Performance of High-Angle Time Projection Chambers in the T2K Near Detector Upgrade

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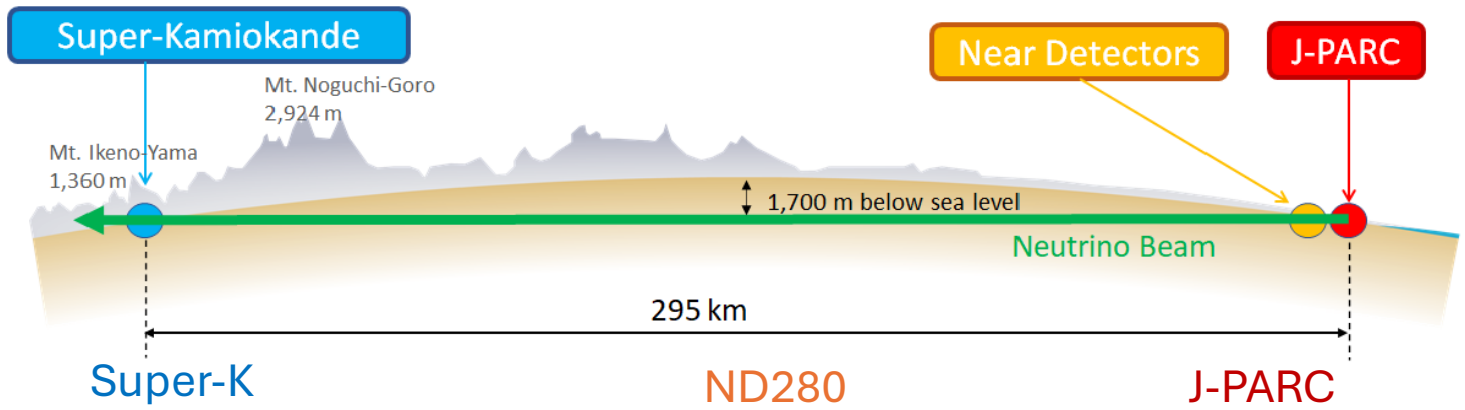
T2K

Overview

1. T2K Experiment
2. ND280 Upgrade
3. HA-TPC components
4. HA-TPC performance

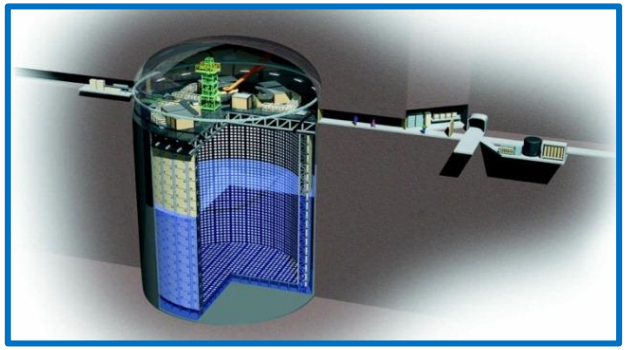
The T2K Experiment

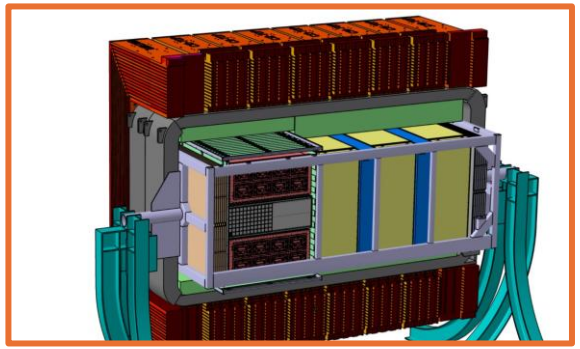
T2K is a long-baseline neutrino experiment from J-PARC to Super-Kamiokande

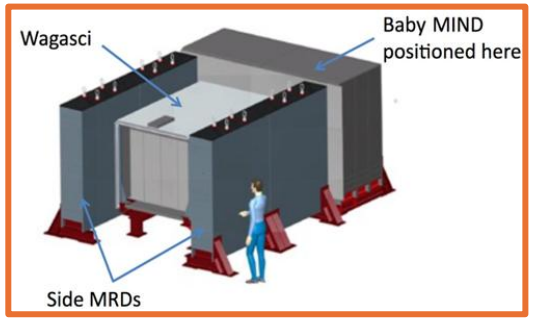


Main goals and results:

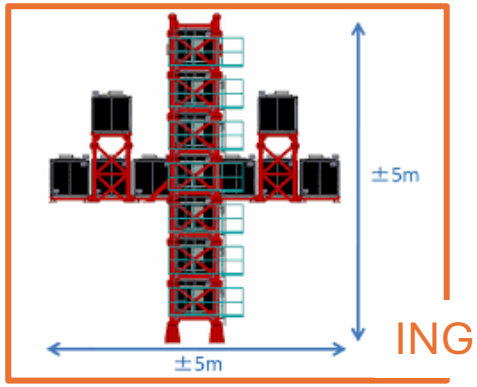
- ν_μ disappearance
  $\theta_{23}, \Delta m^2_{23}$
- ν_e appearance
  θ_{13}, δ_{CP}







WAGASCI – Baby MIND



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Upgrades:

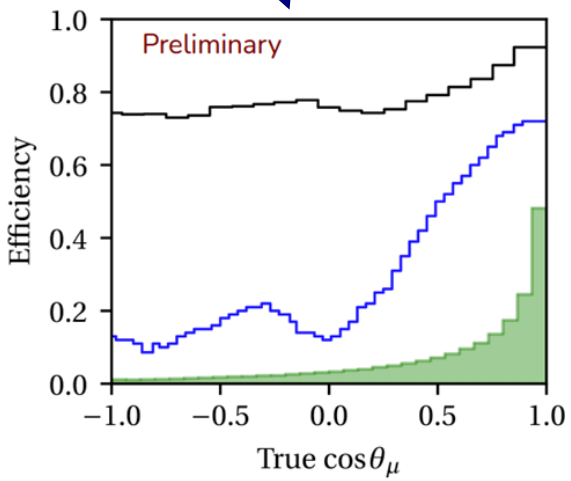
- **MR** beam power reached 840 kW, expecting to reach up to 1.3 MW
- Upgrade of Near Detector **ND280** to decrease systematics

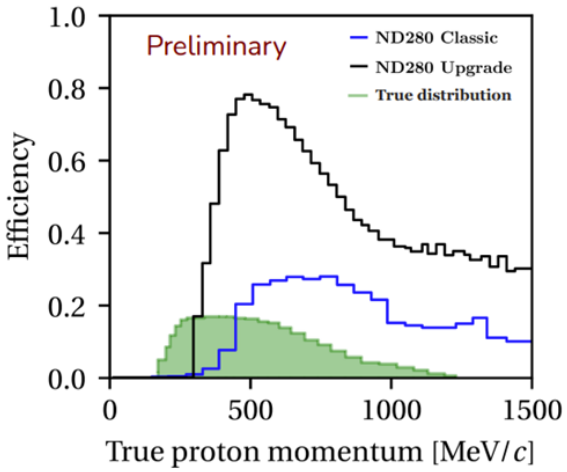
Goal: improve sensitivity to δ_{CP}

Near Detector ND280 Upgrade

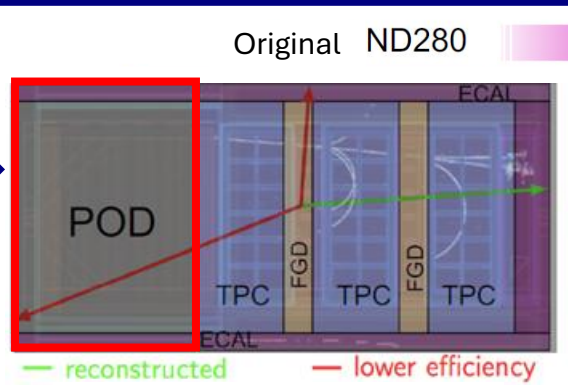
Critical points:

1. **Low acceptance** for tracks with high angle *"Forward Only"*
2. **Low efficiency** in reconstructing **hadronic parts** of interactions

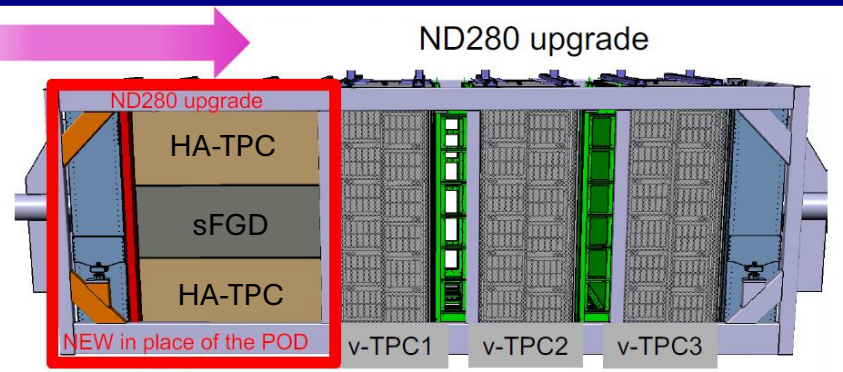




Upgrade



Good acceptance only for forward tracks



+ 6 TOF planes surrounding the new tracker

Upgraded Detector Configuration:

1. **Super Fine Grain Detector (sFGD):**
   Segmented target of cubic scintillators (1 cm side) for the improvement of hadronic part reconstruction
2. **Two High Angle TPCs (HA-TPC):**
   Placed at high angles respect to beam direction to improve Particle Identification for leptons
3. **Time of Flight (ToF):**
   Six planes of scintillators to reduce the background

ND280 Upgrade:

- Overall systematic uncertainty to **4%** (from 6%)
- Near detector for Hyper-K from 2028

See T. Daret's talk

High Angle Time Projection Chambers (HA-TPC)

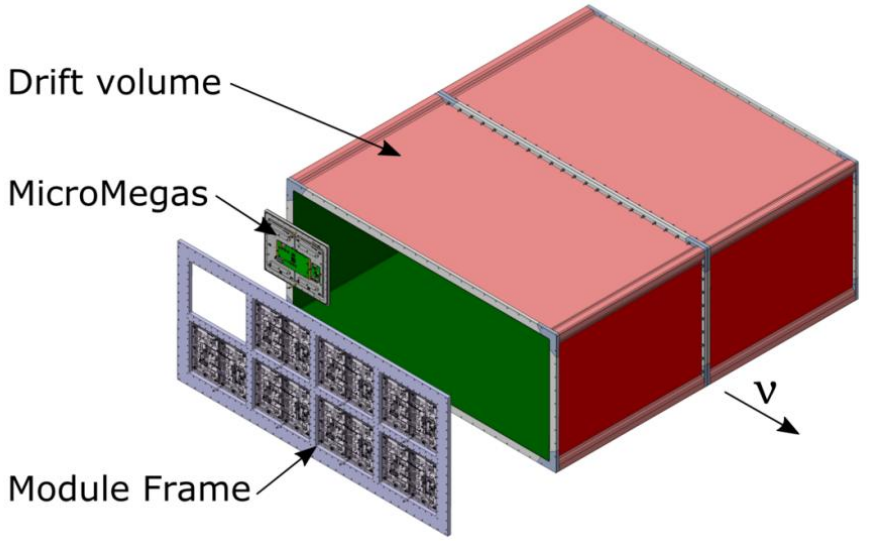
Requirements:

- **Momentum resolution** $\frac{\sigma_p}{p} < 10\%$ at 1 GeV/c → neutrino energy estimation

  ↓

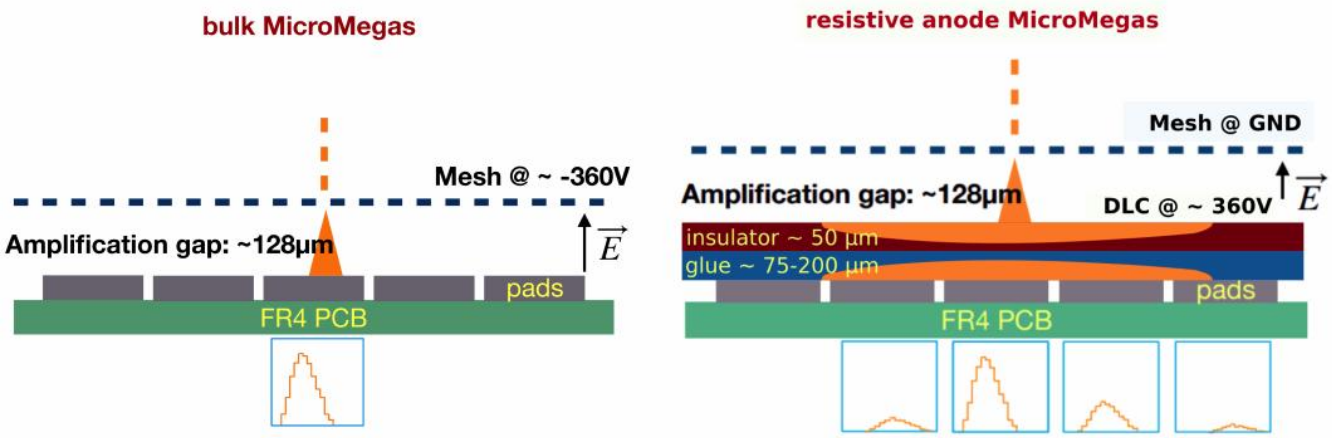
  Spatial resolution O(800 μm) → 3D track reconstruction

- **Energy resolution** $\sigma(\frac{dE}{dx}) < 10\%$ → PID of electrons and muons
- **Low material budget walls**



1. **Field Cage**
   - Thin walls and less space subtracted to active volume
2. **Resistive MicroMegas**

   ERAM: Encapsulated Resistive Anode MicroMegas
   - Charge spread on resistive layer to enhance spatial resolution
   - Spark protection



Operating conditions:

- **T2K gas** $\mathrm{Ar:CF_4:iC_4H_{10} = 95:3:2}$
- **Overall dimension** $\sim 2.0 \times 0.8 \times 1.8\ \mathrm{m^3}$
- **Drift length** 1 m
- **Electric field uniformity** $<10^{-3}$ at 15 mm from walls

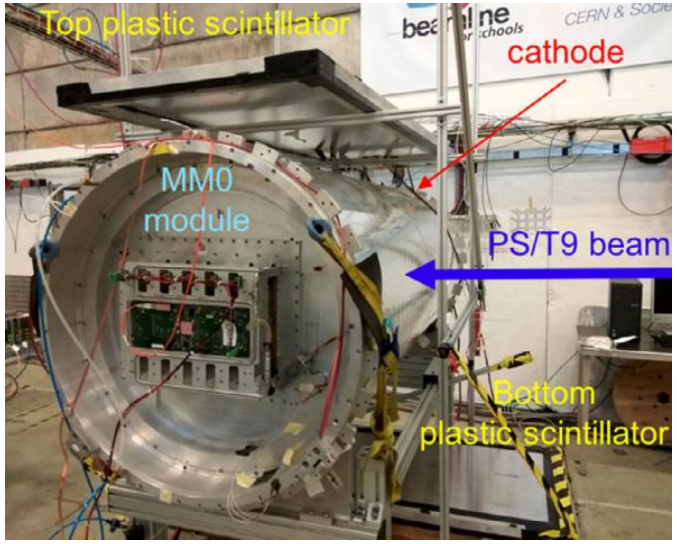
HA-TPC timeline

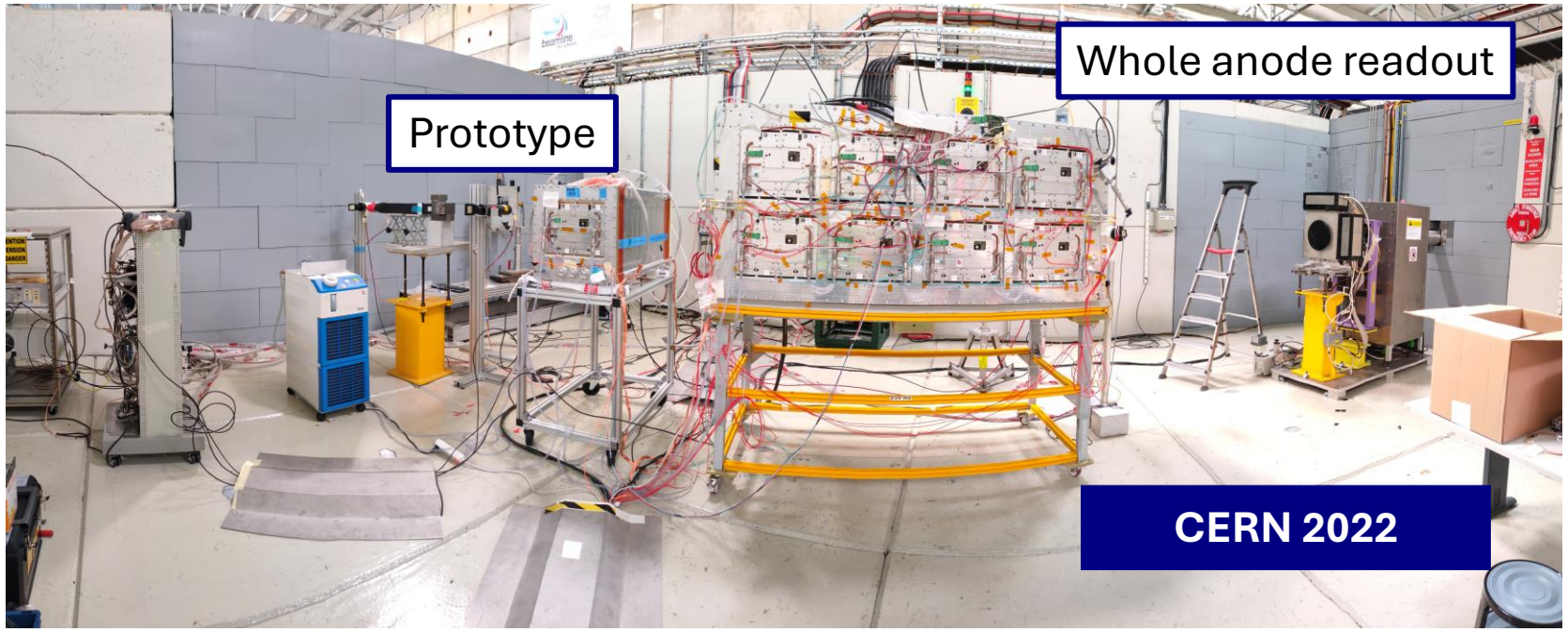
Design and Prototyping phase — **Building phase**

Timeline

- **CERN 2018**
- **DESY 2019**
- **DESY 2021**
- **CERN 2021**
- **CERN 2022** — **8 ERAMs** at the same time
- **2023/2024** — **Installation at J-PARC**

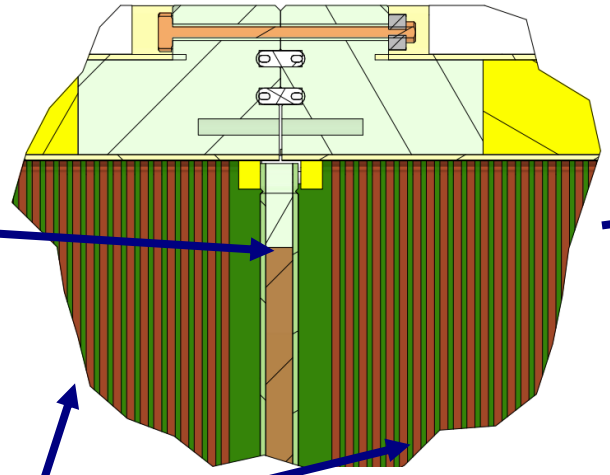
CERN 2018

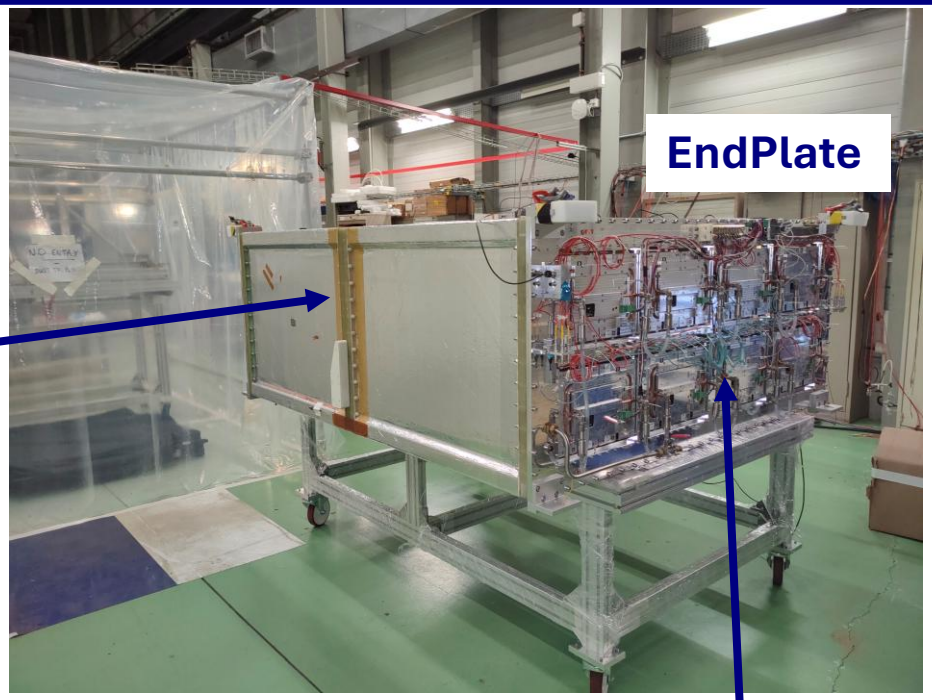




HA-TPC assembly

Assembly of one of the two HA-TPCs at CERN

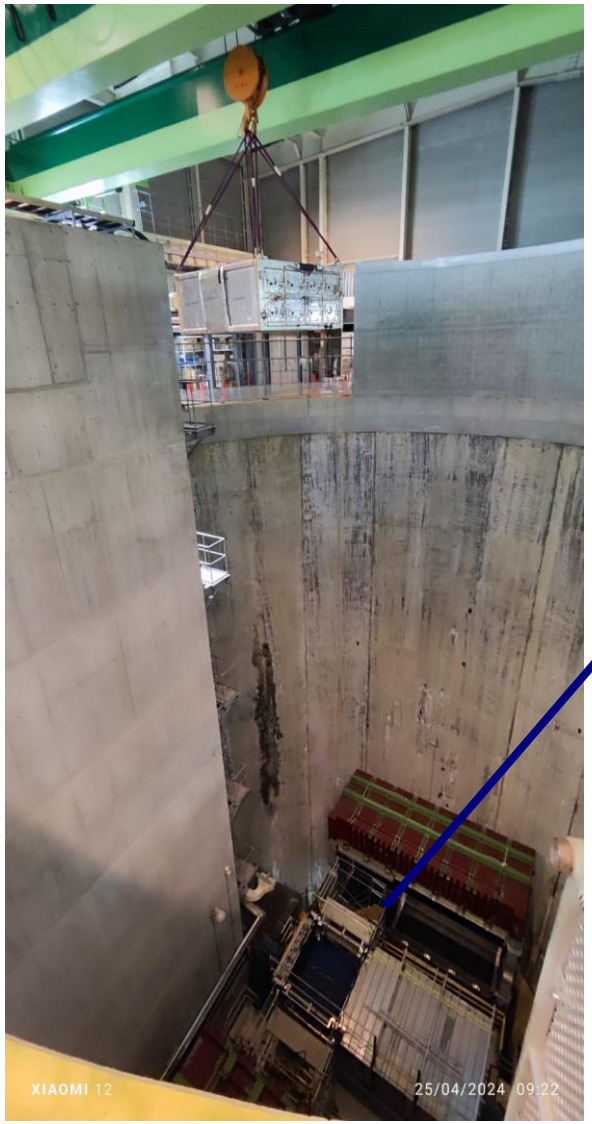


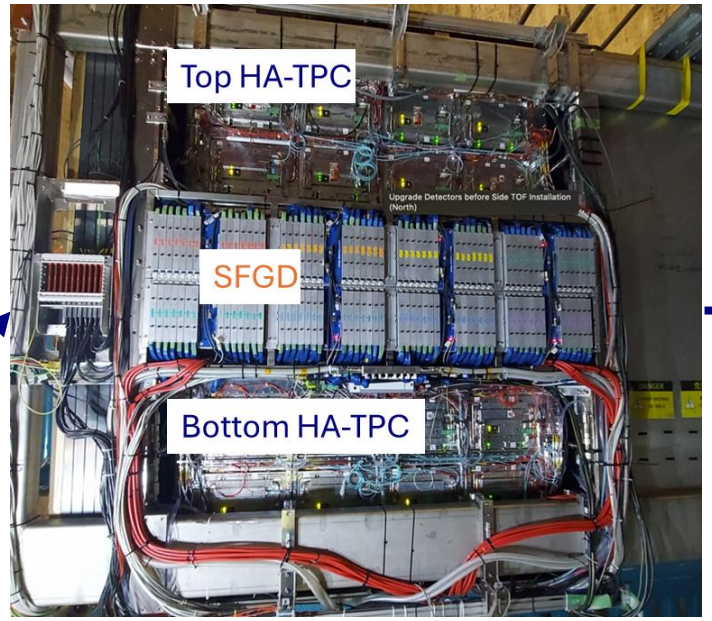


HA-TPCs are formed by two field cages with a common cathode 8 ERAMs per endplate

HA-TPCs installation

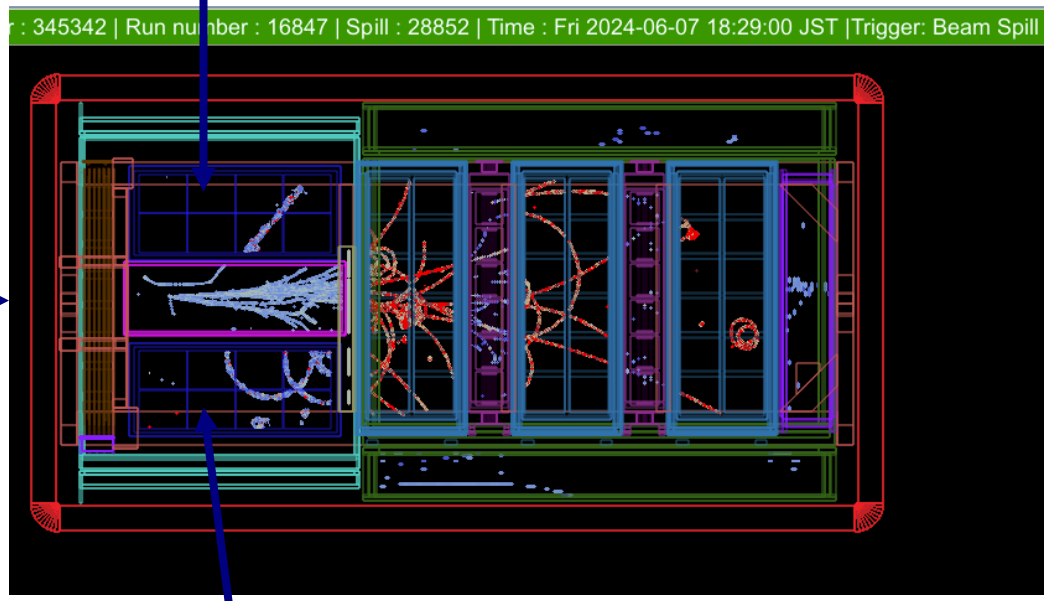
Installation of HA-TPC in ND280 at J-PARC





