Development of MPGD-based hadronic calorimeter for a future Muon Collider experiment

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PhD defense – 36° cycle

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Supervisors

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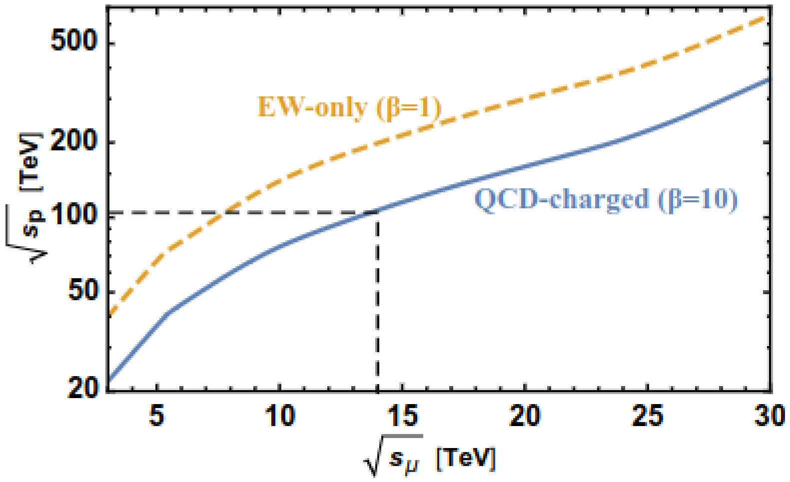
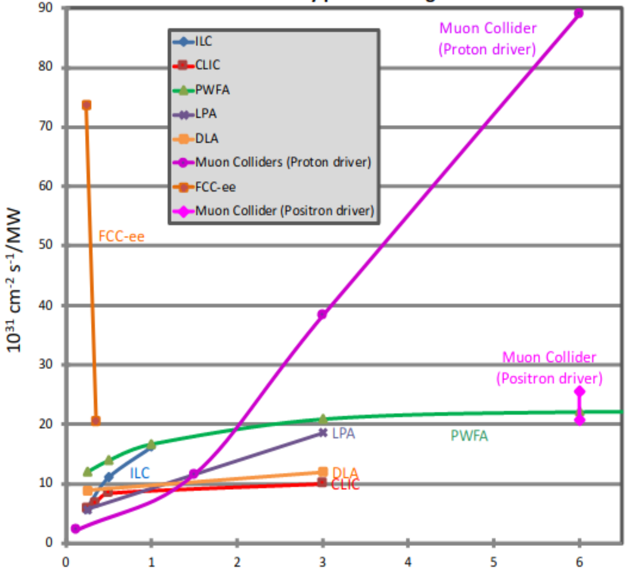
Outline

- **Motivations**
  - MPGD-HCAL at Muon Collider
- **Monte Carlo Simulation in GEANT4 on calorimeter prototype**
  - Shower containment
  - Energy resolution with Digital and Semi-Digital RO
- **Characterizations of MPGD prototypes**
  - Efficiency, Uniformity
- **R&D on small-size calorimeter prototype**
  - Data-MC comparison
- Conclusions and future plans

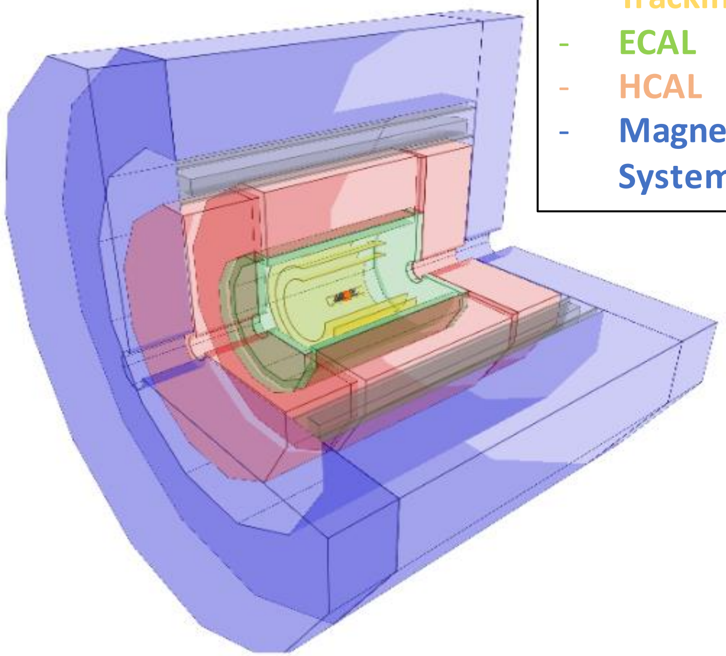
The Multi-TeV Muon Collider experiment

Advantages:
- multi-TeV energy range in **compact circular** machines;
- well **defined initial state** and **cleaner final state**;
- all **collision energy available** in the hard-scattering process.



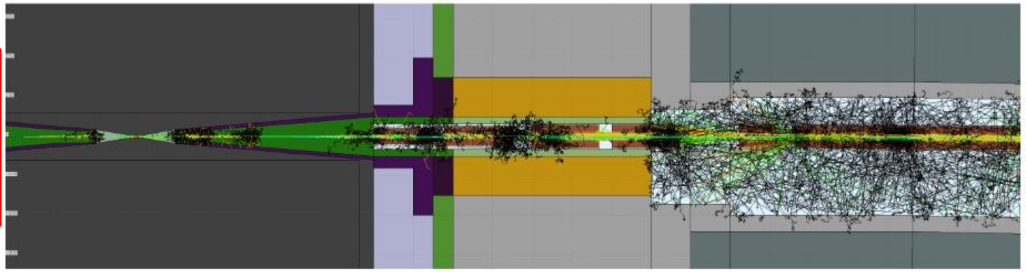


Towards a Muon Collider arXiv:2303.08533



Section of the Muon Collider experiment:
- Tracking system
- ECAL
- HCAL
- Magnet return yoke + Muon System

Tracks of BIB particles in interaction region

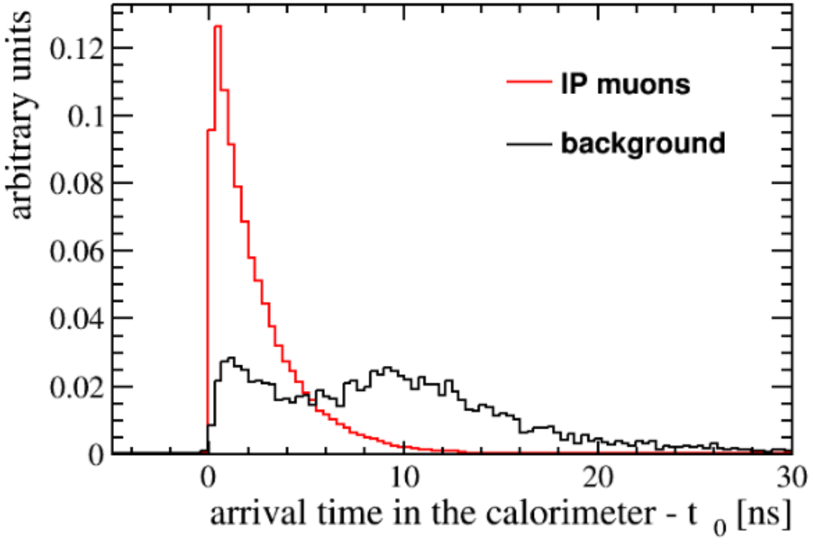


Challenges:
- muon is an **unstable** particle
  intense flux of background particles: **beam-induced background (BIB)**.

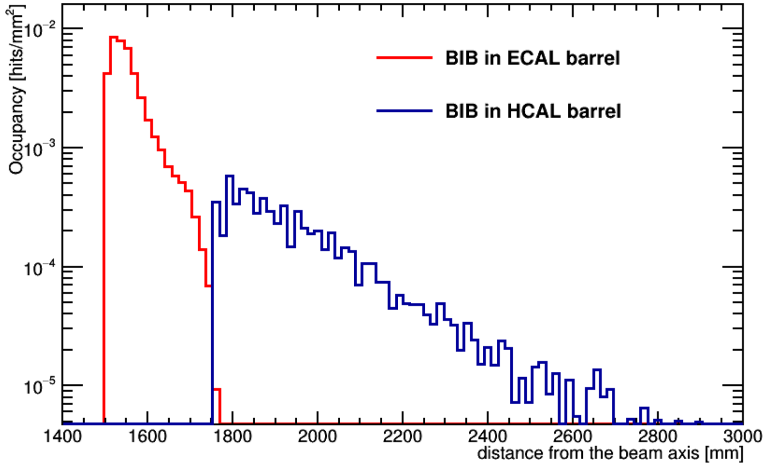
Towards a Muon Collider arXiv:2303.08533

Challenges for HCal design

Beam Induced Background in HCAL:
- Mostly photons (96%) and neutrons (4%)
- Asynchronous time of arrival
- Occupancy ~ 0.06 hit/cm^2 (x10 the one at HL-LHC)



HCAL requirements:
- Radiation hard technology
  - total ionizing dose: 10^{-5} GRad/year
- Good time resolution (O(ns))
- Good energy resolution
  - ~ 10% / √E for ECAL
  - ~ 55% / √E for HCAL
- Fine granularity (1 – 3 cm^2)
- Longitudinal segmentation



MPGD-based HCAL for Muon Collider

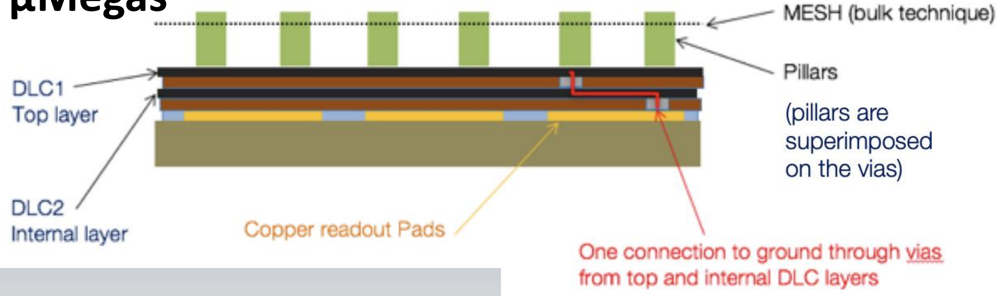
Why resistive MPGDs for calorimeters?

- Radiation hardness (up to few C/cm^2)
- High rate-capability O(MHz/cm^2)
- High granularity
- Response uniformity
- Cost-effective for large area instrumentation
- Operational stability (low discharge rate)
- Time resolution with MIPs of few ns

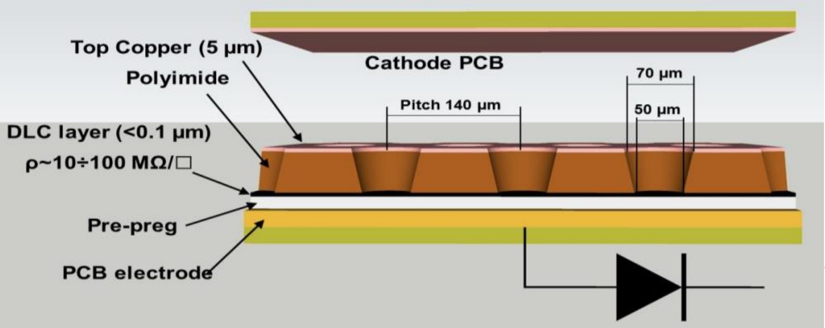
CALICE collaboration investigated the sampling calorimeter with RPCs and MicroMegas

3 MPGD technologies studied in this thesis

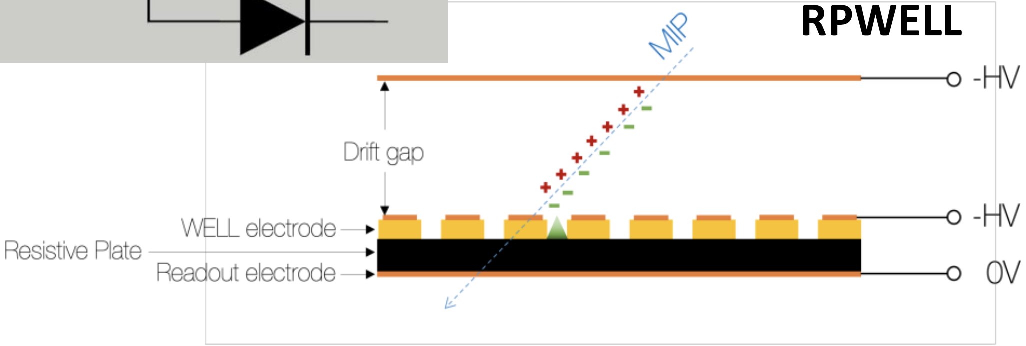
μMegas



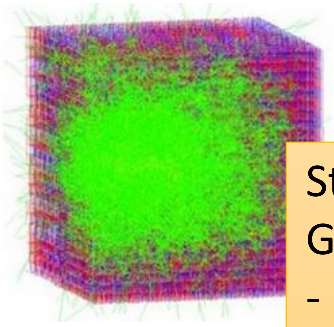
μ-RWELL



RPWELL

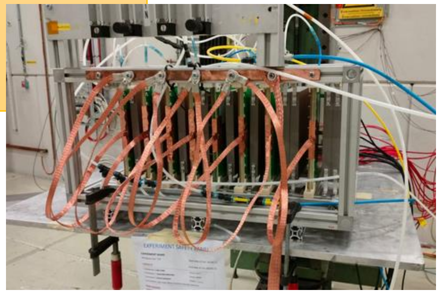


MPGD-HCAL R&D strategy for Muon Collider



Stand-alone simulation with GEANT4
- Design optimization, provide input parameters for full simulation and experimental data

Test on a MPGD calorimeter prototype
- Assess the performance of an active layer and within calorimeter system



GOAL of my work

1. **Proof of MPGD-based HCAL concept with stand-alone Monte-Carlo simulation**
2. **Characterization of the single detector response to MIPs**
3. **Test the performance of resistive MPGD in a calorimeter prototype for the first time**

Monte Carlo Simulation in GEANT4 on a calorimeter prototype

Shower containment

Implemented geometry

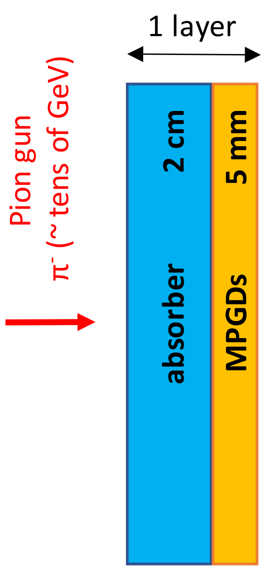
- Sampling calorimeter made of
    - 2 cm for the **absorber** (iron)
    - 5 mm of **active layer** (Ar/CO_2)
    - Cells of granularity
        - $1x1\ cm^2$ and $3x3\ cm^2$
- 30,000 simulated events

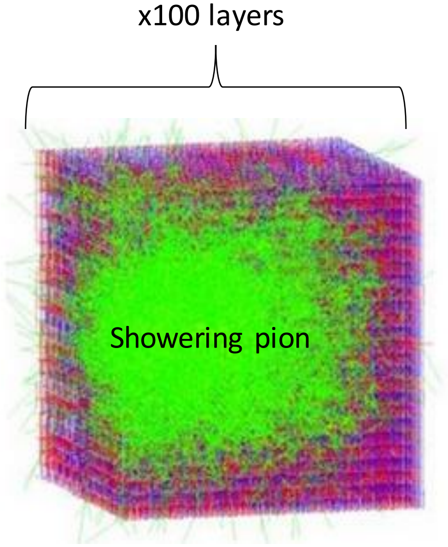
Results:

Energy contained at 90% within

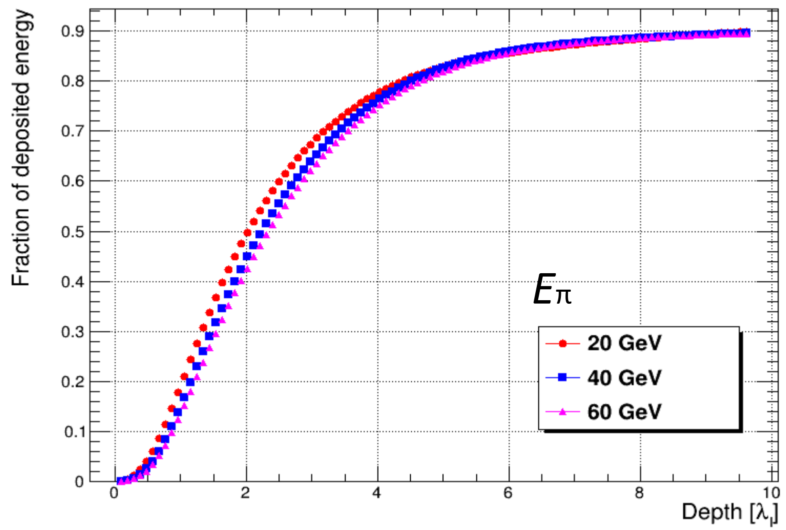
- ~ 10 λ_I in the direction of the incoming π
- ~ 2 λ_I in the orthogonal direction

