Performance of resistive MPGDs for hadron calorimeters

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

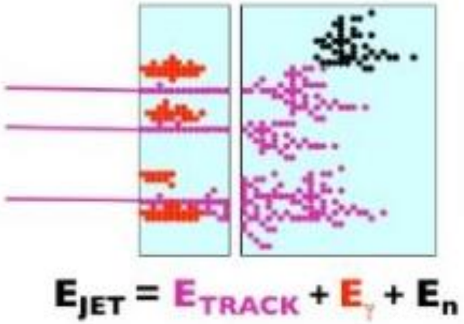
Outline

- **Motivations**
- **Simulation studies**
  →Standalone simulation in G4
  →Simulation within Muon Collider framework
- **Characterizations of MPGD prototypes**
  → Efficiency, Uniformity
- **Development of a calorimeter prototype**
  → Data-MC comparison
- **Lessons learnt**
- **Conclusions and future plans**

MPGD-HCal at Future colliders

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

- Current tendency for R&D on calorimeters:
  High Granularity for Particle Flow
  - 5D calorimeter --> (x,y,z, t) + Energy reconstruction



- Current technology: Silicon, Scintillators, RPCs as active layers

Development of Resistive MPGD Calorimeter with timing measurement (2021-2023)

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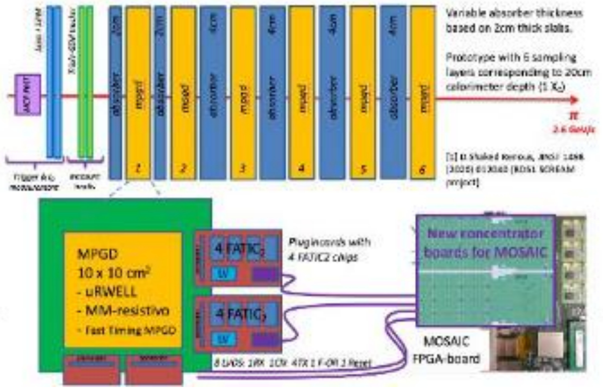
\+ Weizmann Institute of Science

Design of MPGD-based HCAL cell



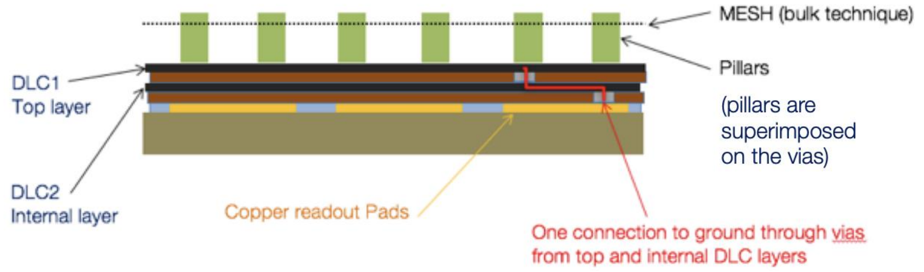
Proposal: high-rate and *possibly ecofriendly* alternative to RPC, **the resistive MPGDs** as active layers of sampling calorimeter

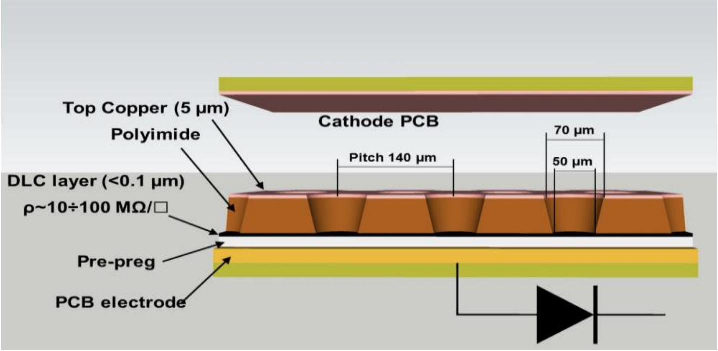
Project initiated in 2021 within the RD51 collaboration and currently framed within the DRD6/DRD1 collaborations

Why MPGDs for calorimeters?

- **Cost-effectivness** for large area instrumentation
- Radiation hardness (up to several **C/cm²**)
- **Discharge rate** non impending operation
- Rate-capability O(**MHz/cm²**)
- Flexible space resolution O(**100 µm**)
  → allow for **high granularity**
- Time resolution with MIPs of **few ns**

MicroMegas



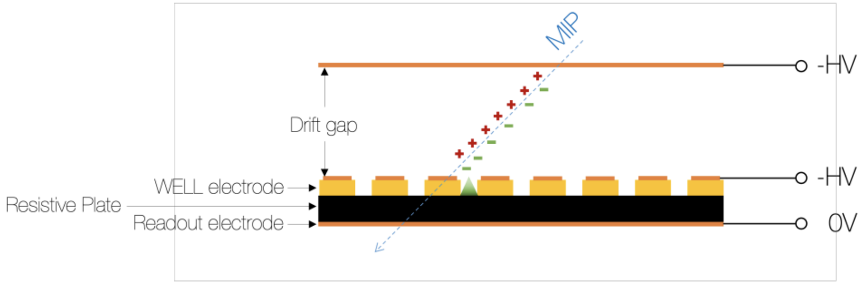


µRWELL

Idea already investigated in

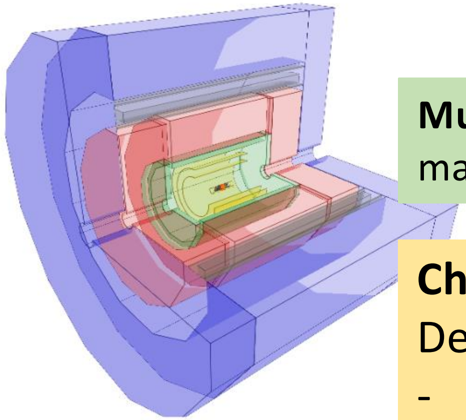
- **Calice** collaboration: sampling calorimeter using RPC and also tested MicroMegas
- **SCREAM** collaboration: a sampling calorimeter combining RPWELL and resistive MicroMegas

RPWELL



Towards a Muon Collider arXiv:2303.08533

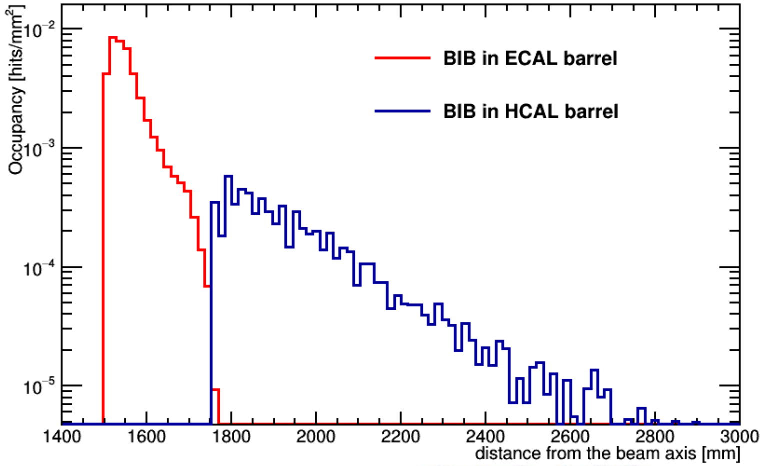
Physics case: HCal at Muon Collider

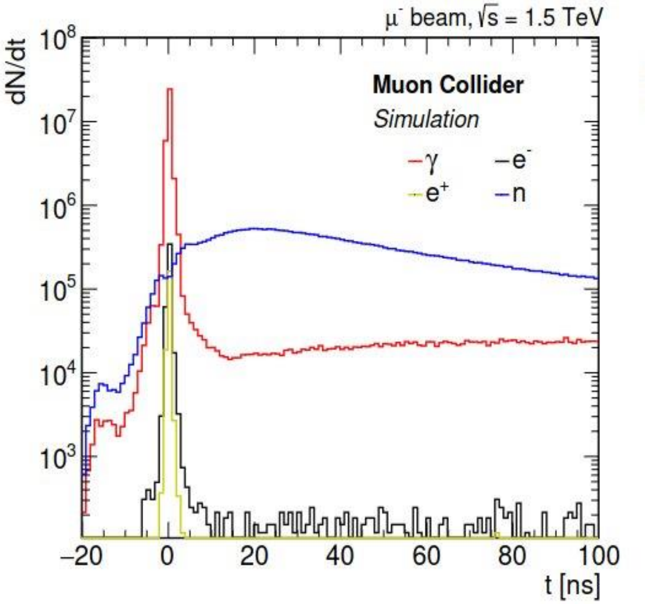


Muon collider: Multi-TeV μ+μ- collider in **compact circular** machines, as possibility for future collider after HL-LHC

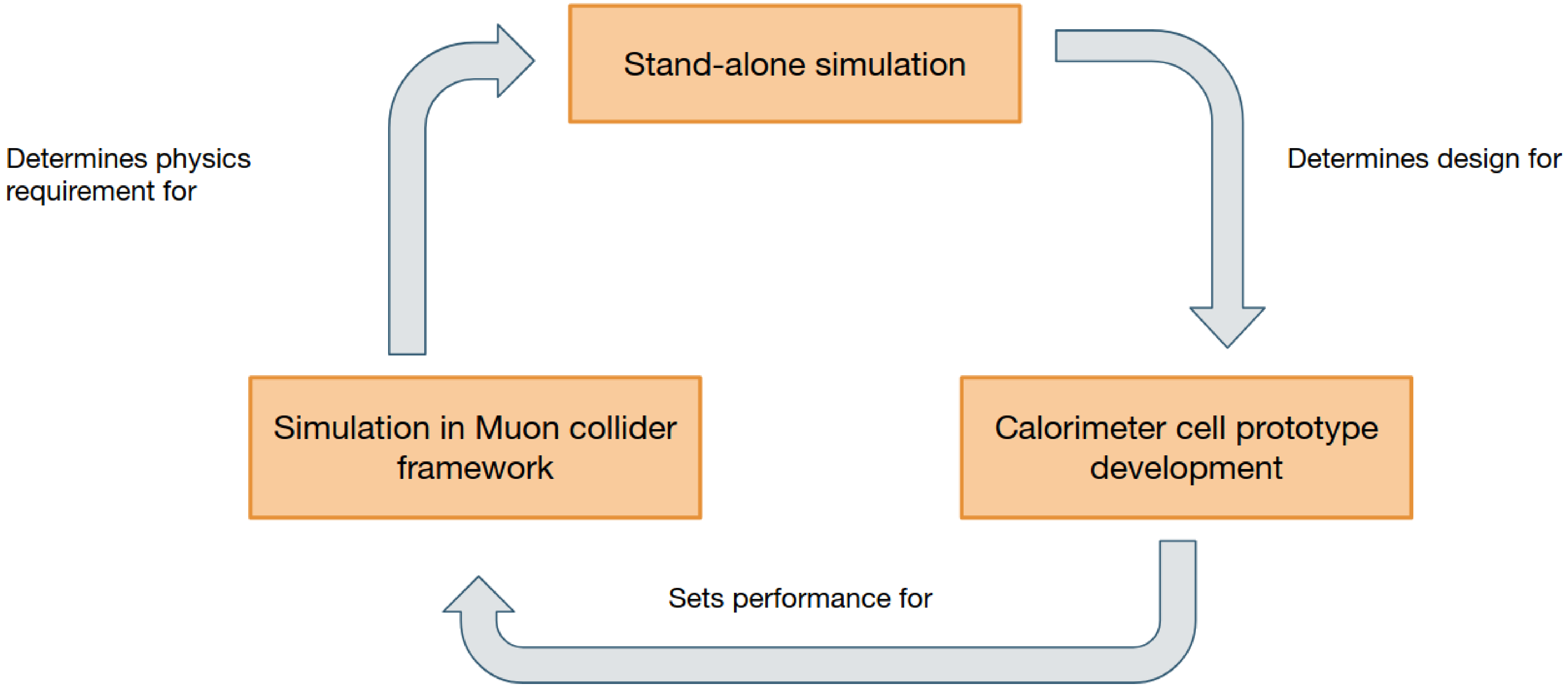
Challenges :
Deal with **Beam Induced Background** in HCAL:
- Mostly photons (96%) and neutrons (4%)
- Large asynchronous components
- Occupancy ~ 0.06 hit/cm^2 (x10 the one at HL-LHC)

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





Strategy for the R&D



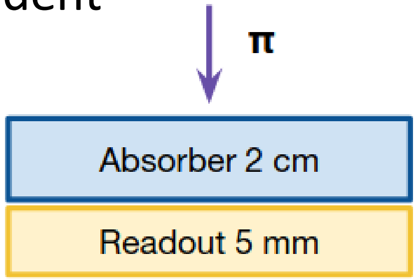
Simulation studies

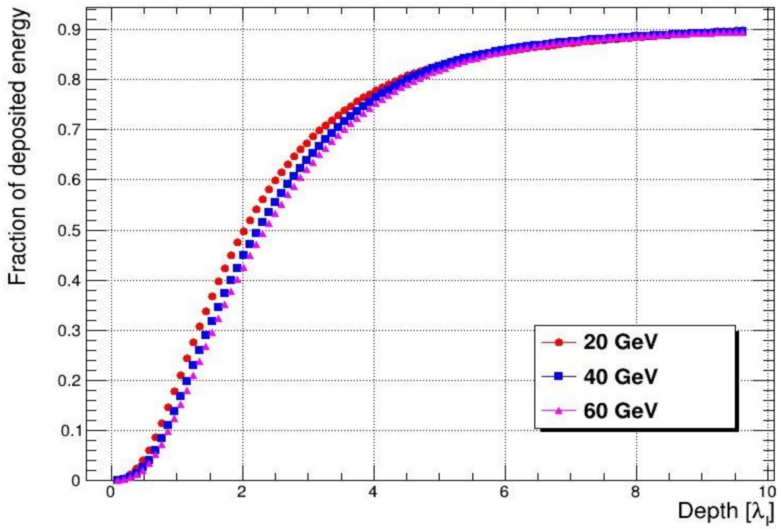
HCal standalone simulation

Standalone Geant4 simulation technology-independent

- Geometry of single layer:
  - 2 cm of iron for absorbers
  - 5 mm gas (Ar/CO_2)

  } $\lambda \sim 26$ cm
- Readout granularity 1x1 cm^2

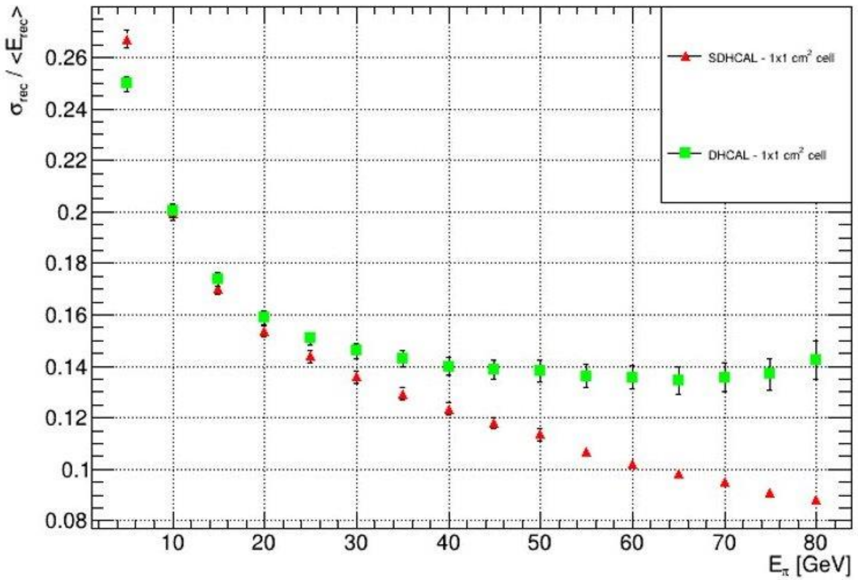




Result: longitudinal containment in 10 λ, transversal in 3 λ

Energy resolution simulated in two scenarios:

- **Digital** calorimeter: shower energy proportional to total number of hits
- **Semi-digital** calorimeter: hits are weighted based on three thresholds $E_\pi = \alpha N_1 + \beta N_2 + \gamma N_3$



