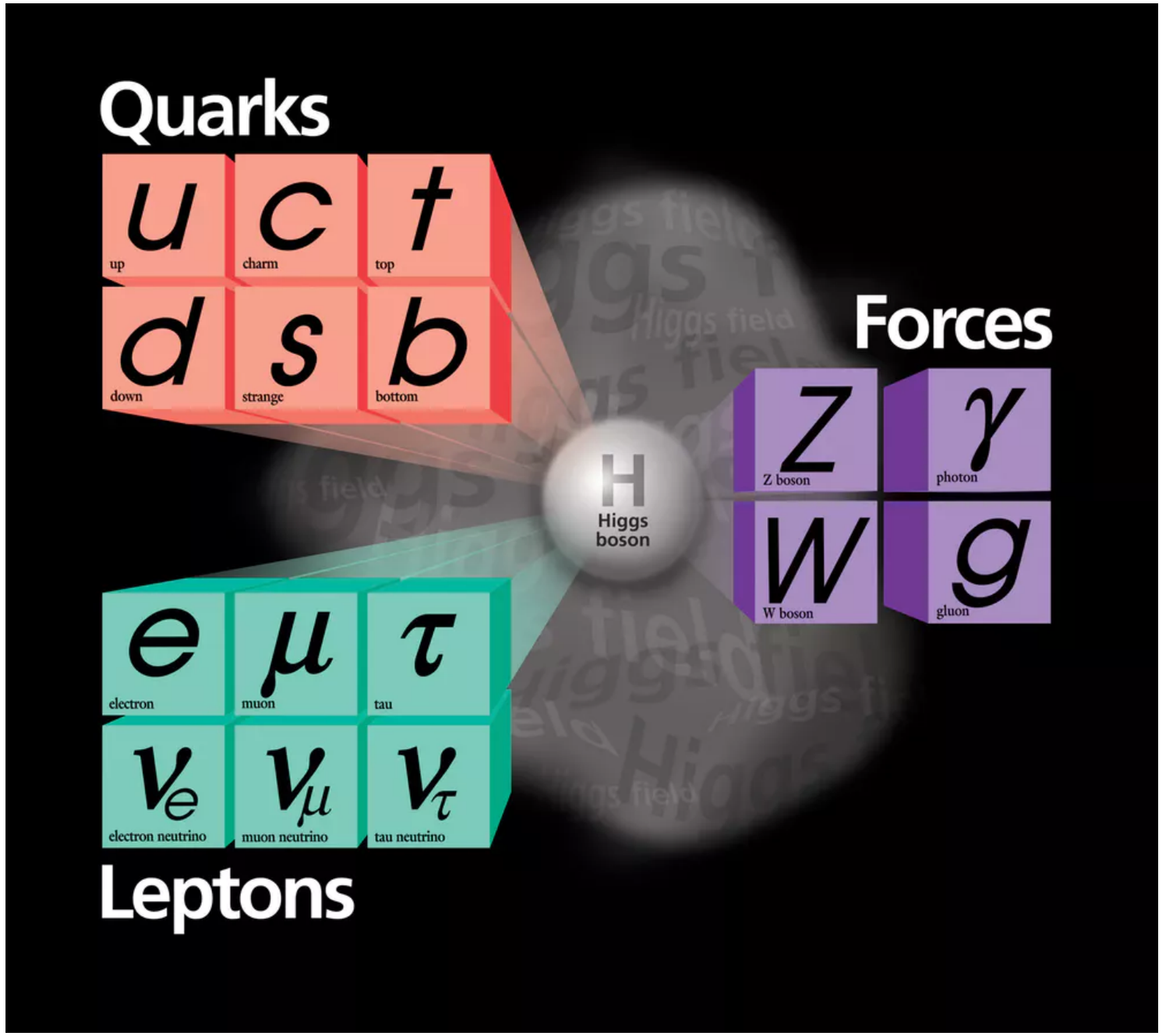
** See lectures by J. Kopp, G. Karagiorgi, B. Littlejohn…*

Part of the material in this presentation is *under copyright* by
Pedro Machado©
(it is from a "4-hands, 2-brains" Neutrino University lecture
Pedro and I have recently given)

Thanks Pedro!

What is BSM?

This is the SM



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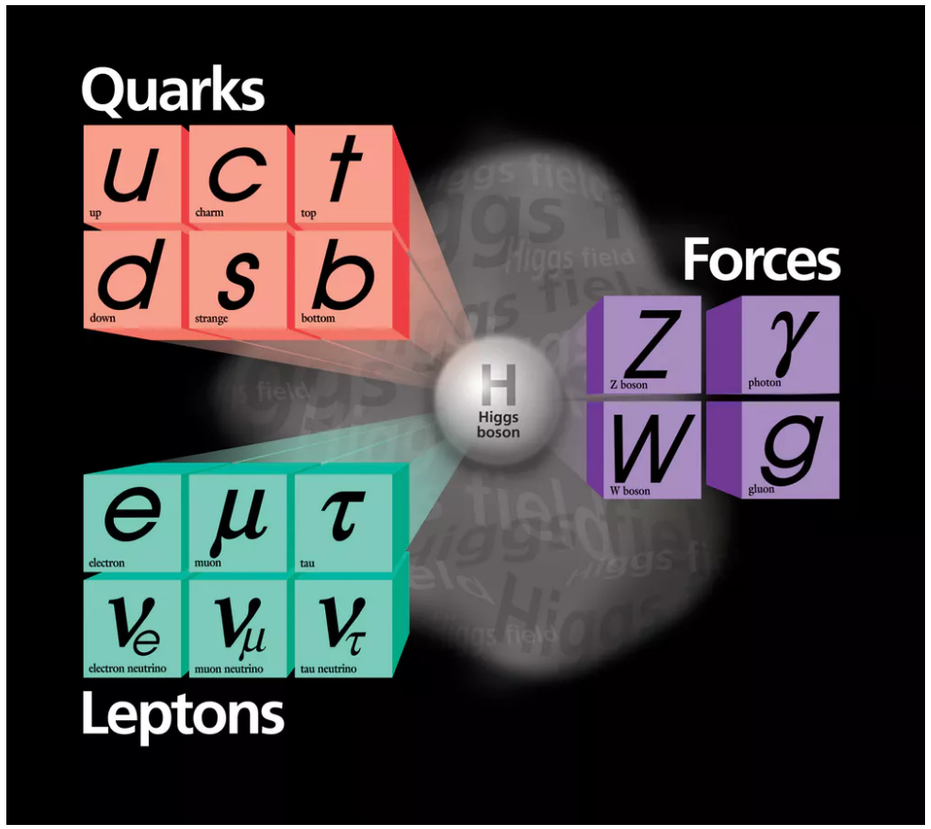

Standard Model:

- Explains most of what we see
- Works like a charm

What is BSM?

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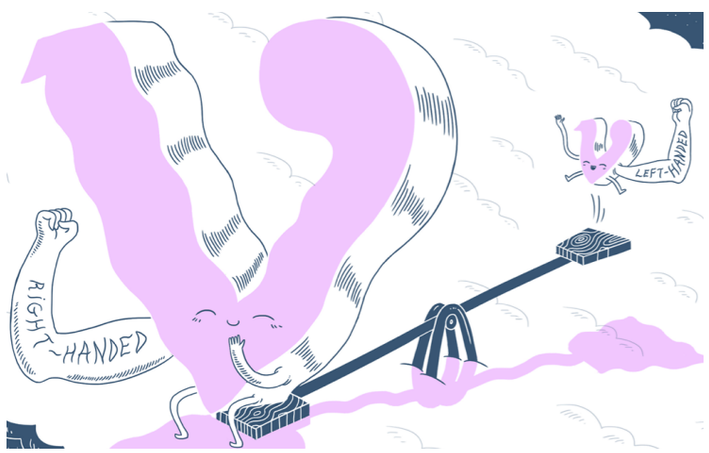
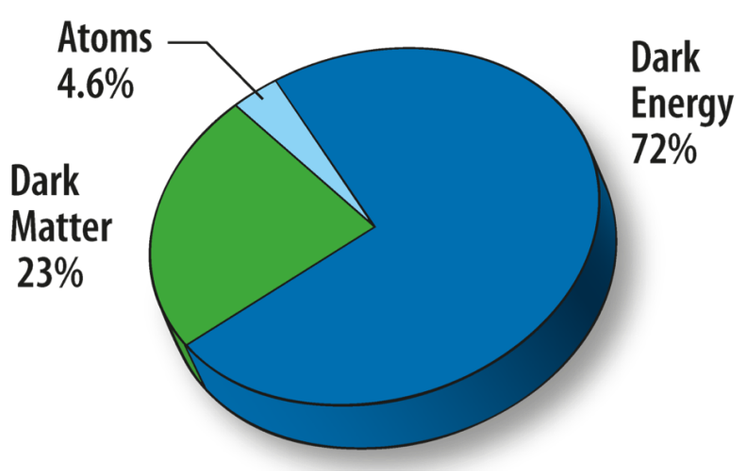


Why should we go beyond it?

- Neutrino masses
- Dark matter
- Matter anti-matter asymmetry
- Accelerated expansion of the universe
- Why 3 families?



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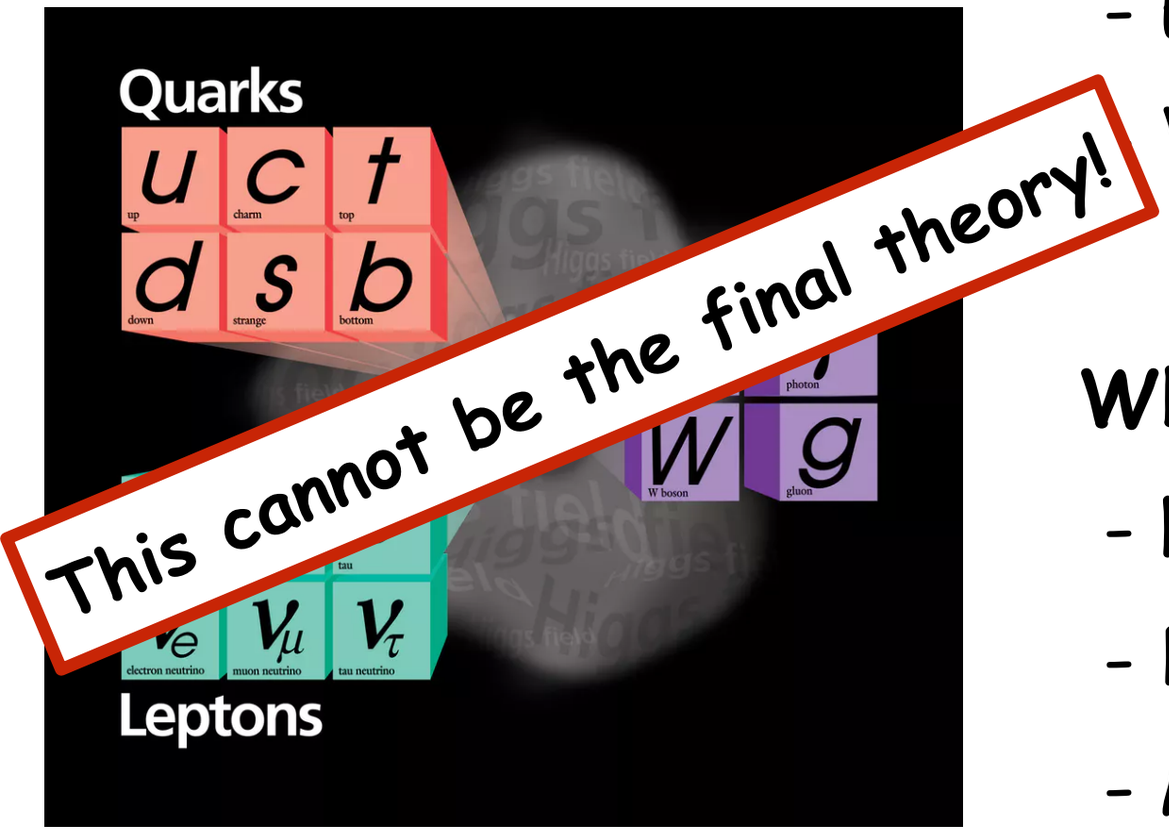

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What is BSM?

What is BSM?

This is BSM

What is BSM?

This is BSM

The mystery:

We know there **needs** to be physics beyond the standard model

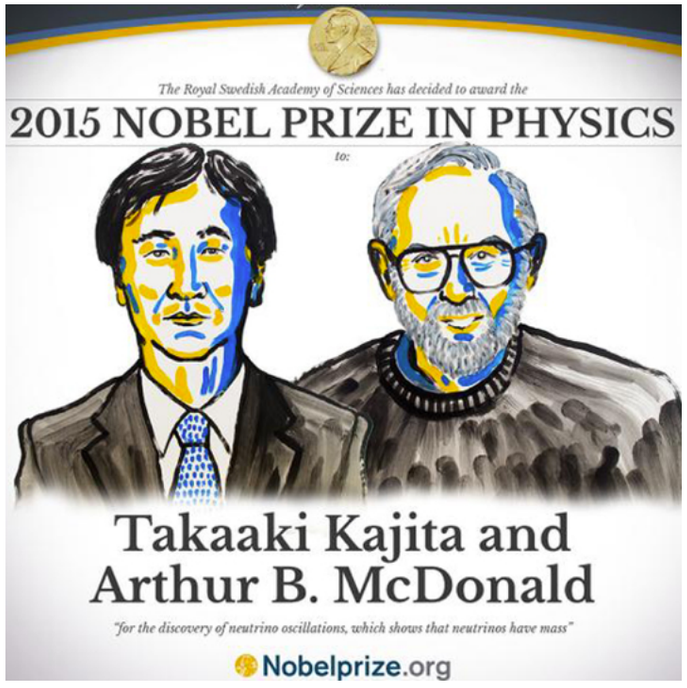
We have **no idea** of what and where that is

Where to study BSM physics?

- There is a worldwide effort to discover BSM Physics.
- BSM searches have been the domain of high-energy colliders (Large Hadron Collider (LHC) @ Cern, Tevatron @ FNAL) for decades.

- There is an increasing interest to search for new physics with high-intensity beams for fixed target and beam-dump experiments.
- Neutrino programs are attracting attention from experimenters and theorists because similar opportunities can be explored.
- Neutrino experiments are fantastic tools to look for **new physics in the neutrino sector** and **beyond**.

Why Neutrinos?

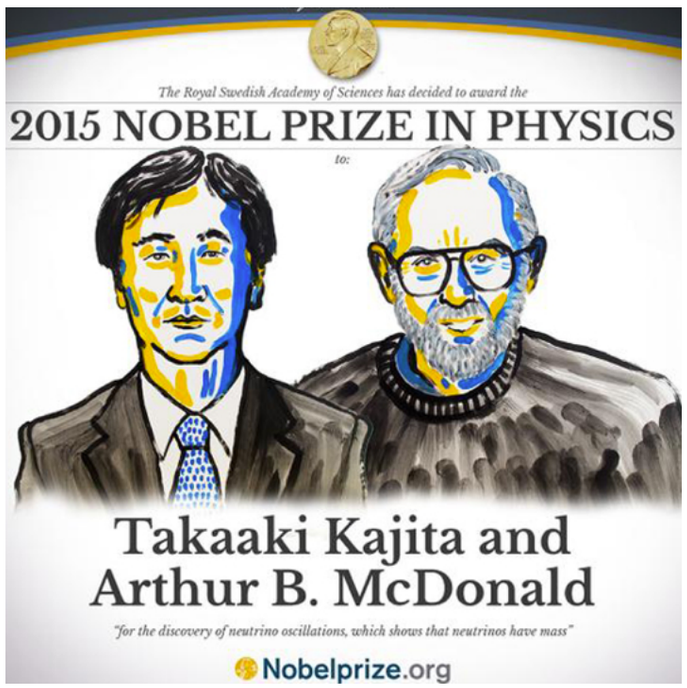


The existence of non-zero neutrino masses, inferred from neutrino oscillation measurements, is the only laboratory-based evidence of physics beyond the standard model

We already know neutrinos break the mold of the Standard Model.

The question is "By how much"?

Why Neutrinos?



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Where do neutrino masses come from?

Are neutrinos the key to the matter-antimatter asymmetry?

Do neutrinos communicate with DM?

Are neutrinos their own antiparticle?

Is lepton number conserved?

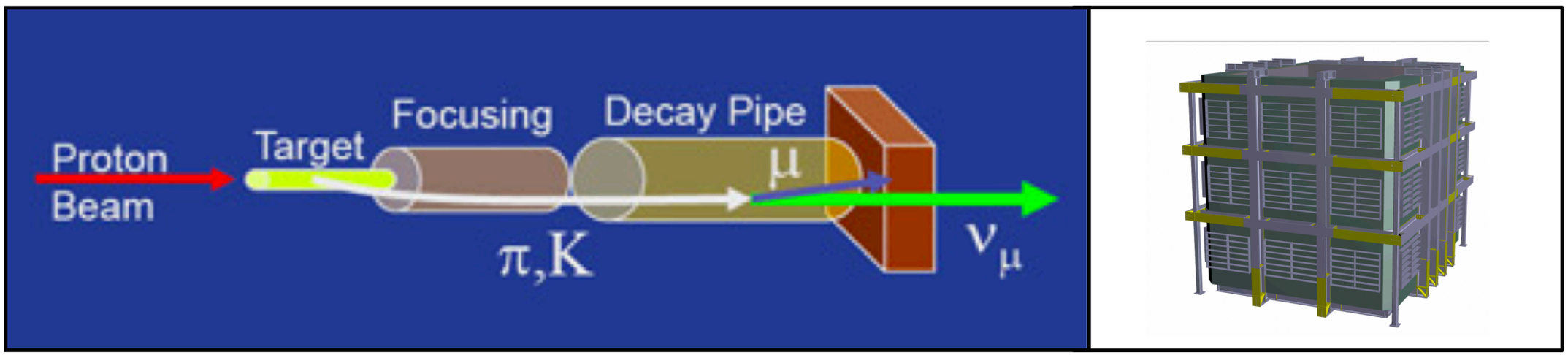
What is going on in LSND/ MiniBooNE?

BSM with Neutrinos

The BSM physics and dark matter models accessible are specific to the neutrino source and neutrino detector used.

Considered in the following is the case of **Liquid Argon Time Projection Chamber** (LArTPC) detectors at **accelerator neutrino beam facilities**.

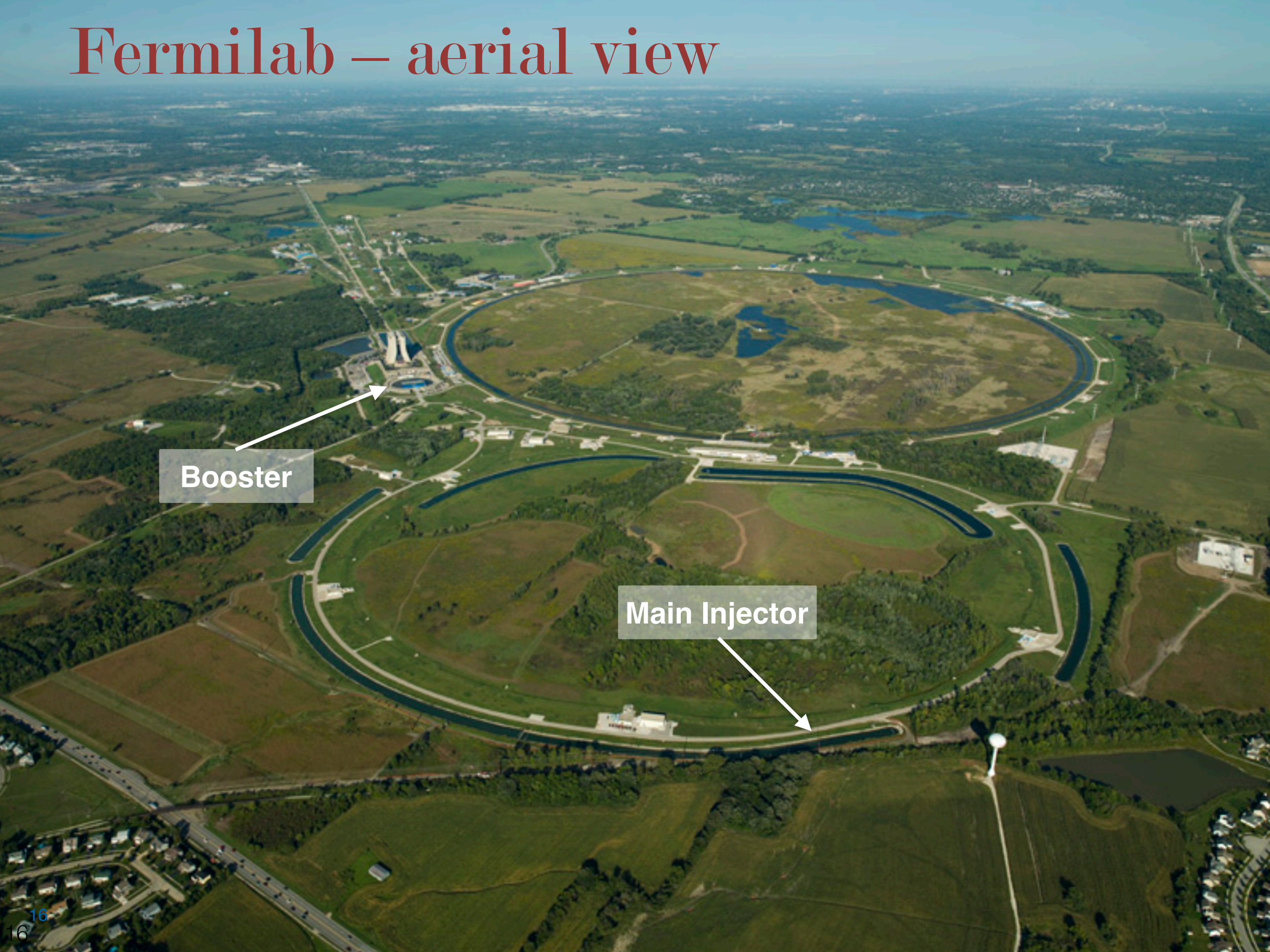
Why BSM in Accelerator Neutrino Experiments?



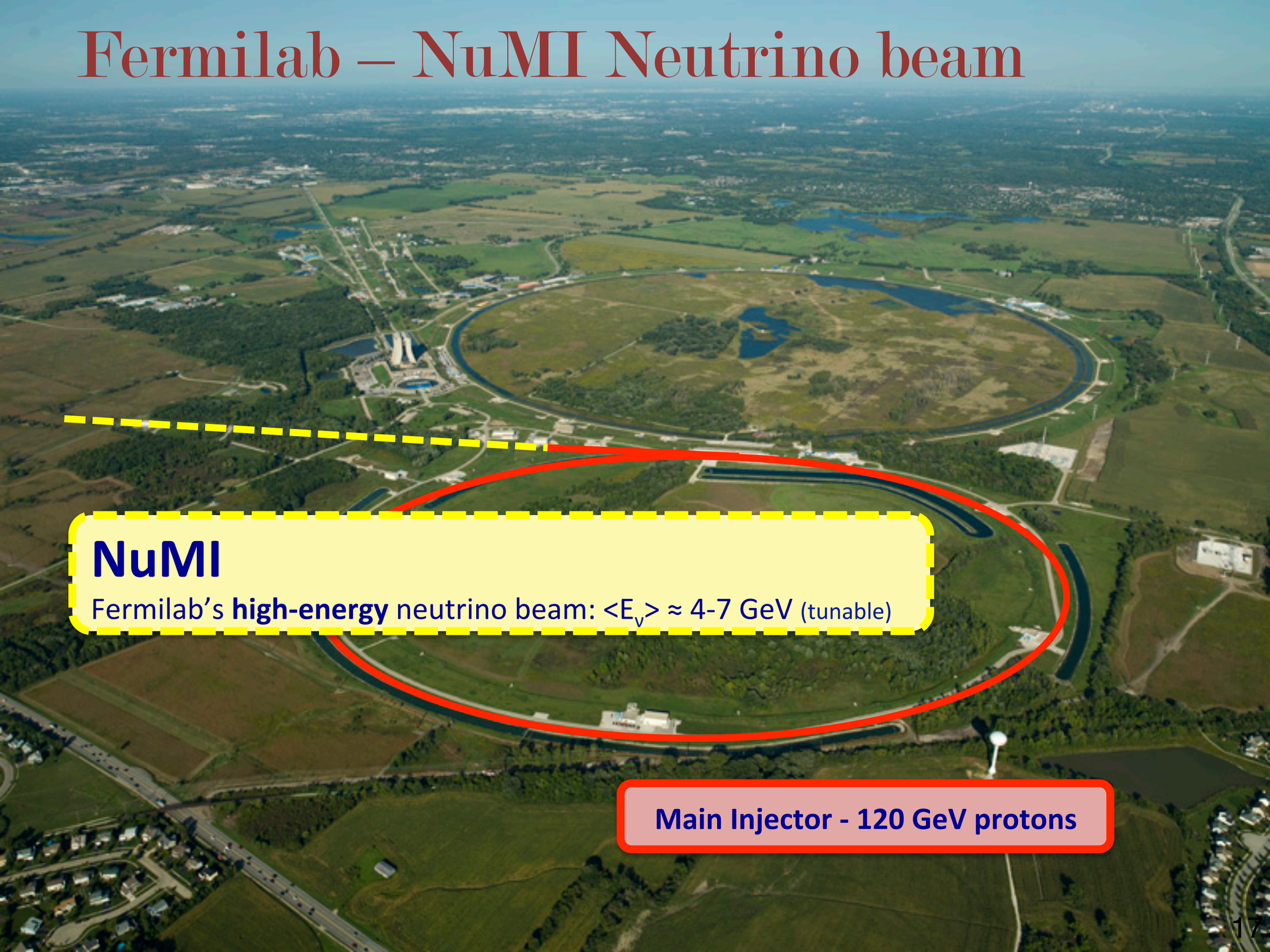
- The combination of:
  - **High-intensity proton beams (high intensity neutrino beams)** for neutrino precision measurements with
  - **Large mass detectors** with
    - Highly precise tracking and energy measurement
    - Excellent timing resolution and
    - Low energy threshold

Enable searches for New Physics scenarios/BSM phenomena

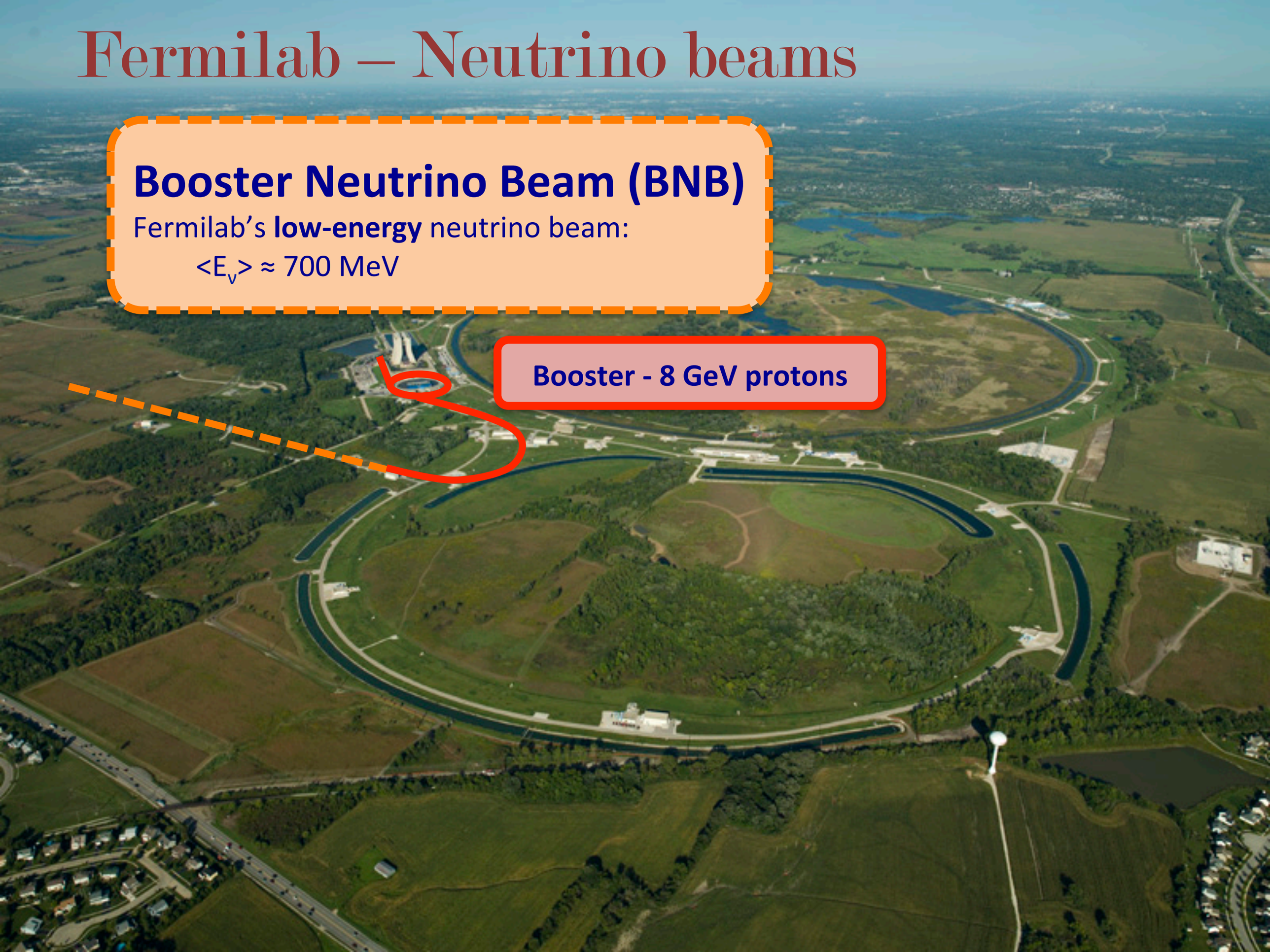
Fermilab – aerial view



Fermilab – NuMI Neutrino beam



Fermilab – Neutrino beams

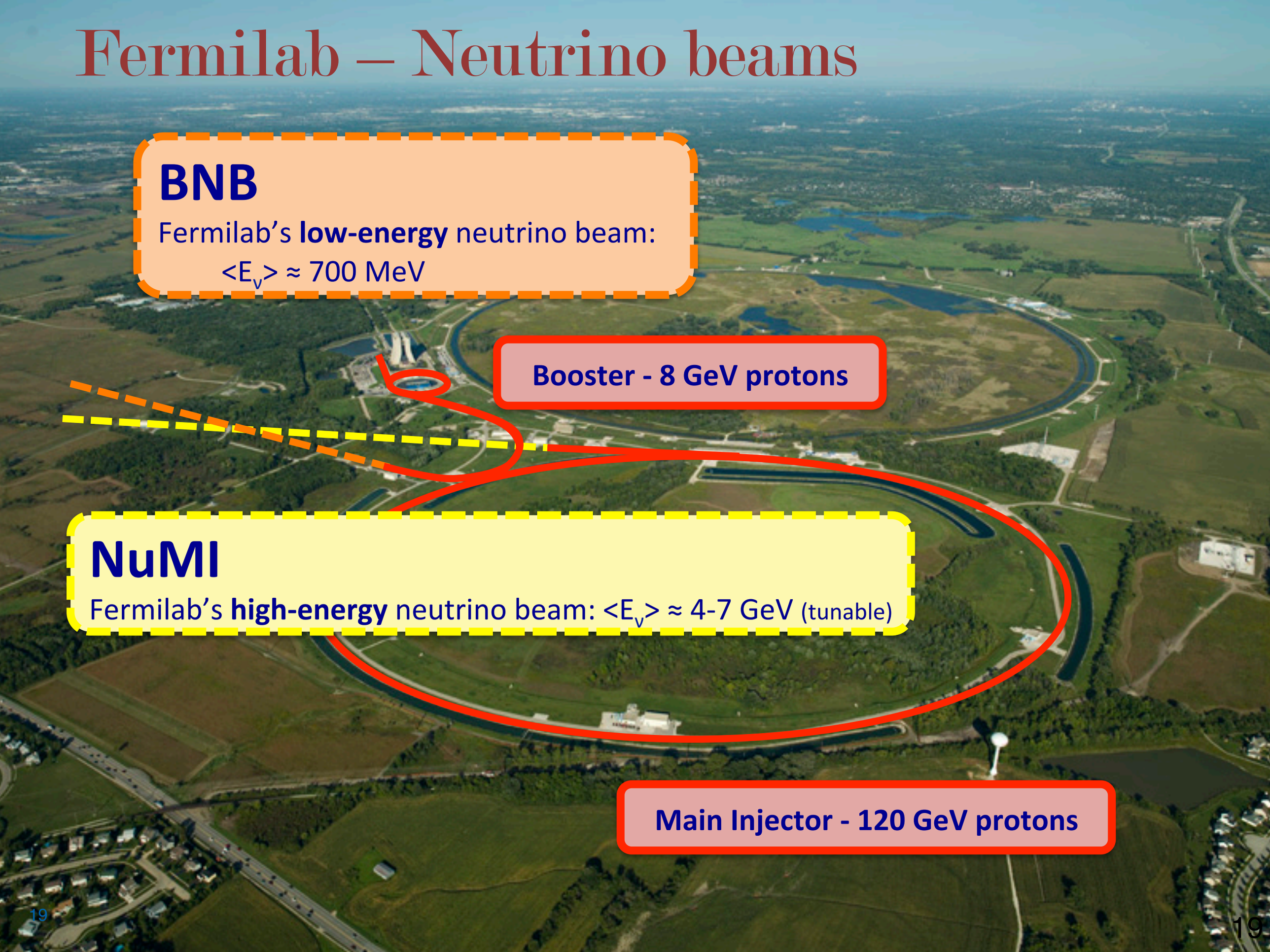


Booster Neutrino Beam (BNB)

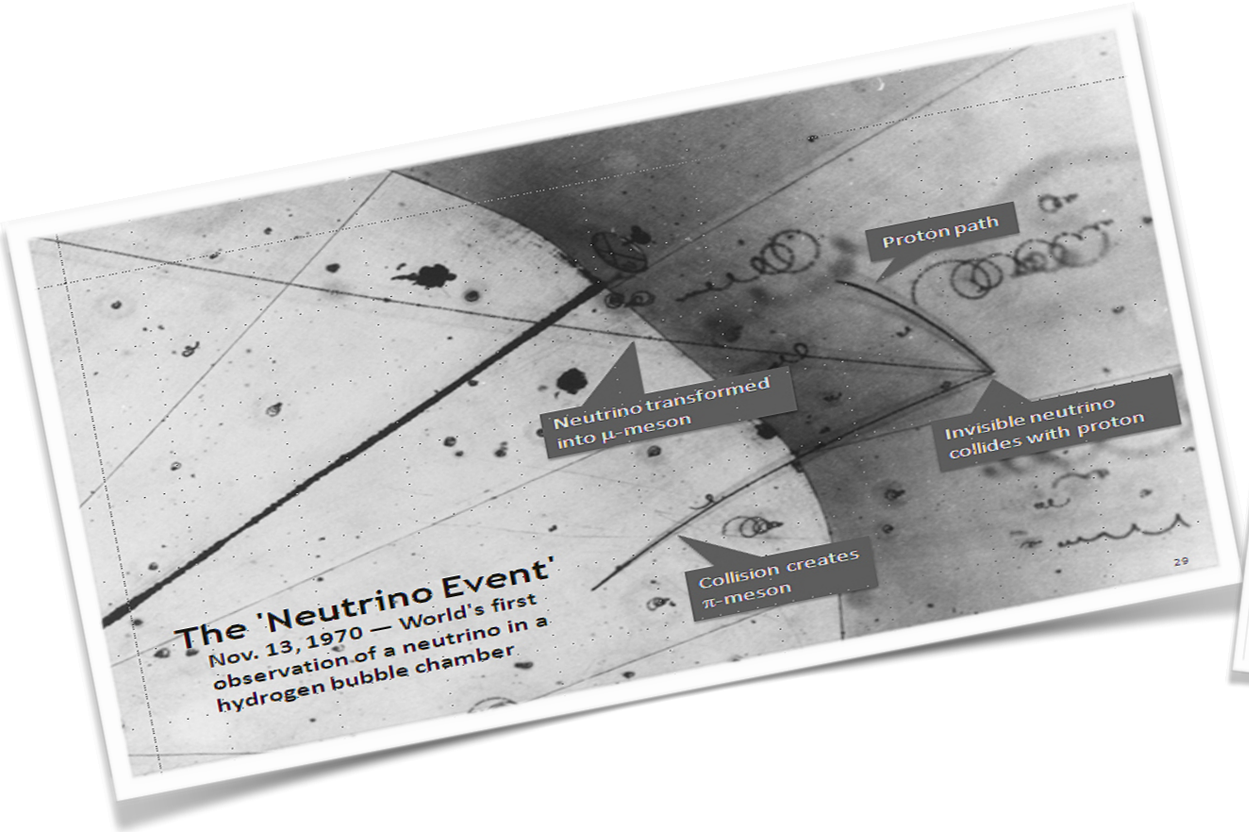
Fermilab's **low-energy** neutrino beam:

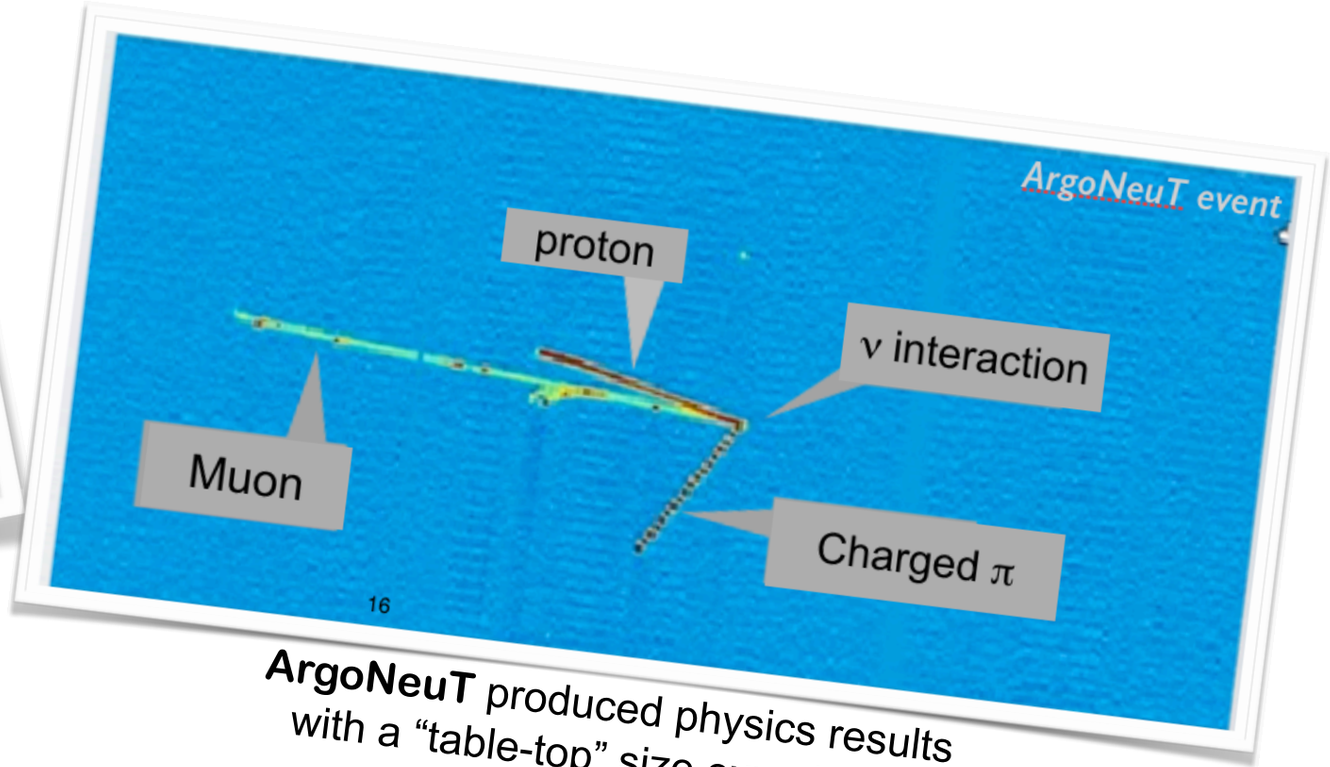
$\langle E_\nu \rangle \approx 700$ MeV

Fermilab – Neutrino beams



Why **Liquid Argon Time Projection Chamber**?