Compatible with geometrical constraints of MuCol experiment

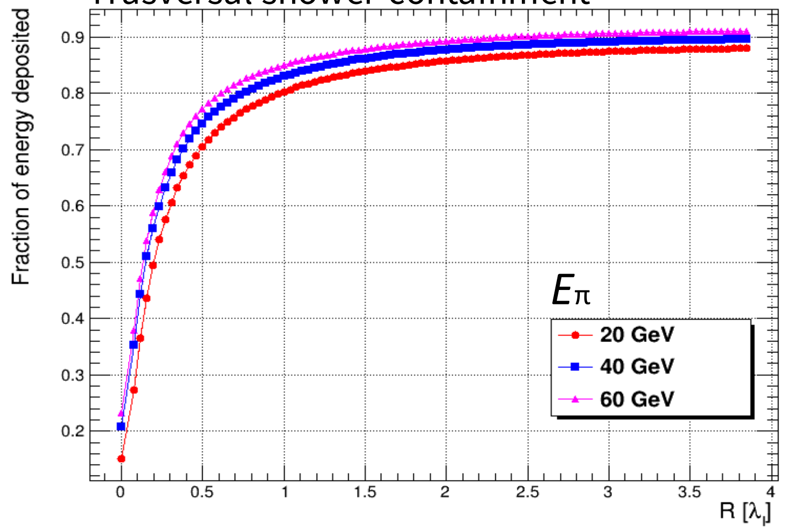




Longitudinal shower containment



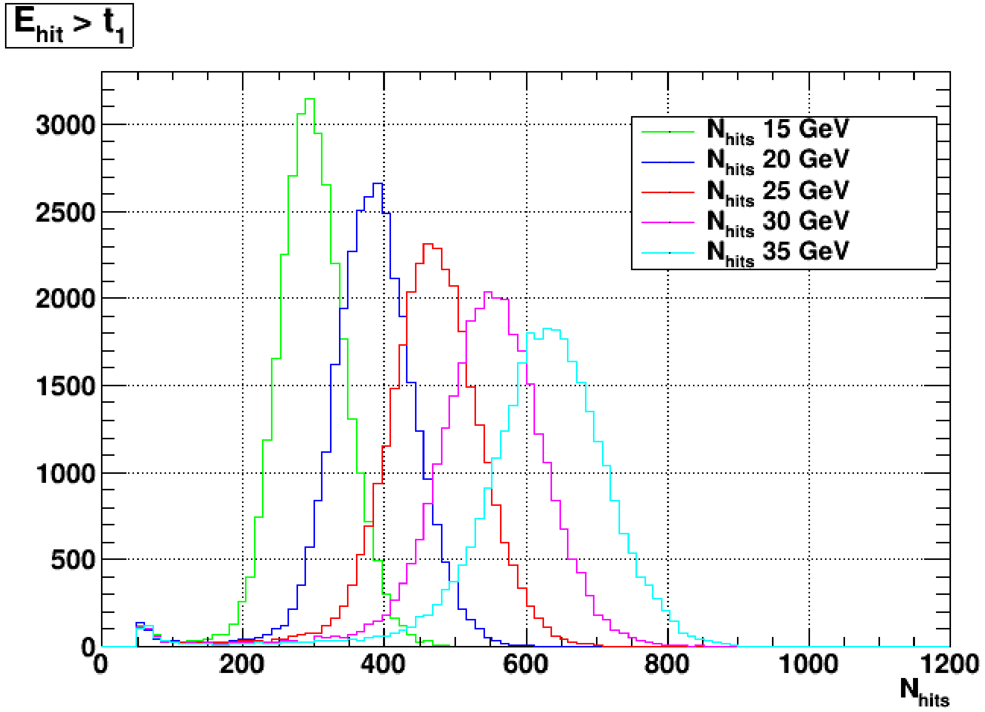
Trasversal shower containment



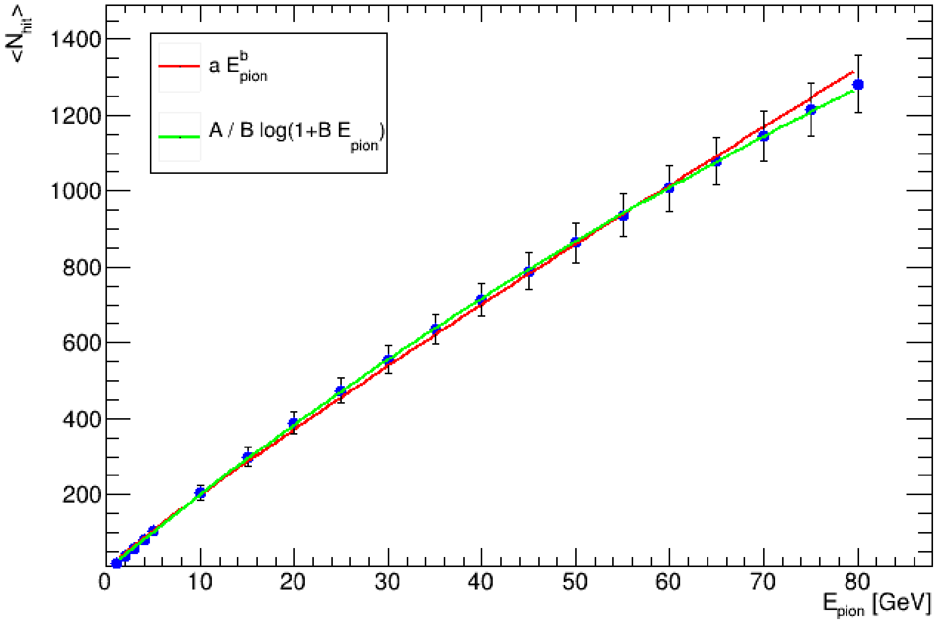
Energy reconstruction: Digital Readout (DHCal)

Working principle: The number of hits is **proportional** to the energy of the hadronic shower

Digitization: 1 hit : 1 cell with deposited energy higher than the applied threshold t_1



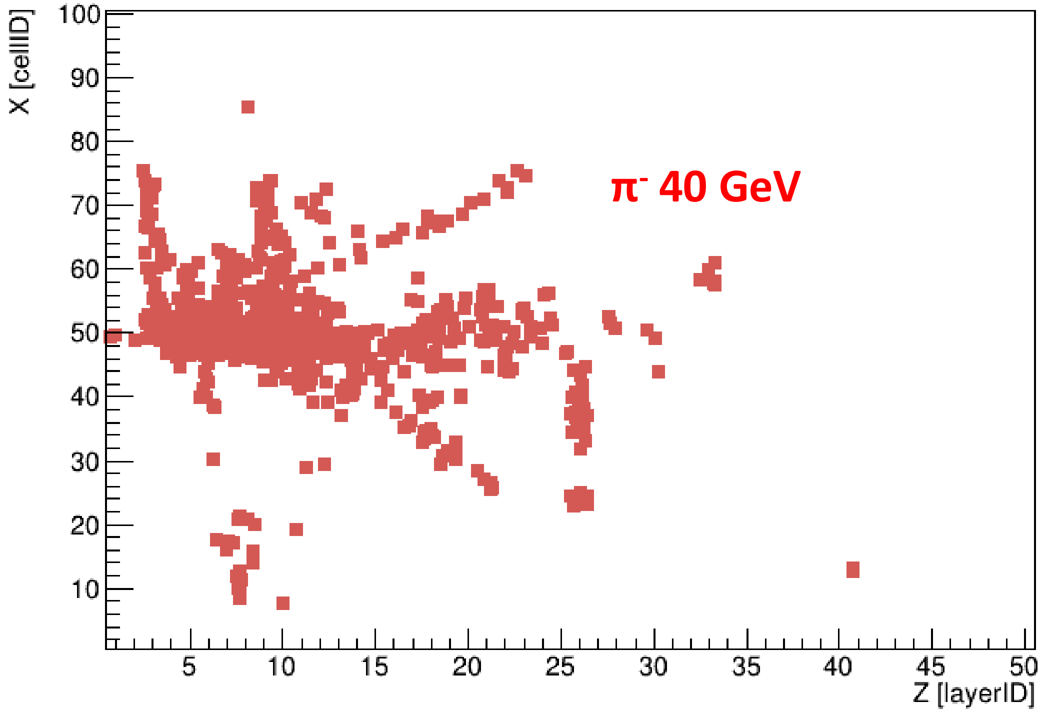
Calorimeter response function: $N_{hit} = f(E_{pion})$



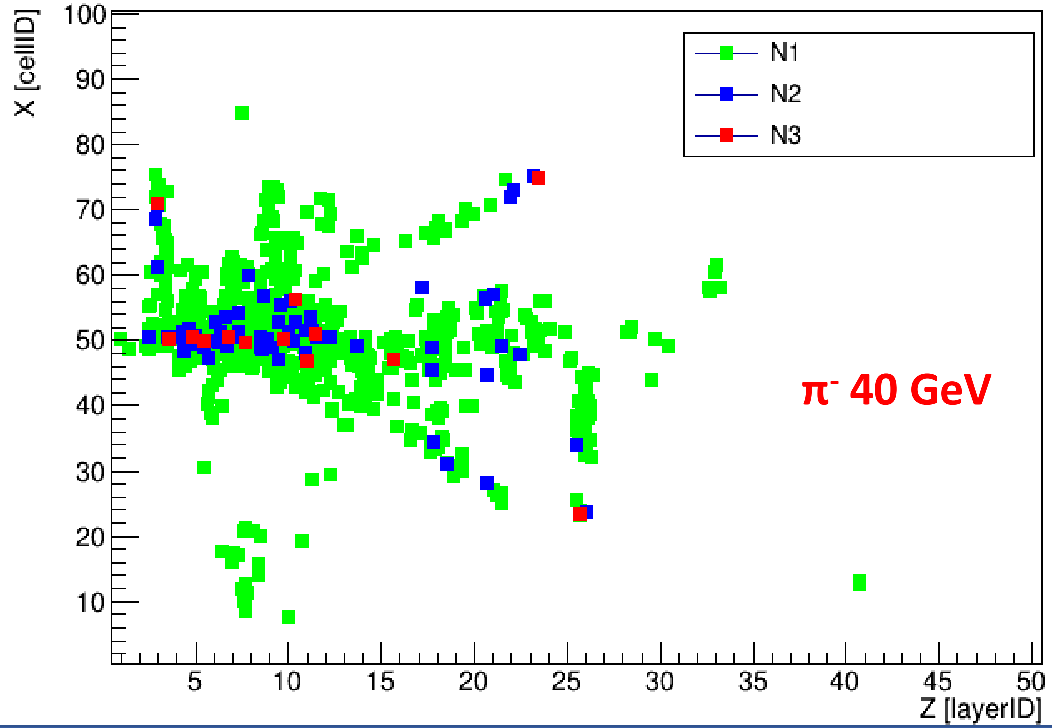
Energy reconstruction: Semi-digital Readout (SDHCal)

- **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
  - α, β, γ parameters obtained by χ^2 minimization procedure

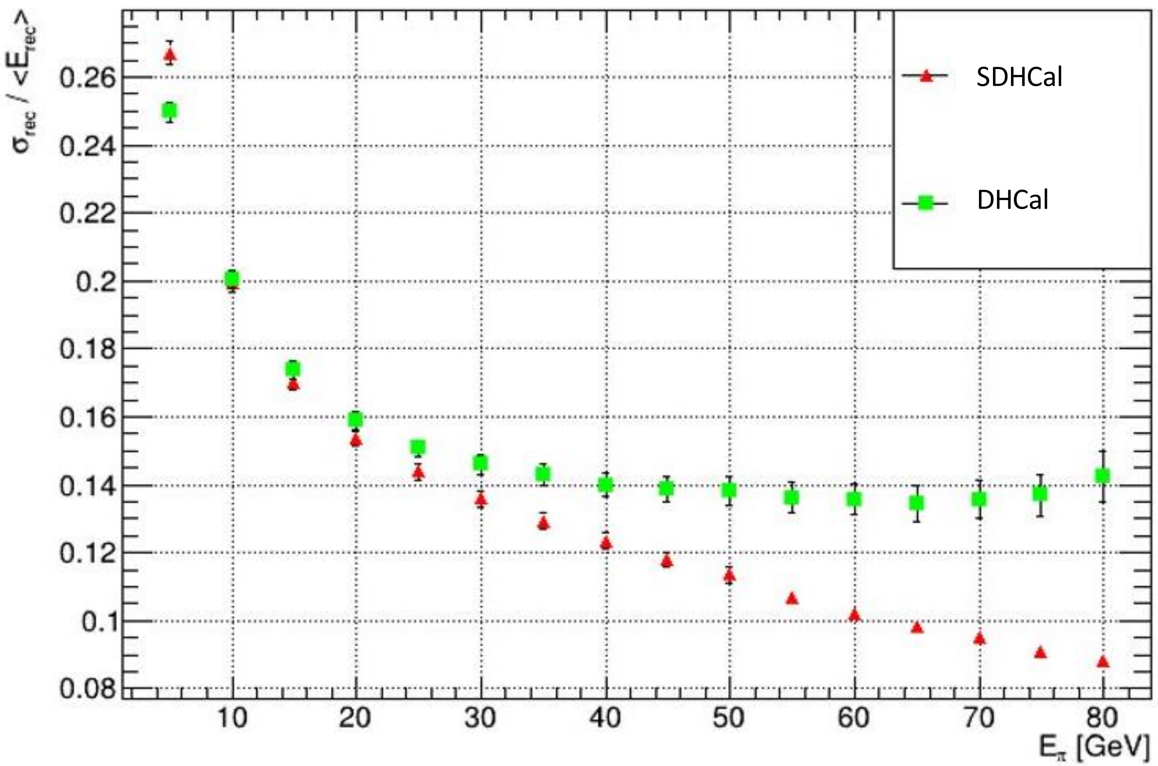
DHCal



SDHCal



Energy resolution – DHCal and SDHCal comparison



Granularity 1x1 cm²

SDHCAL shows better resolution for E_π > 40 GeV
At E_π= 80 GeV, the resolution

- DHcal ~ 14%
- SDHcal ~ 8%

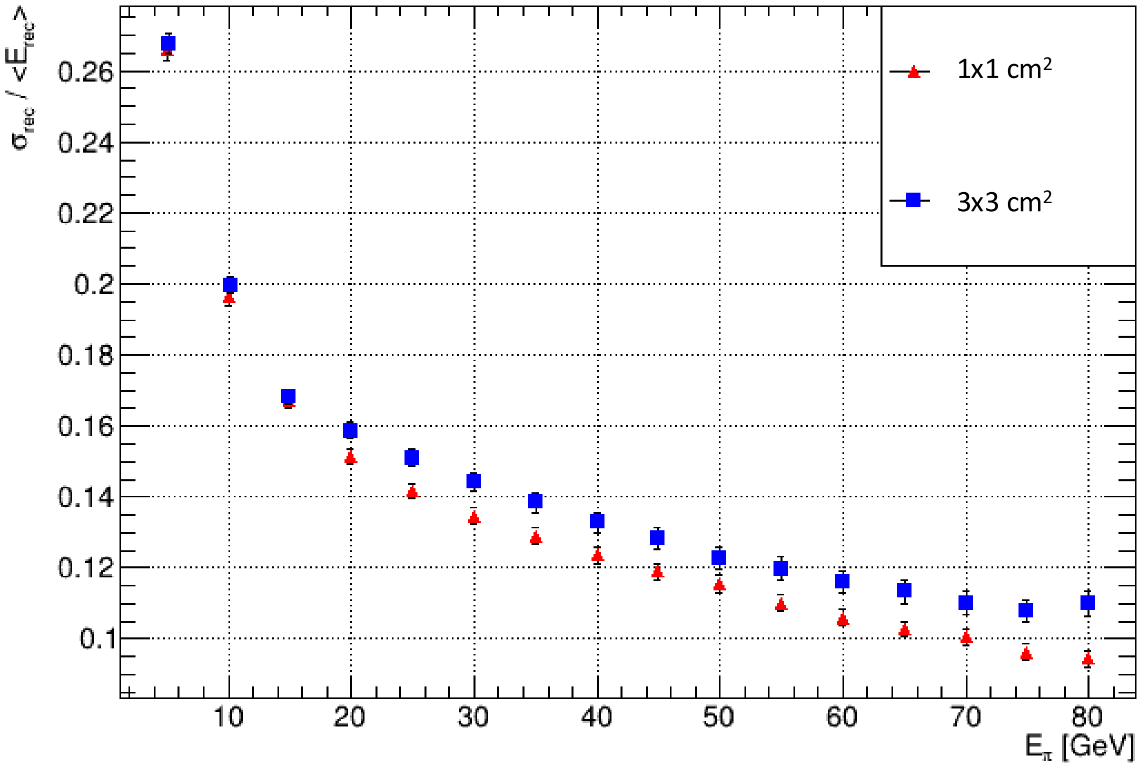
DHcal suffers from **saturation effect** of N_{hit} – the only variable used for reconstruction – for E_π > 40 GeV

Results consistent with CALICE

Presented in PM2022

Energy resolution: 1x1 cm^2 vs 3x3 cm^2 cell size for SDHcal

Workflow implemented also for cell size of 3x3 cm^2 to evaluate impact of granularity on the energy resolution



At E_π= 80 GeV, the resolution

- SDHcal 3x3 cm^2 ~ 11%
- SDHcal 1x1 cm^2 ~ 9%

Comparable results for both granularities with semi-digital RO without including the environmental background effect

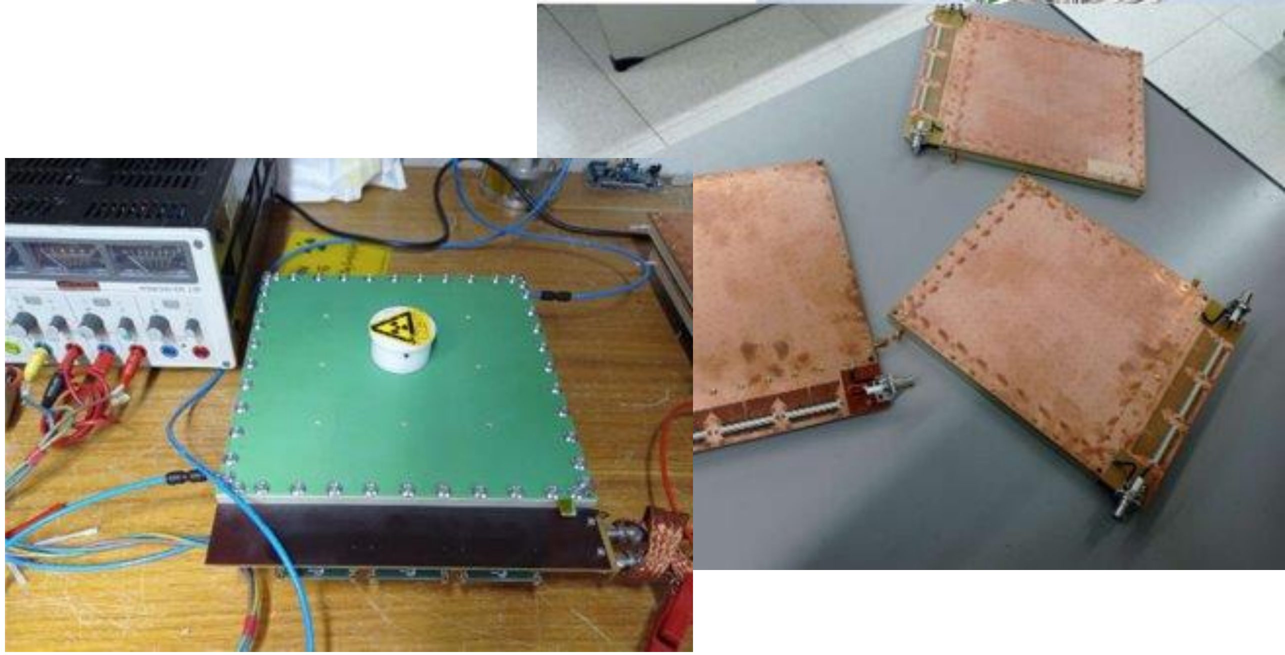
Characterization of MPGD prototypes

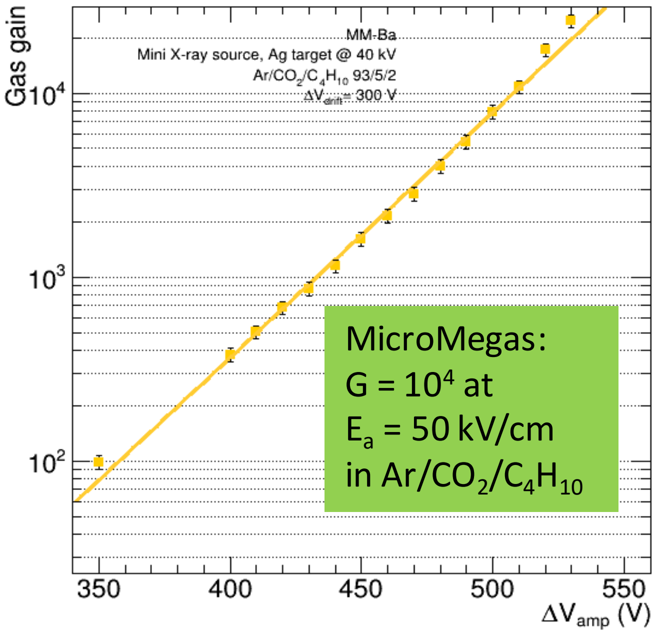
MPGD prototypes

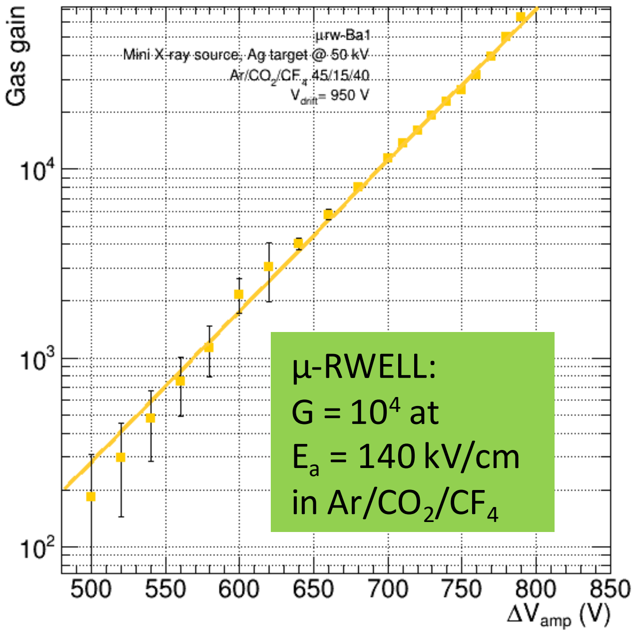
- **MPGD** :
- 7 μ-RWELL (Ba1, Ba2, Fr1, Fr2, Weiz, RM3, Na)
- 4 resistive MicroMegas (Ba, Weiz, RM3, Na)
- 1 RPWELL (Weiz)

