A MPGD Hadronic Calorimeter

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6) CERN
7) University of Padova

A MPGD Hadronic Calorimeter

Group proposal: a sampling hadronic calorimeter with micro-pattern gaseous detector as readout layers

MPGD features:

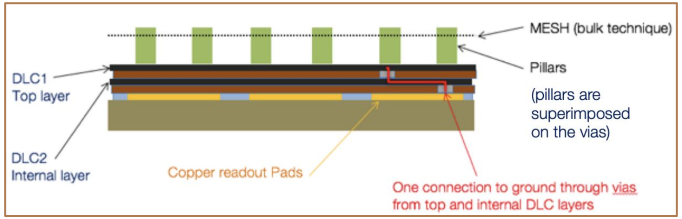
- **cost-effectiveness** for large area instrumentation
- radiation hardness up to several **C/cm^2**
- **discharge rate** not impeding operations
- rate capability O(**MHz/cm^2**)
- high granularity
- time resolution of **few ns**

Past work:

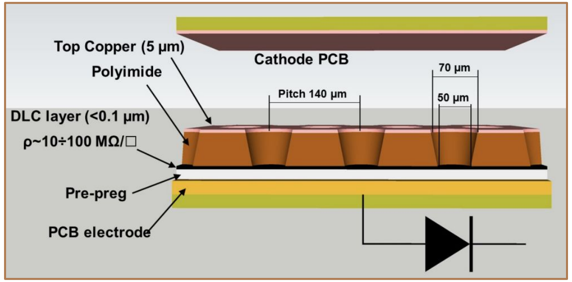
- CALICE collaboration: a sampling calorimeter using **gaseous detectors** (RPC) but also tested MicroMegas
- SCREAM collaboration: a sampling calorimeter combining RPWELL and resistive MicroMegas

Our plan → systematically **compare** three MPGD technologies for hadronic calorimetry: resistive MicroMegas, µRWELL and RPWELL, while also investigating **timing**

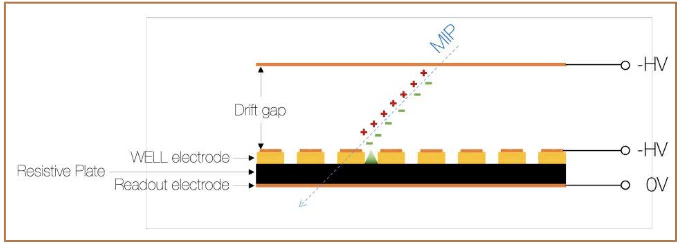
Micromegas (MM)



µRWELL



RPWELL

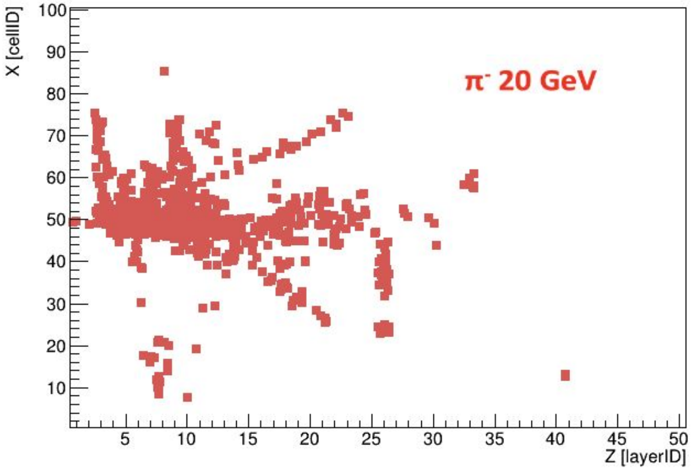


HCAL R&D well included in DRD1-WP5 (Calorimetry) and DRD6-WG1 (Sampling Calorimeter)

Readout: Digital and Semi-digital HCAL

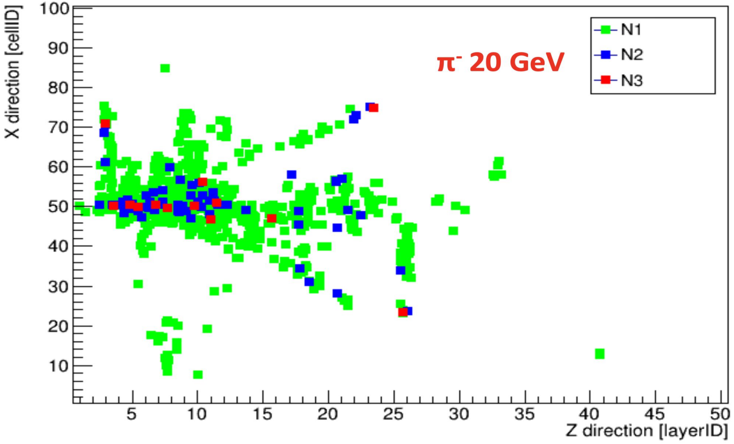
Digital Readout (Digital RO)

- **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)

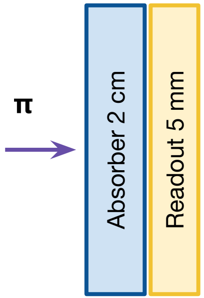
- **Digitization:** defined multiple thresholds
- **Reconstructed energy:** $E_\pi= \alpha N_1+\beta N_2+\gamma N_3$ with:
  - $N_{i=1,2,3}$ number of hits above i-threshold (0.2-4-12 keV)
  - α,β,γ parameters obtained by χ^2 minimization procedure

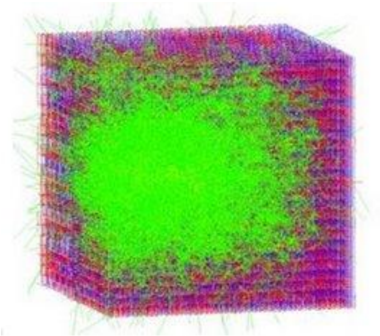


Simulation studies

Simulation: shower containment studies

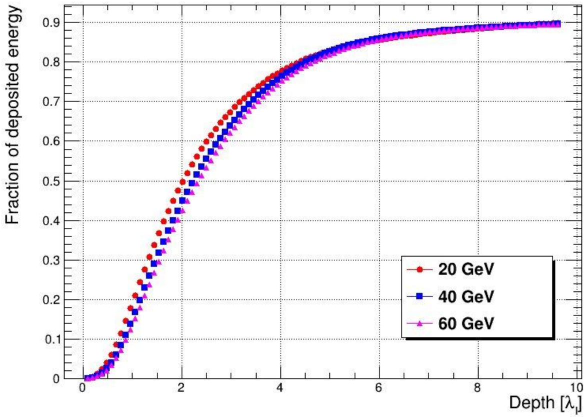
Geant4 simulation of a 100 layers calorimeter



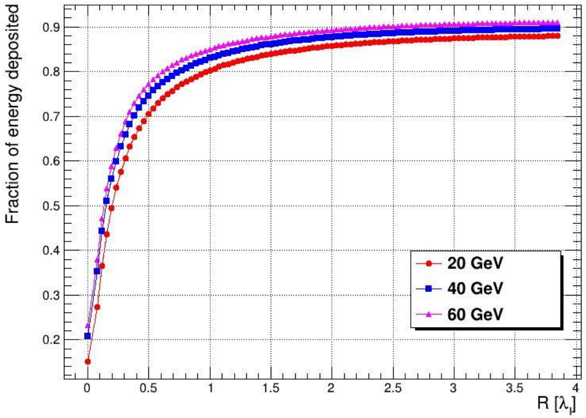


- Geometry: 2 cm iron, 5 mm gas (Ar/CO_2)
- Readout granularity → cell size of
  - 1×1 cm^2
  - 3×3 cm^2
- Pion guns of different energies
- **Result:** longitudinal containment in ~10 λ_I, transversal in ~2 λ_I

