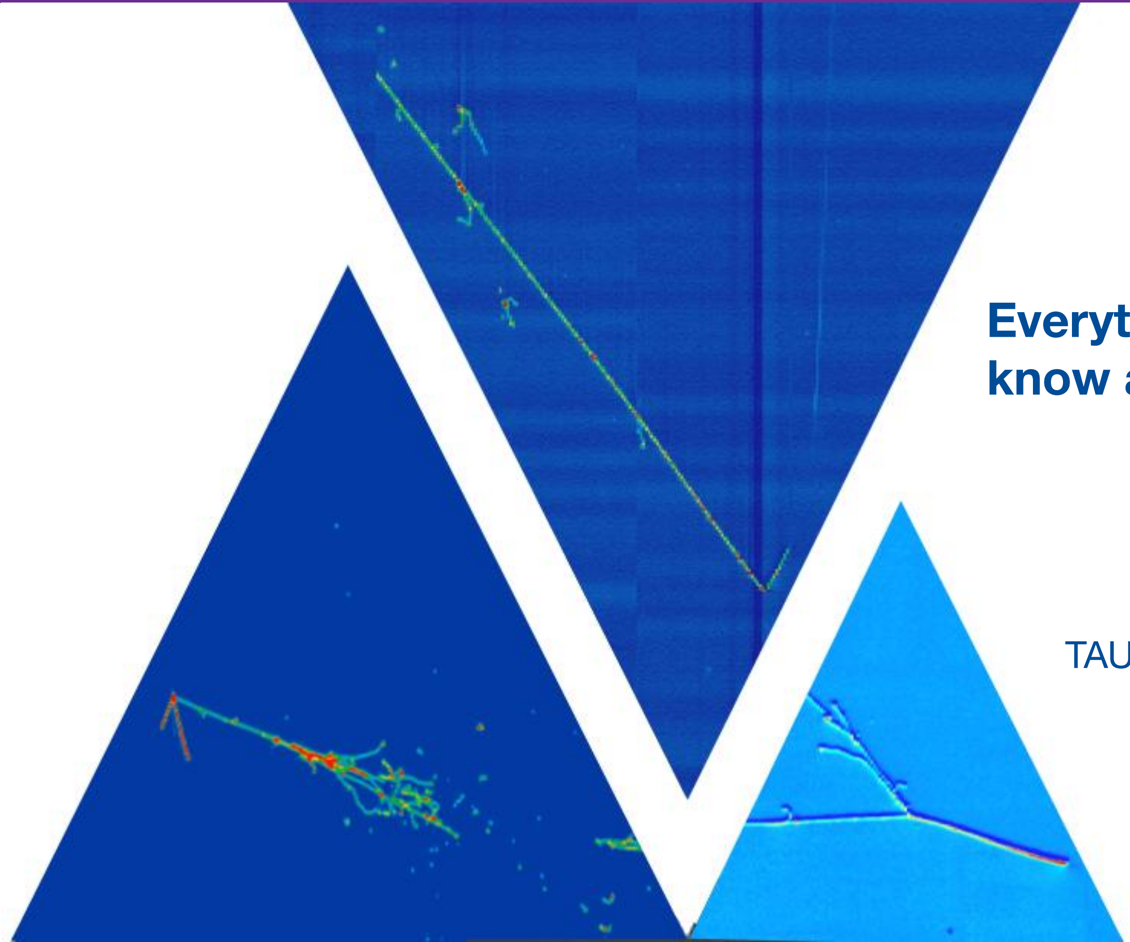


Everything you always wanted to know about the LArTPC technology*

*but were afraid to ask

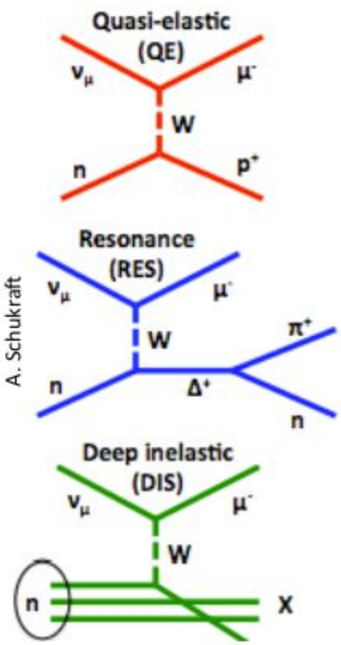
Elena Gramellini

TAU-UoM Workshop, March 27th 2023, Tel Aviv.

What’s your picture of a neutrino interaction?

Different points of view...

Theorists



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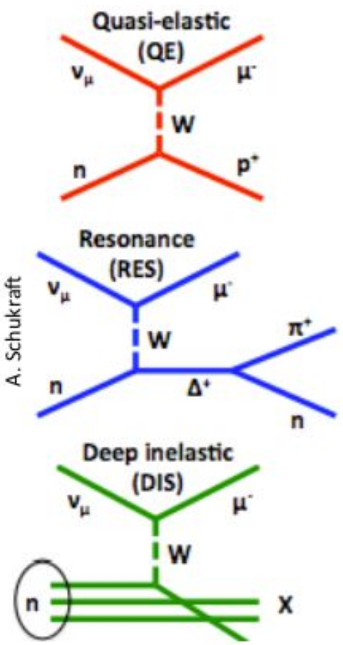
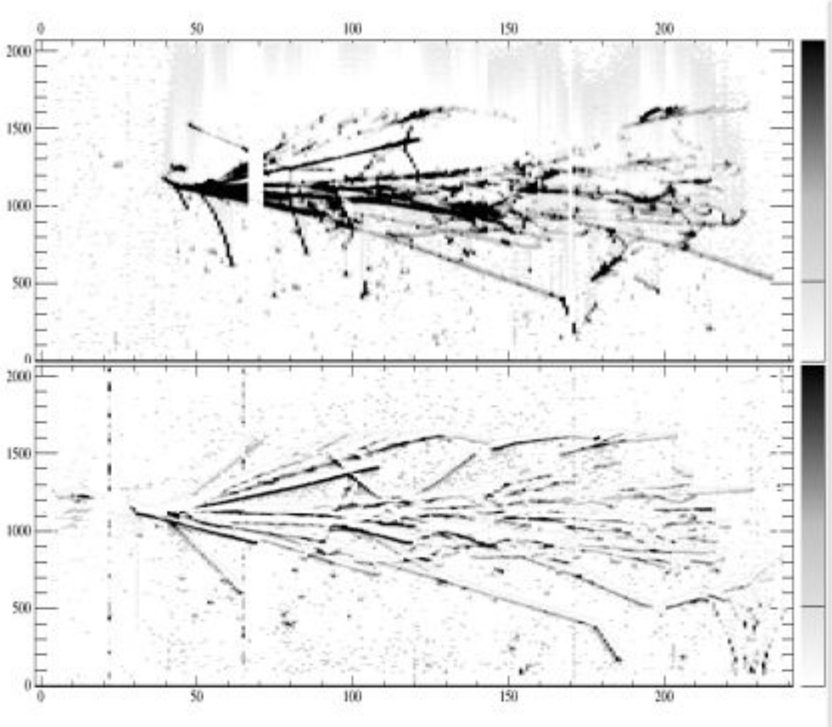


Experimentalists



DIS candidate
As seen by
the ArgoNeut
experiment

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Experimentally, neutrinos are difficult

Neutrinos are the most abundant massive particle in the universe, and one of the least understood.

They are neutral: we can't directly detect them. We can study them only if they interact, but...

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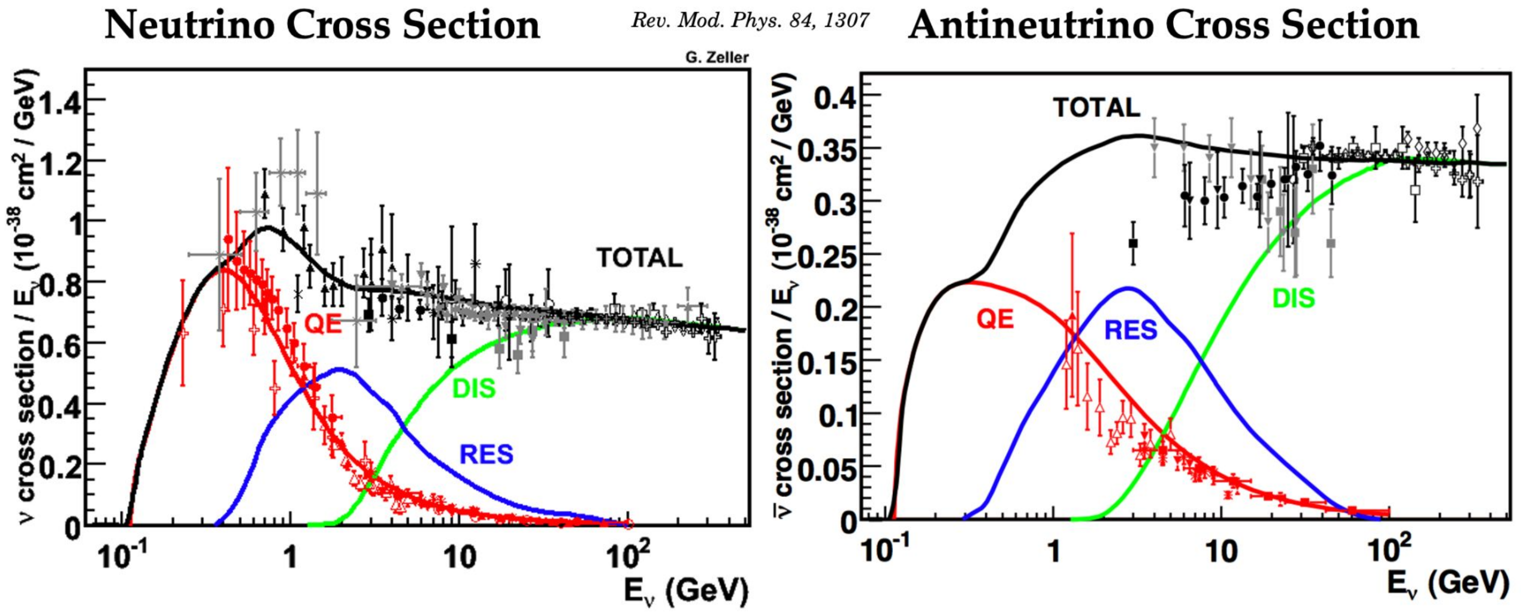

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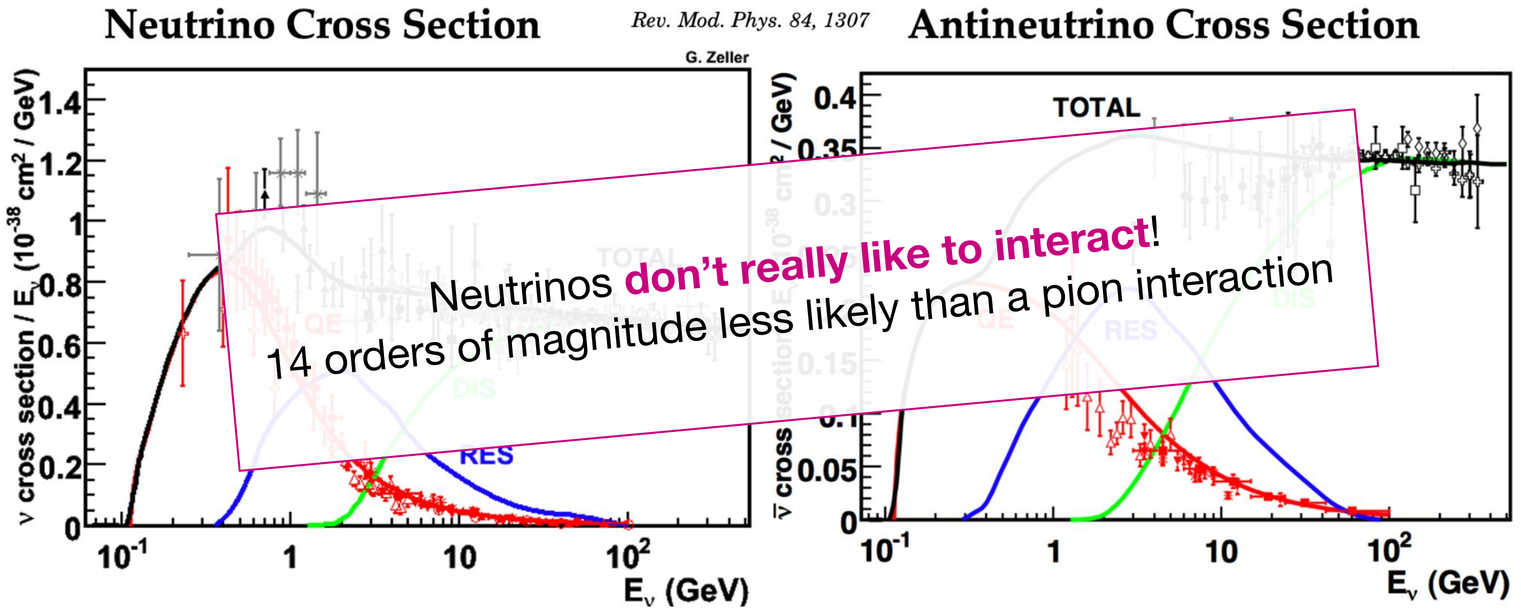


When they do, the particles produced often have low energy (**hundreds of MeV**). And there's more...

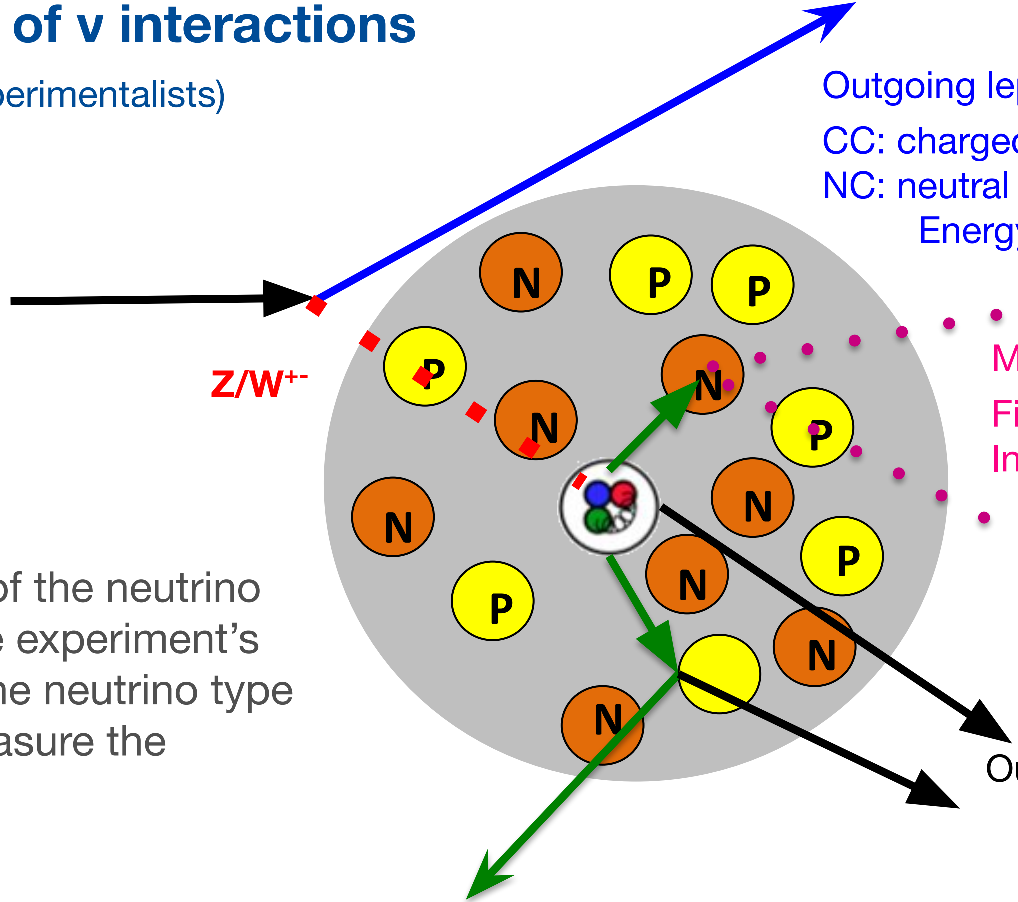
A simplified view of ν interactions

(and of our jobs as experimentalists)

Incoming ν:

Flavor unknown

Energy unknown



Outgoing lepton:

CC: charged lepton

NC: neutral lepton

Energy: measure

Mesons:

Final State Interactions

Energy? Identity?

Outgoing nucleons:

Visible?

Energy?

From the products of the neutrino interactions, it is the experiment's job to understand the neutrino type (ν_e,ν_μ,ν_τ) and to measure the neutrino energy.

Neutrino Detector Wishlist

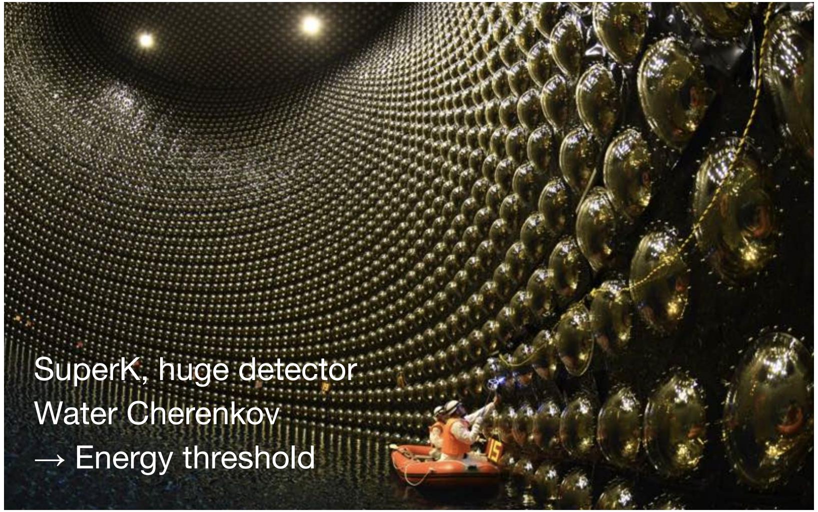
Big and dense detectors exposed to high neutrino flux.

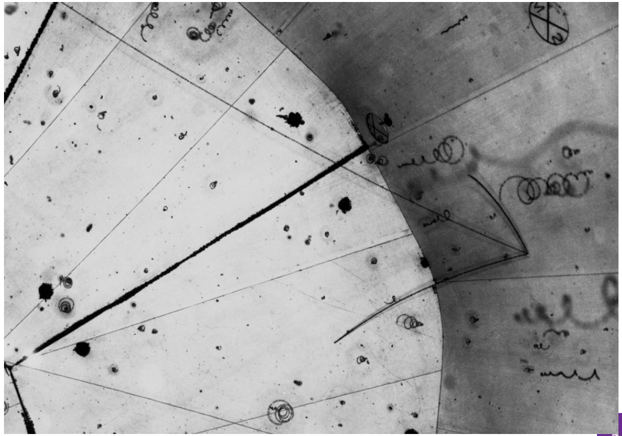
A detector technology able to measure the energy and identity of many particles (calorimetry&PID) even for low energy particles.

A technology able to collect statistically significant samples of neutrino interactions.

An understand and calibrate that technology very well.

Can **Liquid Argon Time Projection Chambers** take the best of these two worlds? Let’s find out!





Bubble chambers: extremely detailed interactions, very stat limited.

Why Argon? And Why Liquid? (and why not Xenon…)

Dense 40% more dense than water → more nuclear centers for the neutrinos to interact

	He	Ne	Ar	Kr	Xe	Water
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120.0	165.0	373
Density [g/cm³]	0.125	1.2	1.4	2.4	3.0	1
Radiation Length [cm]	755.2	24.0	14.0	4.9	2.8	36.1
dE/dx [MeV/cm]	0.24	1.4	2.1	3.0	3.8	1.9
Scintillation [γ /MeV]	19,000	30,000	40,000	25,000	42,000	
Scintillation λ [nm]	80	78	128	150	175	

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~7x 

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Two detection mechanisms: **Ionization Charge and Scintillation Light**
Ionizes easily 55,000 electrons / cm
High e^- lifetime Noble liquid!

~7x

Standard ionization mechanism:
energy transferred from charged particle to the medium knocks off ionization electrons if the energy is high enough
(LAr work function 23.6 eV).

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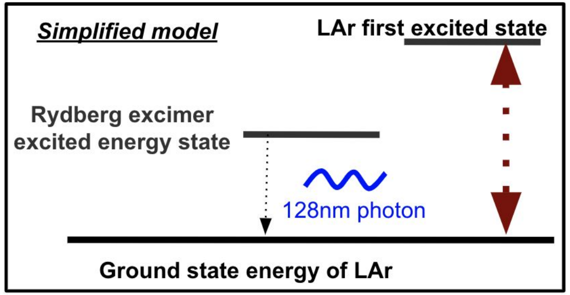
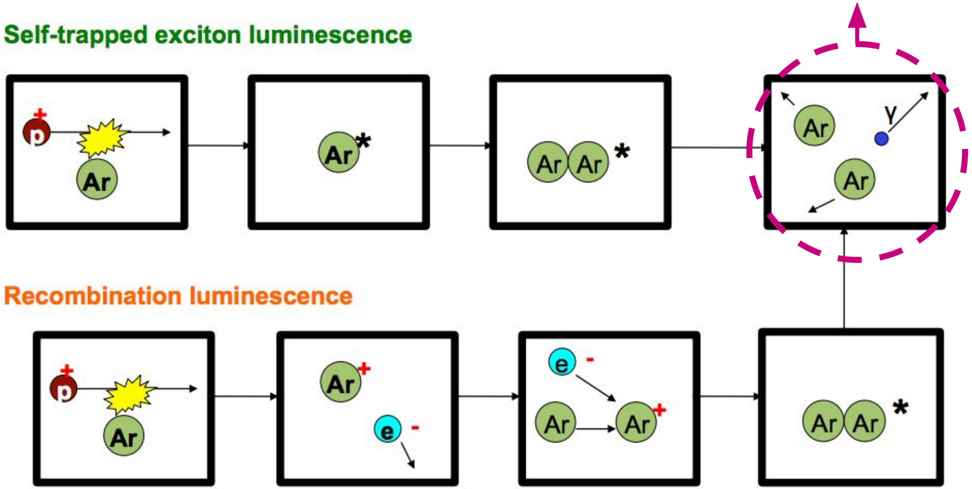
Lots of scintillation light Transparent to light produced (128 nm unfortunately...)





Elena Gramellini | elena.gramellini@manchester.ac.uk
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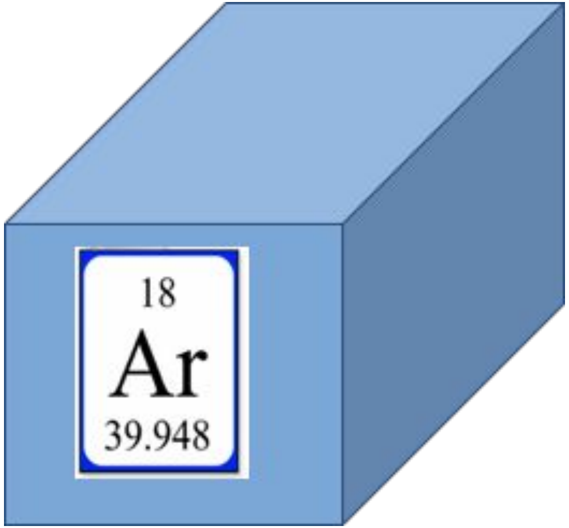
Liquid Argon Time Projection Chamber: The Basis

→ A block of Ar, 0.24 ton (ArgoNeuT) to 10kTon (DUNE)



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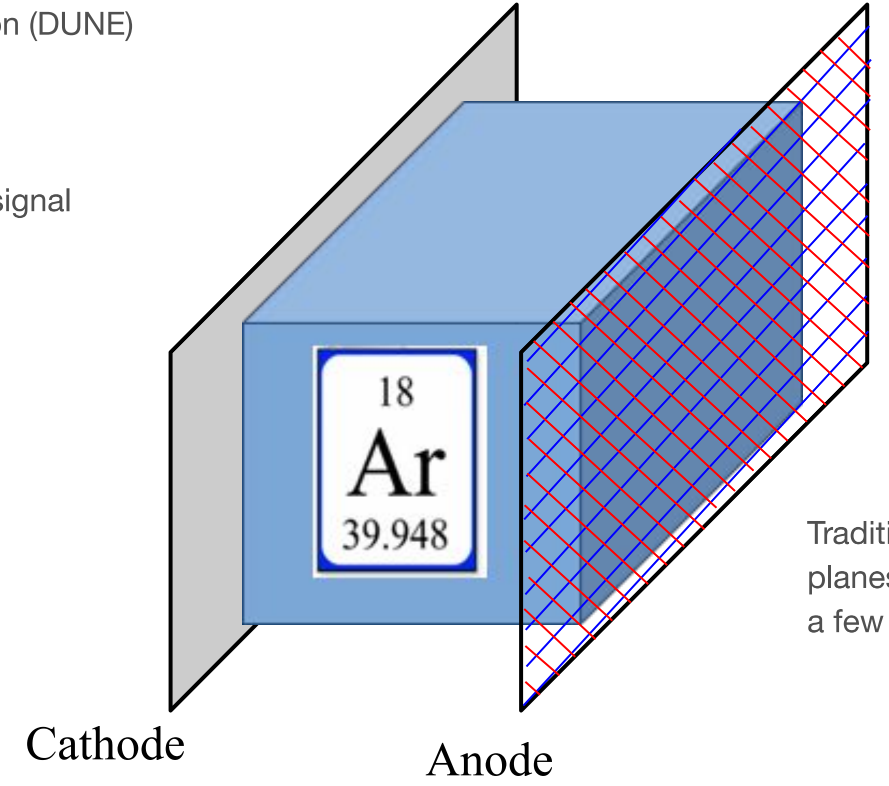
→ Sandwich it in a parallel planes capacitor:
  - Cathode at negative HV
  - Segmented anode to see the charge signal



Traditionally, 2 or more planes of parallel wires a few millimeters apart

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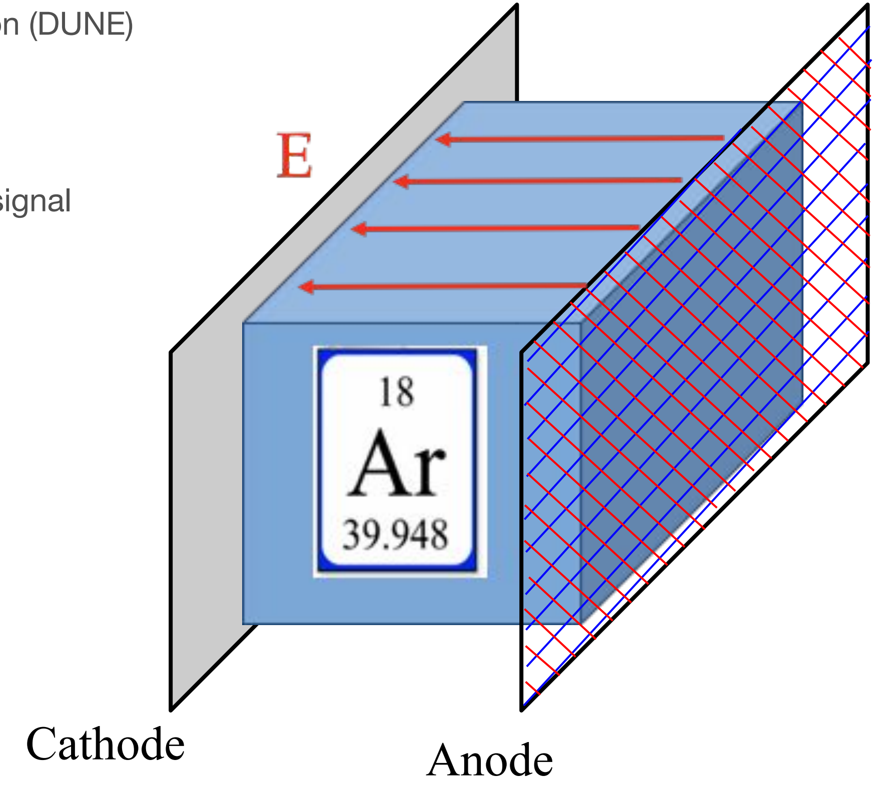
→ Create an electric field as uniform and as constant as possible



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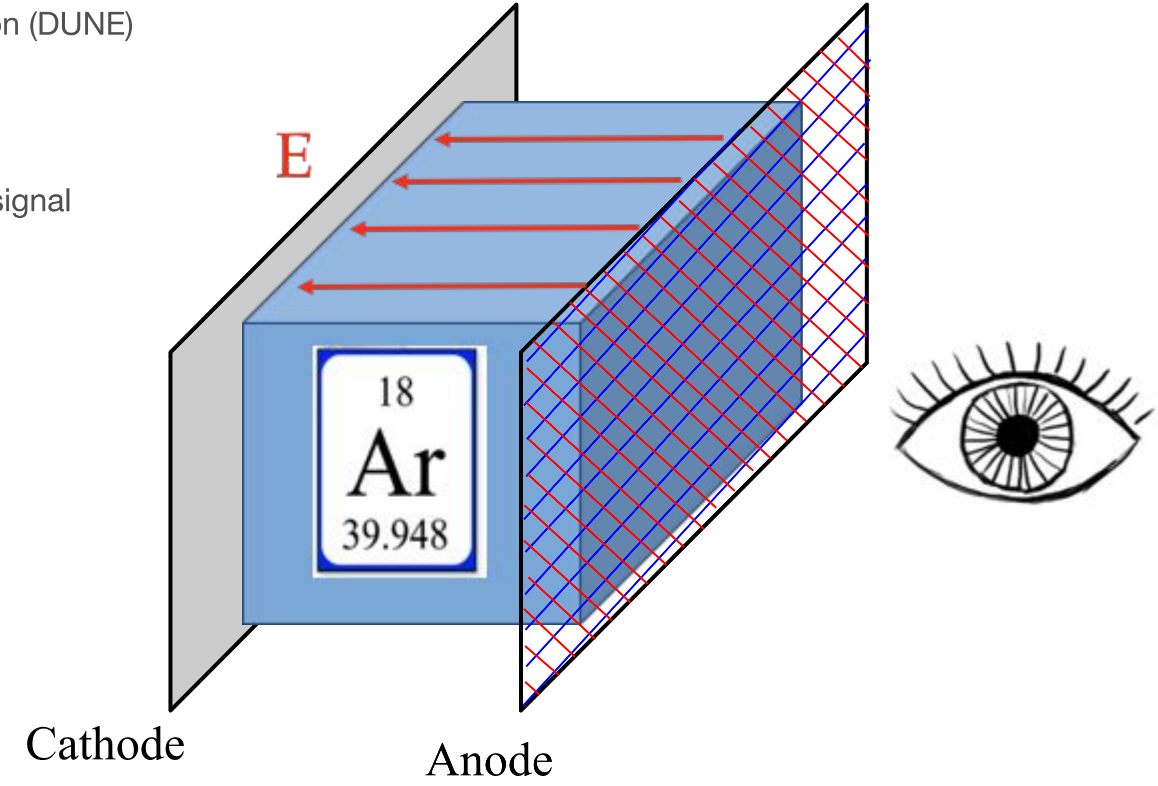