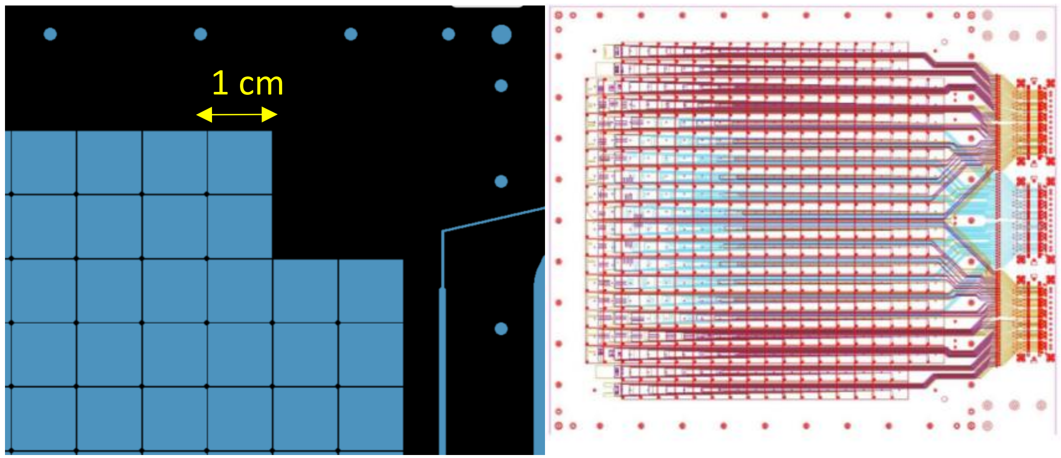
- detector size: 20x20 cm^2
- **Common readout** board
  - $1x1cm^2$ pad→ 384 pads

First characterizations in terms of effective gain using X-ray performed in lab





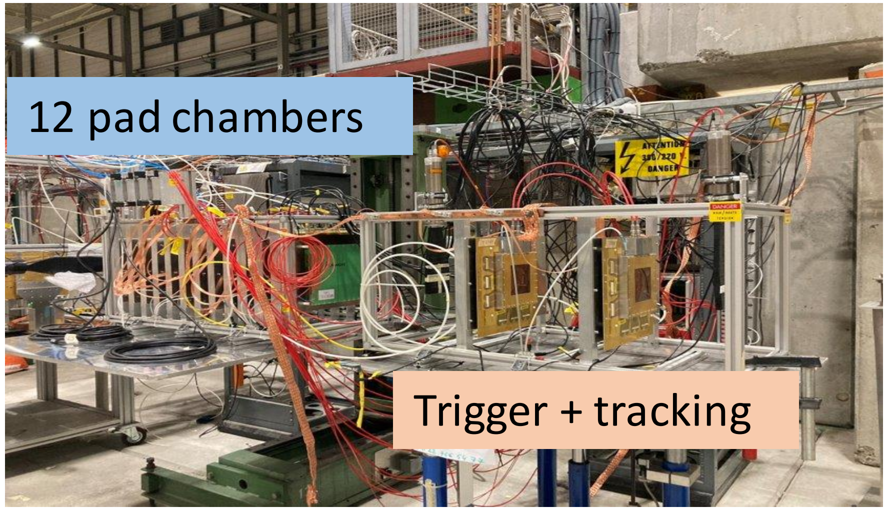


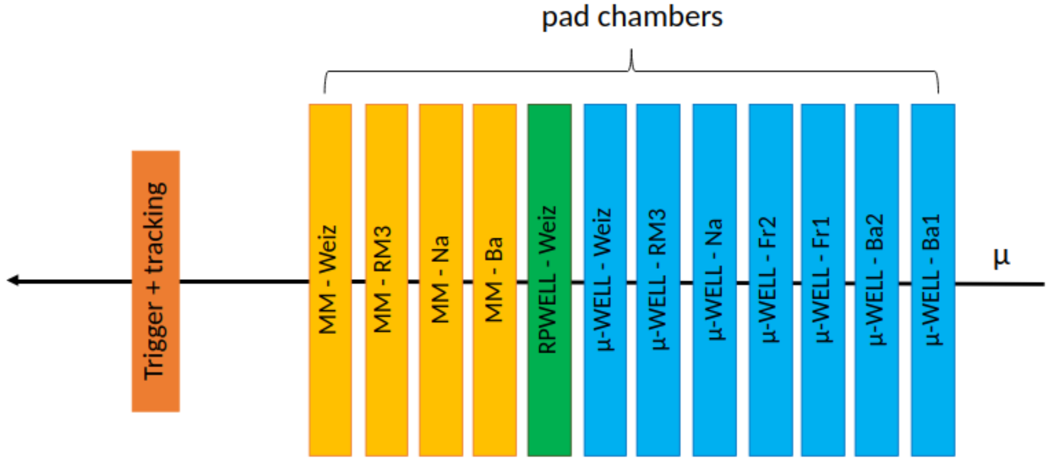


MPGD-HCAL prototype - SPS test beam

SPS test beam with μ beam at O(100 GeV) to validate and compare the technologies measuring:

- **Efficiency**
- **Response uniformity**





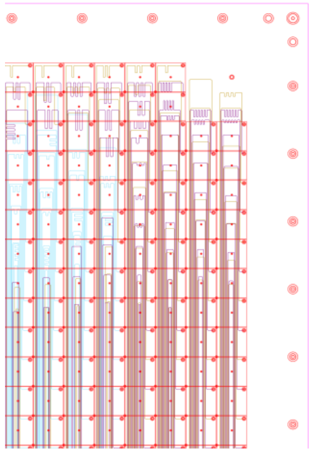
APV25 SRS

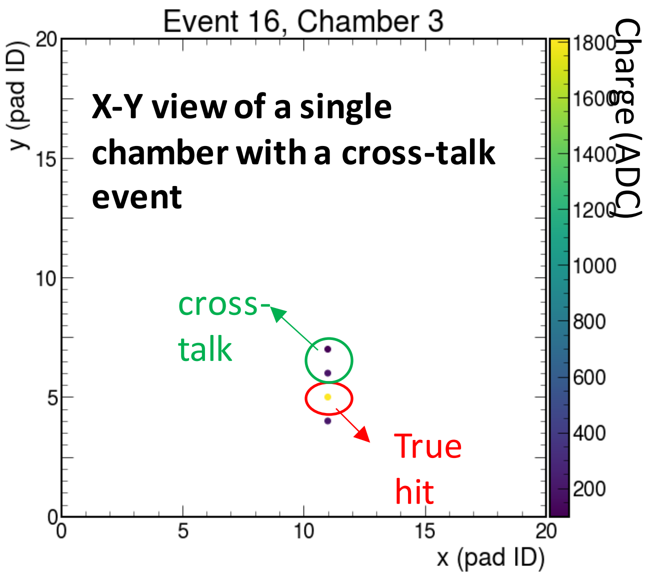
12 *pad chambers* under test flushed with
- $Ar/CO_2/CF_4$ 45/15/40 for μ-RWELL
- $Ar/CO_2/C_4H_{10}$ 93/5/2 for MicroMegas and RPWELL

Data taking based on analog FE

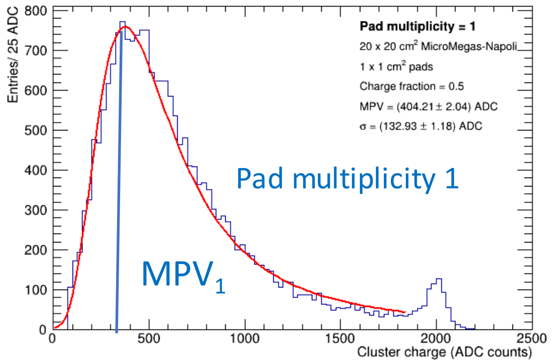
- APV25 + SRS back end system for the DAQ
  - Read 6 chambers at a time
- HV efficiency scan, XY position scan

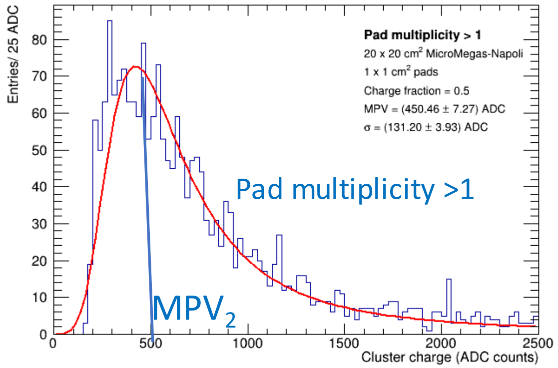
SPS test beam – Cluster reconstruction

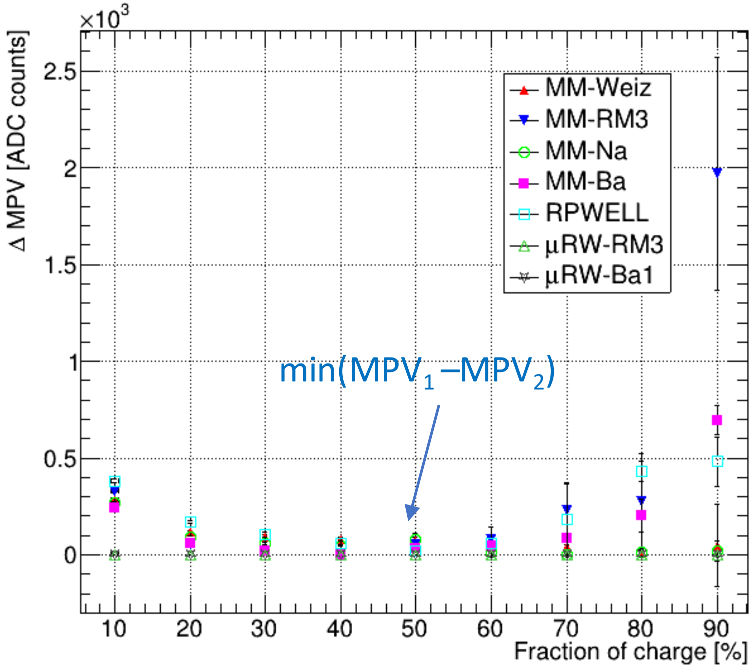




High probability of **cross-talk** effect observed among adjacent pads due to routing of the vias connecting pads to the connectors





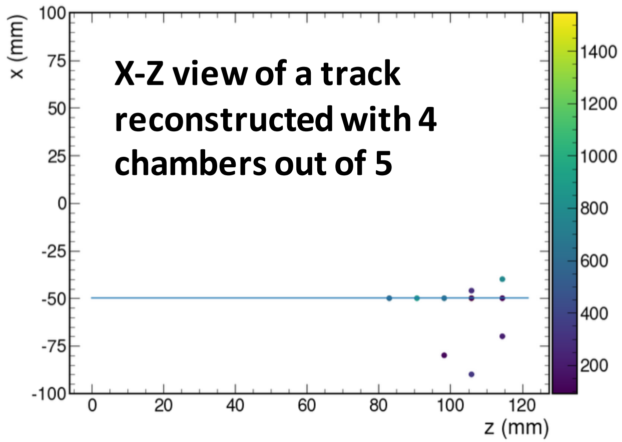


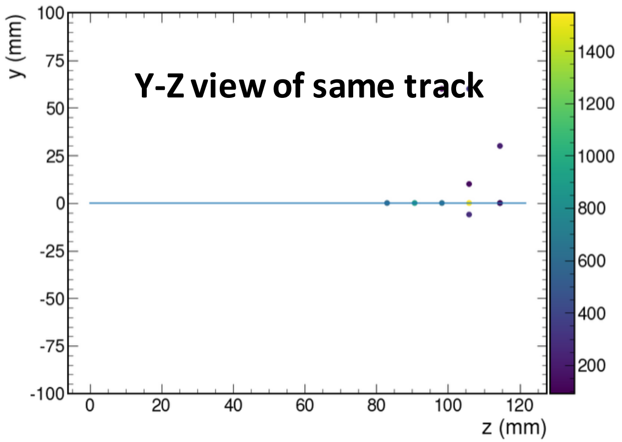
Developed ad-hoc **clustering algorithm** based on charge sharing criterium

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

SPS test beam – Track reconstruction

Track reconstructed with clusters from 5 out of 6 pad chambers, excluding the one under test



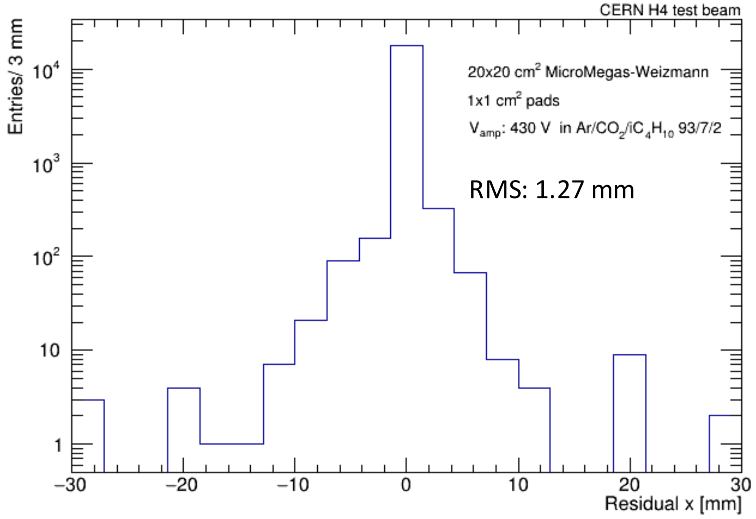


Residual distribution: $hit_{prop} - hit_{rec}$

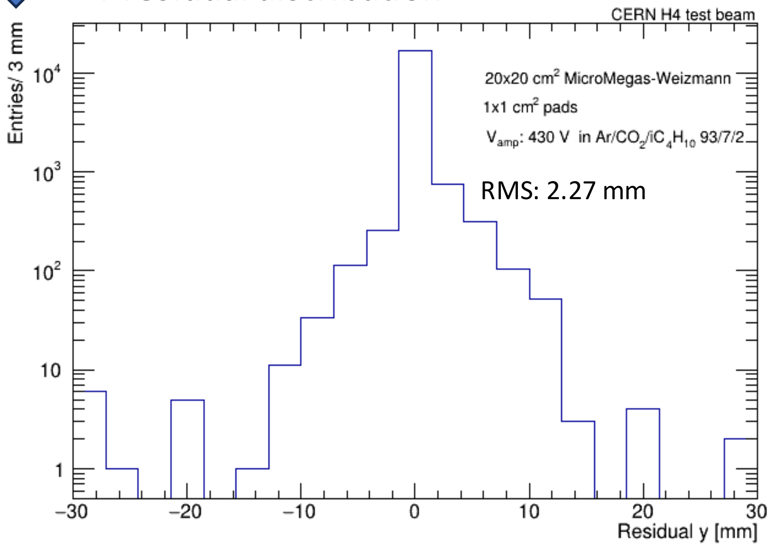
hit_{pro}: (x,y) on chamber extrapolated from the track