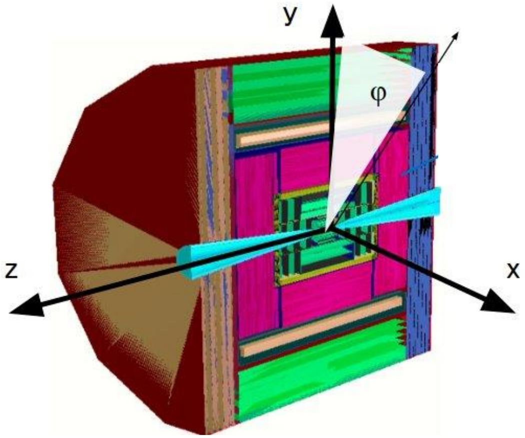
Result:

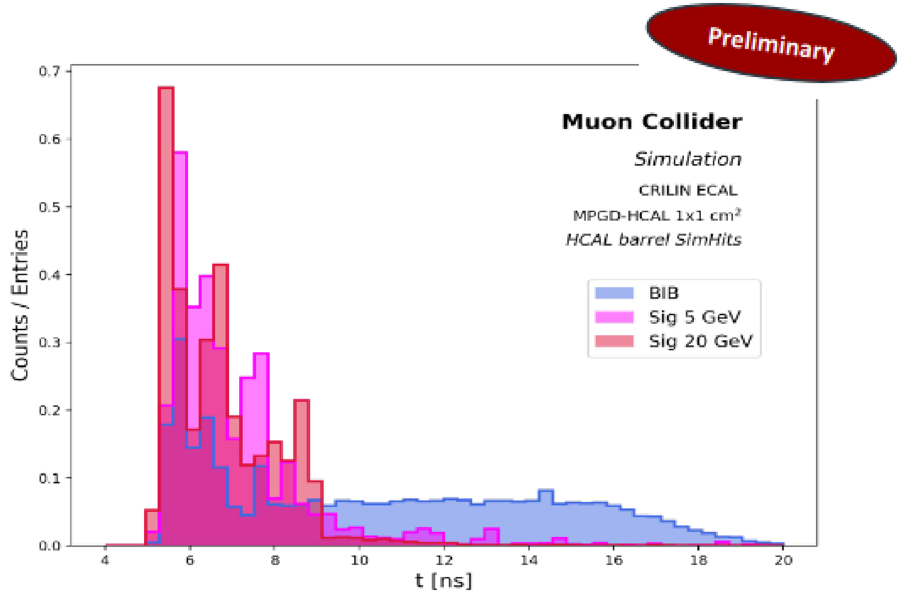
- resolution at **8%** for $E_\pi \sim 80$ GeV with semi-digital readout
- resolution **saturates** at **14%** for $E_\pi \sim 30$ GeV for digital readout

HCal simulation within MuCol framework

Simulation of BIB at a center of mass energy of 1.5 TeV

- BIB containment within the first 20 layers
- Uniform distribution of arrival time in the range 7-20 ns
- Signal arrival time peaks at ~ **6ns**;
- Discrimination possible for t > 9/10 ns
  → **achievable** with MPGD detectors



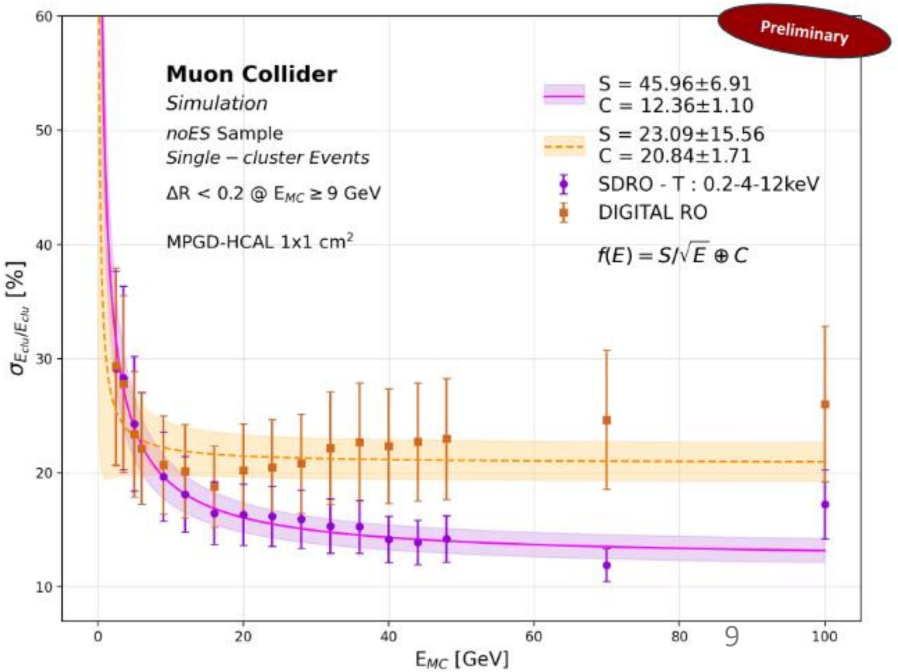


Energy resolution simulated:

- π guns up to 100 GeV
- Selecting π starting shower in HCal

Result:

- overall better performance with semi-digital readout
  $\sigma/E = 46\%/\sqrt{E} \oplus 12\%$
- resolution **saturates** with digital readout



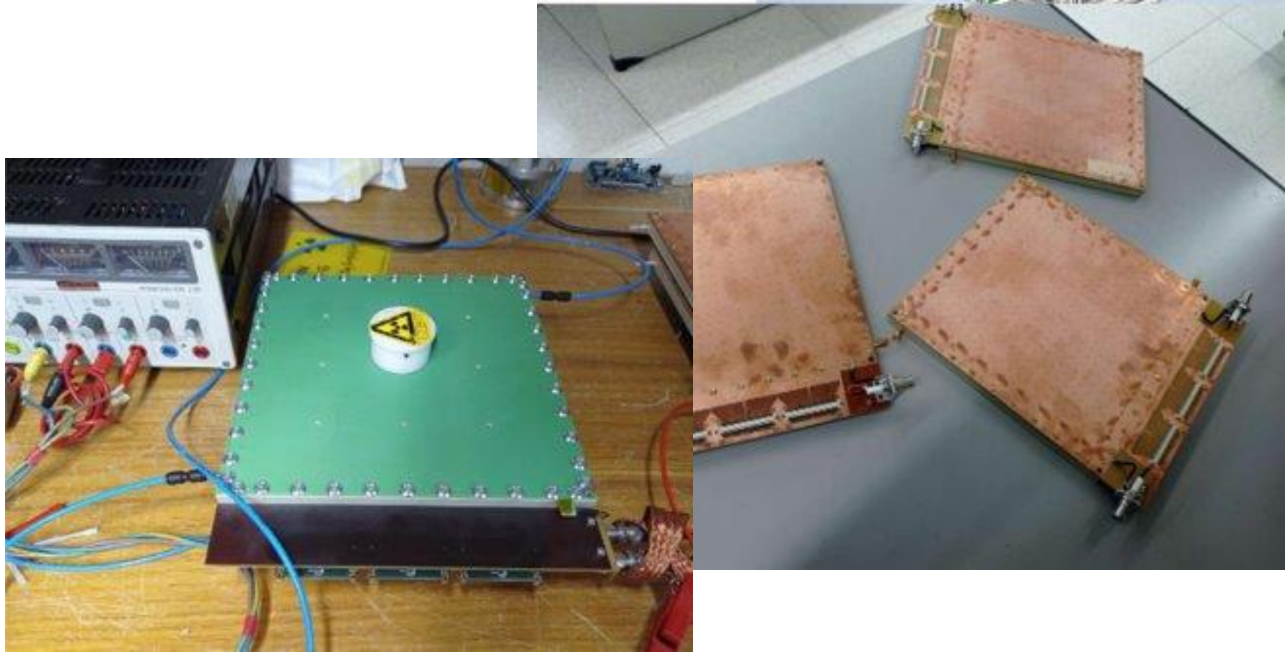
Characterization of MPGD prototype

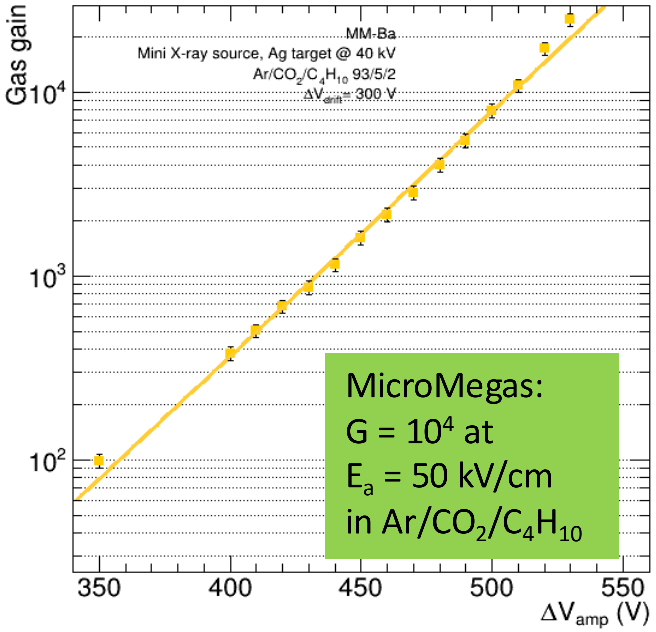
MPGD prototypes

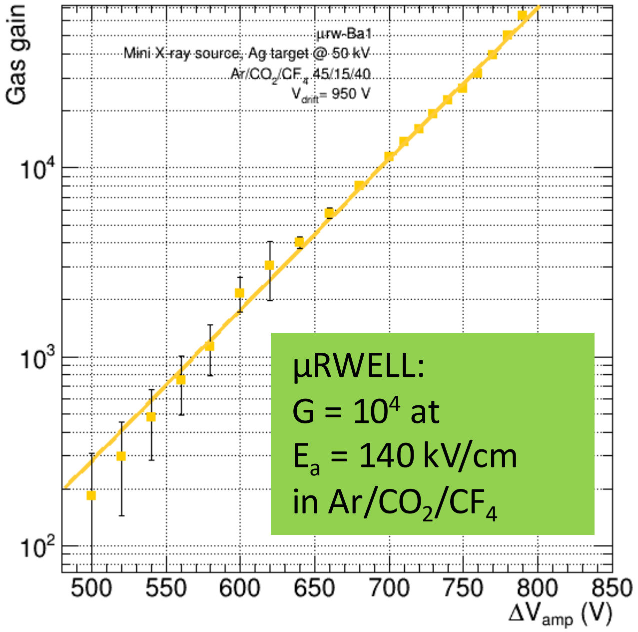
MPGD technologies:

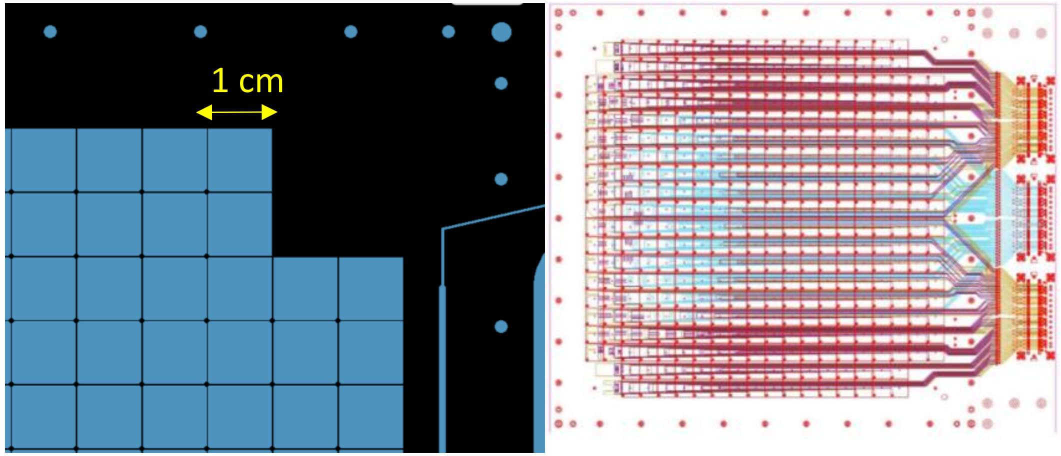
- 7 µRWELL
- 4 resistive MicroMegas
- 1 RPWELL
- Detector **layout**: 20x20 cm^2
  - ~6 mm drift gap
- **Common readout** board: 1x1cm^2 pad→ 384 pads

First characterizations in terms of effective gain using X-ray performed in lab in Frascati, Roma3, Bari, Napoli, Weizmann