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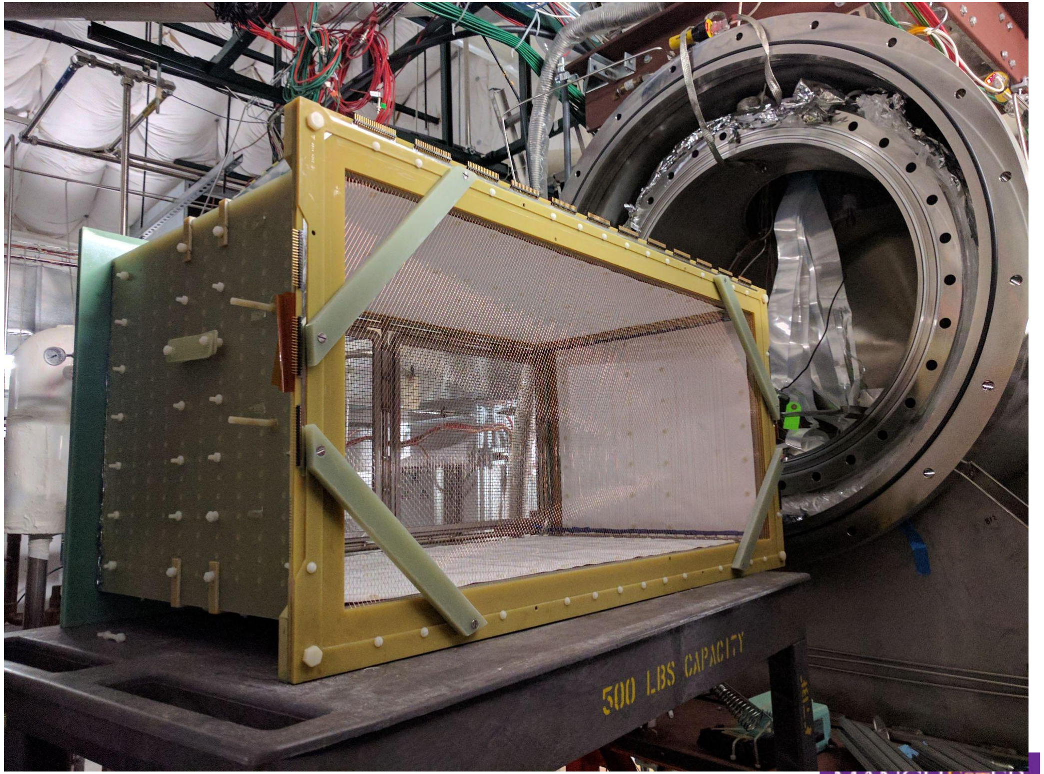
LArIAT TPC



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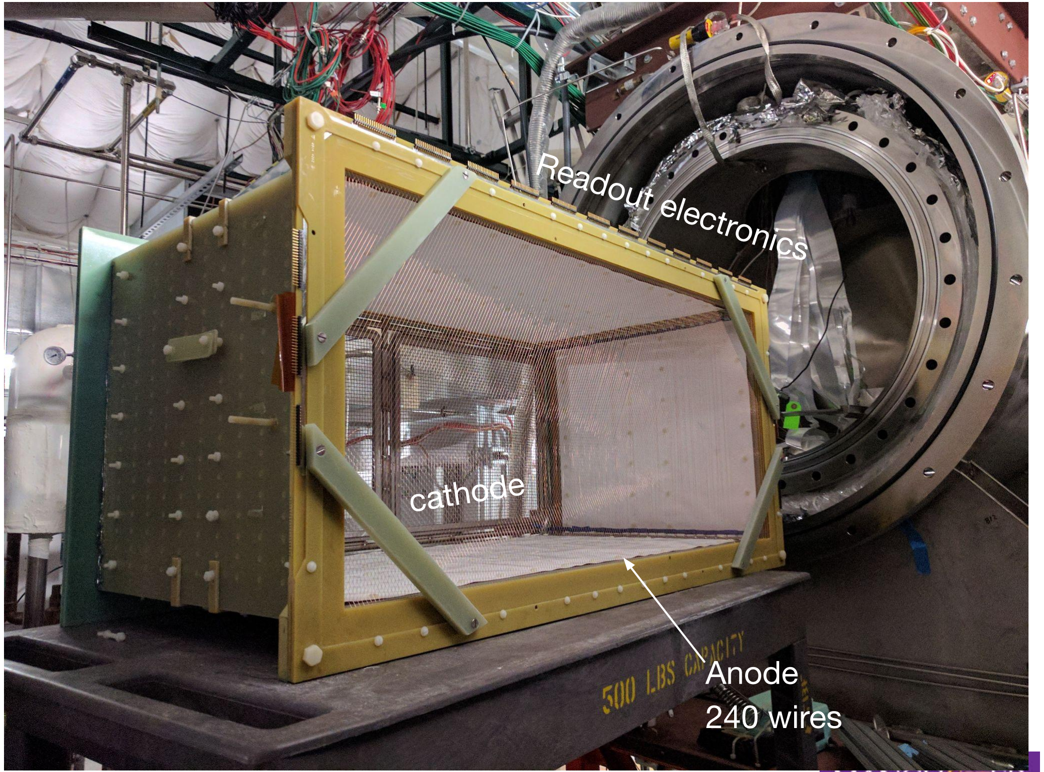

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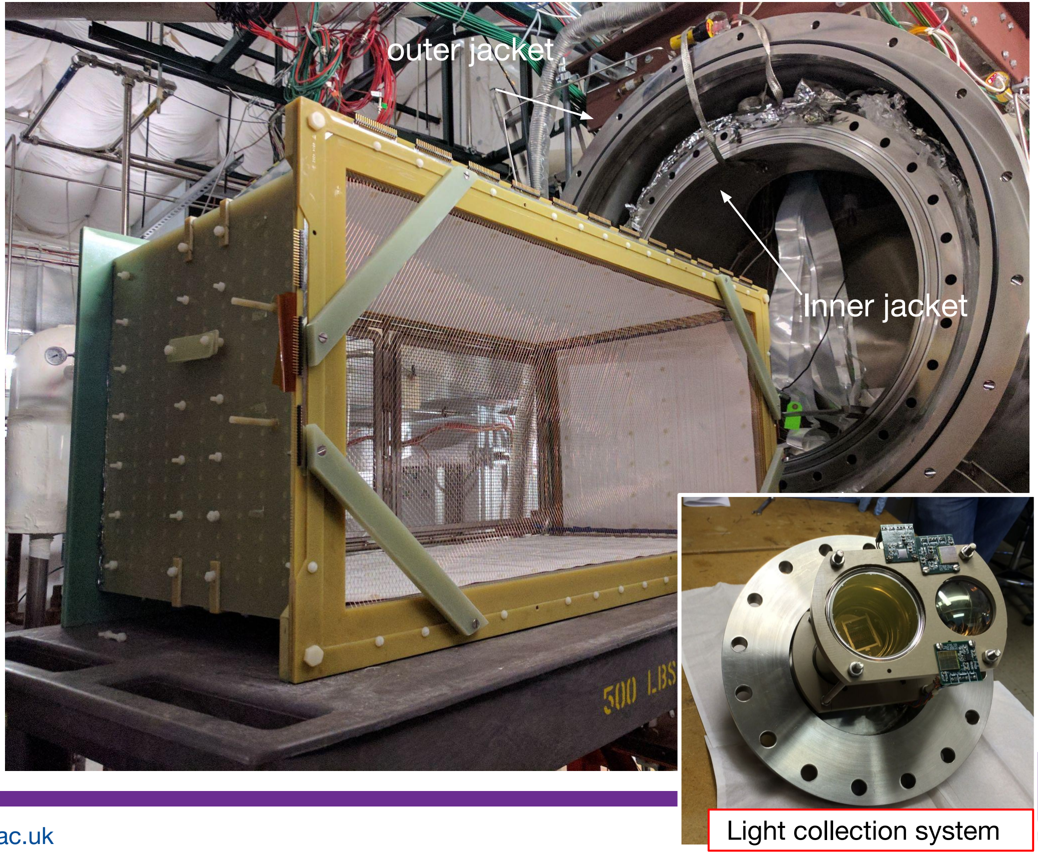
Electronics → preamplifiers: you're reading our Femtocoulomb charge!

Liquid Argon Time Projection Chamber: The Basis

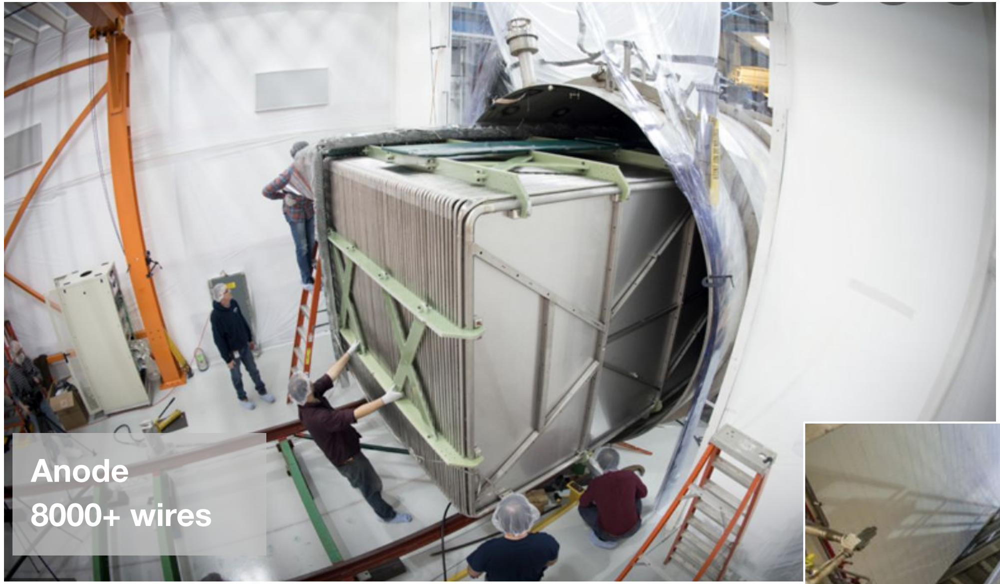
LArIAT TPC

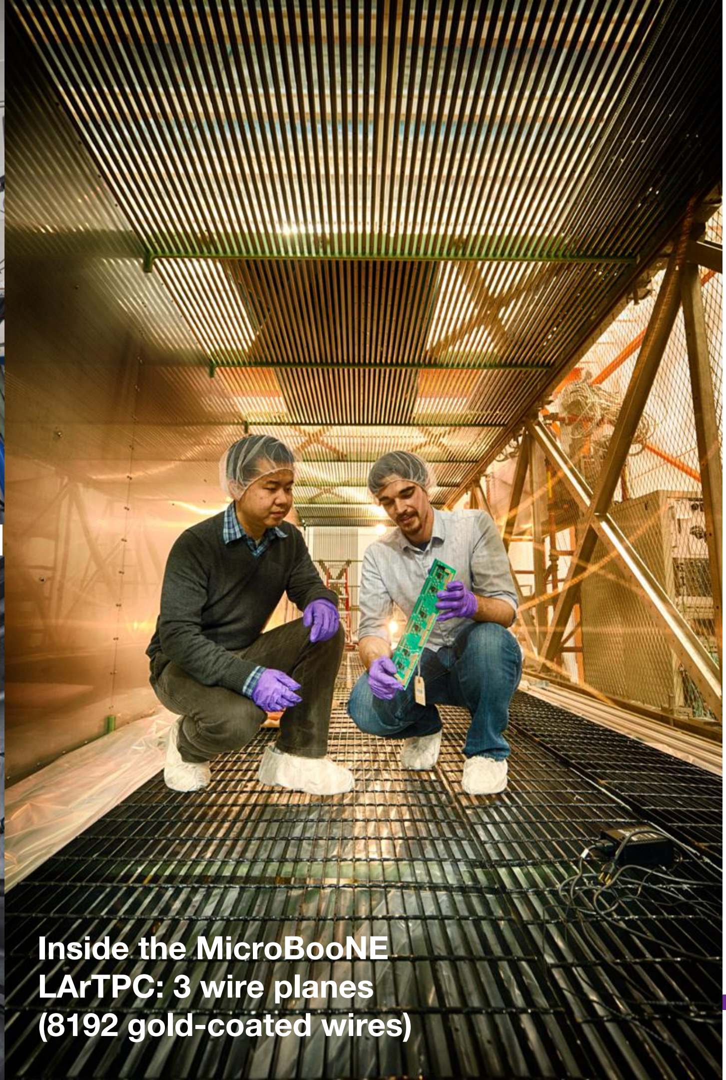


Light collection system

Big TPCs require big cryogenics

MicroBooNE Experiment





MicroBooNE at a glance

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Liquid Argon Time Projection Chamber: Working Principles

1. Energy loss by charged particles:
   Ionization and
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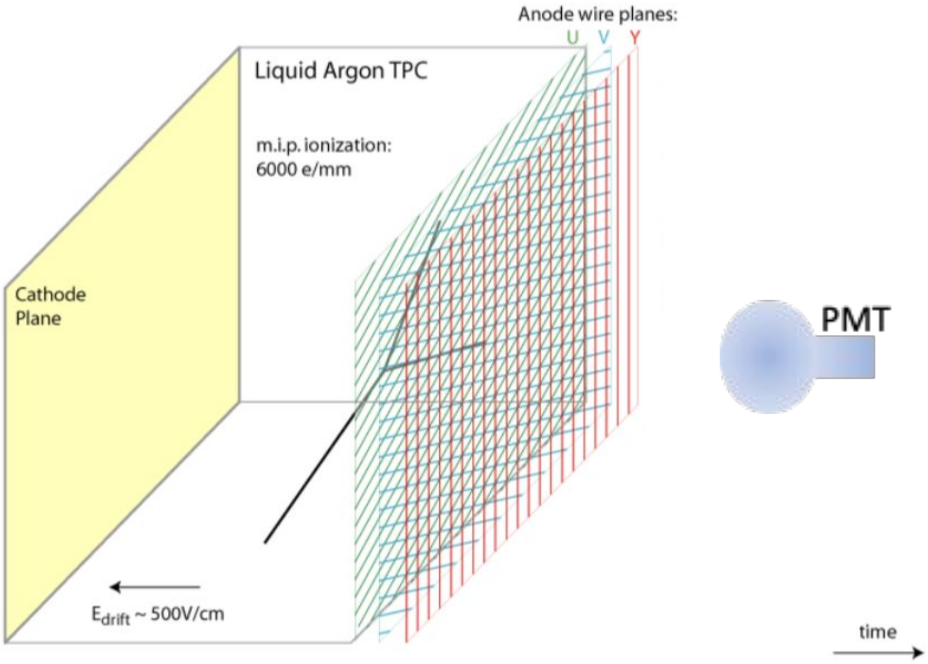
2. Prompt scintillation light emission by Ar_2^+ starts clock:



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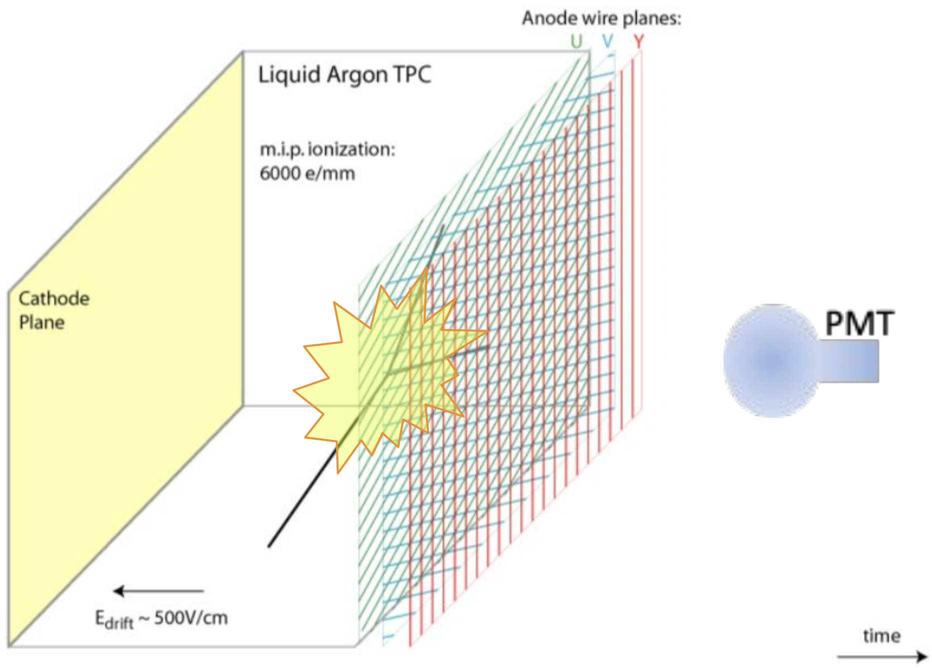

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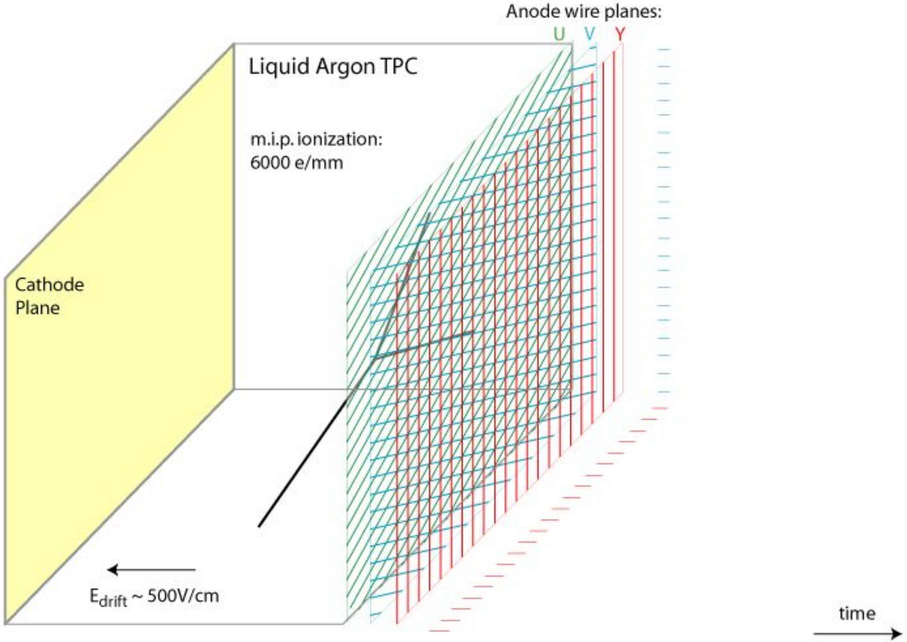
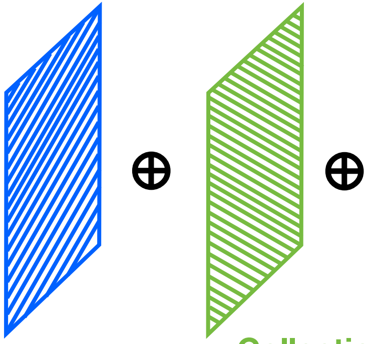
3. Electrons drift to anode: the charge arrives to the anode in
   (Ar^+ ions drift to cathode)

4. Moving electrons induce currents on wires

5. Tracks are reconstructed from wire signals



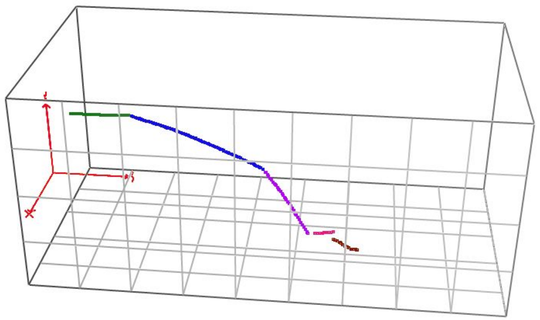
Let’s talk more about the wires a.k.a. y, z, time

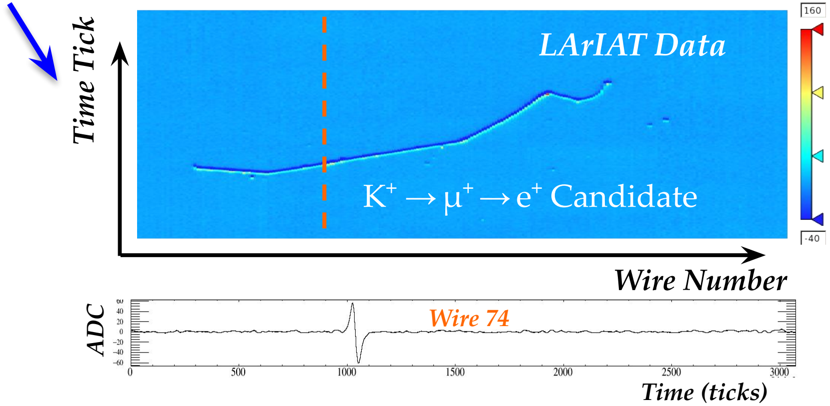


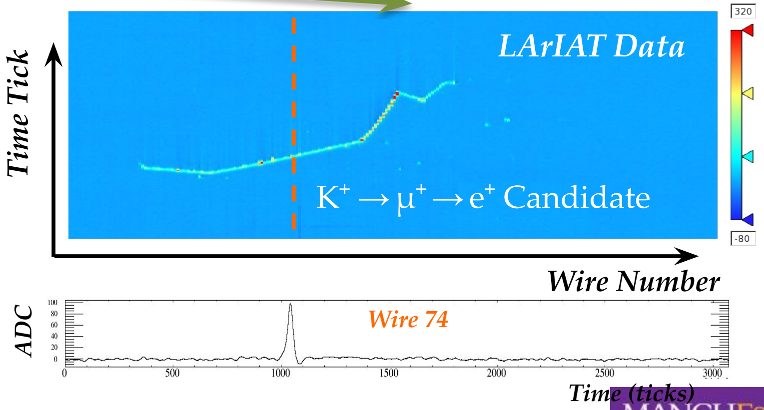
Induction plane

Collection plane

Drift time =







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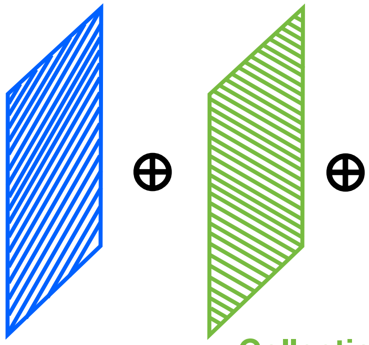

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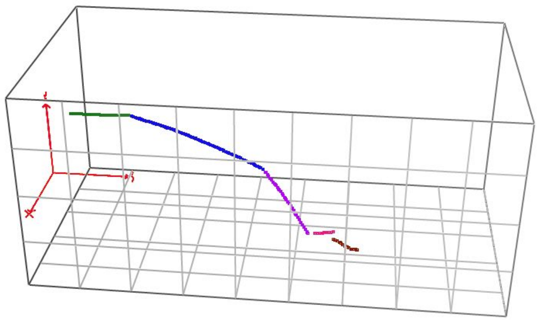
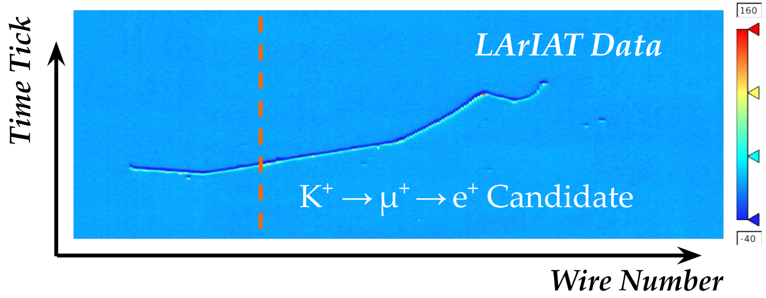
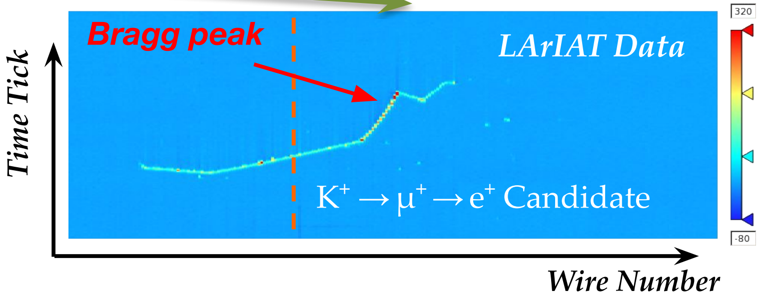






3D imaging with mm space resolution (driven by wire spacing)

Calorimetry: the charge collected is proportional to energy deposited

PID capabilities

An example of event reconstruction workflow

Disclaimer: the rich data from the LArTPC are suitable for many different workflows and event reconstruction techniques.
I'm presenting here an historical/traditional one, but here are more links to less traditional techniques of data processing.

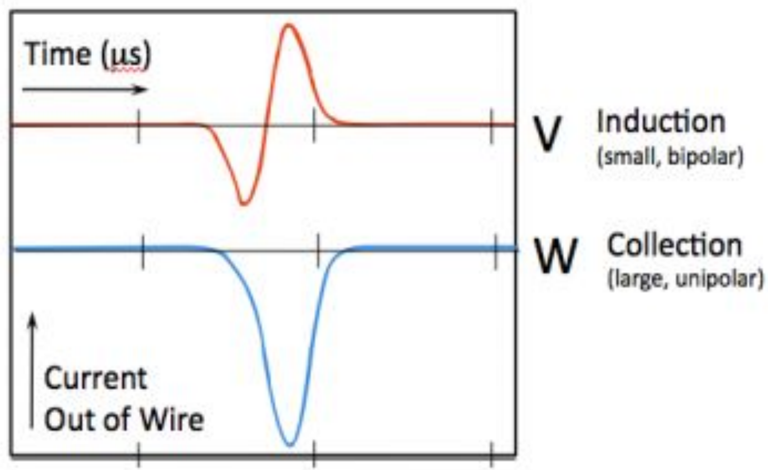
Wire-Cell event reconstruction: https://arxiv.org/abs/2011.01375

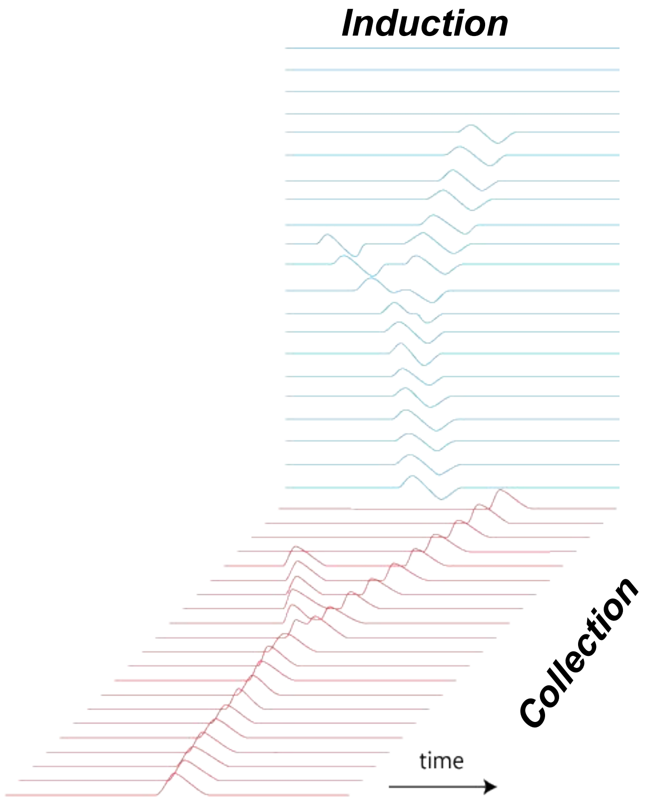
Convolutional Neural Nets: https://www.bnl.gov/isd/documents/94662.pdf

Alright, let's go "old school" on LArTPC event reconstruction...

