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

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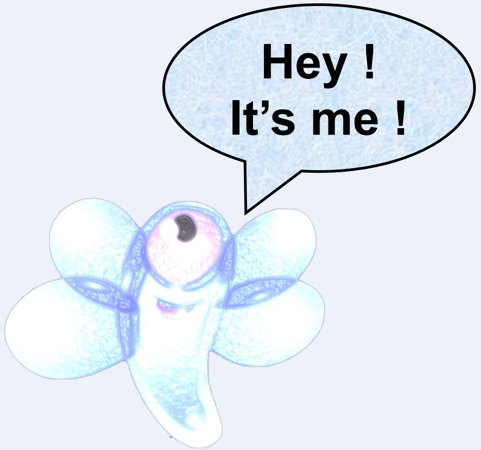
Neutrino oscillation



- There are three leptonic flavors ν_e, ν_μ, ν_τ
- Neutrinos only interact by weak interaction → Small cross section
- **Neutrino oscillation:**
  - ➢ Assumes neutrino masses (SM predict massless for these ones)
  - ➢ Flavor eigenstates (which couple $W^\pm, Z^0$) are different from mass eigenstates during their propagation
- **Flavor states** are a linear combination of mass states: $|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$ avec $\begin{cases} \alpha = e, \mu, \tau \\ \text{i}= 1,2,3 \end{cases}$
- **PMNS mixed matrix** (Pontecorvo-Maki-Nakagawa-Sakata):

$$U_{PMNS} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{Atmospheric}} \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13}\, e^{i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{Reactor \& accelerator}} \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar}}$$

Atmospheric: $\nu_\mu \leftrightarrow \nu_\tau$

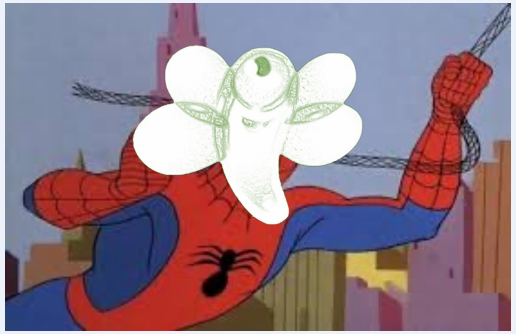
Reactor & accelerator: $\nu_\mu \leftrightarrow \nu_e$

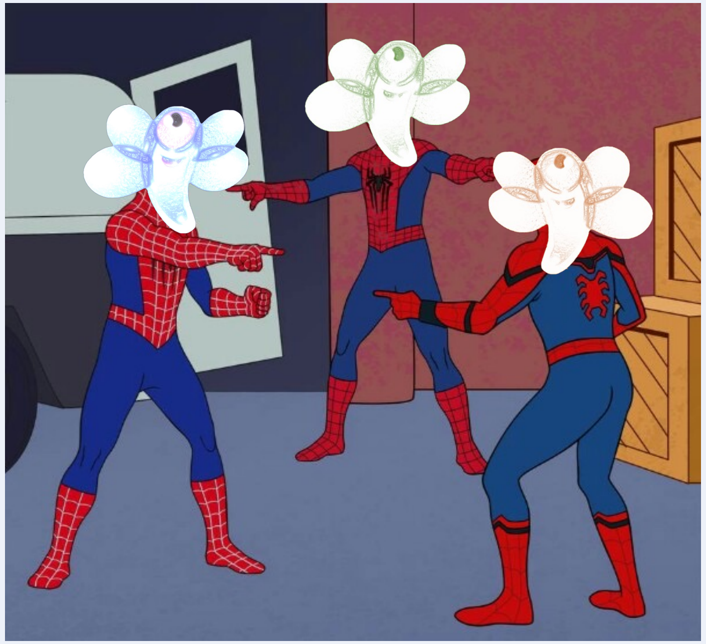
Solar: $\nu_e \leftrightarrow \nu_X$

Neutrino oscillation

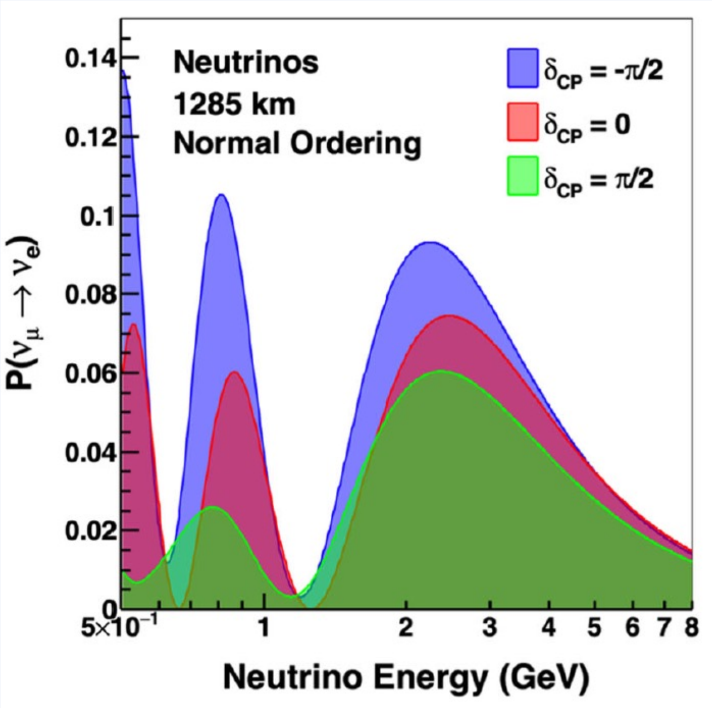
- Probability of neutrino oscillations:

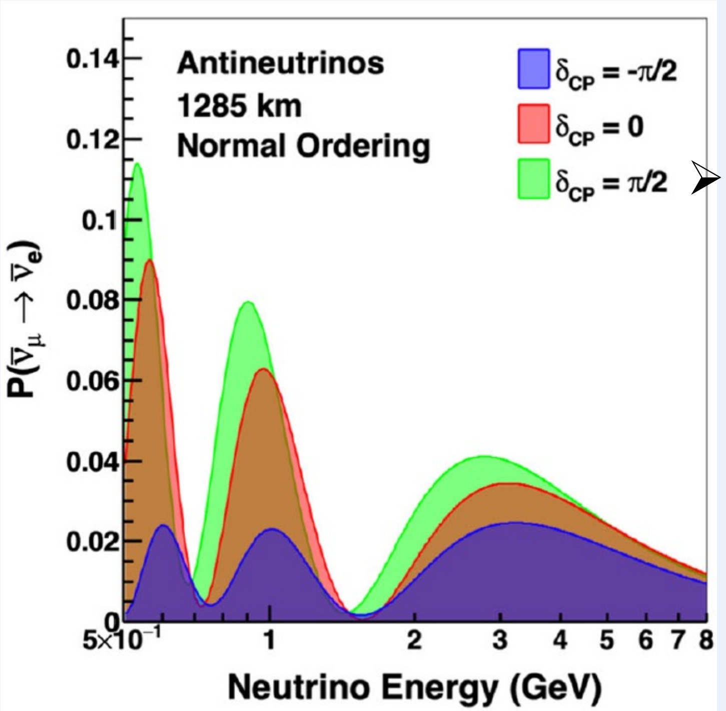
$$P(\nu_\alpha \to \nu_\beta) \equiv P(E_\nu, L)$$





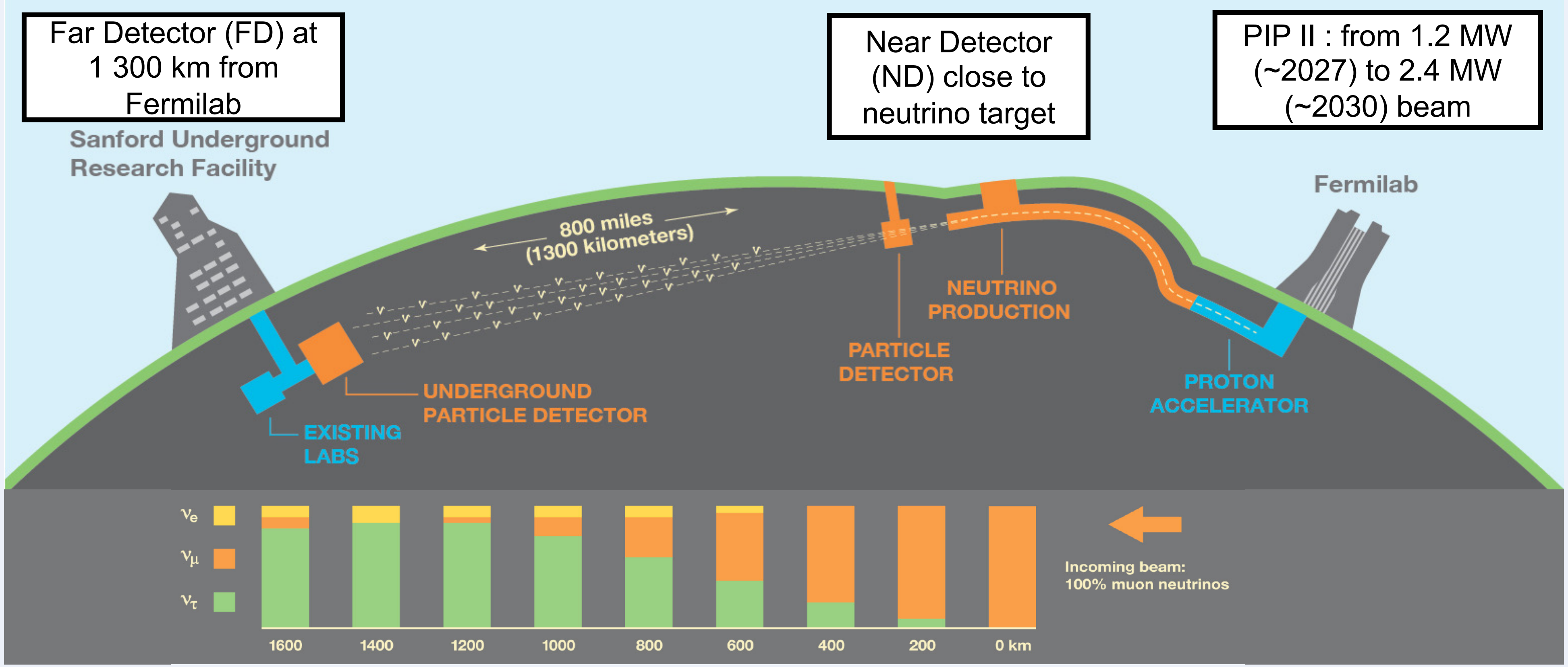
- Depends on 6 parameters: Δm^2_{31}, Δm^2_{21}, θ_{12}, θ_{23}, θ_{13}, δ_{CP}



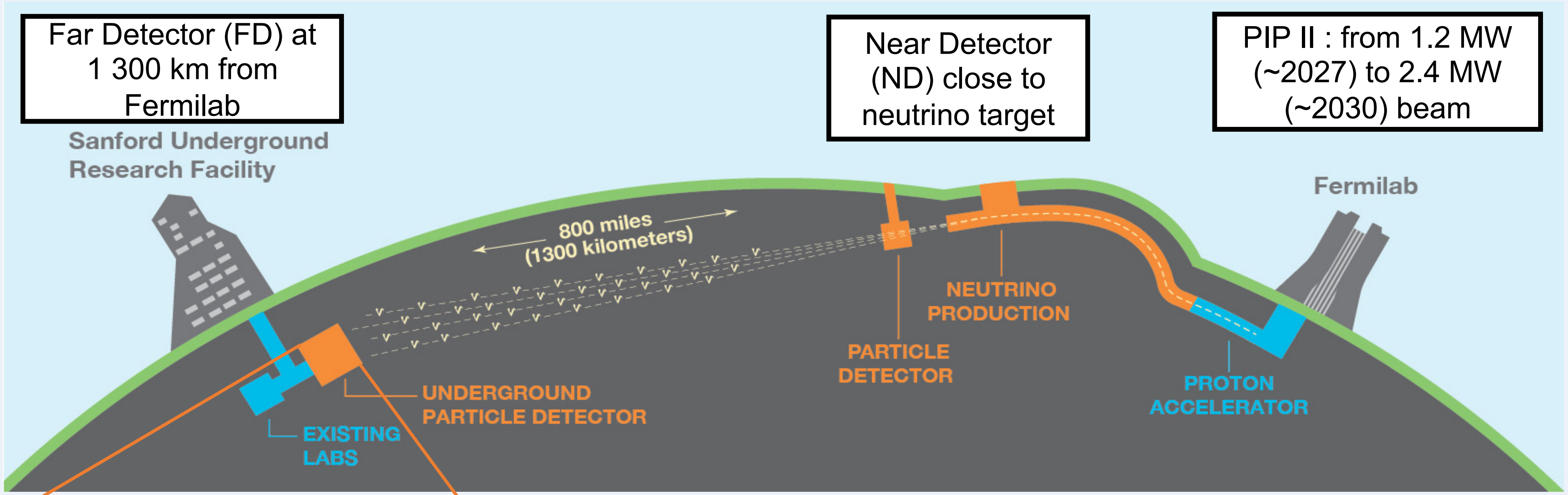


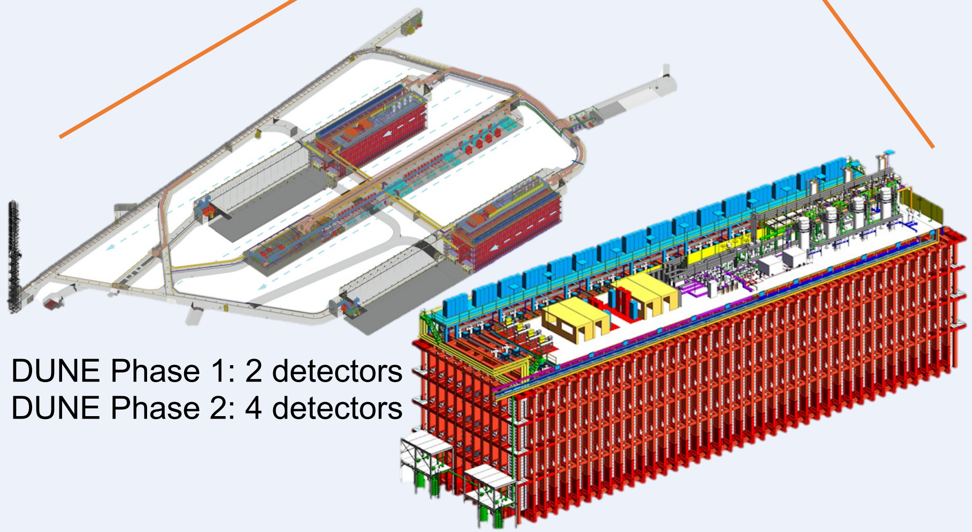
- Unknown parameters:
  - Sign of $|\Delta m^2_{31}|$ → Mass ordering
  - δ_{CP} value → CP symmetry broken on lepton sector
  - θ_{23} value and octant

DUNE project overview



DUNE project overview



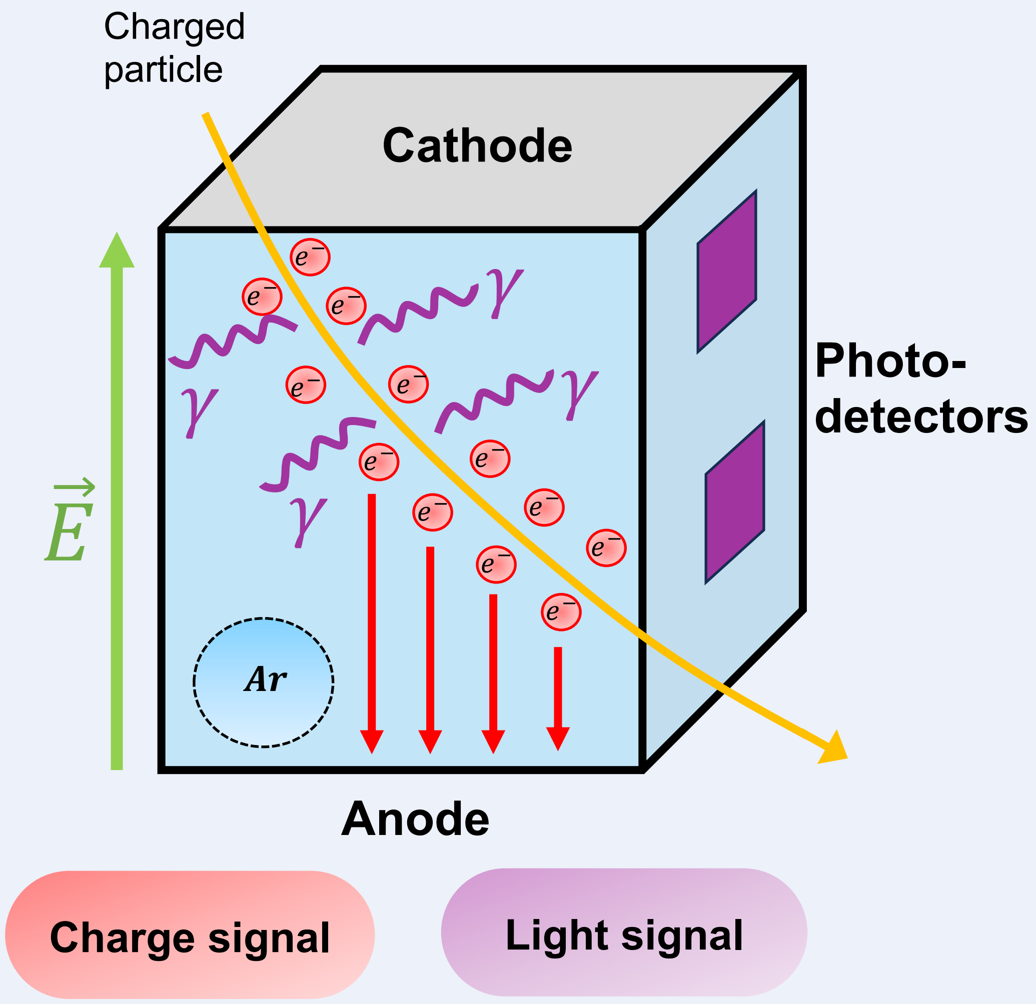


- DUNE Phase 1: 2 detectors
- DUNE Phase 2: 4 detectors

- ➢ 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 : 15 kt Liquid Argon

LArTPC

➢ Liquid Argon:

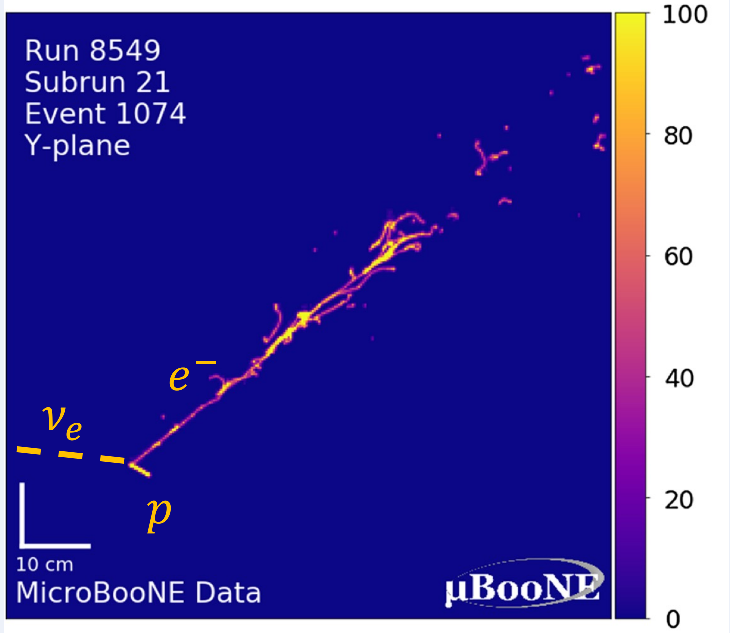


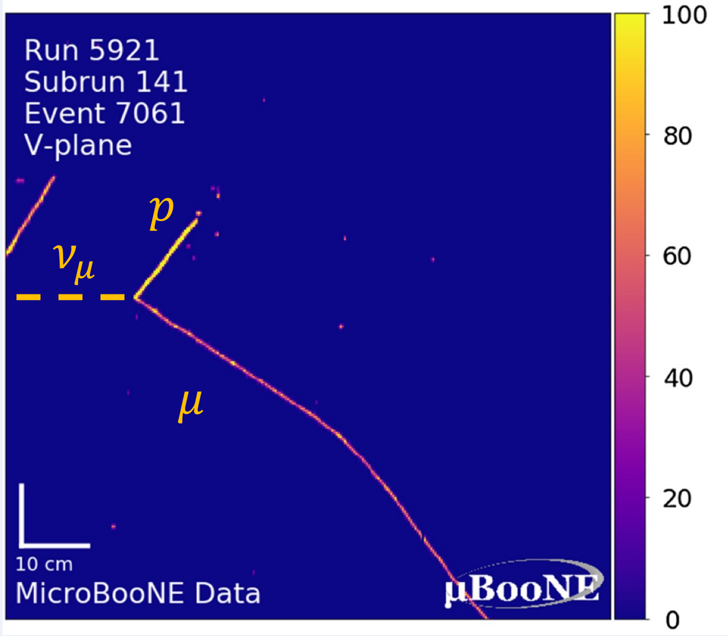
➢ Time Projection Chamber:

- Segmented anodes used to collect charge signal
- $\tau_{drift} \gg \tau_{photon}$ → light signal trigger detection
- Enables large volume
- High spatial resolution (few millimeters)

➢ **Separate ν_e / ν_μ events by track topology identification**

➢ **Calorimetry to have the energy of the primary neutrino**





Vertical drift design

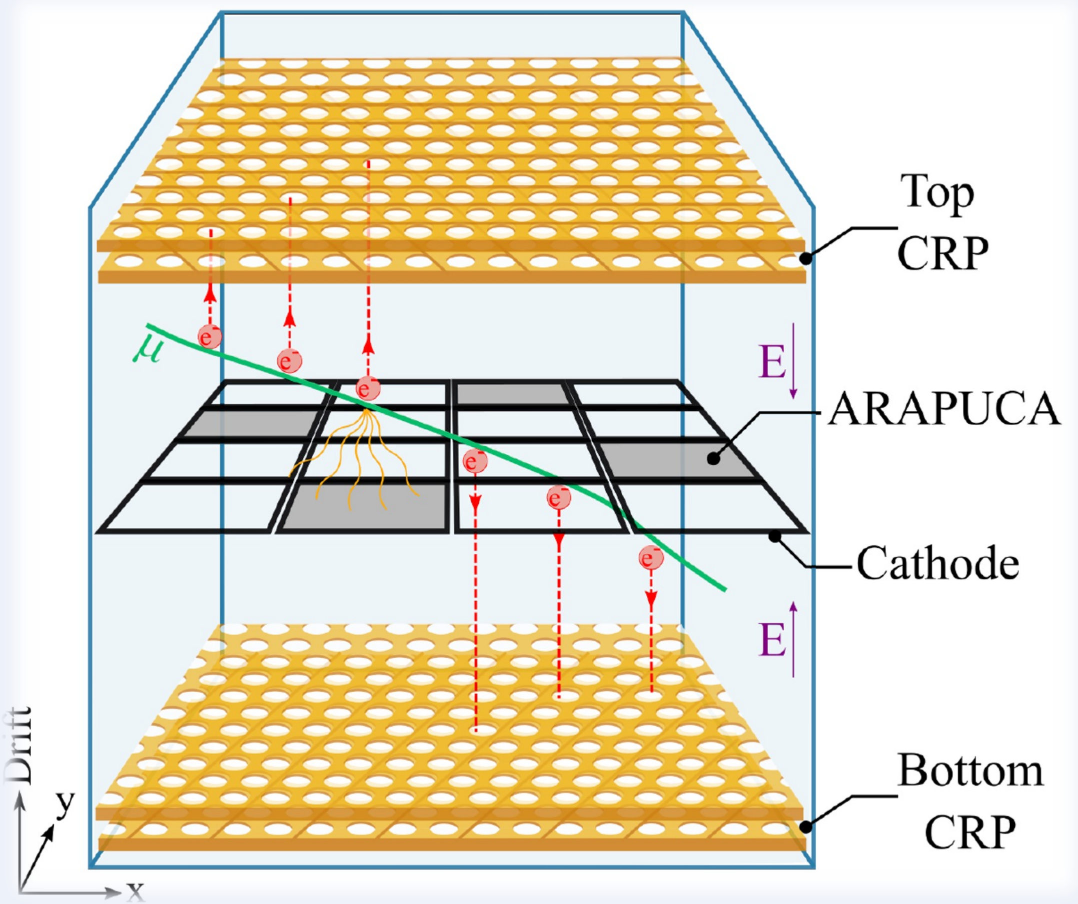


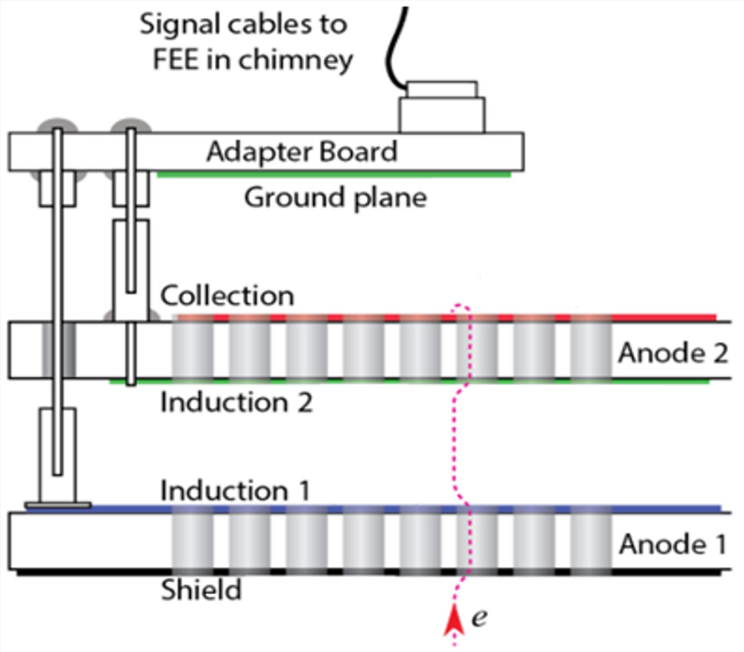
Diagram by L. Zambelli

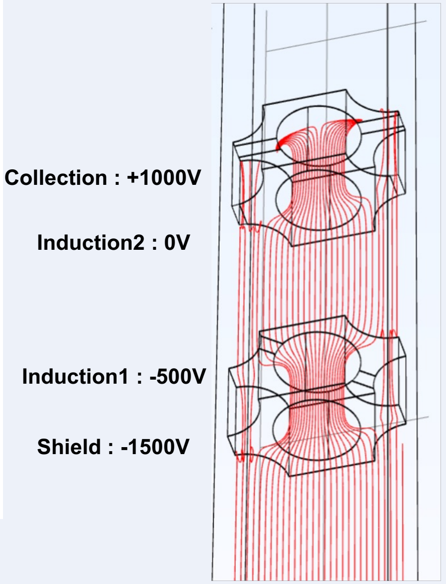
- 2 volumes split by a cathode
  - Electric drift field: $|\vec{\boldsymbol{E}}| = 0.5\ kV/cm$
- X-ARAPUCA* for light detection on the cathode
- The new perforated anode technology
  - Stack of 2 perforated Printed Circuit Boards (PCB)
  - Etched copper electrode strips on each PCB face
  - A sub-centimeter spatial resolution
  - Module called Charge-Readout Planes (CRP) ~ 3x3 m
- DUNE Far detector at SURF:
  - 80 module CRPs for each top and bottom TPC
  - Half will be produced at Grenoble

