MPGD-HCAL for future collider experiments

status and perspectives

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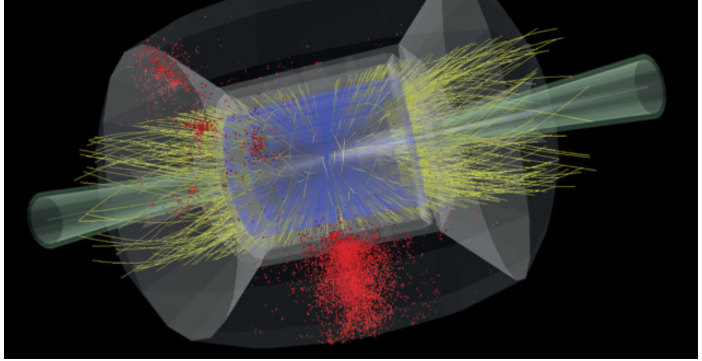
Hadron Calorimetry at Future Colliders

H→bb at a Muon Collider, D. Lucchesi at al.



- **Goals for FCC-ee and Muon Colliders: Higgs coupling and new physics**
- **Benchmark example for (hadron) calorimetry**

✓ Sub-percent precision measurement H→bb

δ(σ×*BR*(H→bb)) ≈ 0.2-0.4 % @FCC-ee and Muon Collider

Requirements for HCAL: 5D calorimetry in Particle Flow

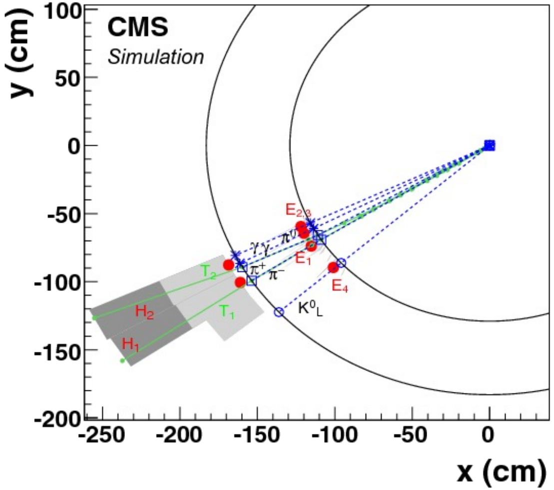
- ***σ*/E ~ O(50%) /√E**

  → jet energy resolution~ 30%/√E

  → σ_m/m comparable with natural width for W/Z
- **High granularity O(1 cm²)**

  track matching and/or reject machine-induced background
- **Time resolution: O(few ns-tenths of ps)**

  reject background and/or improve energy estimation



A.M. Sirunyan *et al* 2017 *JINST* **12** P10003

A MPGD Hadronic Calorimeter

Sampling with micro-pattern gaseous detector (MPGD) as readout layers

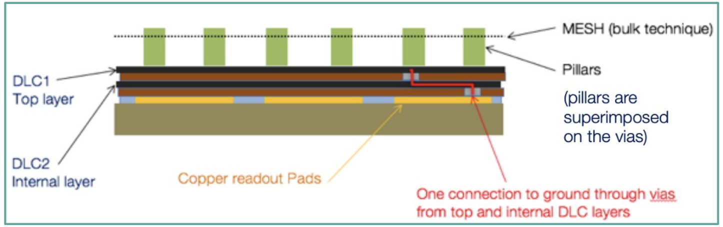
MPGD features:

- radiation hardness up to several **C/cm²**
- rate capability O(**MHz/cm²**)
- high granularity
- time resolution of **few ns**
- **cost-effectiveness** for large area instrumentation

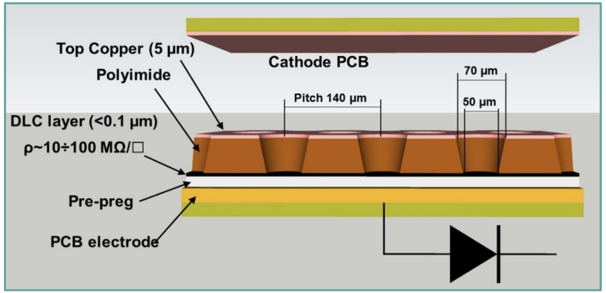
Goals of this project→

- ➢ compare three MPGD technologies for hadronic calorimetry: resistive **MicroMegas, µRWELL** and **RPWELL**
- ➢ investigating **timing**

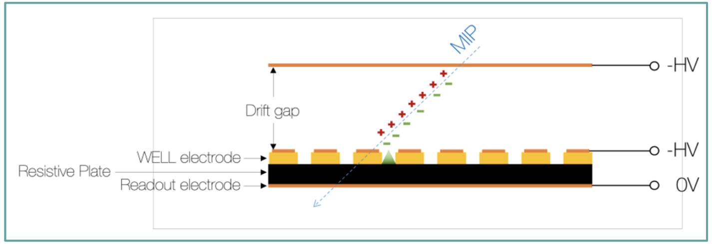
Micromegas (MM)



µRWELL



RPWELL

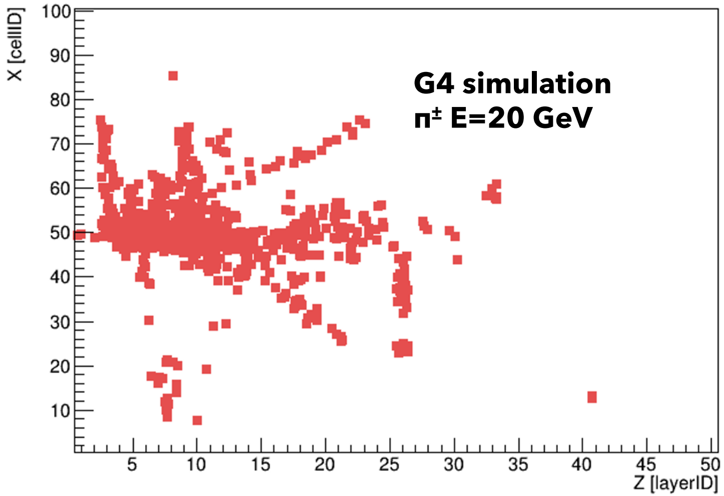


HCAL R&D included in DRD1-WP5 (Calorimetry) and DRD6-WG1 (Sampling Calorimeter)

Readout: Digital and Semi-digital HCAL

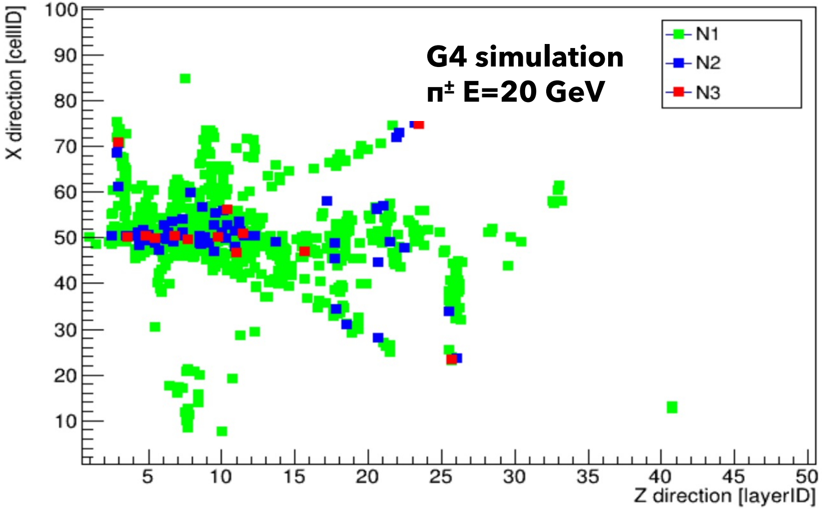
Digital Readout (Digital RO)

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



Semi-digital Readout (SDRO)

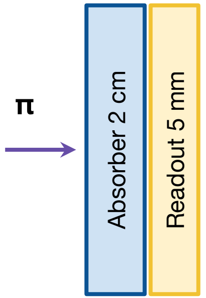
- Digitization: defined multiple thresholds
- Reconstructed energy: $E_\pi= \alpha N_1+\beta N_2+\gamma N_3$:
  - $N_{i=1,2,3}$ number of hits above *i*-threshold (0.2-4-12 keV)
  - α,β,γ parameters obtained by χ^2 minimization procedure

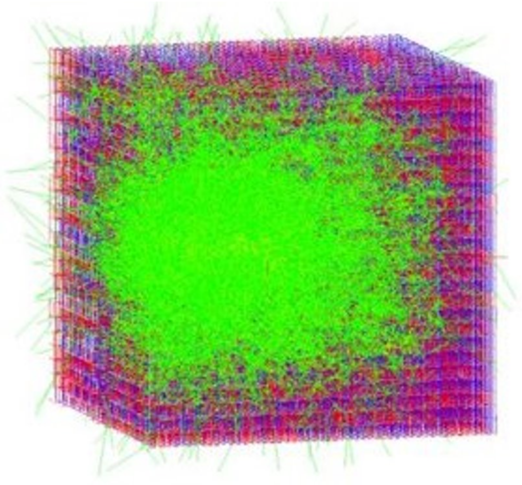


Simulation studies

Standalone Simulation results

Geant4 simulation



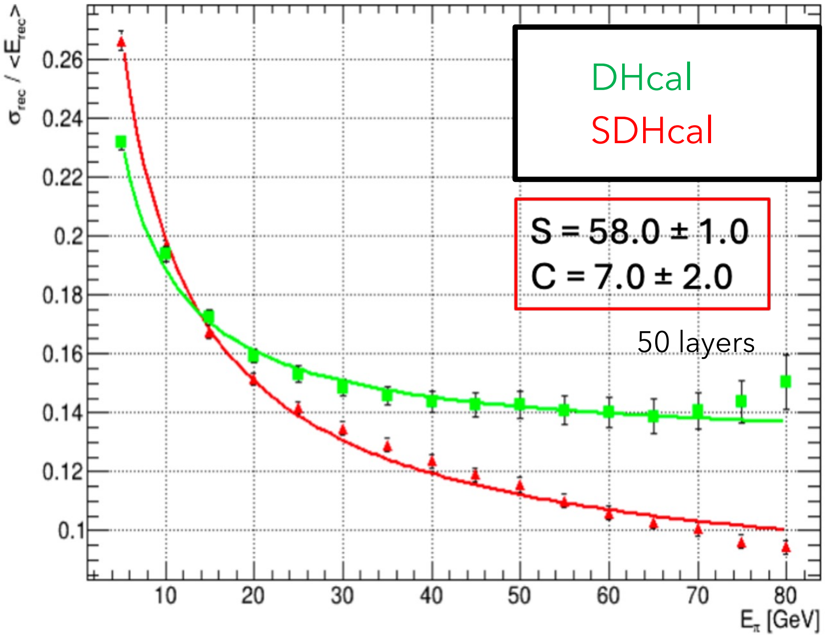


- Geometry: 2 cm iron, 5 mm gas (Ar/CO_2)
- Readout granularity →1×1 cm^2 cell size
- Pion guns of different energies