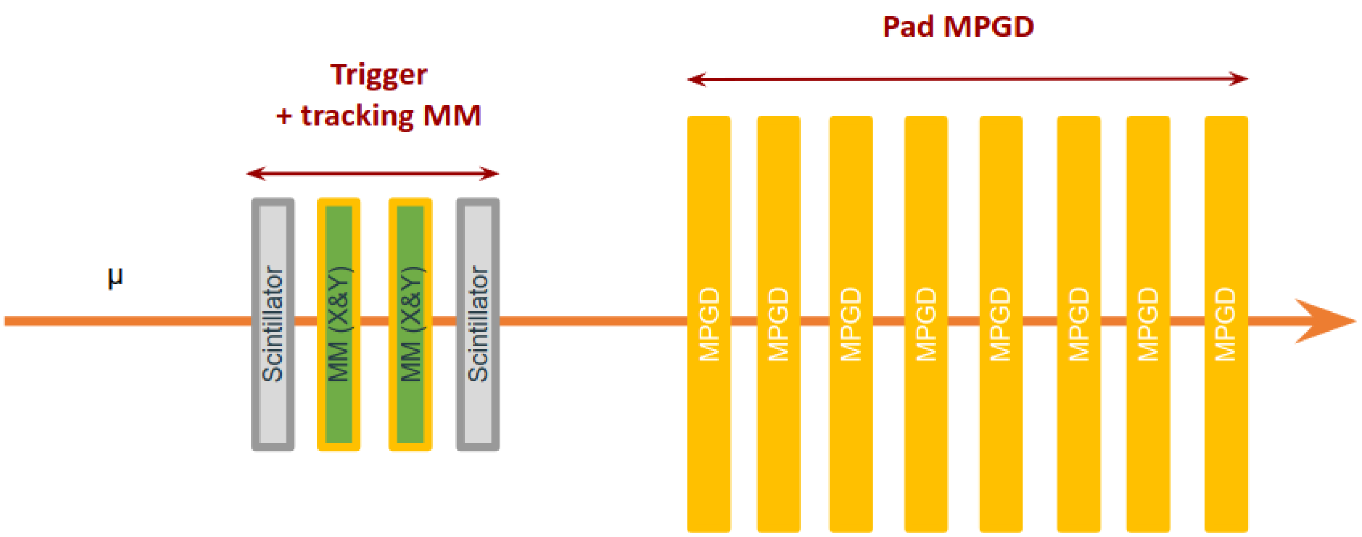


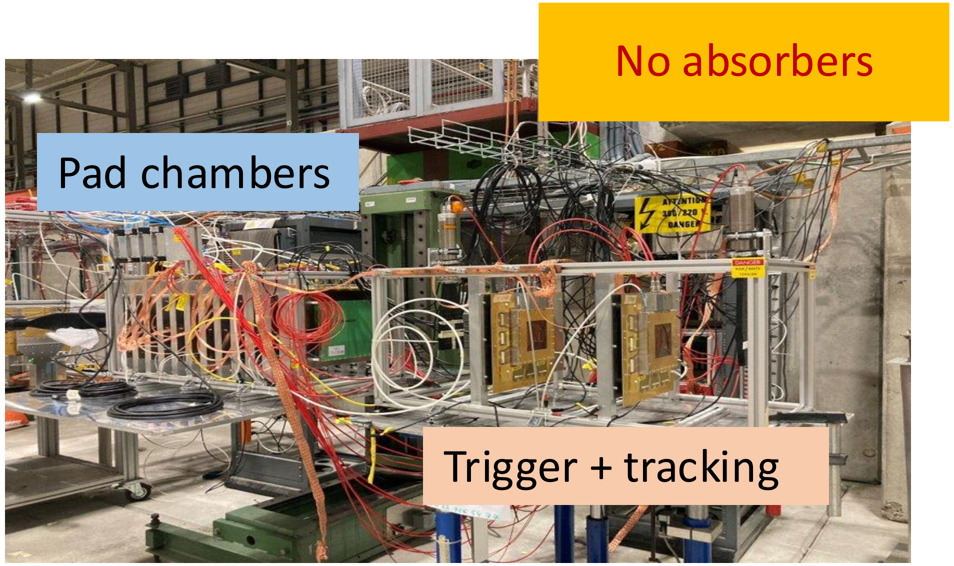






MPGD prototype - test beams at SPS



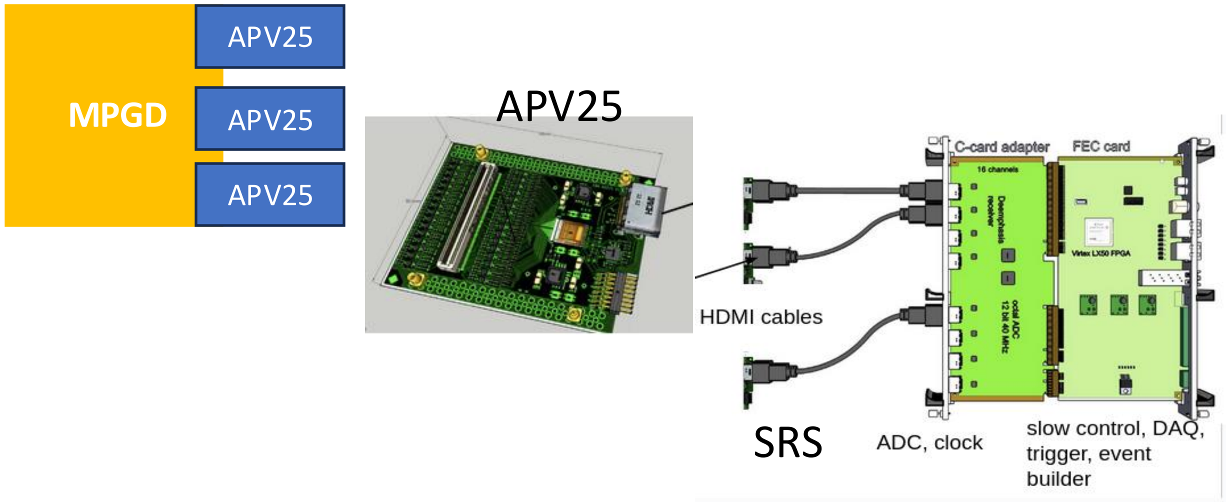


GOAL: Test of readout layers in terms of response to MIPs

- **Tracking**: XY strips TMM (+ GEM at 2024 TB campaign)
- Pad chambers under test (rMM, μ-RWELL, RPWELL)
- $Ar/CO_2/CF_4$: μRWELL - $Ar/CO_2/iC_4H_{10}$: resistive MM
- Particles O(100GeV) μ beam

DAQ chain:

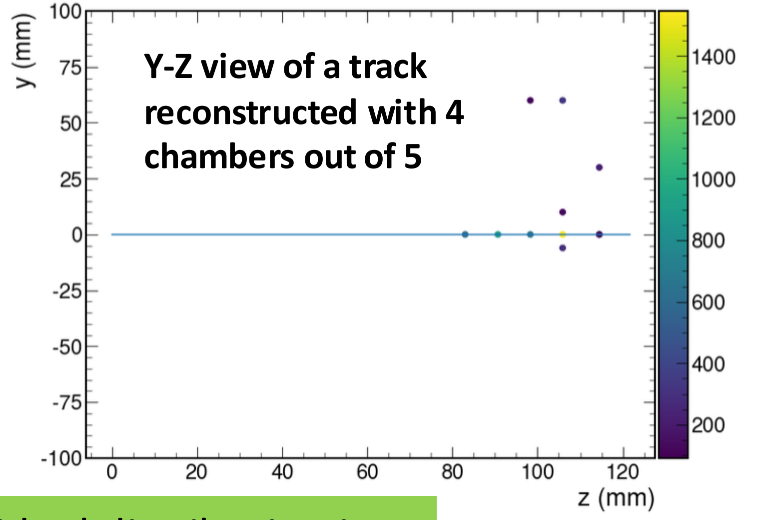
- APV25 for charge and time measurements
- SRS back-end

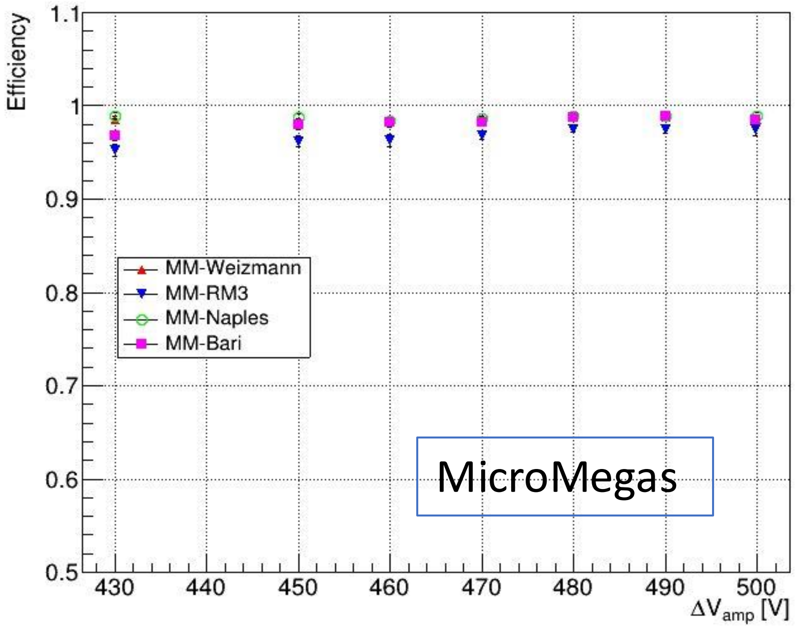


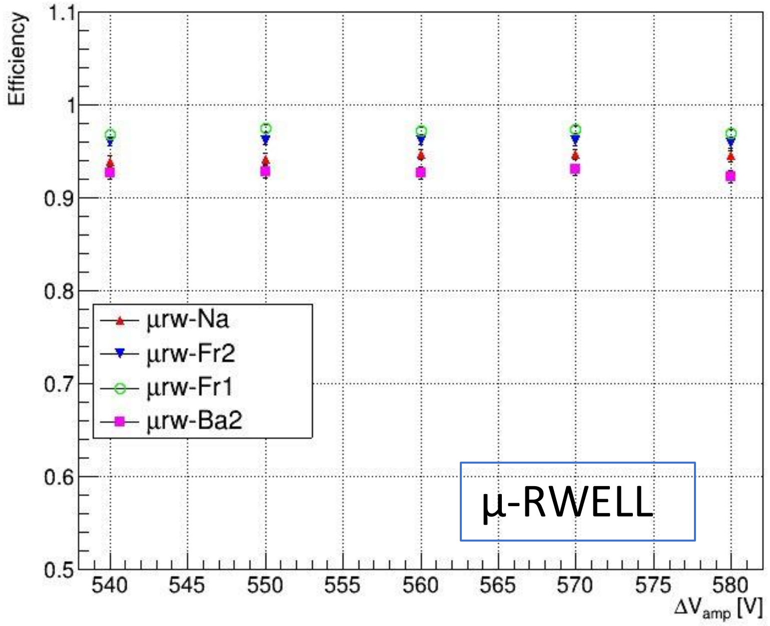
Detector performance – 2023 results

Analysis workflow for **2023 TB**:
- Tracking system unused -> for each detector, tracks reconstructed with clusters from 5 pad chambers out of 6
- Observed high probability of **cross-talk** between pads due to routing of readout vias from pads to front-end
- Patched offline by **clustering** pads based on charge sharing fraction

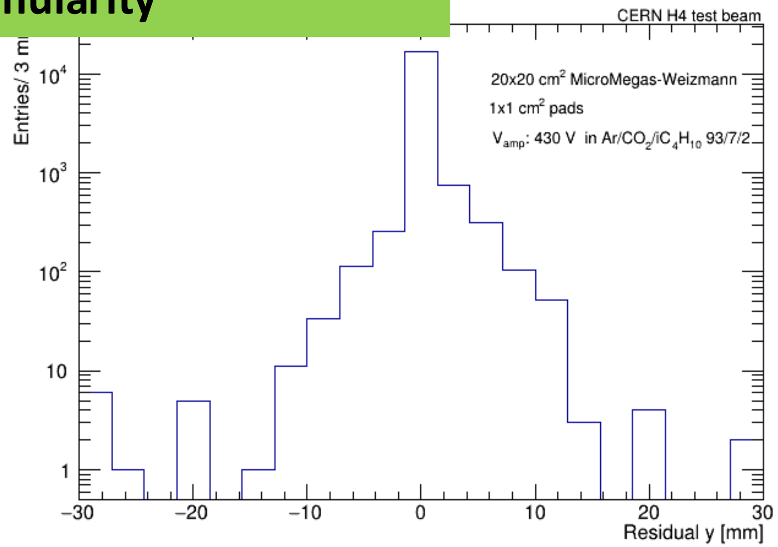
High MIP detection efficiency (detectors always operated at plateau)







Residual distribution in agreement with detector **granularity**



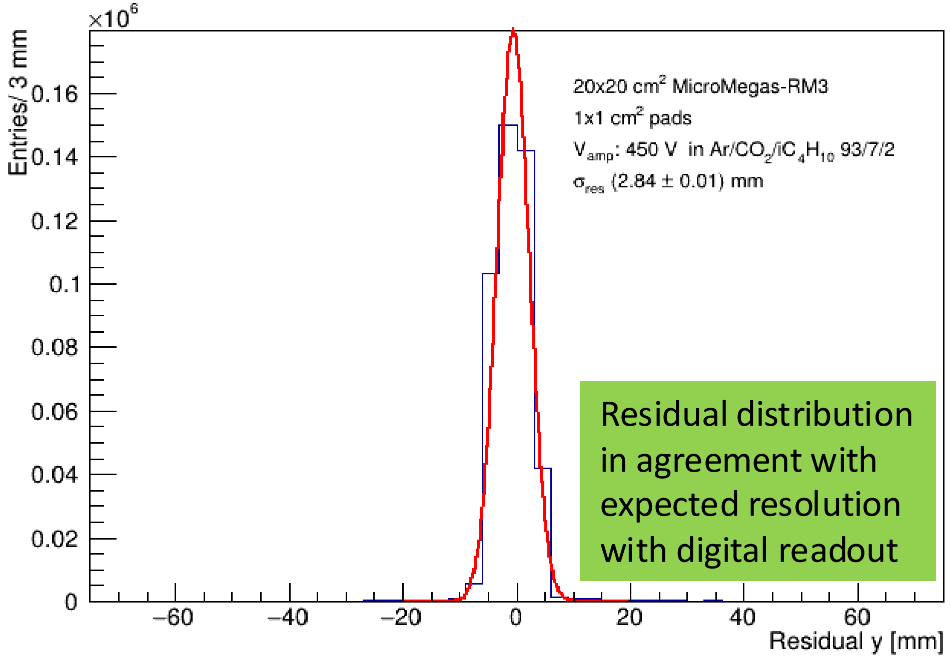
Detector performance – 2024 results

Preliminary

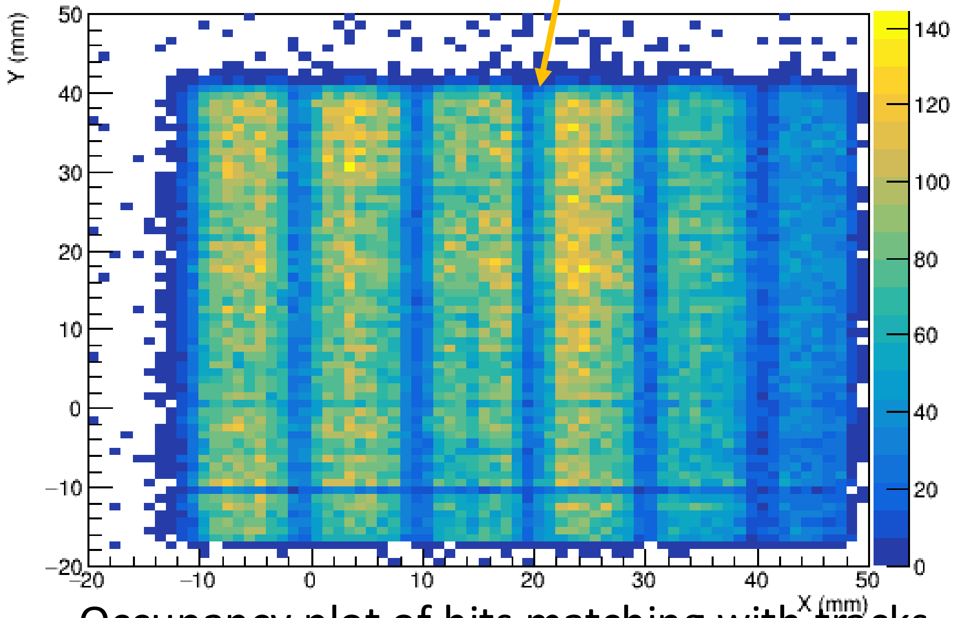
2024 TB **setup**: tracking system + 8 pads chambers under test (3 rMM + 5 µRW)

Analysis workflow for 2024 data

- Track reconstructed with tracking system (TMMs)
- Clustering algorithm developed ad hoc to exclude x-talk pads



Dead areas due to PEP lines in µrwell



Occupancy plot of hits matching with tracks for µ-rwell

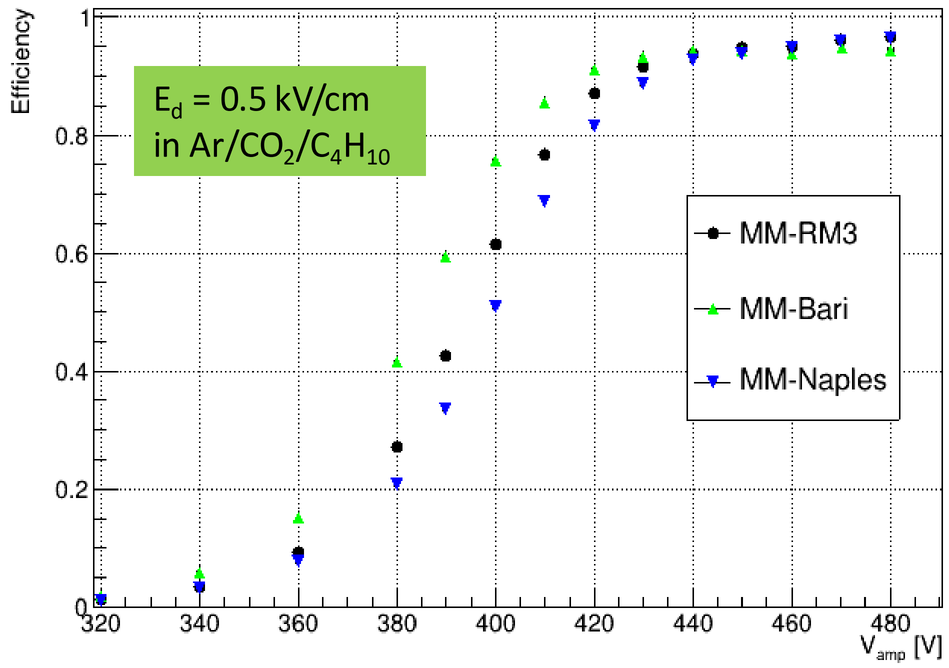
Detector performance – 2024 results

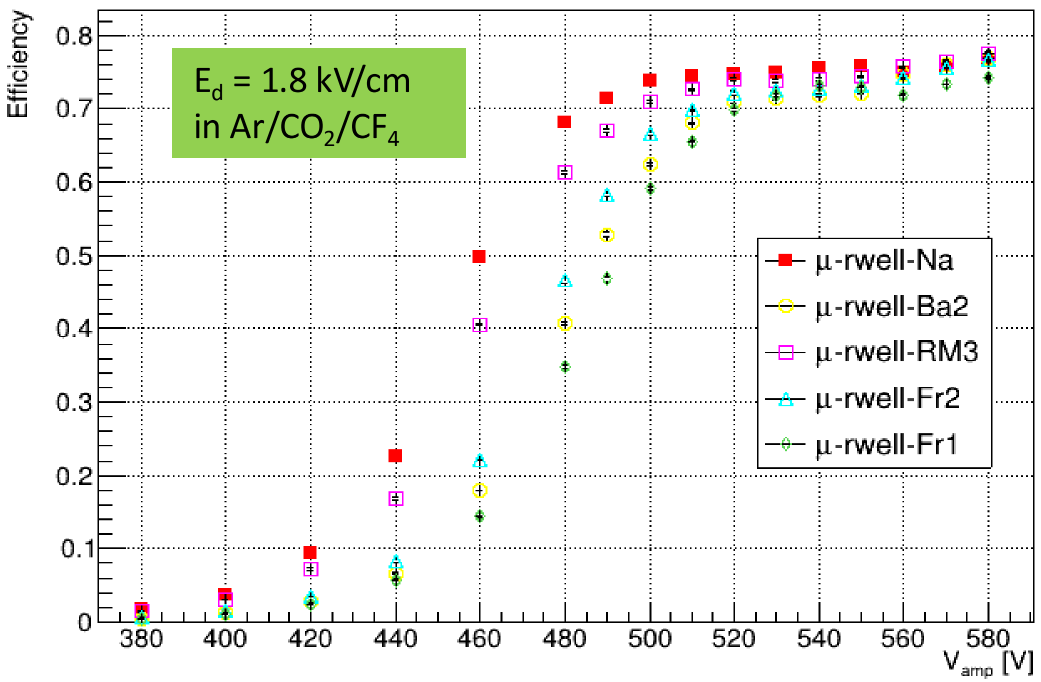
Preliminary

2024 TB **setup**: tracking system + 8 pads chambers under test (3 rMM + 5 µRW)

Results

- Full turn-on efficiency curve measured for both technologies
- Plateau > 90% for MM, ~ 75% for µ-RWELL