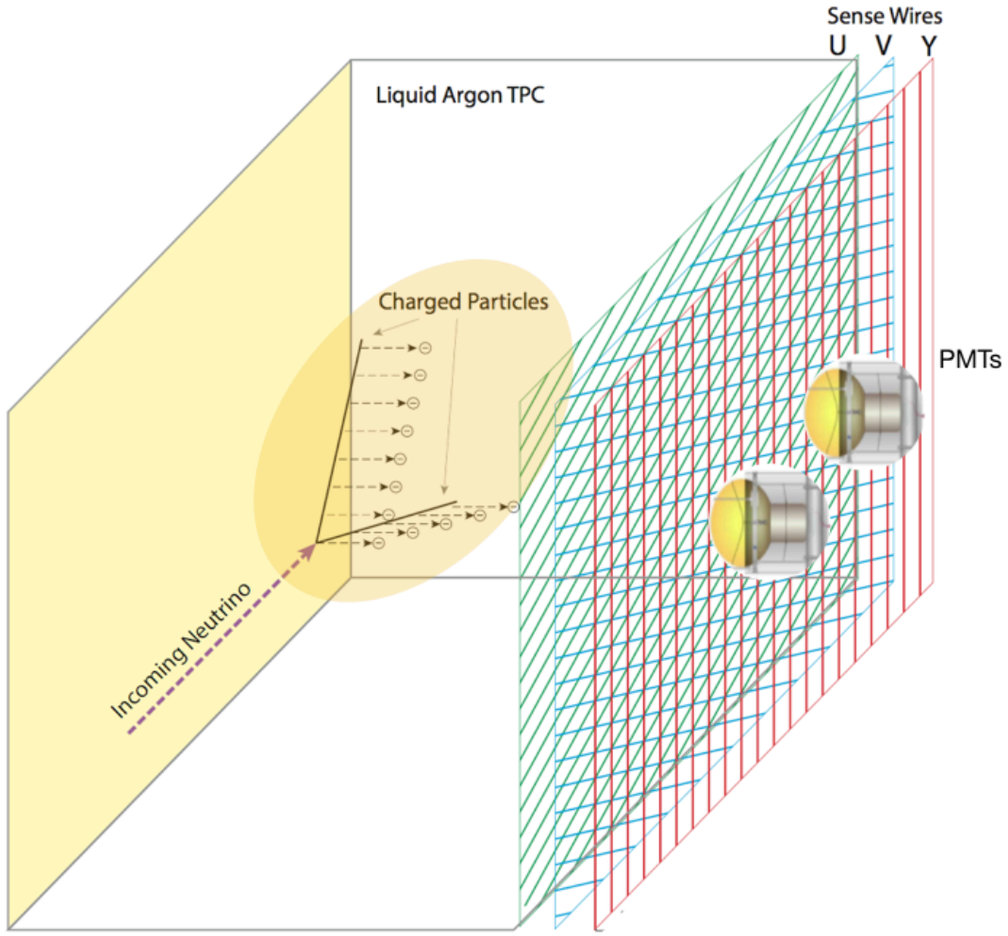




ArgoNeuT produced physics results with a "table-top" size experiment [240 Kg LArTPC]

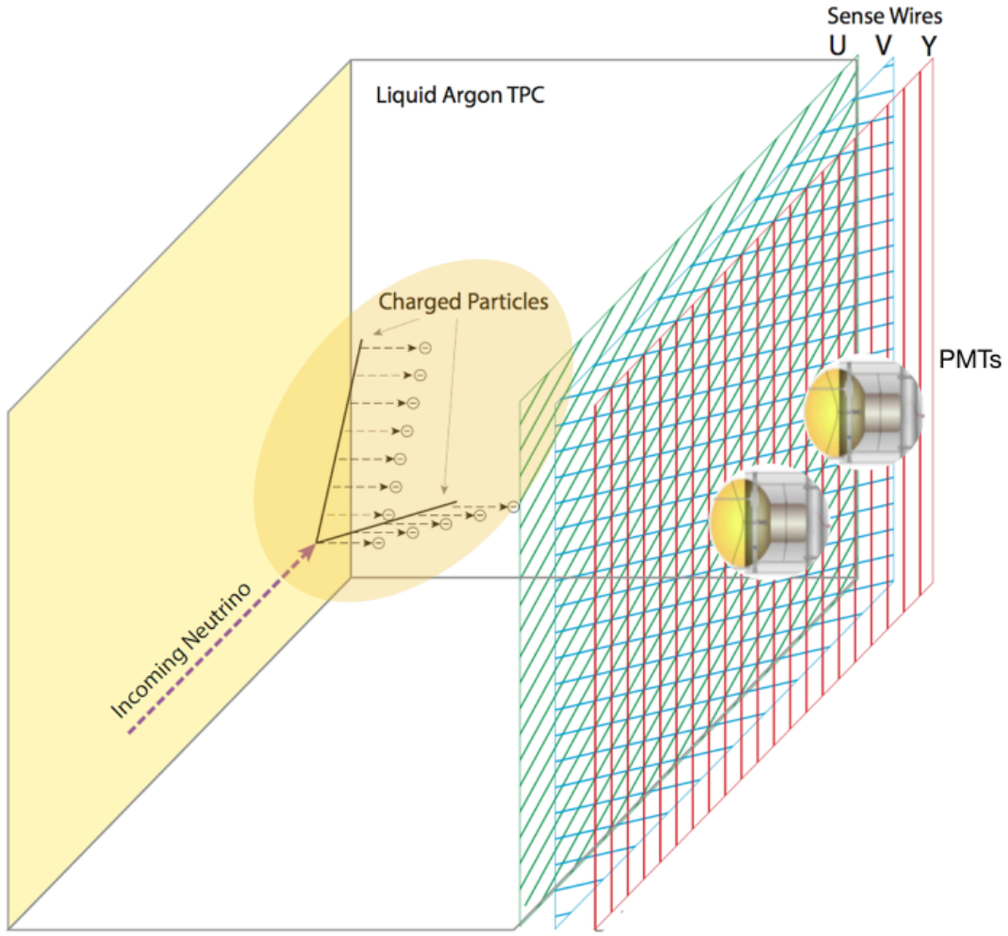
LAr TPC: Bubble chamber quality of data with added calorimetry

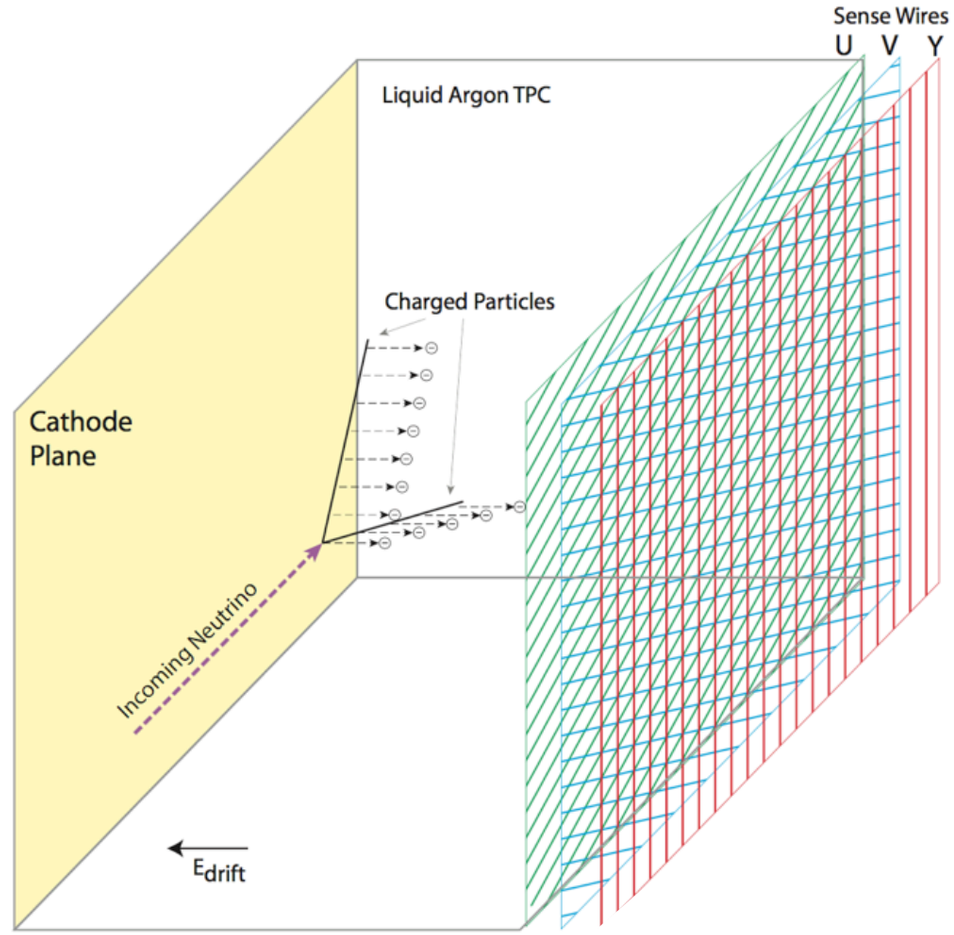
LArTPC at work



Charged particles in LAr produce free <u>ionization electrons</u> and <u>scintillation light</u>

LArTPC at work

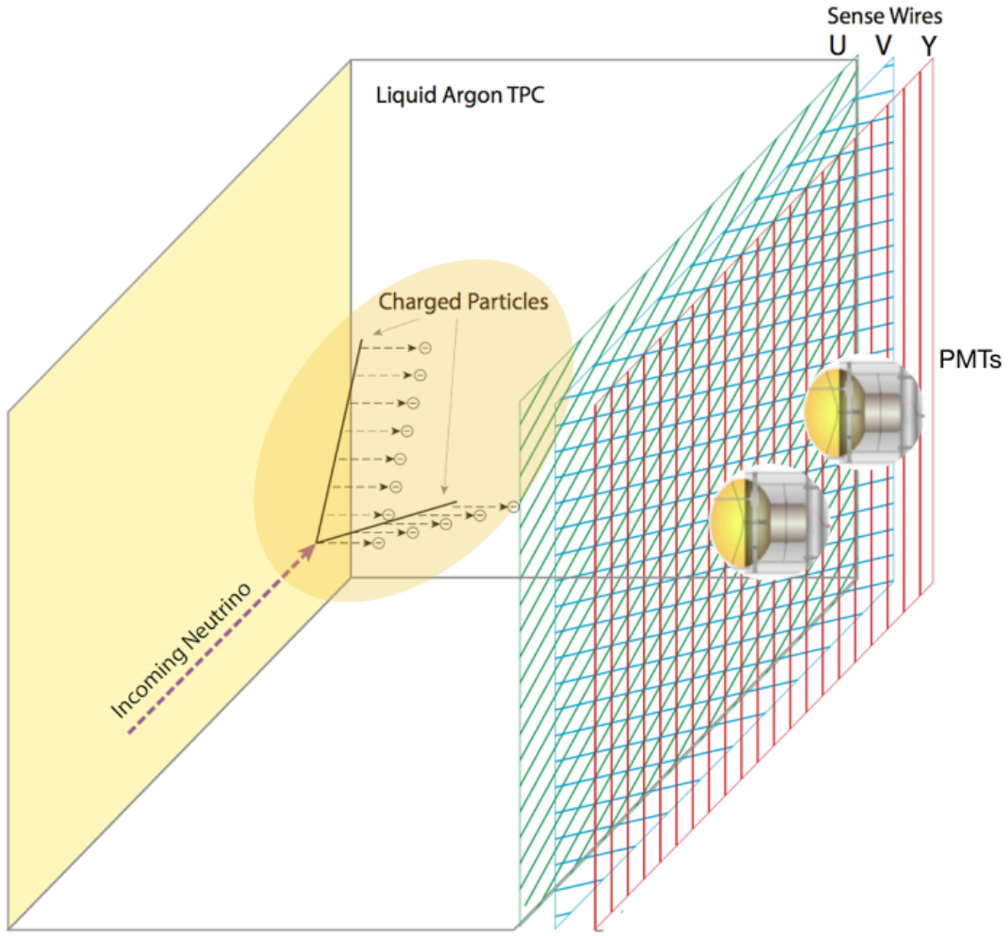


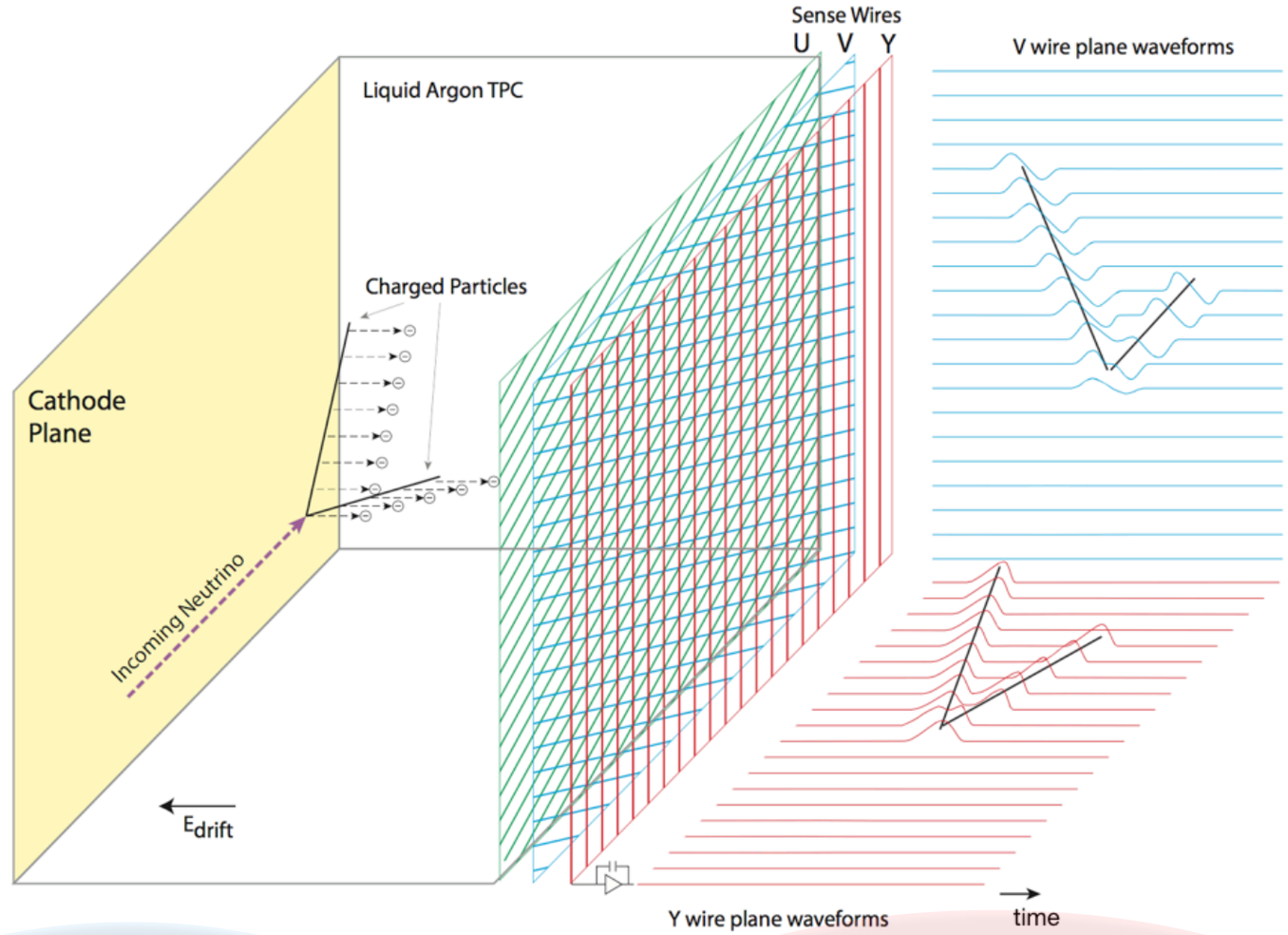


Charged particles in LAr produce free <u>ionization electrons</u> and <u>scintillation light</u>

Ionization charge <u>drifts</u> <u>in a uniform electric</u> field towards the readout wire-planes

LArTPC at work



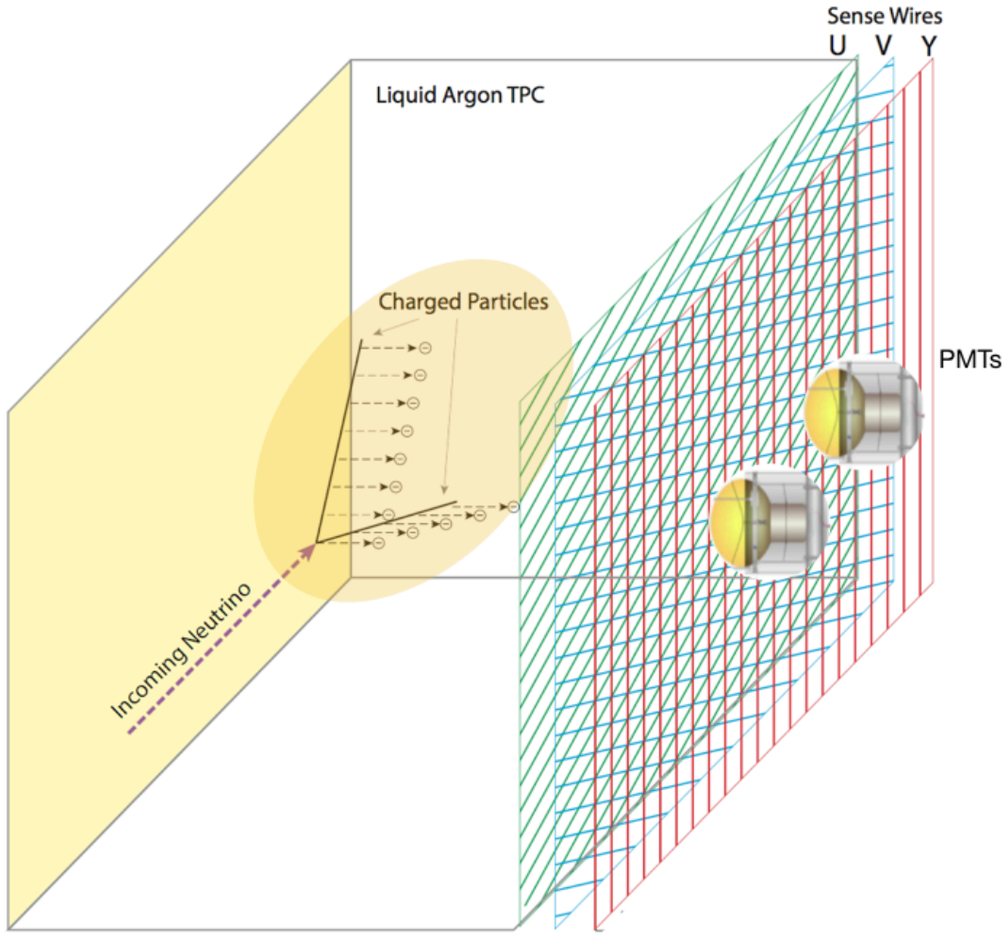


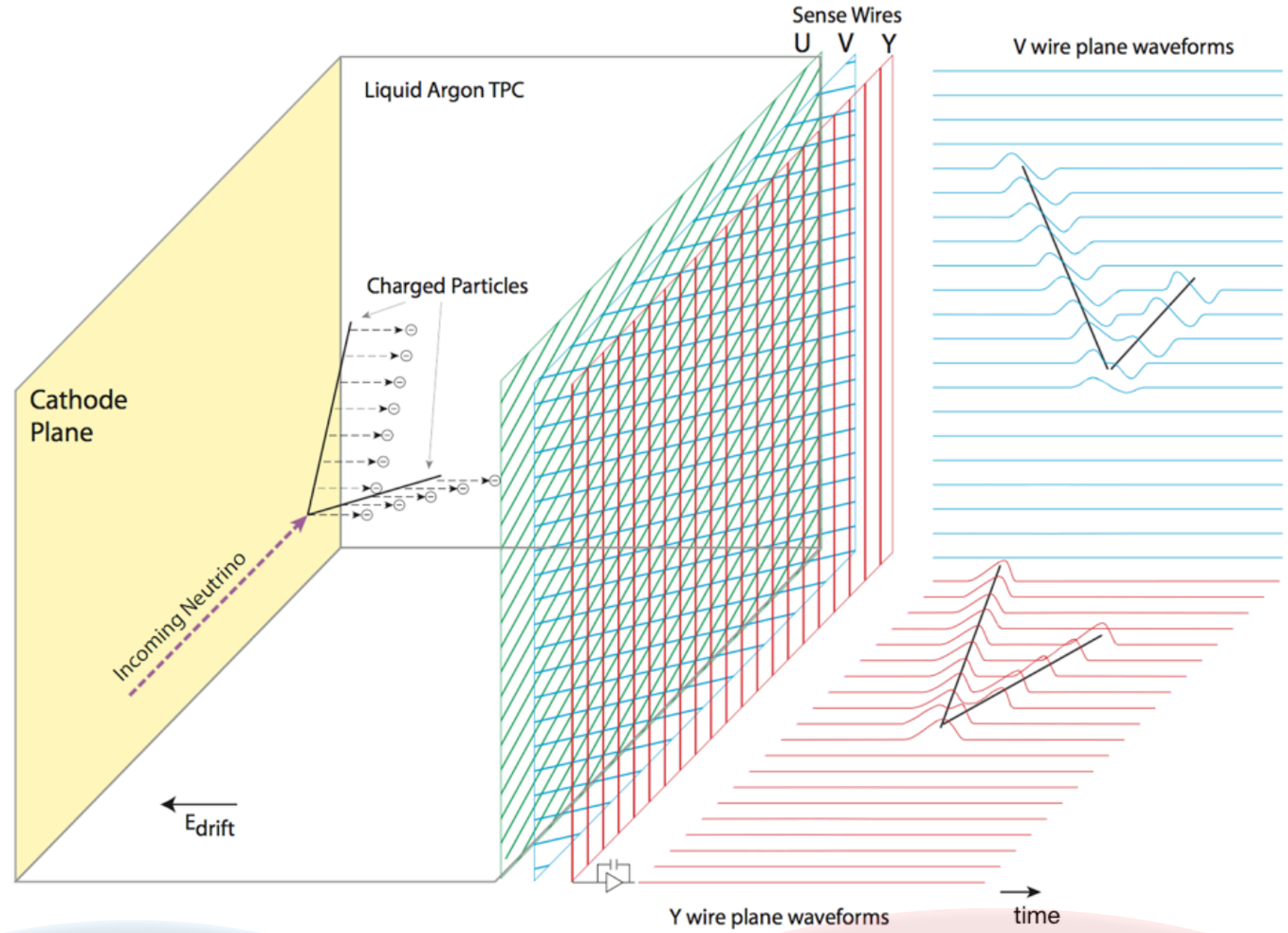
Charged particles in LAr produce free <u>ionization electrons</u> and <u>scintillation light</u>

Ionization charge <u>drifts</u> <u>in a uniform electric</u> 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]

LArTPC at work





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

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VUV photons propagate and are shifted into VIS photons

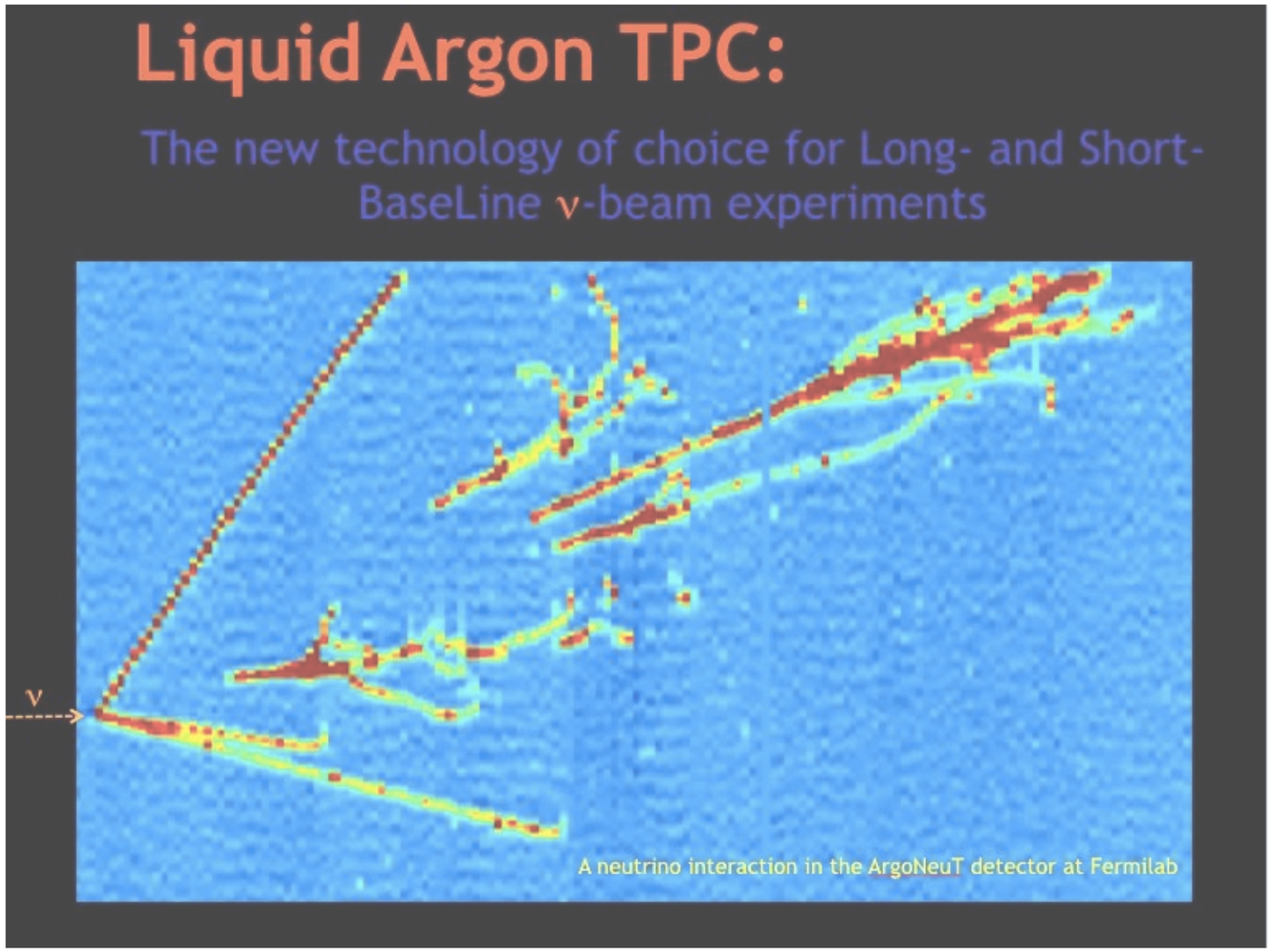
Scintillation light signals from PMTs give event timing

How it looks like?

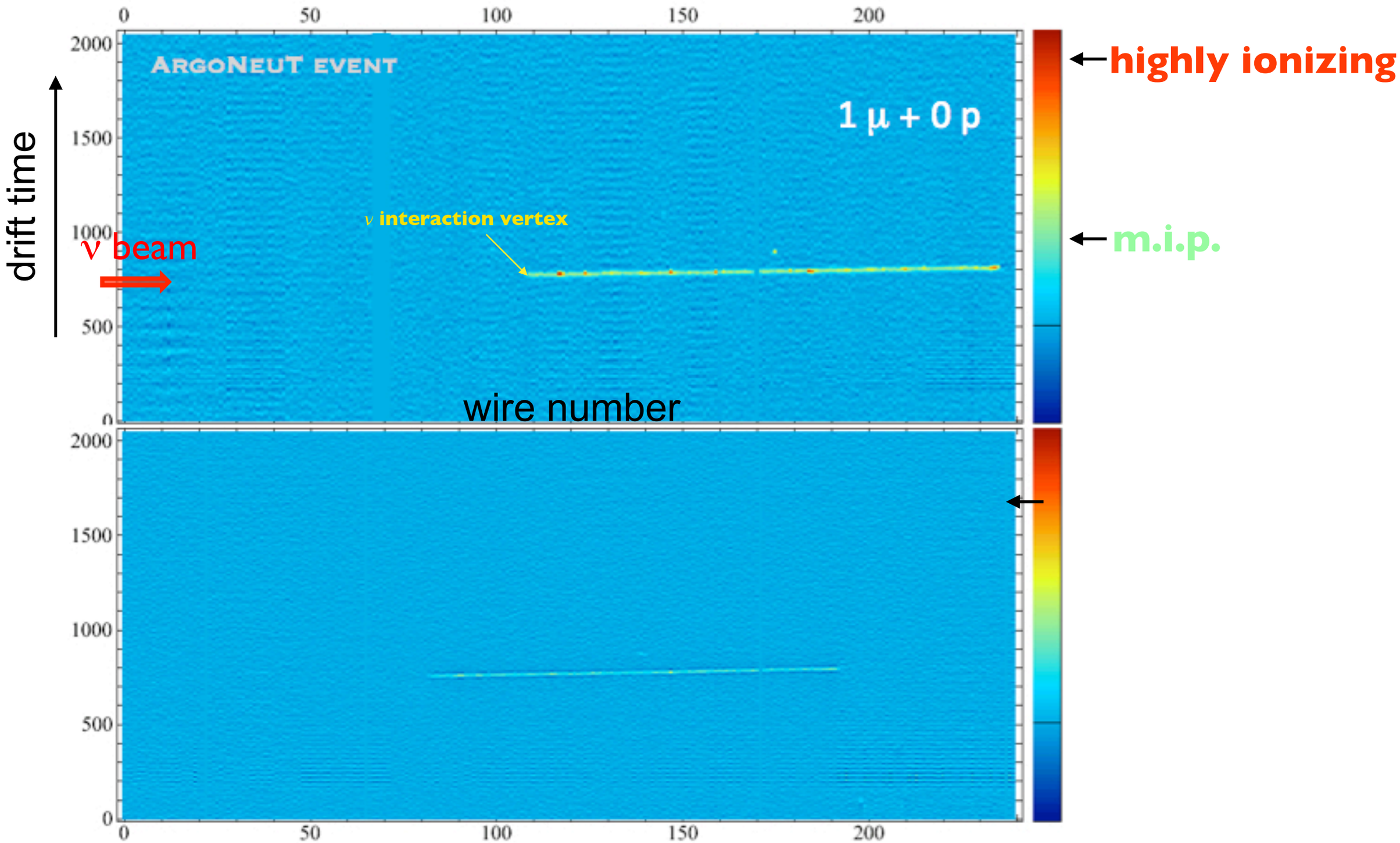
Internal view of the ICARUS-T600 TPC

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**.

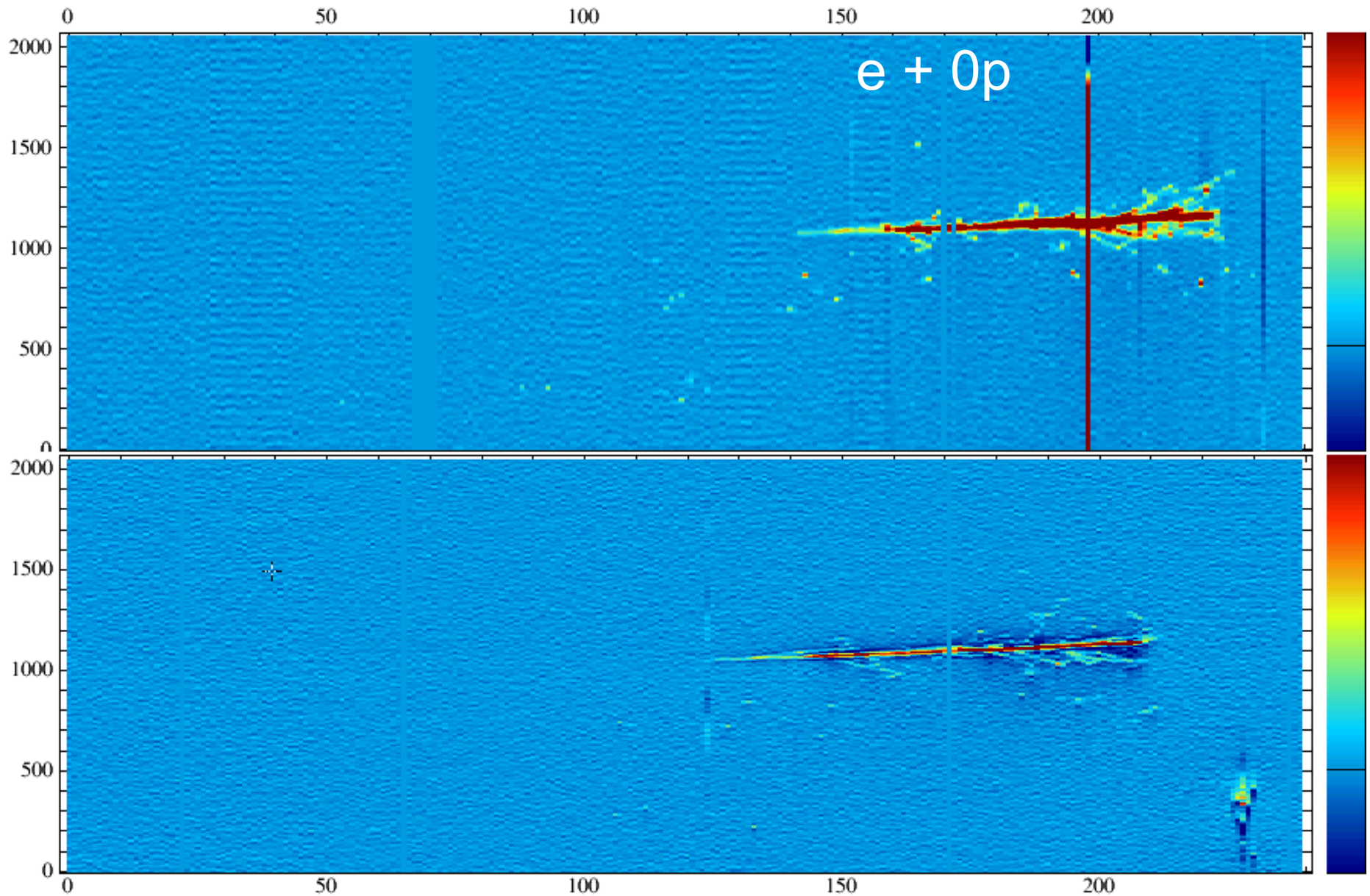


From "easy" to progressively more complicated topologies...



2D views from two wire planes

From “easy” to progressively more complicated topologies...