Result: 95% shower containment

- **~10 λ_I** longitudinal
- **~2 λ_I** transversal

https://doi.org/10.1016/j.nima.2022.167731



SDHCAL: better resolution for E_π > 40 GeV

DHCAL: **saturation effect** for E_π > 40 GeV

At E_π= 80 GeV, the resolution

- DHcal ~ 14%
- SDHcal ~ 8%

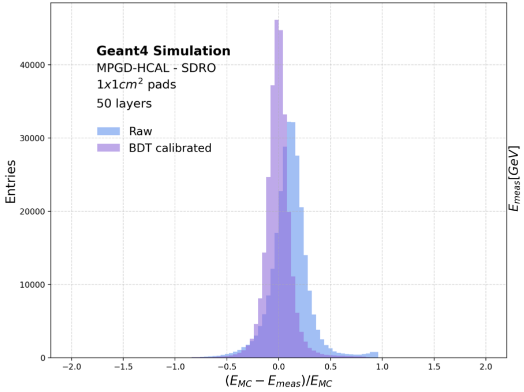
Standalone Simulation results with BDT

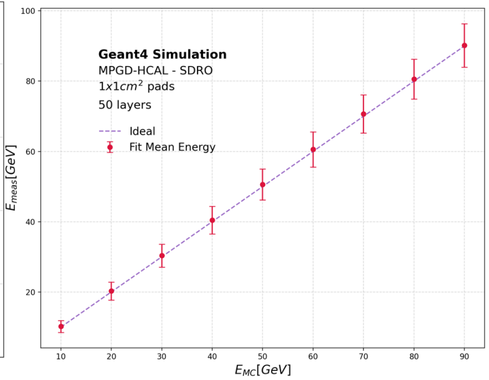
XGBoost squared-error regression to improve the energy calibration, linearity and resolution

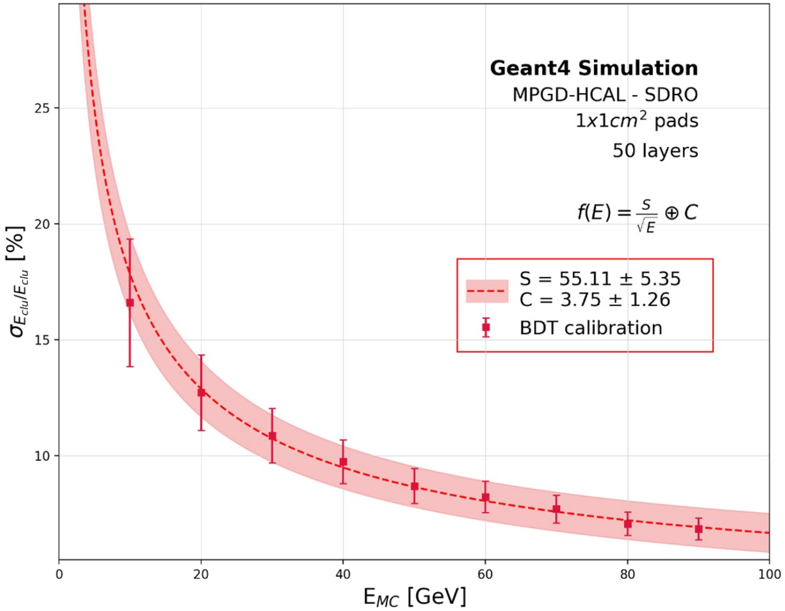
- Training: ~600k events, E_π=2-120 GeV
- Target : (reconstructed energy) / (MC energy)

Input Features :

- Number of hits in HCAL
- Reconstructed shower energy
- Number of hits in the 3 energy ranges
- Number of hits per layer
- Energy Fraction per layer
- X, Y, and Z centroid (weighted by the hit energy)
- Standard dev of hit coordinate X & Y per layer







✓ Stochastic term S compatible with previous results

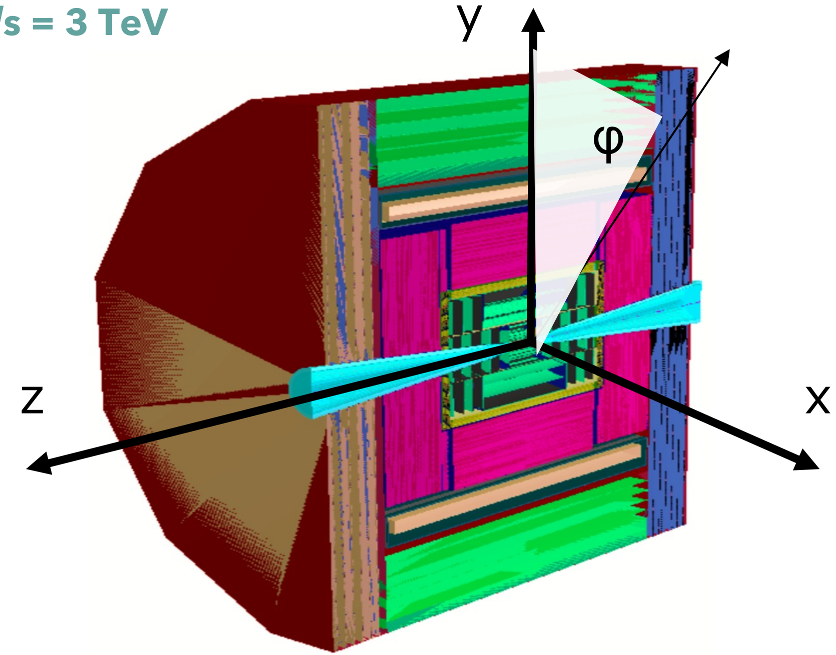
✓ Significant reduction of the constant term

C : **8.0% →3.75 %**

Muon Collider simulations

MPGD HCAL performance studied in Muon Collider $\sqrt{s}$ = 3 TeV (w/BIB) and MUSIC $\sqrt{s}$ = 10 TeV (w/ BIB)

$\sqrt{s}$ = 3 TeV

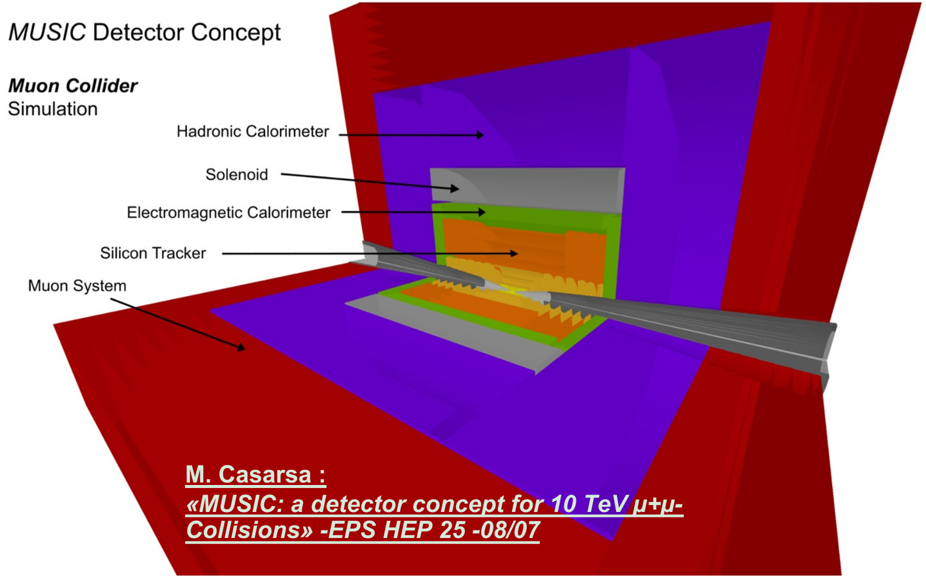


MPGD-based HCAL before solenoid

60-layer SAMPLING CALORIMETER

Layer thickness: **2.65 cm - cell: 1 cm²**

$\sqrt{s}$ = 10 TeV



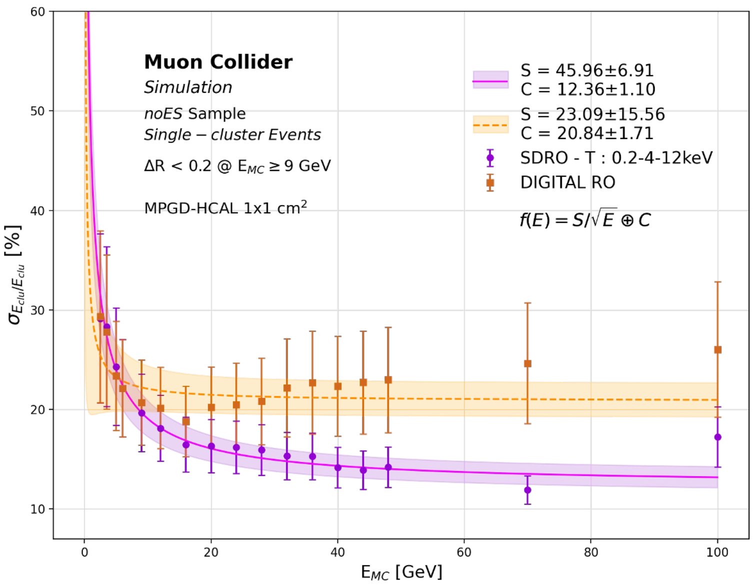
MPGD-based HCAL outside 80 cm solenoid (barrel only)