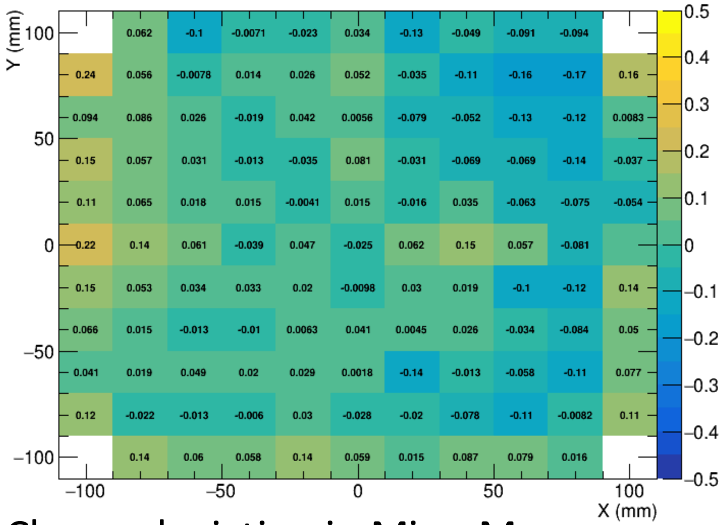


Detector uniformity

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

Uniformity measured using hits matching with tracks

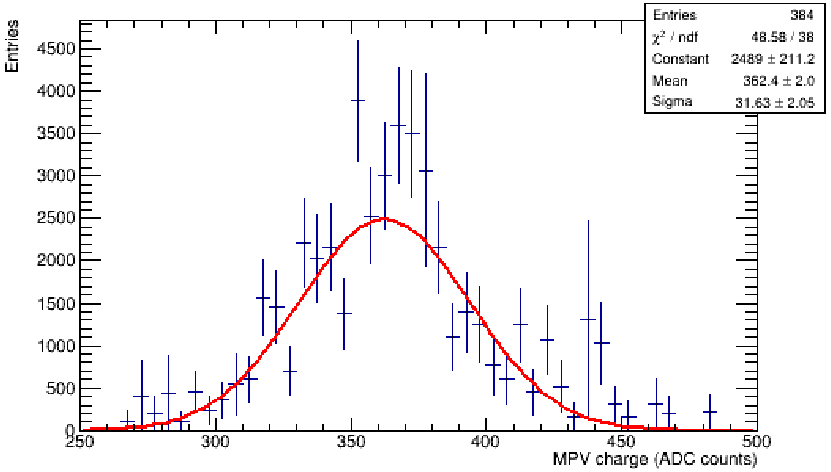
- Good uniformity for MicroMegas and µRWELLs
- Spotted non-uniformity regions in 2 µRWELLs (out of 5 tested)
    - seen in 2023 data and checking for 2024 data

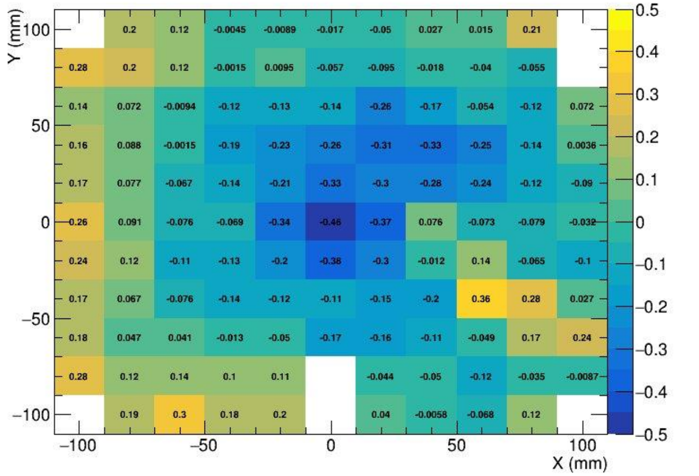


Charge deviation in MicroMegas

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	$(16.3 \pm 1.1)\%$

MicroMegas-Bari



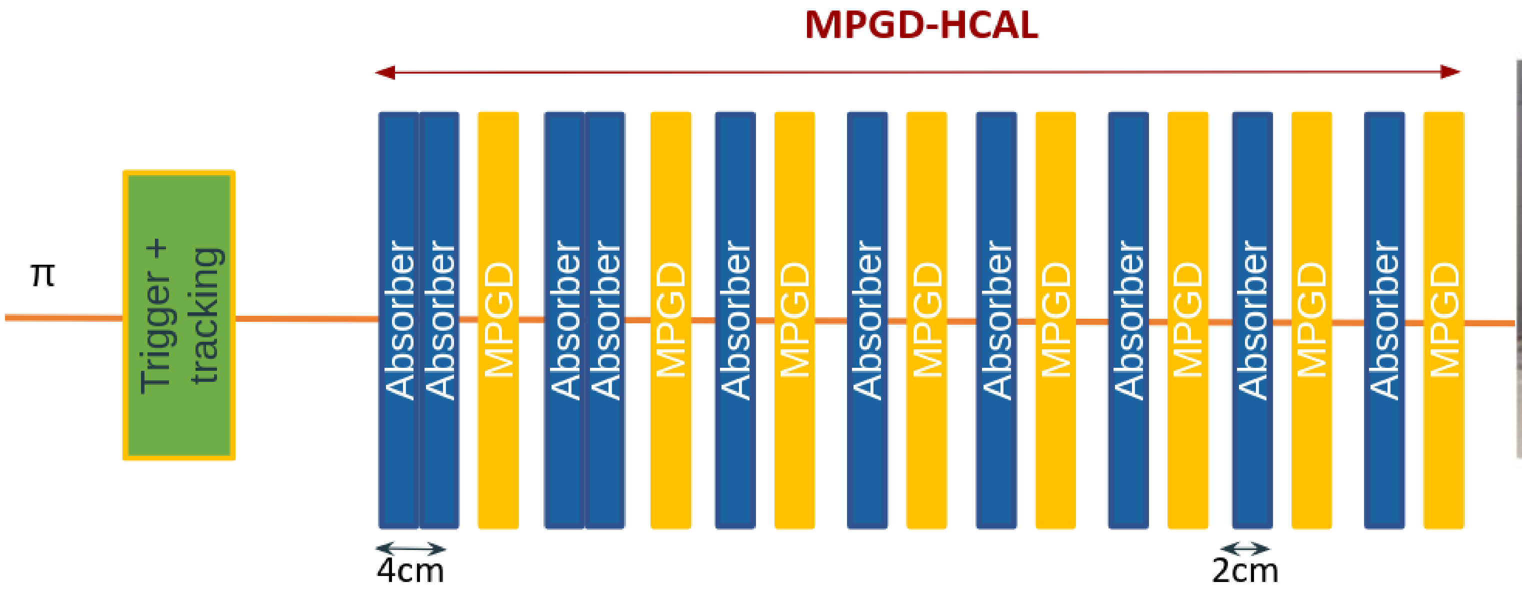


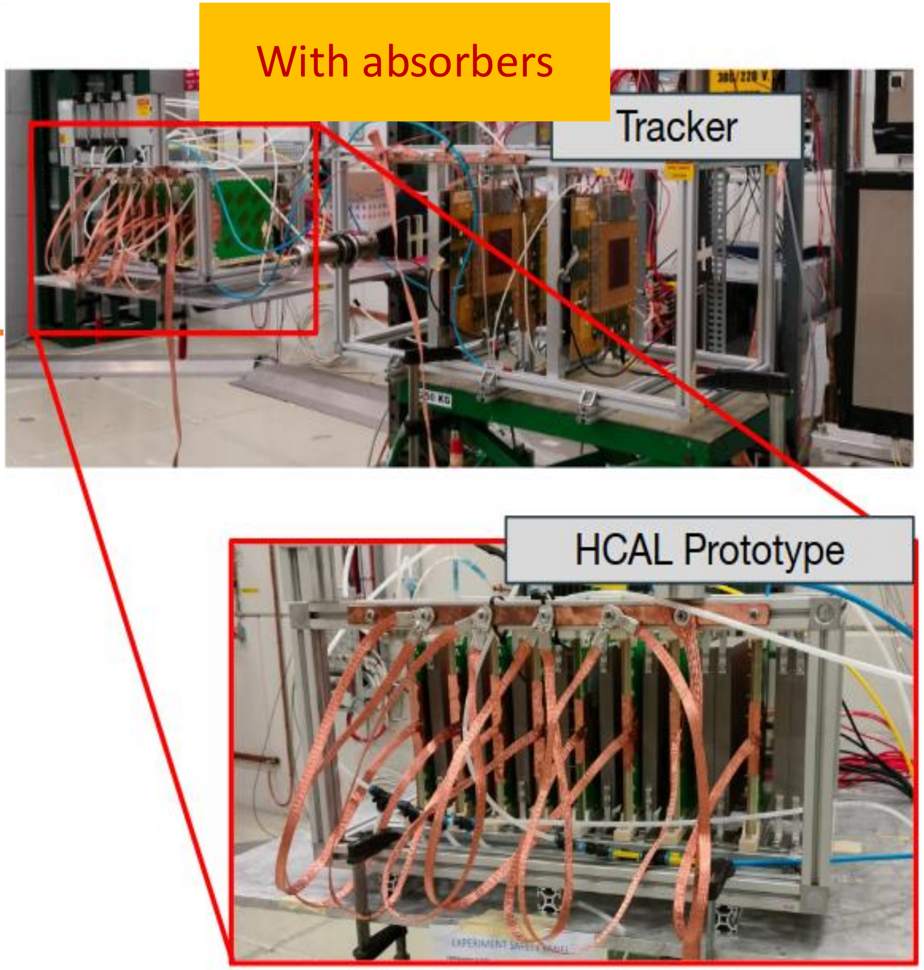
Charge deviation in µRWELL-Frascati1

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

Development of a calorimeter prototype

MPGD-HCAL prototype – PS test beam





HCAL prototype ~ 1 λ_I (8 active layers)

Data taking based on analog FE (APV25 + SRS)

Runs at different π^- energy (up to 11 GeV)

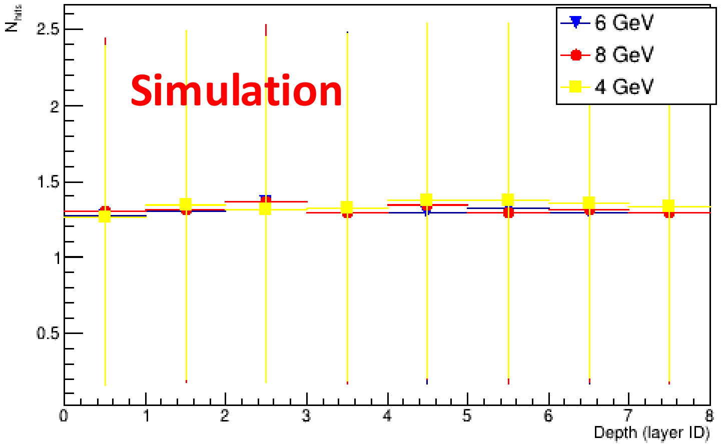
- Two TB campaigns: August 2023, July 2024
- Data analysis ongoing
- Developed G4 simulation for the small prototype, including a digitization algorithm to account for charge-sharing among adjacent pads and detector efficiency

Event selection in Monte Carlo and data

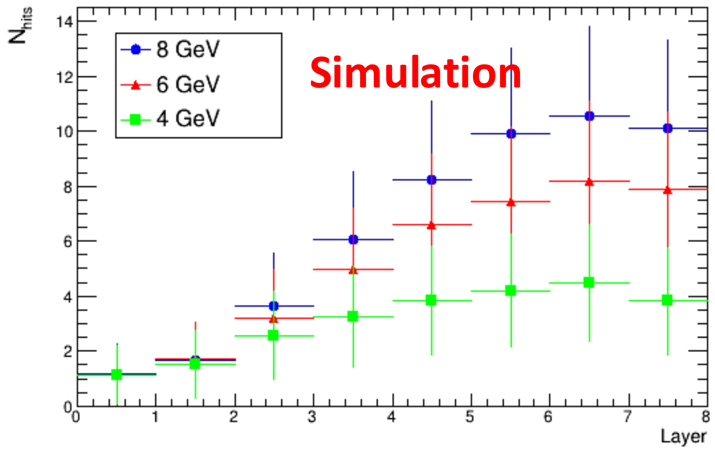
Event **selection criteria** supported by **simulation** using MC truth

- 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



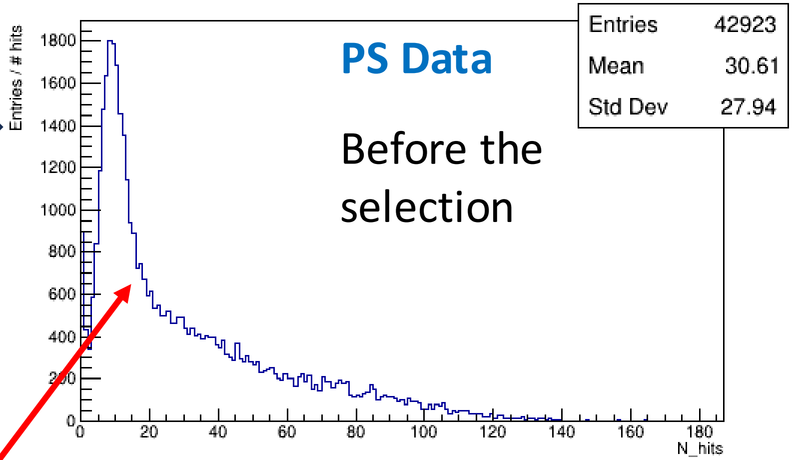
Shower events



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

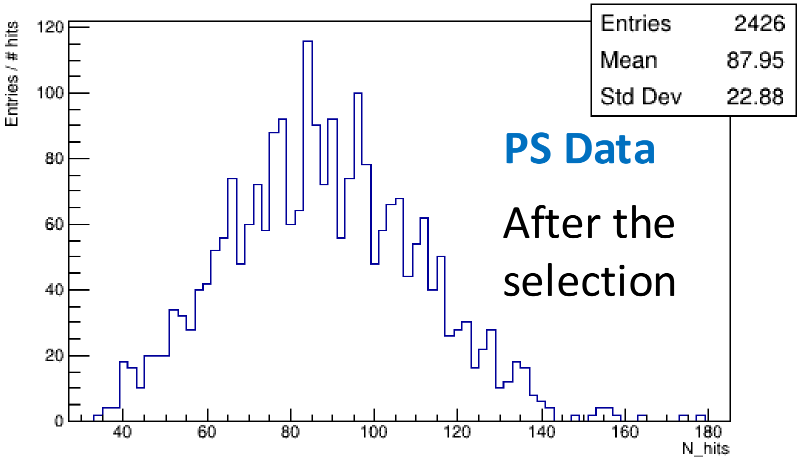
- excluding first 2 detectors (faulty APVs)
- counting only **once** along vias direction to avoid x-talk pads (detectors operated at high gain for APVs)

