The Micromegas detector for the PADME Experiment

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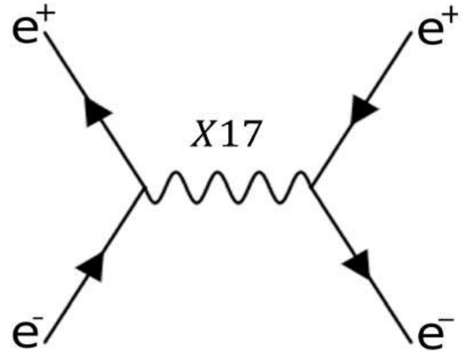
The PADME Experiment and the Search of the X17

ATOMKI Collaboration observed anomalies in the angular correlation of e^+e^- pairs emitted via internal pair conversion in the ^{8}Be, ^{4}He and ^{12}C nuclear de-excitation → results compatible with a new neutral mediator called X17

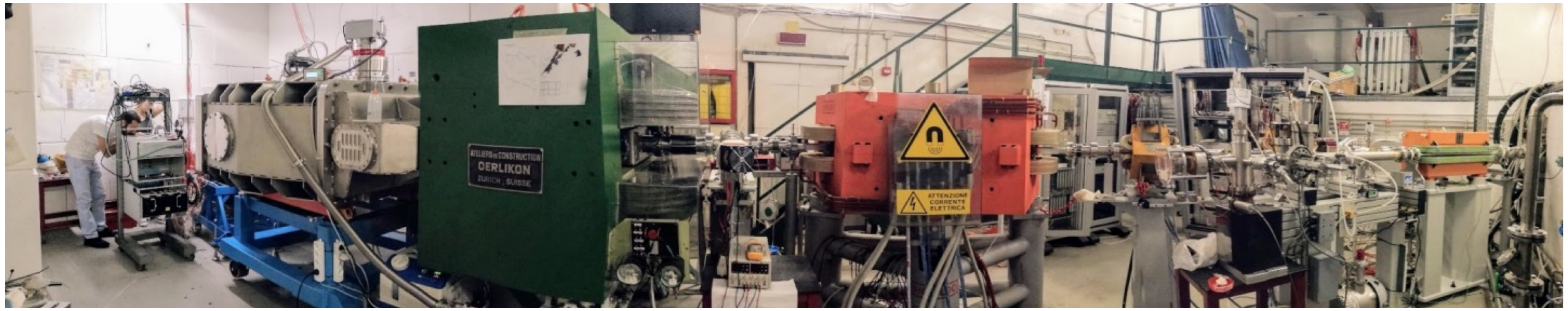
PADME Experiment

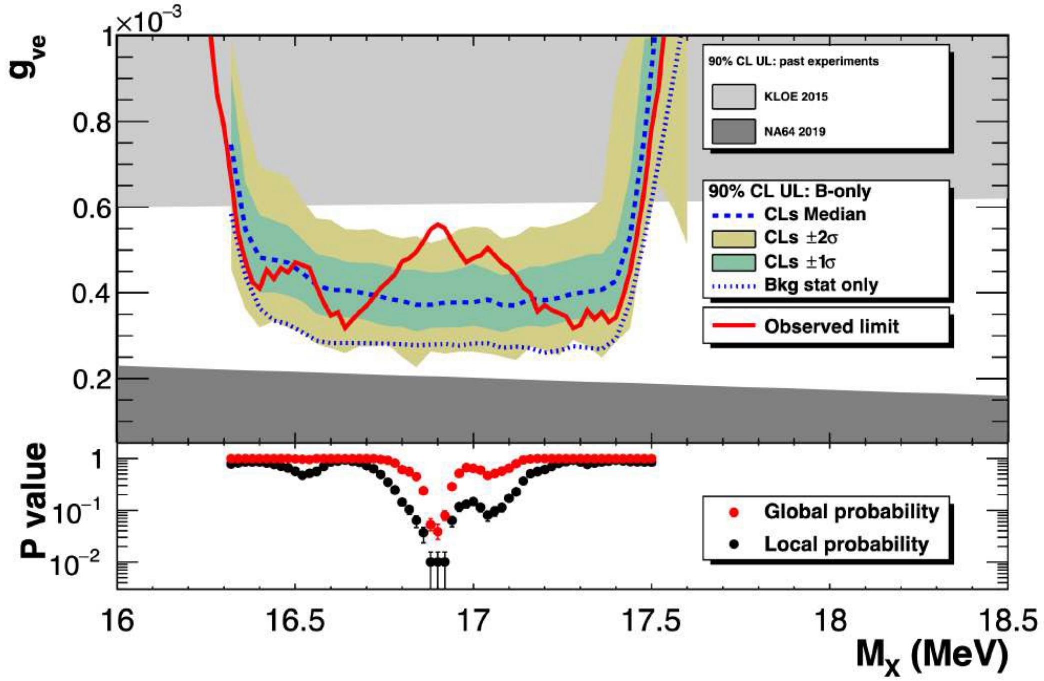
Resonant search on fixed target



e^+e^- annihilation is the main production process

Measurement idea: perform a very fine scan of √s around the hypothetical mass resonance using positron beam with E_{beam} ~ 283 MeV on target
→ measure a 2-body final state





Run III Results

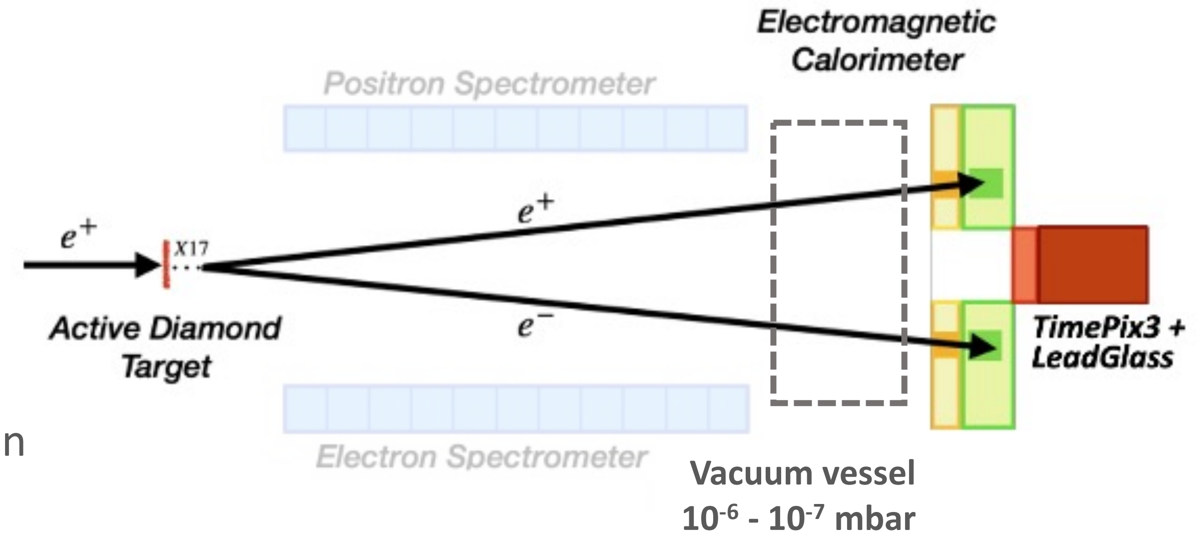
Excess observed, 2.5 σ local, 1.8(2) σ global significance corresponding to mass $M_X = 16.9\ MeV$ and a coupling $g_{ve} = 5 \times 10^{-4}$

PADME Upgrade for Run IV

Run III Experimental setup

- Active target polycrystalline diamond
- ECal: 616 BGO crystals, each 21x21x230 mm^3
- ETagger (scintillator detector) in front of ECal for e/γ discrimination
- TimePix3 high granularity silicon-based detector for beam spot
- LeadGlass luminometer (NA62 Large Angle Veto spare block)

Elements not used: charged particle veto and magnetic field (residual 12.5 G)



The goal of Run IV is to increase sensitivity
to confirm/disprove Run III result

New tracking detectors

- PadMMe Micromegas chamber replaced the Etagger

→ Aiming to significantly improve $e^+e^-/\gamma\gamma$ discrimination

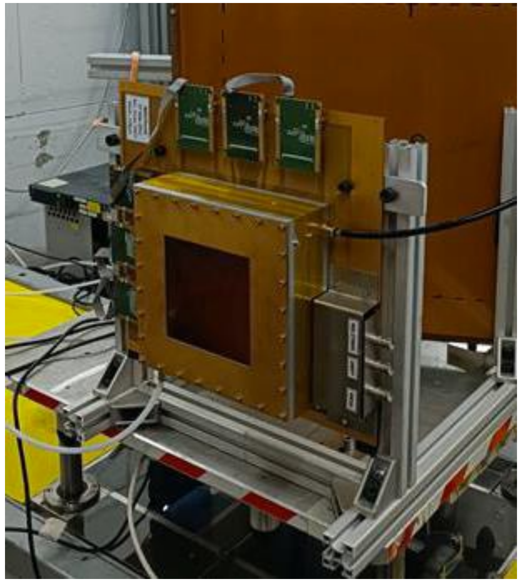
- TMM Micromegas replace the TimePix

→ 3[rd] beam spot monitor together with target & PadMMe

- Also the diamond target position were moved downstream by ~30 cm to increase the ECal acceptance and then the statistics

PadMMe

TMM

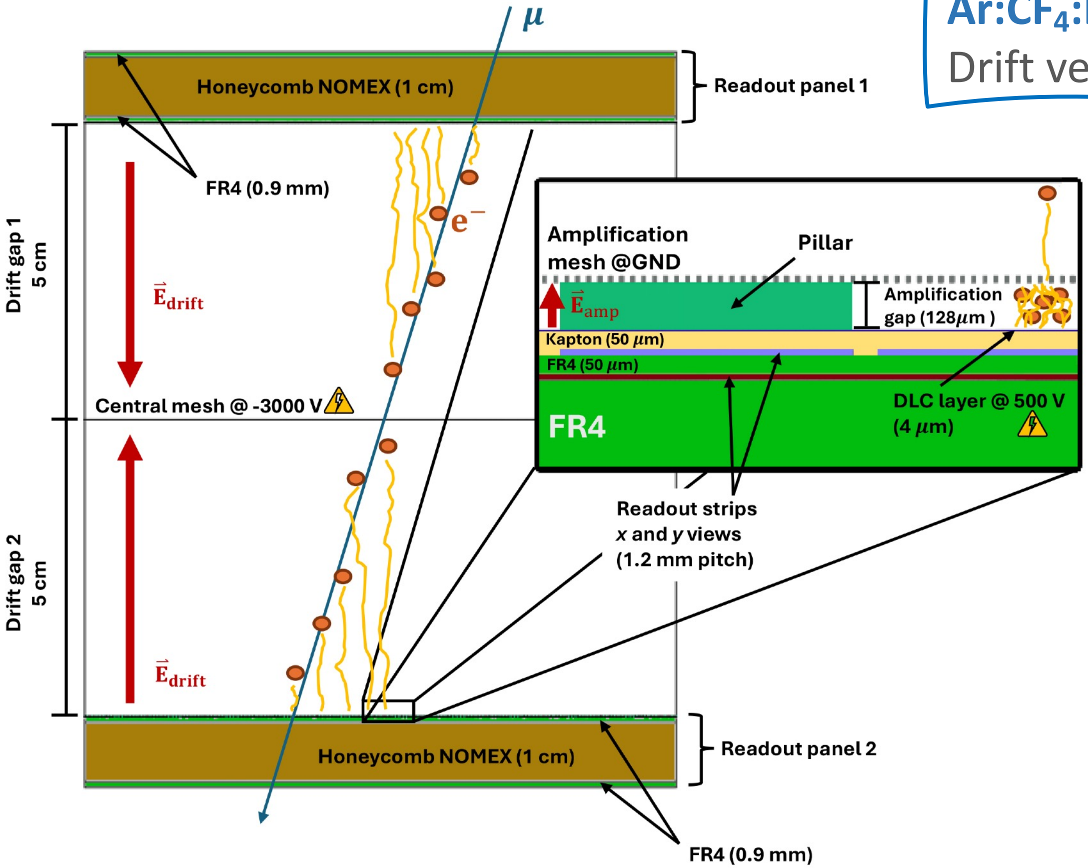


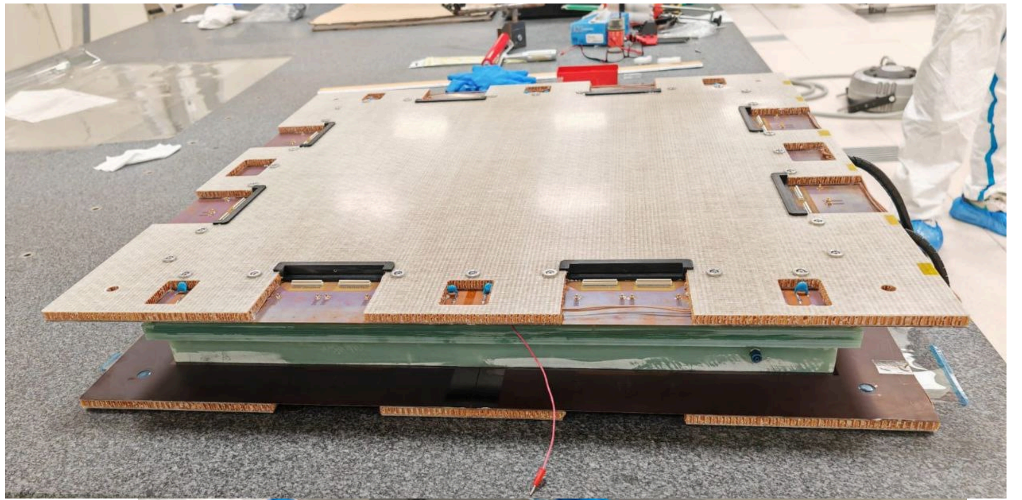
Pad*MMe*: Micromegas tracker

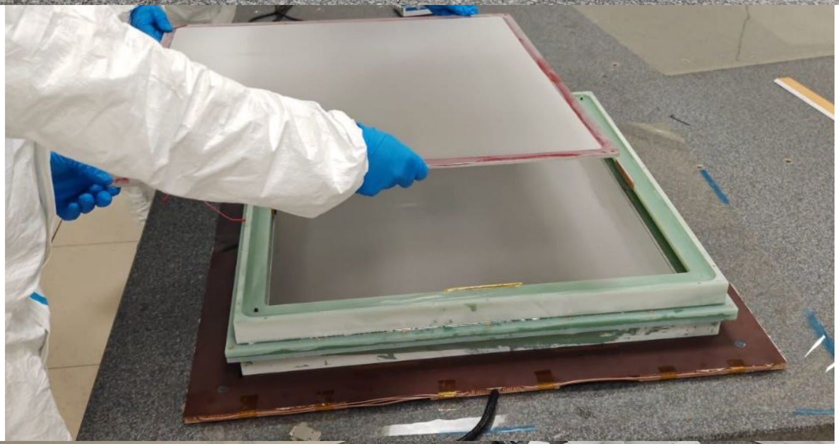
Micropattern gas detector operated in TPC mode

- Detector dimensions **88 × 88 cm² → active area 65 × 65 cm²**
- Two drift gaps of **5 cm** each, sharing same cathode mesh (~3 kV)
- Amplification gap ~ 128 µm

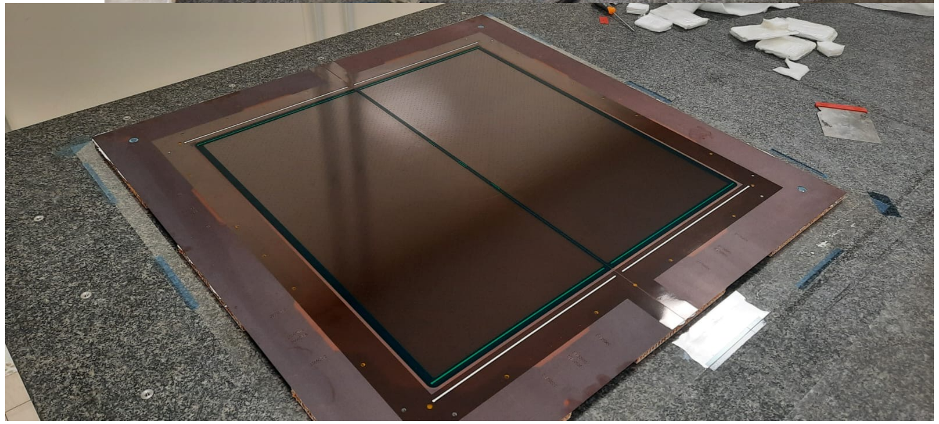
Gas Mixture
Ar:CF_4:Isobutane (88:10:2)
Drift velocity ~ 10.5 cm/µs





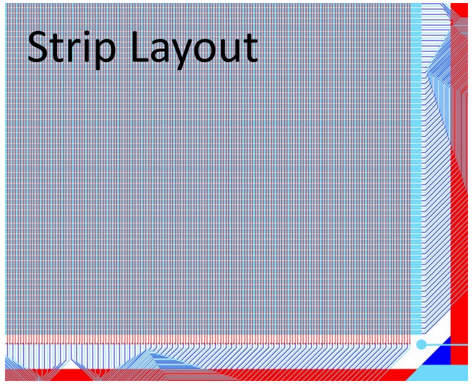


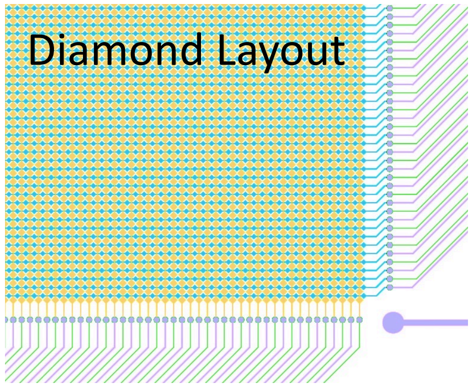
3 stainless steel meshes 45 x 18 pattern



Each readout layer has 2 PCB aligned and vacuum-glued to the panel

PCB design and HV layout





Two alternatives layout for the readout tested

- Straight strips (Strip Layout): two layers of parallel Copper strips to read both x and y coordinates, with 1.2 mm pitch ($\sigma_{x,y}\sim$ 300 µm)
- Rhomboidal strips (Diamond Layout): readout layers made of rhomboidal shaped strips, also with a pitch of 1.2 mm, shifted one to the other to not to overlap the x and y readout pads
  → minimizes the capacitive coupling between the two layers.