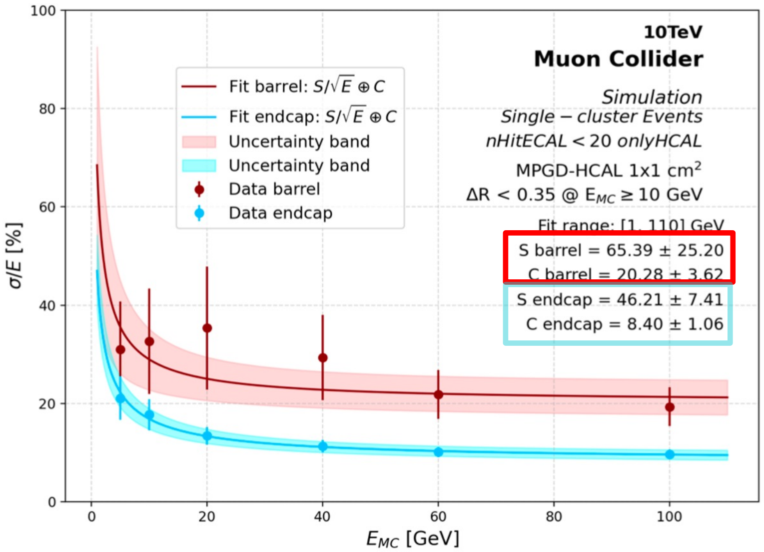
70-layer SAMPLING CALORIMETER

Layer thickness: **2.65 cm - cell: 1 cm²**

Cluster energy resolution

- Pandora Particle Flow clustering
- $\pi^{\pm}$ guns with energy ranging from 2.5 to 100 GeV, **only pions not showering in ECAL**;
- Linear calibration to correct the energy response





- Digital RO: saturation at high energies
- Overall, better performances of the **SDRO**

$\sigma/E = 45.96\%/\sqrt{E} \oplus 12.36\%$

- Just SDRO considered
- Different calibrations for barrel and endcap

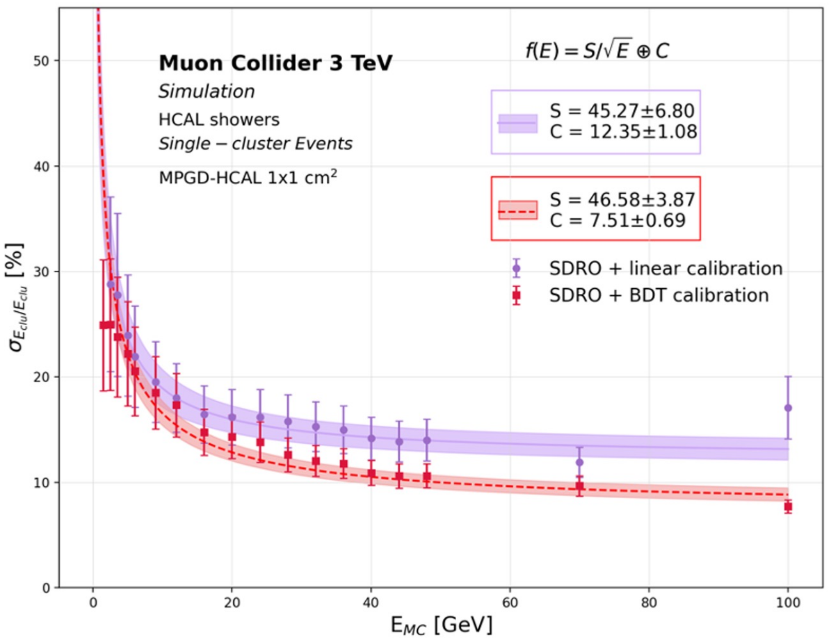
Barrel: **$\sigma/E = 65.39\%/\sqrt{E} \oplus 20.8\%$**

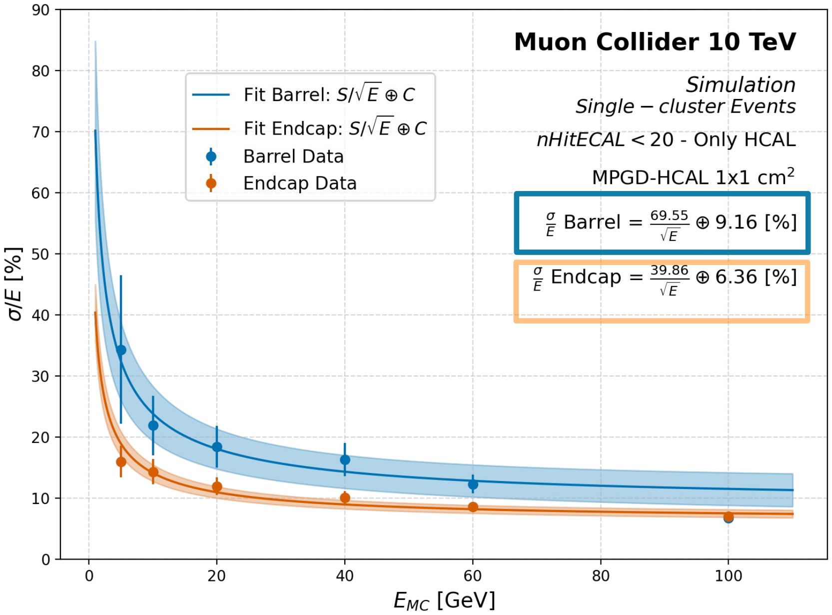
Endcap: **$\sigma/E = 46.21\%/\sqrt{E} \oplus 8.40\%$**

BDT-calibrated cluster energy resolution

Same approach as G4 simulation, some changes in input features, accounting PF clustering

- e.g. cluster size, cluster energy, cluster position





✓ BDT regression improves energy resolution at high energy →**C~12%→7%,** comparable with G4 simulations

✓ Separated calibration for barrel and endcap **→improved results at high energies C ~9.16% barrel, 6.36% in endcap**

Development of a hadronic calorimeter prototype

MPGD-HCAL Test Beam

2 test beam campaigns in 2023 and 2024:

- **without absorbers** for detector characterization,
- **with absorber** for shower studies (~$1\lambda_I$).

12 prototypes of active layers produced and tested

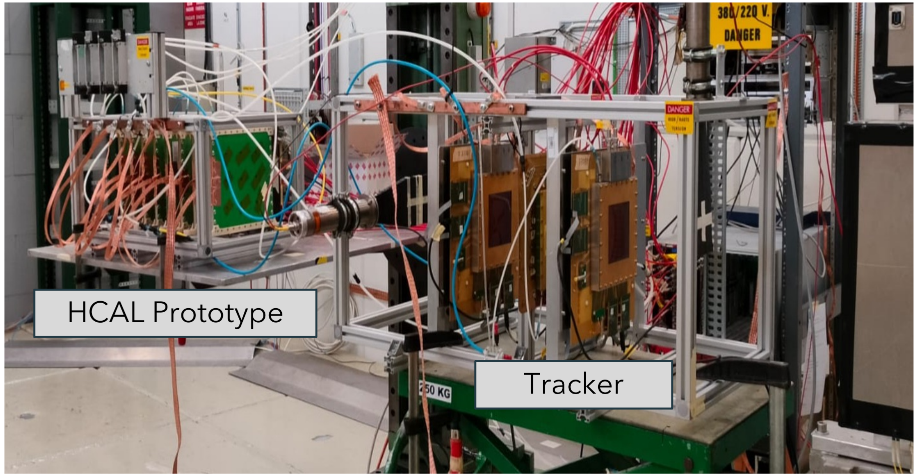
- 7 μ-RWELL
- 4 MicroMegas
- 1 RPWELL

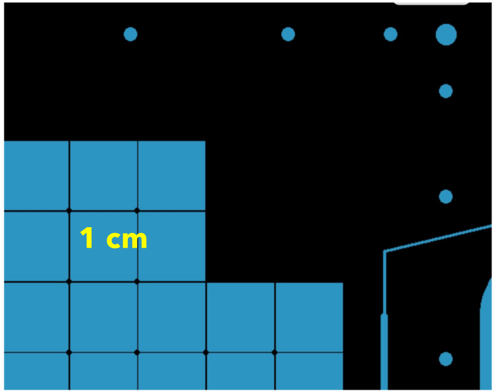
Detector design:

- Drift gap 6 mm
- Active area 20×20 cm^2
- Pad size 1×1 cm^2

HCAL prototype:

- 8 MPGD layers alternated with iron absorbers

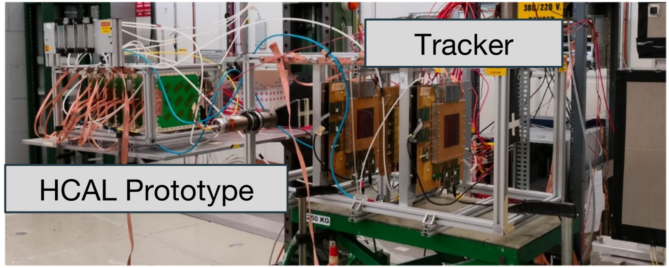




MPGD Characterization

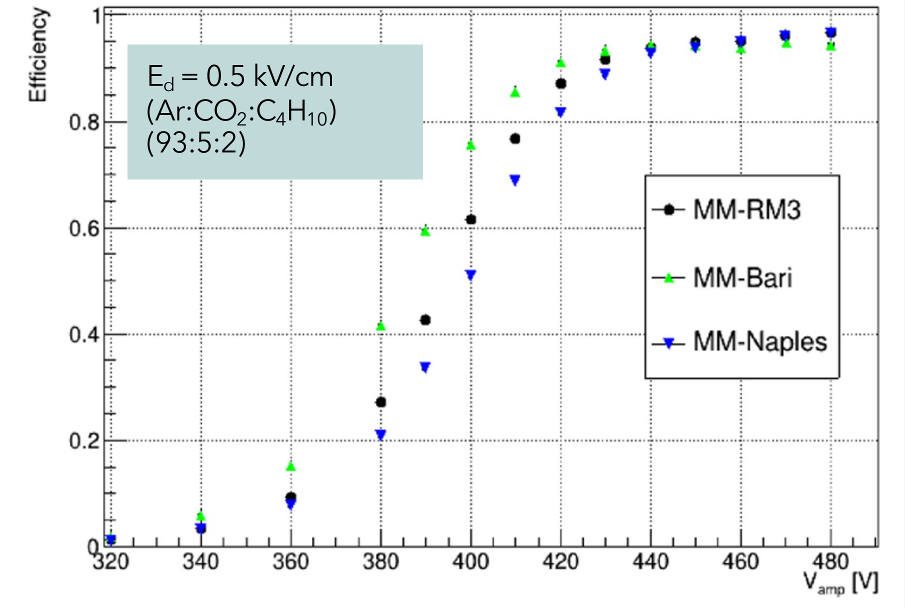
Active layer characterization - efficiency