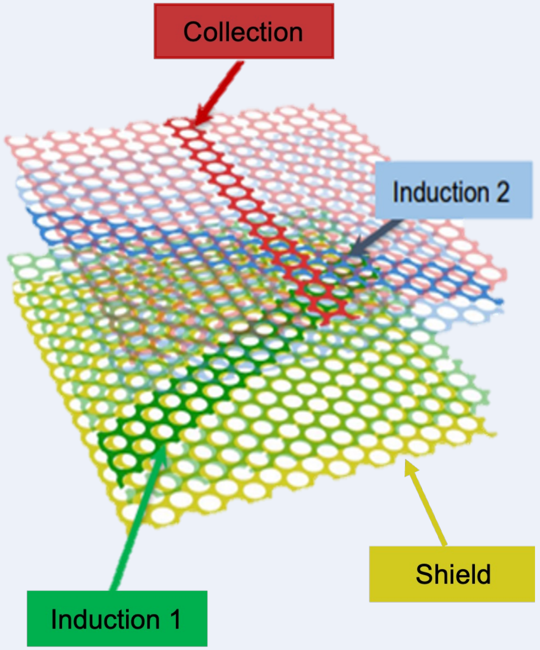
** Light detector device*

The perforated anode technology

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

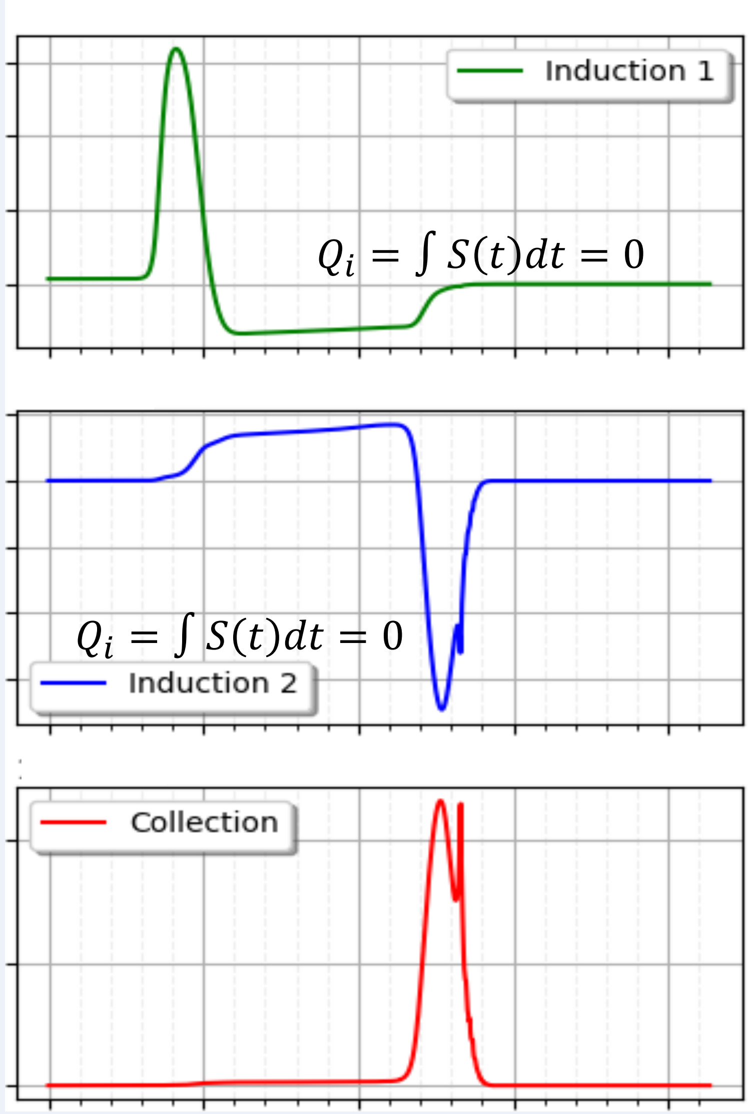






- **Induction views:** Bipolar signals
- **Collection view:** Unipolar signal

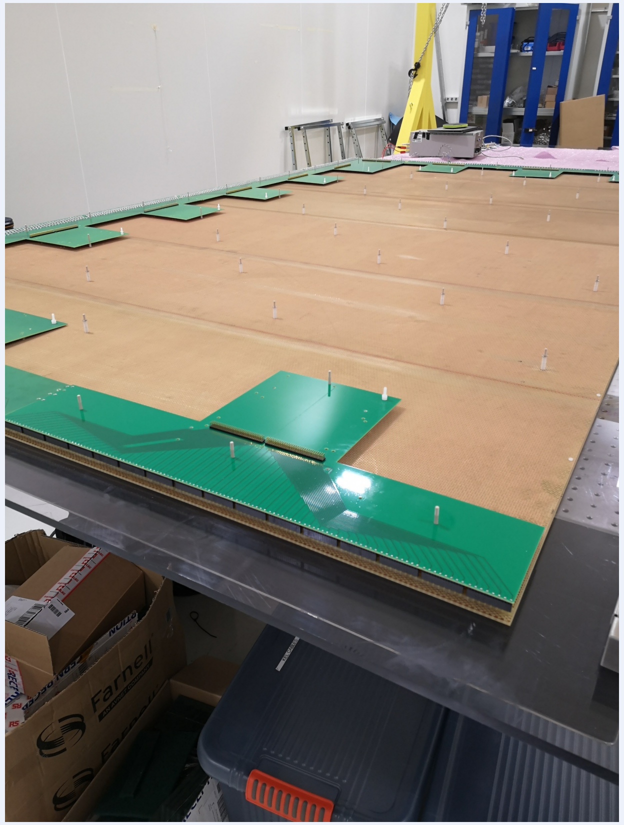
$$Q_{coll} = \int S(t)dt = N_e \times e$$



Signal formation study on anodes

- **Problematic:**
  - Use of new anode technology
  - Important to know the deposited energy in the detector to measure the oscillation parameters
  - Important to know to reconstruct the particle tracks from collected charge

- **My work:**
  - Understanding the waveforms based on energy, track angle and position
  - Understanding the charge lost in the anodes
  - Estimate the different systematics
  - **Study of induced signal formation on the anode**



CRP assembly at CERN

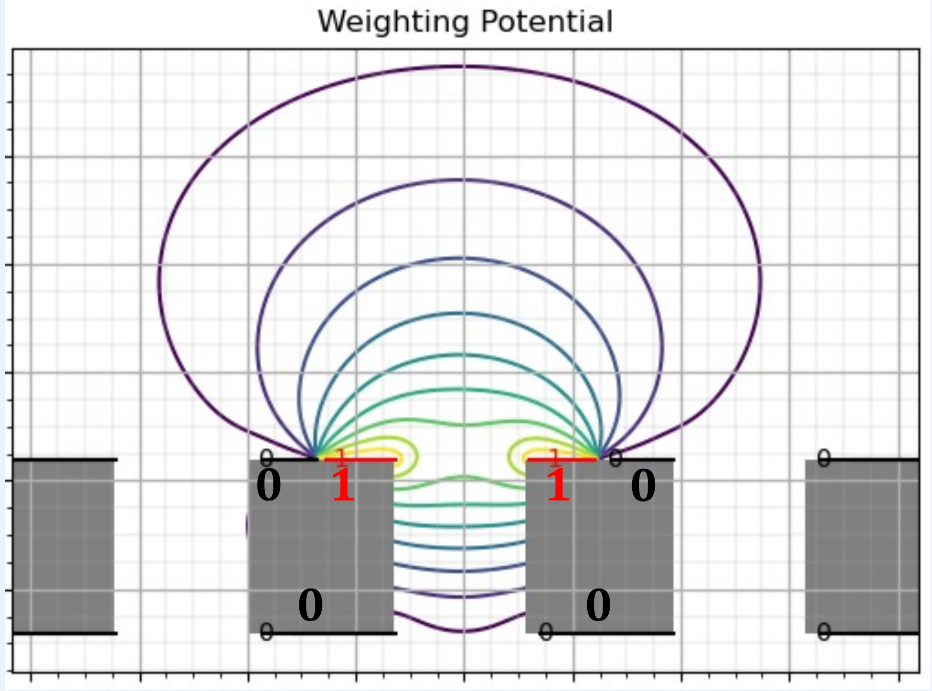

AND GOD SAID
$i(t) = q\,\vec{E}_W \cdot \vec{v}_D$
LIGHTYEAR
SPACE RANGER
AND THEN THERE WAS CHARGE SIGNAL
imgflip.com

Modeling signal formation

➢ **Shockley-Ramo theorem:**

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

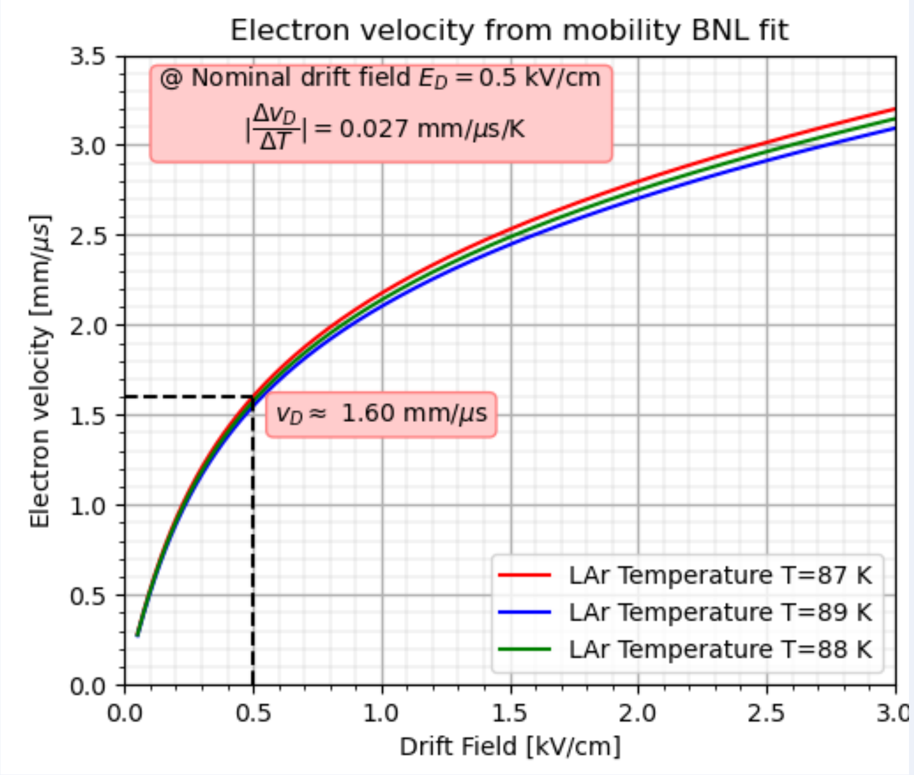
➢ Weighting Field $\vec{E}_w$ is virtual field defined when the **reading strip equal 1 V** and **all others fixed to 0 V**



$\vec{E}_w$: geometry factor
$\vec{v}_D$: physics factor

➢ **Drift velocity:**

$$\vec{v}_D \equiv \vec{v}_D\,(\vec{E}_D, T)$$



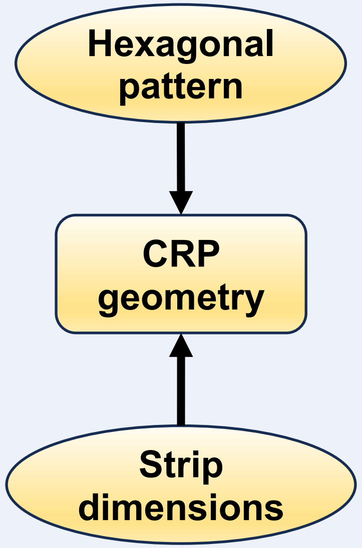
➢ **The instantaneous current is induced by charge motion only**

➢ **Need simulation for complex geometry**

https://lar.bnl.gov/properties/trans.html

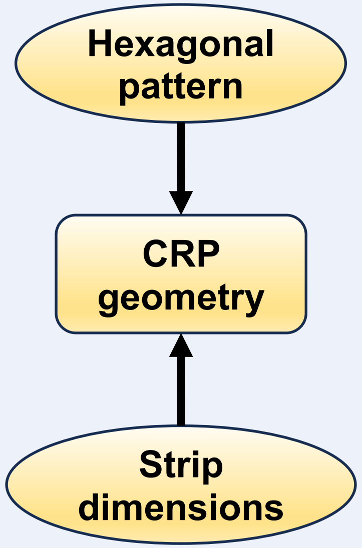
Induced signal simulation

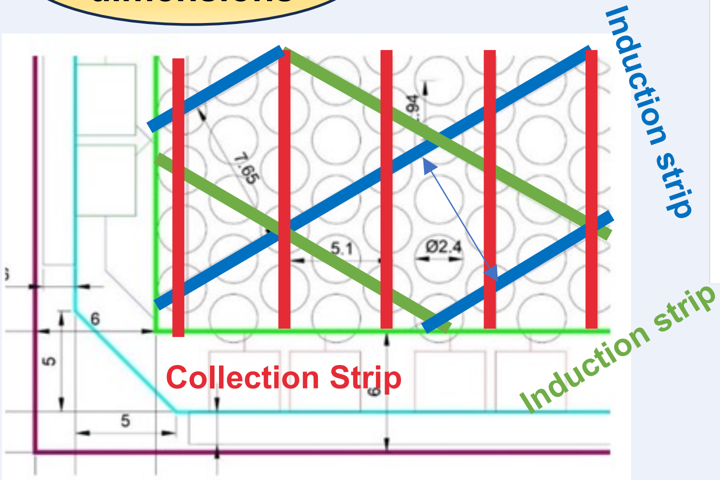
- Design of a simulation on Python

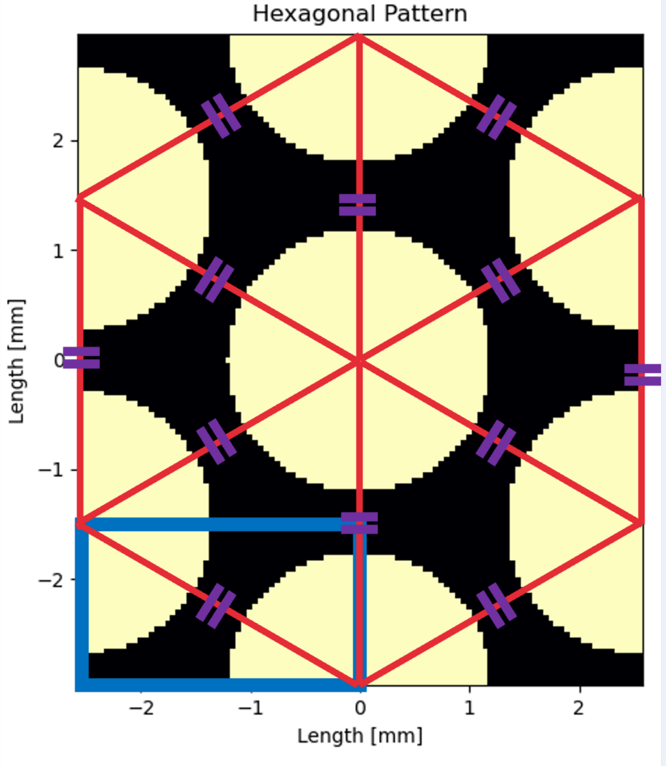


Induced signal simulation

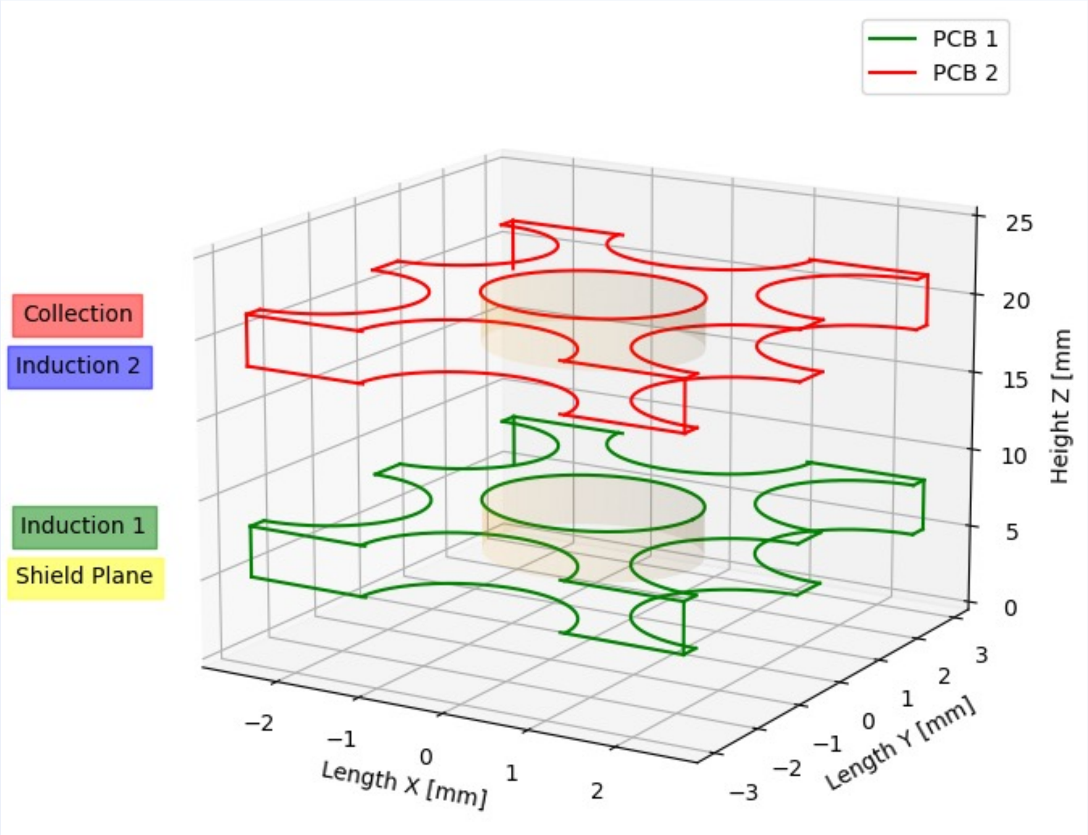
- Numerical simulation on Python
- Implement CRP geometry hexagonal pattern, strips, 2 Printed Circuit Boards, 4 equipotential planes





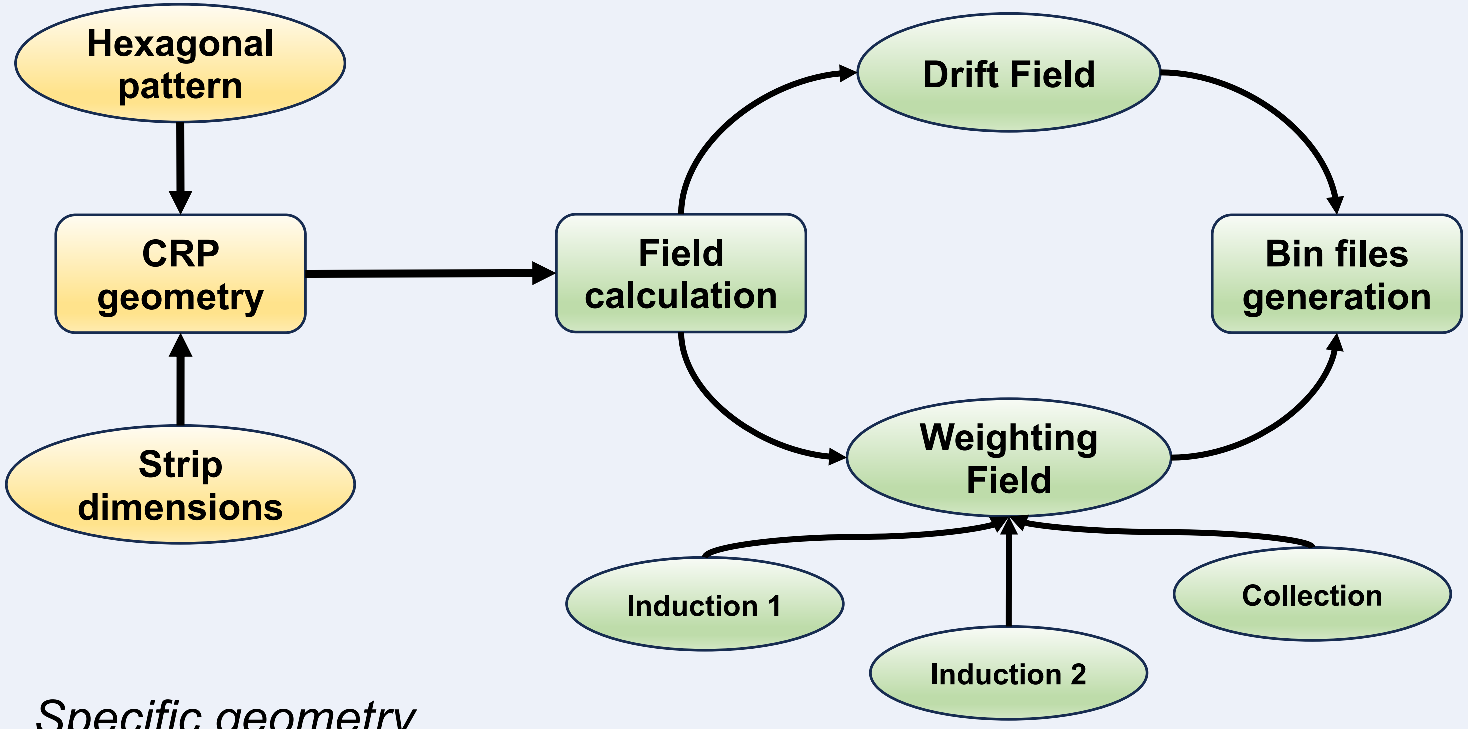


Step used: $50\ \mu m$



Induced signal simulation

- Design of a simulation on Python



1. *Specific geometry setting up*

- Induced signal on the readout strips:

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

- Weighting field $\overrightarrow{E_W}$
- Drift Velocity Field:

$$\overrightarrow{v_D} = \mu(\,|\overrightarrow{E_D}|, T)\times\overrightarrow{E_D}$$

- Solving Laplace's equation in 3D:

