Induction signal characterization in the vertical drift TPC for the DUNE project

1st year PhD work

Journée de Rencontre des Jeunes Chercheurs 2023

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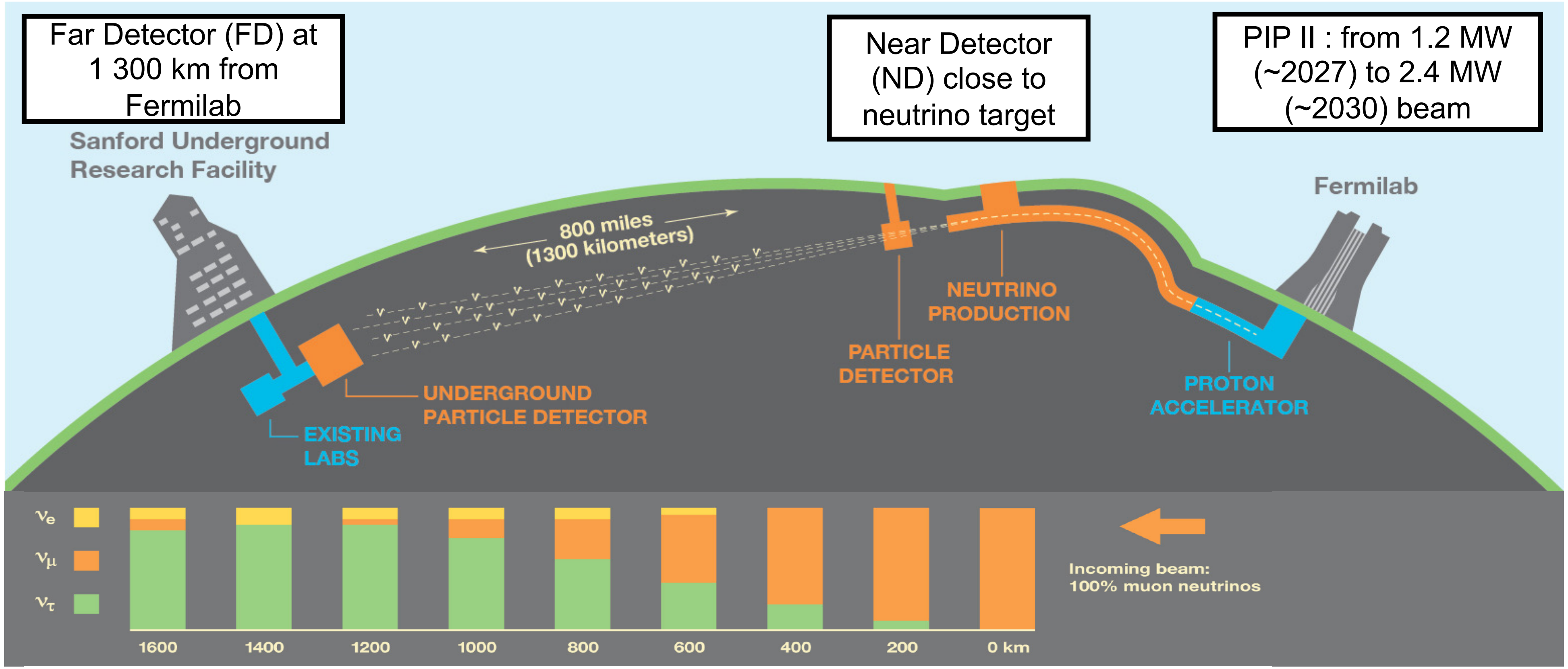
D. DUCHESNEAU – LAPP Annecy

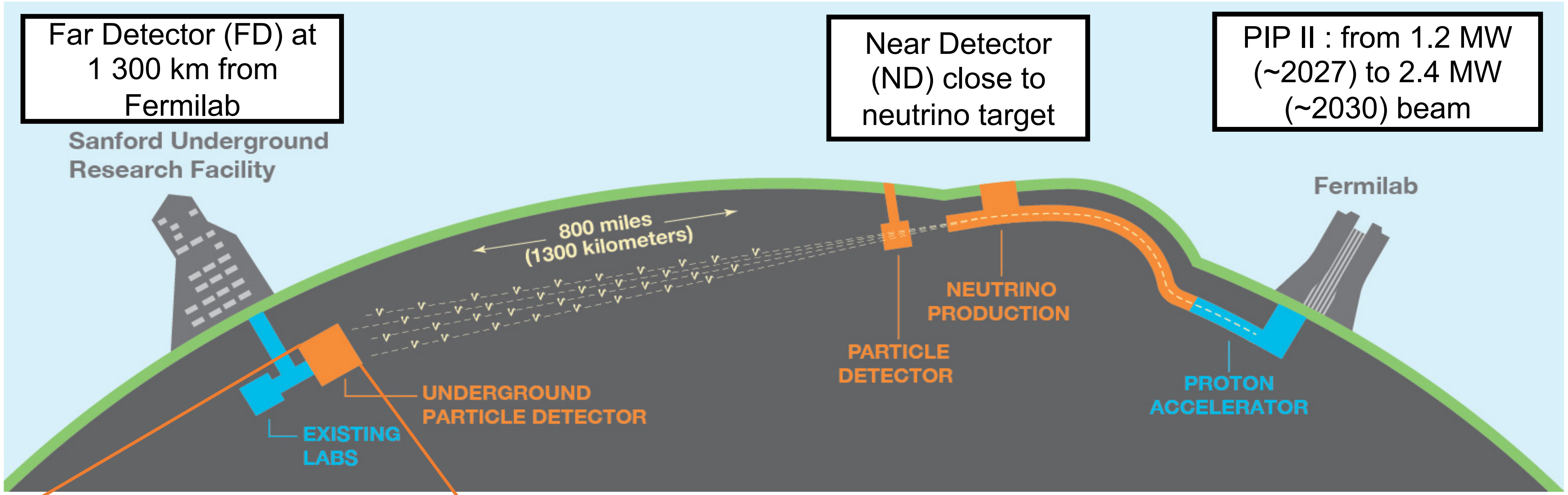
Joshua PINCHAULT

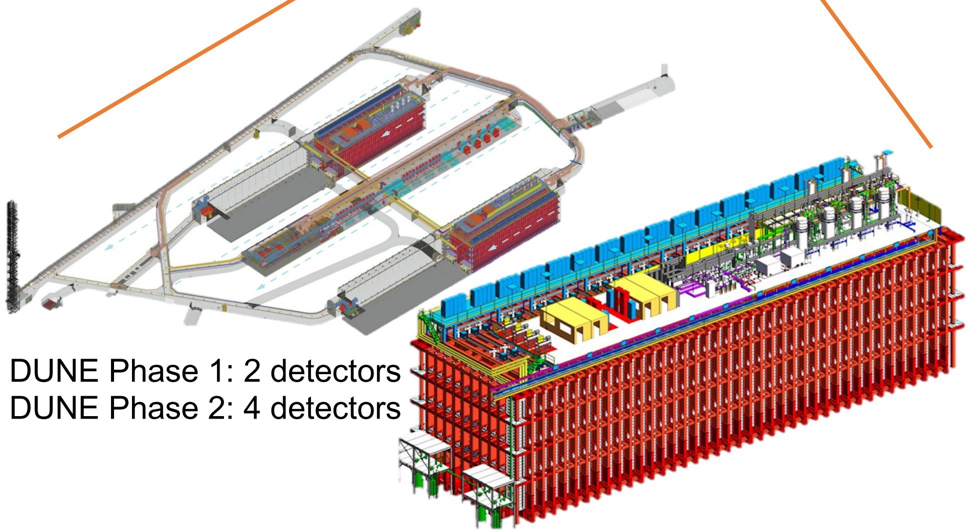
DUNE project overview



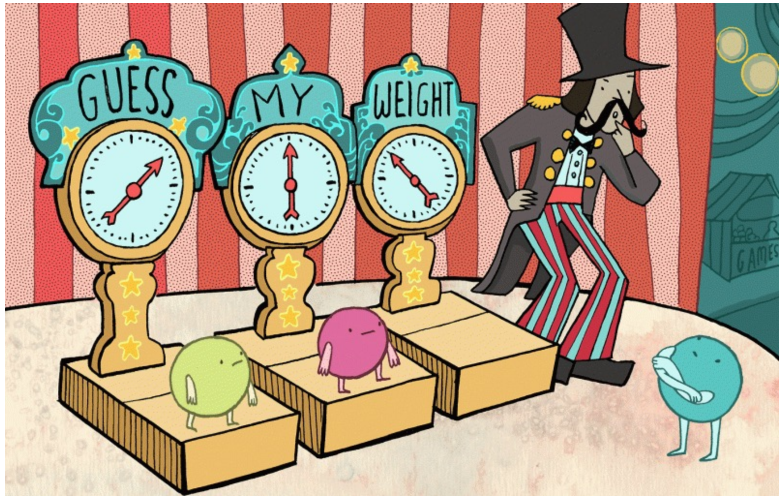
- New generation of long-baseline neutrinos experiment
- Precision measurements of neutrino oscillation parameters (δ_{CP} phase, mass ordering, θ_{23} octant etc.)
- Neutrino beam high power at Fermilab: from 1.2 MW at the beginning to 2.4 MW after upgrades

DUNE project overview

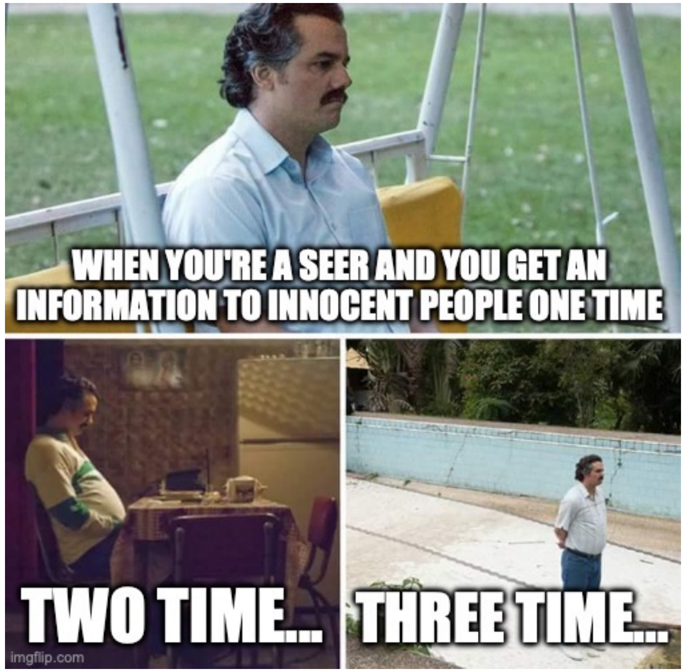




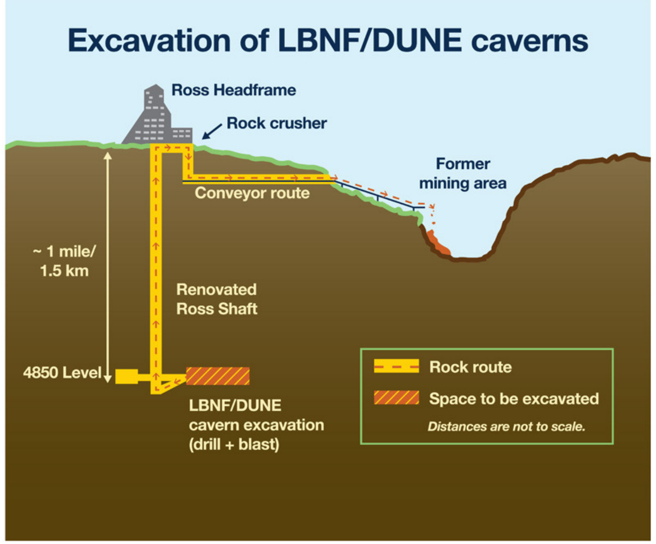
- DUNE Phase 1: 2 detectors
- DUNE Phase 2: 4 detectors

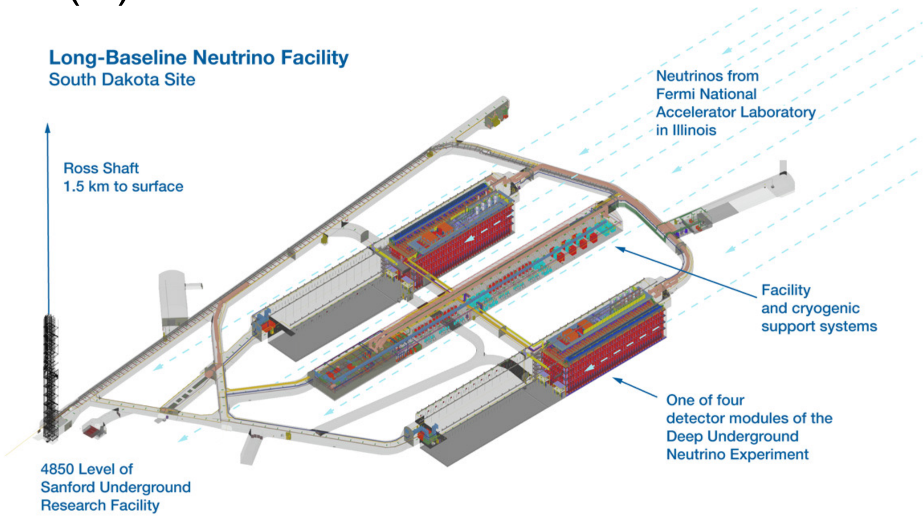


Neutrino detection challenge



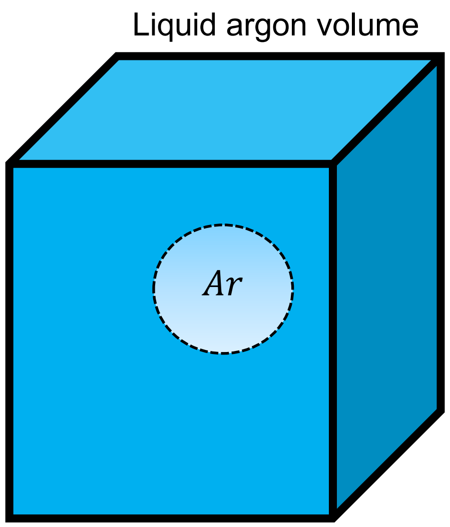
- Neutrino Cross section: $\sigma = 10^{-38} cm^2/nucleon$ → **Very small**
- Located at 1 480 m depth at SURF
- 4 Liquid Argon Time-Projection Chamber (LArTPCs) modules with different designs
- The design of 2 modules has been chosen
- TPC active volume : 12.0 m (W) x 58.2 m (L) x 14.0 m (H)





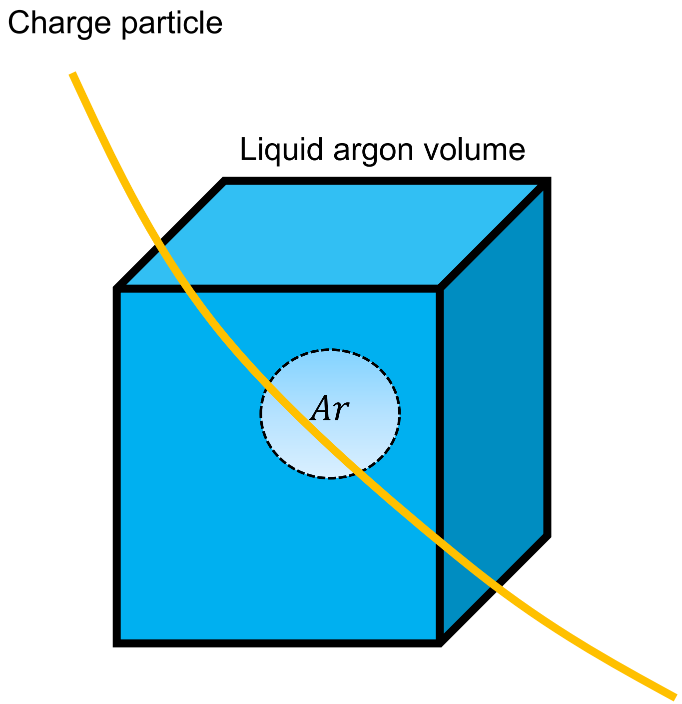
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

Principle of LArTPC detection



➢ Liquid argon is chemically inert and dense ($\rho = 1.39$)

Principle of LArTPC detection



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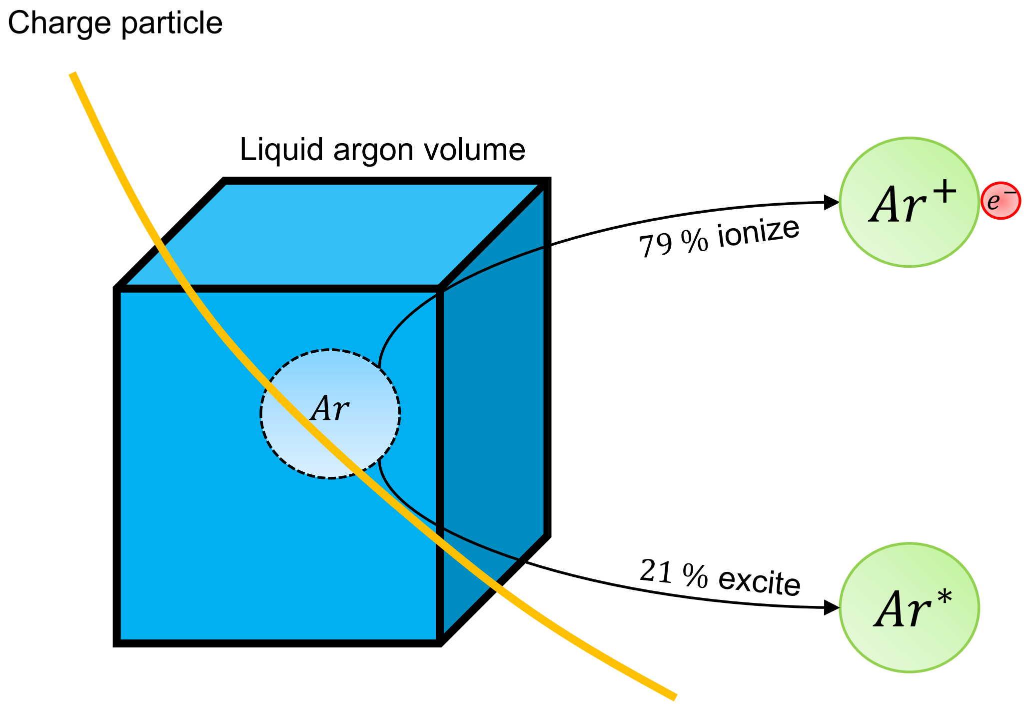
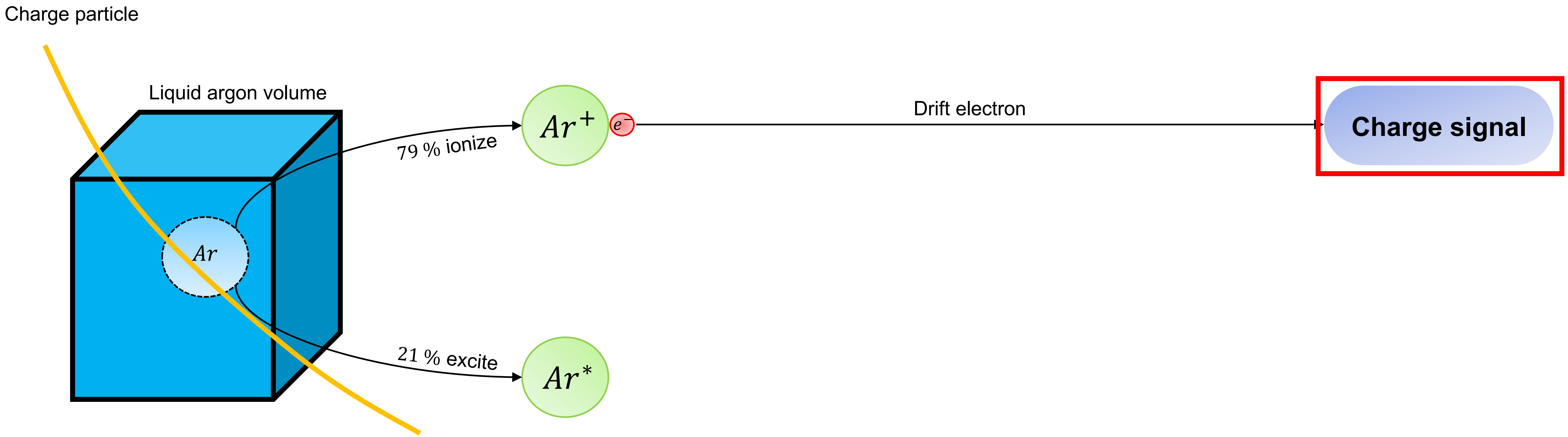


- Liquid argon is chemically inert and dense ($\rho = 1.39$)
- Charged particles ionize (79 %) and excite (21 %) argon atoms.