hit_{rec}: (x,y) recostructed on the test chamber

X residual distribution



Y residual distribution

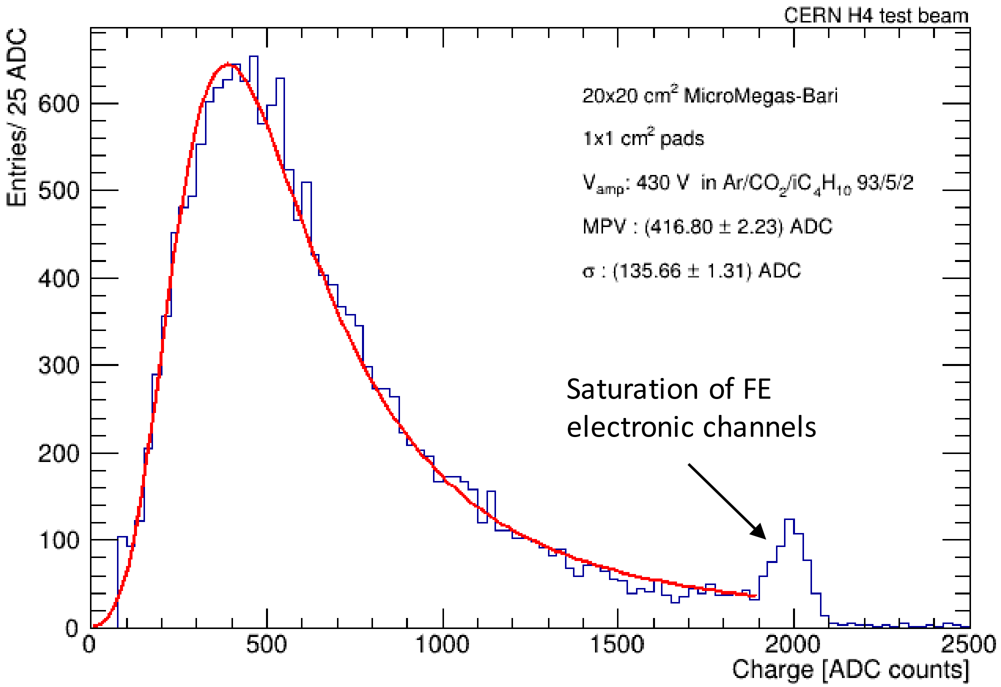


Residual distribution in agreement with detector **granularity**

Cluster **matching** with track: $hit_{prop} - hit_{rec} < 9$ mm ~ $3x\sigma_s$

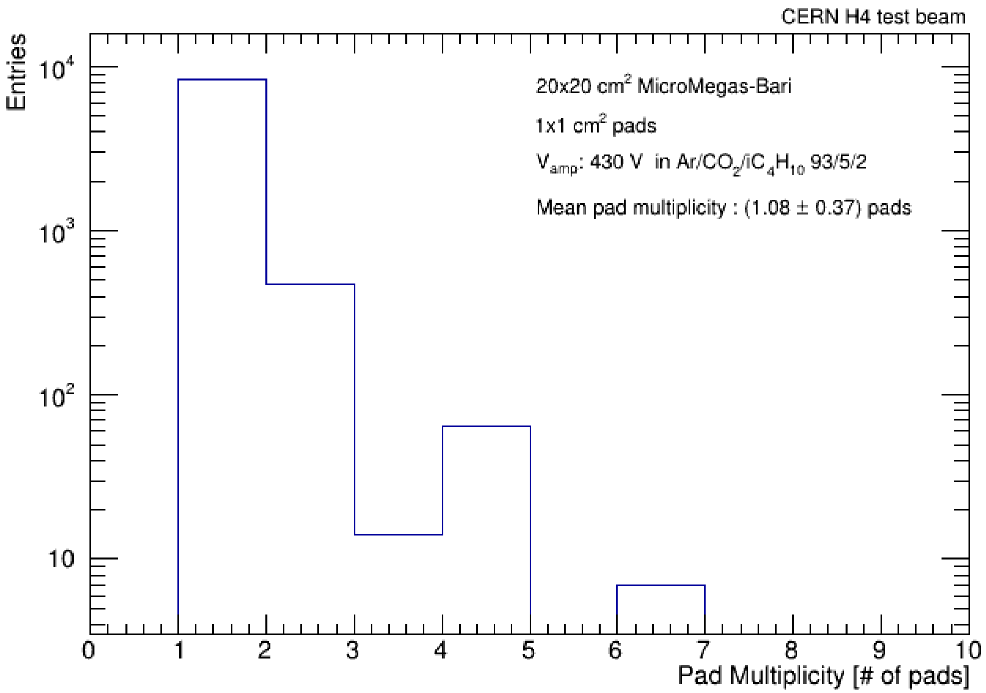
SPS test beam – Results

Charge distribution of clusters matched with track for test chamber MicroMegas-Bari



The charge distributes as a Landau as expected

Pad-multiplicity distribution of clusters matched with track for test chamber MicroMegas-Bari

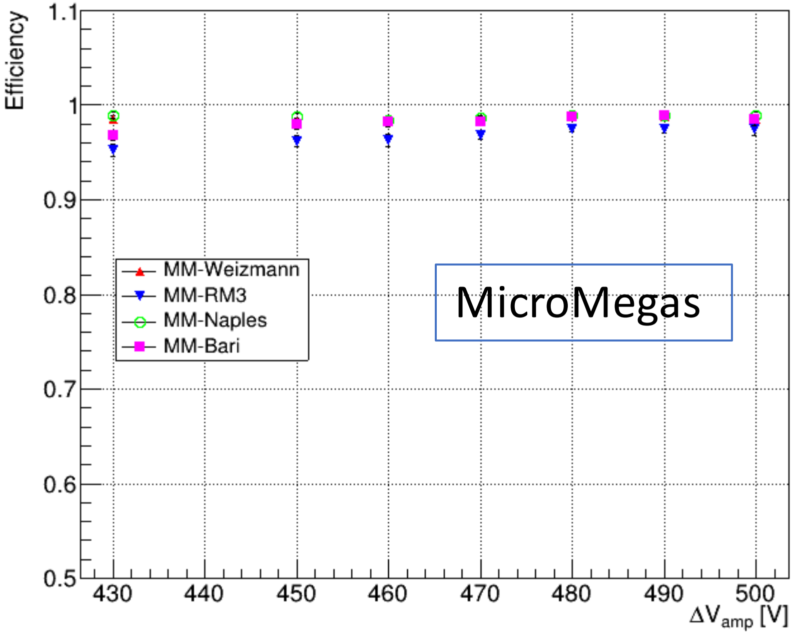


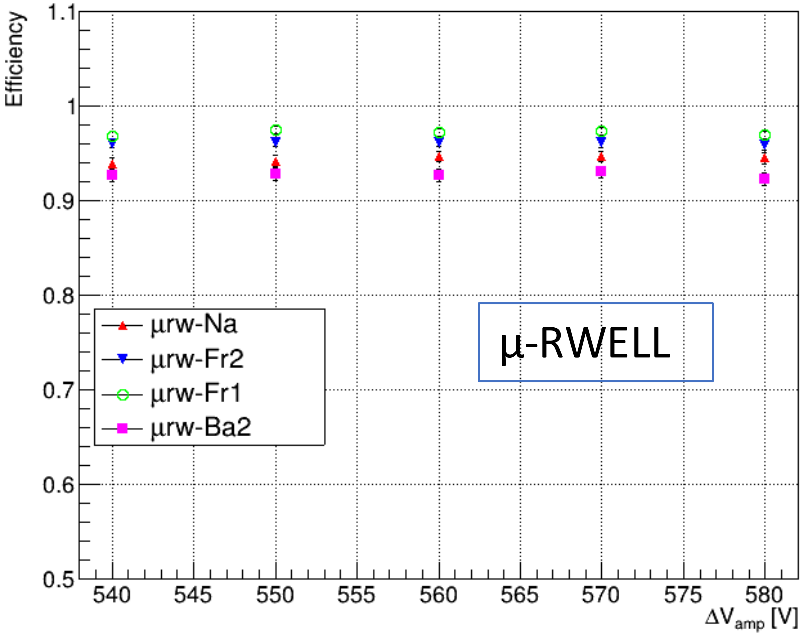
Pad Multiplicity is 1 for more than 90% of the clusters

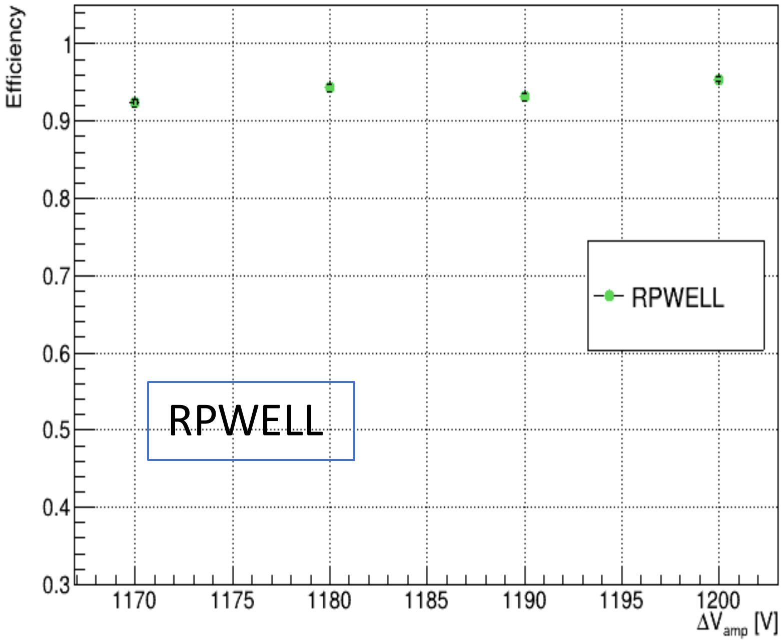
Presented in [IPRD2023]

SPS test beam – Efficiency

- Efficiency = # hits matched with tracks / # tracks
- Measured for each technology as a function of amplification voltages







- High MIP detection efficiency – detectors always operated at **plateau** already at gains < 10^3
- Detectors can be operated with lower gain and still be efficient

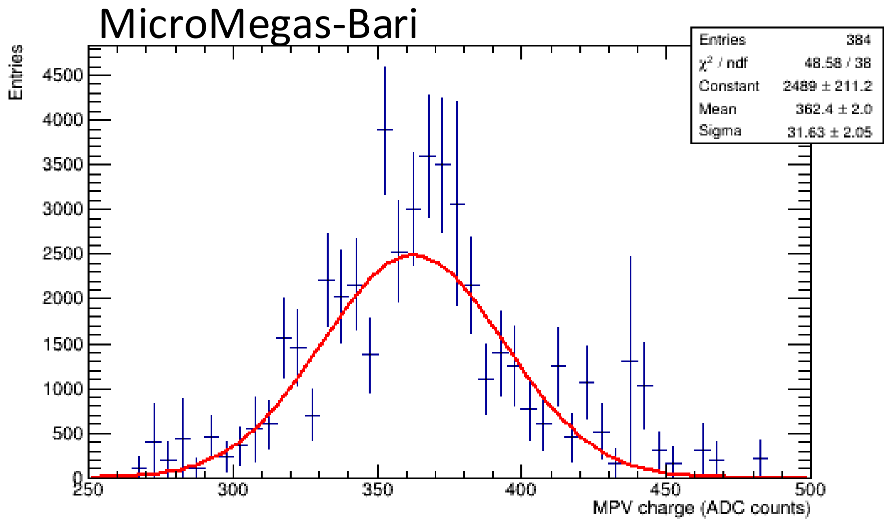
SPS test beam – Response uniformity

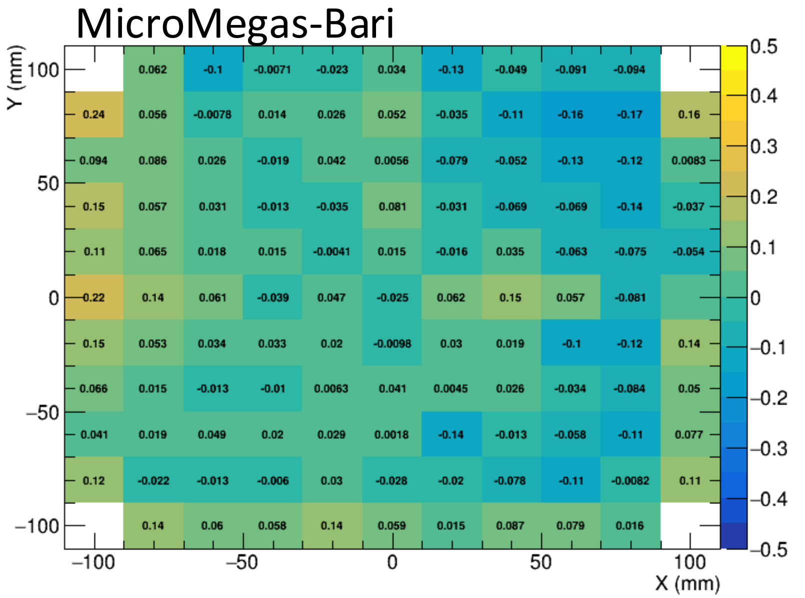
Response uniformity crucial parameter for energy reconstruction for **large area detector**

Uniformity measured using hits matching with tracks

- For each bin in the map, the content is set to
  (**mpv** – μ) / μ
  - Where μ is the mean value of the charge across the whole detector surface
  - **mpv** is extracted from the Landau fit of the charge distribution for that pad

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	$(16.3 \pm 1.1)\%$



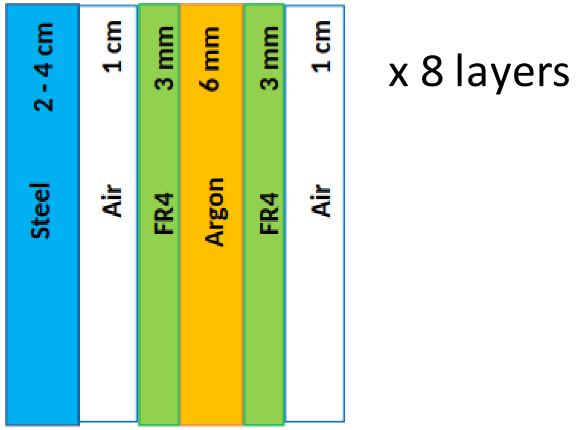


Good uniformity for MicroMegas (σ/μ ~ 10%)
Slightly worse uniformity for μ-RWELL (σ/μ ~ 16%) and RPWELL (σ/μ ~ 22%)

R&D on small-size calorimeter prototype at PS

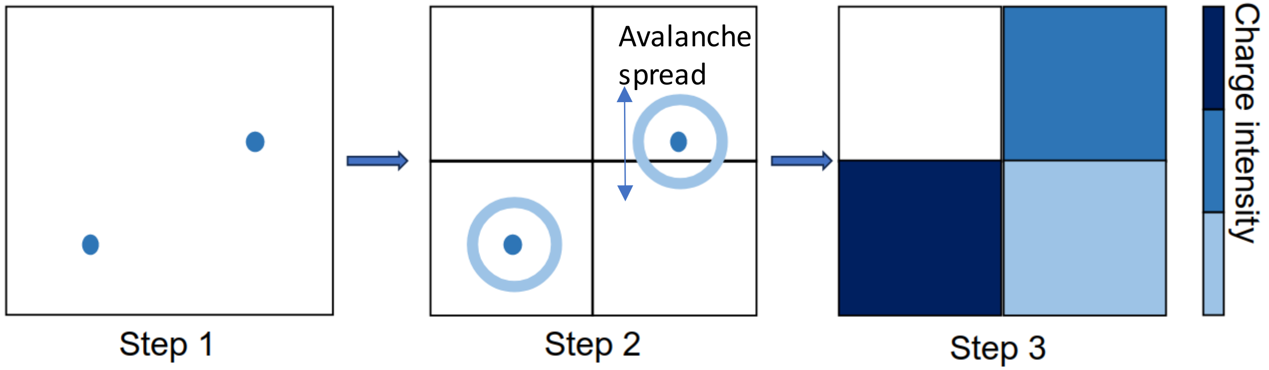
MPGD-HCAL prototype - G4 simulation setup

- Small calorimeter 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)

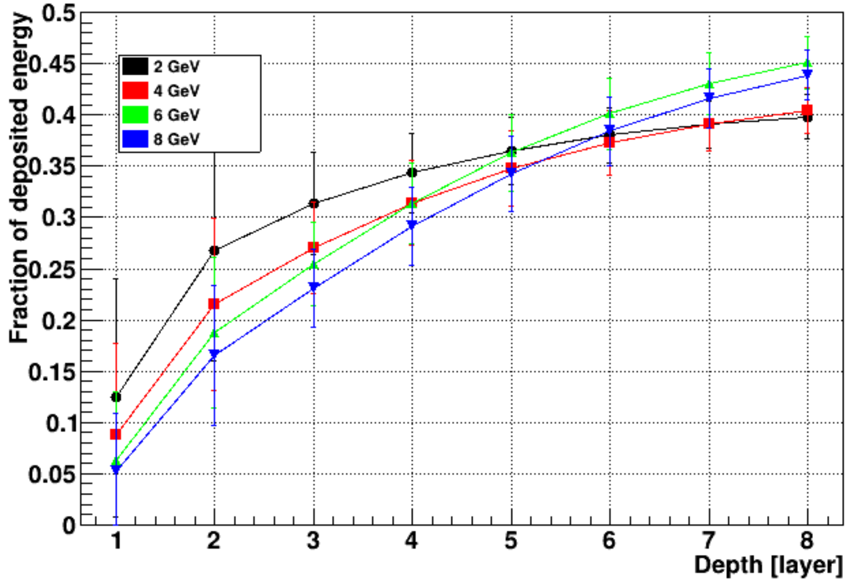


- **Digitization algorithm** implemented to account for charge-sharing among adjacent pads and detector efficiency