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

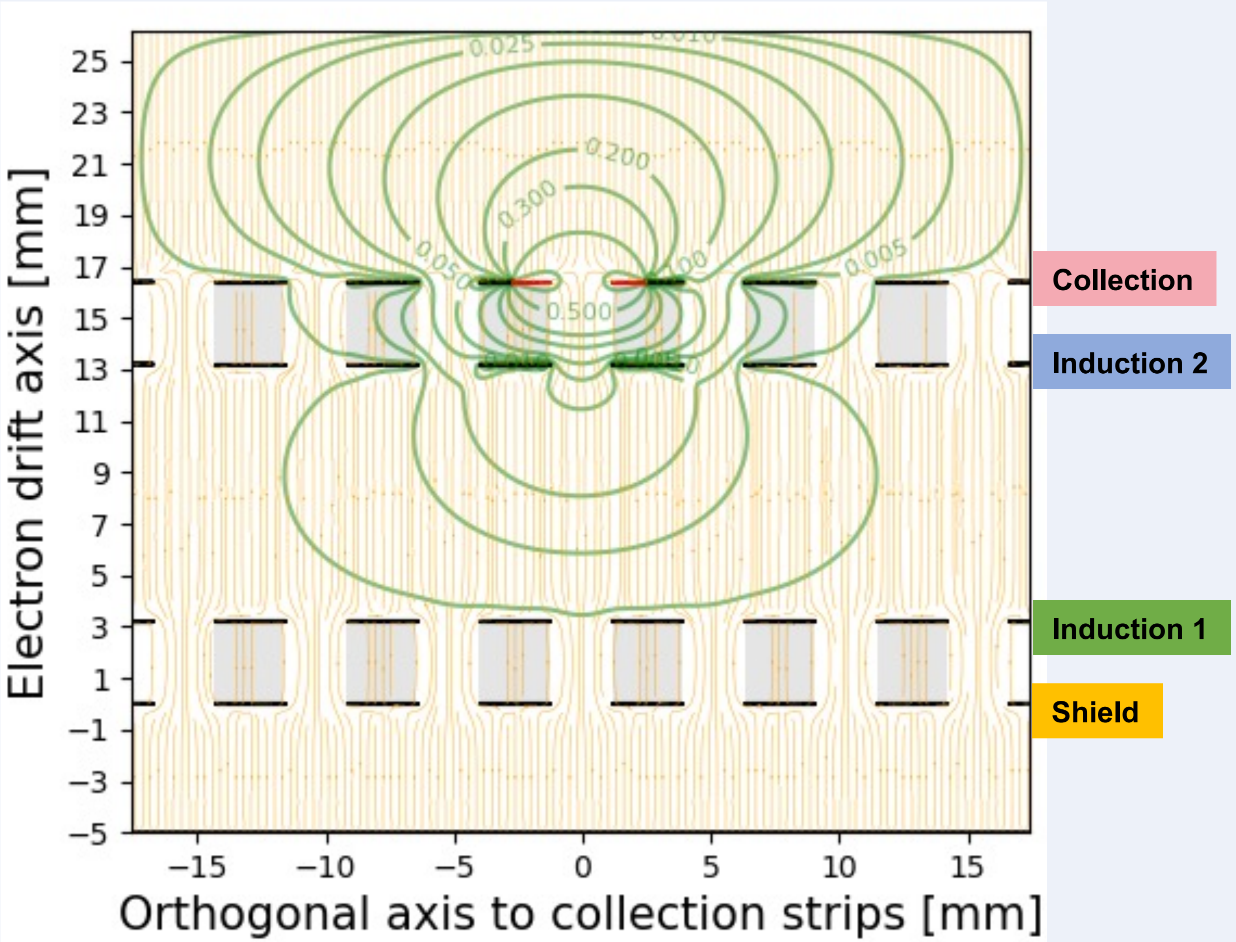
- 3D Finite difference methods (FDM):

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

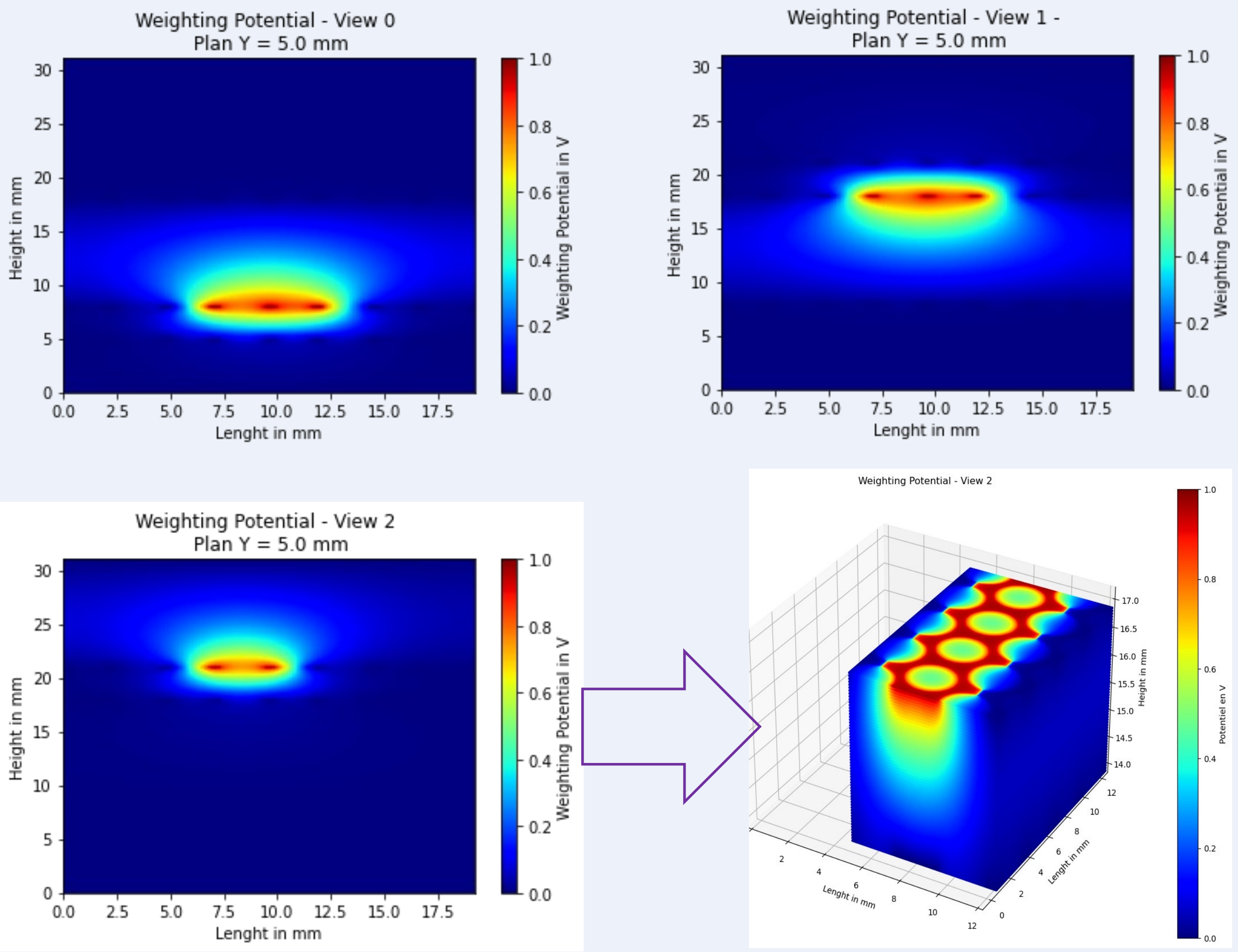
- Iterative method, step by step

Field result

- 2D projection of drift field lines and weighting equipotential



- **Weighting Potential**

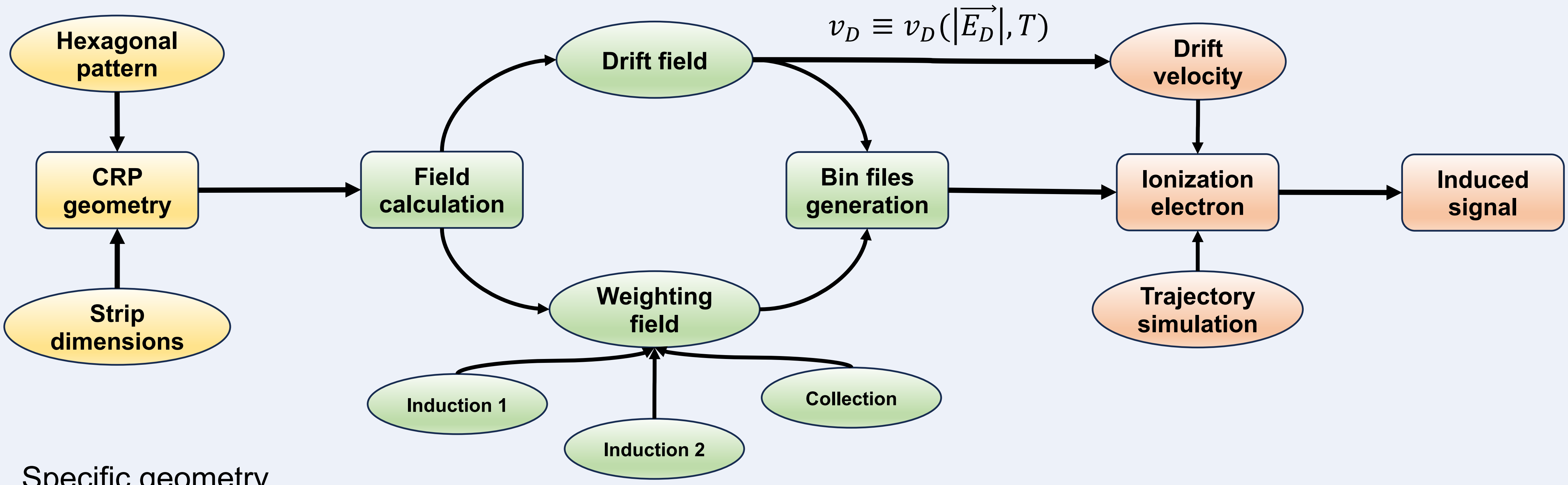


- Induced signal in the nearby strips

Induced signal simulation

$\left|\vec{E}\right| \in [0.5\ ;4\ ]$ kV/cm

- Design of a simulation on Python



1. Specific geometry setting up

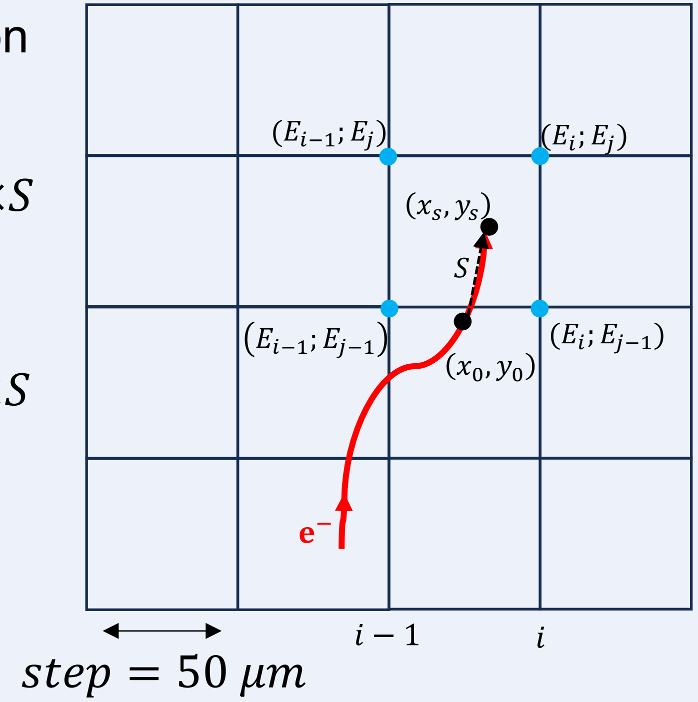
2. Field generation with CRP geometry

Ionization electron generation

- Thermal electron
  - Trajectory follow drift field lines
- The electron trajectory is perfectly defined
- Runge Kunta like simulation

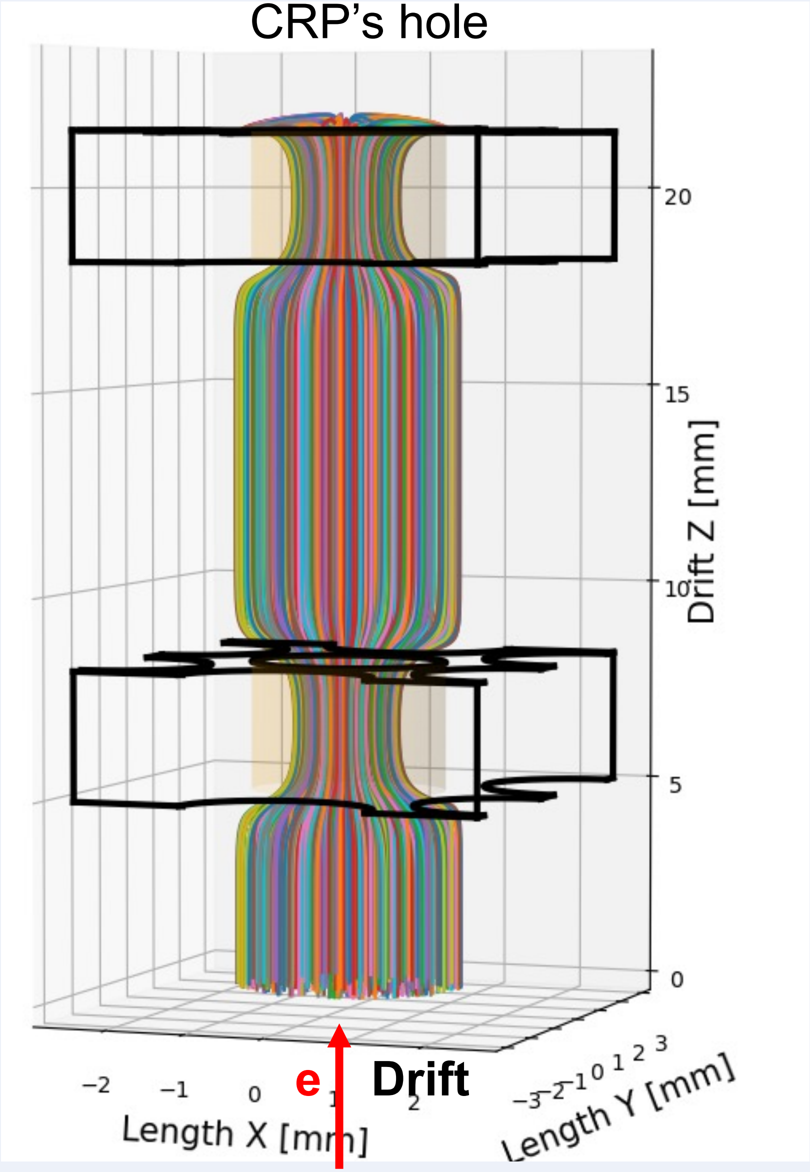
$$x_{i+1} = x_i + \frac{E_x^{interp}(x_i, y_i)}{|E(x_i, y_i)|} \times S$$

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

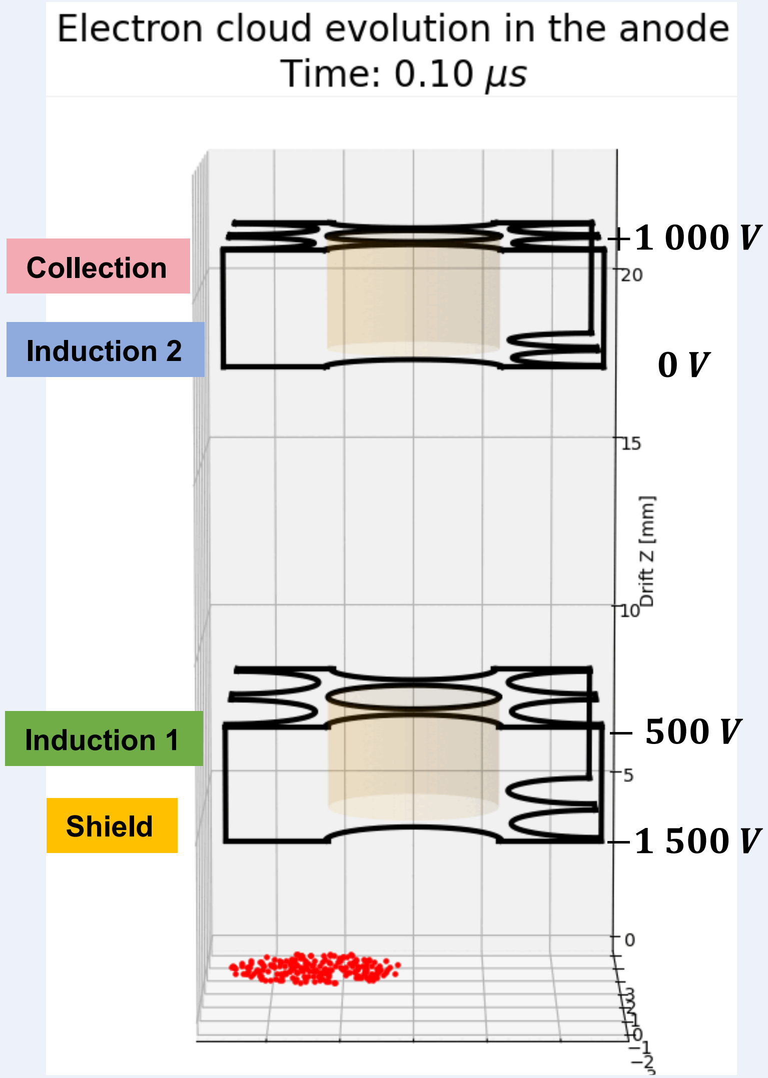


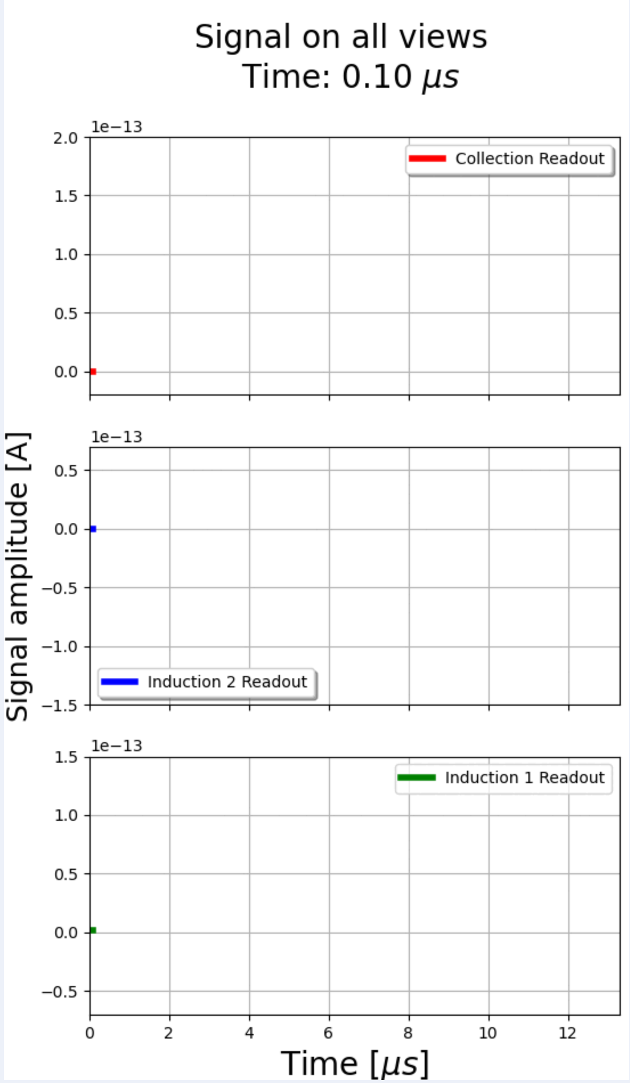
- Drift simulation 5 mm
- Grid of the mesh used for the field calculation

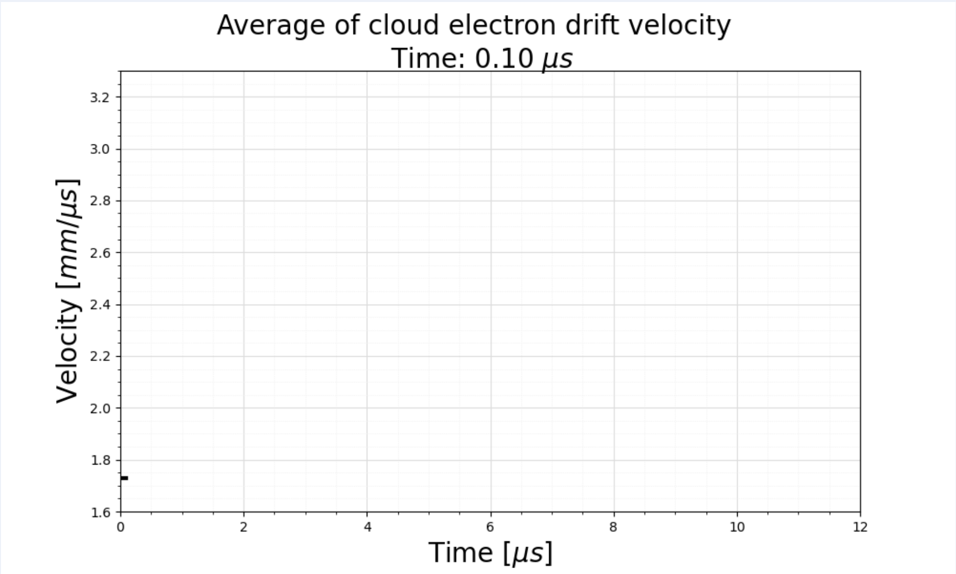
- Electron trajectories passing through a CRP's hole