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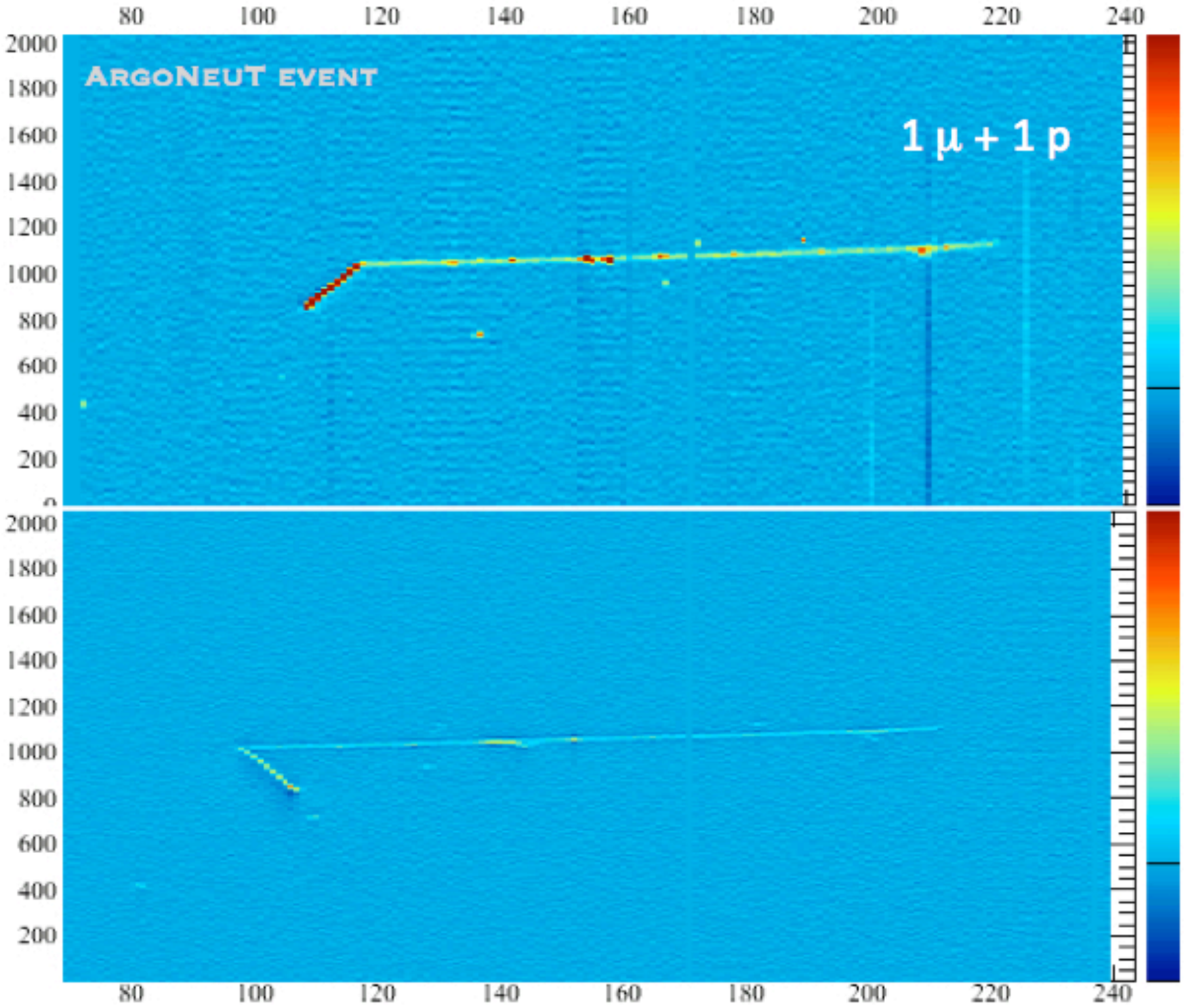

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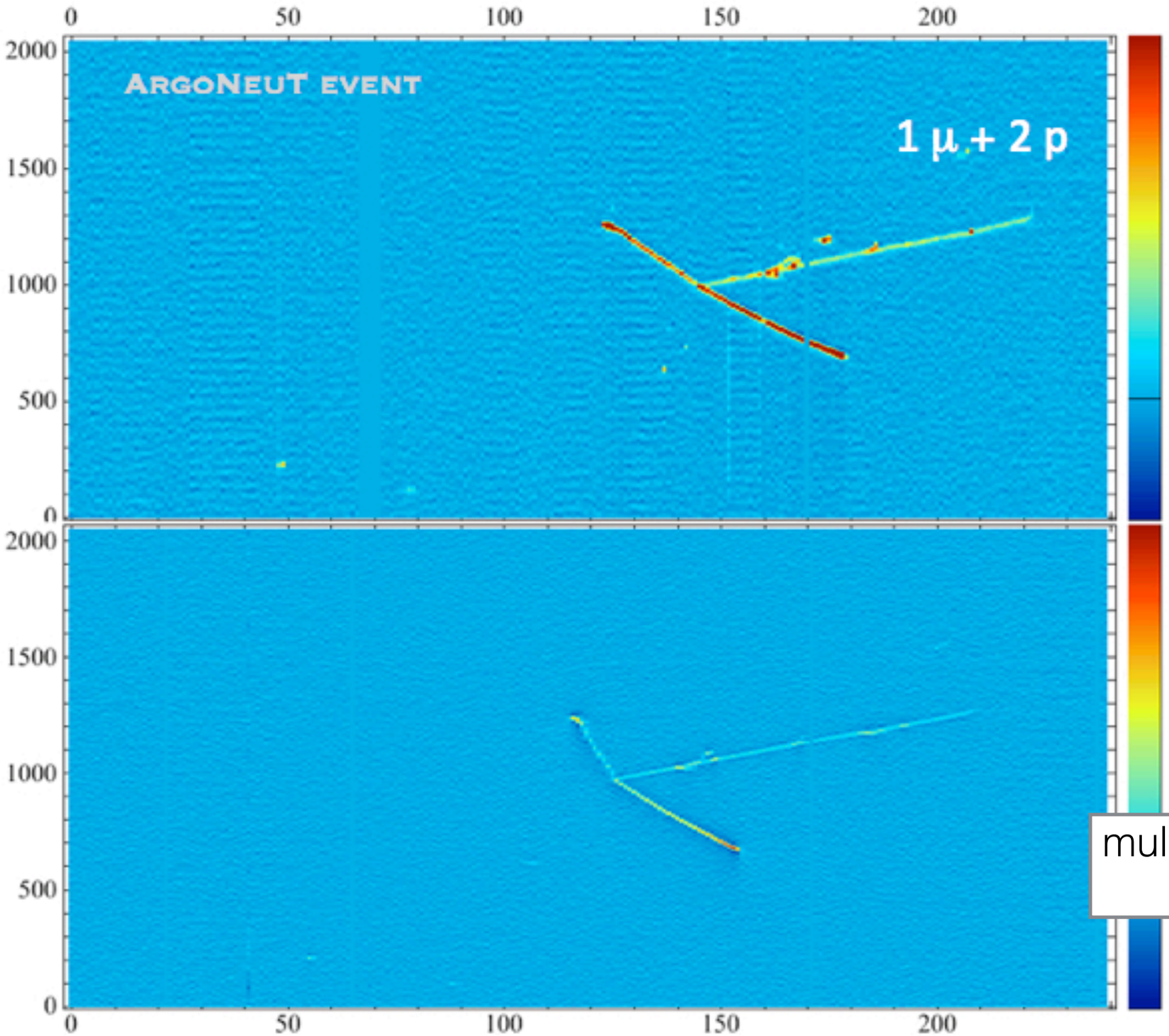

multi-p accompanying the leading muon

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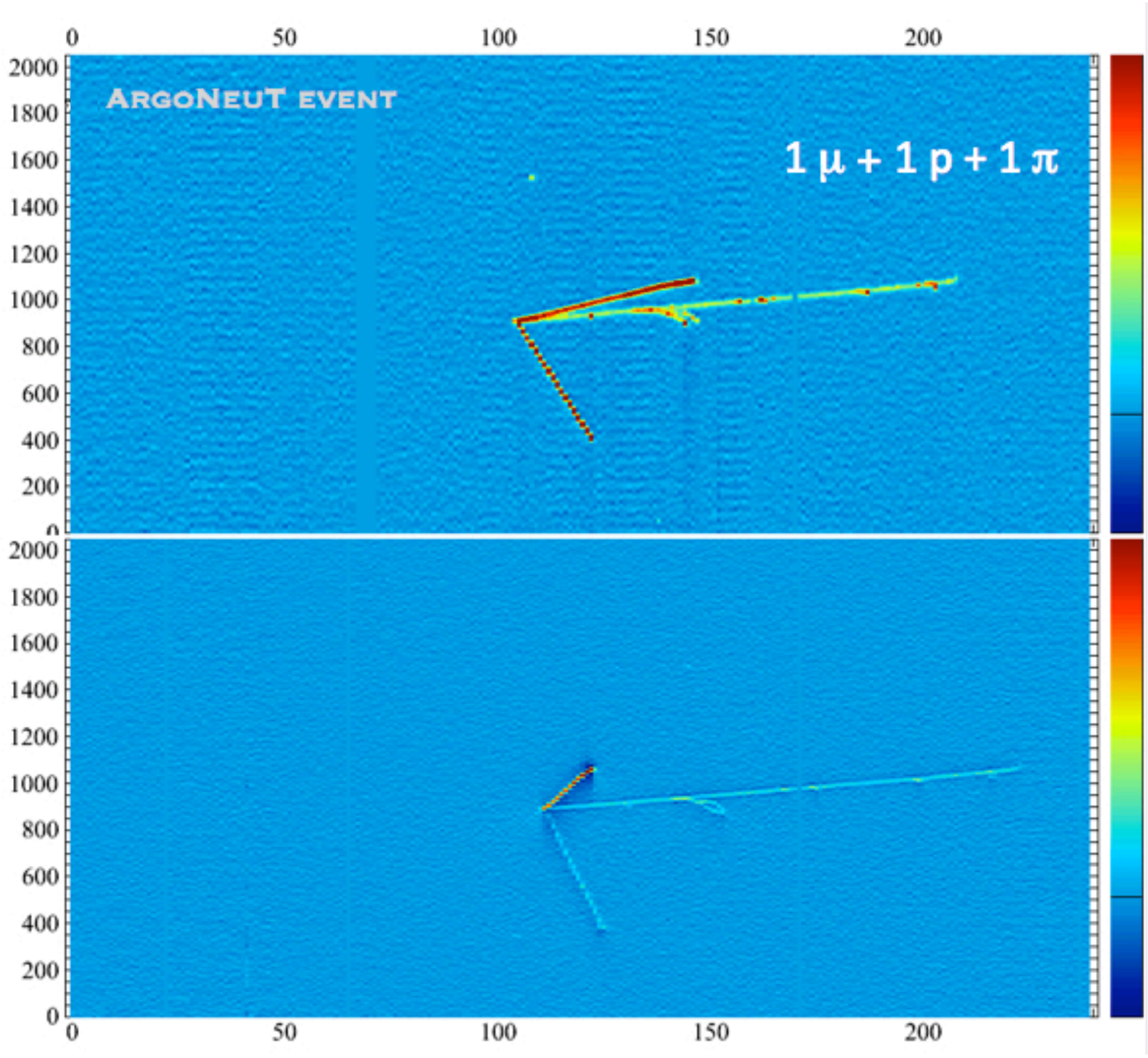

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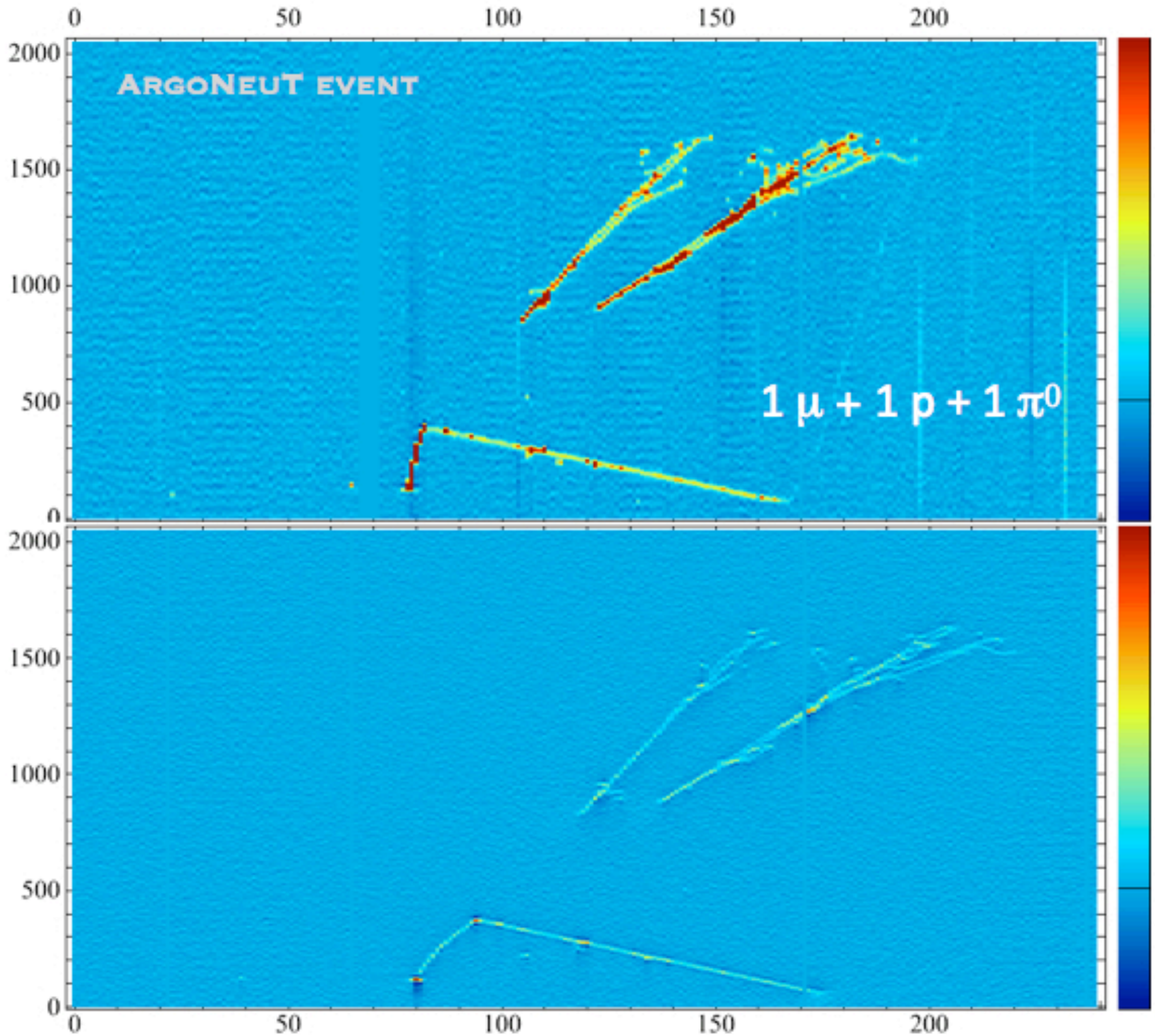

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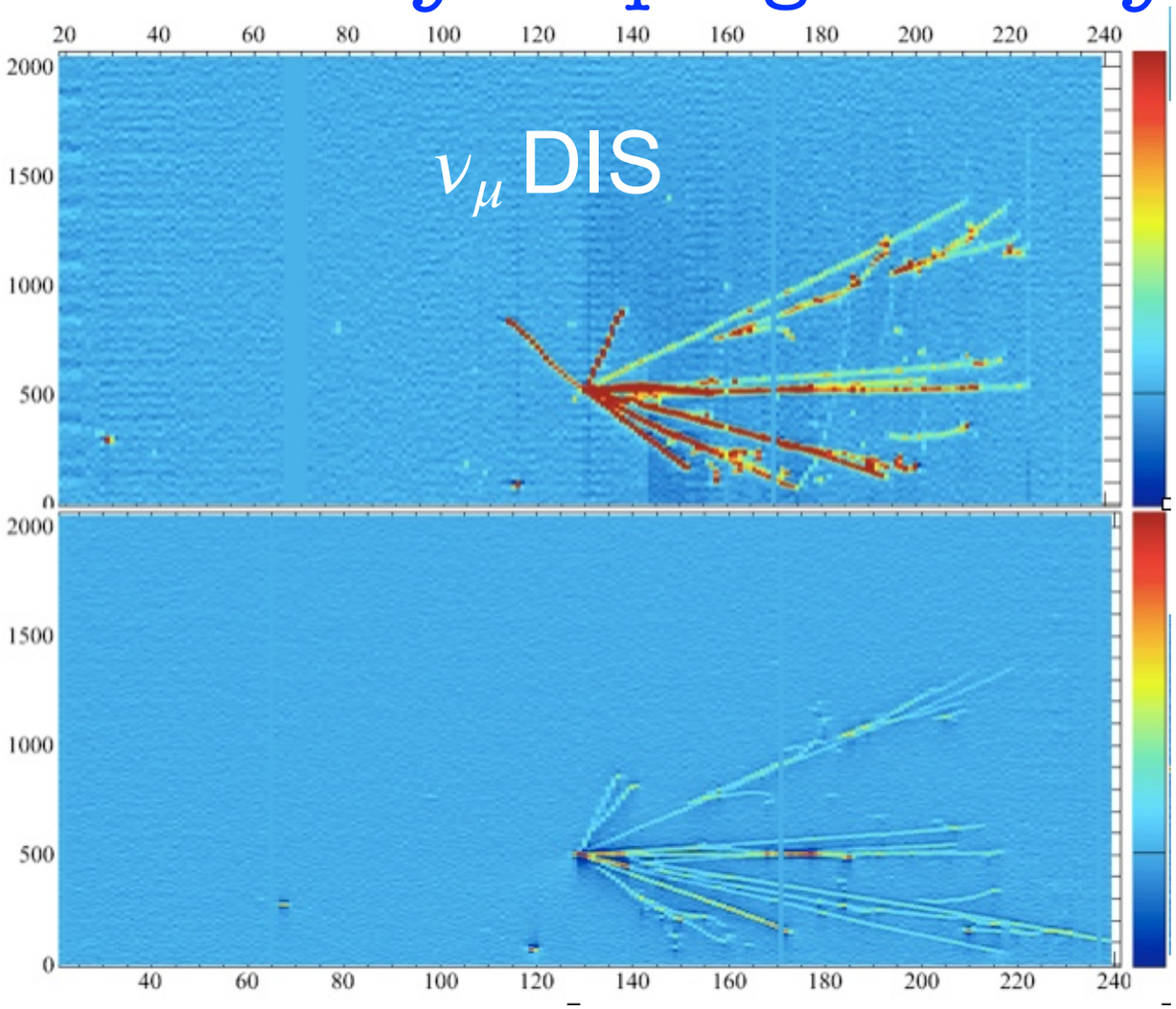
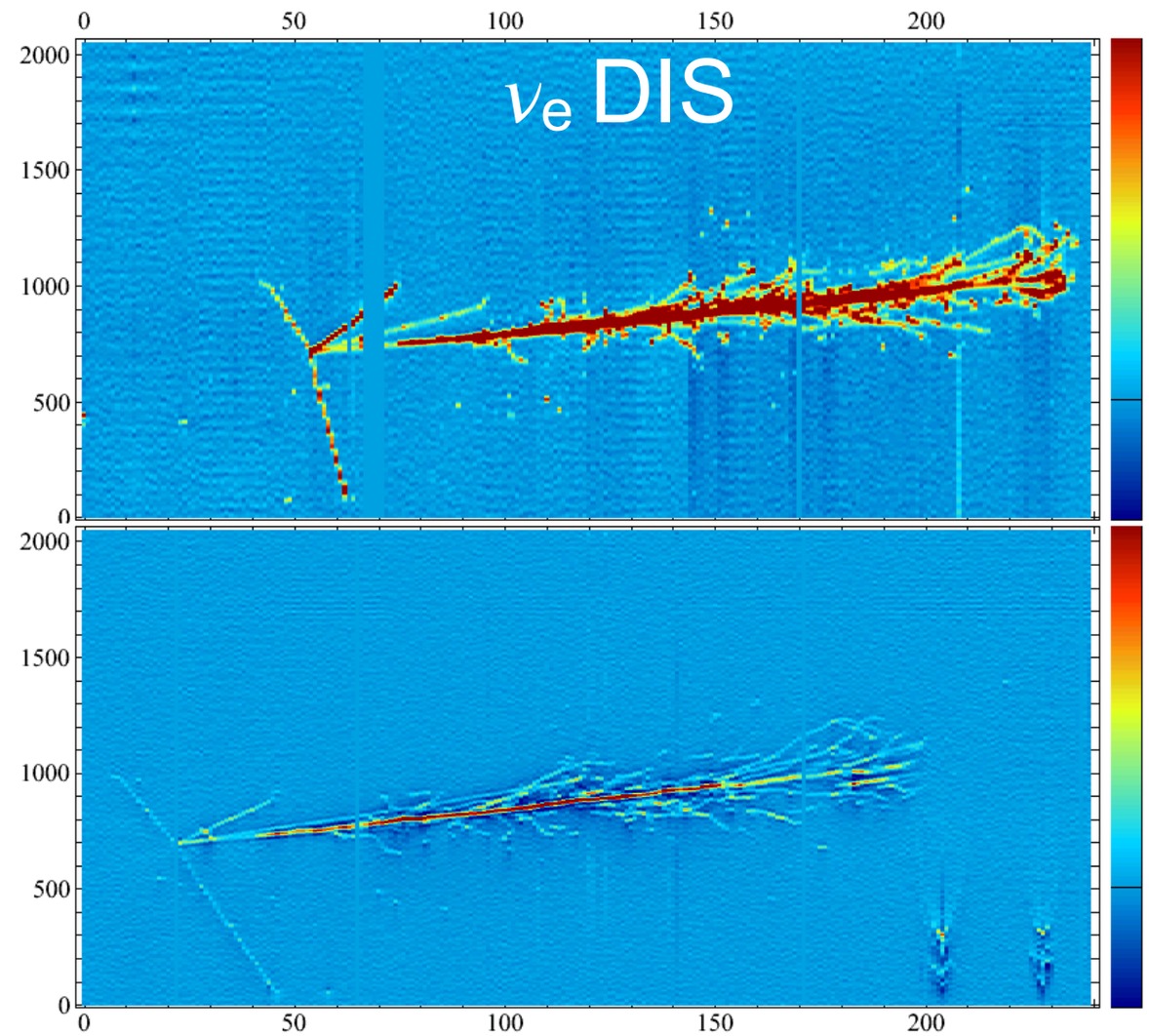
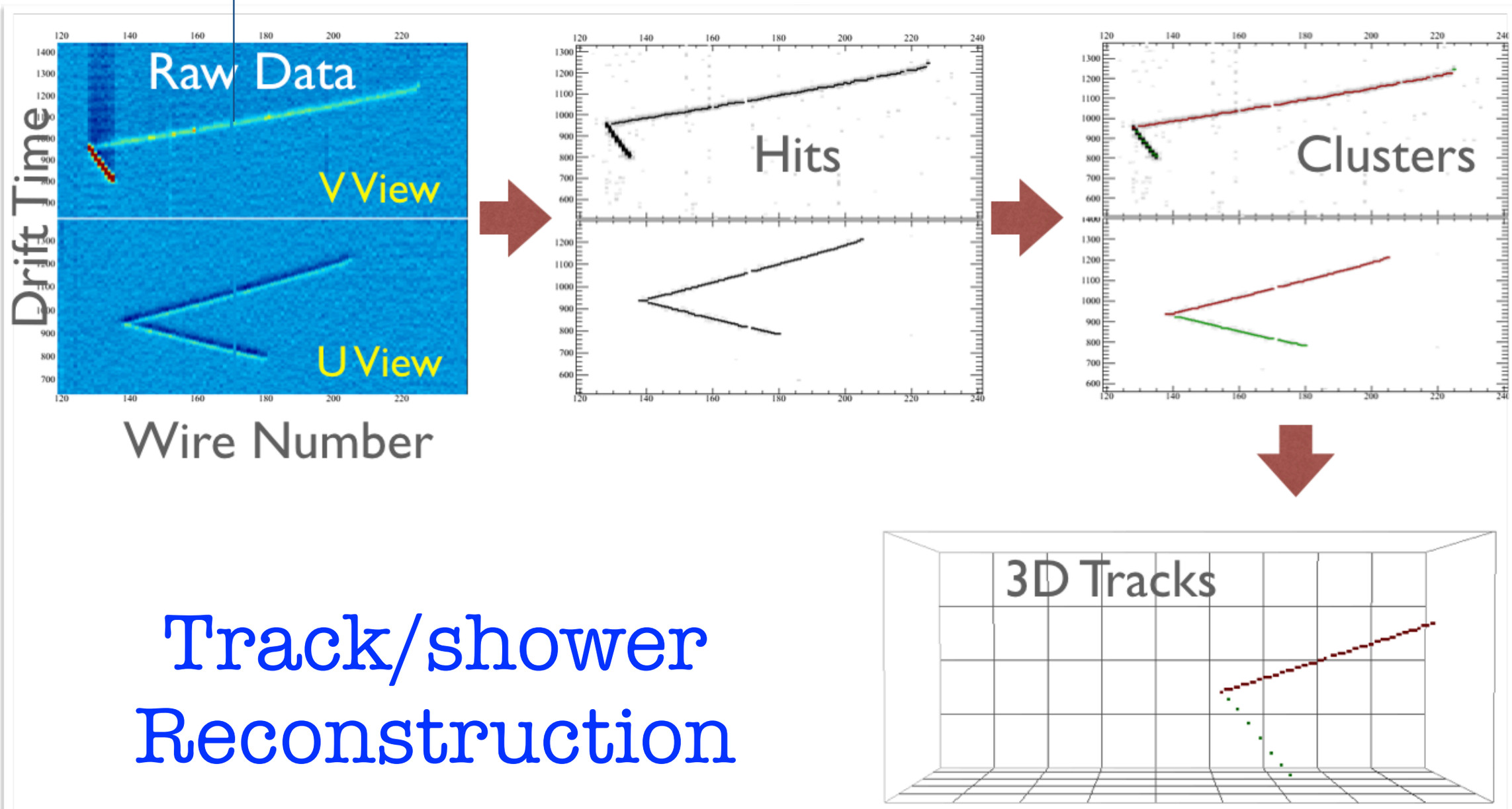


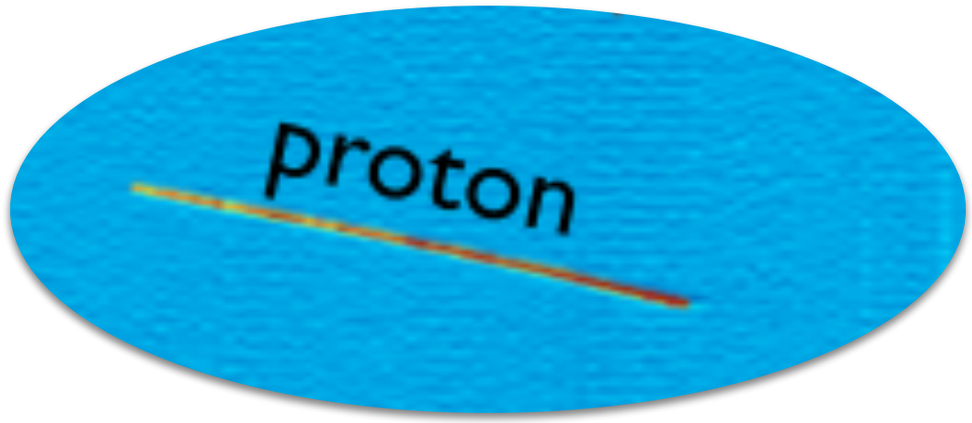


LArTPC at work: imagining and energy

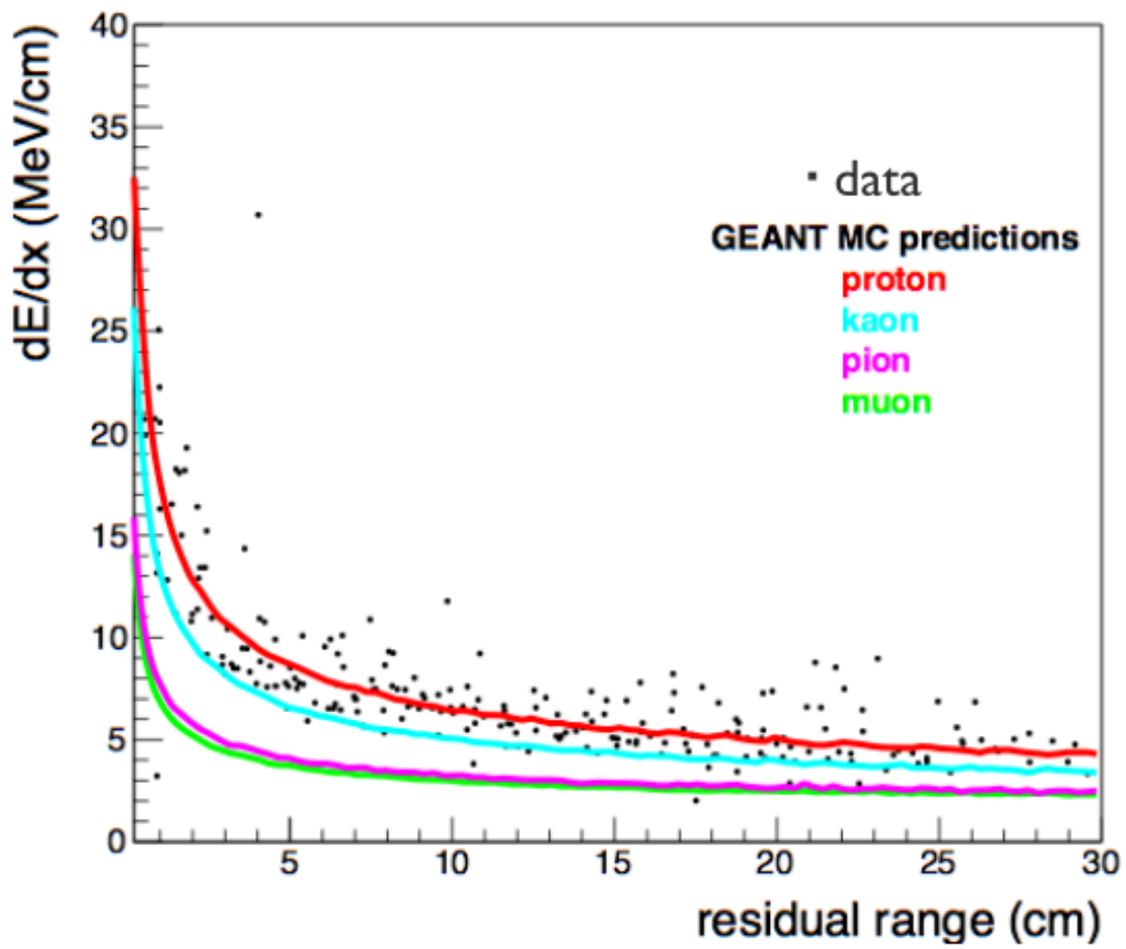


Track/shower Reconstruction

LArTPC at work: imagining and energy



Calorimetry & Particle Identification



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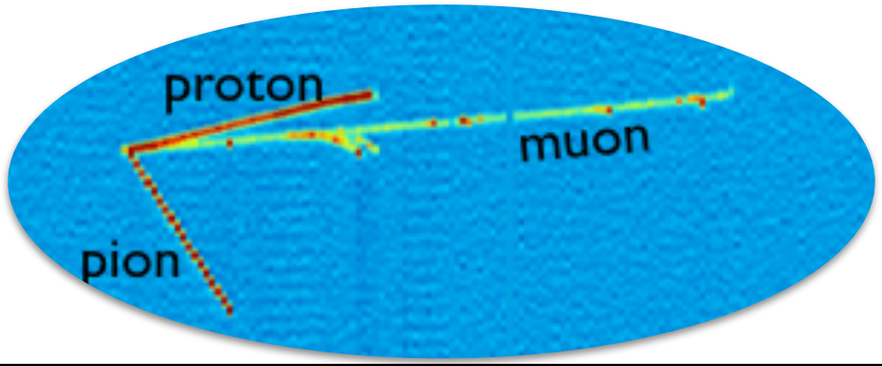
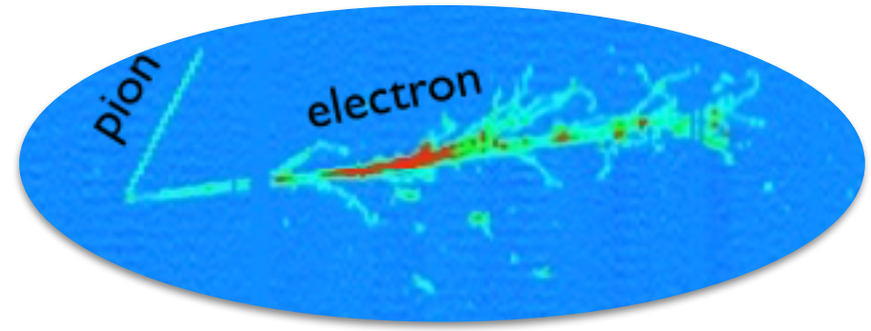
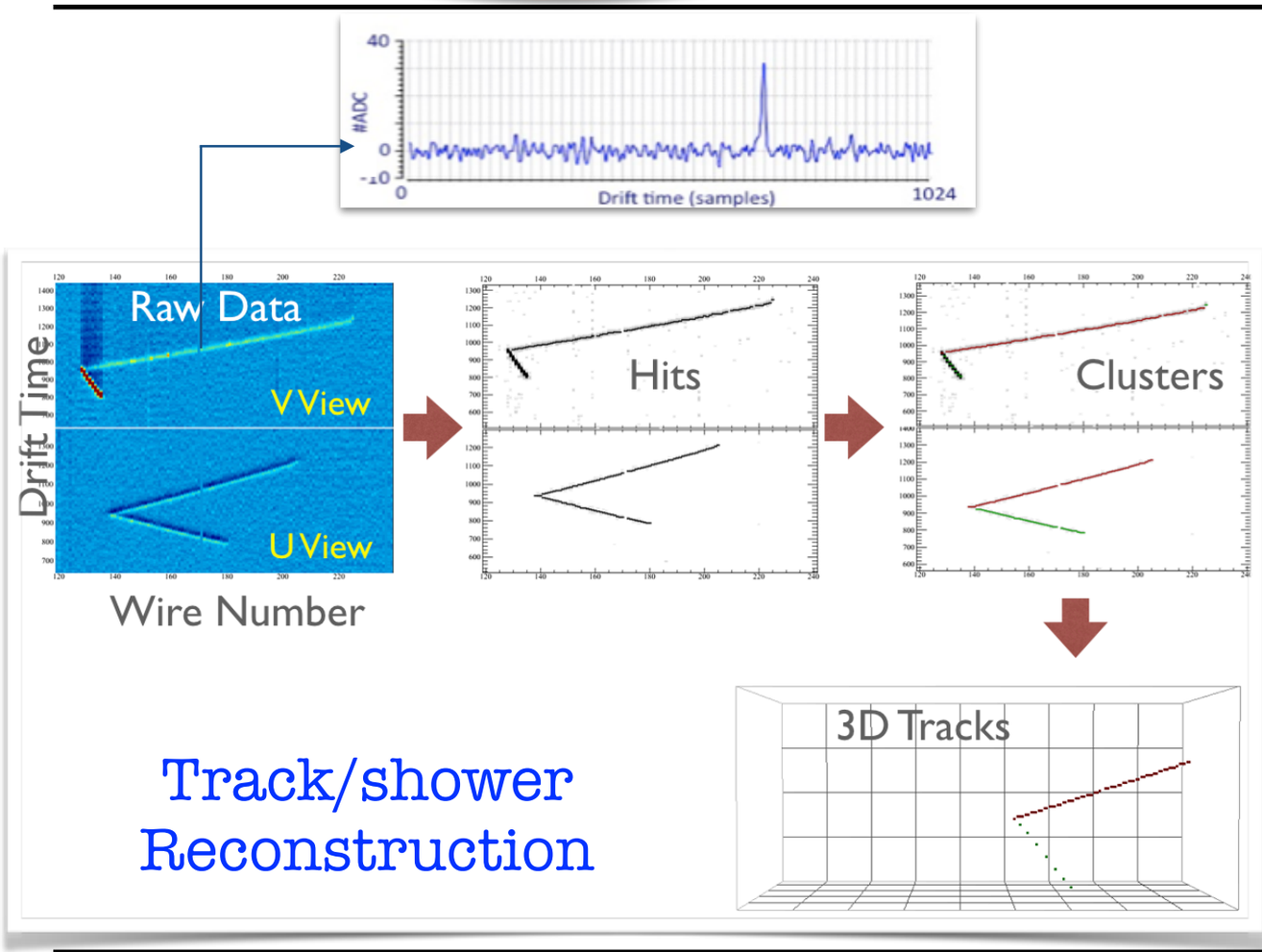
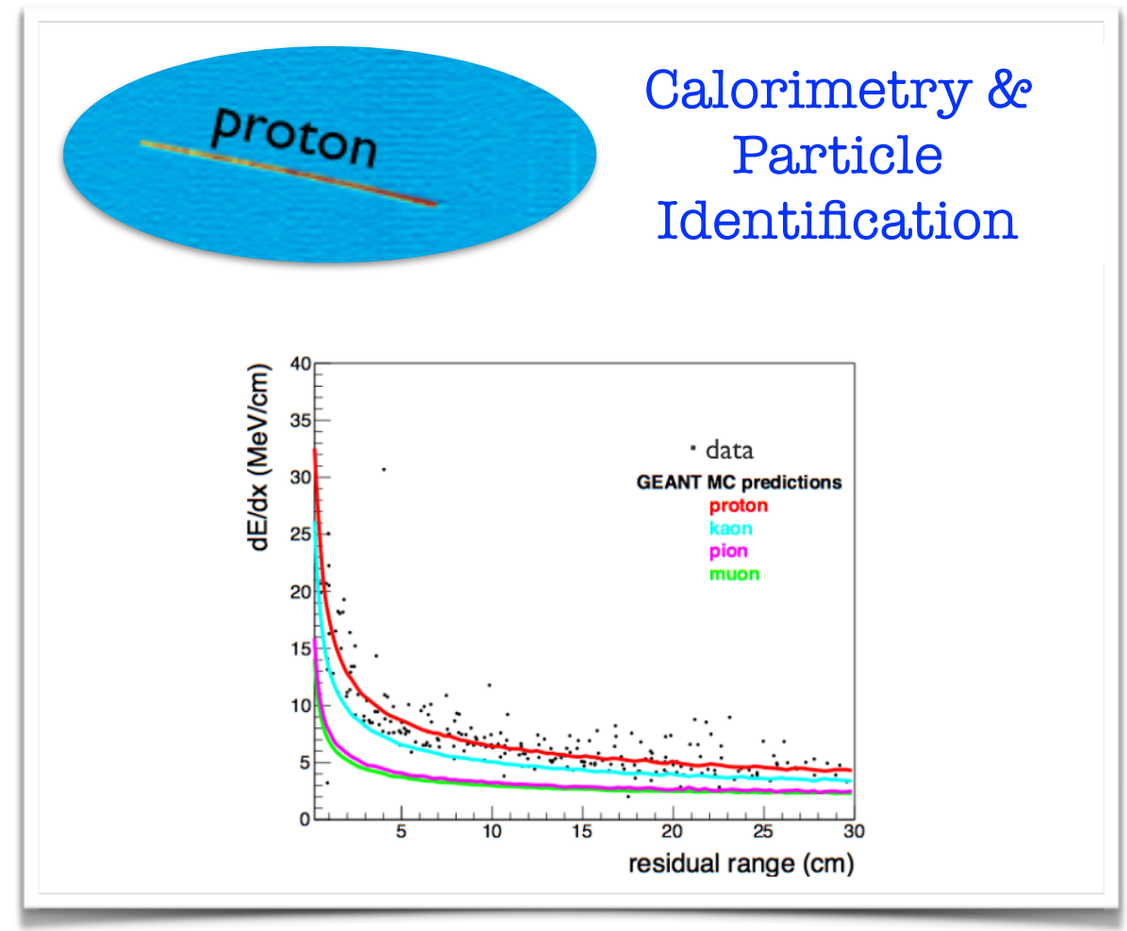






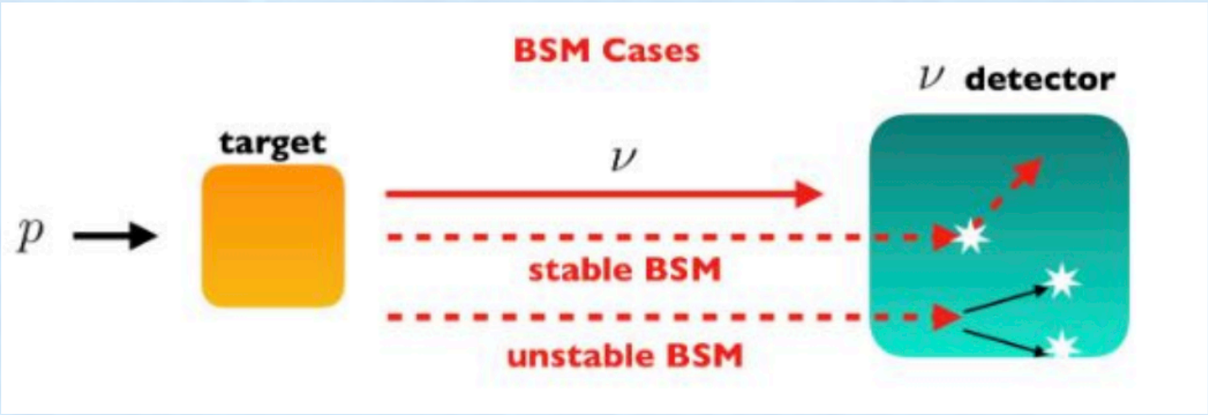


- Multiple 2D and the 3D reconstruction of charged particles tracks ⇒ **Imaging**
- Total charge proportional to the deposited Energy ⇒ **Calorimetry**
- dE/dx along the track ⇒ **Particle Identification**

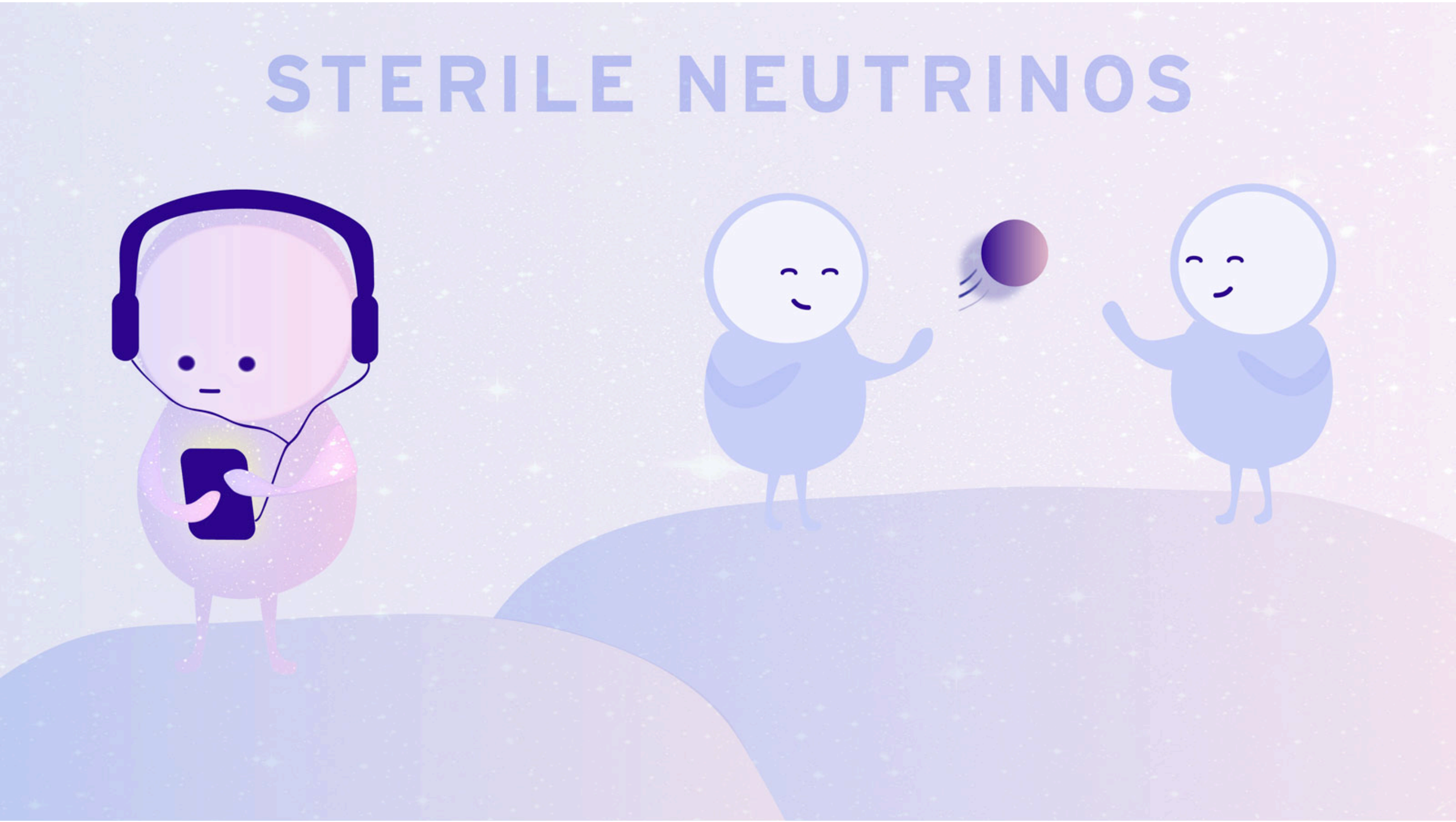
New Physics Opportunities

- The LAr TPC technology, with unprecedented event reconstruction, excellent particle identification, fine-sampling calorimetry, detection isotropy and low energy threshold opens up invaluable opportunities to search for **new physics scenarios Beyond the Standard Model and hidden particles**.
- The proximity to the beam target and large detector mass make LAr TPC detectors 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
    …