An example of event reconstruction workflow

1. Start with raw way forms on your wires and apply noise filter!
   Apply deconvolution (turn bipolar into unipolar)





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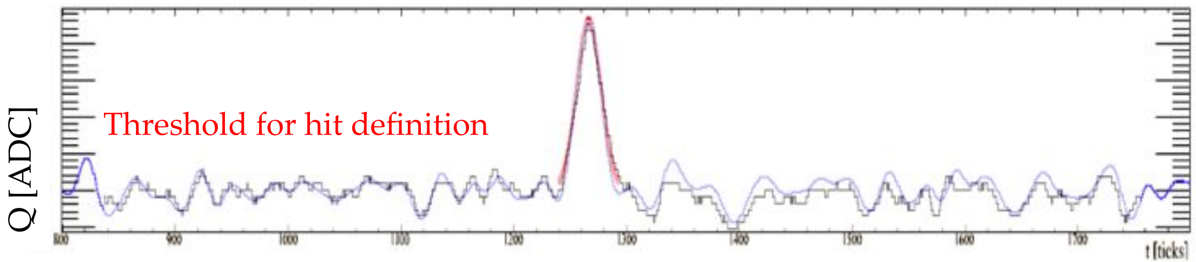
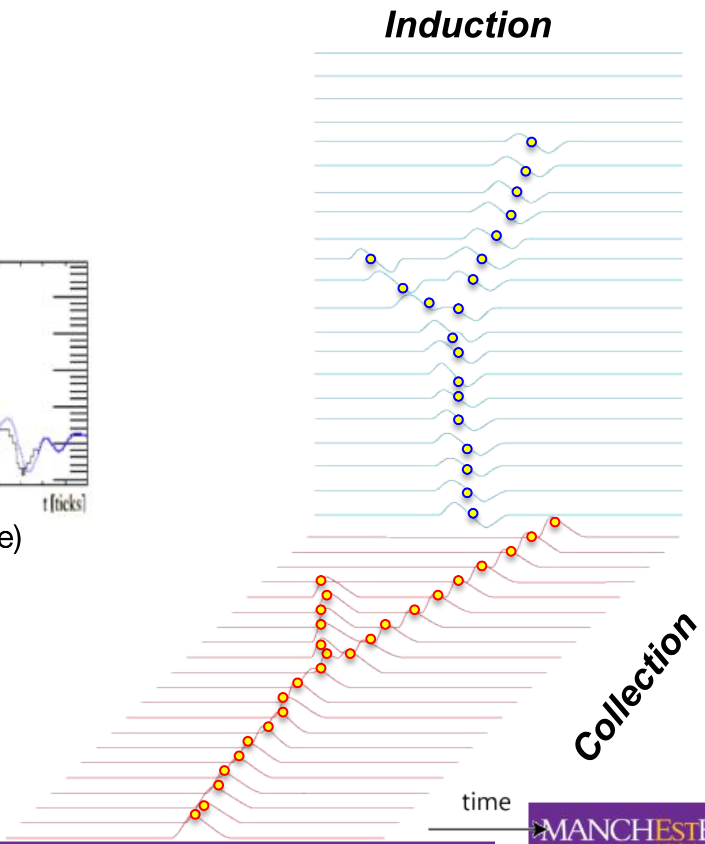


(Only collection shown for illustrative purpose)

Gaussian Fit of a hits which determines :
- Wire number
- Time tick
- Hit Amplitude
- Hit Width



 Elena Gramellini | elena.gramellini@manchester.ac.uk
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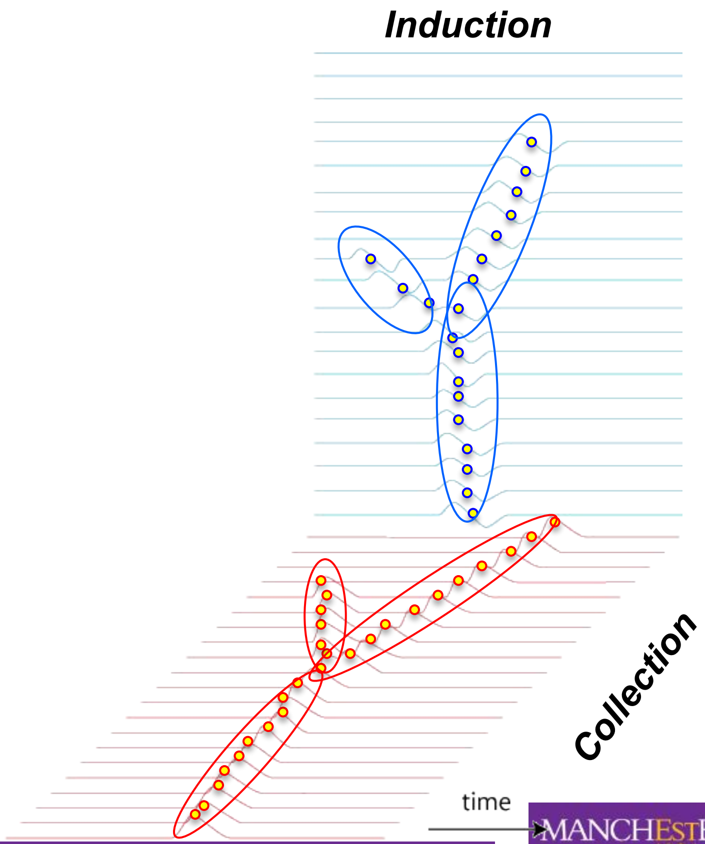
3. Clustering of proximal hits

A density-based Spatial Clustering algorithm clusters close and dense hits together



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An example of event reconstruction workflow

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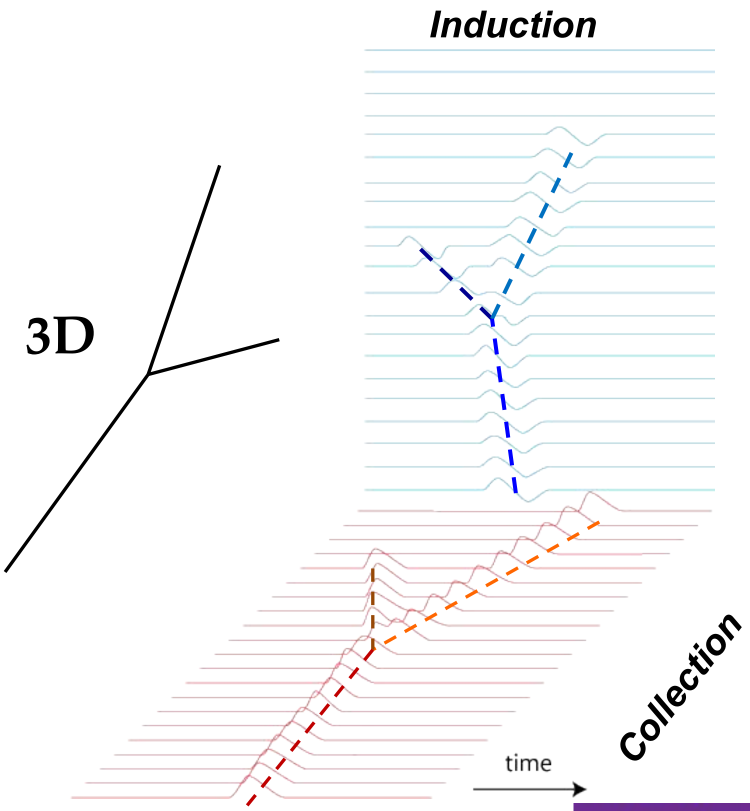
4. 2D line reconstruction

5. 3D line reconstruction

2D lines in the 2 views are combined to
form a 3D track (plane to plane match in time).
A hit-by-hit association
from the 2 planes is then performed to
ensure 3D fine granularity.
Fundamental step for calorimetry



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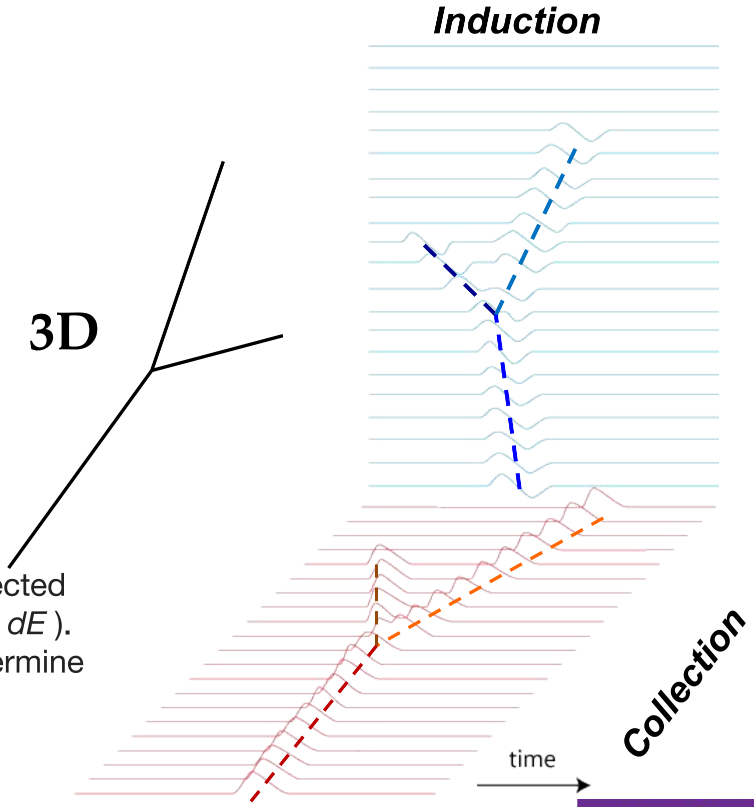
3. Clustering of proximal hits
4. 2D line reconstruction
5. 3D line reconstruction
6. Calorimetry reconstruction of deposited energy



The hits amplitude determines the measurement of the charge collected at the wire planes (proportional to the energy deposited in the TPC, *dE*).
The hit time and spacing between consecutive hits in the track determine the pitch *dx*.
Together, they provide dE/dx: energy deposited per unit length.
This is an important quantity!!

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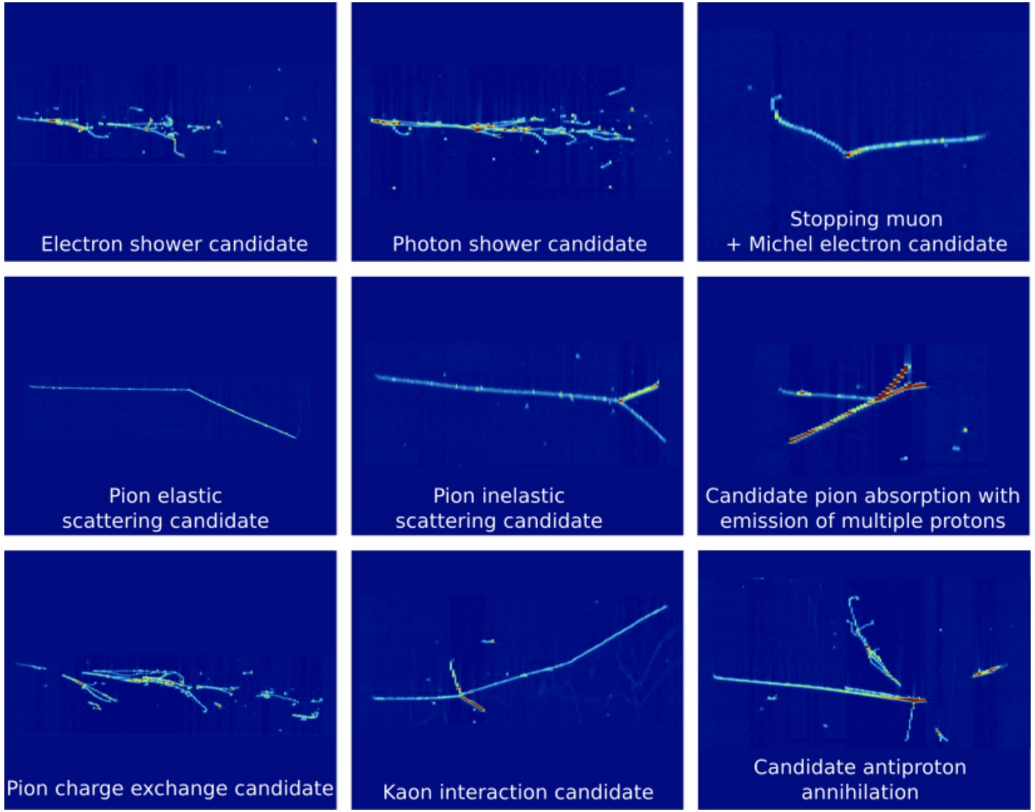
Particle identification (PID). Handle #1: topology

https://arxiv.org/pdf/1911.10379.pdf

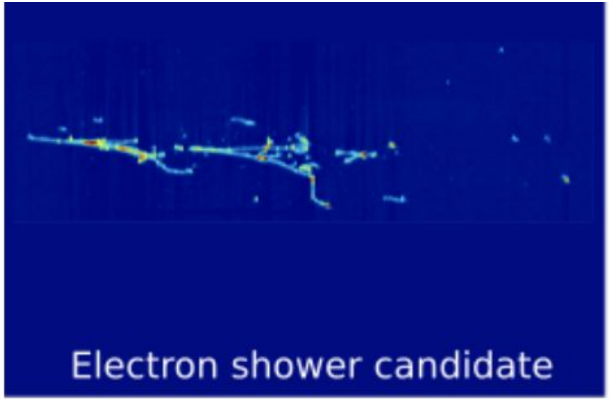


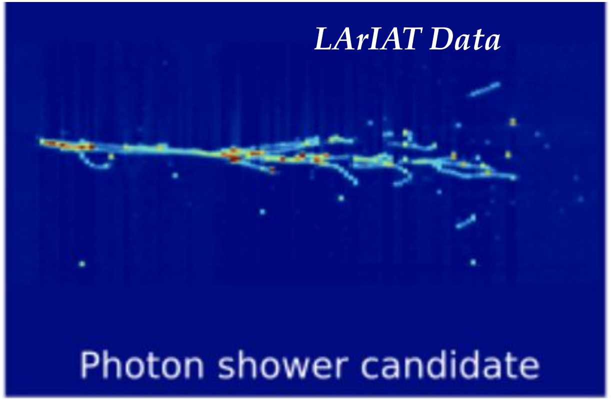
Particles like pions, protons, kaons and muons leave track-like signatures in the LArTPC. Muons tend to be much longer and "cleaner" than other particles, since they don't interact hadronically.

Particles like electrons and photons (as well as neutral pions who immediately decay into 2 photons) leave shower-like signatures in the LArTPC.

Particle identification (PID). Handle #2: dE/dx for showers

How can we distinguish electrons from photons (very important when it comes to neutrino products)?

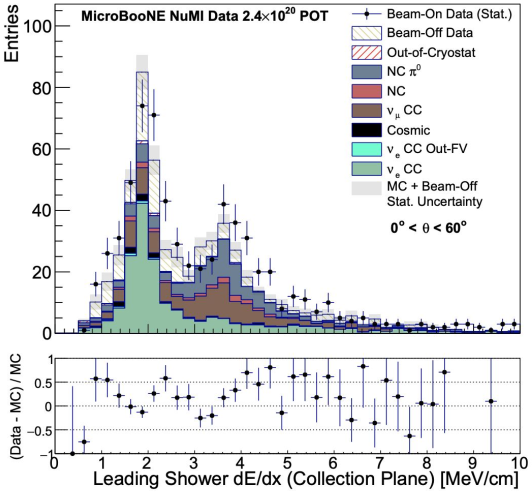


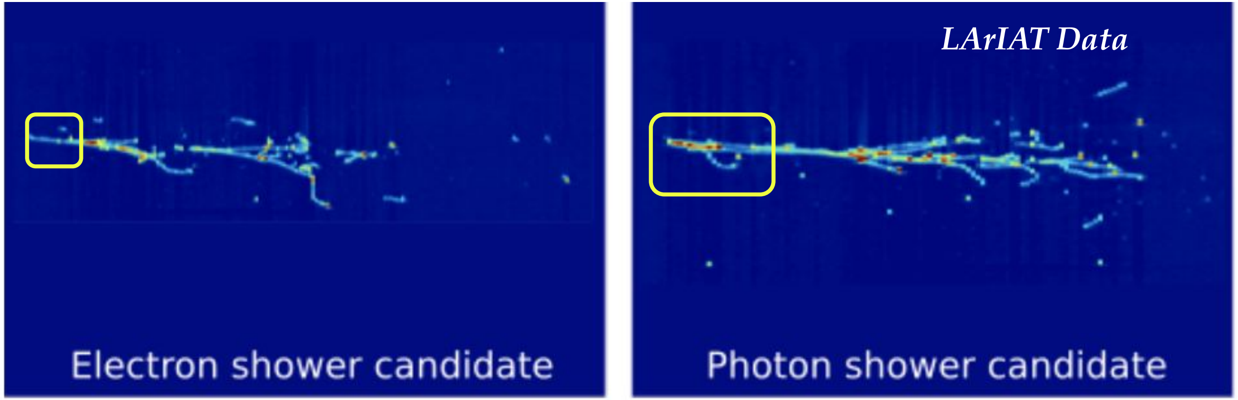


Particle identification (PID). Handle #2: dE/dx for showers

How can we distinguish electrons from photons (very important when it comes to neutrino products)?

Using the dE/dx at the beginning of the shower.

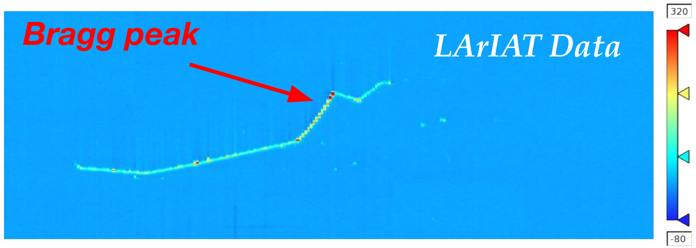




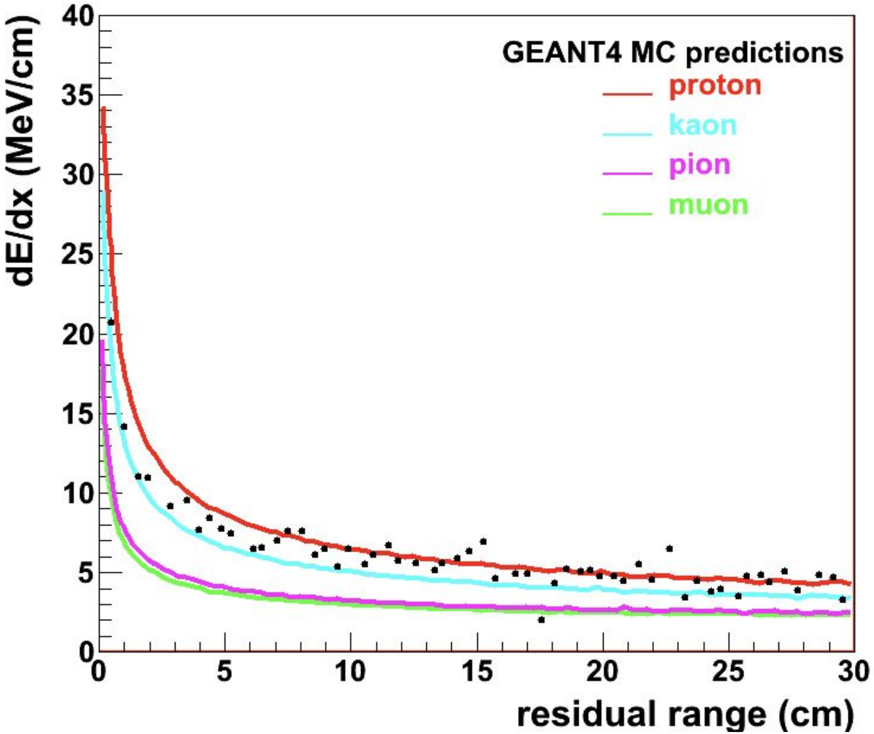
Just like neutrinos, photons are neutral, which means that we can "see" them in the detector only if they interact. An interacting photon "pair converts", which means it creates an electron-positron pair. This pair deposits double the amount of charge per unit length w.r.t the single electron.

https://arxiv.org/pdf/2101.04228.pdf

Particle identification (PID). Handle #2: dE/dx for tracks



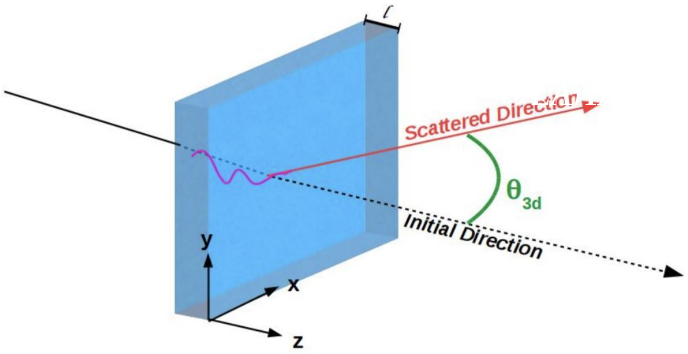
https://arxiv.org/abs/1205.6747

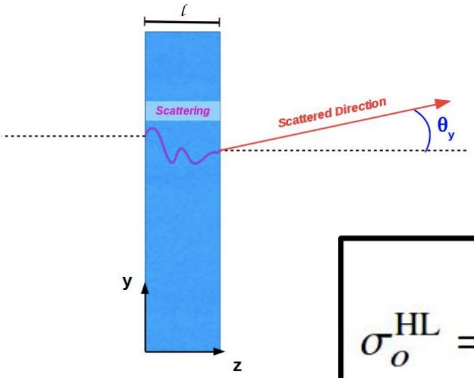


The amount of energy deposited by a particle while stopping in the detector depends on its mass, i.e. the Bragg peak can be used to differentiate particles species.

So, we can use the energy deposited per unit length at each point of a stopping track and where the energy is deposited wrt to the track ending (residual range) to perform particle identification.

Measuring the Muon Momentum: Multiple Coulomb Scattering (MCS)





$$\sigma_o^{HL} = \frac{S_2}{p\beta c} z \sqrt{\frac{\ell}{X_0}} \left[1 + \epsilon \times \ln\left(\frac{\ell}{X_0} \right) \right]$$

Higling formula relates how much the muon "wiggles" in a thickness of Argon to its momentum under a small angles gaussian approximation

σ_o^{HL}	**Width of the Gaussian Scattering Angles**
S_2	**Highland Coefficient (experimental parameter)**
p	**Momentum**
βc	**Velocity**
ℓ	**Target Thickness**
X_0	**Radiation Length**
ϵ	**Highland Constant (experimental parameter)**
z	**Charge of the particle**

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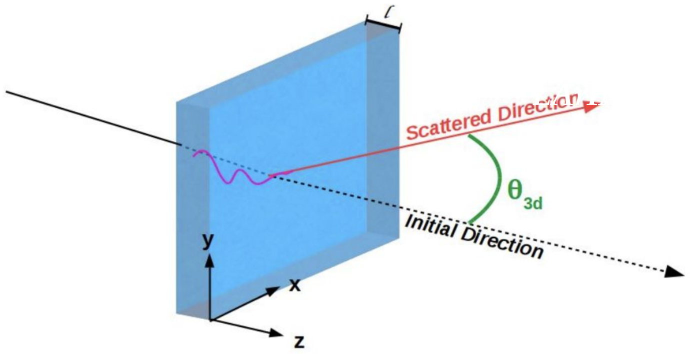
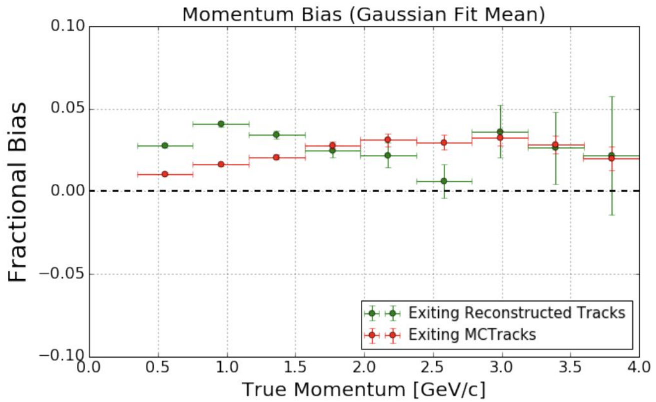
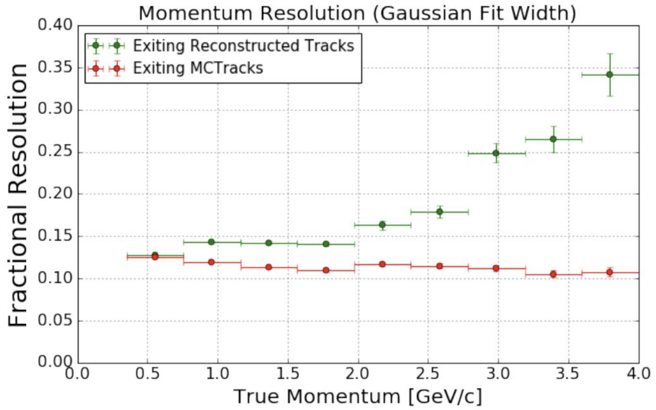
Measuring the Muon Momentum: Multiple Coulomb Scattering (MCS)







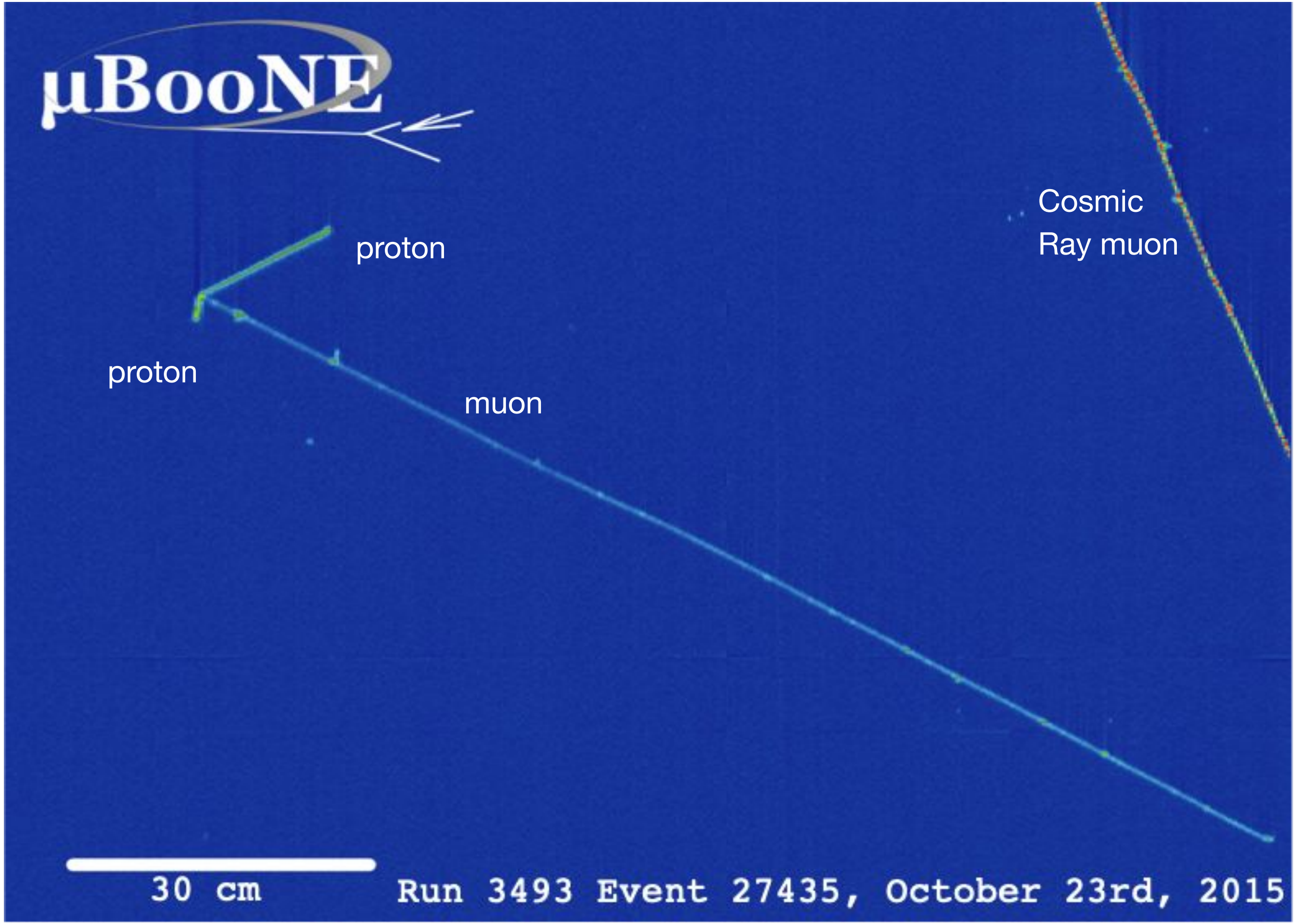
Higling formula relates how much the muon "wiggles" in a thickness of Argon to its momentum under a small angles gaussian approximation

https://arxiv.org/pdf/1703.06187.pdf

Break: the event display game

Now that we are a bit more familiar with “single particle” events, let’s try to piece together what we know and see if we can identify some features of neutrino interactions.

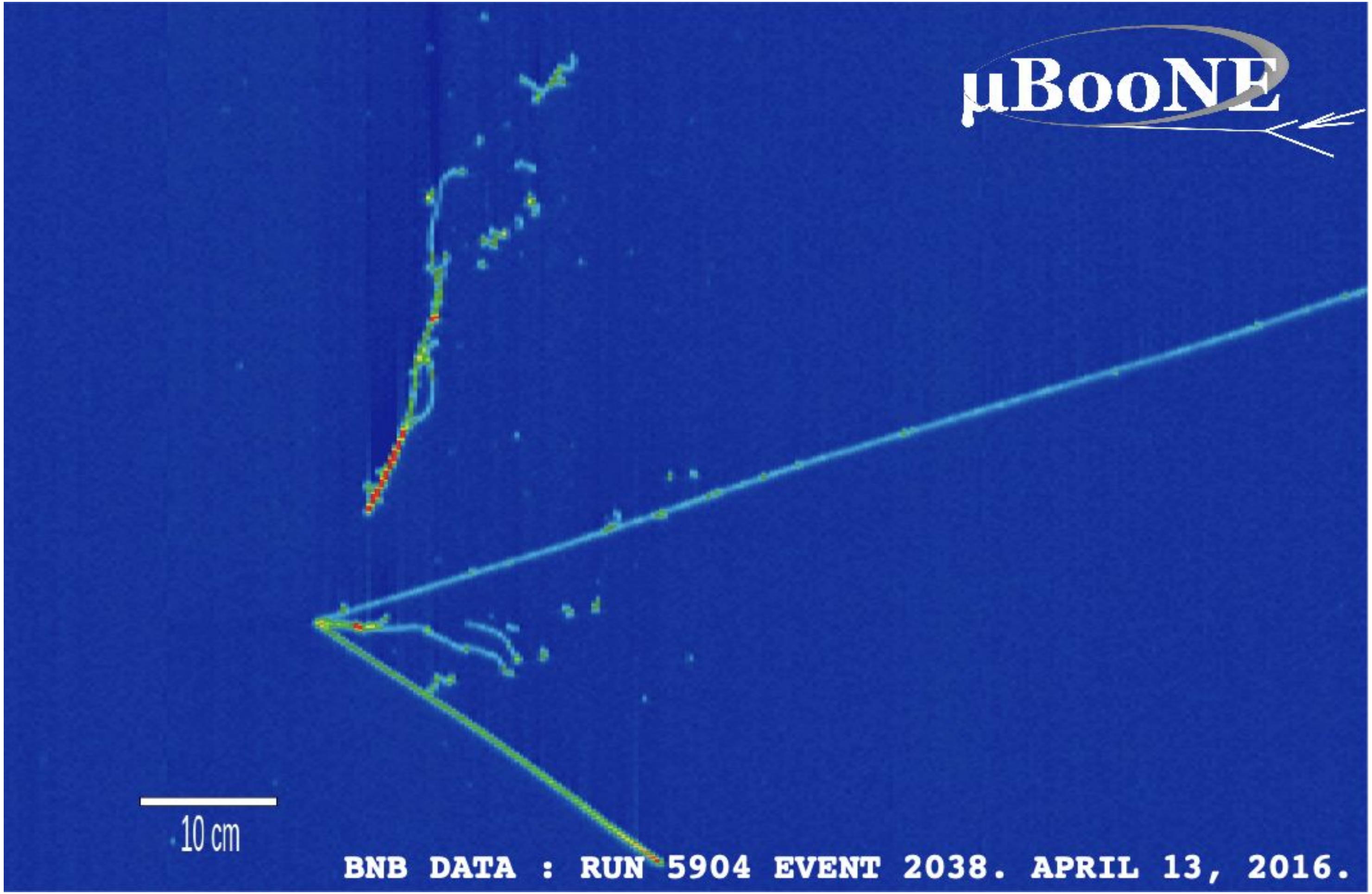

μBooNE
30 cm
Run 3493 Event 27435, October 23rd, 2015

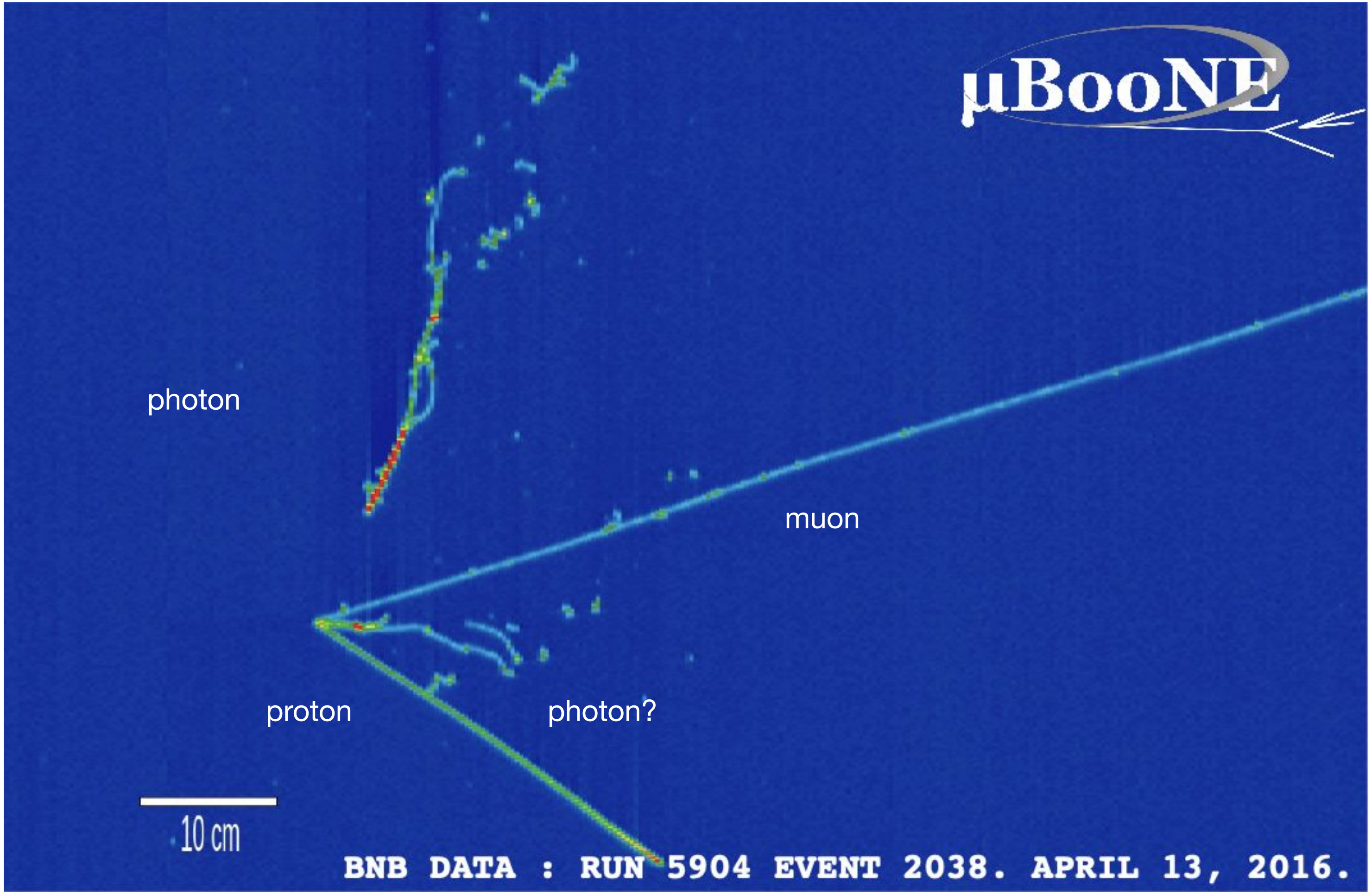


1 long MIP (likely a muon)

2 short highly ionizing tracks (likely protons)

Muon neutrino CC interaction.