Longitudinal shower containment

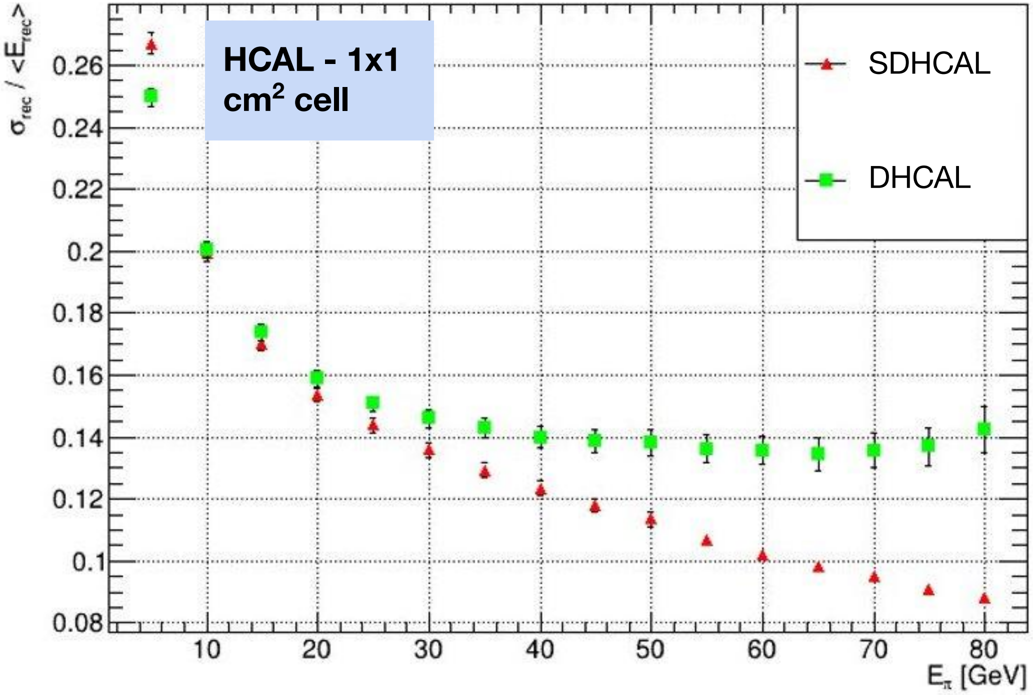


Transversal shower containment



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

Simulation: Digital and Semi-digital HCAL



SDHCAL shows better resolution for E_π > 40 GeV

At E_π= 80 GeV, the resolution

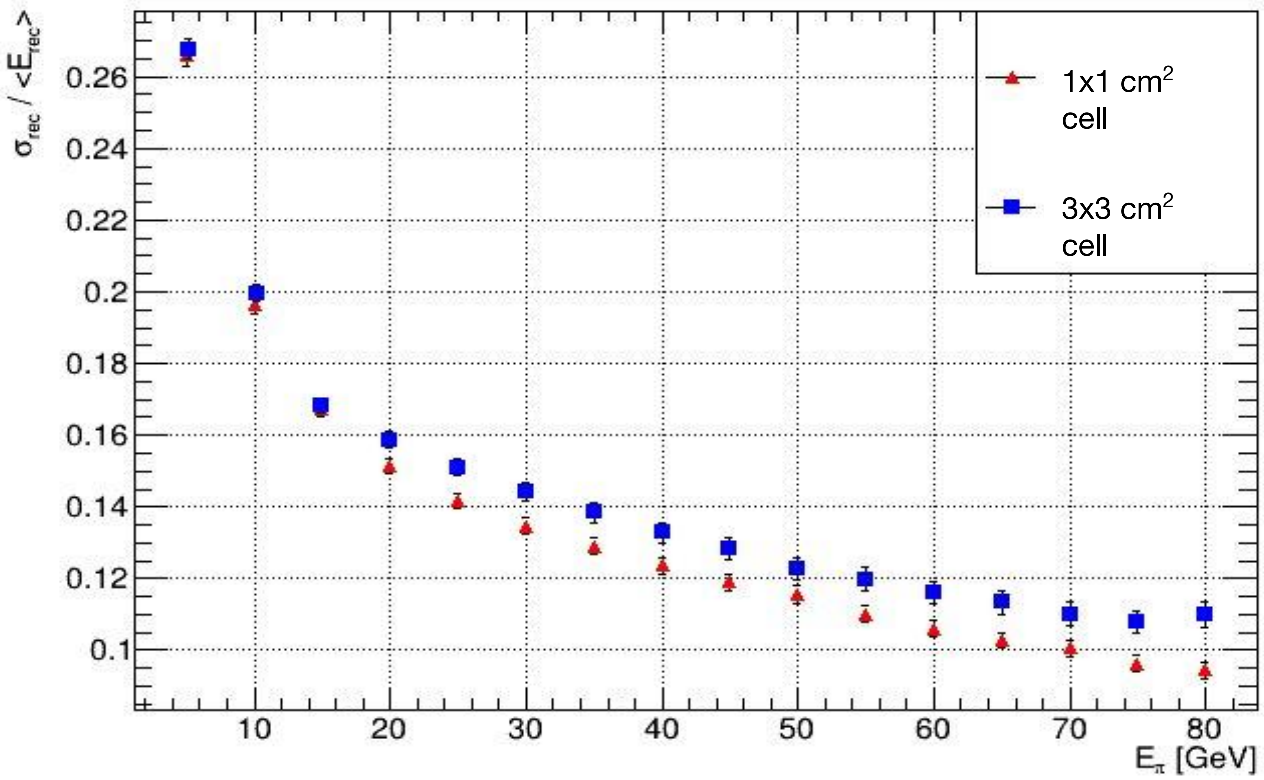
- DHcal ~ 14%
- SDHcal ~ 8%

DHCAL suffers from **saturation effect** for E_π > 40 GeV

Comparable results for granularity of 1x1cm^2 (~9% at 80 GeV) and 3x3 cm^2 (~11% at 80 GeV)

DOI: 10.1088/1748-0221/19/05/C05037

Simulation: Semi-Digital readout



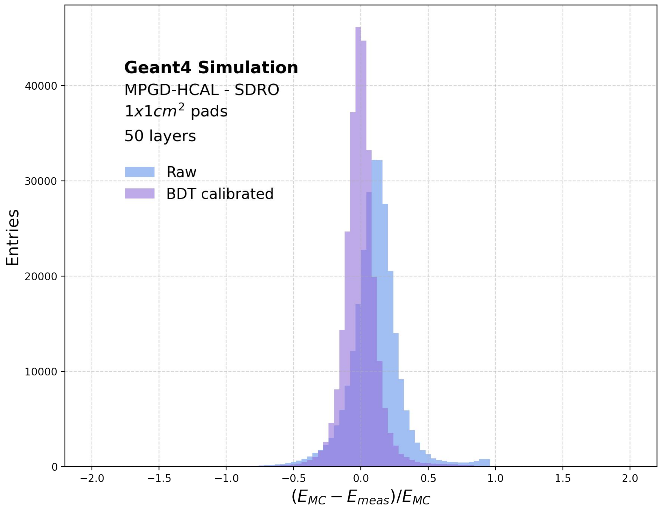
DOI: 10.1088/1748-0221/19/05/C05037

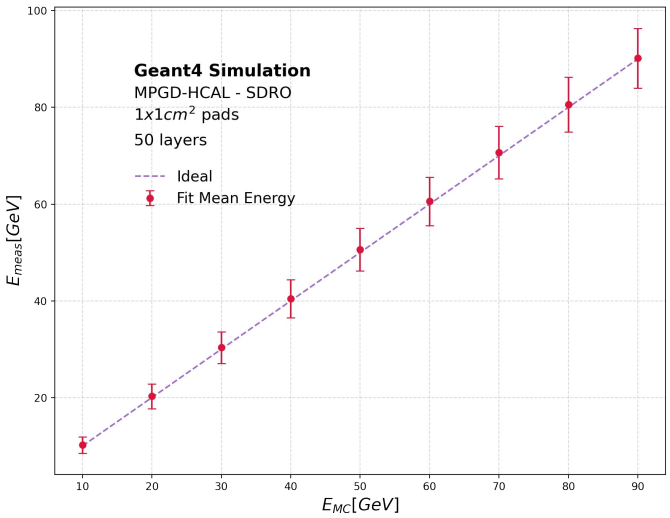
Investigating the possibility to **enhance** semi-digital **readout** with **machine learning technique: BDT regression**

Simulation: BDT for energy calibration

Purpose: improve the energy calibration, linearity and resolution of monochromatic $\pi^\pm$ guns in the GEANT4 Simulation

- only 50 layers considered
- energy range: [10,90] 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 by the hit energy)
  - Standard dev of hit coordinate X & Y per layer





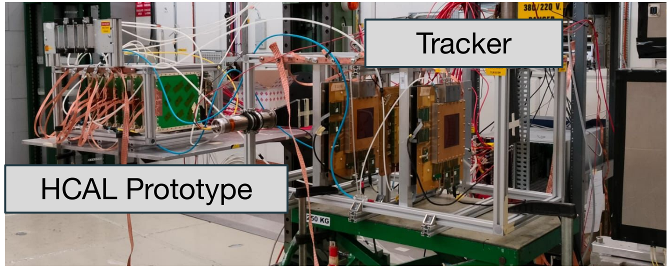
- **Energy response improved** in the BDT calibrated shower energy:
  - Tighter peak, symmetrically centered in 0
- **Good linearity** of the **reconstructed energy** with respect to the **MC true energy**

Development of a hadronic calorimeter prototype

Recent talks:

- DRD6 Collaboration Meeting, Apr25
- DRD1 Collaboration Meeting, Feb25
- DRD1 Collaboration Meeting, Dec24
- MPGD2024
- ICHEP2024, PoS

MPGD-HCAL Test Beam



R&D effort shared between INFN-Ba, INFN-RM3, INFN-Fr, INFN-Na, Weizmann and CERN

2 test beam campaigns in 2023 and 2024:

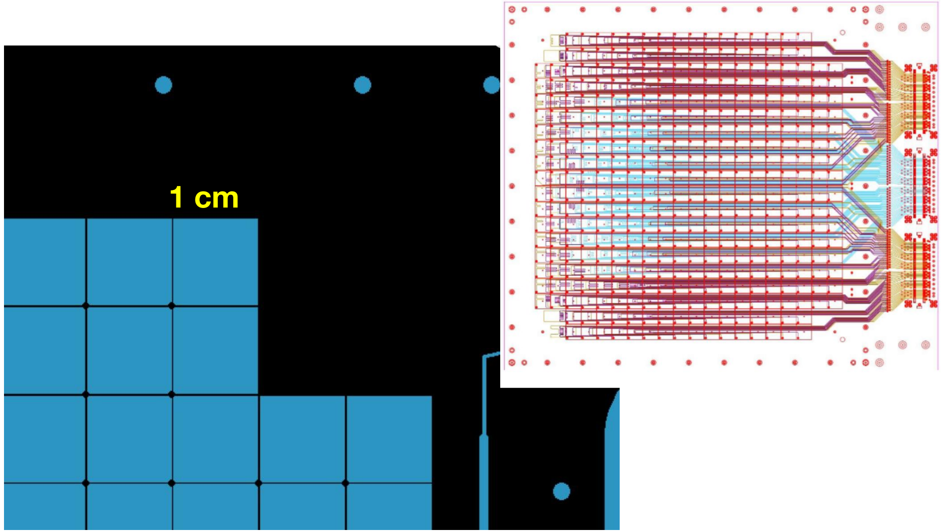
- **without absorbers** for detector characterization,
- **with absorber** for shower studies ($\sim 1\lambda_I$).

12 prototypes produced and tested within **RD51 common project**:

- 7 μ-RWELL
- 4 MicroMegas
- 1 RPWELL

Detector design:

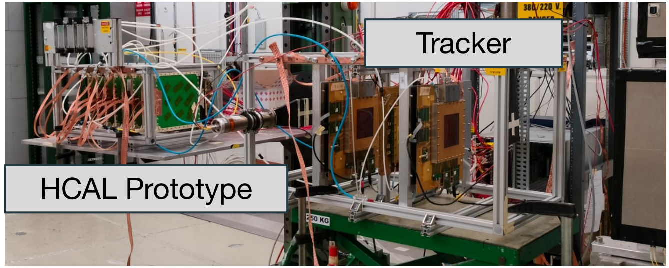
- Active area 20×20 cm^2
- Pad size 1×1 cm^2
- **Common readout** board



HCAL prototype:

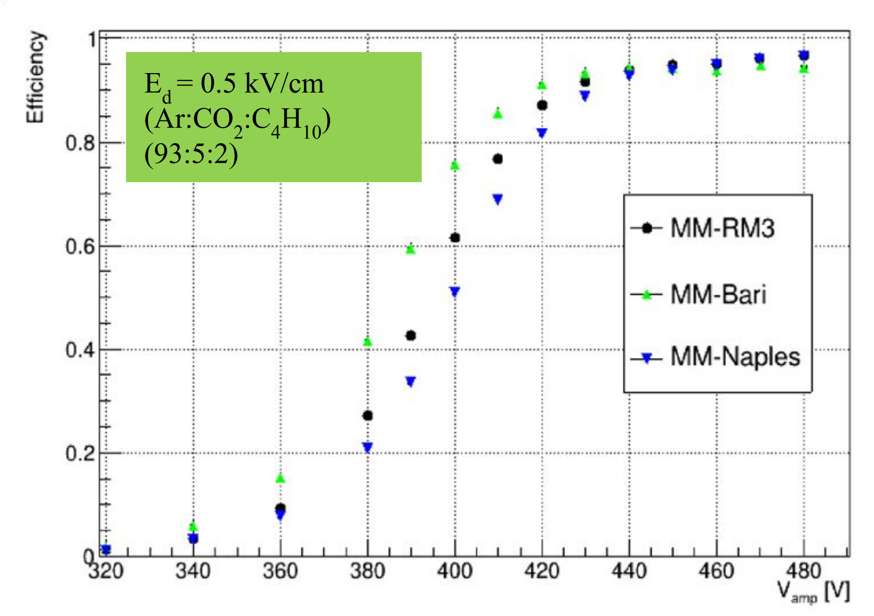
- 8 MPGD layers alternated with iron absorbers
- the first two absorber layers are 4 cm thick; the remaining layers are 2 cm thick