Electron cloud simulation

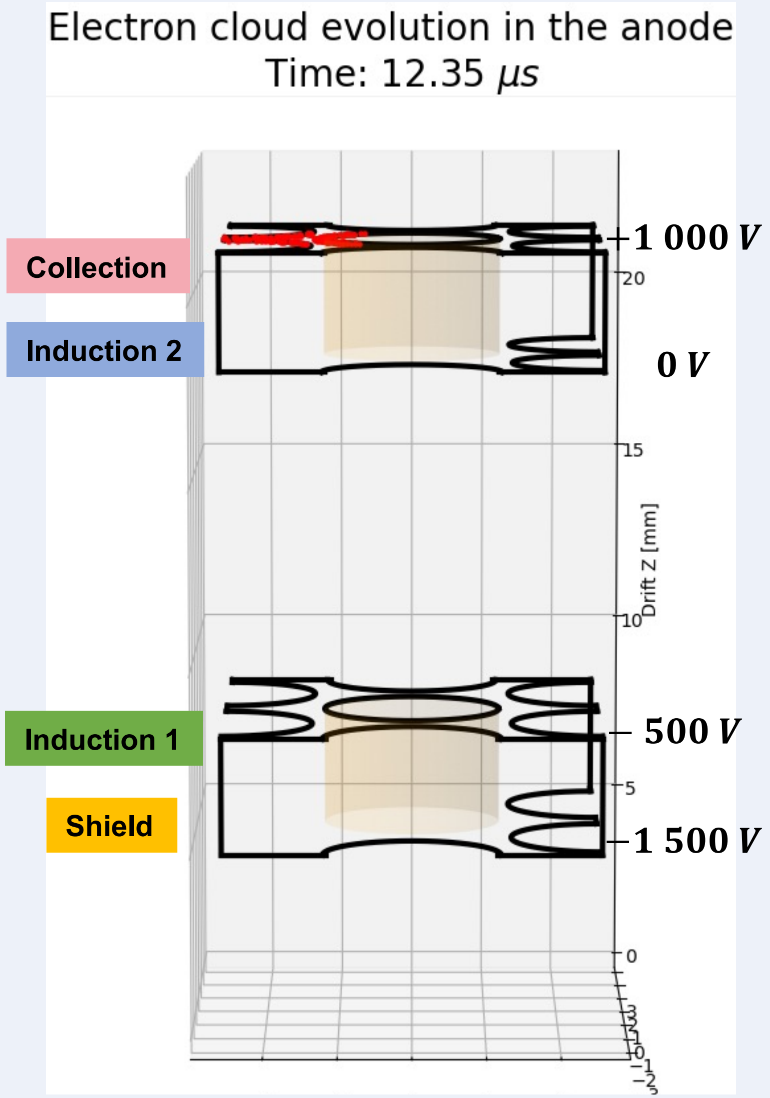


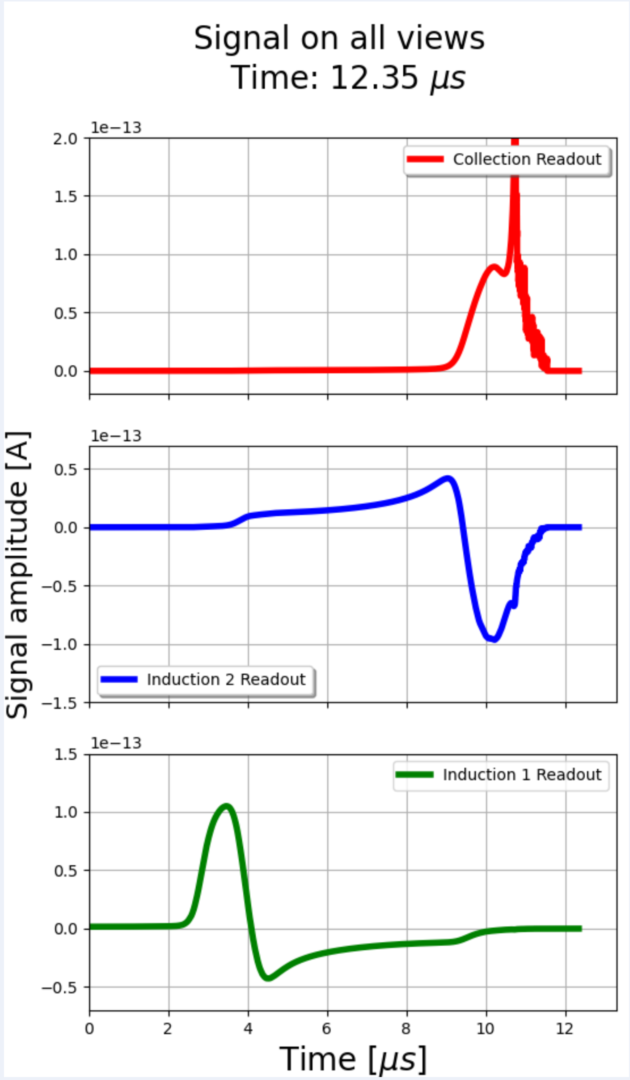


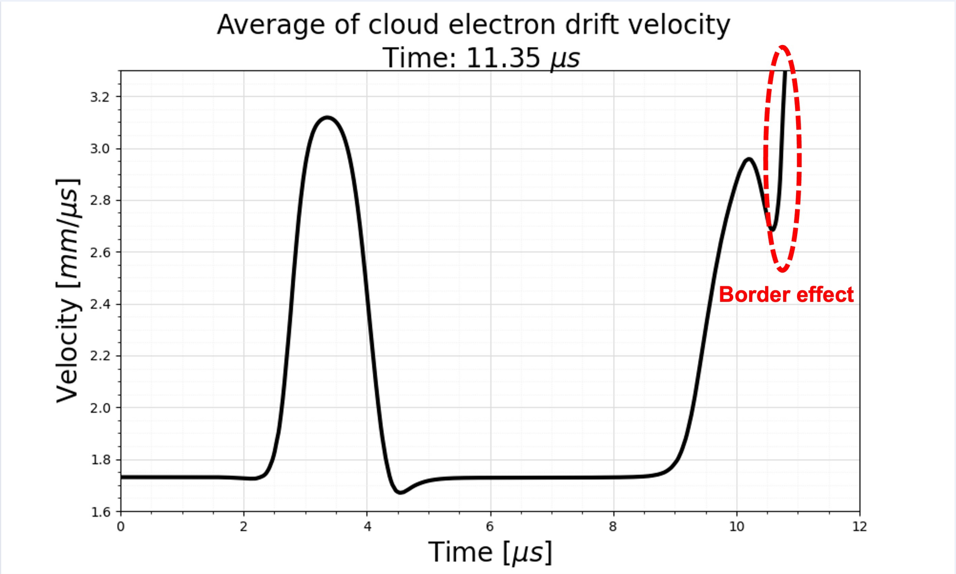


- Border effect near to the collection electrode
- The field takes $\propto 1/r^2$ dependancy which will induce a high frequency signal
- Electronic response will smooth the readout induced current

Electron cloud simulation







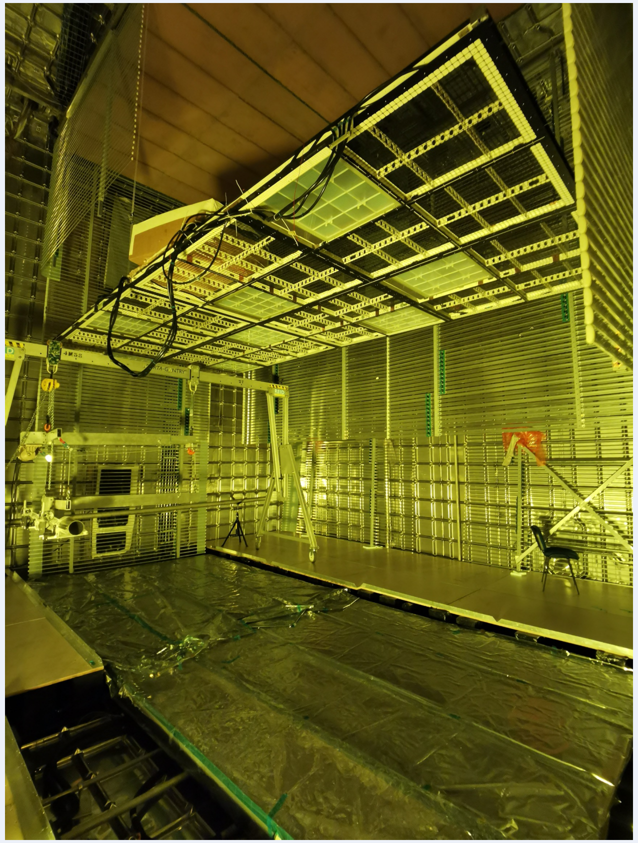
- Border effect near to the collection electrode
- The field takes $\propto 1/r^2$ dependancy which will induce a high frequency signal
- Electronic response will smooth the readout induced current

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 in autumn 2024
- TPC size: 3.0 m (W) × 6.8 m (L) × 6.8 m (H) divided in two vertical drift volumes

2 Top CRP modules



2 Bottom CRP modules

➢ Vertical drift design at CERN
➢ Cryostat inside

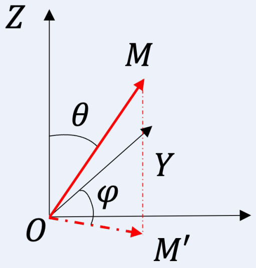
➢ **Coldbox:**

- Liquid argon chamber for testing CRPs with cosmic rays at CERN
- 20 cm drift

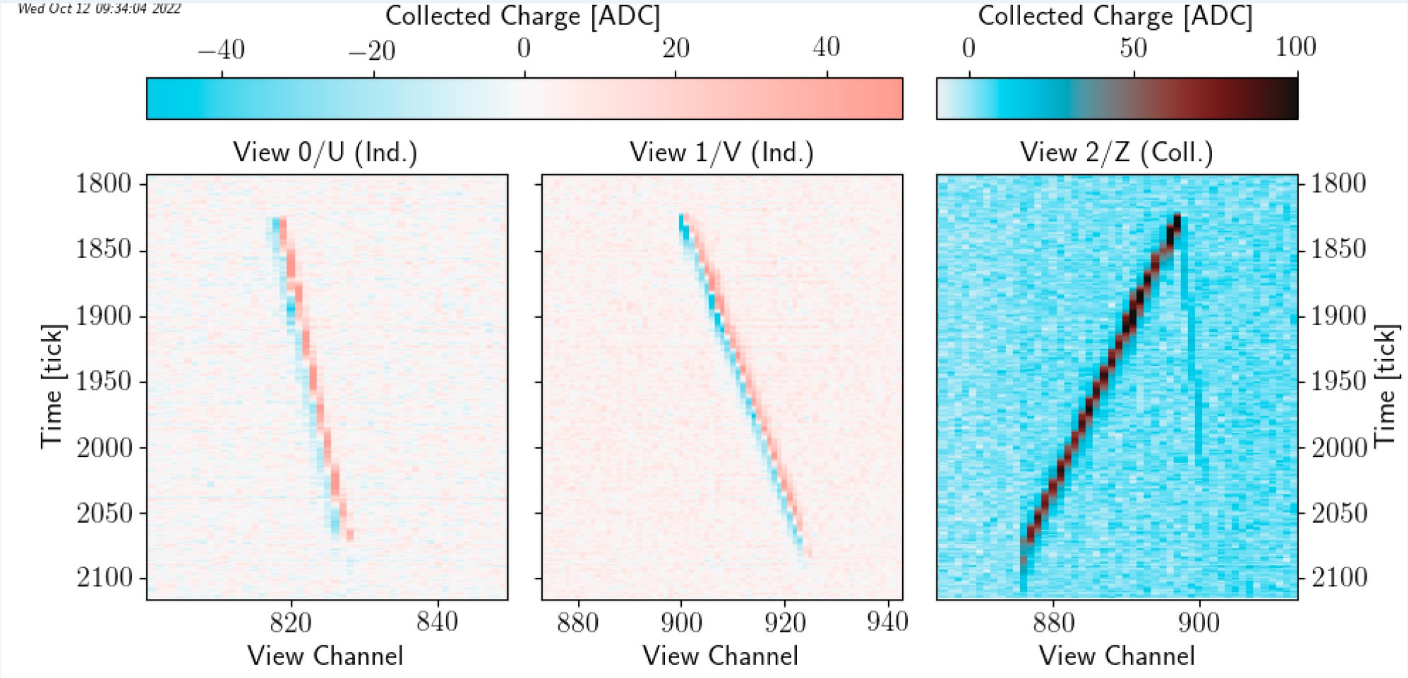
Since 2022

➢ **Use coldbox data to compare with simulation**

Data extraction

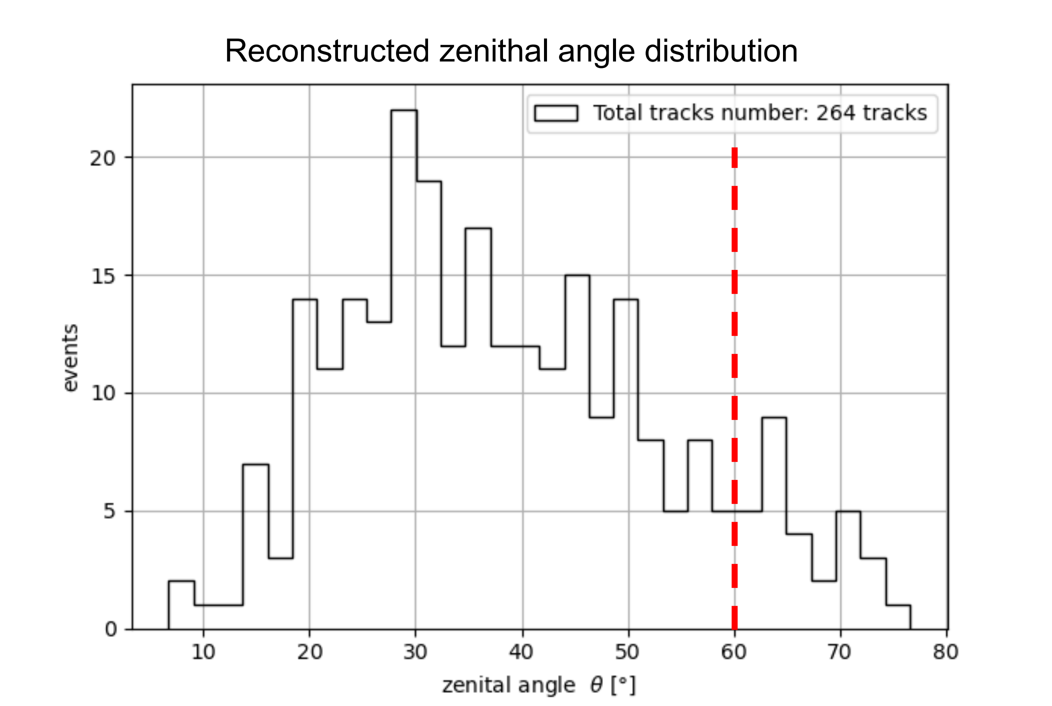


- **Event Display**
  - An example of cosmic ray track from the Coldbox



- Bipolar signals induction view
- Muon events

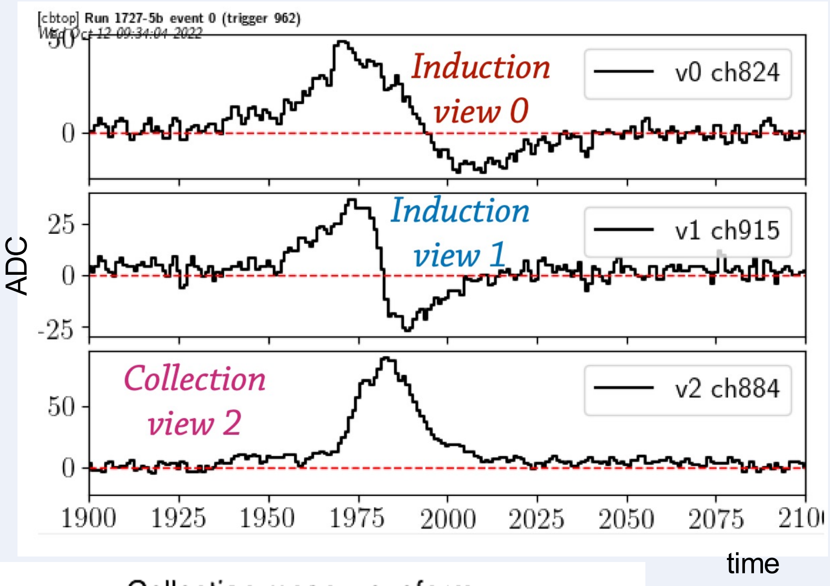
- **Coldbox's data cuts**
  - Tracks with reconstructed angle $\theta > 60°$
  - φ in the cone with $45°$ from the strip readout
  - Track lengths $> 20\ cm$



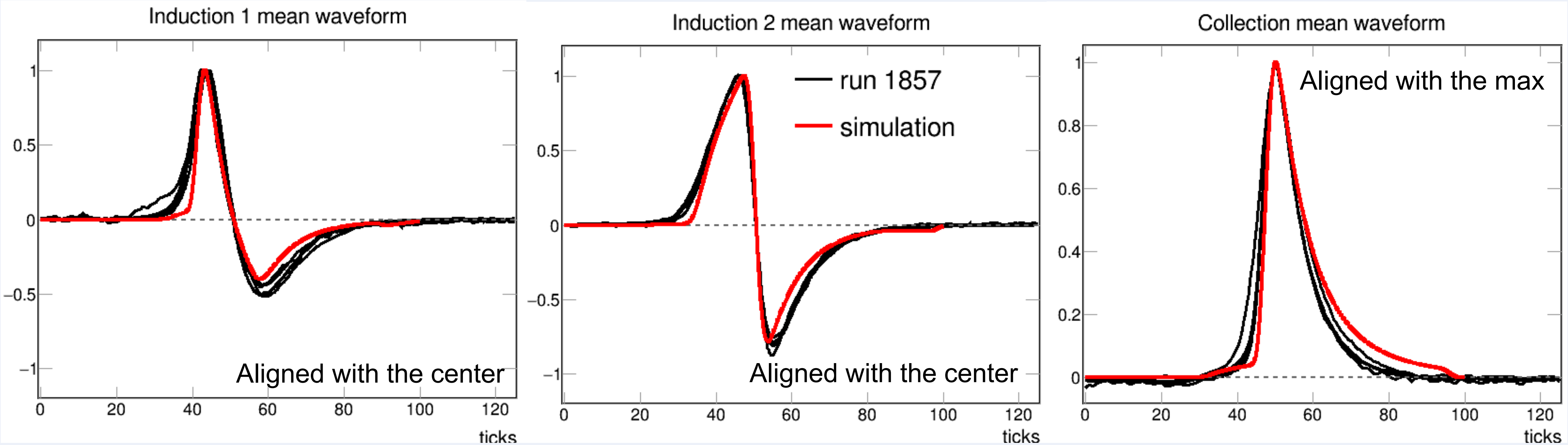
- Data reconstruction with LARDON (software developed by L. Zambelli)

- **Select horizontal track to compare with simulation**

Comparison data VS simulation



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

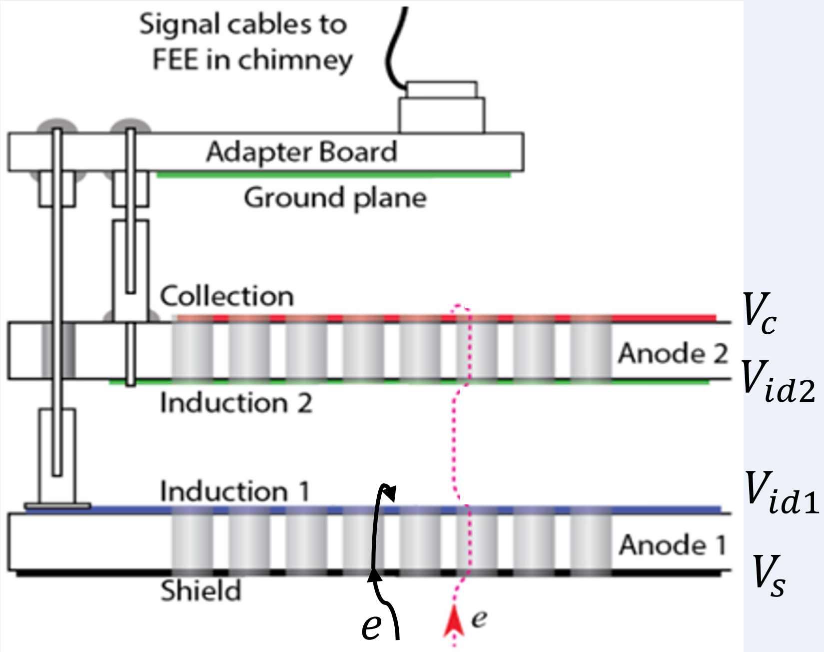


→ **Simulated waveforms in agreement with data**

CRP transparency study

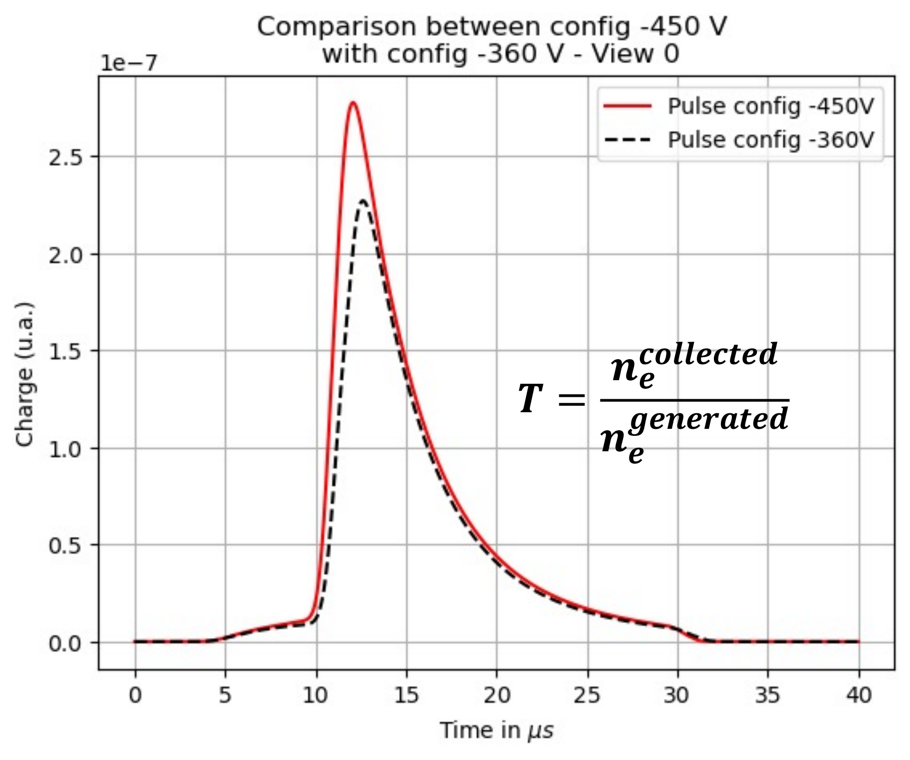
- **Work on signal amplitude to explore the different causes of charge loss**

