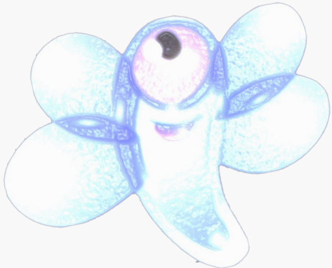
Laboratoire d'Annecy de Physique des Particules

Charge Signal formation in the TPC Vertical Drift design of DUNE

AG Enigmass 8th November 2024 - IPAG



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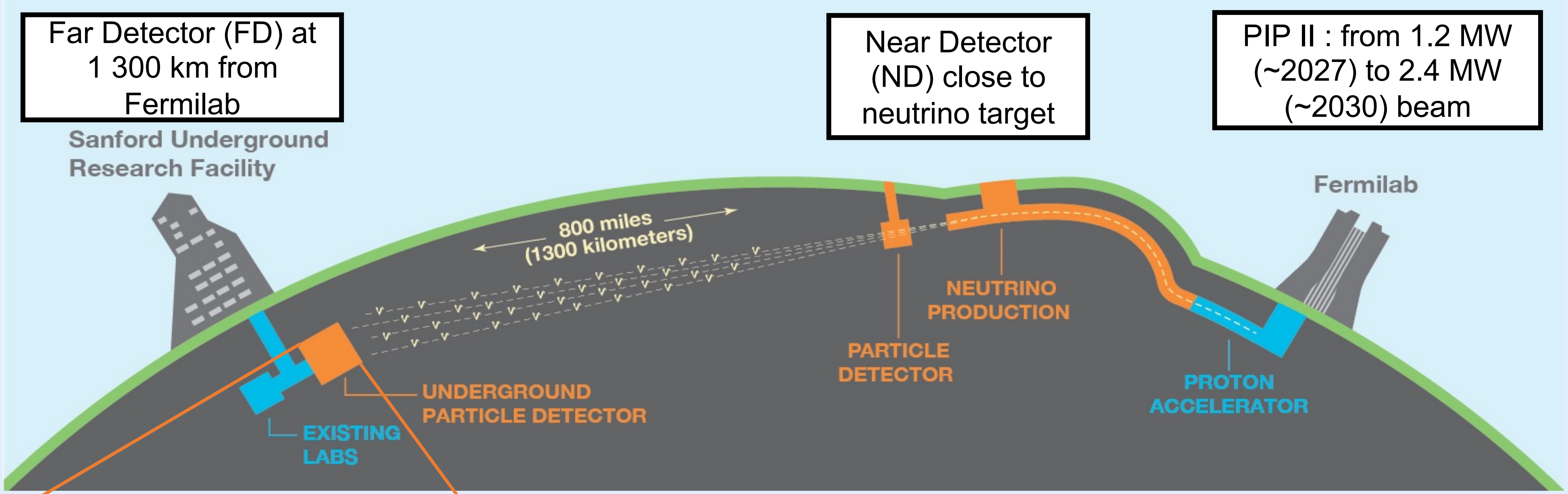
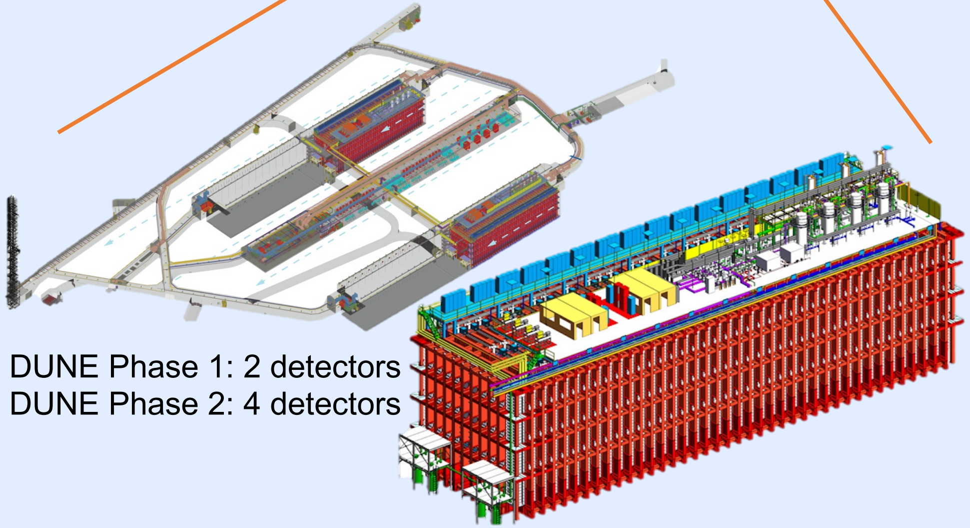
Dominique Duchesnau (LAPP)

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Deep Underground Neutrino Experiment



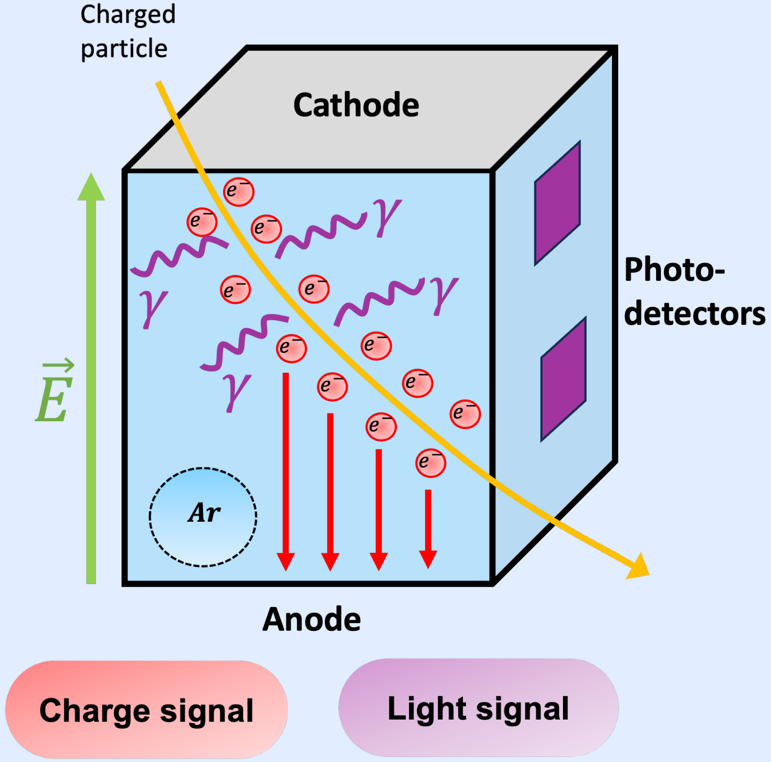


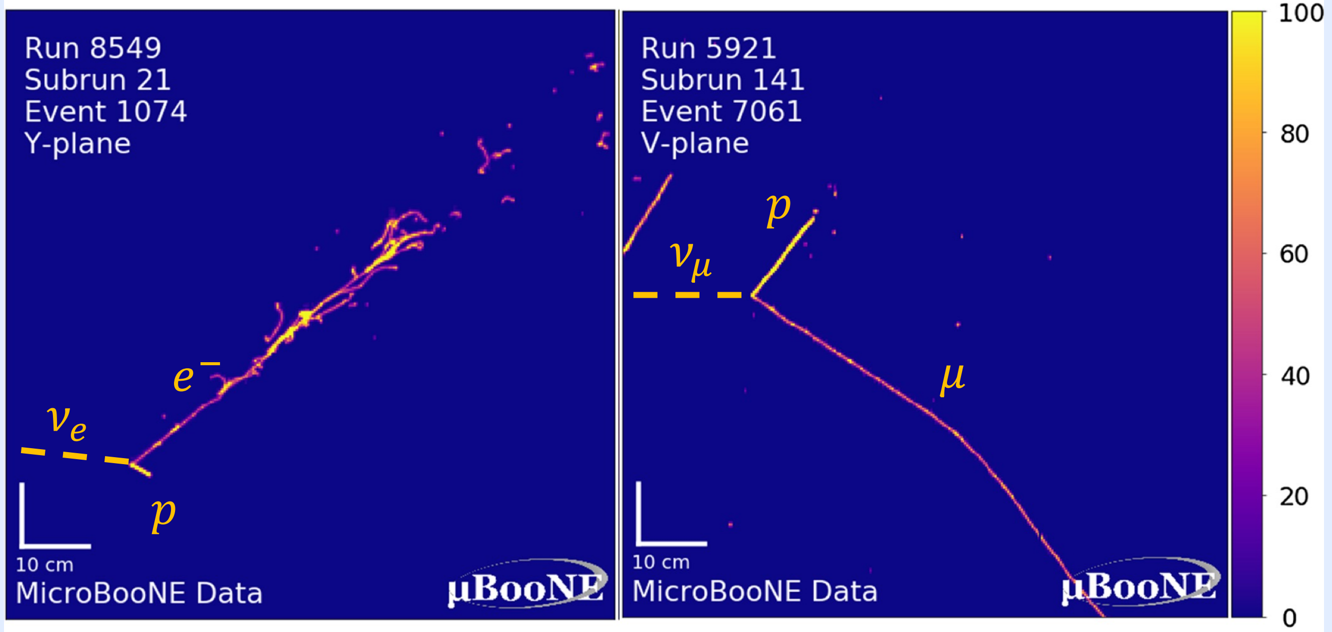
- DUNE Phase 1: 2 detectors
- DUNE Phase 2: 4 detectors

- New generation of long-baseline neutrinos experiment
- Precision measurements of neutrino oscillation parameters (δ_{CP} phase, mass ordering, θ_{23} octant etc.)
- Measurement of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu_e}$
- Far detector is made of 4 Giant LArTPCs (17 kt of liquid argon each) located at 1480 m underground

How LArTPC works?

- **Time Projection Chamber**:
  - Segmented anodes used to collect charge signal
  - $\tau_{photon} \ll \tau_{drift}$ → light signal trigger detection
  - Enables large volume and high spatial resolution





- At GeV-scale (1 – 10 GeV) neutrino interactions are dominated by resonant interaction and deep inelastic scattering processes
- Charged lepton produced by charged-current interactions are used to tag the neutrino flavour

$$\nu_l + \mathrm{n} \rightarrow \mathrm{l}^- + p$$

$$\bar{\nu_l} + \mathrm{p} \rightarrow \mathrm{l}^+ + n$$

- Separate ν_e / ν_μ events by track topology identification
- Neutrino energy reconstructed using calorimetry

Vertical drift design

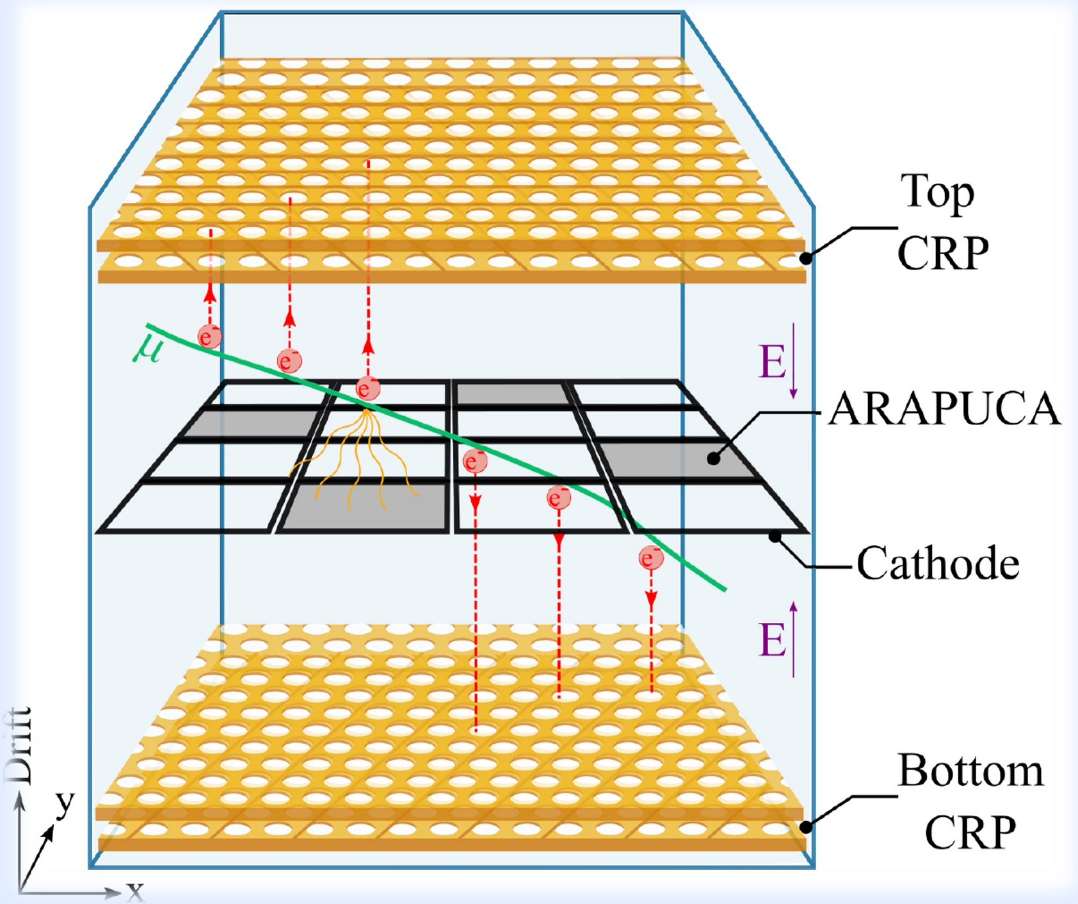
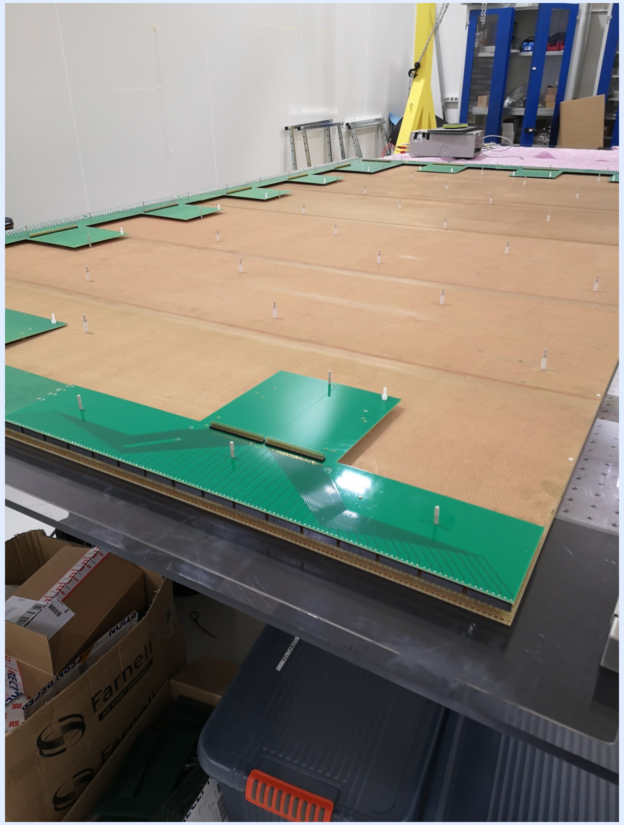