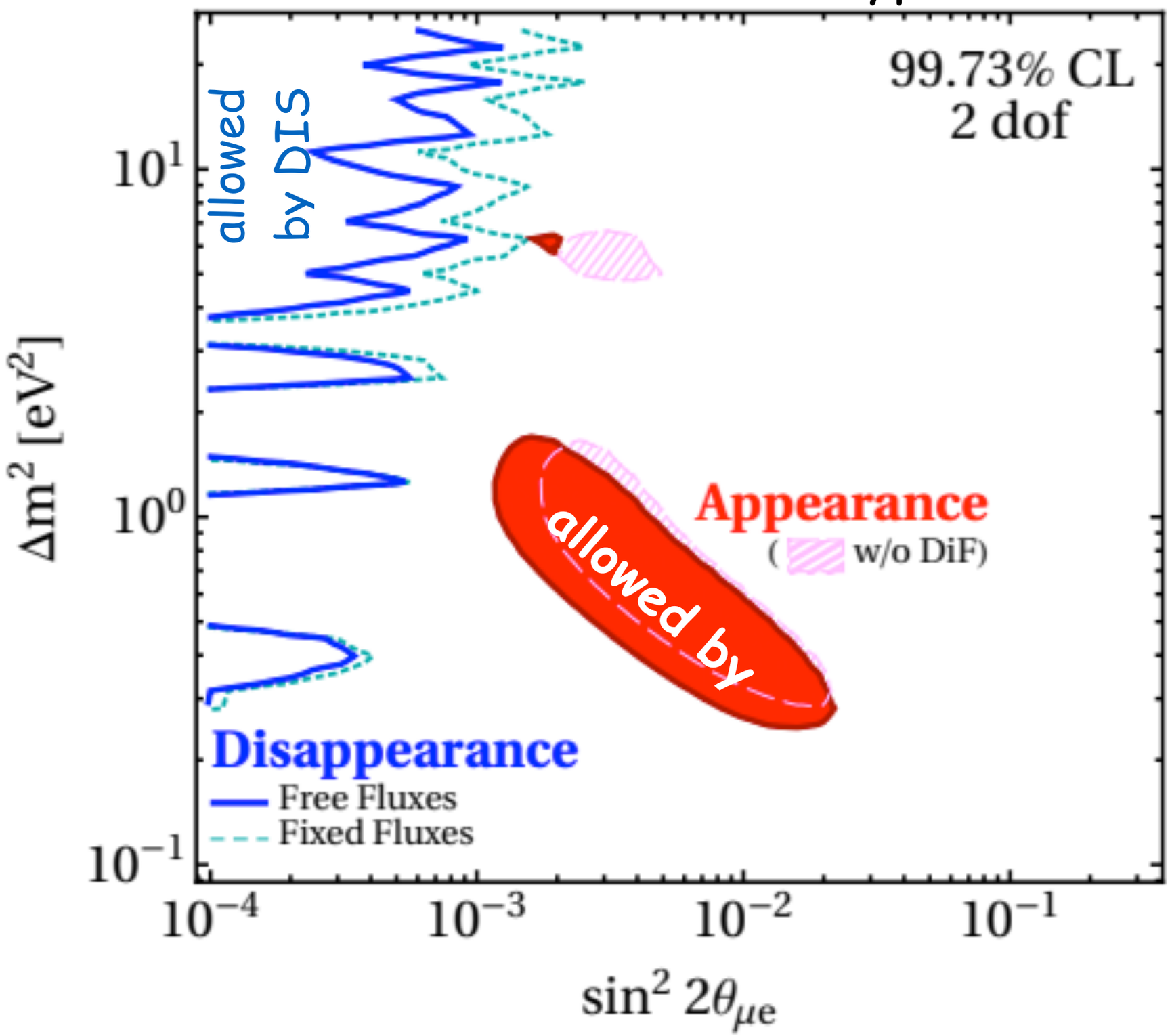


STERILE NEUTRINOS



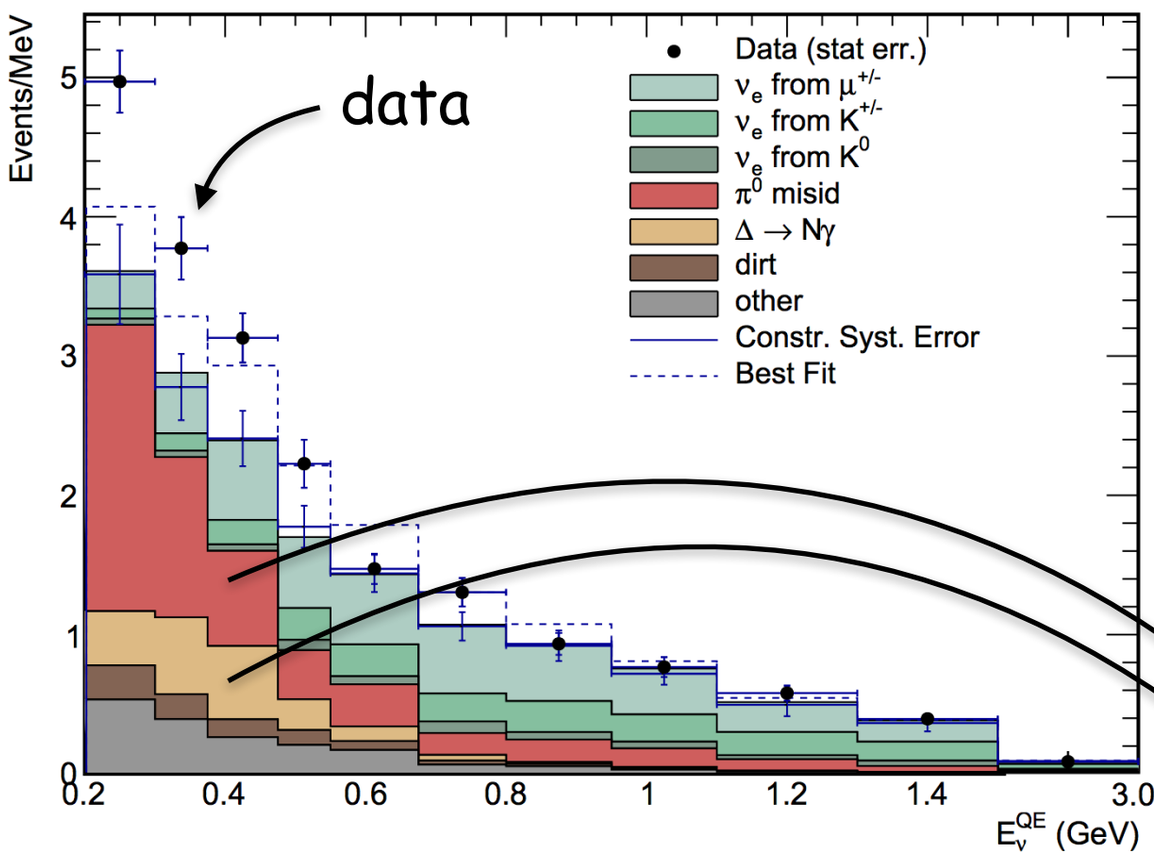
The Light Sterile Neutrino Experimental Landscape

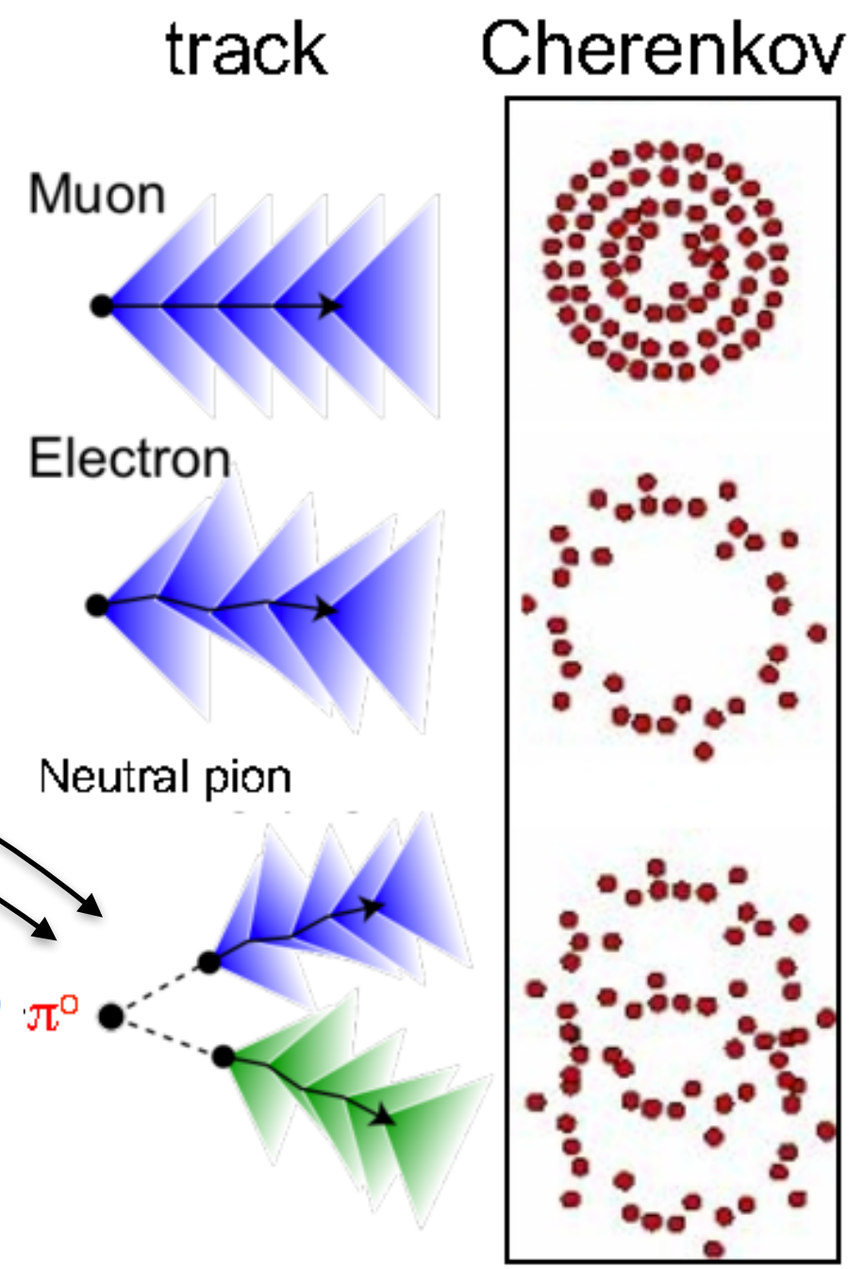
The test of the sterile hypothesis

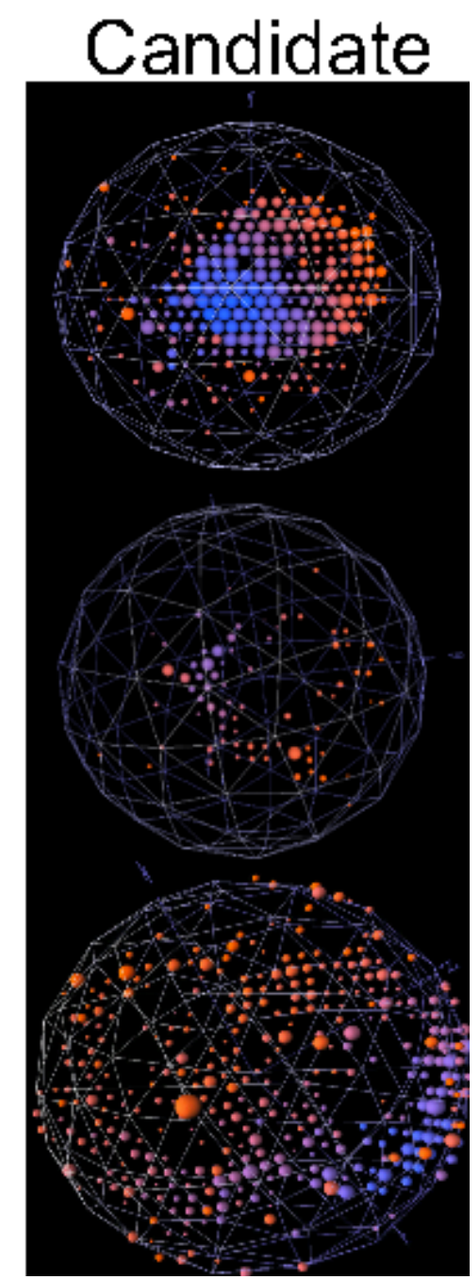


Sterile Neutrinos

What is going on???

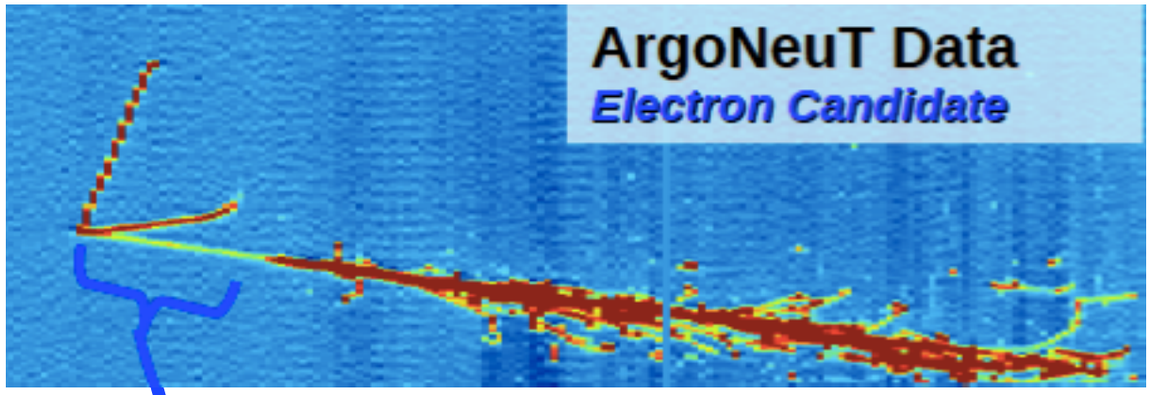


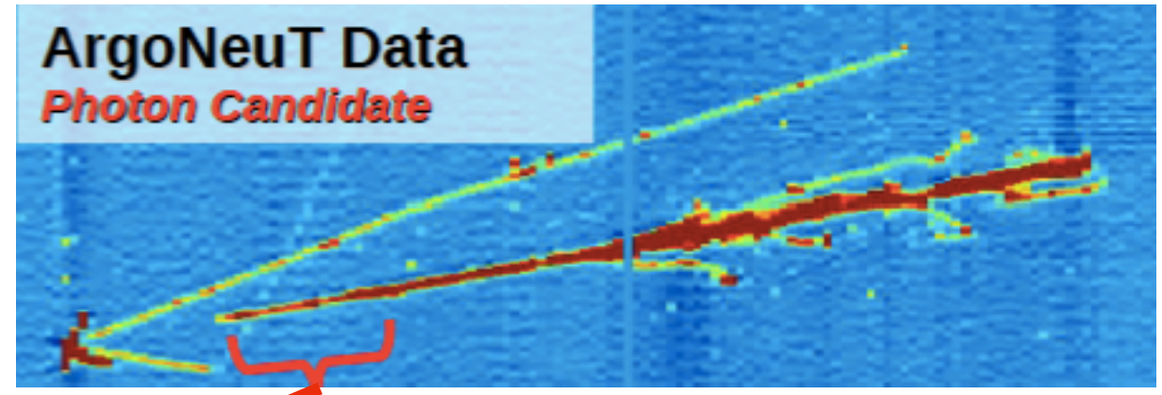


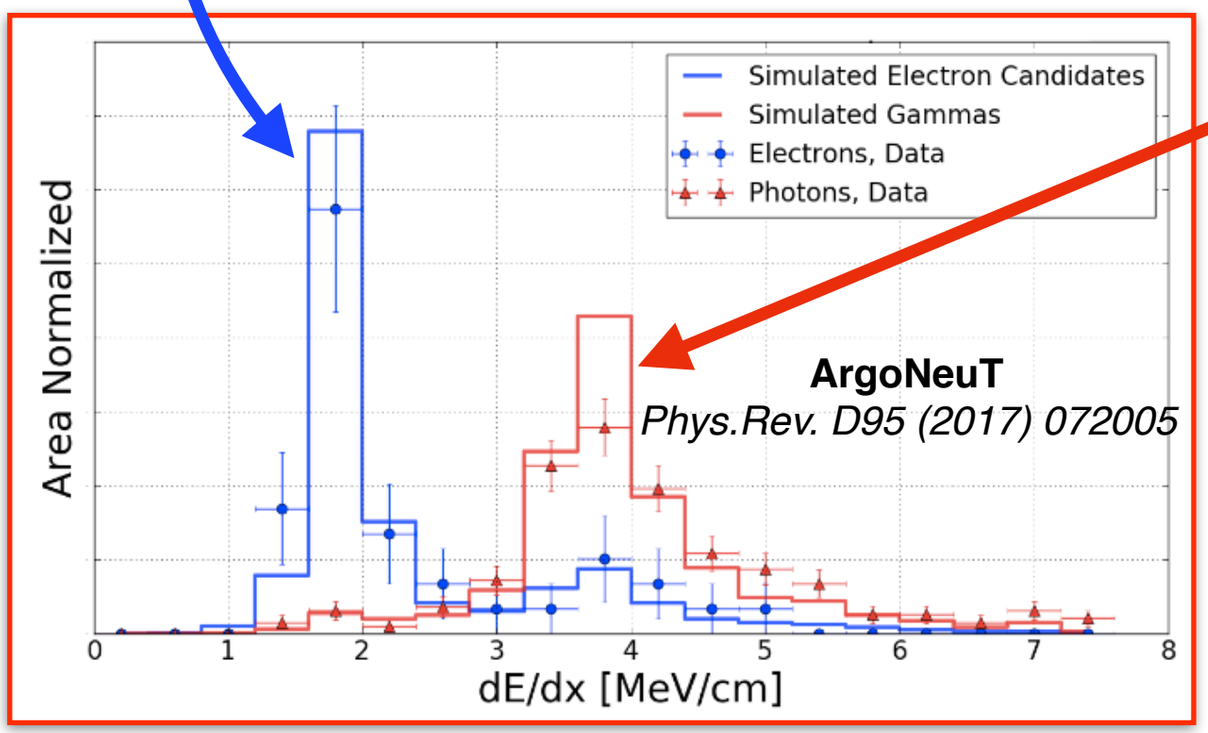


Photons? Electrons?

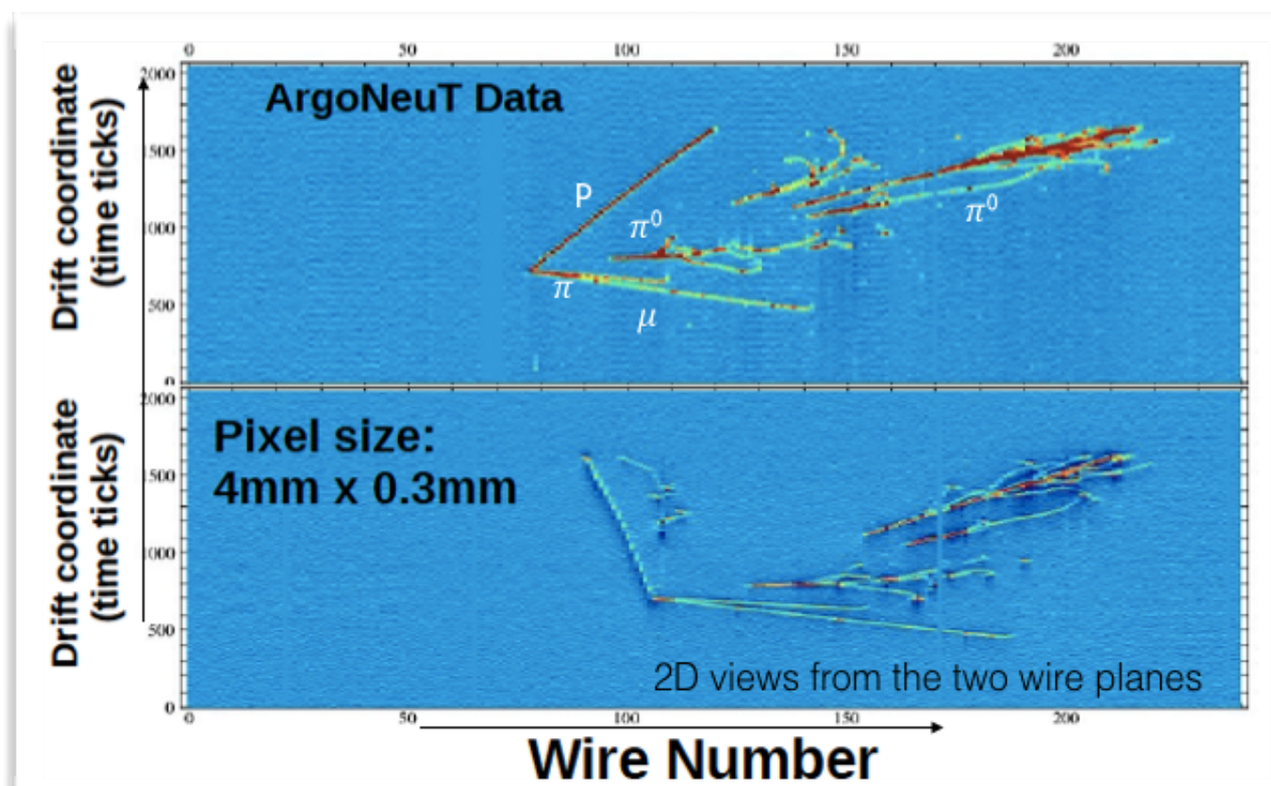
Electron-γ discrimination in LAr



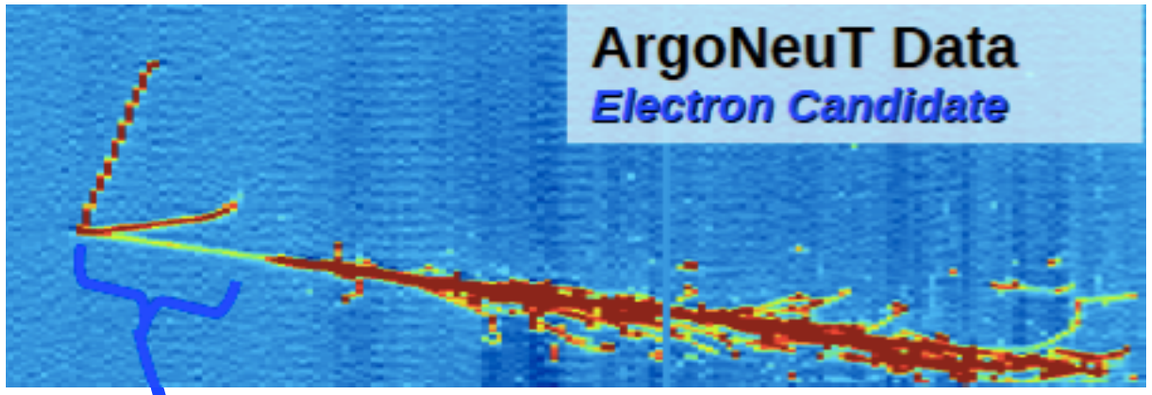


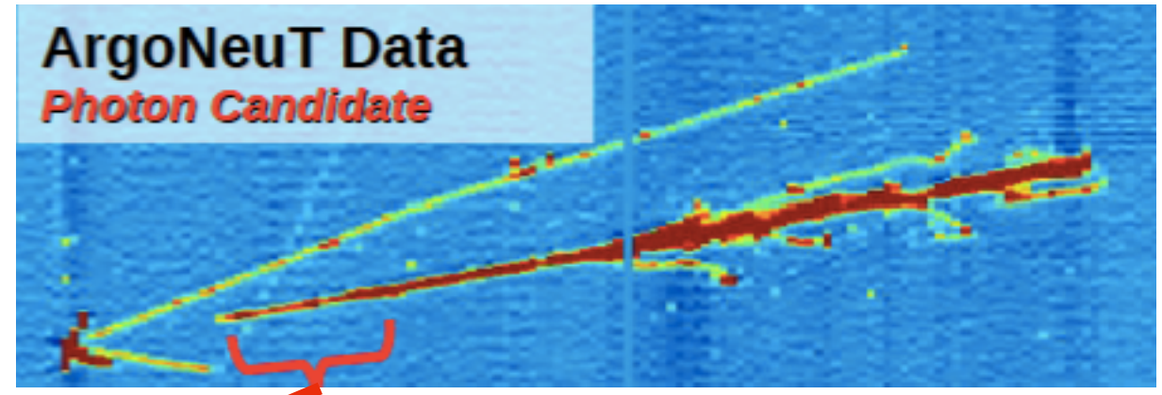


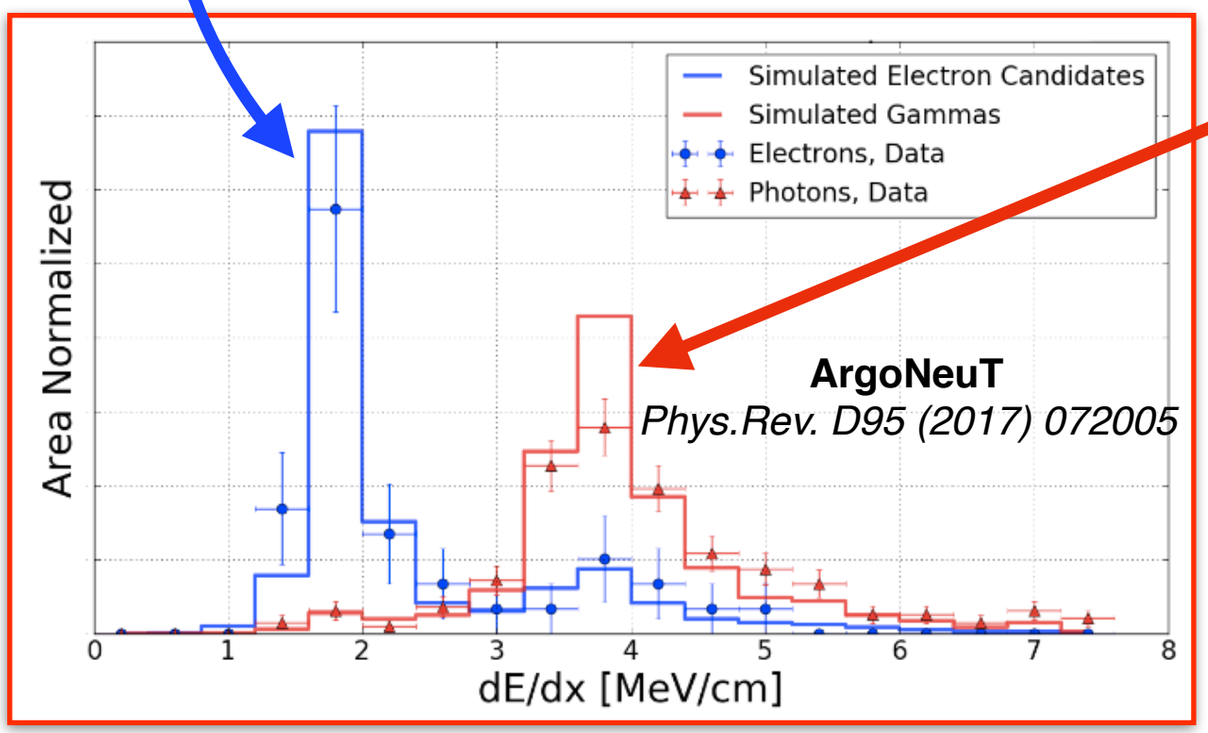
Analyzing topology and dE/dx



Electron-γ discrimination in LAr







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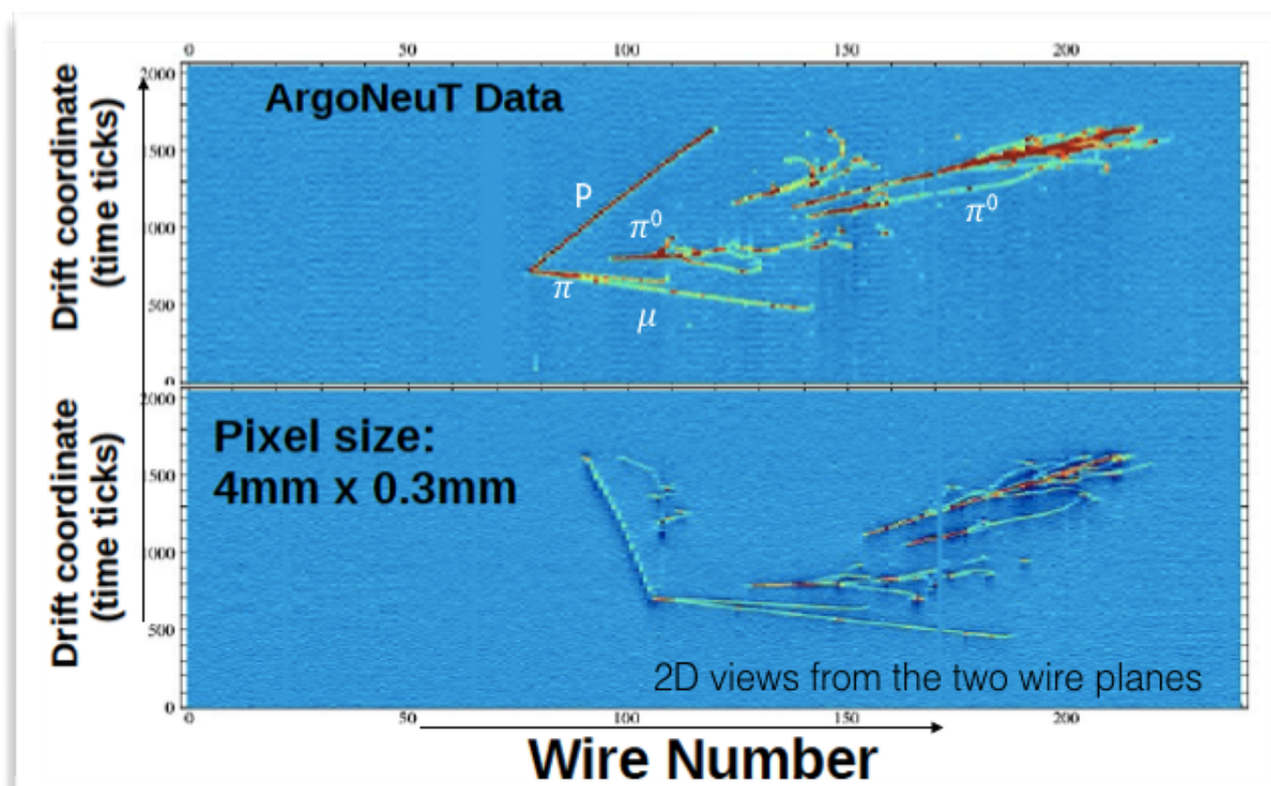
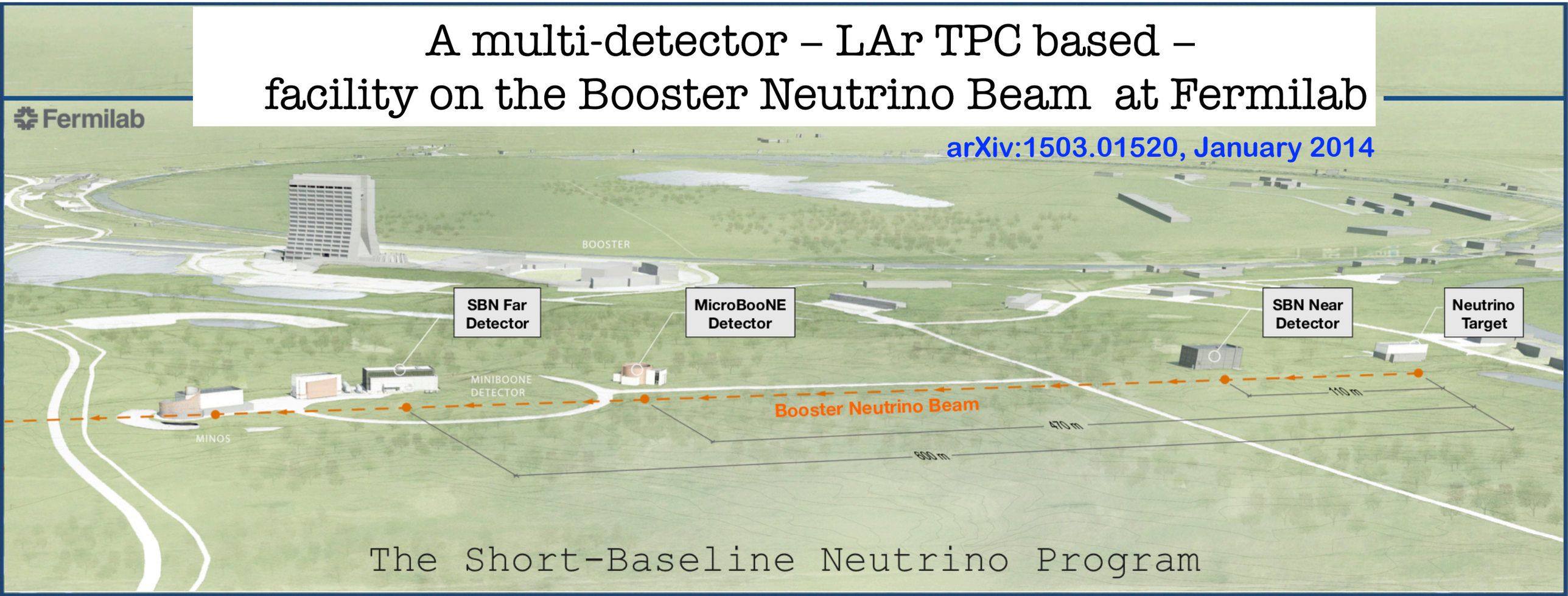


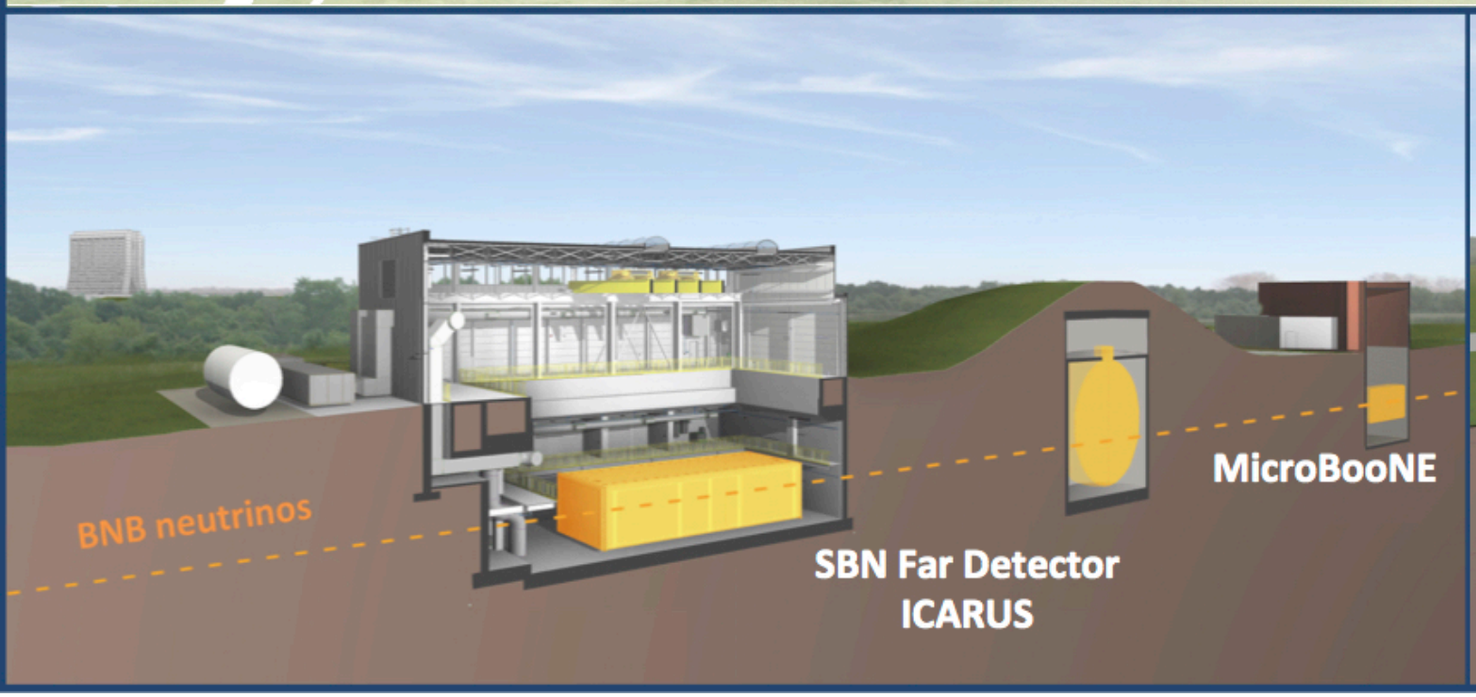
e-γ discrimination capability of LAr is crucial to understand the signal/background nature of the ν_e-like events observed by MiniBooNE