- 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: $V_{id1} = -360\ V$

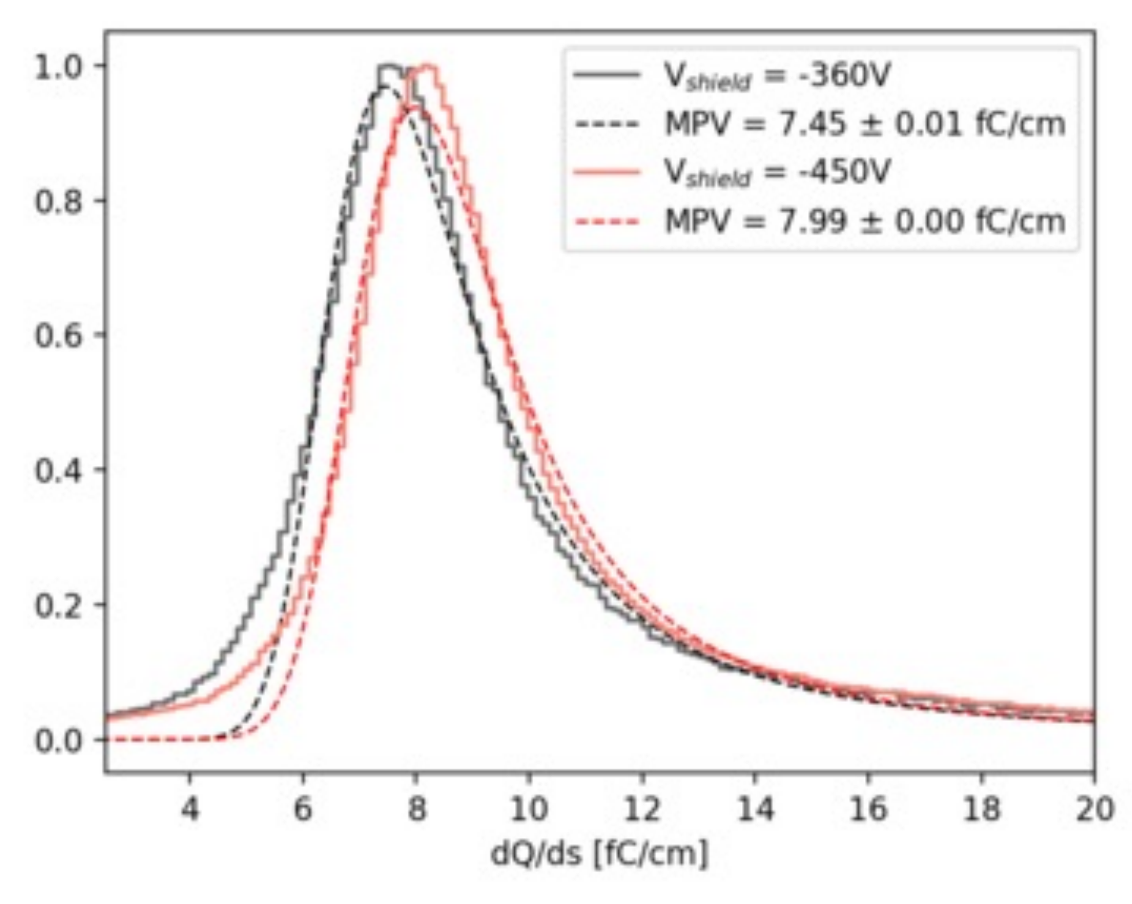


  - Dependency on the biais voltage used

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

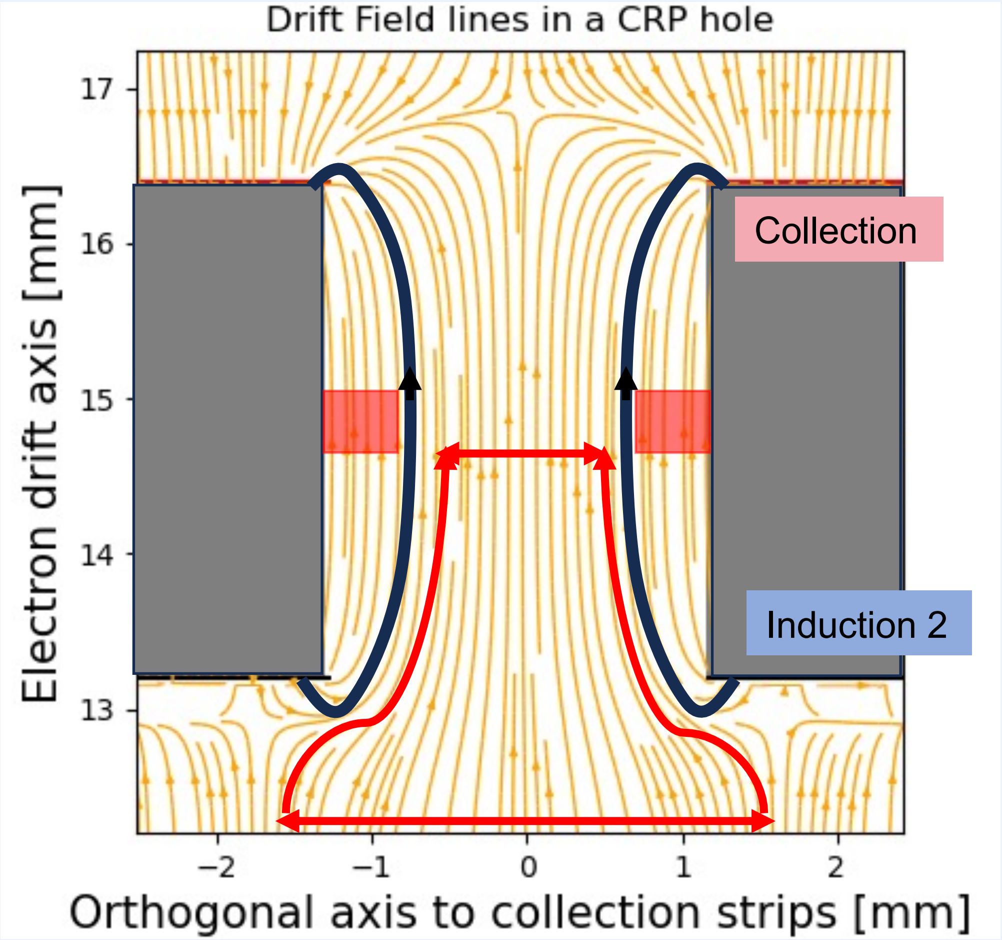
CRP transparency study

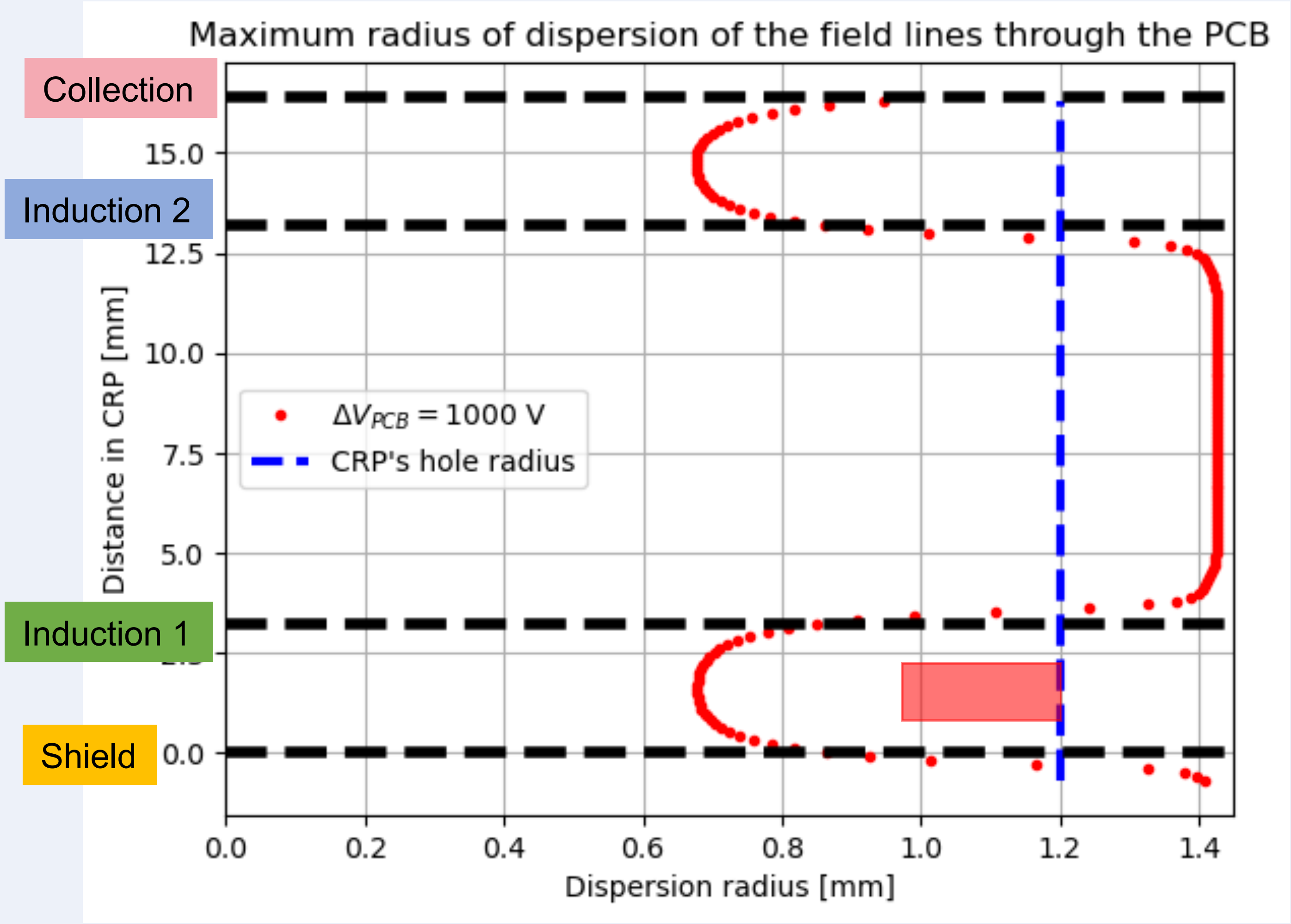
- Coldbox's data with same configuration:
  - dE/dx measured for muons
  - Comparison of the energy reconstruction
- Result:
  - **Increase of 6 % reconstructed energy for the "config -450 V"**
  - **A real effect but smaller than the simulation result**
- **Difference Simulation/Measurements need to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



Holes covering and loss charge

➢ Focalization of drift field lines in the CRP hole





➢ Field line too focused for loss charge → **Electron diffusion**

Transverse electron diffusion

- **Transverse electron diffusion could cause a loss of charge in the CRP**

$$\frac{\partial n}{\partial t} = D_L \frac{\partial^2 n}{\partial z^2} + D_T \left(\frac{\partial^2 n}{\partial x^2} + \frac{\partial^2 n}{\partial y^2} \right)$$ **Fick's equation**

- Gaussian spatial distribution of the electrons over time

- Average diffusion length given by:

$$\sigma_{L,T} = \sqrt{2 D_{L,T} t}$$

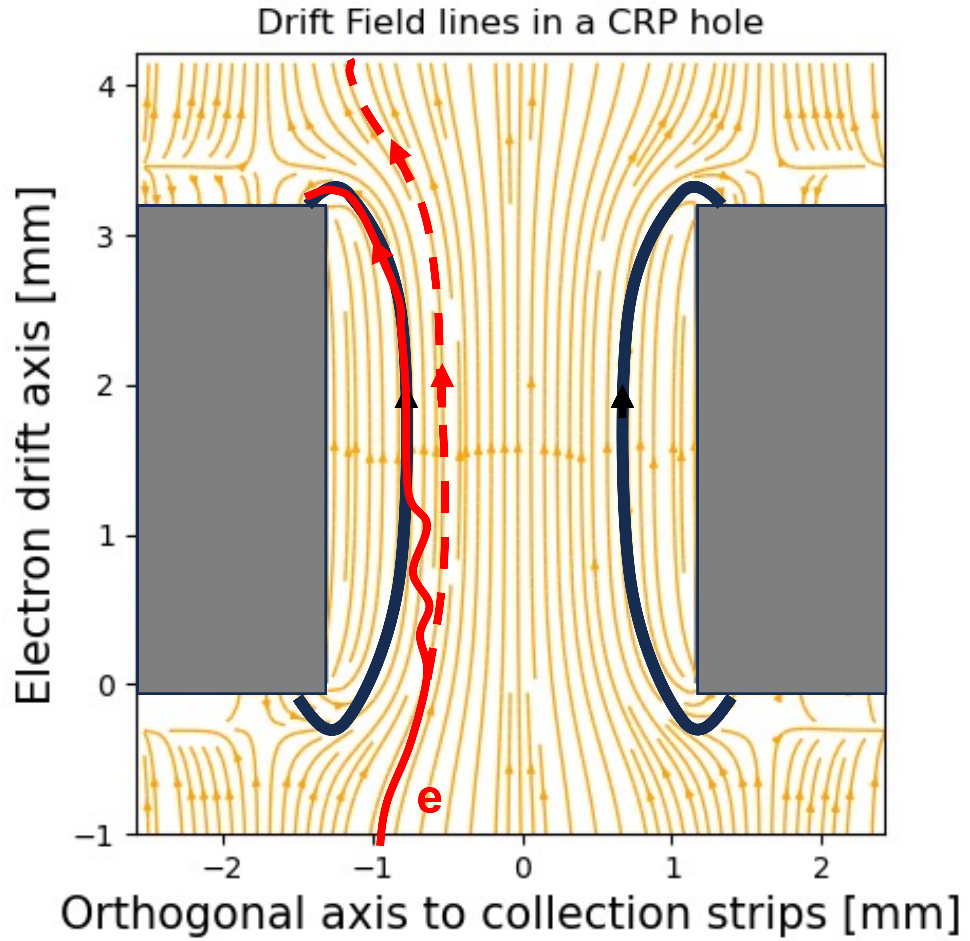
- Transverse diffusion coefficients measurement*:

$$D_T = 13.2\ cm^2/s$$

- Maximal diffusion length for $\sim 7\ m$ drift:

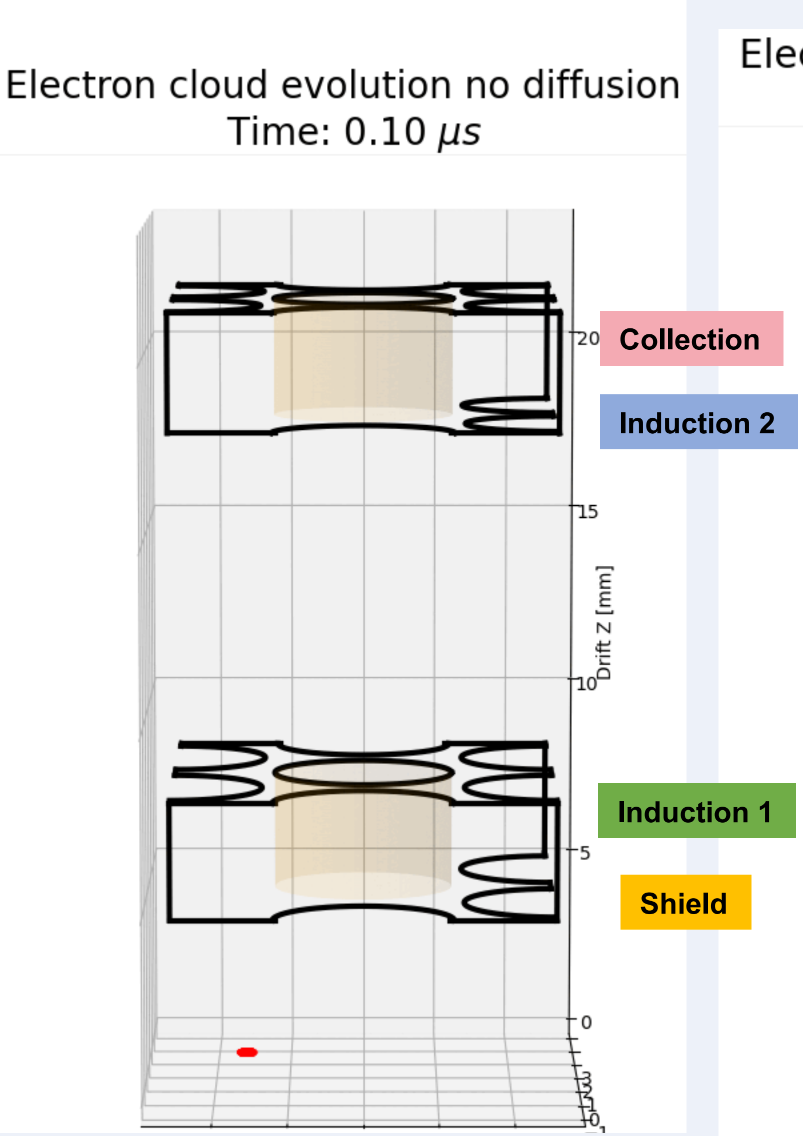
$\sigma_T = 0.34\ cm$ < strip length

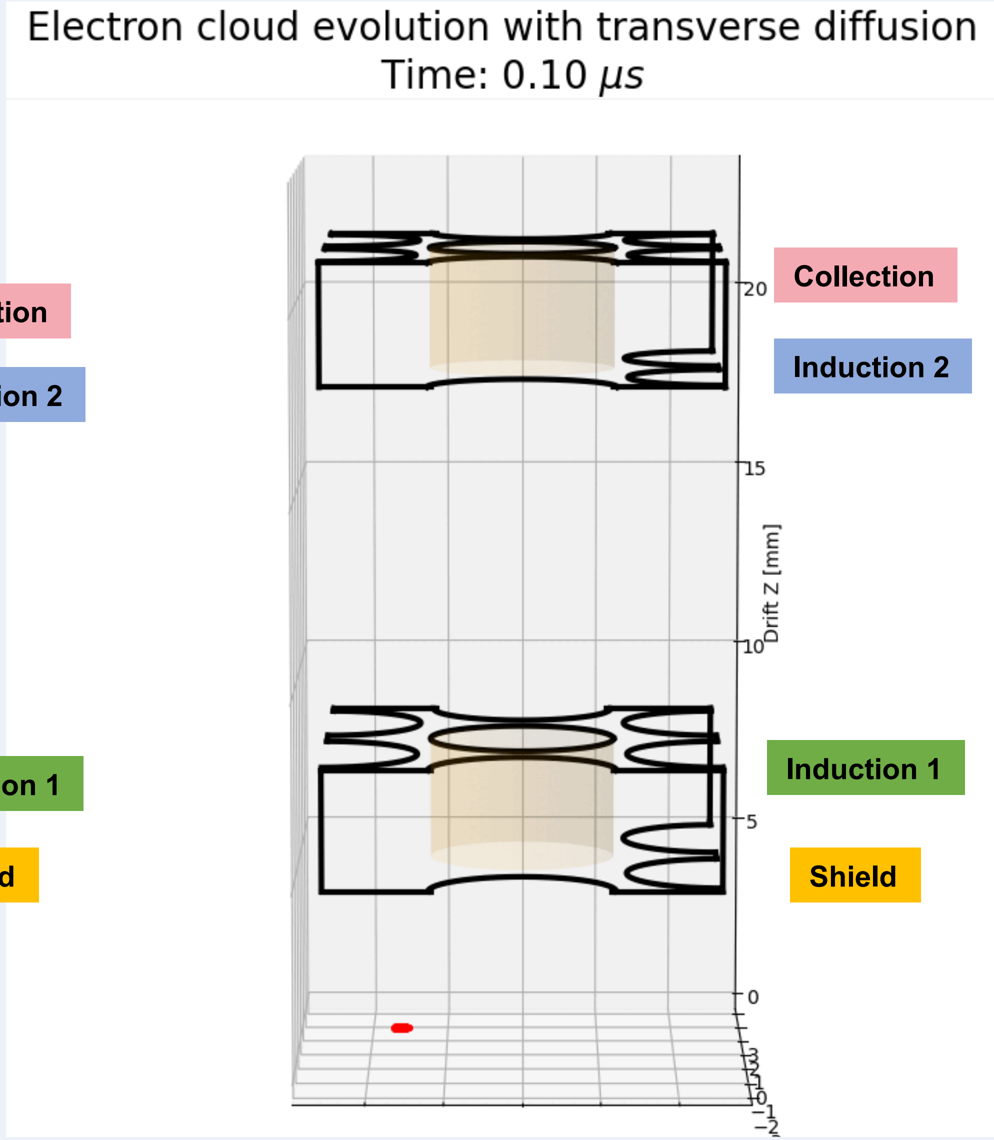
- Electron loss on Induction 1 due to the diffusion

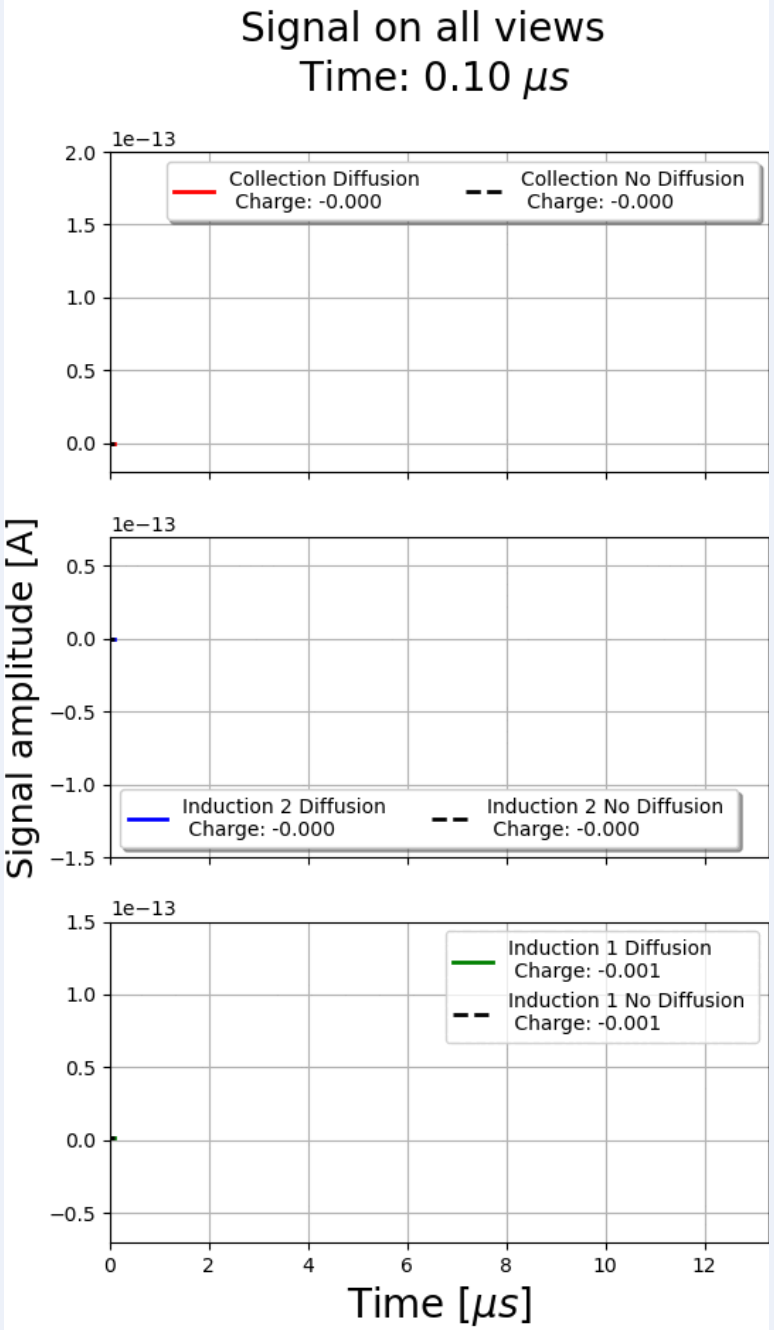


* *https://lar.bnl.gov/properties/trans.html*

Transverse electron diffusion



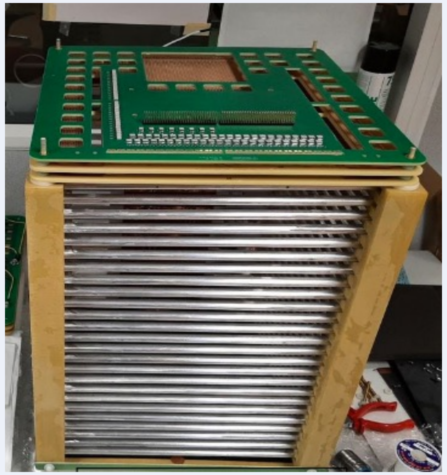




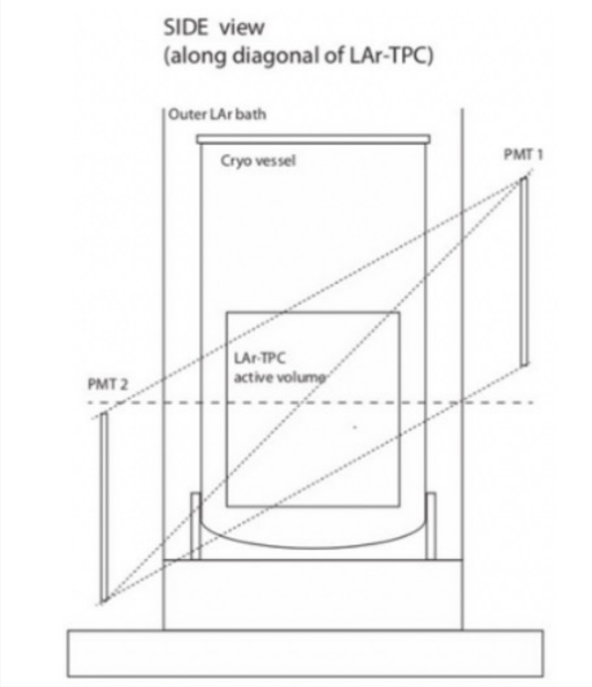
R&D TPC 50 L detector

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

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

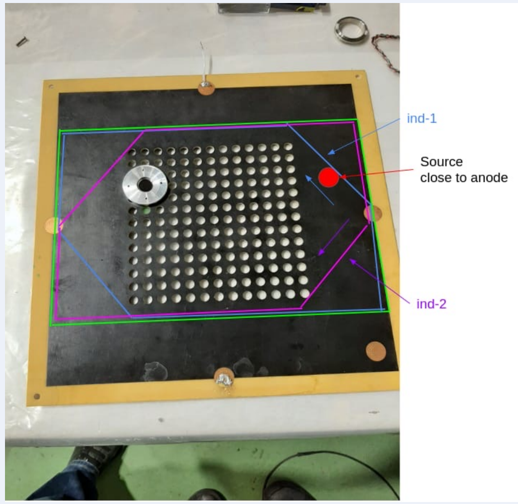


- Cosmic + random trigger

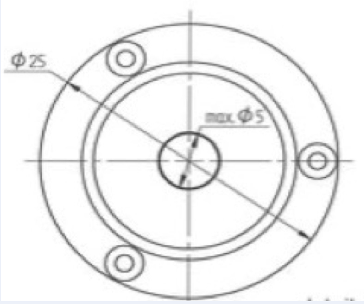


- **But not enough cosmic ray event**

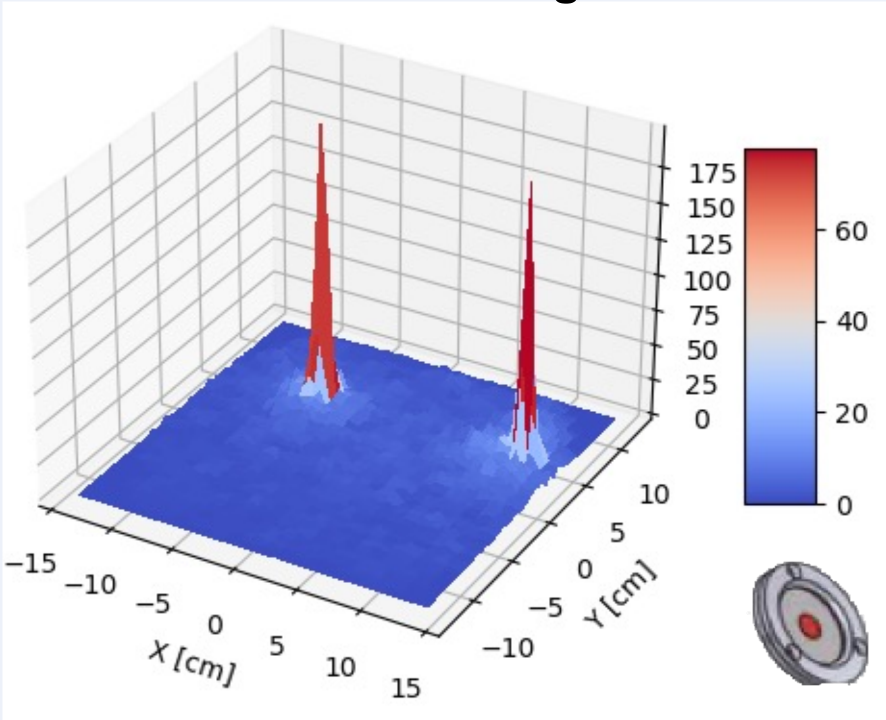
- 207 Bismuth sources
- Hexagonal active area