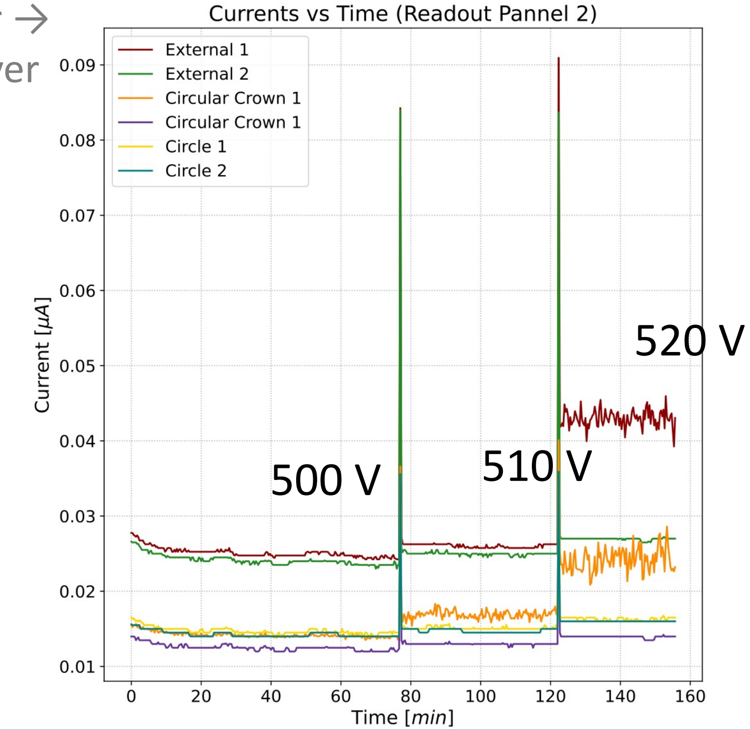
  pad area: 0.49/0.25 mm^2 for up/down layer → same capacitive coupling to the resistive layer but different collected charge (~ 20%) between the two layers

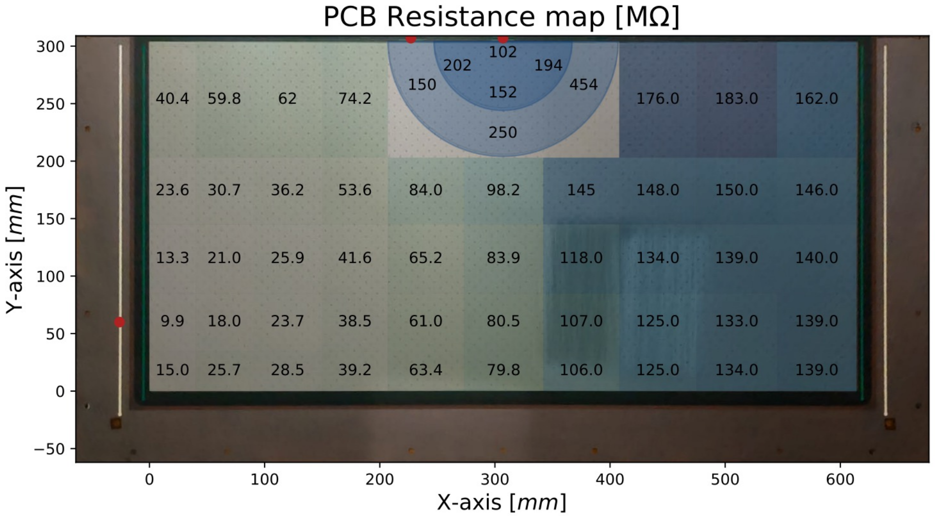
The chamber with Diamond Layout is the one currently installed in PADME

PCB with 3 HV regions

Have a better control on the amplification in the "beam" region

- External regions operating at 490 V
- Inner regions operating at 350 V (no amplification)





Front-End & DAQ

Readout Electronics

APV25

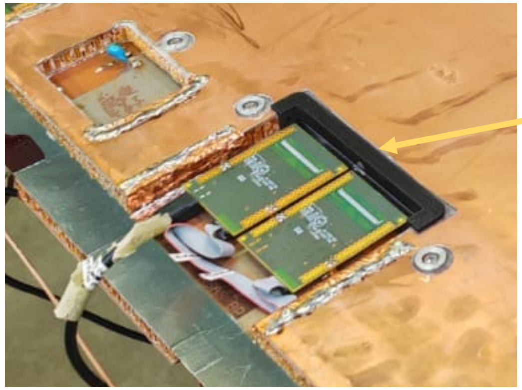
- Time window up to 675 ns for a drift time ~500 ns

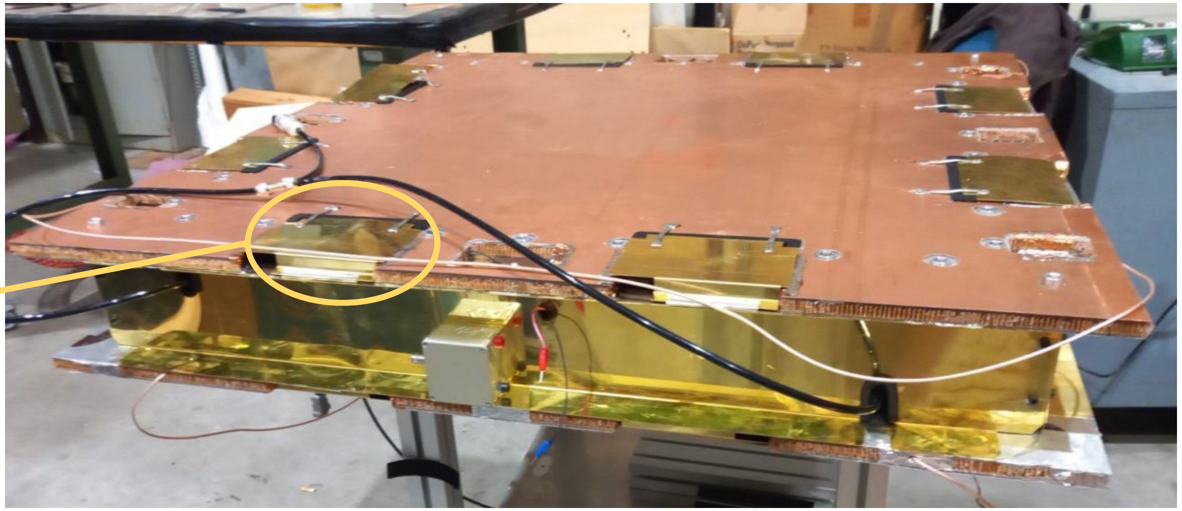
Scalable Readout System

- 2 FECs + CTF for trigger and clock

DAQ

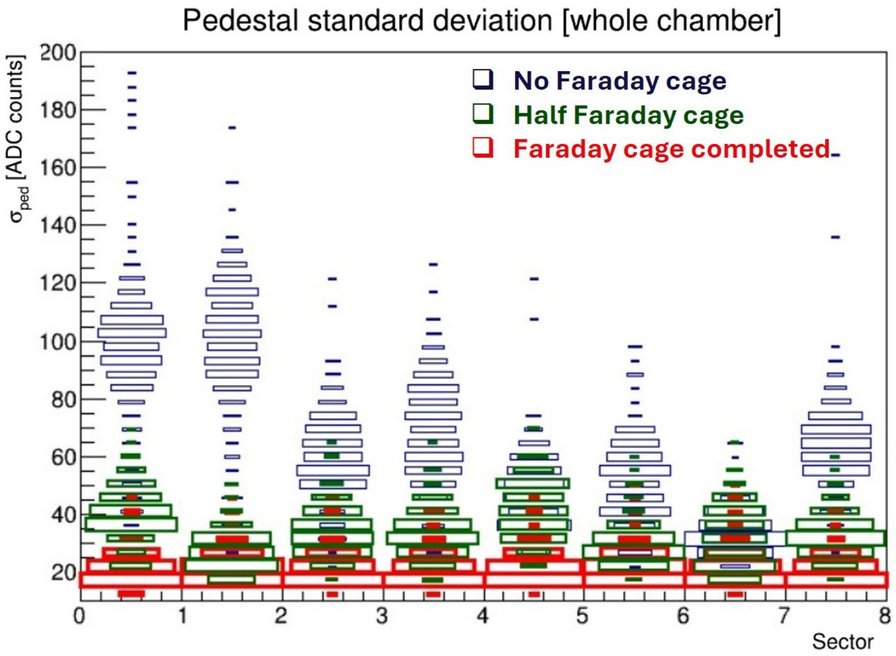
- mmDAQ3

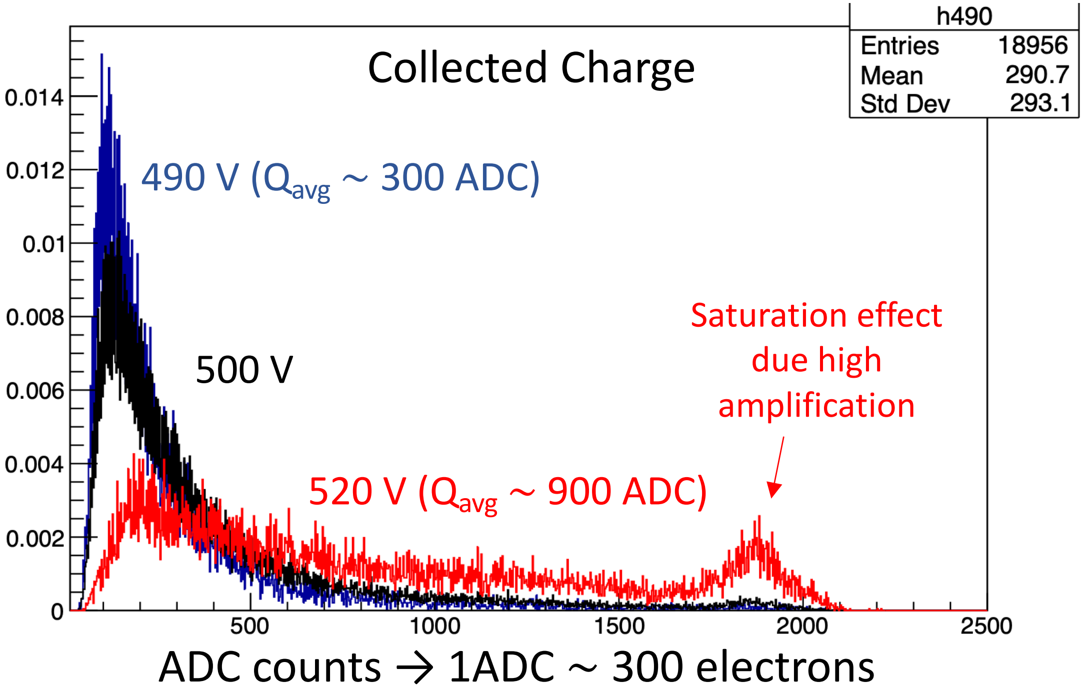




Noise Studies

Faraday cage on the chamber (50 μm copper PCB + brass armor), on the electronics (brass cases), grounding improved





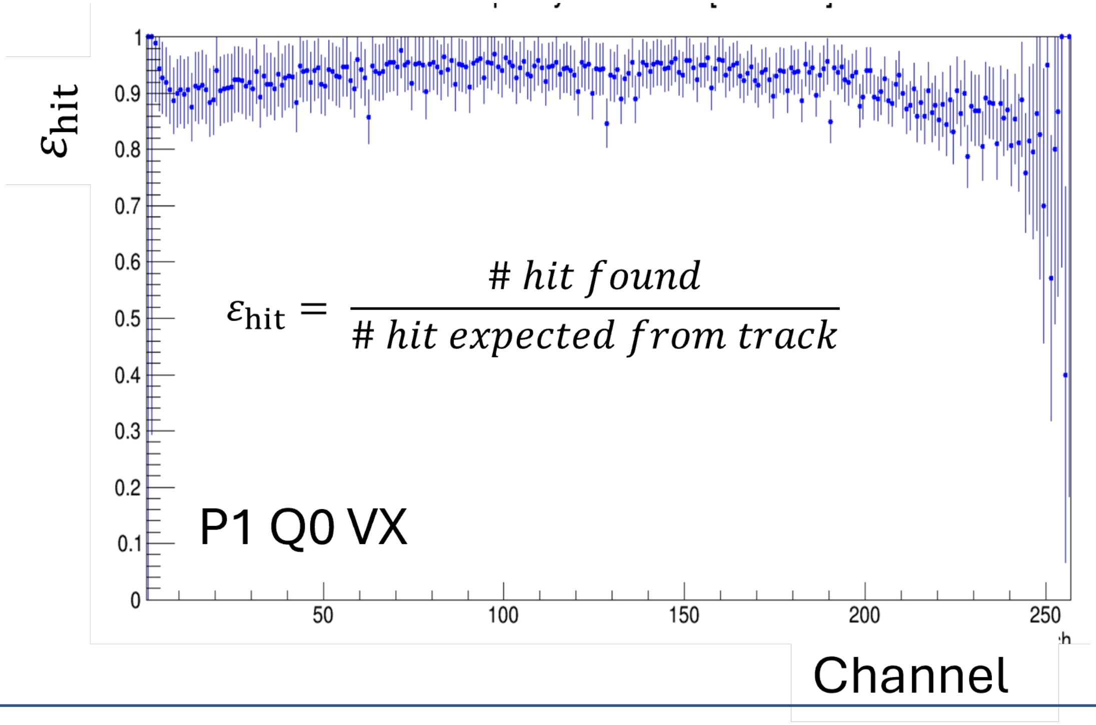
Test @ Cosmic Ray Stand

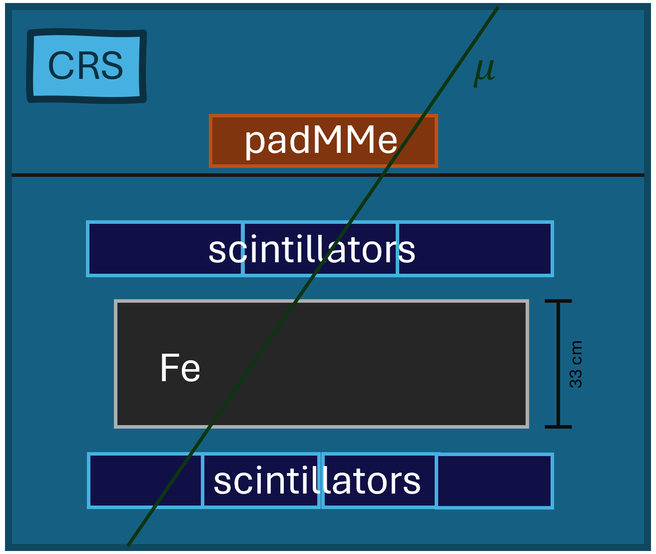
CRS Setup

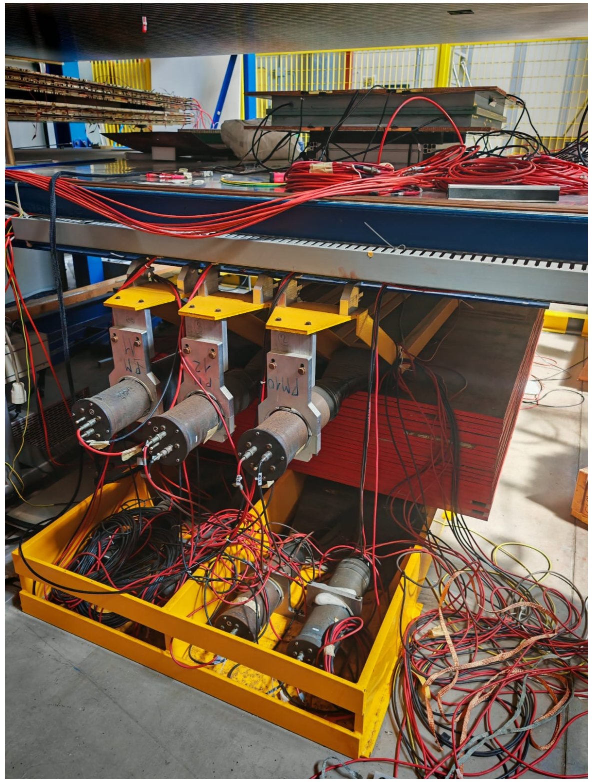
- Trigger: 2 plastic scintillator planes paired with PMTs
- 35 cm of Fe (muons < 0.5 GeV)