MPGD-HCAL Test Beam

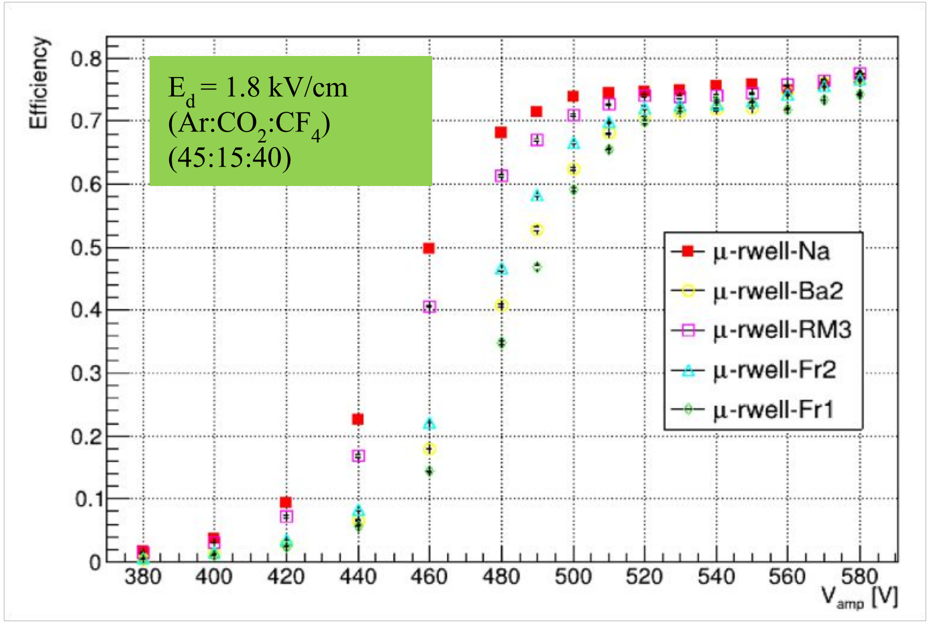


Active layer characterization

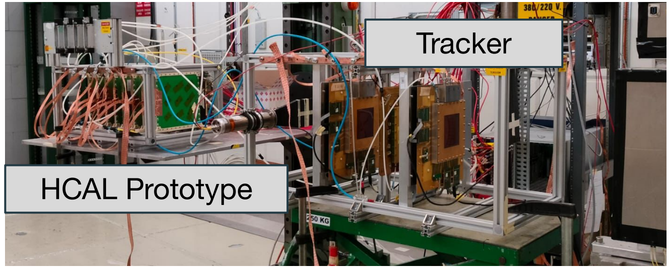
Micromegas efficiency ~ 95%



μRWELL efficiency ~ 75%

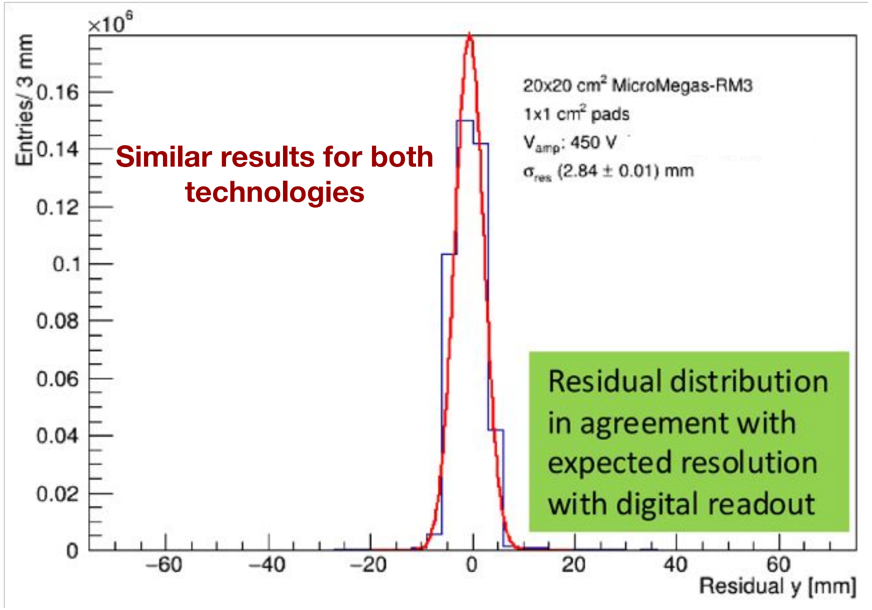


MPGD-HCAL Test Beam

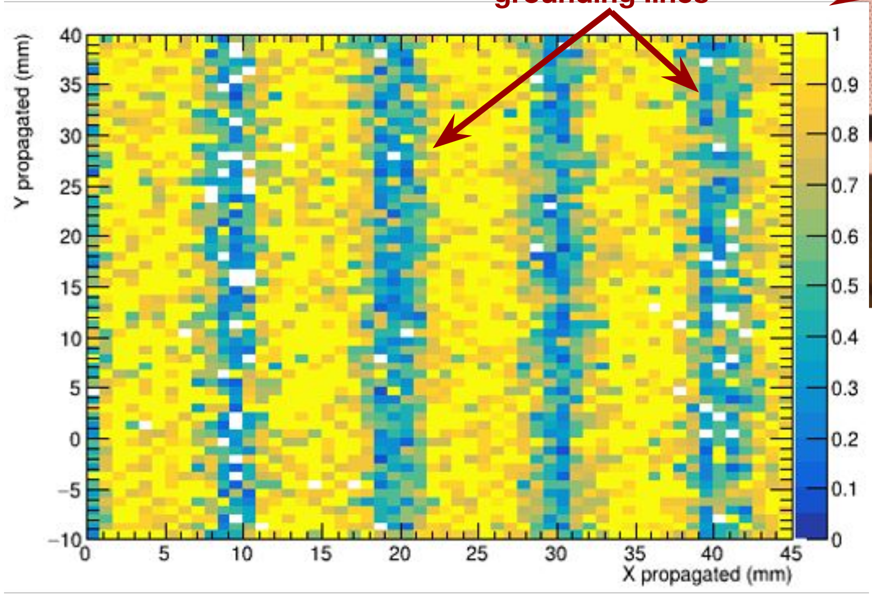


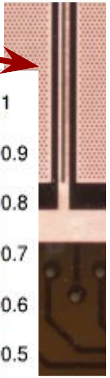
Active layer characterization

Residual distribution

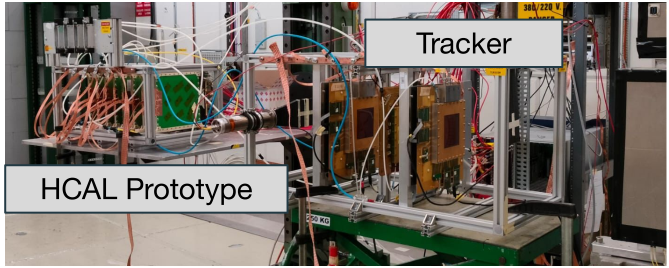


μRWELL occupancy



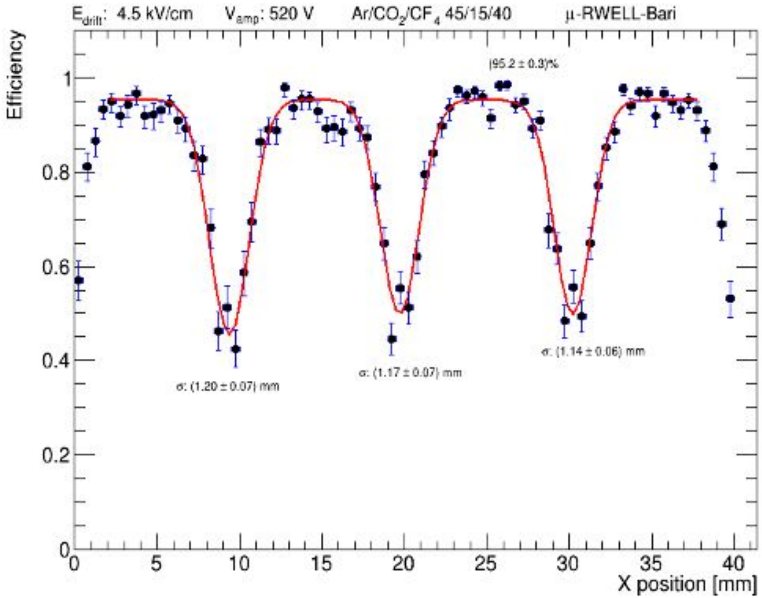


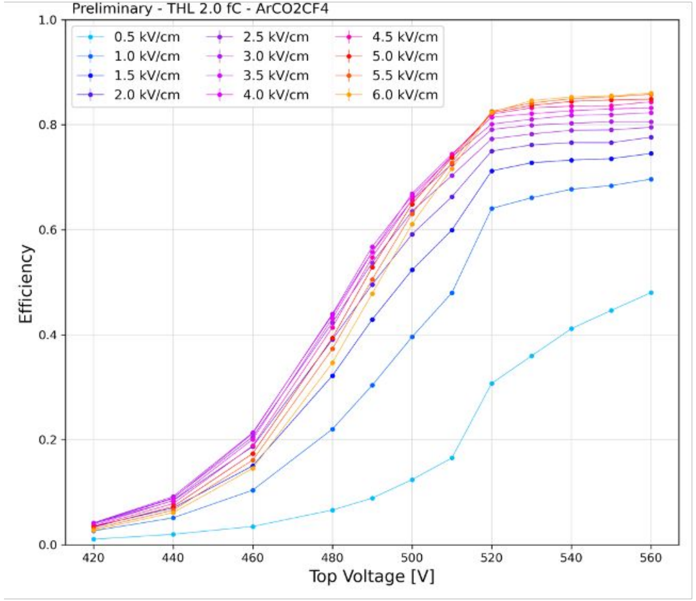
MPGD-HCAL Test Beam



Active layer characterization

µRWELL occupancy

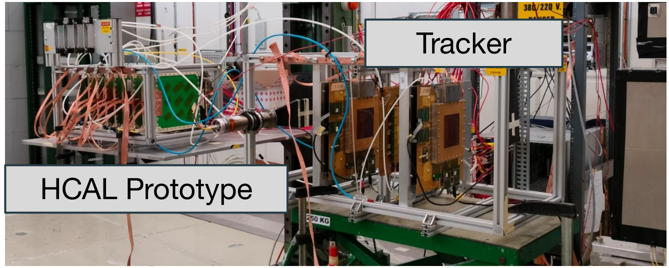




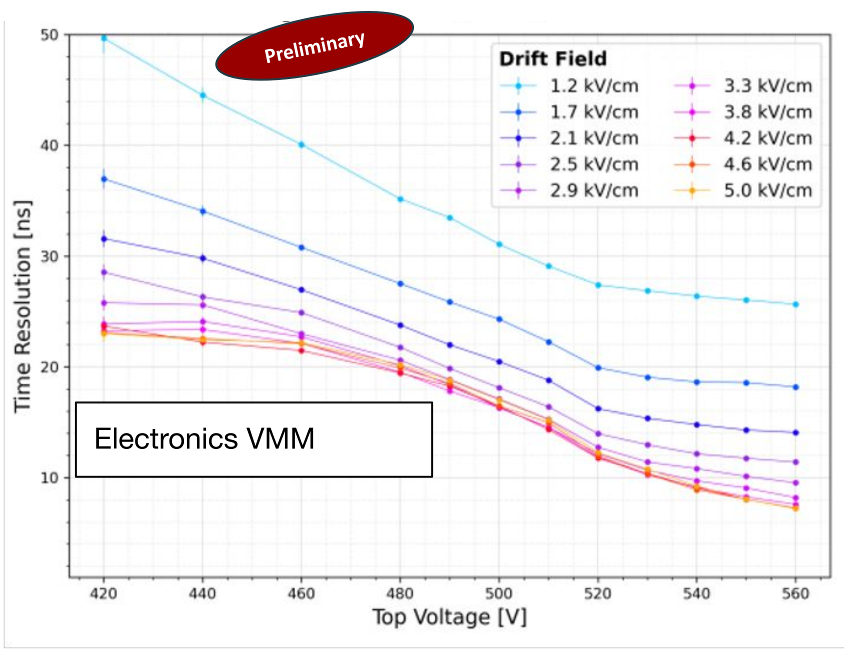
- **Locally very high efficiency ~ 95%**
- Ground lines introduce regions of ~ 1 mm with ~50% efficiency drop
- **Inefficiency** regions can get partially **recovered increasing drift field**

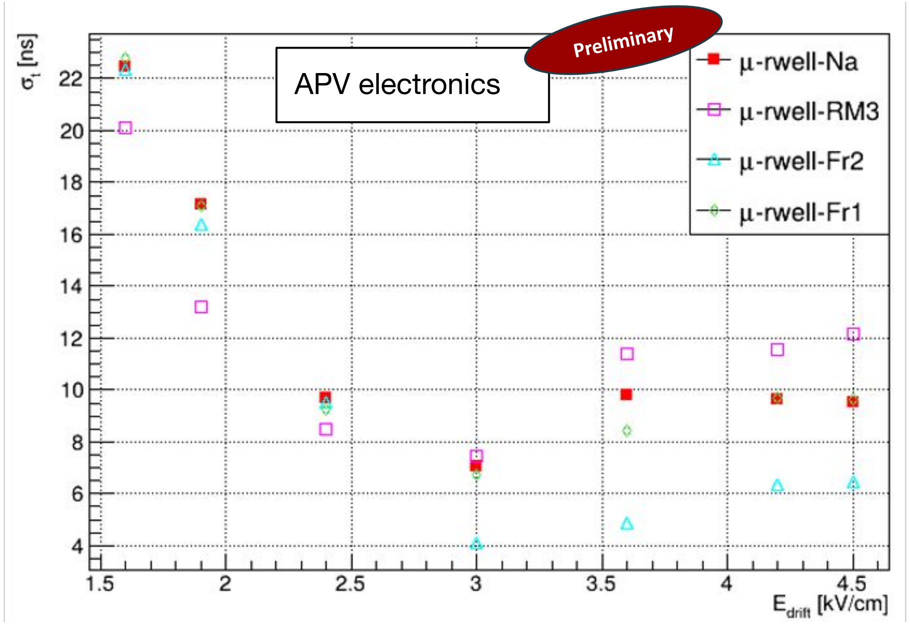
MPGD-HCAL Test Beam

Active layer characterization

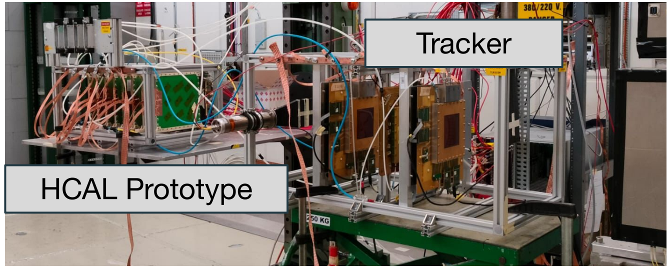