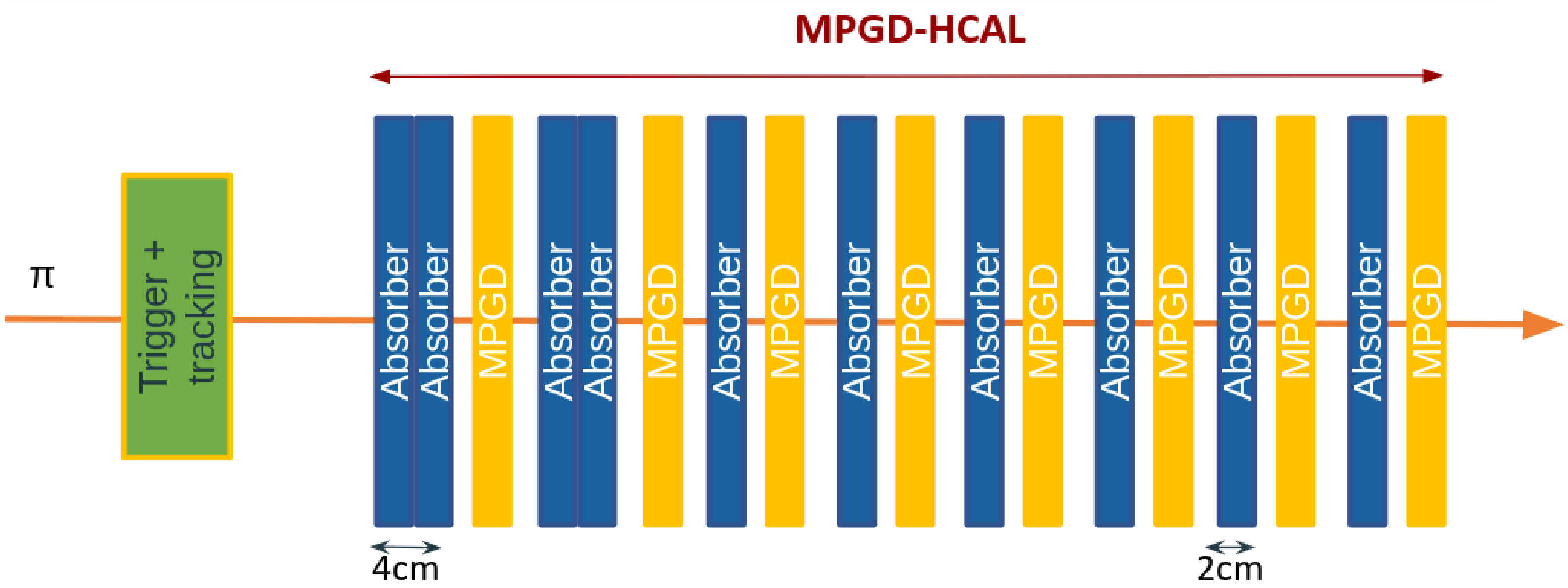
Digitization algorithm

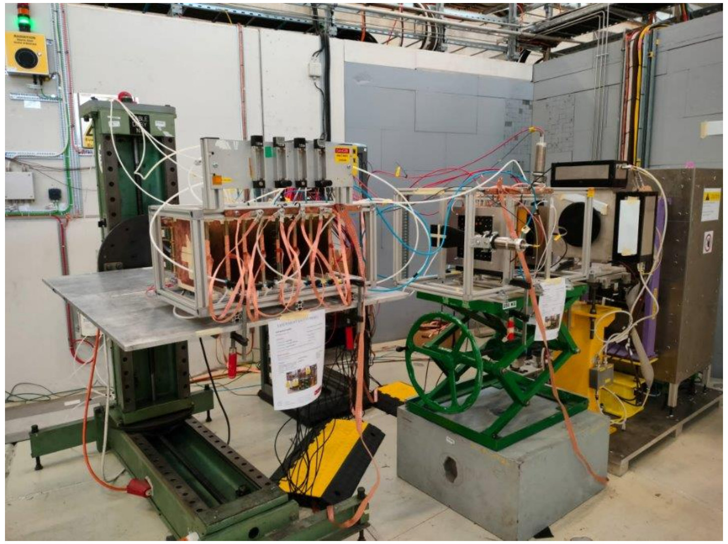


Shower containment



MPGD-HCAL prototype – PS test beam



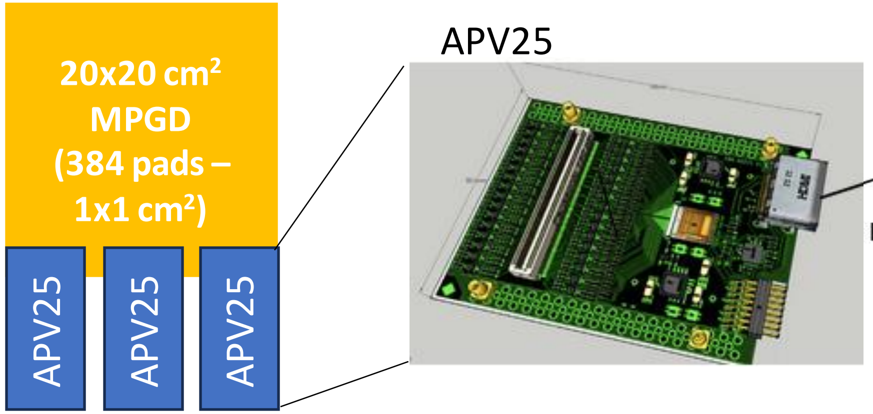


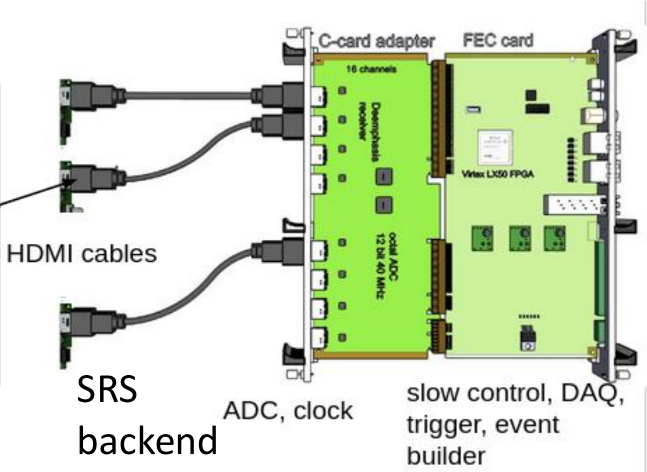
HCAL cell performance ~ 1 λ_I (8 active layers)

Data taking based on analog FE (APV25 + SRS)

Runs at different π^- energy (4 – 8 GeV)

- Cherenkov discriminators used to veto electrons and muons





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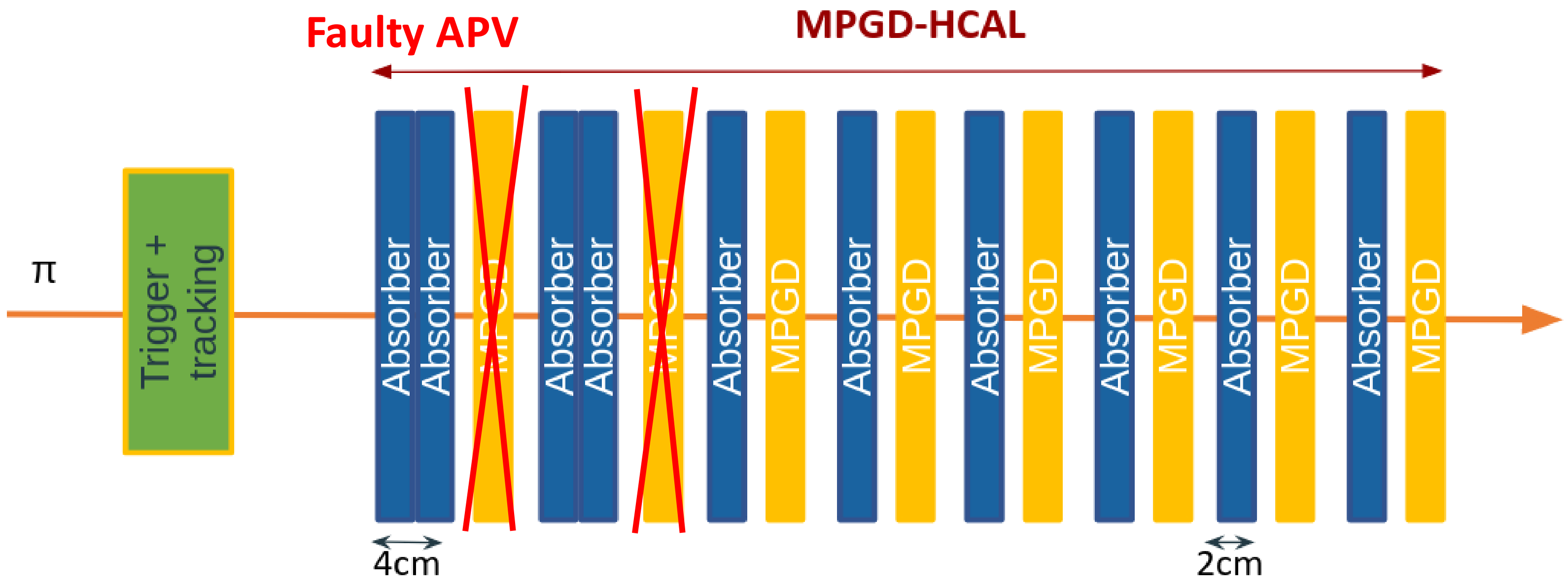

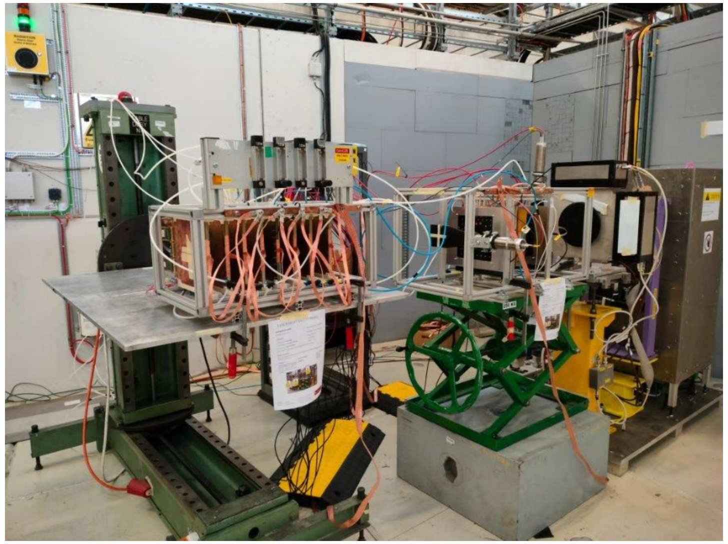

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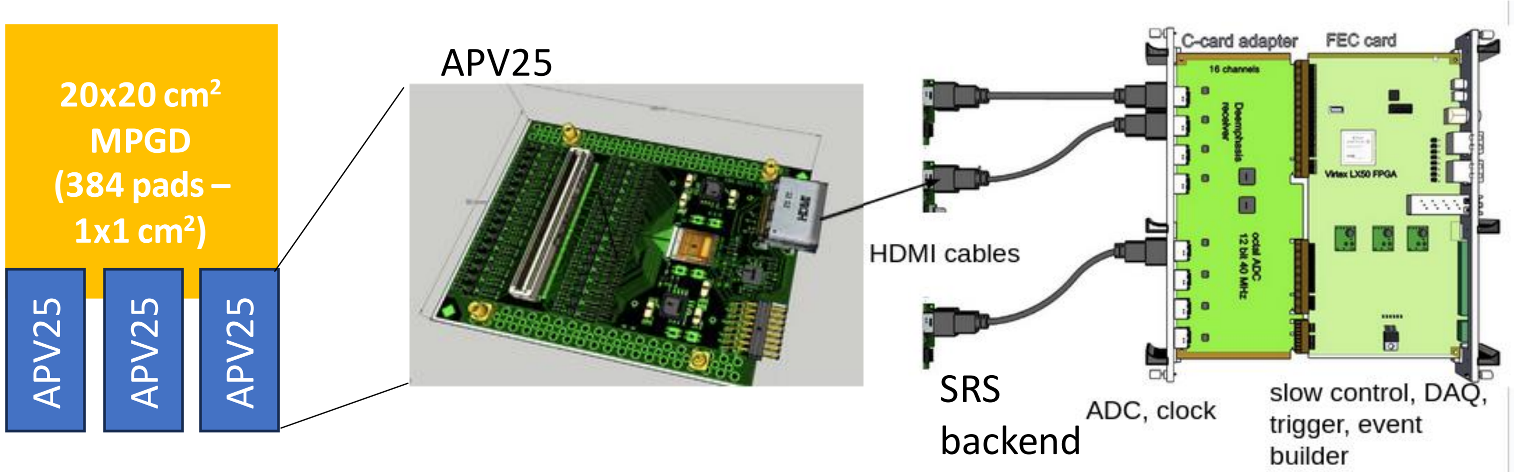
Runs at different π^- energy (4 – 8 GeV)

- Cherenkov discriminators used to veto electrons and muons

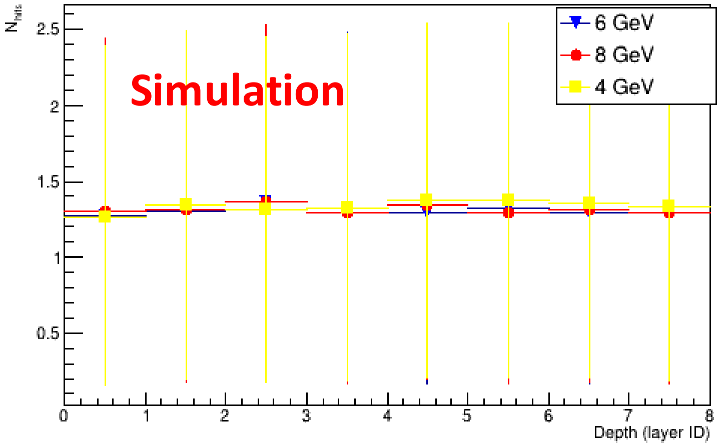


Event selection in Monte Carlo and data

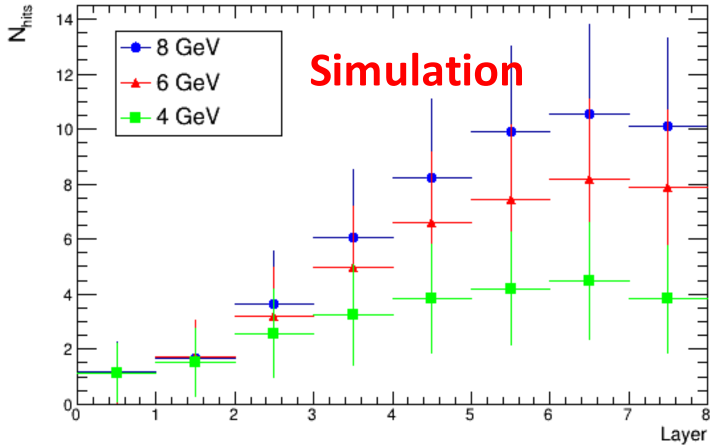
Event **selection criteria** supported by simulation using MC truth

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

MIP-like events

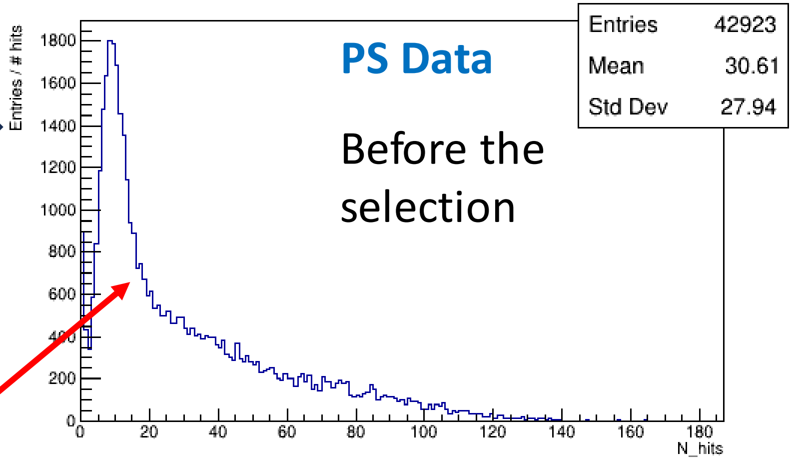


Shower events



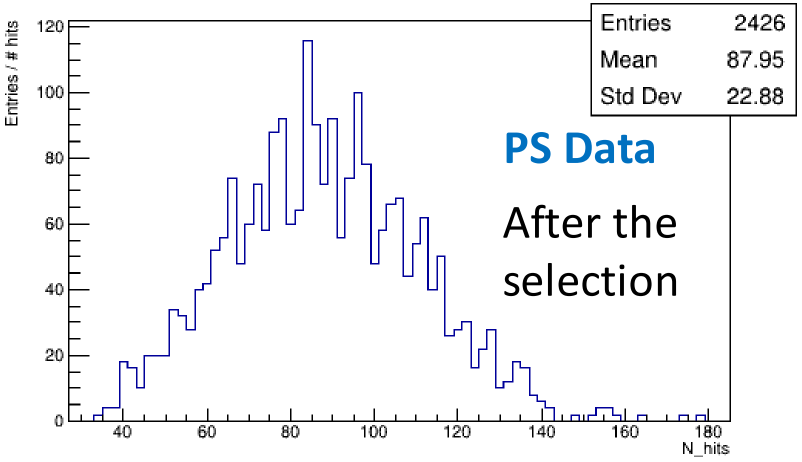
Distribution of the **number of hits** in all active layer from the experimental data

Number of hits for all layers



Peak at ~ 10 hits
-> MIP-like events

Number of hits for all layers

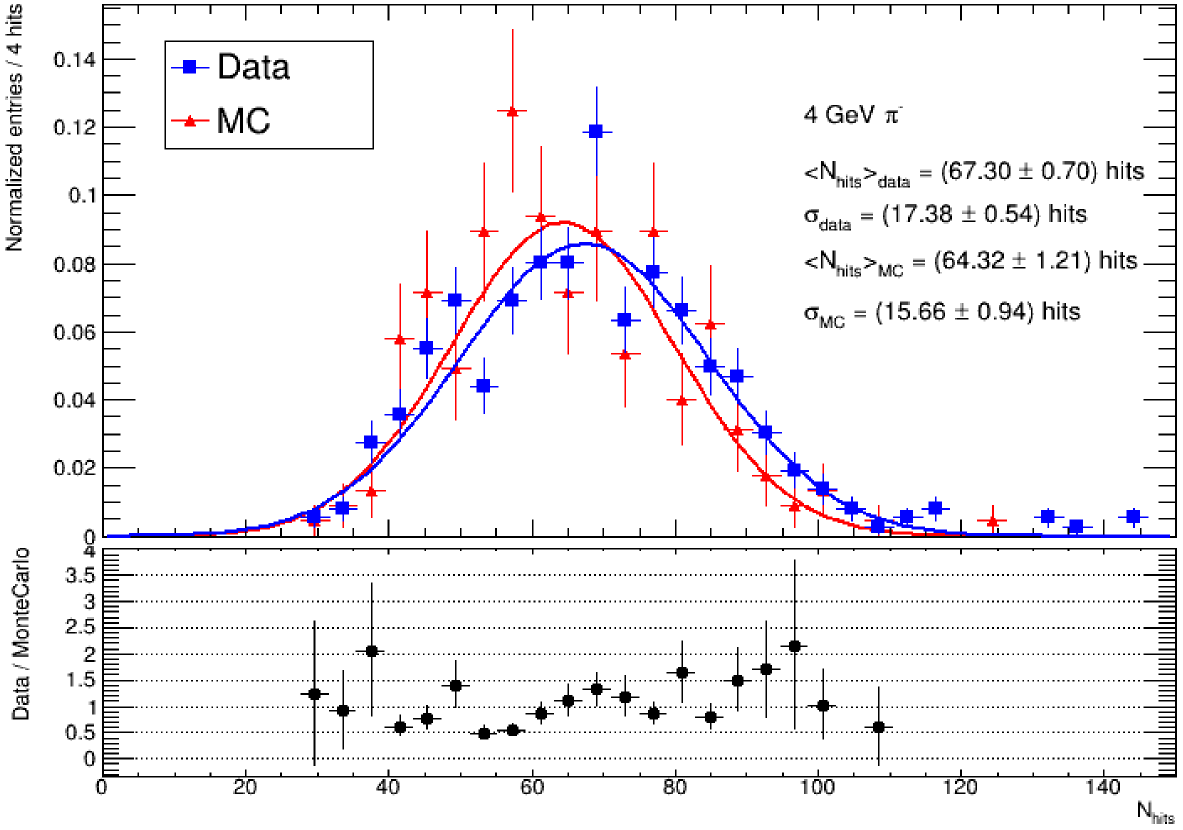


Data-MC comparison

- Distribution of total number of hits for hadronic shower events for experimental data and Monte Carlo simulation
- Distributions fitted with Gaussian to extract mean and sigma