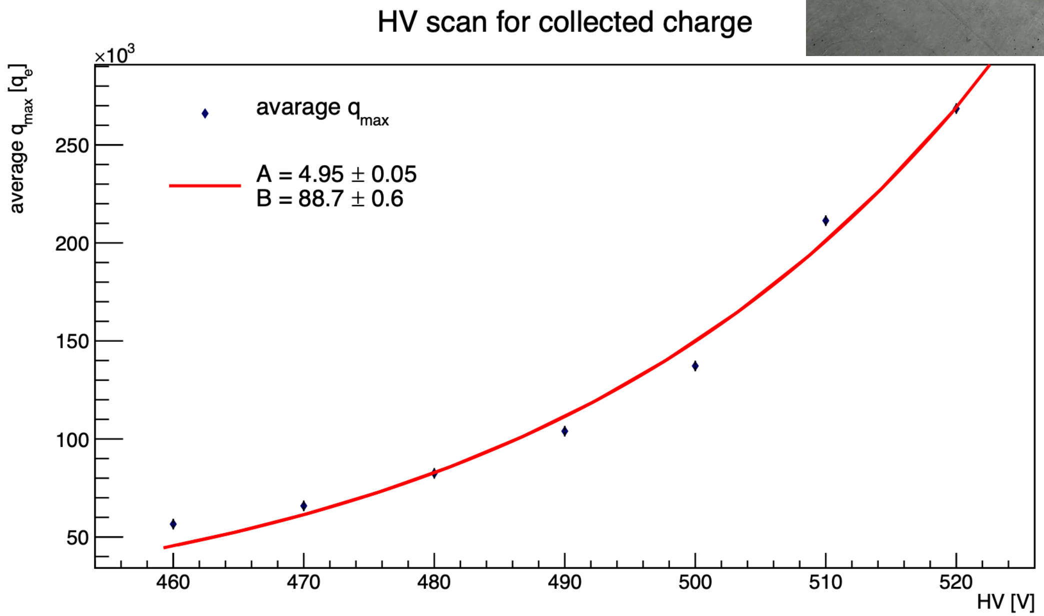
Performance Studies

- Gain estimation as function of HV
- Hit efficiency > 90%









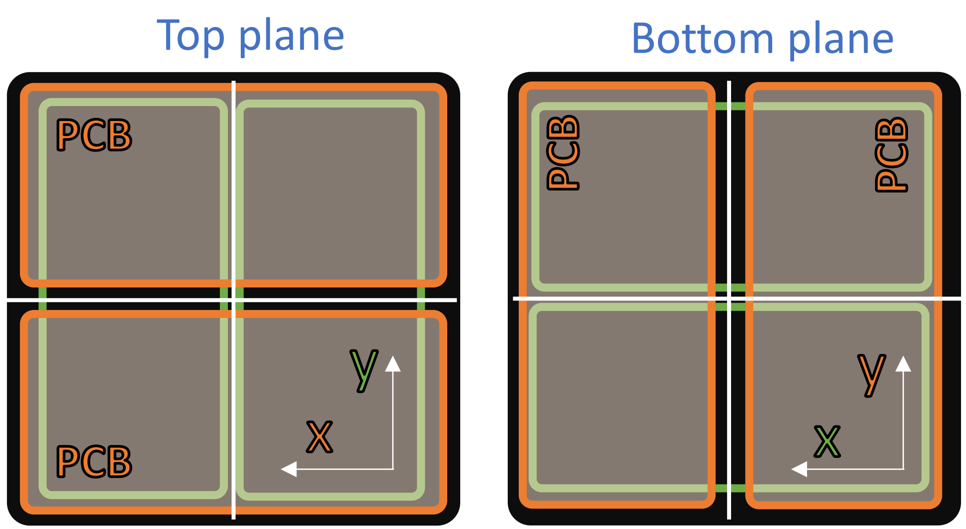
@ 500 V within ADC dynamic range

$G = e^{\alpha d} \sim 10^4$

Tracking @ CRS

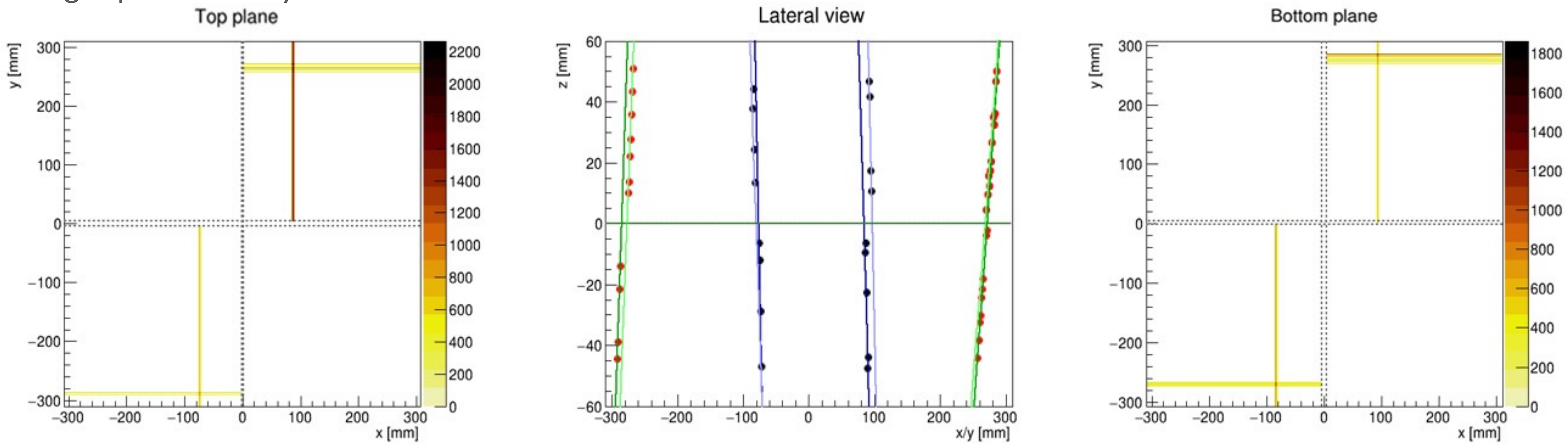
PCB strip layout

- 1st coordinate strips along the PCB, 2nd coordinate strips in the bottom layer discontinued at half → result in four X-Y sector per plane



Tracking algorithm

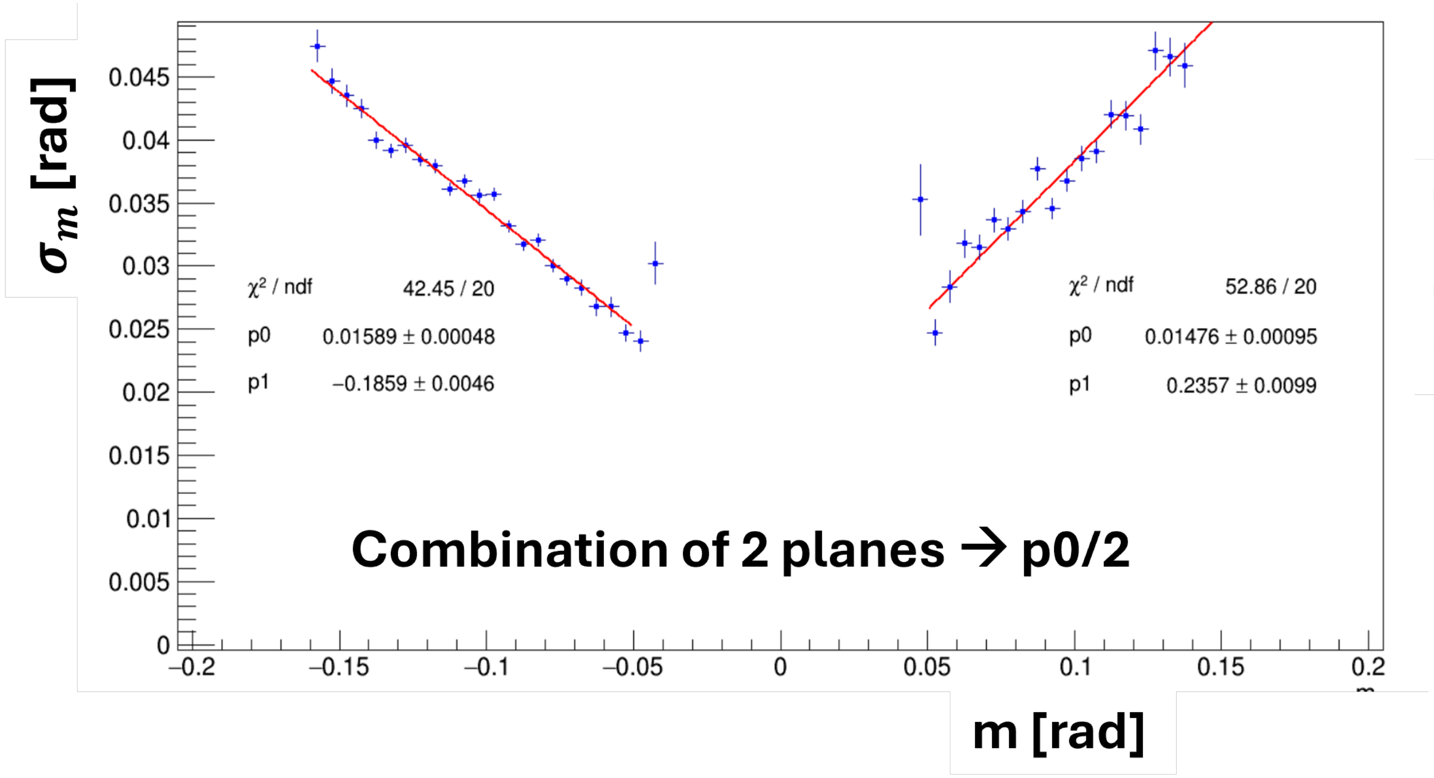
- Find coordinates of the hits in both X and Y strips
- Reconstruct the Z coordinates from the time of the hit
- Clustering the hits in track candidates
- Fitting each candidate to find track parameters
- Matching top-bottom layers and X-Y-views

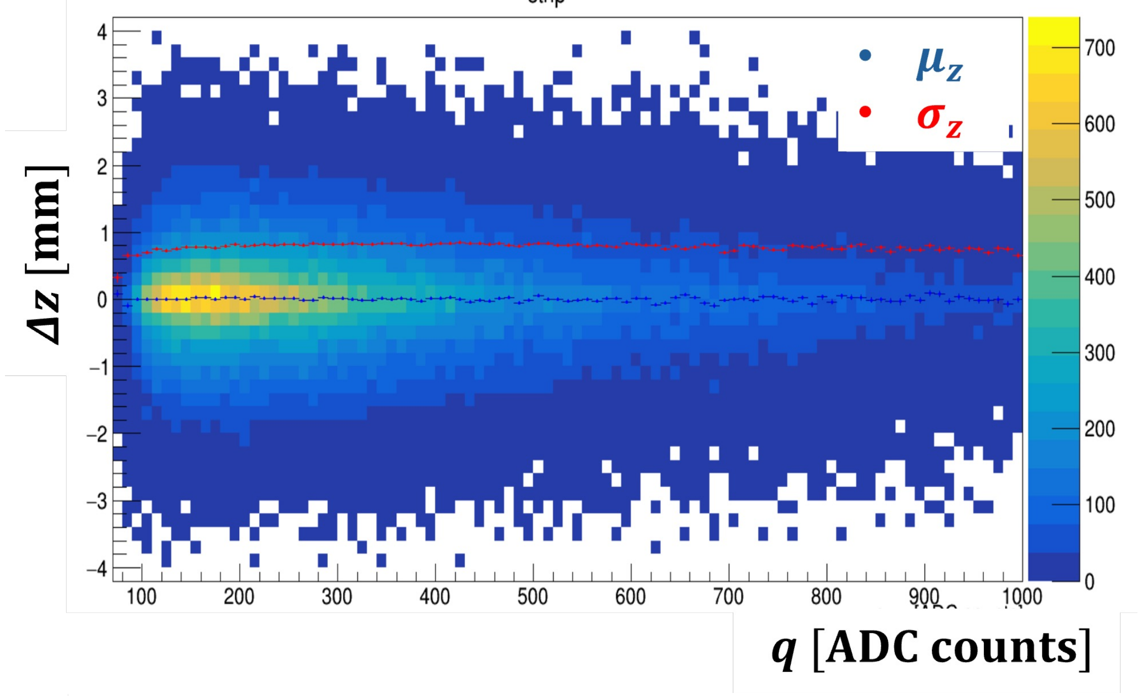


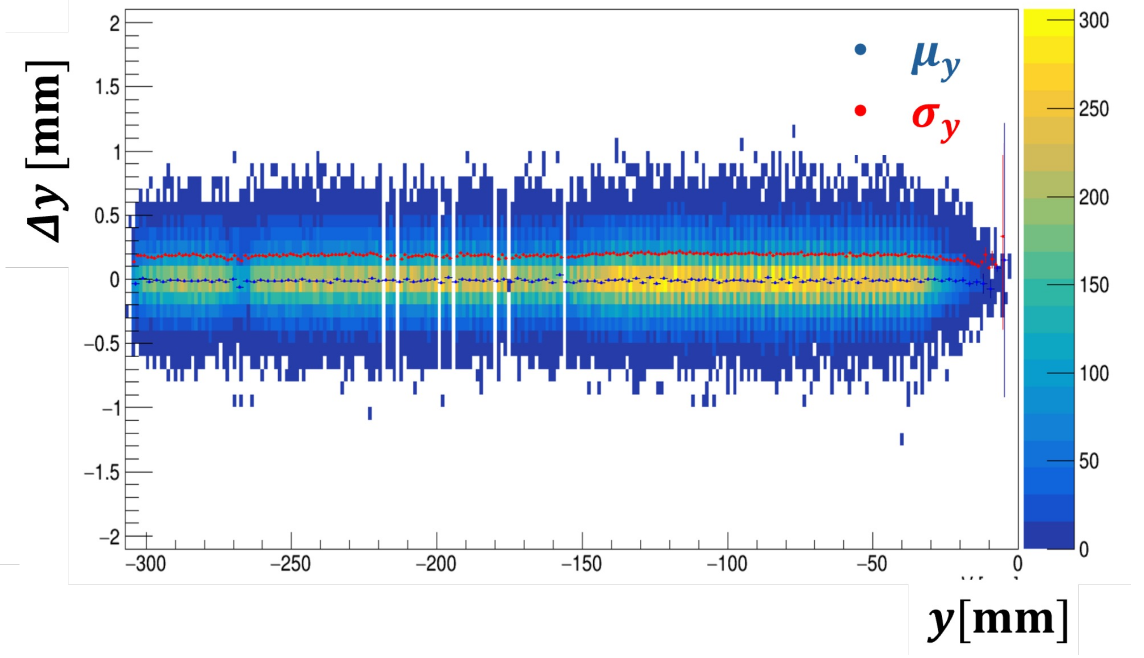
Resolutions @ CRS

Spatial Resolution

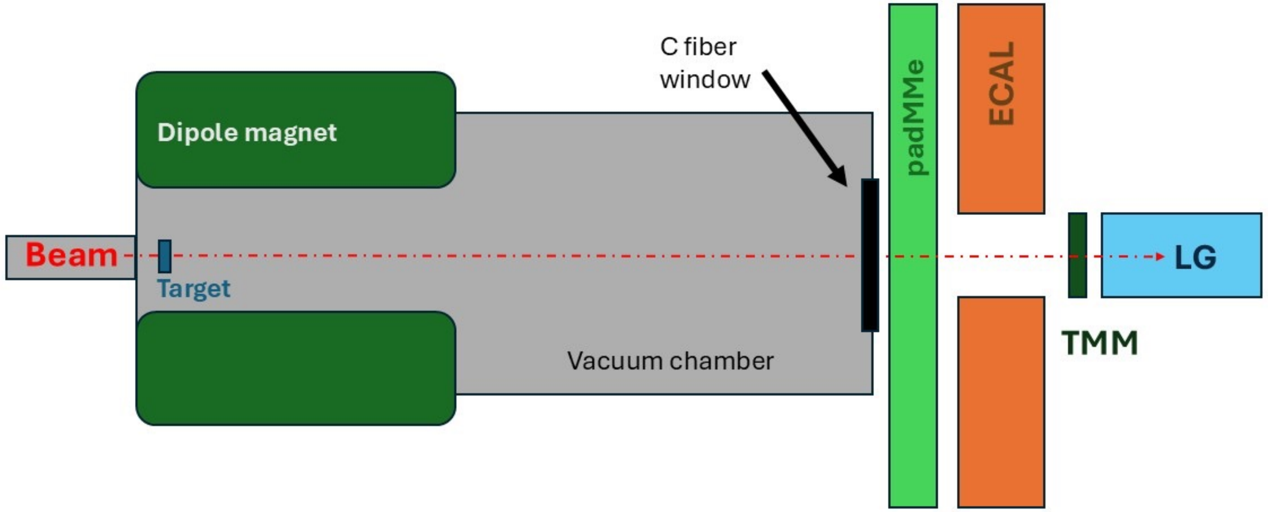
- **$\sigma_{x,y} \sim 100\ \mu m$**
- **$\sigma_z \sim 700\ \mu m$** and constant with charge
- **$\sigma_\theta \sim 7\ mrad + 0.2\ |\theta|$**