Top HA-TPC

Neutrino data since May 2024



Bottom HA-TPC

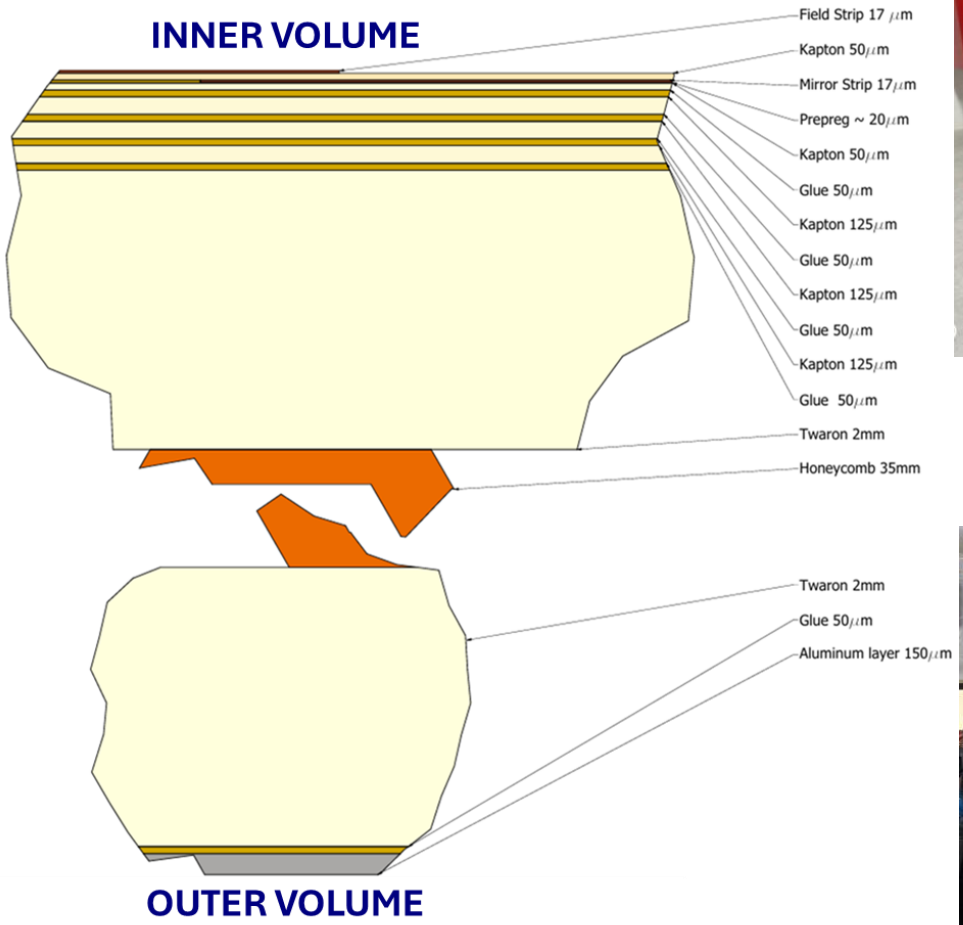
Side view of full ND280 event display

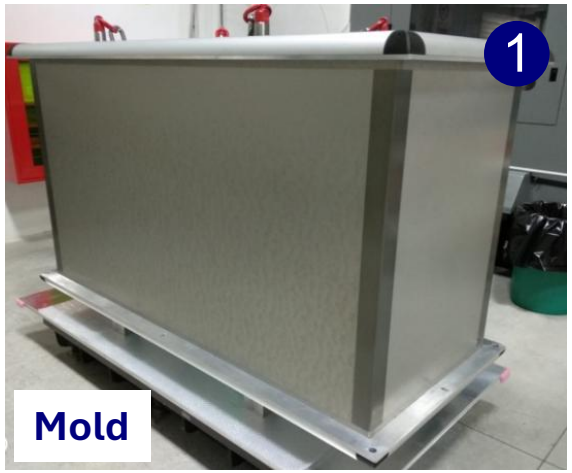
Overview

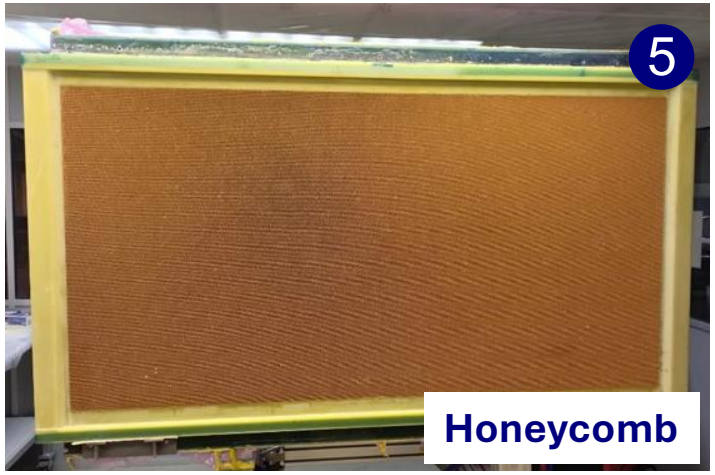
1. T2K Experiment
2. ND280 Upgrade
3. **HA-TPC components**
4. HA-TPC performances

Field Cage Production

Field cages are made of lightweight composite materials, therefore they require multiple steps over a period of about three months to be completed



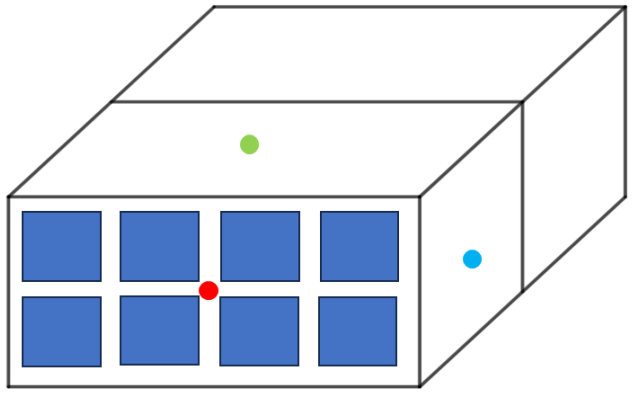




Field Cage Validation

Field Cage properties were evaluated to assess:

1. **Mechanical performances:**
   Load tests, deformation due to over/under-pressure



Data:

Max deformation of **large faces**: $\sim 50 \frac{\mu m}{mbar}$

Max deformation of **small faces**: $\sim 8 \frac{\mu m}{mbar}$

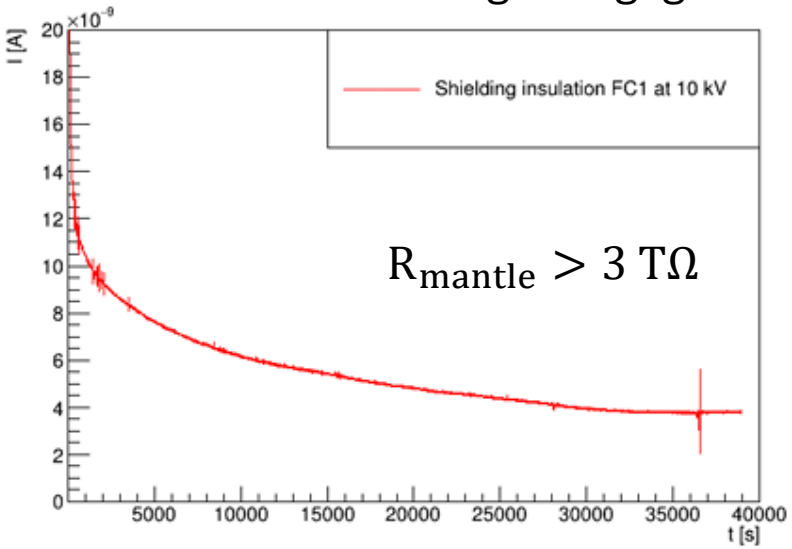
Simulation:

Max deformation of **large faces**: $\sim 50 \frac{\mu m}{mbar}$

Cathode only partly contains walls deformation

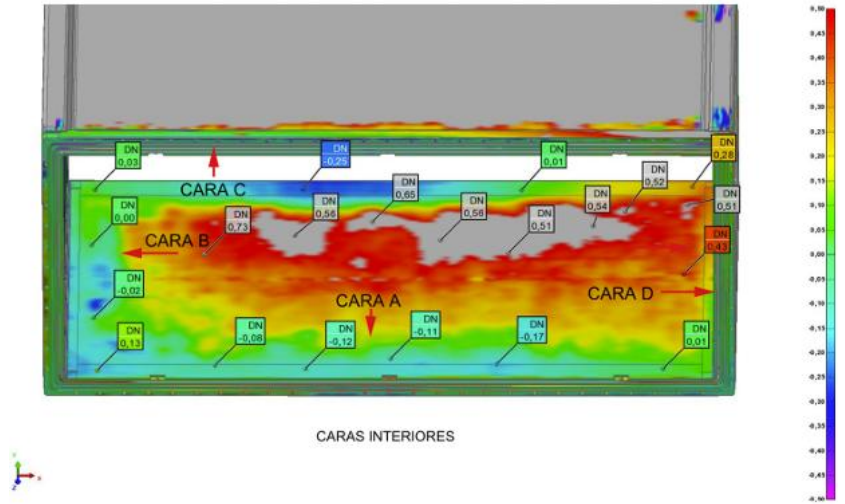
2. **Electrical performances**

Leakage current towards shielding is negligible!



3. **Metrology**

Displacement from the nominal design in **critical regions** did not exceed 500 µm



Electric field studies

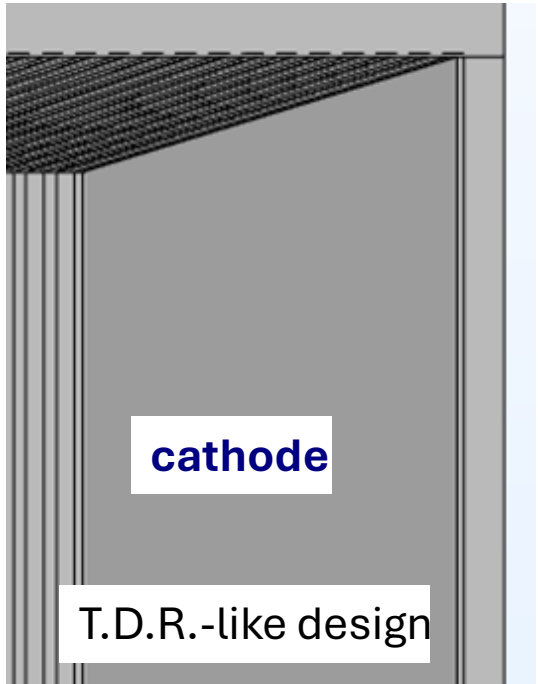
1. The study of cosmics data in HA-TPCs showed an **unexpected behavior** for tracks passing close to the cathode $\Delta x < 20$ cm

2. First, the **quantification of track distortion** was performed on the readout plane and on the drift direction

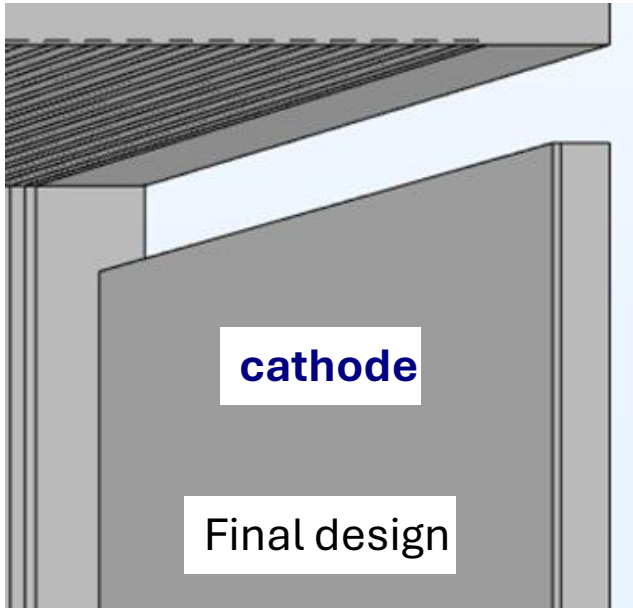
3. Several **sources** were investigated:
   - Space charge effects
   - Modification of cathode side design from TDR Finite Element Methods simulations

The issue could have been solved by an hardware intervention before installation, but due to the very tight schedule it was not spotted in time

- First strip starts close to the cathode
- Cathode close to the wall

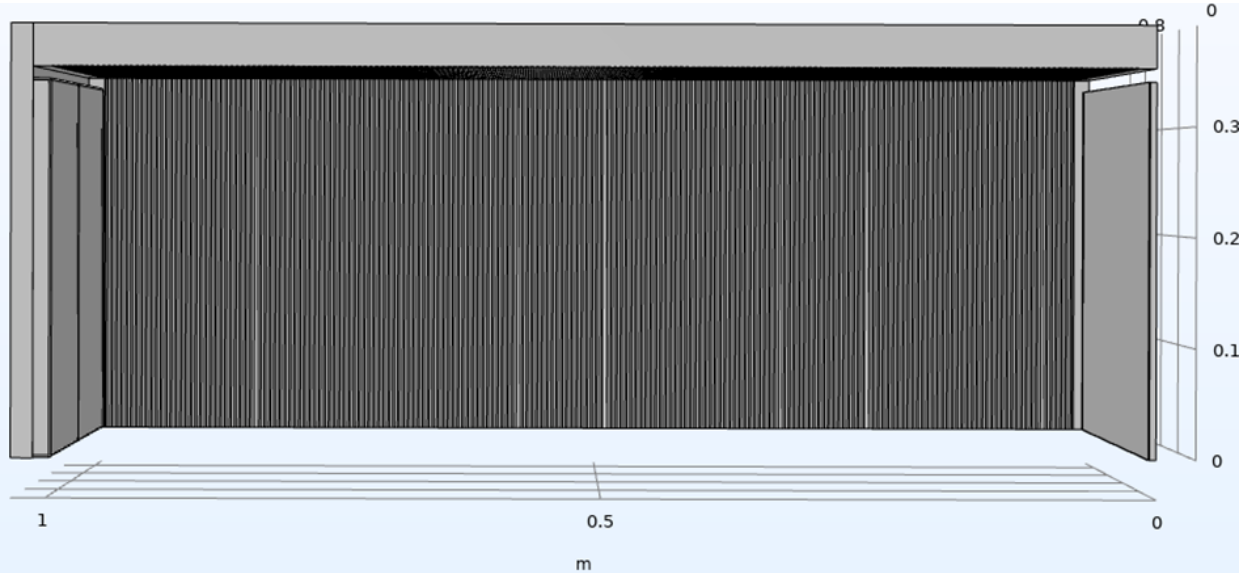


- First strip starts 8 mm away from cathode
- Cathode 12 mm away from to the wall