Number of hits for all layers



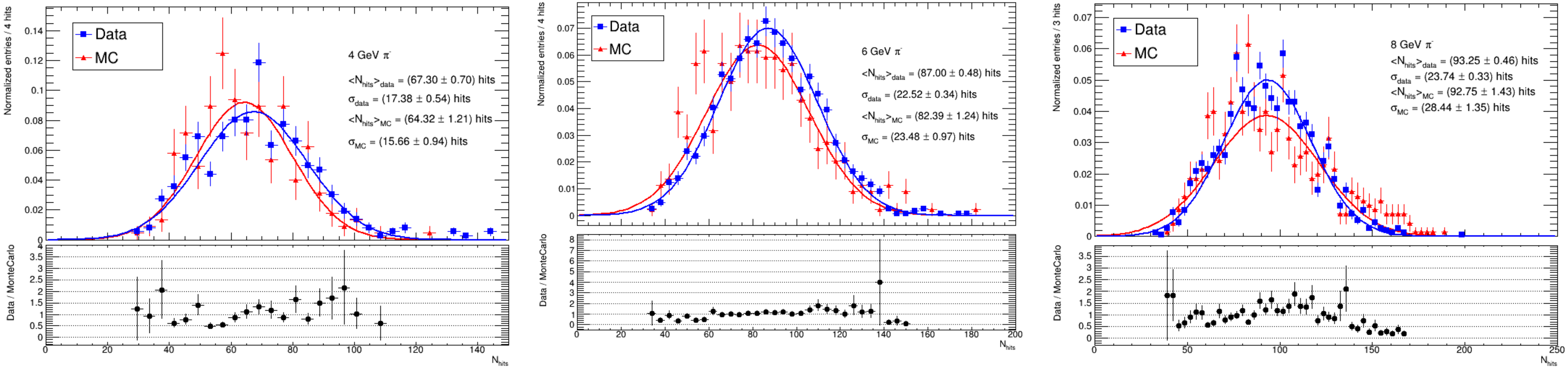
Peak at ~ 10 hits
-> MIP-like events

Number of hits for all layers



2023 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



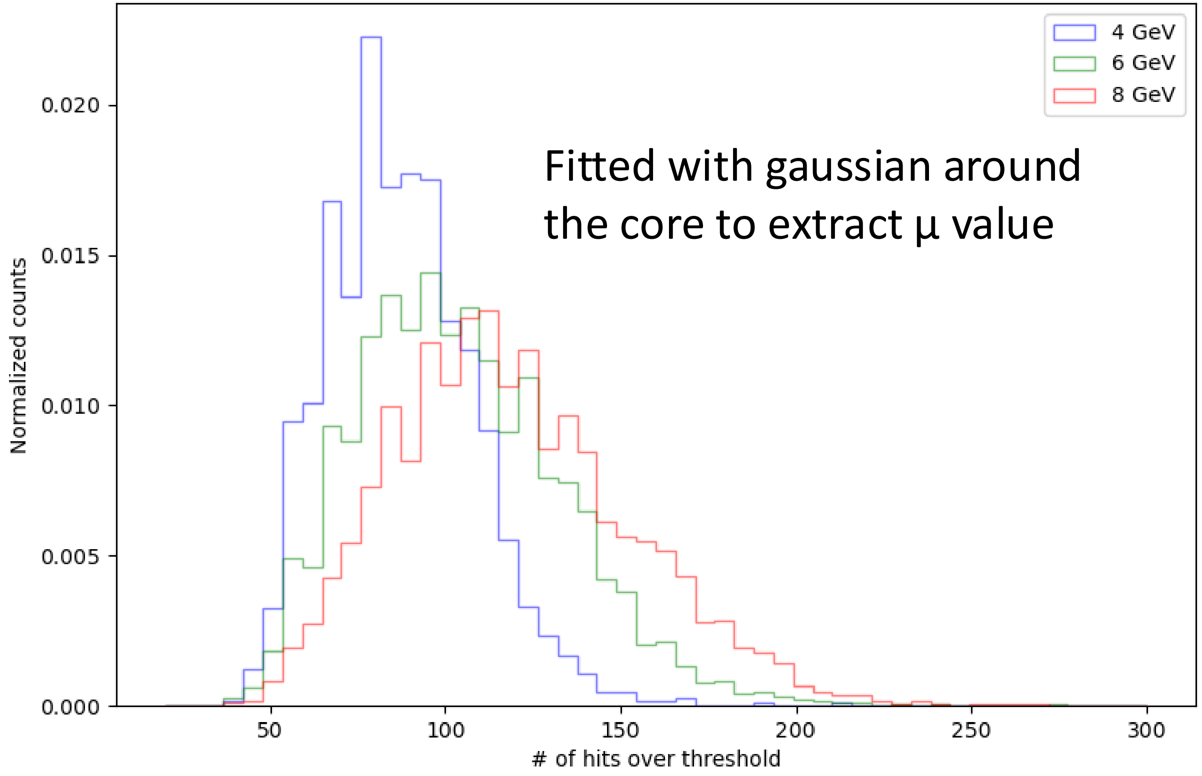
Good agreement between data and Monte Carlo

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

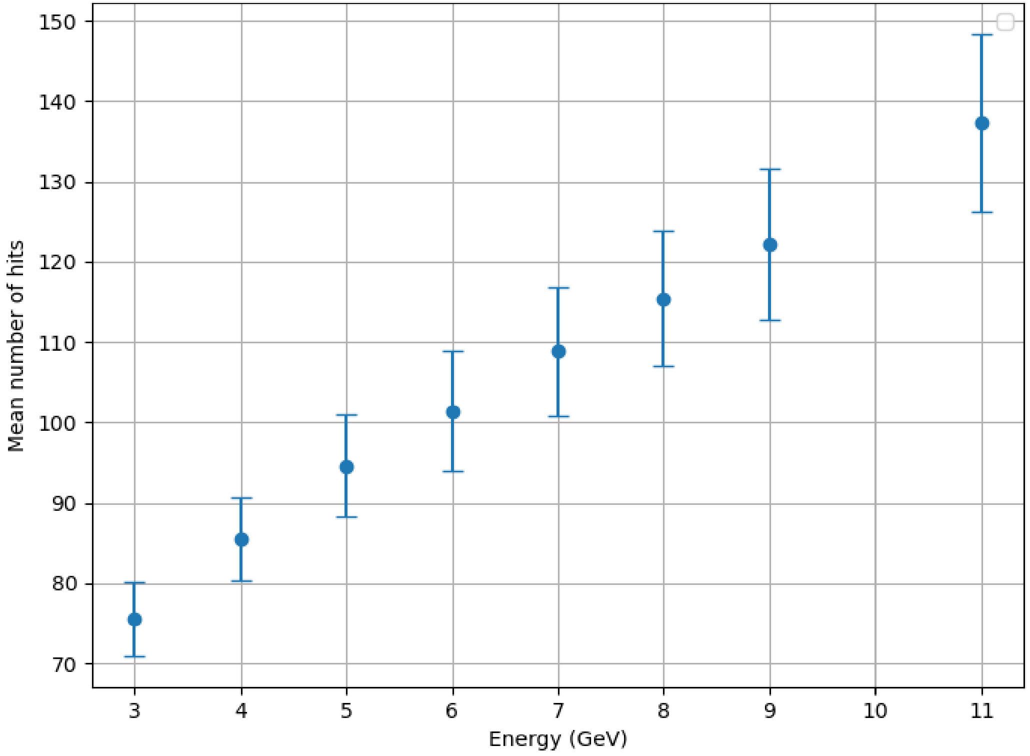
MPGD-HCAL prototype – 2024 Data

Preliminary

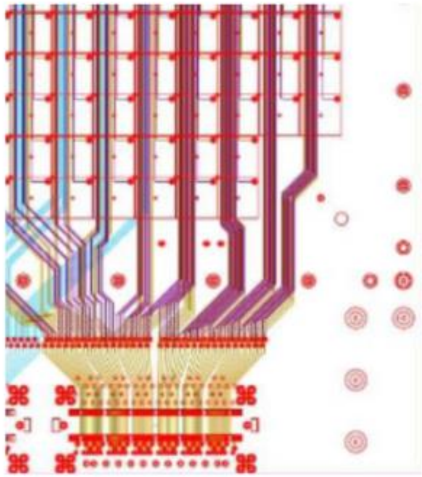
Number of hits for all layers

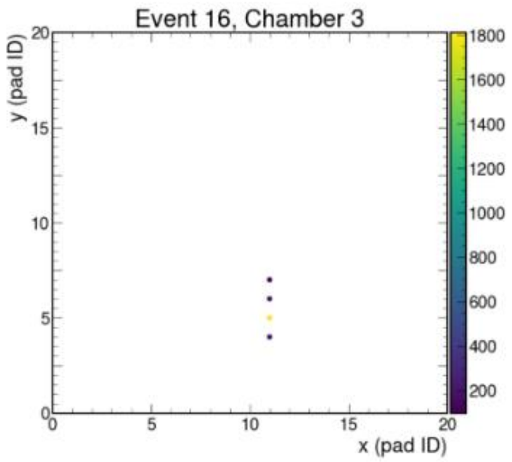


Response function: Total number of hits increases as a function of the energy



Lessons learnt





Cross-talk visible along the y pads

Detector design

- Observed cross-talk due to readout vias routing.

  In next prototype batch:

  → shorten R/O vias at the expense of equalizing signal delays

  → increased distance between planes of RO pads and vias

Readout electronics

- Legacy readout electronics based on APV25 supported by MPGD community is getting less reliable and available

  → Frequent damage (ESD or discharge) on input channels

  → Medium setups (> 20 chips) not easily supported in back-end and DAQ

  → APV25 out of production

Next steps: Planning to move to front-end VMM3 and 2 pad µRWELL already tested in recent TBs with VMM3 (see Darina's talk)

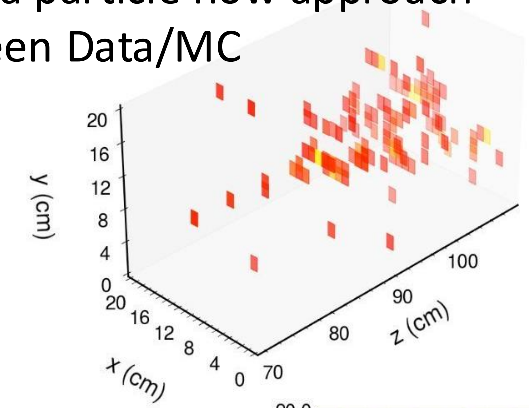
Operational experience and detector characterization

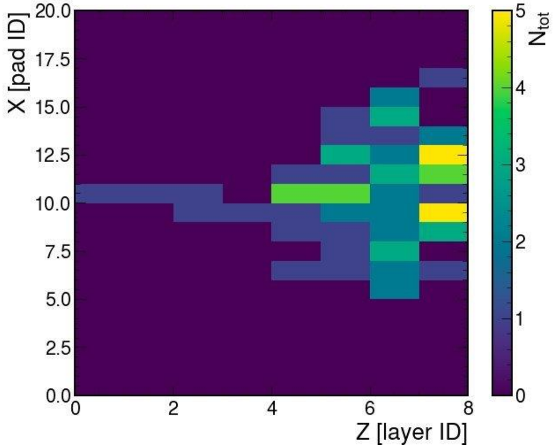
- Working points (amplification field, drift field) to be optimized for better energy resolution to be used in semi-digital mode

Conclusions and next steps

Developments of MPGD-HCAL ongoing in simulations and hardware

- Preliminary results on BIB studies show MPGD technologies are **good candidates** for BIB rejection for Muon collider
- A semidigital readout allows to achieve the requirements needed in the context of a particle flow approach
- Preliminary results on the calorimeter cell prototypes show good agreement between Data/MC





Plans for 2024-2025

- Consolidating results with present prototypes in two test beams in 2024:
  - SPS
    - → full efficiency vs gain
    - → response uniformity
    - → timing (ongoing)
  - PS: test of a fully equipped 8 MPGD layers
- 4 large detectors (50x50 cm^2) to be built
  - Design currently under revision
- Redesign of modular mechanics
- Started **common project with Crilin** (ECAL for MuCol): expected common test beam at the end of 2025

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Backup

Particle-Flow Calorimetry

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

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	$\approx 0.1\ E_j$	$0.55\sqrt{E_{h_0}}$	$0.17\sqrt{E_j}$

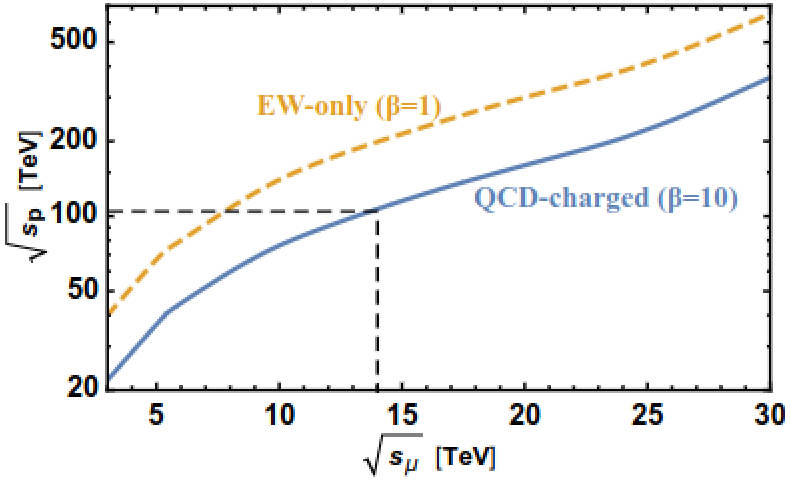
J. Marshall, M. Thomson arXiv:1308.4537

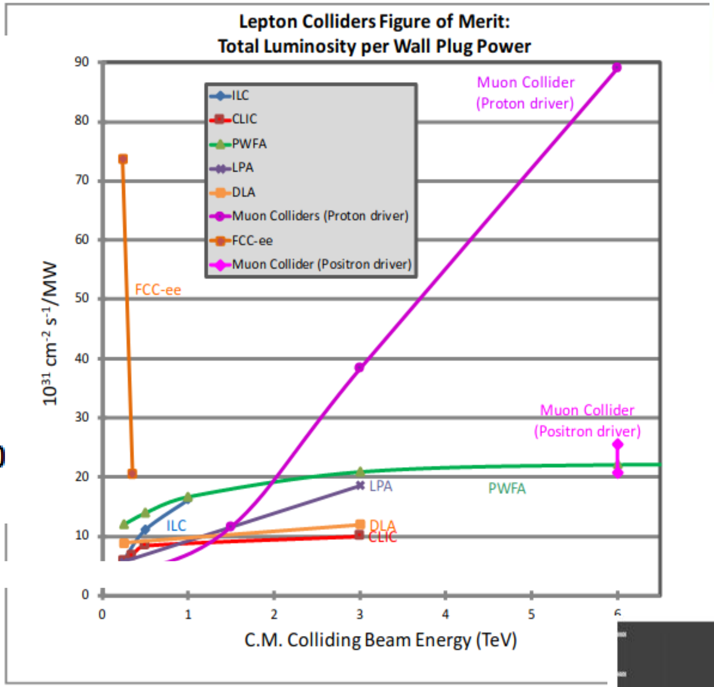
The Multi-TeV Muon Collider experiment

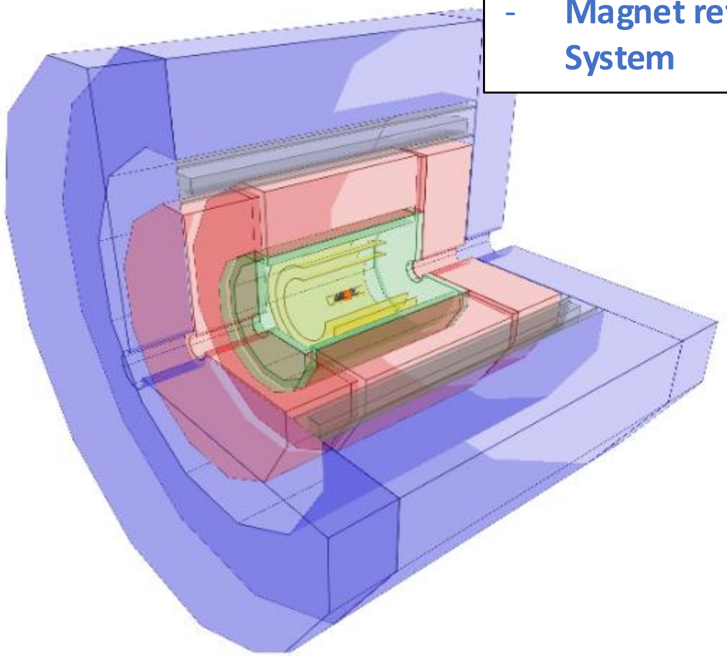
[Towards a Muon Collider arXiv:2303.08533](https://arxiv.org/abs/2303.08533)