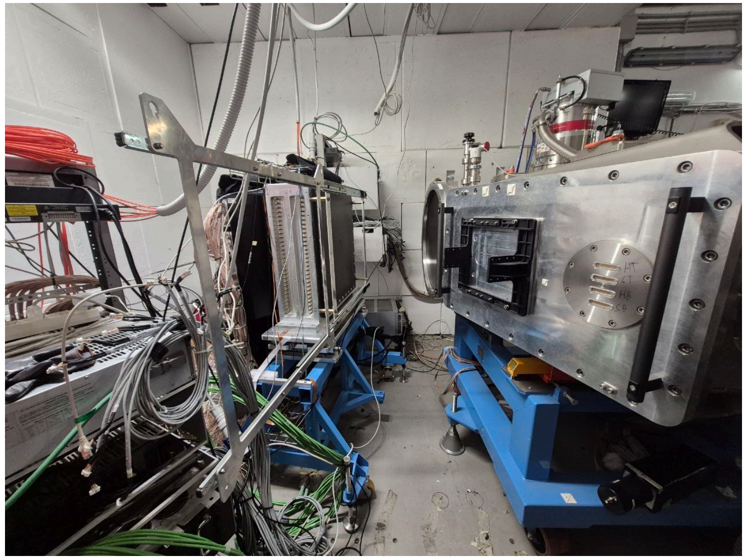




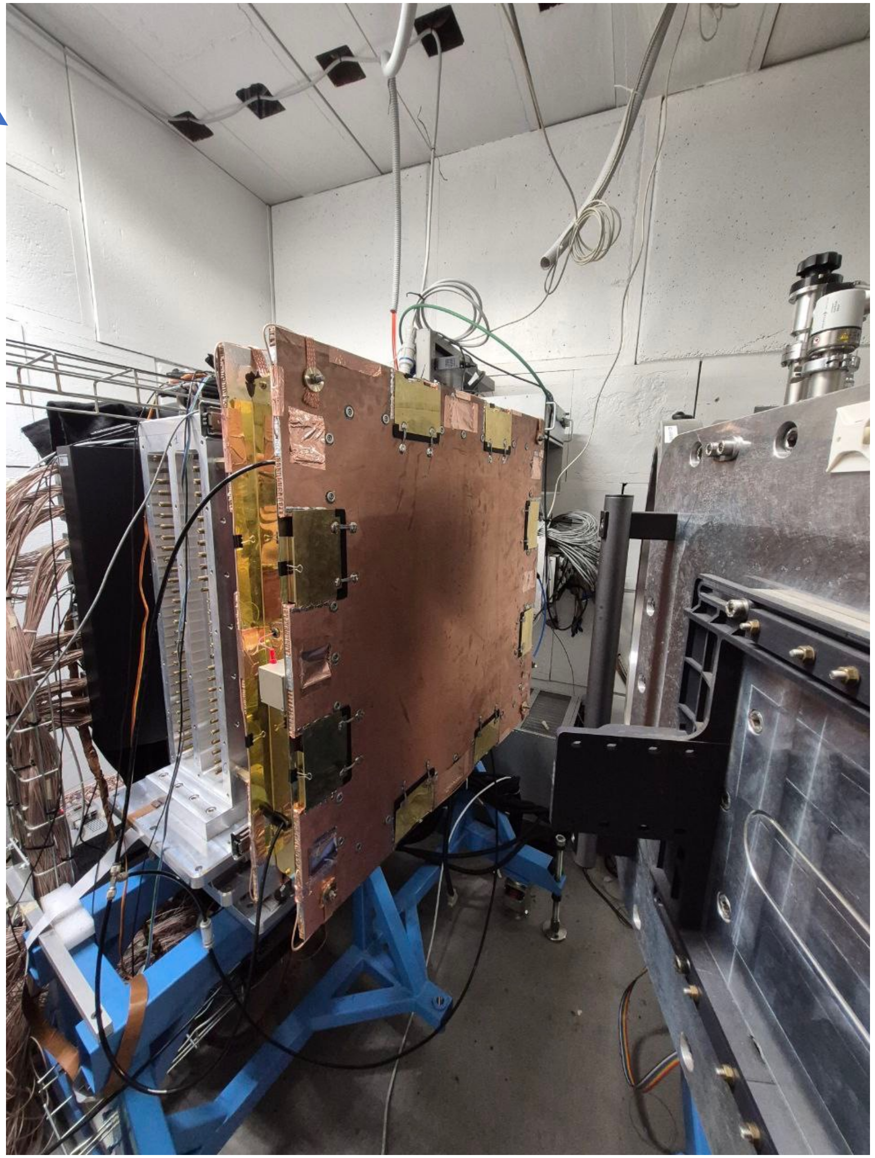
Pad*MMe* Installation in PADME



Sliding mechanics installation



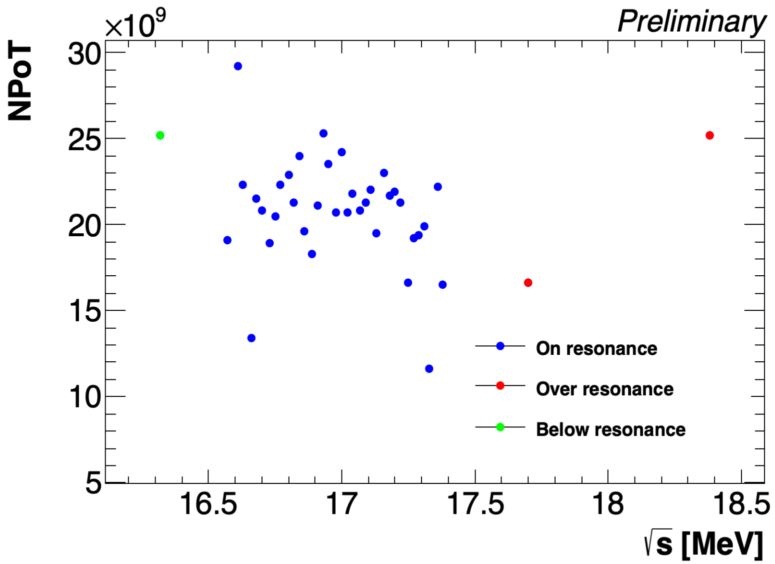
Chamber installed in BTF



After the validation was completed @ cosmic ray stand, chamber was installed in Beam Test Facility hall in PADME experiment in February 2025

PADME Run IV Data Taking

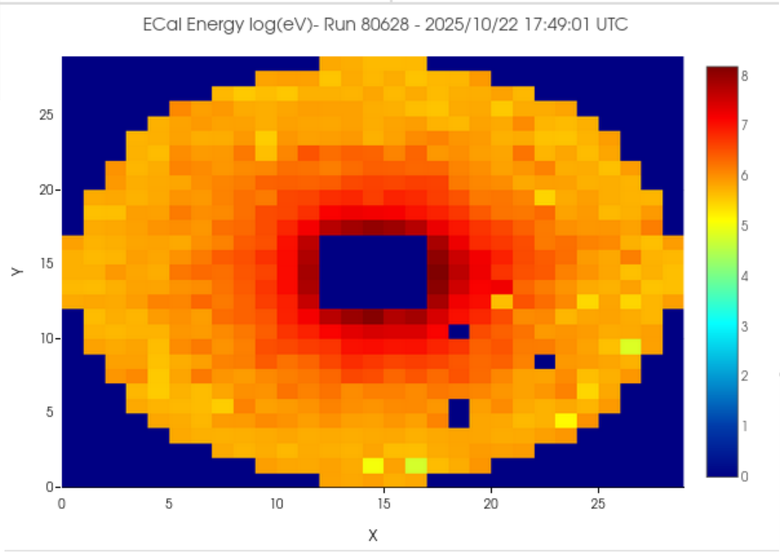
36 points: Scan 1 and 2 18 points each
~2.2x10^{10} PoT per point
268-295 MeV range, with 0.75 MeV spacing
1 point @ 260 MeV
2 points @ 300 and 330 MeV

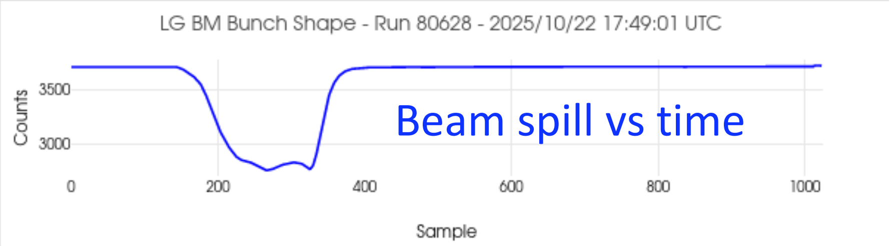


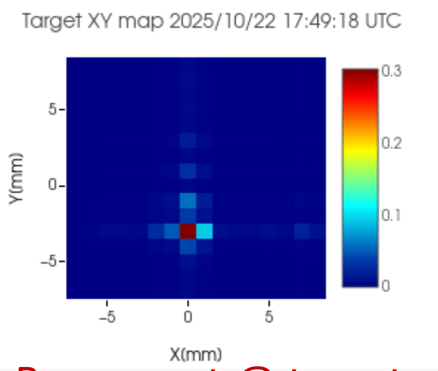
Run IV data taking from May to November 2025

Some online monitoring plots of the data taking

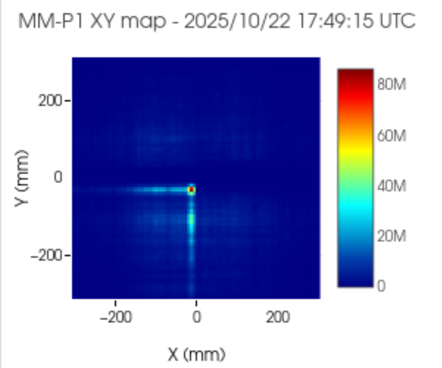
full ECal acceptance available thanks to the target movement



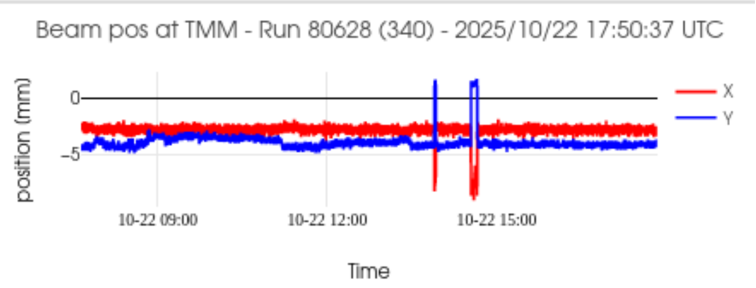




Beam spot @ target



Beam spot @ PadMMe



Beam position @ TMM

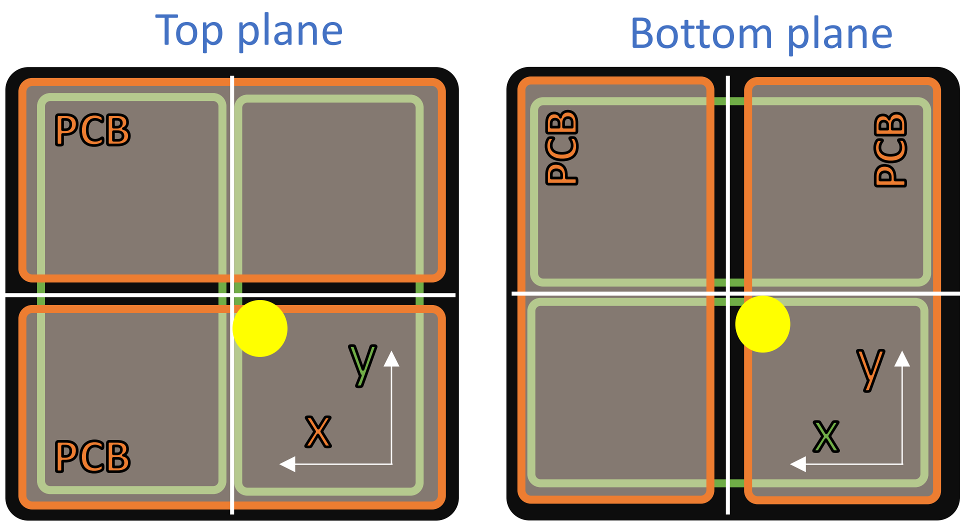
Pad*MMe* for Beam Monitoring

Beam slightly off chamber center to avoid the non-instrumented area in the PCB junction

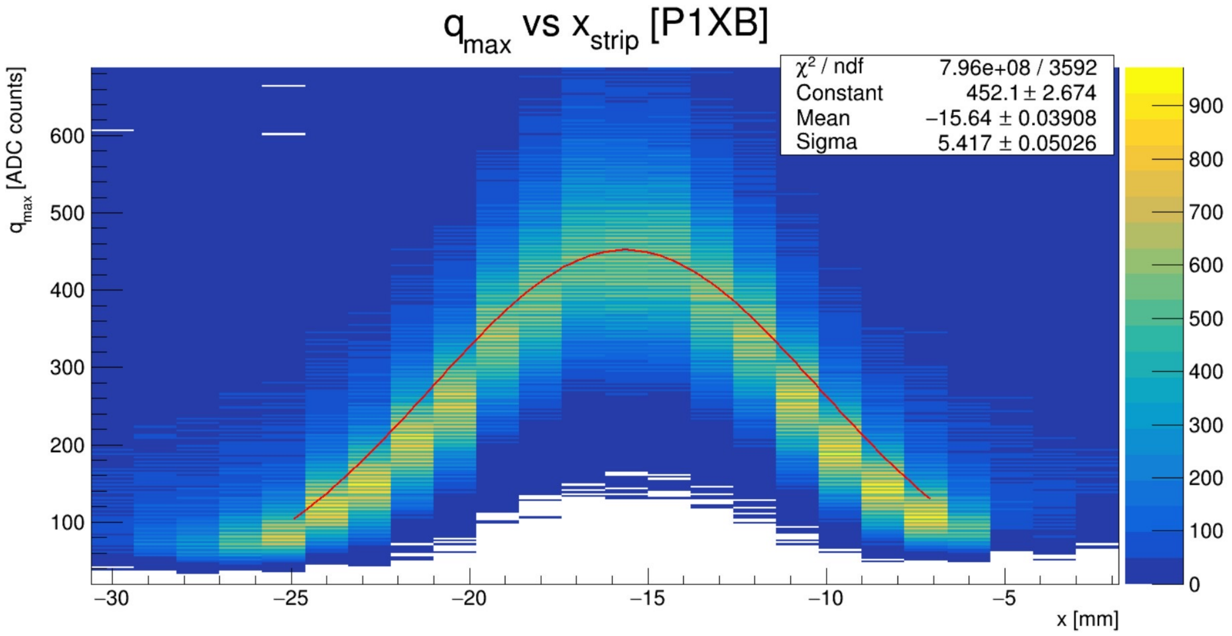
- HV in the central regions @ 350 V to have no amplification

Measured beam spot during commissioning

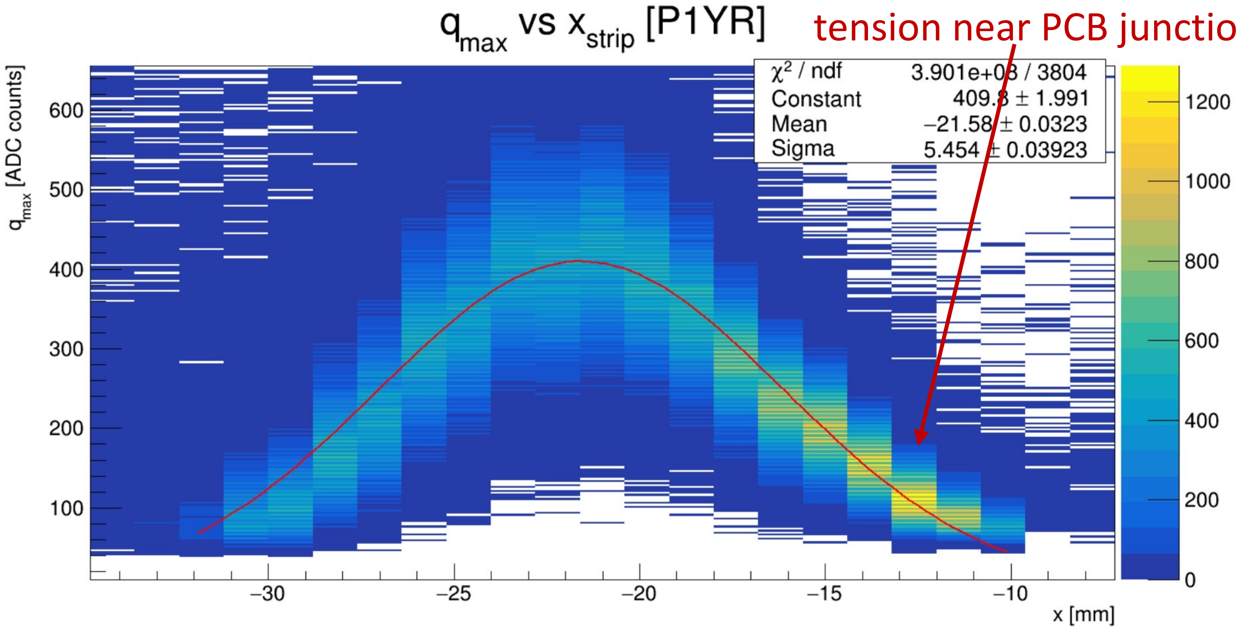
$\sigma_{beam} \sim 5.4 \times 5.4\ mm^2$



