MPGD-based hadron calorimeter for future colliders

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The 2026 International Workshop on the High Energy Circular Electron Positron Collider

Oct 21st - 26th, 2026

1) INFN, sezione di Bari
2) University of Bari
3) Weizmann Institute of Science
4) INFN, sezione di Napoli
5) INFN, sezione di Roma3
6) CERN
7) University of Padova

Hadron Calorimetry at Future Colliders

Requirements for HCAL: 5D calorimetry in Particle Flow

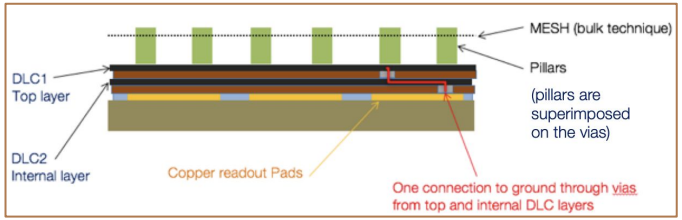
- **σ/E ~ O(50%) /√E**
  → jet energy resolution~ 30%/√E
  → σ_m/m ~ 3% for a di-jet mass resonance of O(100 GeV)
- **High granularity O(1 cm^2)**
  - track matching and/or reject machine-induced background
- **Time resolution**
  - reject background and/or improve energy estimation

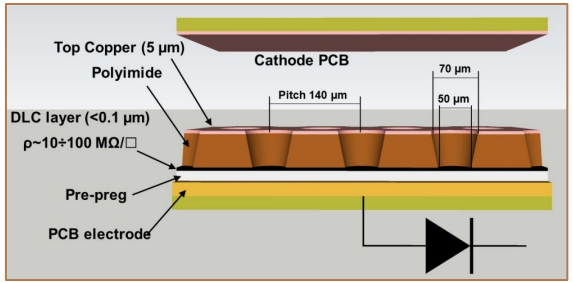
MPGD-HCAL: a sampling hadronic calorimeter (HCAL) with micro-pattern gaseous detector (MPGD) as readout layers

- **cost-effectiveness** for large area instrumentation
- radiation hardness up to several **C/cm^2**
- **discharge rate** not impeding operations
- rate capability O(**MHz/cm^2**)
- high granularity
- time resolution of **few ns**

Candidate technologies

Micromegas (MM)





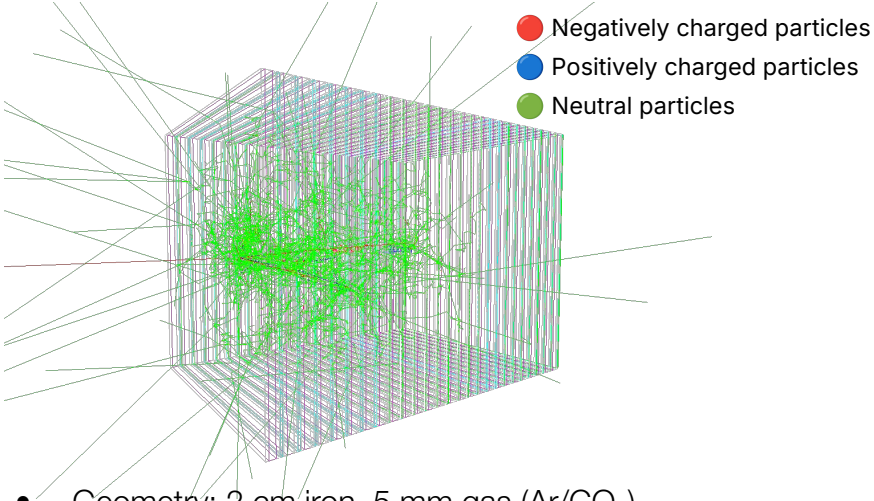
µRWELL

Past work: **CALICE** collaboration (RPC), **SCREAM** collaboration (RPWELL and resistive MicroMegas)

Our plan → systematically **compare** both MPGD technologies, while also investigating **timing** and **tracking performance**

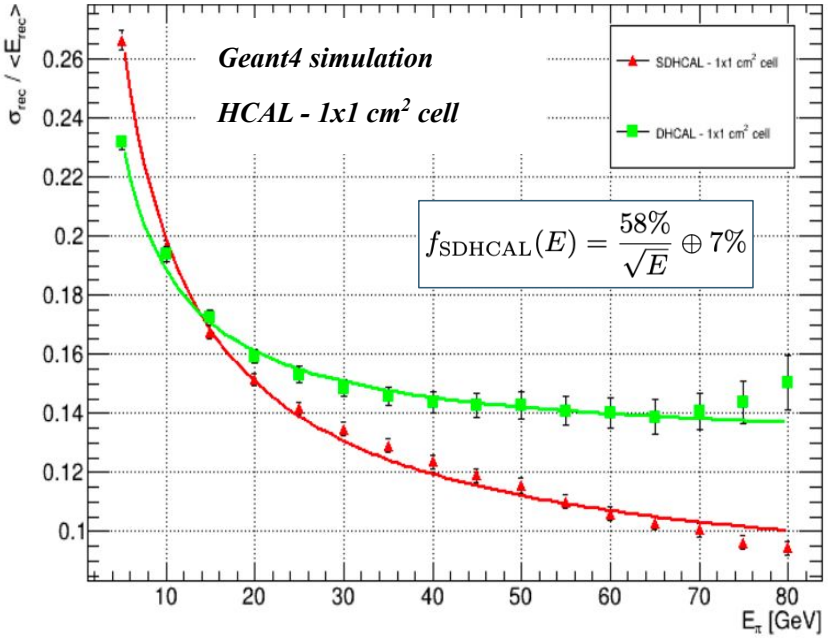
Simulation studies - Geant4

Starting point: standalone **Geant4** simulation targeting an energy reconstruction based on **digital (DO)**, $E_\pi = f^{-1}(N_{hit})$, or **semi-digital (SDO) readout**, $E_\pi = \alpha N_1 + \beta N_2 + \gamma N_3$ *with* N_i *number of hits above i-th thresholds*.



- Geometry: 2 cm iron, 5 mm gas (Ar/CO_2)
- Readout granularity →1×1 cm^2 cell size
- Pion guns of different energies

Result: 95% shower containment
- ~10 λ_I longitudinal
- ~2 λ_I transversal



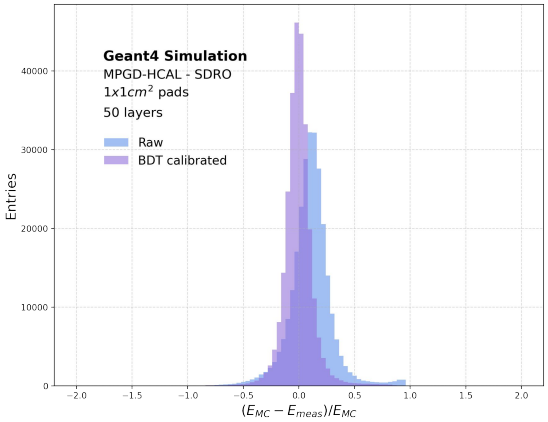
SDHCAL: better resolution for $E_\pi > 40$ GeV

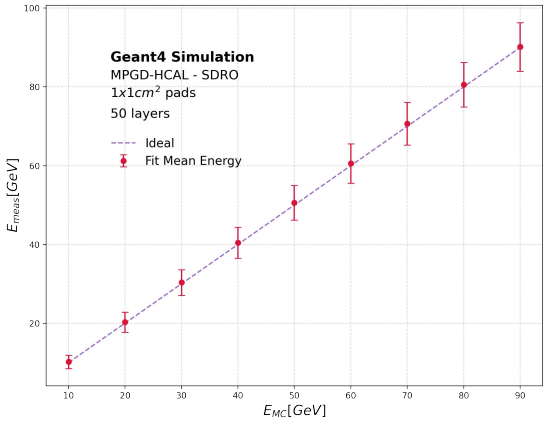
DHCAL: saturation effect for $E_\pi > 40$ GeV

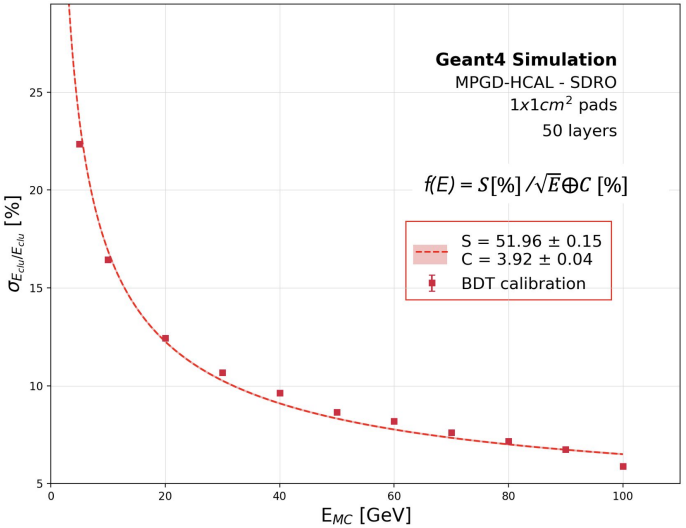
At $E_\pi = 80$ GeV, the resolution
- DHcal ~ 14%
- SDHcal ~ 8%

Simulation studies - BDT calibration

- **XGBoost squared-error regression to improve the energy calibration, linearity and resolution**
- **Training: ~600k events, E_{π}=2-120 GeV**
- calibrated energy = **BDT coefficient** X Semi-digital energy estimate
- **Input Features :**
  - Number of hits in the whole HCAL
  - Shower energy reconstructed with 3-level semi-digital read-out
  - Number of hits in the 3 energy ranges
  - Number of hits per layer
  - Energy Fraction per layer
  - X, Y, and Z centroid (weighted for the hit energy)
  - Standard dev of hit coordinates X & Y per layer



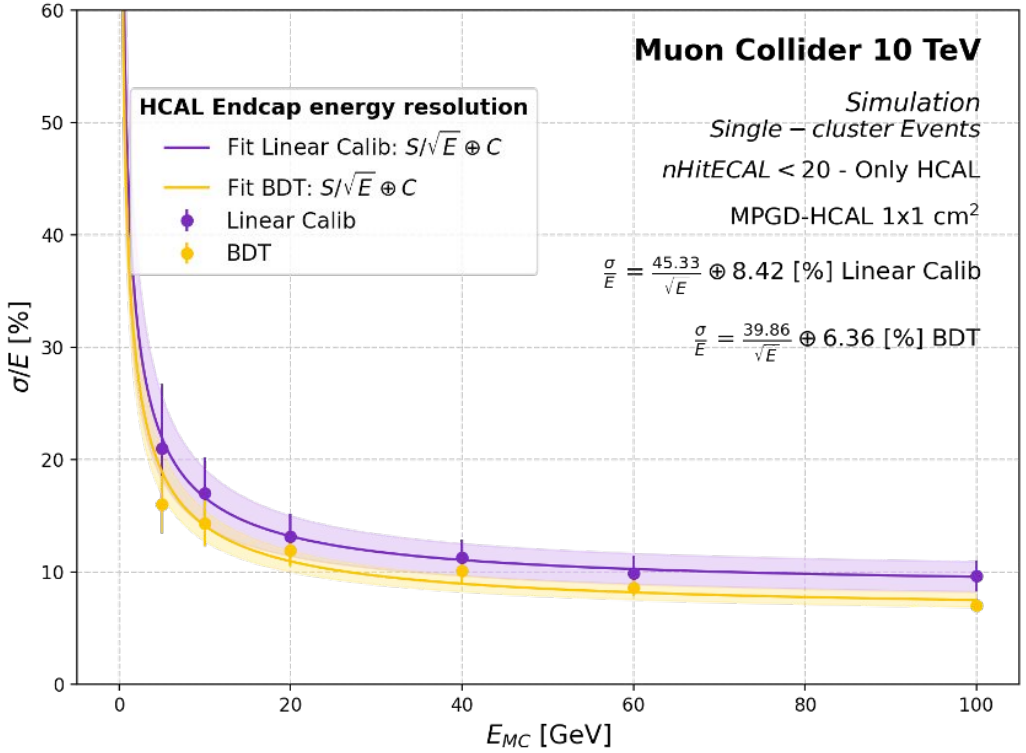




- **Energy response improved** in the BDT calibrated shower energy:
  - Tighter peak, symmetrically centered in 0
- **Good linearity** of the **reconstructed energy** with respect to the **MC true energy**
- Significant **reduction** of the **constant term C : 7.0% →3.9 %**