Diagram by L. Zambelli

- 2 volumes split by a cathode
  - Carried by an electric drift field: $|\vec{\boldsymbol{E}}| = 0.5\ kV/cm$
- The new perforated anode technology
  - Stack of 2 perforated Printed Circuit Boards (PCB)
  - Etched copper electrode strips on each PCB face
  - Few millimeters spatial resolution
  - Module called Charge-Readout Planes (CRP) ~ 3x3 m
- DUNE Far detector at SURF:
  - Top and bottom anode planes made of 80 CRP modules each
  - The top CRPs will be produced at LPSC in Grenoble

Signal formation study on anodes

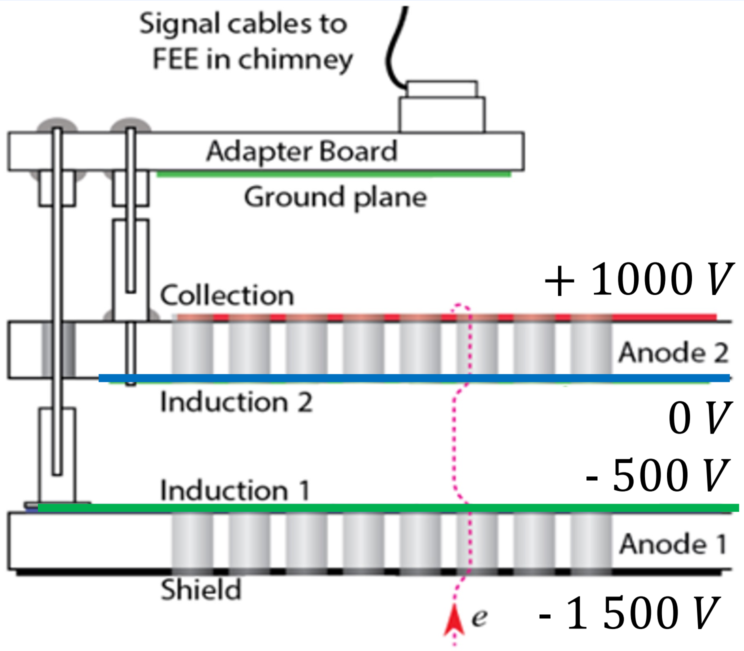
- **Problematic:**
  - ➢ Use of new anode technology
  - ➢ Important to know the deposited energy in the detector to measure the oscillation parameters
  - ➢ Improve tracks reconstruction using the shape of induction signals
- **My work:**
  - ➢ Understand the waveforms based on energy, track angle and position
  - ➢ Understand the charge lost in the anodes
  - ➢ Estimate the different systematics
  - ➢ **Study of induced signal formation on the anode**

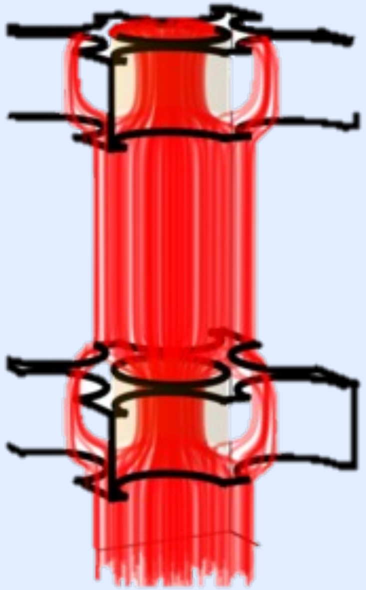


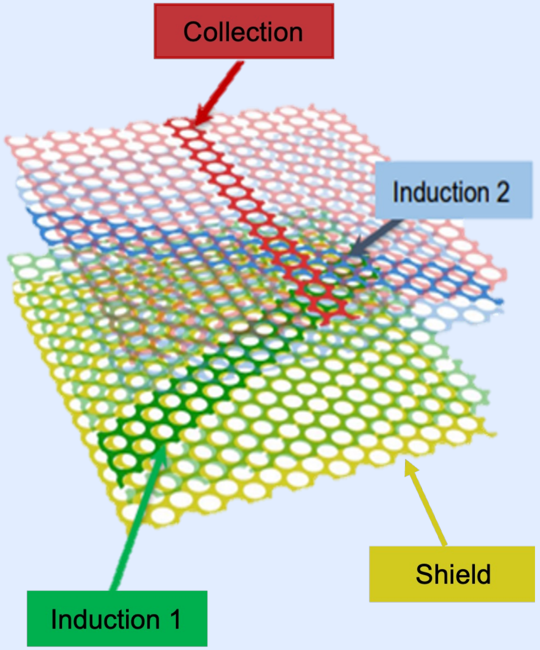
CRP assembly at CERN

The perforated anode technology

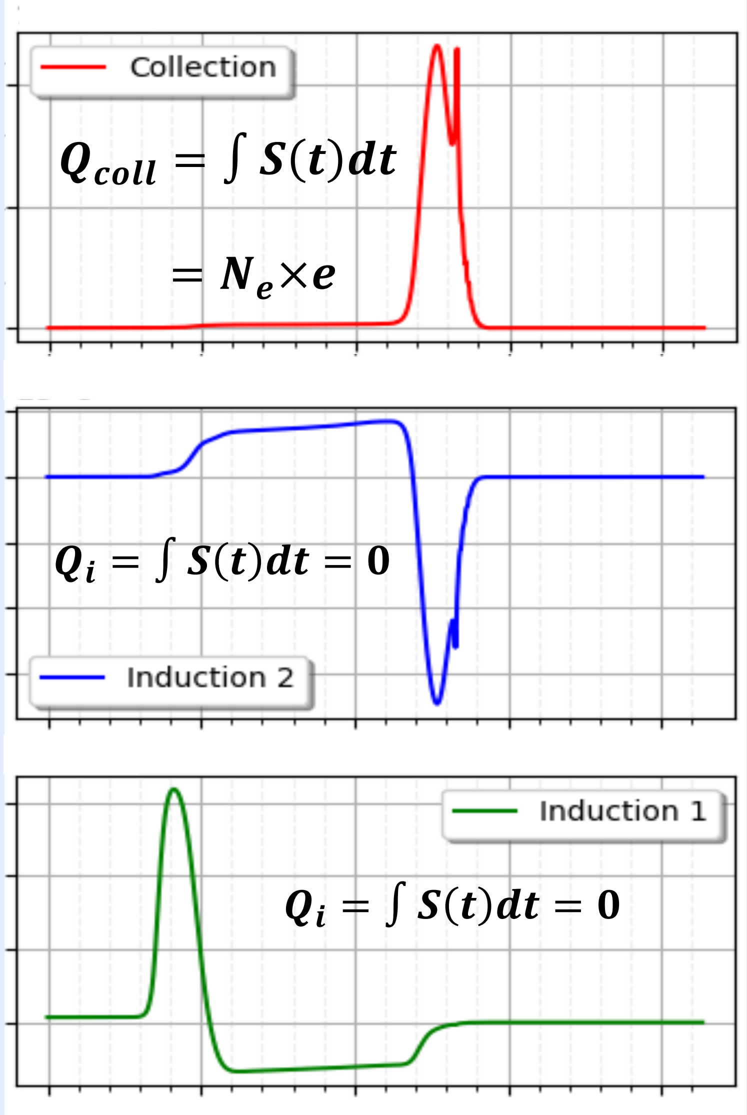
- Shield + 3 different charge readout layers:
  - Induction 1 – strip orientation -30° to beam axis
  - Induction 2 – strip orientation +30° to beam axis
  - Collection – strip orientation 90° to beam axis





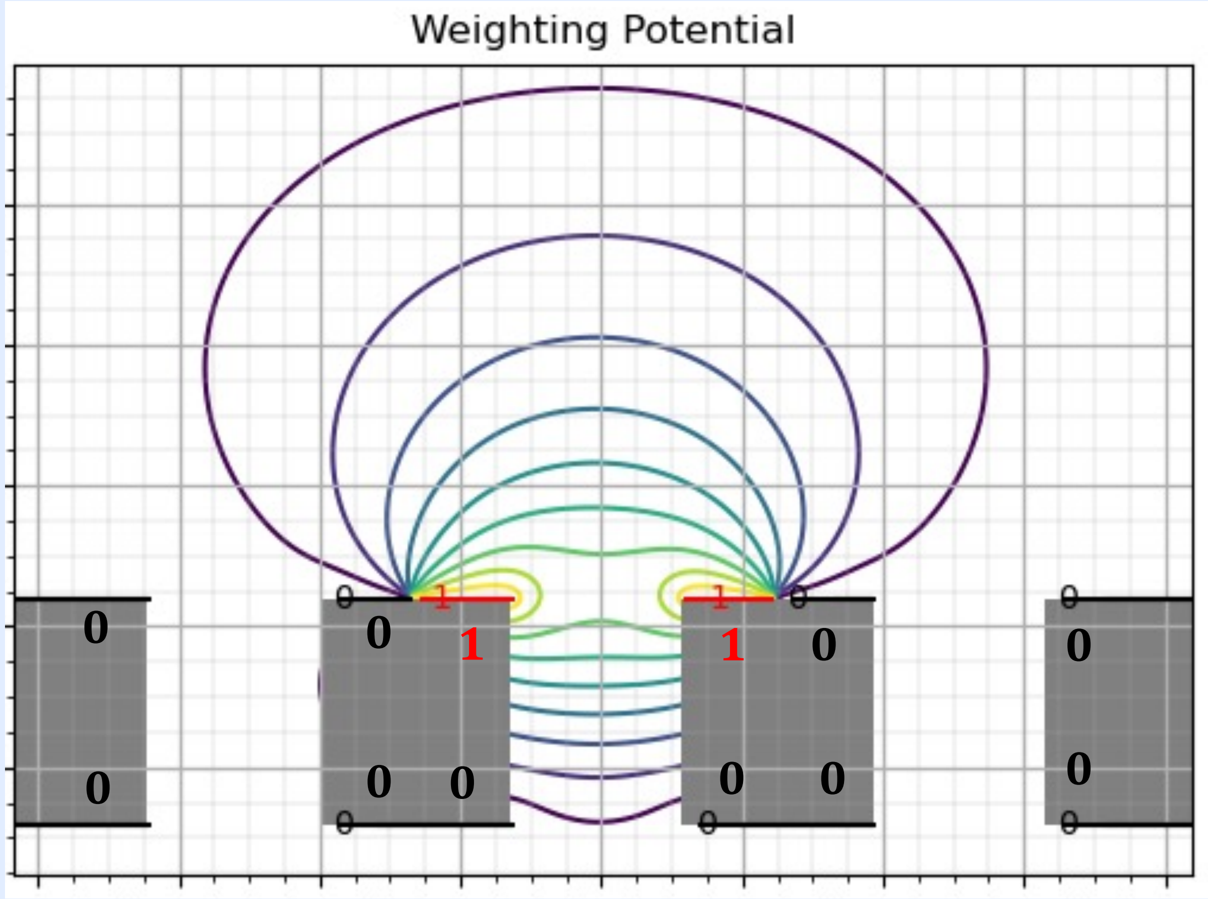


- **Collection view:** Unipolar signal
- **Induction views:** Bipolar signals



Modeling signal formation

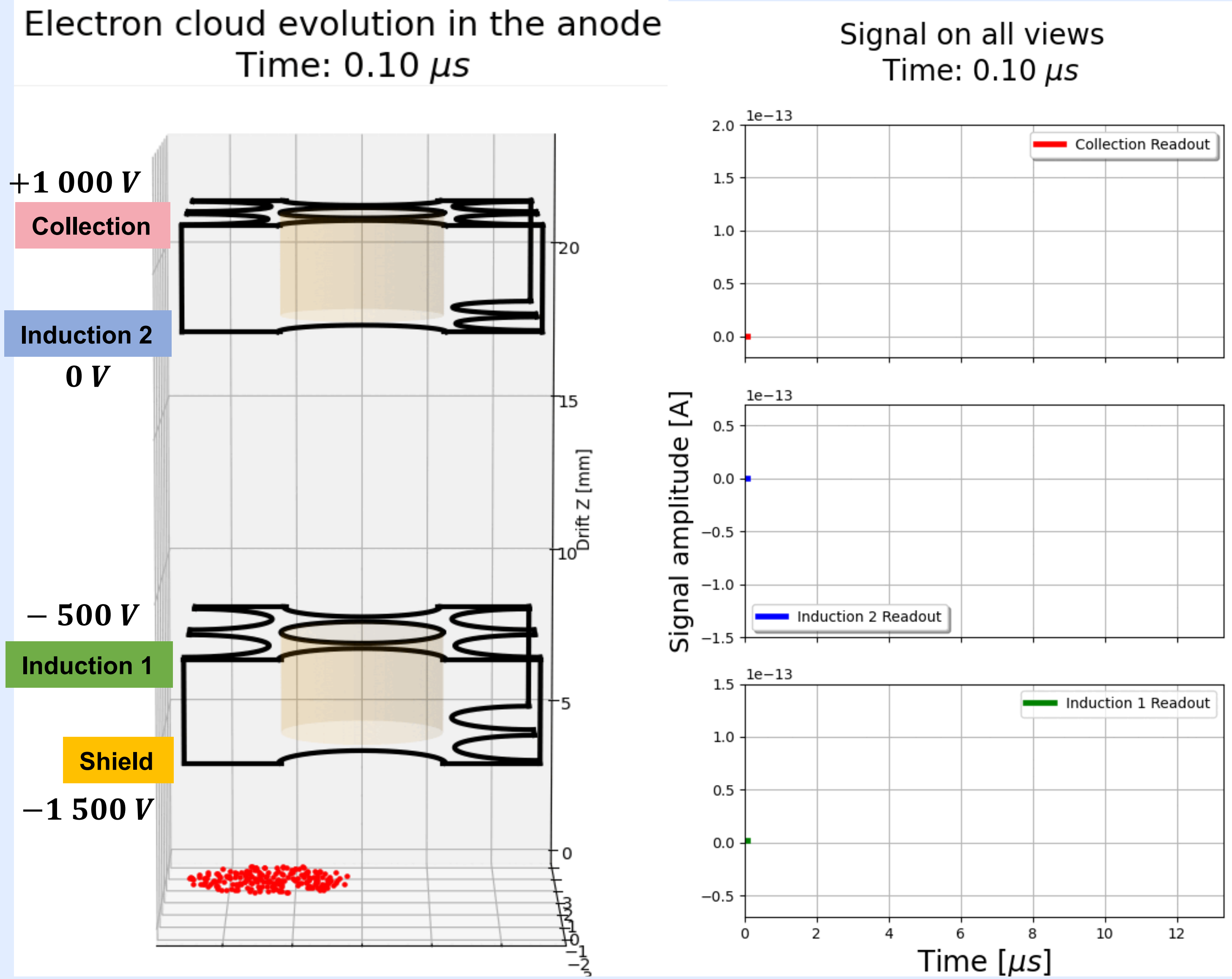
- Shockley-Ramo theorem: $i(t) = q\,\vec{E}_w\,.\,\vec{v}_D$
  - Theorem derives from Maxwell equations
- Drift velocity: $\vec{v}_d = \mu\,\overrightarrow{E_d}$
  - When $E_d > 200\ V\,/\,cm$: electron mobility depends on the electric field
  - We use global model fitted on mobility measurements
- Weighting Field $\overrightarrow{E_w}$:
  - Virtual field defined when the **reading strip equal 1 V** and **all others fixed to 0 V**
  - Depends only on the spatial distribution of the electrodes
- **Induced current is caused only by charge carriers motion**