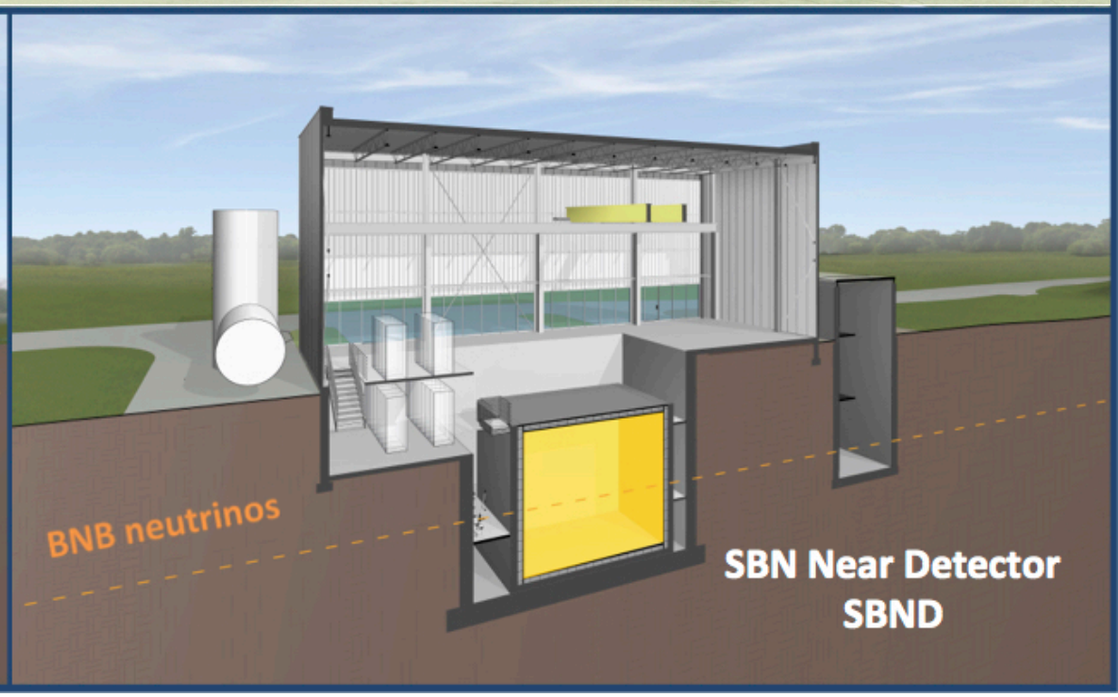
FNAL Short Baseline Neutrino program

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

arXiv:1503.01520, January 2014







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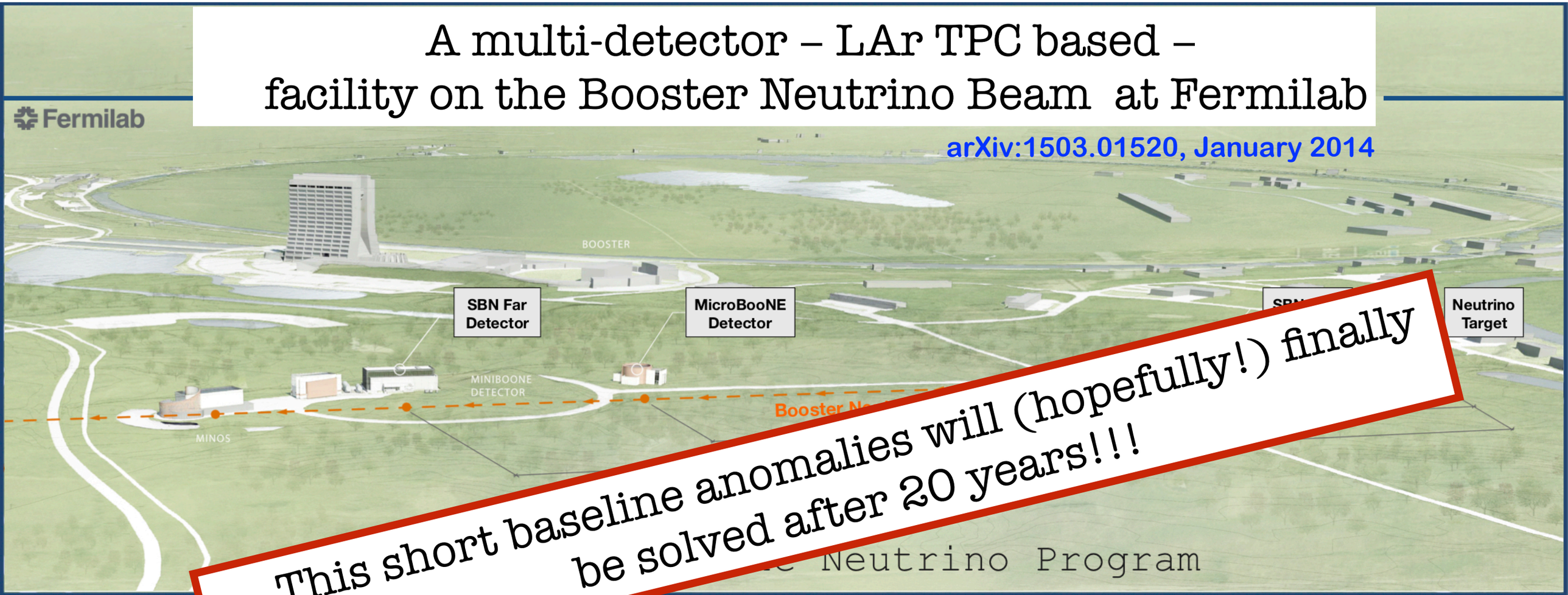
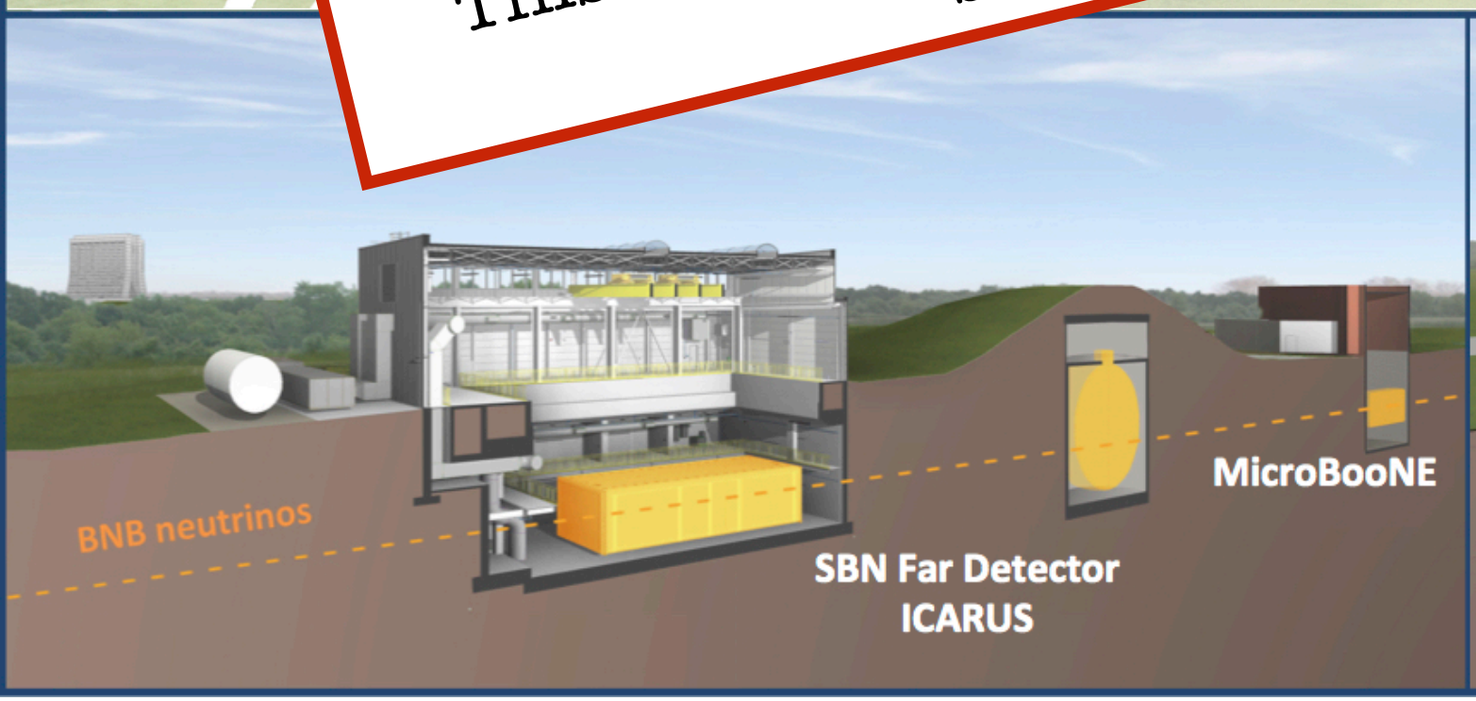
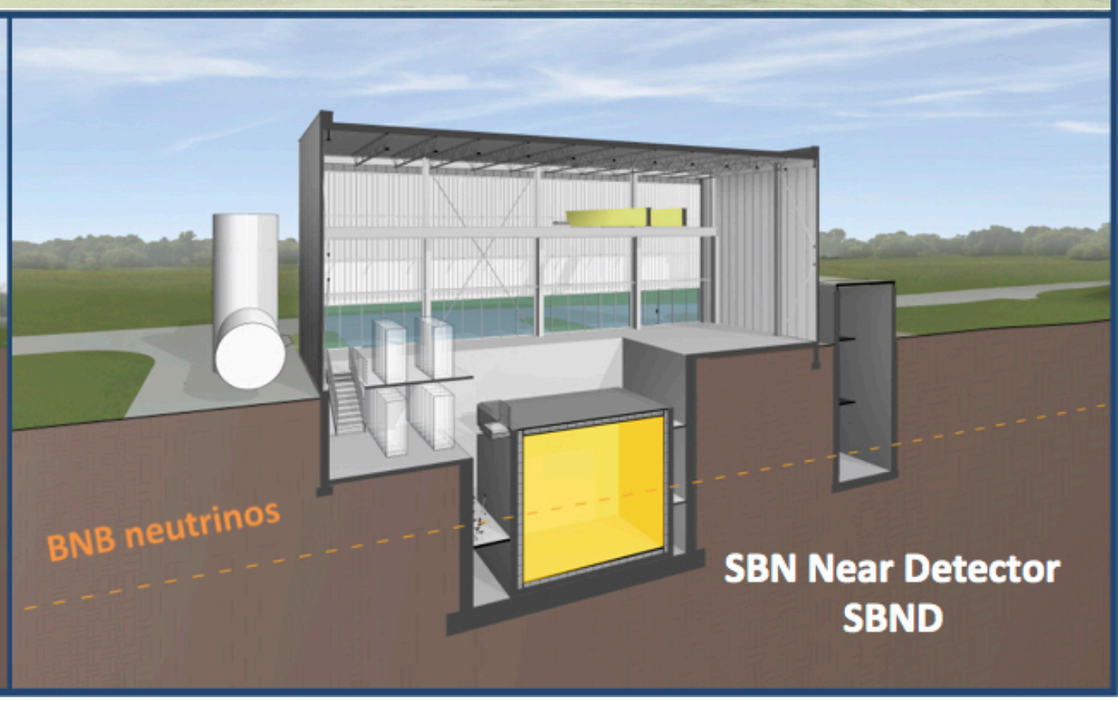
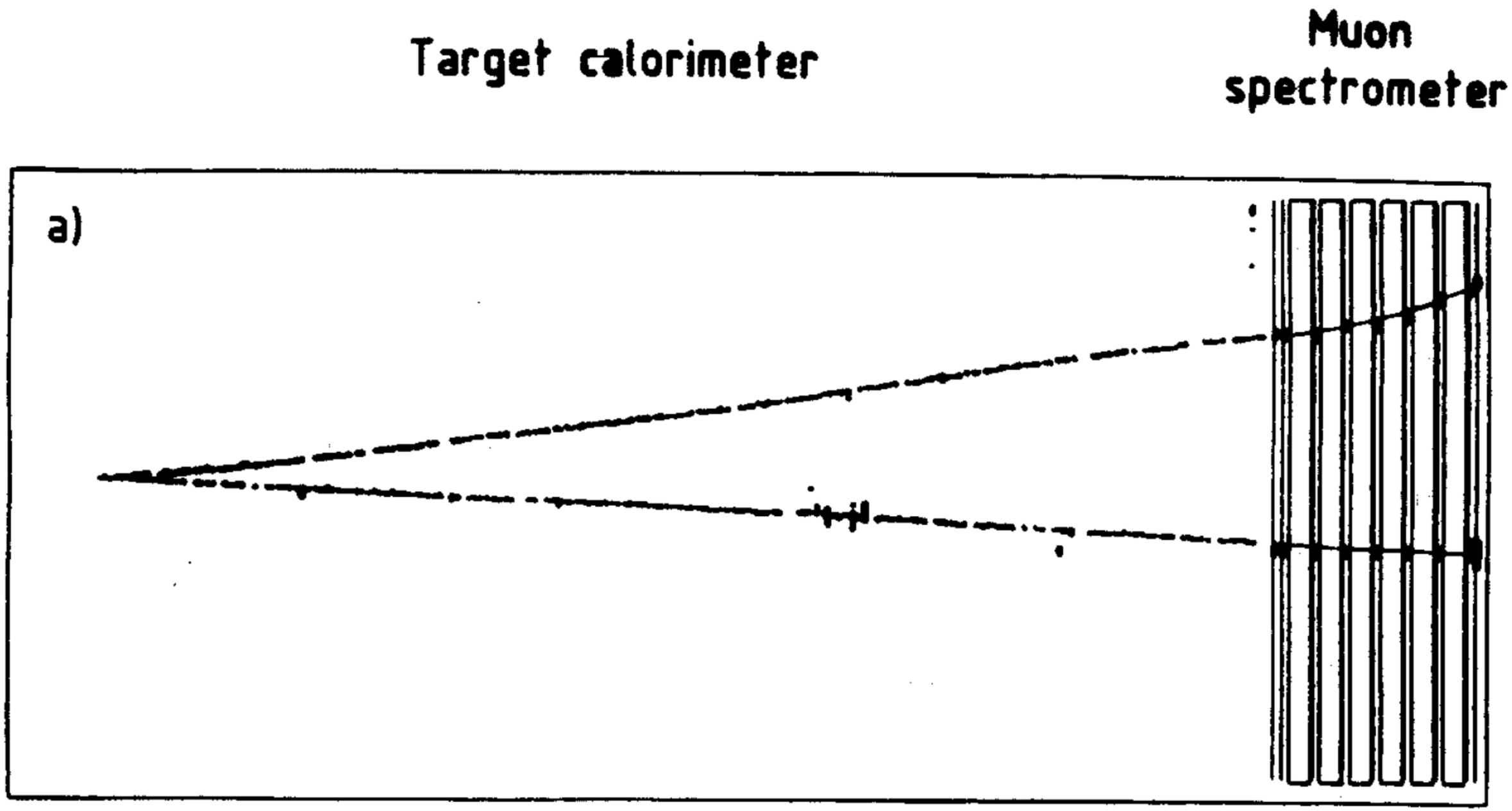


This short baseline anomalies will (hopefully!) finally be solved after 20 years!!!

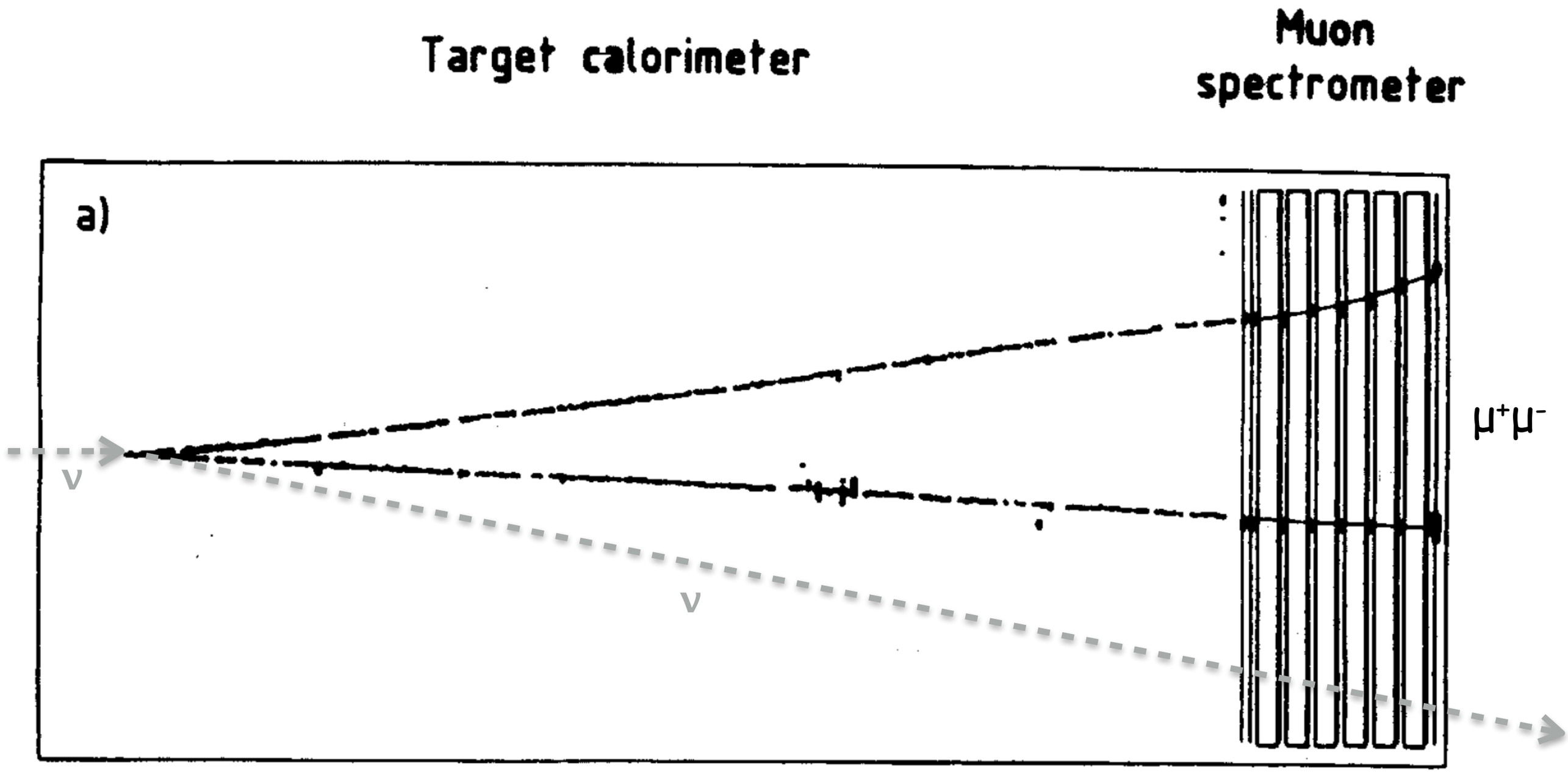




Neutrino Tridents

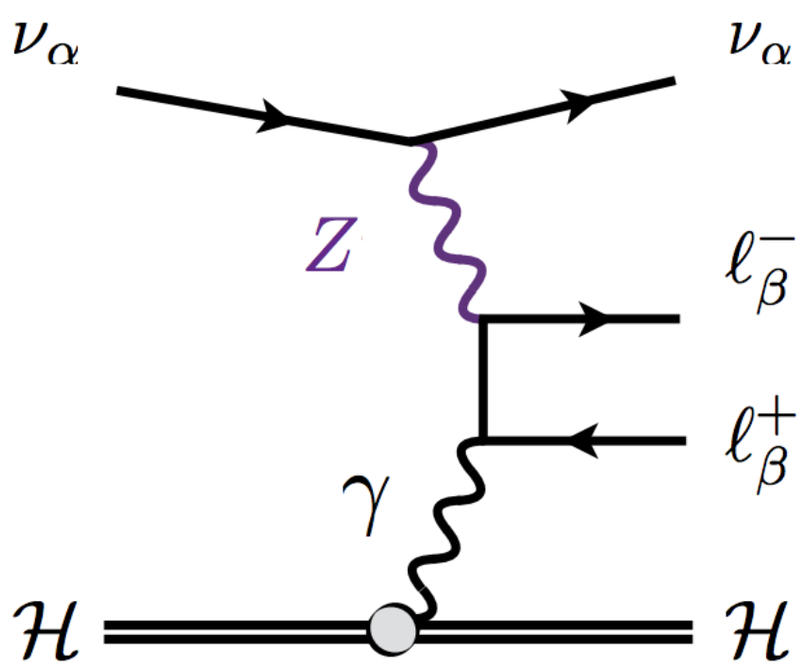


Neutrino Tridents



Neutrino Tridents

Neutrino tridents are standard model processes



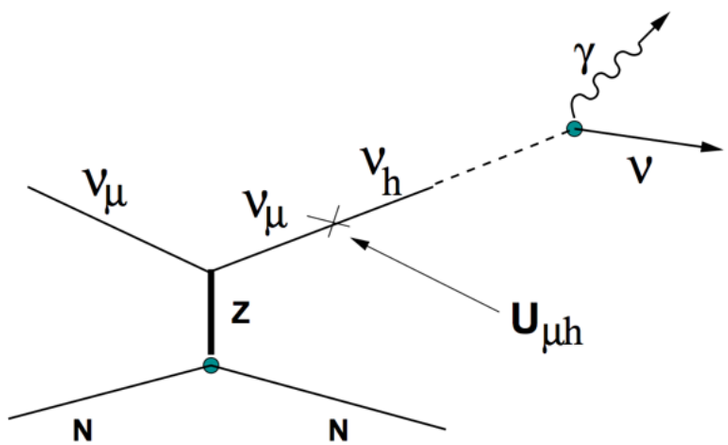
Very rare events

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

Several BSM scenarios can give rise to trident signatures

Neutrino Tridents

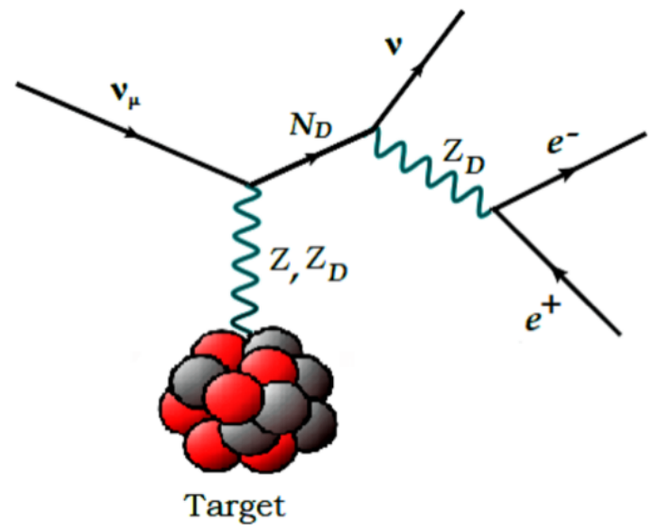
ν magnetic moment



Explains MiniBooNE

Gninenko 0902.3802

Dark neutrinos



Explains MiniBooNE

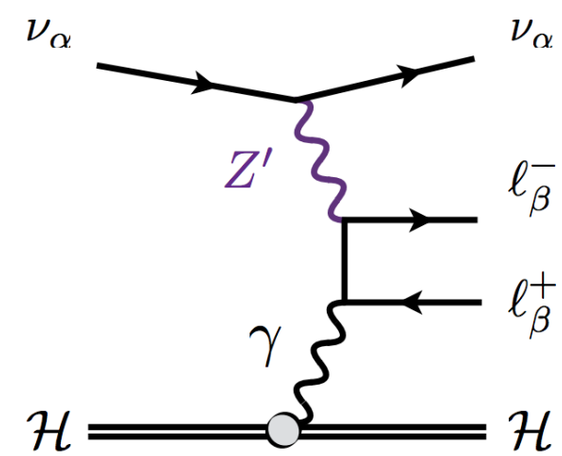
Explains m_ν

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)



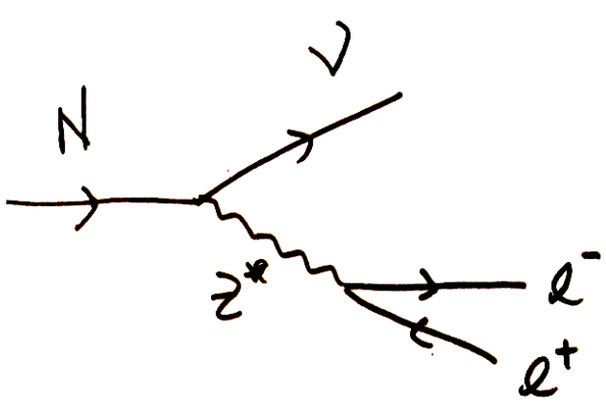
Explains $(g-2)_\mu$

Altmannshofer et al 1406.2332

Ballet et al 1902.08579

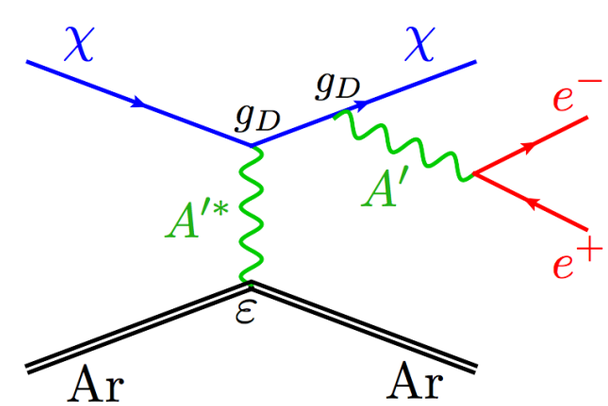
de Gouvêa et al 1809.06388

Heavy neutrinos



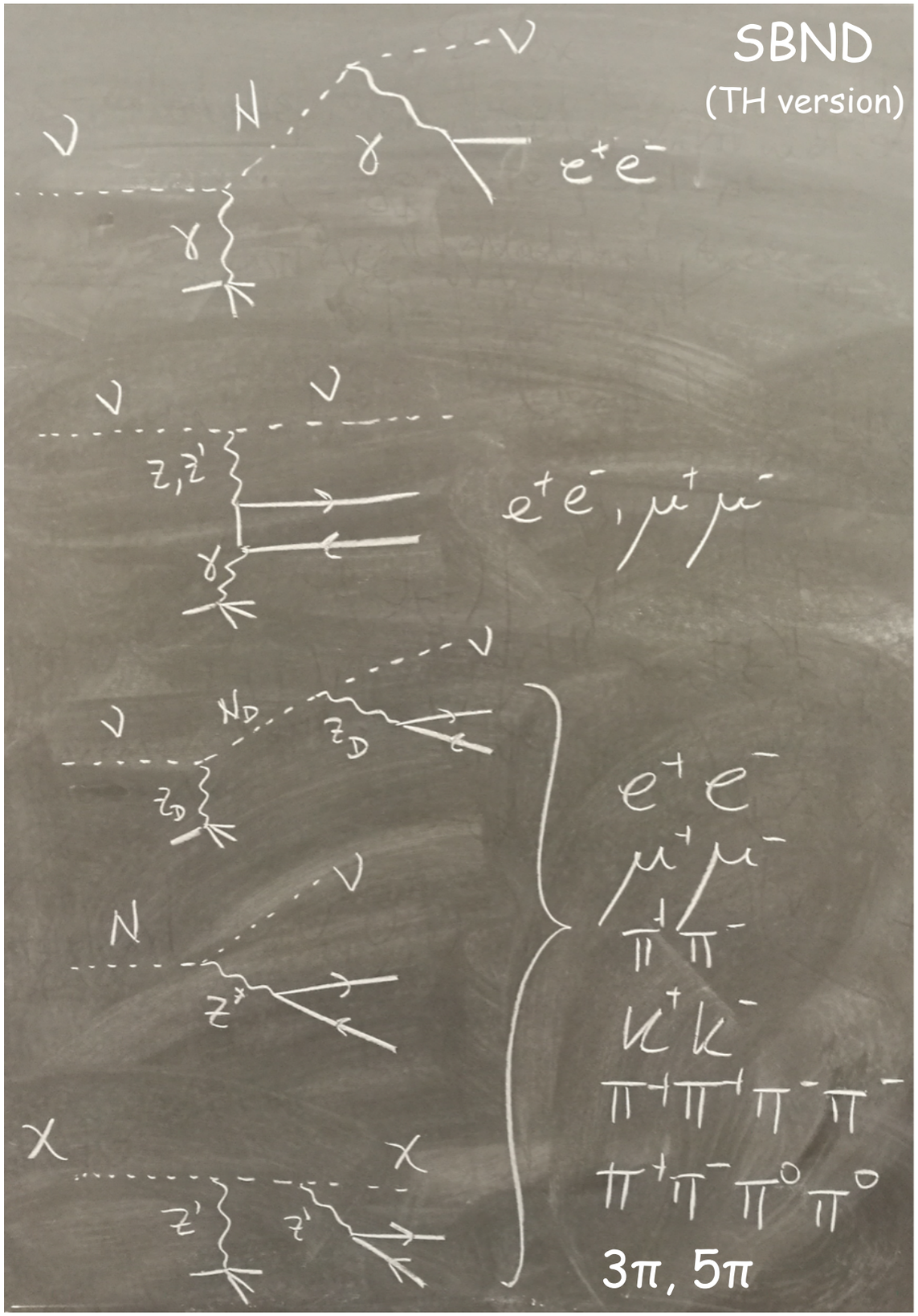
Explains m_ν

Dark tridents



Explains DM

Neutrino Tridents



Transition magnetic moment

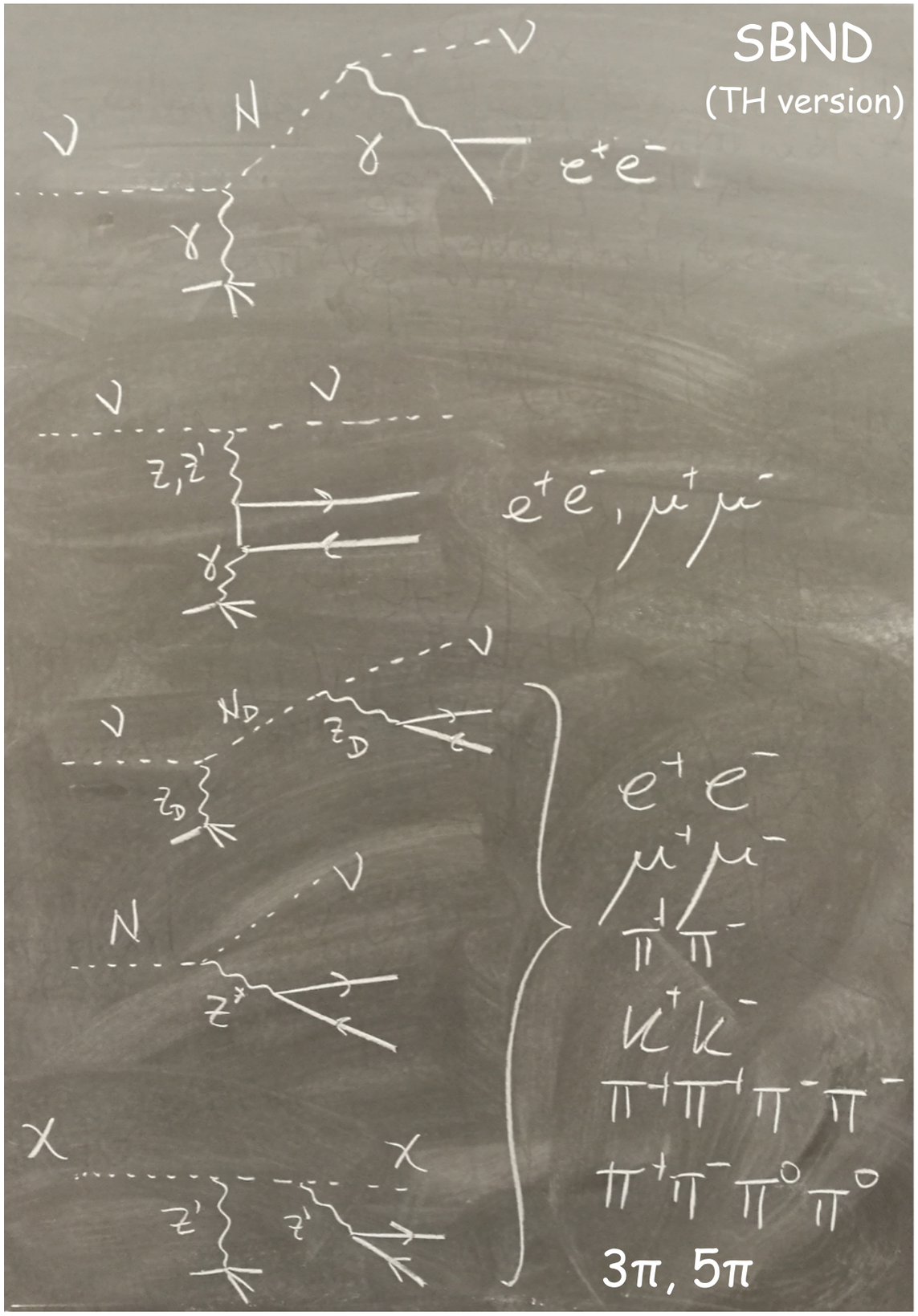
Standard tridents, light Z' (B-L, L_μ-L_τ, ...)

Dark neutrinos

Heavy neutral lepton

Dark matter

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

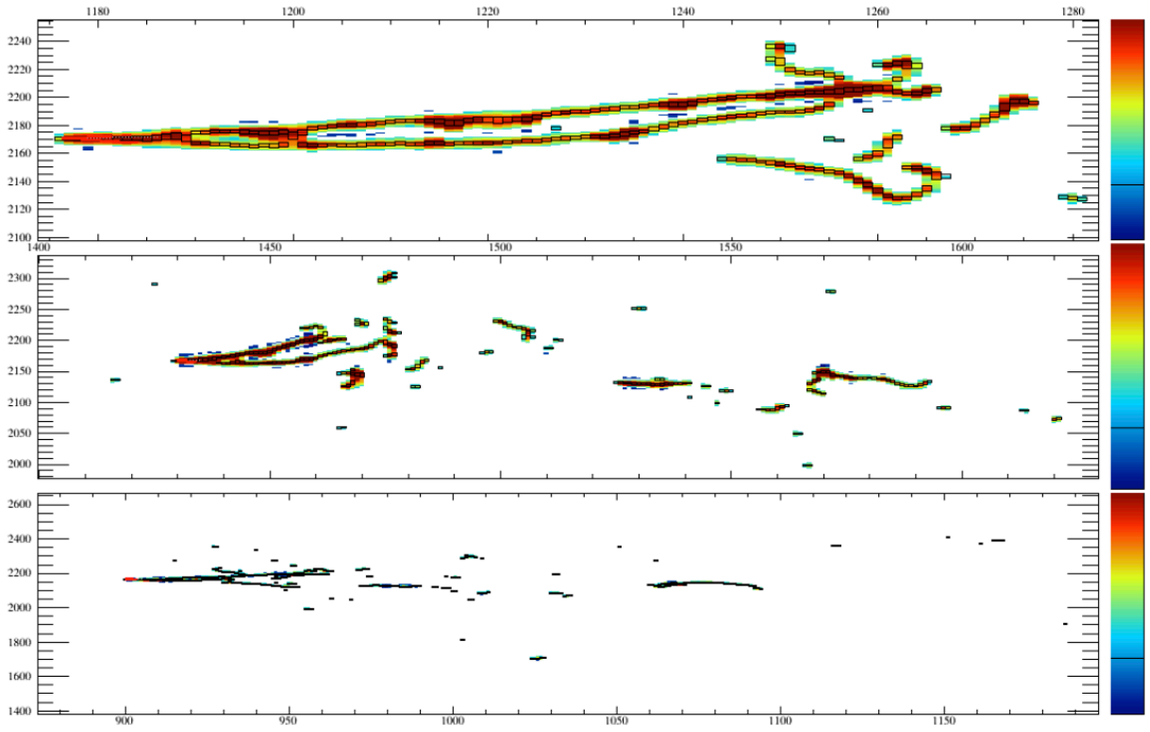
Signatures depend on mass spectrum

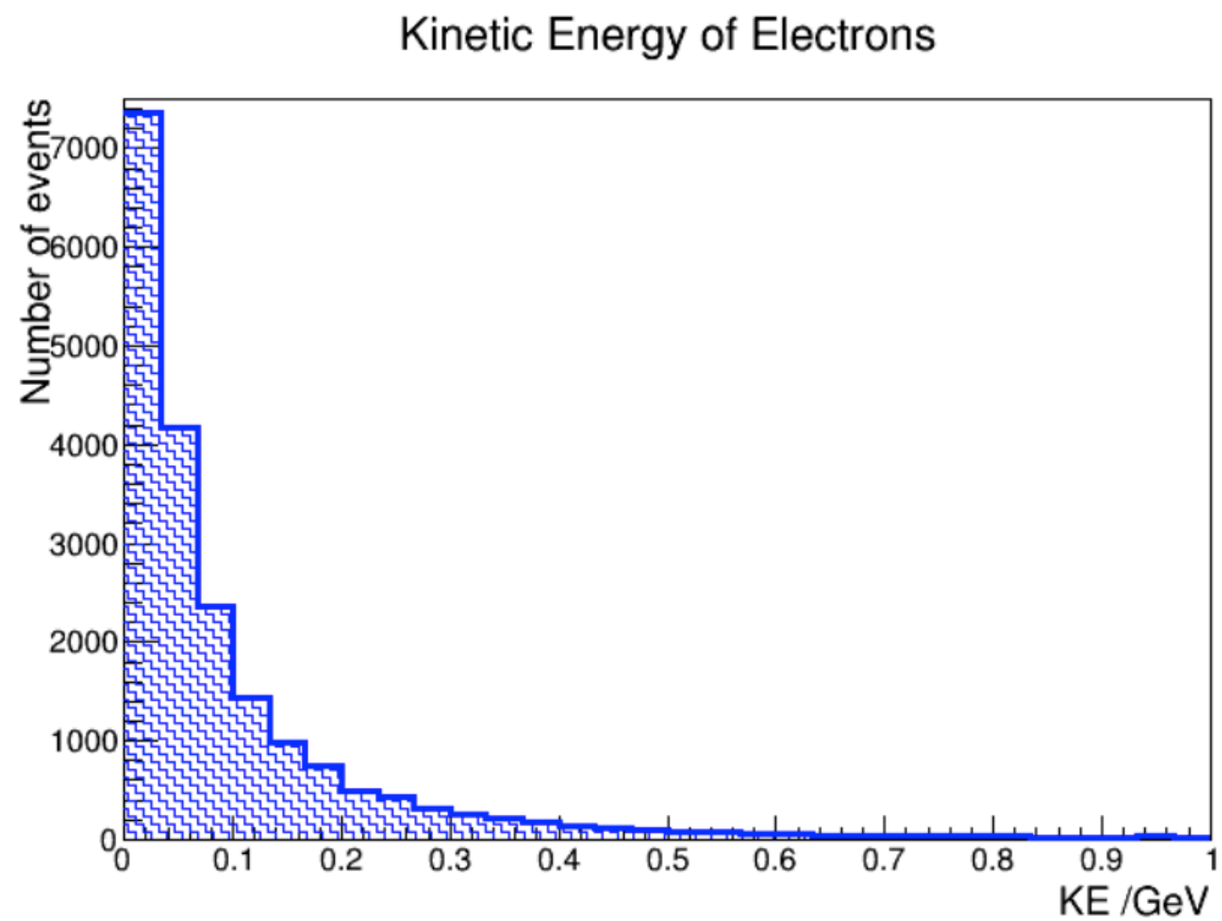
Invariant masses

Angular distributions

dE/dx

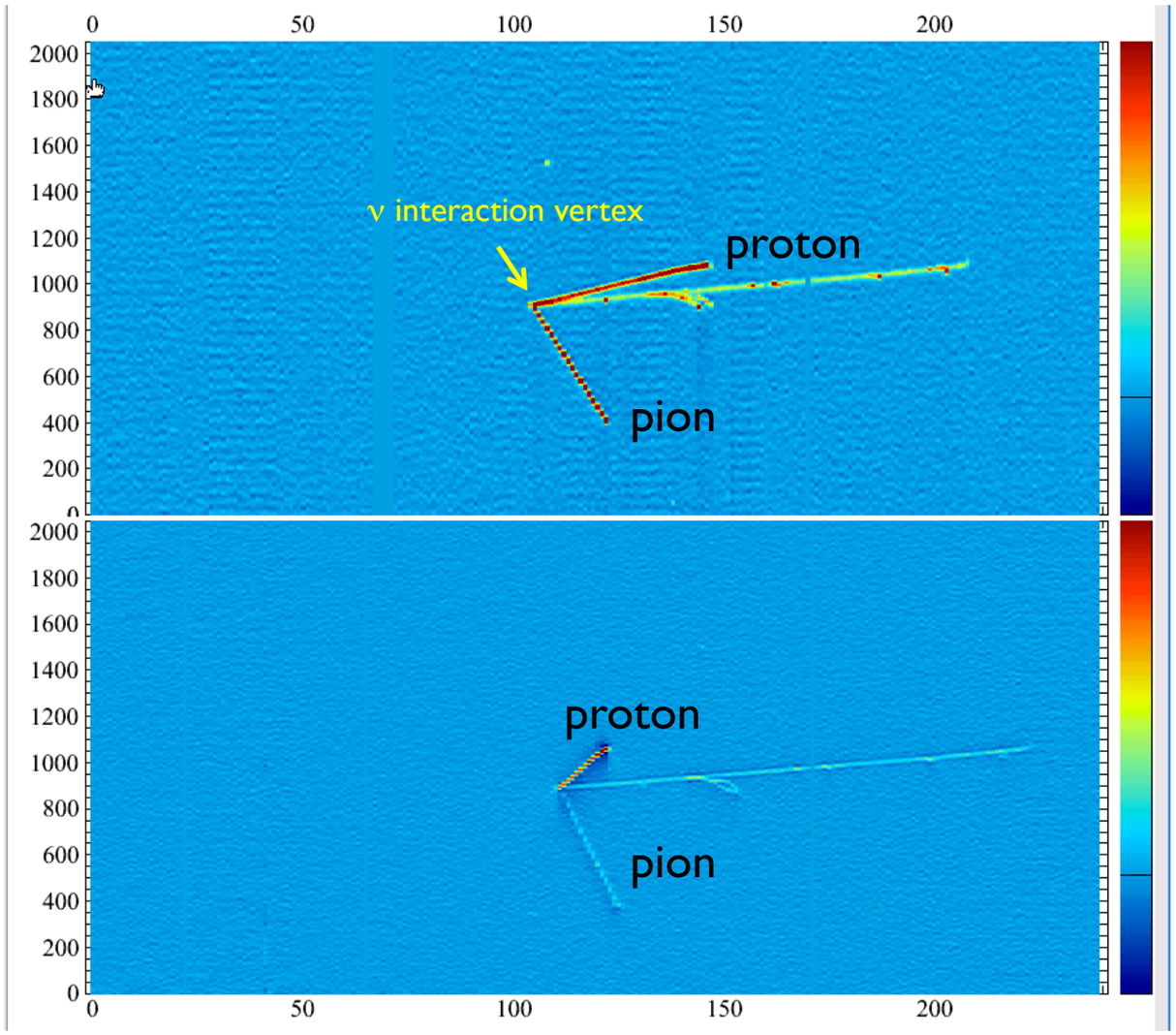
DM decay into an electron-positron pair in the SBND detector (MC simulation)