µBooNE
10 cm
BNB DATA : RUN 5904 EVENT 2038. APRIL 13, 2016.

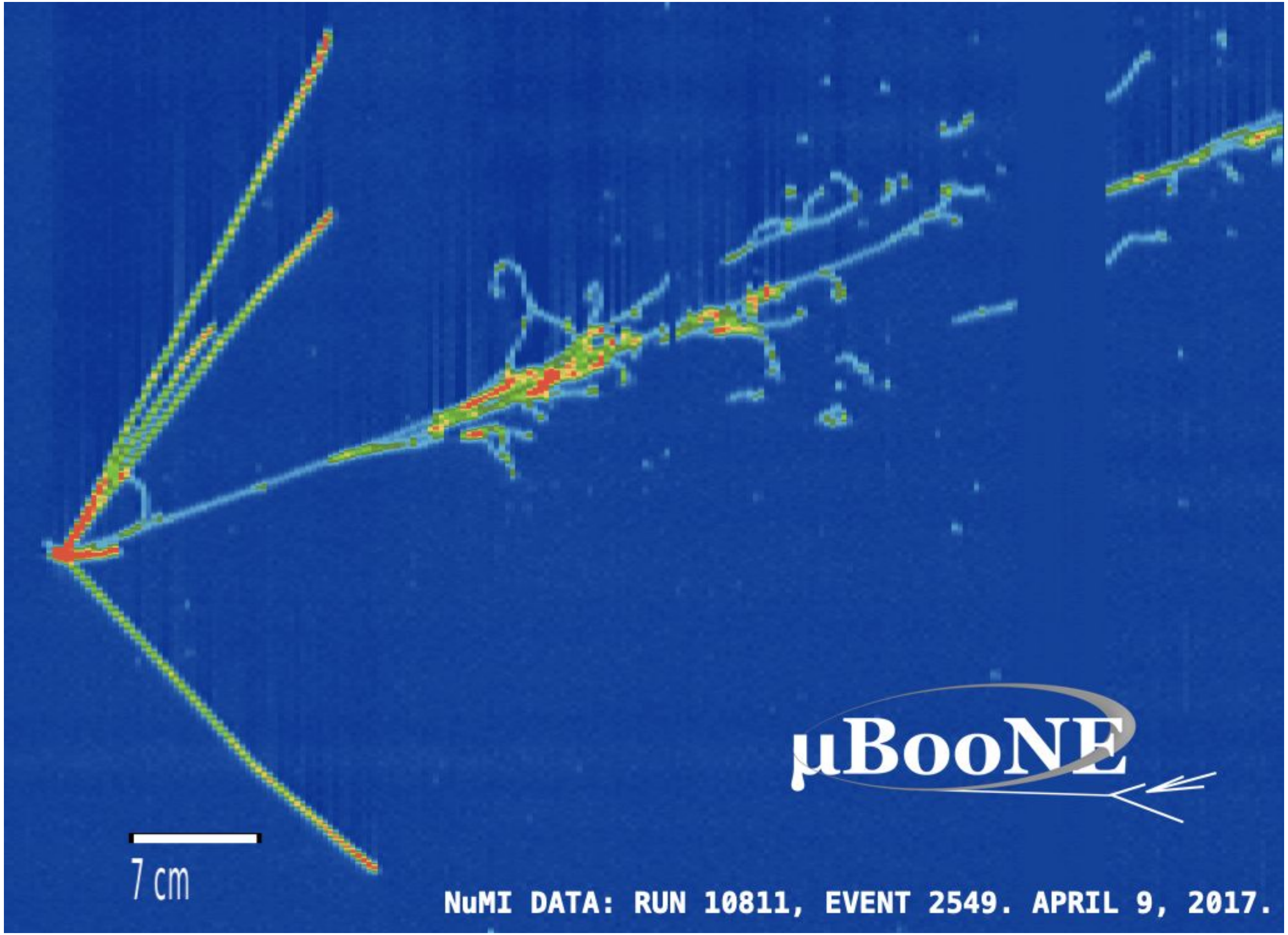


1 long MIP (likely a muon)

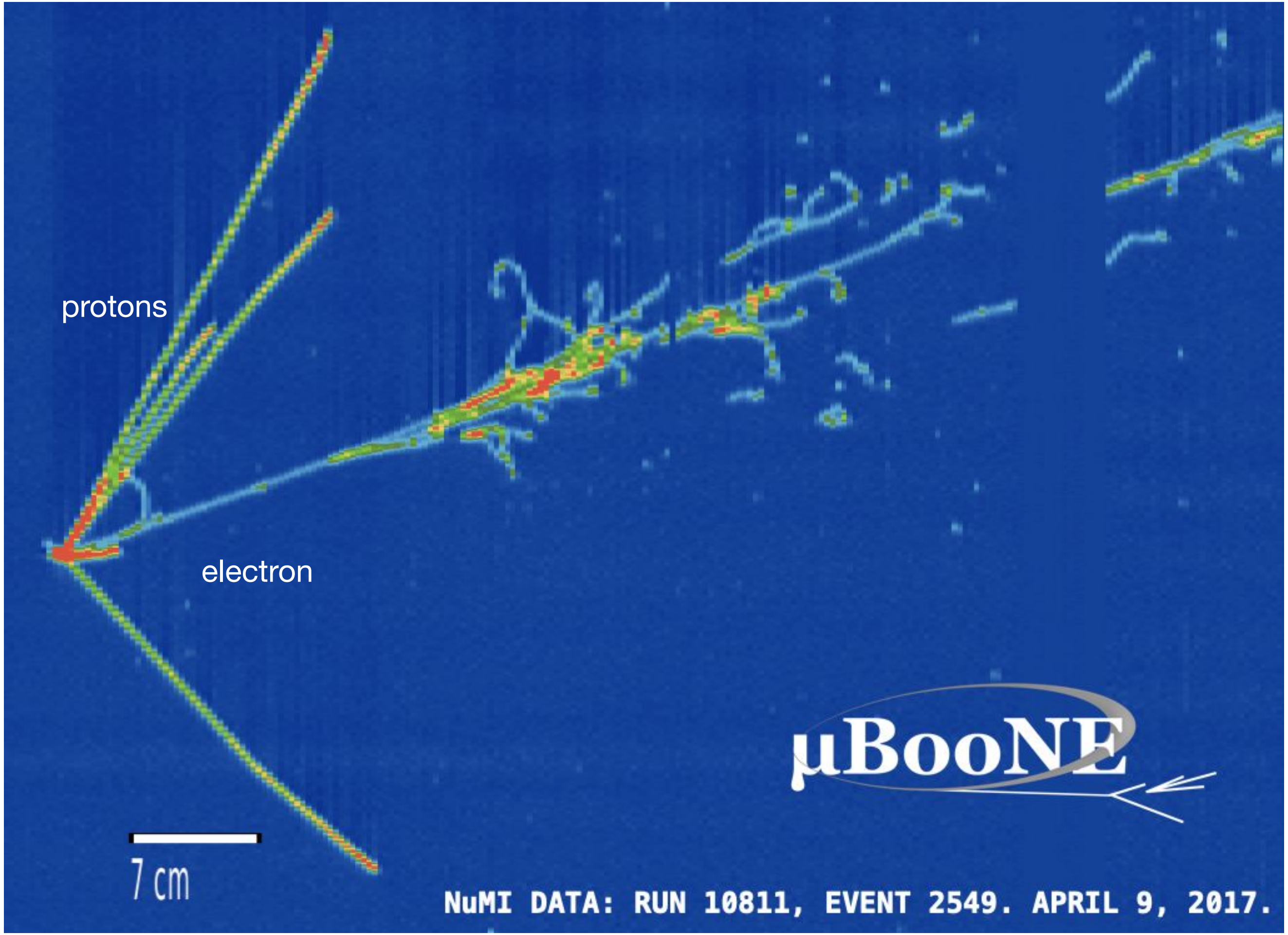
1 short highly ionizing tracks (likely protons)

2 showers pointing at the vertex, one with a detached start (likely a neutral pion)

Muon neutrino CC interaction with pi0 production



µBooNE
7 cm
NuMI DATA: RUN 10811, EVENT 2549. APRIL 9, 2017.

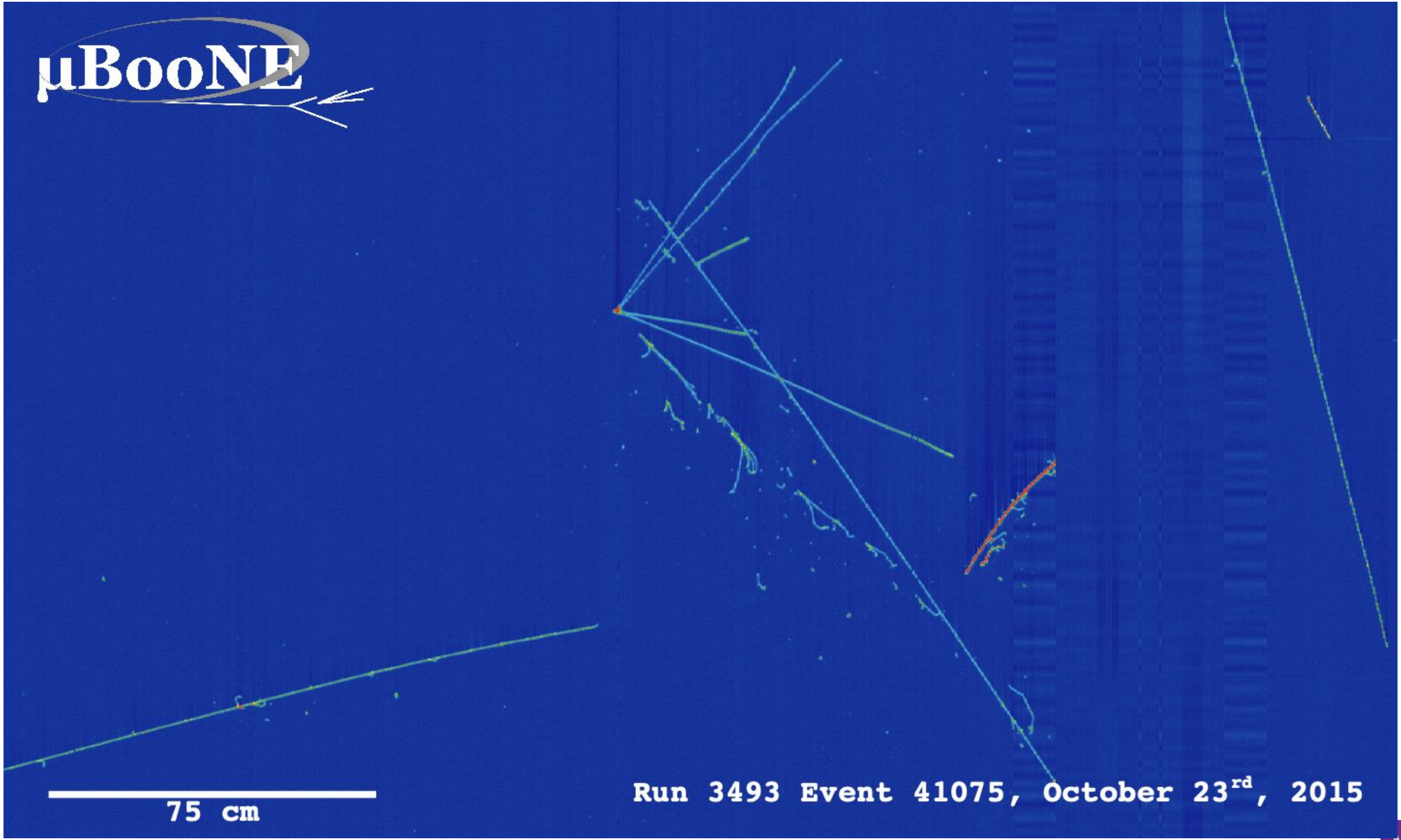


Several short highly ionizing tracks (likely protons)

1 shower attached to the vertex (likely an electron)

Electron neutrino CC interaction

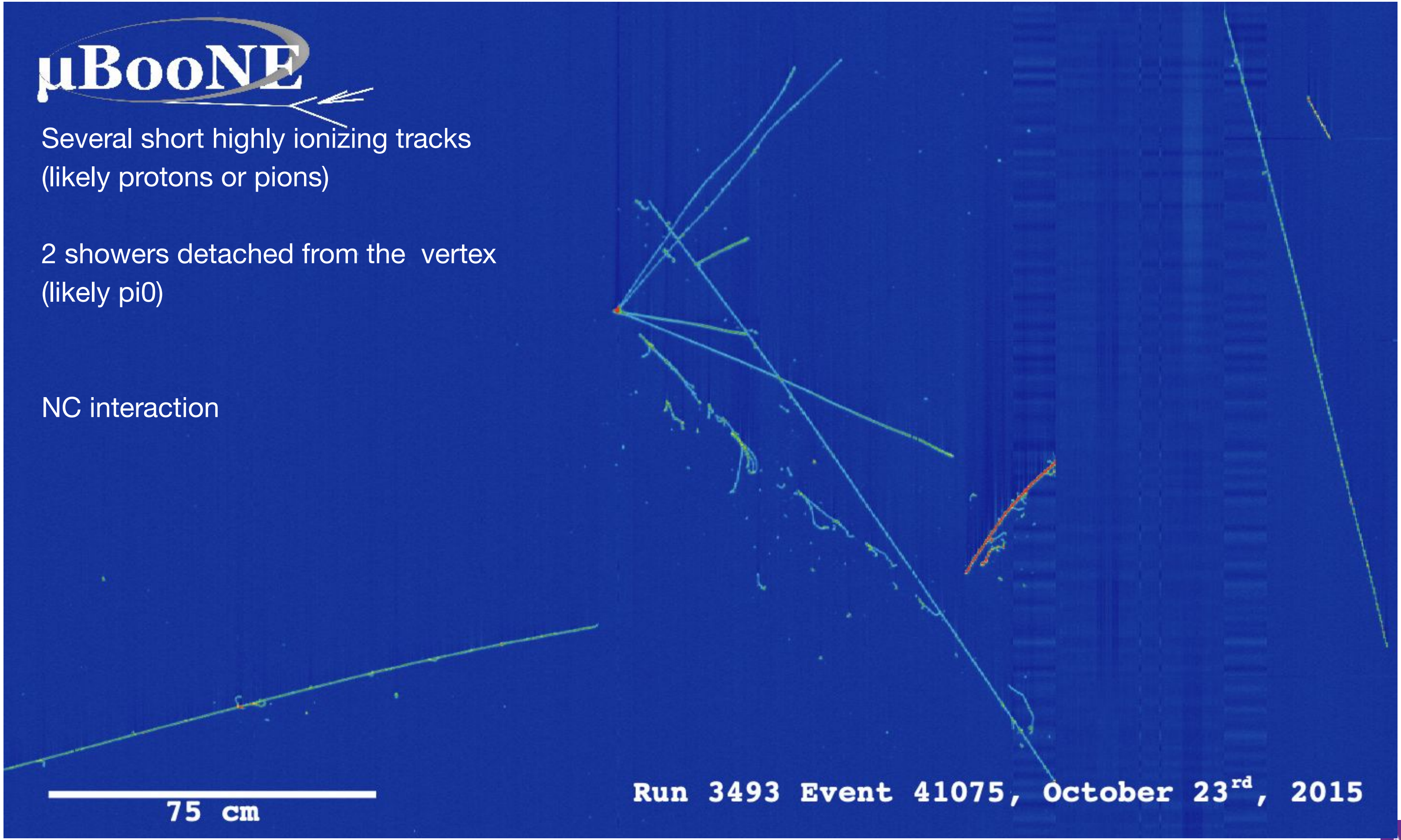
Note. As it will be clearer in a second, you are looking at the measured uncalibrated charge in these event displays: you cannot perform calorimetry by eye.


μBooNE
75 cm
Run 3493 Event 41075, October 23rd, 2015

Several short highly ionizing tracks (likely protons or pions)

2 showers detached from the vertex (likely pi0)

NC interaction



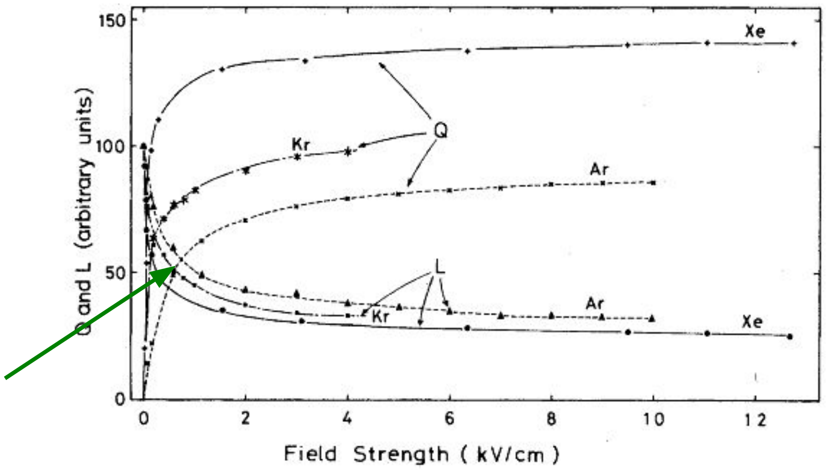
A word on the light: main use case

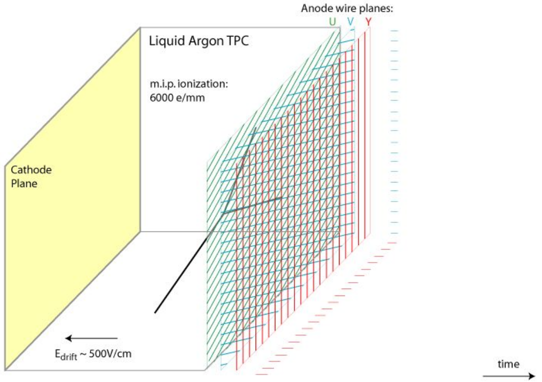
We talked a lot about the charge, because in LArTPC for neutrino reconstruction the main feature is the pattern of the ionization electrons.

At E = 500 V/cm (typical LArTPC field) ½ of half of energy released by charged particles in LAr goes in scintillation light.

The first functional use of the light is to start the clock to measure the electron drift time: when do you know when the charge started drifting? The light tells you!

But this is not the whole story...



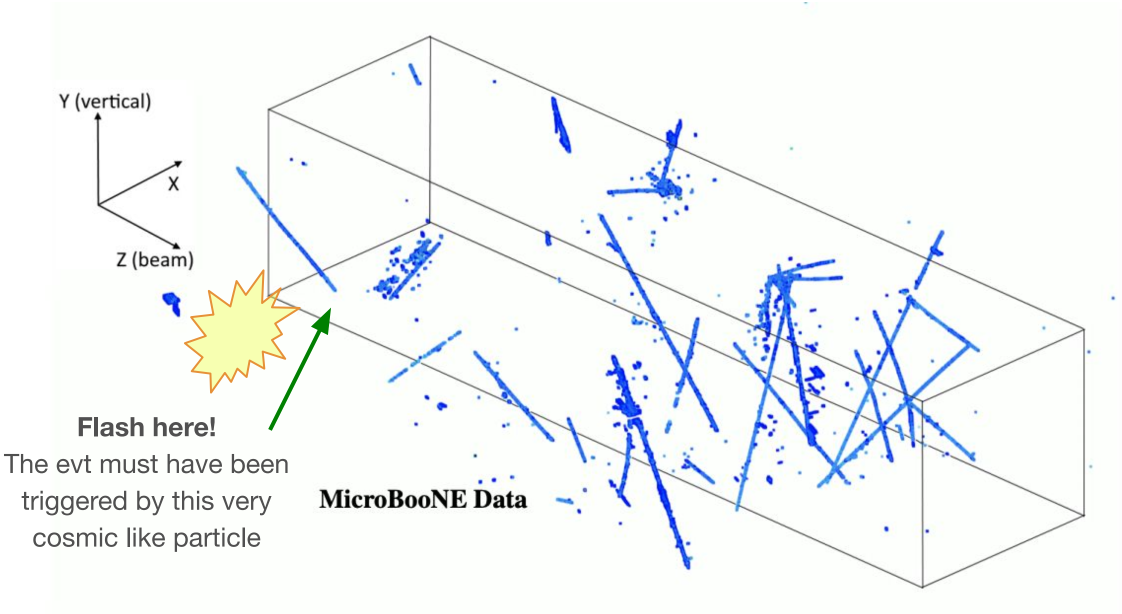


 Elena Gramellini | elena.gramellini@manchester.ac.uk

A word on the light: on the surface

In surface LArTPC the light is used to discriminate between on-beam events and off-beam events: coincidence w/ beam signal. Sometimes no neutrino interacts in the TPC when the beam is sent to your detector. If there's no flash in time with the beam, you can avoid reconstructing the event altogether.

If you have segmented light detection (multiple PMTs), you can use light to determine which portion of the TPC contains a neutrino interaction and discriminate against comic activity. This is called "Flash-matching".



 Elena Gramellini | elena.gramellini@manchester.ac.uk

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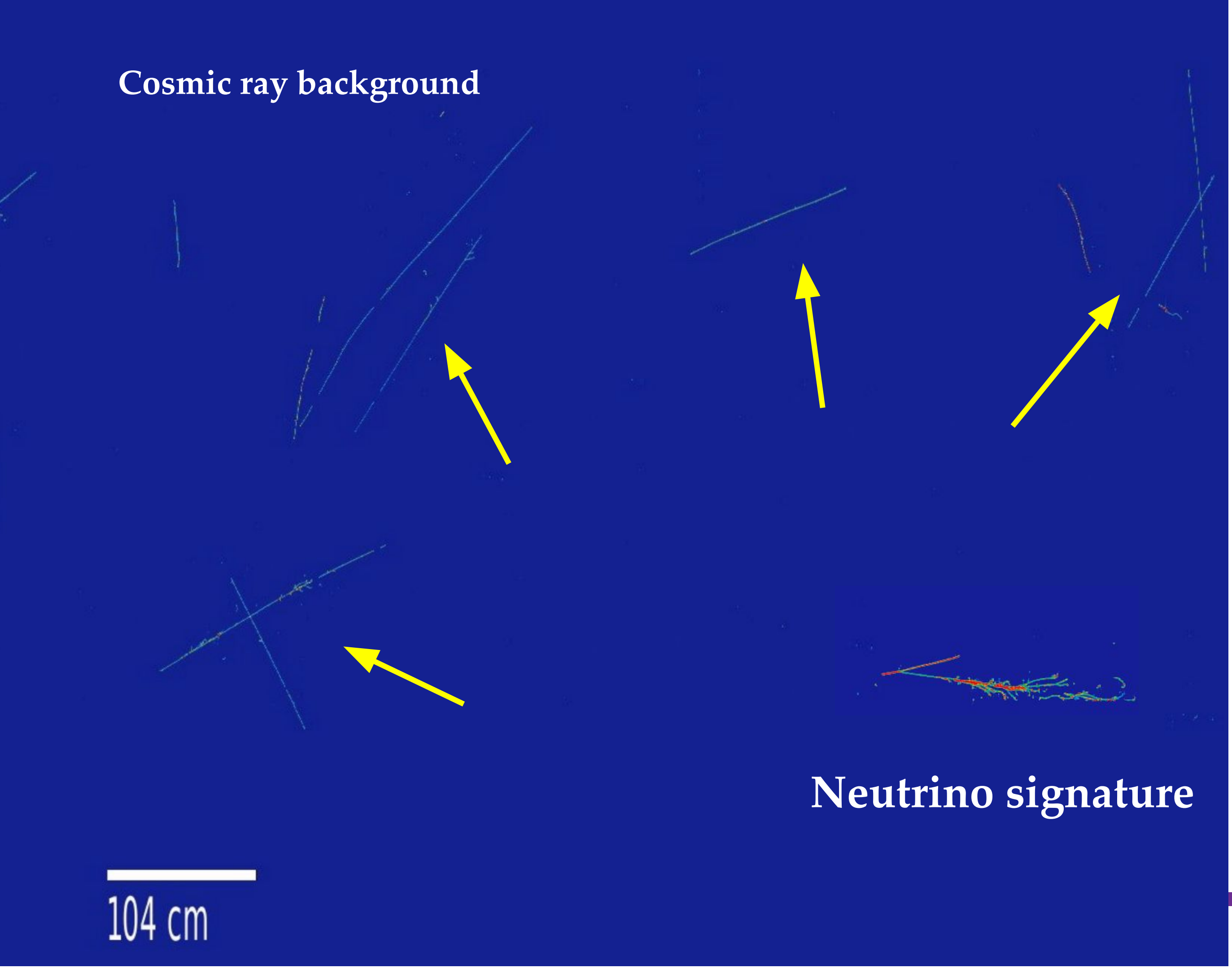


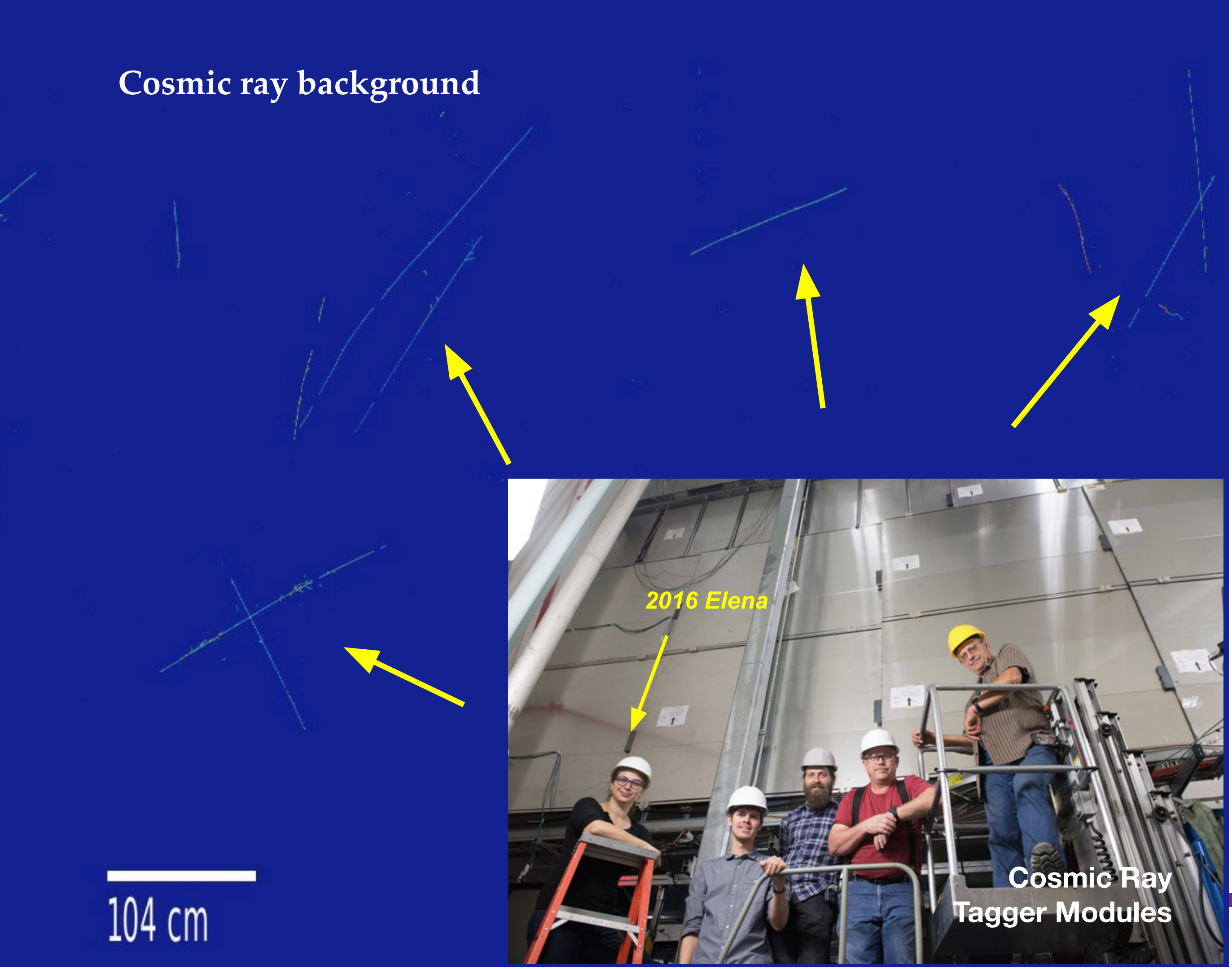
On the surface

For each neutrino in a single event, we get 10-20 cosmic ray muons.