MPGD-HCAL for a Muon Collider

MPGD-HCAL initially proposed for a Muon Collider experiment at $\sqrt{s}$ = 3,10 TeV, for its radiation hardness and the possibility to deal with the expected Beam Induced Background ($\phi_{n,eq}$~10^{12}-10^{13} $n_{eq}/cm^2/y$)



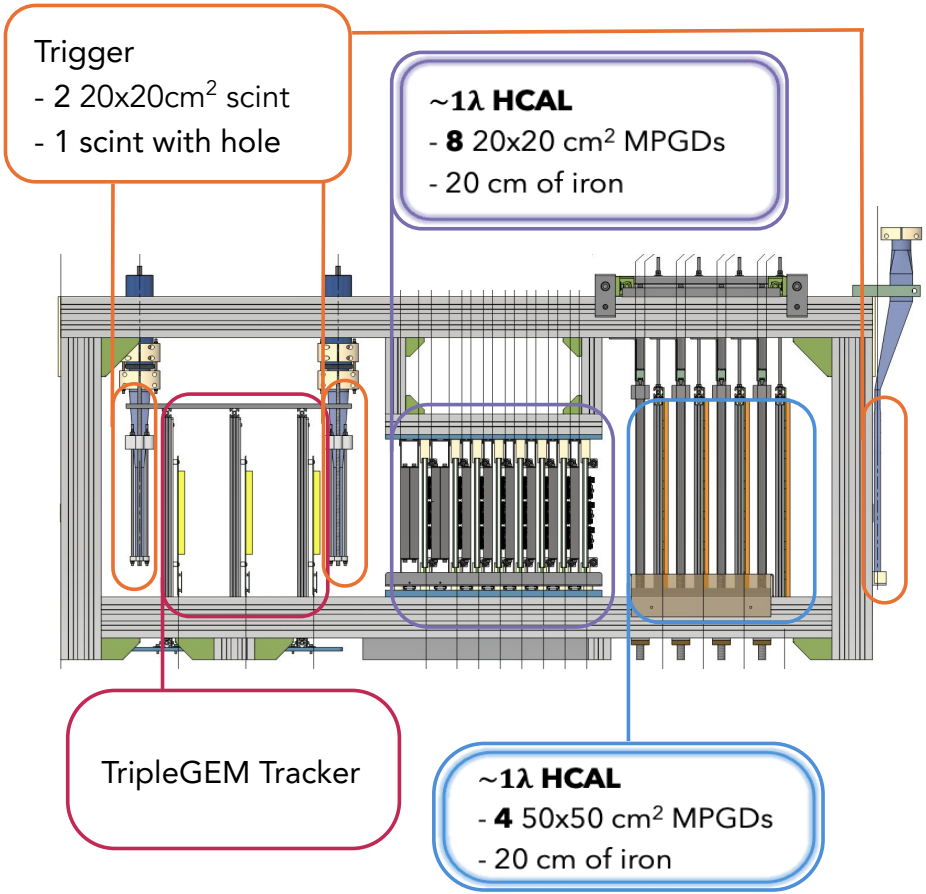
- Pion gun
- Only pions showering in HCAL
- **Energy resolution:**
  - **SDO shows stat term of 45%**
  - **SDO with BDT has stat term of 40%**
  - **Reduction of the constant term**

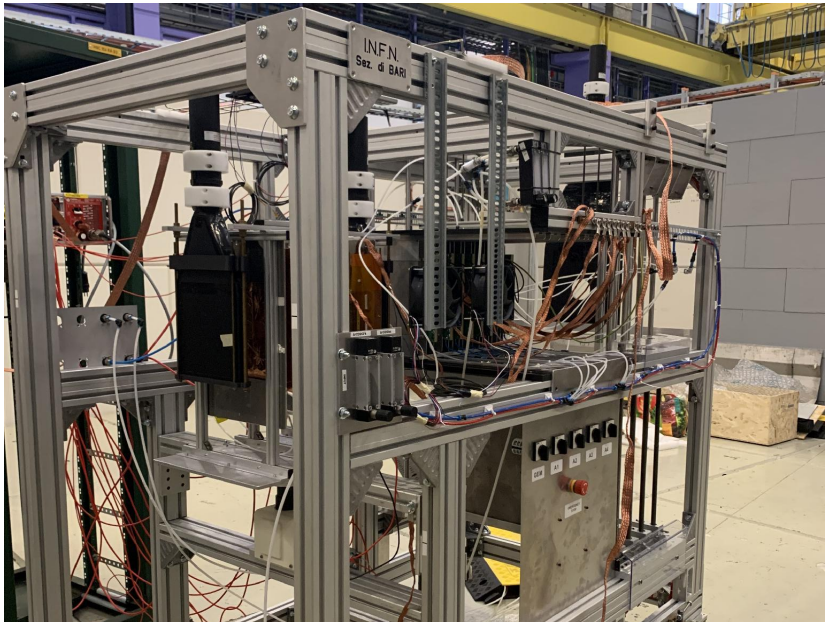
Well within Particle Flow requirements

***Further improvements** from:*

- *future optimization of the **sampling layout***
- *future optimization of the **semi-digital thresholds***

MPGD-HCAL prototype

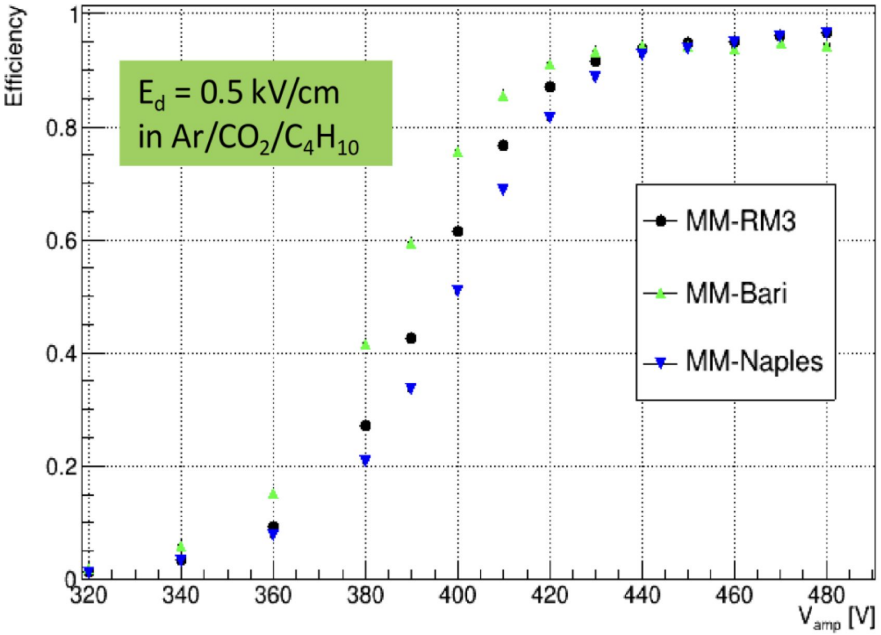


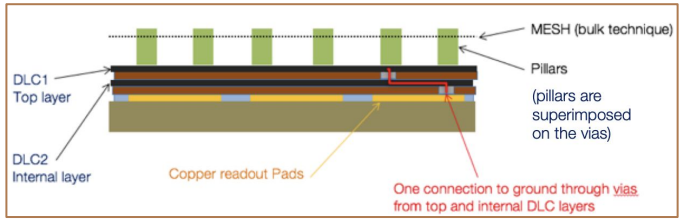


- **Active layers** made of **Micromegas** or **µRWell**
- **Pad size** of ~ **1x1cm²** → **~11300 channels**
- Electronics:
  - **APVs-based** for the **first tests** →used for the small prototype with 8 20x20 cm² active layers
  - Slowly **moving** to **VMM3a electronics**

MPGD-HCAL prototype - active layers

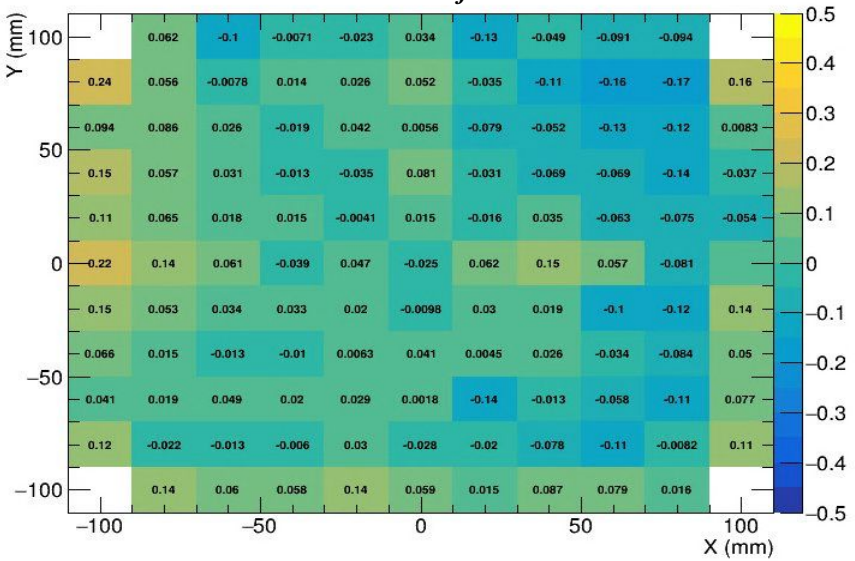
Micromegas - Ar:CO_2:iC_4H_{10} (93:5:2)





- **Efficiency up to ~ 95%**
- **Response uniformity of ~ 10%**

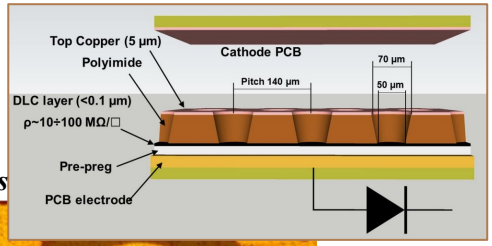
2-D MPV variation for MM-Bari



MPGD-HCAL prototype - active layers

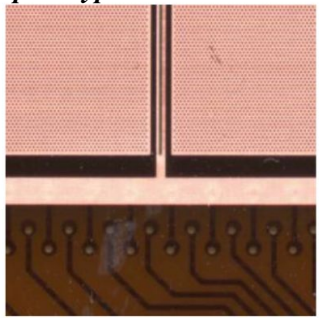
µRWell - Ar:CO_2:CF_4 (45:15:40)

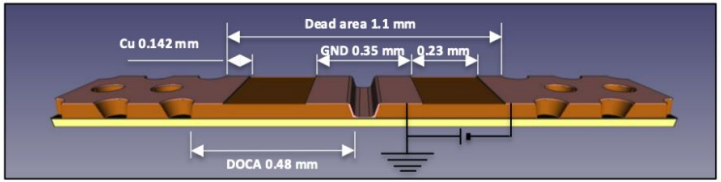
Tested 2 different configurations of grounding schema