Principle of LArTPC detection



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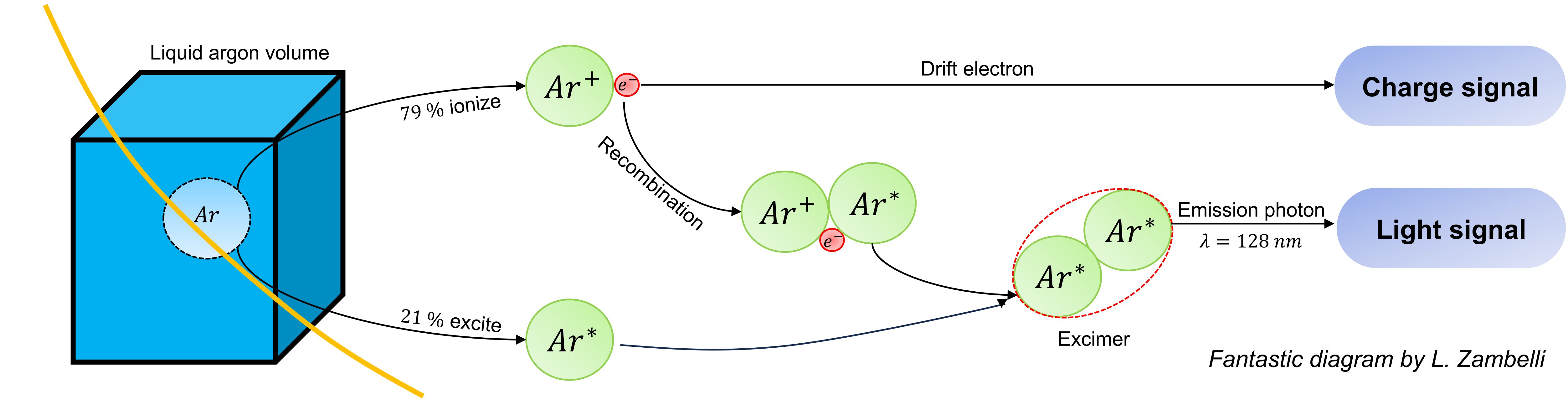
- Charged particles ionize (79 %) and excite (21 %) argon atoms.
- Electrons of ionization drift to the anodes thanks to an electric field

Principle of LArTPC detection



Fantastic diagram by L. Zambelli

- Liquid argon is chemically inert and dense ($\rho = 1.39$)
- Charged particles ionize (79 %) and excite (21 %) argon atoms.
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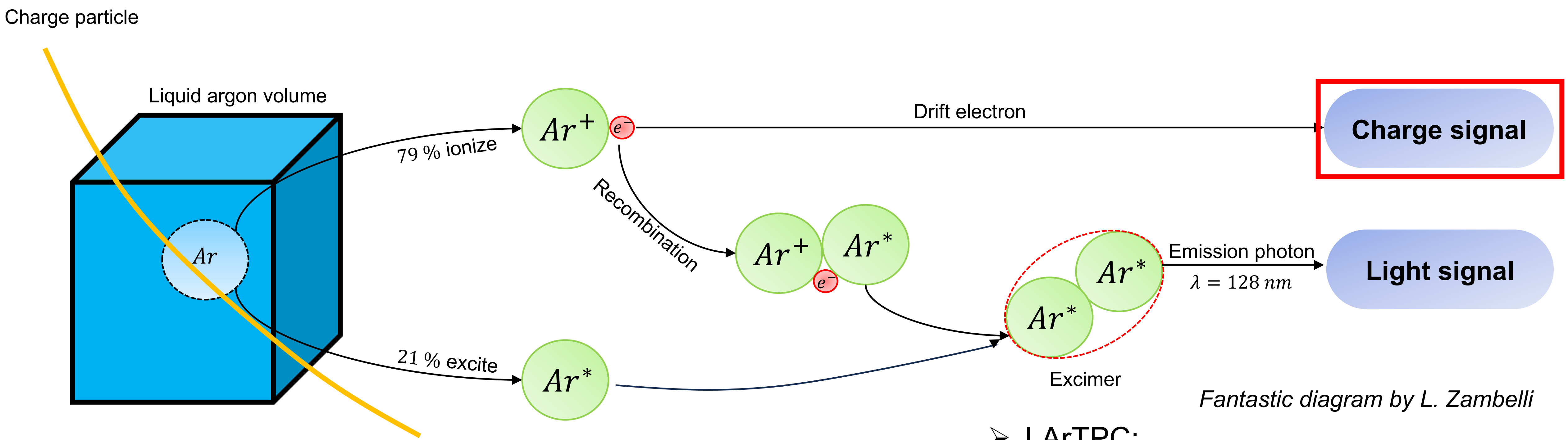
- Scintillation light coming from argon de-excitation ($\lambda = 128\,nm$)

Principle of LArTPC detection



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- LArTPC:
  - Segmented anode used to collect charge signal
  - $\tau_{drift} \gg \tau_{photon}$ → light signal trigger detection

Track and energy reconstruction

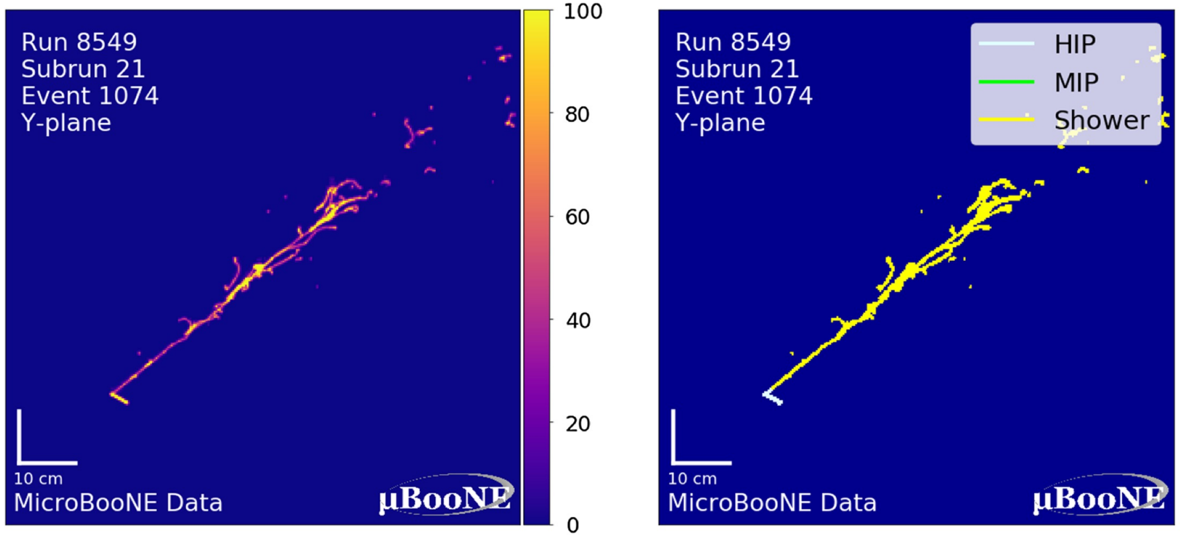
Why use TPC ?

- Very important to discriminate muon and electron
- At GeV-scale $(1 - 10\ \mathrm{GeV})$ neutrino interaction are dominated by quasi-elastic scattering processes
- Charged current interaction gives a charged lepton in the final state used to tag the neutrino flavour

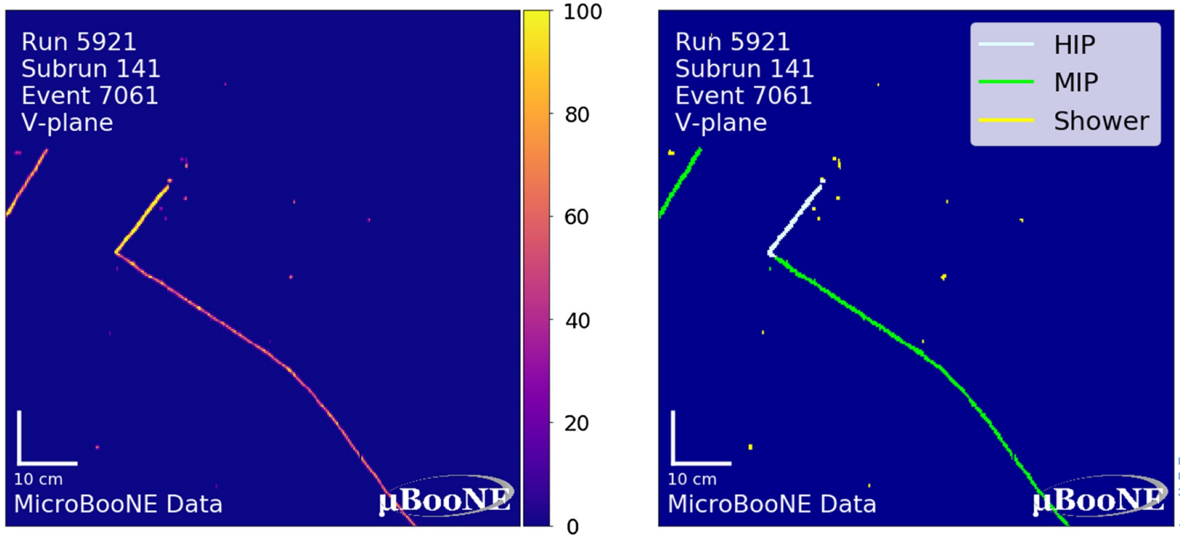
$$\begin{cases} \nu_l + \mathrm{n} \rightarrow \mathrm{l}^- + p \\ \bar{\nu_l} + \mathrm{p} \rightarrow \mathrm{l}^+ + n \end{cases}$$

- Separate ν_e / ν_μ events by track topology studies
- DUNE need to measure the ν_e / ν_μ rate

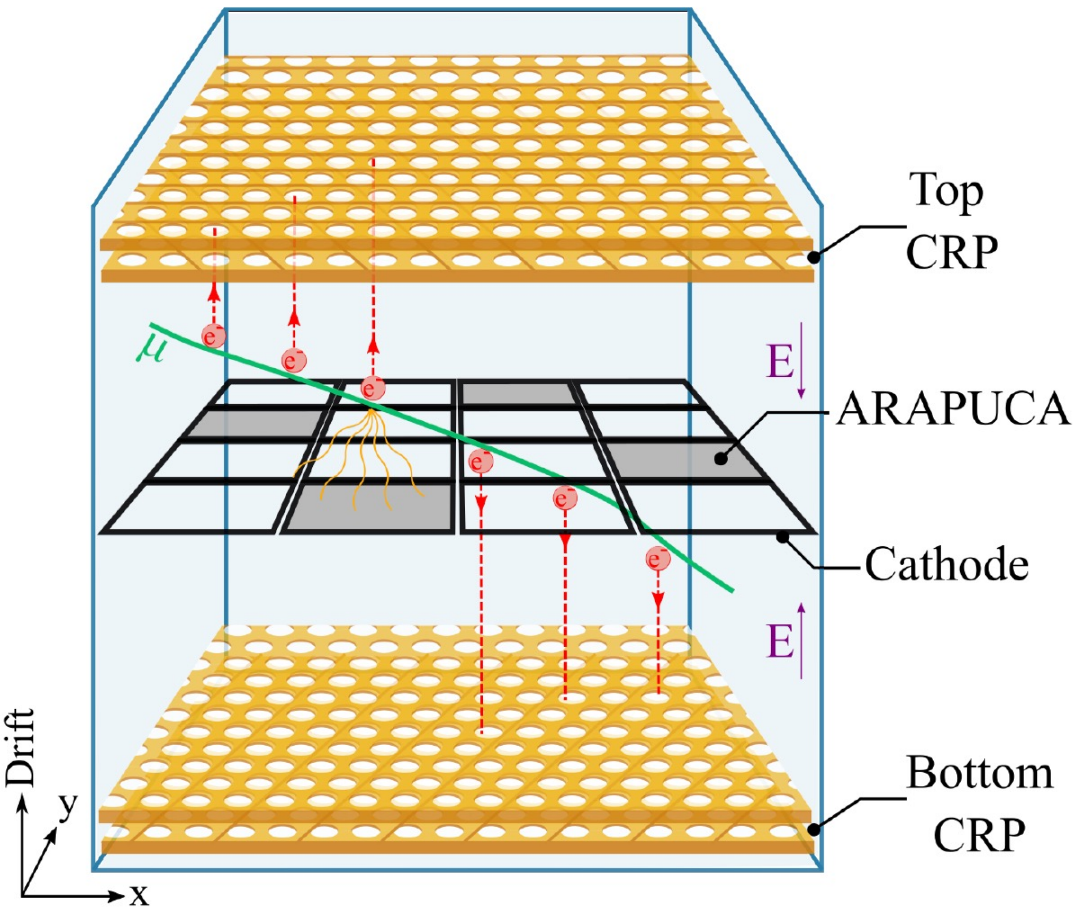
- e and p at the final state



- μ and p at the final state



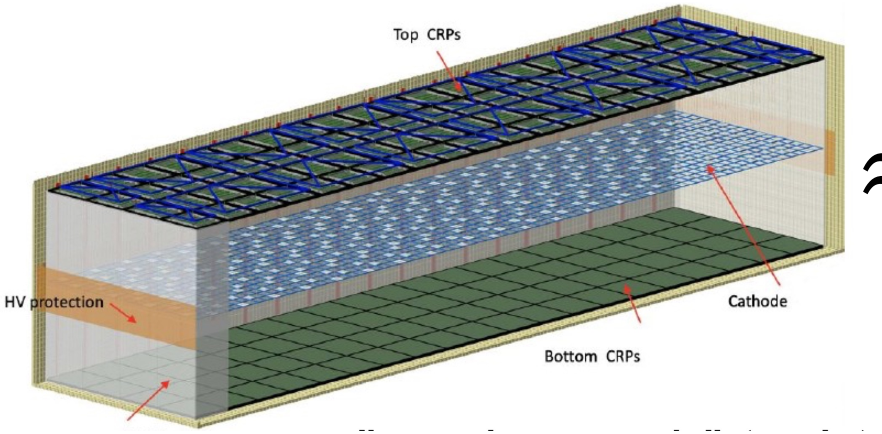
Vertical drift design



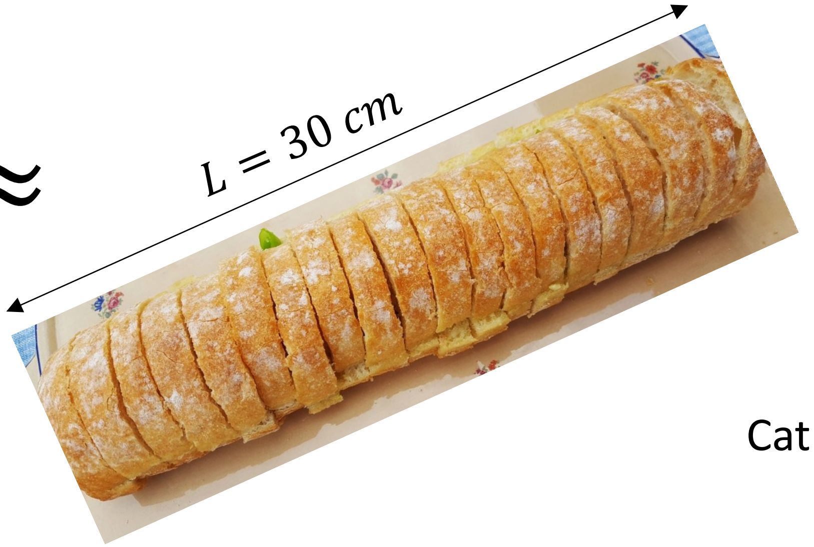
Fantastic diagram by L. Zambelli 2

- 2 volumes split by a cathode
  - Electric drift field: $|\vec{E}| = 0.5\ kV/cm$
- X-ARAPUCA for light detection on the cathode
- The new perforated anode technology
  - Anode module called Charge-Readout Planes (CRP)
  - Stack of 2 perforated Printed Circuit Board (PCB)
  - Etched copper electrode strips on each PCB face
  - A sub-centimeter spatial resolution
- DUNE Far detector at SURF:
  - TPC active volume 12.0 m (W) x 58.2 m (L) x 14.0 m (H)
  - 80 module CRPs for each top and bottom volume

"Préfou-like" approximation

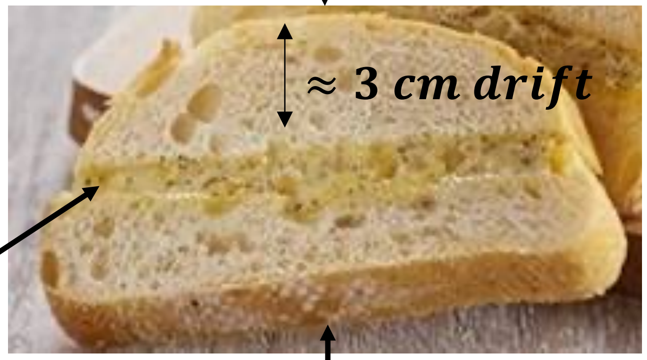


$\approx$



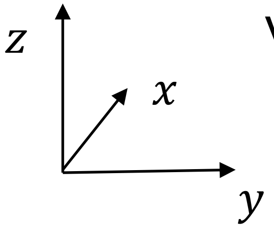
$+$

CRP top préfou like

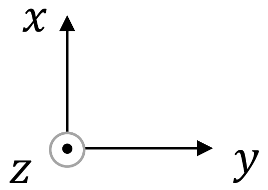


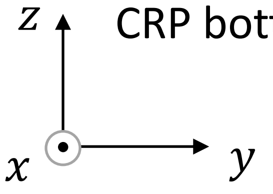
Cathode

CRP bottom préfou like



Vertical drift far detector





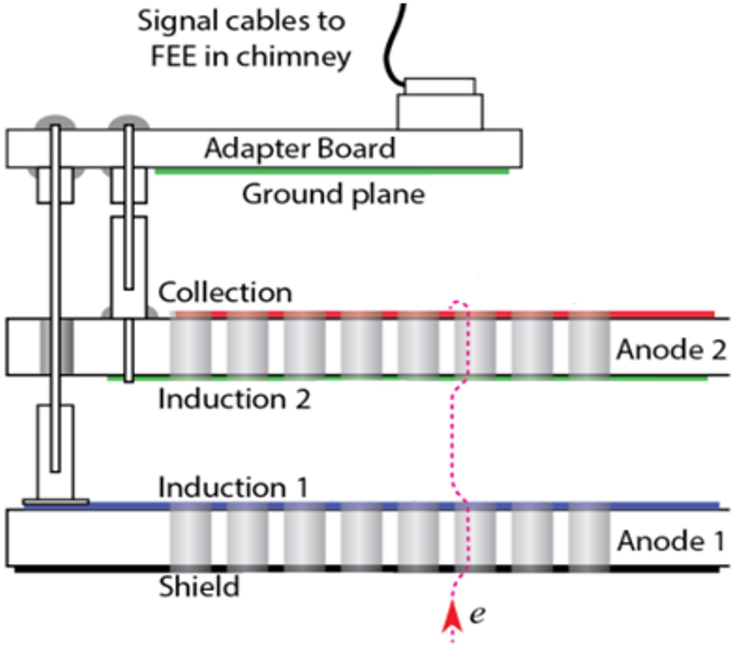
Préfou projection in the space

- Vertical drift volume $\approx 150 \times w_{préfou} \times 200 \times L_{préfou} \times 300 \times h_{préfou} = P \times V_{préfou}$