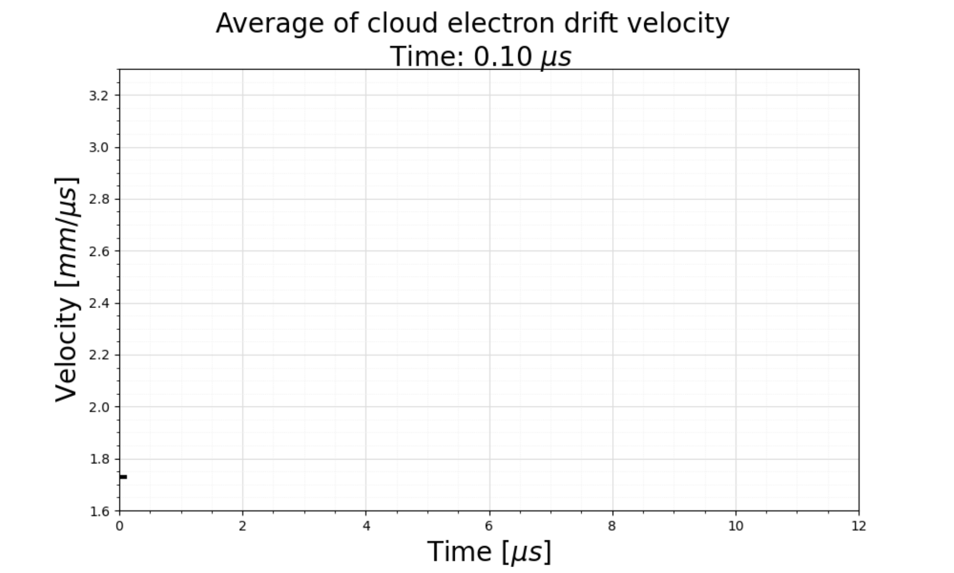


. Li, et al., "Measurement of Longitudinal Electron Diffusion in Liquid Argon", NIMA 816, 160 (2016). [arXiv]

Electron cloud simulation

https://gitlab.in2p3.fr/jpinchau/dunesimanodevd





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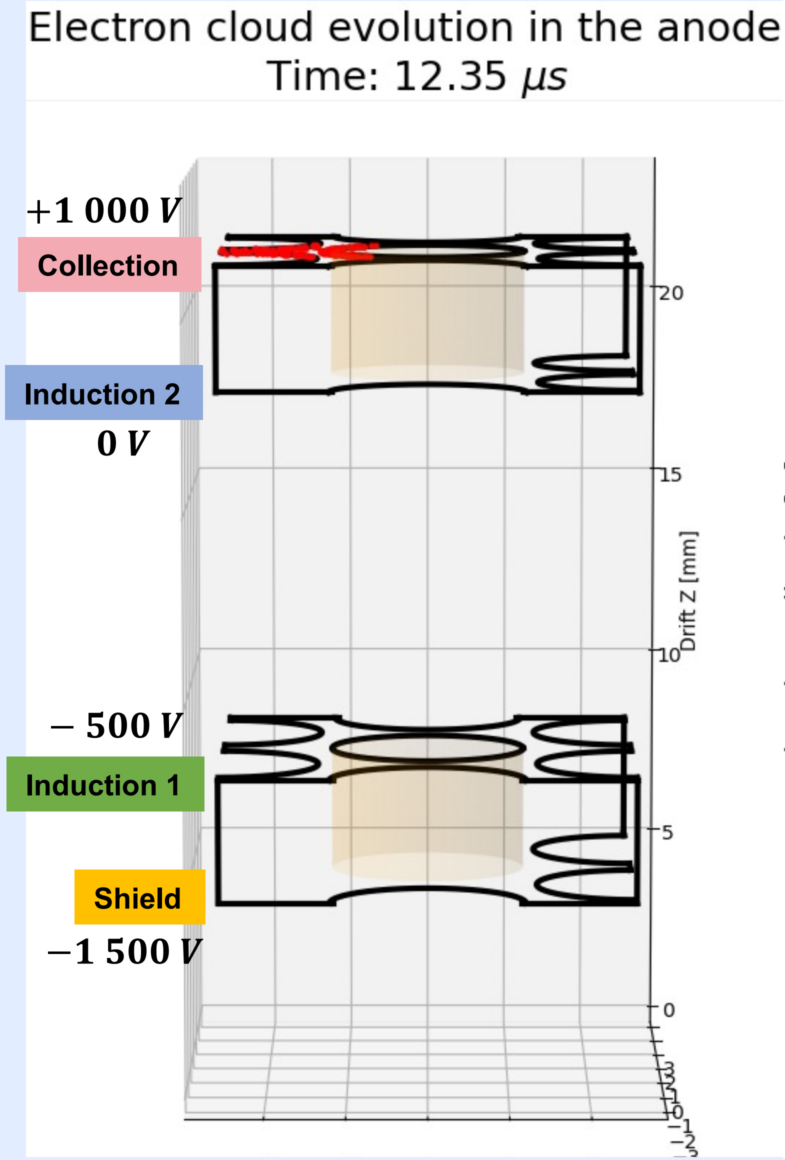
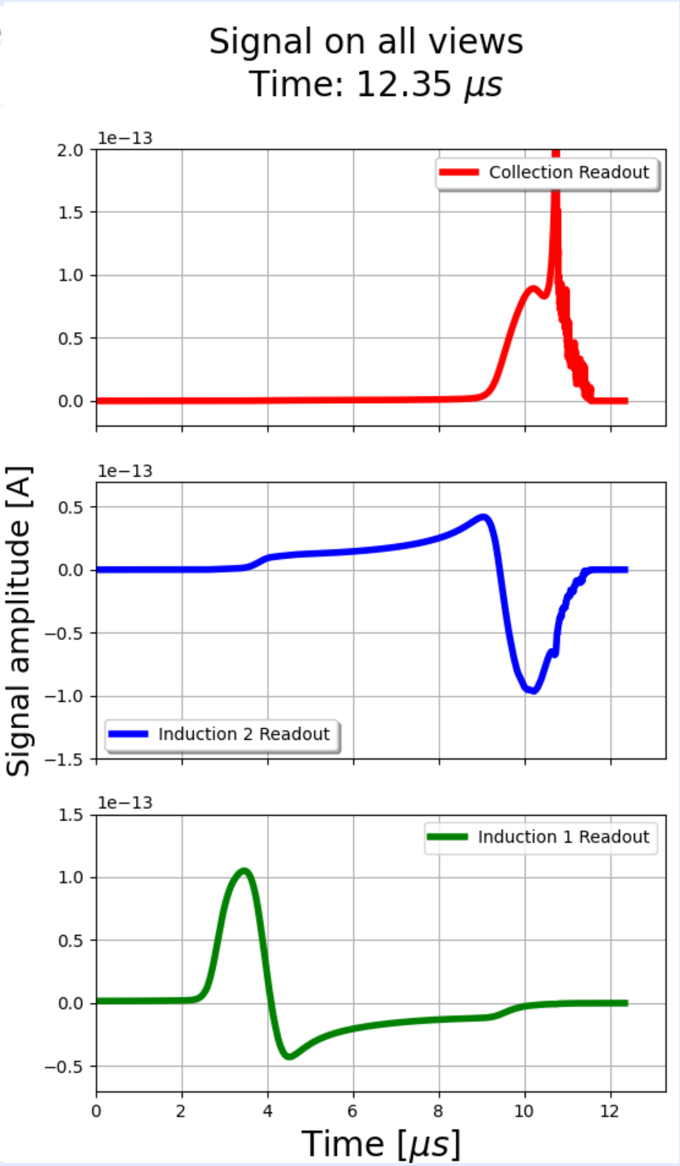
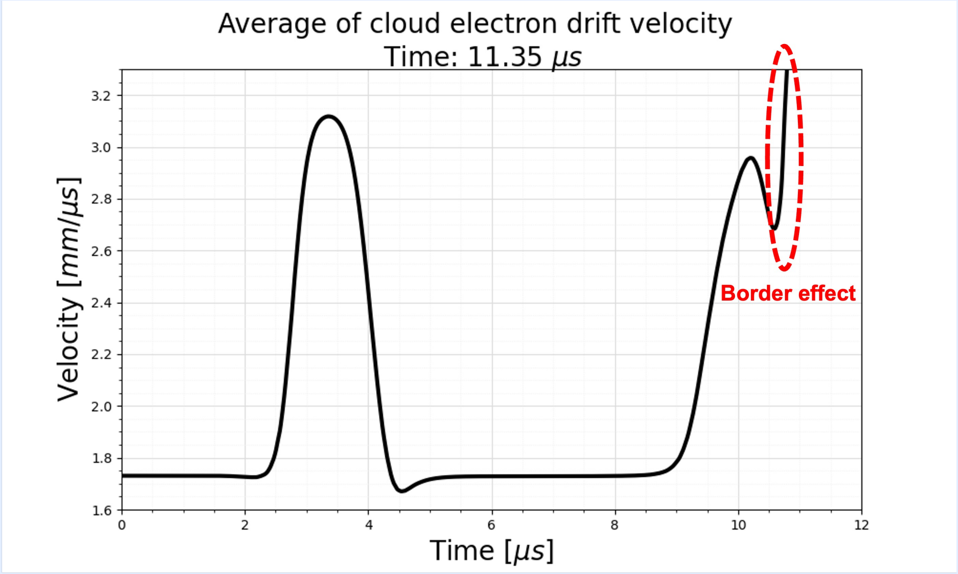






- Border effect near to the collection electrode
- The field takes $\propto 1/r^2$ dependancy which will induce a high frequency signal
- Electronic response will smooth the readout induced current

Charge carriers motion in liquid argon

- **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:

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

- Relationship between longitudinal and transverse diffusion coefficient:

(Einstein's relation) $$D_L = \frac{\epsilon_L \mu}{e}$$

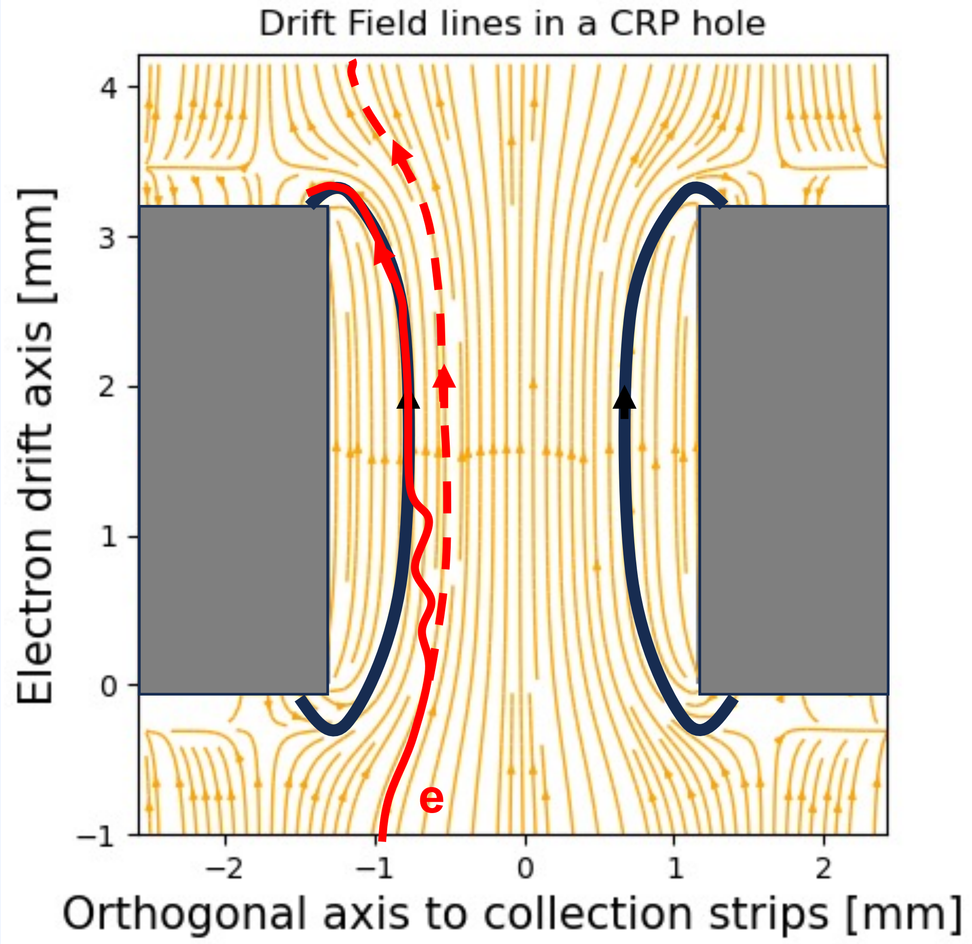
$$\frac{D_L}{D_T} = 1 + \frac{E}{\mu} \frac{\partial \mu}{\partial E}$$