Able to monitor beam position with high precision during runs



Effect of non-uniform mesh tension near PCB junction

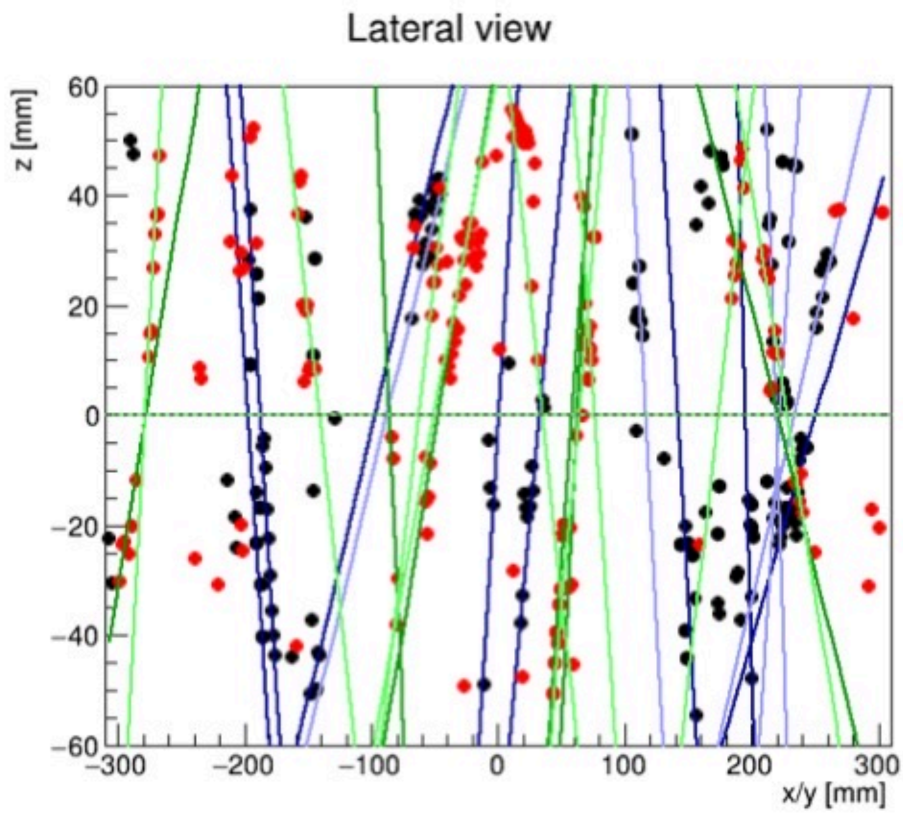


Tracking in PADME

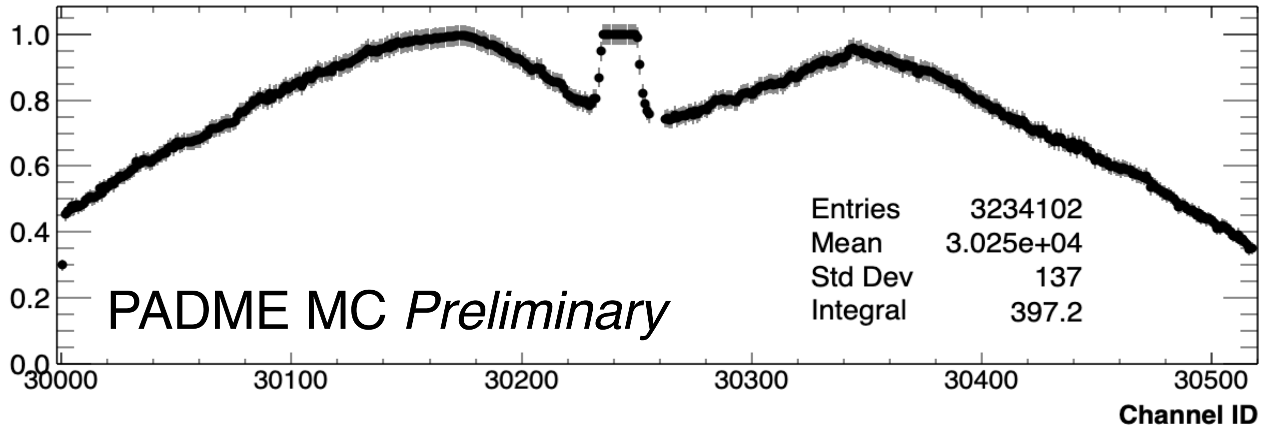
Huge combinatory in pattern recognition with 3000 e^+/spill

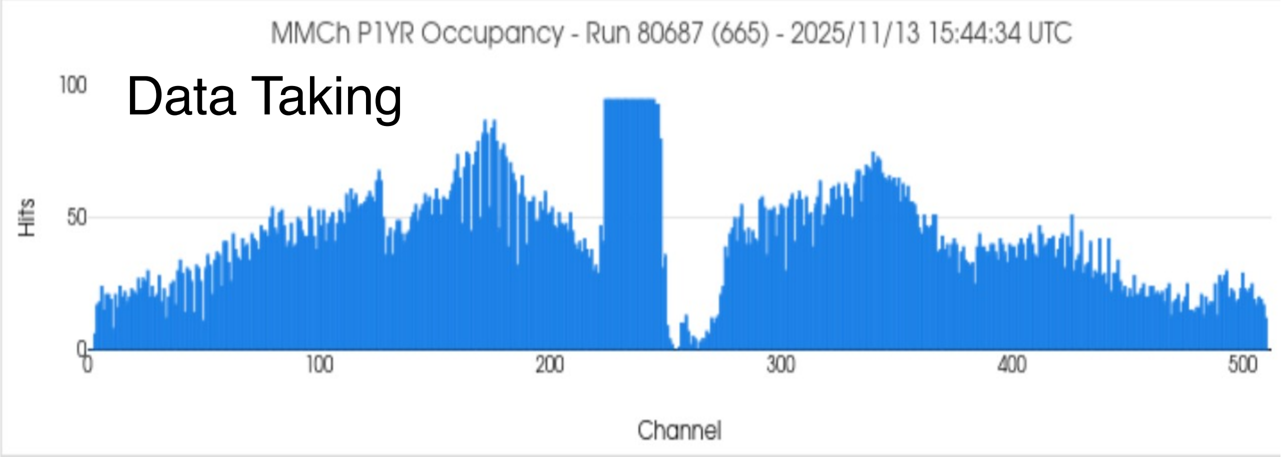
~200 track candidates found without Interaction Point (IP) constraint

→ IP oriented pattern recognition algorithm



High occupancy well modelled in MC

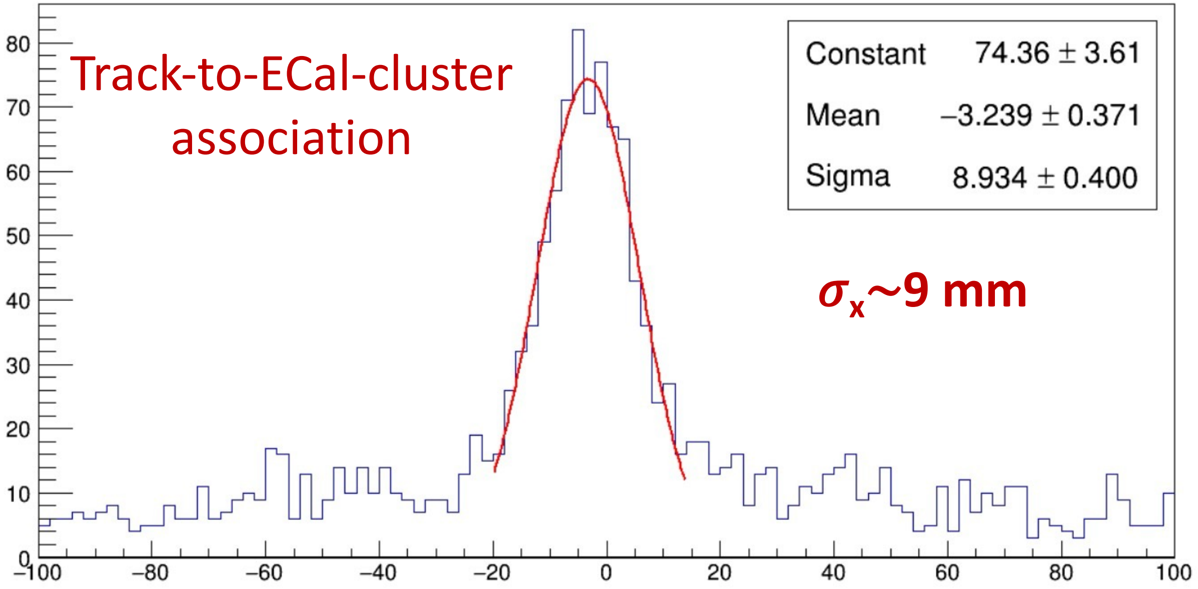


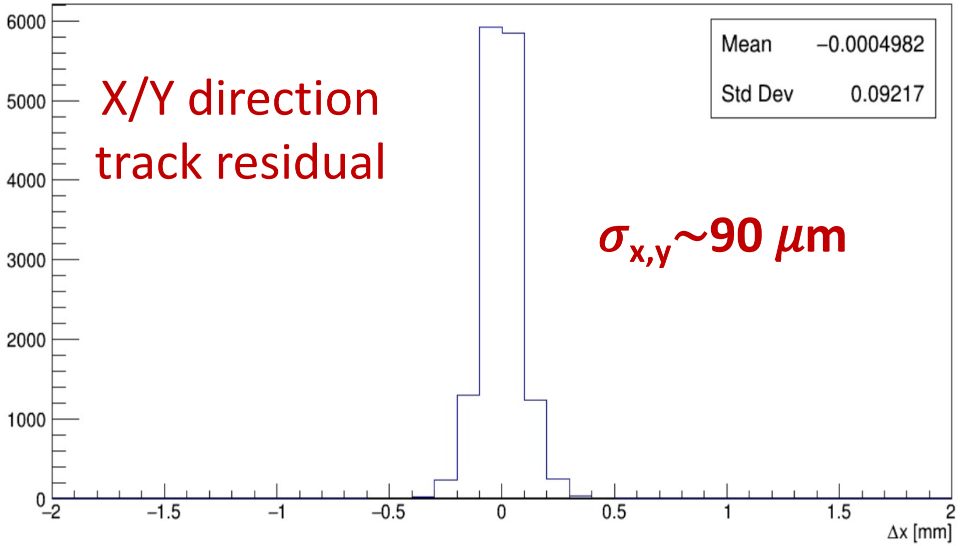


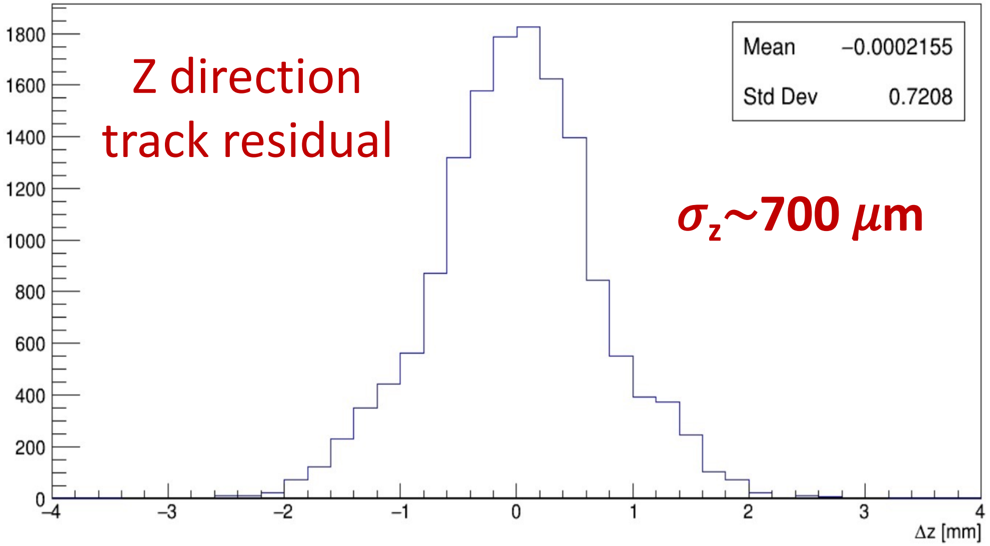
Pad*MM*e Preliminary Performance

Each charged particle measured in 2 planes – both X and Y coordinates

- Level-0 tracks correspond to track segments in each plane and coordinate
  - High efficiency but also high fakes level: need at least 2/3 out of 4 coincidence
    - → Level-1 track: 2 planes coincidence
- Requiring the matching with ECal clusters fakes are further reduced



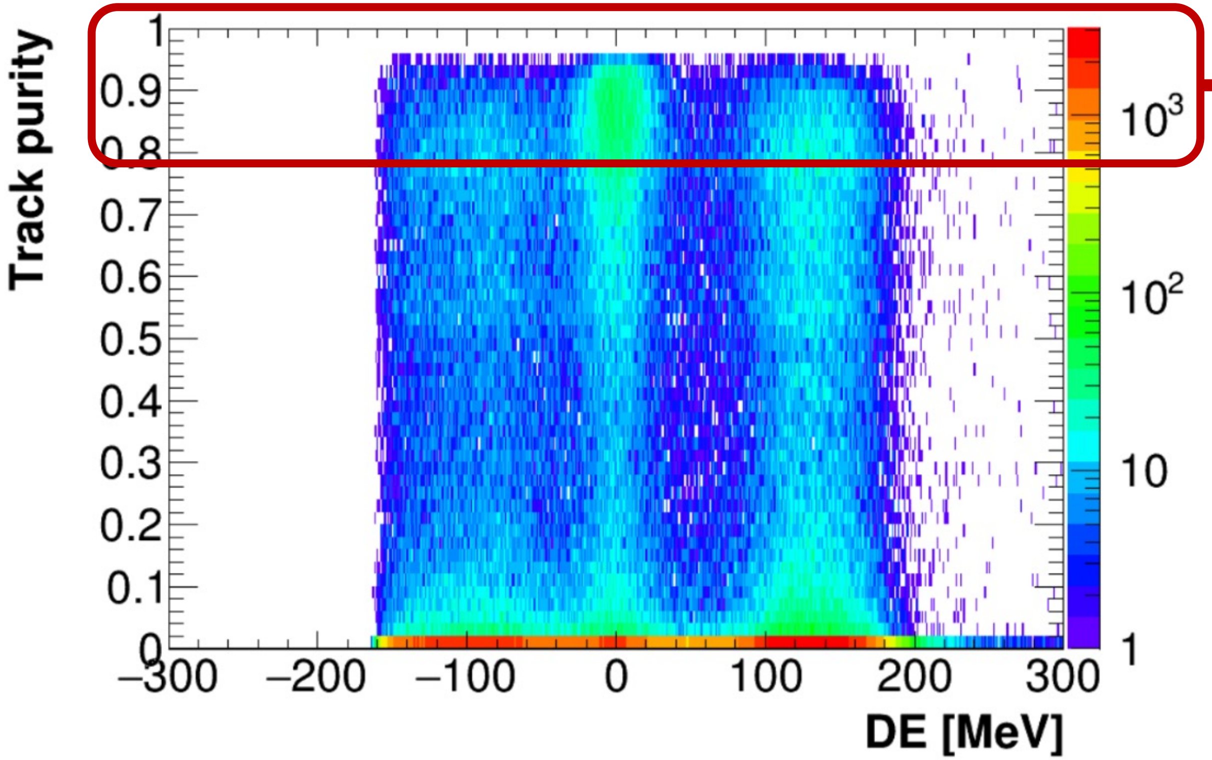




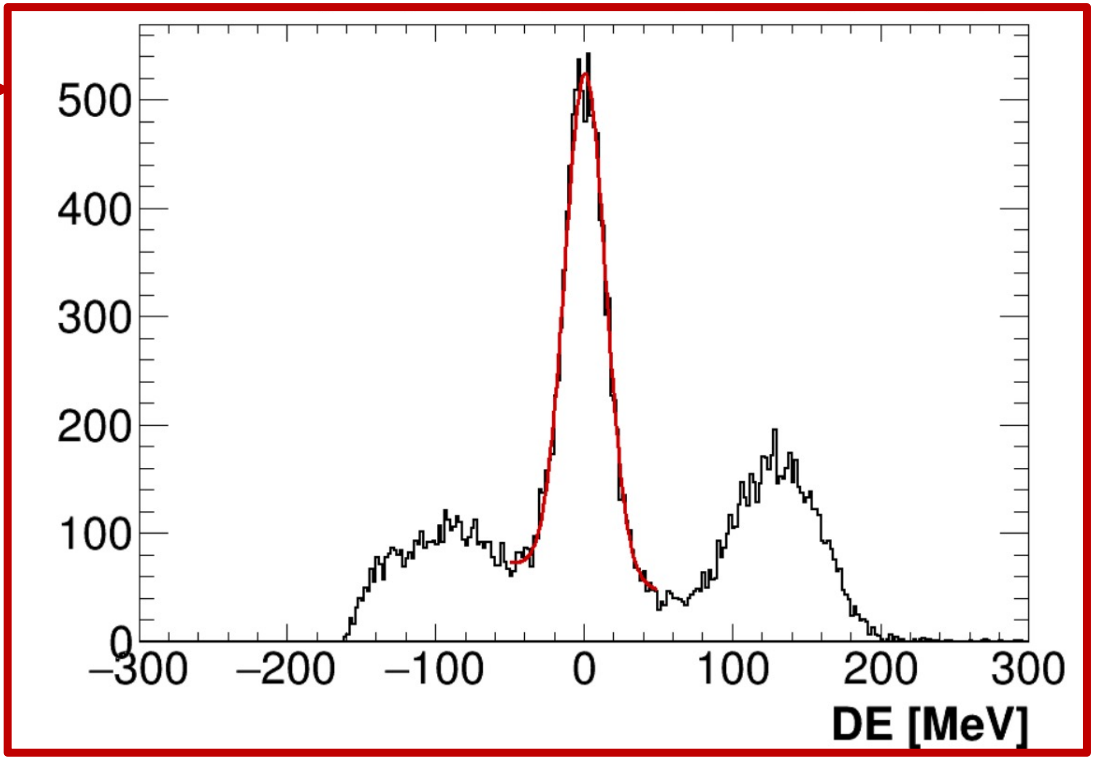
Background Reduction Preliminary Studies