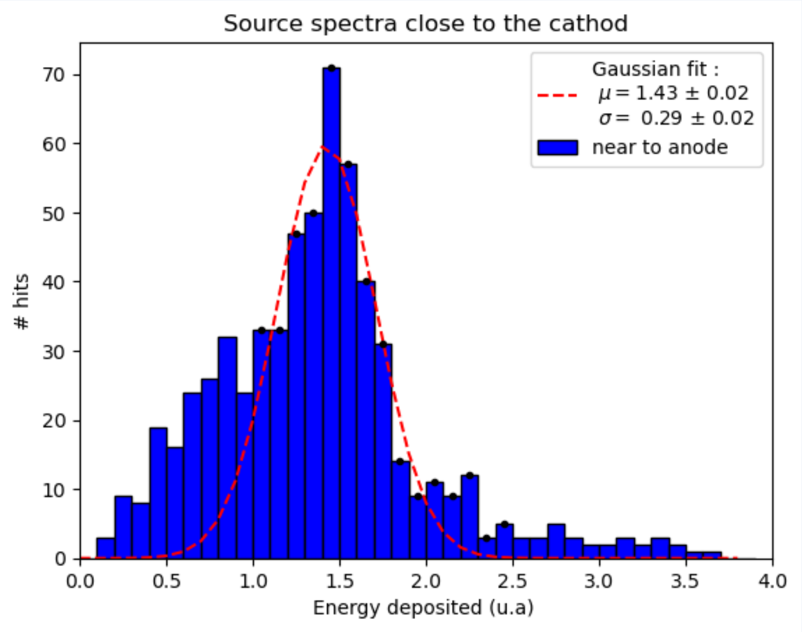
- Electron conversions around 1 MeV
- Range in liquid argon: ≈ 5 mm

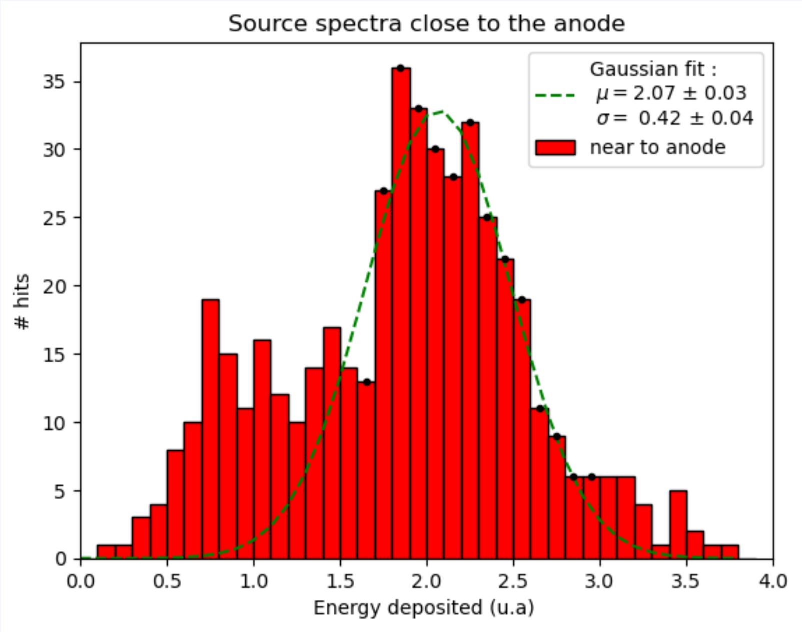


Reconstructed single hits



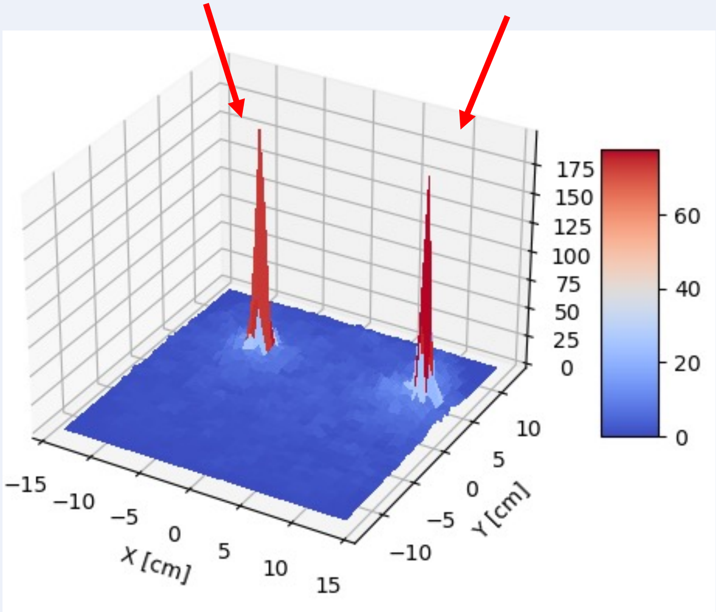
Bi207 Reconstructed Spectra





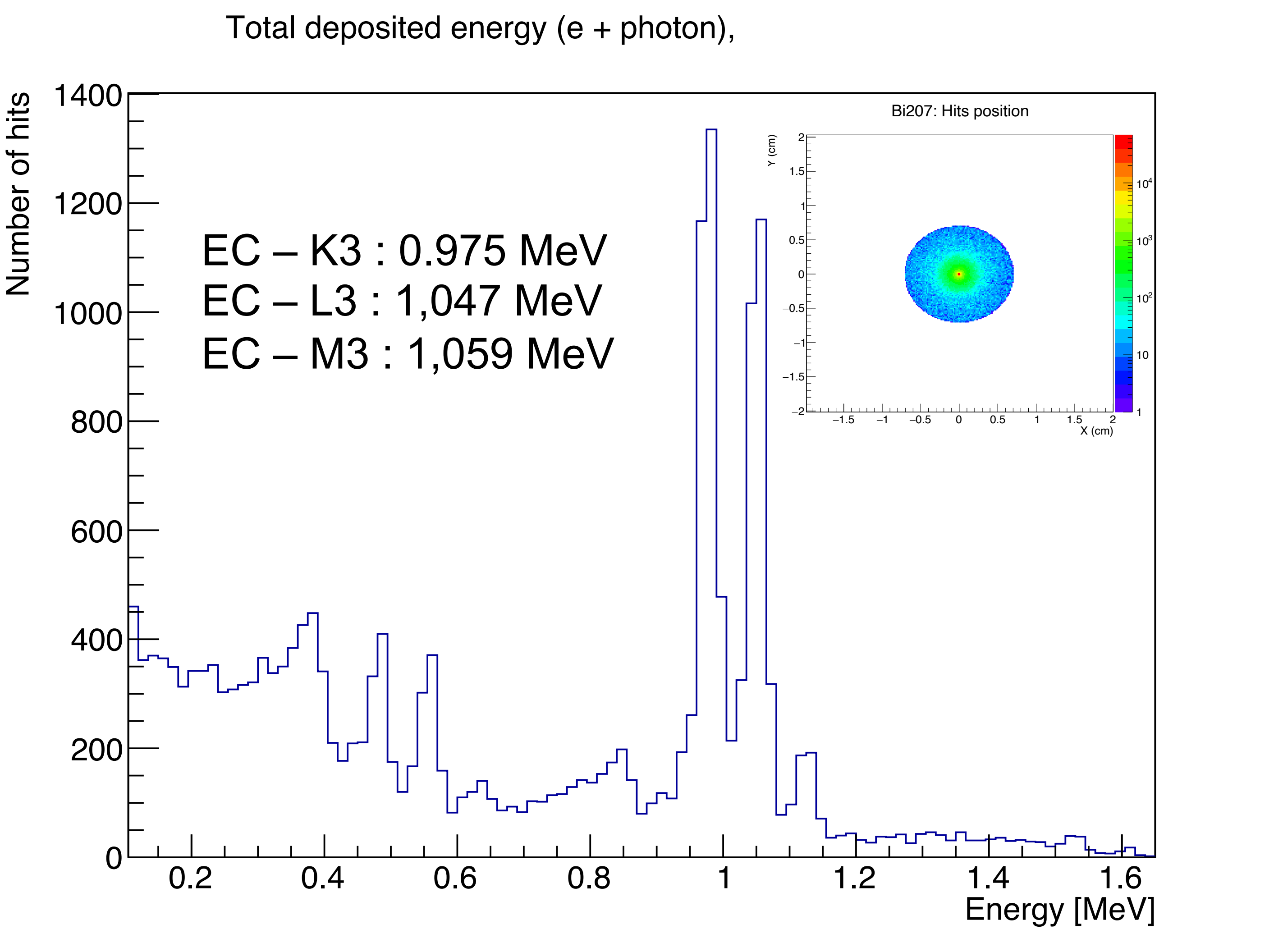
Near cathode

Near anode

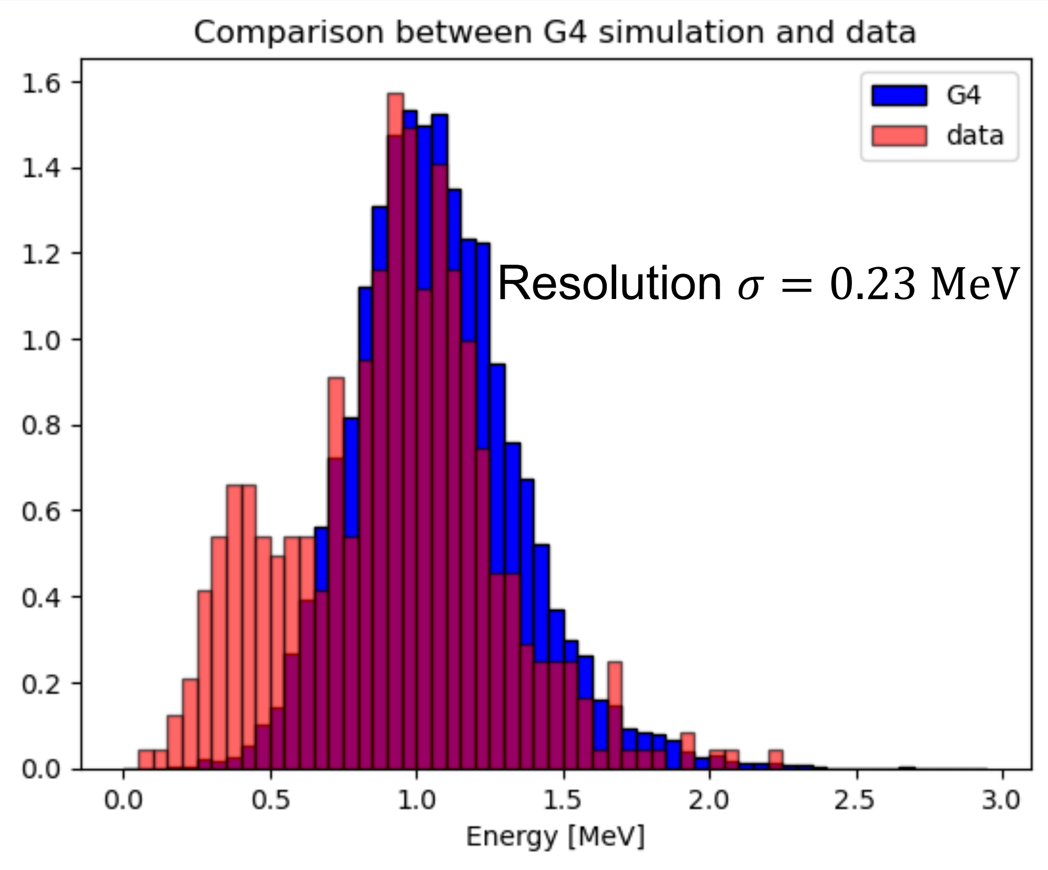


- ➢ Useful to calibrate detector with peak at 1 MeV
- ➢ Red is closer to the anode than blue
- ➢ Not enough single hit events

G4 Simulation



Cut Geant4 $E > 0.8$ MeV



Summary

➢ **Work done:**

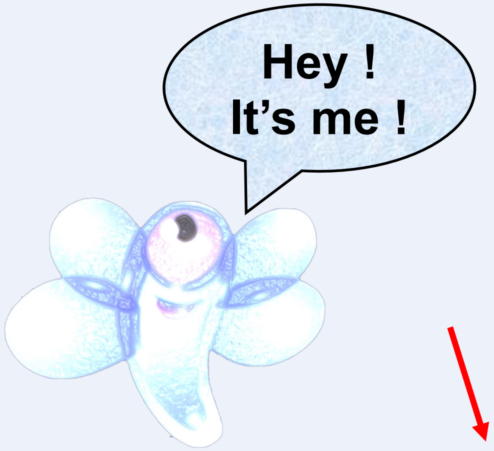
- Numerical simulation conception to understand the formation of induction signals of all views
- Coldbox's data extraction → simulation is good agreement with this
- Get some data and start the analysis of 50 L R&D TPC
- Bizmuth 207 events simulation Geant4 with 50 L and source geometry

➢ **What's next ?**

- Extend the simulation in a bigger volume → track angle studies and position in the TPC (boundary conditions)
- New run 50 L at soon with self-trigger for cosmic ray
- Keep working on the transverse electron diffusion and the impact on the loss charge
- Take part in the analyses of the ProtoDUNE VD at autumn 2024

Back up

Neutrino overview



- Chadwick (1914): Continous β spectra

- Pauli (1930) proposed a neutral fermion called « neutrino »

- There are three lepton flavors ν_e, ν_μ, ν_τ

- Neutrino interact only by weak interaction $\Longrightarrow$ Only left-handed $\Longrightarrow$ Massless in Standard Model

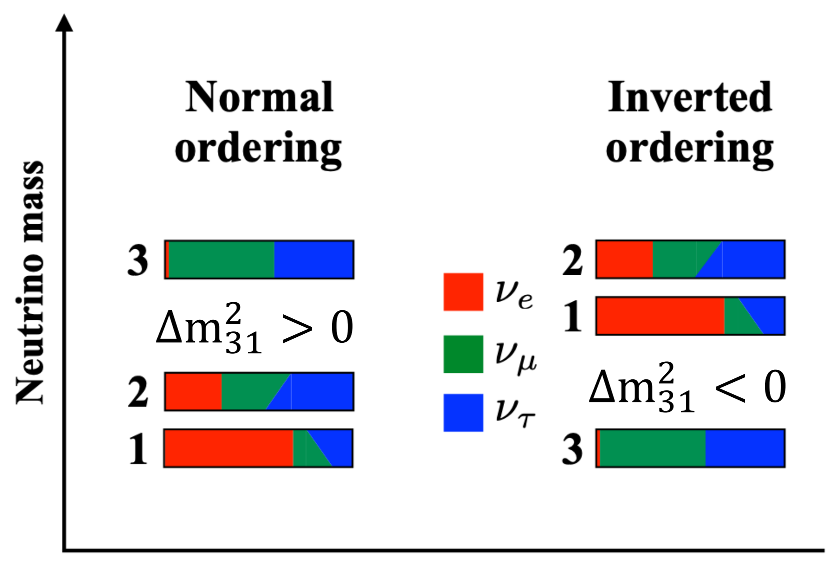
- But neutrino need a mass to oscillate

$$m_{\nu e} < 1\ eV$$

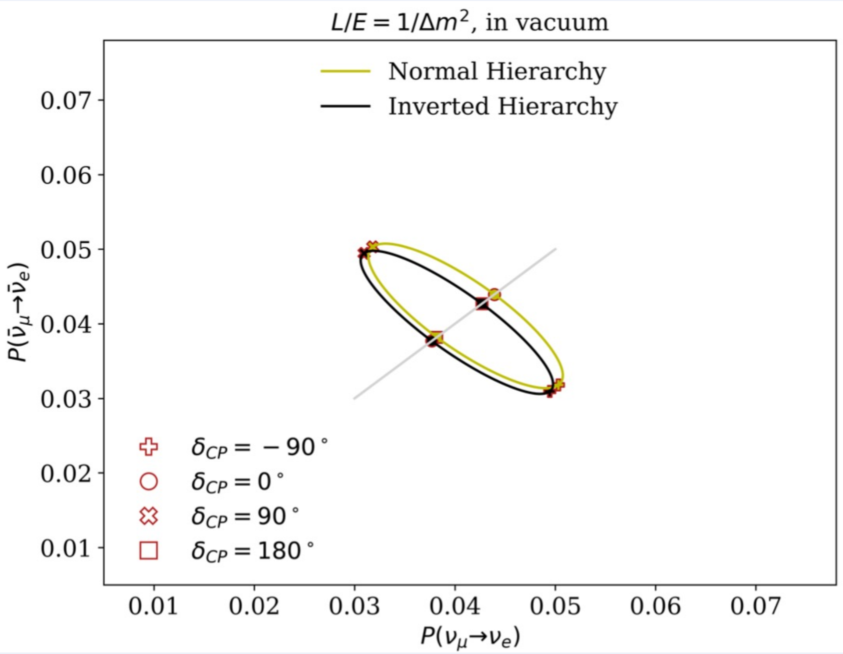
$$\sum m_\nu > 0.06\ eV$$

Mass ordering

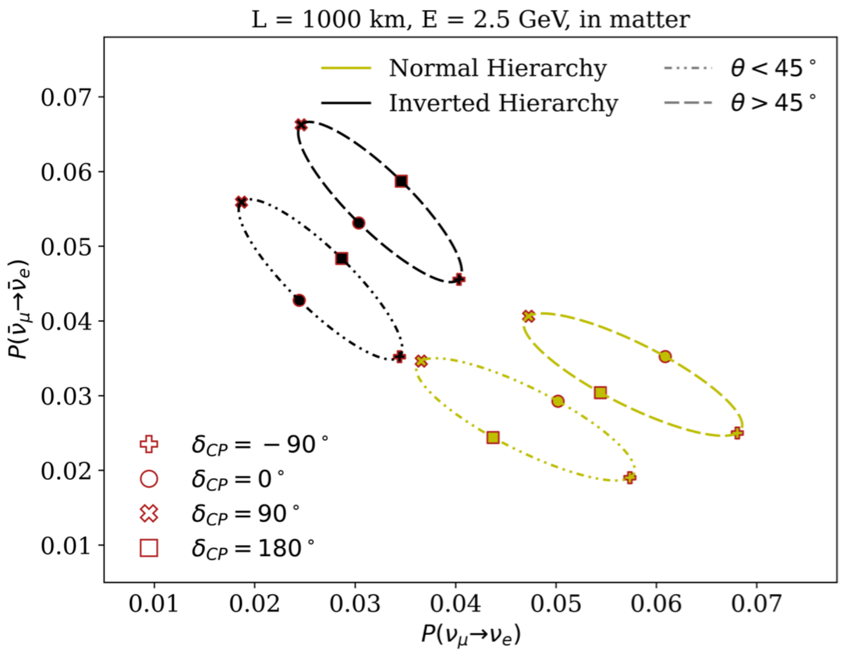
- Sign of $|\Delta m^2_{31}|$ → Mass ordering



Vaccum



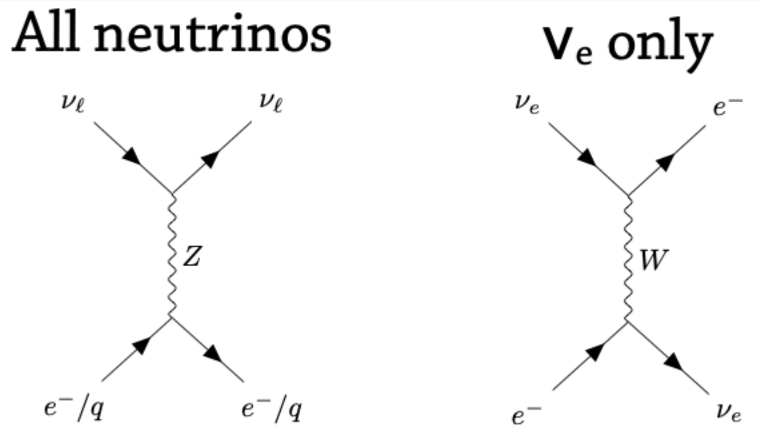
Matter

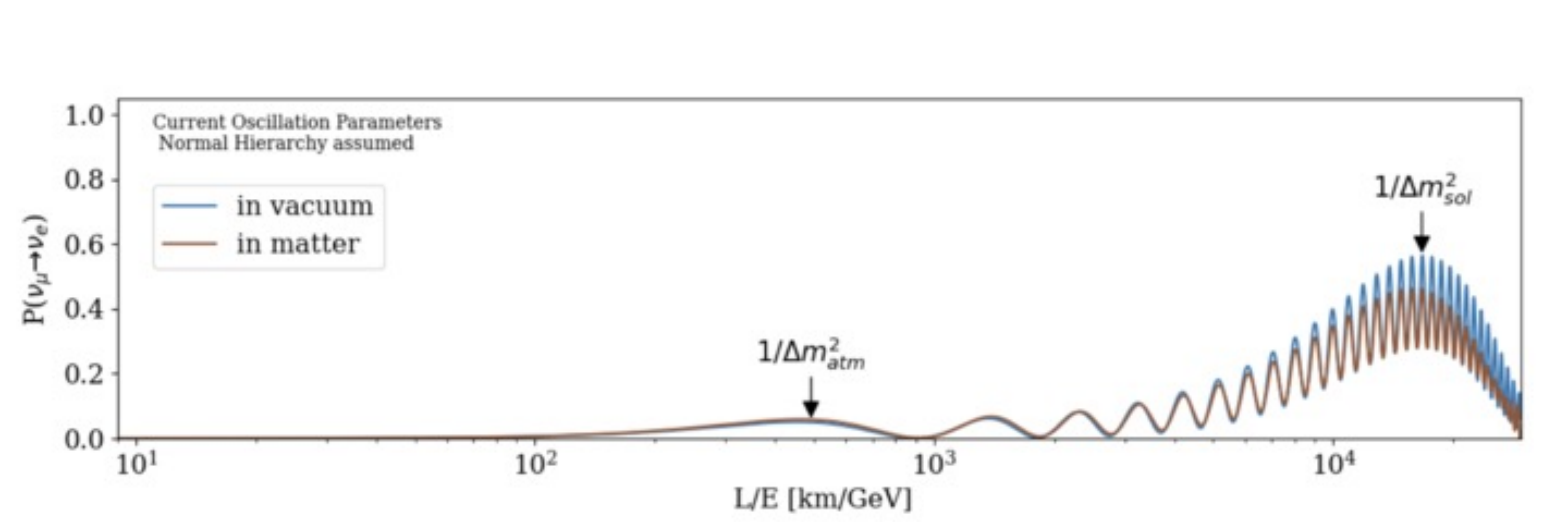


Matter effect

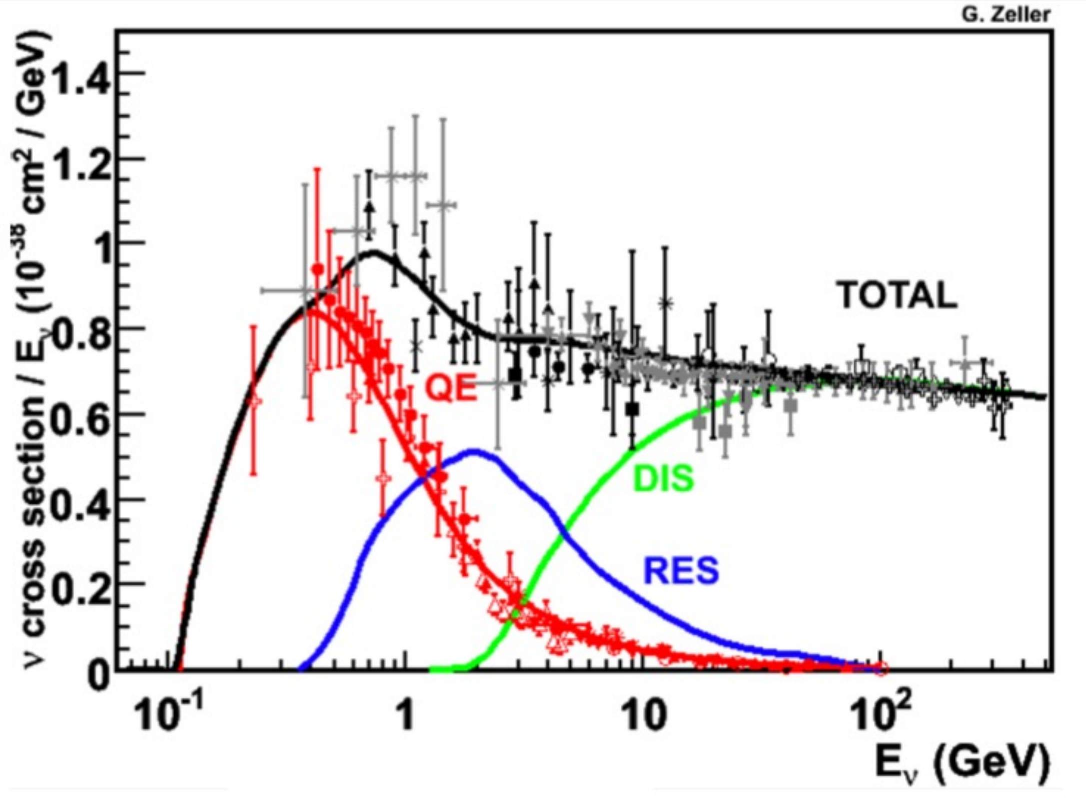
➢ Neutrino oscillations are modified by matter effect