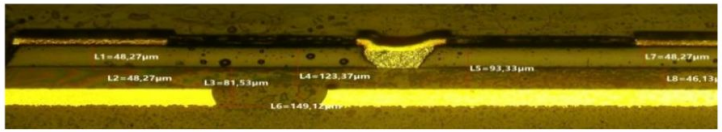


2022 *Adopted for 20x20 cm² prototypes*

PEP-Groove:
DLC grounding through conductive groove to ground line
Pad R/O = 9×9mm²
Grounding:
- Groove pitch = 9mm
- width = 1.1mm
→ 84% geometric acceptance

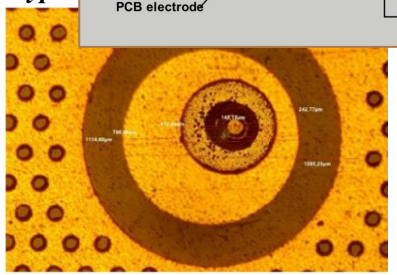




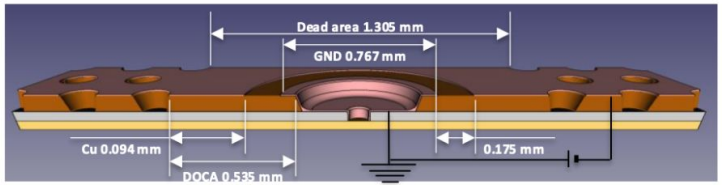


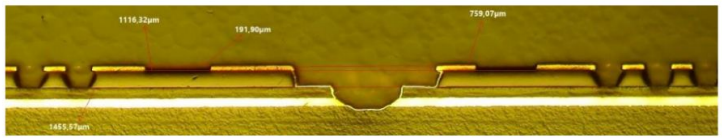
2023 *Adopted for 50x50 cm² prototypes*

PEP-DOT:
DLC grounding through conductive dots connecting the DLC with pad r/outs
Pad R/O = 9×9mm²
Grounding:
- Dot pitch = 9mm
- dot rim = 1.3mm
→ 97% geometric acceptance



DOT → plated blind vias

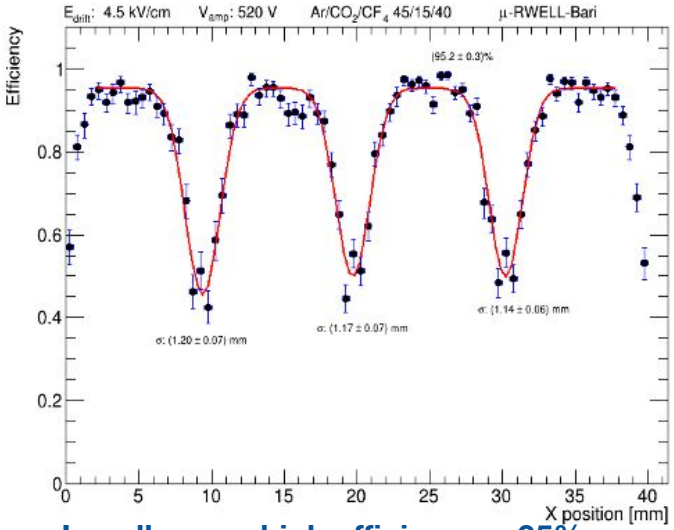




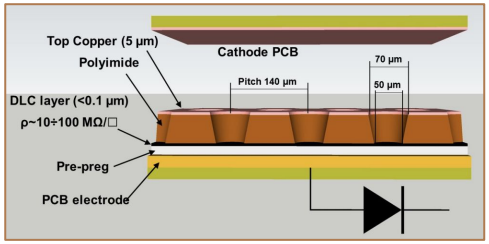
https://indico.cern.ch/event/1413681/contributions/6013367/attachments/2881828/5049134/The%20micro-RWELL%20for%20high-rate.pdf

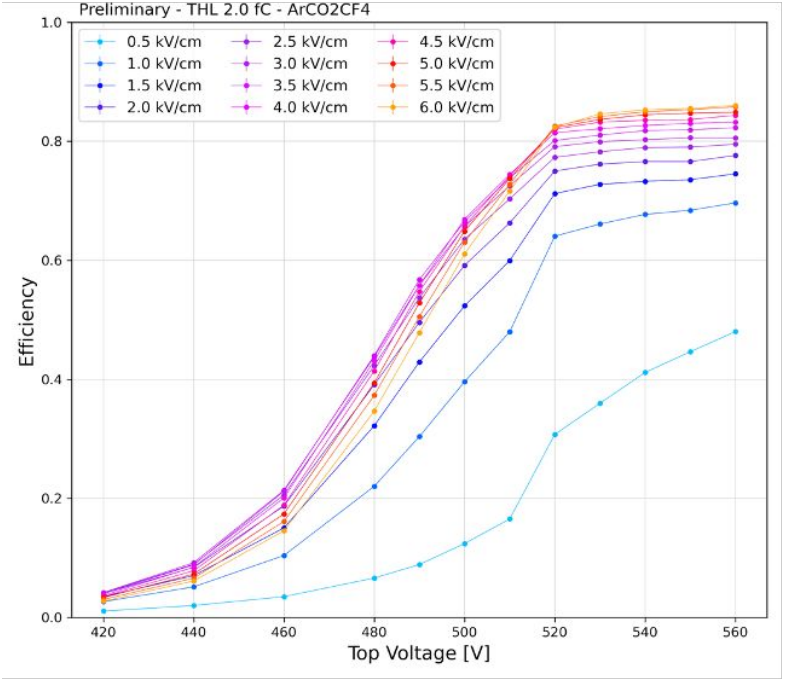
MPGD-HCAL prototype - active layers

μRWell - Ar:CO_2:CF_4 (45:15:40)



PEP dot grounding schema

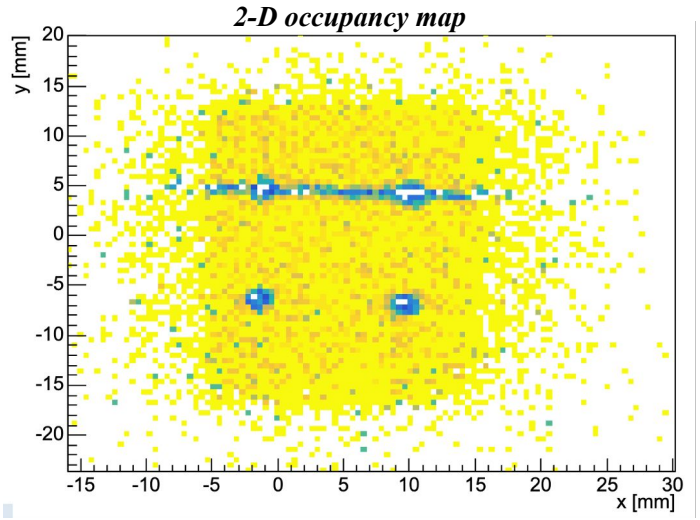




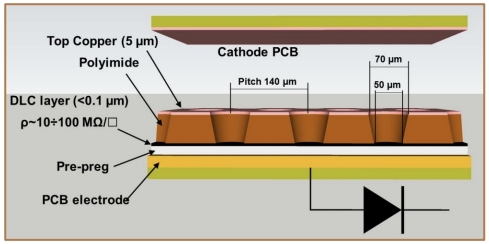
- **Locally very high efficiency ~ 95%**
- Ground lines introduce regions of ~ 1 mm with ~50% efficiency drop
- **Inefficiency** regions can get partially **recovered increasing drift field**
- **15% of response uniformity**

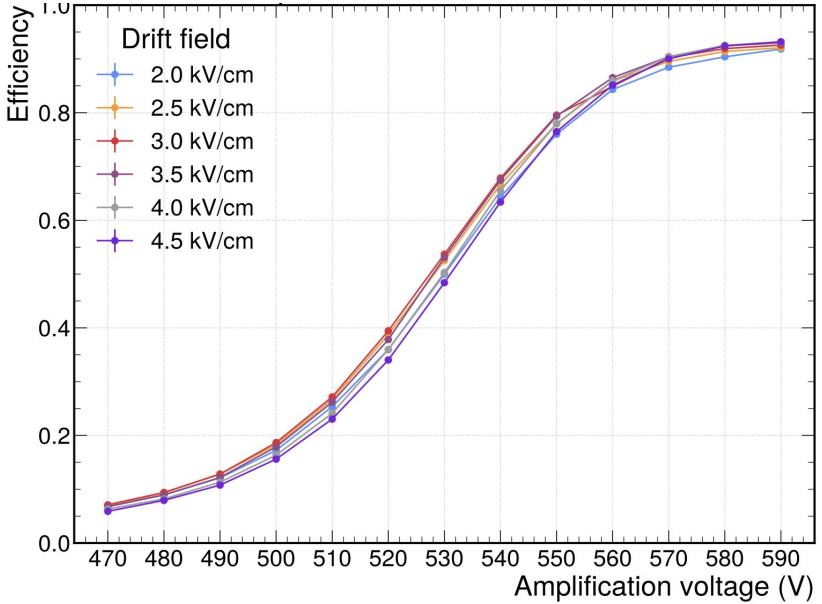
MPGD-HCAL prototype - active layers

μRWell - Ar:CO_2:CF_4 (45:15:40)



PEP dot grounding schema

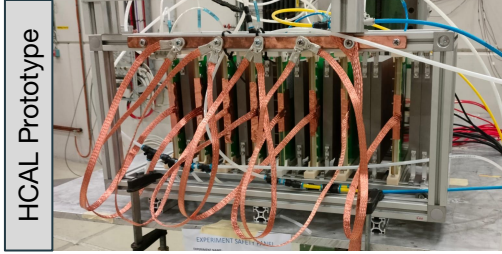


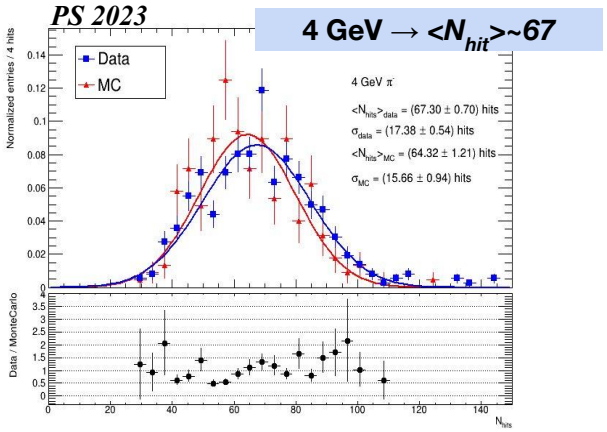


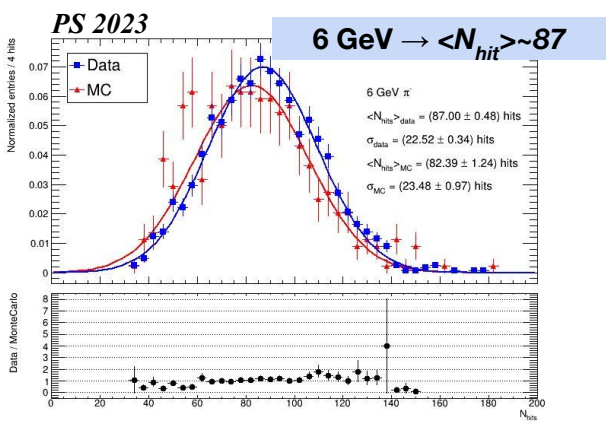
- **Efficiency ~ 95%:**
  - Inefficient regions close to PEP dot and separation lines between 2 HV sectors
- **No dependency** from the applied **drift field**