- With $P = 9 \times 10^6\ SI$; the "préfou-scale"

The perforated anode technology

- Shield + 3 different charge readout layers:
  - Induction 1 – strip orientation -30° to beam axis
  - Induction 2 – strip orientation +30° to beam axis
  - Collection – strip orientation 90° to beam axisc

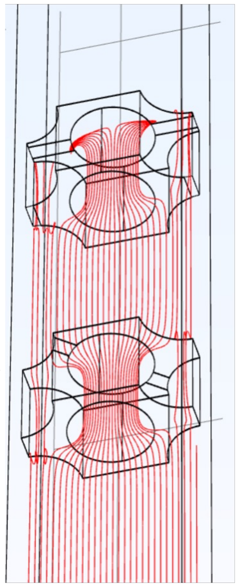


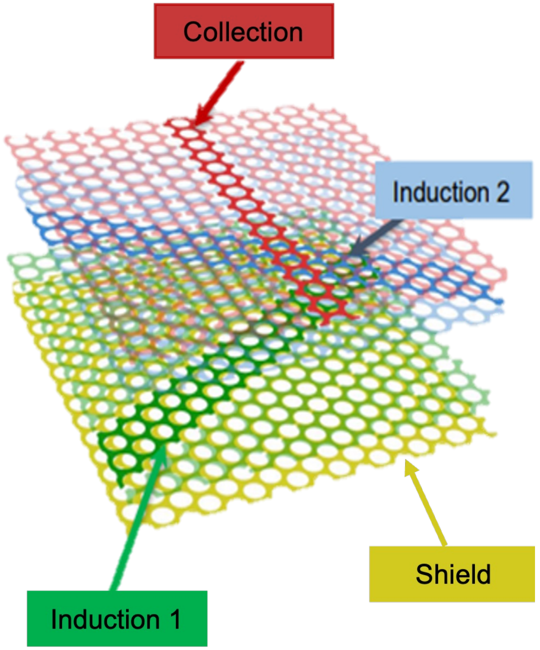
Collection : +1000V

Induction2 : 0V

Induction1 : -500V

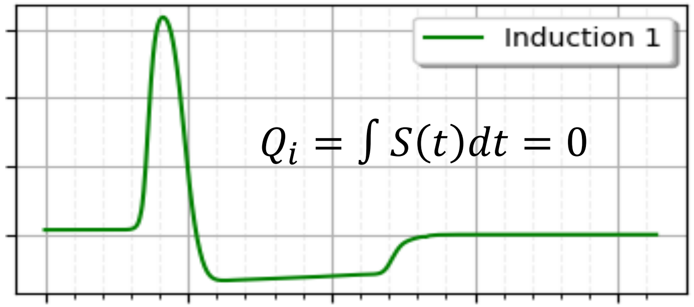
Shield : -1500V

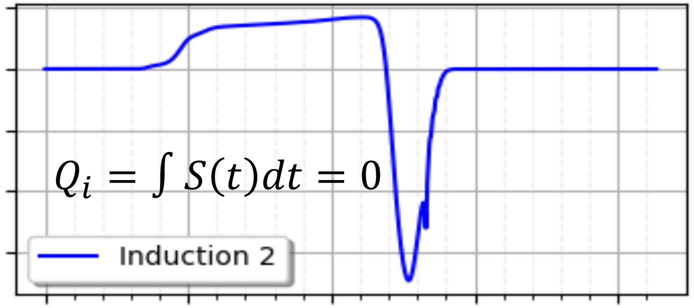


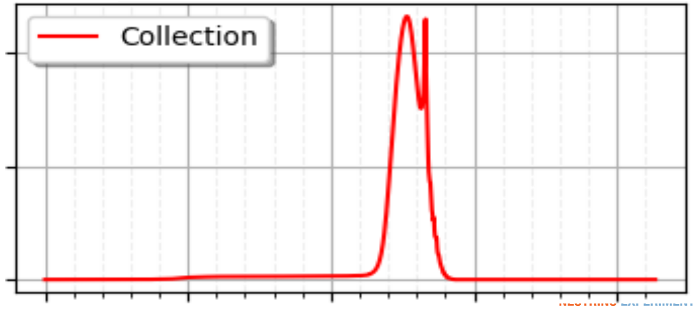


- **Induction views:** Bipolar signals
- **Collection view:** Unipolar signal

$$Q_{coll} = \int S(t)dt = N_e \times e$$

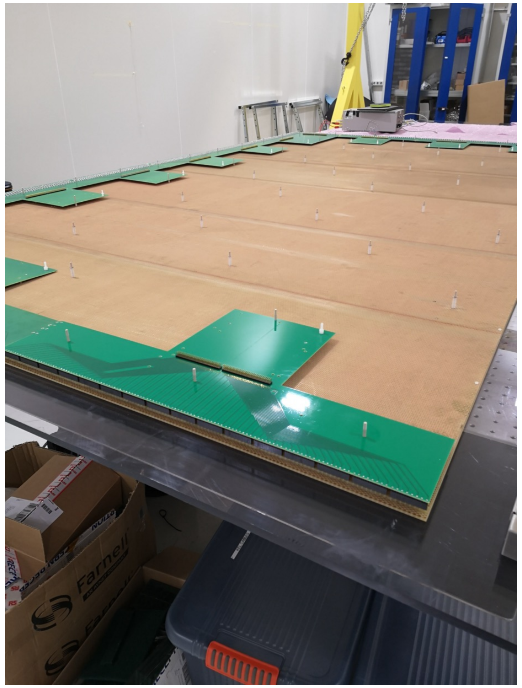






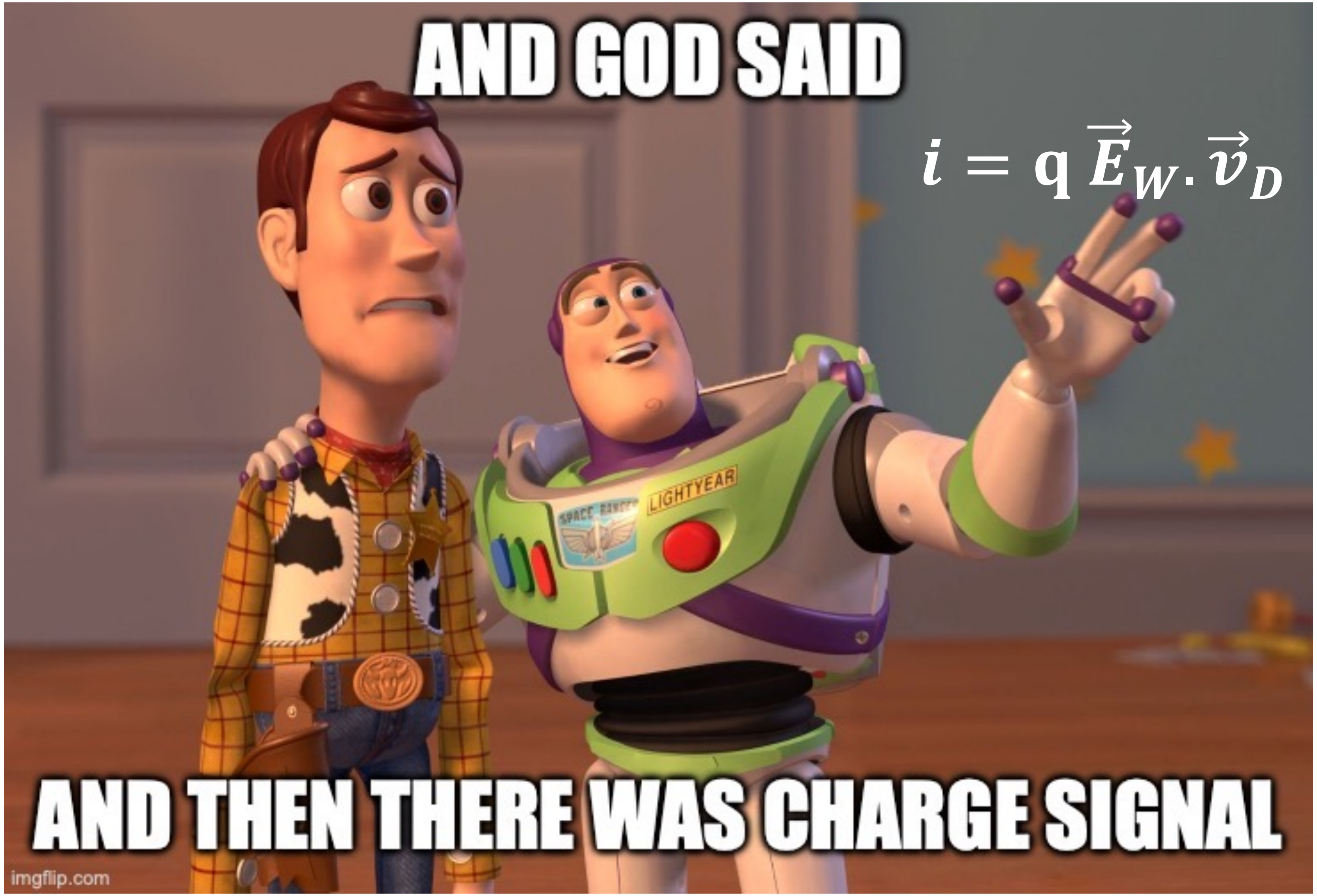
Study of electric signal formation on CRPs

- **Problematic:**
  - Use of new anode technology
  - Important to know the deposited energy in the detector
  - Tracks reconstruction from collected charge
  - Induced signals depend on energy, position, track angle etc.
  - **Understanding the waveforms based on these dependencies**



CRP assembly at CERN

Modeling signal formation



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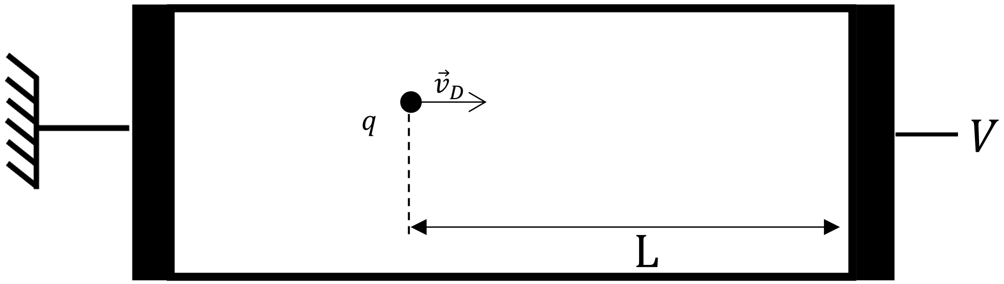
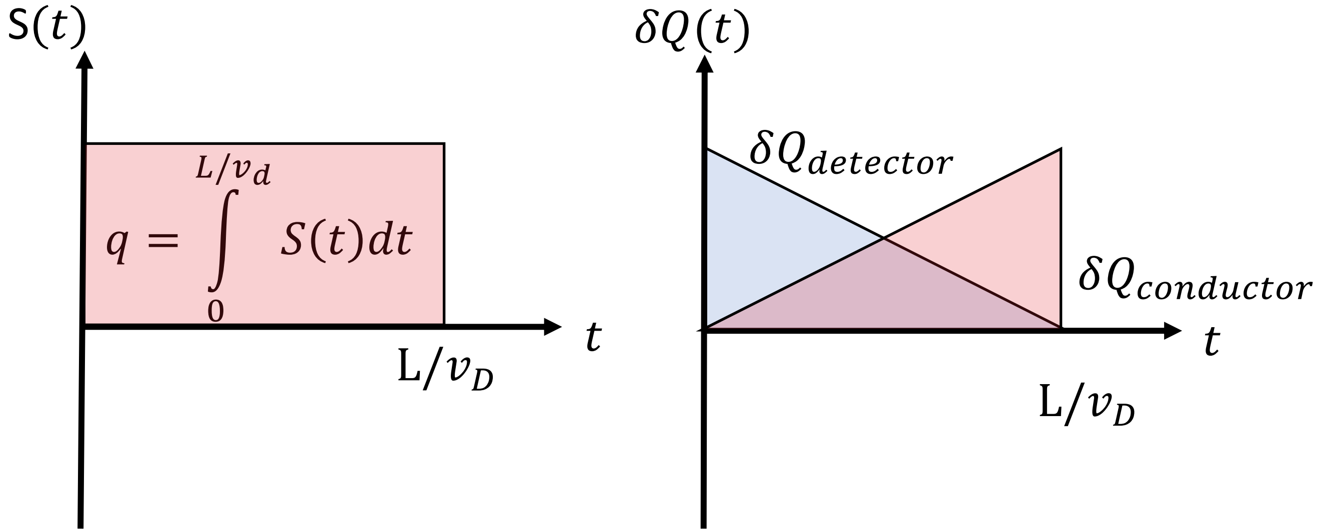
Modeling signal formation

- The simplest case of charge signal generation



- Mirror effect to the partial charge induced δQ between the detector and the conductor



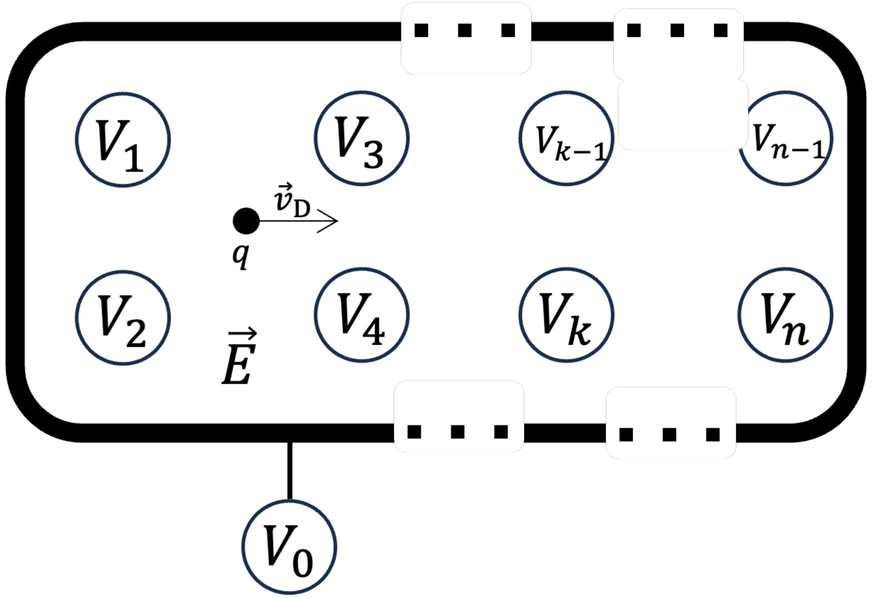
- Partial charge conservation $\delta Q_{conductor} + \delta Q_{detector} = q$

- The charge q is neutralized by its « mirror charge » q when it is near the surface of another conductor.

- **<u>The instantaneous current is induced by charge motion only</u>**

Modeling signal formation

➢ General case – **Shockley-Ramo theorem**

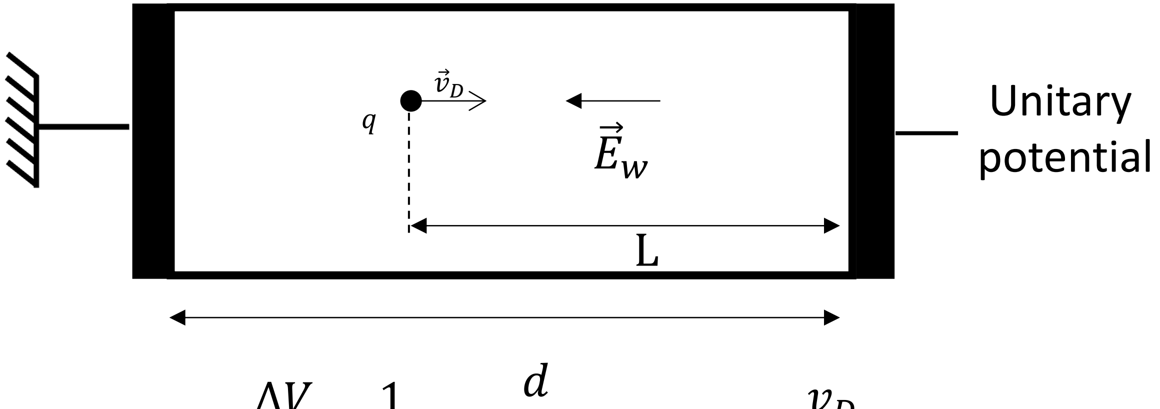


- **If electrodes get a fixed potential and the velocity of the charge particle is know, then the induced current on any electrode k is given by:**

$$i_k(t) = q\,\vec{E}_w\,\vec{v}_D$$

➢ Weighting Field $\vec{E}_w$ is virtual field that would exist in the case where the charge is removed, the reading strip equal 1 V and all other fixed to 0 V.