Generally speaking, these are backgrounds to the neutrino interaction…

We try to tag them to get rid of them.

On the surface



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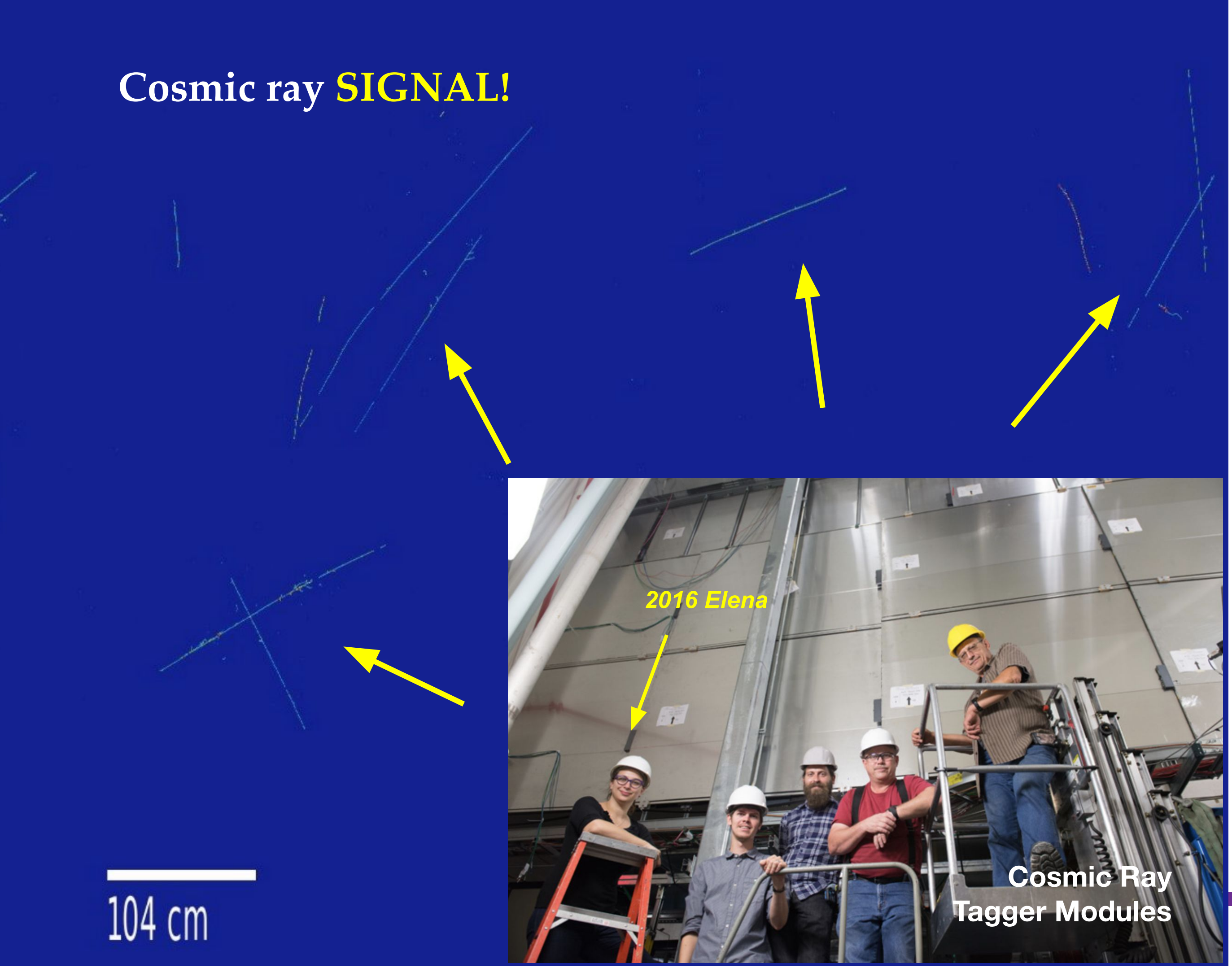
Panels of plastic scintillator strips surrounding the TPC. Very fast detectors (10 ns). We also take cosmic only data for bkg modeling.



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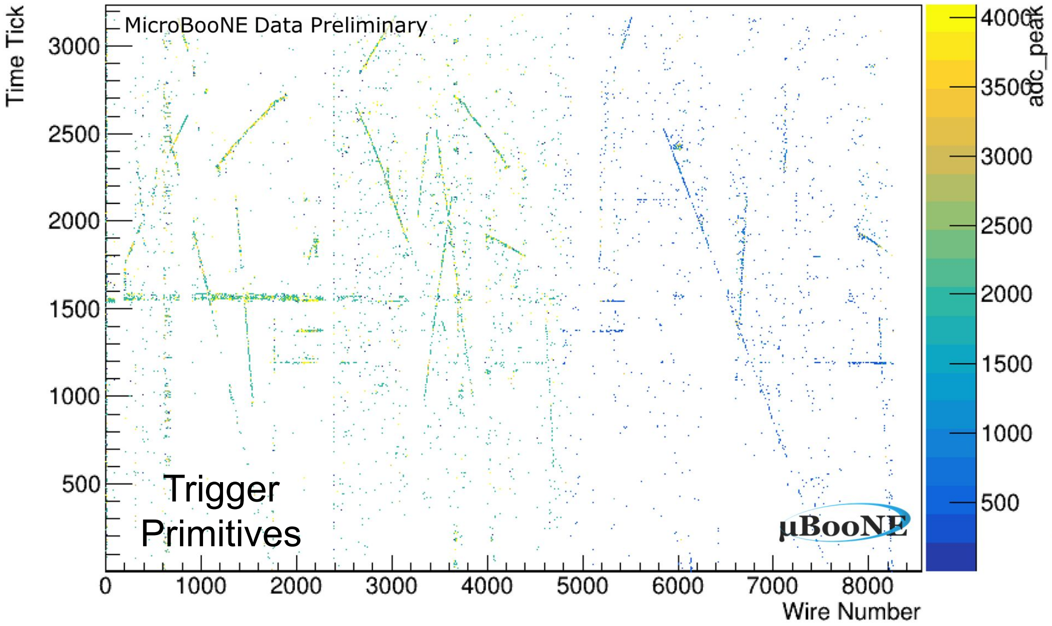
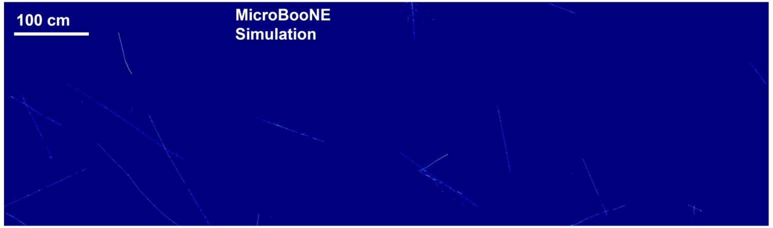
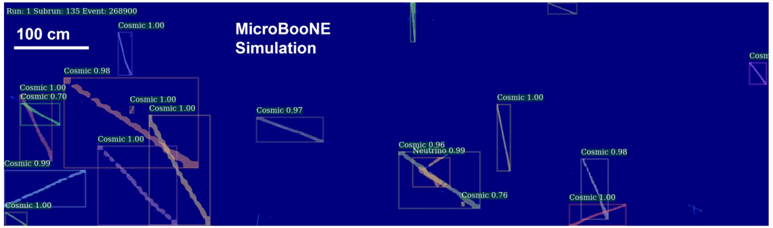
Cosmic Data



MICROBOONE-NOTE-1081-PUB

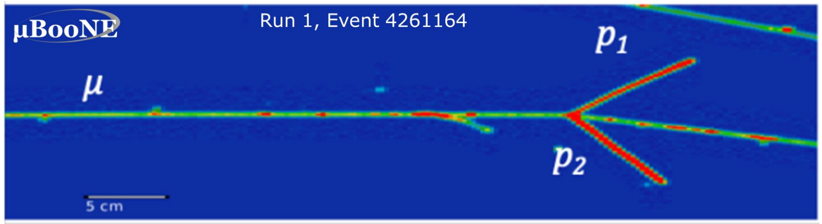


(a) An example of an input image as given to sMask-RCNN to process



(b) A simulated neutrino interaction overlaid on cosmic ray muons from data, labeled by sMask-RCNN

Reconstructing cosmic muon scatter events in MicroBooNE



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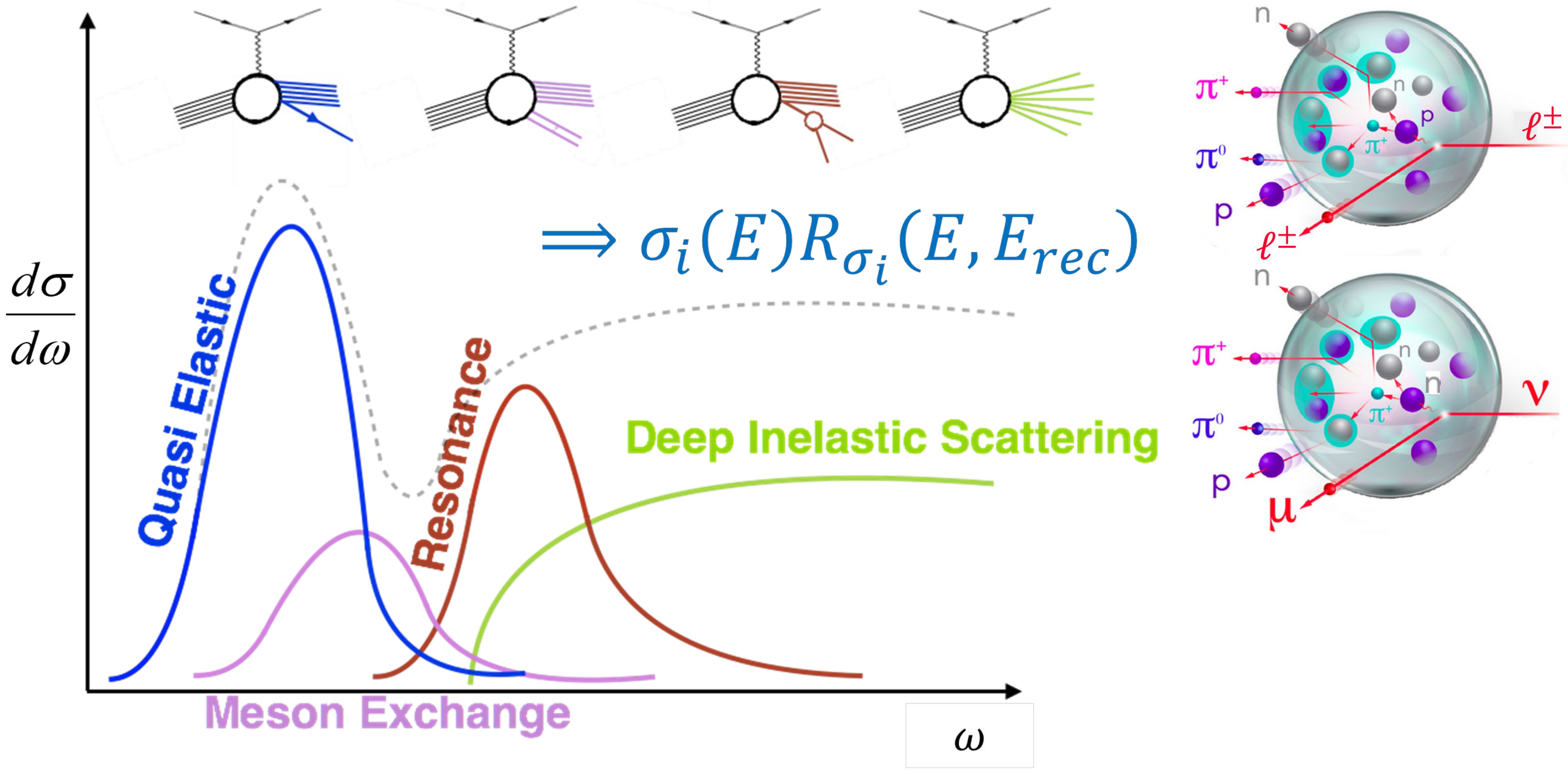
Nuclear effects for neutrino interactions



Dark Matter In the Cosmics: Motivations

Search for **mediators between dark** and **visible matter** that couple **preferentially to muons**

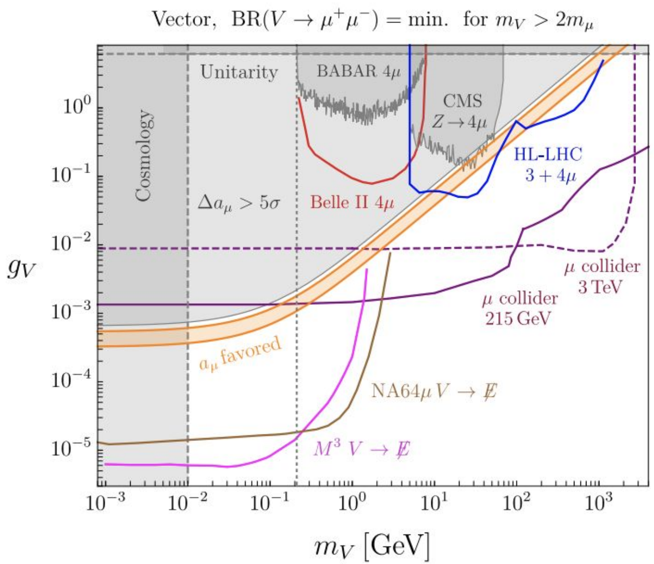
The **cosmic dataset** in LArTPC at the surface can be thought of as an extra "experiment": **a free "beam" of muons on a 4π fully instrumented calorimeter.**

Interesting because:

→ these light, weakly-coupled muon-philic particles are able to reconcile the 4σ muon g-2 anomaly & DM freeze-out

→ sizable couplings to visible particles, but very difficult parameter space for direct detection & colliders searches

→ near $0 cost (doable in current datasets!)



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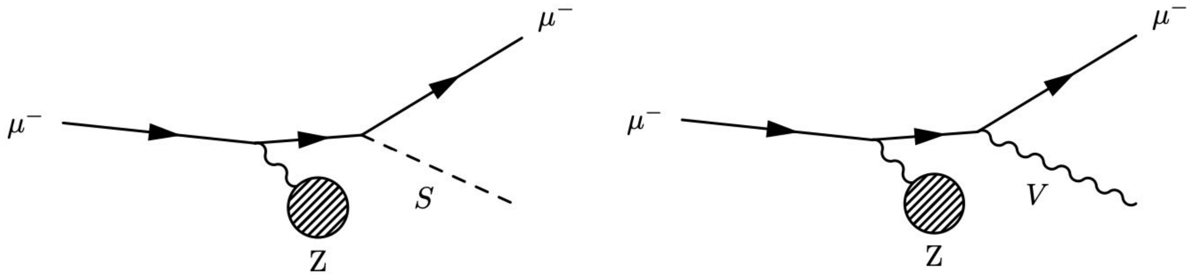
Missing Momentum Technique

Relativistic muon beam is incident on fixed target and scatters coherently off it to produce the new muon-philic particle as radiation that decays invisibly.
Exploits the radiative production process: $\mu N \rightarrow \mu N \not{E}$ Dark Bremsstrahlung

$\not{E}$ is the final state missing energy (arising from production of muon-philic particle).
Signal is defined by:

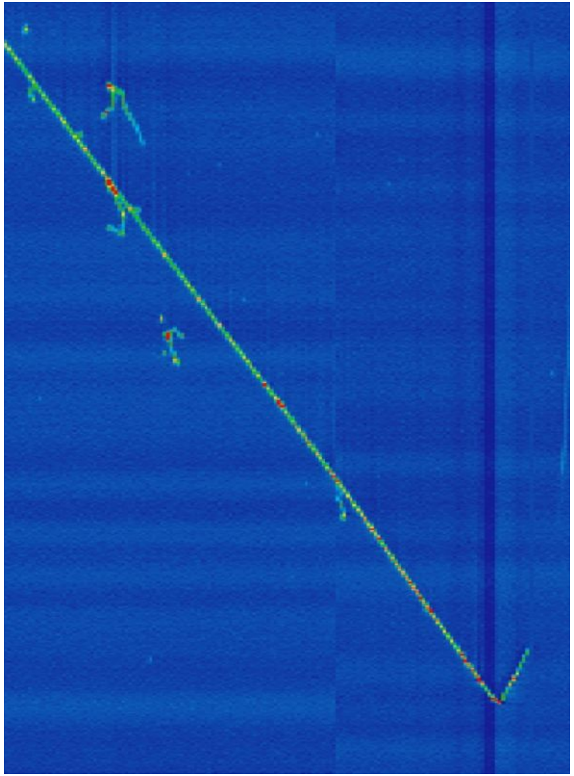
- outgoing muon has around 50% less energy/momentum than incoming muon.
- muon-philic particle decays invisibly to DM or neutrinos: no additional activity



https://arxiv.org/pdf/2108.00040.pdf

What can we see experimentally?

The vast majority of our muons look like this in our detector: a muon happily going about its day.



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If we have a long enough track (~1 m)
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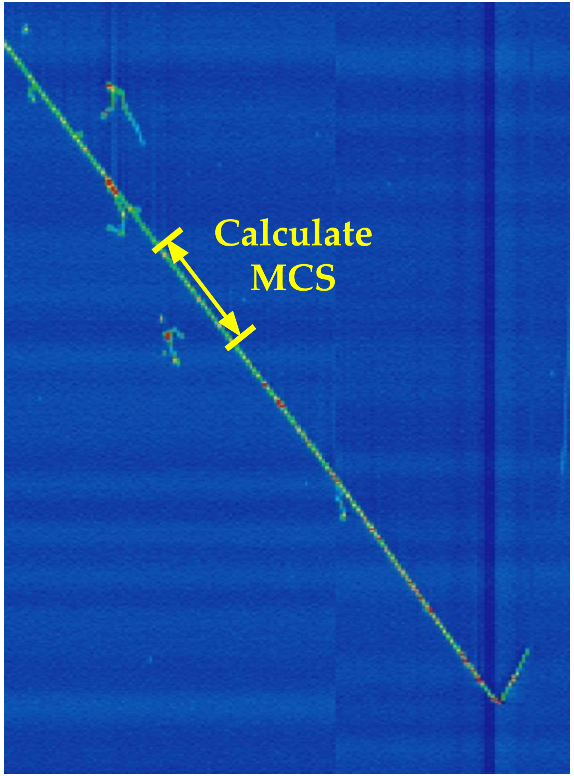

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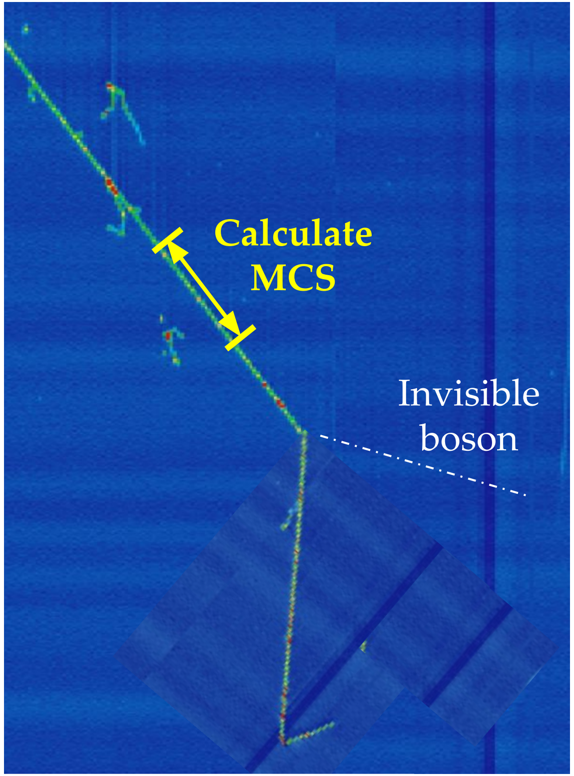
(Photoshopped) **SIGNAL** event!



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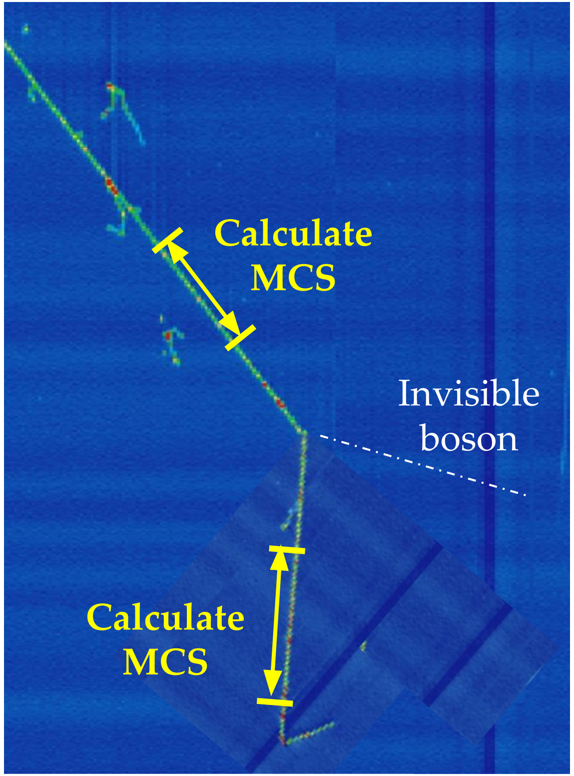
(Photoshopped) **SIGNAL** event!
Calculate MCS for outgoing muon.
$\Delta p = p_{out} - p_{in}$ = missing momentum



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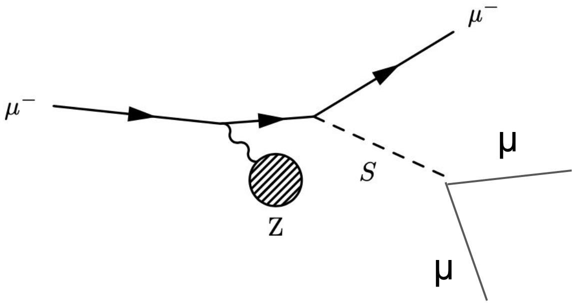
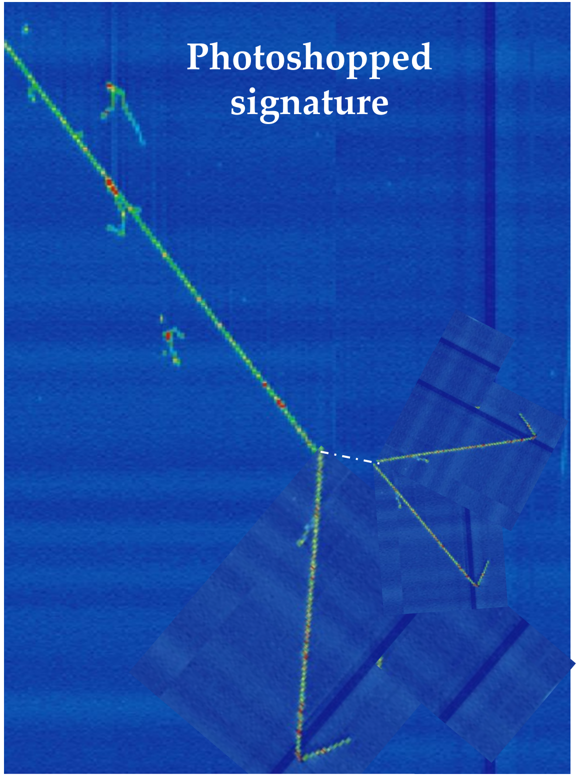
More signatures if boson decays visibly

μN → μN + S/V → μN + μμ (ee, γγ)

the radiated scalar boson decays in μμ or ee or γγ





Extra handles: gap + invariant mass of the reconstructed pair. Need a model of decay length and opening angle.

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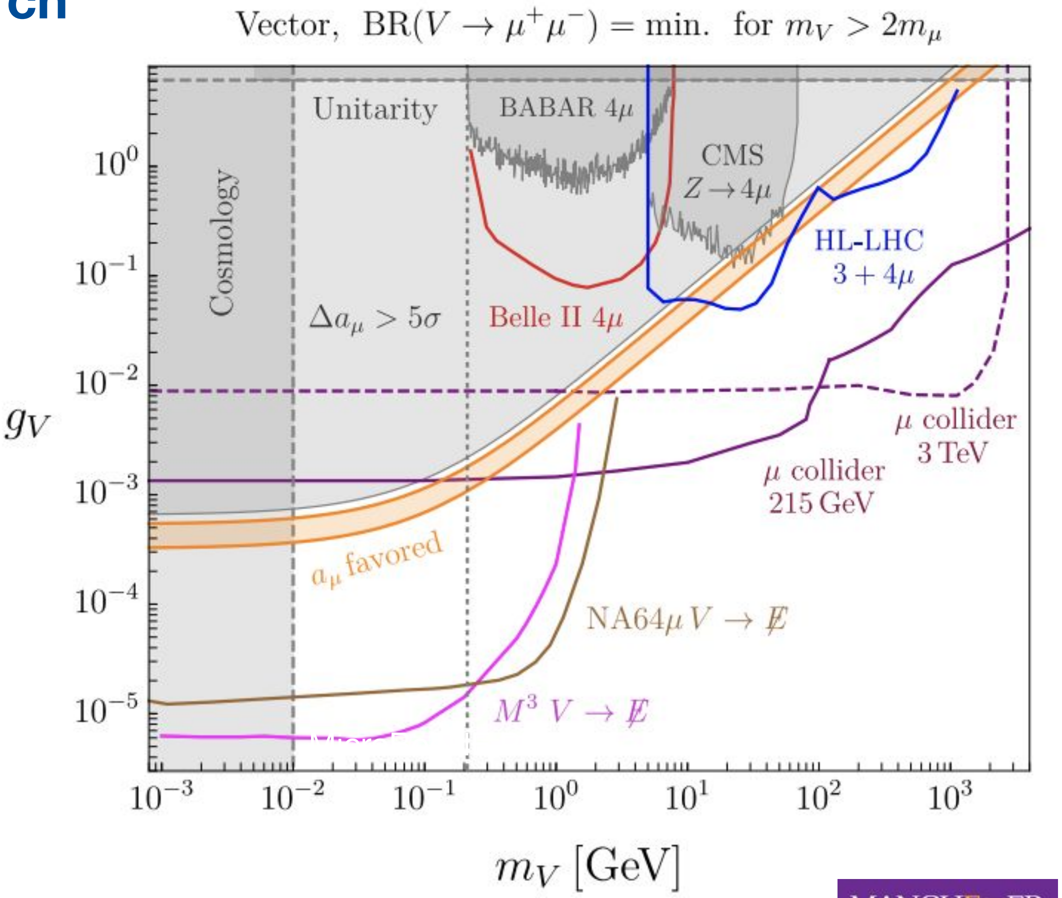
Scope of the week for this search

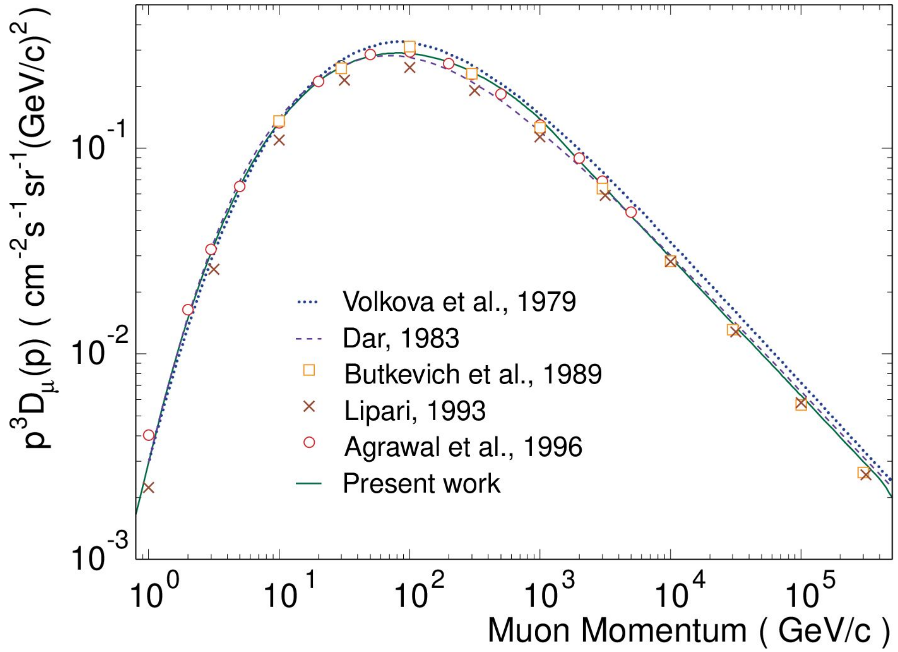
A “LArTPC-on-surface” sensitivity line on this plot.



Common challenges between DM & μ4ν in LArTPC

Characterize our "beam", i.e. understanding:
→ the muon energy spectrum
→ the muon energy resolution in the GeV region
→ the pion/proton contamination

Get ALL THE MUONS (rare process need 10^{10} MoT):
→ Development of a dedicated trigger to:
1. "see" the total cosmic flux
2. keep only the interactions of interest



Atmospheric muon flux at sea level, underground and underwater

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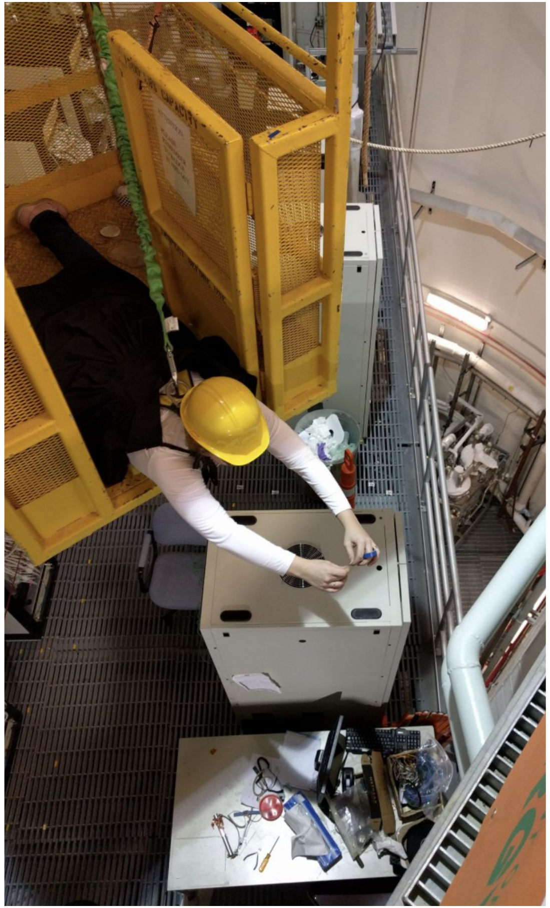
Summary

Liquid Argon Time Projection Chambers are at the forefront of neutrino detection in the few GeV range, as they provide a wide range of **experimental handles** for PID and energy reconstruction: **detailed event topology, fine grained calorimetry, PID, light detection**.

When on the surface, LArTPC can be thought as **4π active calorimenter** of several **m^3 volume** exposed to **a beam of muons**.