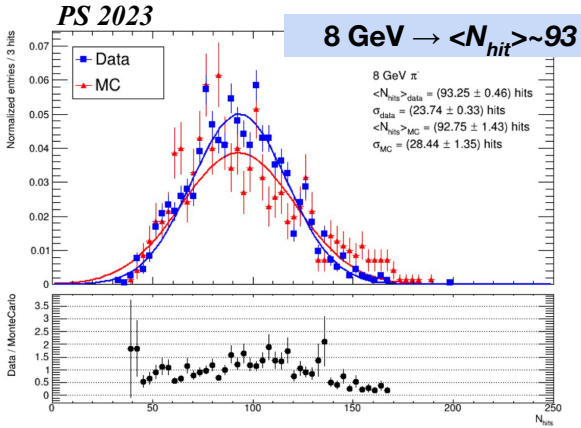
MPGD-HCAL prototype

First results with a small **8 20x20 cm^2 layers prototype** read by **APVs** electronics









- **Increase** of the **number of hits** as a function of impinging **pion energy**
- Nice **data - MC agreement**

MPGD-HCAL prototype

PS test beam - Oct 25

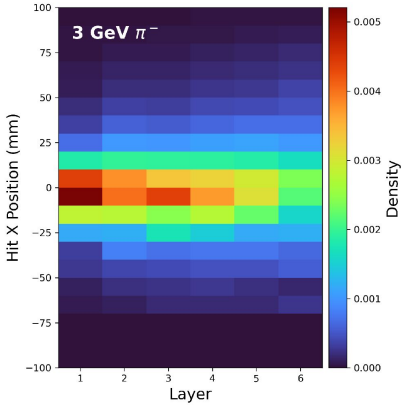
Large prototype equipped with **VMM3a electronics** for the first **6 layers**

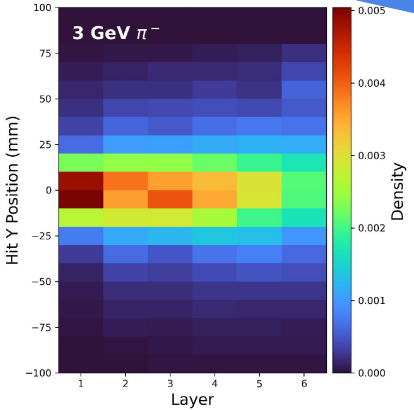
Energy Scans

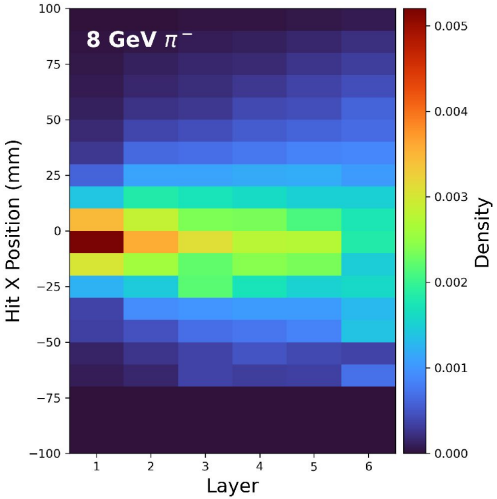
From 1 to 11 GeV with:

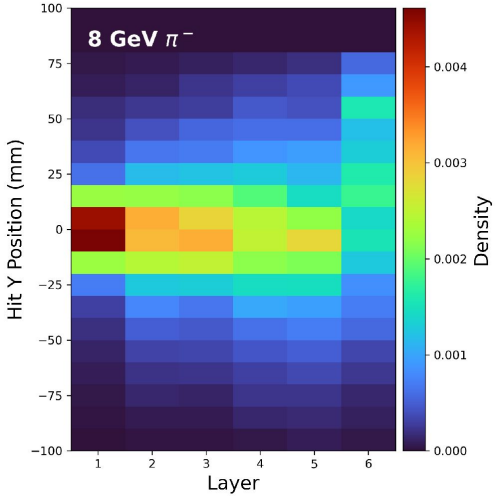
- negative (π^-) beams
- positive (p, π^+, K^+)

+ PS Cherenkov detector for PID

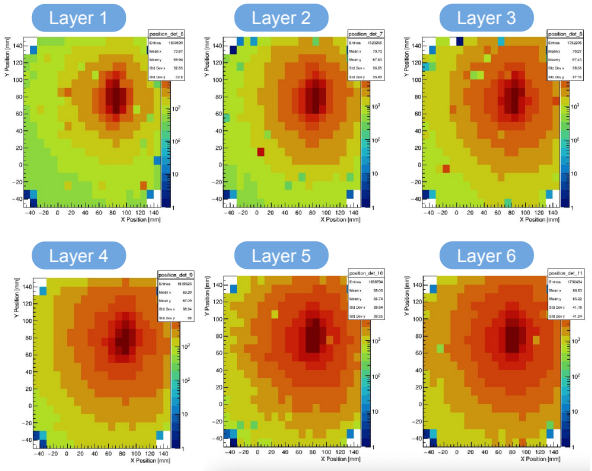








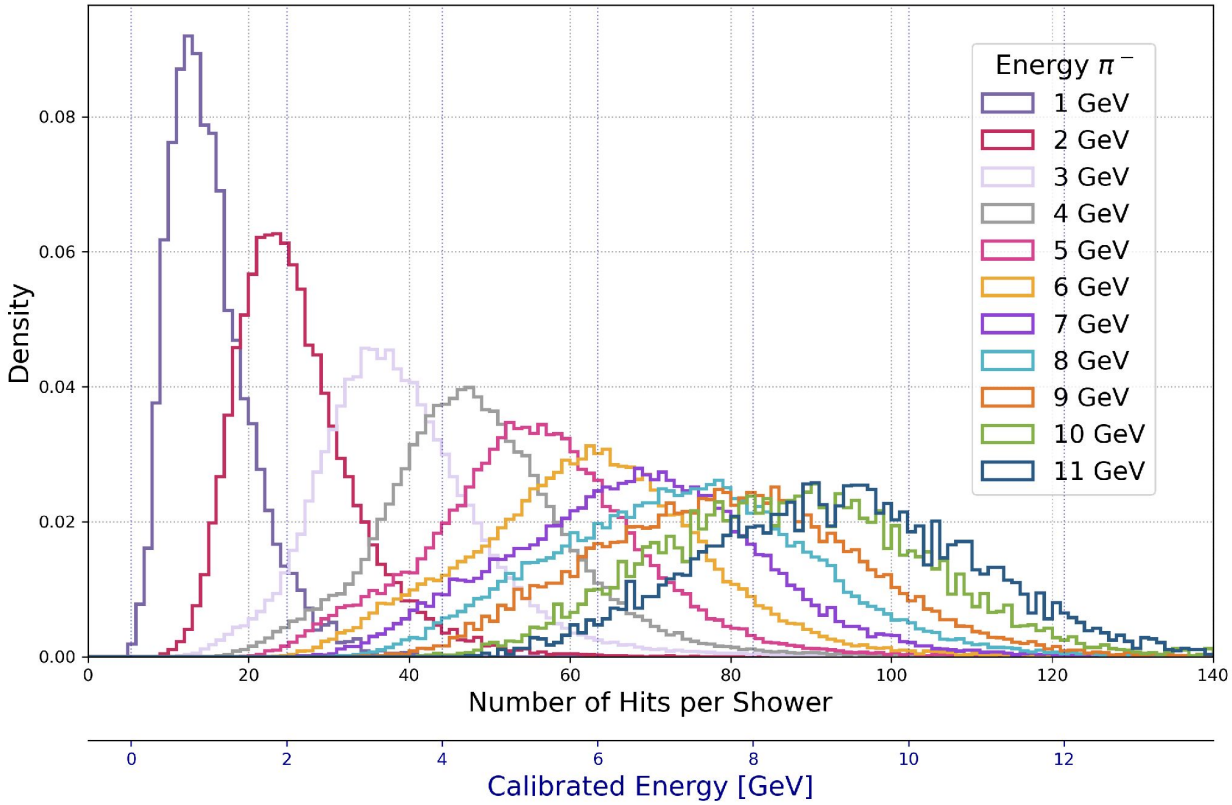
11 GeV π^- shower



MPGD-HCAL prototype

PS test beam - Oct 25

Large prototype equipped with **VMM3a electronics** for the first **6 layers**

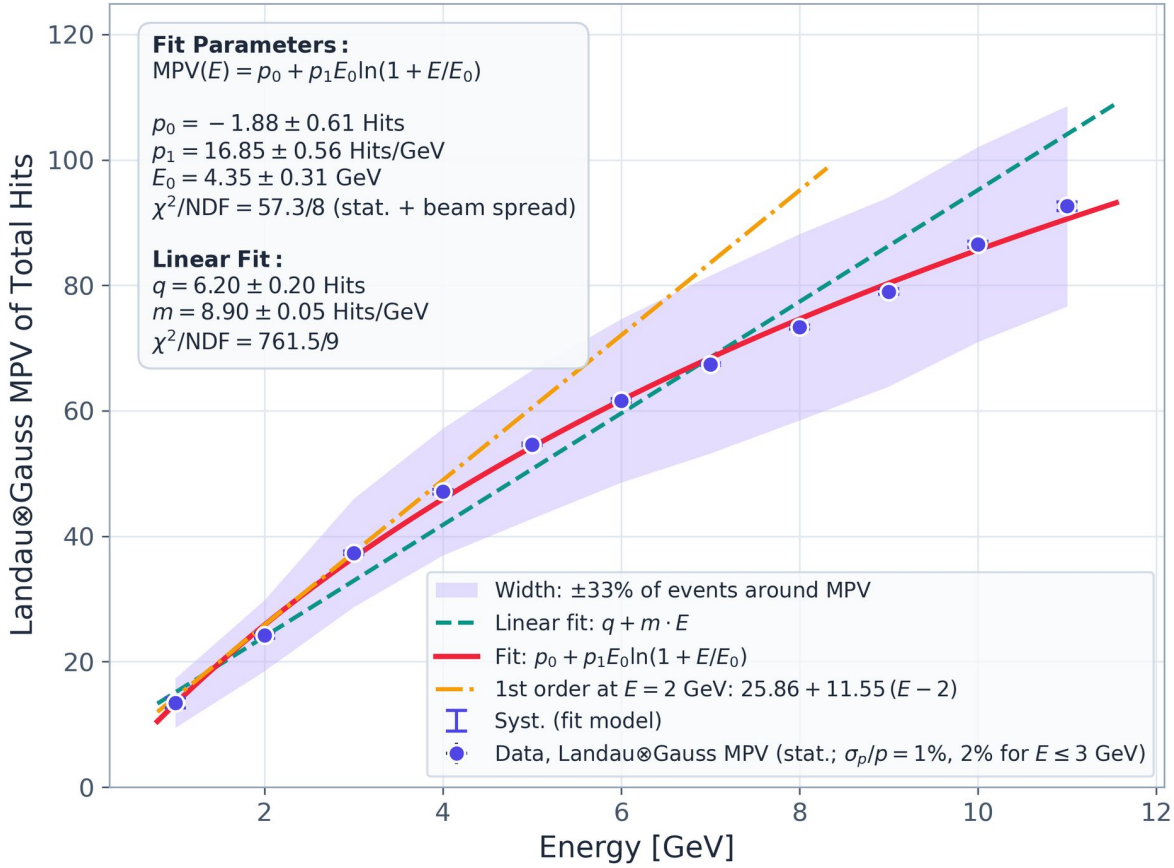


- Considered only shower starting before the 4rth layer to mitigate longitudinal leakage
- Energy calibration based on the total number of hits (Digital ReadOut)

MPGD-HCAL prototype

PS test beam - Oct 25

Large prototype equipped with **VMM3a electronics** for the first **6 layers**



- Total hits MPV value follow a logarithmic behaviour
- Observed the start of the saturation for energy above 5 GeV
- First order Taylor expansion shows the linear behaviour up to 4 GeV