➢ Add a effective potential to the Hamiltonian

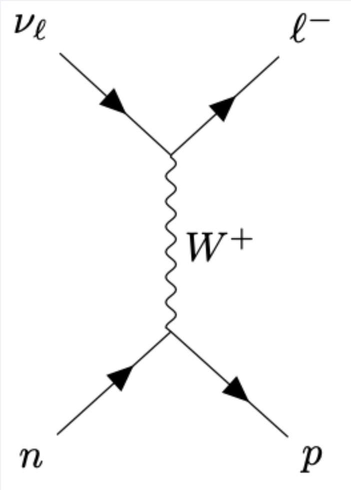




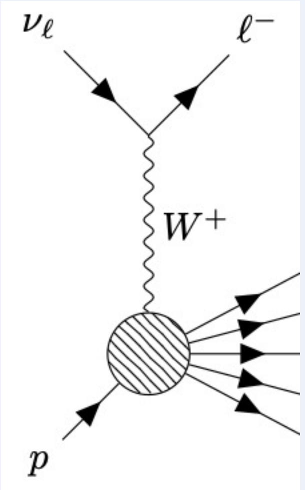
Charged currents cross section



QE: Quasi elastic

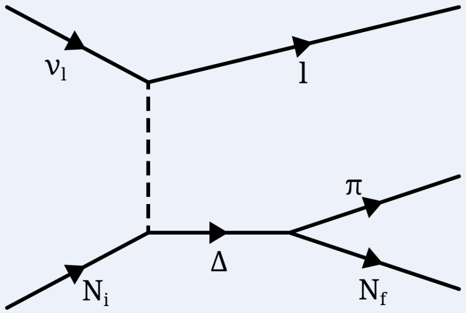


DIS: Deep inelastic



Interaction with quarks

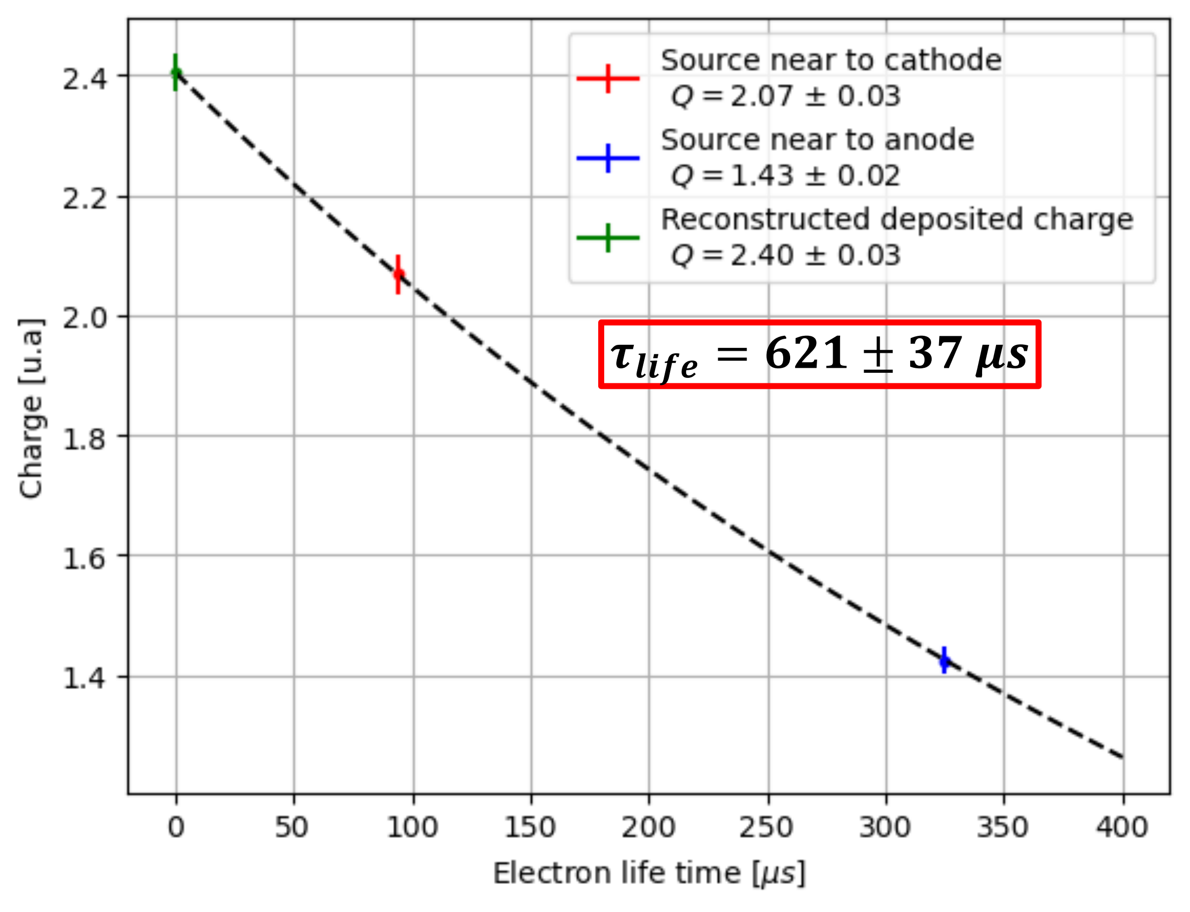
RES: Resonant

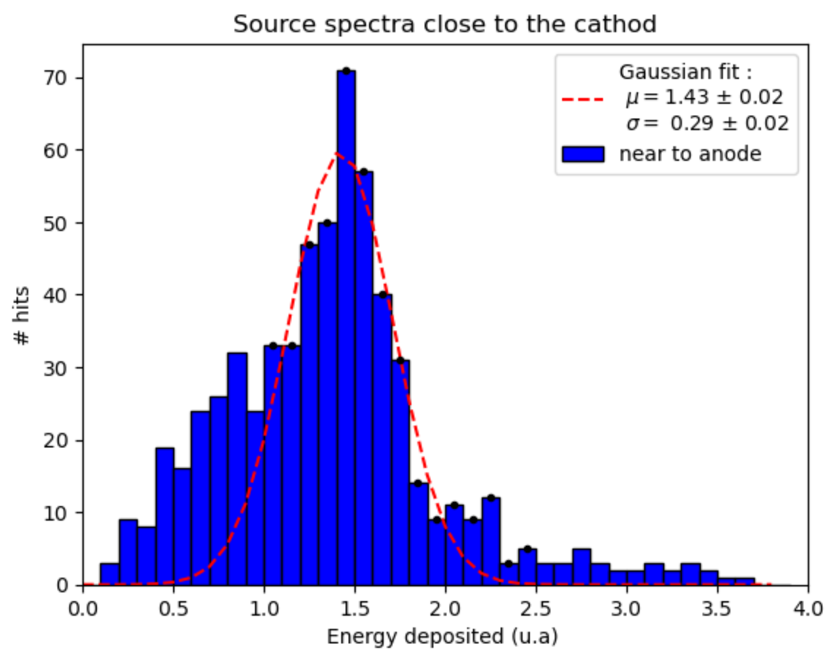


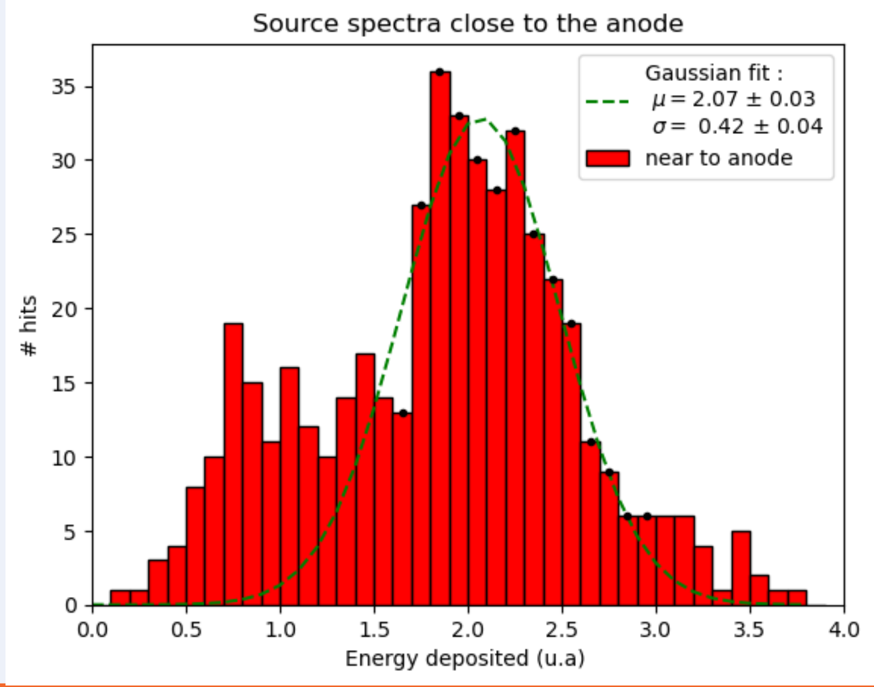
Electron life time

- To reconstruct the charge, it is necessary to take into account impurities (N_2, O_2, etc.):

$$\tau_{life} \approx \frac{300}{\rho(impurities)}$$







Boundary conditions (annexe ?)

- Mirror boundary conditions

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

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

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

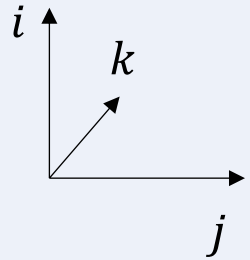
$$\phi_{i,j,-1} = \frac{\phi_{i+1,j,k} + \phi_{i-1,j,k} + \phi_{i,1,k} + \phi_{i,-1,k} + \phi_{i,j,k-1} + \phi_{i,j,k+1}}{6}$$

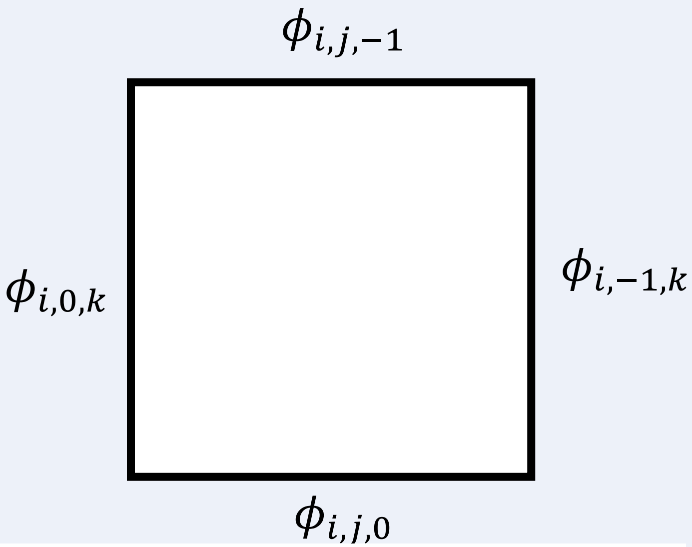
- Dirichlet boundary conditions

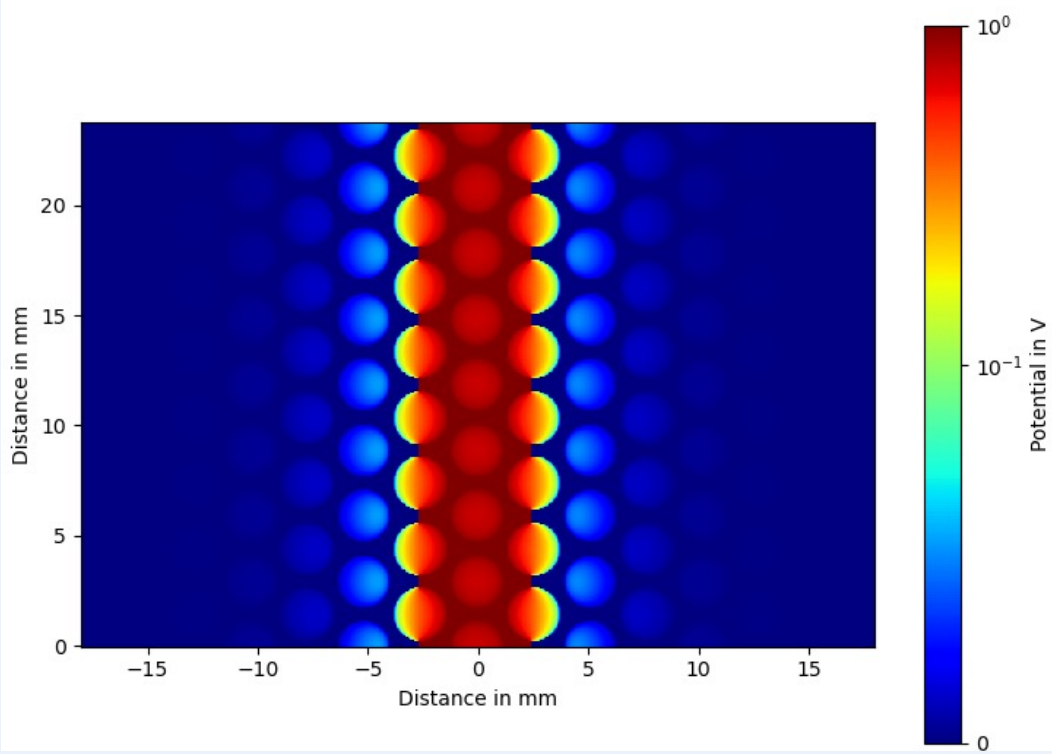
$\phi_{i,0,k} = 0$

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

Valid for a calculation windows ≥ 7 strips







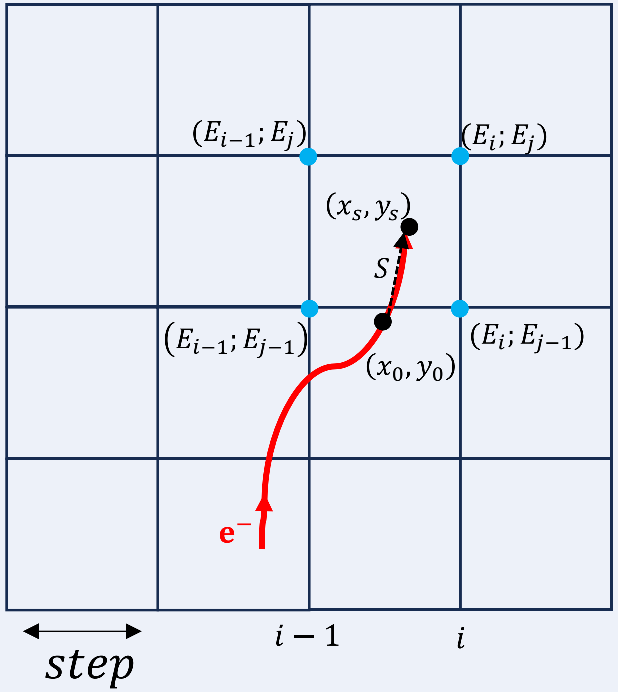
Ionization electron generation

- Thermal electron
  - Trajectory follow drift field lines

- Runge Kunta like simulation

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

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

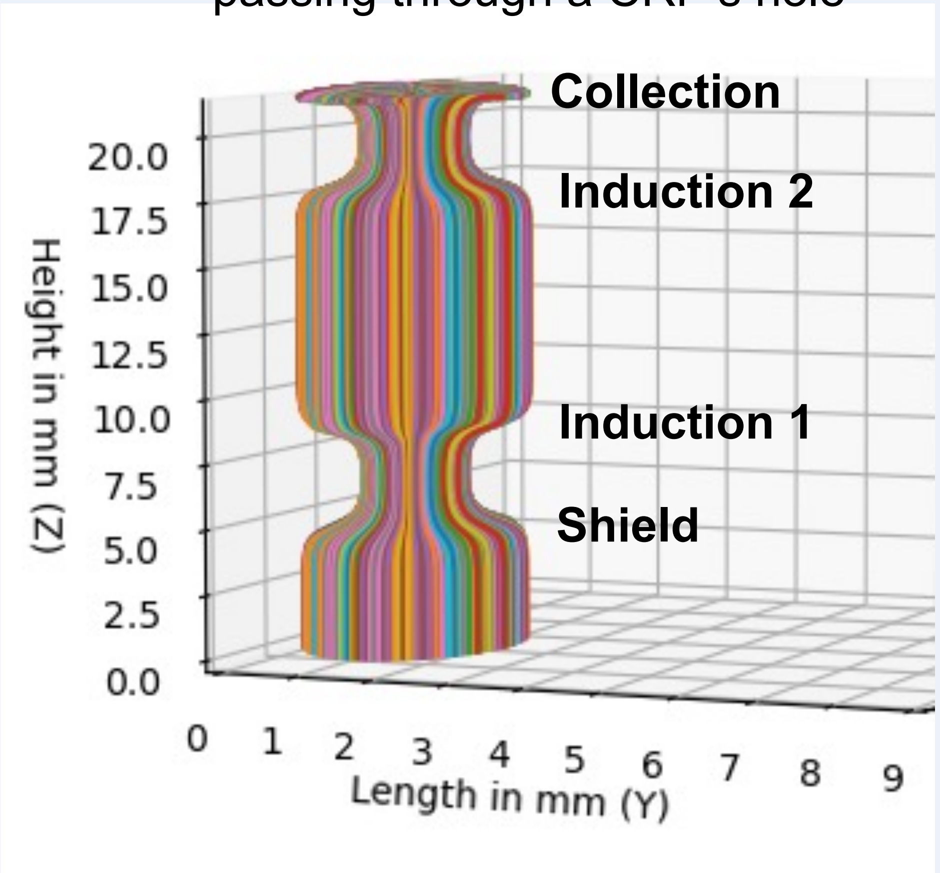


- Field interpolation

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

- Drift simulation 5 mm

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



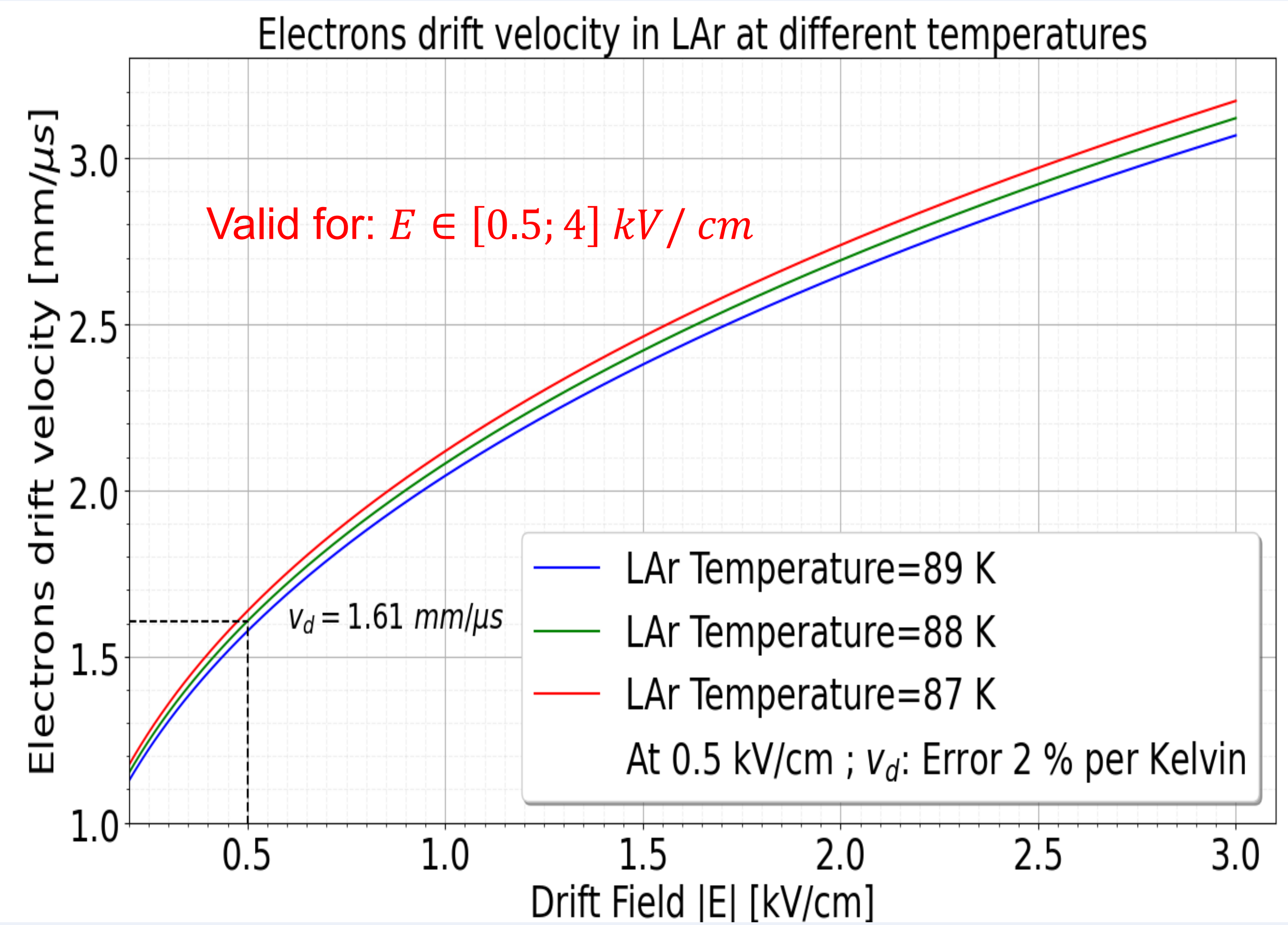
Drift velocity: Walkowiak Fit

- Walkowiak fit (1999):

$$v_D \equiv v_D\left(|\vec{E}|, T\right)$$
$$= \left(P_1(T - T_0) + 1\right)\left(P_3|\vec{E}|\ln\left(1 + \frac{P_4}{\vec{E}}\right) + P_5\vec{E}^{P_6}\right)$$
$$+ P_2(T - T_0)$$

With P_1, P_2, P_3, P_4, P_5 *and* P_6 *fit parameters*

$$\begin{cases} P_1 = -0.01481 \pm 0.00095\ K^{-1} \\ P_2 = 0.0075 \pm 0.0028\ K^{-1} \\ P_3 = 0.141 \pm 0.023\ \left(\frac{kV}{cm}\right)^{-1} \\ P_4 = 12.4 \pm 2.7\ \left(\frac{kV}{cm}\right) \\ P_5 = 1.627 \pm 0.078\ \left(\frac{kV}{cm}\right)^{-P_6} \\ P_6 = 0.317 \pm 0.021 \\ T_0 = 90.371\ K \end{cases}$$



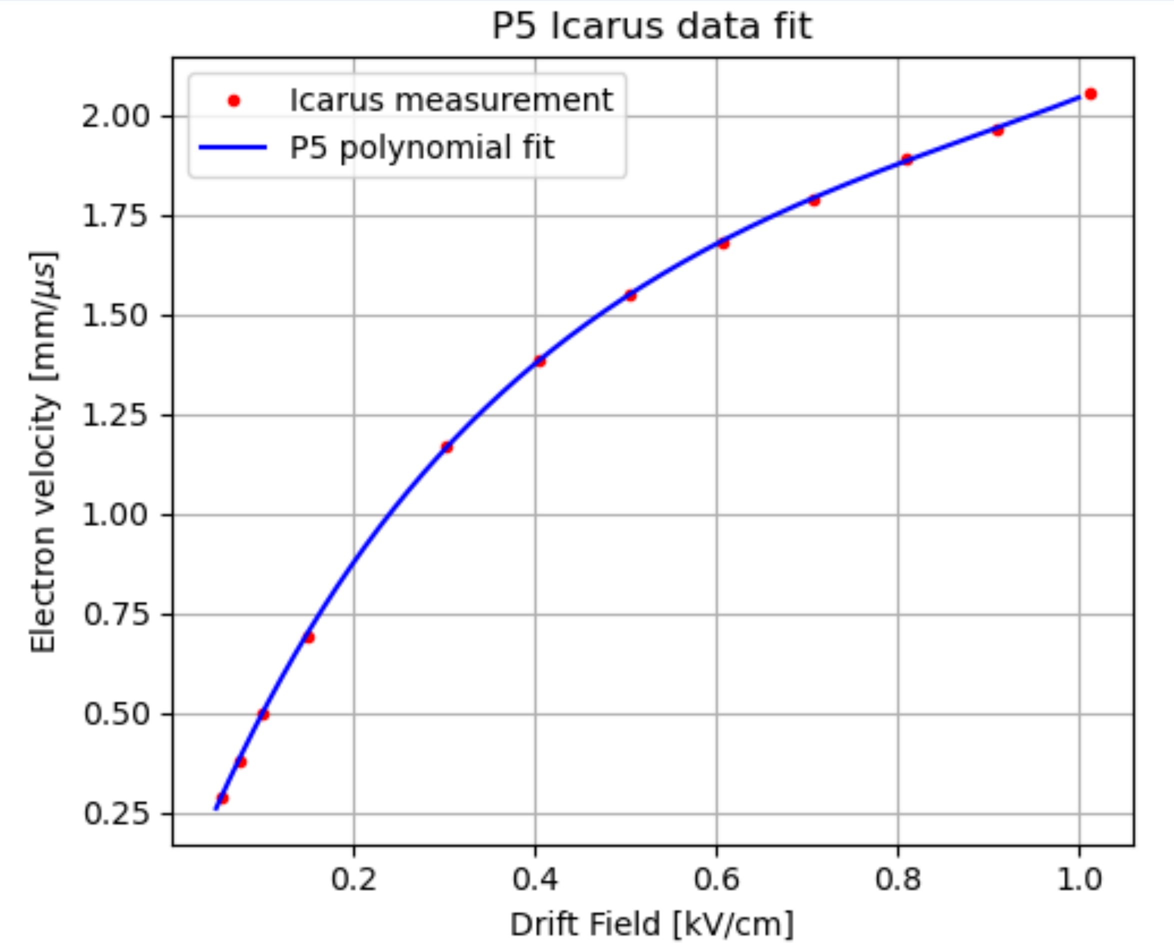
W. Walkowiak. Drift velocity of free electrons in liquid argon 1999