Track purity vs ECal Cluster Energy correlation

- Modelling P(χ^2) distribution of the tracks identifying a signal and a background component
  → Track purity = S/(S+B)
- Difference in energy (DE) between the reconstructed cluster energy and the expected energy that match the tag



Projection with Track Purity >0.8



Possible PADME Upgrade towards a Spectrometer

Current Status of the X17 resonance search

- Beam Energy Scan → resolution O(10^{-2}) , due to beam energy spread and electron motion in the target
- Observable is ratio of number of 2-body final states over the expected SM background per positron on target → dependent from beam multiplicity

$$g_R(s) = \frac{N_2(s)}{N_{PoT}(s) \cdot Bkg(s)}$$

Proposal for future upgrades

- Final state invariant mass measurement using reconstructed momentum → **resolution O(10^{-3})** , completely dependent from tracker → Need better **tracking performance in magnetic field**
- Make use of angular dependency to be independent from the N_{POT} → Need **charge measurement with magnetic field**

Future detector studies on-going

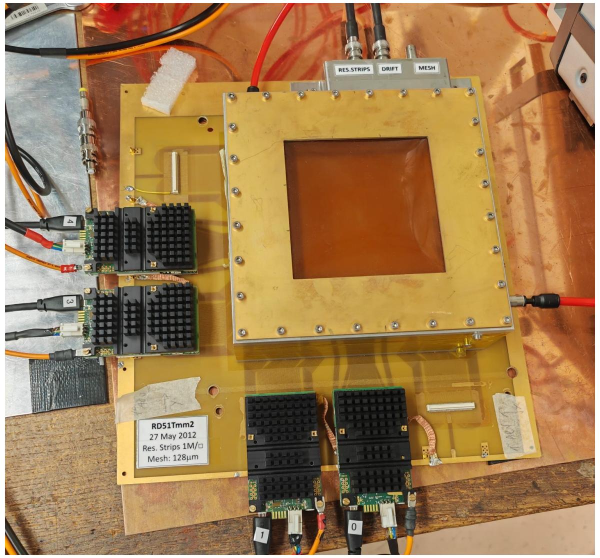
Need larger gap of at least 50 cm to be able to track in the magnetic field

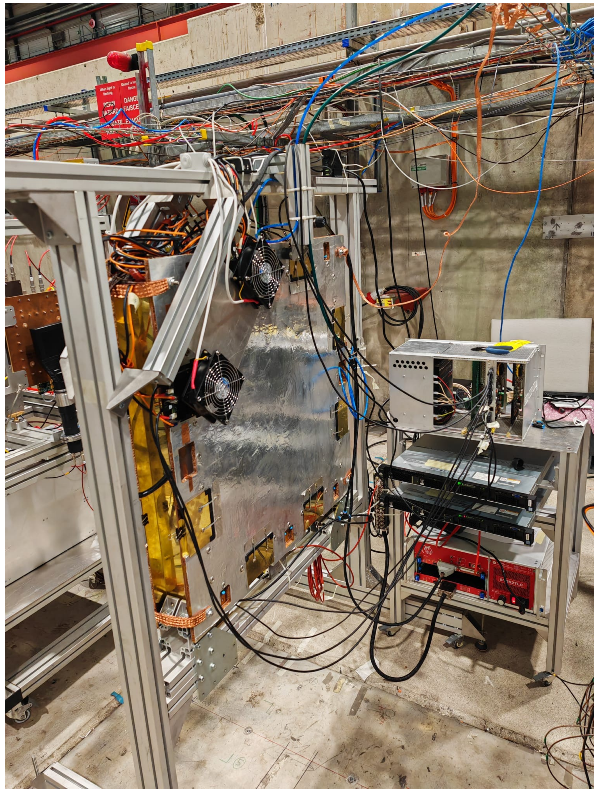
- PadMMe-like detector with readout plane not instrumented in the beam region but mylar window to reduce occupancy
- A detector “inside” the magnet able to measure the particle trajectory on the bending plane

Possible Readout & DAQ Upgrade: VMM3

Current setup with APV limited in time window due to the limited data size → not possible to measure 50 cm drift time

- **Proposal: use of the VMM3**
    - ADC+TDC embedded in the FE, no limit in time window acquisition
- Started test the new system on a small TMM @ CRS in Frascati with the VMM3 + SRS DAQ

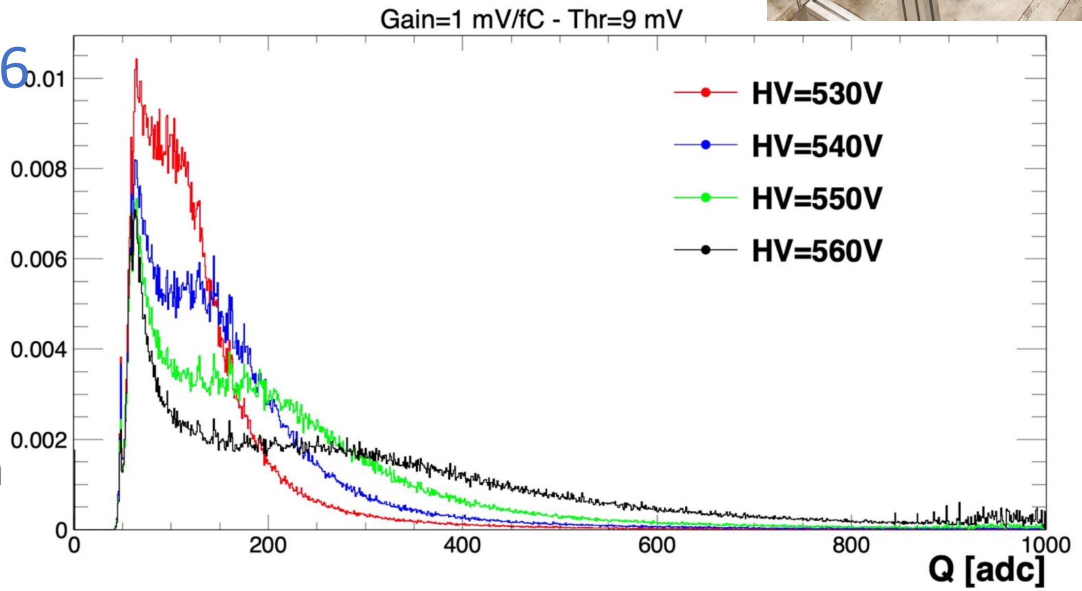




Test beam @CERN concluded end of July 2026

- twin PadMMe (straight-strip) chamber partially instrumented
- Using ATLAS gas mixture Ar:CO_2:Iso (93:5:2)

    → HV stable up to 560 V!
- Still high noise level that needs further investigation
- Data analysis work in progress



Conclusions

The PADME **Run III** data analysis shows an excess @ 16.9 MeV, with global p-value equivalent to 1.8(2)σ. **Run IV** data needed to clarify

New Micromegas tracker PadMMe for identification and reconstruction of charged particles

- Micromegas detector as TPC with 2 gap of 5 cm and 2 readout planes able to read both x/y coordinate each
- From cosmic analysis hit efficiency of >90% @ 500 V with a 10^4 gain
- Successfully installed and commissioned in PADME and joined the Run IV data taking
  - Able to monitor the beam with high precision
  - Limited by high occupancy
    - Optimization of the IP oriented pattern recognition algorithm to reduce the fakes
      - Preliminary resolutions of $\sigma_{x,y}{\sim}90\ \mu m$ and $\sigma_z{\sim}700\ \mu m$
    - Preliminary study to estimate the background reduction very promising

Possibility to significantly increase the sensitivity of the experiment in future running campaign using also the magnetic fields to be able to reconstruct the momentum and to reduce the material budget

- Upgrade the FE electronics and DAQ to be able to deal with longer drift time

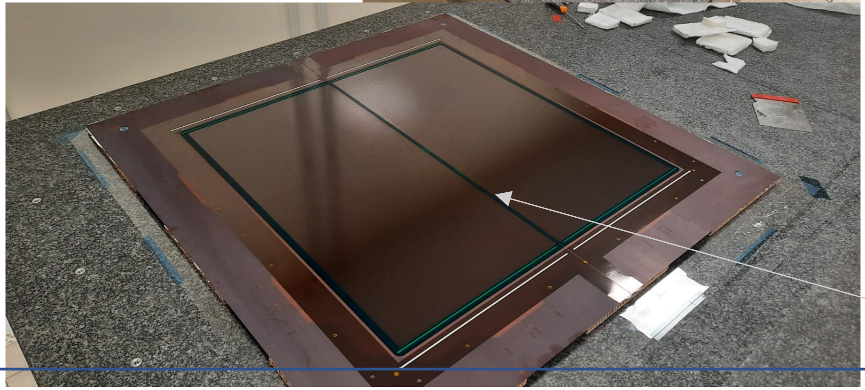
Thanks for the attention!

Micromegas Construction

- Pre-assembly
  - Construction of PCB panel (gluing the PCB on the panel, electrical connection for the HV)
  - Cleaning the mesh and drift gap preparation
- Chamber assembly

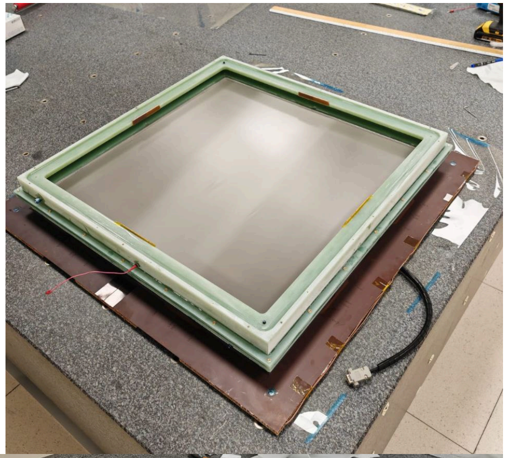
*The 2 readout panels are placed orthogonally to avoid to have overlap of the dead areas and for performance reason