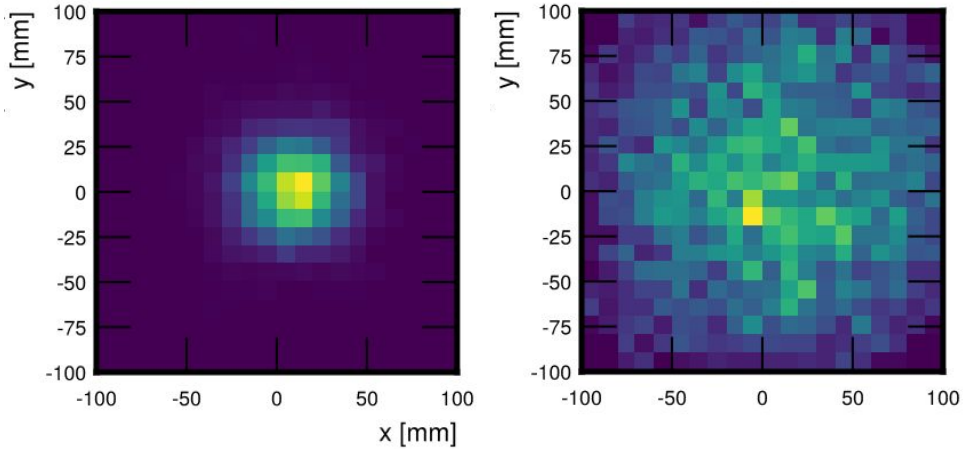
MPGD-HCAL prototype

Joint test beam with **Crilin** (PbF2 semi-homogeneous ECAL) in **July 2026**

- Synchronized ECAL + HCAL data using trigger counters

Goal: measuring **HCAL shower development combining ECAL information**

1 GeV π^- shower profile in the first HCAL layer



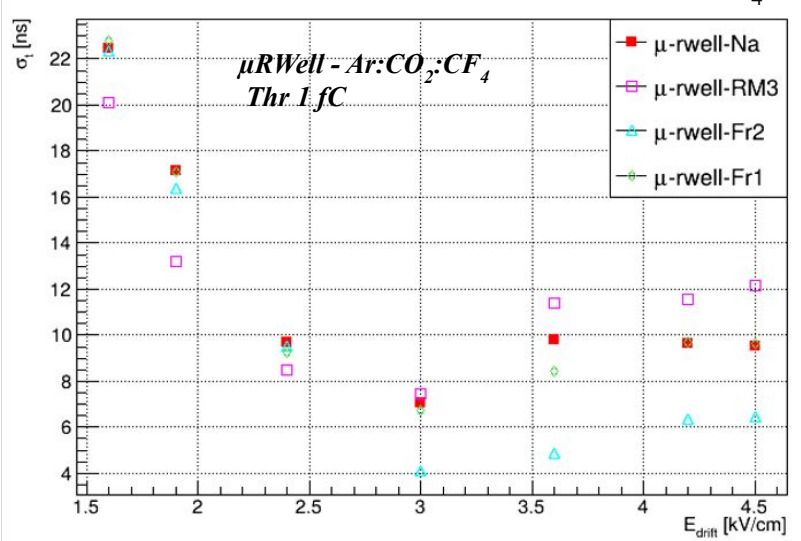
No ECAL **ECAL installed**

PS test beam - July 26



MPGD-HCAL next steps

- New prototype still not fully equipped with VMM3a electronics:
  - 11300 channels → dedicated commissioning is needed
  - VMM3a electronics is not the final choice but allows a full layers characterization and an offline ad-hoc optimization for SDO
- Timing information:
  - MPGD can reach time resolution of O(ns) but with CF_4 (high GWP)

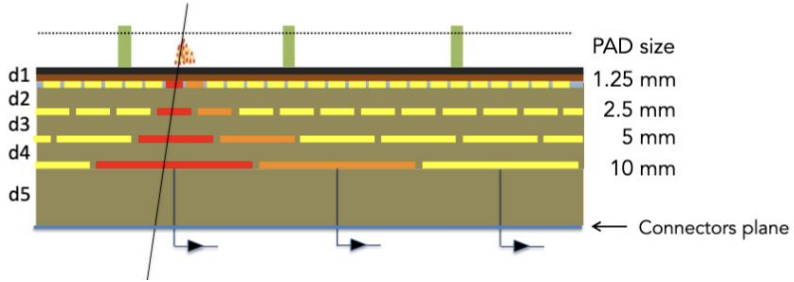


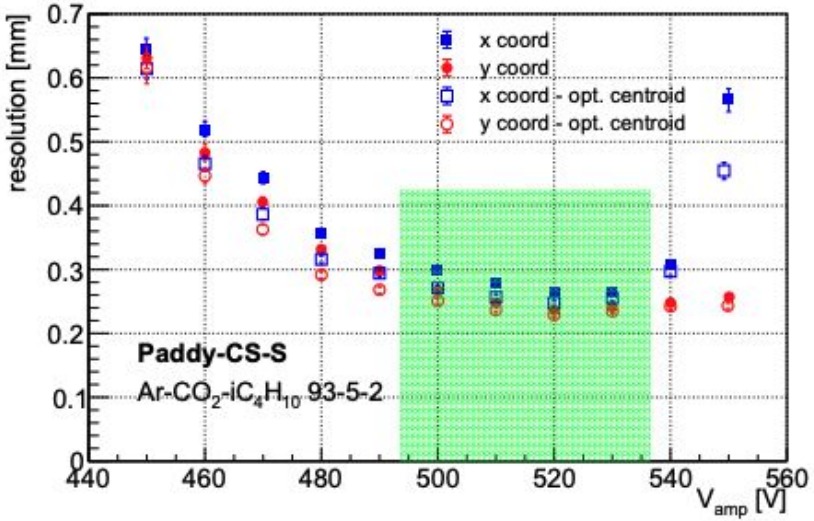
  - Further investigations on different drift gap and alternative gas mixtures, without CF_4, to push on timing info
  - Evaluate the impact of the best timing information achieved on the shower energy reconstruction



MPGD-HCAL next steps

- Evaluate the impact of a capacitive sharing layer for tracking purpose:





  - Capacitive sharing allows spatial resolution of ~ 300 μm keeping the same numbers of channels for a 1x1 cm^2 pad layout configuration [link]
  - Balance between performance on track and energy reconstruction

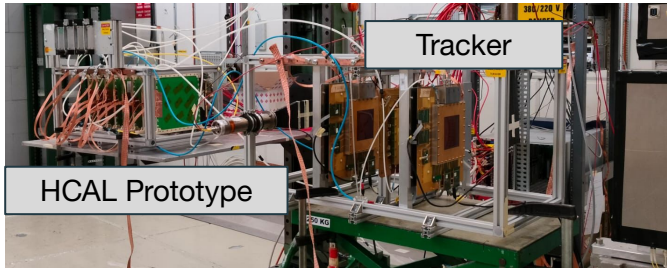
- Design and production of large area detector (~ 100x50 cm^2) focusing on knowledge transfer to industry:
  - Ongoing technology transfer to ELTOS S.p.A. for Micromegas production, with promising results demonstrated on 10 × 10 cm^2 prototypes [link]
  - Industrial production of large-area active layers is essential for large-scale experiments, where scalability and cost-effectiveness are major challenges.