µRWELL timing w/ Ar:CO_2:CF_4 → few ns (~ 6ns) with Drift field of 3 kV/cm; similar results with different electronics





MPGD-HCAL Test Beam

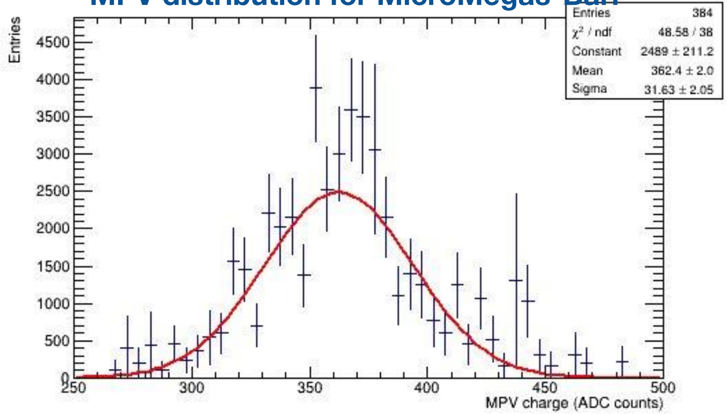


Active layer characterization

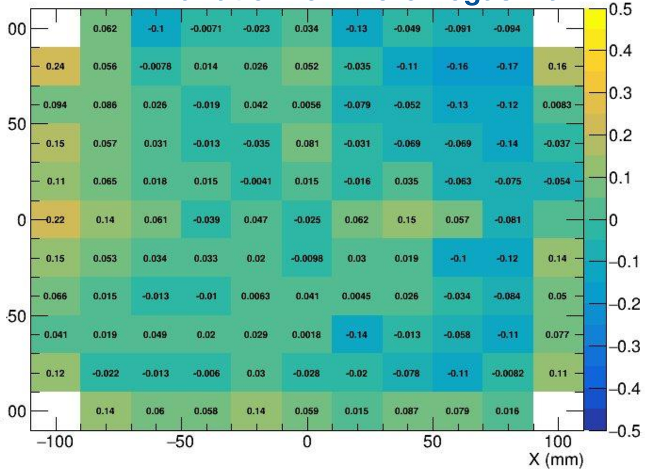
Response uniformity measured using clusters matching muon tracks

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

MPV distribution for MicroMegas-Bari



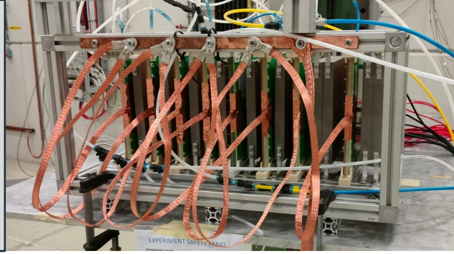
2D-MPV variation for MicroMegas-Bari



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

MPGD-HCAL Test Beam

HCAL Prototype

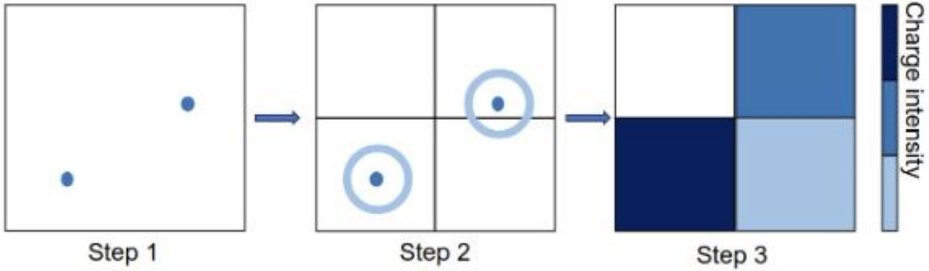


Prototype simulation

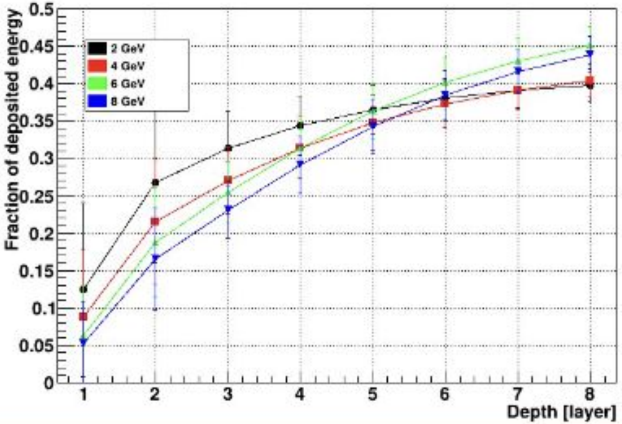
- Small detector geometry implemented
    - 8 layers of alternating of 2 cm stain-less steel absorbers and MPGD
        - First 2 layers with 4 cm absorbers to increase probability of shower development in the first layers
    - 20x20 cm^2 active surface
    - 1x1 cm^2 pad granularity
- Pion gun of energy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