Good agreement between data and Monte Carlo

Successful **validation** of MPGD-HCal prototype with 8 layers of 20x20 cm^2



Conclusions

Firts study of the resistive MPGDs for hadron calorimeter in challenging radiation environment such as the experiment at Muon Collider

MPGD-HCal simulation in G4– response to single π (up to 80 GeV): **1x1 m² – 50 layers with RO DHCal e SDHCal**

- 90% energy contained within 10 λ_I longitudinally, 2 λ_I trasversely
- Energy resolution: **digital RO** (single thr) e **semi-digital** (multiple thr) for cell-size di 1x1 cm² and 3x3 cm²
    - RO SDHCal achieves **resolution of 8% at 80 GeV** wrt DHCal (14%)
    - RO SDHCal 3x3 cm² and 1x1 cm² **comparable** -> possibility of reducing the # of electronic channels

Characterization on MPGD single layer at SPS test beam: **20x20 cm² active area – 1x1 cm² RO pads– 12 detectors with µMegas, µ-RWELL, RPWELL**

- MIP efficiency > 90% for all technologies
- Response uniformity of ~10% for MM, ~16% for µ-RWELL, ~22% for RPWELL
- Identified few areas of improvements for detector design

Characterization of MPGD-HCal prototype at PS test beam:

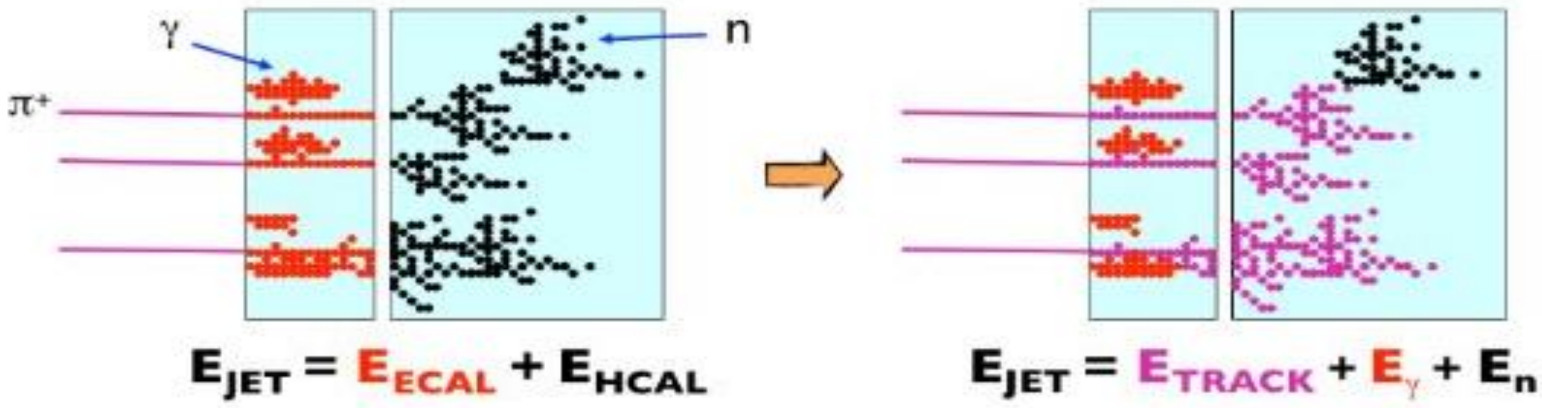
- First operation of the small prototype performed succesfully
- Good agreement between data and simulation on the distribution of the number of hits

Backup

Particle-Flow Calorimetry

Traditional approach
- Jet reconstructed as a whole
- Energy measured combining ECAL + HCAL
- ~ 70 % of jet energy measured in HCAL with relatively low resolution (<60%)

Particle Flow approach
- Reconstruct individual particles of the jets
- Exploit the most accurate subdetector system
- ~ 10 % of jet-energy carried by long-lived neutral hadrons is measured in HCAL
- High granularity for calorimeter system is required



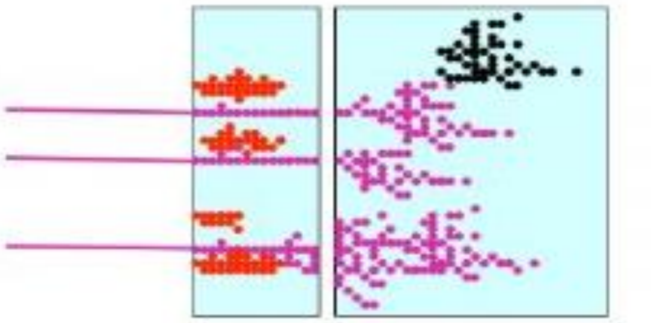
J. Marshall, M. Thomson arXiv:130

Particle-Flow Calorimetry

GOAL for future colliders:
Jet energy resolution for Z/H separation:
σ_E /E< 3% - 4%

Particle Flow approach

- Reconstruct individual particles of the jets
- Exploit the most accurate subdetector system to measure each particle
    - ~ 60% charged hadrons measured by tracking system
    - ~ 30% photons measured by ECAL
    - ~ 10 % of jet-energy carried by long-lived neutral hadrons measured in HCAL
- High granularity for calorimeter system is required



$E_{JET} = E_{TRACK} + E_{\gamma} + E_n$

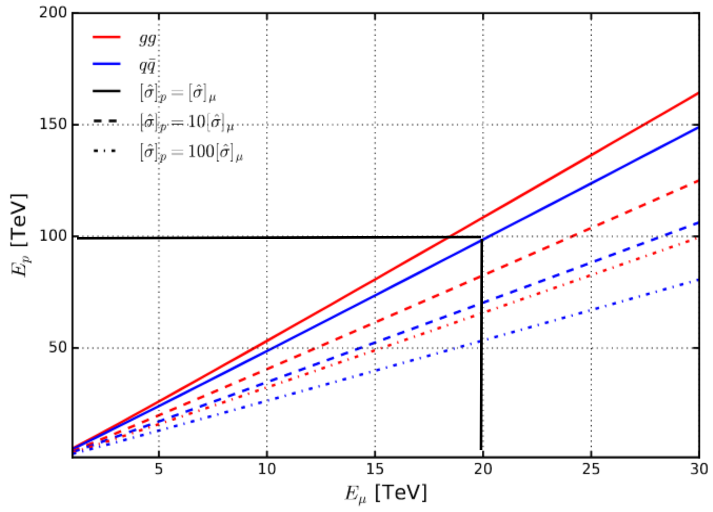
Component	Detector	Energy Fraction	Energy Res.	Jet energy res.
Charged particles (X)	Tracker	$\approx 0.6\ E_j$	$10^{-4} E_X^2$	$< 3.6 \times 10^{-5} E_j^2$
Photons (γ)	ECAL	$\approx 0.3\ E_j$	$0.15\sqrt{E_\gamma}$	$0.08\sqrt{E_j}$
Neutral hadrons (h_0)	HCAL	$\approx 0.1\ E_j$	$0.55\sqrt{E_{h_0}}$	$0.17\sqrt{E_j}$

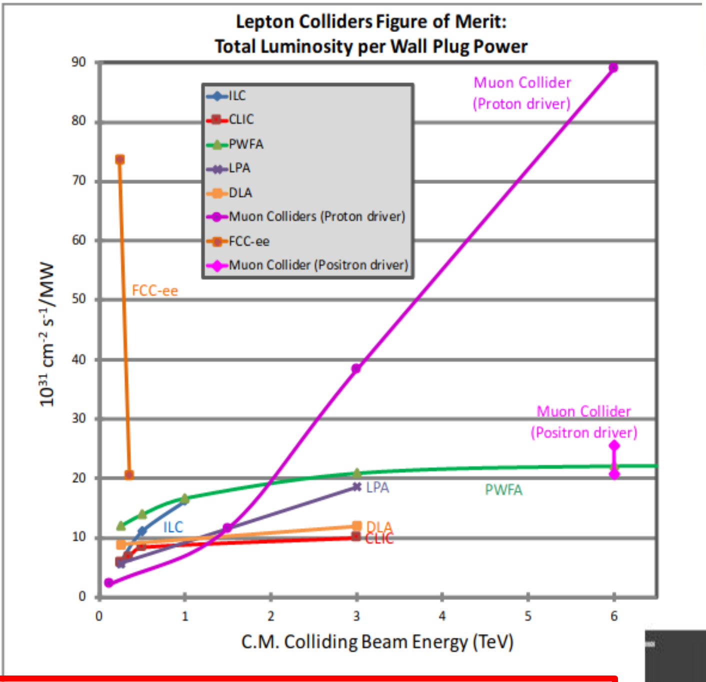
J. Marshall, M. Thomson arXiv:1308.4537

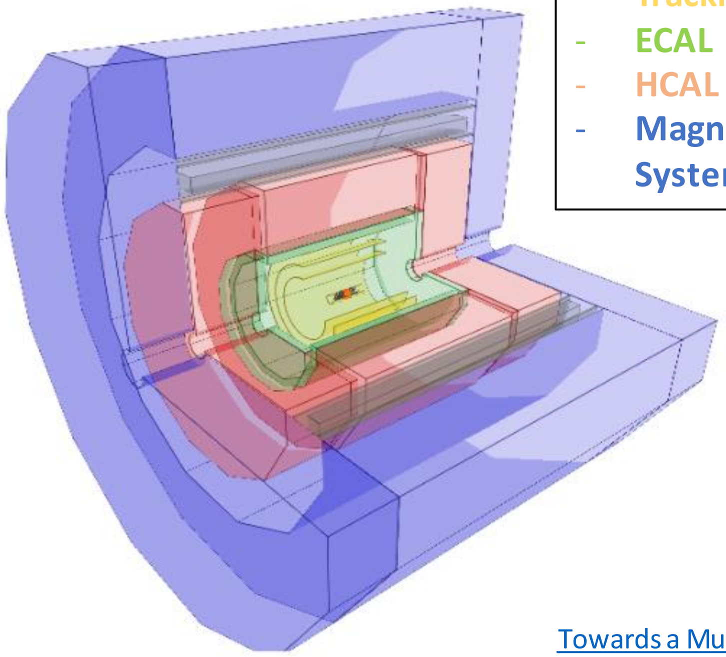
The Multi-TeV Muon Collider experiment

Advantages:
- multi-TeV energy range in **compact circular** machines;
- well **defined initial state** and **cleaner final state**;
- all **collision energy available** in the hard-scattering process.

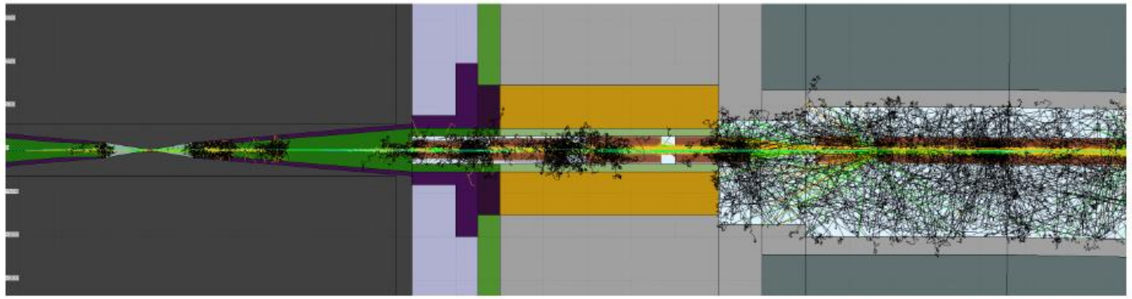
Section of the Muon Collider experiment:
- Tracking system
- ECAL
- HCAL
- Magnet return yoke + Muon System







Towards a Muon Collider arXiv:2303.08533

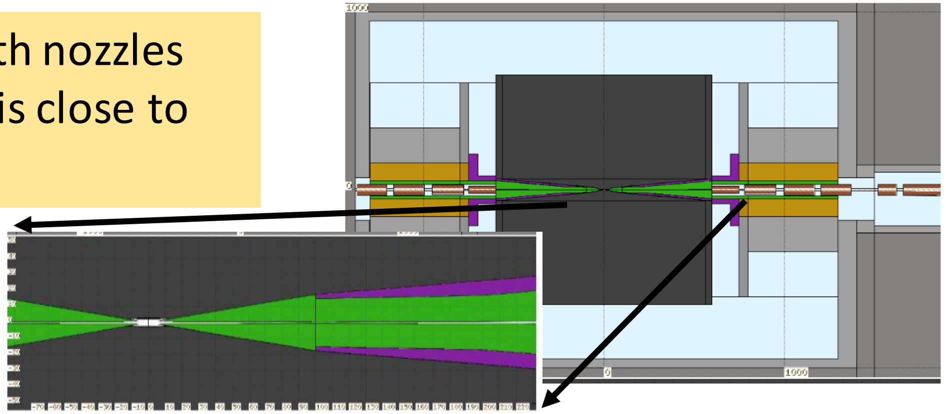


Challenges:
- muon is an **unstable** particle
  - intense flux of background particles: **beam-induced background (BIB)**.

Beam-induced background

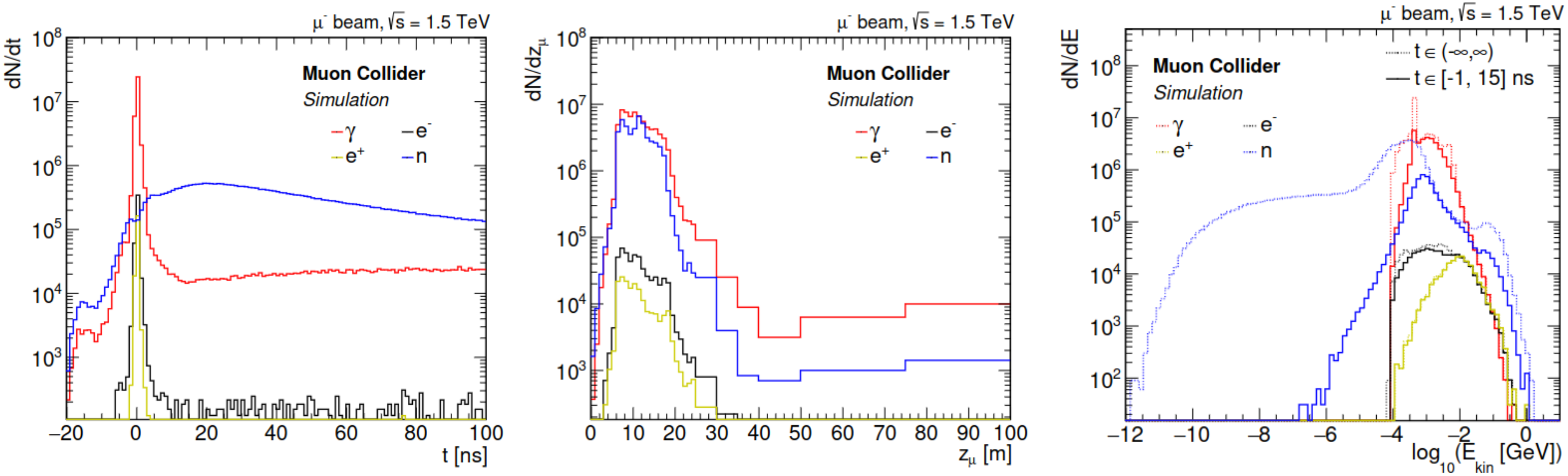
Challenges:
- muon is an unstable particle
    - intense flux of background particles: **beam-induced background (BIB)**.

BIB partially mitigated with nozzles built around the beam axis close to the interaction point



Characteristics of the BIB entering the detector:

Asynchronous time of arrival | Displaced arrival point | Low kinetic energy

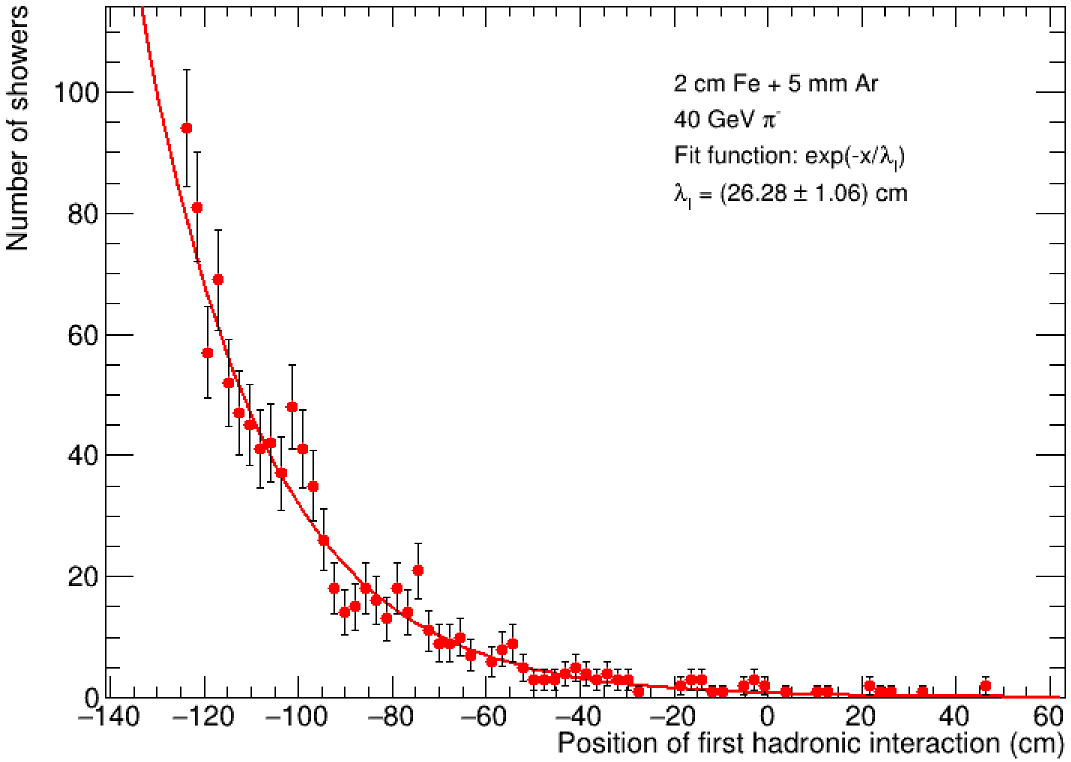


Nuclear interaction length

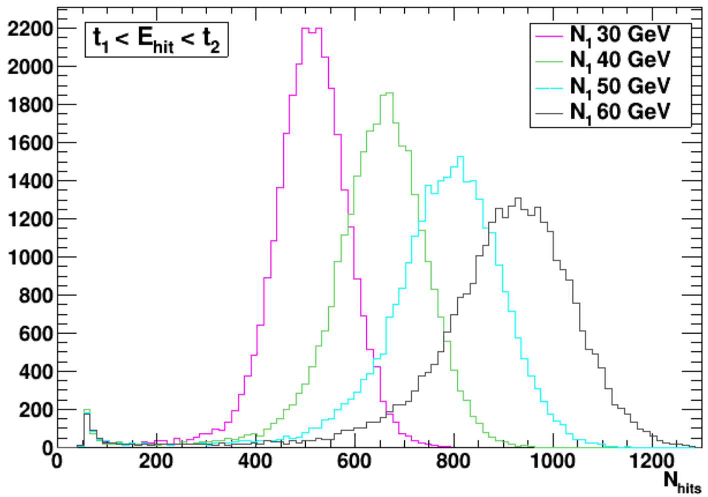
Position of the first hadronic interaction fitted with