$\vec{E}_w$: geometry factor
$v_D = \mu(\vec{E},T)\,\vec{E}$: physics factor

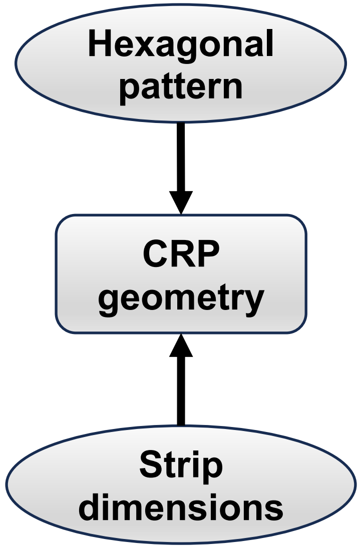


$$E_w = \frac{\Delta V}{d} = \frac{1}{d} \qquad i(t) = q \times \frac{v_D}{d} = cste$$

→ **Need simulation for complex geometry**

Induced signal simulation

- Conception of a simulation on Python



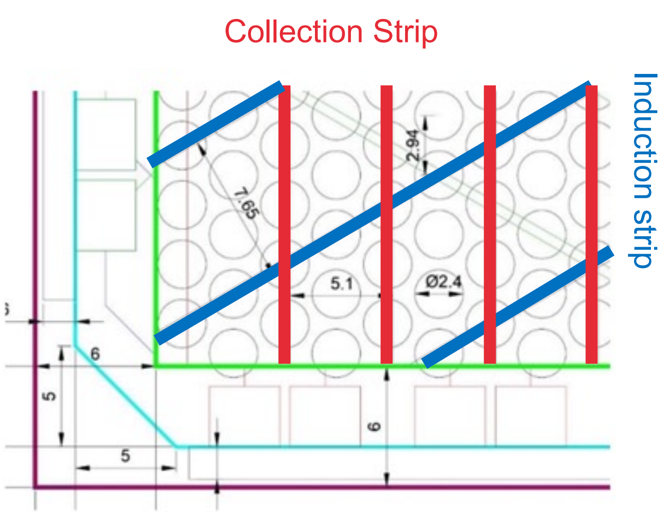
Induced signal simulation

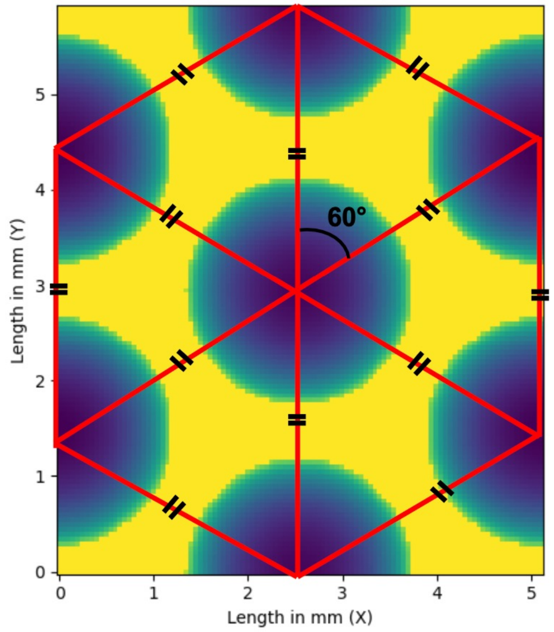
- Conception of a simulation on Python

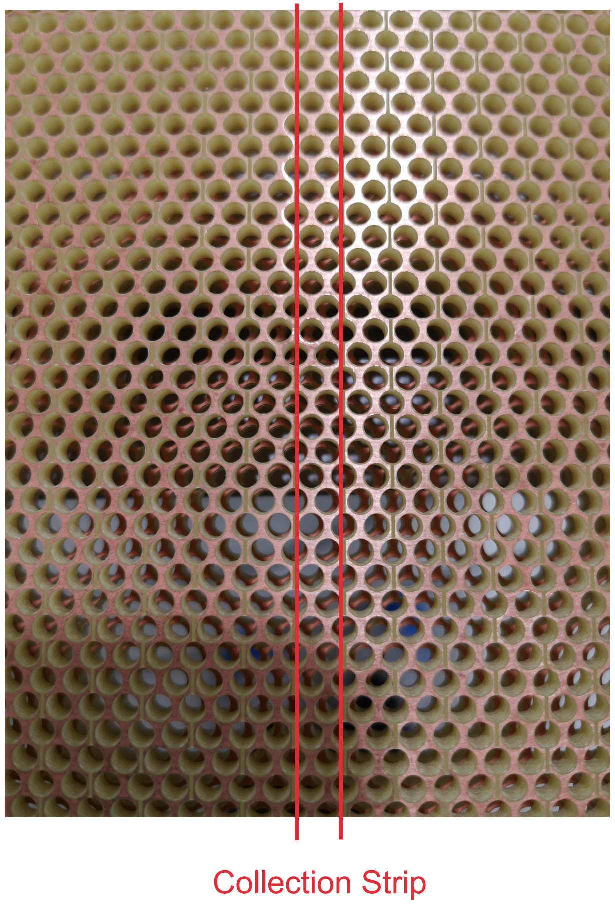
Hexagonal pattern → CRP geometry ← Strip dimensions

- Implement CRP geometry hexagonal pattern, strips, 2 Printed Circuit Board , 4 equipotential planes
  - **Shield:** -1 500 V
  - **Induction 1:** -500 V
  - **Induction 2:** 0 V
  - **Collection:** 1 000 V

- Photography of Printed Circuit Board at CERN





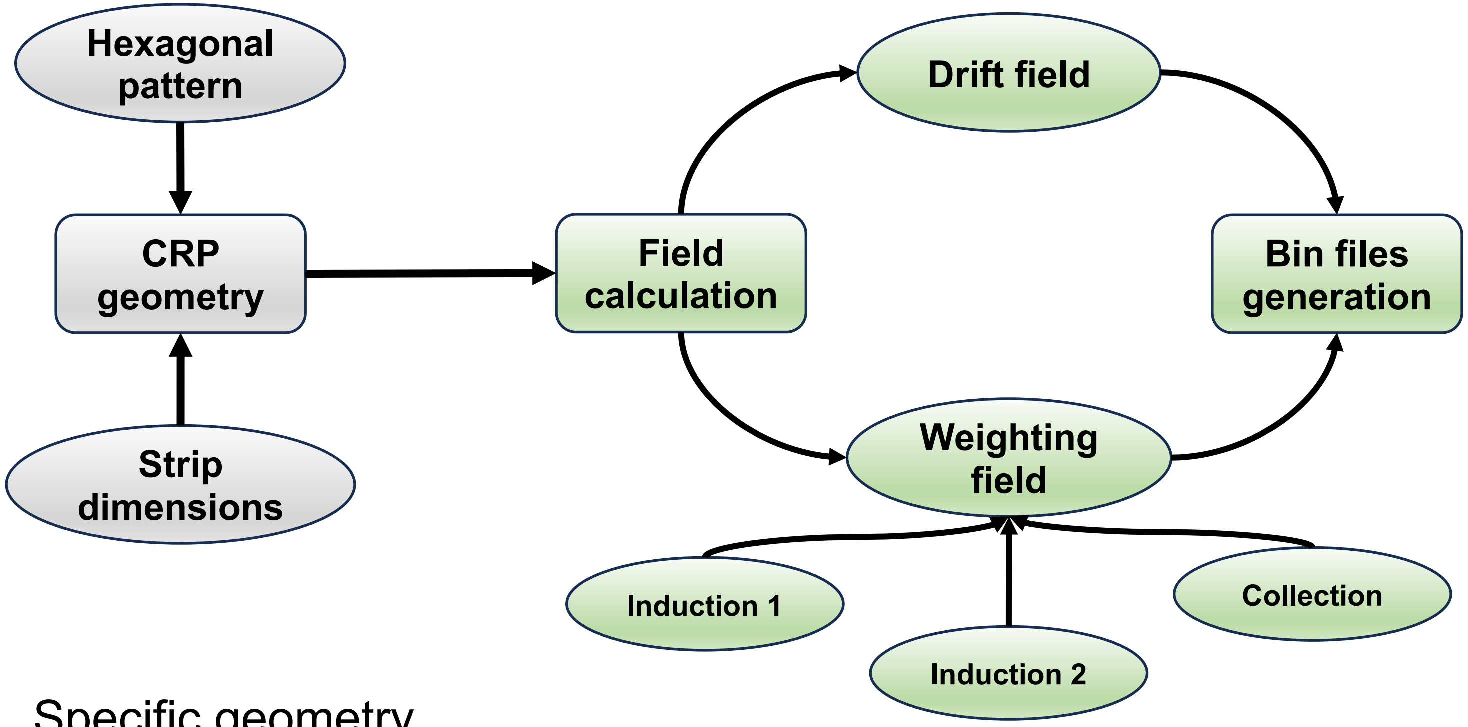


- Collection strip **is larger than** induction strips

(Collection strip is like a discount supermarket préfou and induction strip like real Vendéen préfou)

Induced signal simulation

- Conception of a simulation on Python



1. Specific geometry implementation

- Induced signal on the readout strips:

$$i(t) = q\,\overrightarrow{E_W}.\overrightarrow{v_D}$$

- Weighting field E_w
- $v_D \equiv v_d(|\overrightarrow{E_D}|, T)$

- Solving Laplace's equation in 3D:

$$\Delta\phi(x, y, z) = 0$$

- 3D Finite difference methods (FMD):

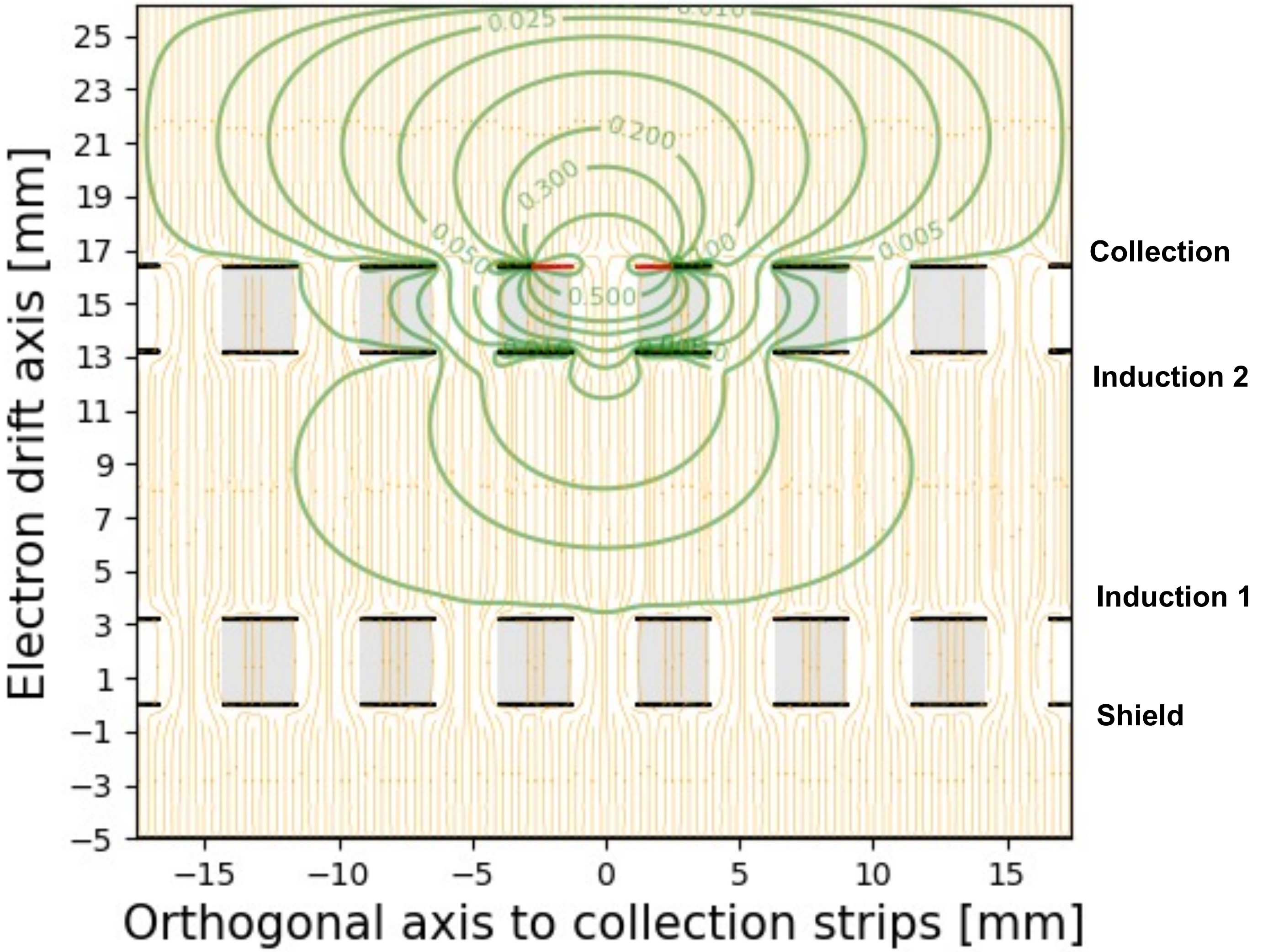
$$\phi_{i,j,k} = \frac{\phi_{i\pm1,j,k} + \phi_{i,j\pm1,k} + \phi_{i,j,k\pm1}}{6}$$

- Iterative method, step by step

Field result

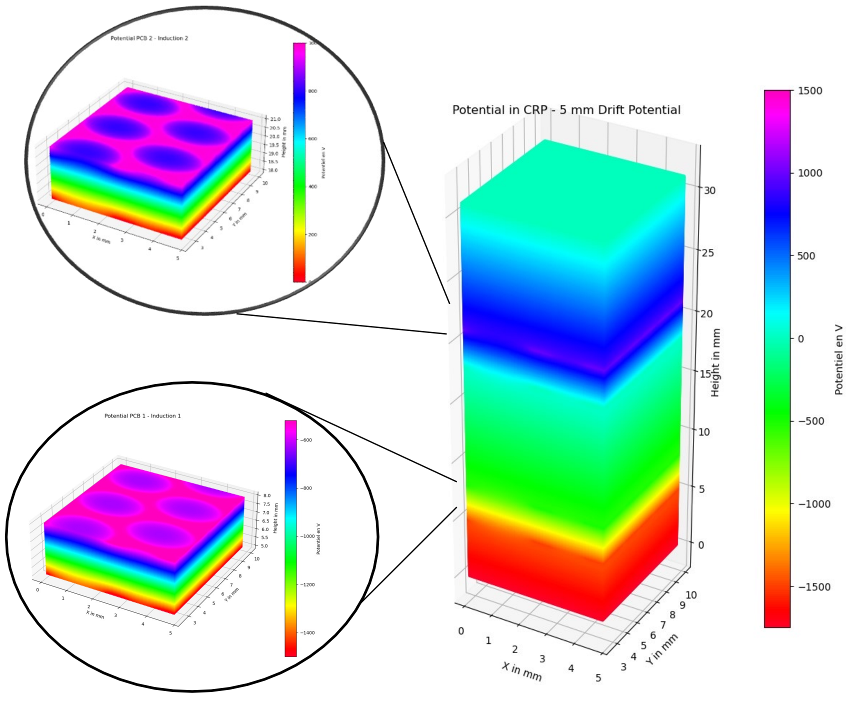
- Red equipotential equal to unitary potential
- All other black equipotential fixed to 0 V.

2D projection of drift field lines and weighting equipotential



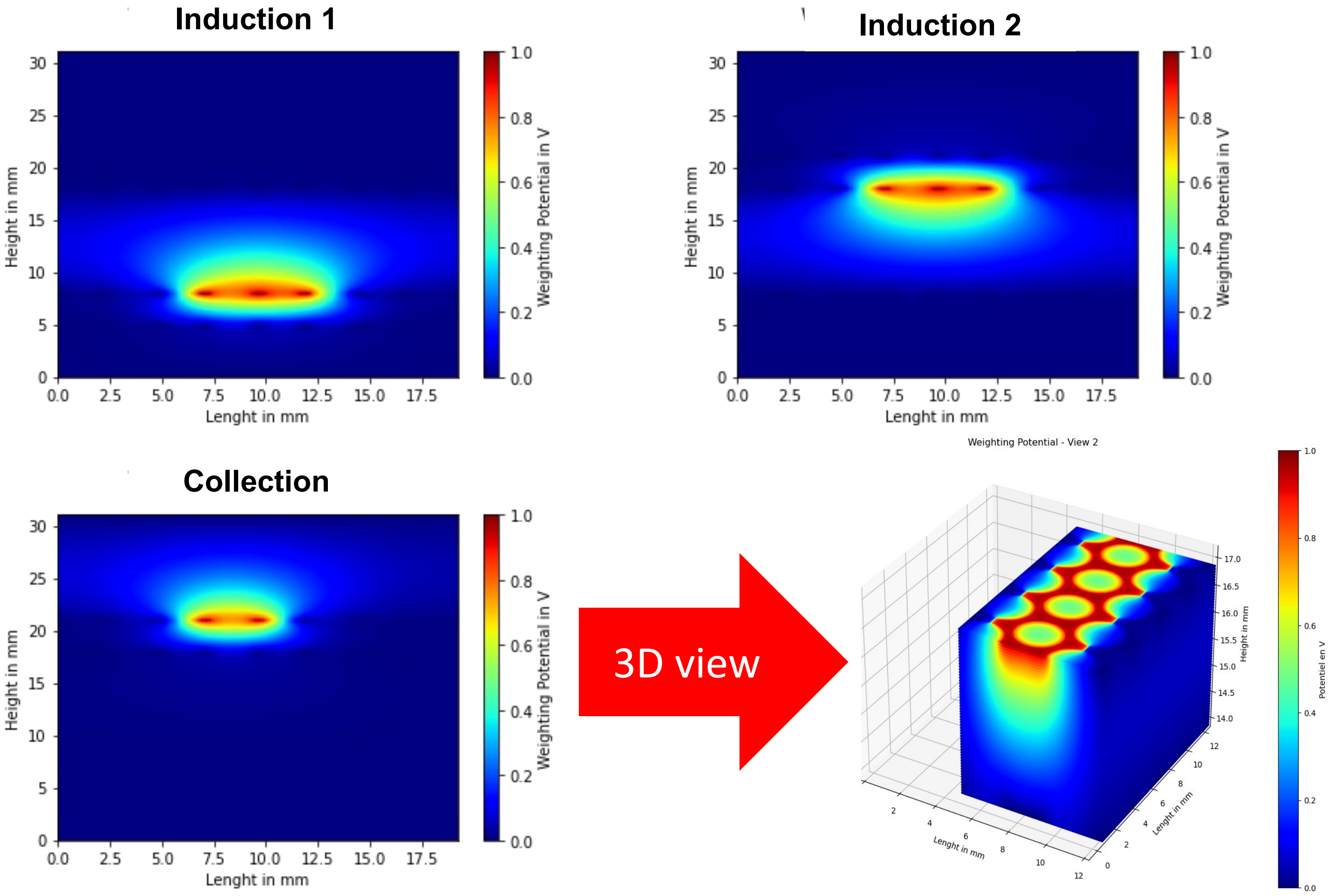
Fields visualization

- **Drift Potential**



- Distribution of the drift potential inside the CRP
- Bias configuration:
  (-1 500 V; -500 V; 0 V, 1 000 V)

- **Weighting Potential**



- Not directly equal to 0 when moving far from the readout strip.
- Lead to a induced signal in the nearby strips

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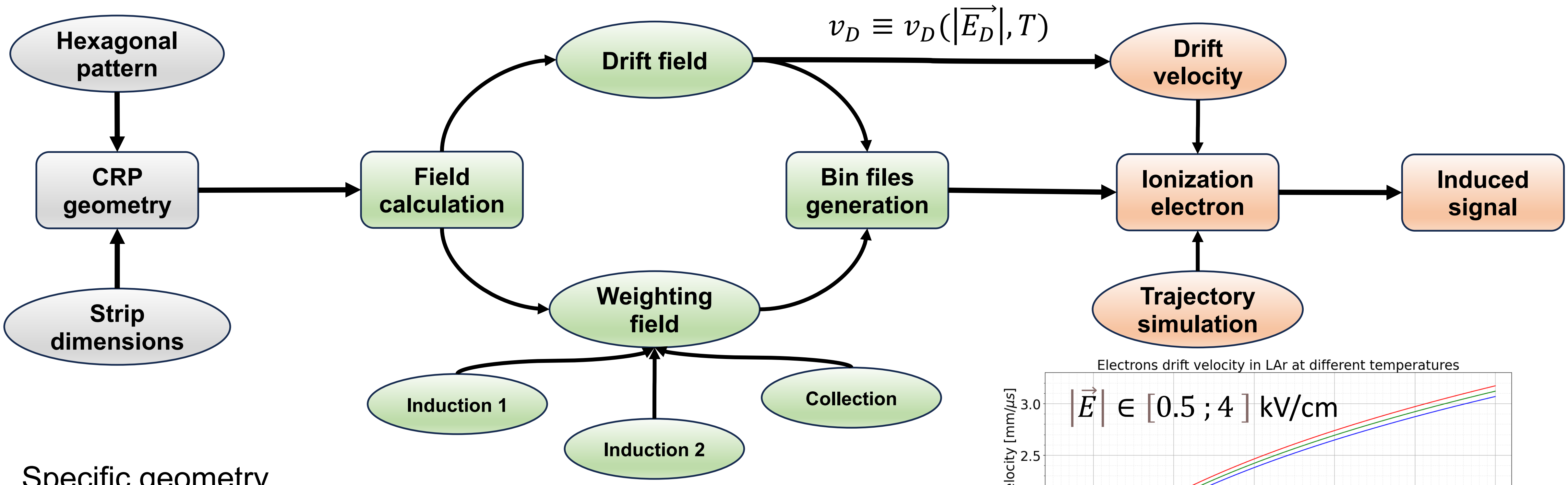
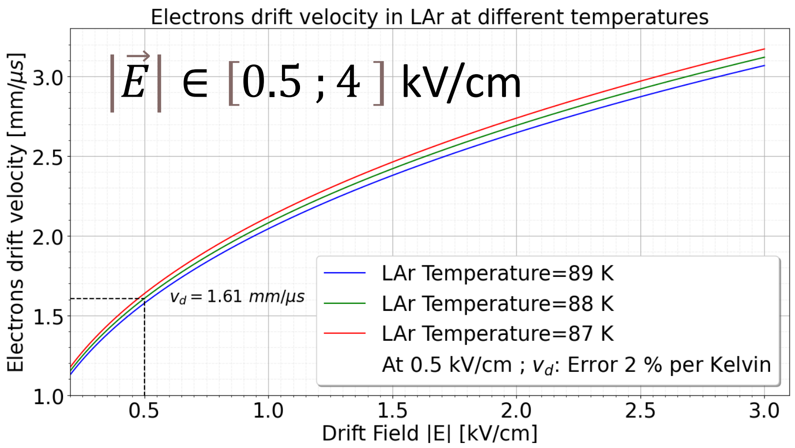
Induced signal simulation