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

Digitization algorithm

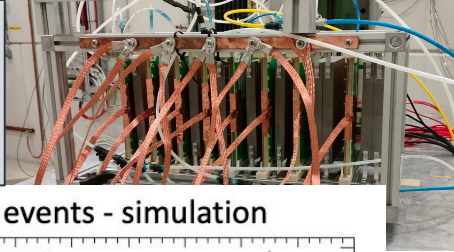


Shower containment



INFN MPGD-HCAL Test Beam

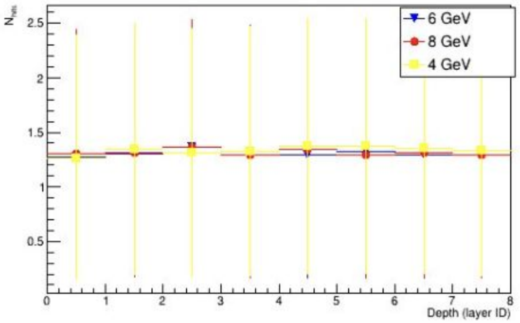
HCAL Prototype



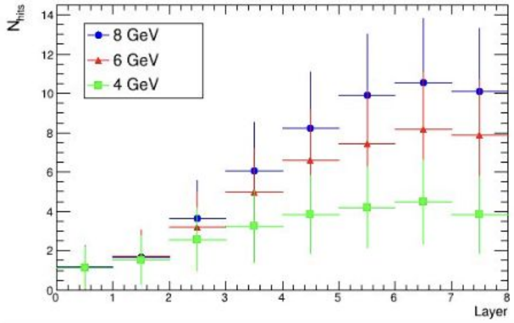
Prototype simulation

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

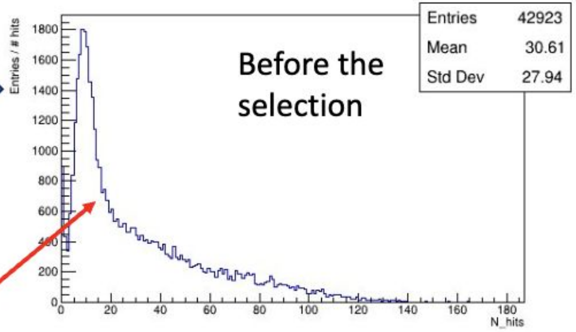


Shower events - simulation



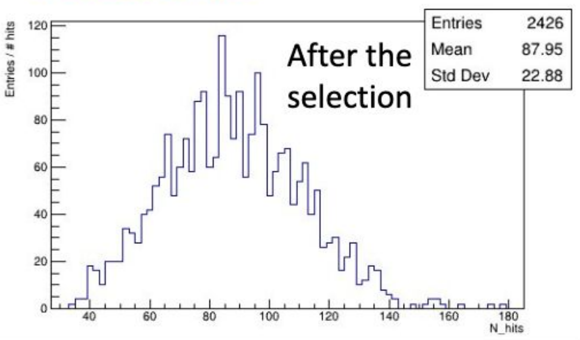
Distribution of the **number of hits** in all active layer from the **experimental data**

Number of hits for all events



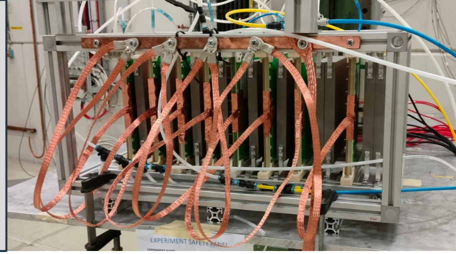
Peak at ~ 10 hits
-> MIP-like events

Number of hits for showers event



MPGD-HCAL Test Beam

HCAL Prototype

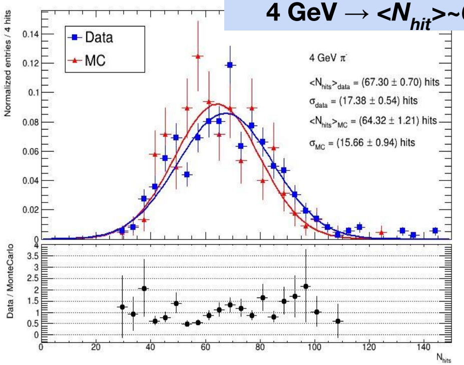


Number of hits distributions for MC and data at different pion energies ($E_\pi = f^{-1}(<N_{hit}>)$)

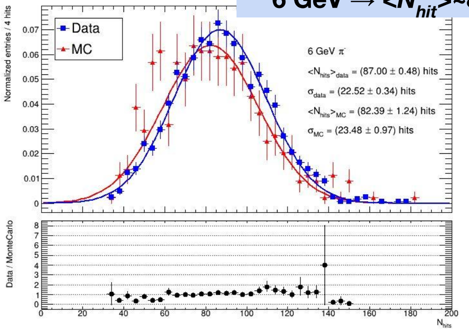
Preliminary

2023 Data

4 GeV → $<N_{hit}>$~67

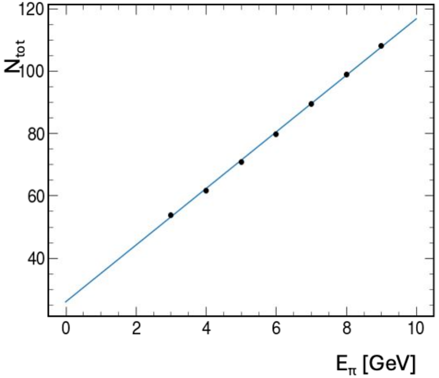


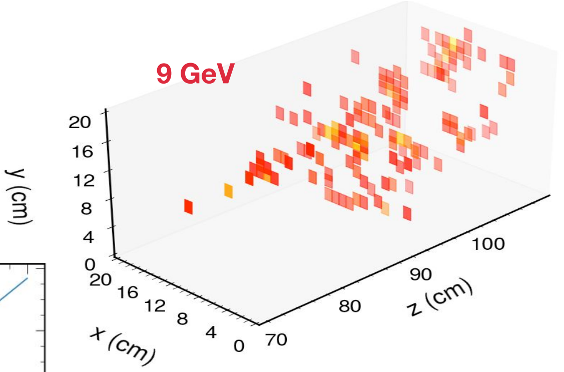
6 GeV → $<N_{hit}>$~87

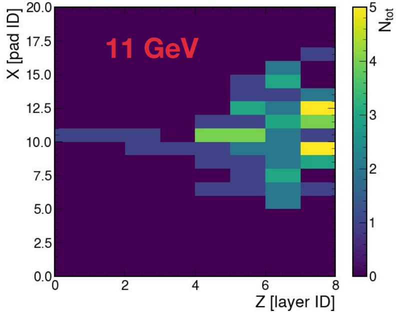


Preliminary

2024 Data





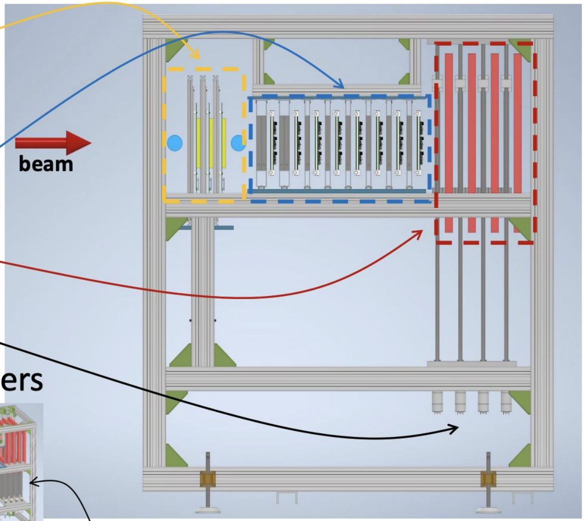


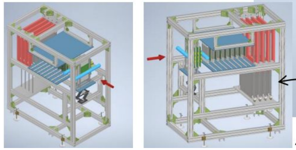
MPGD-HCAL future activities

- Finalize the studies with digital/semi-digital readout for the small prototype:
  - Current semi-digital thresholds not optimized for MPGDs
- Development of a new cell prototype of ~$2\lambda_I$, including 8 20x20cm^2 chambers plus 4 50x50cm^2 chambers:
  - 2 MicroMegas and 2 μRWELL 50x50 cm^2 under production → ready in July/August
  - μRWELL produced with new grounding schema to reduce dead area (ground dots instead of ground lines)

New cell prototype

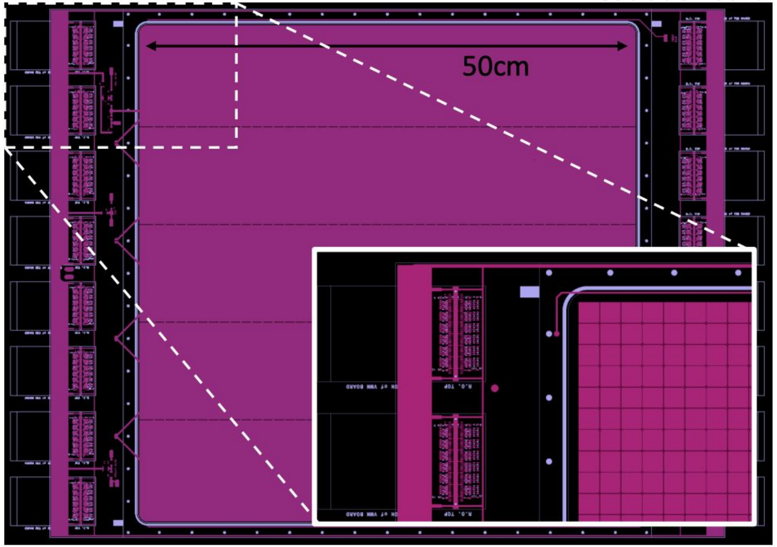
- Triple-GEM tracker
  - Moveable to scan entire surface
- 1λ with 20x20cm^2
  - 8 dets, 8x2cm steel
- 1λ with 50x50cm^2
  - 4 dets, 4x4cm steel
- Allows to insert / extract steel absorbers





Absorbers extracted

Readout Board



Conclusions

- Strong R&D effort on both simulation and characterization at test beam

- Calorimeter prototype and chambers characterization:
  - ~95% efficiency for MicroMegas but lower efficiency for µRWELL (~ 75%) → possibility to recover it changing grounding schema; µRWELL reaches 95% in the area not close to ground lines
  - Good uniformity, ~10% for MicroMegas and ~15% for µRWELL
  - Timing resolution of ~ 6ns → further studies needed in order to reduce time resolution while reducing or replacing CF_4
  - Good linearity between pion beam energy and total number of hits on the calorimeter prototype
  - Good agreement between testbeam data and standalone Geant4 simulation
  - Extension calorimeter prototype to ~ 2 λ_I → important to define the electronics required to fully equip the new prototype.