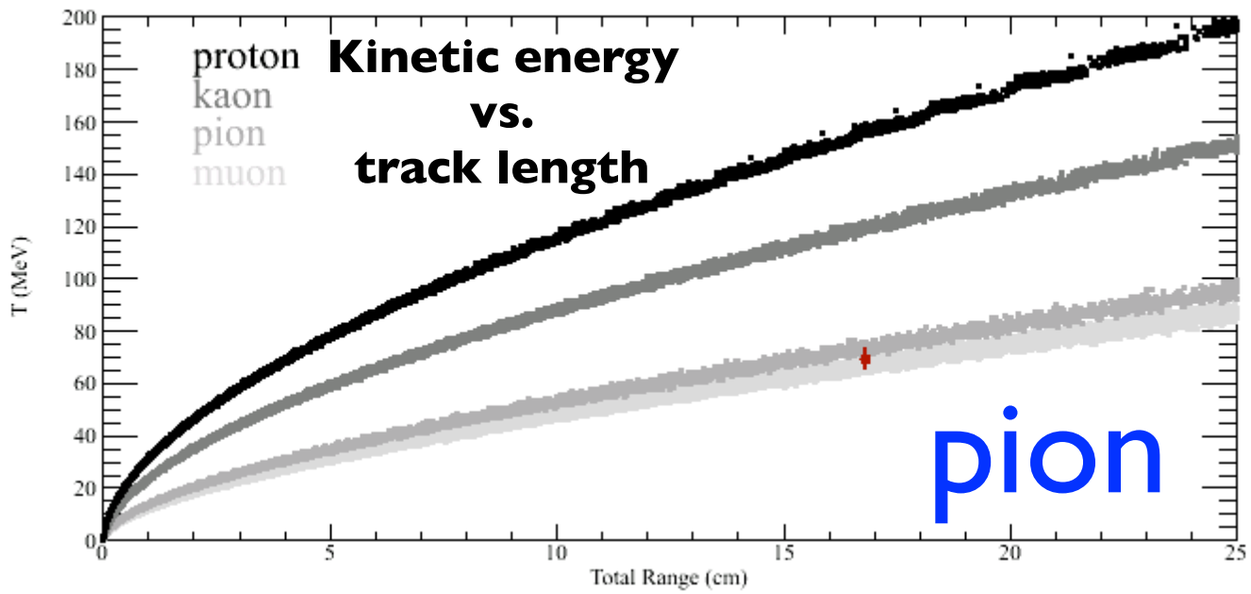


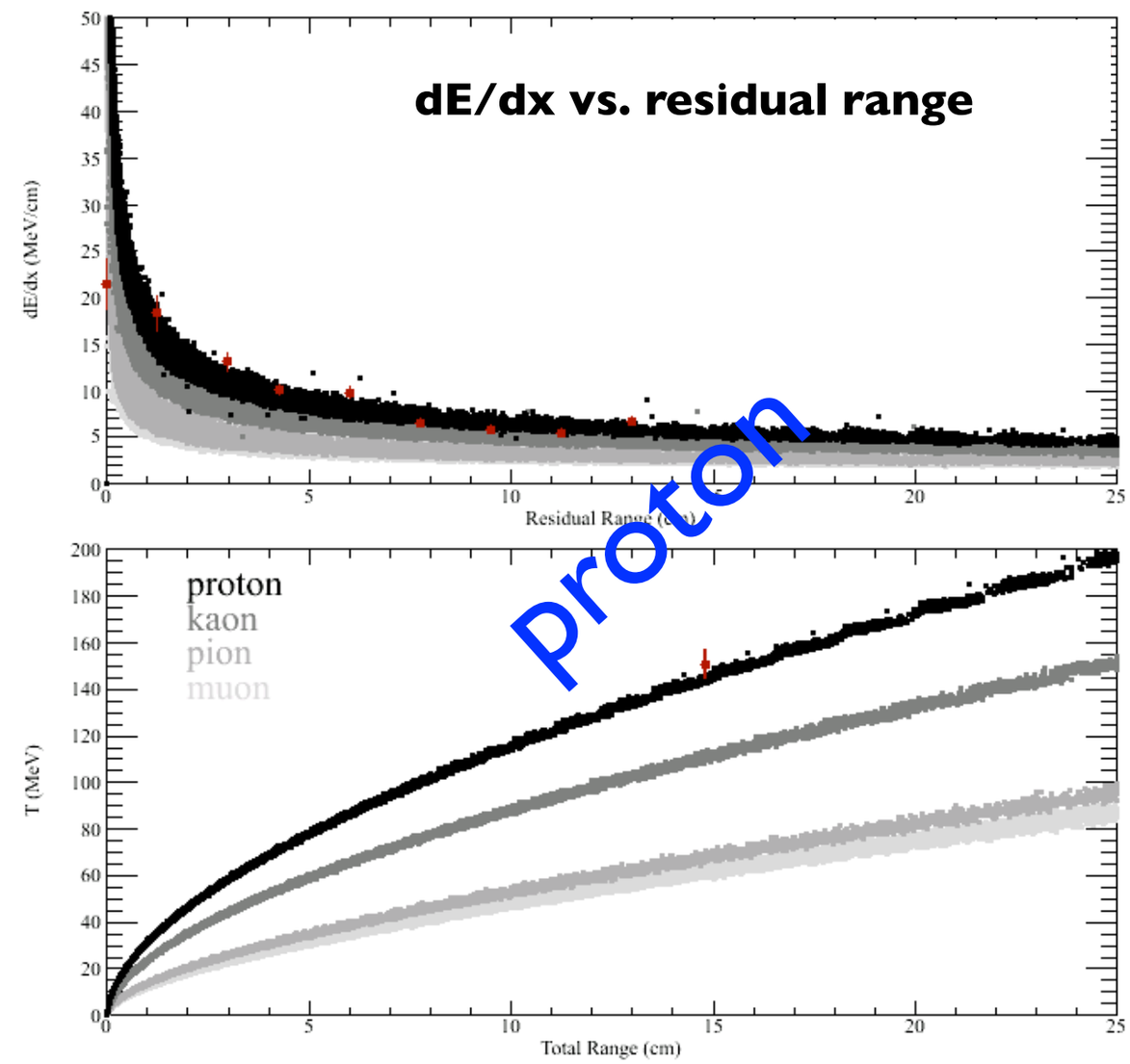


Background: single photon events

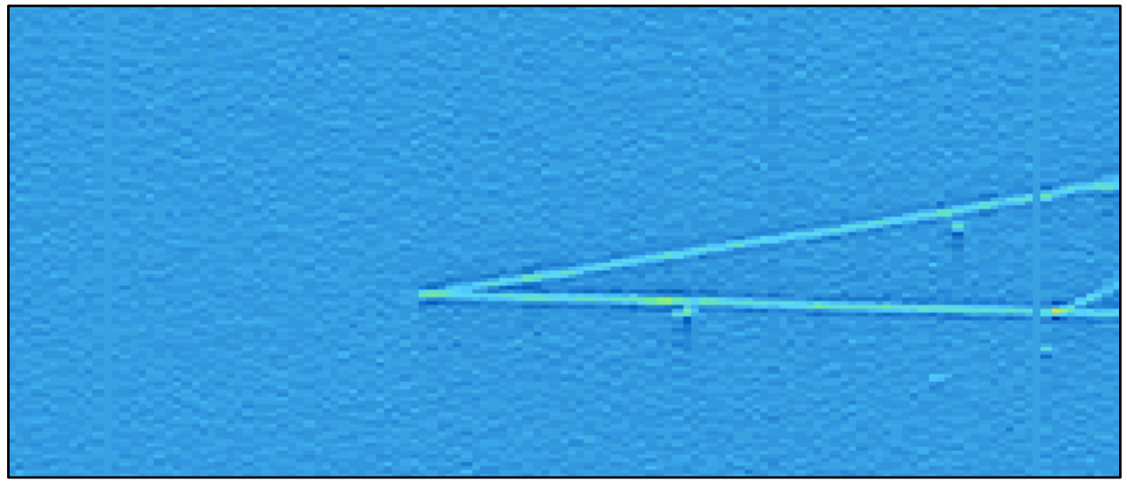
Proton/π± identification







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



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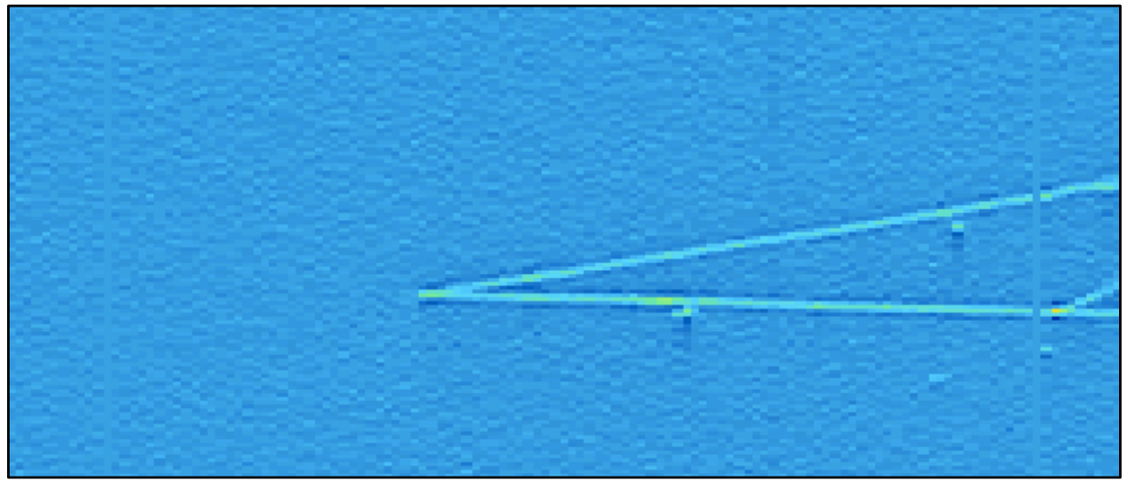
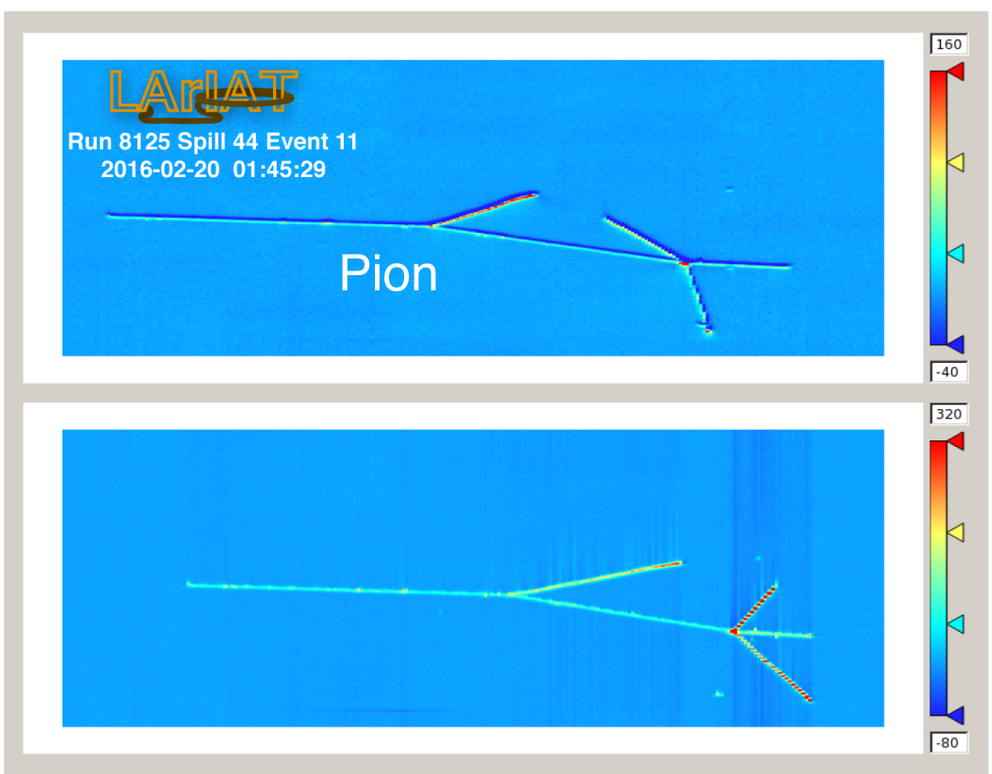
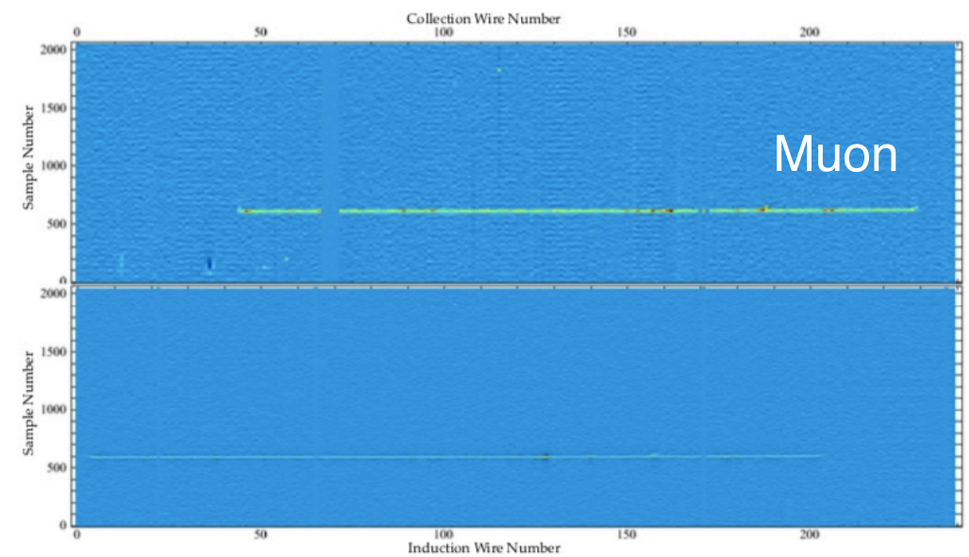


Muon/$\pi^\pm$ identification

Muon/pion separation is a challenge!

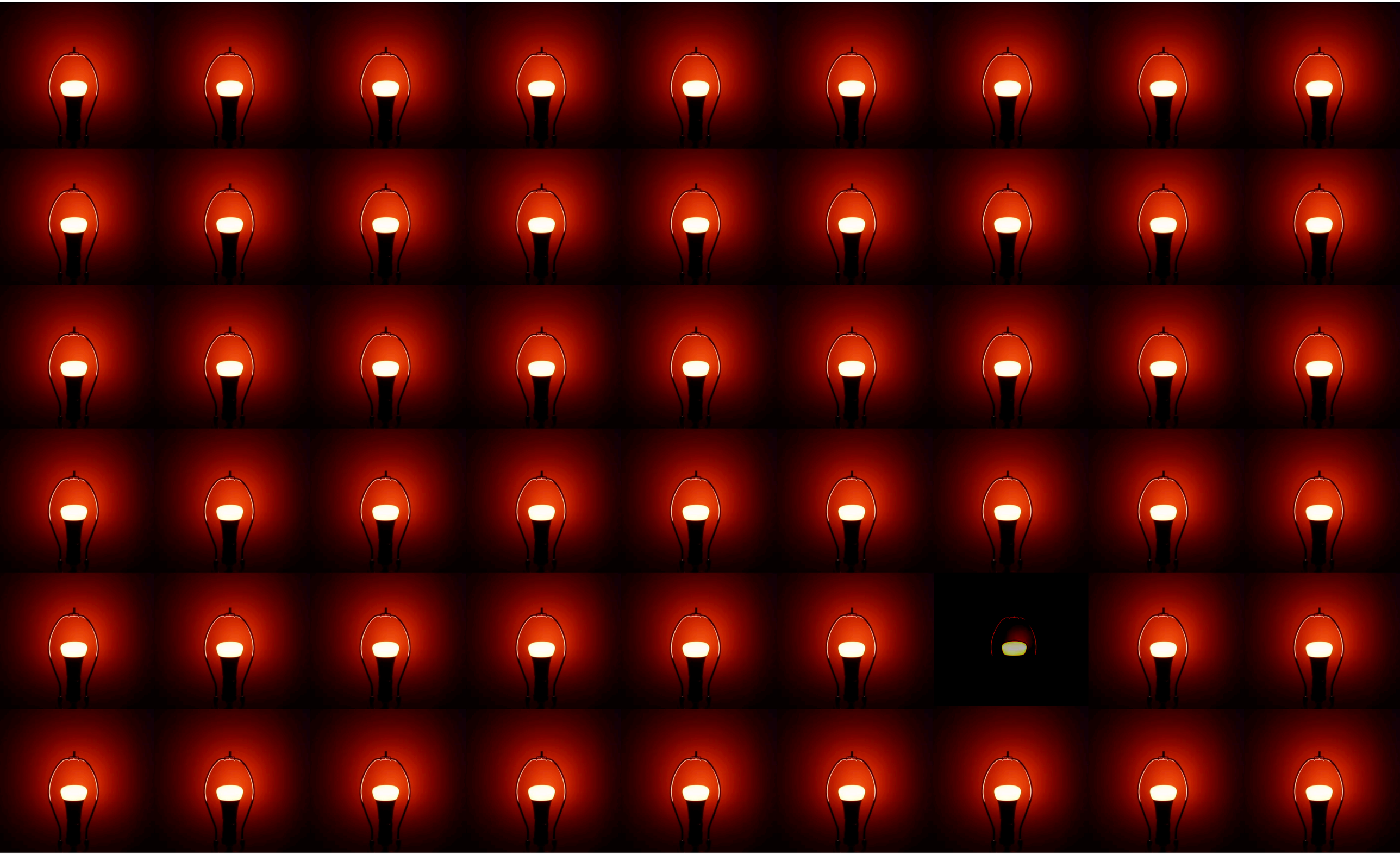




Muons penetrate further

Charged pions can have multiple interactions along their path

Millicharged Particles



Millicharged Particles

All electric charges, in the SM, are multiples of the down quark charge

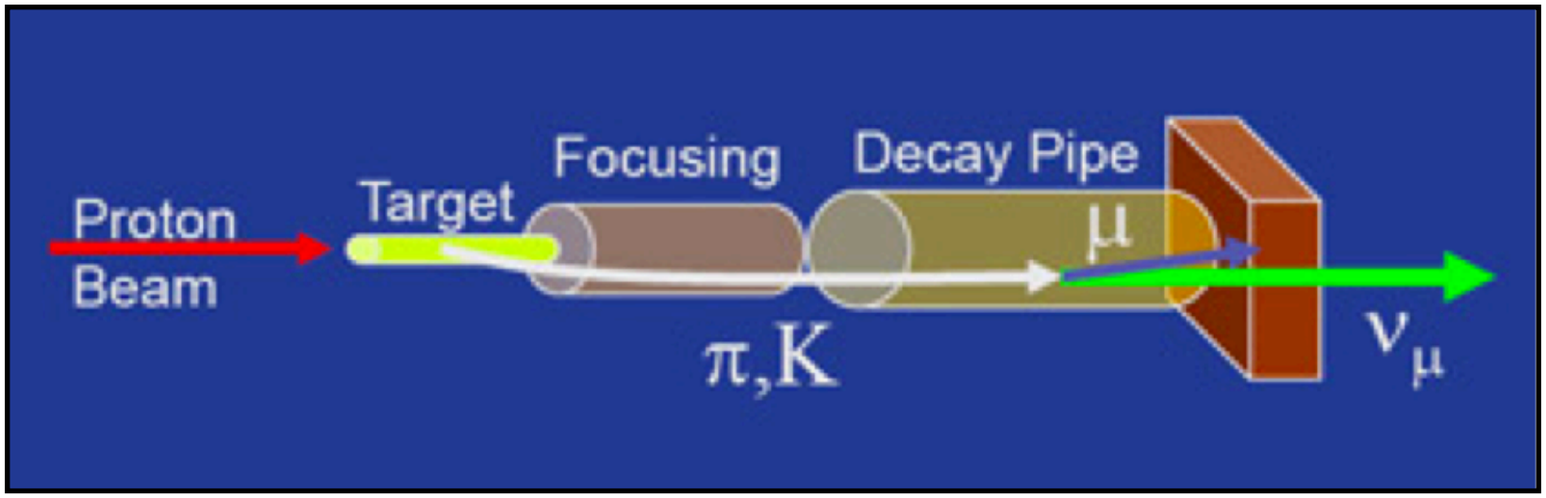
Q(down quarks) = -1/3 Q(up quarks) = +2/3 Q(e,μ,τ) = -1

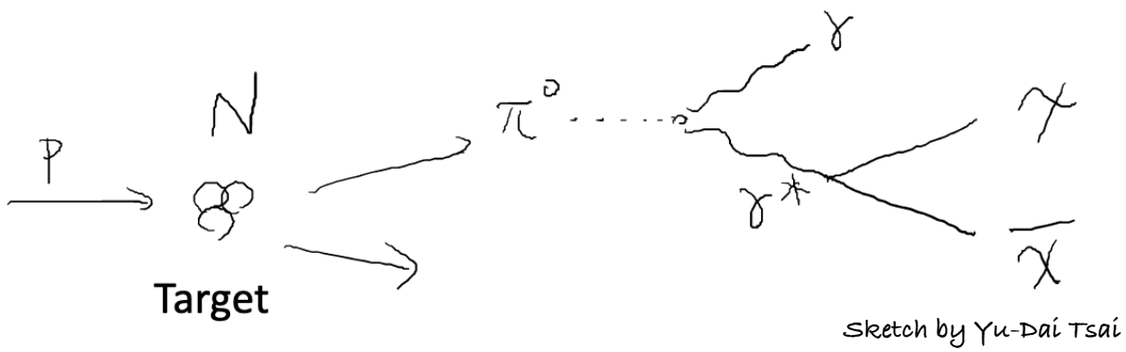
Are there particles with tiny charges ϵ?

“Dark electromagnetism” typically leads to millicharged particles

Millicharged Particles (production)

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





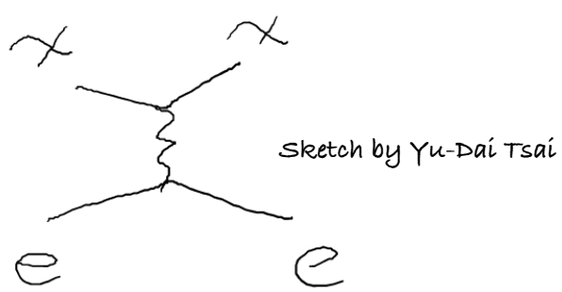
- production:
  meson decays

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)



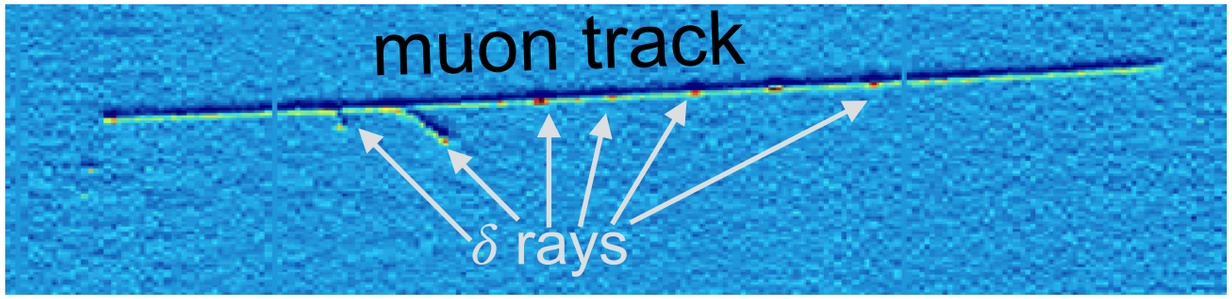
- detection:
  scattering electron

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

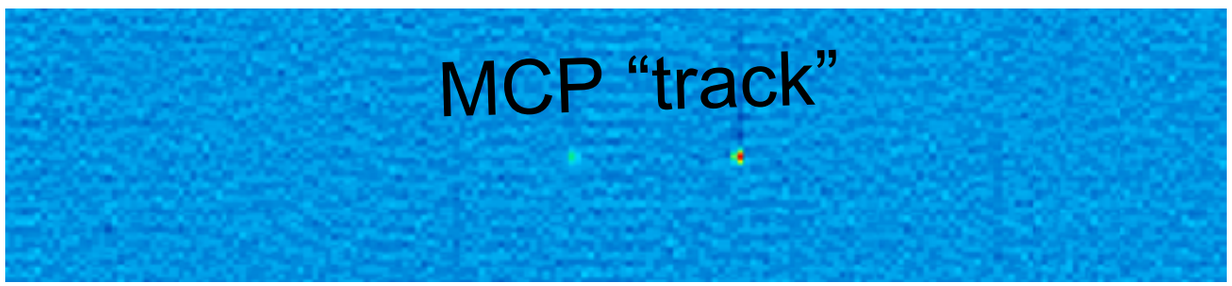
with small angular deflection $\Longrightarrow$ **mCP point back to the target**

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.

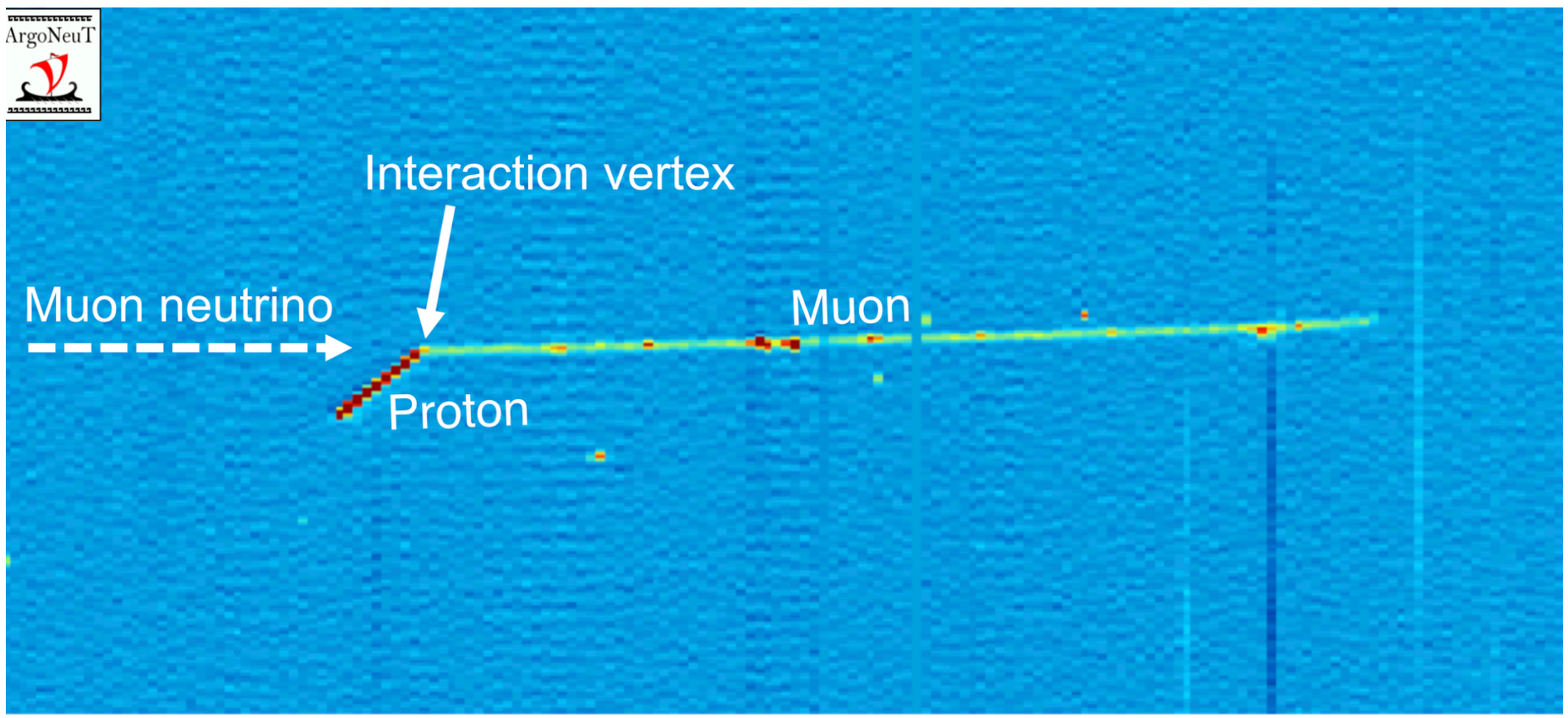


The low energy frontier

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*"



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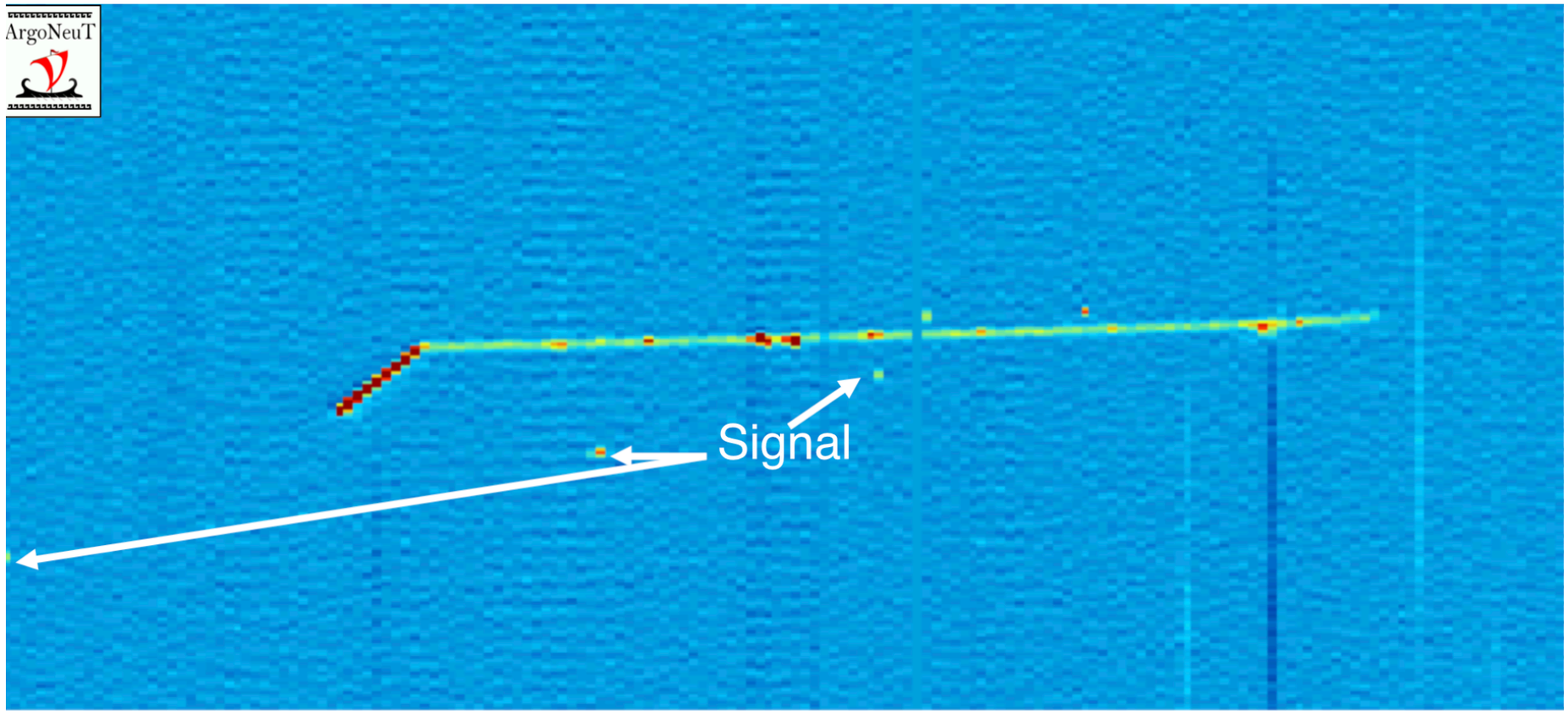
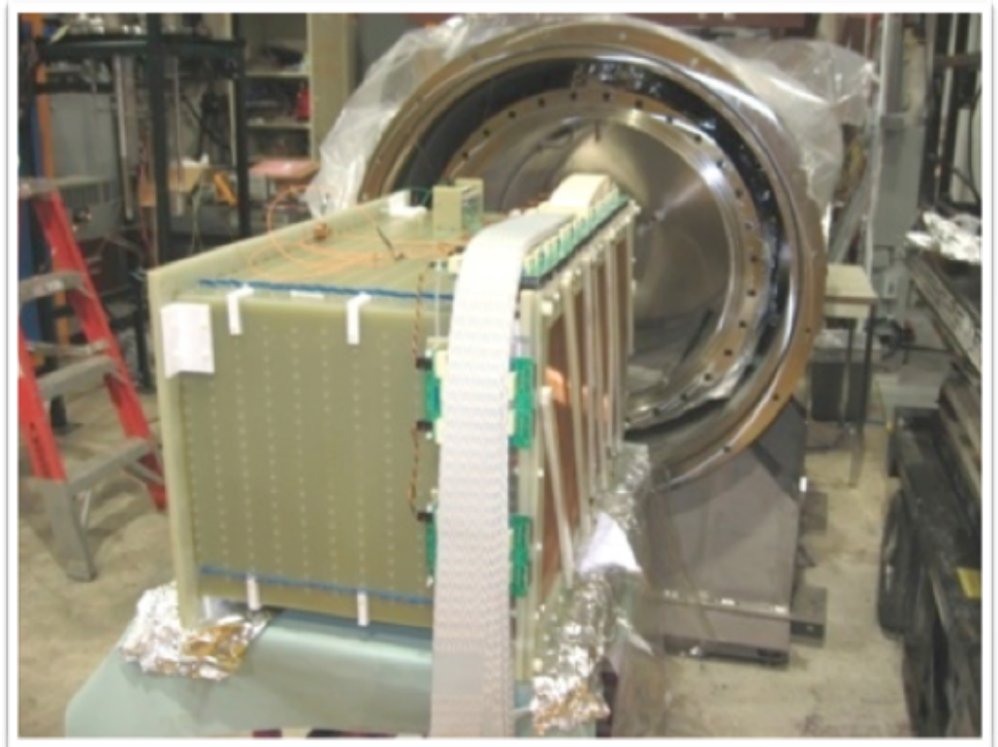