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

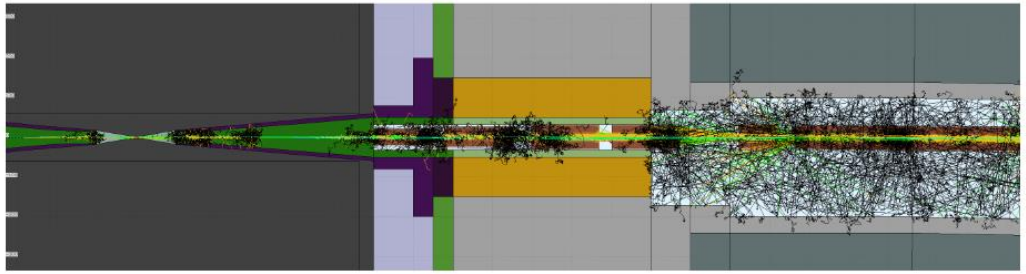
Advantages:
- multi-TeV energy range in **compact circular** machines;
- well **defined initial state** and **cleaner final state**;
- all **collision energy available** in the hard-scattering process.







Tracks of BIB particles in interaction region

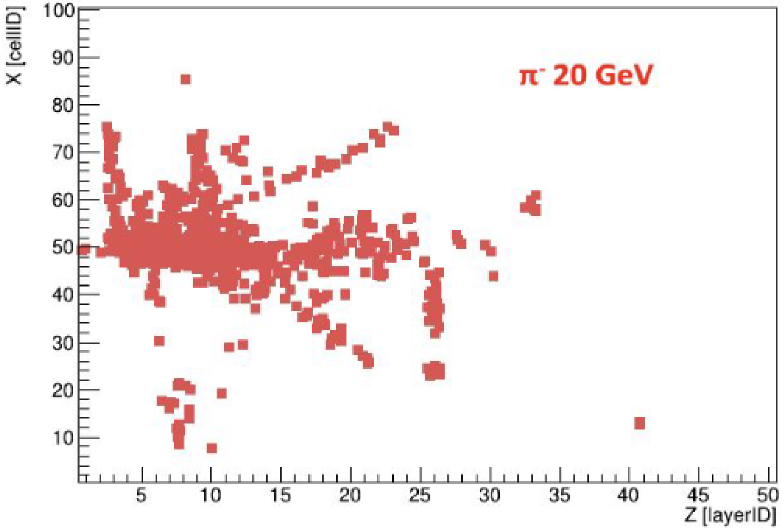


Challenges:
- muon is an **unstable** particle
  intense flux of background particles: **beam-induced background (BIB)**.

Digital vs Semi digital readout

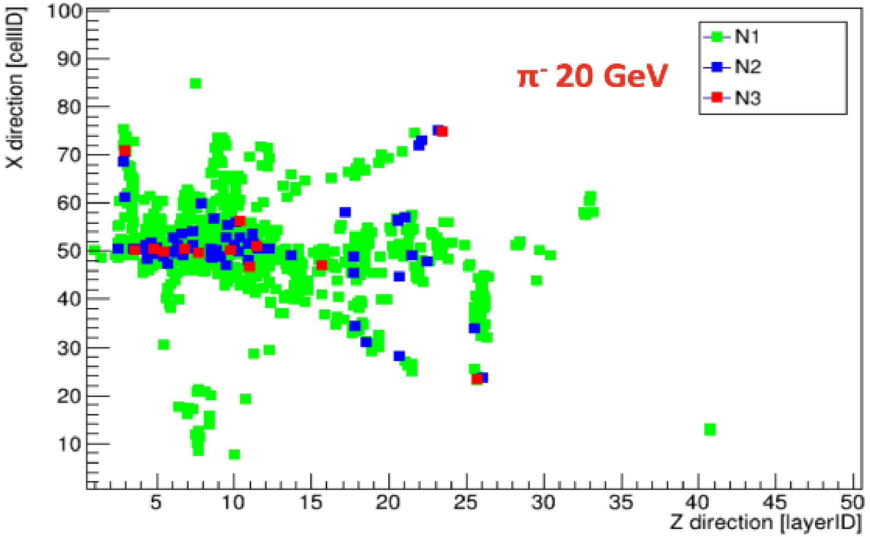
Digital Readout (Digital RO)

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

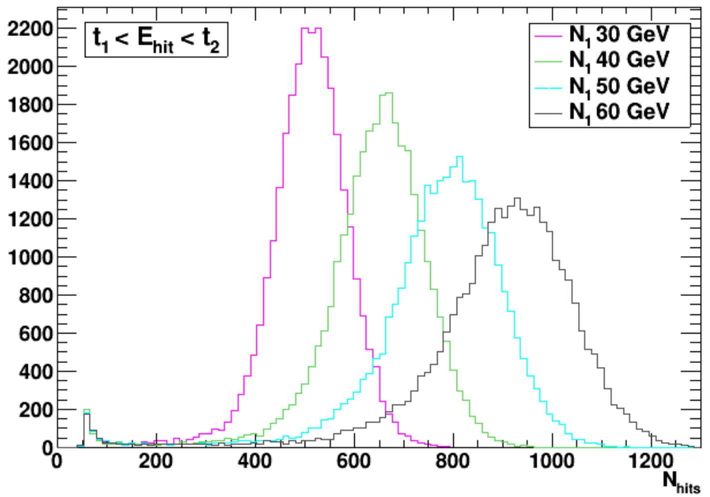


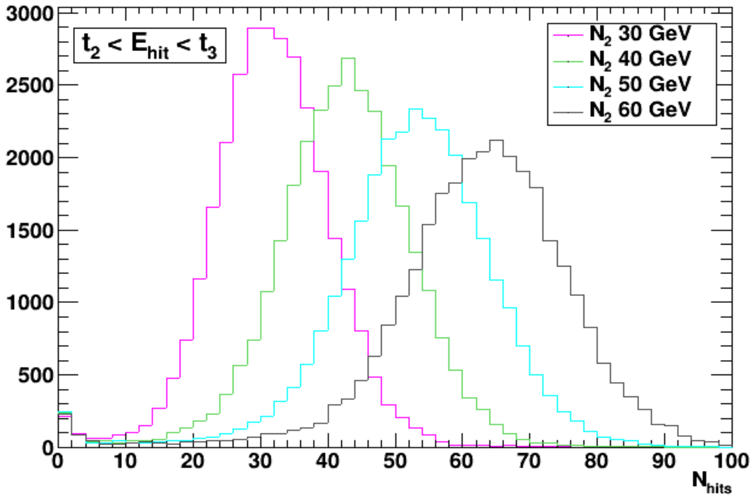
Semi-digital Readout (SDRO)

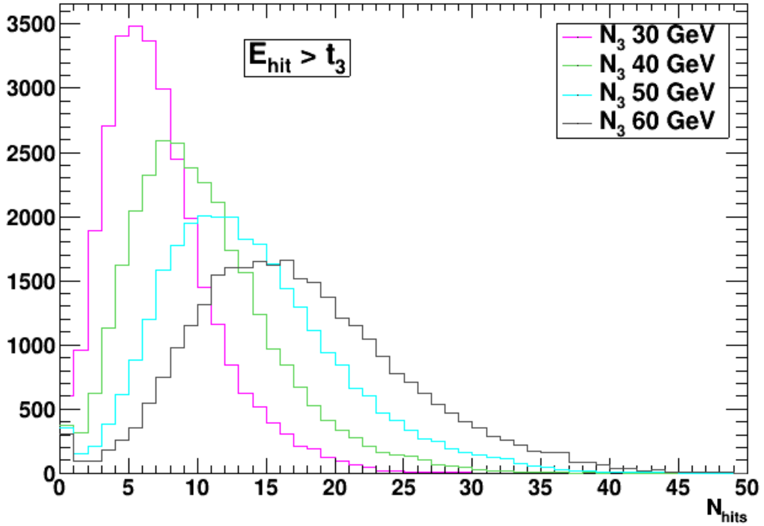
- **Digitization:** defined multiple thresholds
- **Reconstructed energy:** $E_{\pi}= \alpha N_1+\beta N_2+\gamma N_3$ with:
  - $N_{i=1,2,3}$ number of hits above i-threshold
  - α,β,γ parameters obtained by χ^2 minimization procedure



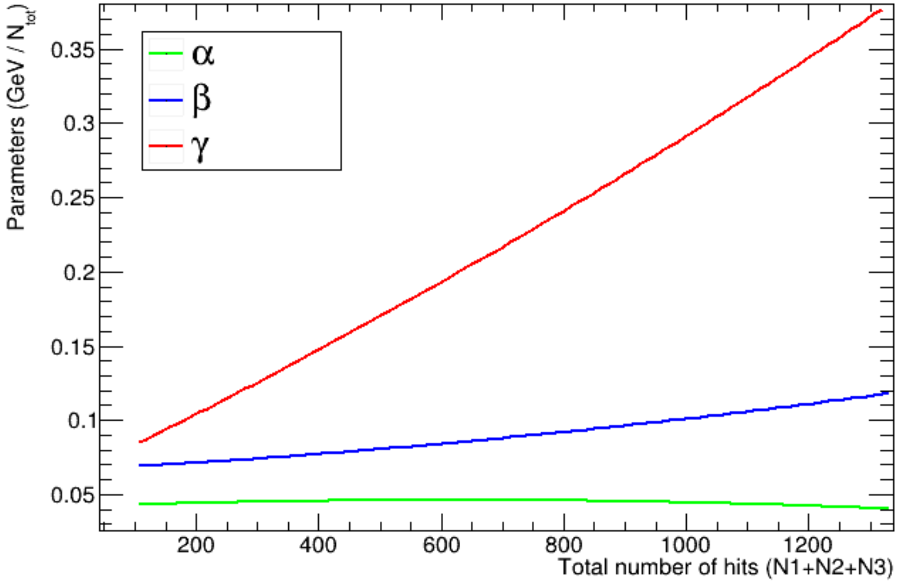
Energy reconstruction: Semi-digital Readout (SDHCAL)





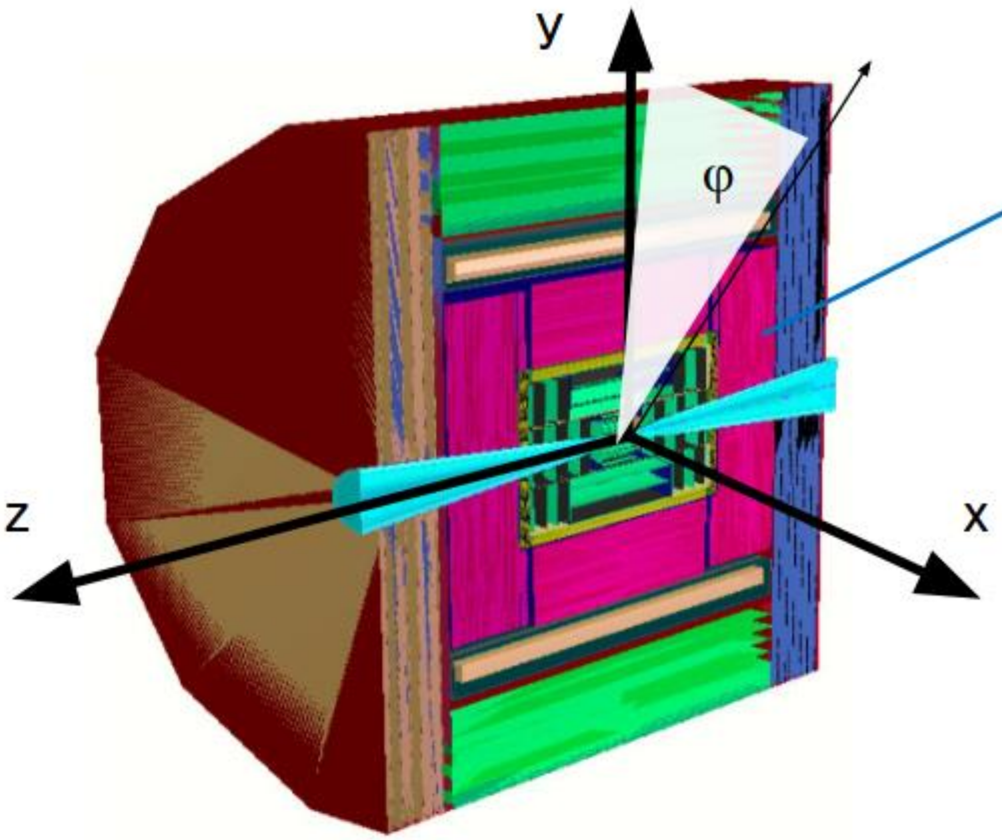


- **Digitization:** defined multiple thresholds
  - t_1 = 0.01 MIP
  - t_2 = 4 MIP
  - t_3 = 12 MIP
- **Reconstructed energy:** $E_\pi = \alpha N_1 + \beta N_2 + \gamma N_3$ with:



HCal simulation within MuCol framework

Geometry considered for the hadronic calorimeter



MPGD-based HCAL

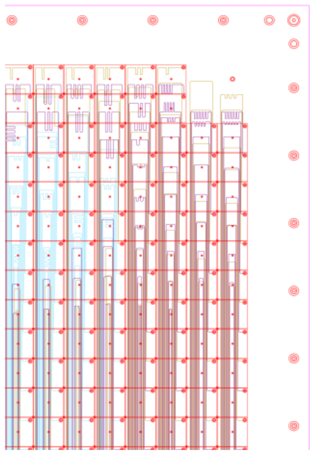
60-layer SAMPLING CALORIMETER

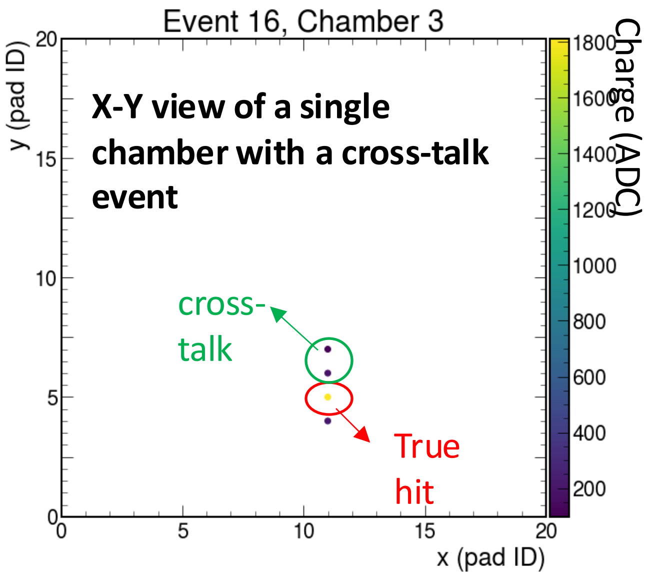
Layer thickness: **2.65 cm** - cell: **1 cm²**