- SPS@CERN: ~100 GeV muon beam
- Trigger and tracking with micromegas with 250 strip pitch

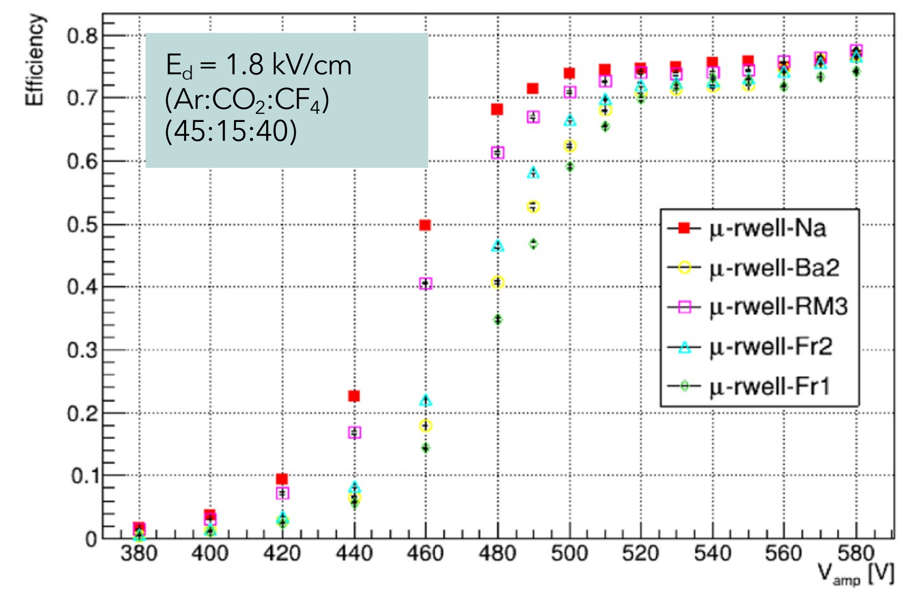


Electronics: APV25 chip + SRS back-end

Micromegas efficiency ~ 95%



µRWELL efficiency ~ 75%

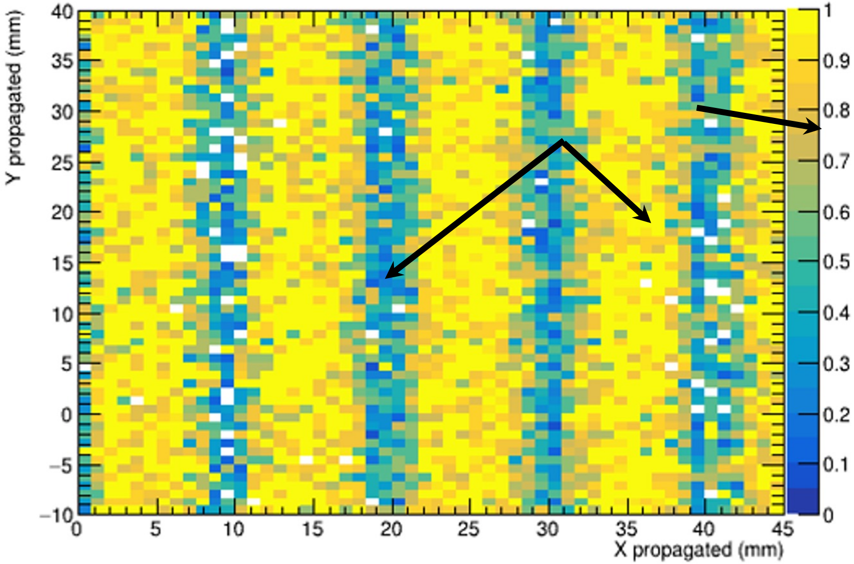


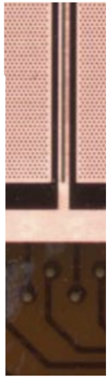
MPGD-HCAL Test Beam

Active layer characterization - efficiency

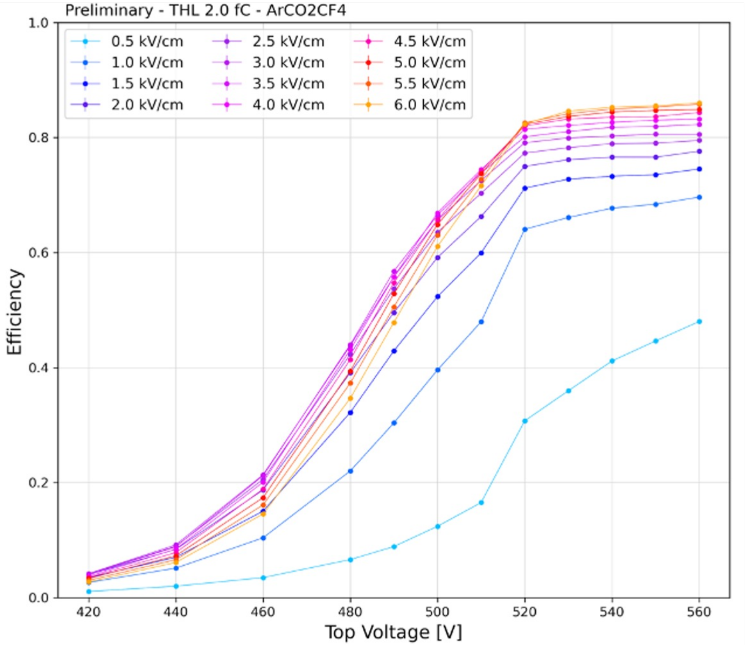
Understanding µRWELL results
Per Pad efficiency measurement

Dead areas due to grounding lines





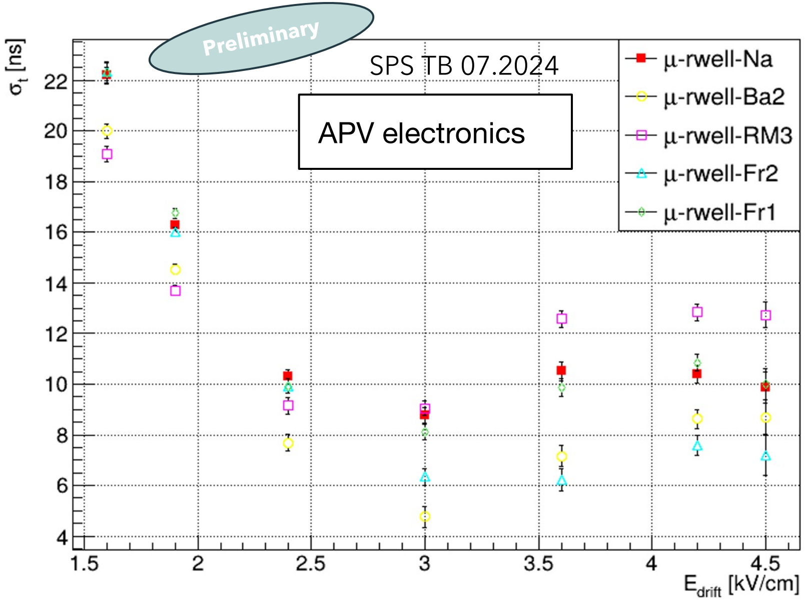
Inefficiency regions can get partially recovered increasing drift field

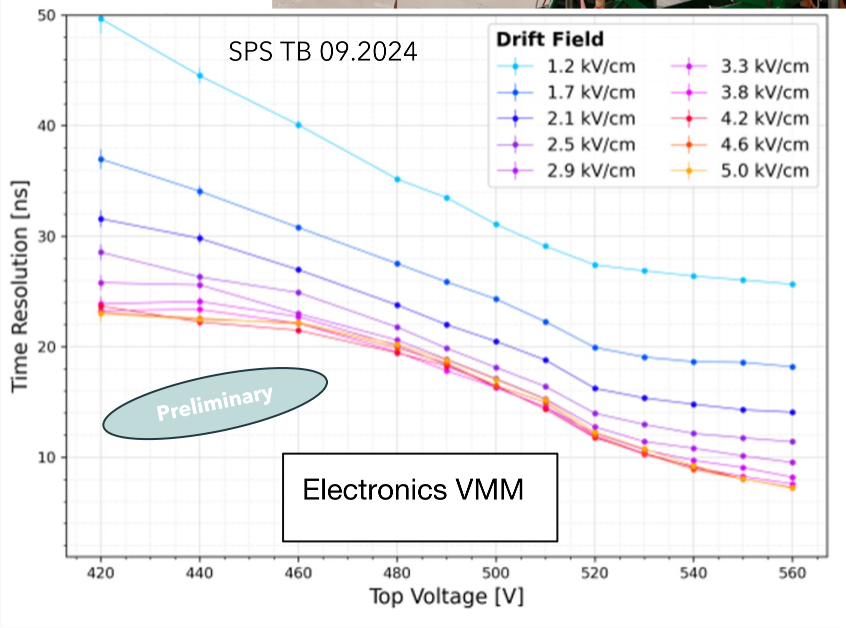


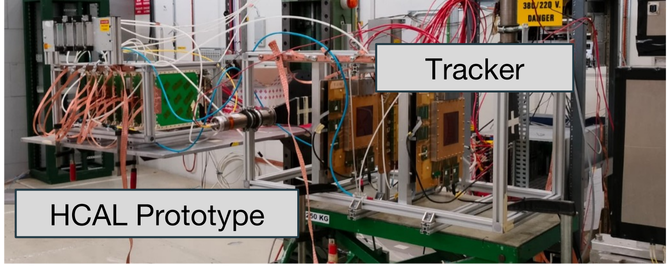
- Locally very high efficiency ~ 95%
- Ground lines introduce regions of ~ 1 mm with ~50% efficiency drop