ϵ_L: longitudinal effective electron energy

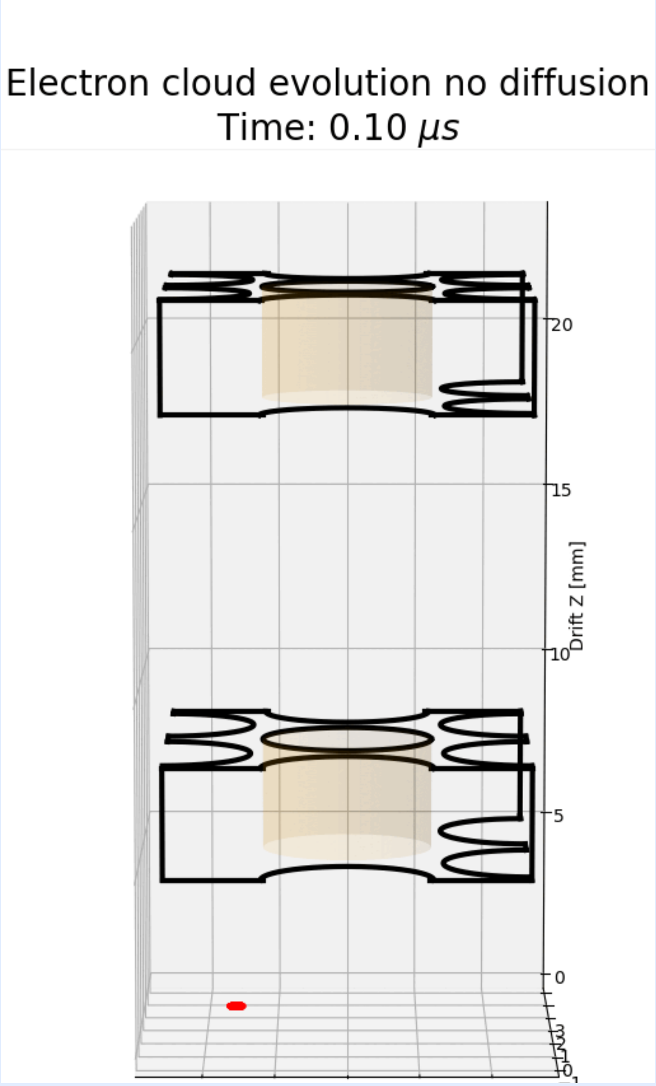
μ: electron mobility

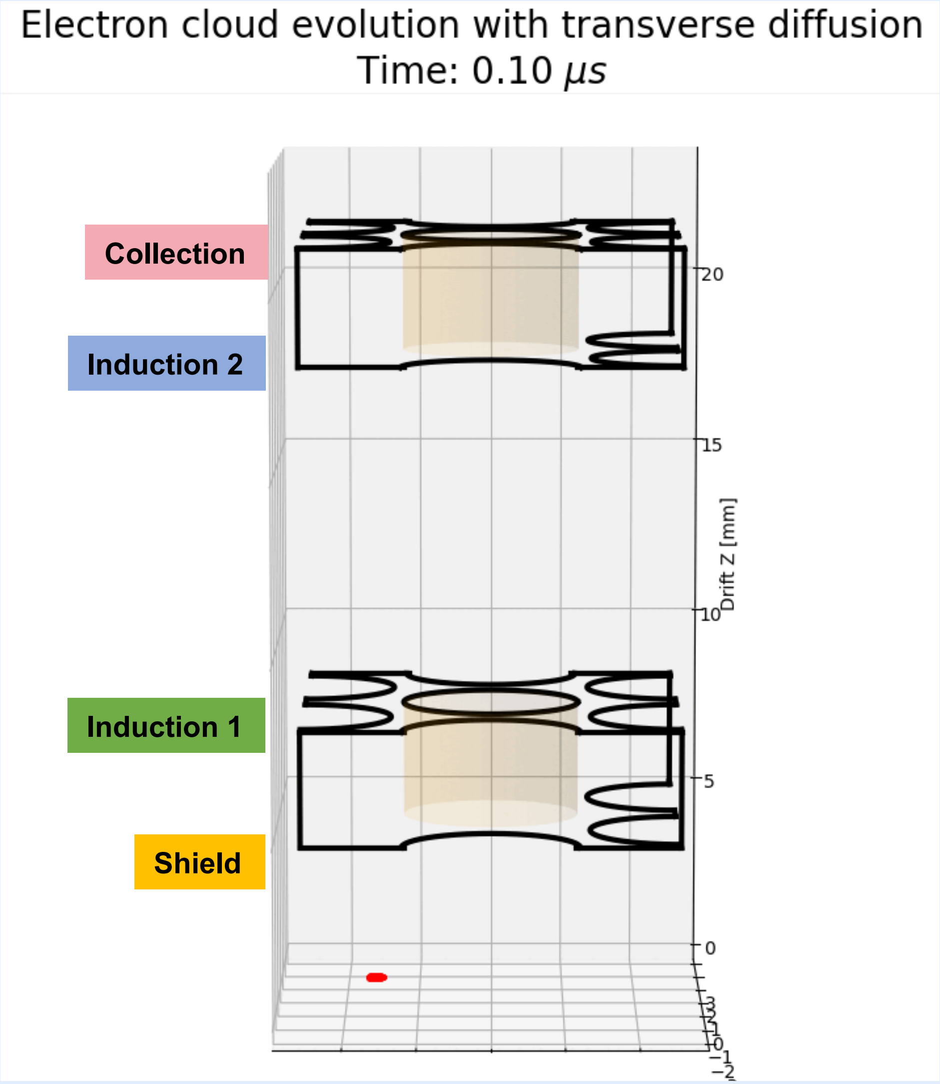
. Li, et al., "Measurement of Longitudinal Electron Diffusion in Liquid Argon", NIMA 816, 160 (2016). [arXiv]

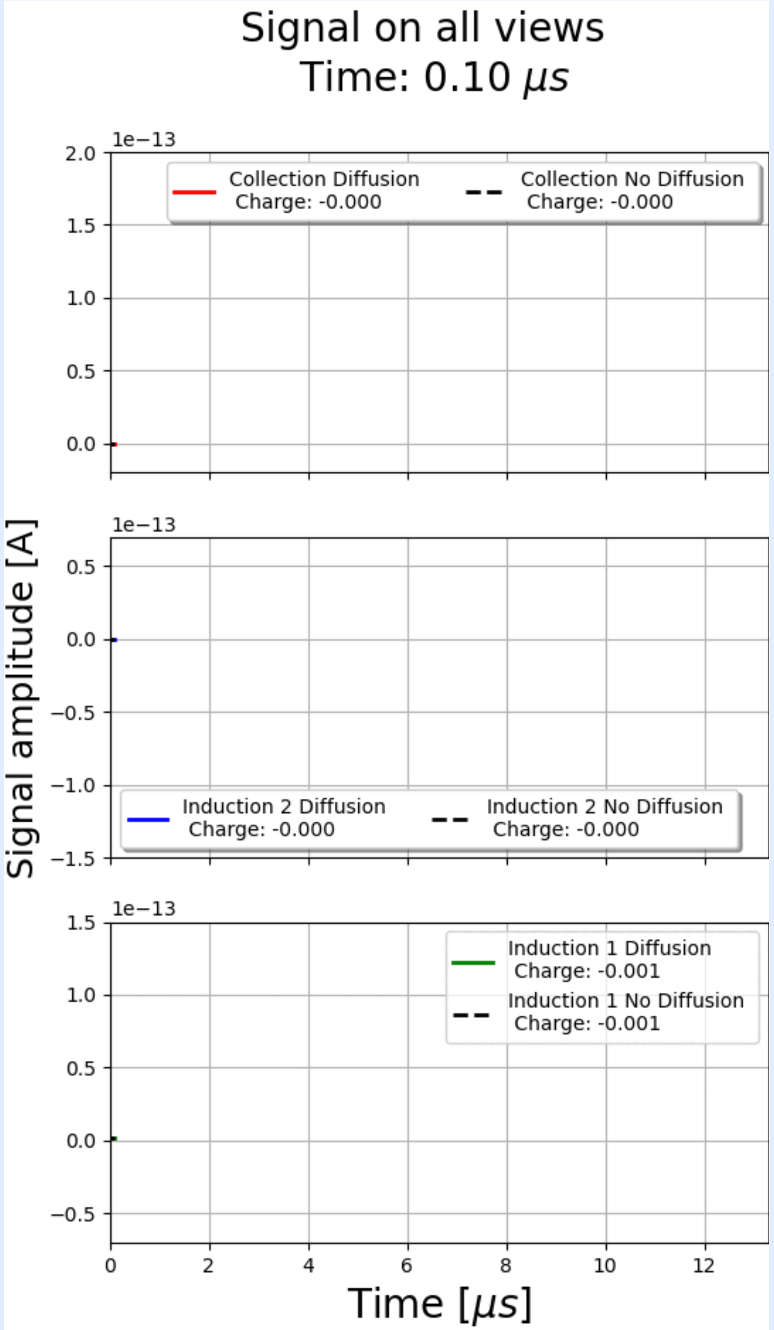
- Electron loss on view 0 due to the diffusion



Electron diffusions







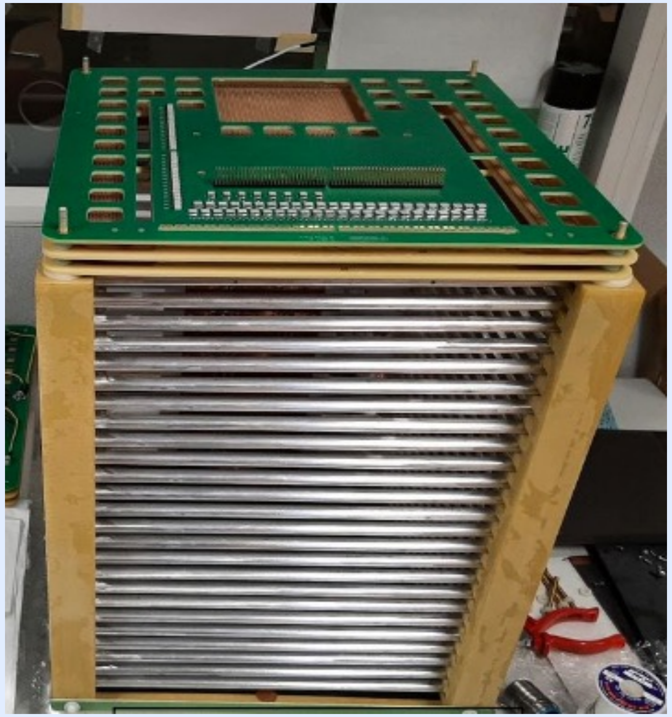
- Diffusion causes 10 % of charge loss (simulation)

R&D TPC 50 L detector

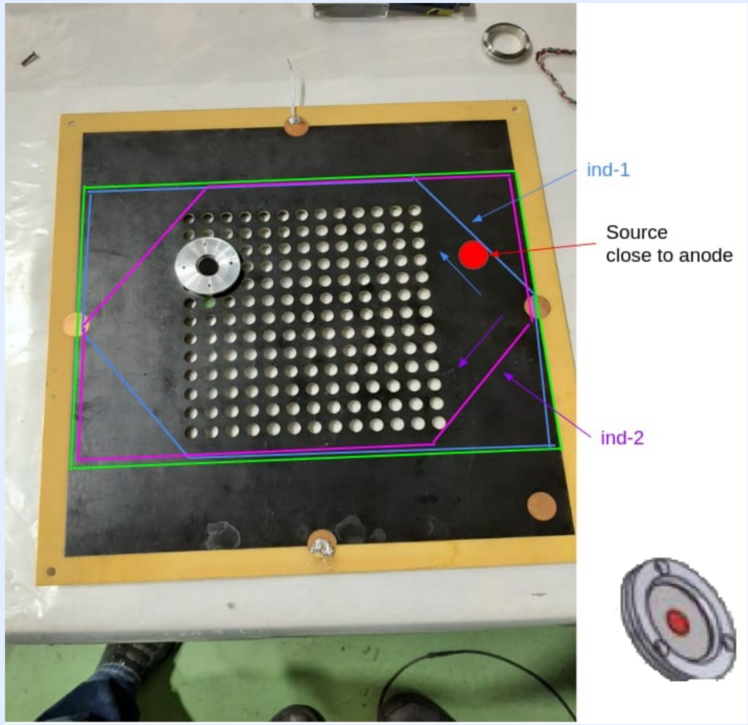
- ➢ Data-taken on R&D TPC at CERN last summer
- ➢ Need to compare with simulation

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

➢ **Not enough cosmic ray event**



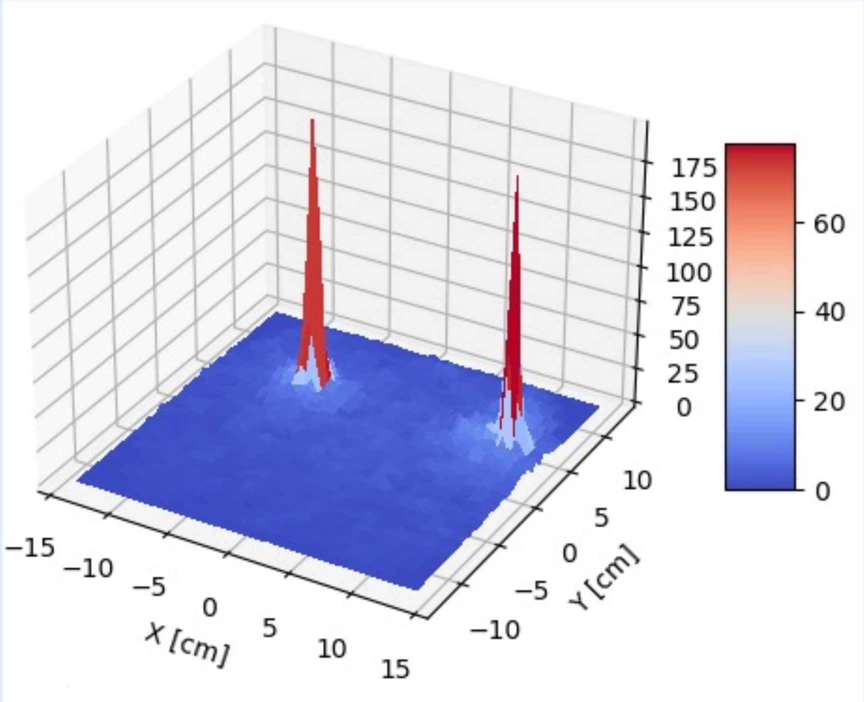
- 2 ^{207}Bi sources put inside TPC
- Activity: both at 37 kBq
- Main conversion electron rays at around 1 MeV
- Range in liquid argon: ≈ 5 mm < strip length → single hits