- Investigate MPGD-HCAL performance at FCC-ee

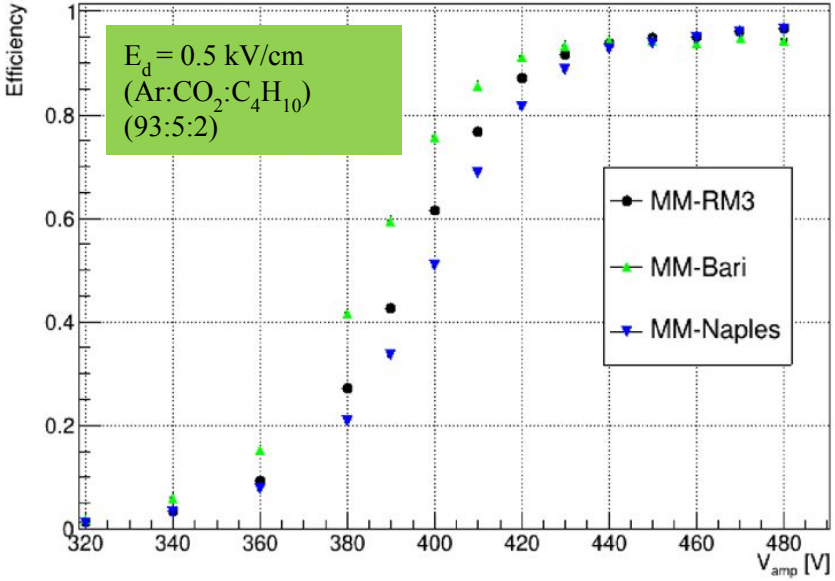
Backup

MPGD-HCAL Test Beam

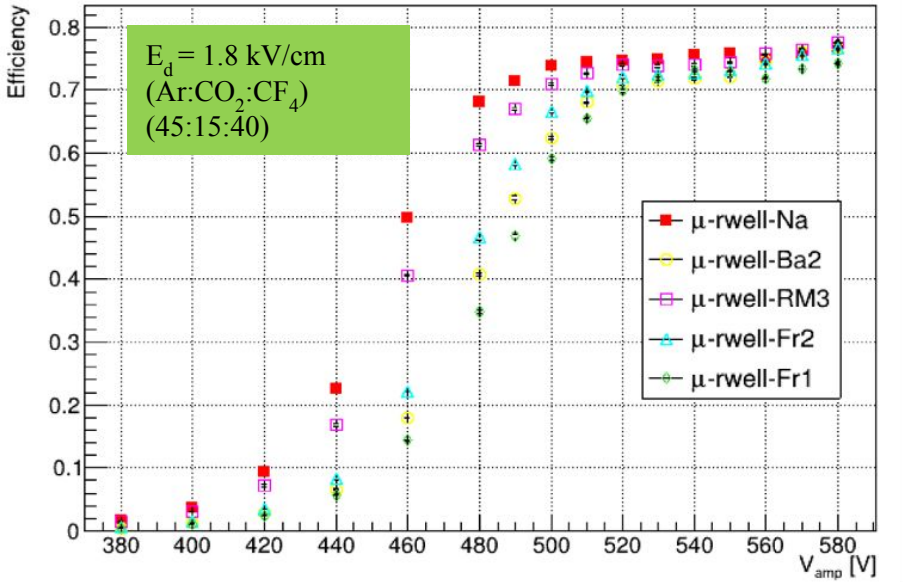
Active layer characterization



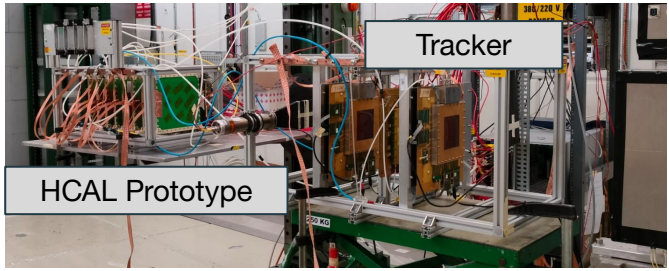
Micromegas efficiency ~ 95%



µRWELL efficiency ~ 75%

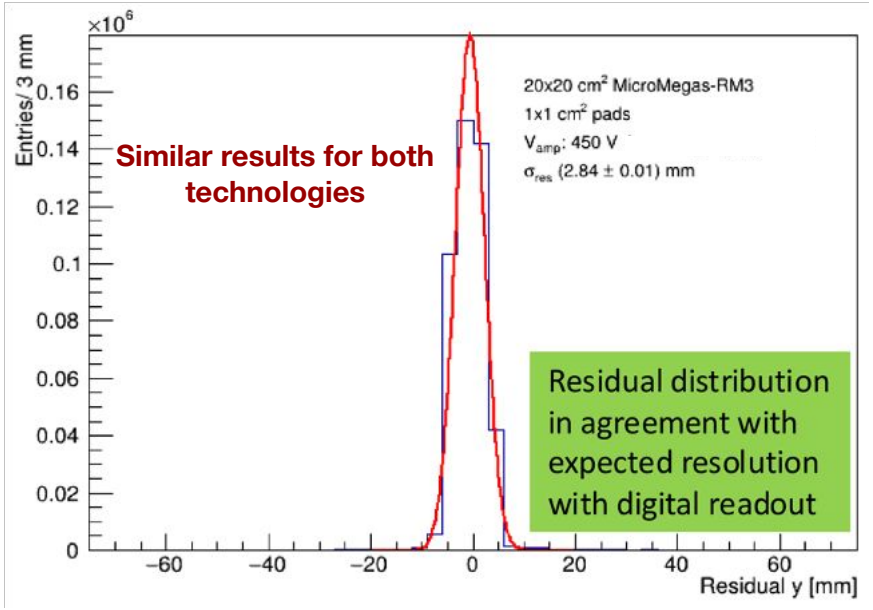


MPGD-HCAL Test Beam

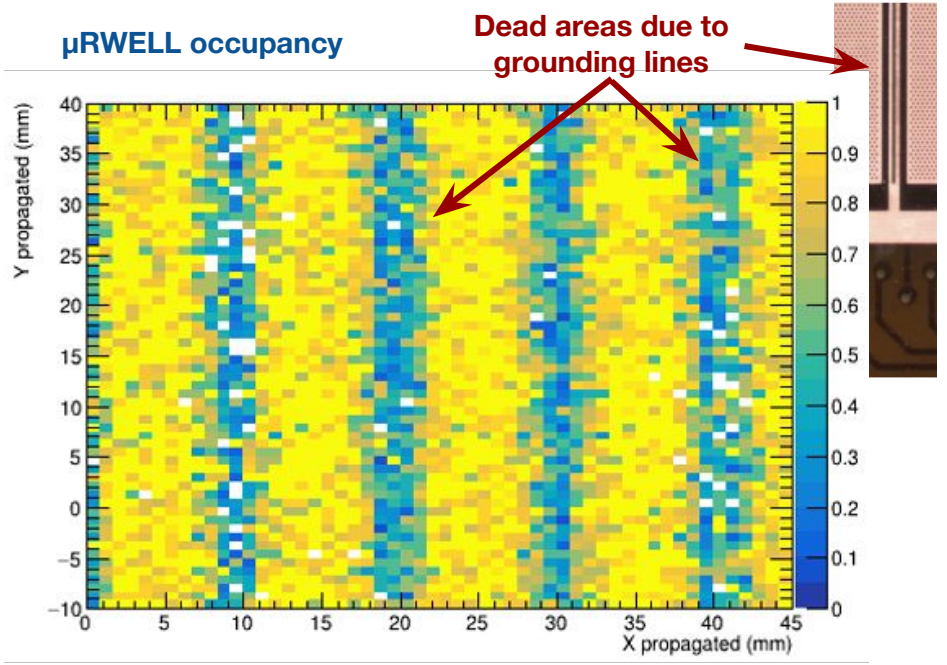


Active layer characterization

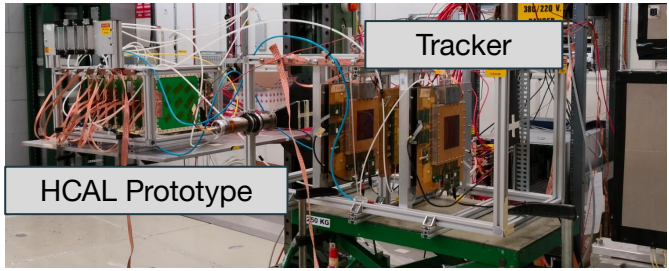
Residual distribution



µRWELL occupancy



MPGD-HCAL Test Beam

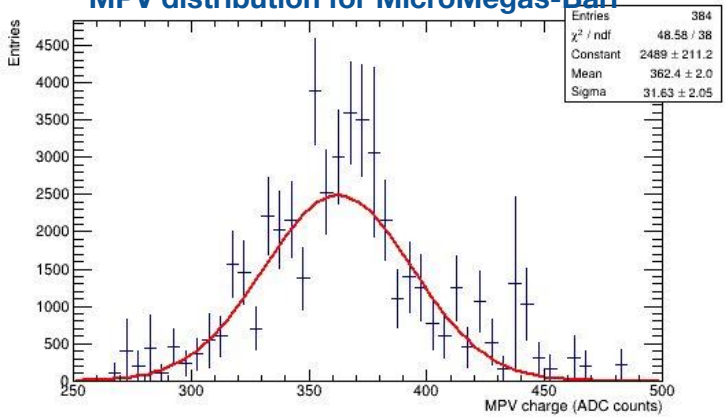


Active layer characterization

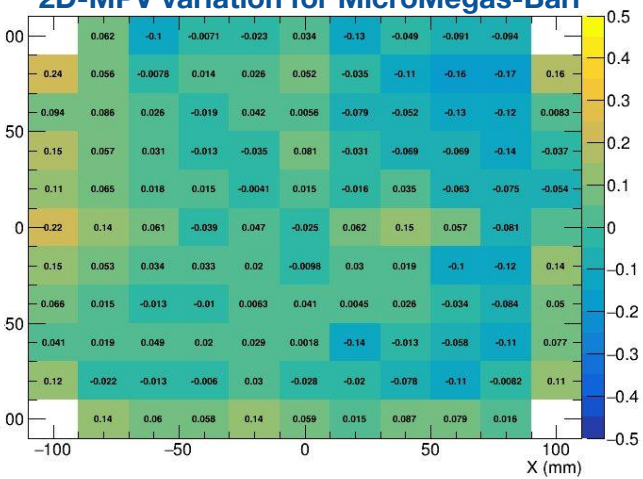
Response uniformity measured using clusters matching muon tracks

- Good uniformity for **MicroMegas** (~10%)
- Regions of non-uniformity observed on some **μ-RWELLs** → under investigation in lab

MPV distribution for MicroMegas-Bari



2D-MPV variation for MicroMegas-Bari

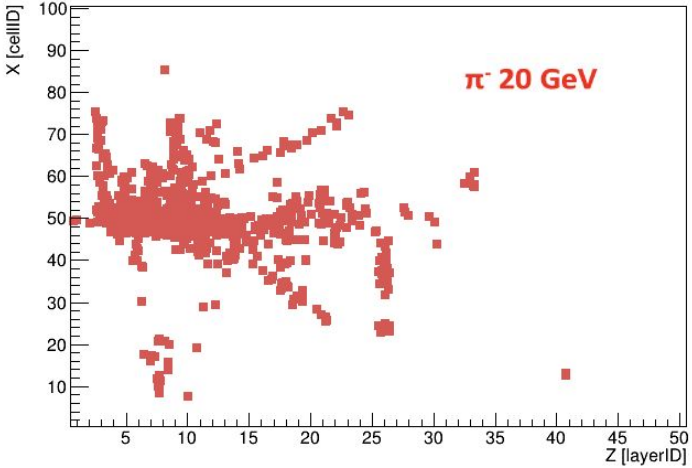


Detector	Uniformity (%)
MM-RM3	$(12.3 \pm 0.8)\%$
MM-Na	$(11.6 \pm 0.8)\%$
MM-Ba	$(8.0 \pm 0.5)\%$
RPWELL	$(22.6 \pm 4.7)\%$
μrw-Na	(11.3 ± 1.0) %
μrw-Fr2	$(16.2 \pm 1.7)\%$
μrw-Fr1	$(16.3 \pm 1.1)\%$

Readout: Digital and Semi-digital HCAL

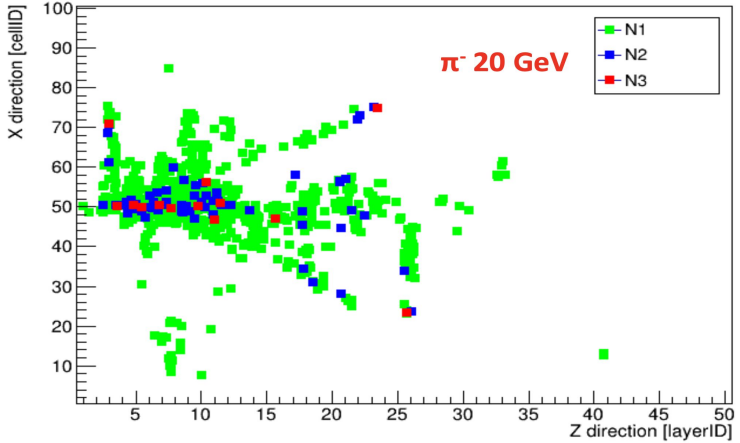
Digital Readout (Digital RO)

- **Digitization:** 1 hit=1cell with energy deposit higher than the applied threshold
- **Calorimeter response function:** $\langle N_{hit} \rangle = f(E_\pi)$
- **Reconstructed energy:** $E_\pi = f^{-1}(\langle N_{hit} \rangle)$



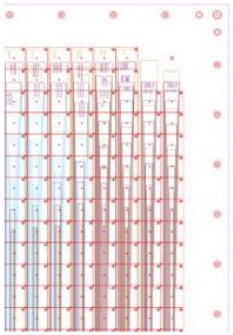
Semi-digital Readout (SDRO)

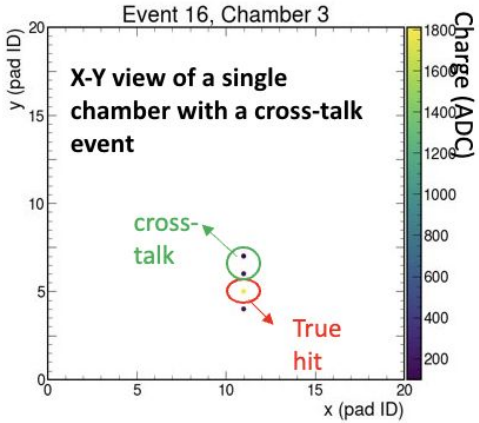
- **Digitization:** defined multiple thresholds
- **Reconstructed energy:** $E_\pi = \alpha N_1 + \beta N_2 + \gamma N_3$ with:
  - $N_{i=1,2,3}$ number of hits above *i*-threshold (0.2-4-12 keV)
  - α, β, γ parameters obtained by χ^2 minimization procedure



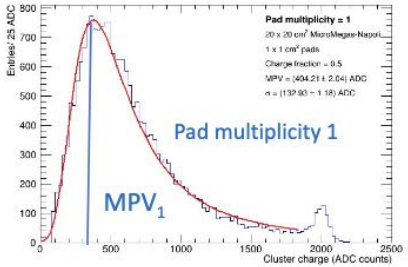
Cluster reconstruction

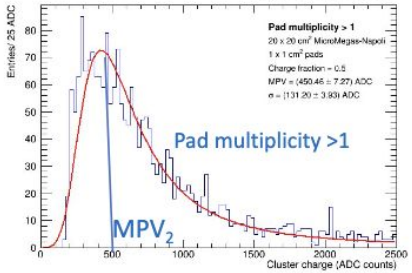
Preliminary

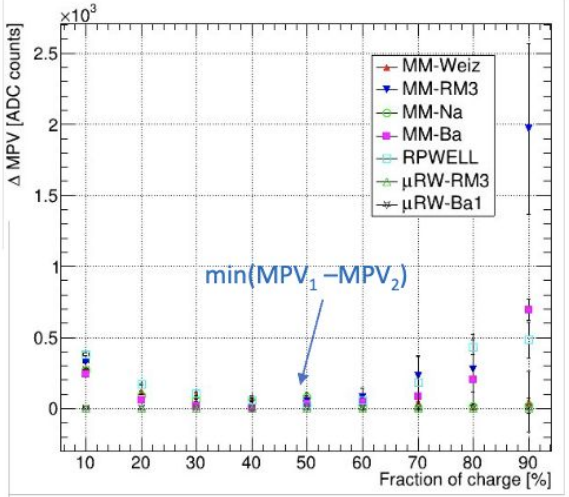




High probability of **cross-talk** effect observed among adjacent pads due to routing of the vias connecting pads to the connectors