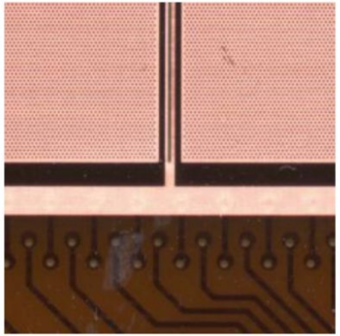
Backup

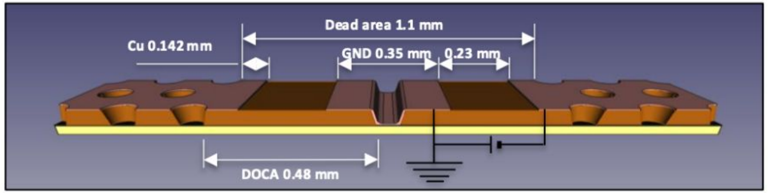
PEP lines Vs PEP dots

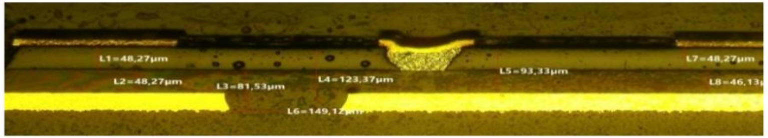
2022

PEP-Groove:
DLC grounding through conductive groove to ground line
Pad R/O = 9×9mm^2
Grounding:
- Groove pitch = 9mm
- width = 1.1mm

→ 84% geometric acceptance



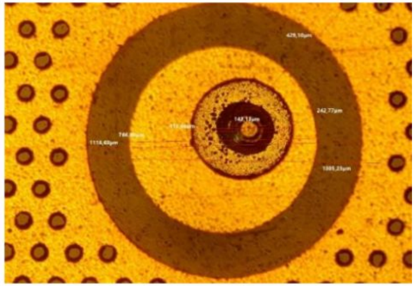




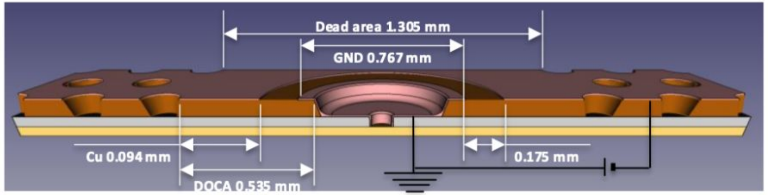
2023

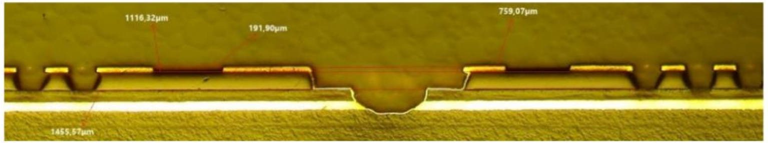
PEP-DOT:
DLC grounding through conductive dots connecting the DLC with pad r/outs
Pad R/O = 9×9mm^2
Grounding:
- Dot pitch = 9mm
- dot rim = 1.3mm

→ 97% geometric acceptance



DOT → plated blind vias

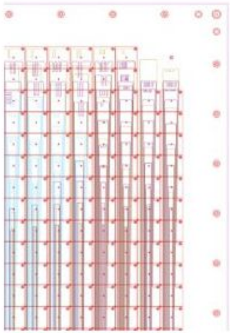


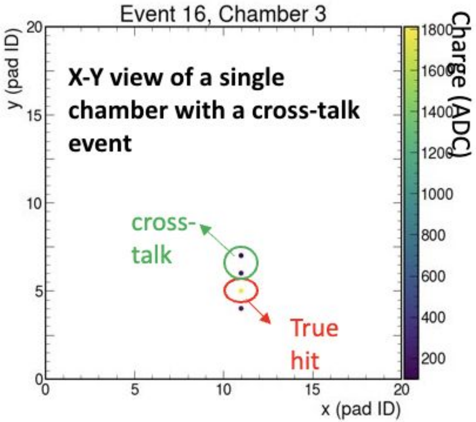


https://indico.cern.ch/event/1413681/contributions/6013367/attachments/2881828/5049134/The%20micro-RWELL%20for%20high-rate.pdf

Cluster reconstruction

Preliminary

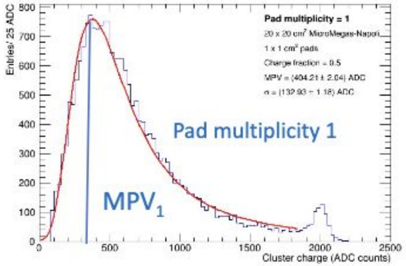


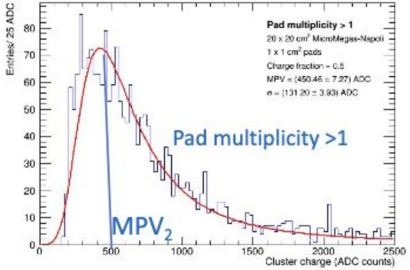


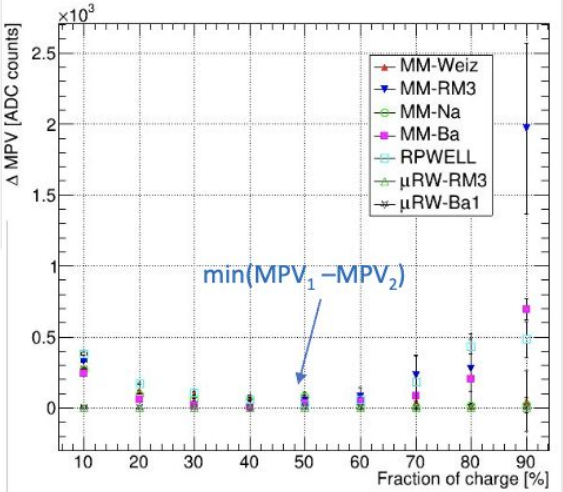
High probability of **cross-talk** effect observed among adjacent pads due to routing of the vias connecting pads to the connectors