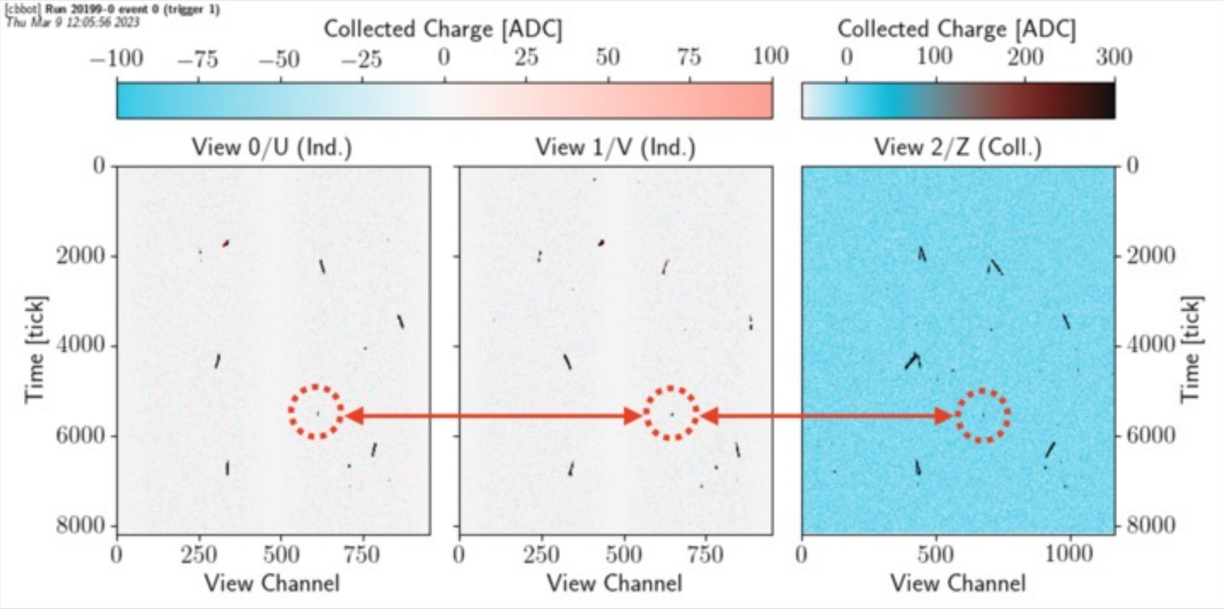


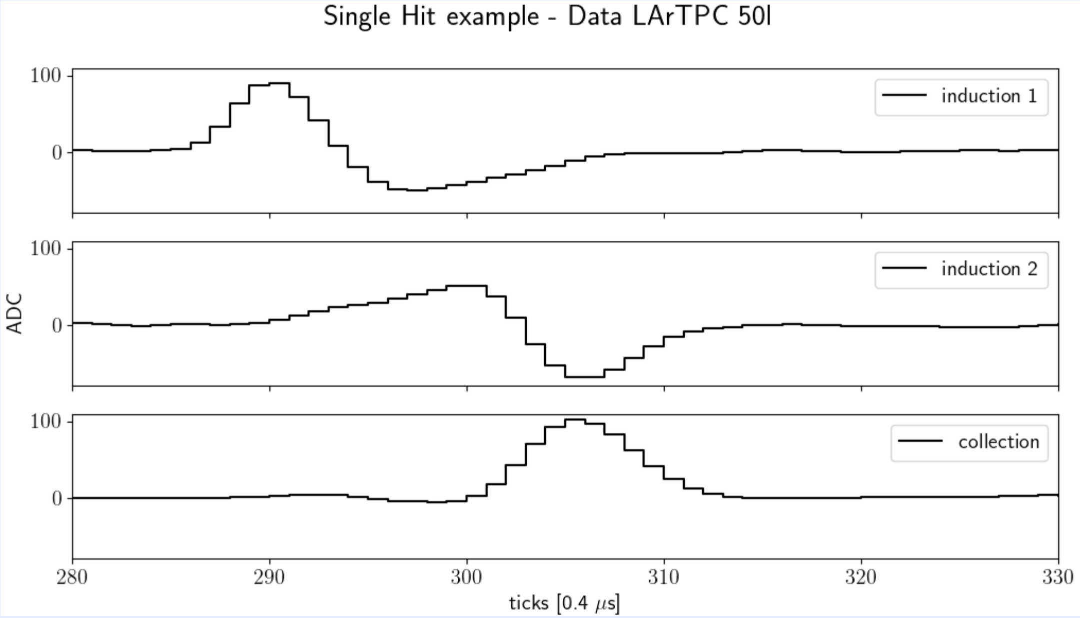
Single hits

- Reconstructed events by using Lardon developped L. Zambelli
- Isolated hit on three views correlated in time

Reconstructed single hits



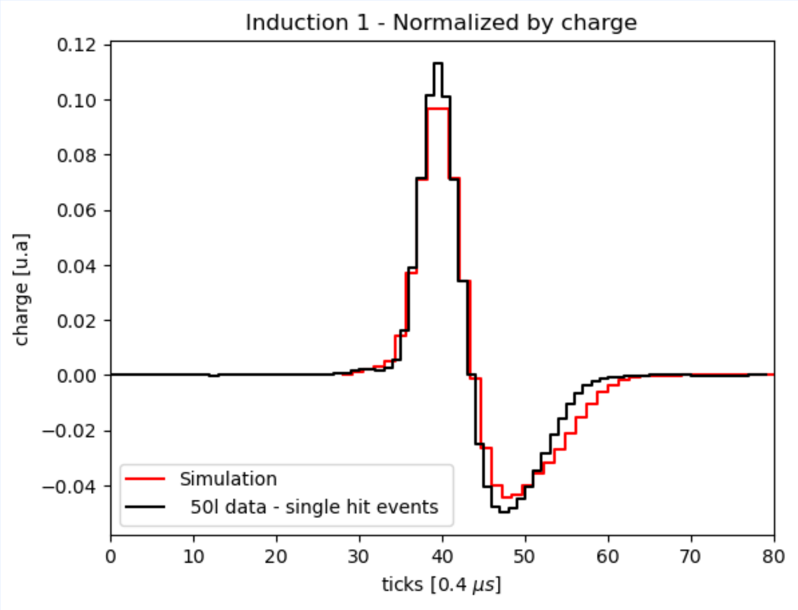


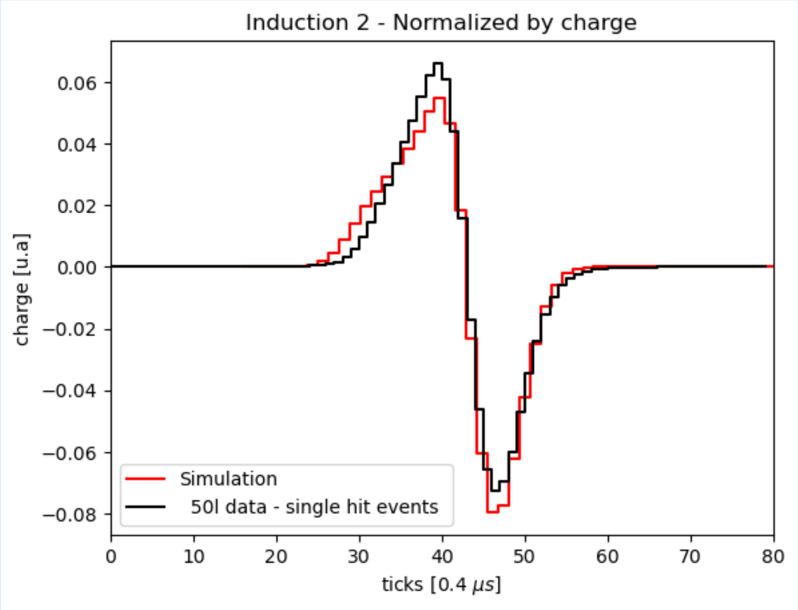


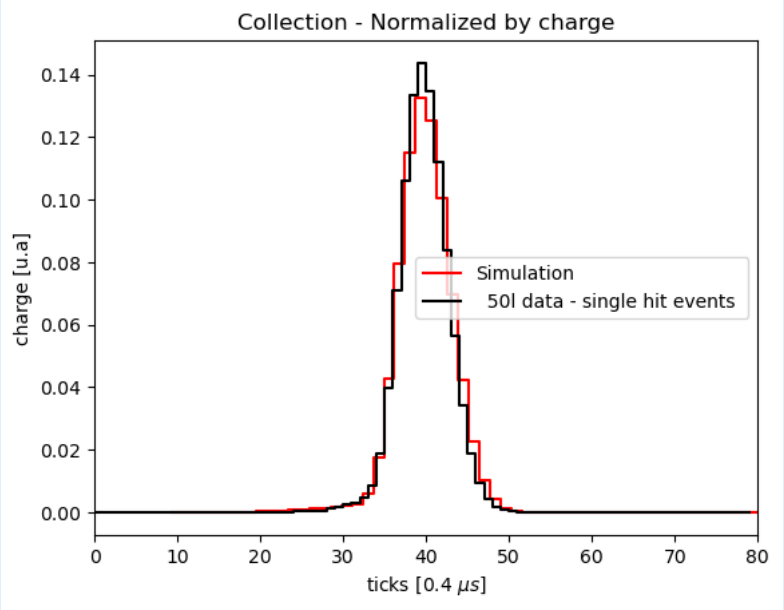
Results

- Total reconstructed single hits: 17 334 hits → 1542 hits after cut off
- Each signal has been added to reduce the white noise
- Normalized by charge to compare the shape with simulation

$$S_{norm}(t) = \frac{S(t)}{\int |S(t)|\, dt} = \frac{S(t)}{Q^{+}_{ind} - Q^{-}_{ind}}$$



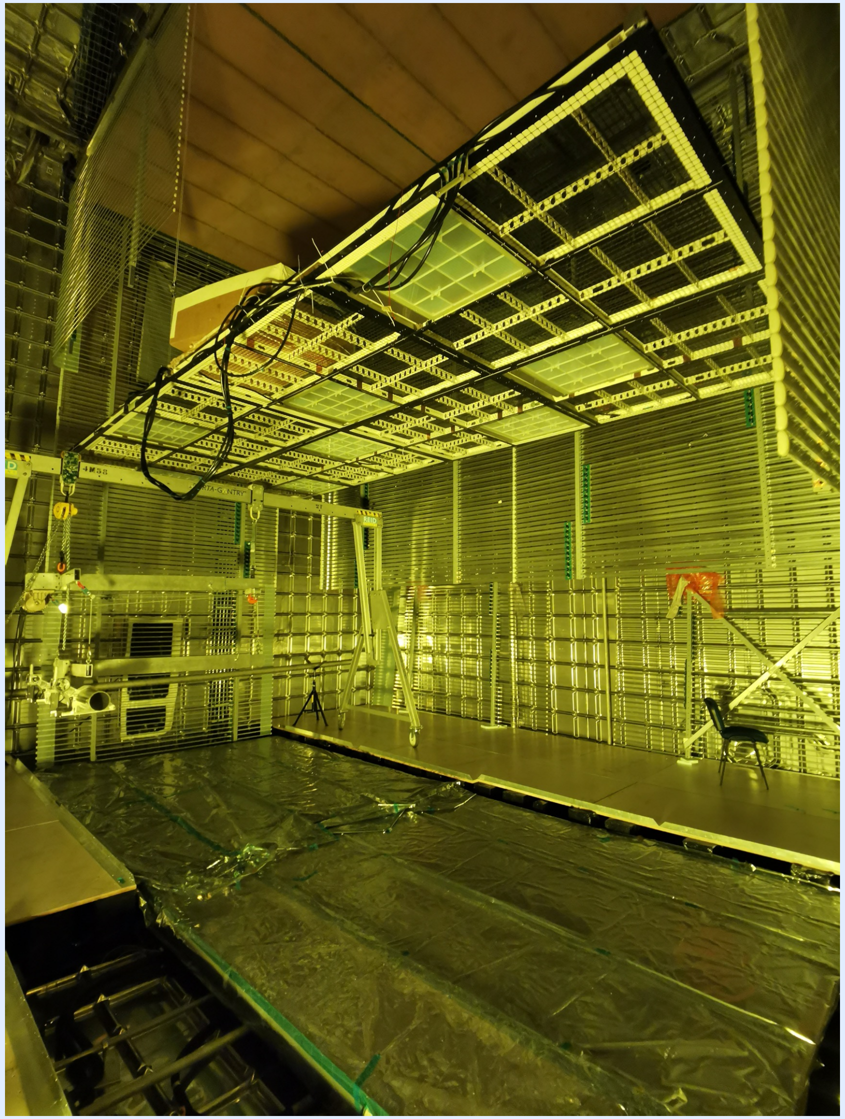




➢ **Simulated waveforms in good agreement with data taken**

- Only single hit was considered → extend the simulation at large scale

Prototypes at CERN



➢ ProtoDUNE Vertical Drift (VD):

- A prototype built at CERN to test the Vertical Drift technology at large scale (TPC size: 3.0 m (W) × 6.8 m (L) × 6.8 m (H))
- Data-taking should start early in 2025
- Top CRPs have accessible electronics and bottom CRPs have embedded cold electronics
- Will enable to analyse some data of cosmic to show induction waveforms as a function of track angle

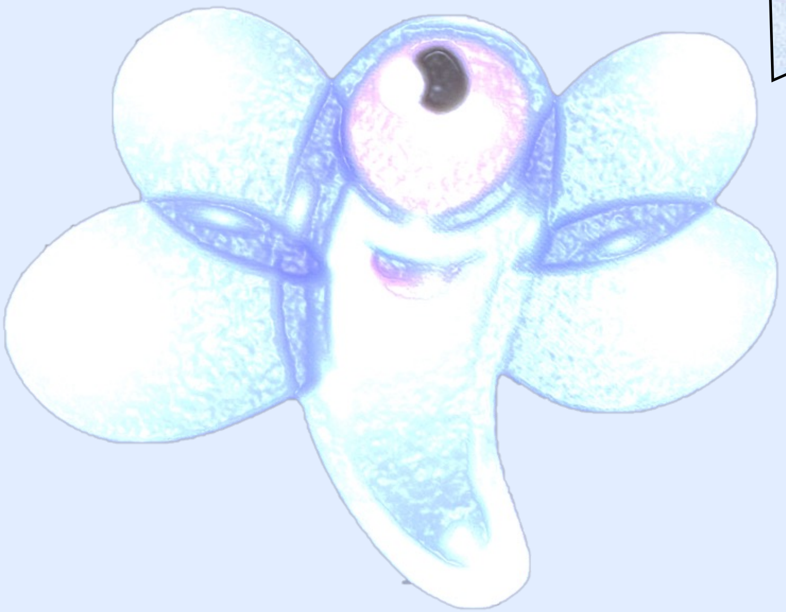
Summary

➢Work done:

- Numerical simulation design to understand the formation of induction signals of all views
- Analyse 50L TPC data and compare with simulation → Very good agreement
- Electron diffusion seems to cause a loss of charge inside the anode

➢What's next ?

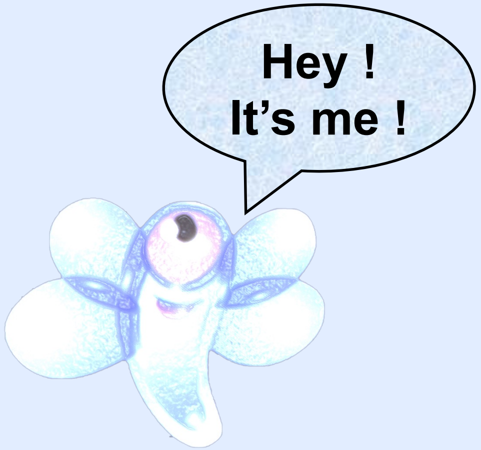
- Extend the simulation in a bigger volume → One goal of simulation is to understand the waveforms in order to improve track reconstruction.
- Data-taking at early 2025 with protoDUNE-VD
- Further study the impact of electron diffusion on the anode transparency – the charge loss in the induction 1 on data seems to be more important than simulation → Work in Progress
- (and write a thesis)



Thanks for your attention !!