- Numerical simulation **conception** on Python



1. Specific geometry implementation

2. Field generation with CRP geometry



W. Walkowiak. Drift velocity of free electrons in liquid argon 1999

Ionization electron generation

- Thermal electron
  - Trajectory follow drift field lines

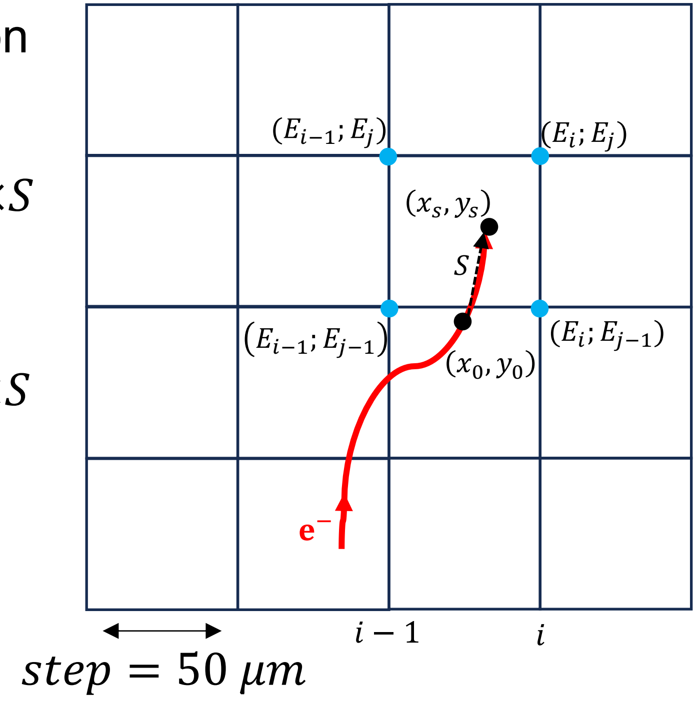
- The electron trajectory is perfectly defined

- Runge Kunta like simulation

$$x_{i+1} = x_i + \frac{E_x^{interp}(x_i, y_i)}{|E(x_i, y_i)|} \times S$$

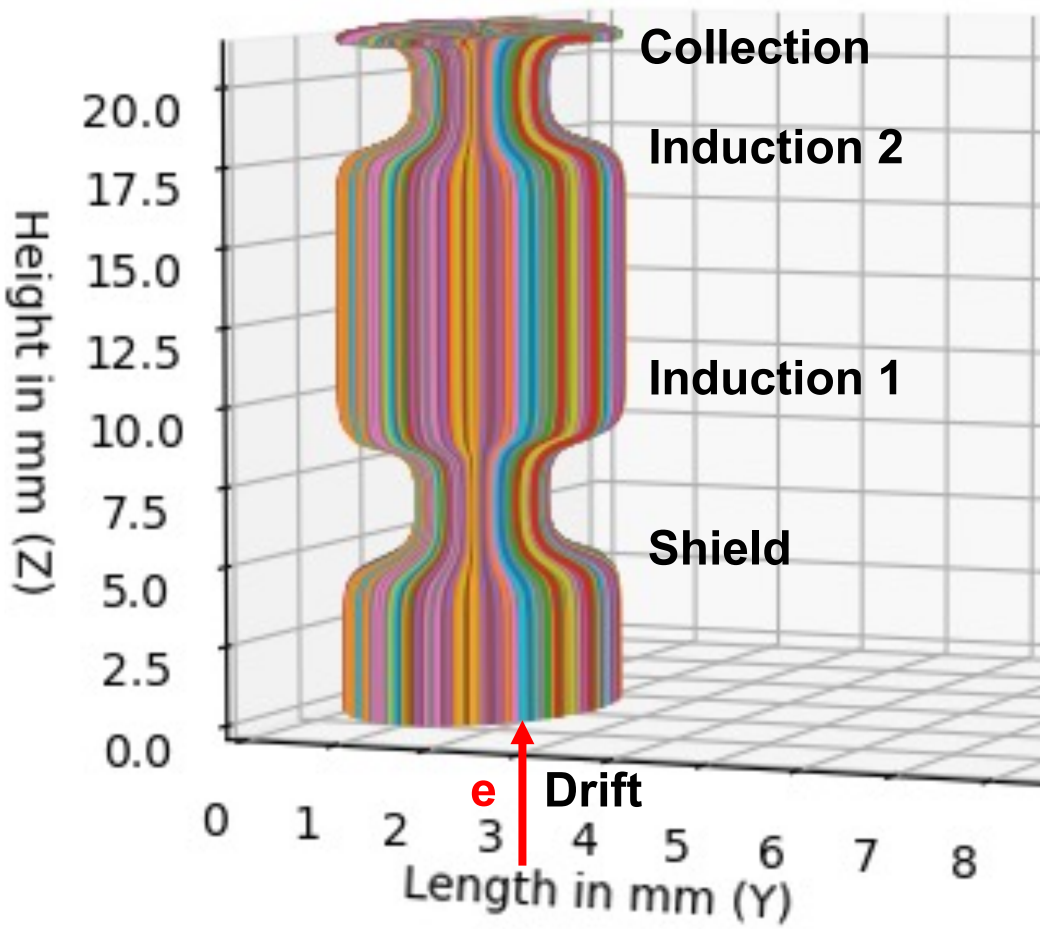
$$y_{i+1} = y_i + \frac{E_y^{interp}(x_i, y_i)}{|E(x_i, y_i)|} \times S$$

- Drift simulation 5 mm



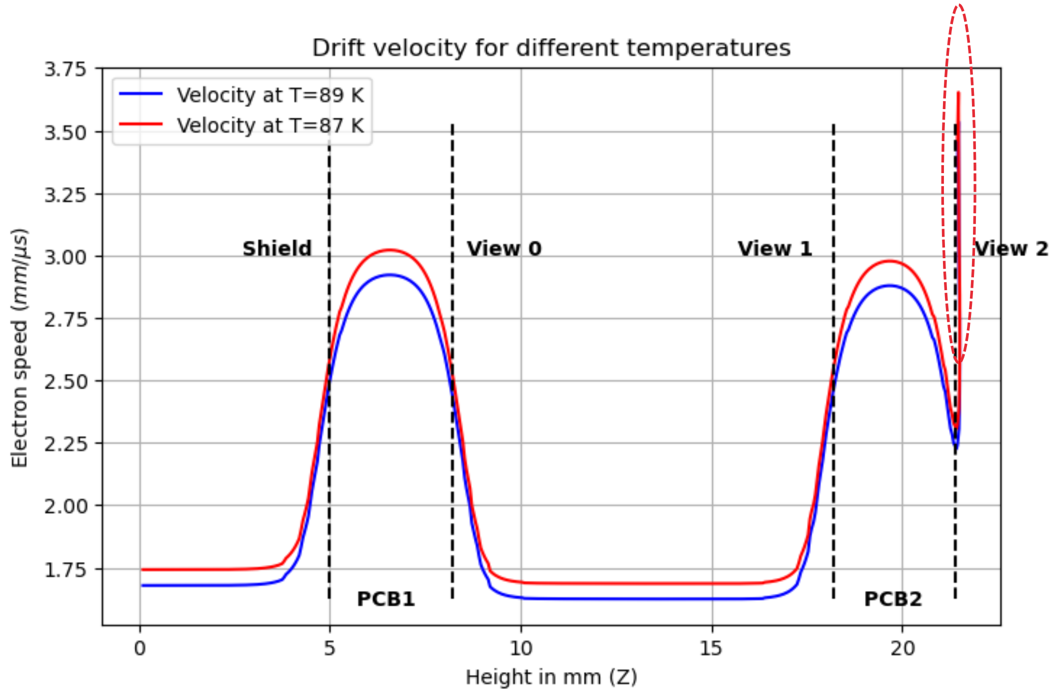
- Grid of the mesh used for the field calculation

Electron trajectories passing through a CRP's hole



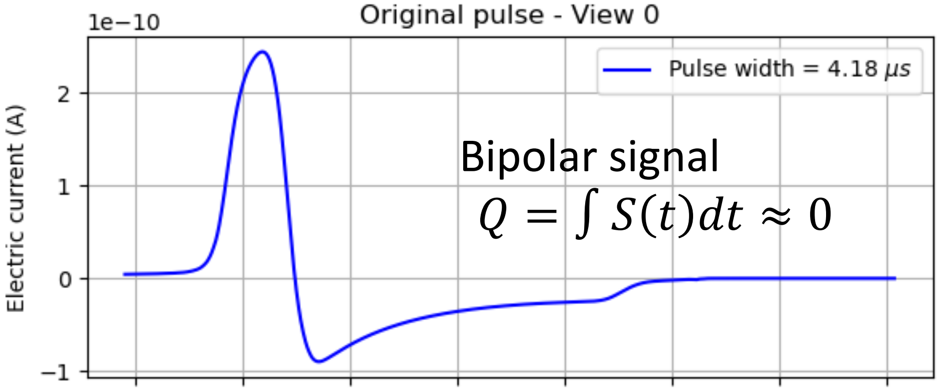
My simulation results

- Drift velocity evolution for an electron inside CRP

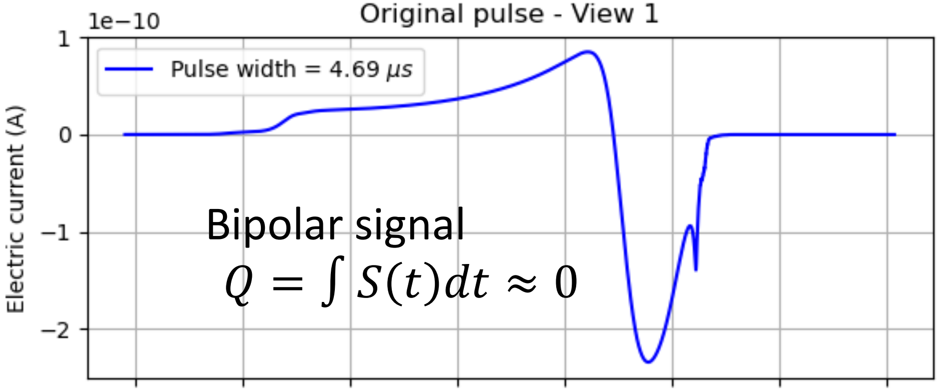


- Border effect near to the collection electrode
- The field takes $\propto 1/r^2$ dependancy which will induce a high frequency signal
- Electronic response will smooth the readout induced current

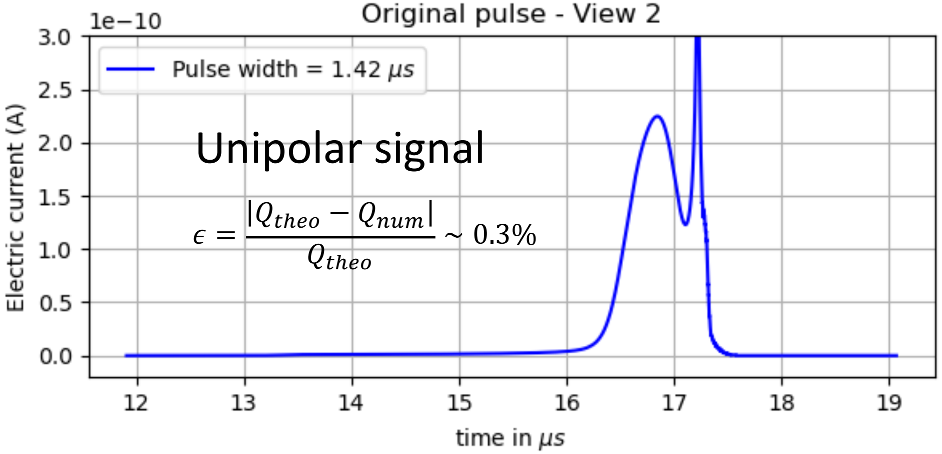
Induction 1



Induction 2



Collection



Does my simulation reflect reality?

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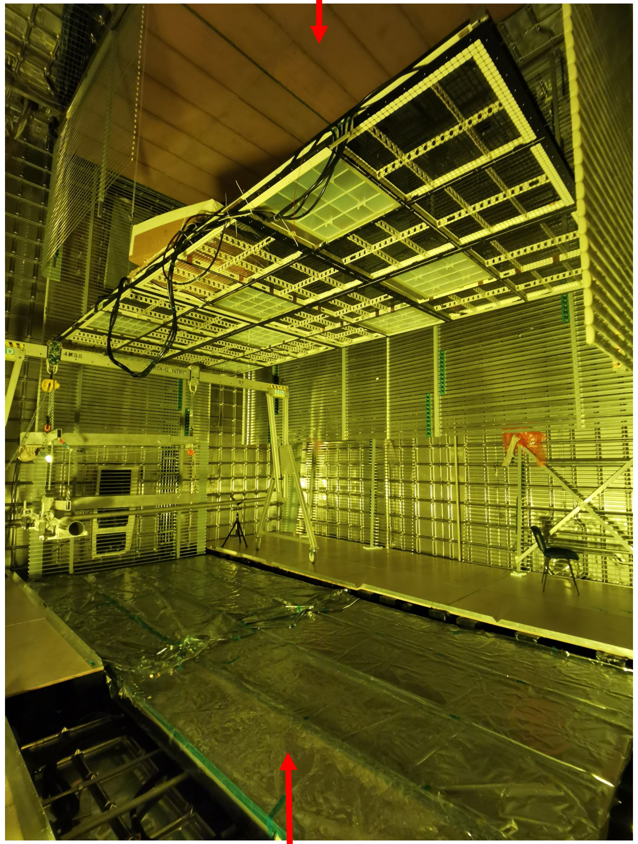
Prototype at CERN

➢ **ProtoDUNE Vertical Drift (VD):**

- A prototype built at CERN to test the Vertical Drift technology at large scale.
- Data-taking should start early 2024
- TPC size: 3.0 m (W) × 6.8 m (L) × 6.8 m (H) divided in two vertical drift volumes
- Top CRPs have accessible electronics and bottom CRPs have embedded cold electronics

2 Top CRP modules



2 Bottom CRP modules

➢ Vertical drift design at CERN
➢ Cryostat inside

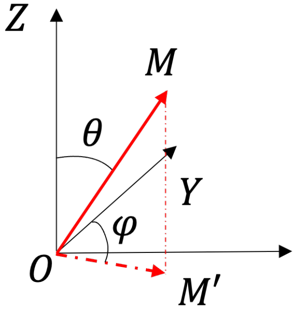
➢ **Coldbox:**
- Liquid argon chamber for testing CRPs with cosmic rays at CERN
- 20 cm drift

Data-taking in 2022/2023

➢ Use coldbox's data to compare with simulation

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

Data extraction

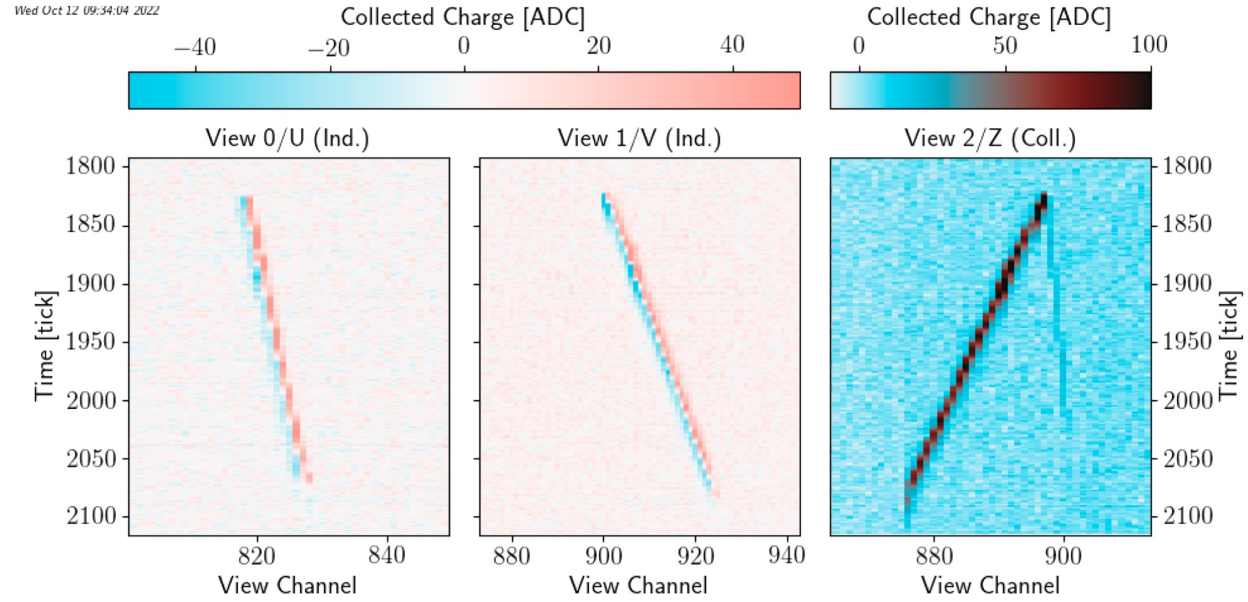


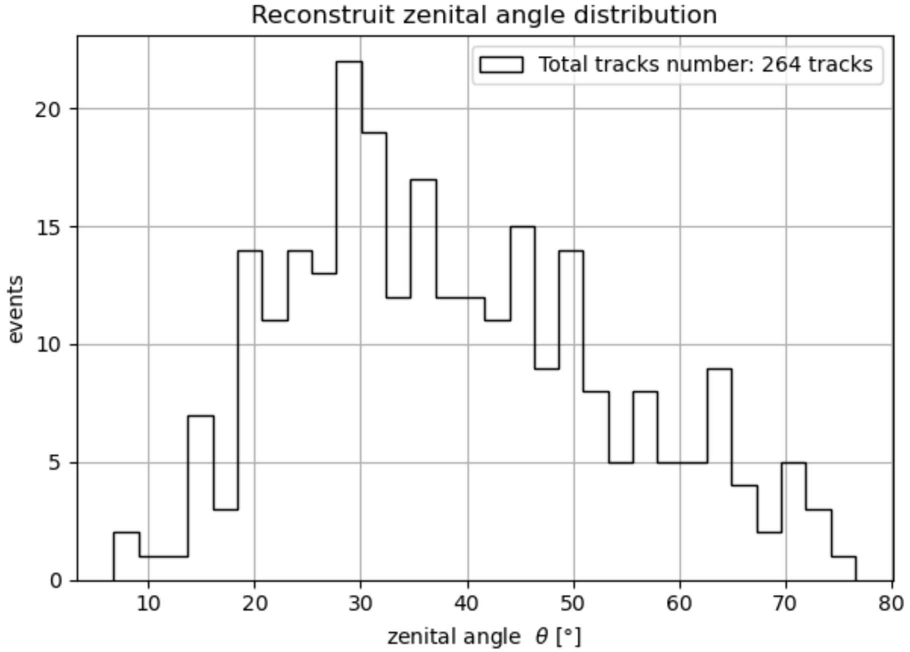
➢ **Coldbox's data cuts**

- Tracks with reconstructed angle $\theta > 60°$
- φ in the cone with $45°$ from the strip readout
- Track lengths $> 20\ cm$