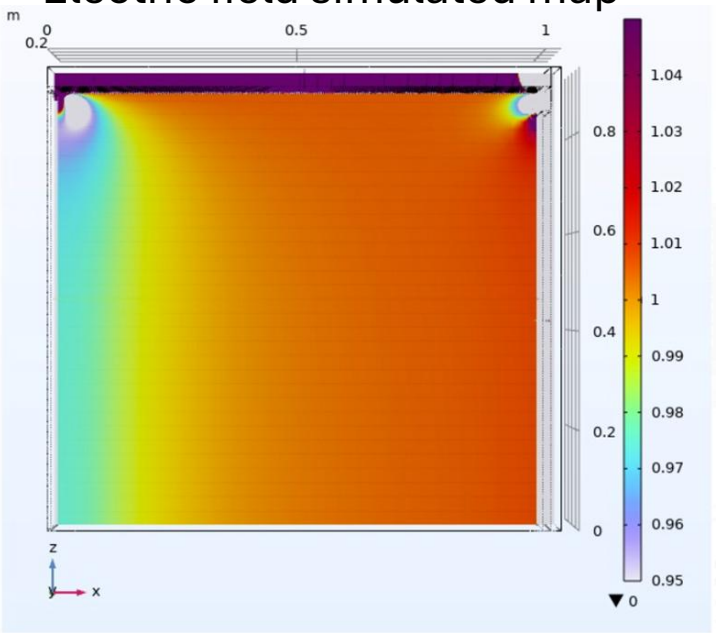
Electric field studies

Design of HA-TPC geometry in COMSOL

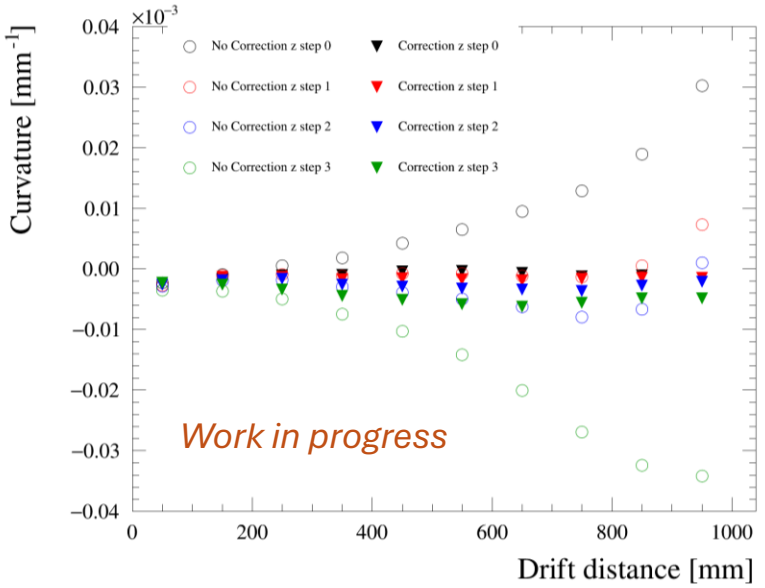


Electric field simulated map

$\frac{|\vec{E}|}{E_{th}}$

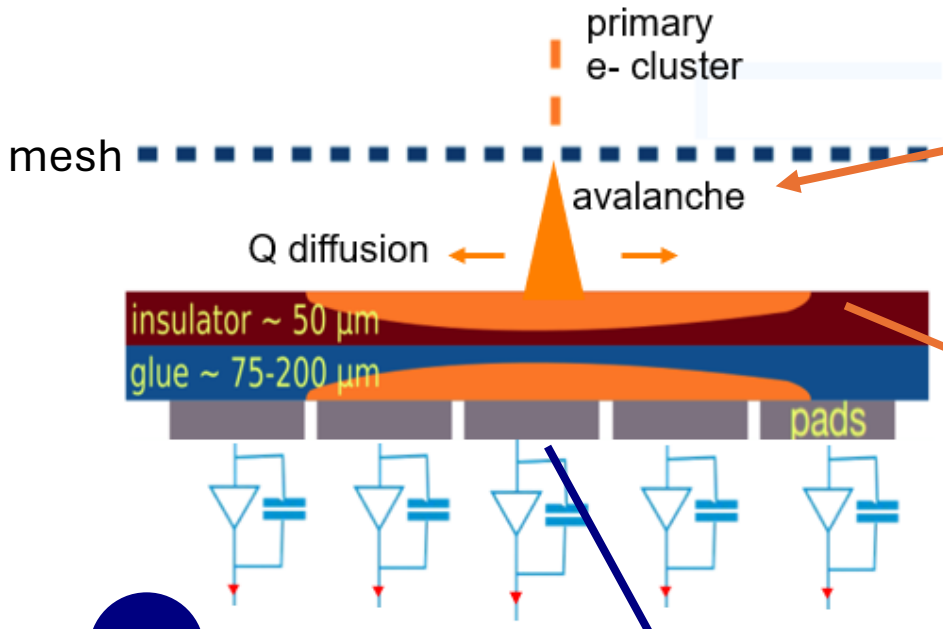


The application of Electric field map on reconstructed events reduces their *apparent curvature* (in absence of B field)



Resistive MicroMegas Sensors (ERAMs)

ERAM response characterization was performed at CERN on a test bench with a 55-Fe source



1

Primary electrons create avalanches in the amplification gap

2

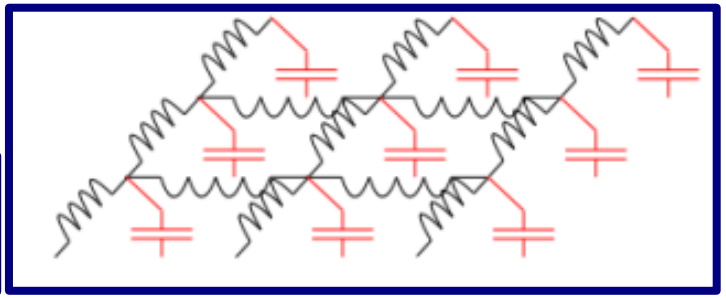
Signal has same time scale as shaping time O(100 ns)

2D diffusion equation

$$\rho(r,t) = \frac{RC}{4\pi t}\exp\left(-\frac{r^2 RC}{4t}\right)$$

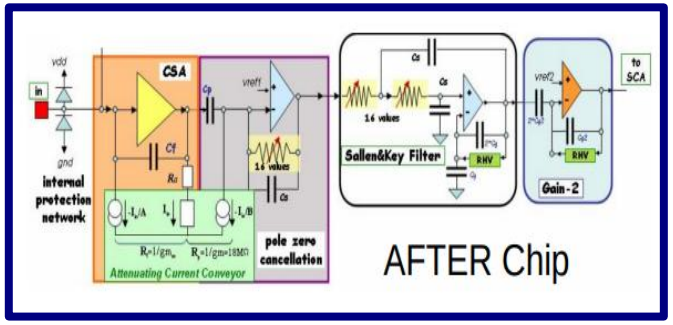
3

Electrical model of the sensor



4

FEE response function



ERAMs Validation and Characterization

From the measurements performed on the test bench, three parameters are estimated

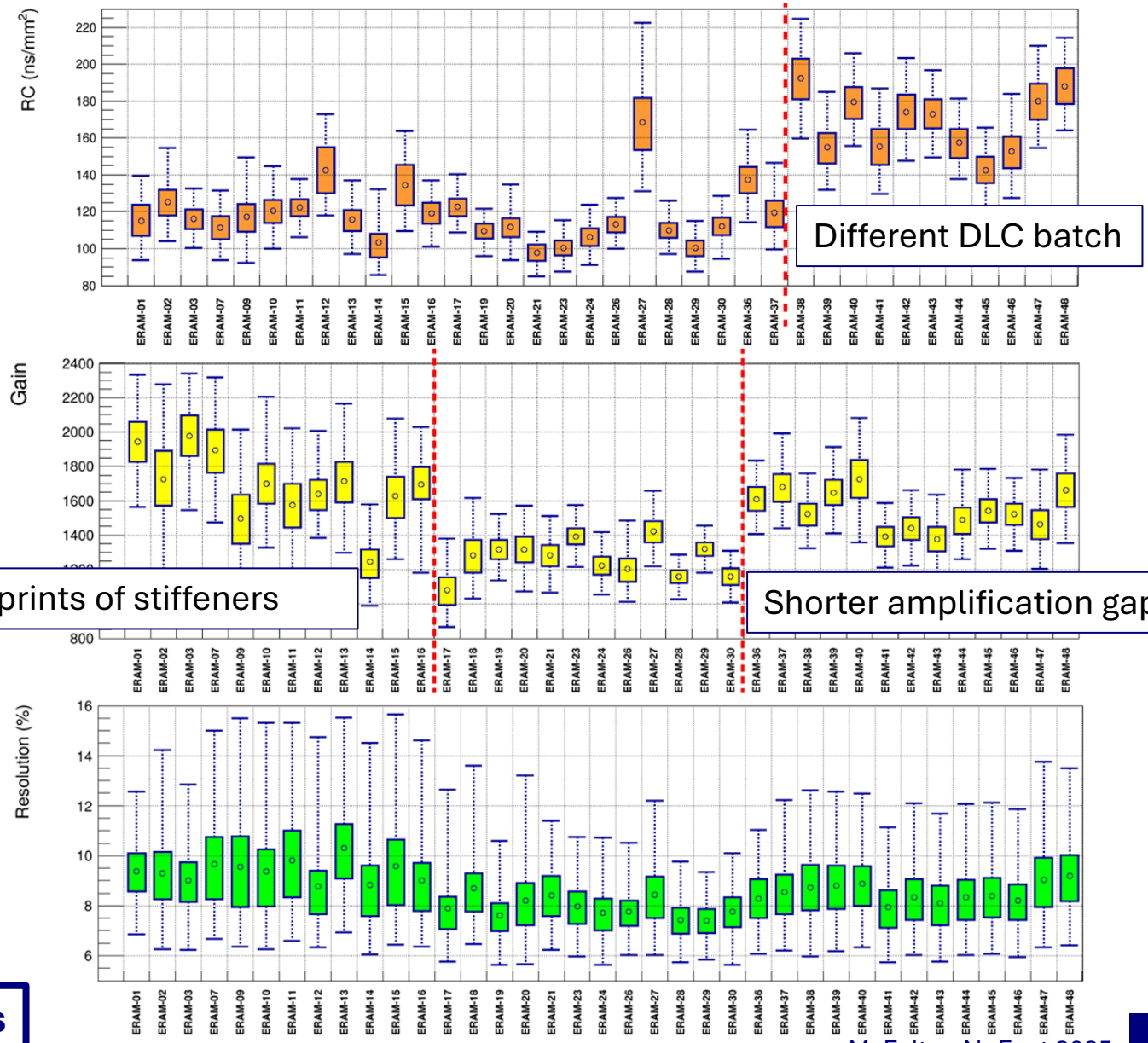
- RC
- Gain
- Resolution

thanks to a detailed model that includes:

1. X-ray propagation in gas
2. Avalanche formation
3. Charge spreading on DLC
4. Signal formation

Plots summarize the 3 properties of each pad in every ERAM for

- **identification of defects**
- **choosing the final detectors for HA-TPCs**



Candle plots

Gas Monitoring Chamber

Gas used in HA-TPCs and vertical TPCs is monitored via two Gas Monitoring Chambers (GMCs) at J-PARC to calibrate:

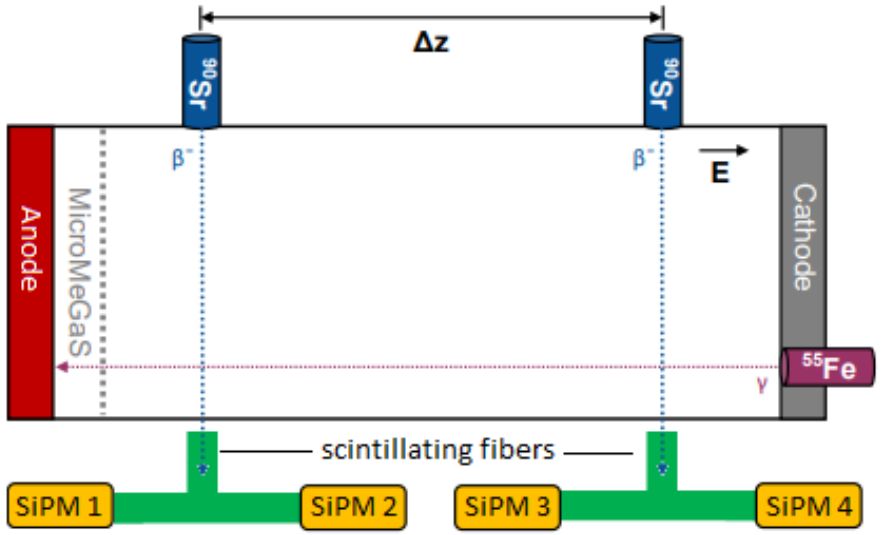
- **Electron drift velocity**

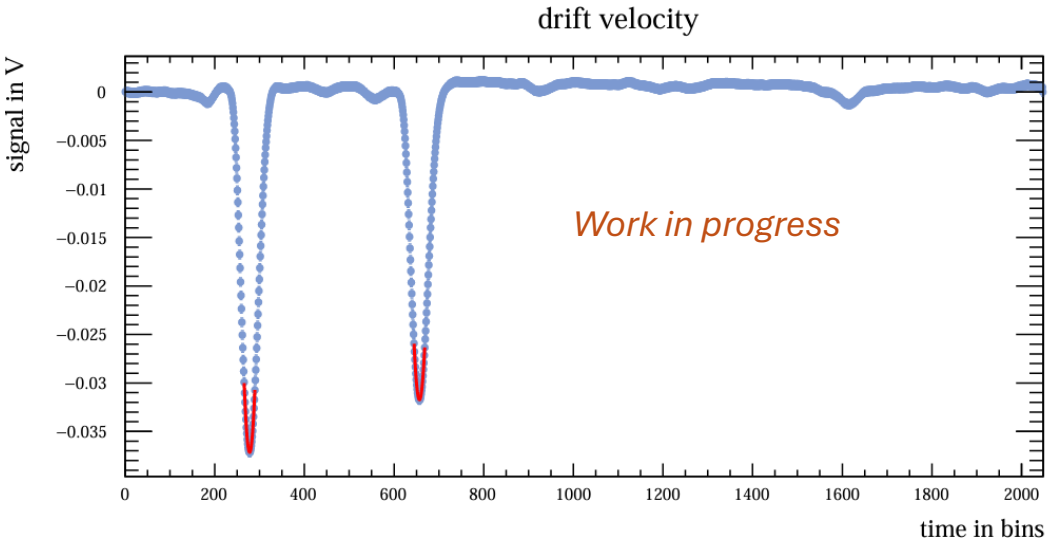
Timing of arrival w.r.t. the triggered SiPM and the anode signal

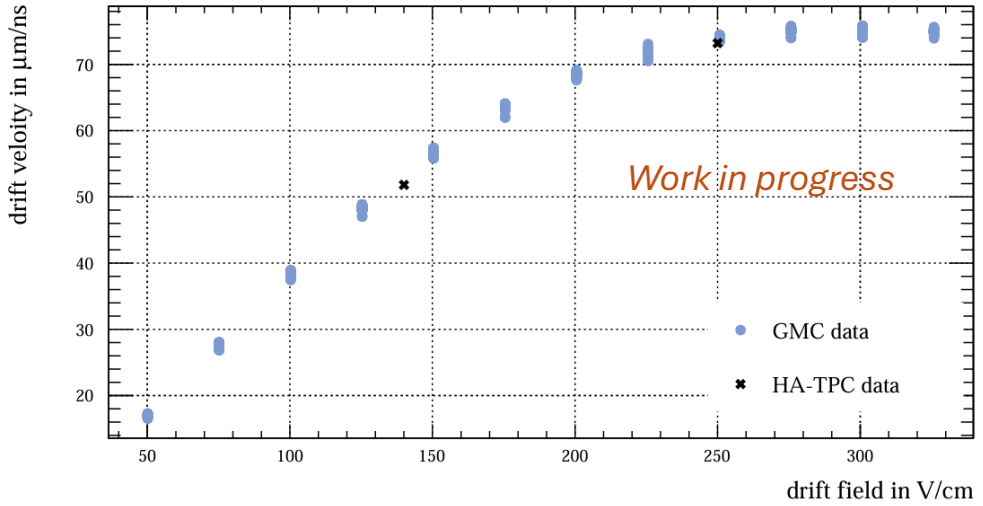
- **Gain**

Charge signals from a $Fe - 55$ X-ray source on dedicated pads

HA-TPCs and GMCs independent estimations of drift velocity are in good agreement







HA-TPC Simulation

Simulations are based on GEANT4, which propagates particle through the whole ND280

Electric and Magnetic field maps in HAT regions are based on COMSOL simulations

1. Primary electrons drift is described by **Langevin equation**

$$\overrightarrow{V_d} = \frac{\mu}{1+(\omega\tau)^2}\left(\vec{E} + (\omega\tau)\frac{\vec{E}\times\vec{B}}{|\vec{B}|} + (\omega\tau)^2\frac{(\vec{E}\cdot\vec{B})\vec{B}}{|\vec{B}|^2}\right)$$

$$\mu = \frac{e}{m}\tau \qquad \omega = \frac{eB}{m}$$

2. Signal is amplified through **avalanches** that are modelized as a **Polya distribution**

$$P_m(g) = \frac{m^m}{\Gamma(m)}\frac{g^{m-1}}{G^m}\exp\left(-m\frac{g}{G}\right)$$

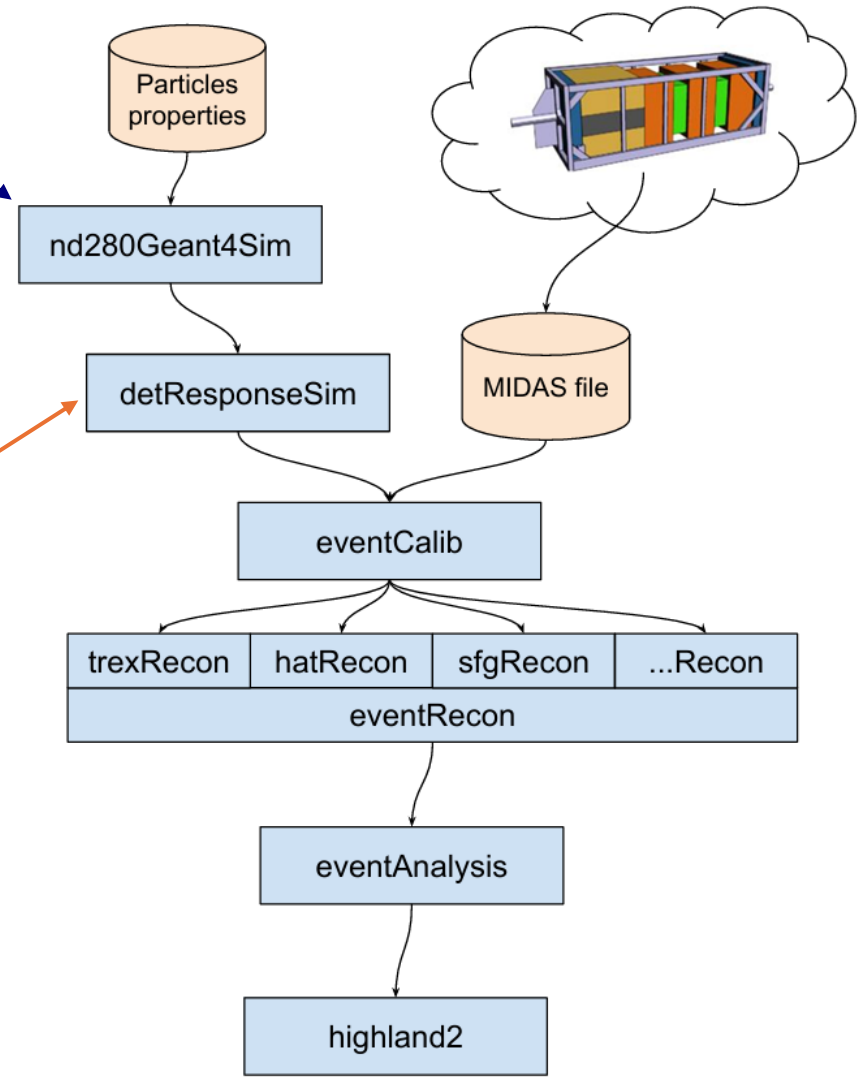
G= gain from X-ray studies

m is tuned to obtain 10% energy resolution

3. A **2D spreading** on DLC is simulated depending on parameter *RC*

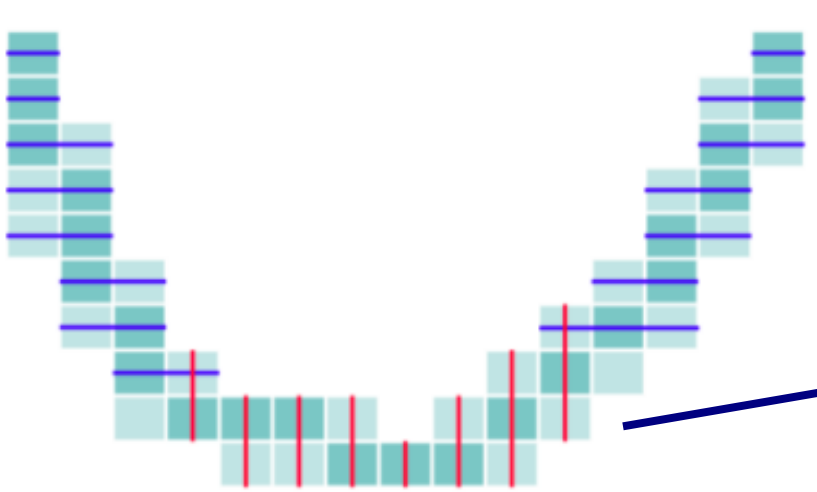
$$\rho(r,t) = \frac{RC}{4\pi t}\exp\left(-\frac{r^2RC}{4t}\right)$$

4. A **convolution** with electronic response is performed

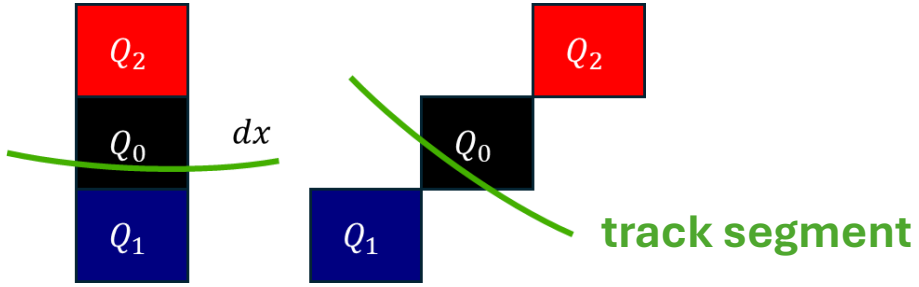


HA-TPC Reconstruction

Pads that collect a signal are grouped into tracks and successively into **clusters** perpendicularly to local track direction

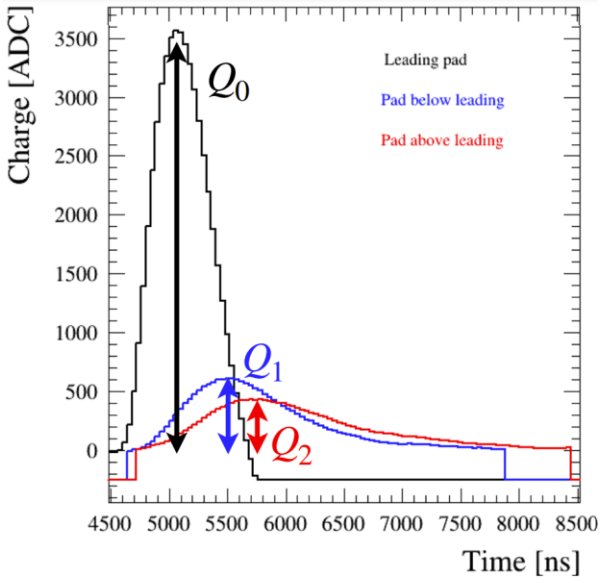


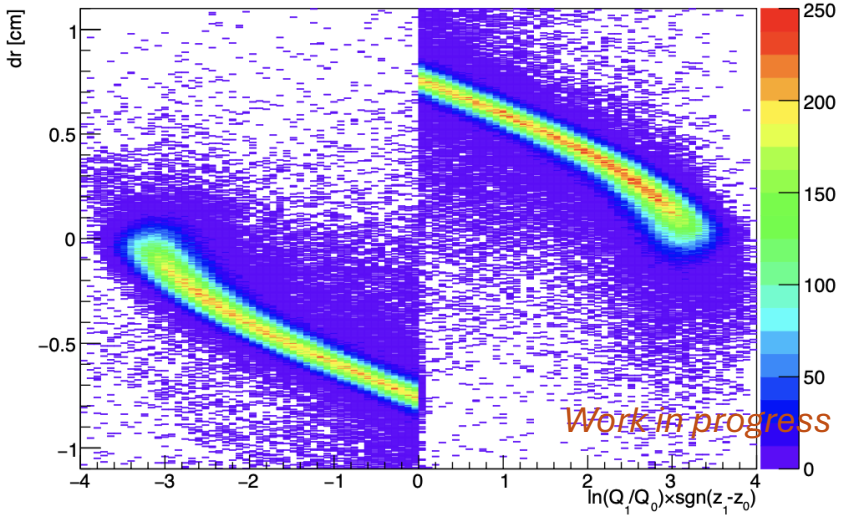
Leading pad: signal is induced from avalanches
Secondary pads: signal is induced by charge moving on the DLC