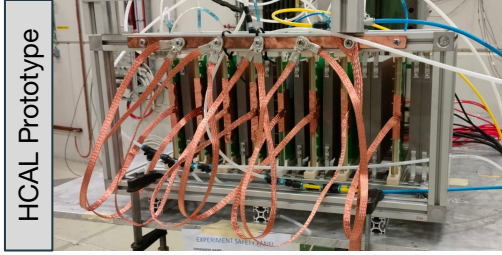




Developed ad-hoc **clustering algorithm** based on charge sharing criterium

- Selected pad with **highest charge** Q_{max}
- Add a second pad if Q = 50% Q_{max}

MPGD-HCAL Test Beam



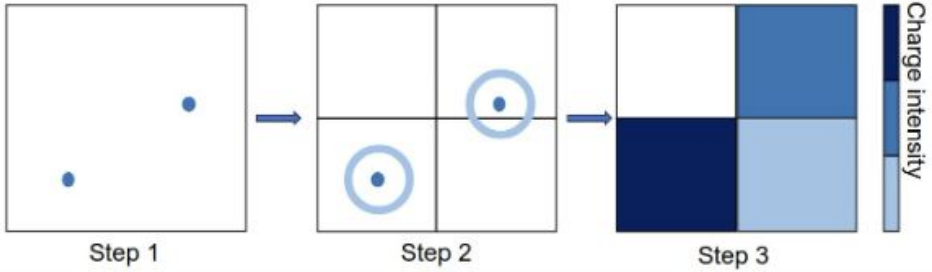
Prototype simulation

- Small detector geometry implemented
  - 8 layers of alternating of 2 cm stain-less steel absorbers and MPGD
    - First 2 layers with 4 cm absorbers to increase probability of shower development in the first layers
  - 20x20 cm^2 active surface
  - 1x1 cm^2 pad granularity
- Pion gun of energy range available at PS (4 – 8 GeV)

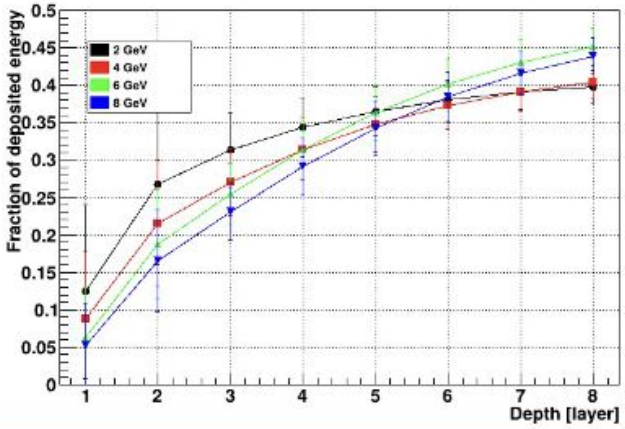
Steel	2 - 4 cm
Air	1 cm
FR4	3 mm
Argon	6 mm
FR4	3 mm
Air	1 cm

- **Digitization algorithm** implemented to account for charge-sharing among adjacent pads and detector efficiency

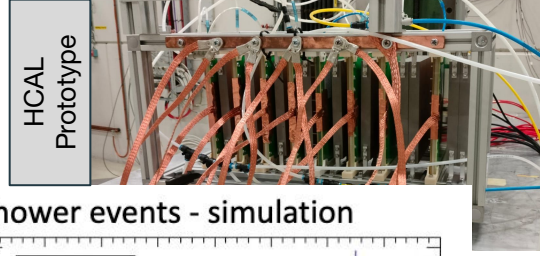
Digitization algorithm



Shower containment



MPGD-HCAL Test Beam

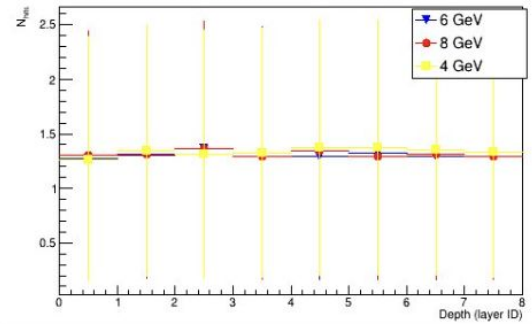


Prototype simulation

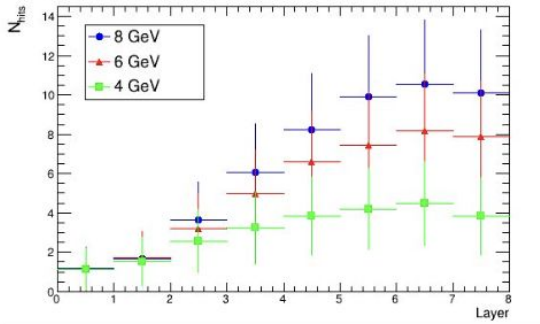
Event **selection criteria** supported by **simulation** using MC truth

- MIP-like events:
  - single hit in each layer
- Shower events:
  - more than 4 hits per layer starting from layer 3

MIP-like events - simulation

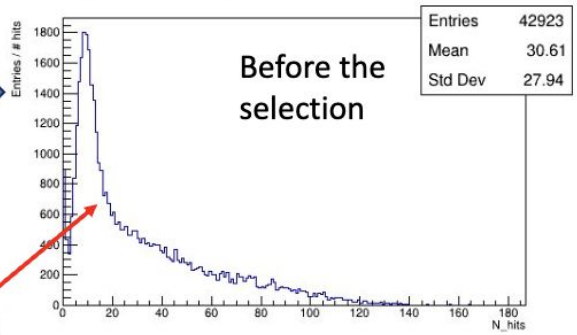


Shower events - simulation



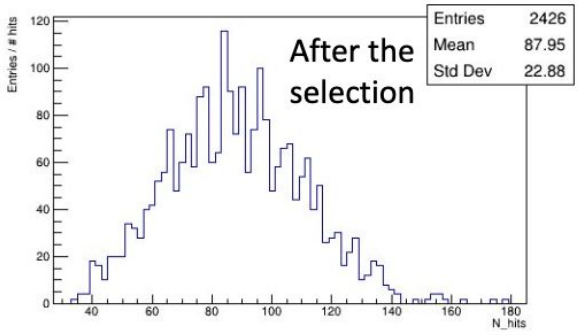
Distribution of the **number of hits** in all active layer from the **experimental data**

Number of hits for all events



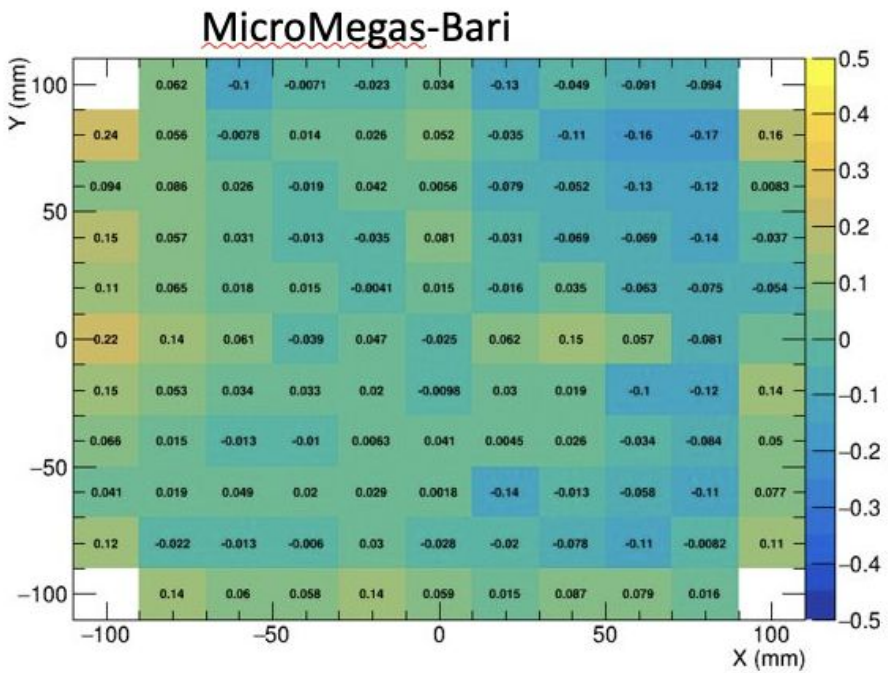
Peak at ~ 10 hits
-> MIP-like events

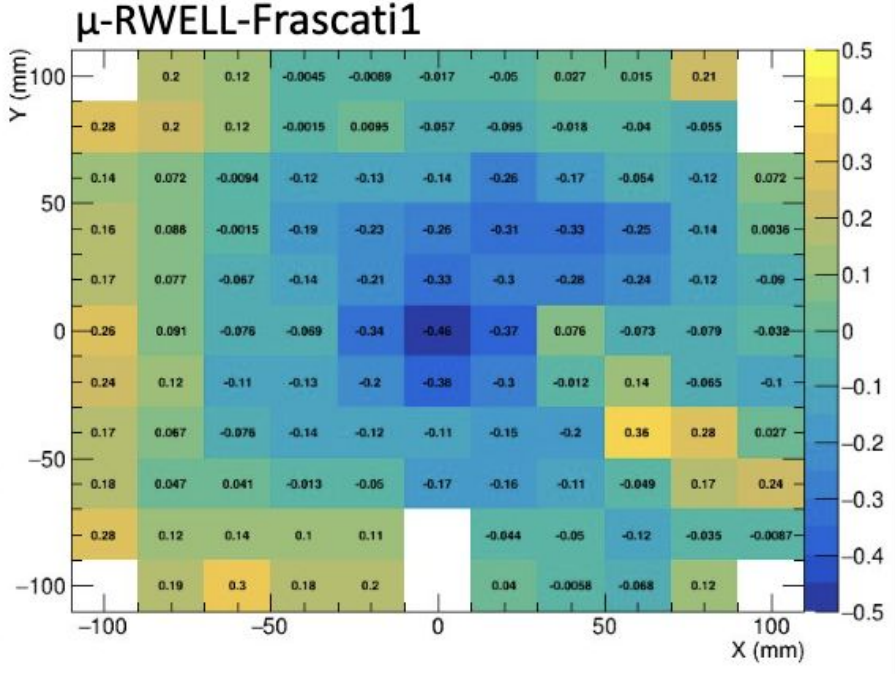
Number of hits for showers event



Response uniformity

Preliminary



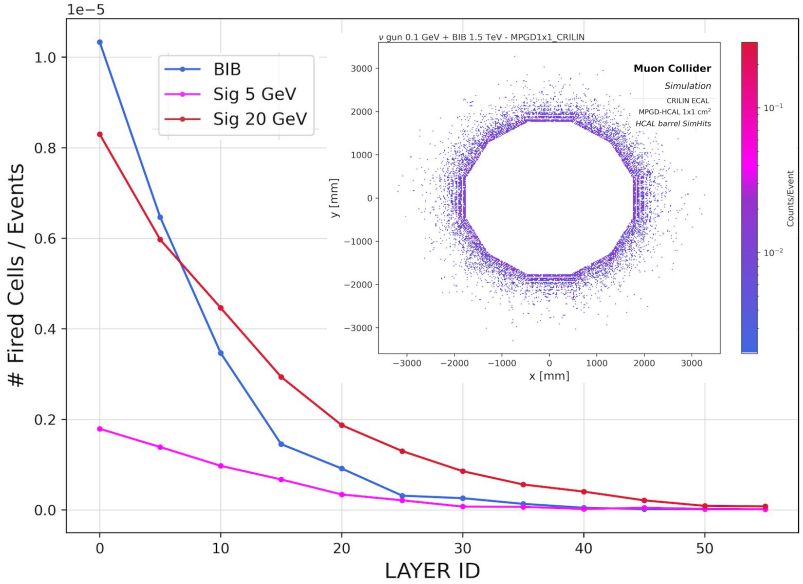


MPGD-HCAL BIB studies

Simulation: 60 layers of Iron (19mm) + Ar (3mm); **3 TeV layout; HCAL within the solenoid**