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

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

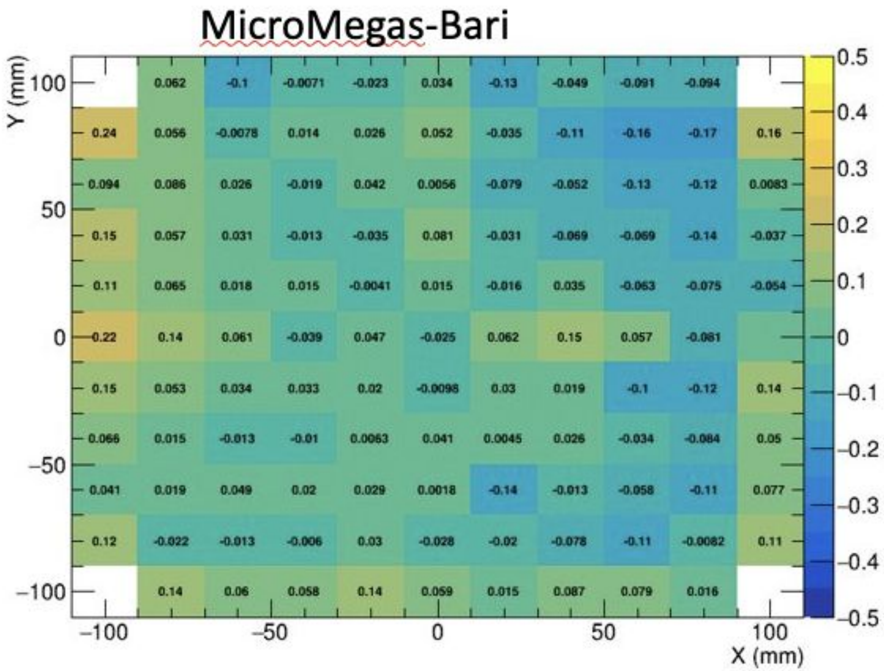


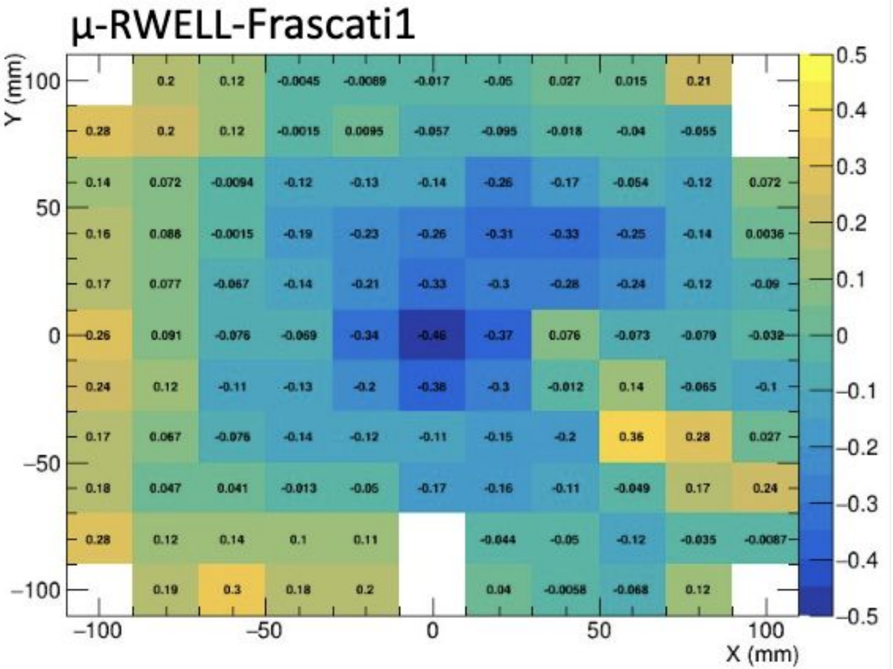




Response uniformity

Preliminary





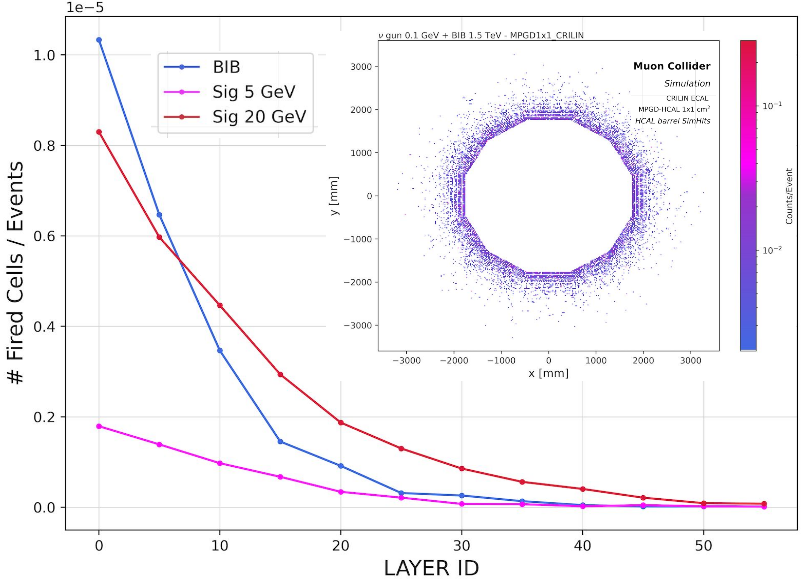
Application example

MPGD-HCAL BIB studies

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

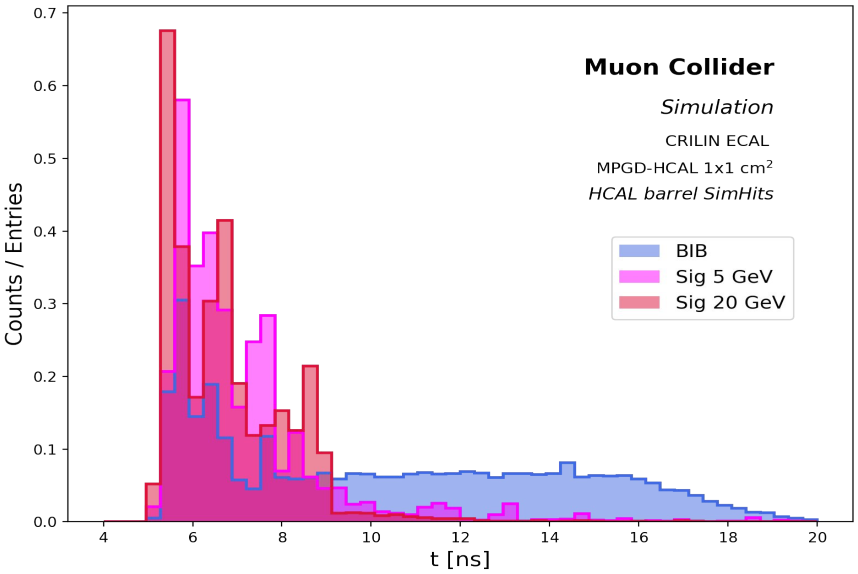
Hit Occupancy:

- **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



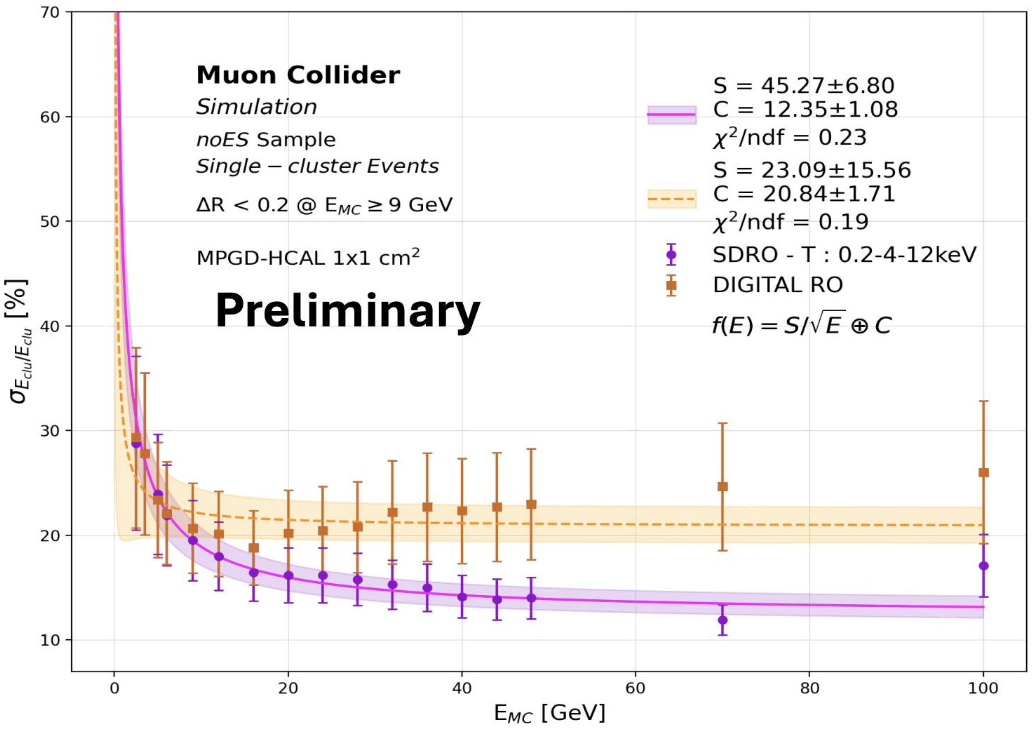
Arrival time:

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



Digital Vs Semi-digital readout

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



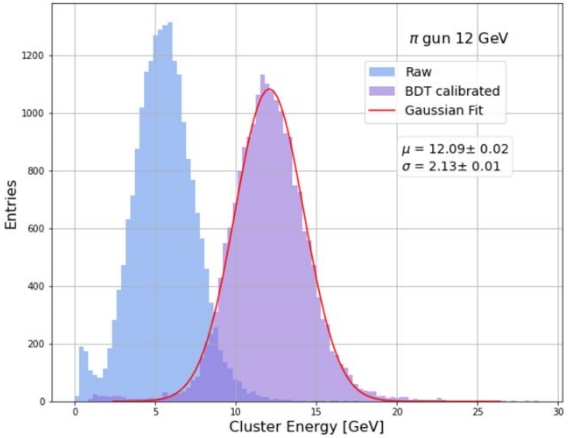
- $\pi^{\pm}$ guns with energy ranging from 2.5 to 100 GeV;
- MPGD-HCAL with 1x1cm^2 pads
- **only pions not showering in ECAL**;
- Digital ReadOut (RO) and SemiDigital RO (SDRO), with **linear calibration**
- fit function $f(E)=S/\sqrt{E}\oplus C$;
- comparable performances below 6 GeV between Digital RO and SDRO
- **Digital RO: saturation at high energies**
- **Overall, better performances of the SDRO**
  - $\sigma/E \sim 45\%/\sqrt{E}\oplus 12\%$

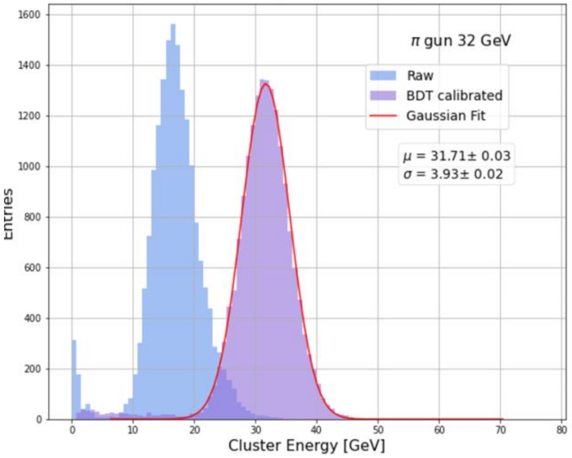
Semi-digital readout with BDT calibration

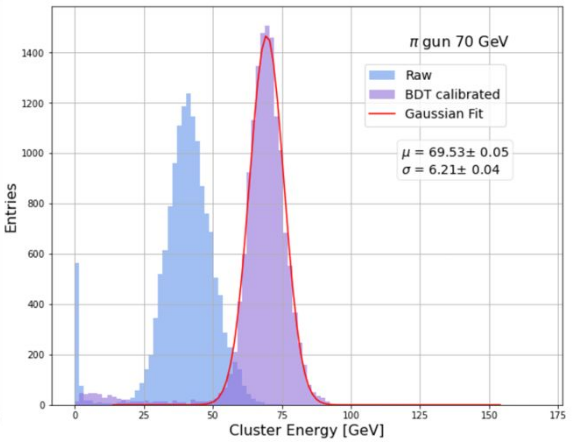
Calibrated energy = BDT output coefficient x Raw cluster energy