➢ **Event Display**

- An example of cosmic ray track from the Coldbox





➢ Data reconstruction with LARDON (fantastic software developped by Laura Zambelli)

➢ Bipolar signals on induction view

➢ Muon events

➢ Need horizontal track to compare with simulation

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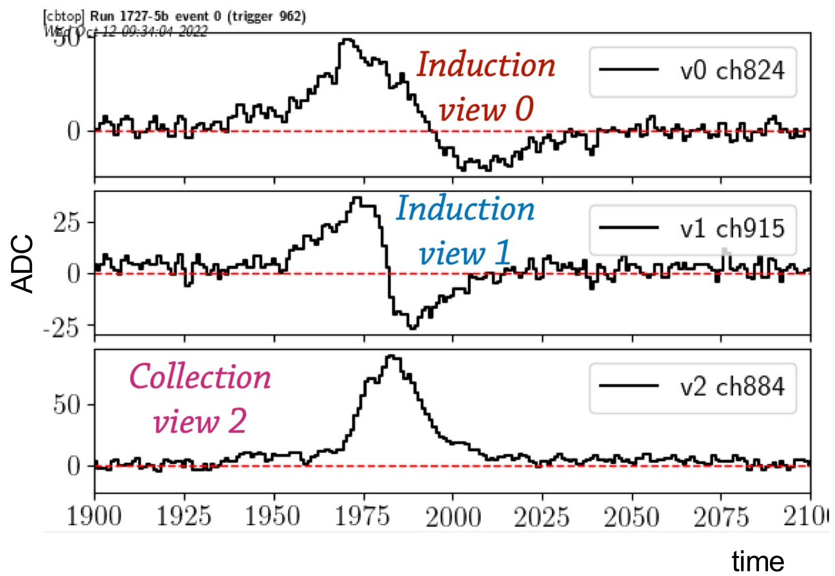
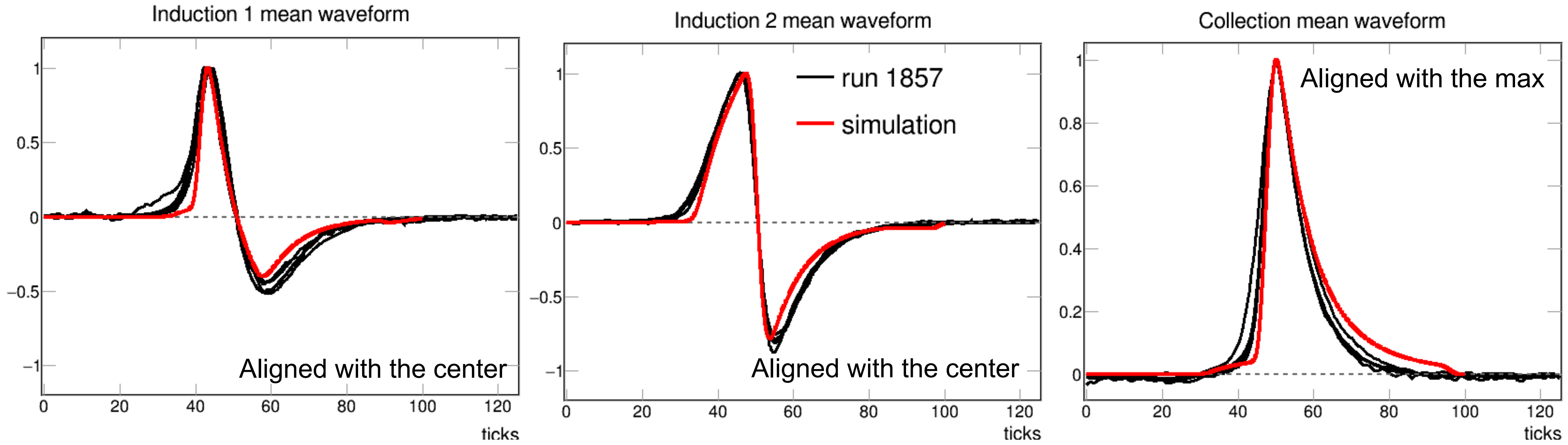
Comparison data VS simulation



- **Mean waveform**
  - Signals sommation on each readout channel
    → To reduce the incoherent noice
  - Mean signal creation for each track



→ **Simulated waveforms are good agreement with data**

- *Some weak effects need to be understood*

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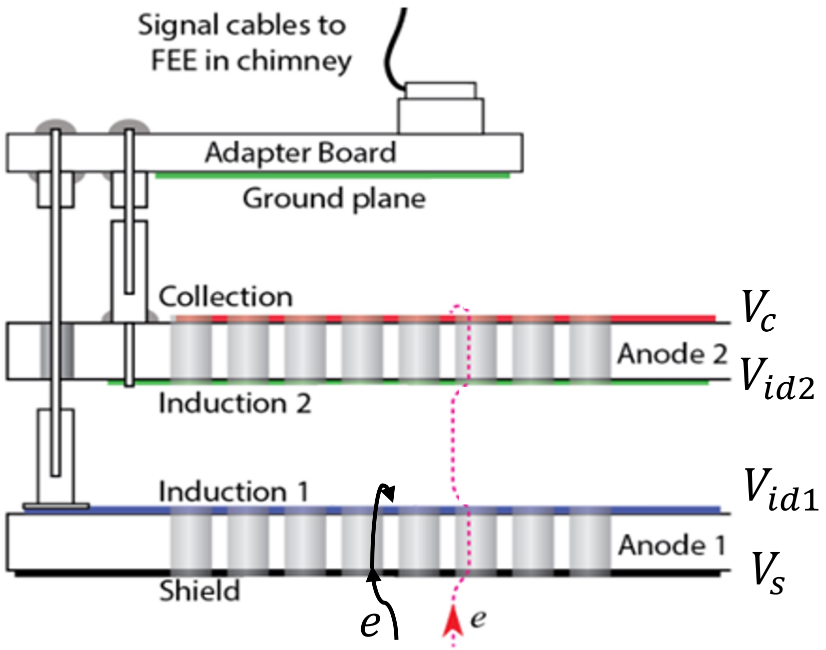
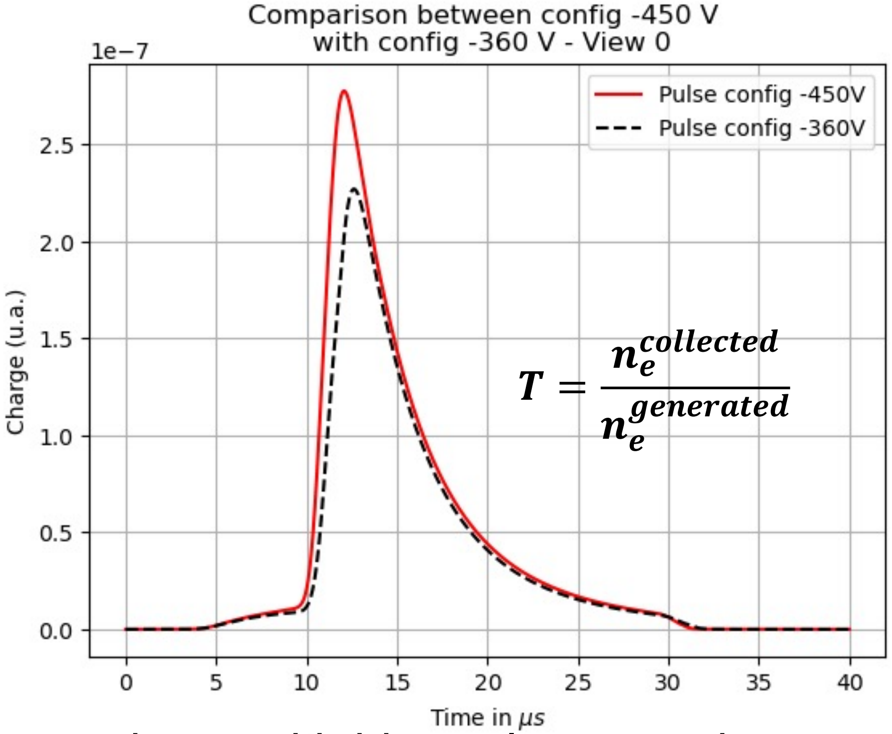
CRP transparency study

- **Work on amplitude signal to explore the different causes of charge loss**
- Using two PCB can lead to loss of total CRP transparency:



  - Some electrons are collected by the induction 1 plane
  - Collected charge decreases

- The simulation has shown a significative effect between two bias configurations used in the coldbox tests:
  - Config 1: $V_{id1} = -450\ V$
  - Config 2: $V_{id1} = -360\ V$



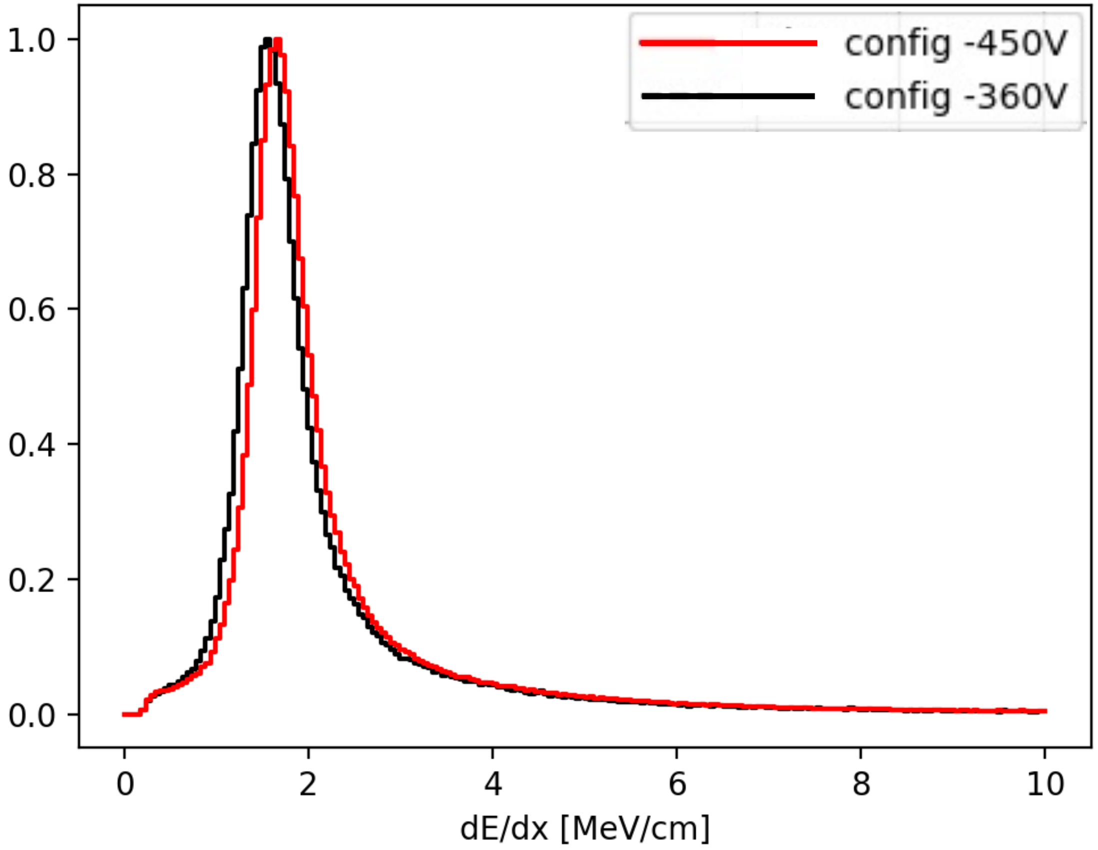
$$T = \frac{n_e^{collected}}{n_e^{generated}}$$

  - Dependency with bias voltage used

$$T_{sim} = \frac{Q_{tot}(-360)}{Q_{tot}(-450)} = 14\ \%$$

CRP transparency study

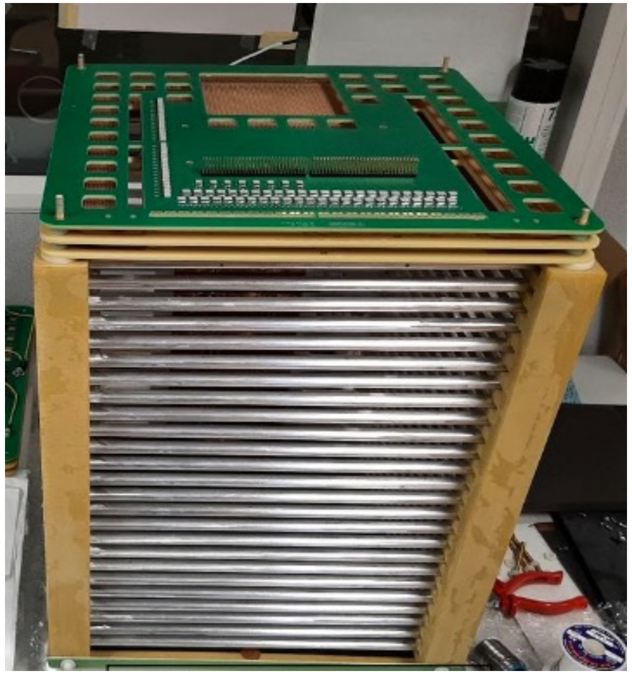
- Coldbox's data with same configuration:
  - dE/dx measured for muons
  - Comparison of the energy reconstruction
- Result:
  - **Increase of 6 % reconstructed energy for the "config -450 V"**
  - **An real effect but too small than the simulation result**
- **Difference Simulation/Measurements need to be understood**



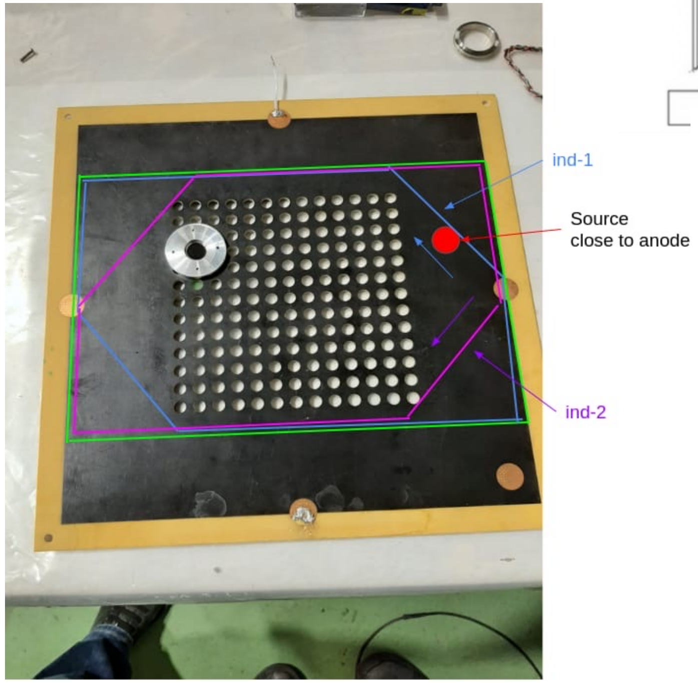
R&D TPC 50 L detector

- Data-taken on R&D TPC at CERN this summer
- Each run with a different voltage bias

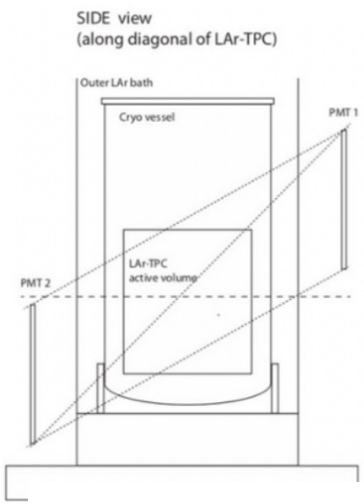
- $\sim 32\times32\ cm$ active area
- 52 cm drift

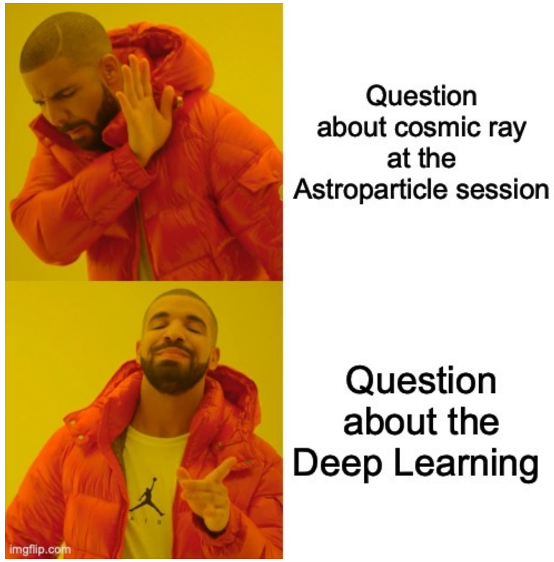


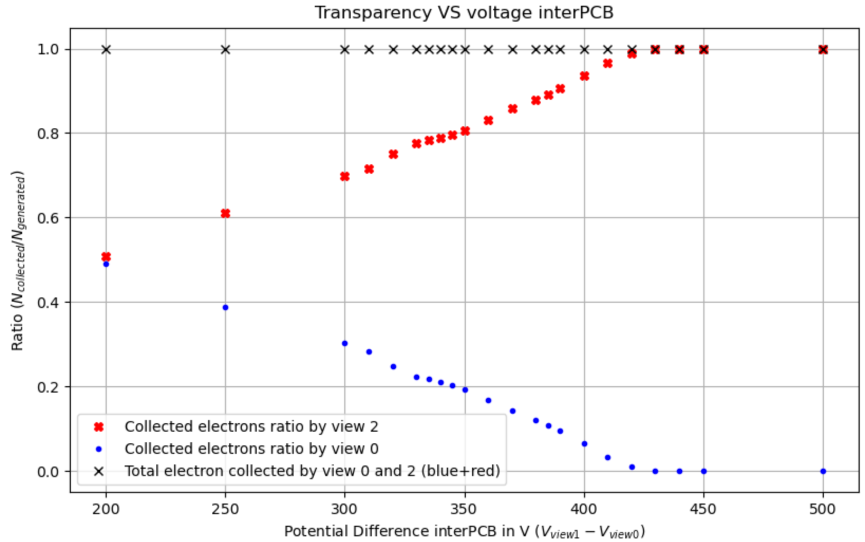
- 207 Bismuth sources
- Hexagonal active area



- Cosmic + random trigger







- Preliminary study with a standard run using a nominal set-up $(-1\,500\ V; -500\ \ V; 0\ V; 1000\ V)$