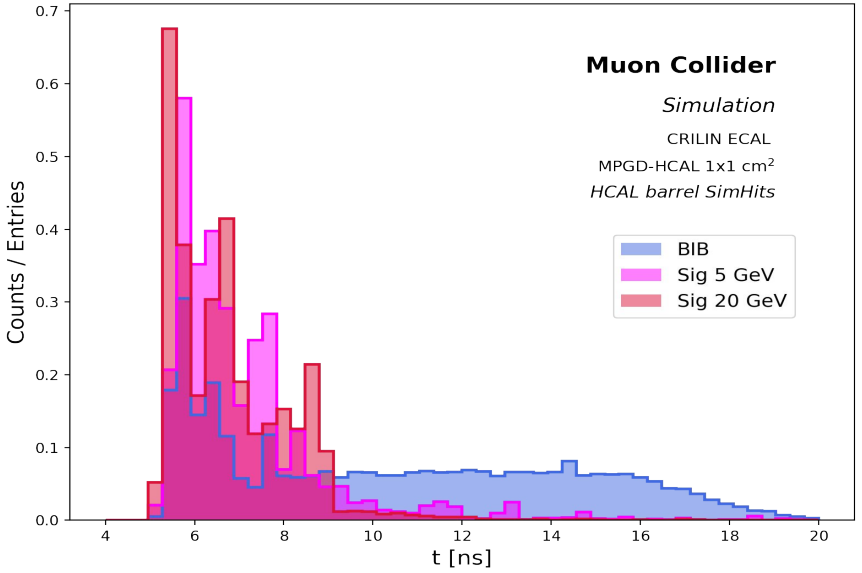
Hit Occupancy:

- **BIB** containment within the **first 20 layers** of HCAL
- Probability of a cell to be fired in the first layer :
  - **BIB** : ~ 1 x 10-5
  - **$\pi^{\pm}$ 5 GeV** : ~ 0.2 x 10-5
  - **$\pi^{\pm}$ 20 GeV** : ~ 0.8 x 10-5
- Challenge for low energy pion reconstruction



Arrival time:

- **BIB** arrival time distribution uniform in the **range 7-20 ns**;
- **signal** arrival time peaks at **~ 6ns**;
- discrimination possible for ***t>9/10 ns*** → **achievable with MPGD detectors**

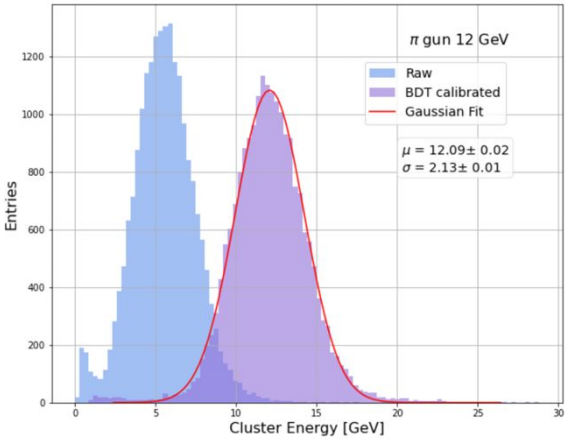


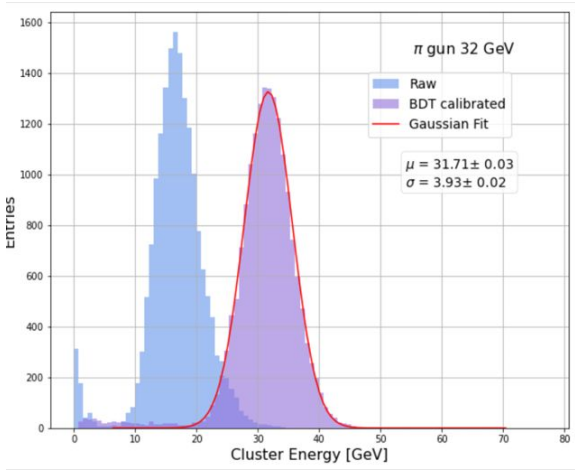
Semi-digital readout with BDT calibration

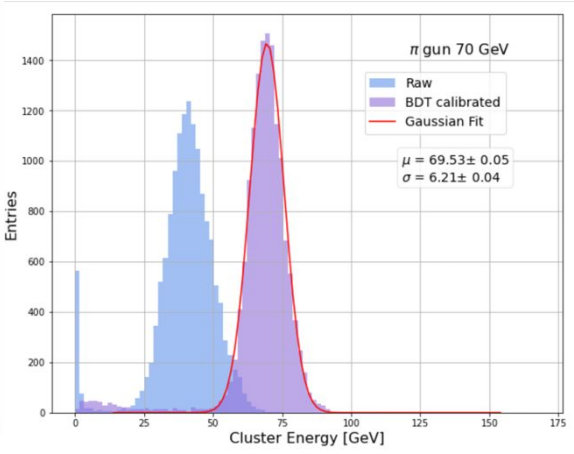
Calibrated energy = BDT output coefficient x Raw cluster energy

BDT implementation details

- **XGBoost** squared-error regression
- **Features dataset from pandora:**
  - Cluster energy and 3D centroid position
  - (Cluster size) / ln (cluster energy +1)
  - Number of hits in ECAL and in HCAL
  - Number of HCAL hits below and above the 2nd threshold of the semi-digital RO
  - Total energy in ECAL and in HCAL
  - Total fraction of hits/energy in ECAL and in HCAL
  - Number of hits for each layer of ECAL and HCAL
  - Energy Fraction for each layer of ECAL and HCAL







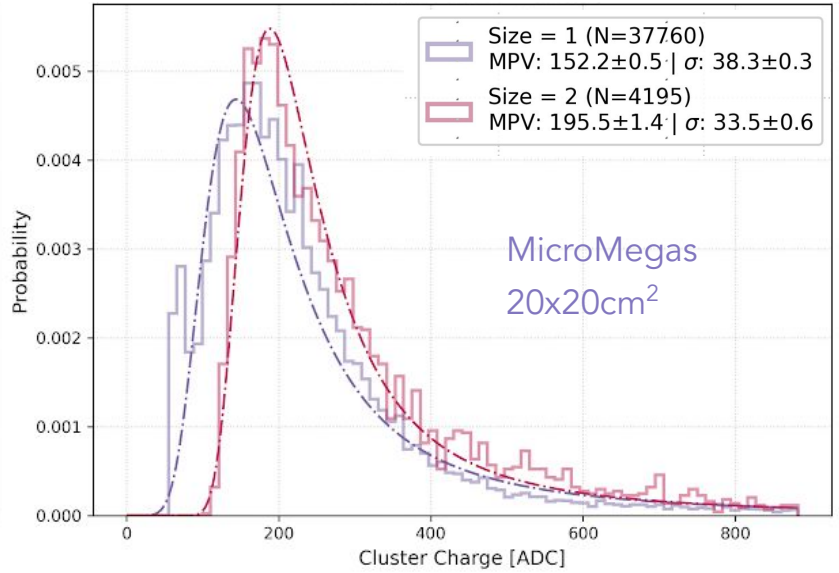
PS Test Beam - October 2025

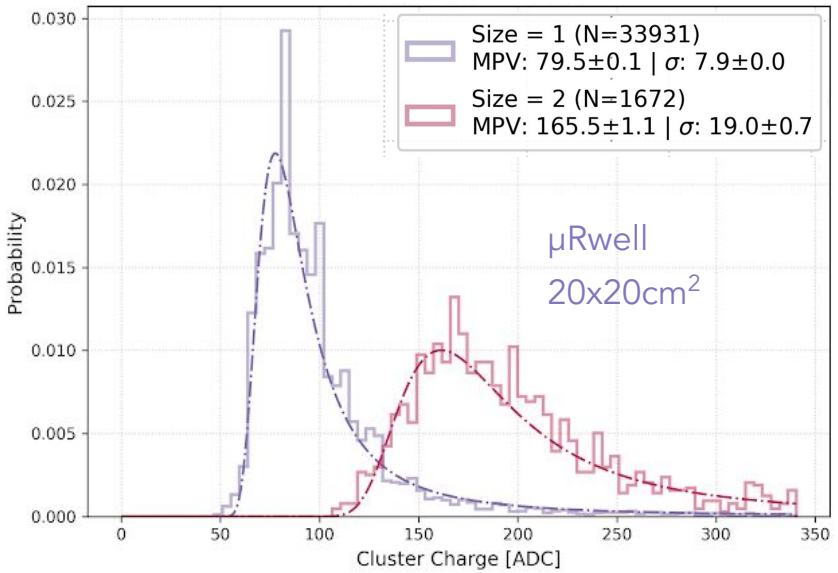
Measurements without absorbers

HV and drift scans

- fix MPGDs working points and evaluate efficiencies
- observe charge spectra of MIP clusters

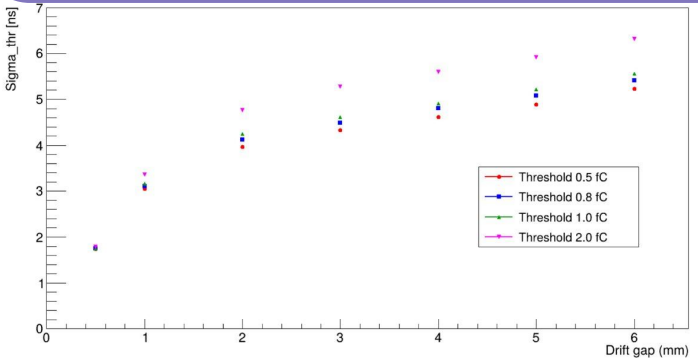
 Charge calibrations needed to equalize the responses of the single active layers for SDRO

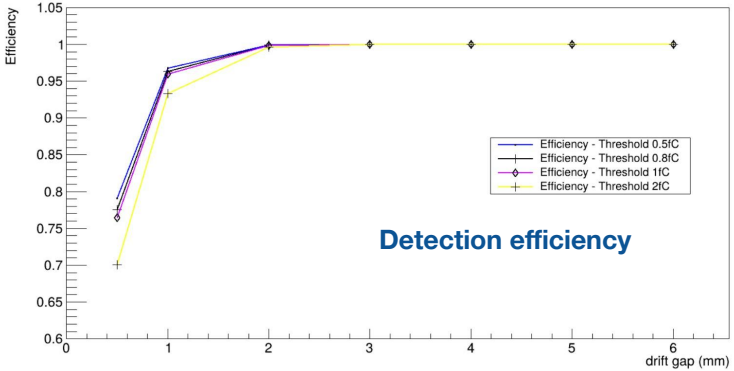




MPGD: μRWELL drift gap optimization

- Improvements in timing resolution help for delayed neutron rejection and consequently improve energy reconstruction
- Garfield simulation to improve timing performance for a μRWELL with a Ar:CO2 (70:30) gas mixture (Bari master student's thesis):
  - Optimizing drift gap looking at "time of arrival"
  - Different fC thresholds considered





- **Drift gap of 1-2mm would allow a reduction of the intrinsic resolution of the detector with minor efficiency loss**
- **The same study must be conducted on Micromegas technology**
- **For 2027:**
  - **production of cathodes with different drift gap dimensions (1-6 mm)**
  - **Evaluate the timing performance using different gas mixture and focusing on the optimization of the HV working point**