MPGD Characterization

Active layer characterization – Time resolution



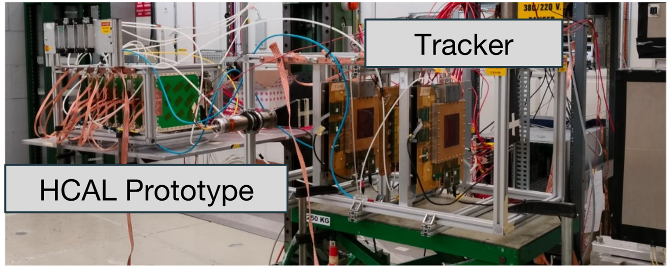




- ✓ μRWELL time resolution w/ Ar:CO_2:CF_4 → **few ns (~ 6ns) with Drift field of 3 kV/cm**;
- ✓ similar results with different electronics

MPGD Characterization

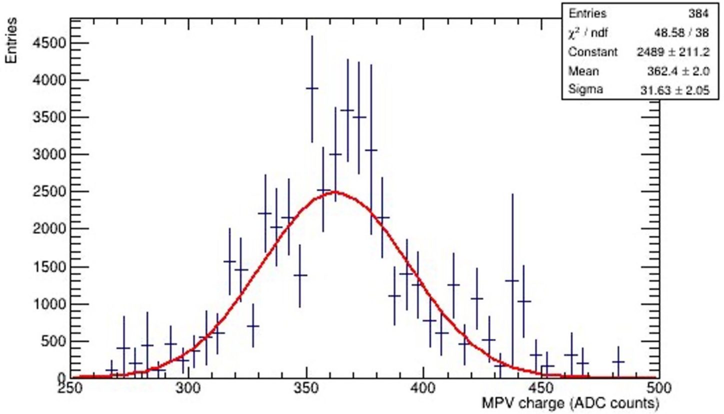
Active layer characterization – Response uniformity



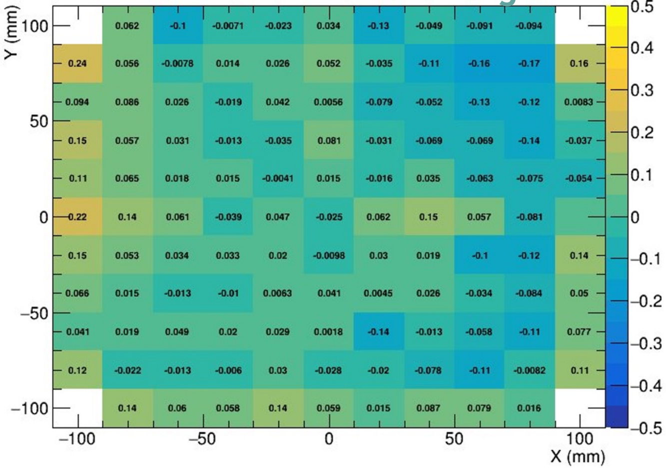
Response uniformity measured using clusters matching muon tracks

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

Charge 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	$(11.3 \pm 1.0)\ \%$
μrw-Fr2	$(16.2 \pm 1.7)\%$
μrw-Fr1	$(16.3 \pm 1.1)\%$

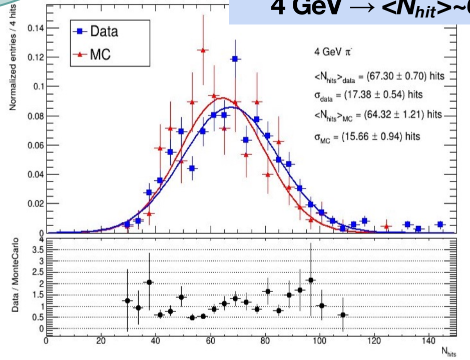
MPGD-HCAL Test Beam

MPGD HCAL prototype test at CERN PS with pion beams with energy in 2-10 GeV

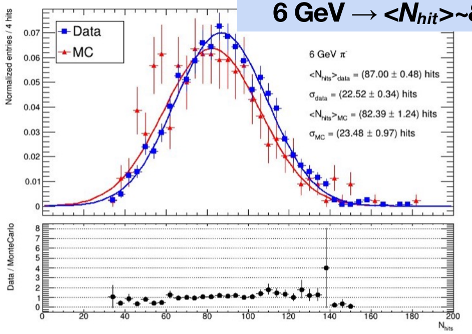
Preliminary

2023 PS Pion beams

4 GeV → $\langle N_{hit} \rangle$~67



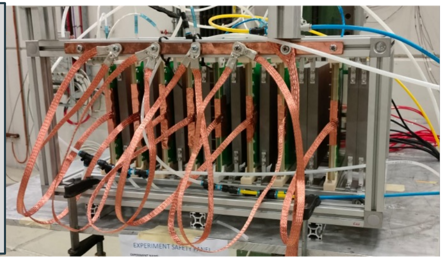
6 GeV → $\langle N_{hit} \rangle$~87

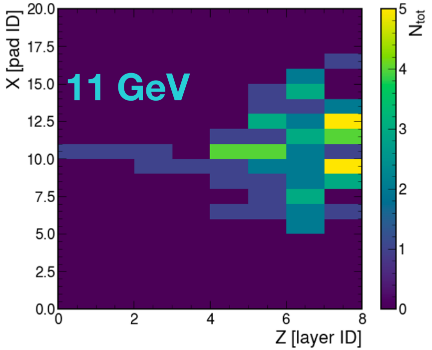


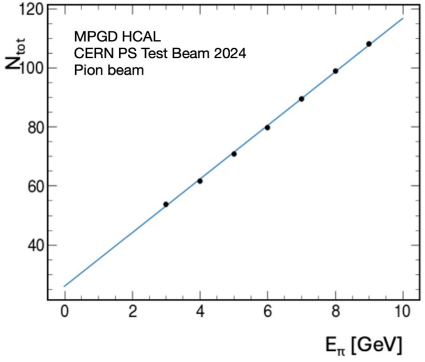
✓ Data-MC agreement in number of hits

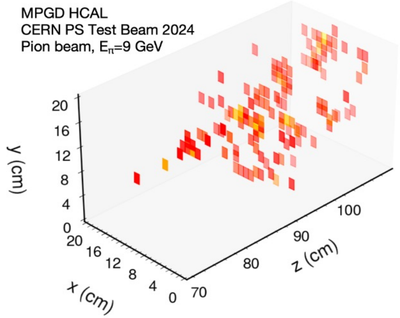
2024 PS Pion beam

HCAL Prototype









✓ Linearity between pion beam energy and total number of hits

Conclusions and next steps

MPGD HCAL R&D ongoing: simulation and characterization with test beam

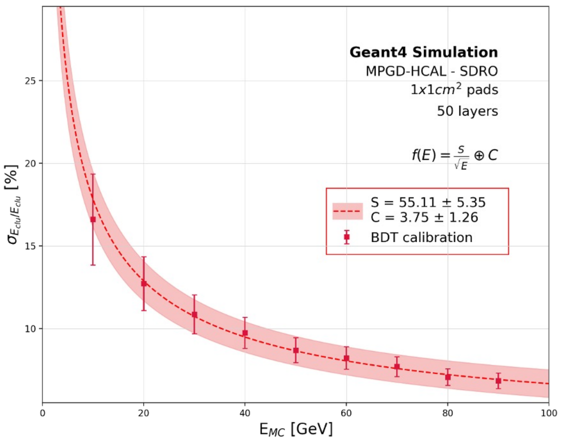
- **Simulations in G4 and Muon Collider:** promising results, **compatible with PF requirements**

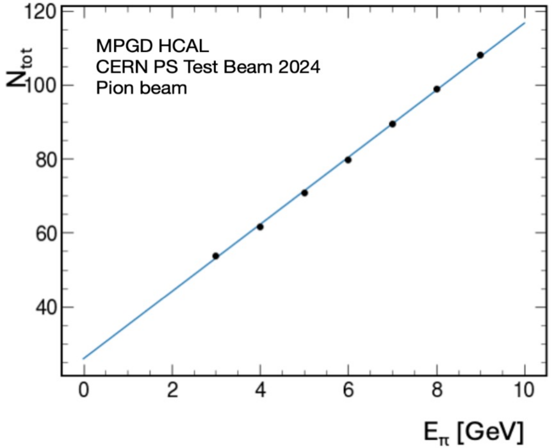
  S~40-60%, C~4-9% depending on geometry and clustering

- **Calorimeter prototype and MPGD characterization**:
  - Efficiency: ~95% for MicroMegas, ~ 75% for μRWELL
  - Response uniformity: ~10% for MicroMegas and ~15% for μRWELL
  - μRWELL timing resolution of ~ 6ns
  - Good **linearity** between pion beam energy and total number of hits

Next steps: Extension calorimeter prototype to ~ 2 λ_I

- μRWELL with new grounding schema to reduce dead area
- 2 MicroMegas and 2 μRWELL 50x50 cm^2 under production





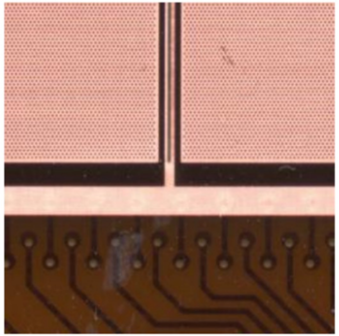
Backup

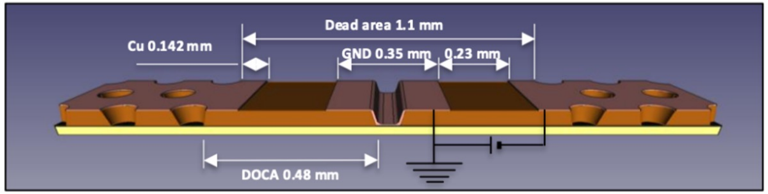
PEP lines Vs PEP dots

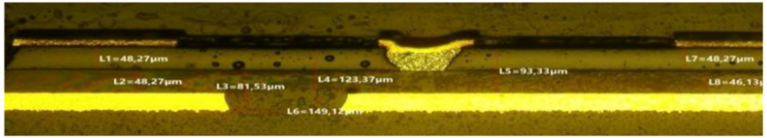
2022

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



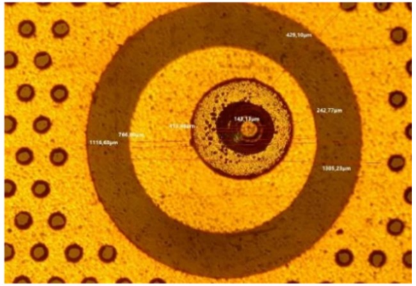




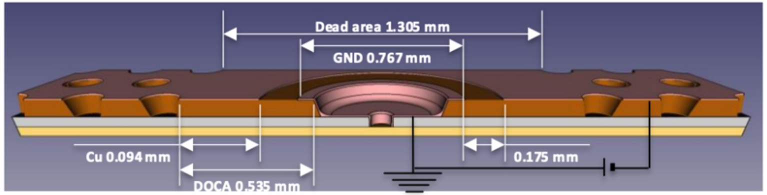
2023

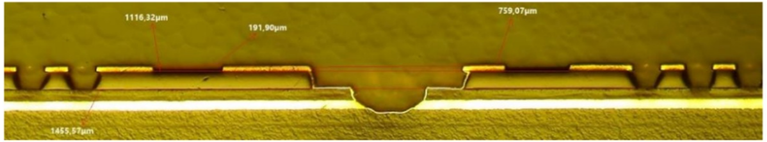
PEP-DOT:
DLC grounding through conductive dots connecting the DLC with pad r/outs
Pad R/O = 9×9mm²
Grounding:
- Dot pitch = 9mm
- dot rim = 1.3mm