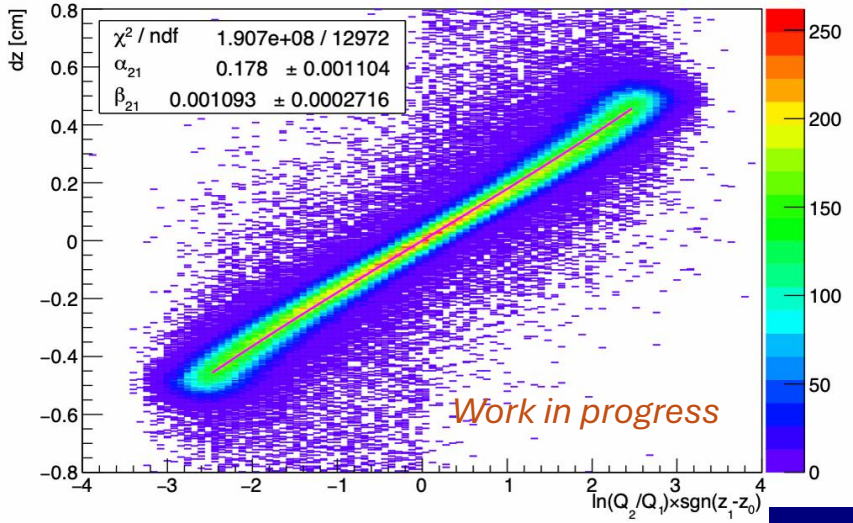


$$dx = \alpha_{10} \ln^3\left(\frac{Q_1}{Q_0}\right) + \beta_{10} \ln\left(\frac{Q_1}{Q_0}\right)$$

$$dx = \alpha_{21} \ln^3\left(\frac{Q_2}{Q_1}\right) + \beta_{21} \ln\left(\frac{Q_2}{Q_1}\right)$$







HA-TPC Simulation and Reconstruction

Tracks divided over distance from leading pad centre

Ratio of Q_1/Q_0 close to the anode for vertical tracks:

Drift region x<10 cm:

- Diffusion effects are expected to be negligible
- Overall agreement **when lowering the RC measured parameters by 20% in simulations**

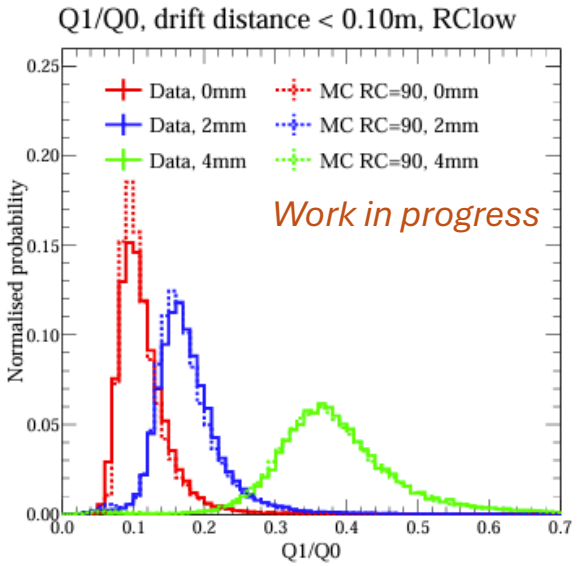
$$\mathrm{RC_{low}} = 112\,\frac{\mathrm{ns}}{\mathrm{mm^2}} \longrightarrow \mathrm{RC_{low}} = 90\,\frac{\mathrm{ns}}{\mathrm{mm^2}}$$

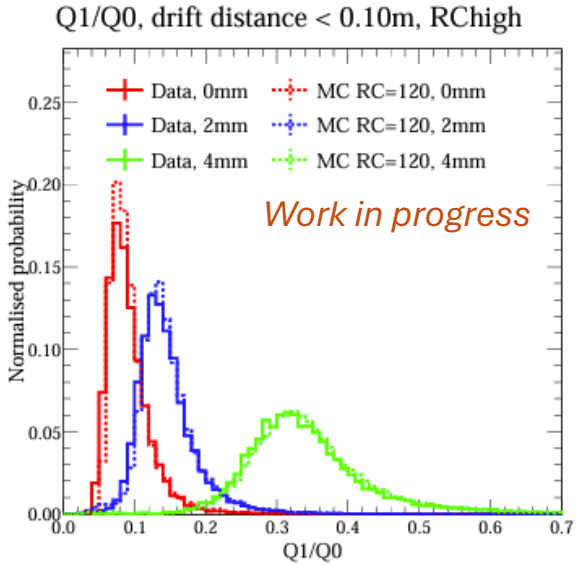
$$\mathrm{RC_{high}} = 158\,\frac{\mathrm{ns}}{\mathrm{mm^2}} \longrightarrow \mathrm{RC_{high}} = 120\,\frac{\mathrm{ns}}{\mathrm{mm^2}}$$

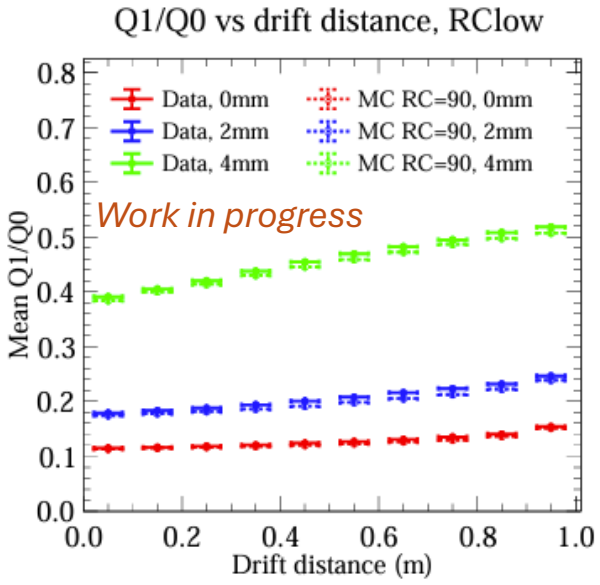
Considering the **whole drift distance:**

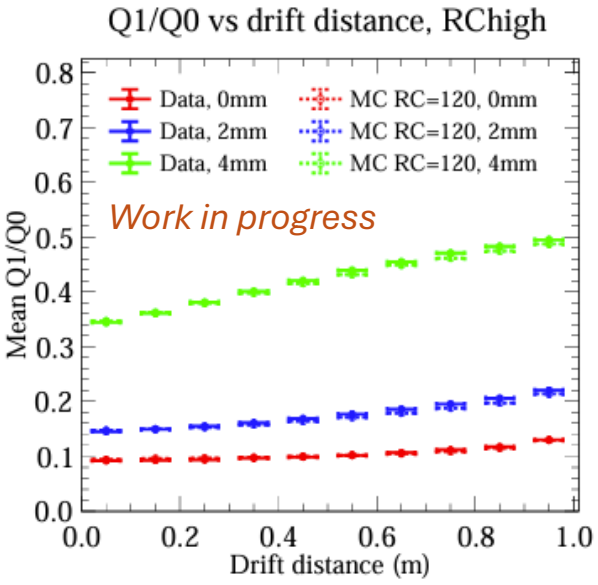
- Small underestimation persists in simulation

Current efforts are dedicated to improve signal formation modeling







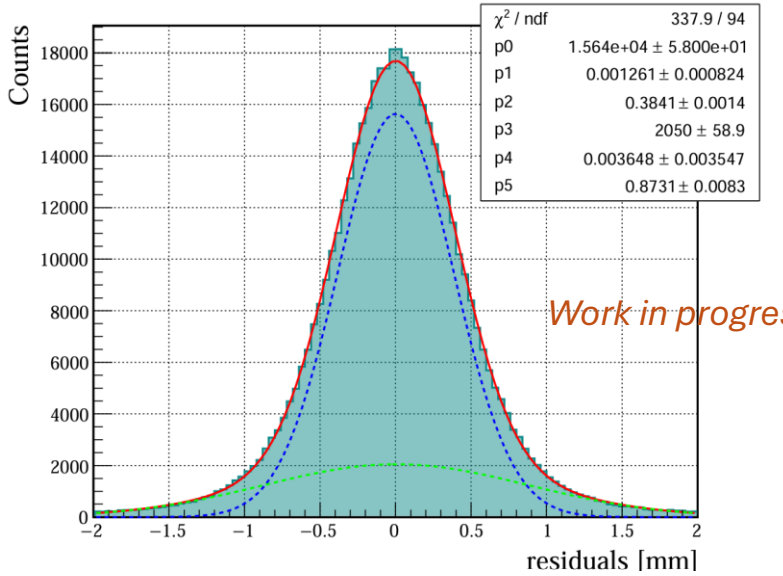


Spatial resolution

Performances of HA-TPCs are evaluated by looking at their residuals with respect to the helix fit of the track

$$residuals = \sqrt{\left(y_{rec} - y_{fit}\right)^2 + \left(z_{rec} - z_{fit}\right)^2} - R$$

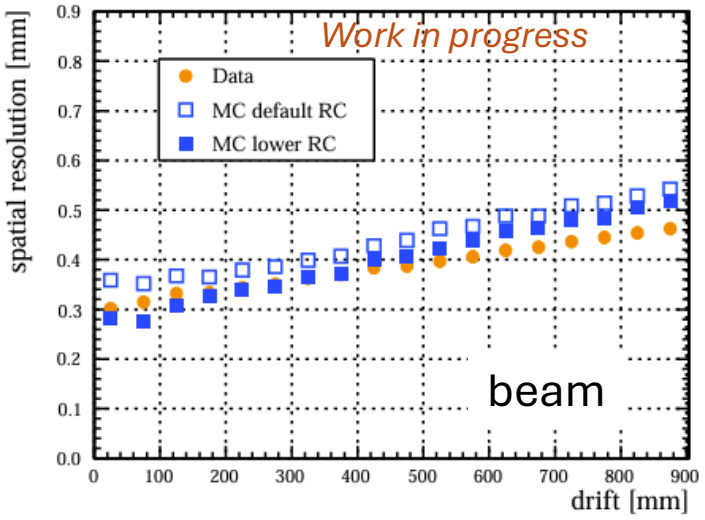
Spatial resolution is defined as the width of the gaussian fit of the residuals distribution

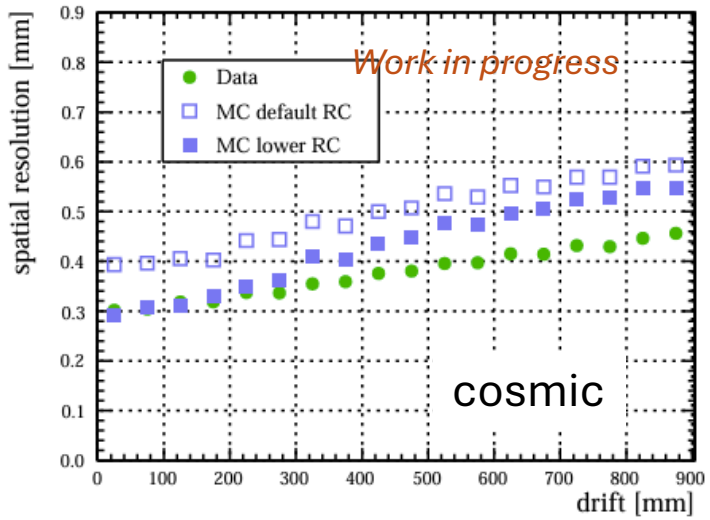


Considering tracks with a drift distance 500-550 mm:

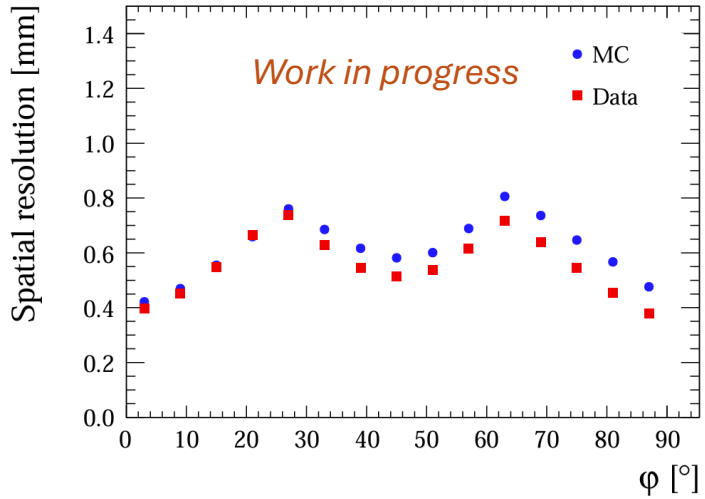
$$\sigma \sim 400\ \mu m$$

Spatial resolution v. drift distance



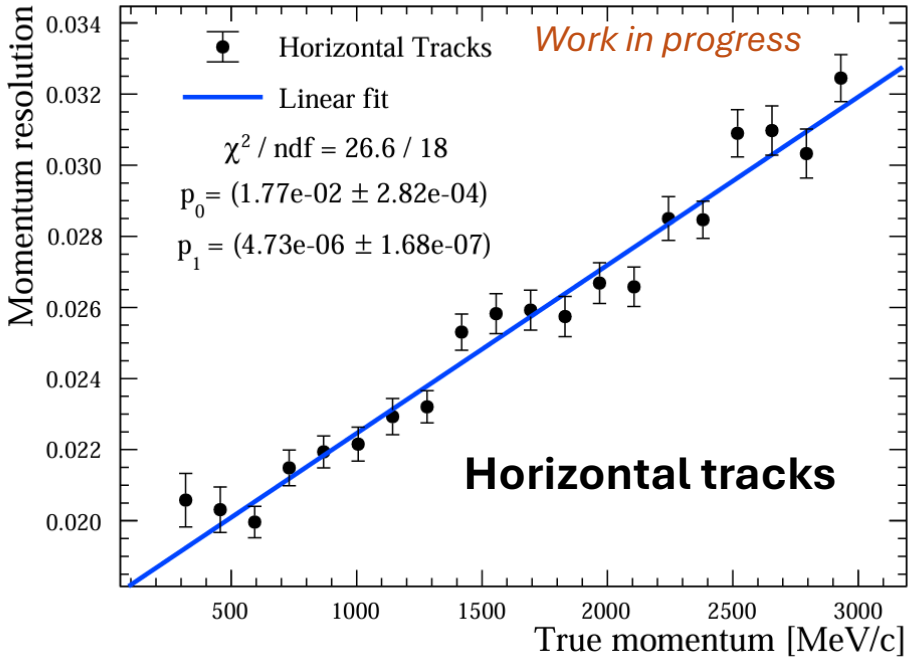


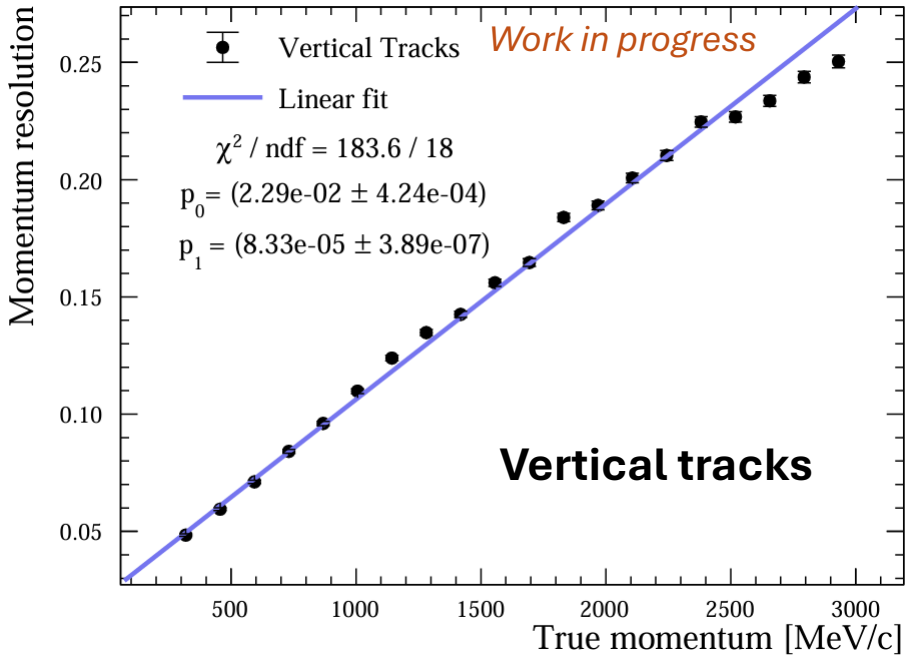
Spatial resolution v. angle on ERAM plane