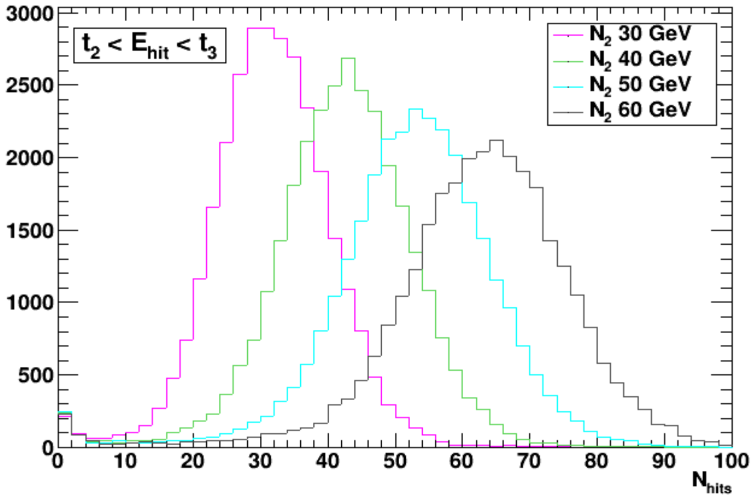
$$\exp(x/\boldsymbol{\lambda}_N)$$

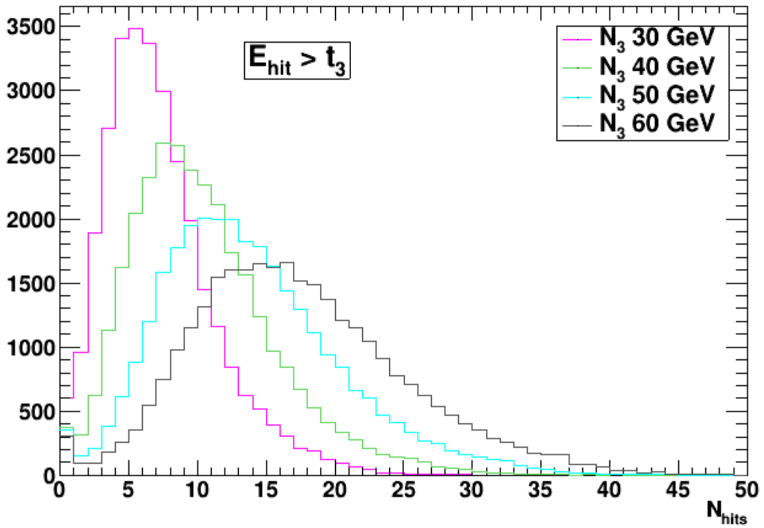
To extract $\boldsymbol{\lambda}_N \sim 26$ cm



Energy reconstruction: Semi-digital Readout (SDHCAL)

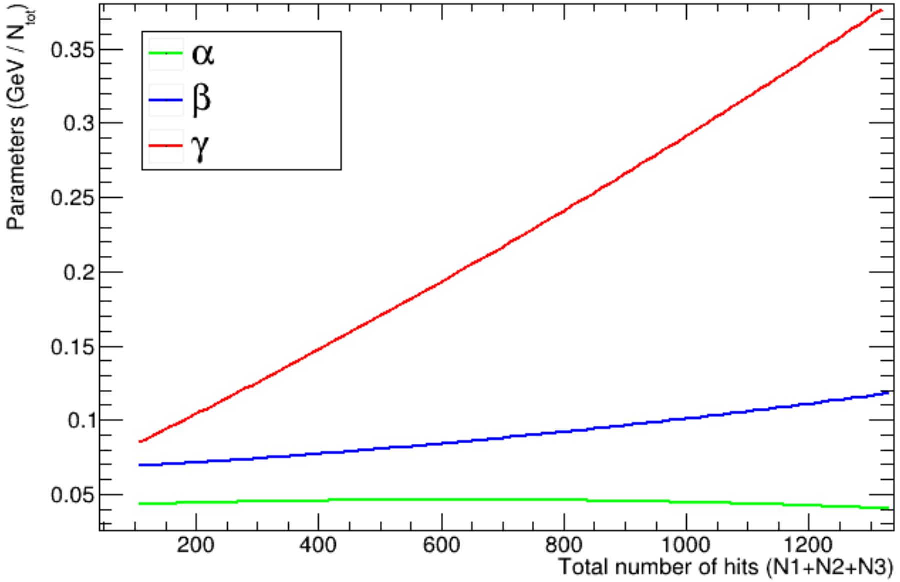




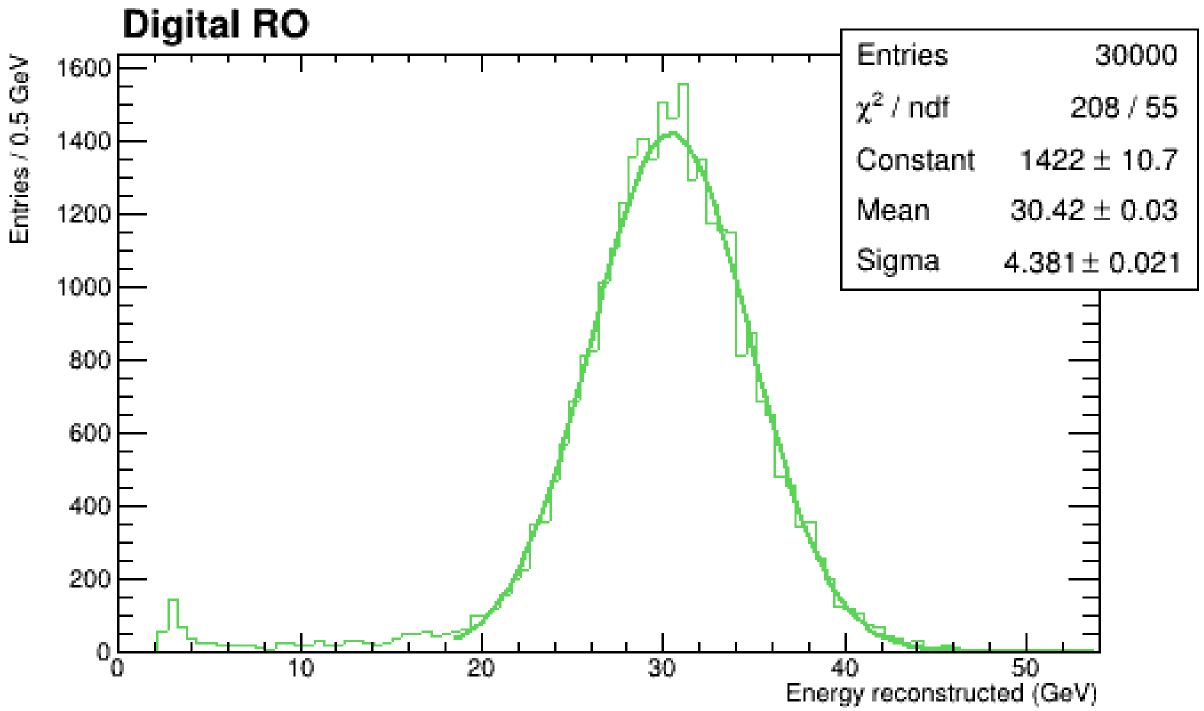


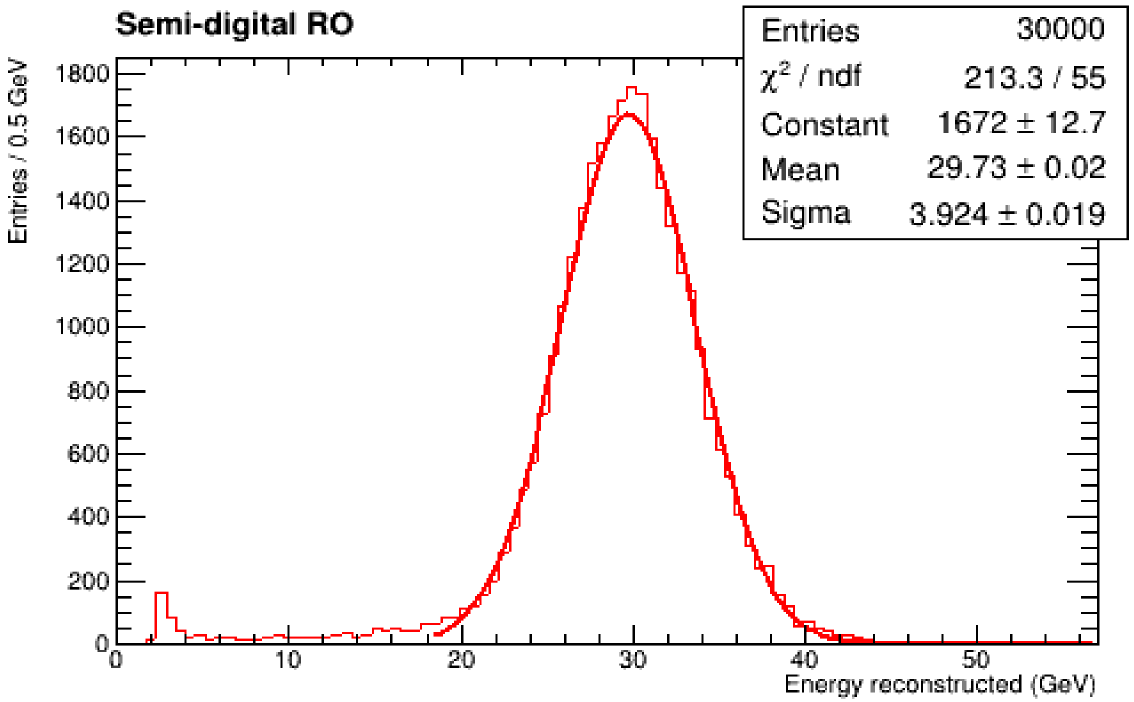
- **Digitization:** defined multiple thresholds
  - $t_1 = 0.01$ MIP
  - $t_2 = 4$ MIP
  - $t_3 = 12$ MIP

- **Reconstructed energy:**
  $E_\pi = \alpha N_1 + \beta N_2 + \gamma N_3$ with:



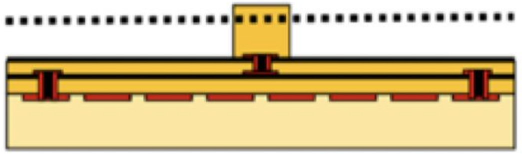
Energy reconstruction: SDHCal vs DHCal

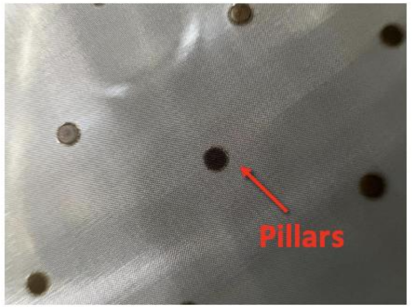




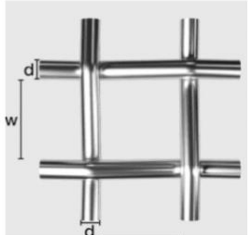
MPGD technologies

Micromegas (MM)

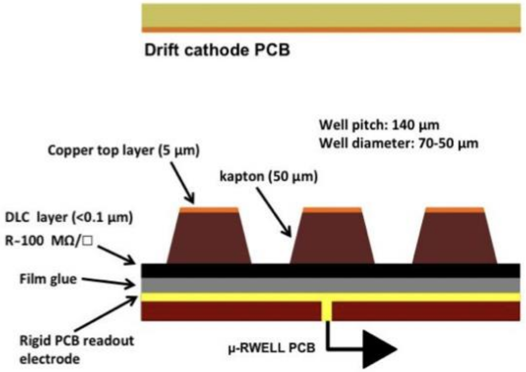




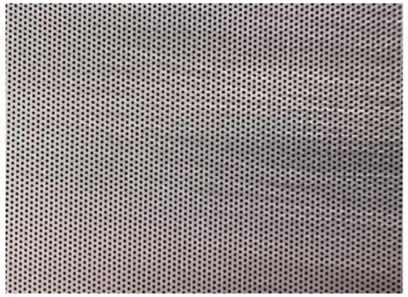
d= 18 µm
w= 45 µm
Pillar size =?



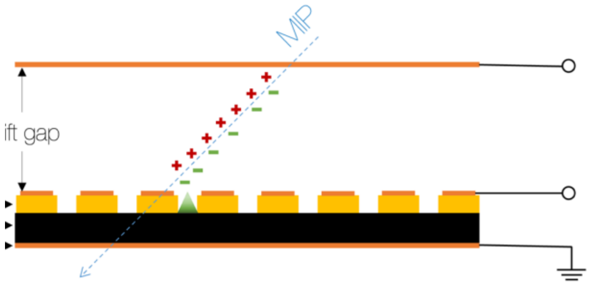
uRWELL



µRWELL seen at the microscope



RPWELL



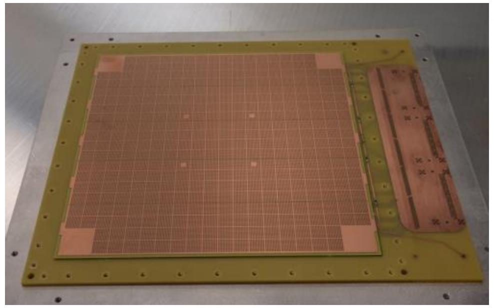
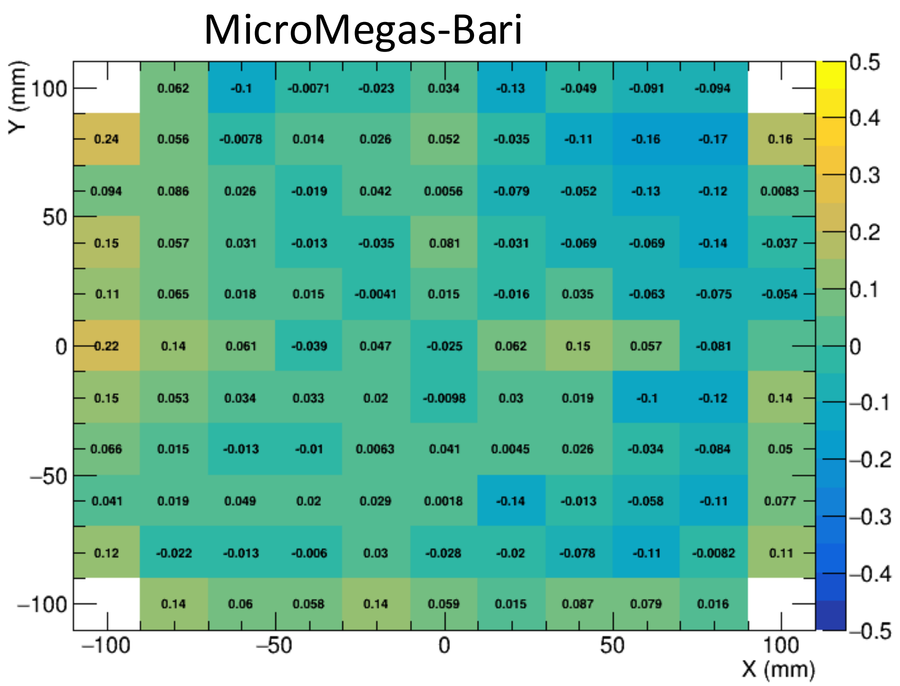
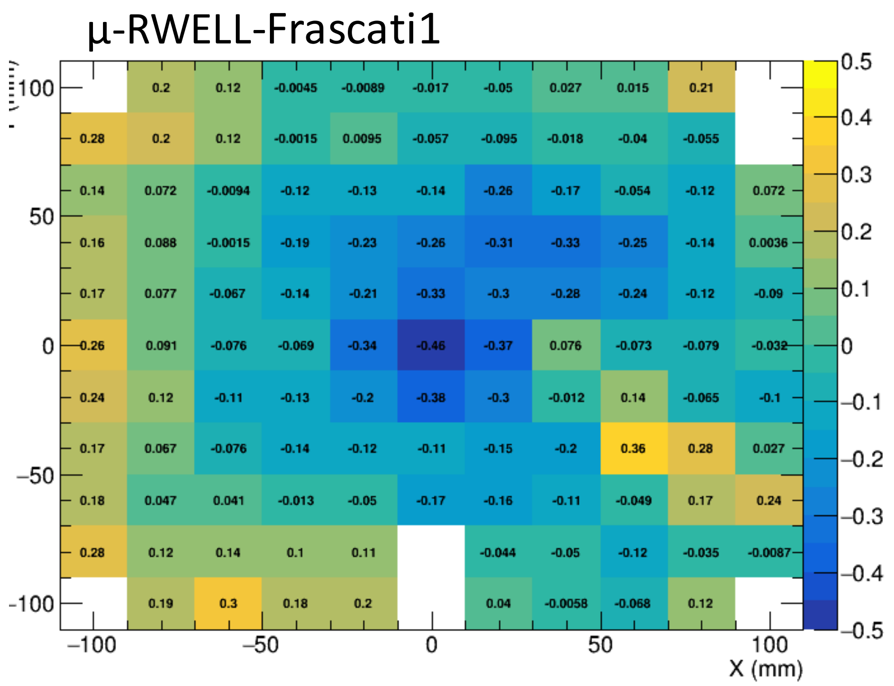


Table 3.2: Characteristics of the resistive MPGD prototype tested in this work. The brute value of the resistivity refers to the value of the DLC foil at production; the value after curing is the one measured after the curing procedure of the DLC foil.