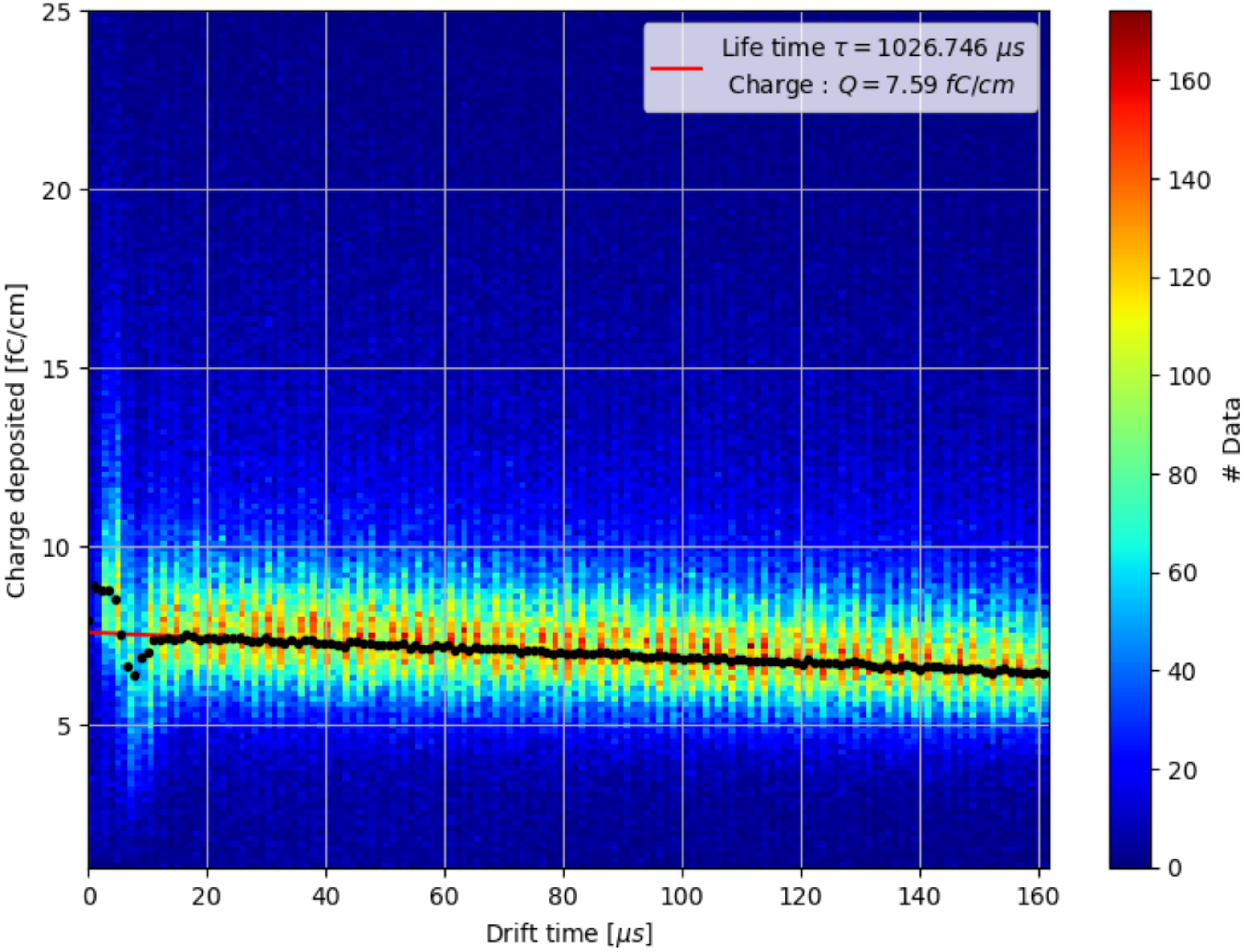
Liquid argon purity

- To reconstruct the charge, it is necessary to take into account impurities ($N2$, $O2$ etc.) which reduce the measured charge:

$$Q_{recon} = Q_{dep} \exp\left(-\frac{t}{\tau_D}\right)$$

  - with $\tau_D \approx \frac{300}{\rho(impurities)}$ the drift time and $\rho(impurities)$ the impurities concentration

- **However, not enough cosmic ray in the 50 L run**



- Example of purity determination with coldbox's data

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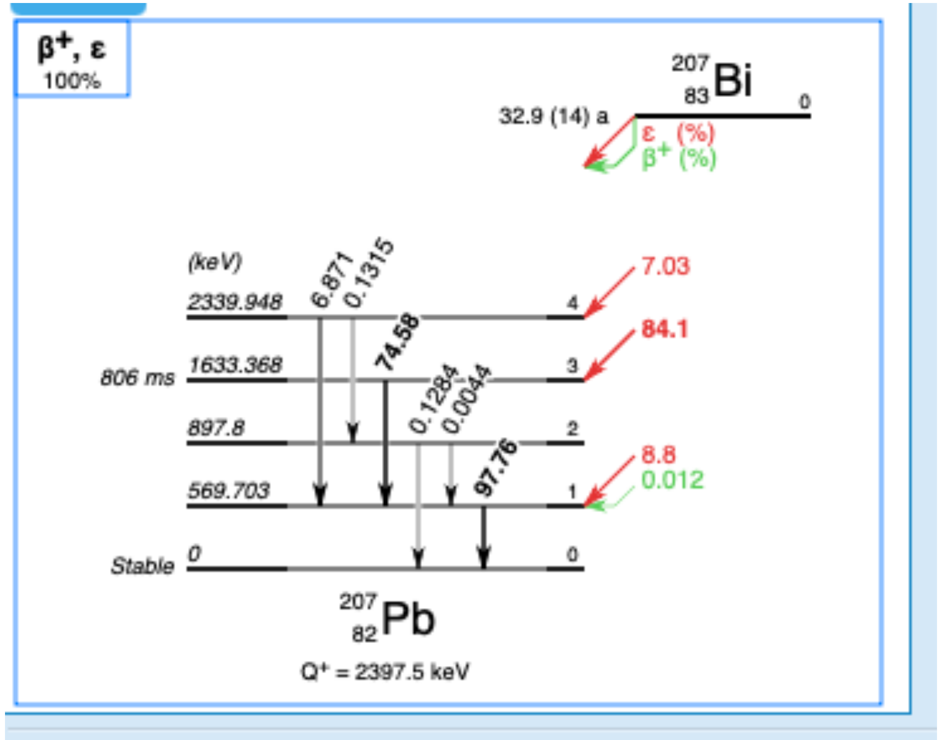
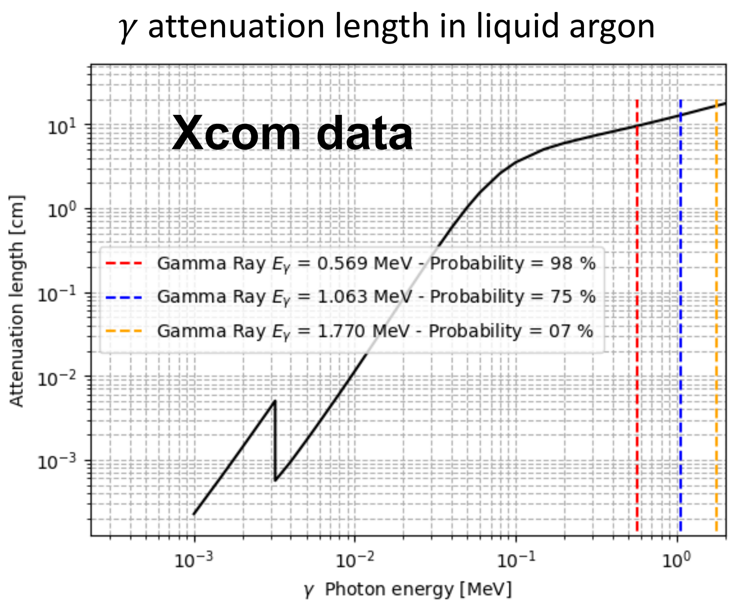
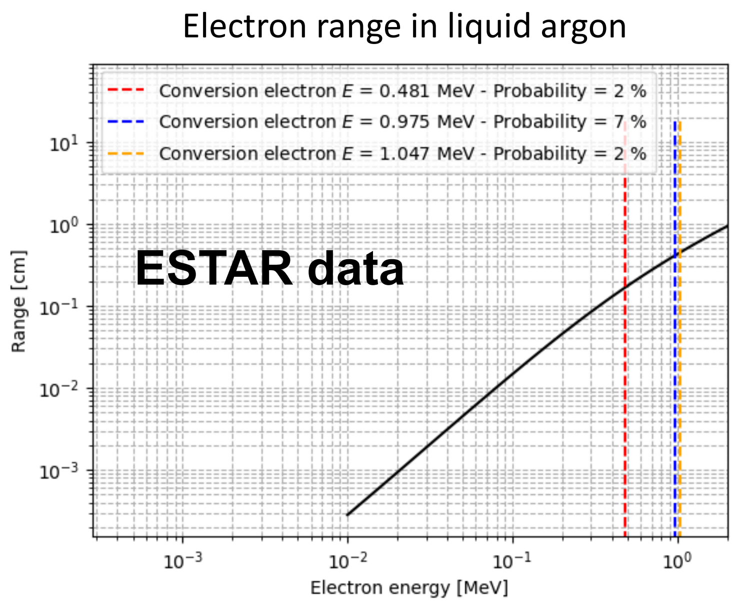
BI207 sources

- Decay by electronic capture







- γ attentuation length $> 10\ cm$
- Conversion electron range $\approx 1\ cm$

- Need to find Bi207 events from 50 L data
  - Electron range very short
  - Looking for only one signal from strips on all induction views → called a single hits

- Main γ rays:
  - $\approx 570\ keV$
  - $\approx 1\ MeV$
  - $\approx 1.7\ MeV$

- More complicated:
  - Conversion Electron $\approx 1\ MeV$

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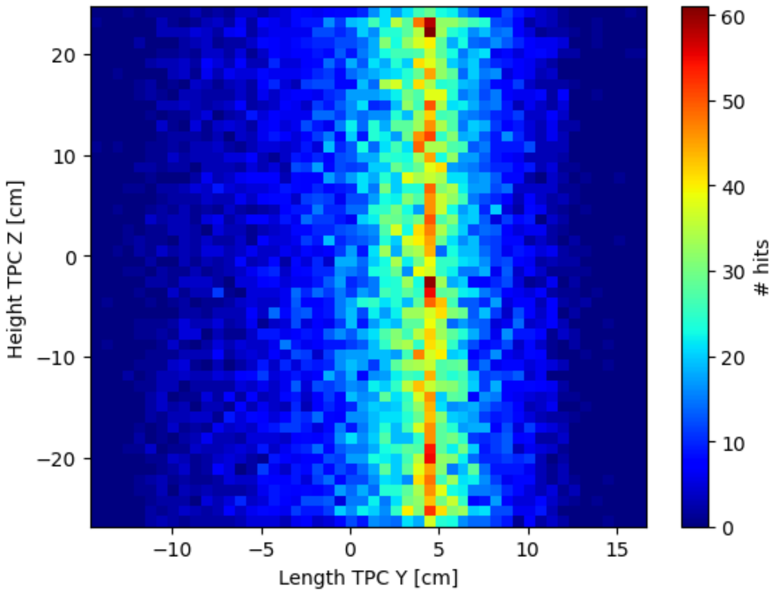
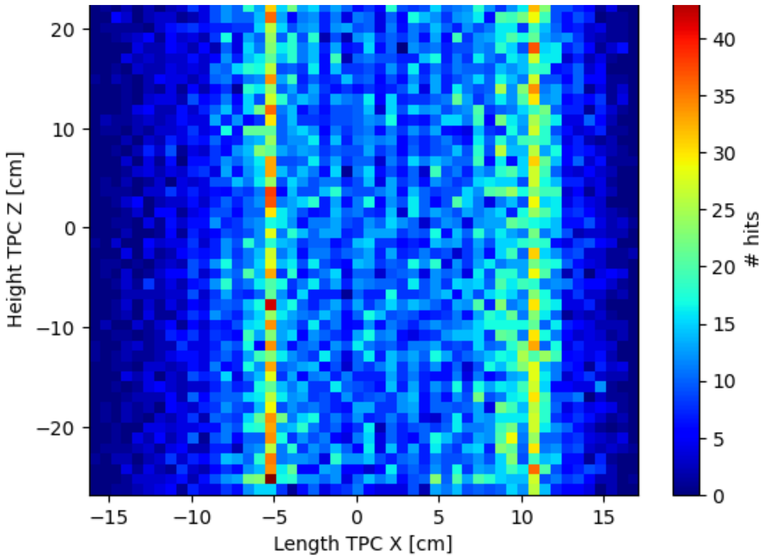
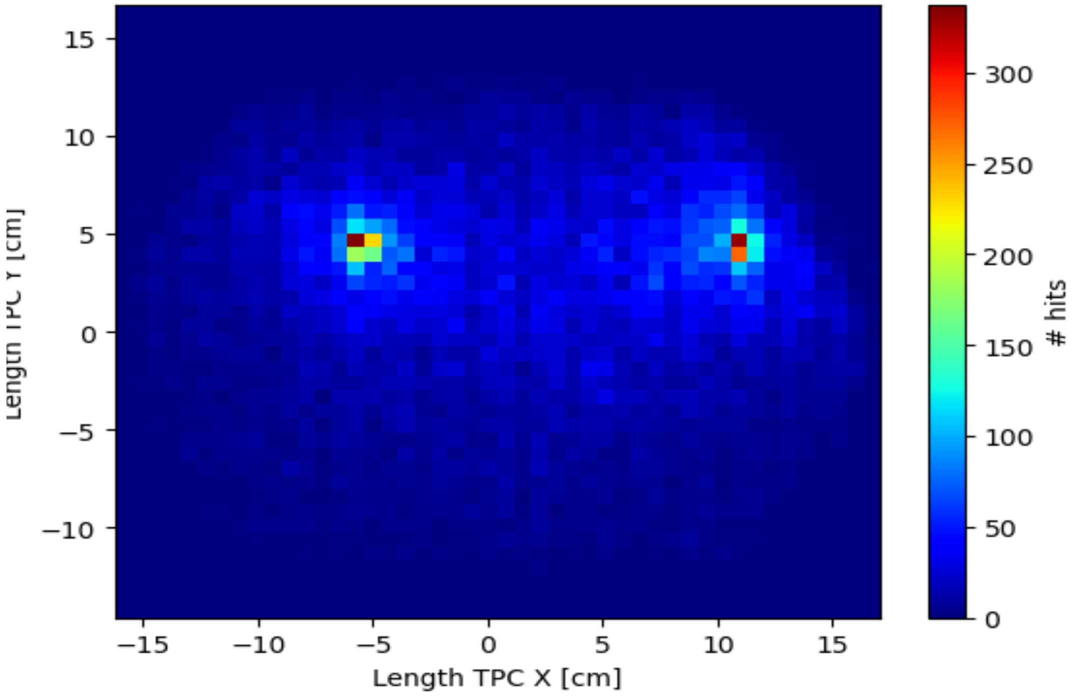
Preliminary study

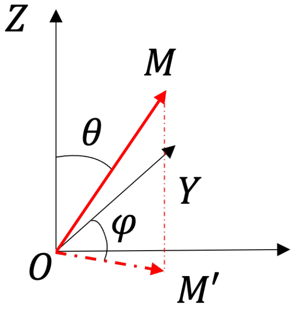
- ➢ Single hits reconstruction in the transverse plane



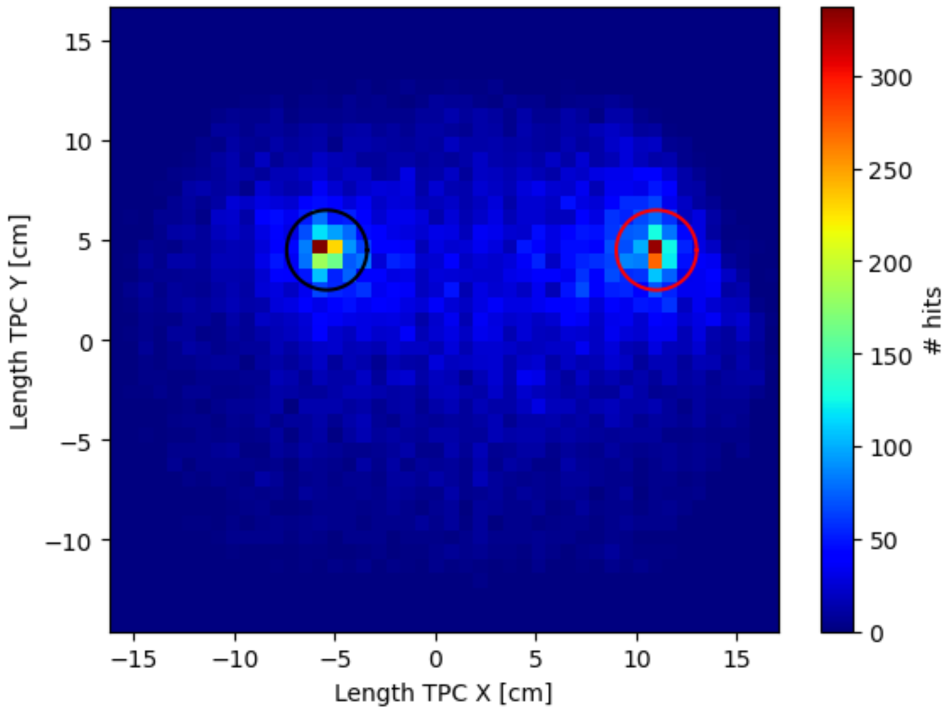




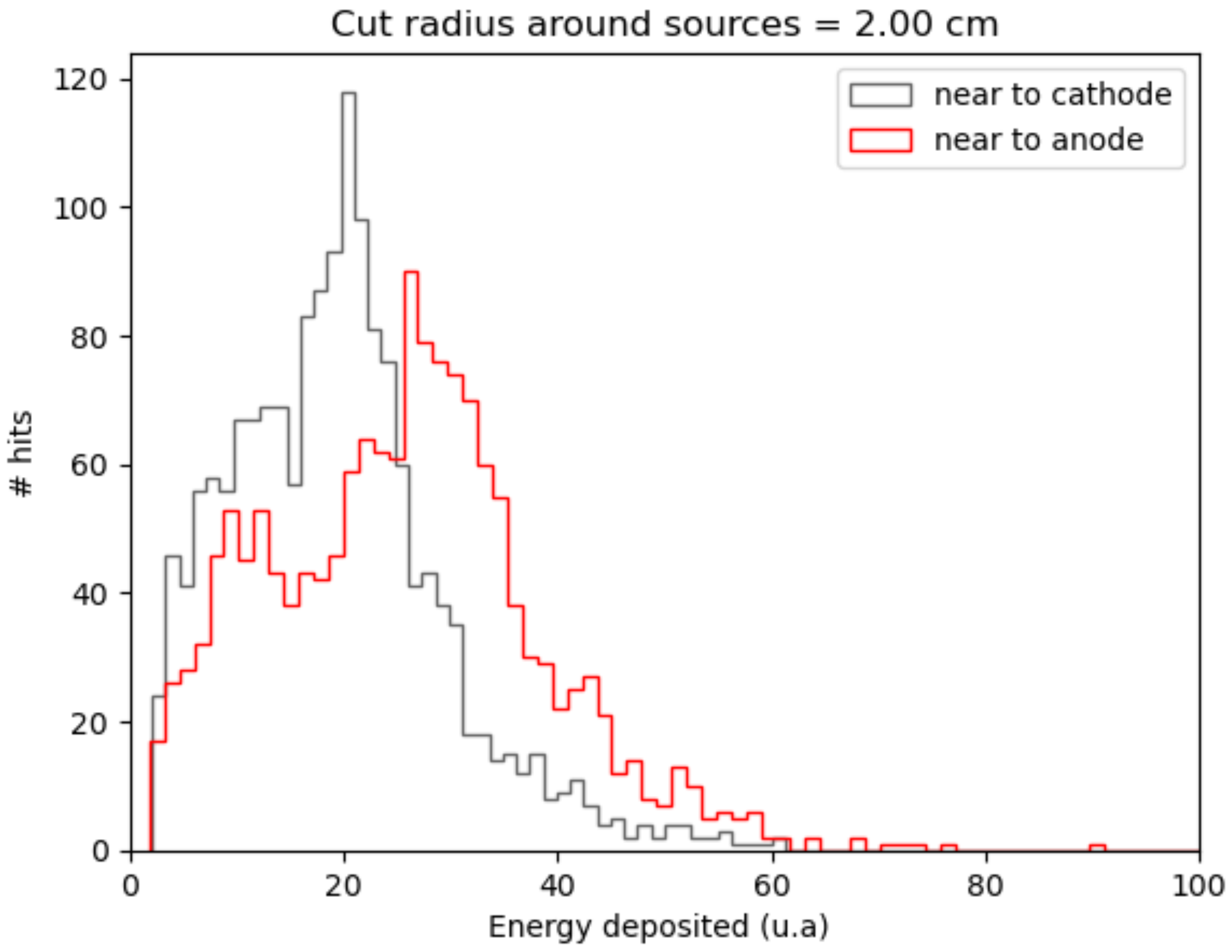
- ➢ Give no information on Bi207 source height because random trigger