Momentum Resolution

Momentum resolution is defined as $\frac{(p_{reco}-p_{true})}{p_{true}}$ and reported as a function of p_{true}





Spatial and momentum resolution are related thanks to the Gluckstern equation

$$\frac{\sigma_{p_t}}{p_t} = \sigma_{yz}\,[m]\,\frac{p_t\left[\frac{GeV}{c}\right]}{e\,B\,[T]l^2[m^2]}\sqrt{\frac{720}{N_p+4}}$$

A linear trend in resolution is expected from the equation $\frac{\sigma_{p_t}}{p_t} \propto p_t$

Spatial resolution on drift coordinate

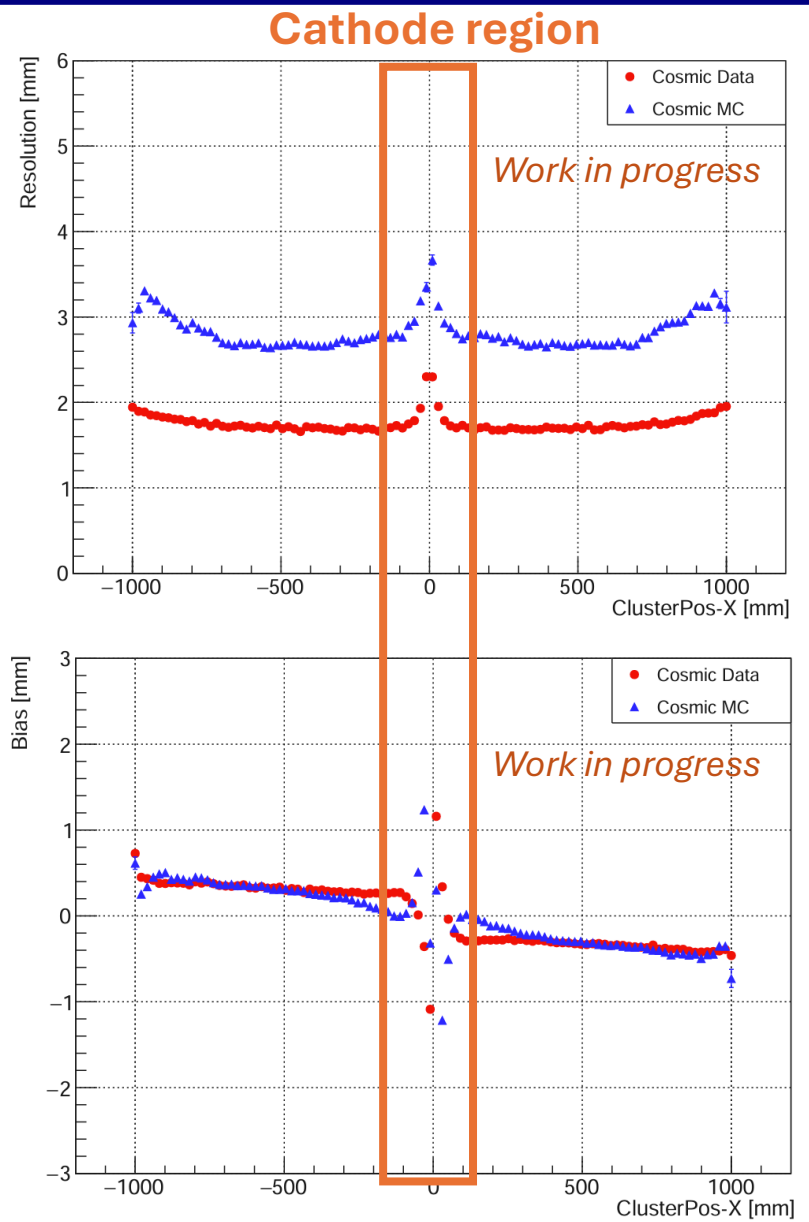
Residuals are estimated in the drift direction using **cosmic rays** sample and no **B field**

Resolution is estimated by fitting the residual distribution with a gaussian

A comparison between data and MC is performed

1. **Resolution** is uniform along the drift distance with a steep increase in the cathode region
2. A **bias** is present with a coherent trend, increasing near the cathode

The behaviour is similar across the two drift regions (cathode is at 0)



Energy Loss per unit of Length (dE/dx)

The reconstruction of dE/dx combined with momentum information is crucial for obtaining a good Particle Identification

Energy loss estimation is performed by considering a track as a continuous linear density

For a linear track:

$$\rho_{1D}(z, y, t; p0, p1, \lambda) = \frac{\lambda}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(-y + p1 * z + p0)^2}{2(1 + p1^2)\sigma^2}\right)$$

The total charge on a pad is given by the charge density over its area:

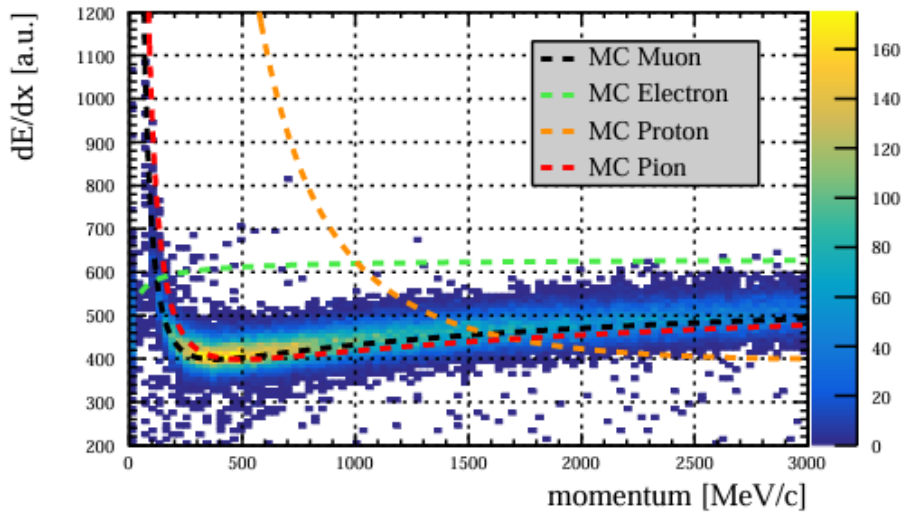
$$Q_{pad}(t) = \int \int_{pad} \rho_{1D}(y, z, t) dy dz$$

The total energy loss over the track length is given by the sum of pads contribution

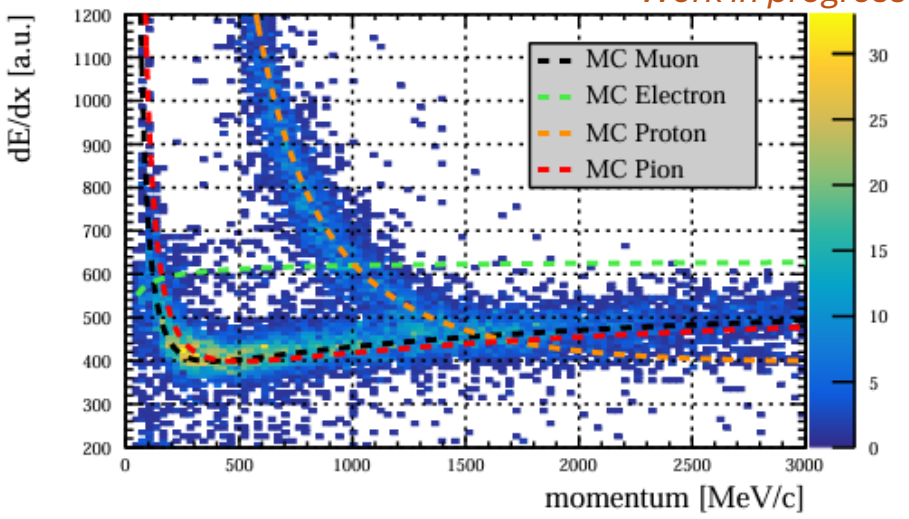
$$\left\langle \frac{dE}{dx} \right\rangle_{event} = \frac{\sum_{pad} dE_{pad}}{\sum_{pad} dx_{pad}}$$

Good agreement between data and MC

Horizontal negative tracks *Work in progress*



Horizontal positive tracks *Work in progress*



dE/dx resolution

The evaluation of dE/dx resolution is performed by:

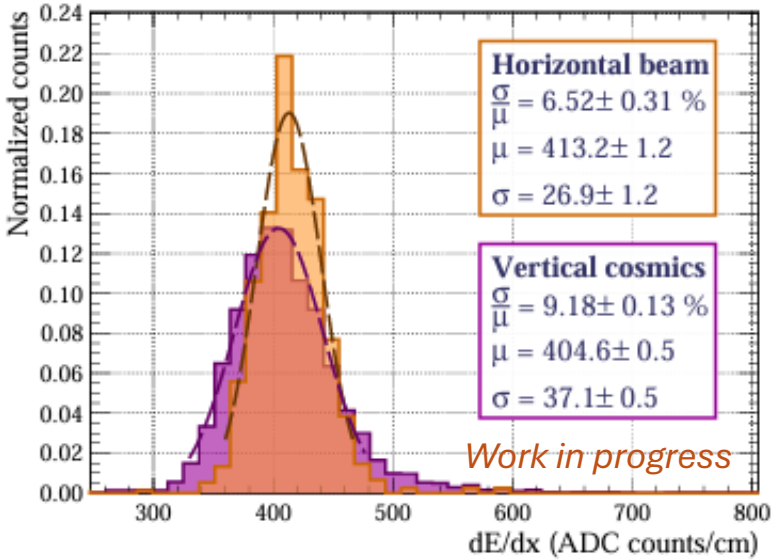
1. Binning data in momentum slices
2. Each slice was fitted with a gaussian and the ratio $\frac{\sigma}{\mu}$ is extracted
3. Range 300 MeV/c – 500 MeV/c is considered

Events from beam and cosmic datasets are reported

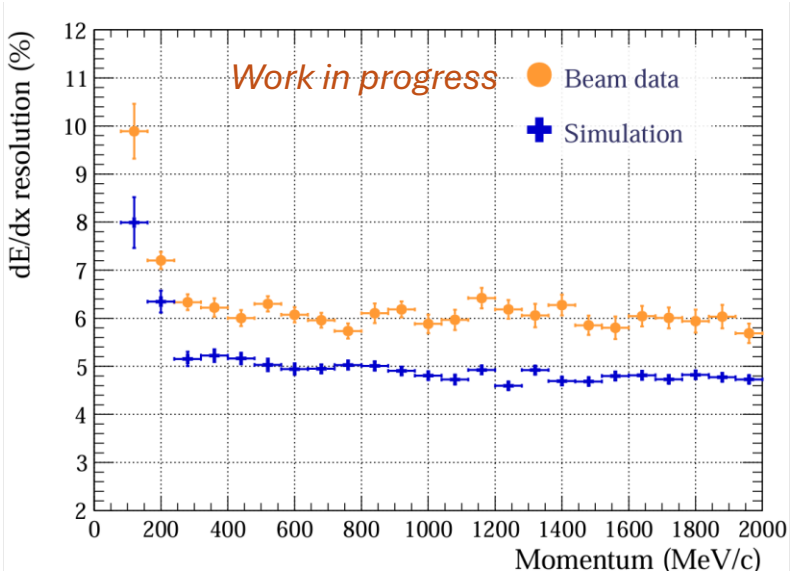
$$\left(\frac{\sigma}{\mu}\right)_{cosmics} = (9.2 \pm 0.1)\%$$

$$\left(\frac{\sigma}{\mu}\right)_{beam} = (6.5 \pm 0.3)\%$$

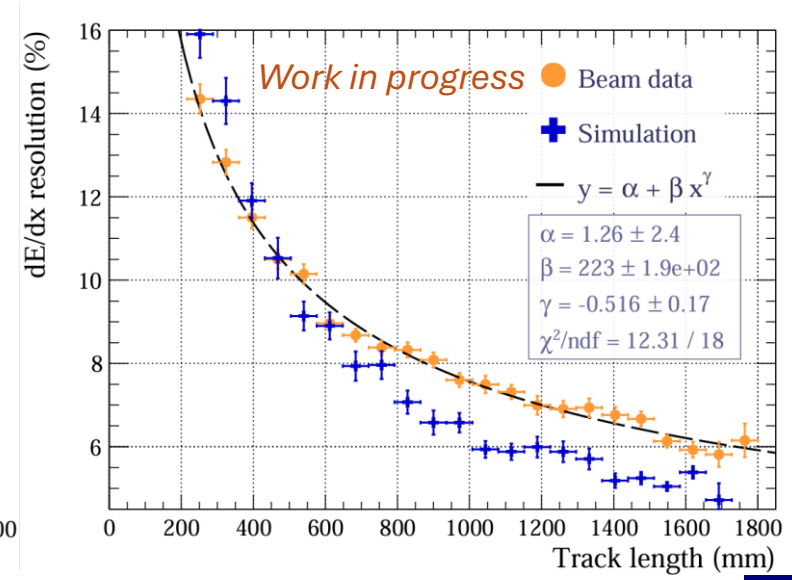
The resolution satisfies the requirements in the region of interest of the detector



dE/dx resolution v. Momentum



dE/dx resolution v. track length



Conclusions

The realization of HA-TPCs required the design, prototyping, construction, validation and characterization of their components since 2018

Both detectors were successfully installed at J-PARC by May 2024

HA-TPCs performances were evaluated using cosmic rays and neutrino beam data at J-PARC

Comparisons between data and MC show a reasonable agreement achieving:

- **Spatial resolution** better than 800 μm
- **dE/dx resolution** better than 10%

meeting their design performance targets

HA-TPCs are expected to continue their operations as a part of **Hyper-K** long baseline program!