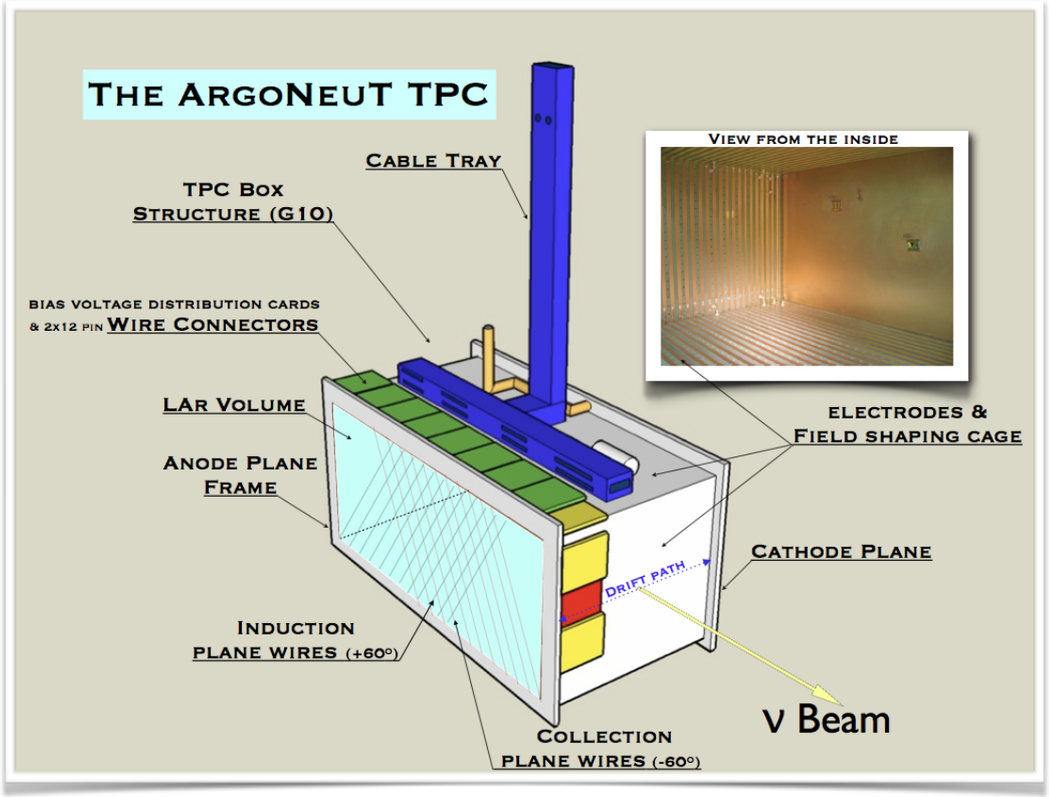
ArgoNeuT in the NUMI Beam line

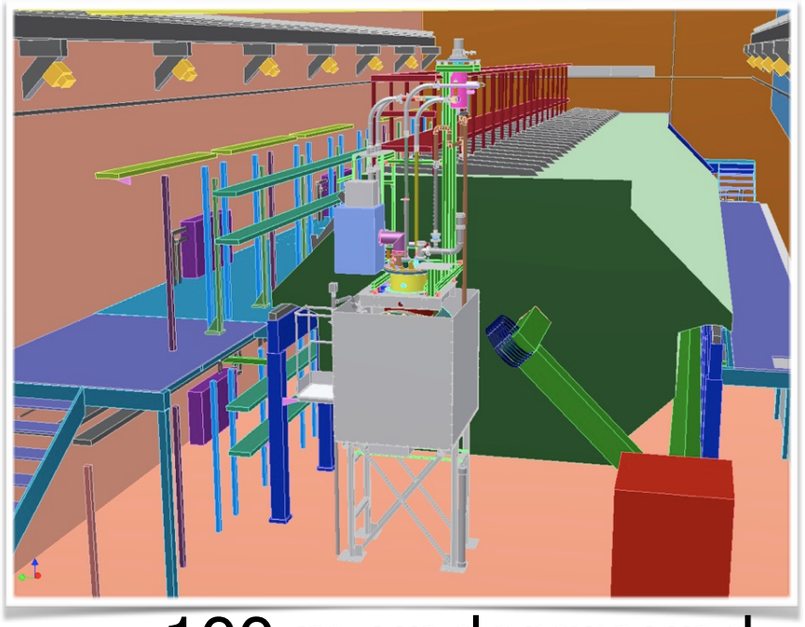
0.24 tons active volume

LAr TPC

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

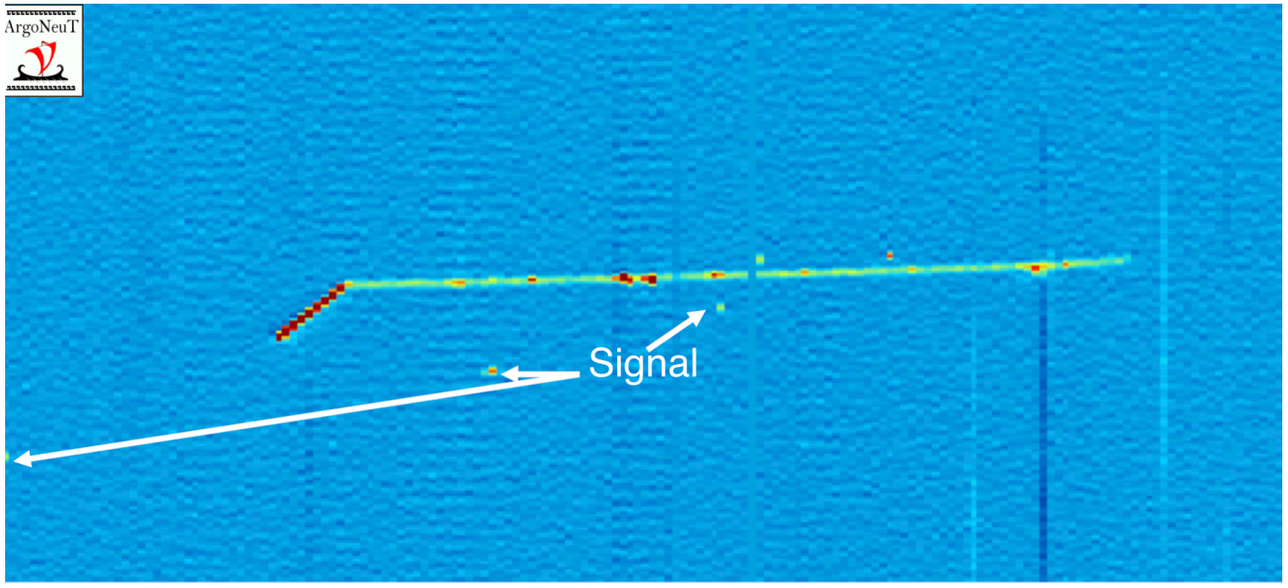


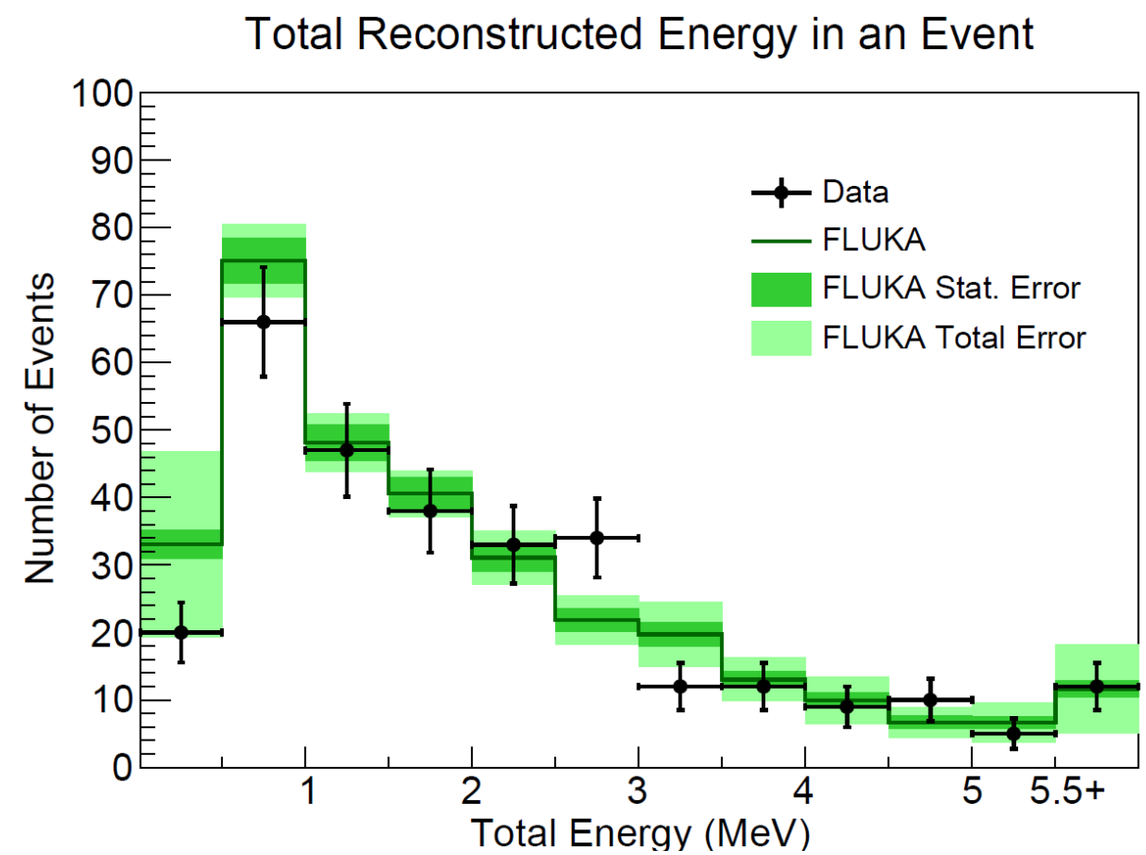




100 m underground
MINOS ND as muon spectrometer
for ArgoNeuT events

MeV-scale physics in LAr TPC



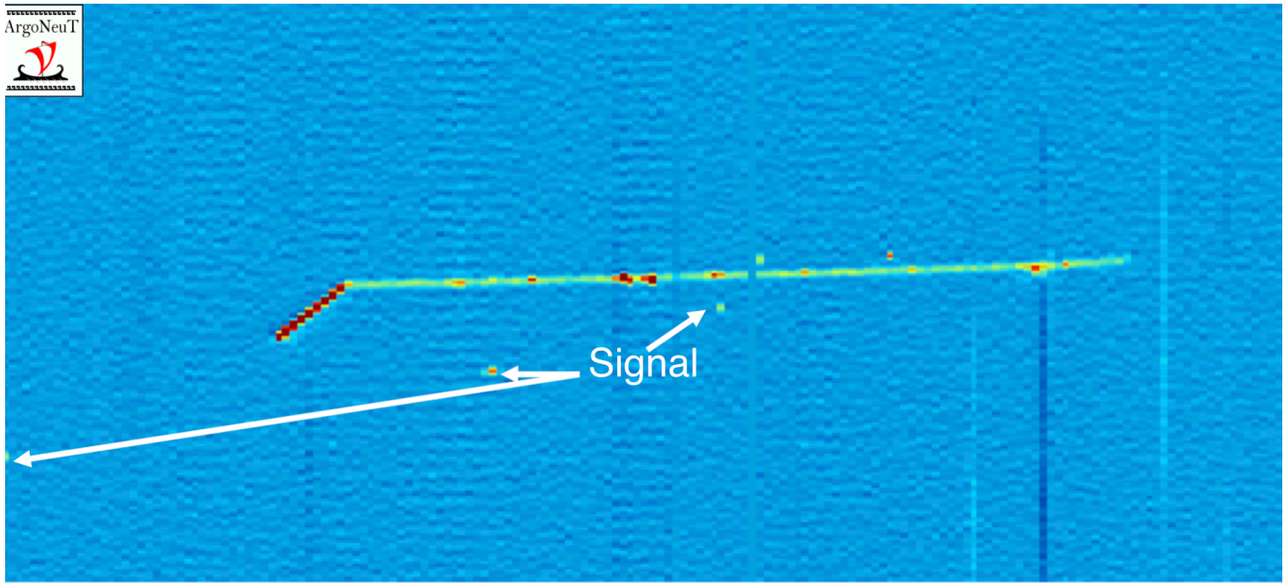


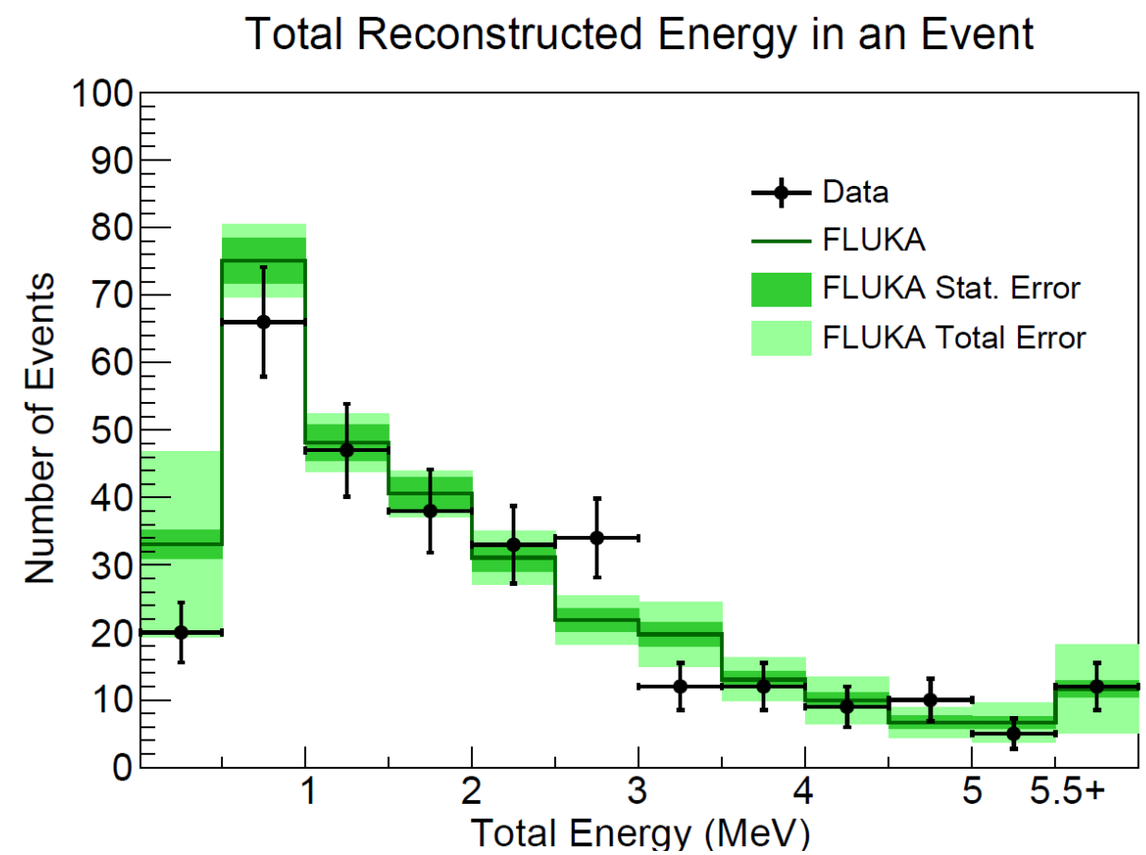
300 KeV threshold!

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

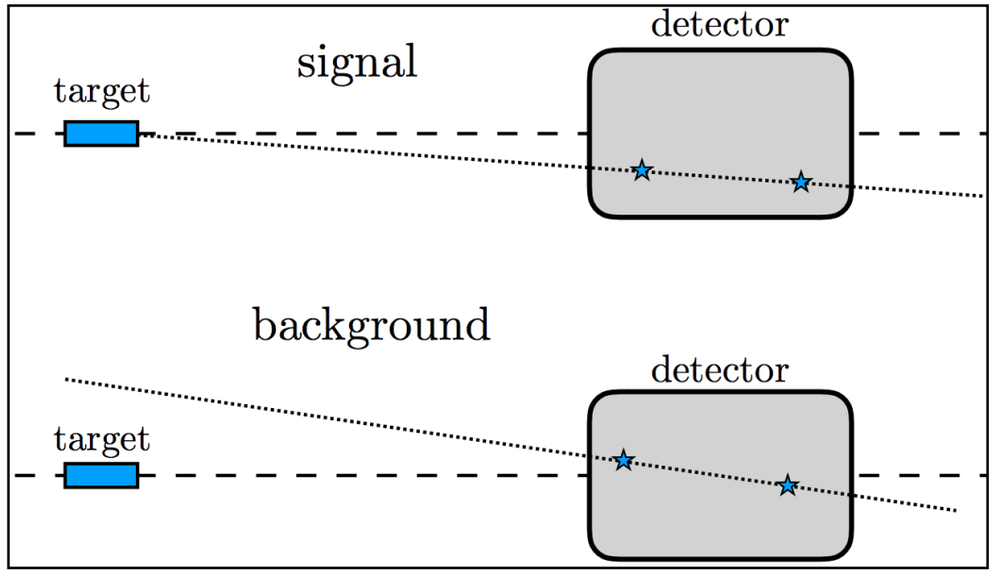
MeV-scale physics in LAr TPC



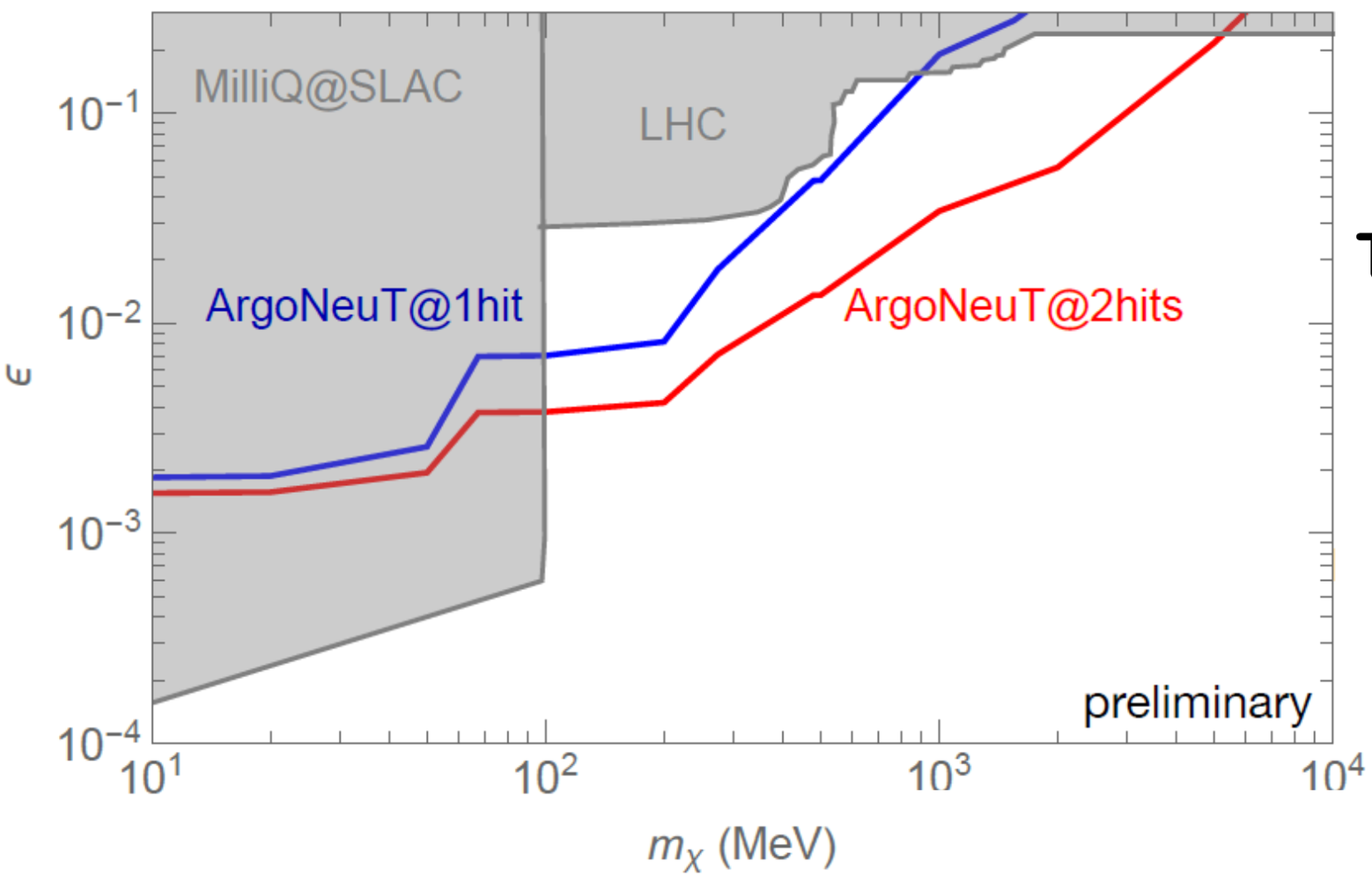


The capability to resolve the individual collisions down to a threshold of around MeV or less enables to search for **millicharged particles (mCPs)** in LAr TPC in neutrino beams.

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

A few extra BSM scenarios we could not talk about

Large extra dimensions

Light mediators

Pseudo-Dirac neutrinos

Proton decay

Light dark matter

Violation of CPT and Lorentz symmetires

Extradimensional shortcuts

Neutral current non-standard interactions

Ultra-light dark matter

Low scale neutrino mass models

Secret neutrino interactions

Charged current non-standard interactions

Non-unitarity

Summary

Neutrino oscillations is a clear indication of physics **B**eyond **S**tandard **M**odel

Next generation neutrino experiments will be fantastic tools to look for new physics in the neutrino sector and beyond

Good example of interplay between theorists and experimentalists

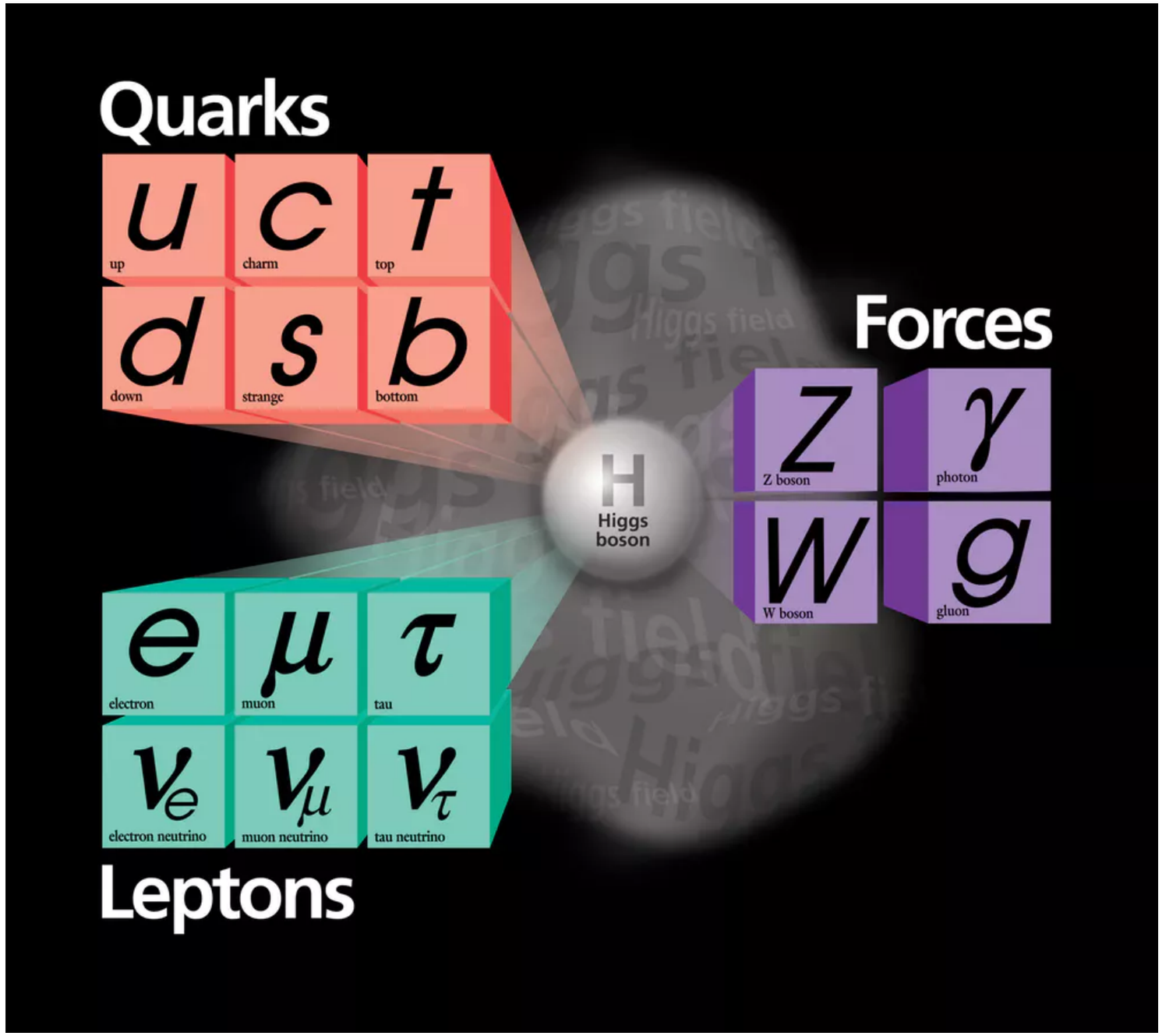
Now is the right time!

Here is the right place!

Overflow

What is BSM?

This is the SM



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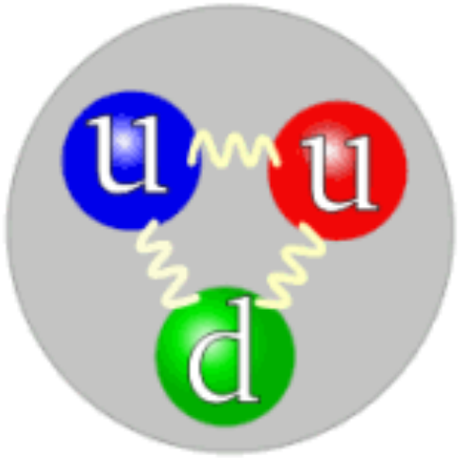
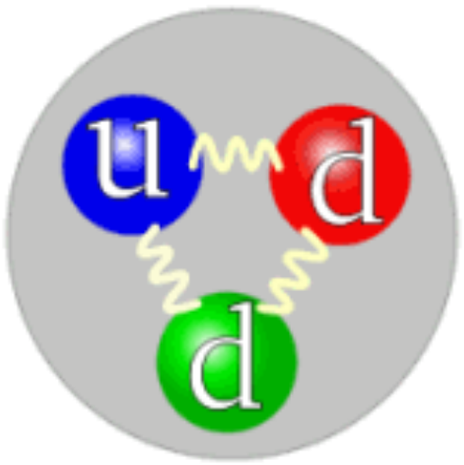
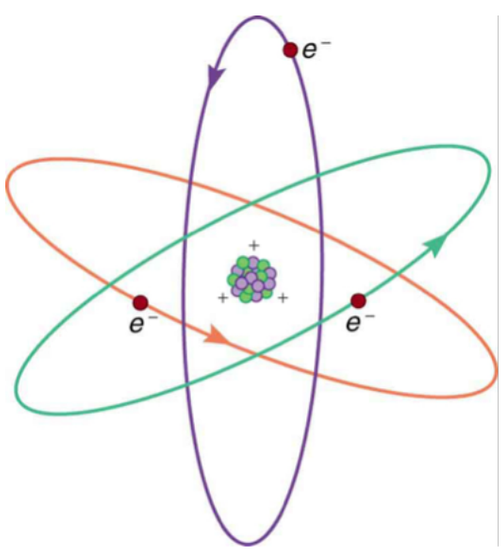


Proton



Neutron



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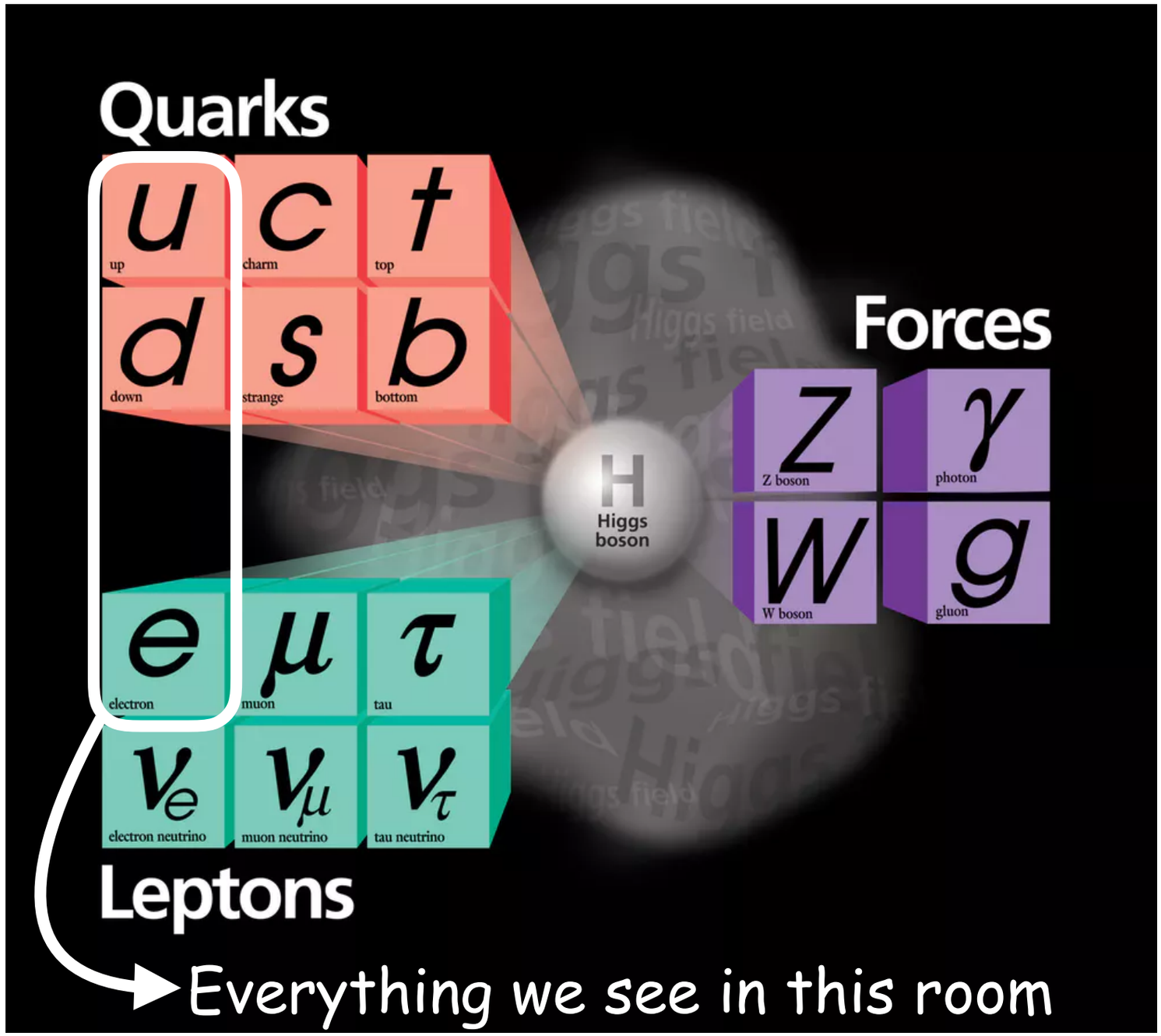

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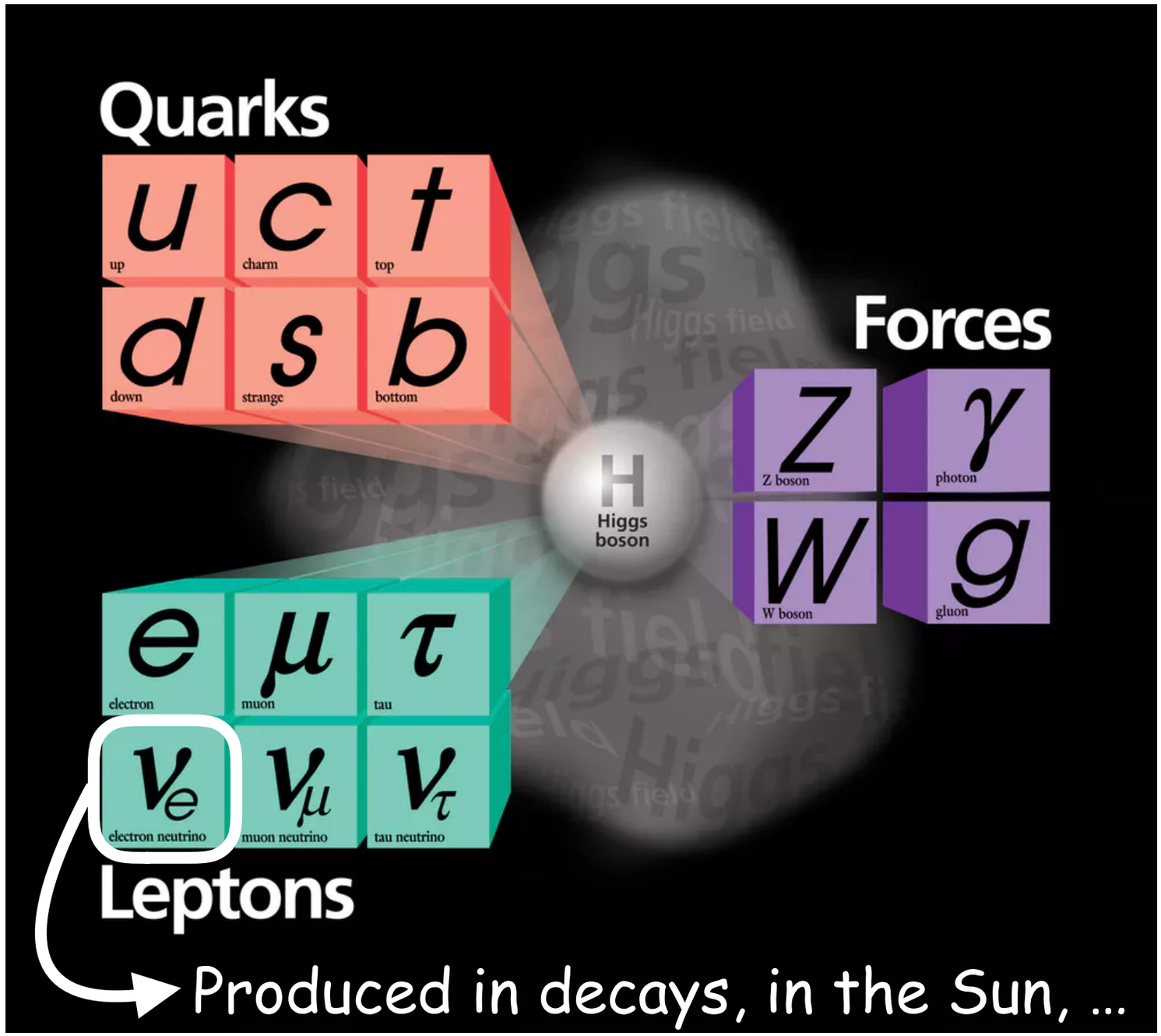

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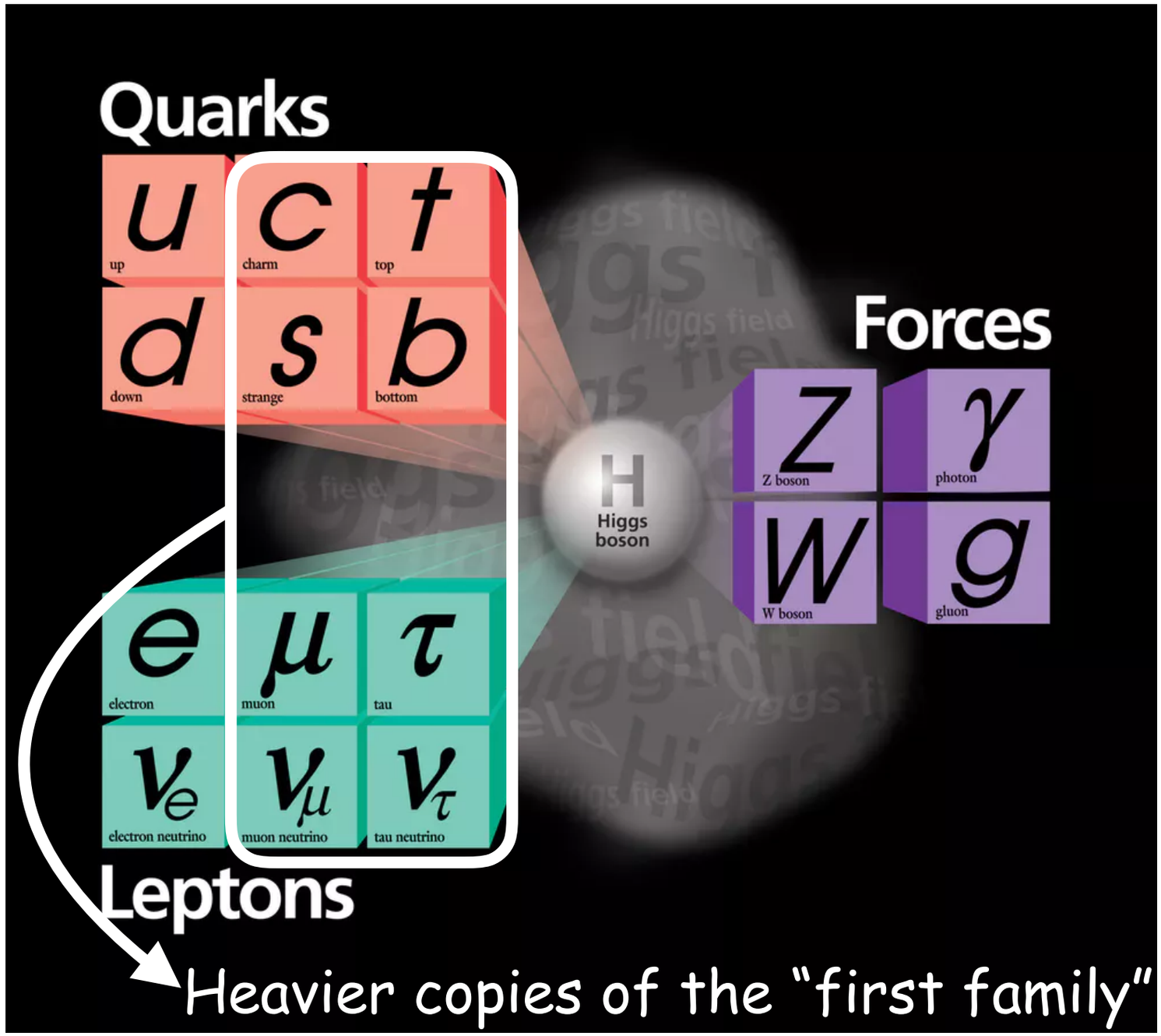

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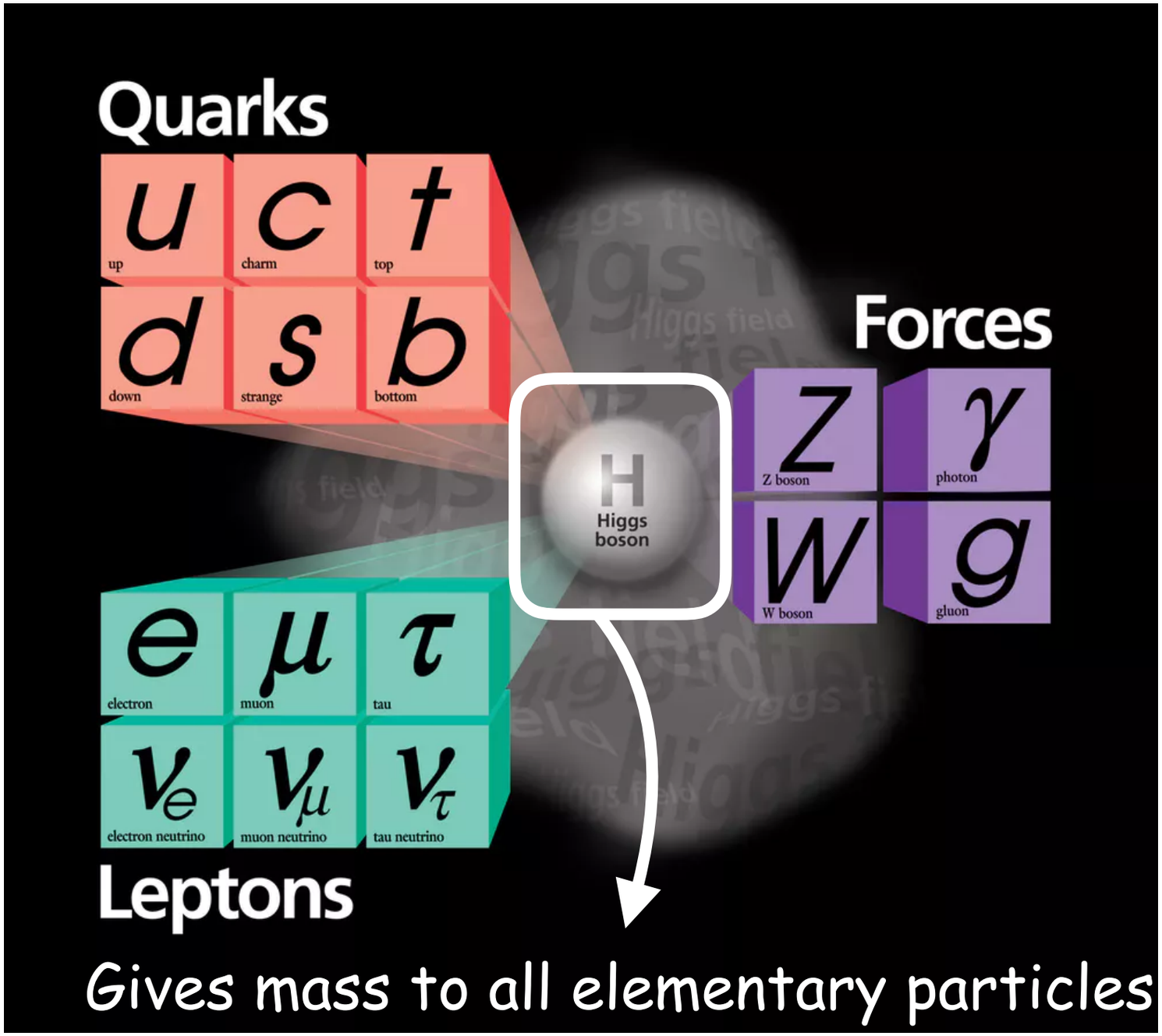

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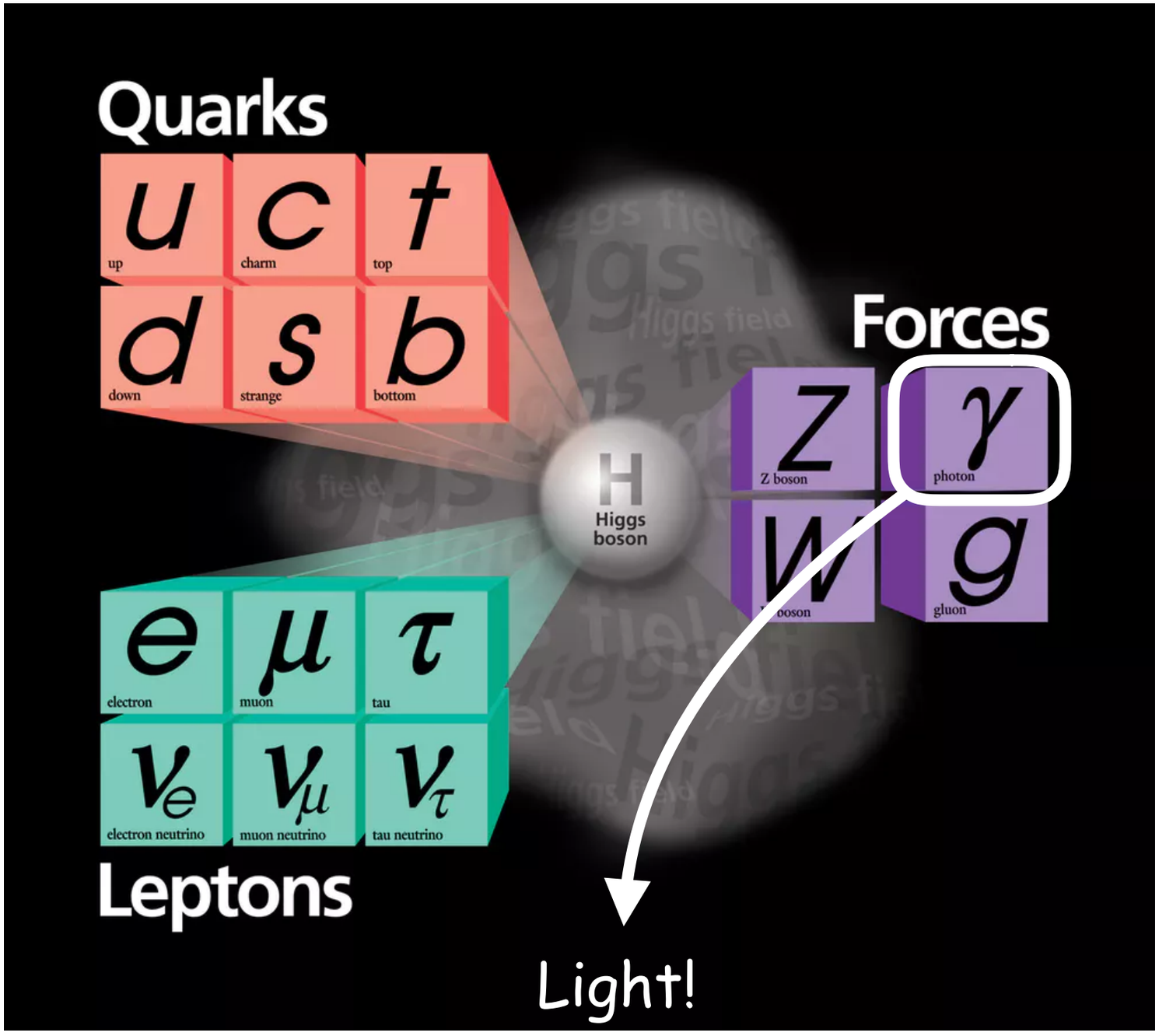