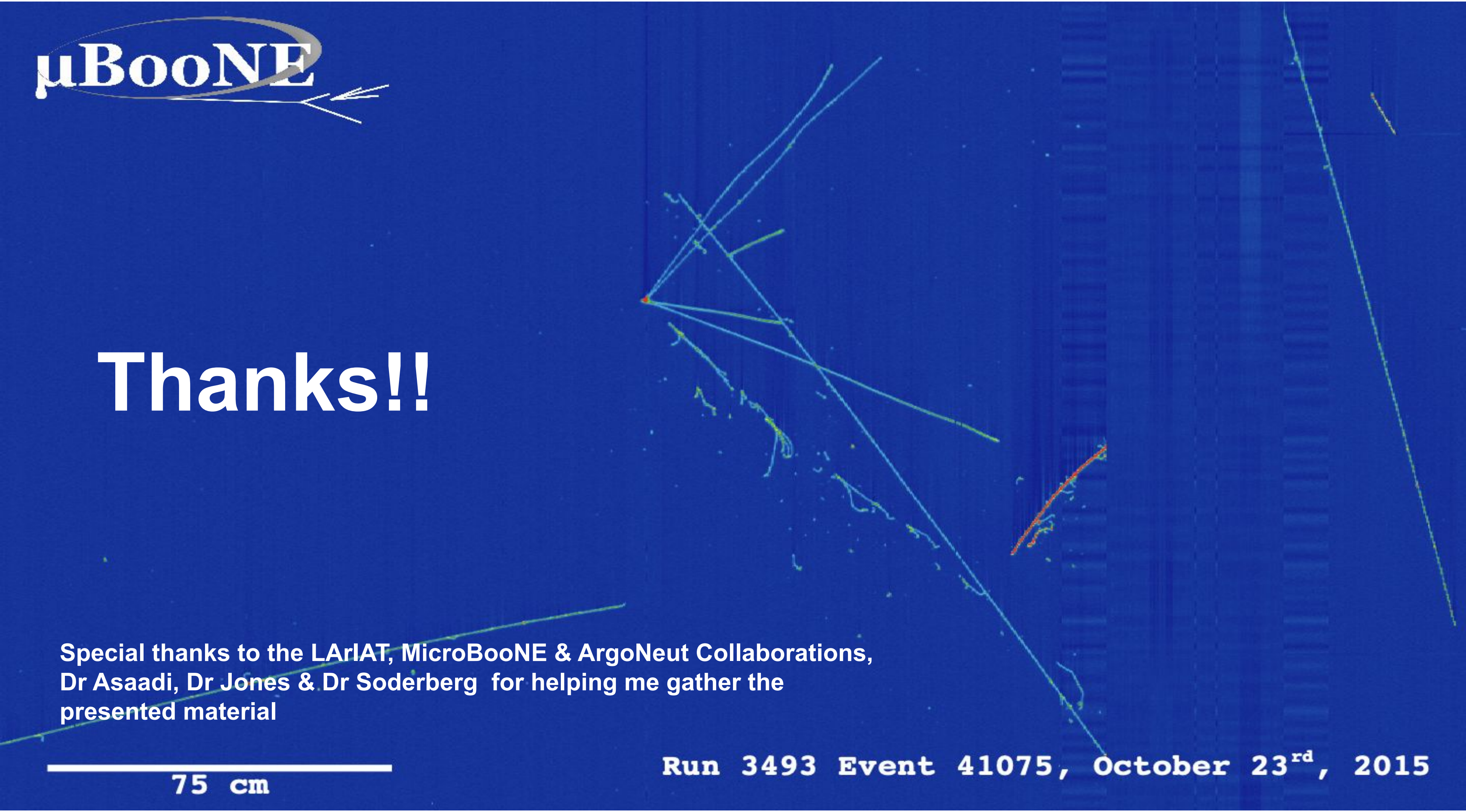
We want to leverage this “free” beam of muons to enhance our understanding of nuclear effects in neutrino interactions, and to perform an innovative muon-philic dark matter search

…LET’S DO IT DO IT!!!



Thanks!!

Special thanks to the LArIAT, MicroBooNE & ArgoNeut Collaborations, Dr Asaadi, Dr Jones & Dr Soderberg for helping me gather the presented material



Literature review

LArTPC intro: Chapter 2
https://lss.fnal.gov/archive/thesis/2000/fermilab-thesis-2018-24.pdf
Recombination: https://arxiv.org/pdf/1306.1712.pdf
Lifetime: https://arxiv.org/pdf/0910.5087.pdf
Space charge: https://arxiv.org/pdf/2008.09765.pdf
Signal processing: https://arxiv.org/pdf/1802.08709.pdf
https://arxiv.org/pdf/1804.02583.pdf
LArIAT Detector description: https://arxiv.org/pdf/1911.10379.pdf
Scintillation Light: https://dspace.mit.edu/handle/1721.1/101327

Complications...

Most of the physics handles highlighted hinge on the proper assessment of the energy deposited by the particles in the TPC (dE/dx) via the measurement of the charge seen by the anode wires (dQ/dx).

A number of detector effect complicate this relationship, and event reconstruction in general.

We'll treat:

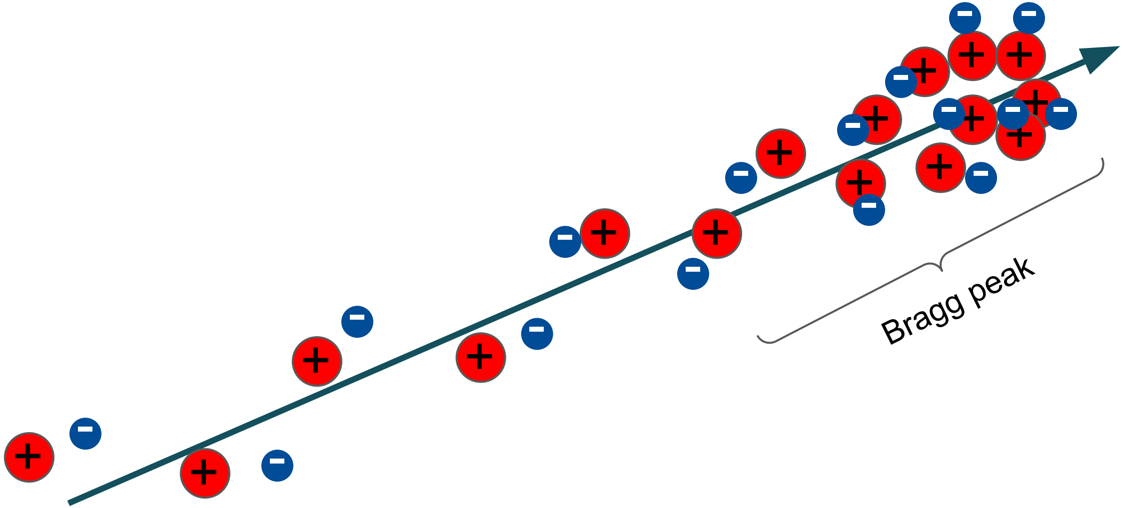
- Recombination effects → affects amount of charge produced by the particle
- Electron Lifetime → affects amount of charge arriving at the wires
- "Space charge" (i.e. local distortion of the electric field) → affects position reco
- Diffusion → affects position reco

These are important effects every LArTPC need to assess and calibrate for.

Where did my charge go? Recombination

The passage of charged particles in the medium ionizes the Ar.

Example: Stopping proton



Where did my charge go? Recombination

The passage of charged particles in the medium ionizes the Ar.
What would happen to the charge in absence of electric field?

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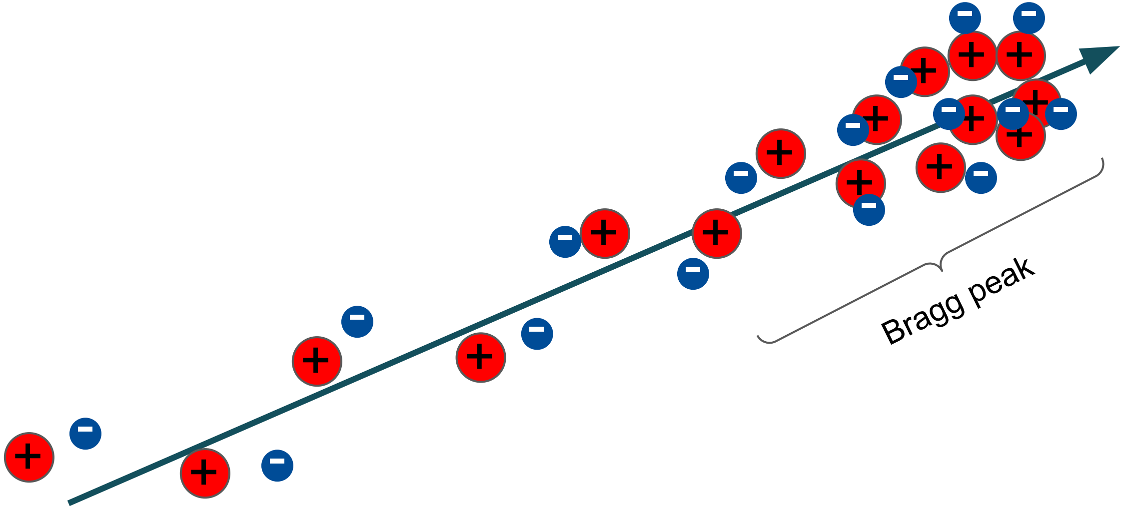

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The passage of charged particles in the medium ionizes the Ar.
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Electrons and ions are termalized and feel each other's electric field:
they all live at 87k in the same space, with enough time they'll find each others.
All electrons and ions recombine → excited states

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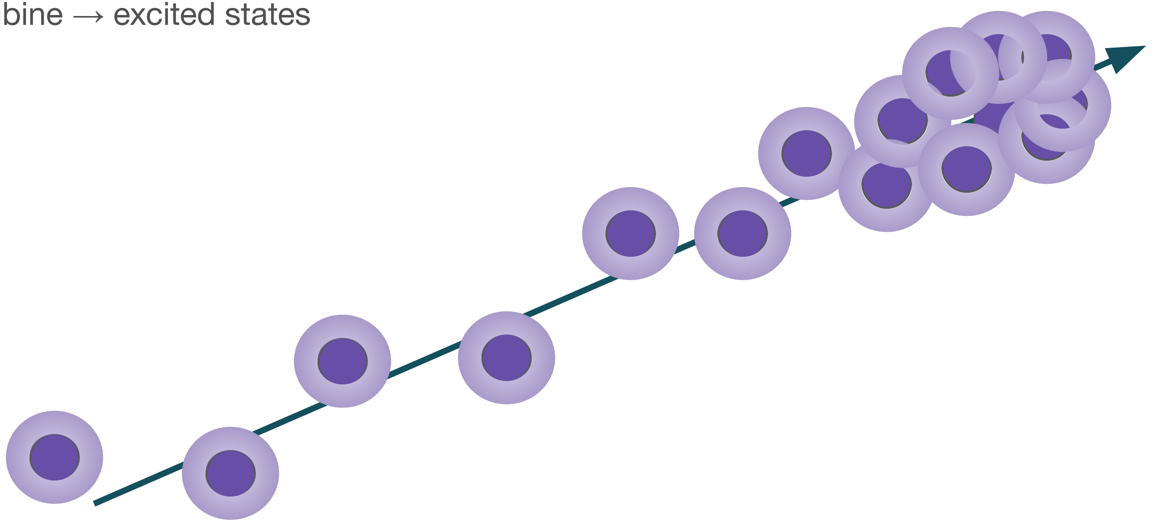

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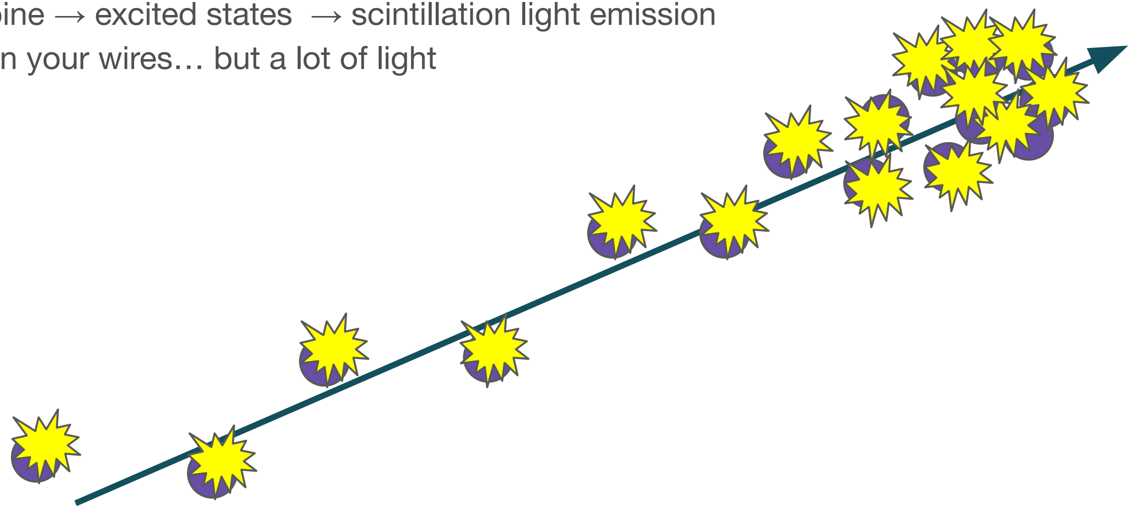
All electrons and ions recombine → excited states → scintillation light emission
You get exactly zero charge on your wires… but a lot of light

Example: Stopping proton



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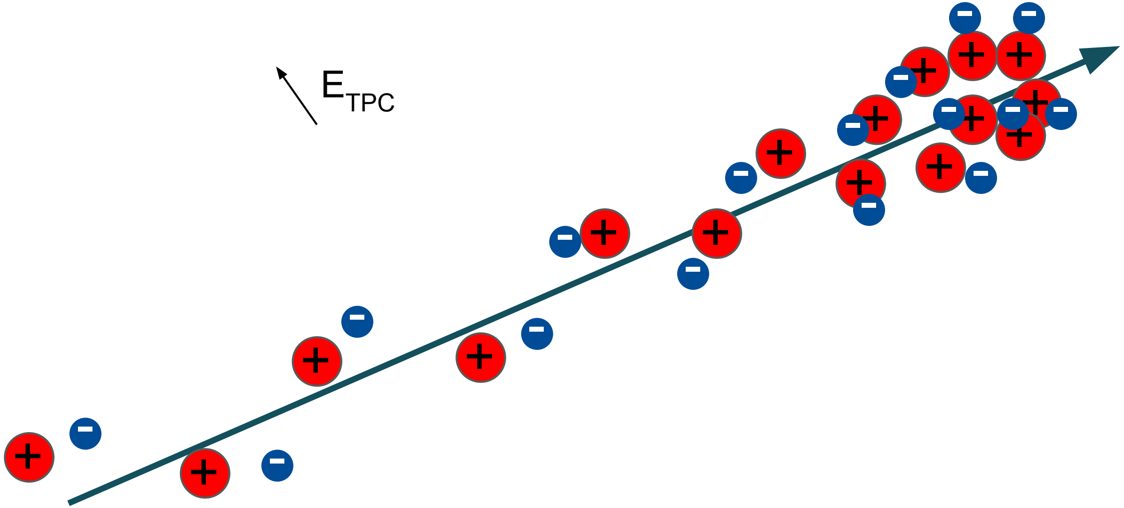
Where did my charge go? Recombination

The passage of charged particles in the medium ionizes the Ar.
Let's add the electric field!

Example: Stopping proton



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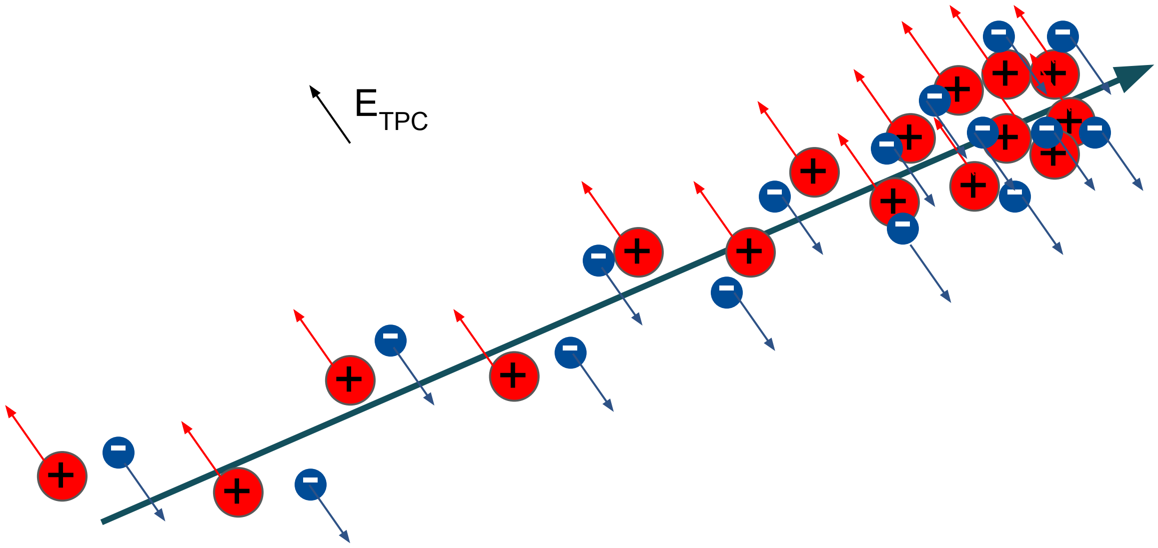
Where did my charge go? Recombination

The passage of charged particles in the medium ionizes the Ar.
The electric field in the TPC drifts positive ions and negative electrons in opposite directions.

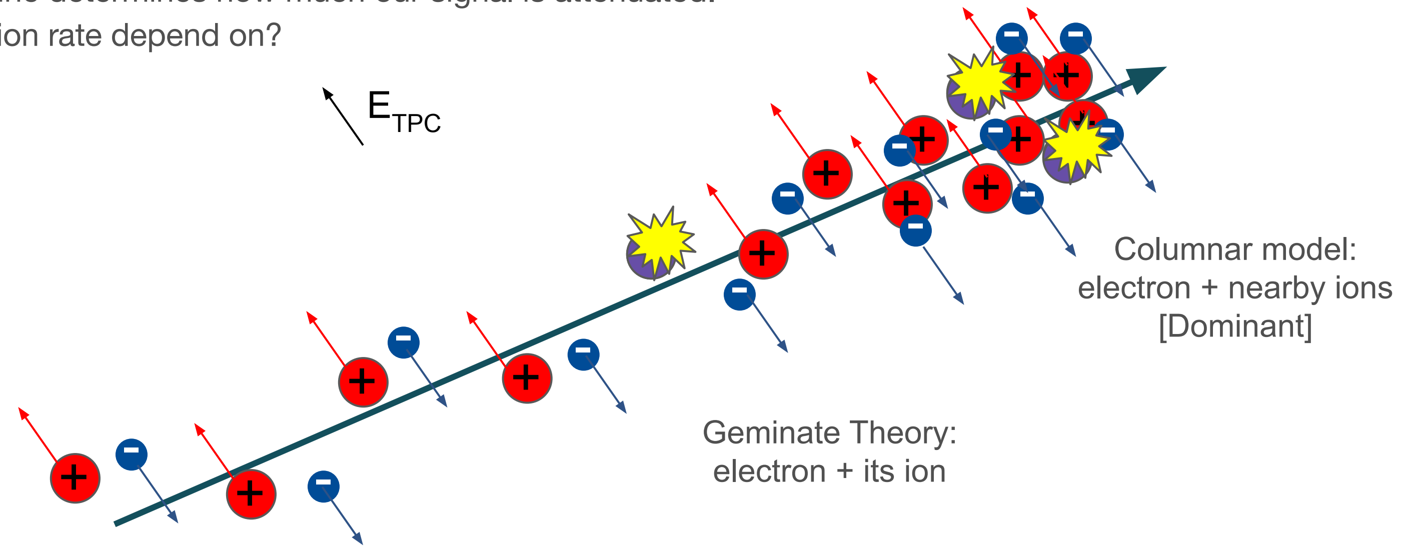
Example: Stopping proton



Where did my charge go? Recombination

The passage of charged particles in the medium ionizes the Ar.
The electric field in the TPC drifts positive ions and negative electrons in opposite directions. Some of the electron charge “gets eaten” by the Ar^{+}.
How much charge recombine determines how much our signal is attenuated.
What does the recombination rate depend on?

Example: Stopping proton



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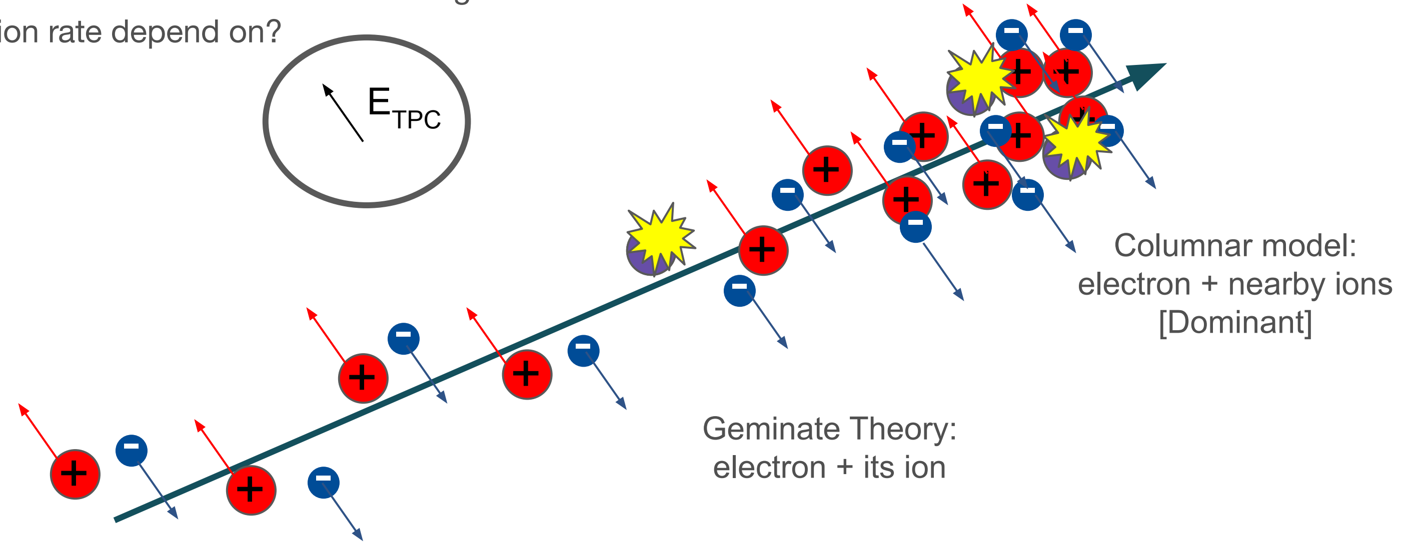
What does the recombination rate depend on?

Example: Stopping proton



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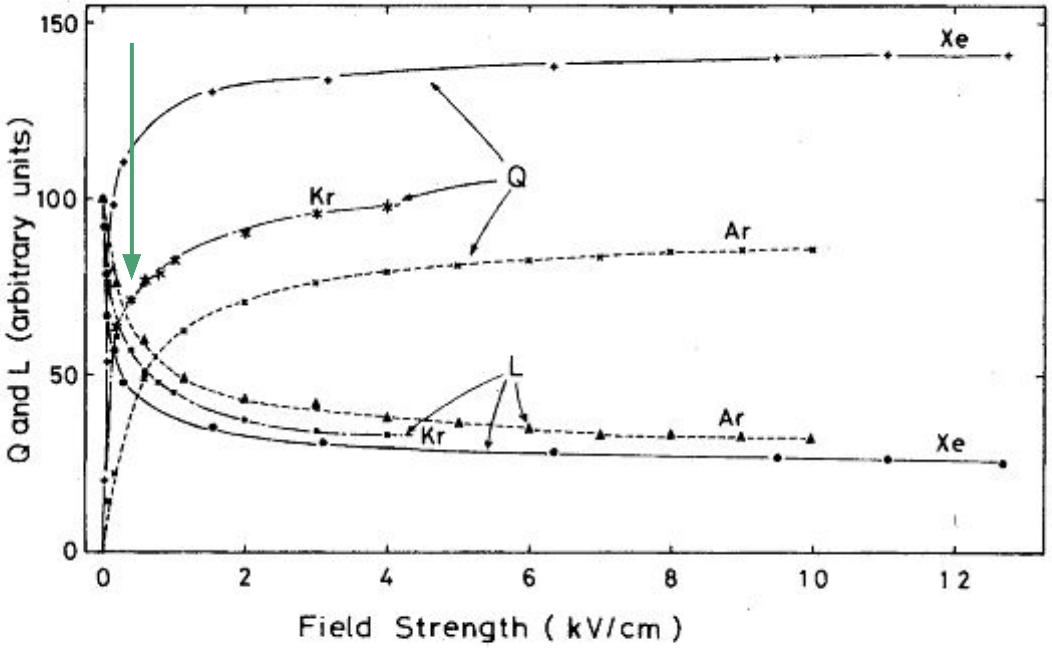
Recombination depends on: the LArTPC E field

The higher the field the smaller number of electron-ion pair which recombine.

This conservation of charge & energy explains the inverse relationship between the light (L)
and charge (Q) yield in noble elements.

Most LArTPCs live HERE!
500 V/cm

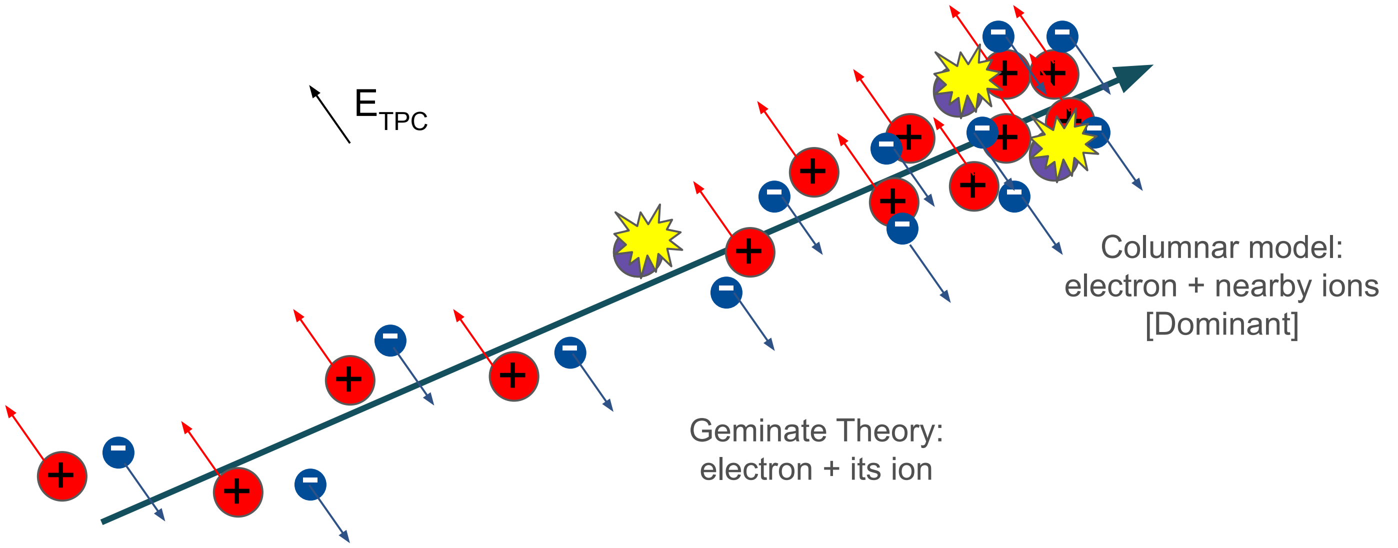
Phys. Rev. B, vol. 20, no. 8, p. 3486, 1979



Recombination depends on: the particles' dE/dx

Collective effects are shown to be dominant for recombination:
spatial distribution of the ions & electron plays a role → dQ/dx

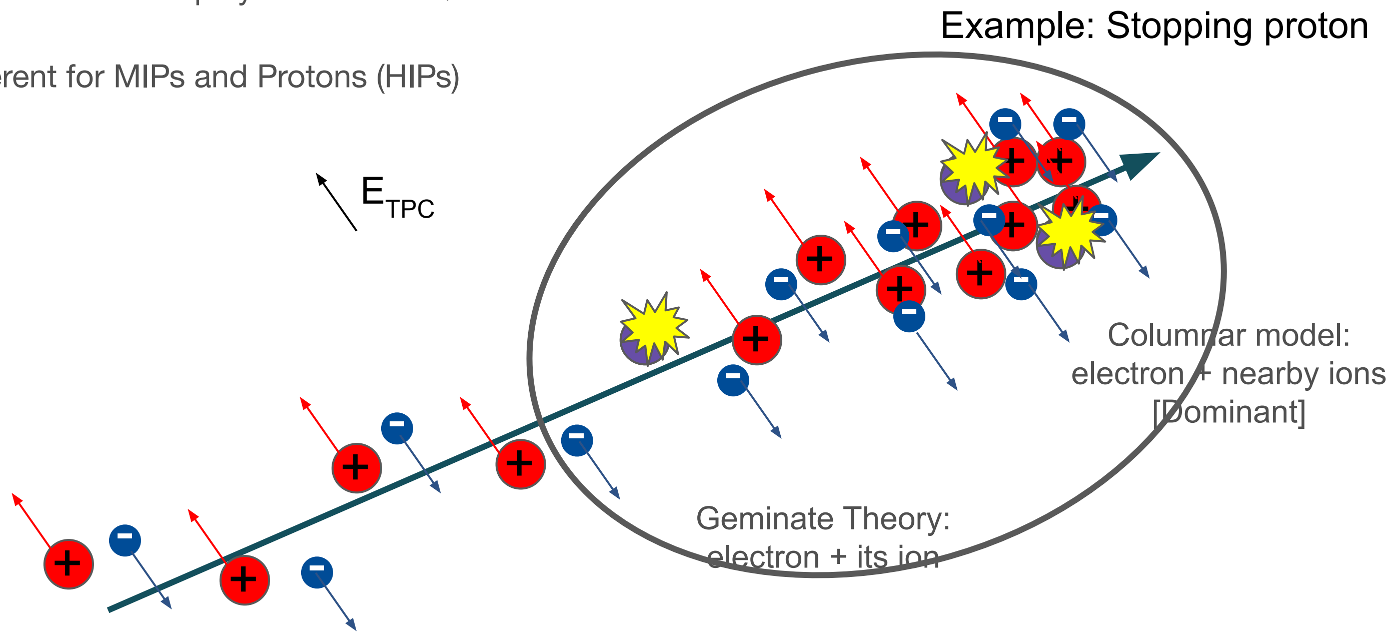
Example: Stopping proton



Recombination depends on: the particles' dE/dx

Collective effects are shown to be dominant for recombination: spatial distribution of the ions & electron plays a role → dQ/dx

Recombination is then different for MIPs and Protons (HIPs)



Recombination theoretical models: Birks and Box

https://arxiv.org/pdf/1306.1712.pdf

The Birks model → gaussian spatial distribution around the particle trajectory during the entire recombination phase and identical charge mobility for ions and electrons. It considers the charge diffusion coefficient.

$$dE/dx = \frac{dQ/dx}{A_B/W_{ion} - k_B \cdot (dQ/dx)/\mathscr{E}}$$

The Box model → assumes that electron diffusion and ion mobility are negligible in liquid argon during recombination.

$$\mathscr{R}_{\mathrm{Box}} = \frac{1}{\xi} ln(\alpha + \xi), \quad \text{where} \quad \xi = k_{\mathrm{Box}} N_o / 4a^2 \mu \mathscr{E}.$$

These models are generally in accordance to data only in specific regimes: the Birks model for low dE/dx, the Box model for high dE/dX. LArTPC experiments tend to measure the recombination parameters as part of the detector calibration.