Drift velocity: Icarus fit

- ICARUS detector using TPC technologie (2004)
- P5 Polynomial fit:

$$v_D(E, T = 89\ K) \\ = a + bE + cE^2 + dE^3 + eE^4 + fE^5$$

- Fit valid only: $T = 89\ K$



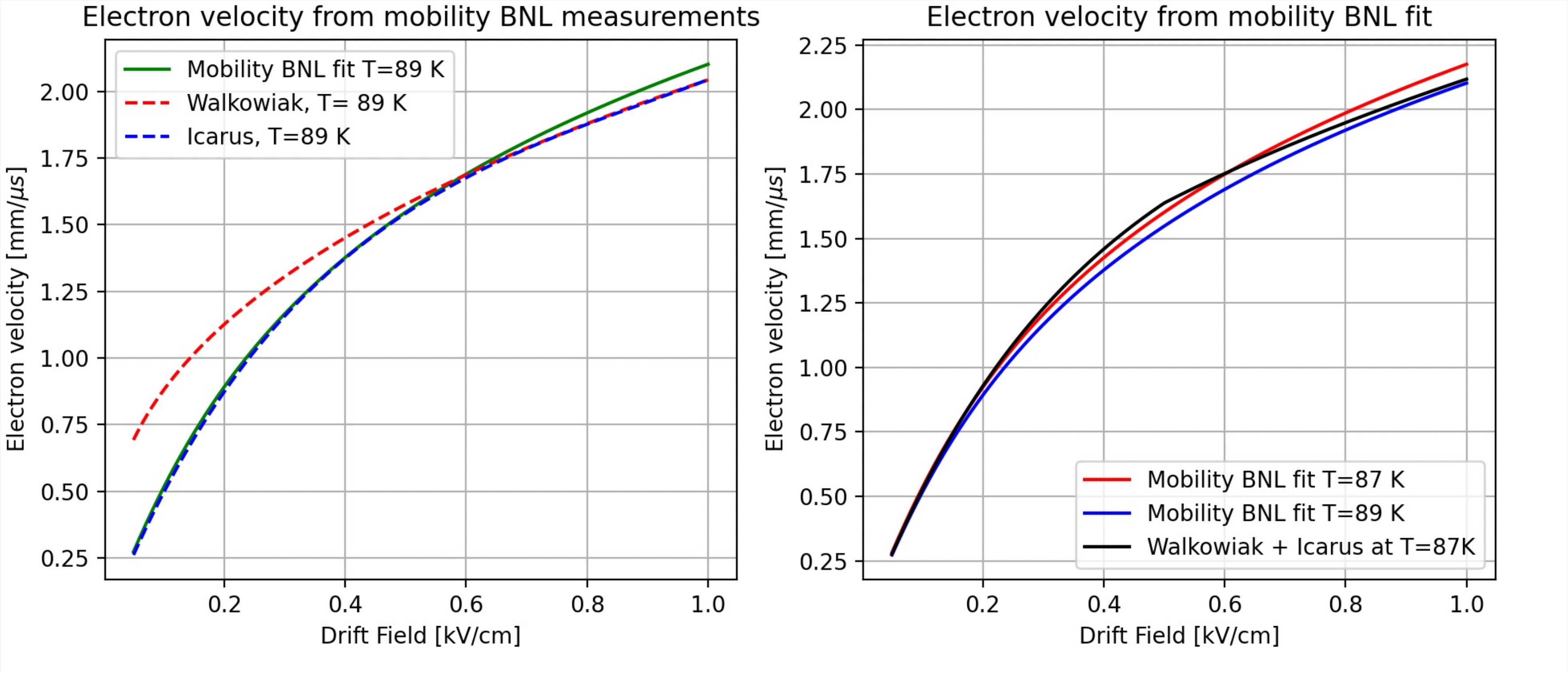
ICARUS Collaboration, Analysis of the liquid argon purity in the ICARUS T600 TPC, 2004

Drift velocity: Brookhaven fit

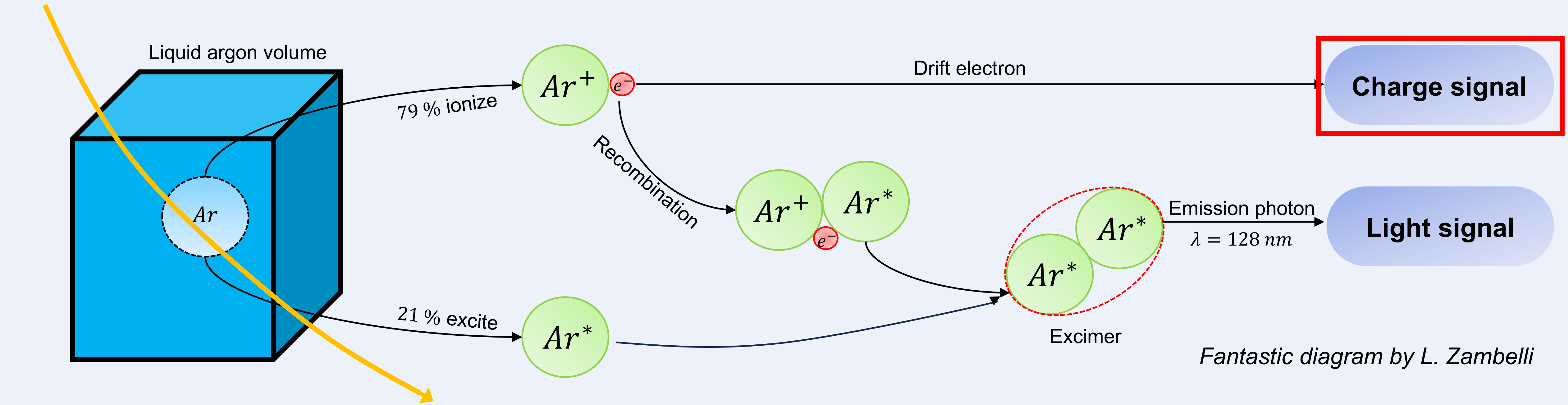
- Global data fit scaled at $T = 89\ K$
- Drift velocity: $\overrightarrow{v_D} = \mu\left(\left|\vec{E}\right|, T\right)\vec{E}$ Avec:

$$\mu = \frac{a_0 + a_1 E + a_2 E^{3/2} + a_3 E^{5/2}}{1 + (a_1/a_0)E + a_4 E^2 + a_5 E^3}\left(\frac{T}{T_0}\right)^{-3/2}$$

$$\begin{cases} a_0 = 551.6 \\ a_1 = 7158.3 \\ a_2 = 4440.43 \\ a_3 = 4.29 \\ a_4 = 43.63 \\ a_5 = 0.2053 \end{cases}$$



Principle of LArTPC detection



Fantastic diagram by L. Zambelli

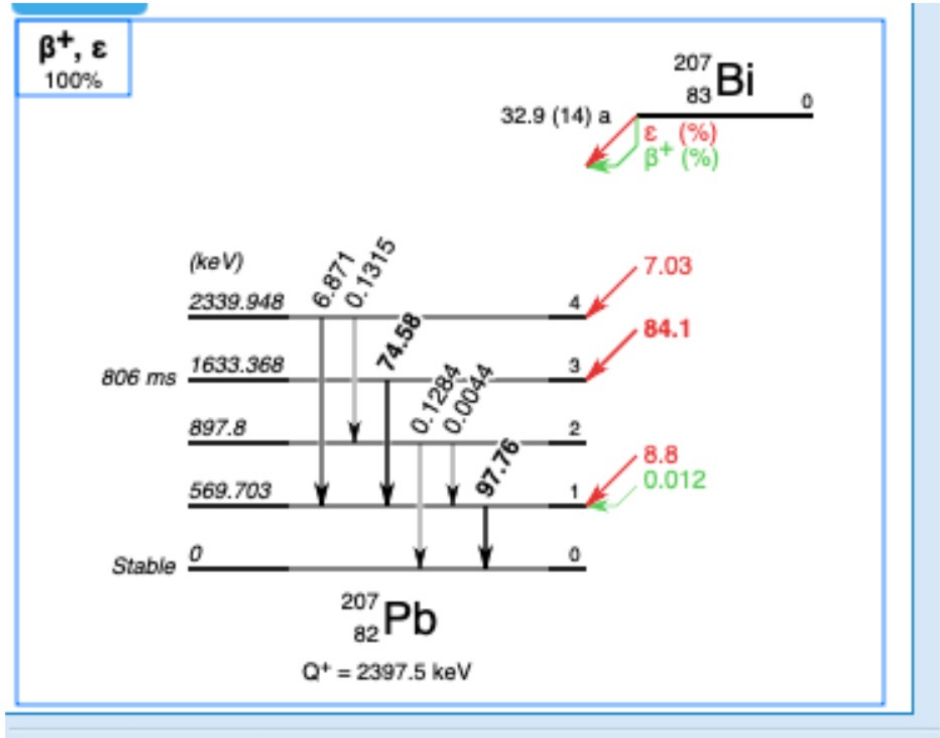
- Argon is chemically inert and dense
- Charged particles ionize (79 %) and excite (21 %) argon atoms.
- Scintillation light coming from argon de-excitation ($\lambda = 128\ nm$)
- Electrons of ionization drift to the anodes thanks to an electric field

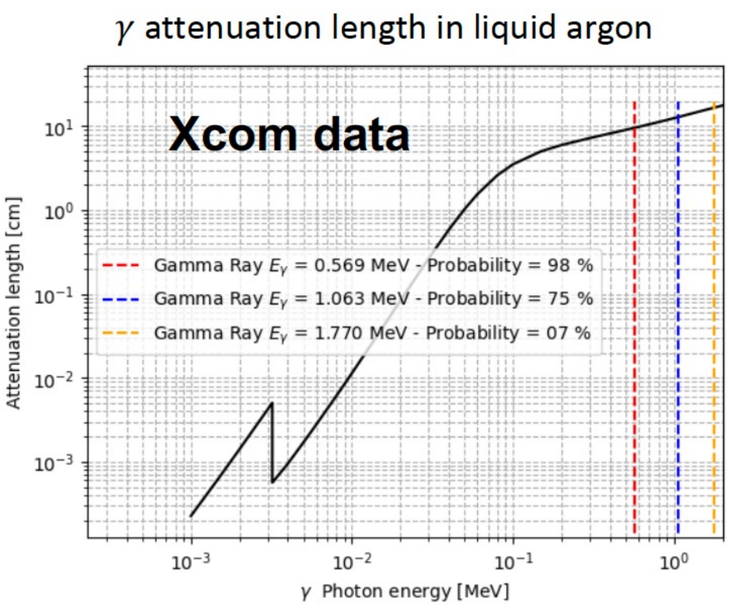
- LArTPC:
  - Segmented anode used to collect charge signal
  - $\tau_{drift} \gg \tau_{photon}$ → light signal trigger detection

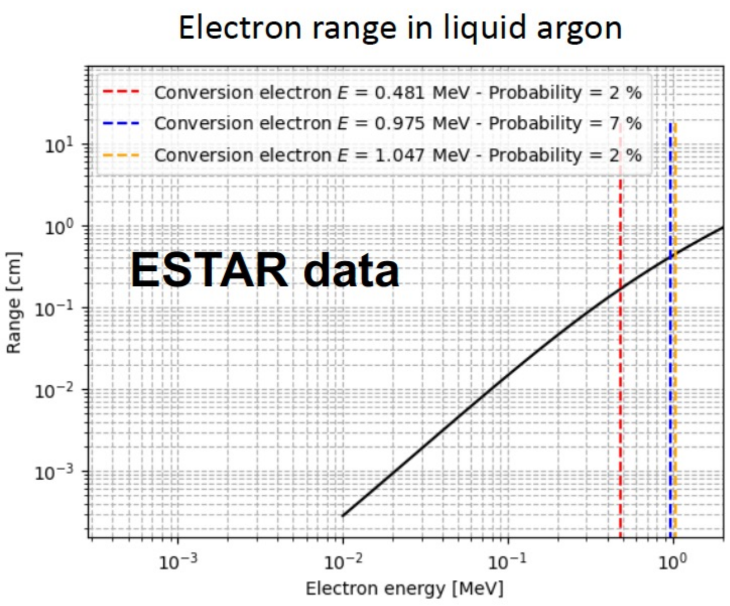
Track and energy reconstruction

BI207 sources

- Decay by electronic capture







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

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

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

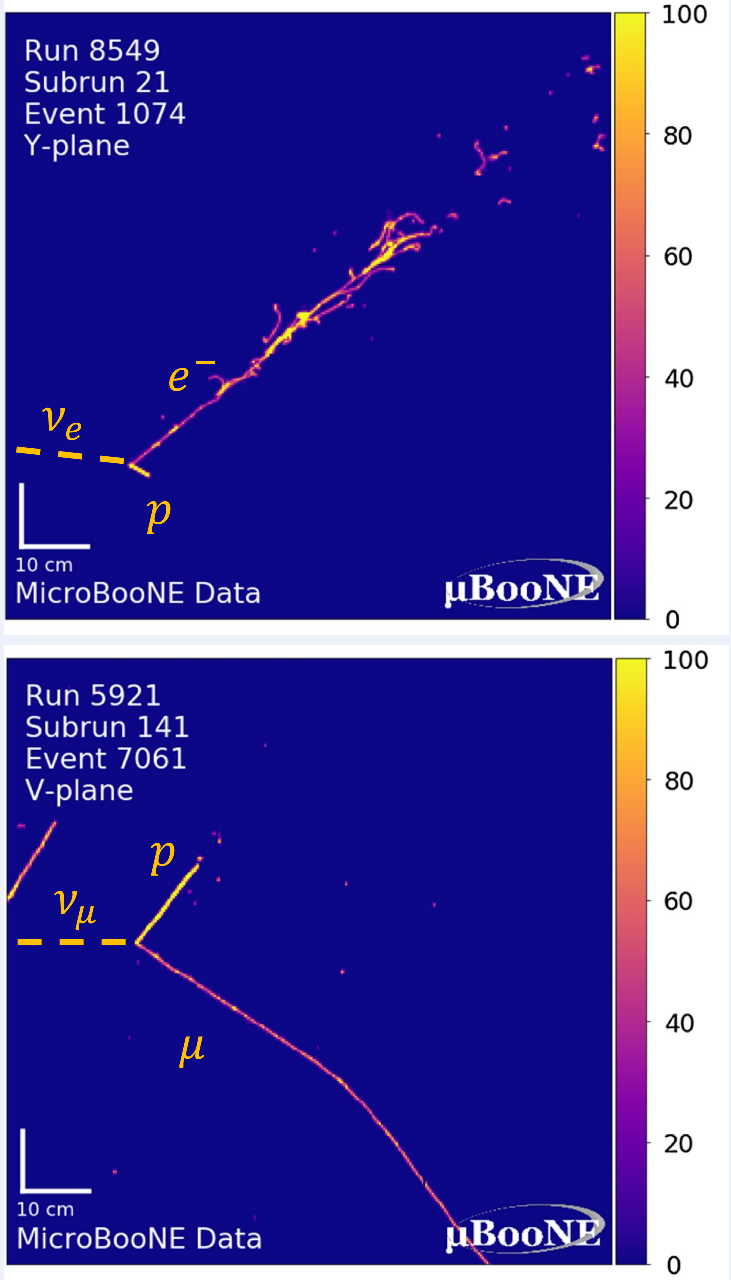
- Need to find Bi207 events from 50 L data
  - Electron range very short
  - Looking for only one signal from strips on all induction views → called a single hits

Why use TPC ?

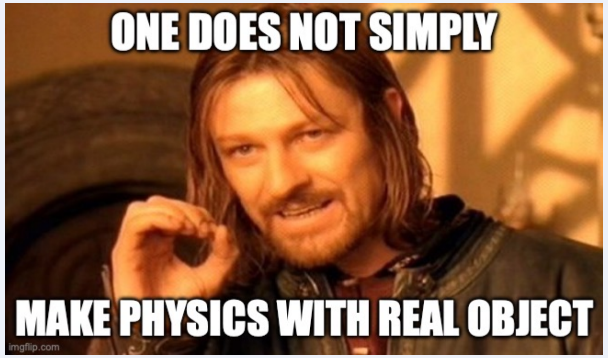
- Very important to discriminate muon and electron
- At GeV-scale $(1 - 10\ \mathrm{GeV})$ neutrino interaction are dominated by quasi-elastic scattering processes
- Charged current interaction gives a charged lepton in the final state used to tag the neutrino flavour

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

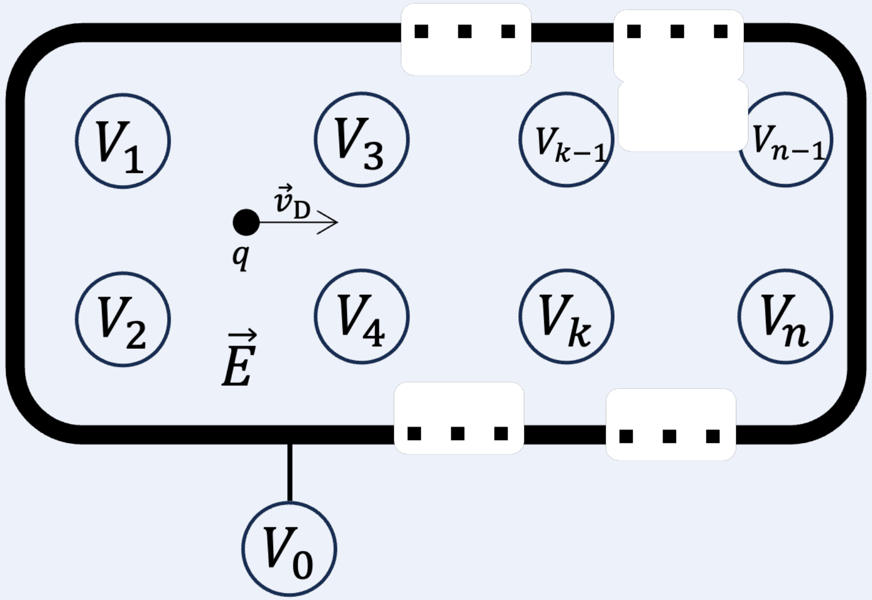
- Separate ν_e / ν_μ events by track topology studies
- DUNE need to measure the ν_e / ν_μ rate



Modeling signal formation



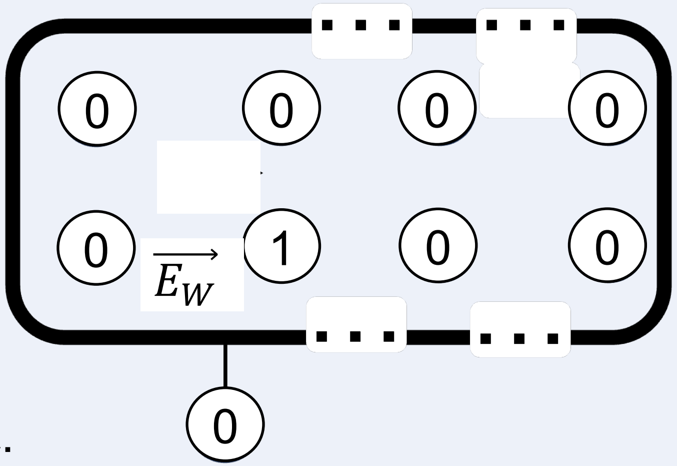
- General case – **Shockley-Ramo theorem**



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

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

- Weighting Field $\overrightarrow{E_W}$ is virtual field that would exist in the case where the charge is removed, the reading strip equal 1 V and all others fixed to 0 V



- Drift velocity:

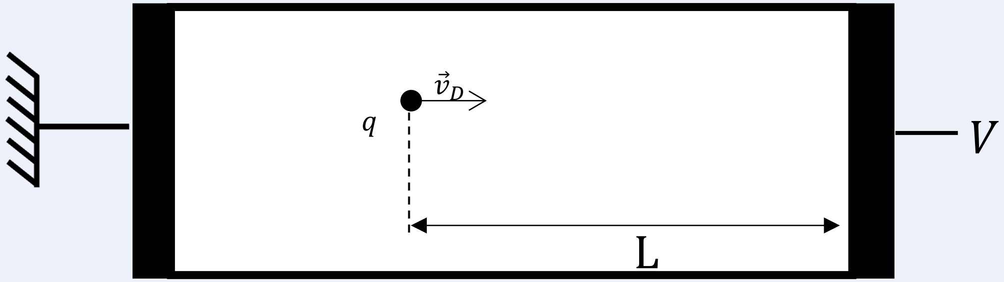
$$\overrightarrow{v_D}(\vec{E},T) = \mu\left(\overrightarrow{E_D},T\right)\times\overrightarrow{E_D}$$

as a function of the **electron's mobility** in the medium.

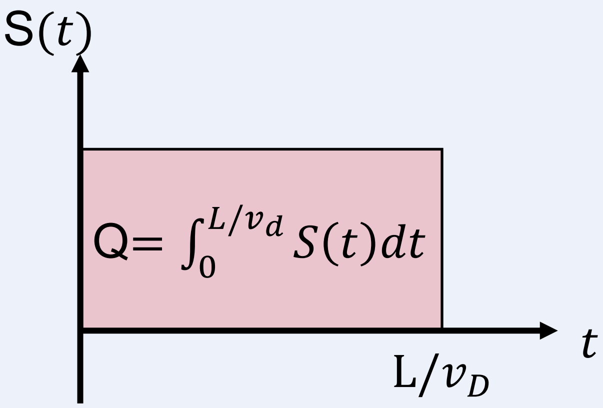
$$\begin{cases} \overrightarrow{E_W}\text{: geometry factor} \\ \overrightarrow{v_D}\text{: physics factor} \end{cases}$$

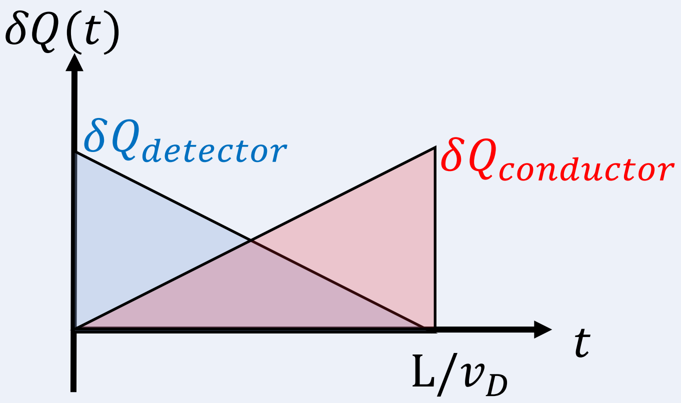
Modeling signal formation

- The simplest case of charge signal generation



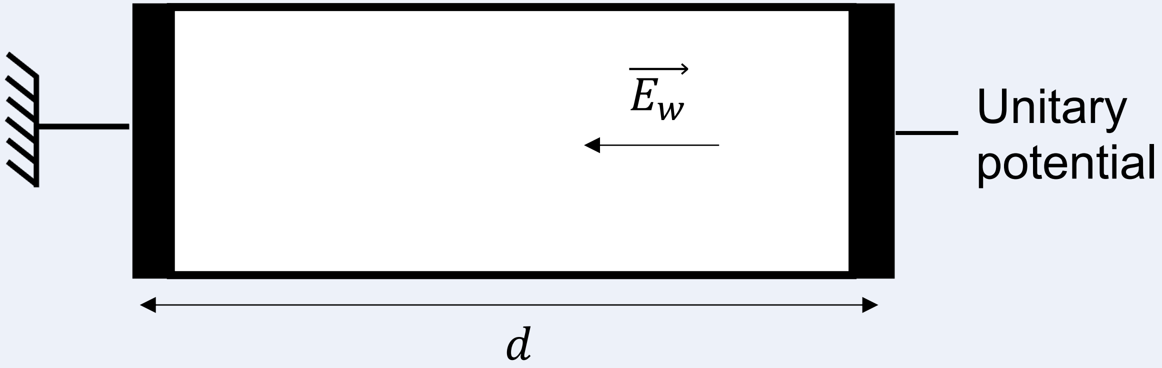
- Mirror effect to the partial charge induced δQ between the detector and the conductor





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

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



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

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

- **Need simulation for complex geometry**