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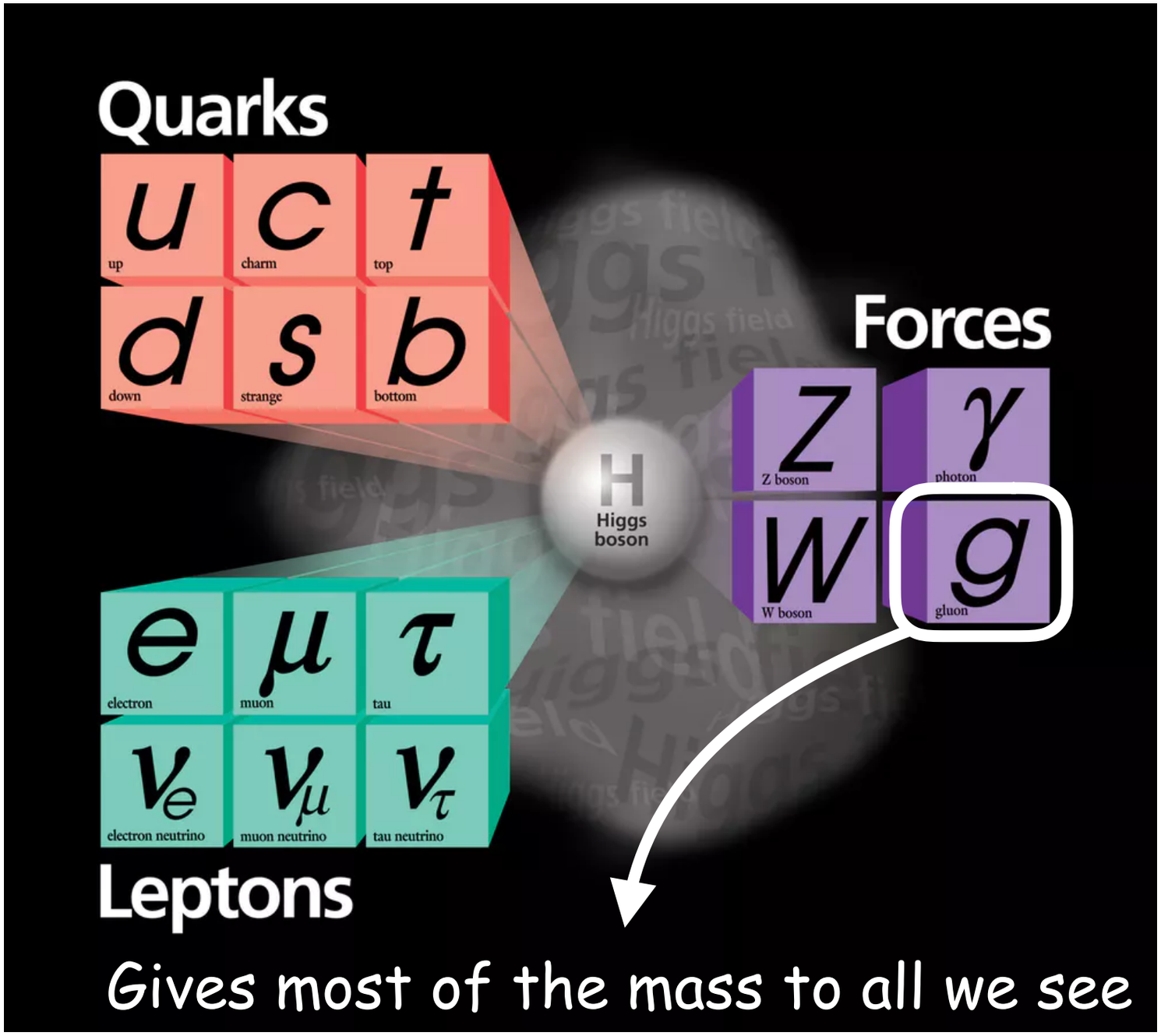


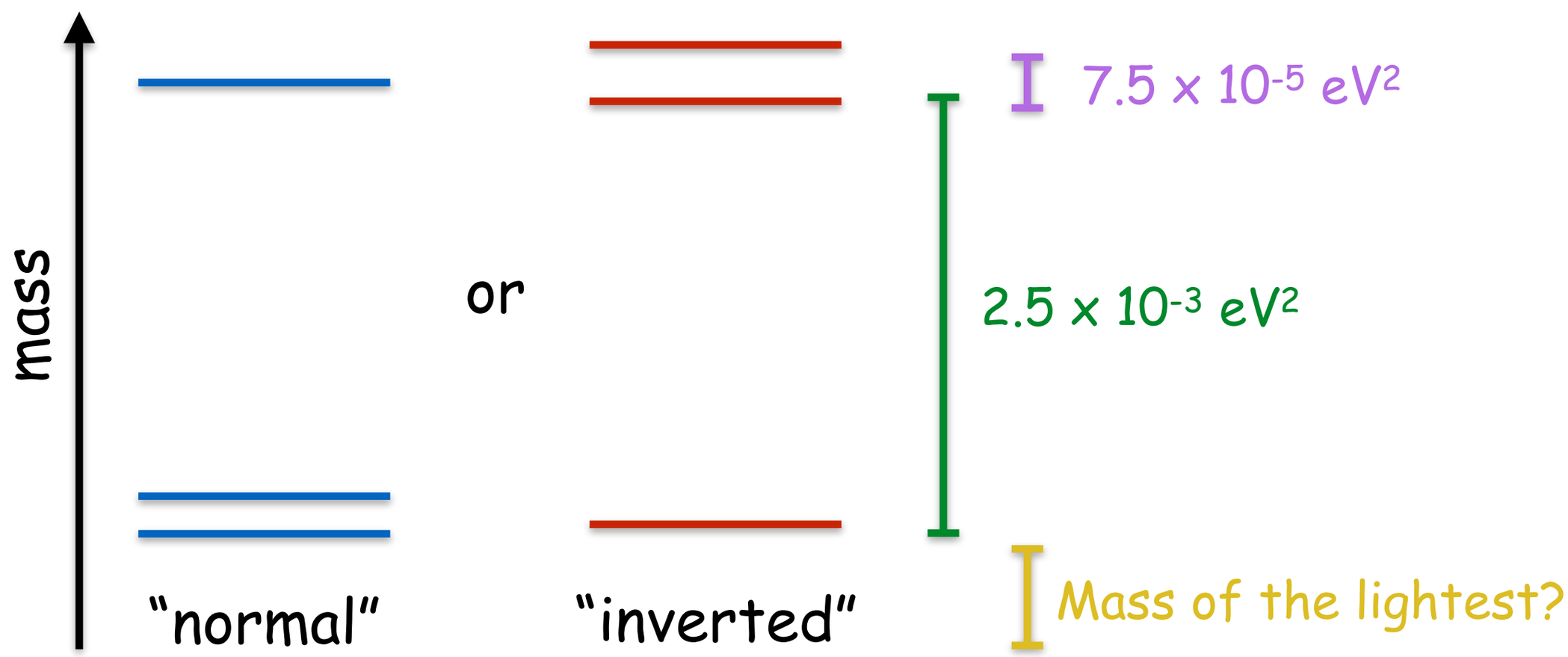
Sterile neutrinos

Neutrino oscillations roughly go like this:

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2 \left(1.27 \frac{\Delta m^2 [\mathrm{eV}^2]\, L[\mathrm{km}]}{E[\mathrm{GeV}]} \right)$$

The SM predicts only 3 neutrinos

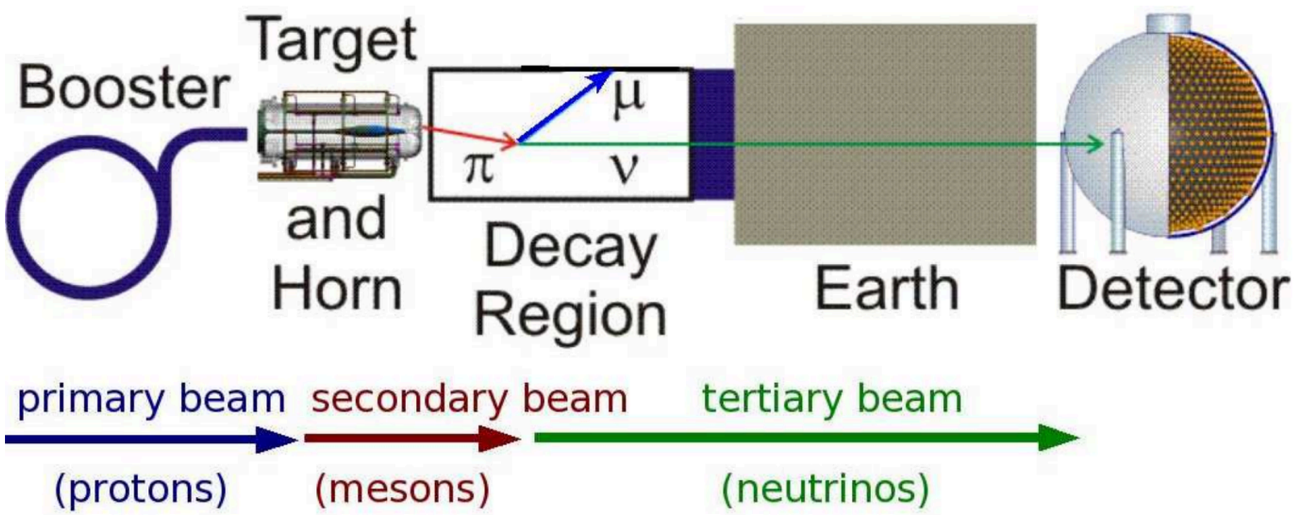
Several exps. at different L and E indicate two mass splittings

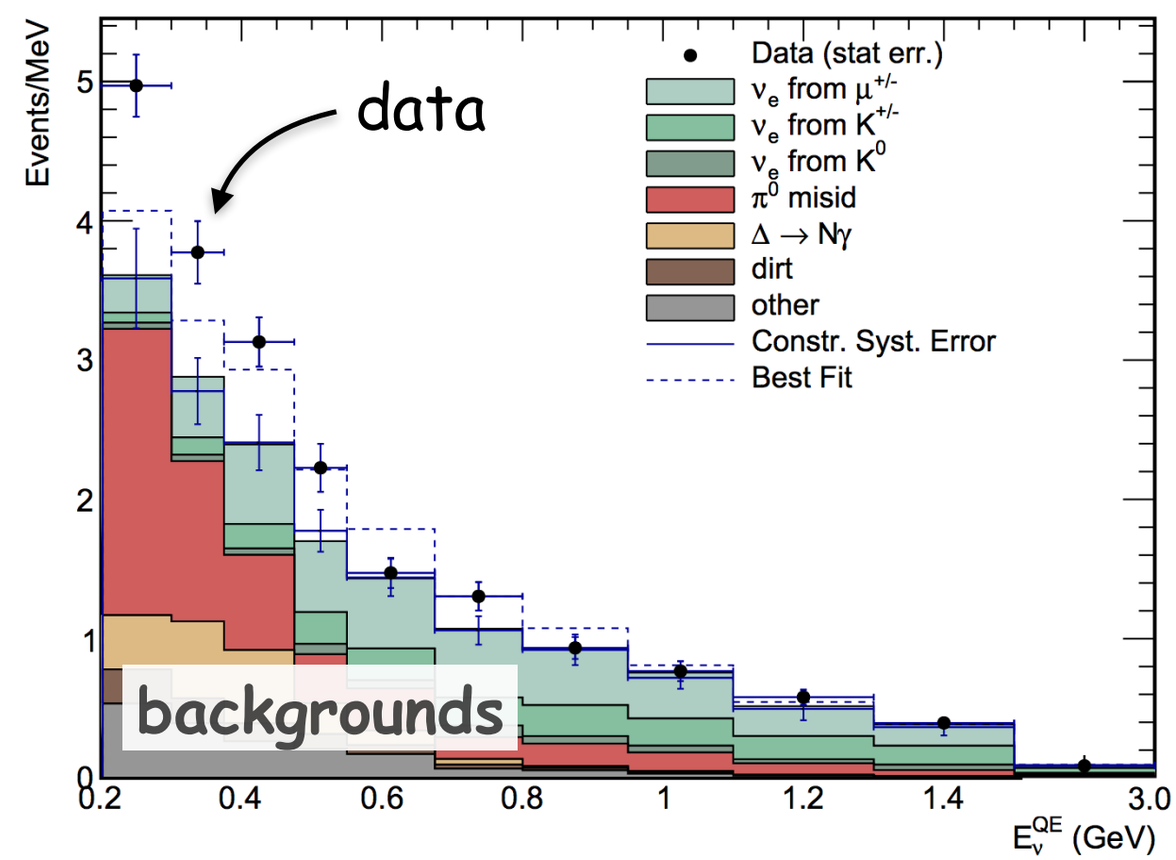


Sterile neutrinos

But 20 years ago, the LSND experiment indicated the existence of another, **much larger splitting** (~ 1 eV^2)

Recently, the MiniBooNE experiment here at FNAL also observes something consistent with a **larger mass splitting**

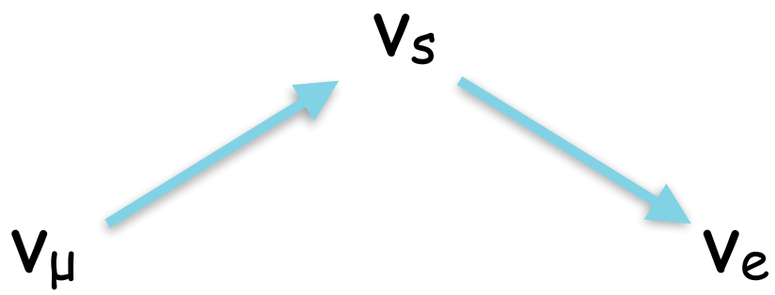




Did we finally find physics beyond the standard model???

Sterile neutrinos

ν_μ to ν_e oscillations at short baselines via sterile neutrinos



To have ν_μ to ν_e oscillations at SBL,
both ν_μ and ν_e need to oscillate to ν_s!

At SBL:
$P(\nu_\mu \text{ to } \nu_e) \neq 0$

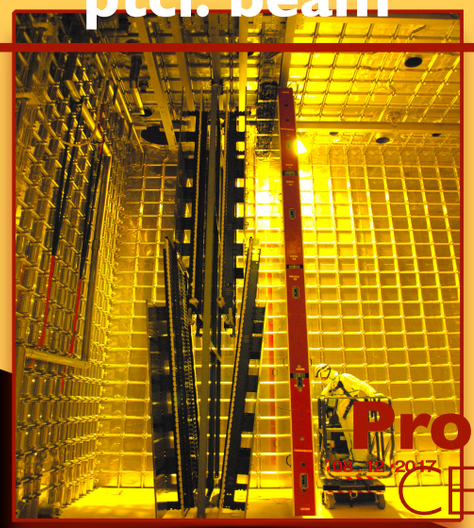
requires

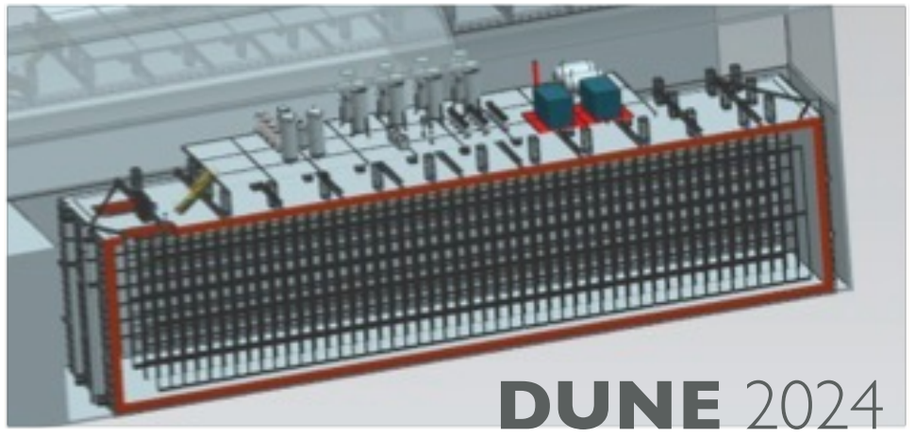
$P(\nu_\mu \text{ to } \nu_\mu) \neq 1$
$P(\nu_e \text{ to } \nu_e) \neq 1$

LAPD
FNAL
2010-11

35 t
FNAL 2013-16

CERN NP charged ptcl. beam





DUNE 2024

R&D
1986-2000

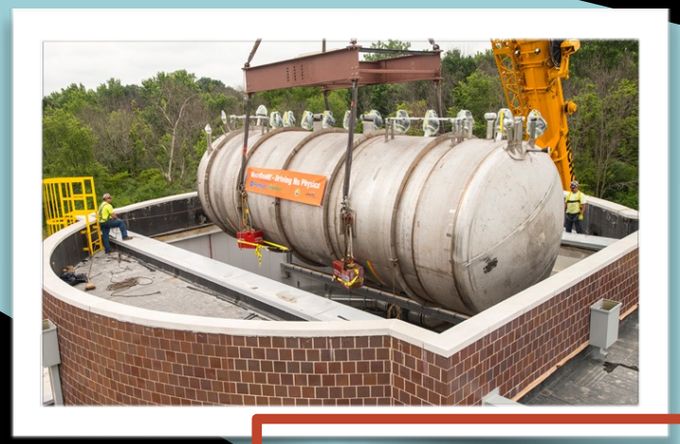
ICARUS

LNGS→FNAL
2010-13→2018

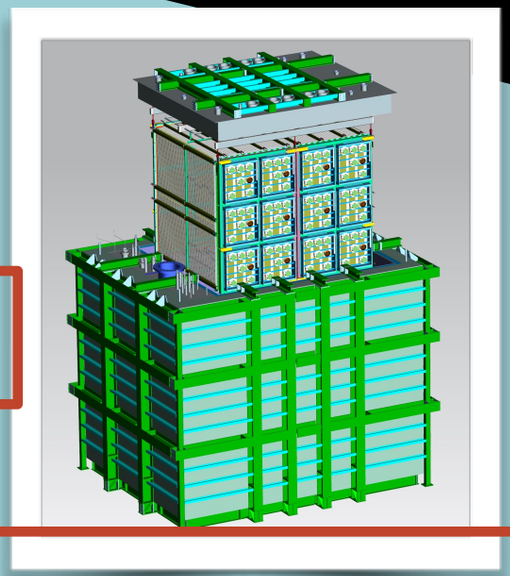
ProtoDUNE
CERN 2018
in run

Long Baseline ν at SURF-SD

μBooNE
FNAL - 2015-in run



SBND
FNAL - 2020



Booster beam

ArgoNeuT
FNAL
2009-10

Yale TPC 2007

LArIAT FNAL
2014-2018

Short Baseline ν at FNAL

NuMI beam

FTBFcharged ptcl. beam

Why liquid Argon?

- Noble elements are ideal materials for detection of ionising radiation.
  - Do not attach electrons (long drift paths possible in liquid phase).
  - High electron mobility except He, Ne (≈ quasi-free drift electrons).
  - Commercially easy to obtain (in particular, liquid Argon).
  - Can be made very pure and many impurities freeze out at low temperature.
  - Inert, not flammable.

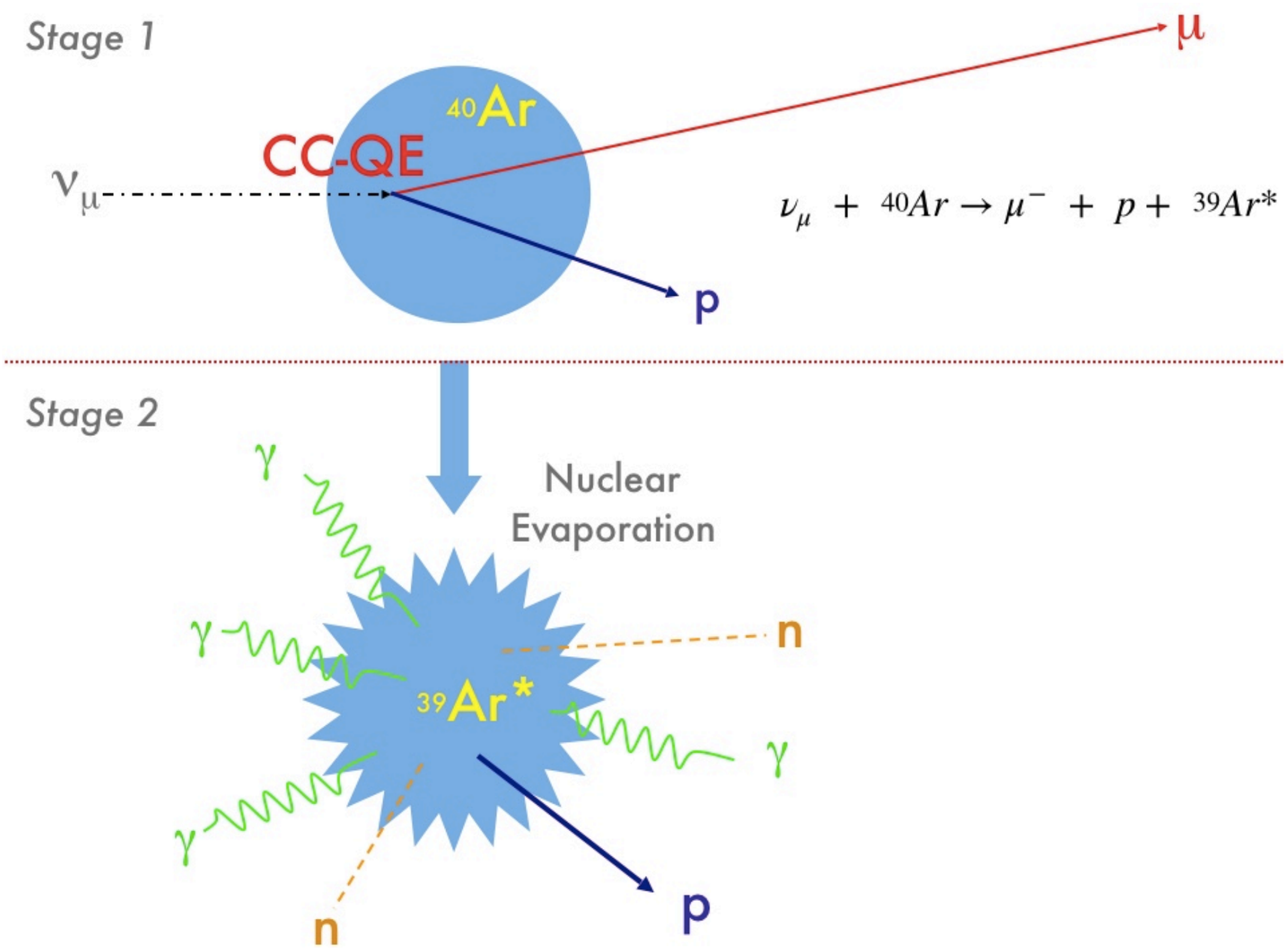
	Water	He	Ne	Ar	Kr	Xe
Boiling Point [K] @ 1atm	373	4.2	27.1	87.3	120.0	165.0
Density [g/cm^3]	1	0.125	1.2	1.4	2.4	3.0
Radiation Length [cm]	36.1	755.2	24.0	14.0	4.9	2.8
Scintillation [γ /MeV]	-	19,000	30,000	40,000	25,000	42,000
dE/dx [MeV/cm]	1.9		1.4	2.1	3.0	3.8
Scintillation λ [nm]		80	78	128	150	175

- Liquid phase preferred
  - High density (≈ g/cm^3 ≈ 10^3 x ρ_{gas}) increases cross section.
  - Homogeneity and uniformity guarantee precise movement of the ionisation electrons.
  - Need for scalability to large-scale excludes solids (cracks, medium transitions, etc).

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

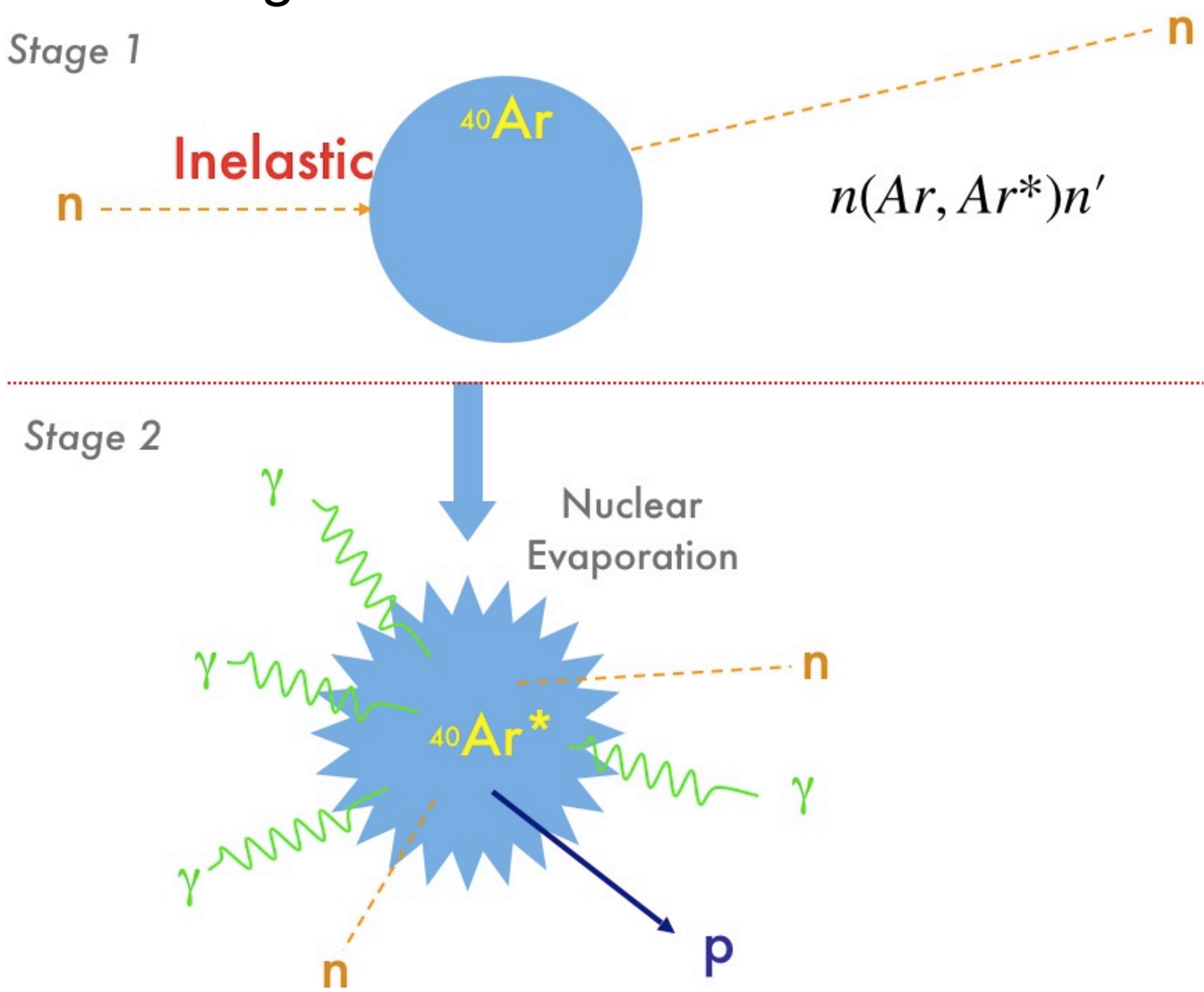


$$\nu_\mu + {}^{40}Ar \rightarrow \mu^- + p + {}^{39}Ar^*$$

Low Energy Photon Production

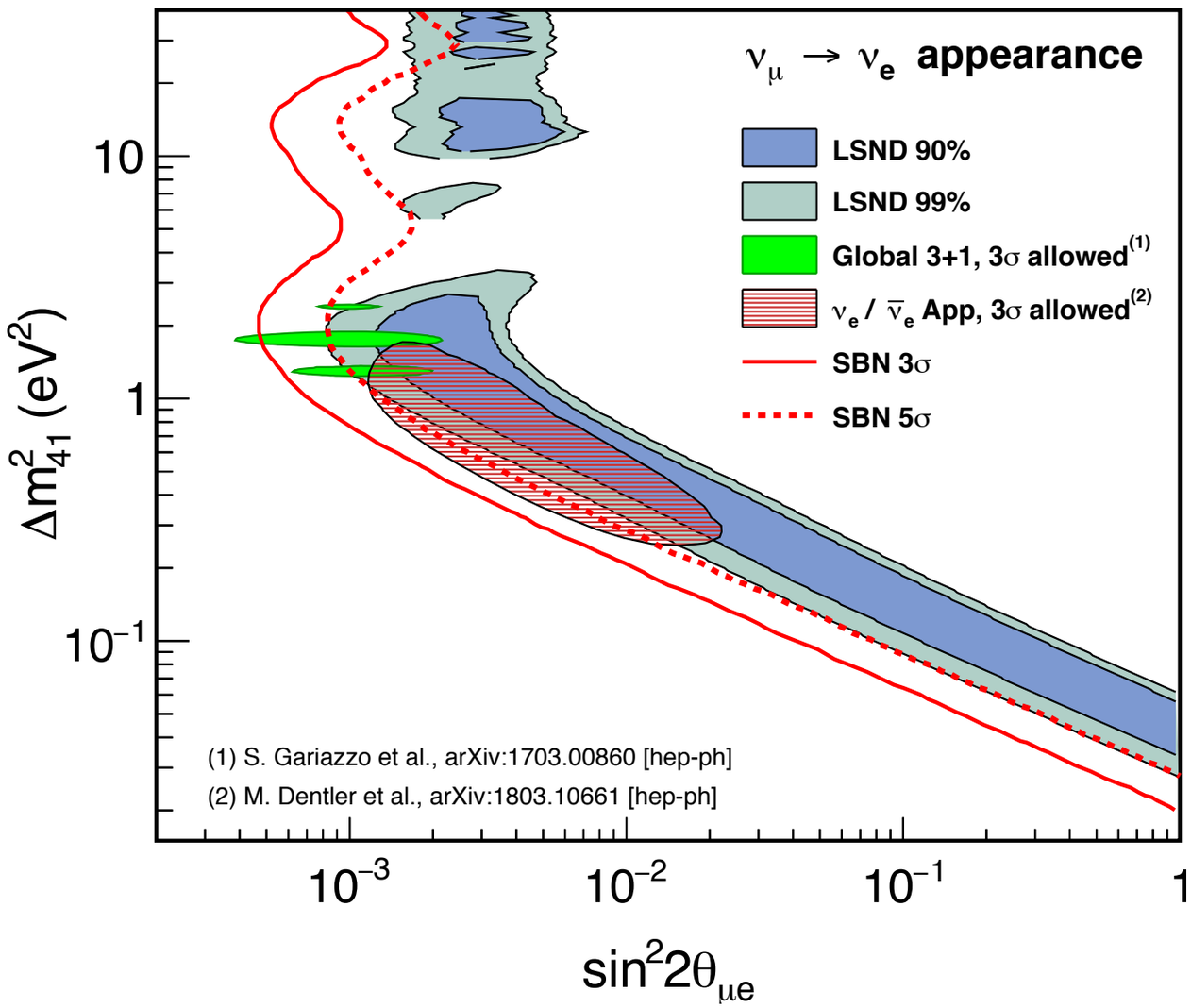
Low Energy (MeV) Photons can be produced in GeV neutrino-argon interactions by two possible mechanisms:

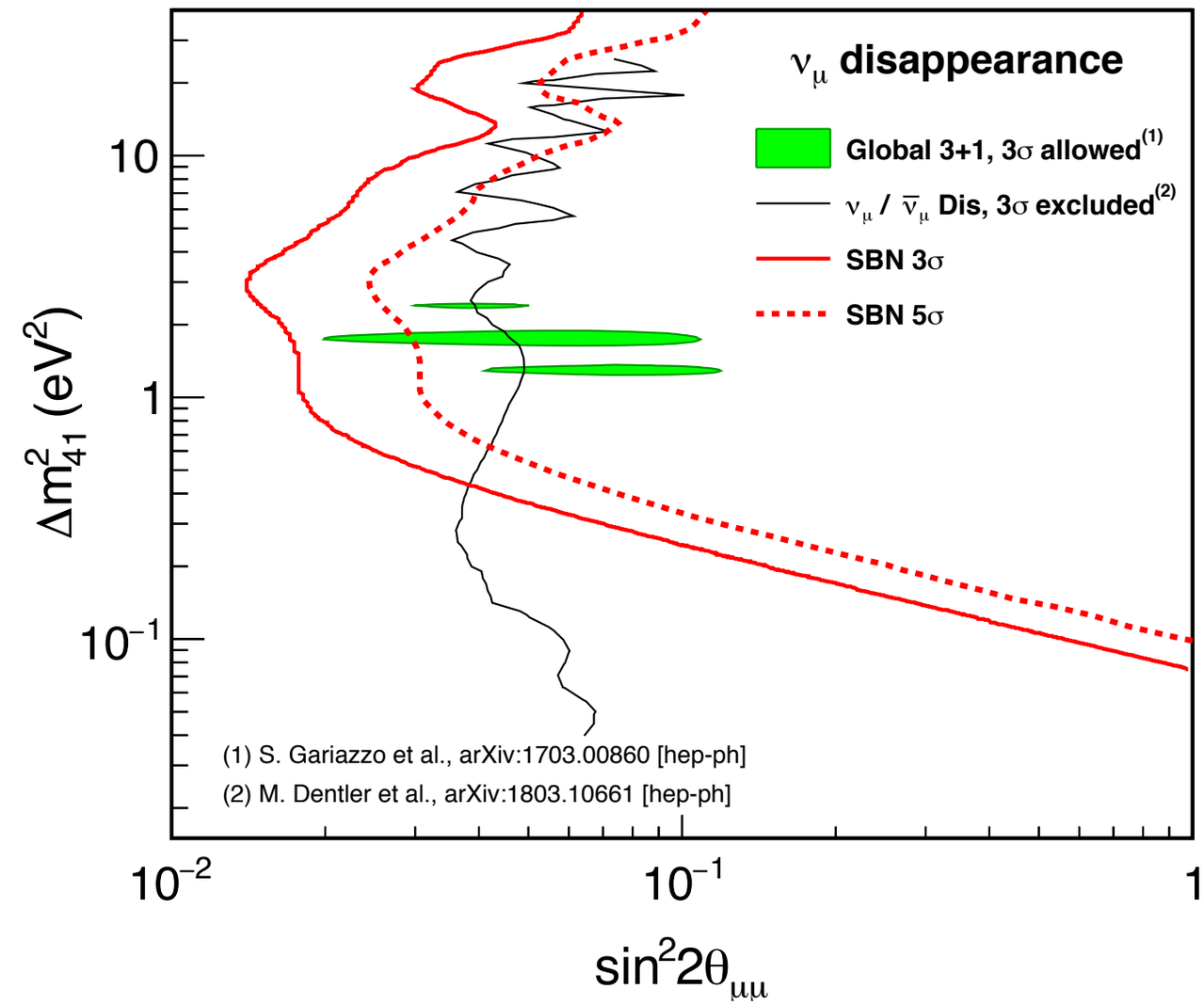
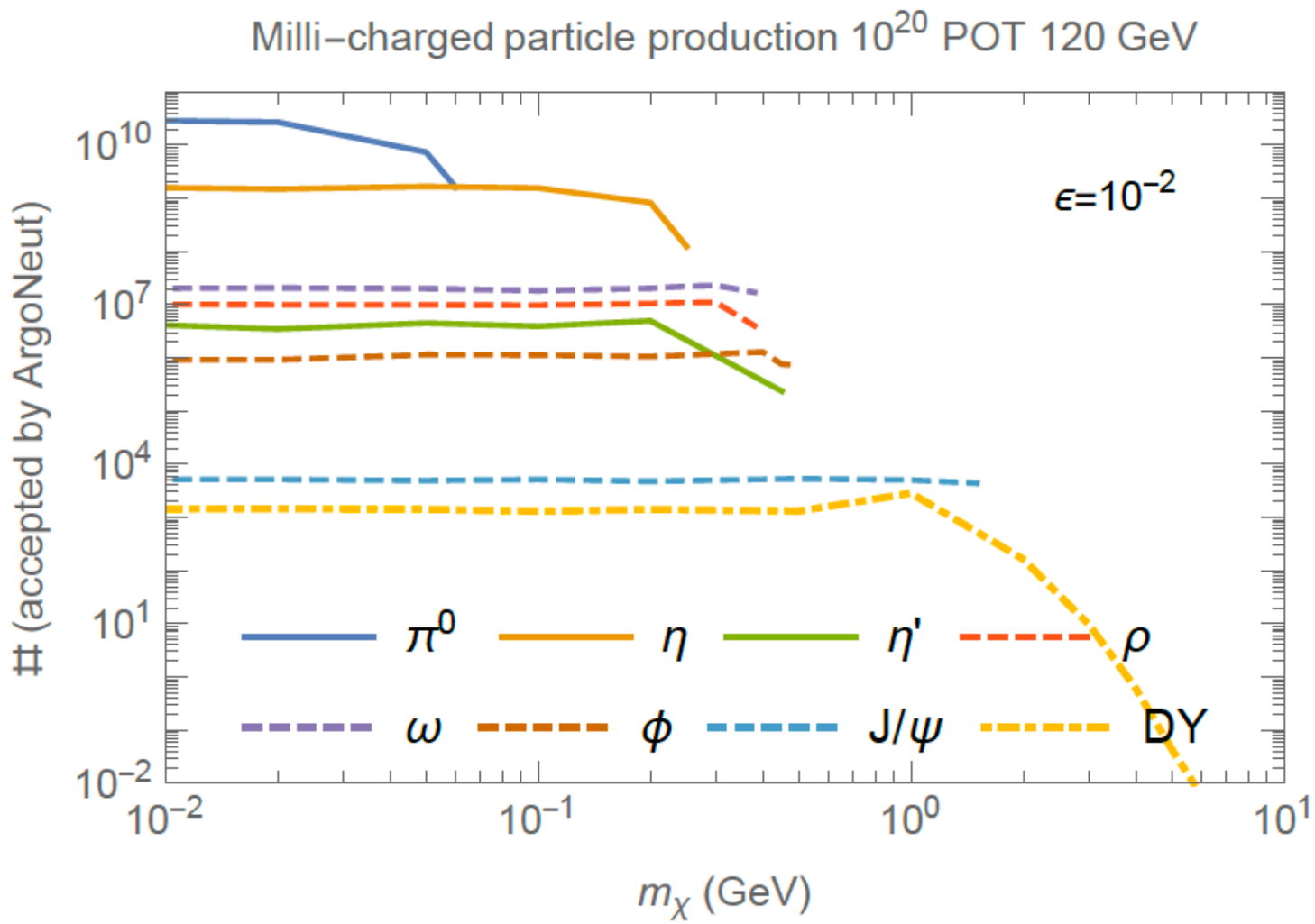
1. De-excitation of the target nucleus
2. Inelastic scattering of neutrons



SBN sensitivity to sterile neutrinos

Machado Palamara Schmitz 2019





Millicharged production @ ArgoNeuT