→ 97% geometric acceptance



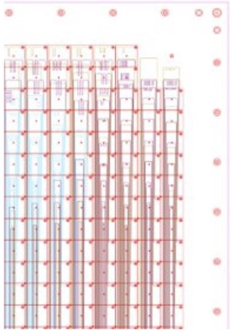
DOT → plated blind vias

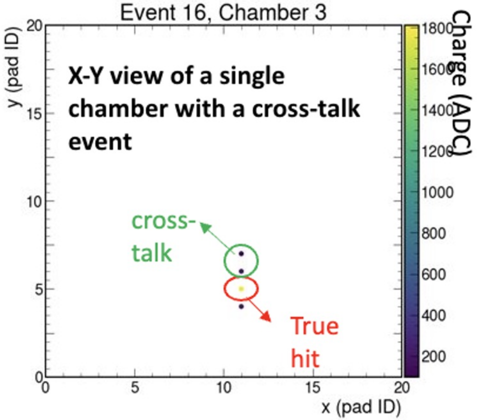




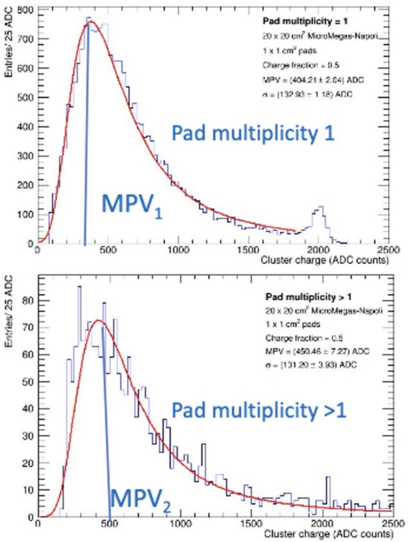
https://indico.cern.ch/event/1413681/contributions/6013367/attachments/2881828/5049134/The%20micro-RWELL%20for%20high-rate.pdf

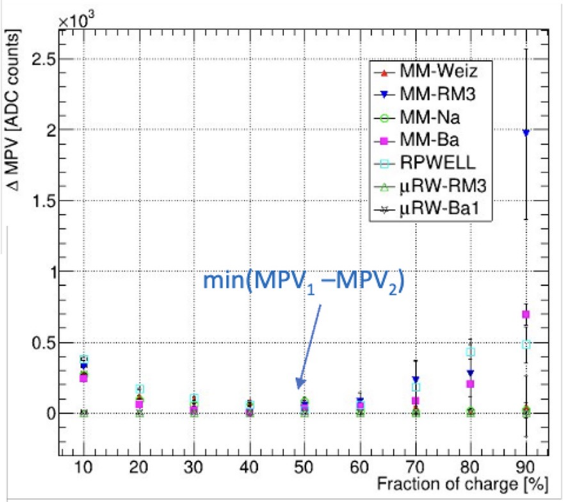
Cluster reconstruction





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



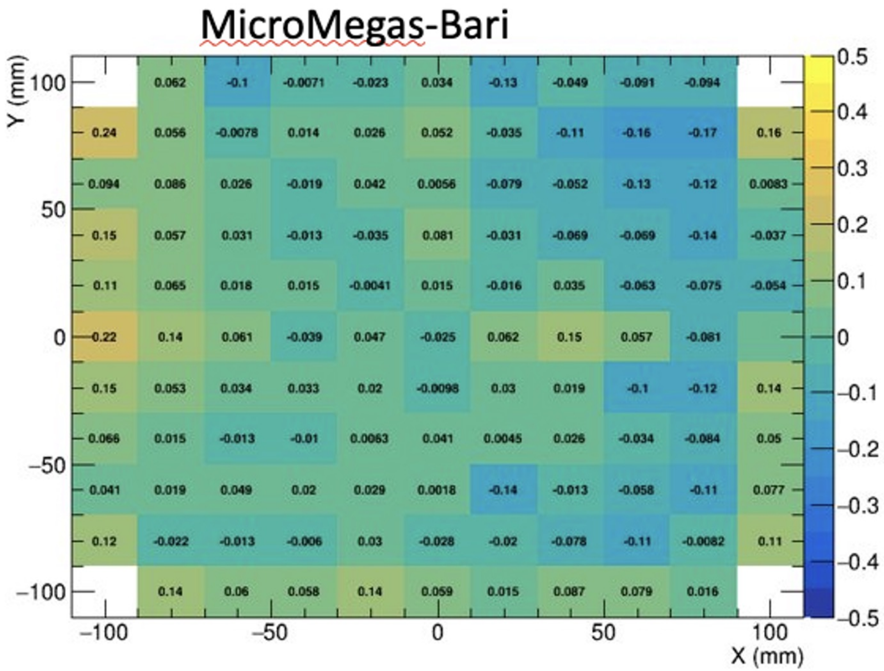


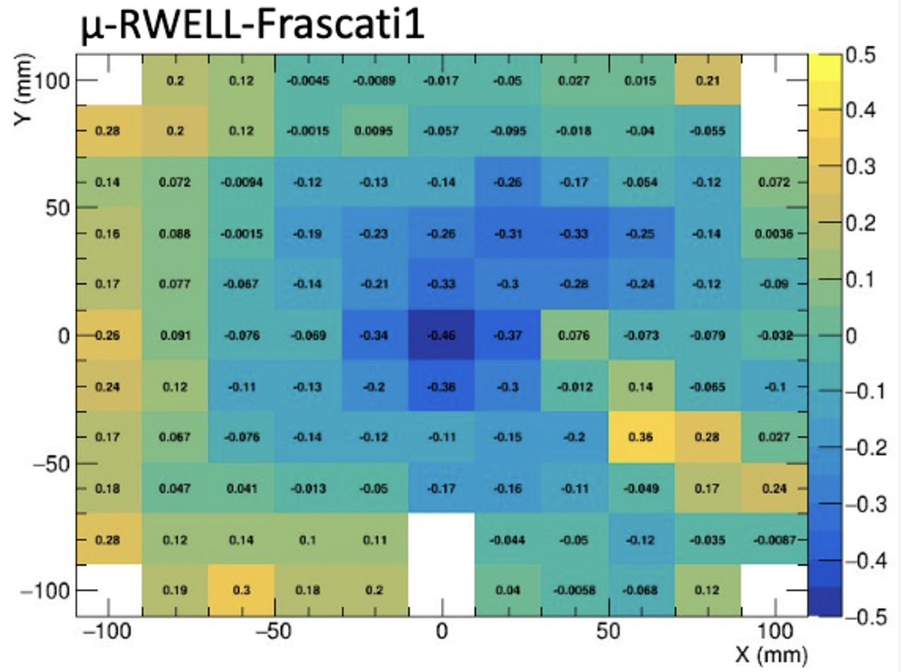
Developed ad-hoc **clustering algorithm** based on charge sharing criterium

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

Response uniformity

Preliminary



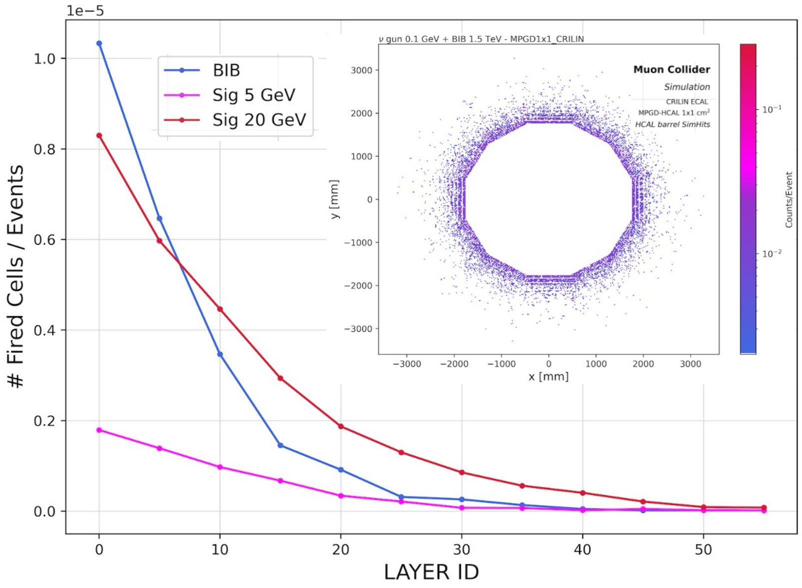


MPGD-HCAL BIB studies

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

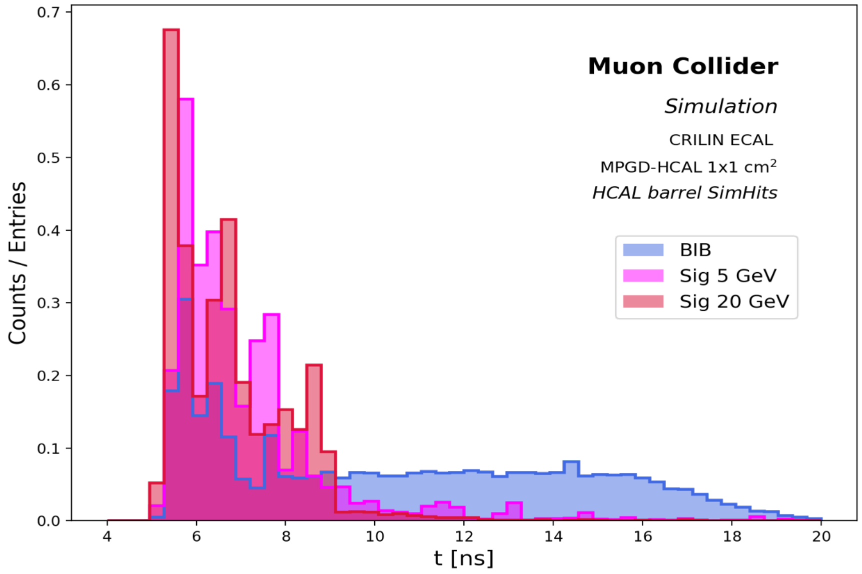
Hit Occupancy:

- **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
  - **π± 5 GeV** : ~ 0.2 x 10-5
  - **π± 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**

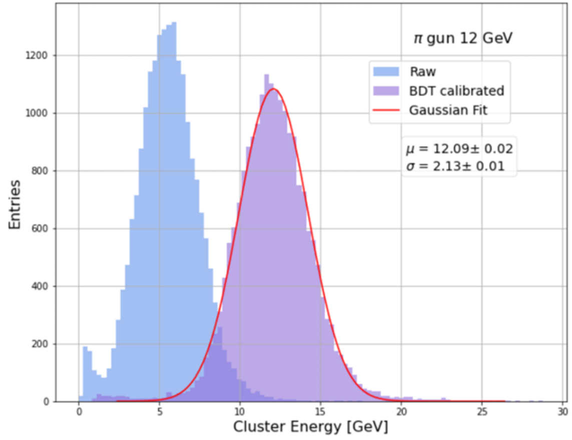


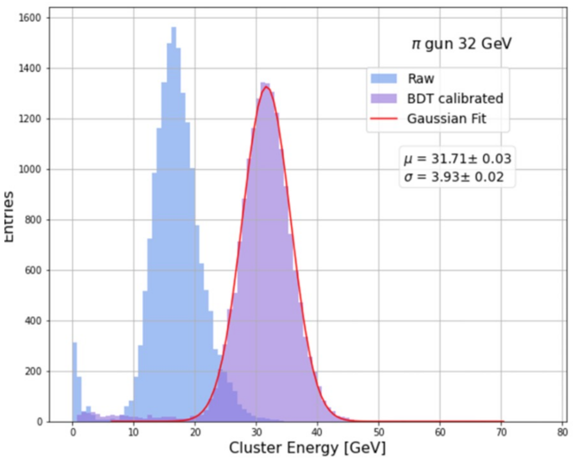
Semi-digital readout with BDT calibration

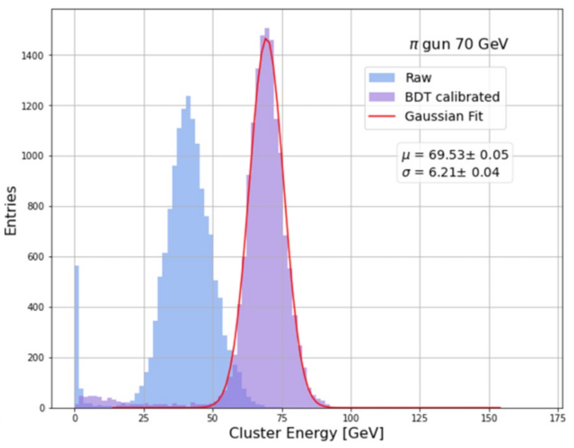
Calibrated energy = BDT output coefficient x Raw cluster energy

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



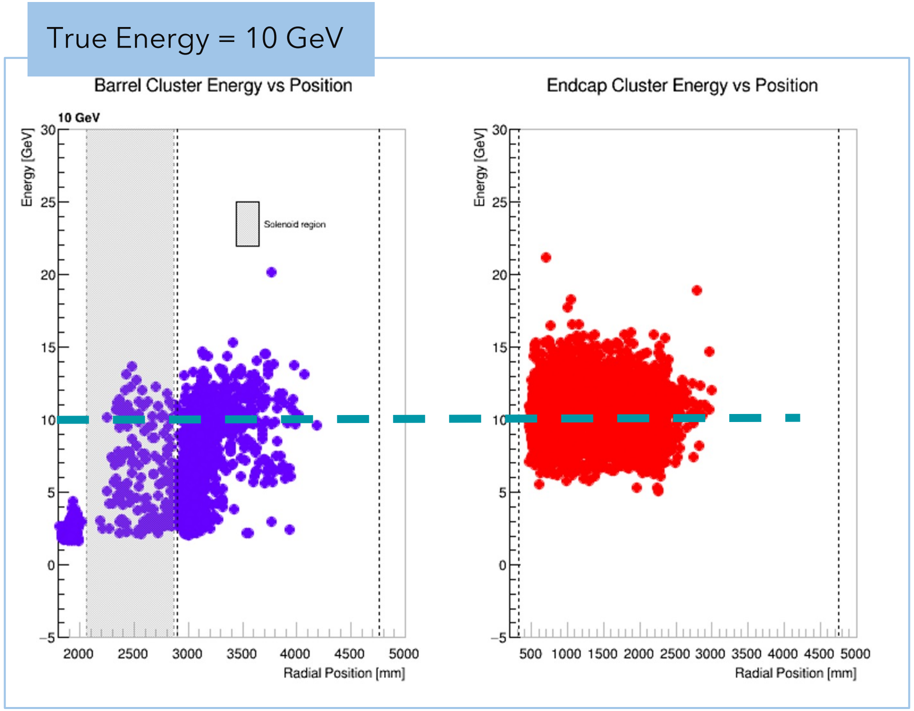


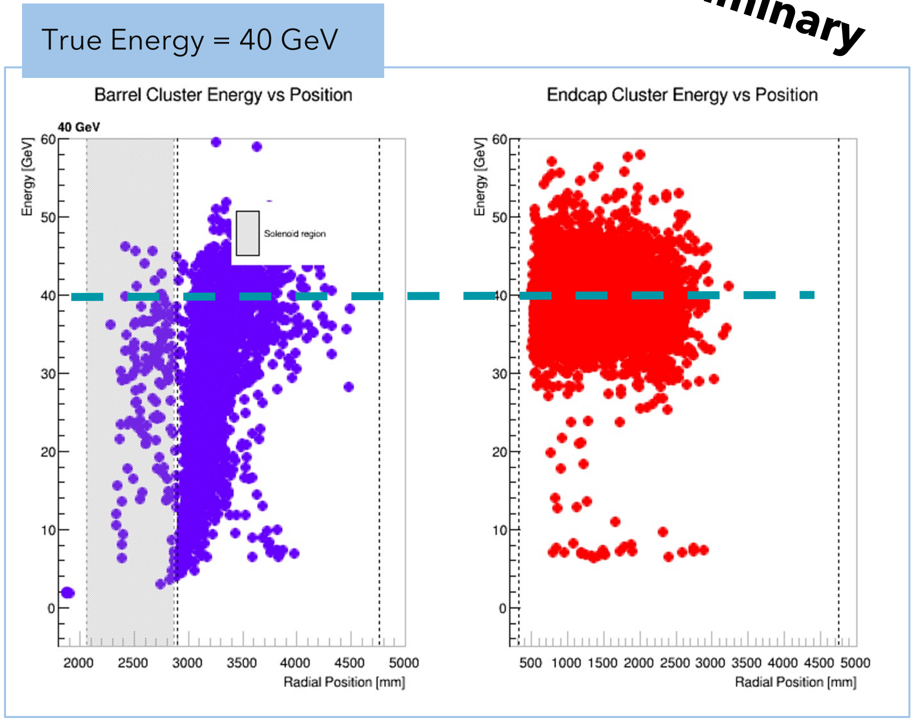


MPGD-HCAL within MUSIC - 10 TeV

Impact of the solenoid on HCAL - pion guns

Preliminary

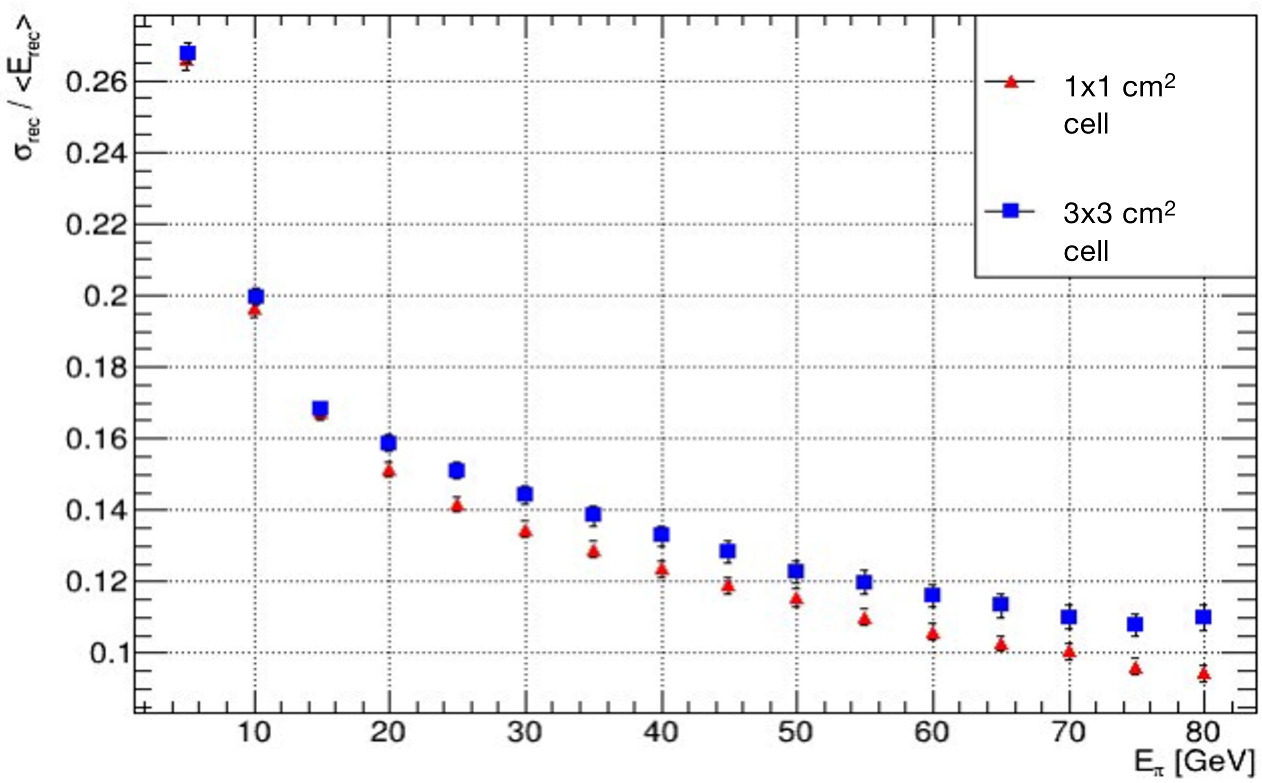




Depending of the hadrons energy, the **shower can initiate in the solenoid**:

- part of the shower is lost
- **Barycenter of the cluster** falls in the **solenoid region** or close to the **boundary** between **HCAL** and **solenoid**
- **Reconstructed energy** shifts towards **lower values**

Simulation: Semi-Digital readout



Investigating the possibility to **enhance** semi-digital **readout** with **machine learning technique: BDT regression**

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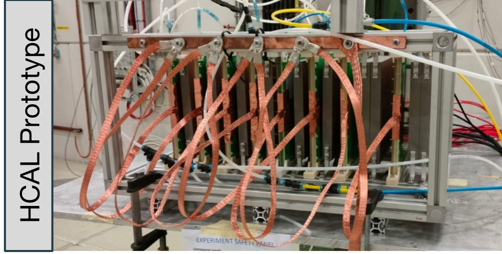
MPGD-HCAL Test Beam

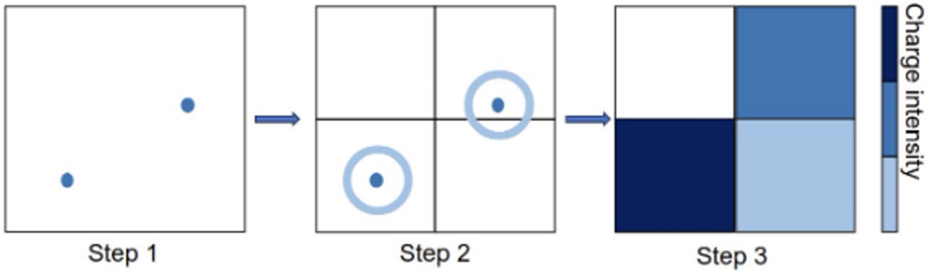


Prototype simulation

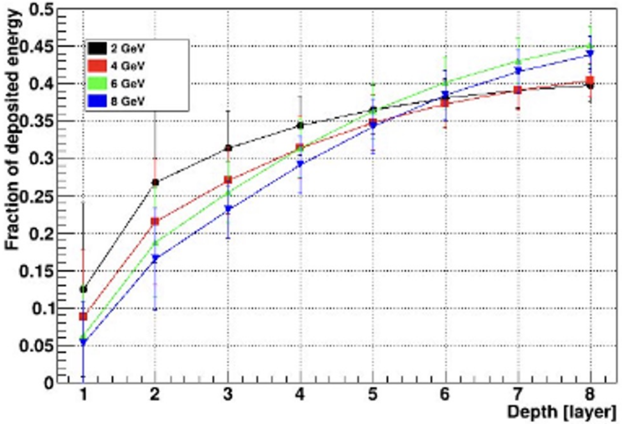
- Small detector geometry implemented
  - 8 layers of alternating of 2 cm stain-less steel absorbers and MPGD
    - First 2 layers with 4 cm absorbers to increase probability of shower development in the first layers
  - 20x20 cm^2 active surface
  - 1x1 cm^2 pad granularity
- Pion gun of energy range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

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

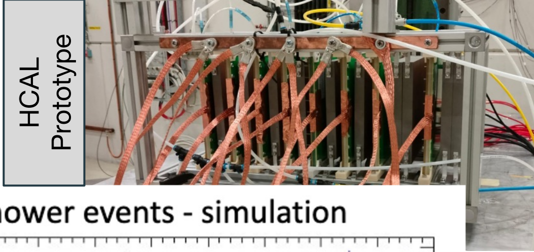
Digitization algorithm



Shower containment



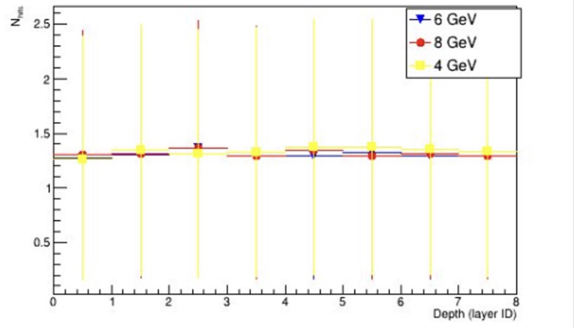
MPGD-HCAL Test Beam



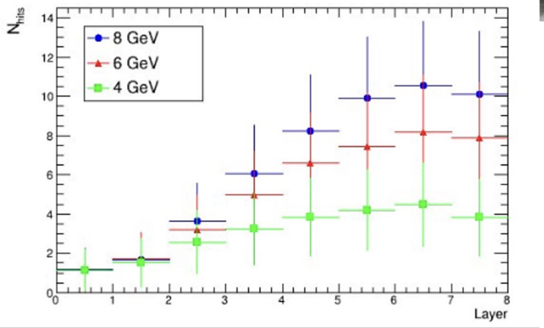
Prototype simulation

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

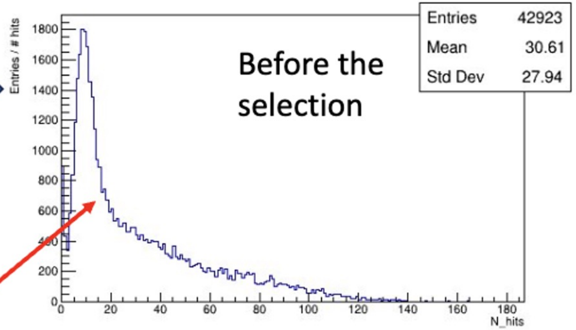


Shower events - simulation



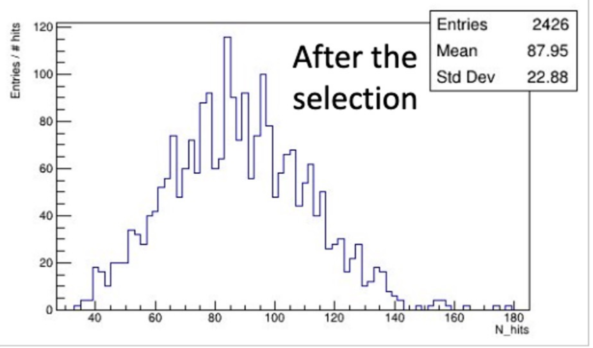
Distribution of the **number of hits** in all active layer from the **experimental data**

Number of hits for all events

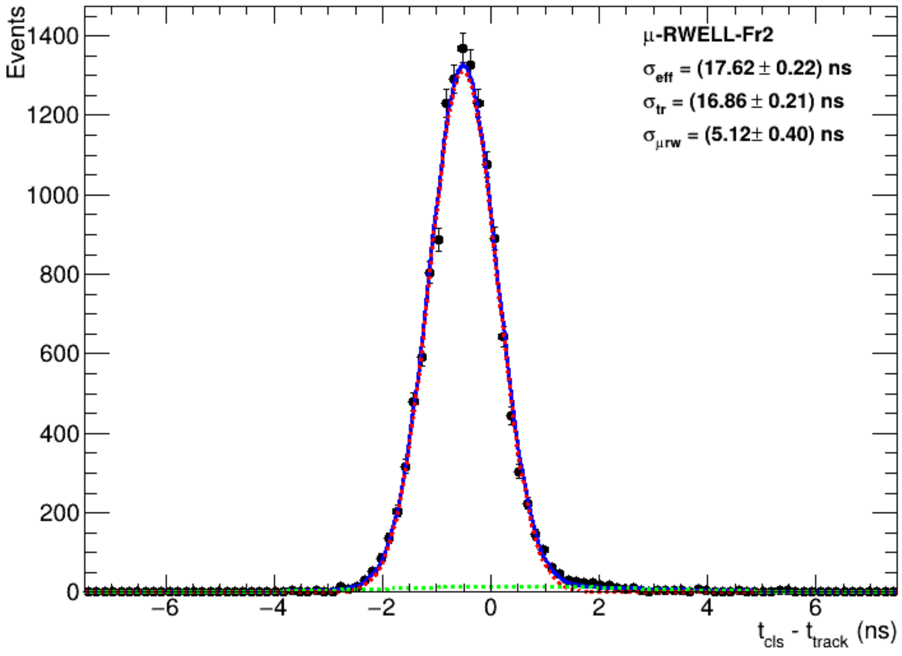


Peak at ~ 10 hits
-> MIP-like events

Number of hits for showers event



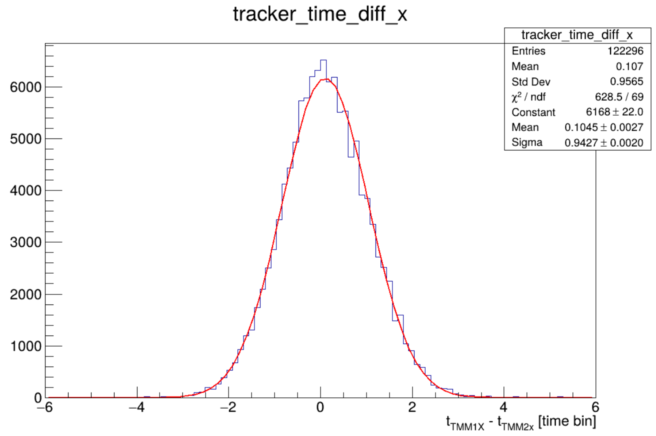
µrwell time resolution measurement



Gaussian fit of

$$\Delta t = t_{clus} - t_{track} \rightarrow \sigma = \sqrt{\sigma_{cls2} + \sigma_{track}}$$

Study $\sigma_{cls} = \sigma_{uRwell} = \sqrt{\sigma - \sigma_{track}}$ wrt DF and TV



TMM layer x (lower charge layer) is taken as reference for timing and corrected per time walk