Backup

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):

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

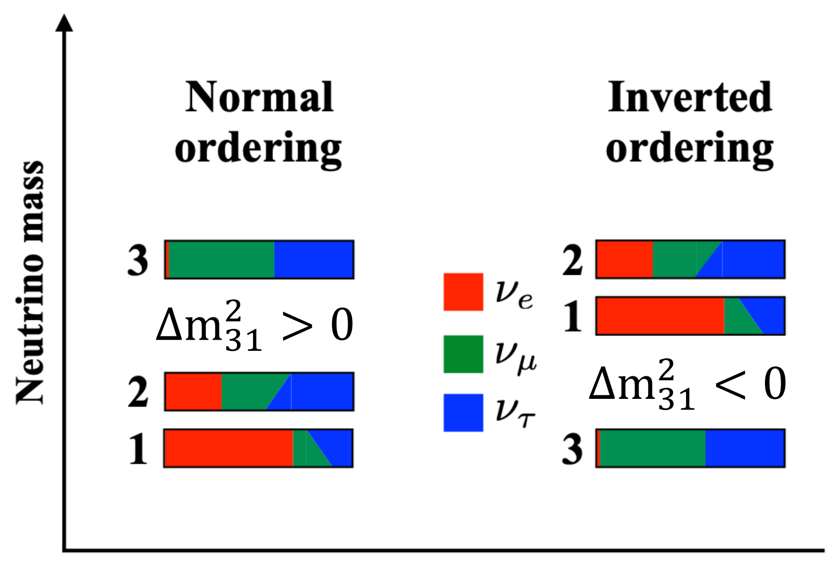
Atmospheric $\nu_\mu \leftrightarrow \nu_\tau$

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

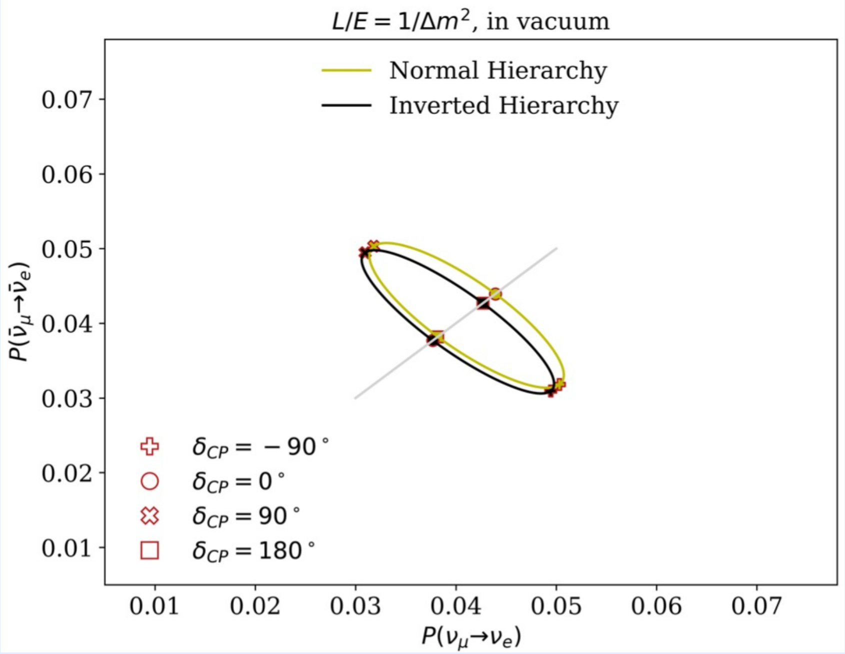
Solar $\nu_e \leftrightarrow \nu_X$

Mass ordering

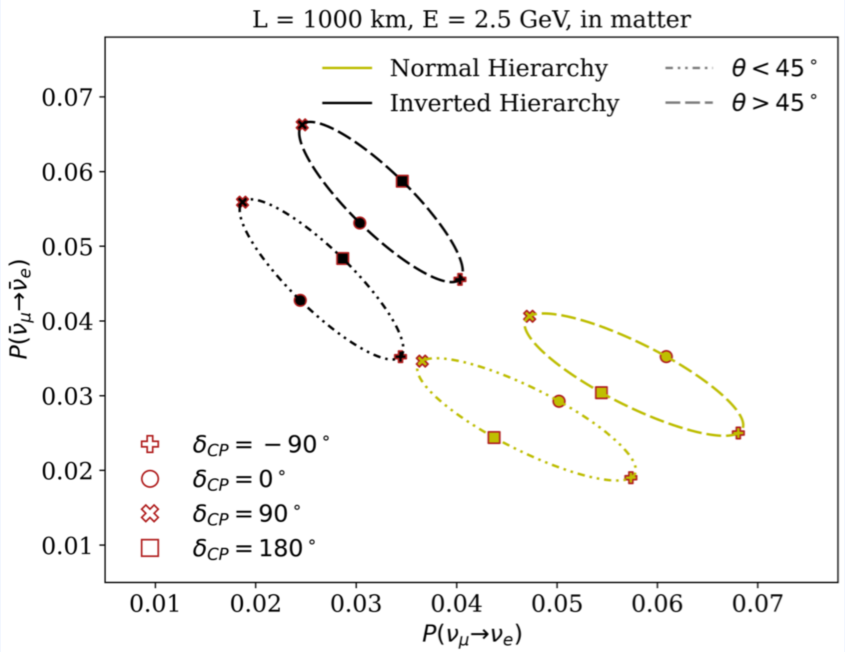
- Sign of $|\Delta m_{31}^2|$ → Mass ordering



Vaccum

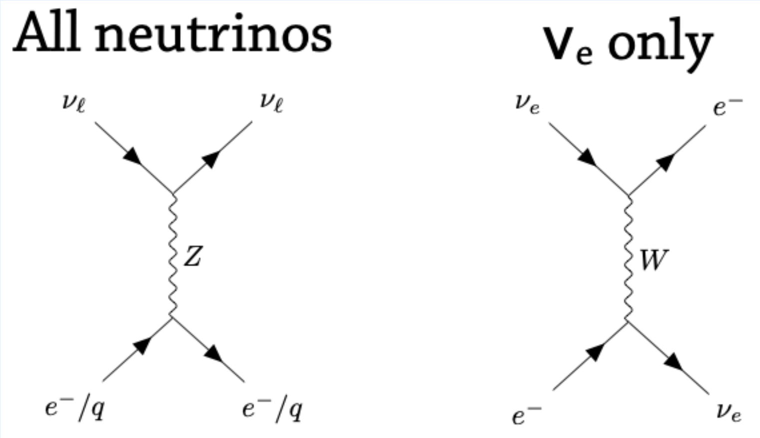


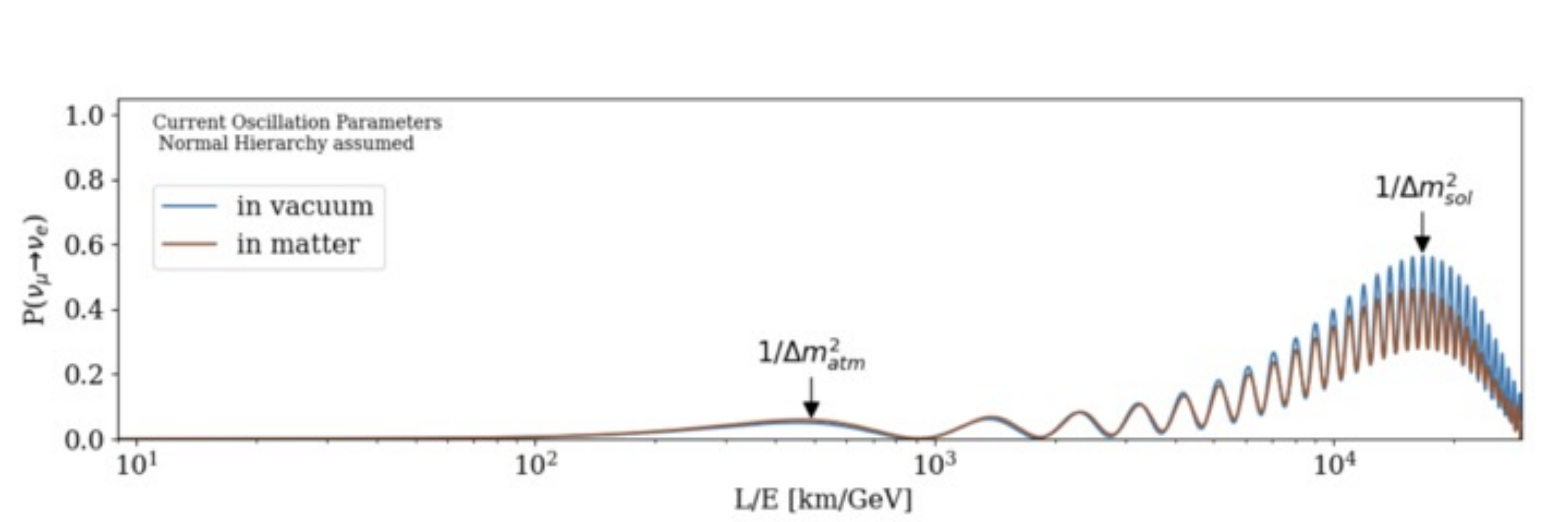
Matter



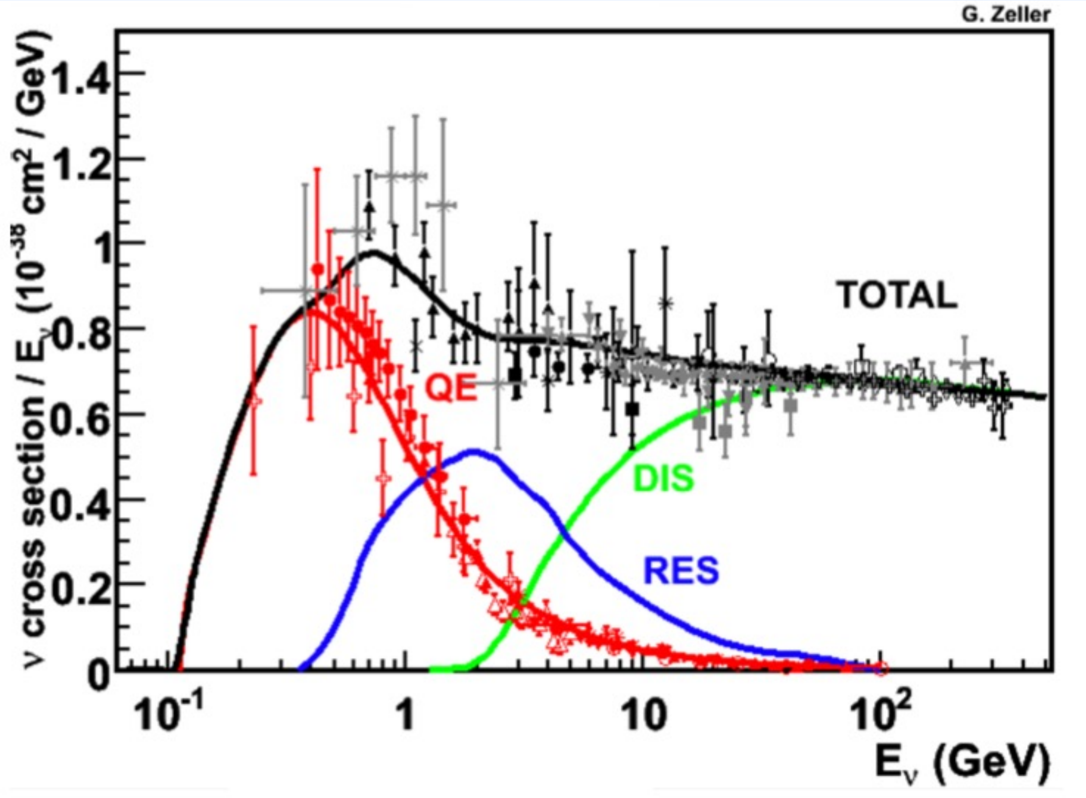
Matter effect

- Neutrino oscillations are modified by matter effect
- Add a effective potential to the Hamiltonian

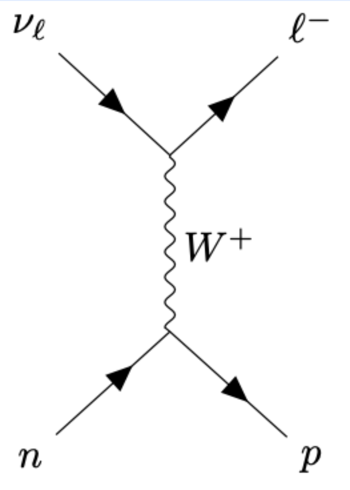




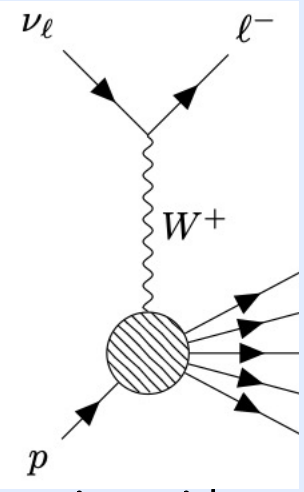
Charged currents cross section



QE: Quasi elastic

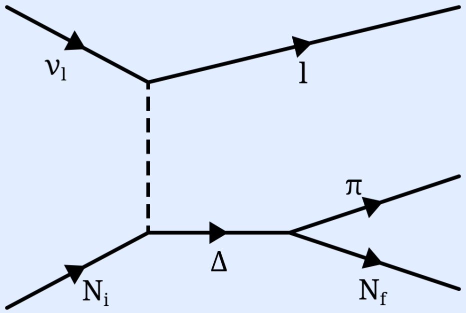


DIS: Deep inelastic



Interaction with quarks

RES: Resonant



Principle of LArTPC detection

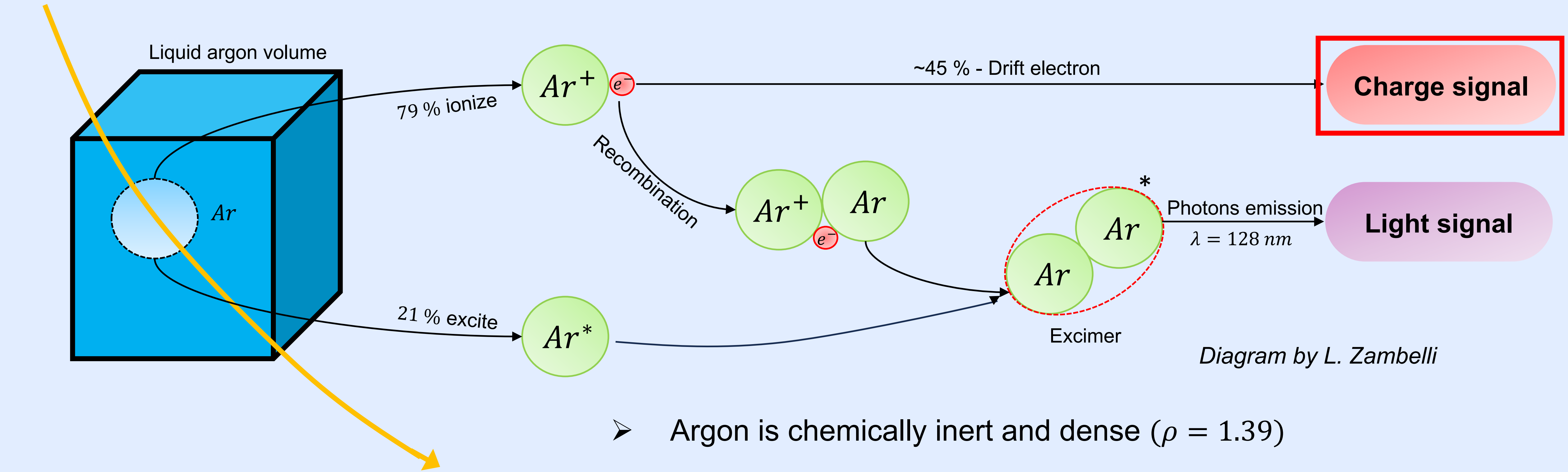


Diagram by L. Zambelli

- Argon is chemically inert and dense ($\rho = 1.39$)
- Charged particles ionize (79 %) and excite (21 %) argon atoms.
- Electrons of ionization drift to the anodes thanks to an electric field
- Scintillation light coming from argon de-excitation ($\lambda = 128\ nm$)