HCAL LAYER COMPOSITION:

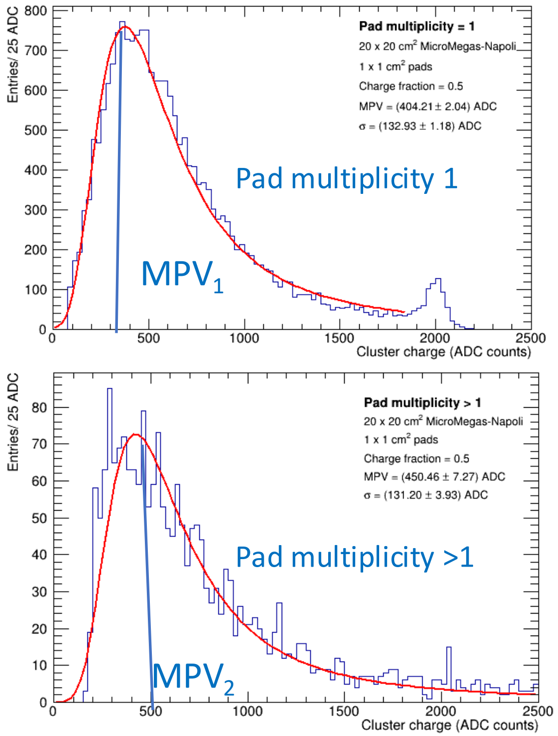
Iron (absorber)	20 mm
Argon (active material)	3 mm
Copper (RO electronics)	0.1 mm
PCB (RO electronics)	0.7 mm
Air (environment)	2.7 mm

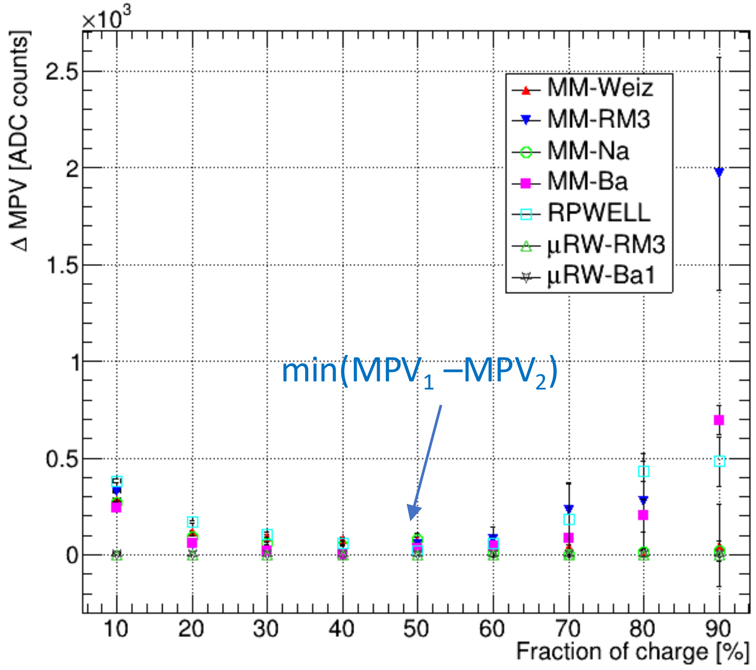
Cluster reconstruction





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





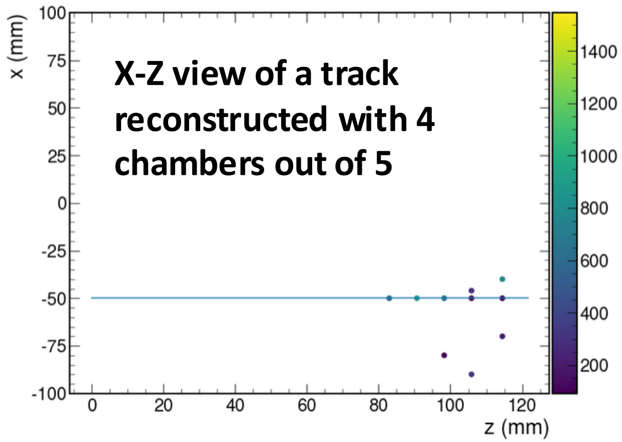
Developed ad-hoc **clustering algorithm** based on charge sharing criterium

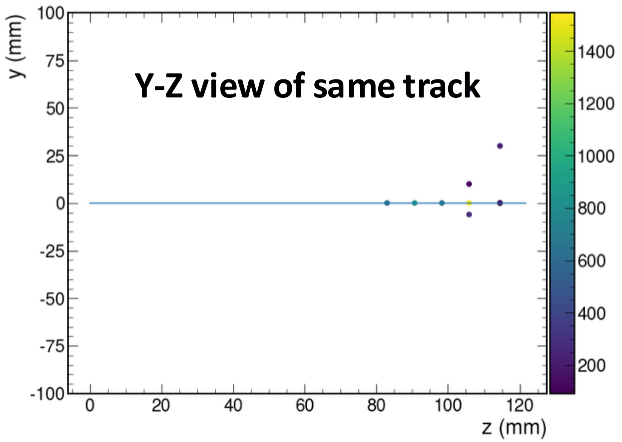
- Selected pad with **highest charge** Q_{max}
- Add a second pad if $Q = 50\% \ Q_{max}$

SPS 2023 test beam – Track reconstruction

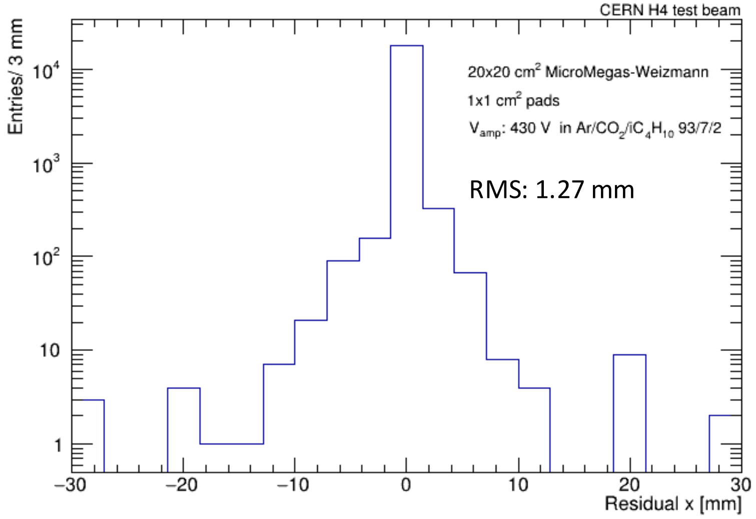
Track reconstructed with clusters from 5 out of 6 pad chambers, excluding the one under test

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

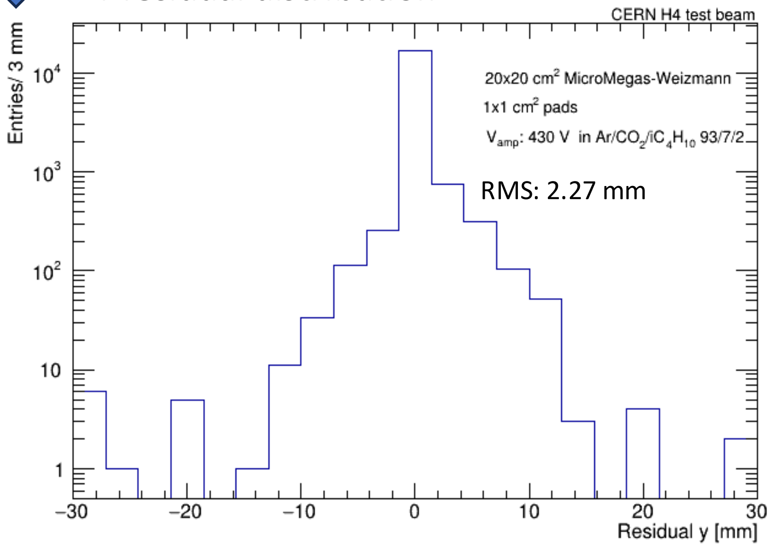




X residual distribution



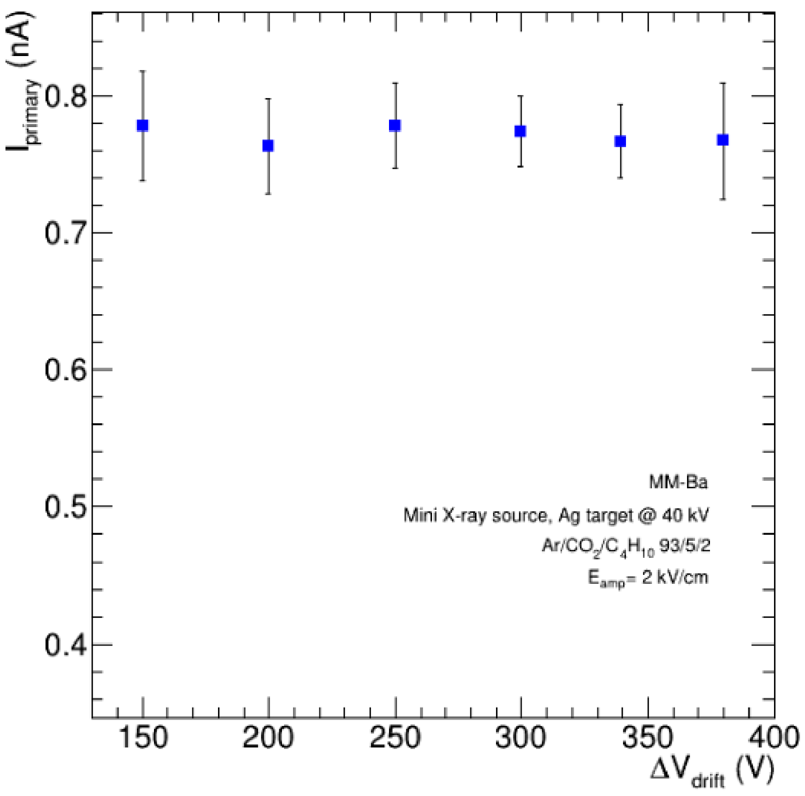
Y residual distribution



Residual distribution in agreement with detector **granularity**

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

Primary currents measured in Bari with x-ray as a function of the drift field



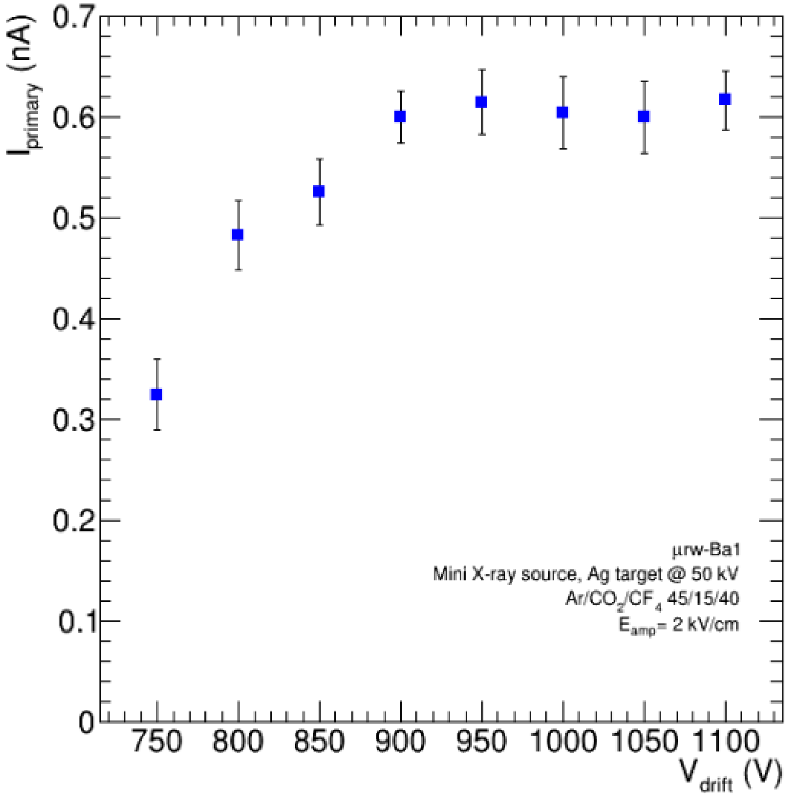
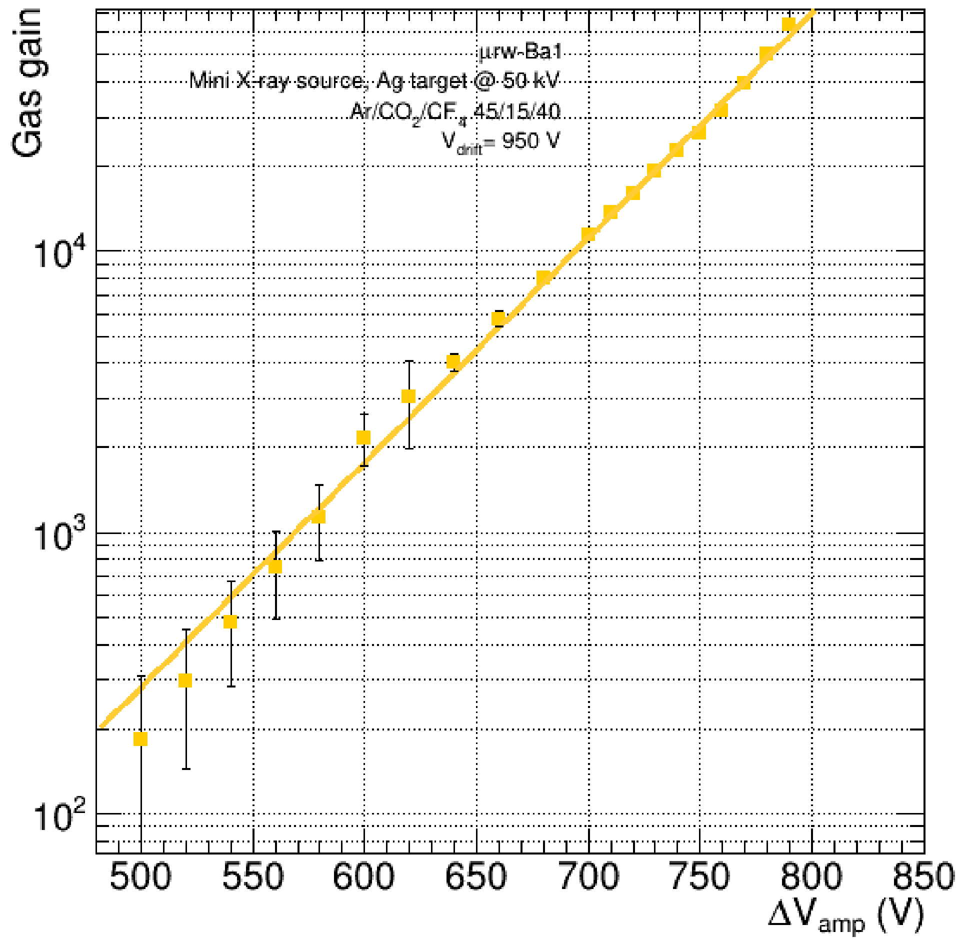


Figure 3.9: The primary current as a function of the drift voltage for the MicroMegas (on the left) and μ-RWELL (on the right) detectors tested in Bari.