First Readout panel

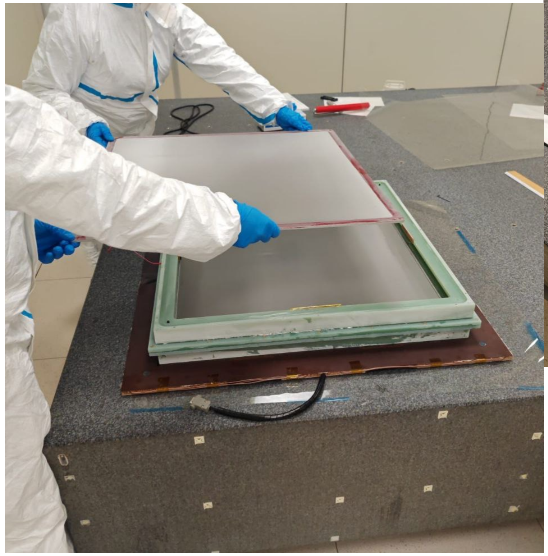


This junction produce a dead space of ~8 mm along the precision coordinate*

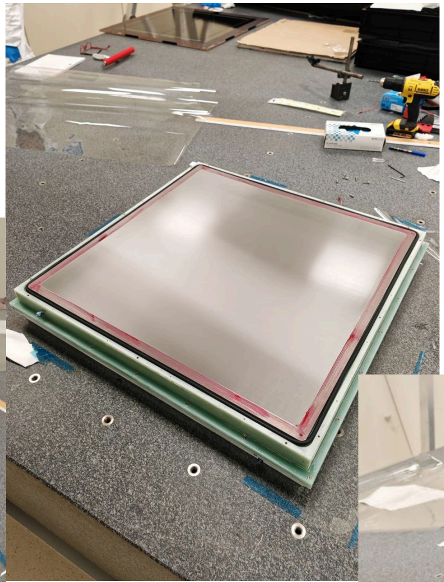
Drift bi-Gap



mesh installation

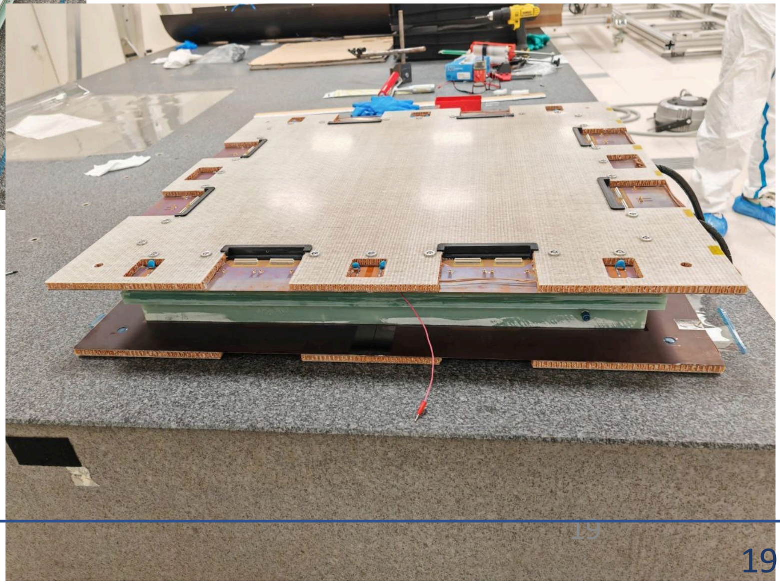


Mesh installed



After second readout panel installed

→ **Chamber is closed!**

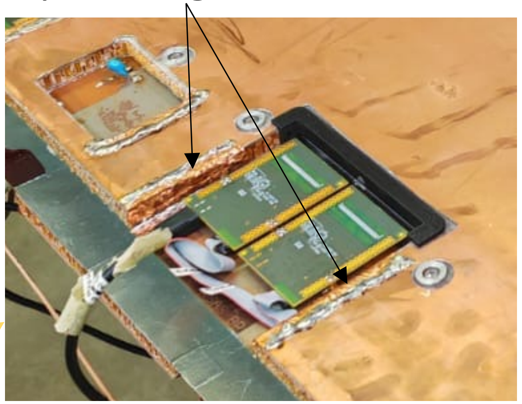


Micromegas Test @ Cosmic

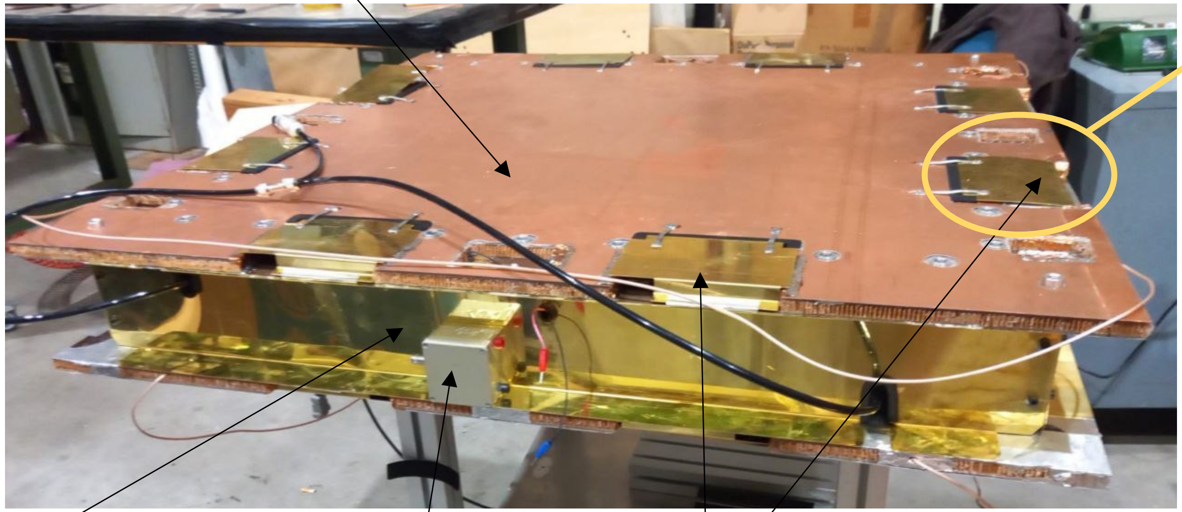
Noise Studies

- Faraday cage on the chamber, on the electronics, grounding improved

Improved ground connection



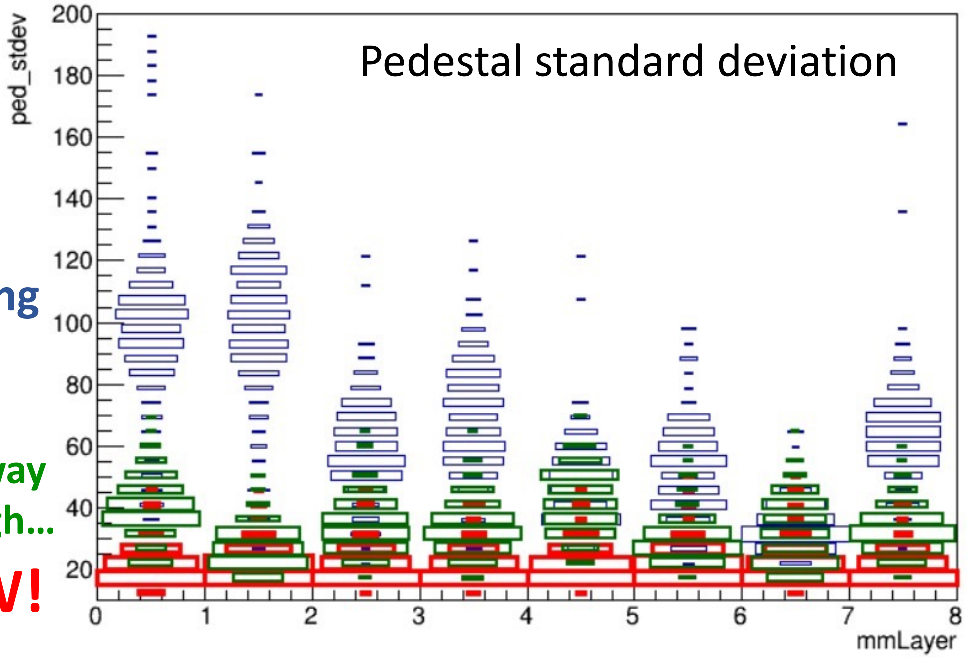
Dremel machined PCB 50 µm copper



Brass *armor* + connection between two planes

Shielding HV drift

Brass case for the electronics + connection with PCB

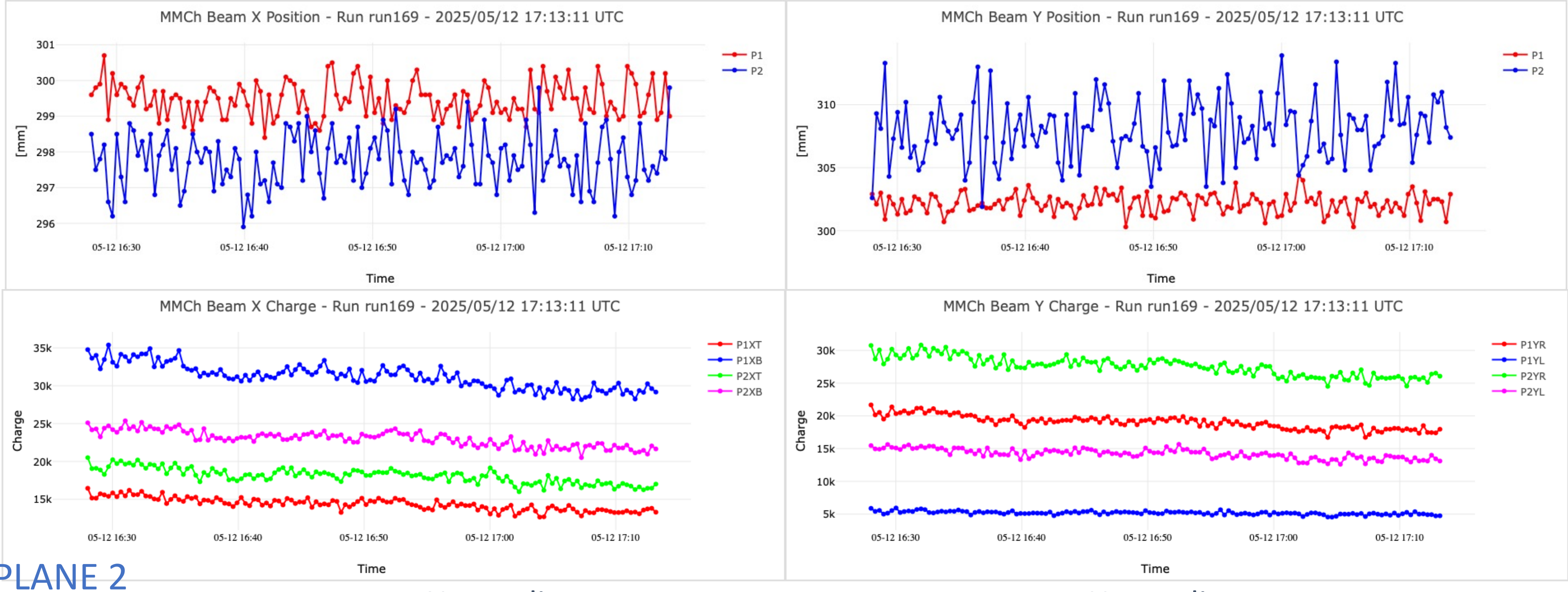


Micromegas Commissioning

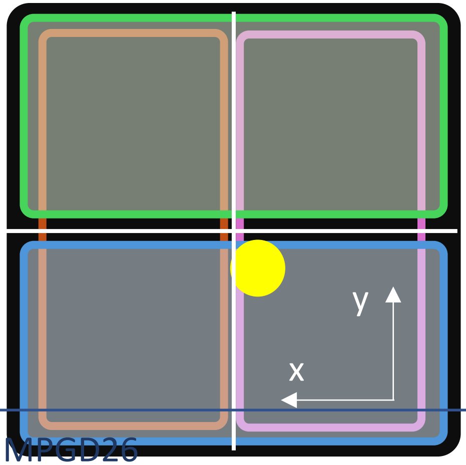
Beam Monitoring

- Beam position monitored live in time

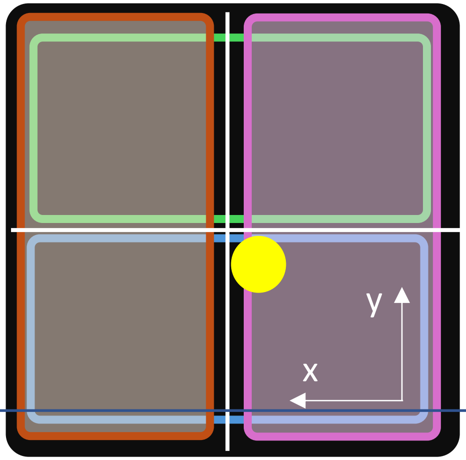
- Possibility to monitor also the beam intensity
  - Different intensity based on where the beam is



PLANE 1



PLANE 2



X coordinate:
Intensity P1 > Intensity P2

Y coordinate:
Intensity P2 > Intensity P1

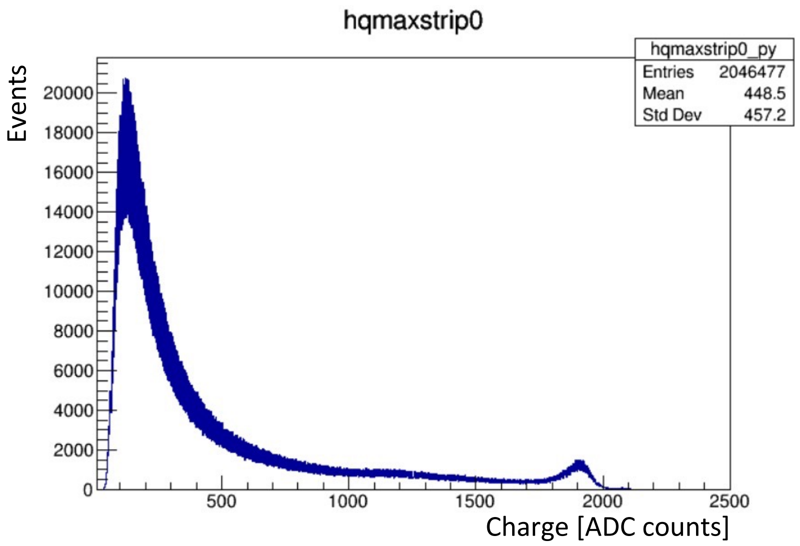
For how the PCBs are done, the strips to read one coordinate (ex. X) are ”on top” of the other strips (ex Y). The one ”on top” collect larger fraction of charge → **this can be seen in the beam intensity plots!**

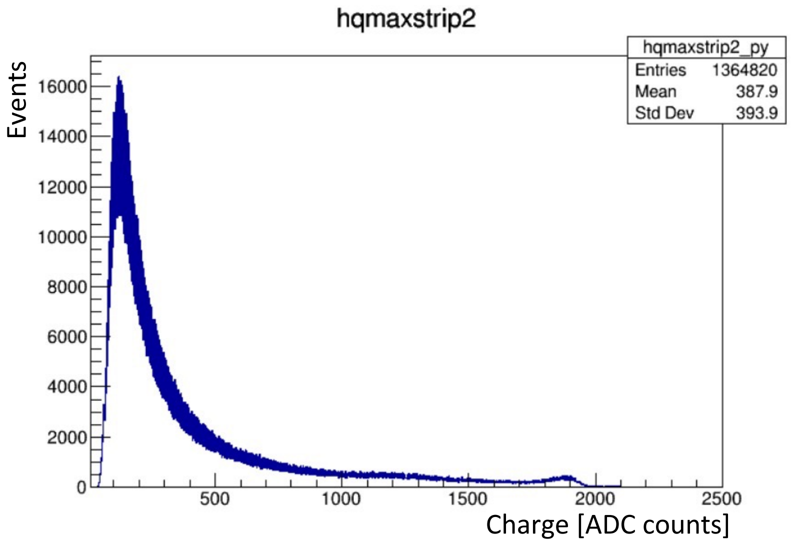
- The two readout planes have been put orthogonally also for this reason, to have the ”best” performance on both coordinates

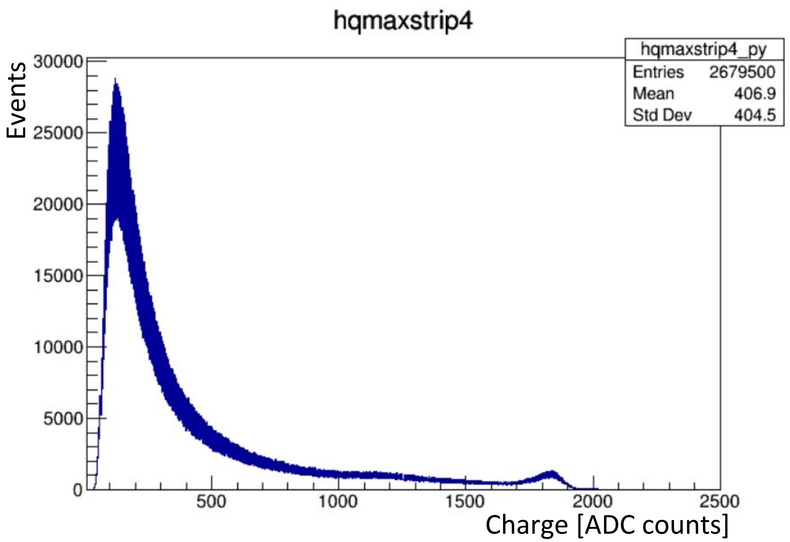
Micromegas Commissioning

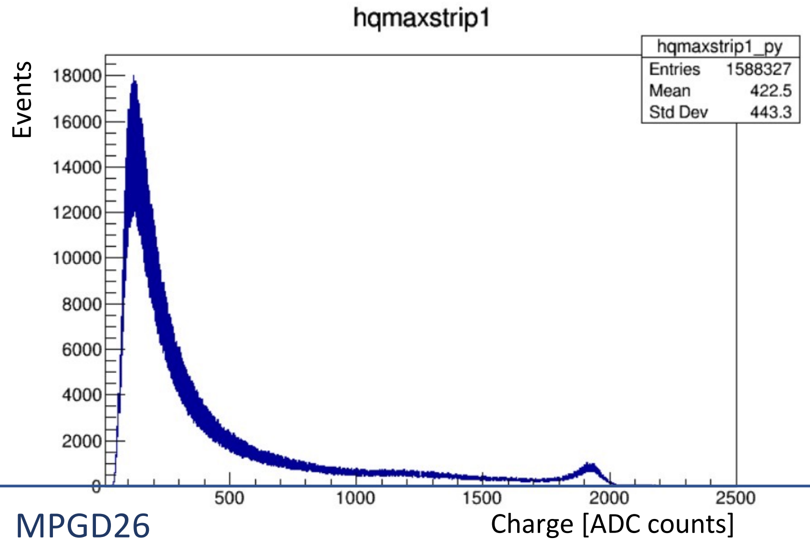
Charge Amplification

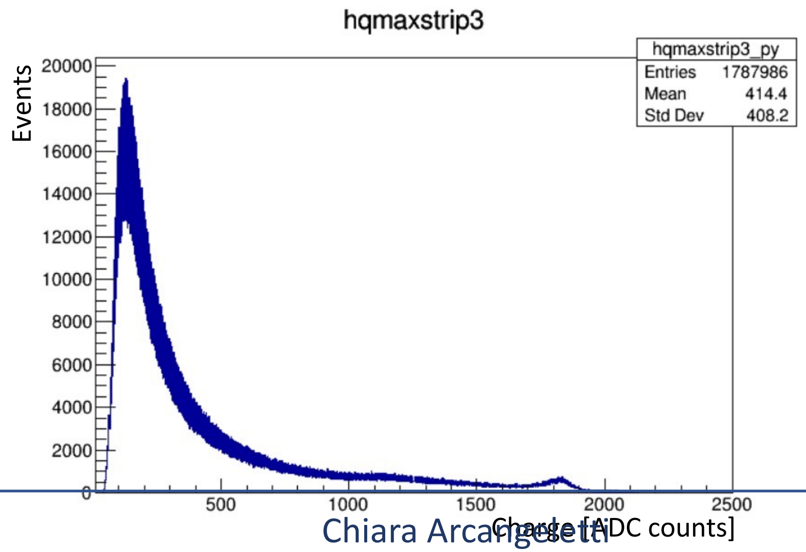
Charge ~ 380 – 450 ADC counts
with multiplicity 3000 particles, HV inner @ 350 V + external @ 500 V