Drift velocity: Walkowiak Fit

- Walkowiak fit (1999):

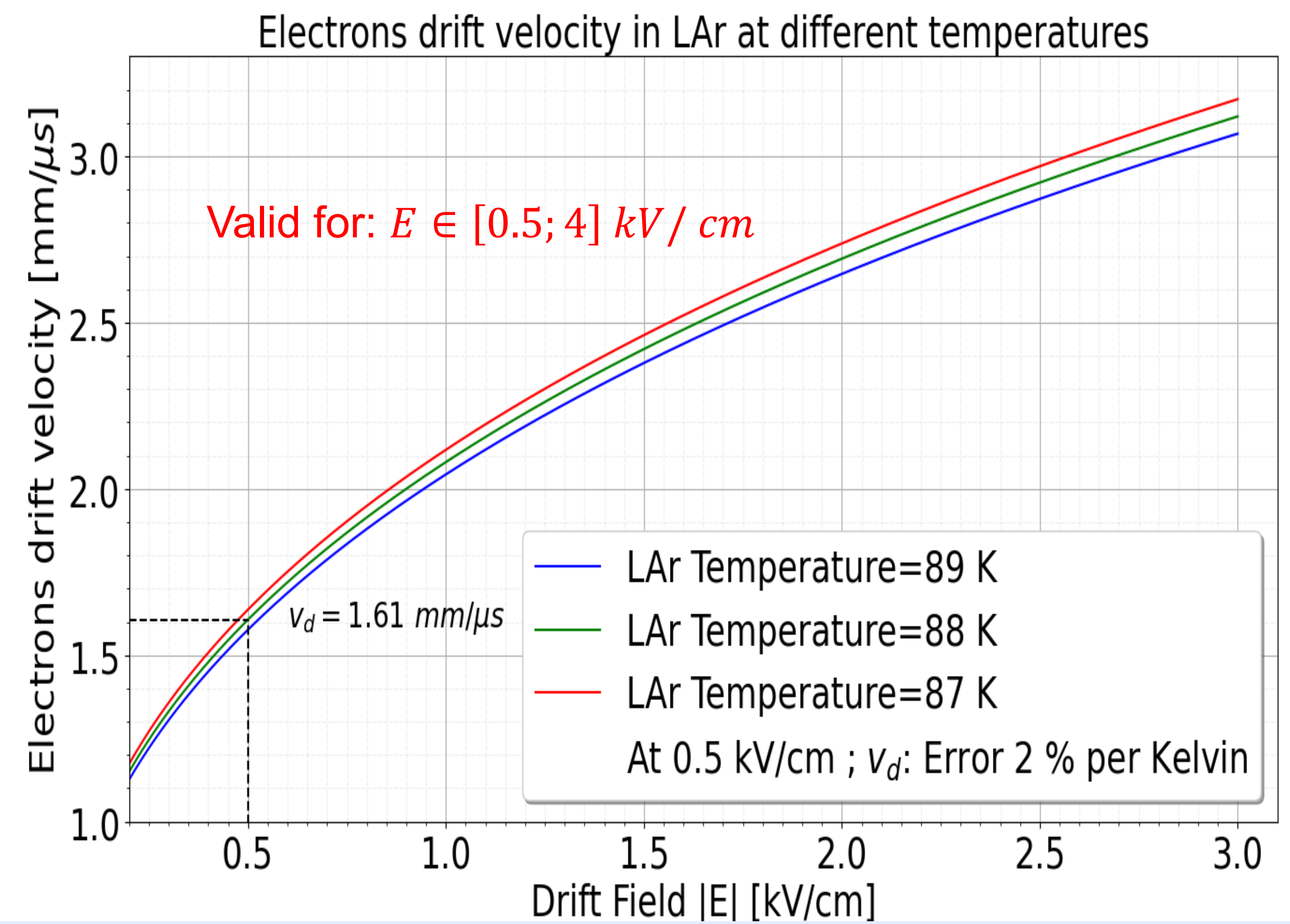
$$v_D \equiv v_D\left(|\vec{E}|, T\right)$$

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

$$+ P_2(T - T_0)$$

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

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



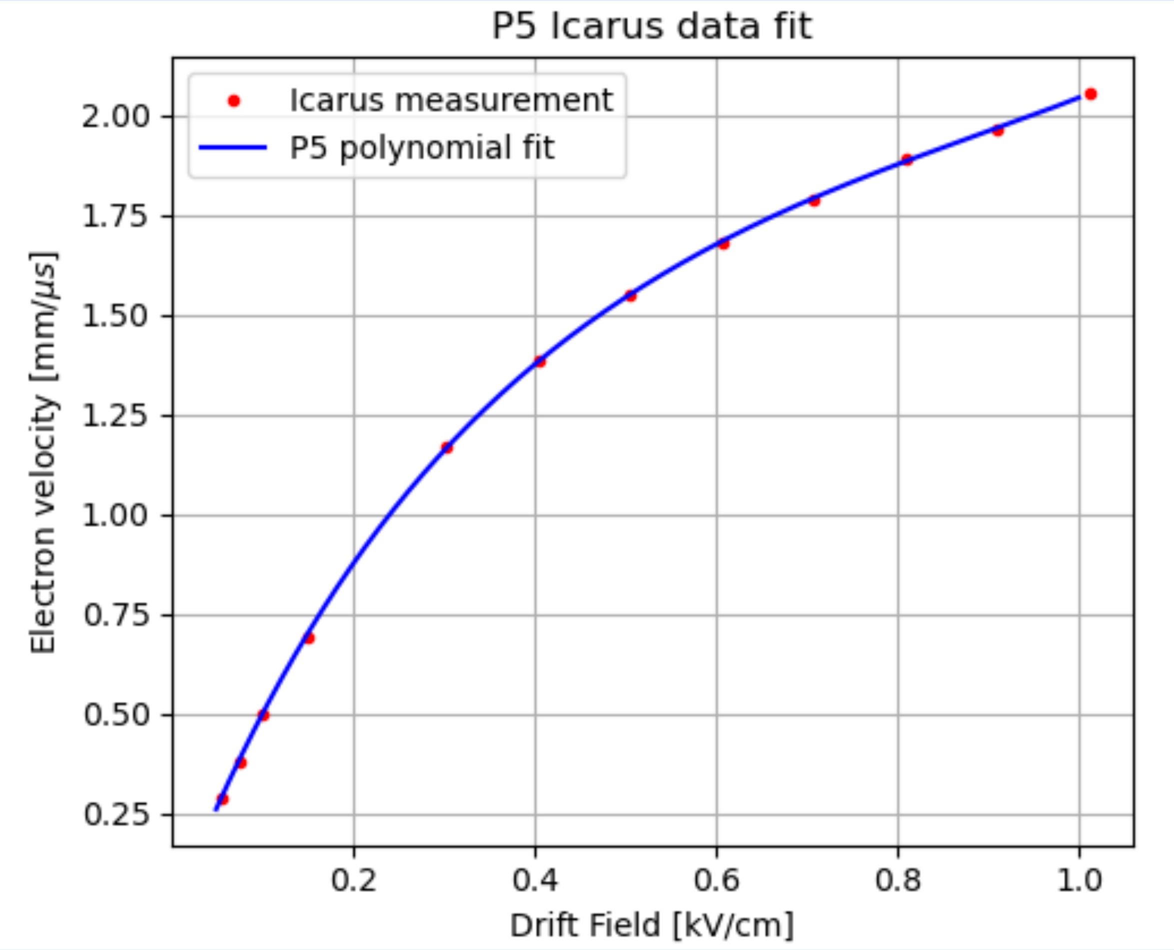
W. Walkowiak. Drift velocity of free electrons in liquid argon 1999

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: $T = 89\ K$



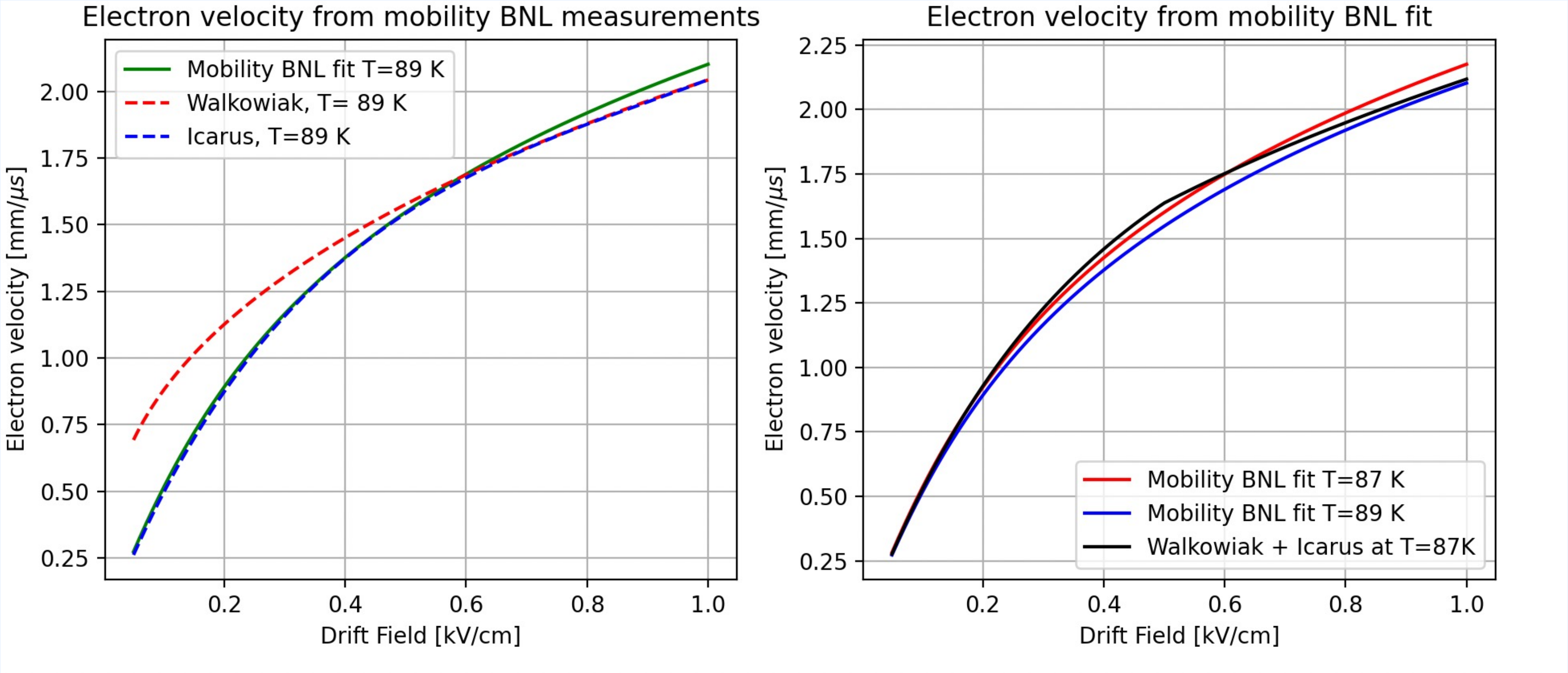
ICARUS Collaboration, Analysis of the liquid argon purity in the ICARUS T600 TPC, 2004

Drift velocity: Brookhaven fit

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

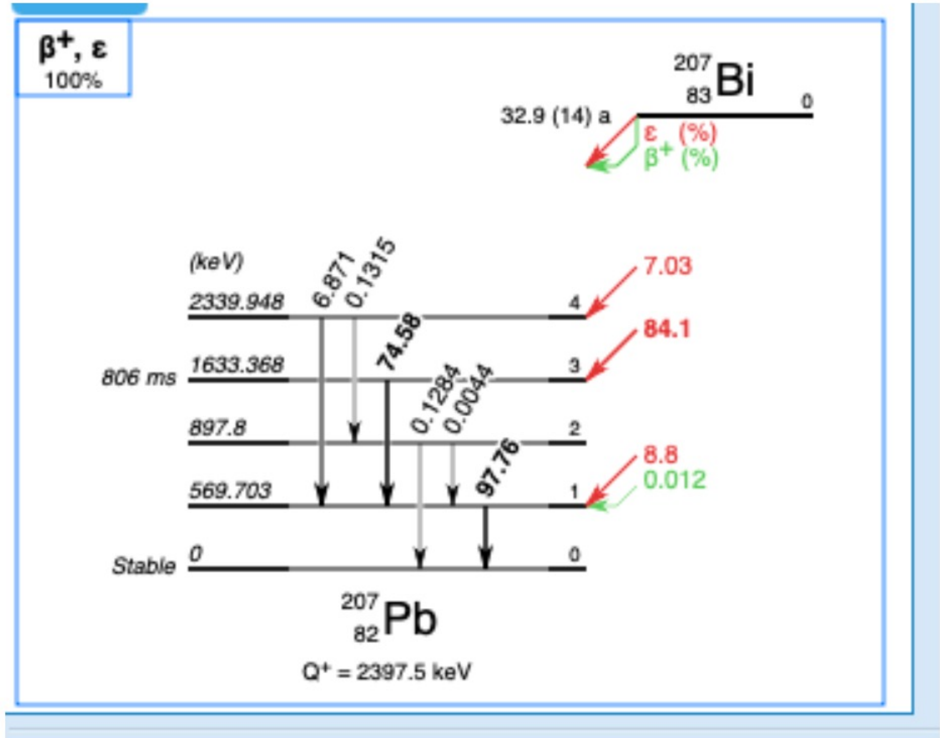
$$\mu = \frac{a_0 + a_1 E + a_2 E^{3/2} + a_3 E^{5/2}}{1 + (a_1/a_0)E + a_4 E^2 + a_5 E^3}\left(\frac{T}{T_0}\right)^{-3/2}$$