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

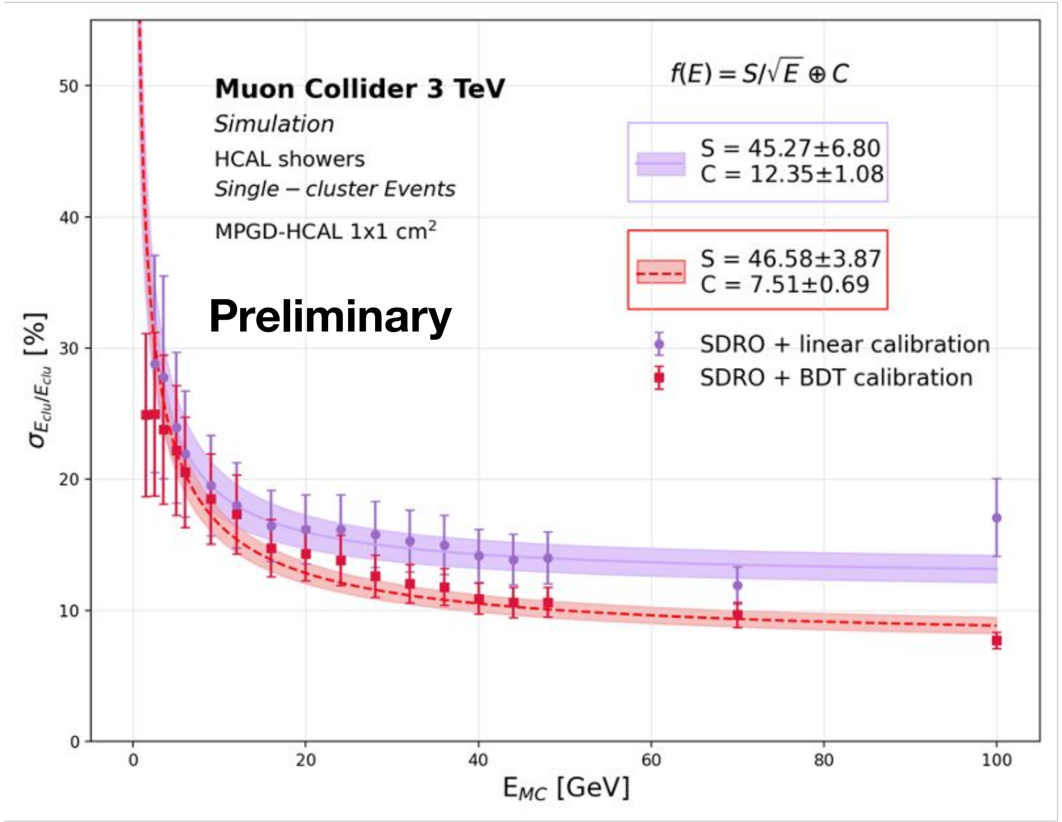






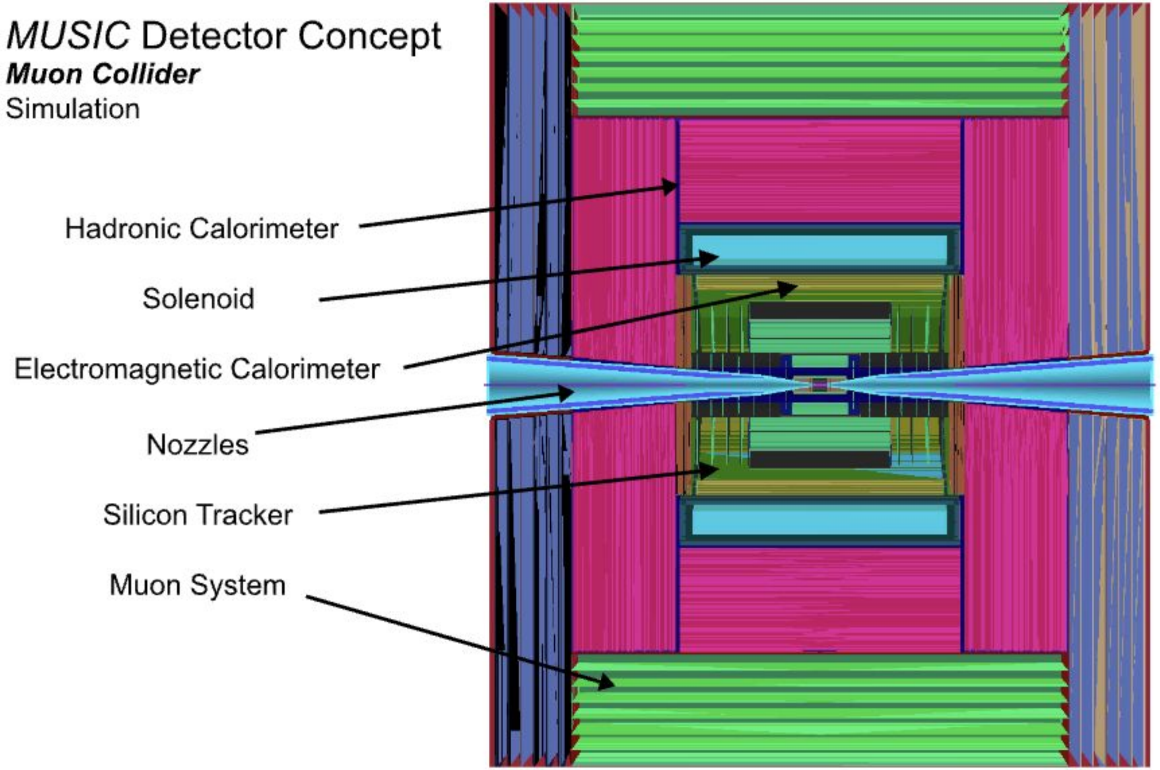
Semi-digital readout with BDT calibration

Calibrated energy = BDT output coefficient x Raw cluster energy



- **only pions not showering in ECAL**;
- fit function $f(E)=S/\sqrt{E}\oplus C$;
- **Better energy resolution for E_{MC}>10 GeV**
- compatible stochastic term S ~ 45%
- **Significant reduction of the constant term C: 12% → 7%**

MPGD-HCAL within MUSIC - 10 TeV



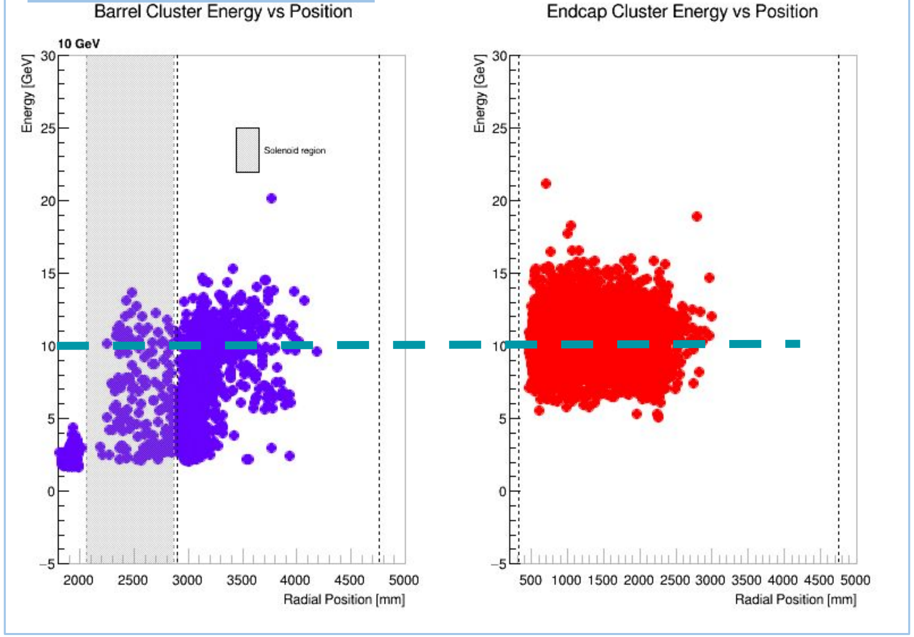
- **70 Layers of ArCO2 (3mm)/ Iron (20mm)**
- **HCAL is outside the 80 cm solenoid (barrel only)**

MPGD-HCAL within MUSIC - 10 TeV

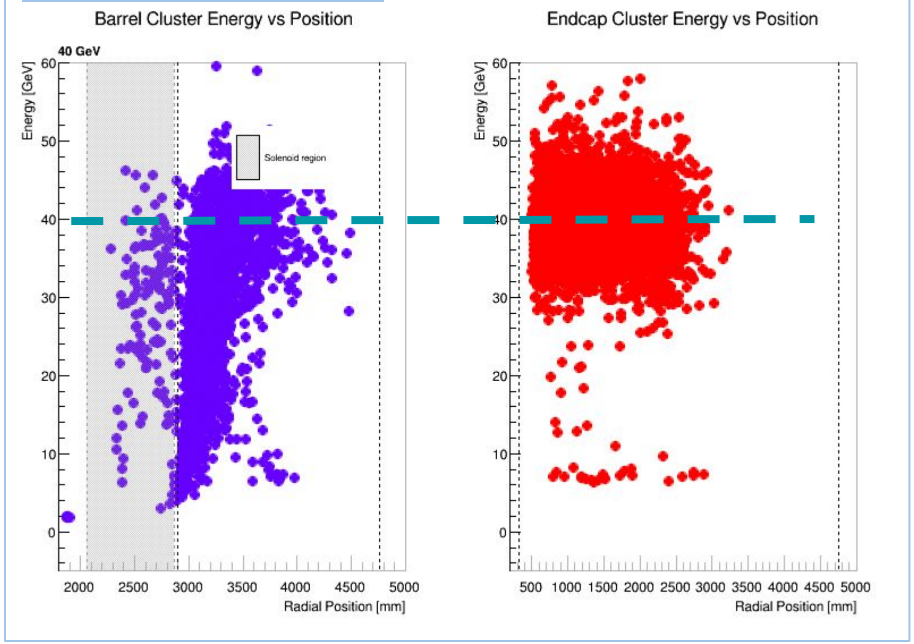
Impact of the solenoid on HCAL - pion guns

Preliminary

True Energy = 10 GeV



True Energy = 40 GeV

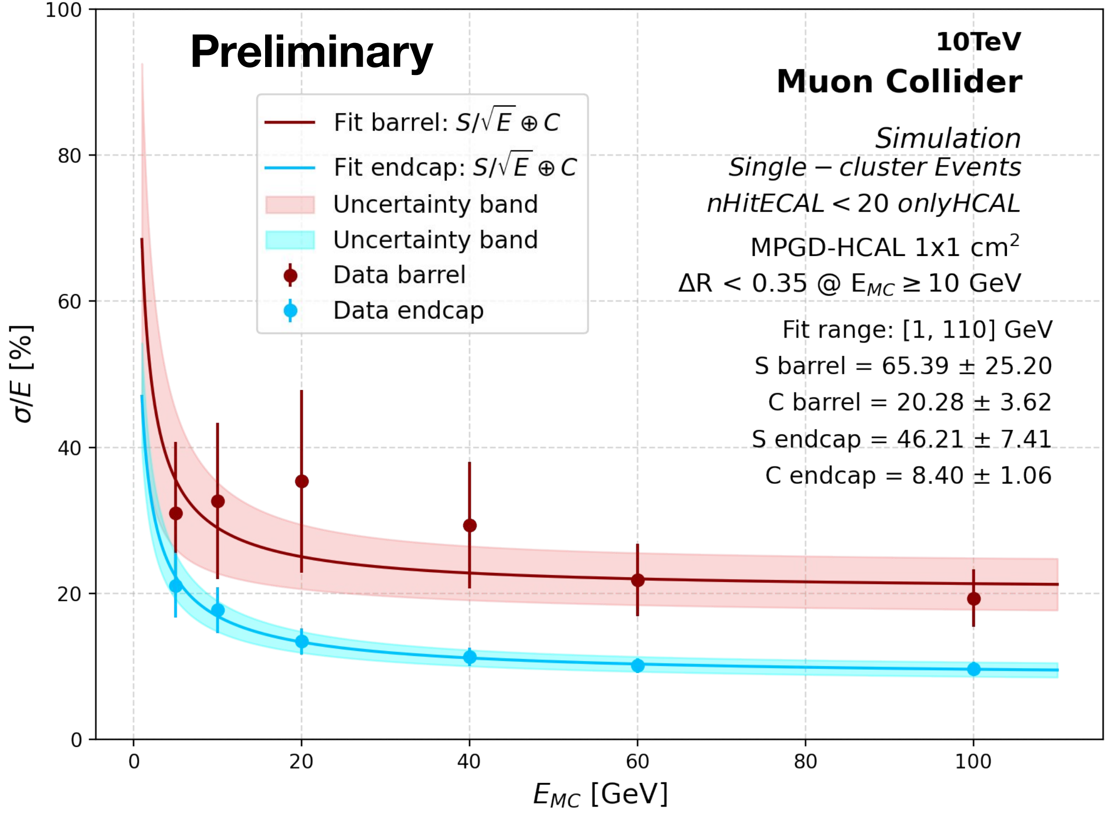


Depending of the hadrons energy, the **shower can initiate in the solenoid**:

- 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**

MPGD-HCAL within MUSIC - 10 TeV

Impact of the solenoid on HCAL - pions gun



- **only pions not showering in ECAL**;
- SemiDigital RO (SDRO), with linear calibration
- Energy resolution evaluated separately between end-cap and barrel region;
- **End-cap resolution compatible with 3 TeV, even with better constant term:**
  - Improvement thanks to the 10 extra layers
- **Worsening of barrel resolution:**
  - Further development needed to recover the hadrons showering in the solenoid