Preliminary study



➢ Reconstruction of deposited energy spectra



➢ Probably useful to calibrate detector with peak at 1 MeV

➢ The shift in the spectra suggests that red is closer to the anode than black

Summary

➢ **Work done**

- Understanding the formation of inductions signals
- Numerical simulation conception to calculate the induced signals on all views
- Coldbox's data extraction and comparison between data/sim → **good agreement between both**
- Get some data and start the analysis of 50 L detector

➢ **What's next ?**

- Extend the simulation in a bigger volume + strip orientation implementation → track angle studies and position in the TPC (boundary conditions)
- Geant4 simulation for the Bi207 sources with 50 L geometry
- Work on 50 L data
- ProtoDUNE should start at early 2024
- Try to cook a préfou

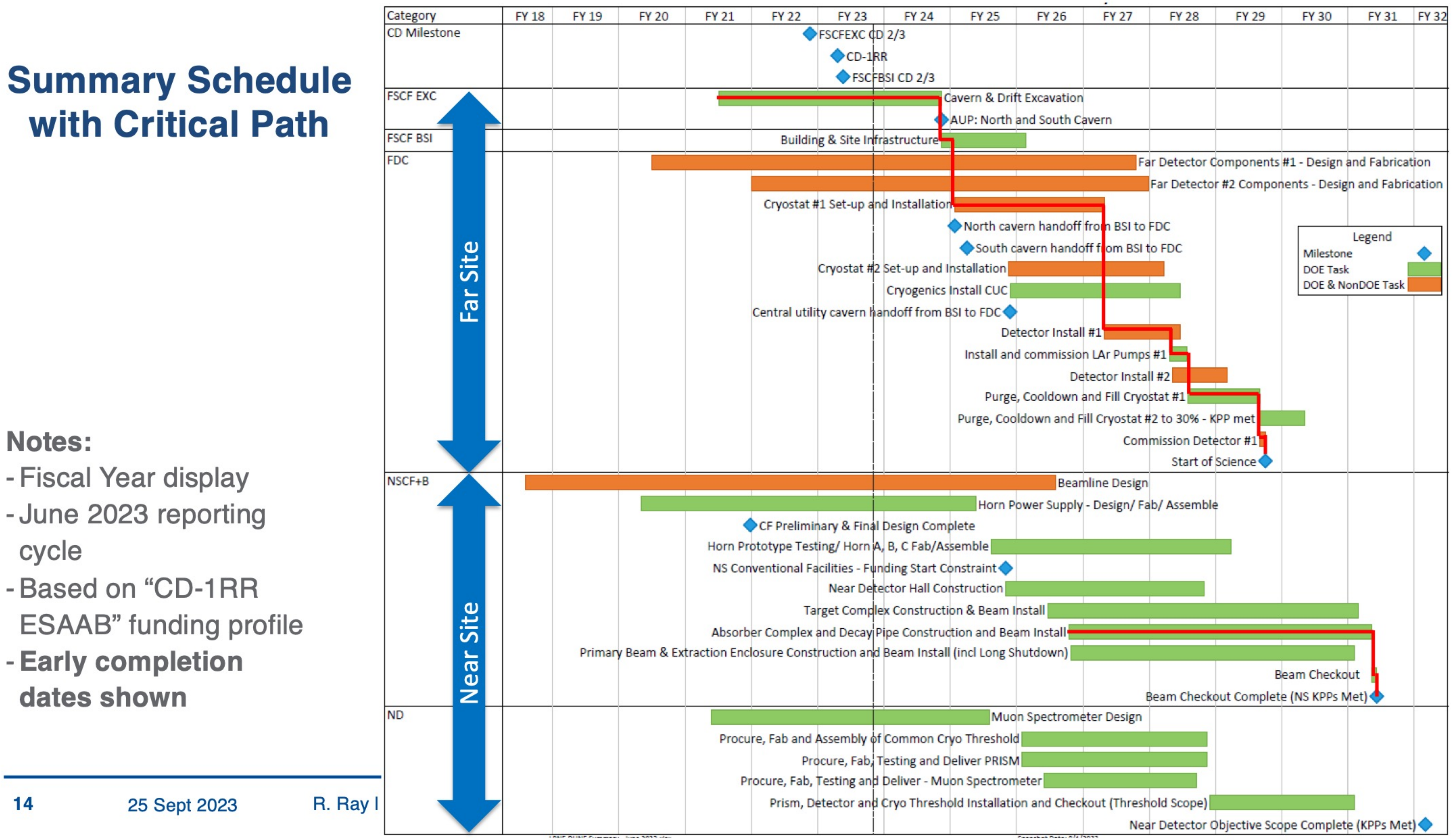
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT


Thanks for your attention
and for this week


Thanks for your attention
and for this week

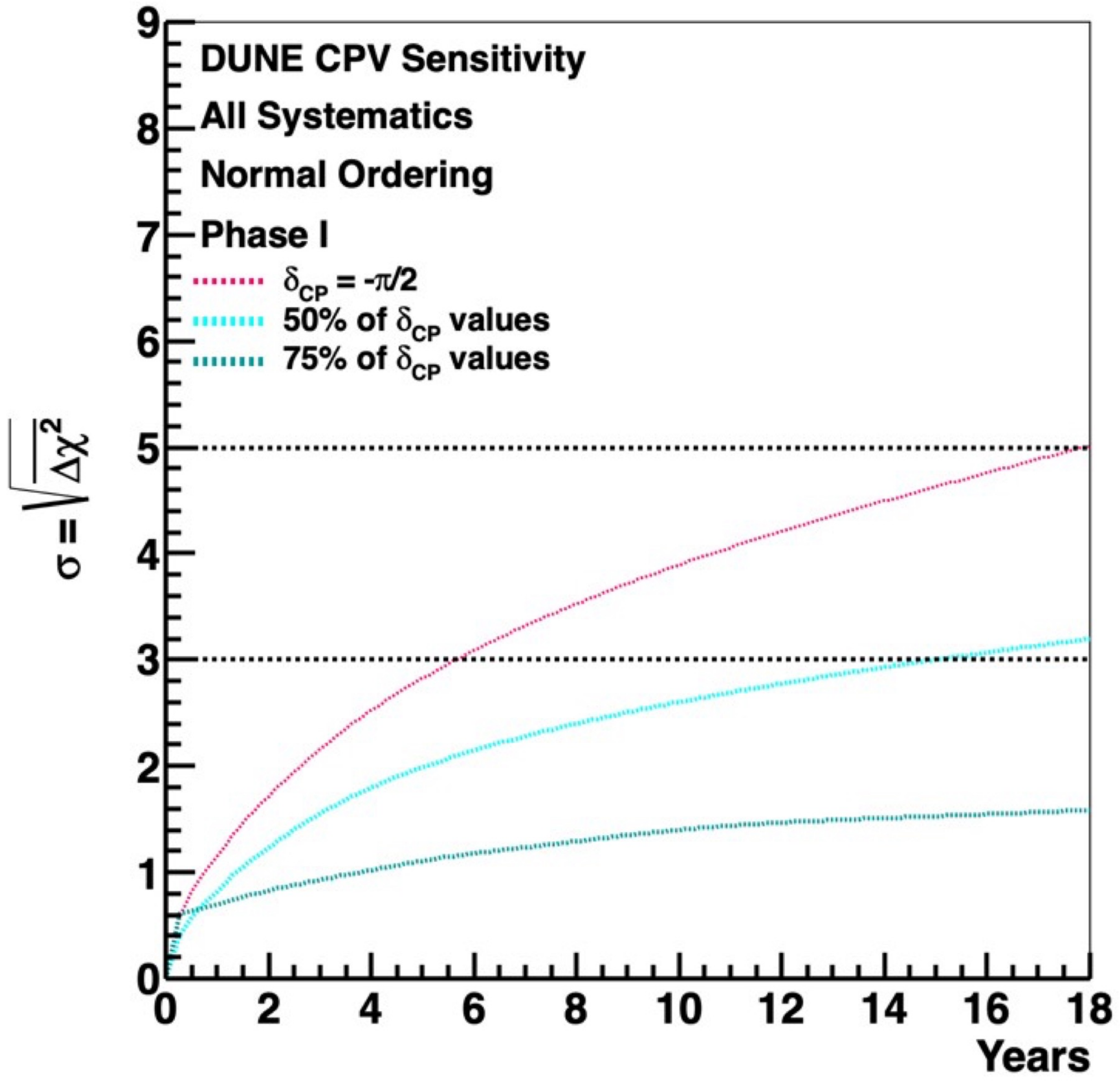
Back up

DUNE time lapse



DUNE ”physics status” time lapse

- Start of science $\approx end\ 2029$
- Beam is going on half 3031
- Near detector at start 2032
- $\delta_{CP} = \pm 90°$, CP violation can be measured at 3σ in Phase 1 < 6 years after data-taking



Boundary conditions (annexe ?)

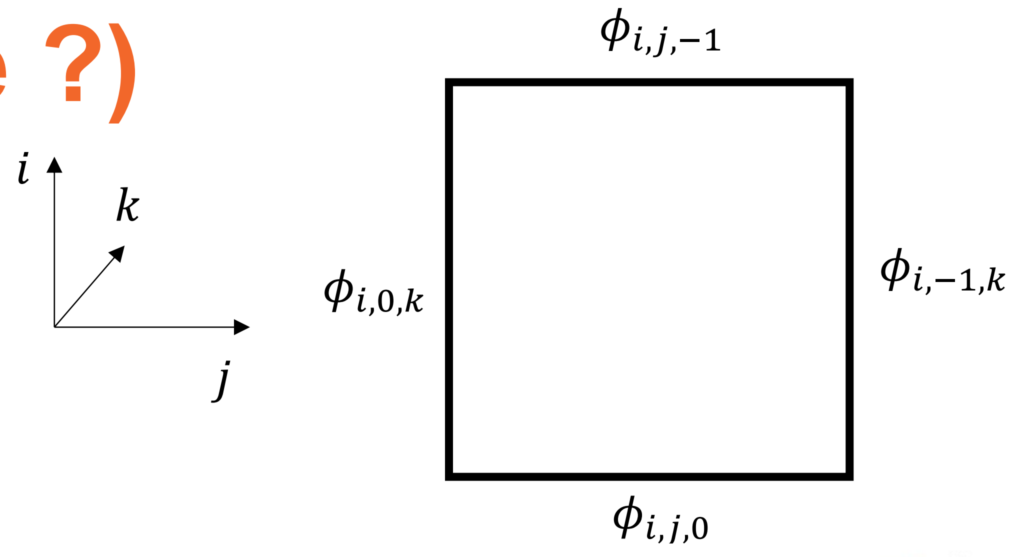
- Mirror boundary conditions

$$\phi_{i,0,k} = \frac{\phi_{i+1,j,k} + \phi_{i-1,j,k} + \phi_{i,1,k} + \phi_{i,-1,k} + \phi_{i,j,k-1} + \phi_{i,j,k+1}}{6}$$

$$\phi_{i,-1,k} = \frac{\phi_{i+1,j,k} + \phi_{i-1,j,k} + \phi_{i,1,k} + \phi_{i,-1,k} + \phi_{i,j,k-1} + \phi_{i,j,k+1}}{6}$$

$$\phi_{i,j,0} = \frac{\phi_{i+1,j,k} + \phi_{i-1,j,k} + \phi_{i,1,k} + \phi_{i,-1,k} + \phi_{i,j,k-1} + \phi_{i,j,k+1}}{6}$$

$$\phi_{i,j,-1} = \frac{\phi_{i+1,j,k} + \phi_{i-1,j,k} + \phi_{i,1,k} + \phi_{i,-1,k} + \phi_{i,j,k-1} + \phi_{i,j,k+1}}{6}$$

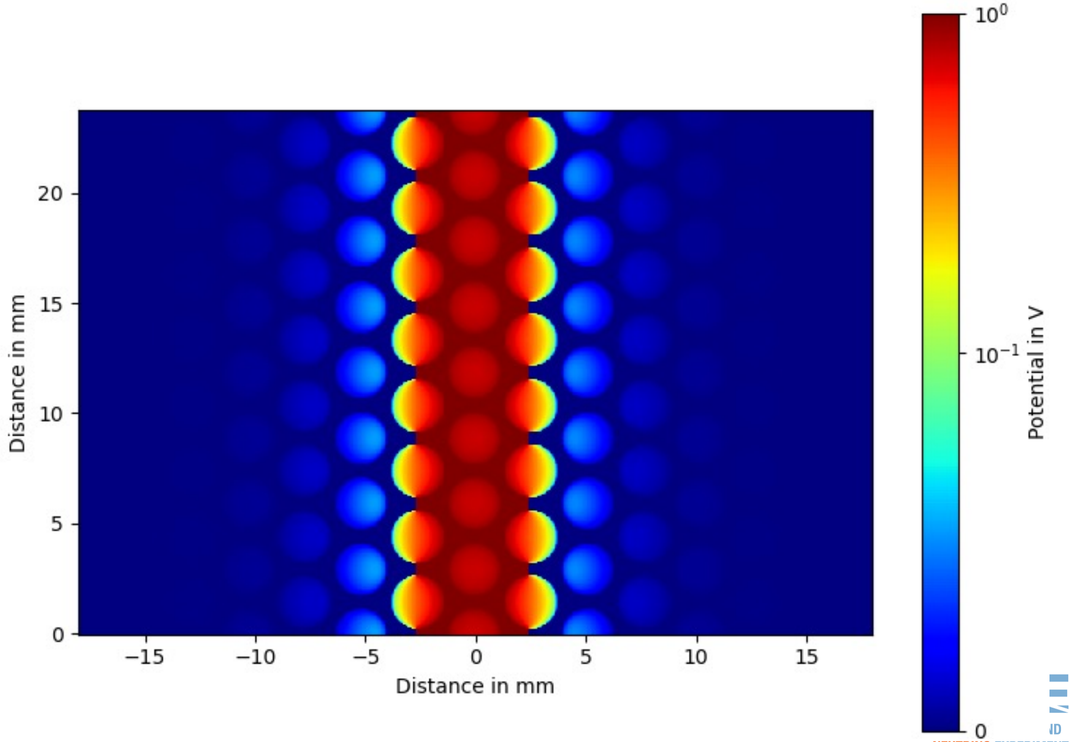


- Dirichlet boundary conditions

$$\phi_{i,0,k} = 0$$

$$\phi_{i,-1,k} = 0$$

Valid for a calculation windows ≥ 7 strips



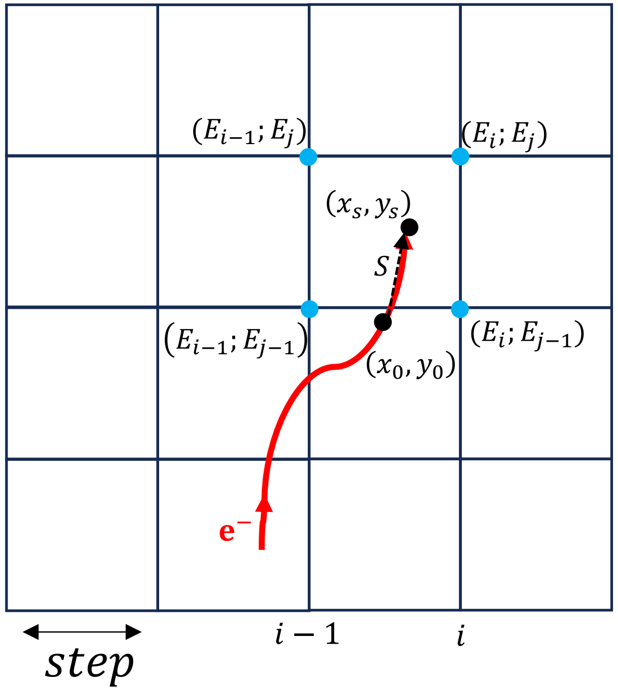
Ionization electron generation

- Thermal electron
  - Trajectory follow drift field lines

- Runge Kunta like simulation

$$x_S = x_0 + \frac{E_x^{interp}(x_0, y_0)}{|E(x_0, y_0)|} \times S$$

$$y_s = y_0 + \frac{E_y^{interp}(x_0, y_0)}{|E(x_0, y_0)|} \times S$$

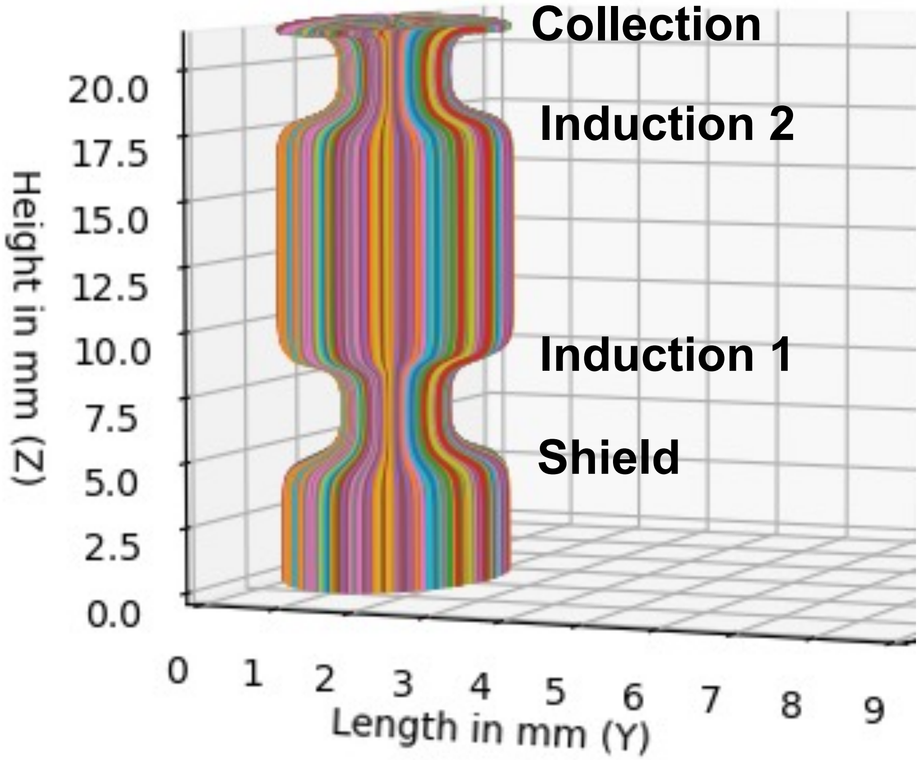


- Field interpolation

$$E_x^{interp} = E_{i-1} + \left(\frac{x_0}{step} - (i-1)\right) \times (E_i - E_{i-1})$$

- Drift simulation 5 mm

- Simulation of electron trajectories passing through a CRP's hole



Weighting field evaluation in CRP