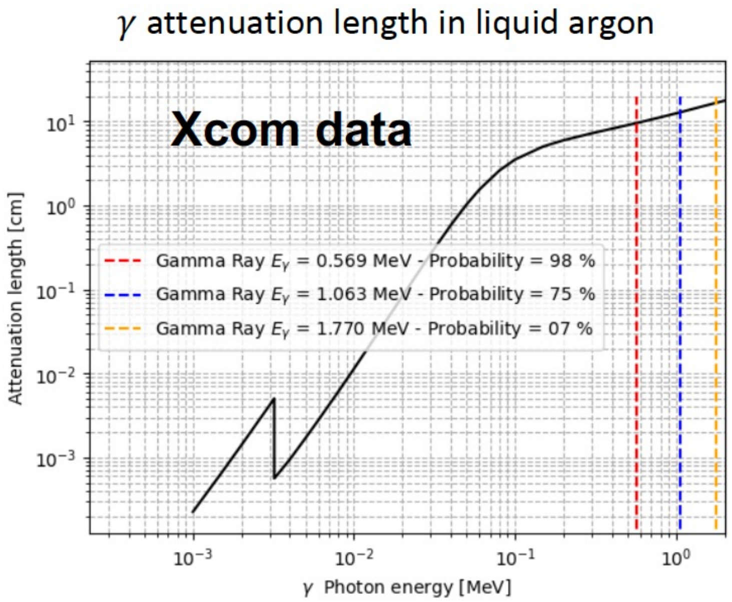
$$\begin{cases} a_0 = 551.6 \\ a_1 = 7158.3 \\ a_2 = 4440.43 \\ a_3 = 4.29 \\ a_4 = 43.63 \\ a_5 = 0.2053 \end{cases}$$

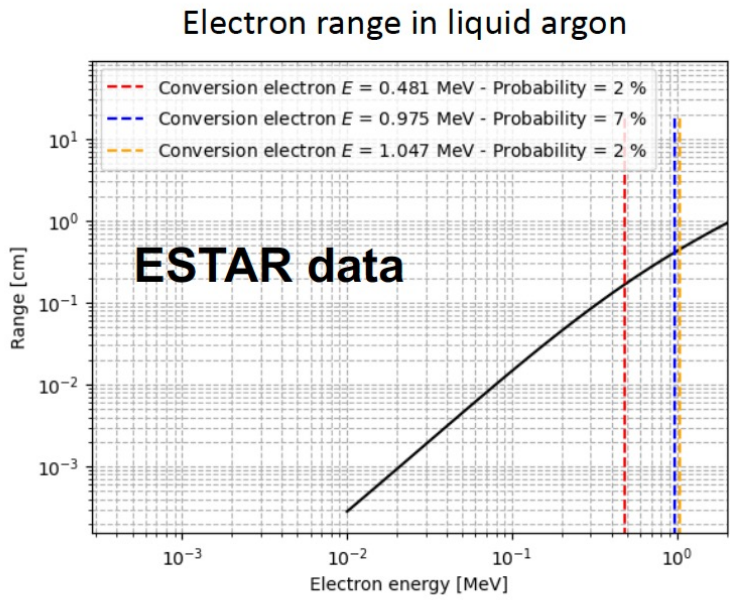


BI207 sources

- ➢ Decay by electronic capture







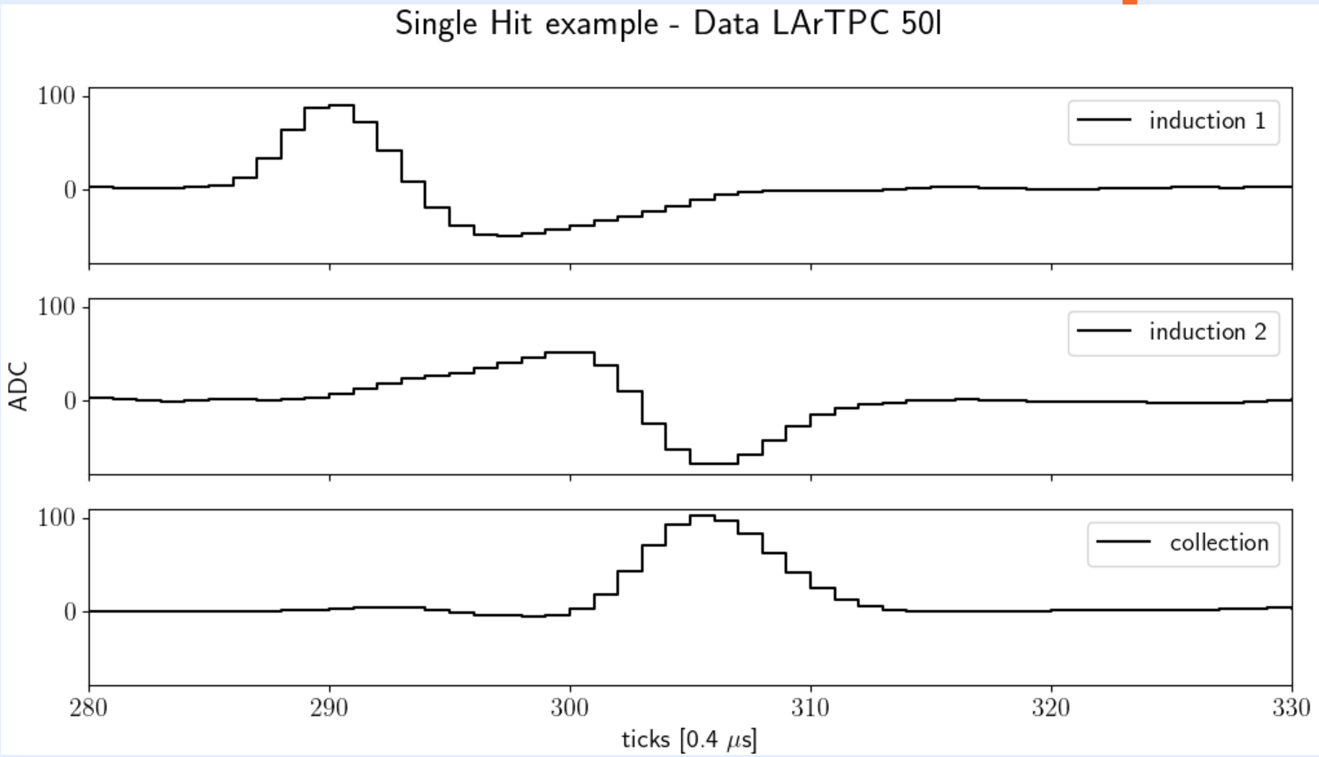
- γ attentuation length $> 10\ cm$
- Conversion electron range $\approx 1\ cm$

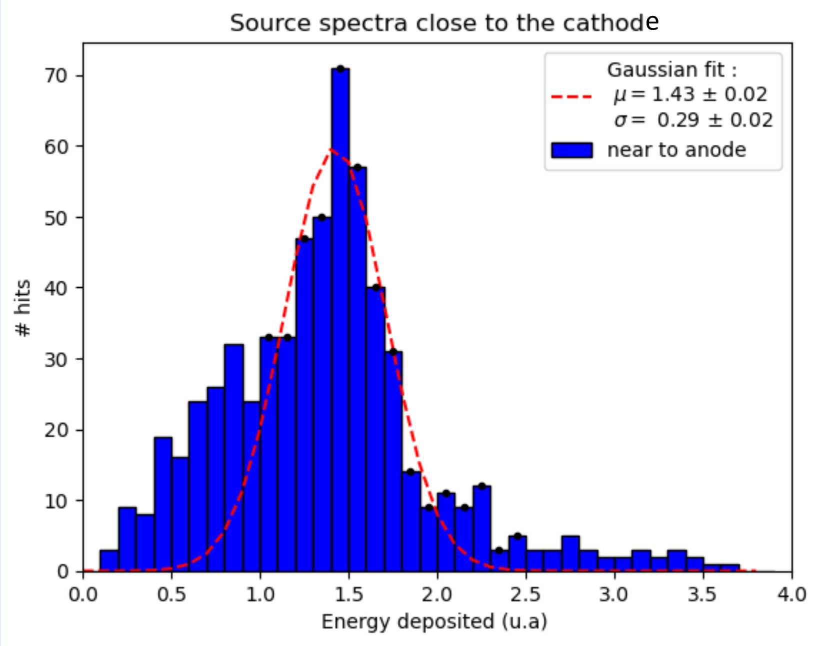
- ➢ Main γ rays:
  - $\approx 570\ keV$
  - $\approx 1\ MeV$
  - $\approx 1.7\ MeV$

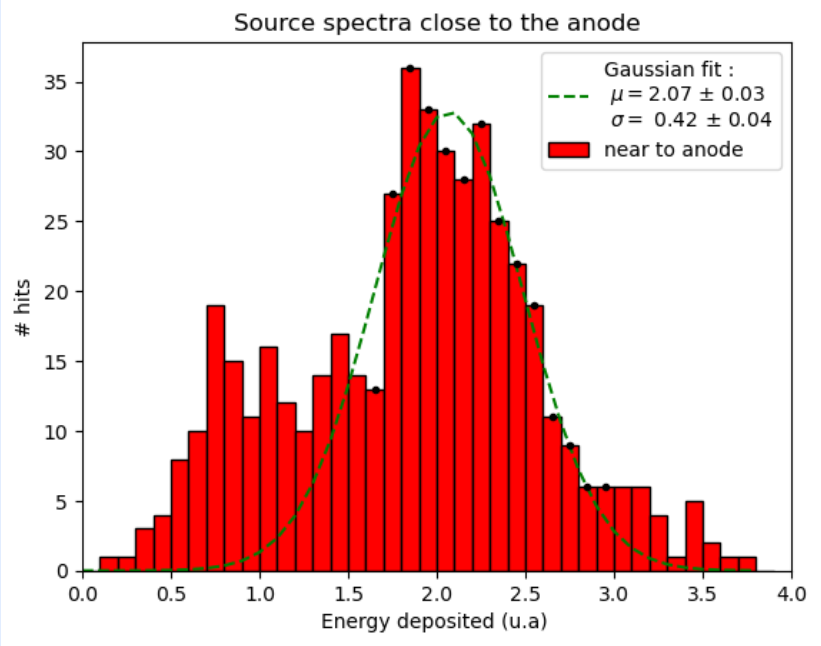
- ➢ More complicated:
  - Conversion Electron $\approx 1\ MeV$

- ➢ 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

Bi207 Reconstructed Spectra





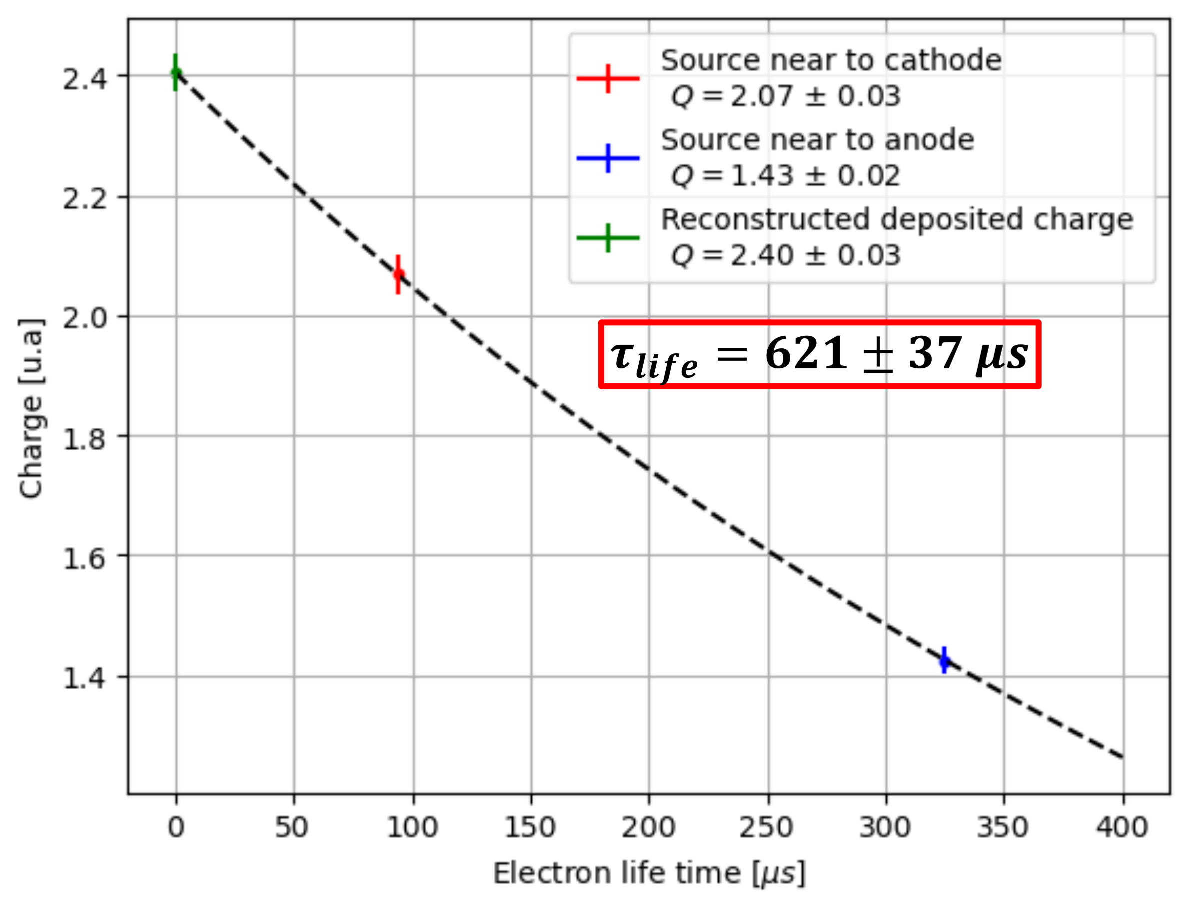


- Cut hits at 7 mm around both sources
- Useful to calibrate detector with peak at 1 MeV
- Red is closer to the anode than blue
- Not enough single hit events - data acquisition too short (~ few hours)

Electron life time

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

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



$$\tau_{life} = 621 \pm 37\ \mu s$$