From the ArgoNeuT experiment

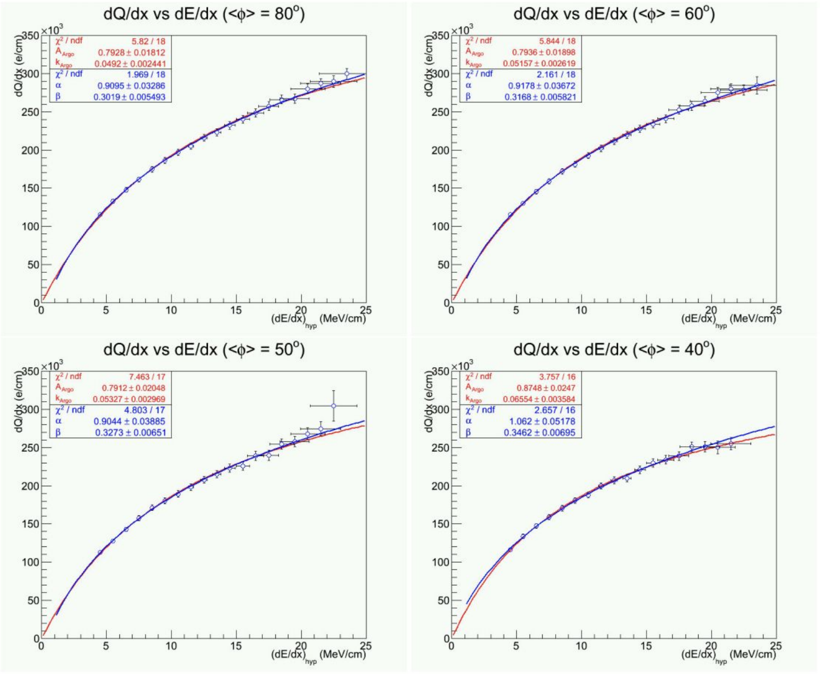


Figure 10. Recombination fits to dQ/dx vs $(dE/dx)_{hyp}$ for all angle bins. The red (blue) curves and text represent Birks model (modified Box model) fits.

Where did my charge go? Electron lifetime

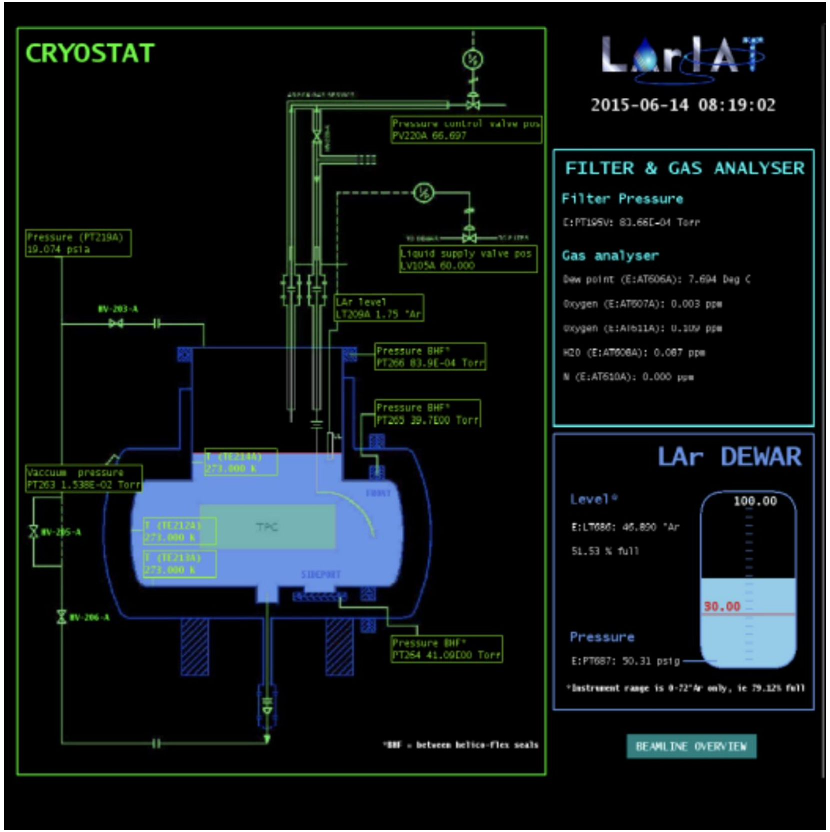
https://arxiv.org/pdf/1911.10379.pdf

Ionization electrons drift towards the anode, but electronegative contaminants in the argon can neutralize their charge
→ signal loss!
Electronegative contaminant = Oxygen and Water vapor.

Contaminants are controlled at the source: commercial Ar is usually graded for 1 ppm of O_2 and H_2O, but for LArTPC operation you need 1 part per trillion!

Argon is filtered and analyzed for contaminants before it fills the cryostat.

Outgassing (release of water-vapor/O_2 from plastic-like component) is constant → the Argon in the TPC is constantly purified, either from constant injection of new argon (small TPCs) or re-circulation and cleaning (big TPCs).
The go-to choice for plastic components in the TPC is G10 because of low outgassing, particularly important at the ullage.



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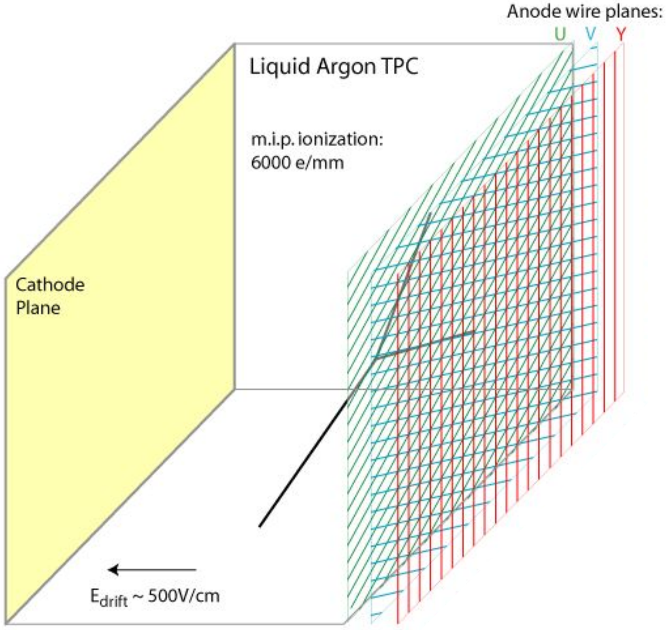
In the presence of such contaminants, the amount of charge collected at the wire planes depends on the distance the charge travels to reach the wire planes, or equivalently, the drift time. For a given charge deposited in argon, the charge collected decays exponentially with drift time. Why?



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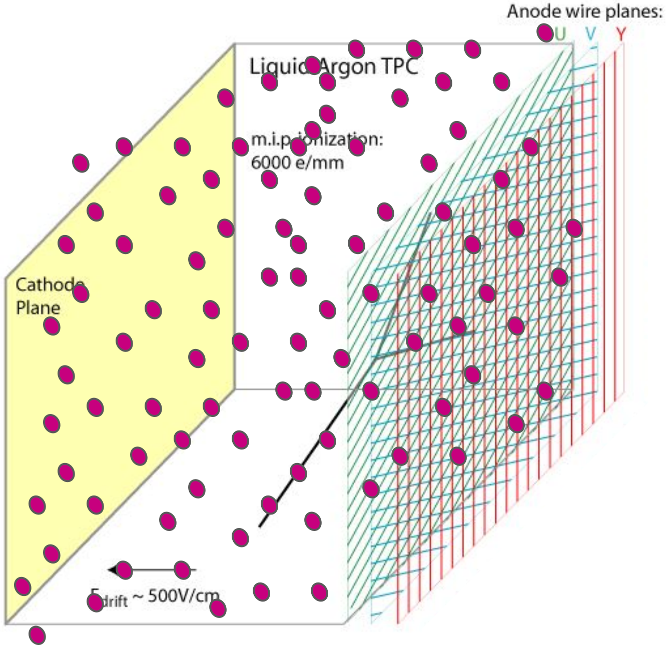
The contaminants are uniformly distributed in the Ar volume. My moving charge has the same constant probability of getting neutralized every moment along its journey: dQ = -λ dt

Usually we express λ as 1/τ and we call τ electron lifetime.
Solving the differential equation...



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… and remembering that we usually measure dQ/dx in the detector, we get

$$\frac{dQ}{dx} = \left(\frac{dQ}{dx}\right)_0 e^{-t_i/\tau}$$

Lifetime

Drift time

Charge per unit length seen by my wires

Charge deposited when the charge started drifting

How do we measure and monitor this lifetime, (aka how do we calibrate) if potentially the amount of contaminants changes overtime? With a calibrated source of dQ/dx. Any guess at what that could be?

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Where did my charge go? Electron lifetime

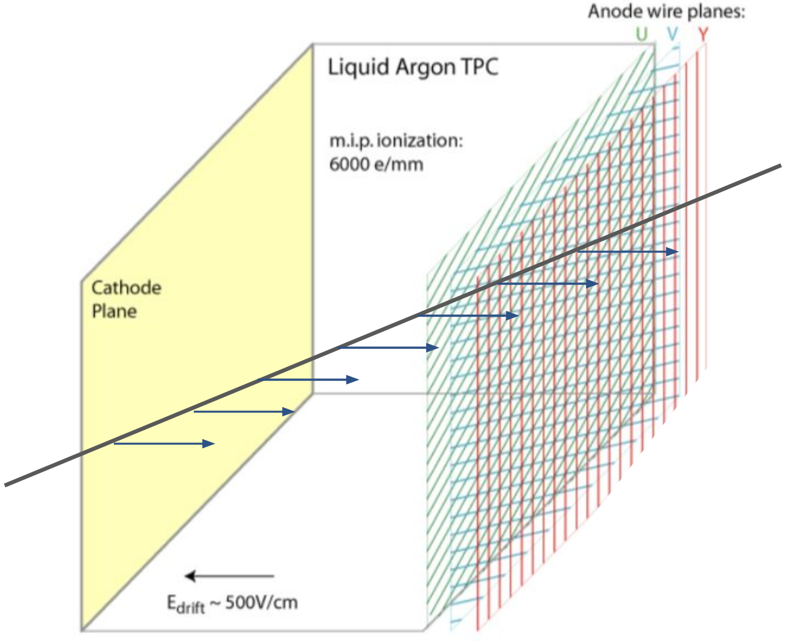
https://arxiv.org/pdf/1911.10379.pdf

Our calibration should be a source which deposits the same amount of charge everywhere along its path, so that I know this term, and I measure this and this!

$$\frac{dQ}{dx} = \left(\frac{dQ}{dx}\right)_0 e^{-t_i/\tau}$$

High energy muons that cross both the anode and the cathode are the perfect calibration source:
the always deposit about 2 MeV/cm along their path.

So the difference in the charge collected from the portion of the muon close to the cathode and the portion of the muon close to the anode corresponds to how much charge is “eaten” by the contaminants. We can measure that!



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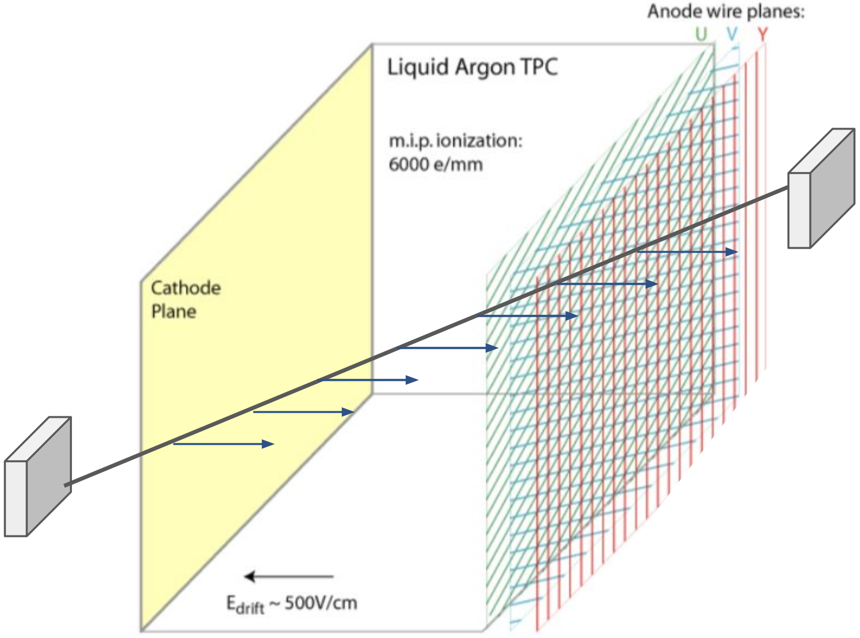
Step 1: select a bunch of crossing tracks

There are several ways to do this, a common one is relying on external scintillator detectors placed outside TPC and requiring signal coincidence and track matching.



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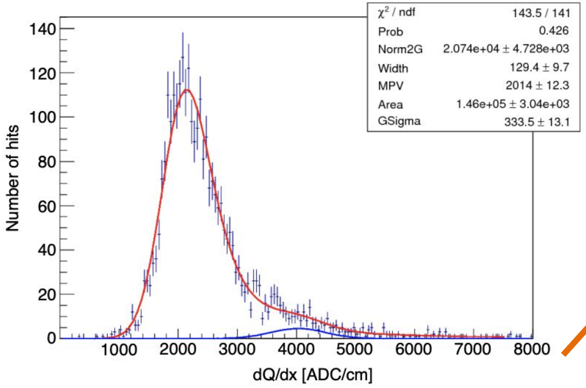
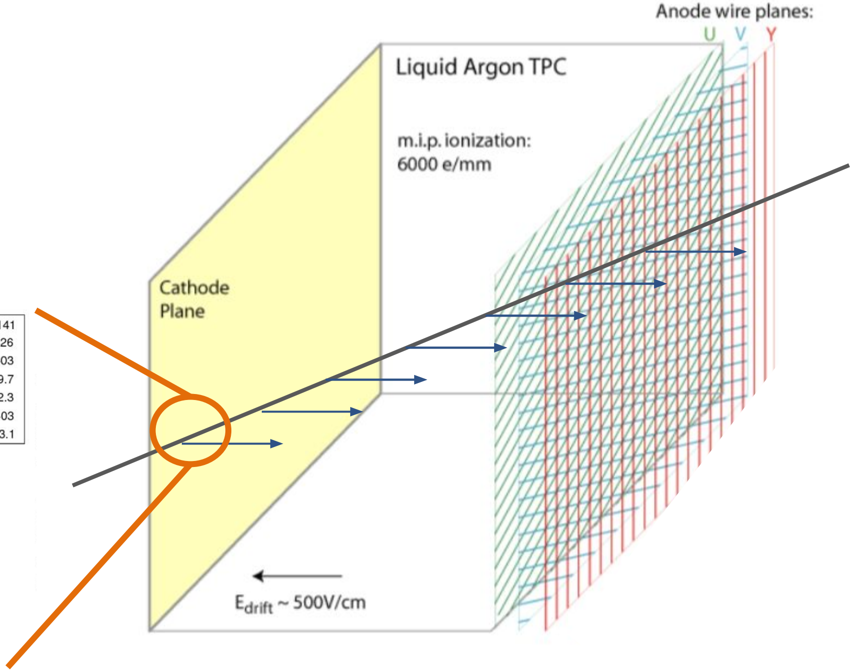
$$\frac{dQ}{dx} = \left(\frac{dQ}{dx}\right)_0 e^{-t_i/\tau}$$

Step 2: plot the measure dQ/dx in chunks of arrival time

So, this, many many many times.

Landau+Gaussians!





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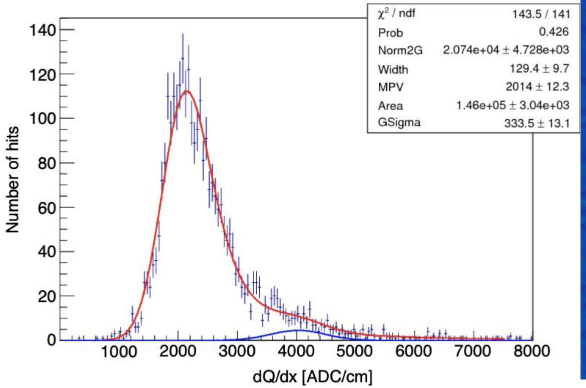
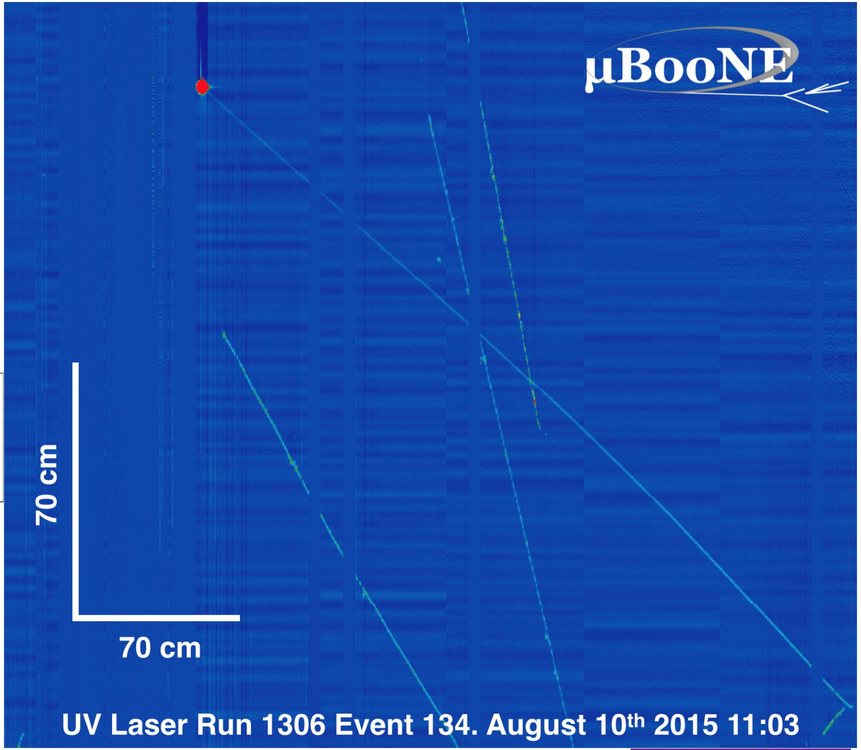
Brief detour





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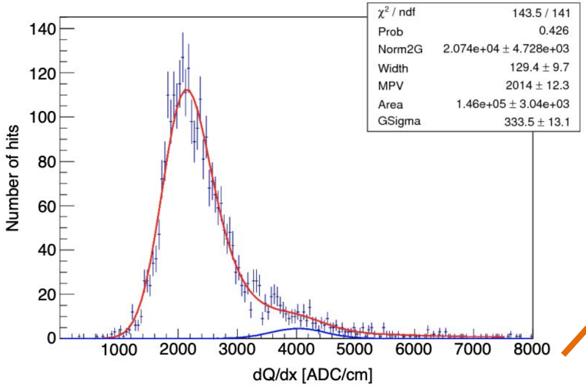

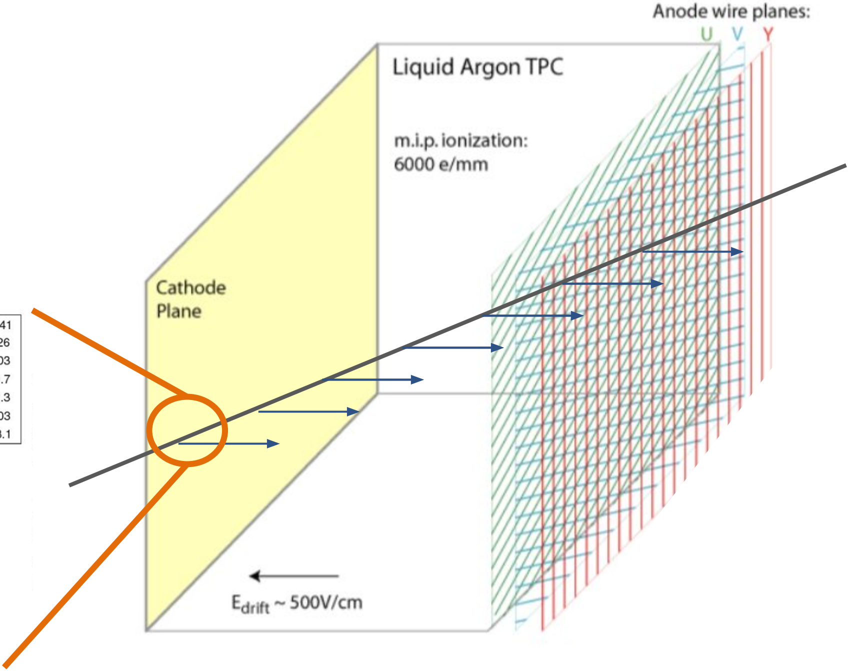

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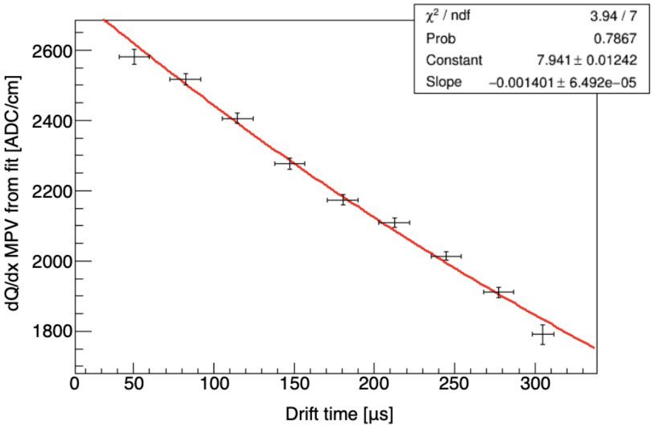
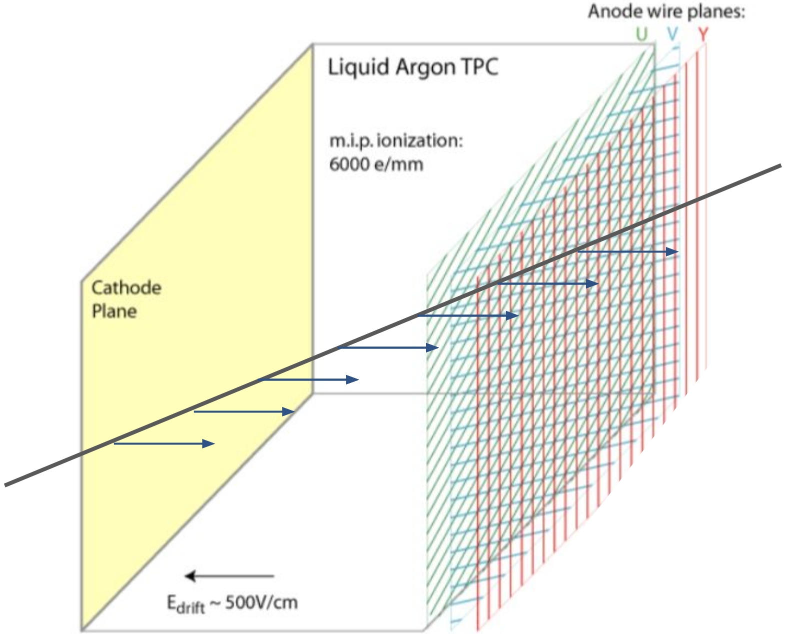
$$\frac{dQ}{dx} = \left(\frac{dQ}{dx}\right)_0 e^{-t_i/\tau}$$

Step 3: plot all the landaus' MPV, as a function of time fit with exponential

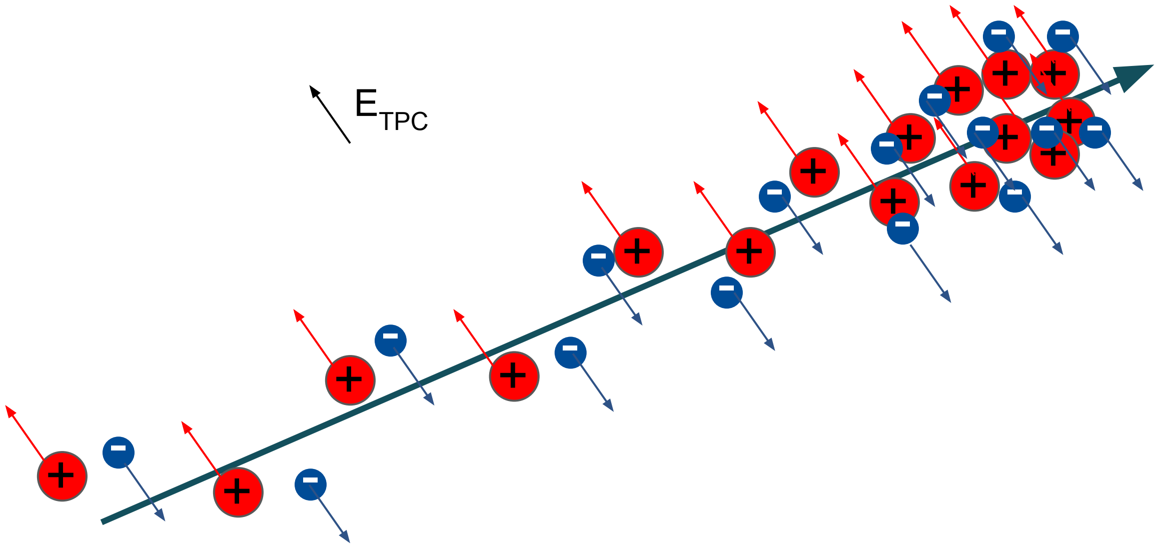




Did my charge move? Diffusion

Diffusion is the spread of the electron cloud over time.

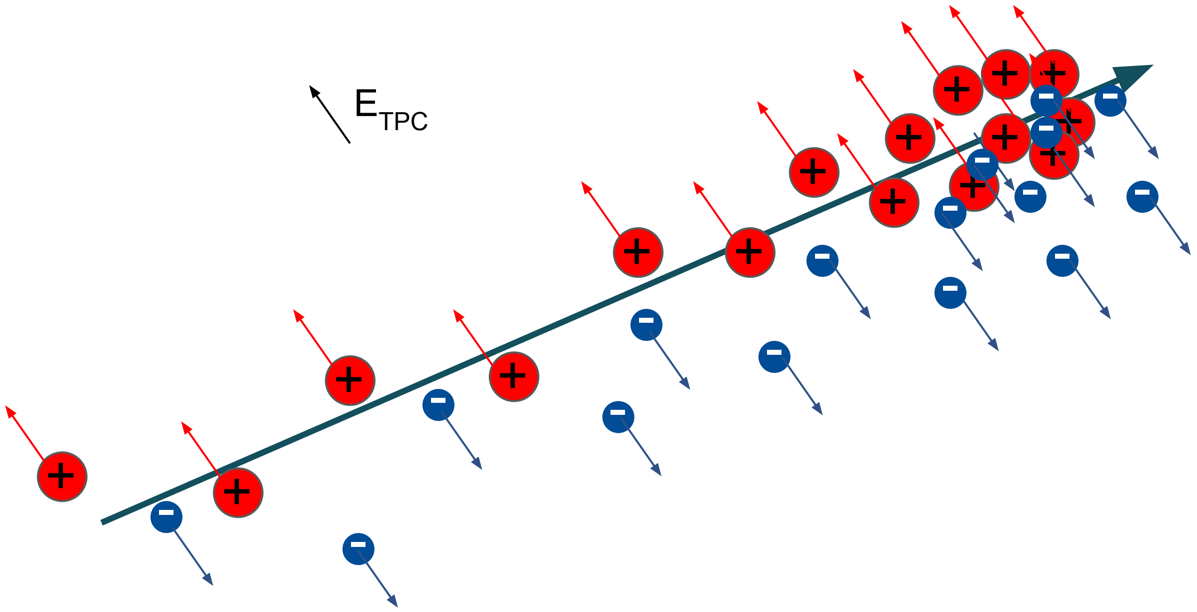
Example:
Stopping proton at time t_0



Did my charge move? Diffusion

Diffusion is the spread of the electron cloud over time.