Performance of the High-Angle Time Projection Chambers in the Upgraded T2K Off-Axis Near Detector

Abstract

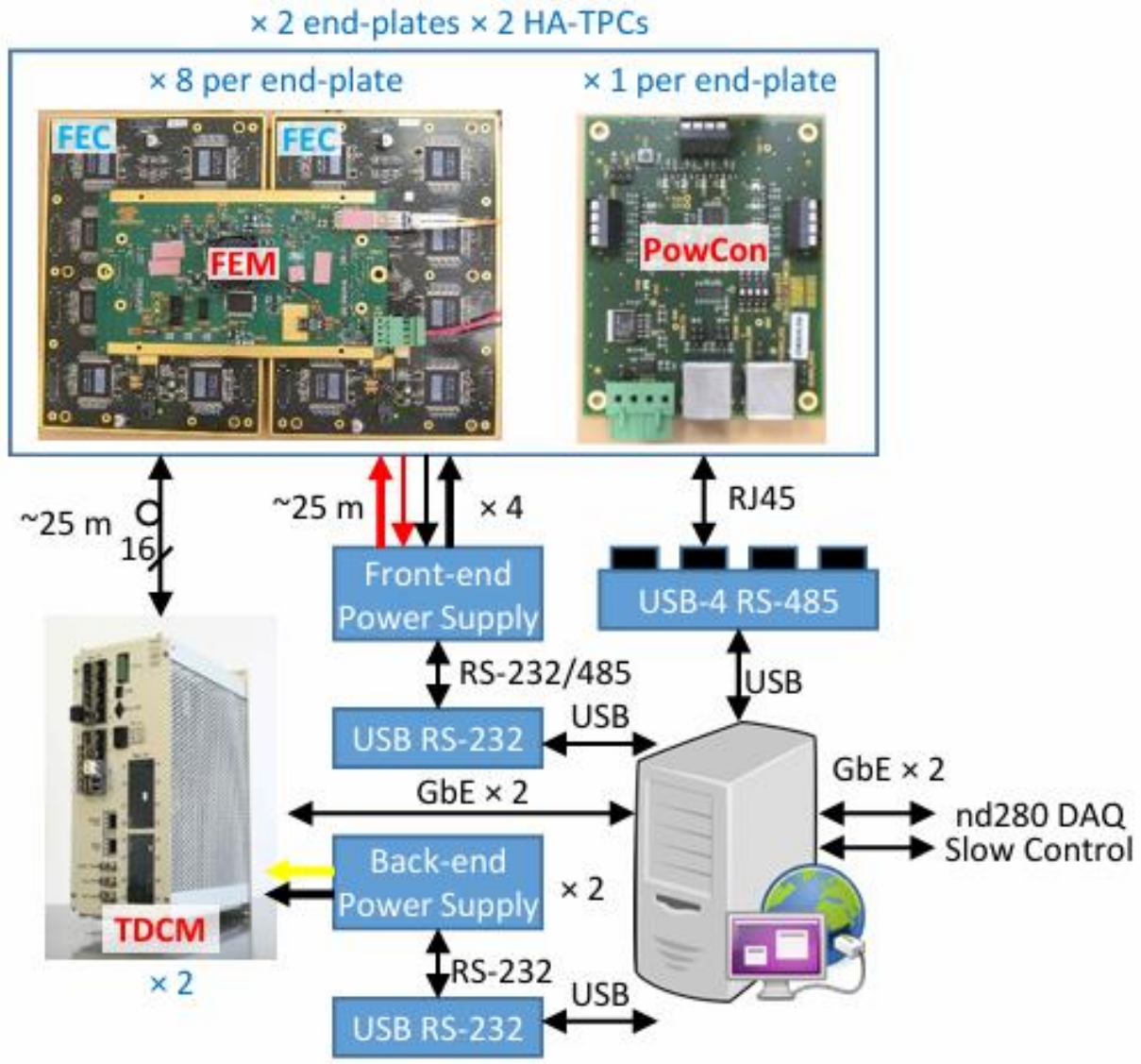
The off-axis magnetic near detector of the T2K experiment has undergone a significant upgrade, including the construction and installation of two new Time Projection Chambers featuring innovative resistive Micromegas technology and a field cage composed of thin composite walls. This paper provides a detailed description of the new components of the chambers, including the gas system, gas monitoring chambers, and data acquisition system. Additionally, it reports the results of extensive testing using both neutrino beams and cosmic rays, with comparisons between data and Monte Carlo simulations. The new detectors achieve improved spatial resolution and enhanced particle identification capabilities which are crucial for the precision goals of the T2K experiment.

Keywords: Time Projection Chambers, Resistive Micromegas, Field Cage, spatial and momentum resolution, dE/dx resolution

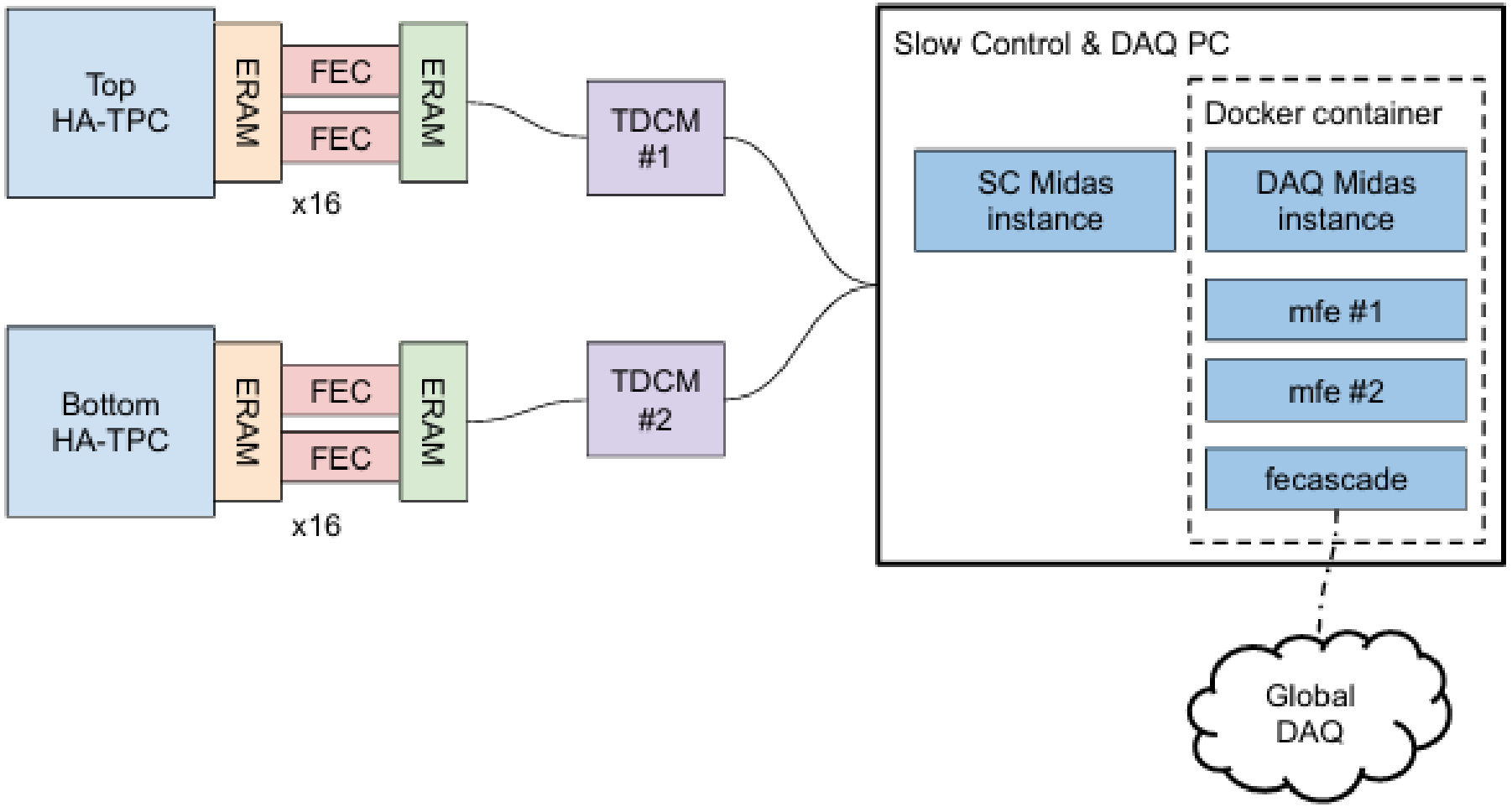
Paper in preparation!

Thanks for your attention!

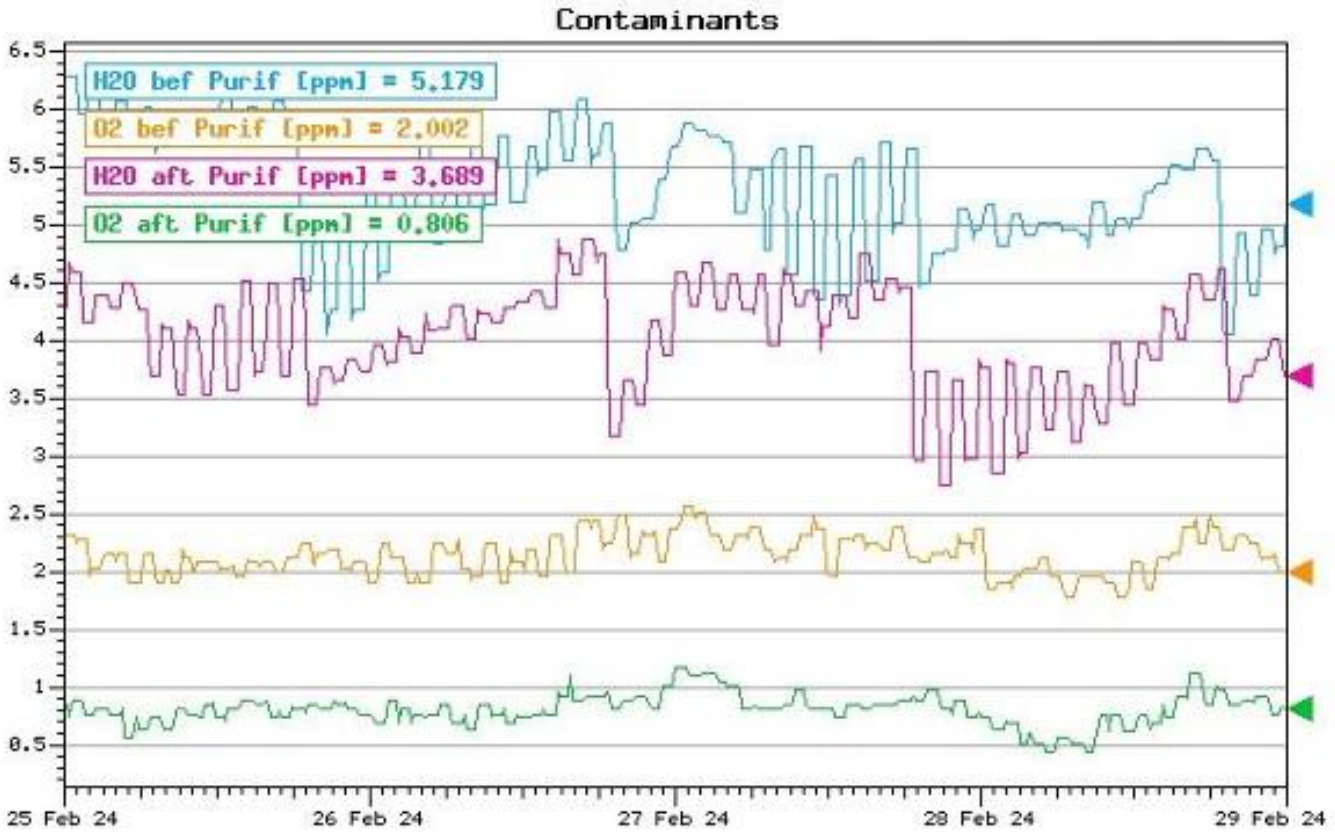
Electronics



Slow Control and DAQ



Gas System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O2 bef Purif [ppm] = 2.002
H2O aft Purif [ppm] = 3.689
O2 aft Purif [ppm] = 0.806
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
25 Feb 24
26 Feb 24
27 Feb 24
28 Feb 24
29 Feb 24