Technology	Amplification gap	Drift gap	Resistivity (brute value)	Resistivity (after curing)
resistive Micromegas	$\approx 100\ \mu m$	≈ 6 mm	(100 ± 30) MΩ/□	≈ 45 MΩ/□
μ-WELL	$\approx 50\ \mu m$	≈ 6 mm	(200 ± 60) MΩ/□	$85 \div 110$ MΩ/□
RPWELL	$\approx 400\ \mu m$	≈ 5 mm	≈ 2 GΩ·cm (bulk)	

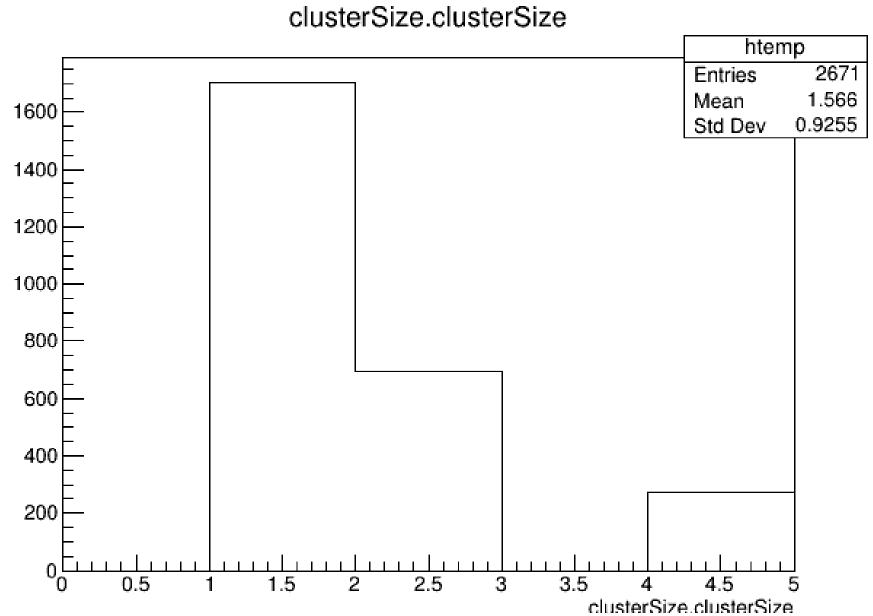
SPS test beam – Response uniformity

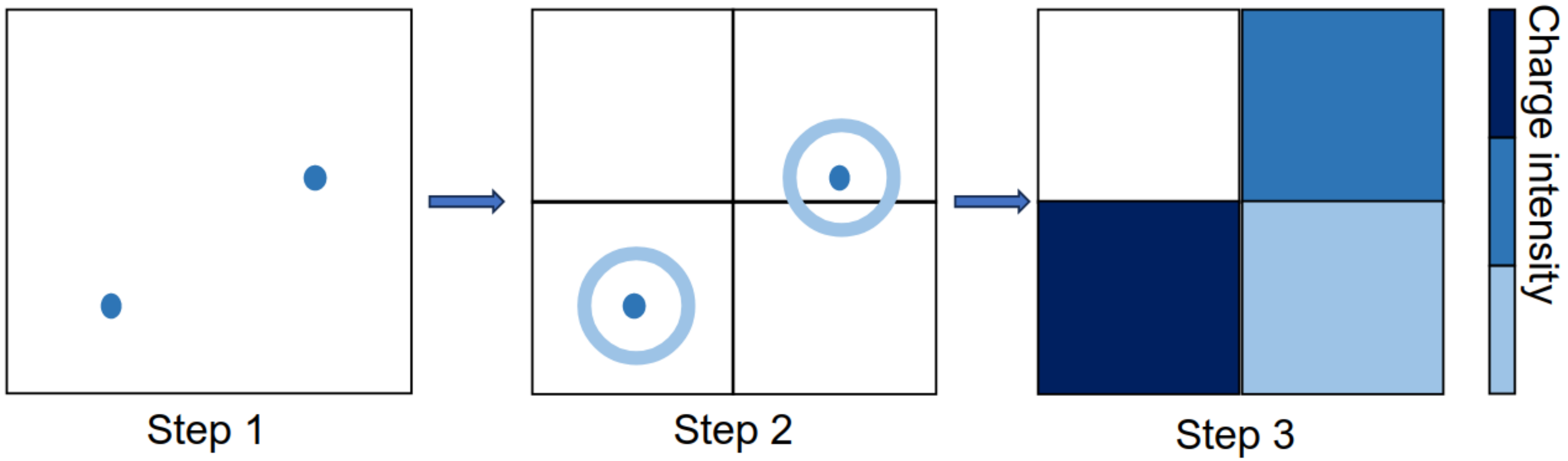


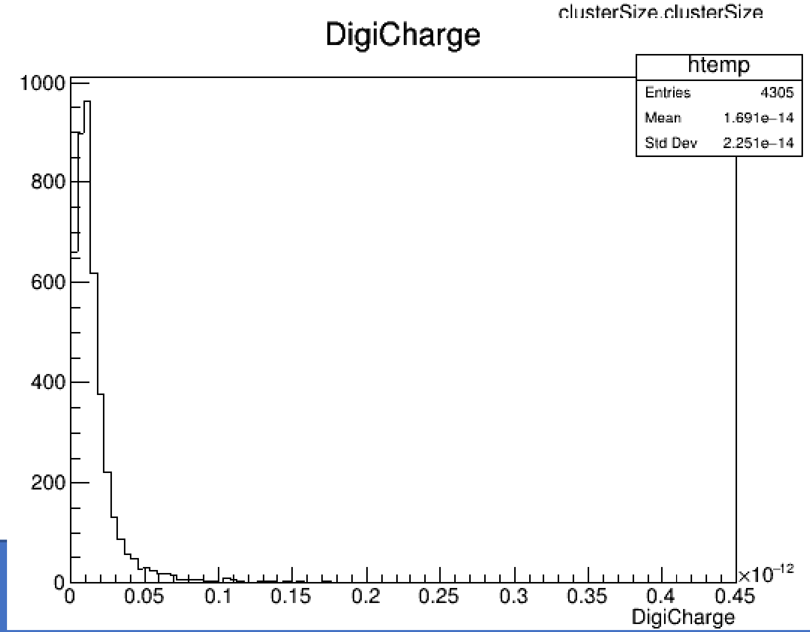


MPGD-HCAL prototype - G4 simulation setup

- Digitalization: simulate detector response in terms of **cluster size** and **efficiency** of the detector
- from (x,y) position of track in the active layer (step 1), define a gaussian distribution centered in (x,y) and with sigma related to the measured pad multiplicity (step 2)
- include in the cluster all the pads in which the gaussian extends
- Assign to each pad a fraction of charge according to the portion of gaussian "occupying" the pad (step 3)







MPGD-HCAL prototype – Faulty APVs

Simulation – beam profile per layer

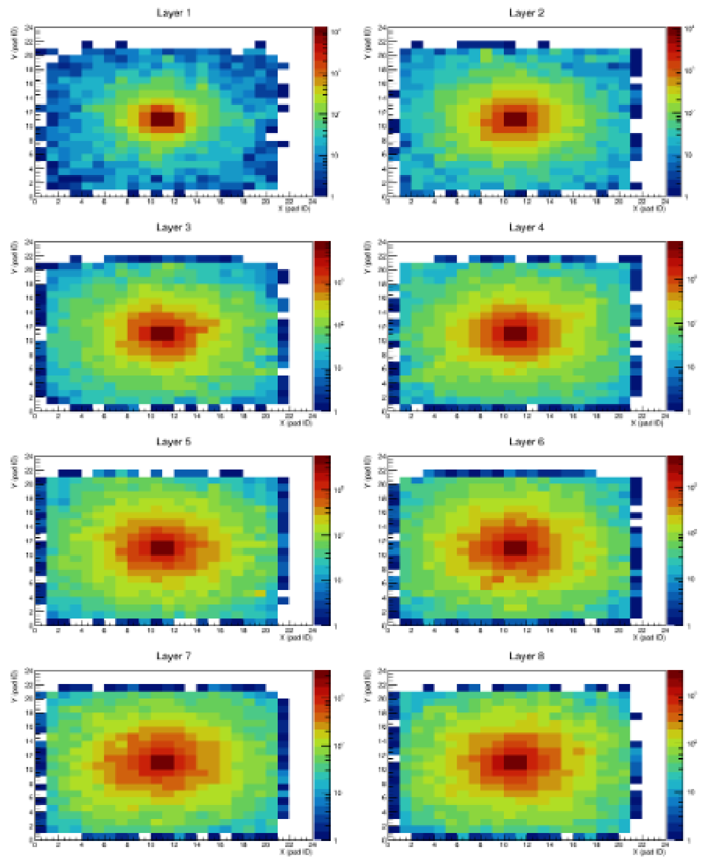


Figure 4.18: X-Y distributions of hits per each active layer after the digitization algorithm. These distributions are obtained with 30 thousand π^- of 6 GeV. The z-axis is the number of fired pads considering the whole set of events.

Experimental data– beam profile per layer

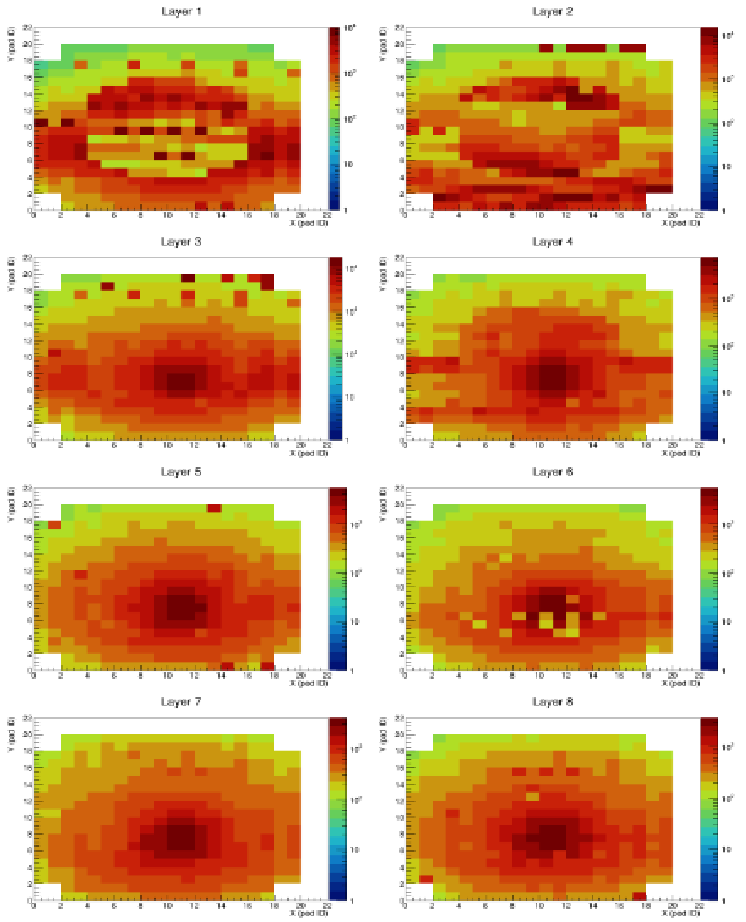
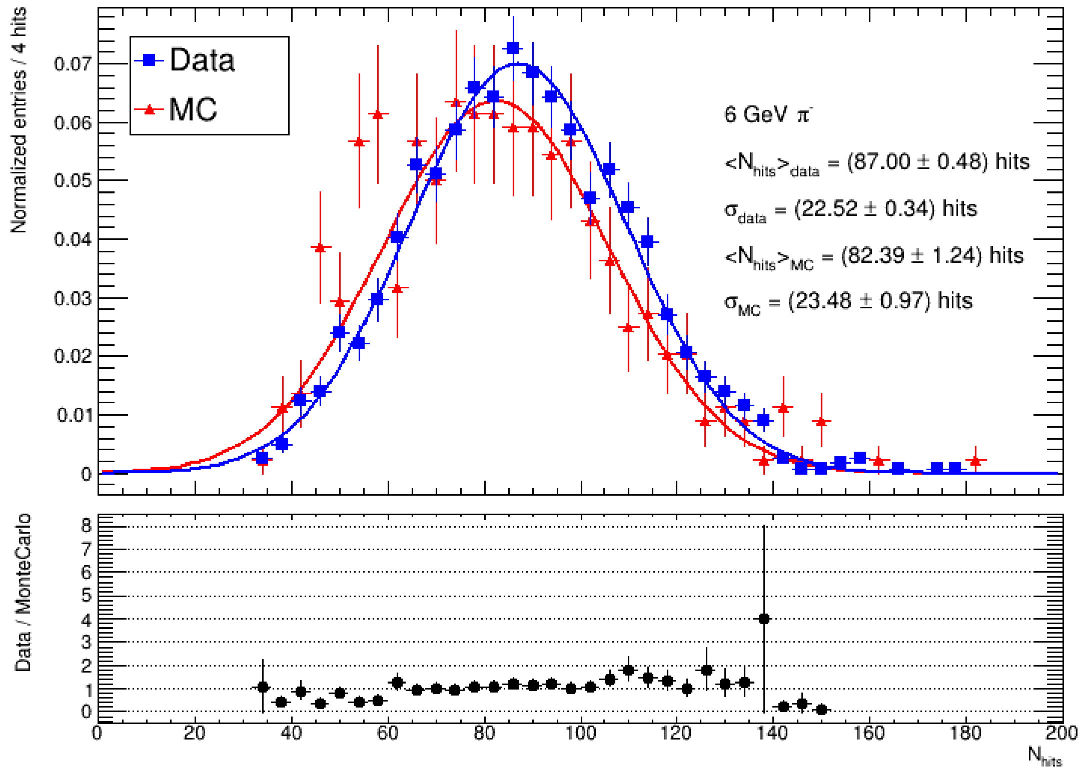
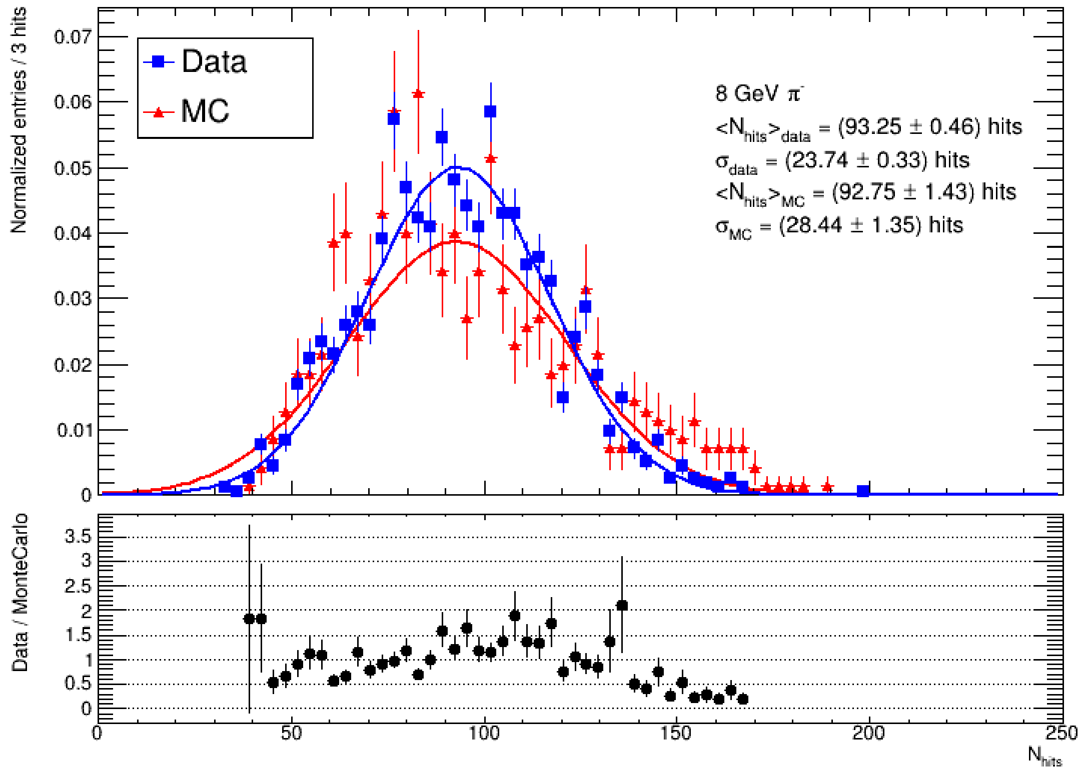


Figure 5.6: X-Y distributions of hits per each MPGD layer obtained for the run with pion energy of 6 GeV. The z-axis is the number of fired pads, in logarithmic scale, considering the whole set of events.

MPGD-HCAL prototype – Data-MC preliminary comparison





Moving forward for MPGD-HCal R&D

MPGD-HCal simulation in G4– response to single π: **1x1 m^2 – 50 layer with RO DHCal e SDHCal**

- Single pion response in presence of the BIB
- **threshold optimization** (t_1, t_2, t_3) for RO SDHCal for MPGD technology

Characterization on MPGD single layer: **20x20 cm^2 active area – 1x1 cm^2 RO pads– 12 detectors with µMegas, µ-RWELL, RPWELL**

- build and test **50x50 cm^2 active area detector with optimized design** based on presented results

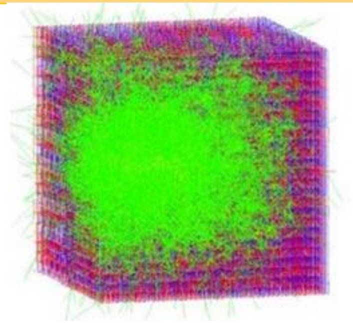
Characterization of MPGD-HCal prototype:

- Finalize energy calibration
- Extend the current prototype to include 50x50 cm^2 prototype

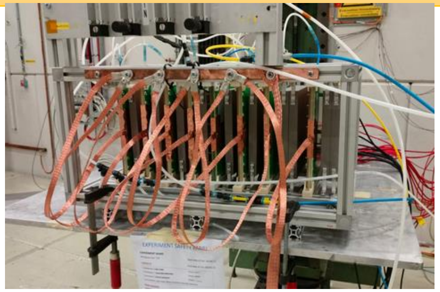
- The results of this study will be used as input for the implementation in the Muon Collider software

MPGD-HCAL R&D general strategy for Muon Collider

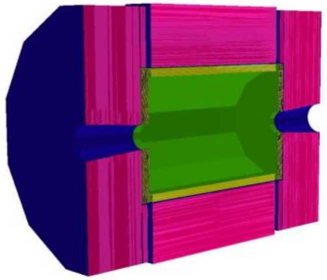
Stand-alone simulation with GEANT4
- Design optimization, provide input parameters for full simulation



Test on a MPGD calorimeter prototype
- Assess the performance of an active layer and within calorimeter system



Simulation in the Muon Collider framework
- Sets geometrical constraints, physics requirements



GOAL of my work

1. **Proof of MPGD-based HCAL concept with stand-alone Monte-Carlo simulation**
2. **Characterization of the single detector response to MIPs**
3. **Test the performance of resistive MPGD in a calorimeter cell prototype for the first time**