Example:
Stopping proton at time t_1

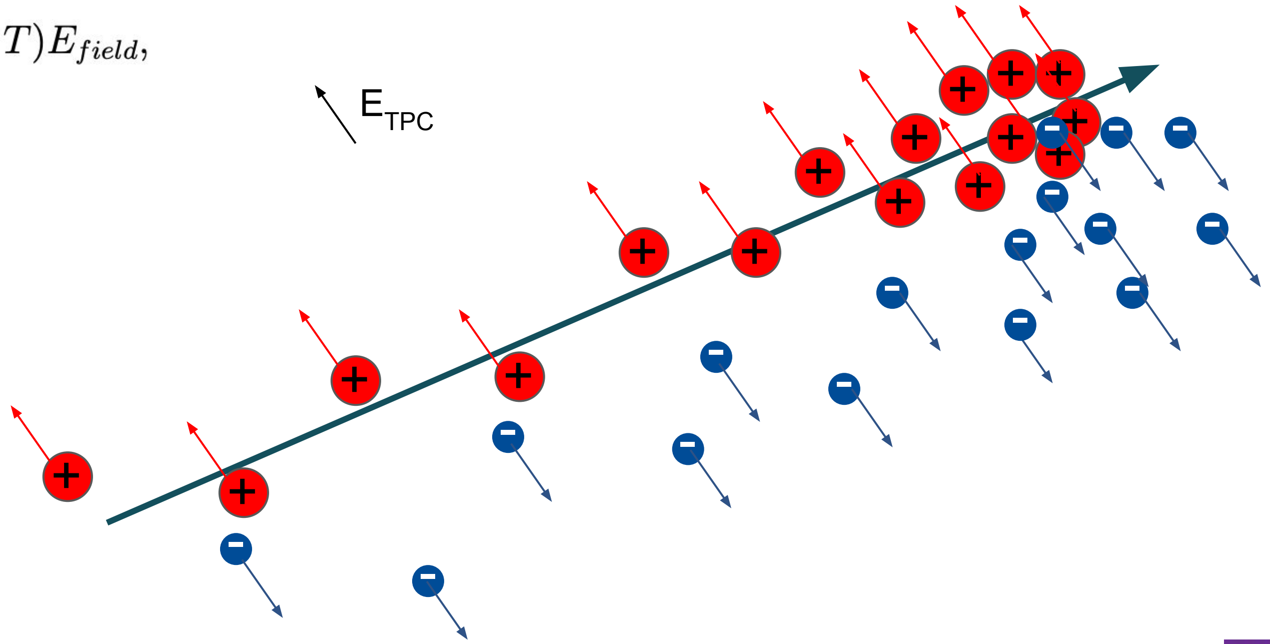


Did my charge move? Diffusion

Diffusion is the spread of the electron cloud over time. The ions move too, but since their mobility is an order of magnitude less than the electrons, their drift velocity is much smaller.

$$v_{drift} = \mu(E_{field}, T)E_{field},$$

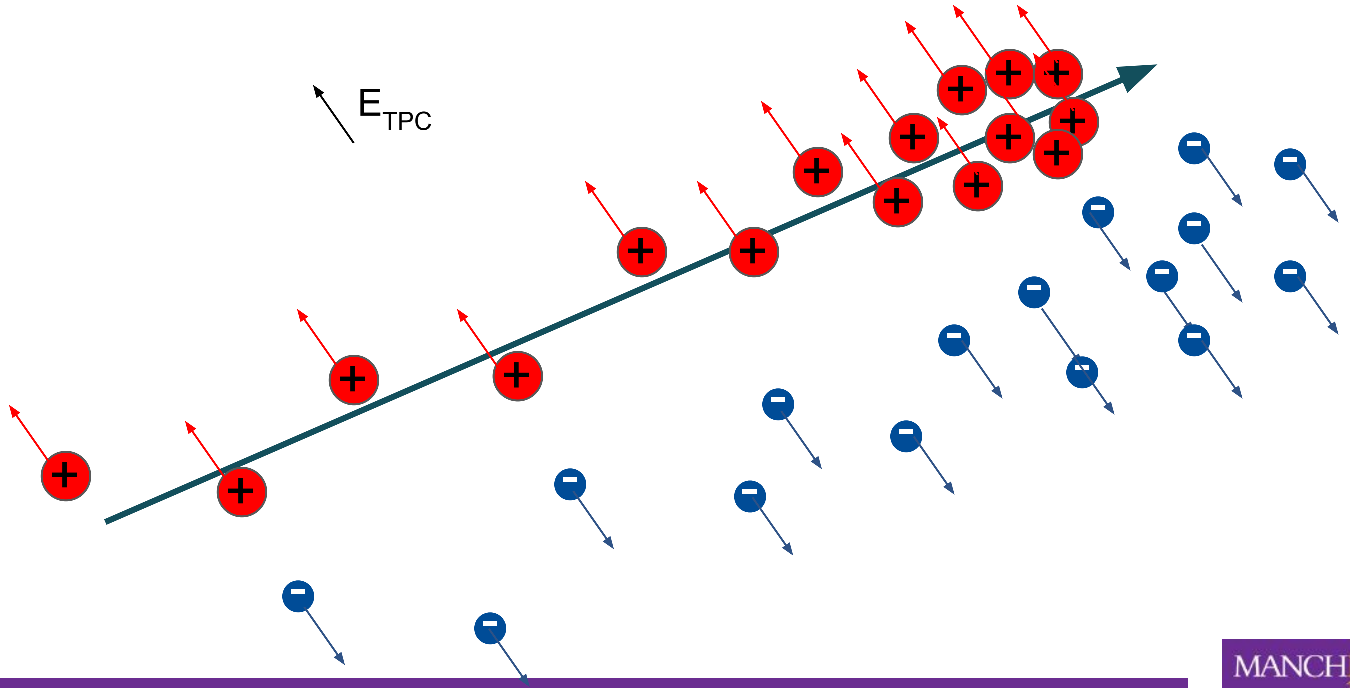
Example:
Stopping proton at time t_2



Did my charge move? Diffusion

Diffusion is the spread of the electron cloud over time.
Even if there is a preferential direction of motion, the charge is still affected by thermal random motion → it will spread out!

Example:
Stopping proton at time t_3



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Did my charge move? Diffusion

https://arxiv.org/pdf/2104.06551.pdf

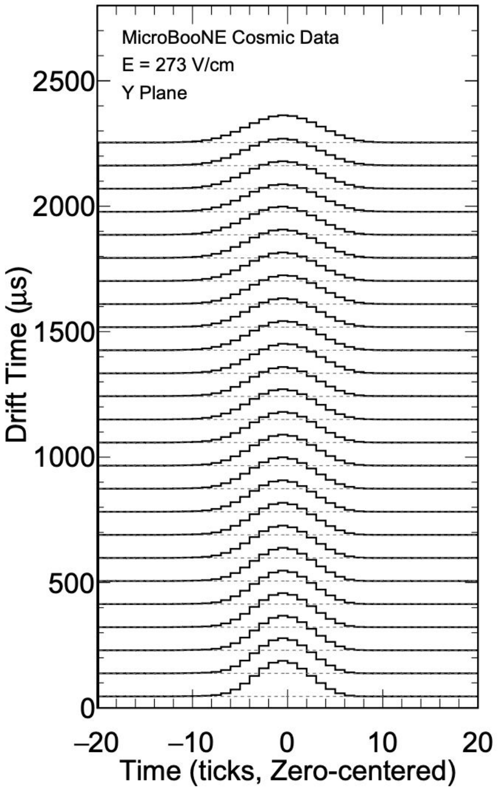
The LArTPC is an anisotropic detector by construction: not all directions in space "are created equal" because the electric field determines the direction of the electrons' drift (*X*).

The spread of the electron charge is then calculated and measured in two separated direction: the longitudinal diffusion D_L (along the drift direction) and the transverse diffusion D_T (perpendicular to the drift direction).

The transverse diffusion determines how well you can know the position of the charge in the YZ plane. For meters long TPC, the spread if order of mm: it is not convenient to have wire pitches less than 3 or 4 mm apart.

For a measurement of D_L is obtained sampling a calibrated source like cosmic ray muons and using:

$$\sigma_t^2(t) \simeq \sigma_t^2(0) + \left(\frac{2D_L}{v_d^2}\right) t,$$



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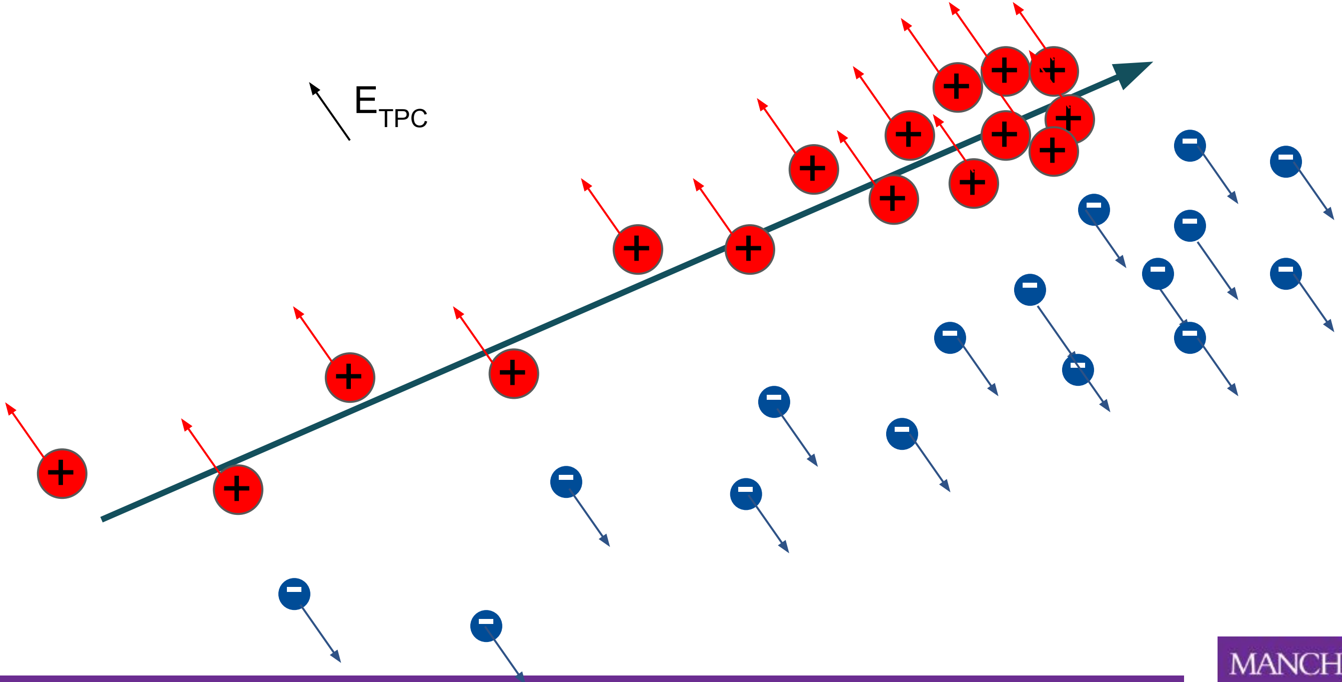
Did my charge move? Space charge effect

https://arxiv.org/pdf/2008.09765.pdf

Remember the Ar^+ ions which are slowly moving towards the cathode?

Where do they go?

Example:
Stopping proton at time t_3



Did my charge move? Space charge effect

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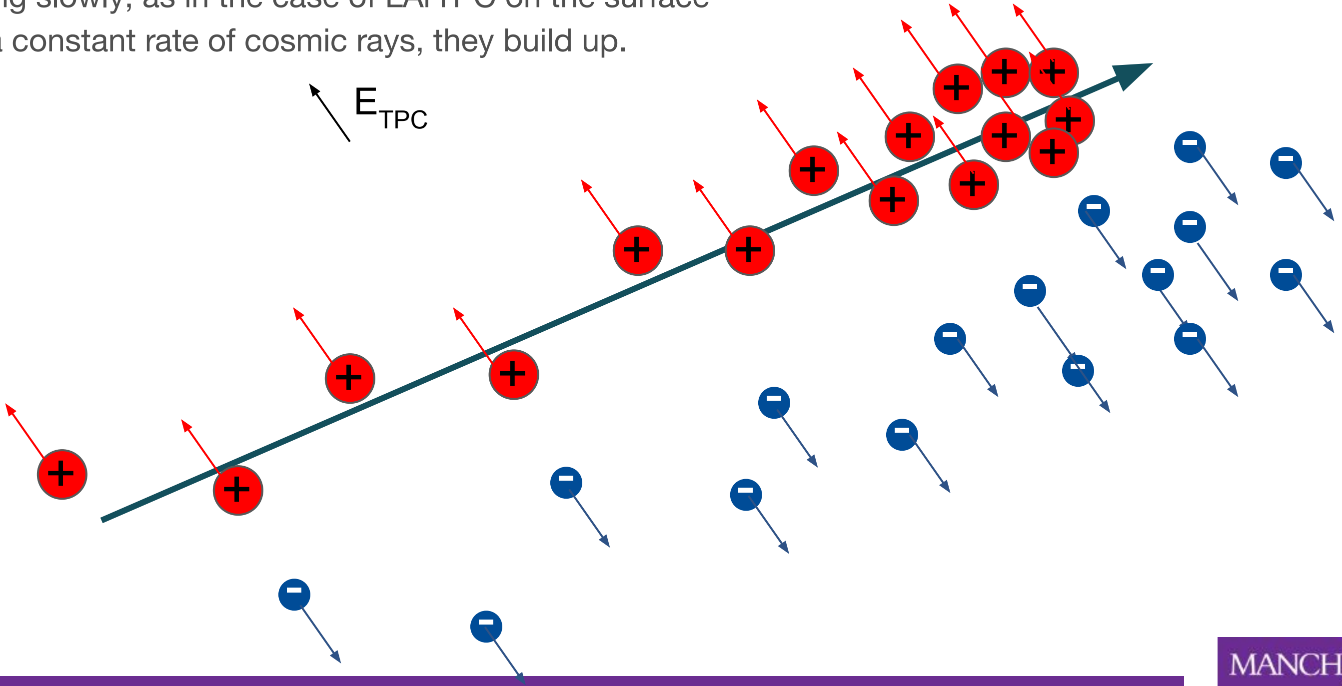
Remember the Ar^{+} ions which are slowly moving towards the cathode?
Where do they go?
They are absorbed by the cathode, but if you have a constant production of ions which are moving slowly, as in the case of LArTPC on the surface which are exposed to a constant rate of cosmic rays, they build up.

Why is this "bad"?

Example:
Stopping proton at time t_3



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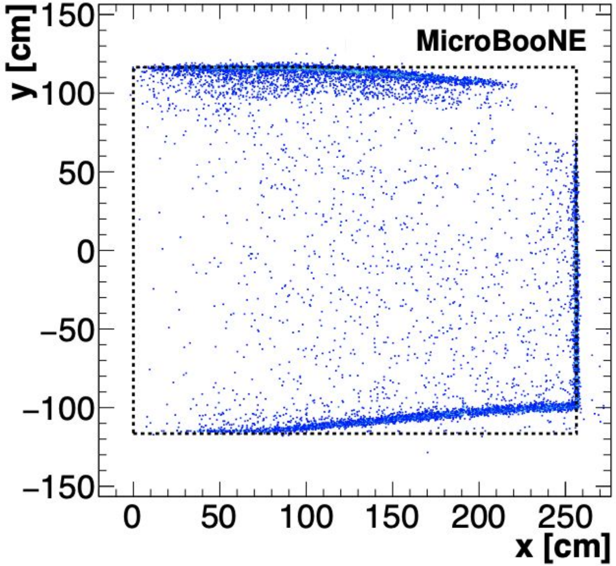
Why is this “bad”?

Because ions are positive charges, so they distort the electric field around them → your position reconstruction is affected,
and so is recombination.

E.g. Entry/exit points of reconstructed cosmic muon tracks coincider with a signal from a muon counter located outside of the cryostat.
The points are shown in the x–y plane. W/o SCE and its associated non-uniform electric field in the detector volume, the points should be located strictly along the TPC boundaries (dashed lines).
The anode is located at x = 0 cm while the cathode is at x = 256 cm.

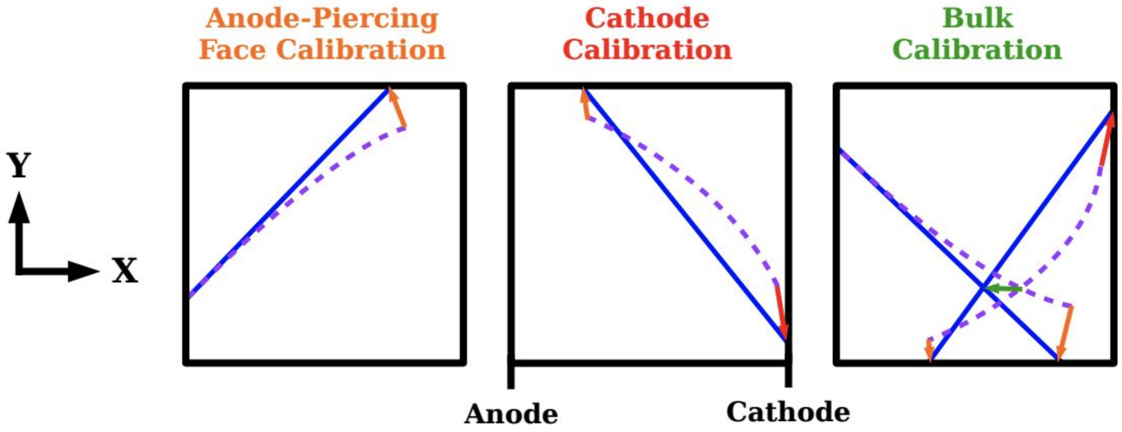


Did my charge move? Space charge effect

https://arxiv.org/pdf/2008.09765.pdf

Calibration relies again on "mapping" the electric field in the whole TPC volume.

1. You select muon events where you know where the charge was deposited either via external detectors or anode and cathode piercing tracks. Or, you map out the TPC by shining a laser w/ know direction ("perfect" muon).
2. you see what your event reconstruction tells you about the reconstructed muon position (position of each hit)
3. you calculate the difference in each x,y,z point in the detector

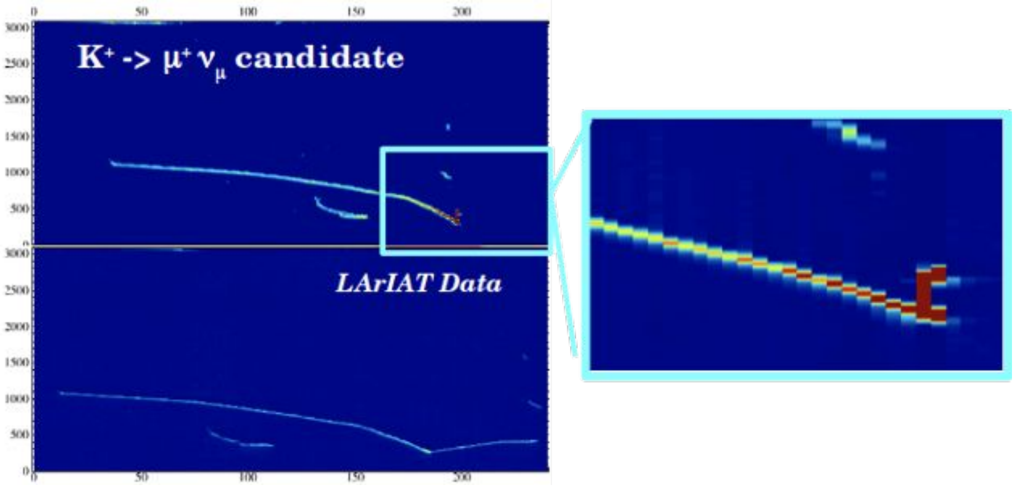


Blue: true muons path
Purple: reconstructed position distorted by SCE (exaggerated)

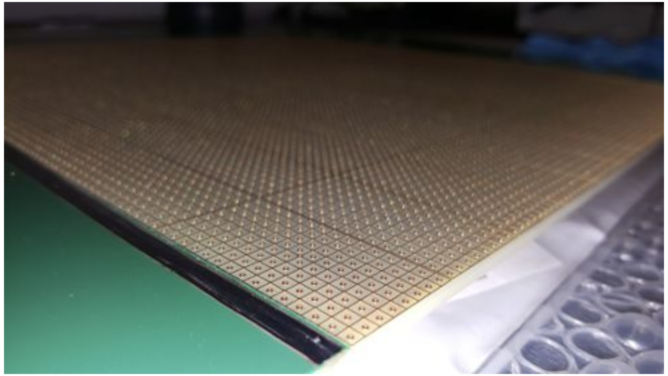
Making the LArTPC better

A fundamental issue with LArTPC w/ projective readouts (wires): highly **anisotropic detectors**... the readout **affects the possibility of maintaining the intrinsic 3D quality of the events.**

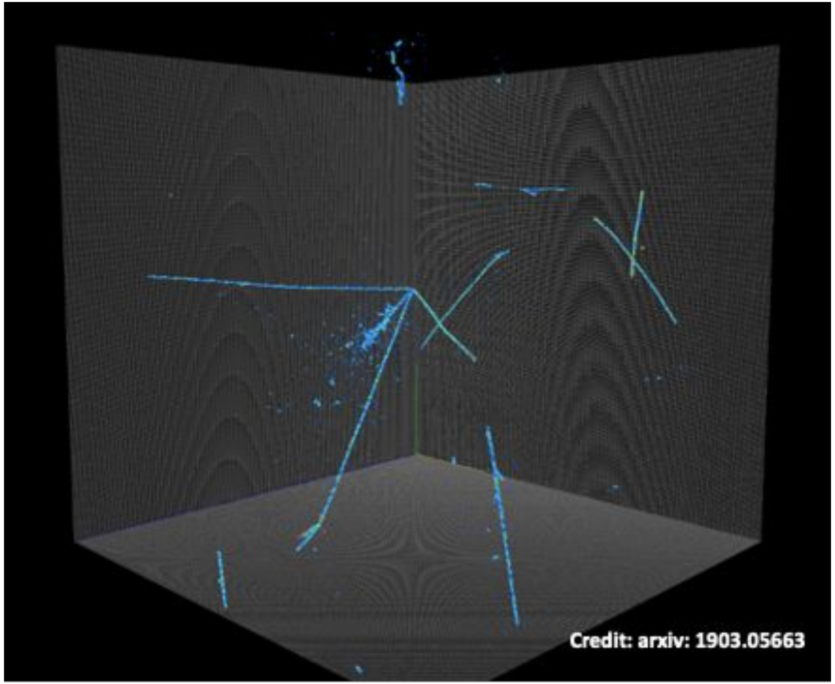
In 2D projective readouts, the readout space **DOES NOT coincide w/ the physical space:** traditional LArTPCs use sets of wire planes at different angles to reconstruct the transverse position → automatic plane matching is difficult, especially for complex topologies.



Constructing anode planes with pixels instead of wires can **solve a number of shortcomings** of 2D projective readouts.



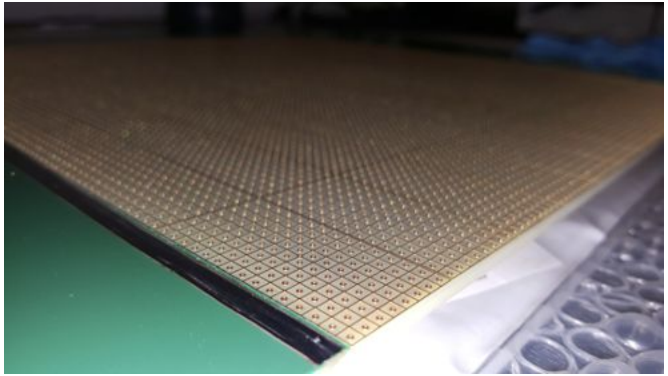
Pixels!



More resilient against single point failure and simpler to construct.

Small pixels sizes (4x4 mm^2) provide **comparable spatial resolution**, but the **readout space coincides w/ the physical projected space**:
→ native 3D reconstruction
→ abated ambiguities (mm vs m projections)

Shortcoming: massive amounts of readout channels "Pixelizing"



a massive detector such as a 10kTon DUNE module requires **O(130.0 million) pixels vs**

O(1.5 million) wires.

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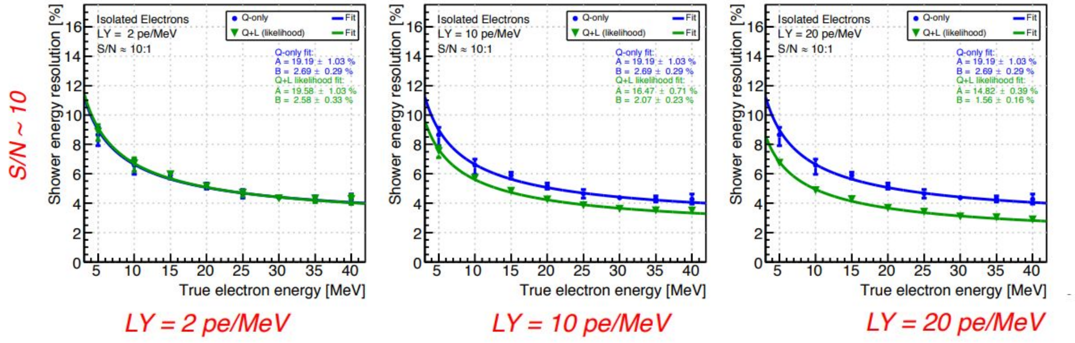
A word on the light: explorations

In surface LArTPC the light is used to discriminate between on-beam events and off-beam events: coincidence w/ beam signal. Sometimes no neutrino interacts in the TPC when the beam is sent to your detector. If there's no flash in time with the beam, you can avoid reconstructing the event altogether.

If you have segmented light detection (multiple PMTs), you can use light to determine which portion of the TPC contains a neutrino interaction and discriminate against comic activity. This is called "Flash-matching".

Lastly, light can augment your energy resolution for low energy particle. This is called "light augmented calorimetry"

LArIAT https://arxiv.org/abs/1909.07920



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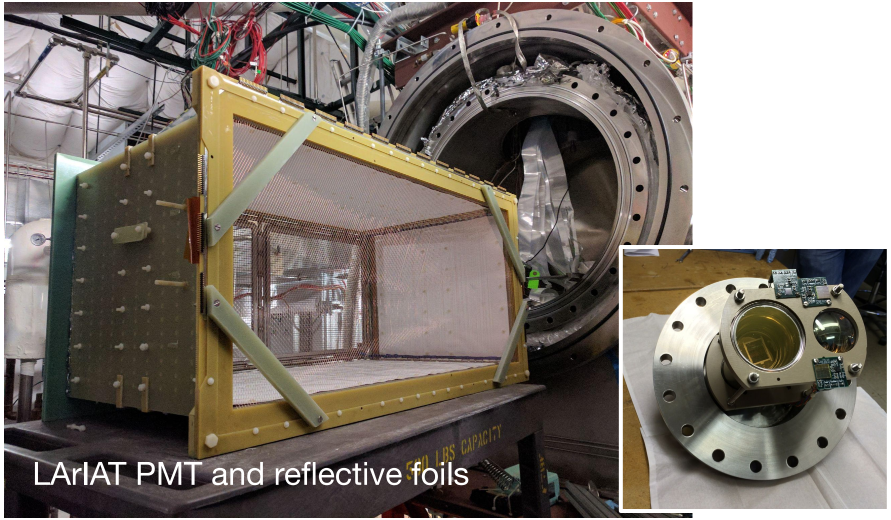
A word on the light

Light detection is historically performed with cryogenic PMTs. Since PMTs can only see visible light, argon’s 128nm light is shifted to visible w/ TBP: this is often not ideal because you loose light directionality and you take an efficiency in the number of collected photons → active development of new sensors and ideas for light uniform yield.



LArIAT PMT and reflective foils

MicroBooNE PMT

Elena Gramellini | elena.gramellini@manchester.ac.uk

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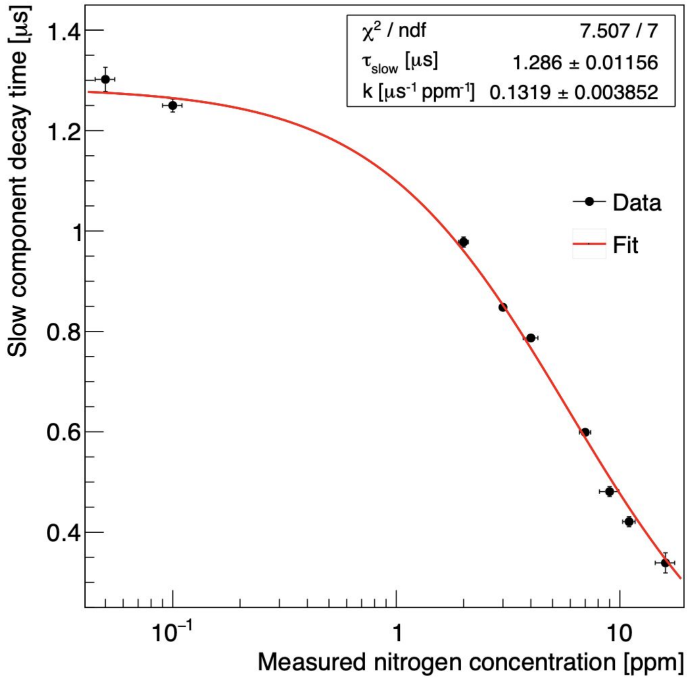
As for the charge, light can also be quenched by contaminants.
In particular nitrogen, which is usually very difficult to clean with the molecular filters with used to remove water and oxygen.



Proposed Two-Phase Experiment for M^3

- Phase 1: muon g-2 search
  - Flux of 10^{10} muons on target (MOT)
  - Existing detector technology
  - Probe entire parameter space not currently excluded by experiments for
    Vectors with $m_V \leq 500$ MeV
    Scalars with $m_s \leq 100$ MeV
  which couple exclusively to muons and decay invisibly.
  - Can be completed with minimal modifications to Fermilab muon source.
  - A null result would decisively rule out invisibly-decaying muon-philic particles less than 100 MeV as a new-physics explanation of muon g-2 anomaly.

Proposed Two-Phase Experiment for M^3

- Phase 2: Thermal muon-philic DM search
  - Larger flux of 10^{13} MOT
  - Upgraded detector performance to reject background at the level of 10^{-13}
  - Probe a significant portion of parameter space for which DM is thermally produced through $U(1)_{L_\mu - L_\tau}$ gauge interactions, with V as the gauge boson.
  - Models like this are inaccessible to traditional WIMP searches and many direct detection of sub-GeV DM experiments and fixed target experiments with electron and proton beams.

Types of Backgrounds

There are three types of bakcgrounds:

1. Beam-related backgrounds
2. Reducible backgrounds
3. Irreducible backgrounds

1) Beam-related Backgrounds

- **Muon energy spread:**
  - Fermilab muon beam is produced from in-flight decays of a 32 GeV pion beam.
  - Before muon beam arrives at target, it passes through an iron shield that absorbs any surviving pions.
  - Muons lose energy and scatter in the shield, resulting in energy spread between 10 - 30 GeV.
- **Pion Contamination:**
  - Pions which decay in the target could create false-positive signals (as the pion mass is so close to the muon mass).
  - The current 12 feet iron shield is enough to provide a beam purity (pion contamination) of 10^{-6}, sufficient for Phase 1.
  - Additional hadron absorber will be needed for Phase 2, where beam purity of 10^{-9} is required.

2) Reducible Backgrounds

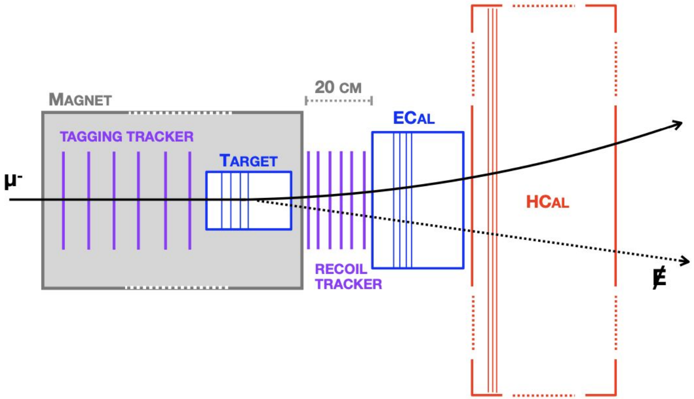
- Single bremsstrahlung: $\mu N \to \mu N \gamma$
  - When a real photon escapes detection in the calorimeter.
  - This was shown to be negligible for electrons in LDMX.
  - So further suppressed by $\left(\frac{m_e}{m_\mu}\right)^2$ for muon beams.
- Bremsstrahlung-initiated hadronic events: $\mu N \to \mu N \gamma, \gamma N \to$hadrons
  - Rare hadronic processes could fake signal events.
  - But again these are processes generated by real photons, which will be suppressed by $\left(\frac{m_e}{m_\mu}\right)^2$.
- Muon pair production:
  - Small rate for Phase 1 luminosity, but dominant reducible background in Phase

3) Irreducible Backgrounds

- Z-mediated Neutrino Pair Production:
  - The only process resulting in real missing energy.
  - But cross section for this process is negligible at 15 GeV muon beams.

Detector and Beam Parameters

- 15 GeV muon passes through tagging tracker which measures its momentum using the magnet.
- The muon passes through target which is 50 X_0 long.
- Outgoing muons are detected with the recoil tracker and their momentum is measured with the magnetic fringe field.
- ECAL and HCAL detect SM-induced background.



Signal region is defined by:

- outgoing muon < 9 GeV
- 10 – 20 MeV energy deposited in target