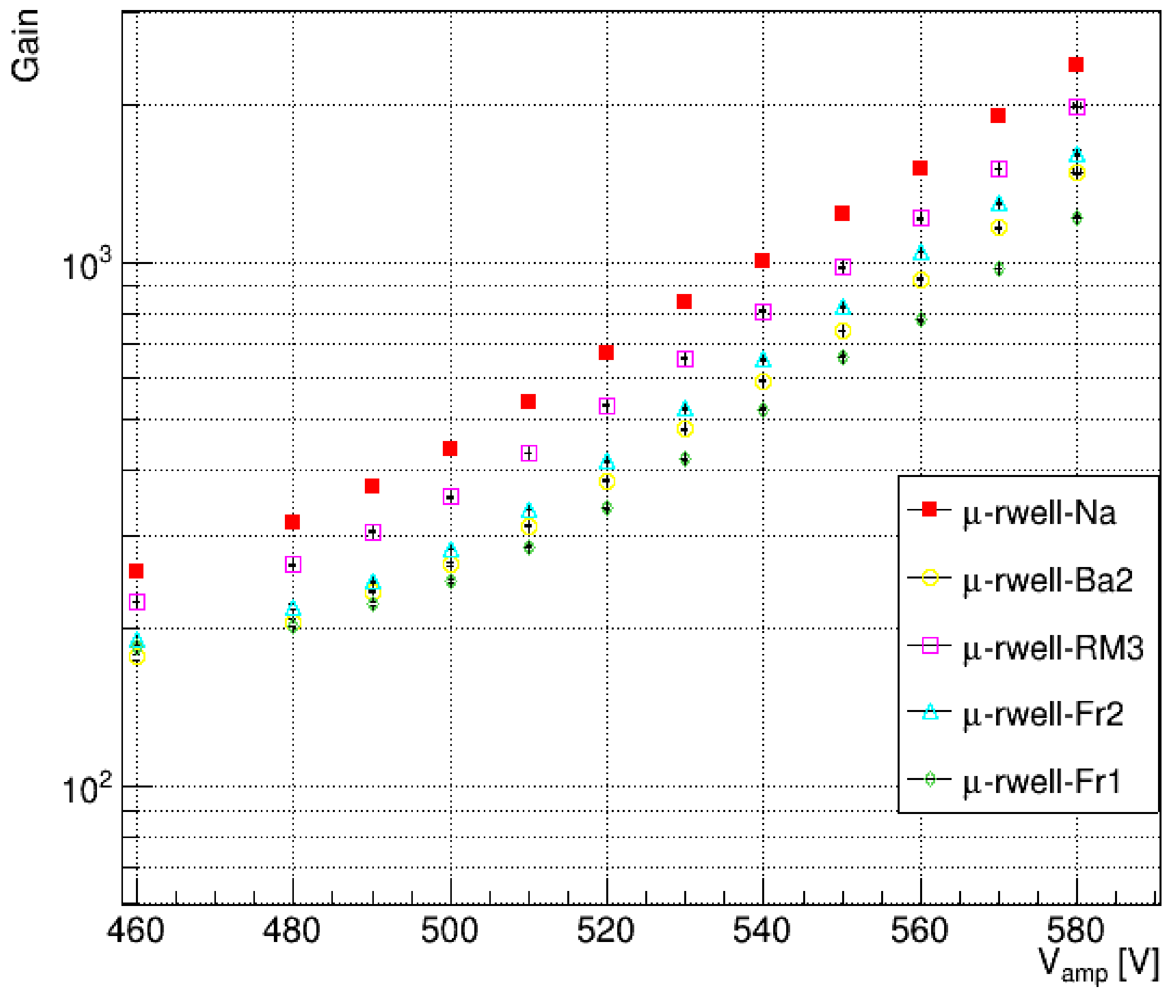
Gain – 2024 Data

Preliminary

Gain measured in Bari with x-ray with silver target



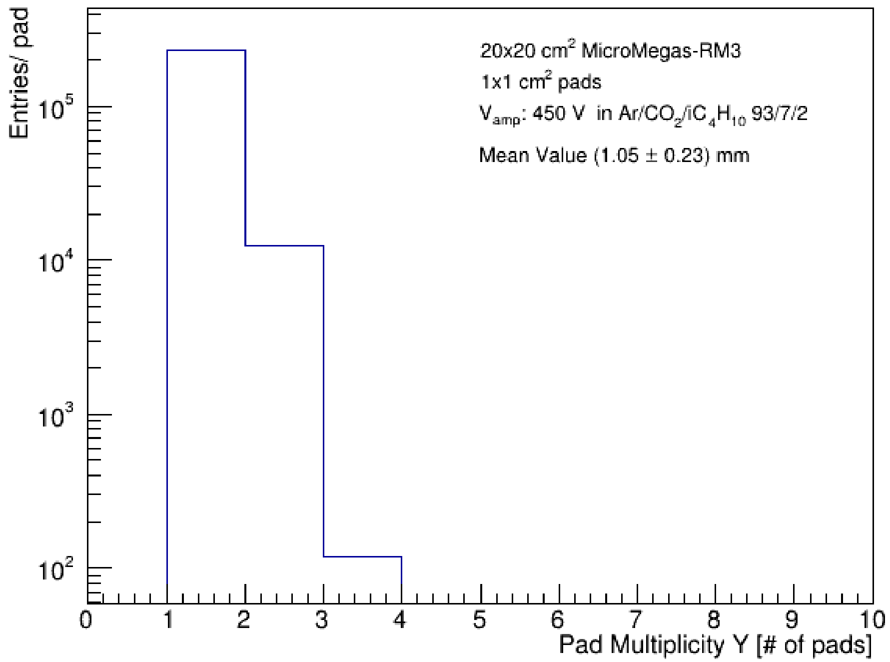
Gain measured with µ at SPS test beam



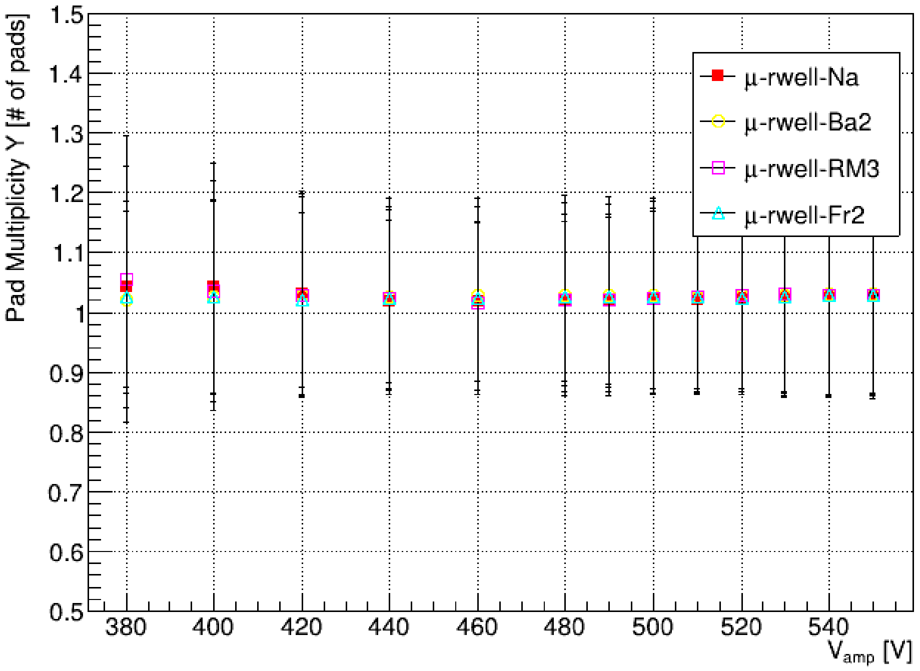
Pad multiplicity - 2024 Data

Preliminary

Pad multiplicity along Y for clusters matching with tracks

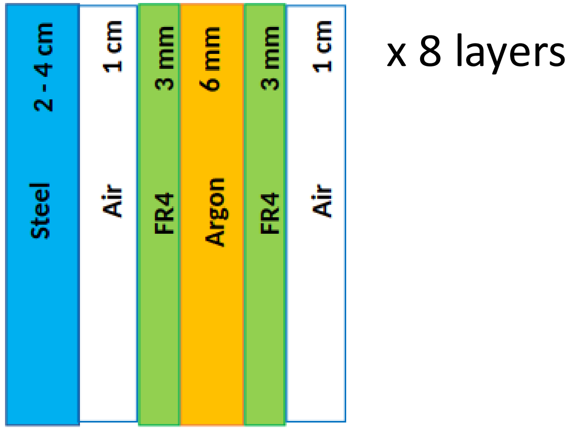


Pad multiplicity vs HV for µrwell



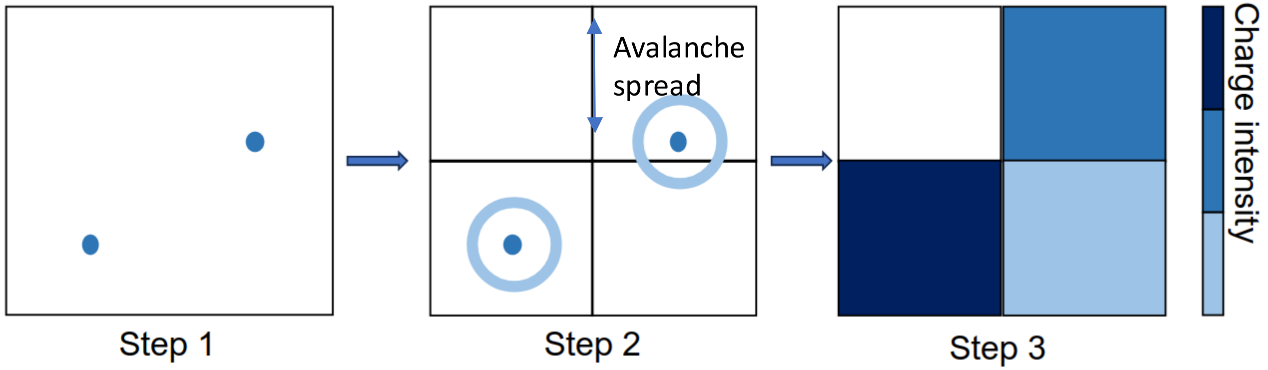
MPGD-HCAL prototype - G4 simulation setup

- 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 number of showers developing early
  - 20x20 cm^2 active surface
  - 1x1 cm^2 pad granularity
- Pion gun of energy range available at PS (4 – 8 GeV)

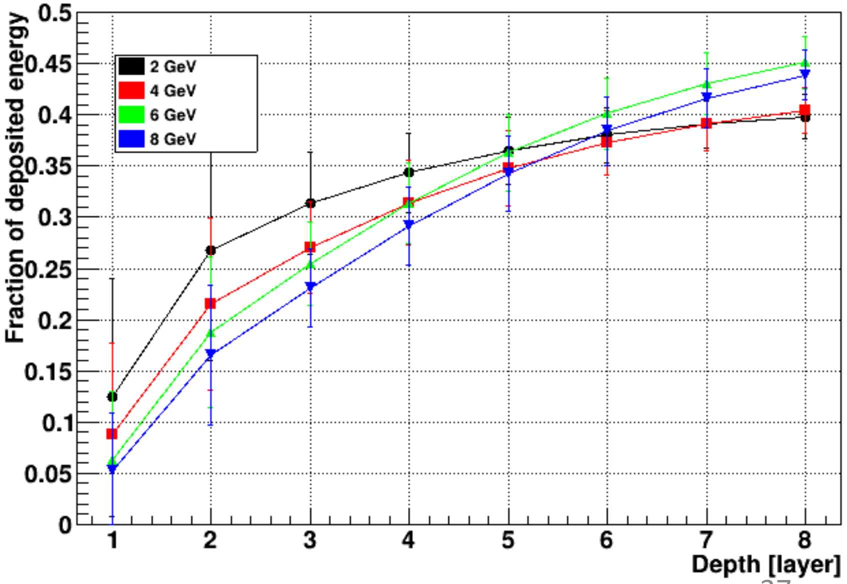


- **Digitization algorithm** implemented to account for charge-sharing among adjacent pads and detector efficiency

Digitization algorithm



Shower containment



MPGD-HCAL prototype – Faulty APVs

Simulation – beam profile per layer

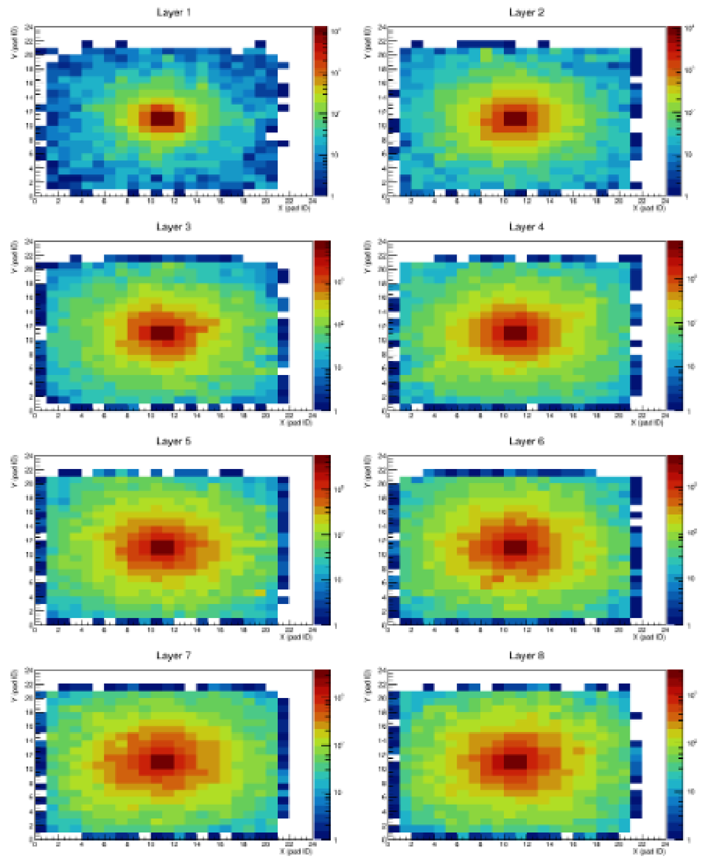


Figure 4.18: X-Y distributions of hits per each active layer after the digitization algorithm. These distributions are obtained with 30 thousand π^- of 6 GeV. The z-axis is the number of fired pads considering the whole set of events.

Experimental data– beam profile per layer

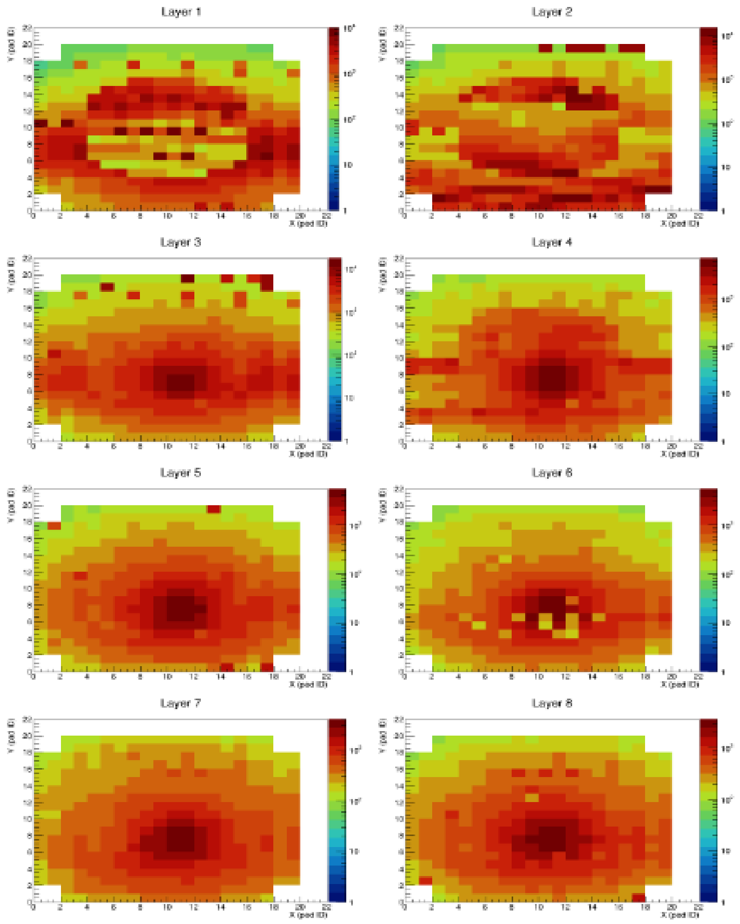


Figure 5.6: X-Y distributions of hits per each MPGD layer obtained for the run with pion energy of 6 GeV. The z-axis is the number of fired pads, in logarithmic scale, considering the whole set of events.