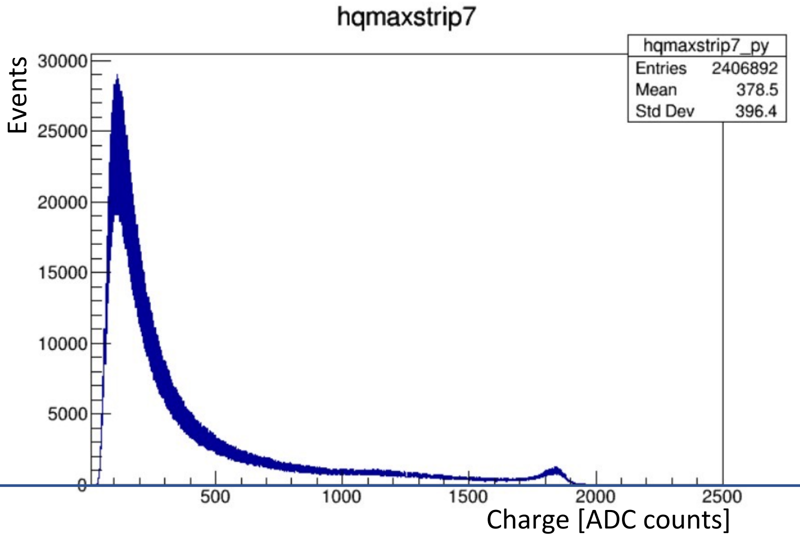












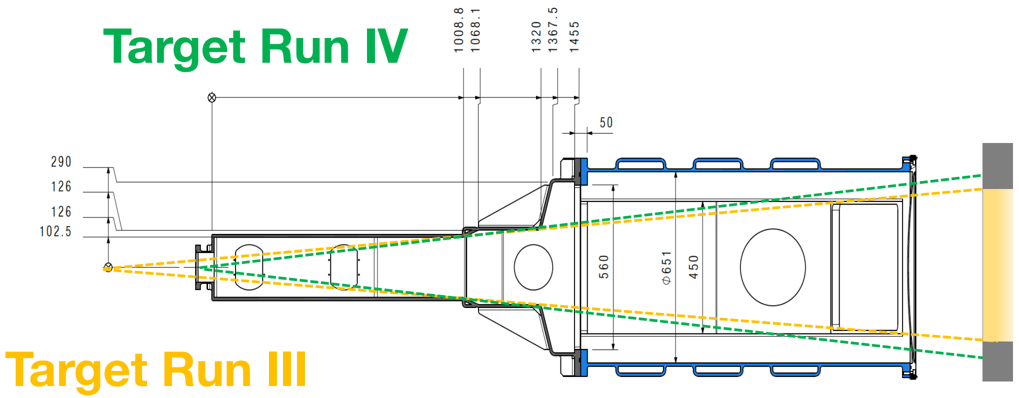
Diamond Target

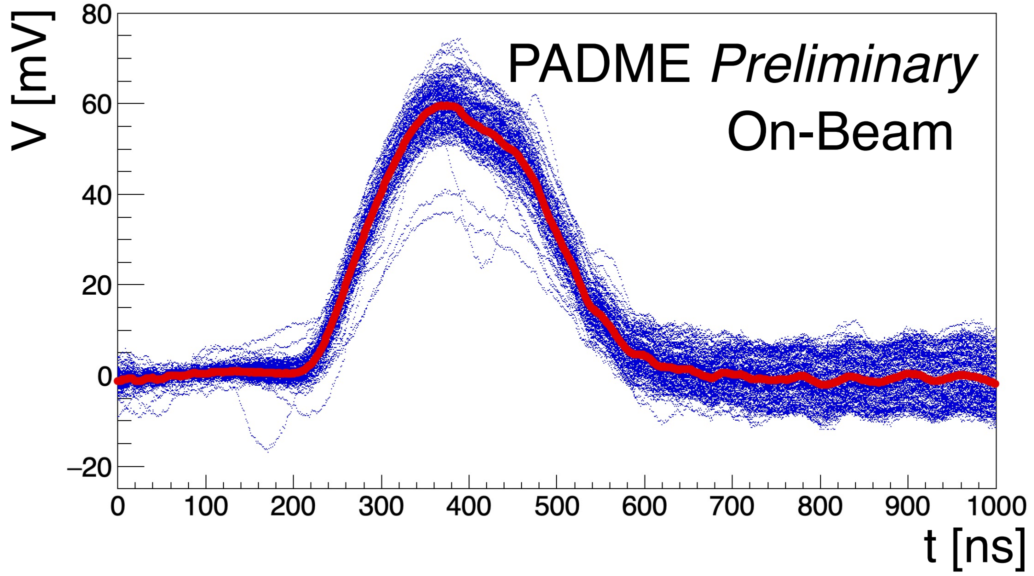
Target position changed from 3.70 m to 3.36 m

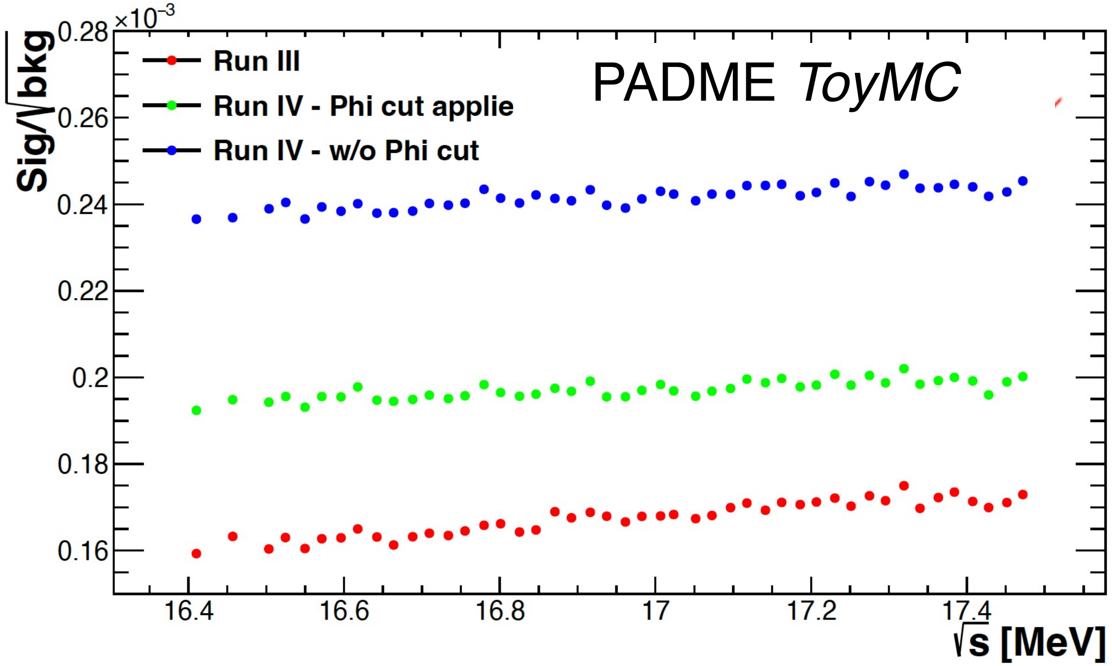
- ϕ_{lab} -cut can be totally removed or adapted
- Acceptance region enlarged → luminosity increases by a factor of 2.5

Reconstruction optimization

- Target waveform affected by common-mode noise
  → Average over $\mathcal{O}(100)$ waveforms
- Beam multiplicity $\propto Q = \sum_{t_{start}}^{t_{stop}} \frac{V(t)}{Z}$







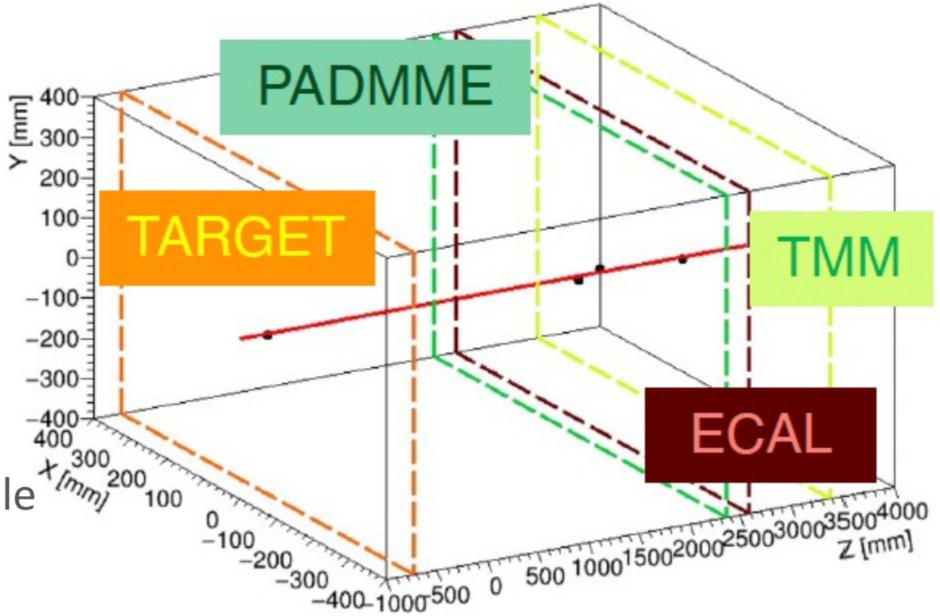
Beam Conditions

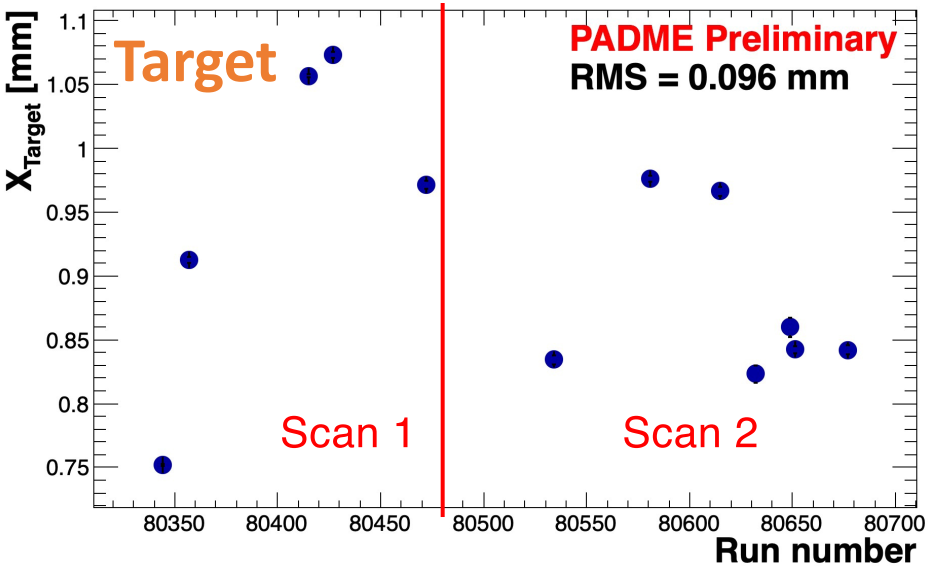
Beam monitor at 4 different levels using different methods to measure position, angle, beam spread and beam divergence

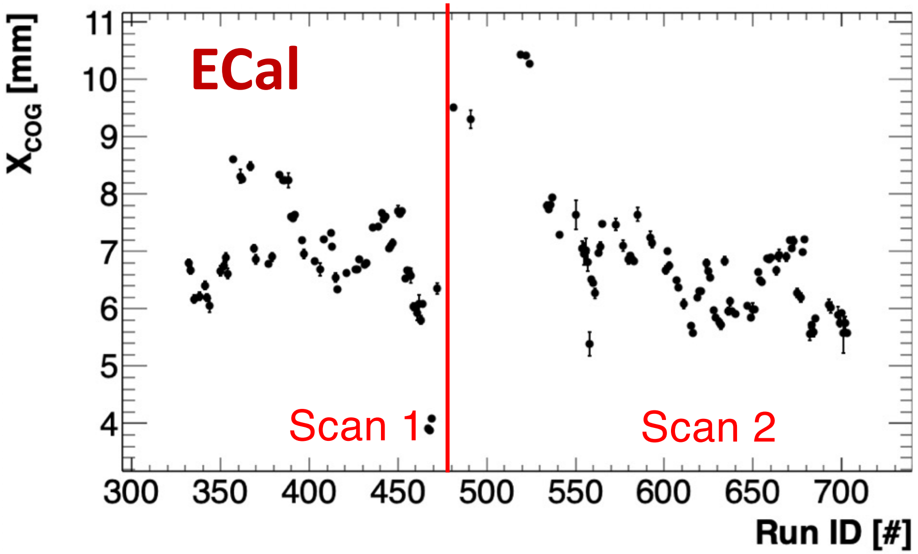
Target: charged-weighted mean over the 3 fired strips: beam position stable within 100-150 µm. Full scan evaluation ongoing

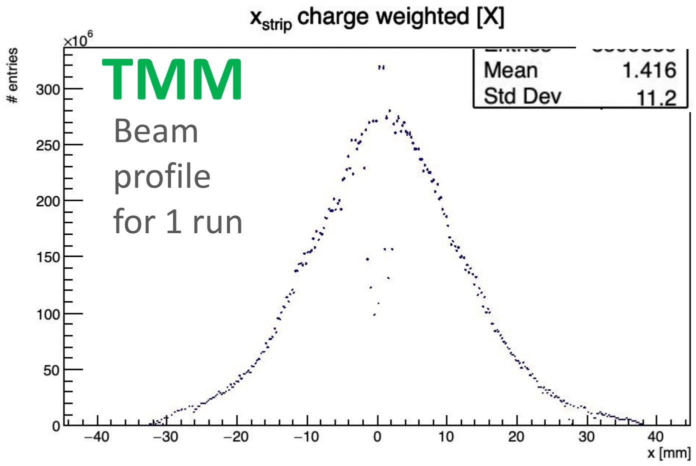
PadMMe and TMM analysis ongoing: preliminary estimation of the beam profile from weighted position with strip charge→ work on strip charge calibration

ECAL: beam parameters estimated using the two-clusters center of gravity (CoG): beam position stable at few mm level in X and at cm level in Y







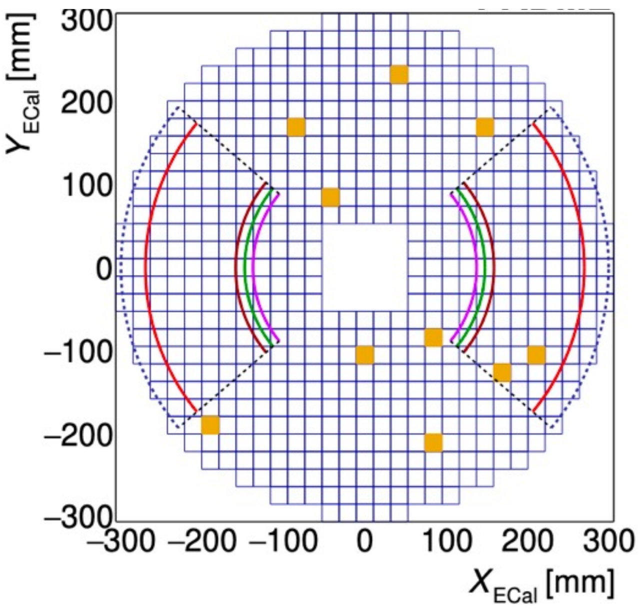


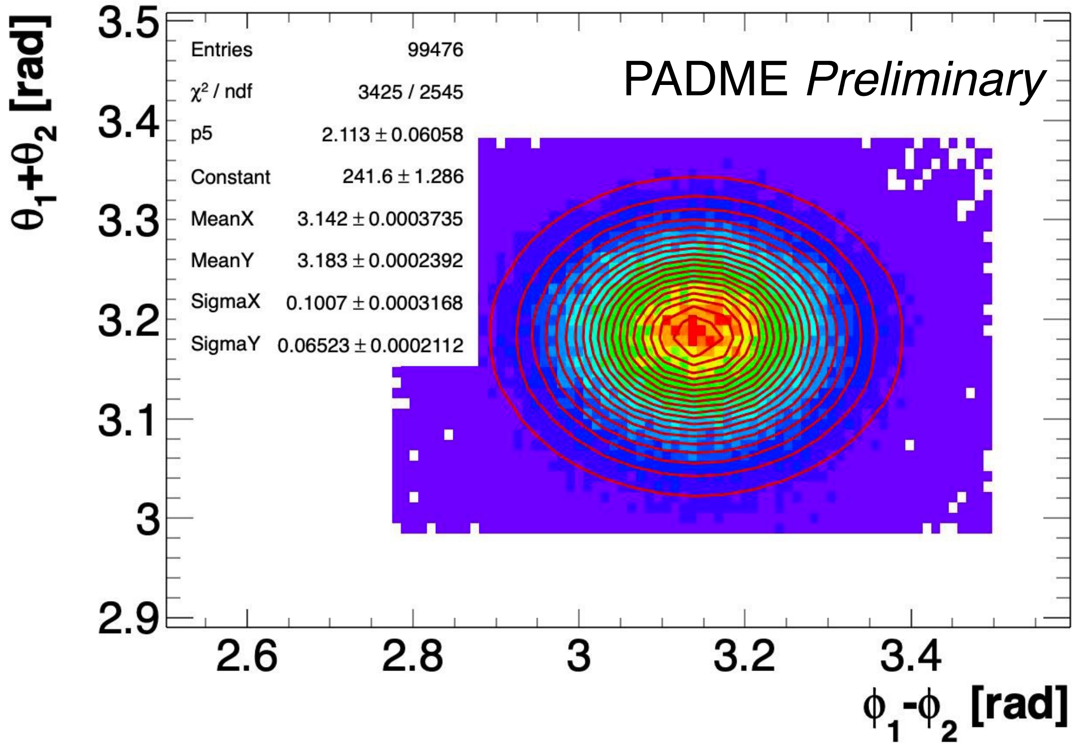
Run IV Preliminary Event Selection and Background

As for Run III, two body final states selected using ECal clusters position information

Acceptance study with some preliminary estimations without Bremsstrahlung subtraction and missing lead-glass calibration:

- With ϕ_{lab} cut: yield increases x1.5 (as expected from MC studies)
- No ϕ_{lab} cut: yield increases >x2.5 and enlarging the low-energy cluster acceptance (expected 2.3 from ToyMC)





Preliminary flat background estimation

- Selected events signal can be fitted with a 2D Gaussian + constant
- Preliminary Flat Bkg ~7% (was 4% at Run III)
- Improvement in S/√(S+B) by a factor 1.5 wrt to RunIII
- Stat error on the yield aimed at ~0.35% for $1\text{x}10^{10}$ POT