MPGD-based Hadronic calorimeter towards a future experiment at Muon Collider

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ICHEP conference

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Multi-TeV Muon Collider

Advantages:

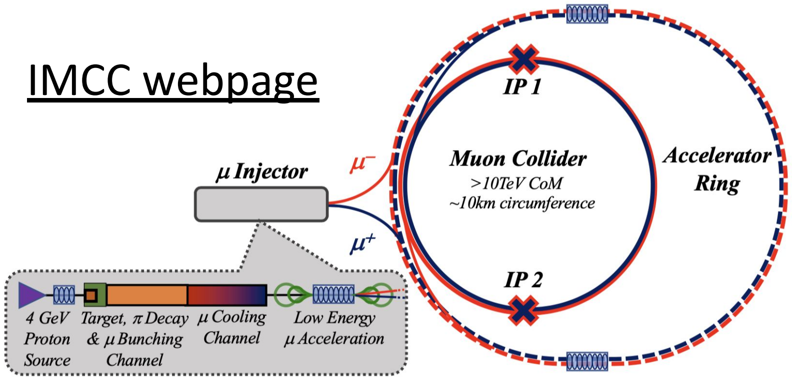
- multi-TeV energy range in **compact circular** machines;
- well **defined initial state** and **cleaner final state**;
- **all collision energy available** in the hard-scattering process.

Challenges:

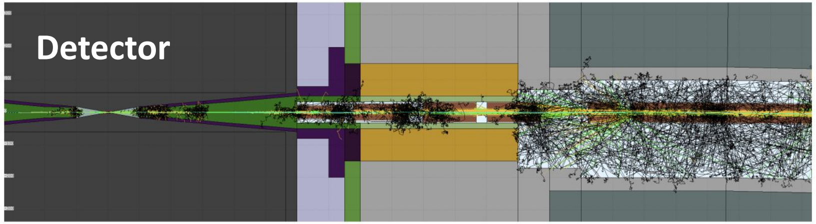
- muon is an **unstable particle**; its decay products interact with the machine elements generating an intense flux O(10^{10}) of background particles: **beam-induced background** (BIB).
- Two conical tungsten shieldings (**nozzles**), cladded with borated polyethylene, allow the reduction of background by 2-3 orders of magnitude:
  - photons (~10^8),
  - neutrons (~10^8),
  - electrons/positrons (~10^6)

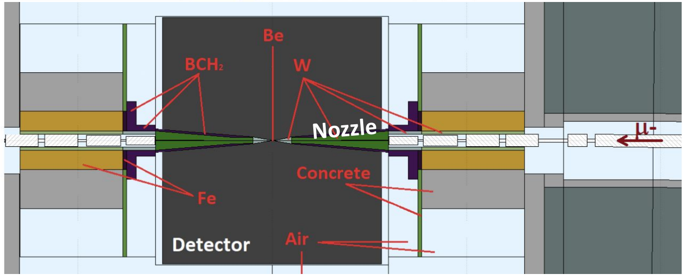
More details in D. Lucchesi Talk

IMCC webpage



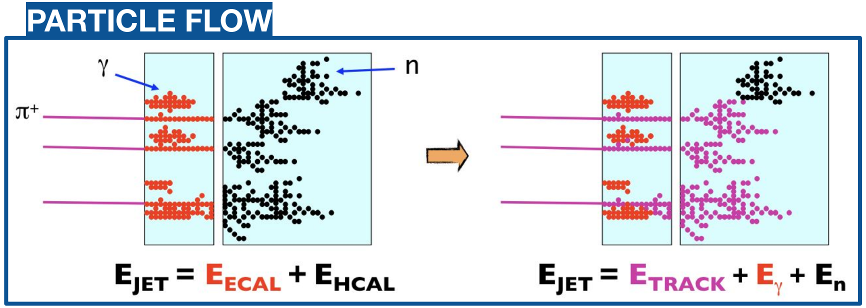
2021 JINST 15 P11009





BIB in the calorimeter system

The **BIB** comes mainly from **photons** (96%) and **neutrons** (4%):
- BIB depends on increasing the distance from the beam axis;
- average deposited energy lower than 1 GeV.



Requirements for a Hadronic Calorimeter in Particle Flow approach at Muon Collider:
- **high granularity**, to reduce overlap with BIB particles;
- **Longitudinal segmentation**, to discriminate between signal and BIB energy profile;
- **Good timing**, to reduce out-of-time component of BIB;
- **Energy resolution** per single neutral particle:
  - HCAL: ~ 60%/√E or lower.
- **Radiation hardness**.

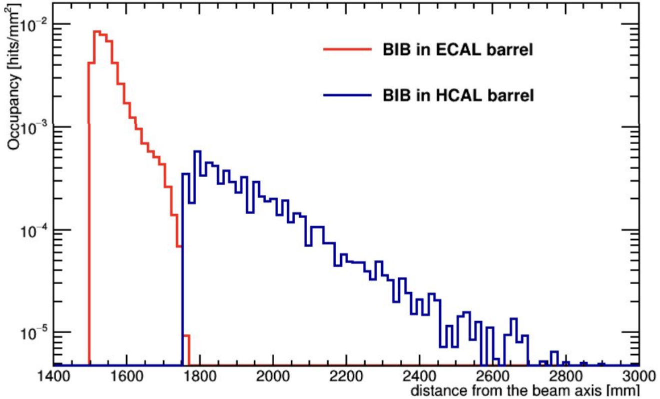


Fig. 25 BIB hit occupancy in the calorimenter barrel region in a single bunch-crossing.

https://arxiv.org/pdf/2303.08533

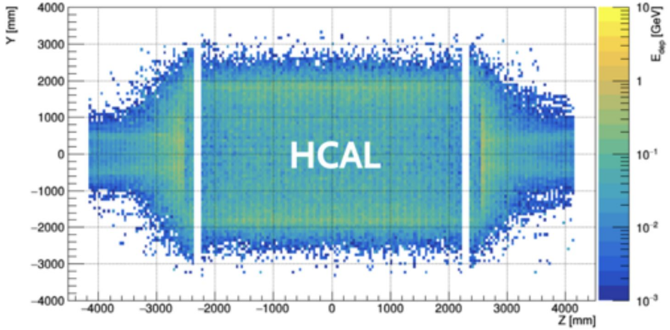


Fig. 28 Energy deposited by the BIB in a single bunch-crossing in the HCAL.

HCAL readout with MPGD

Proposal: micro-pattern gaseous detectors as readout layers for a sampling hadronic calorimeter

MPGD features:

- **cost-effectiveness** for large area instrumentation
- radiation hardness up to several **C/cm²**
- **discharge rate** not impeding operations
- rate capability O (**MHz/cm²**)
- high granularity
- time resolution of **few ns**

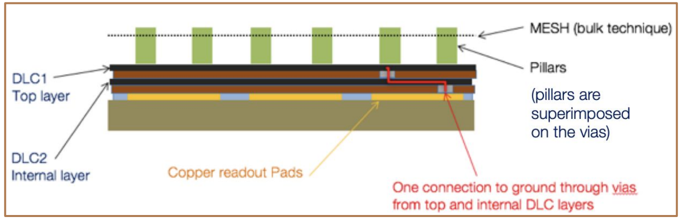
Resistive MPGDs

Past work:

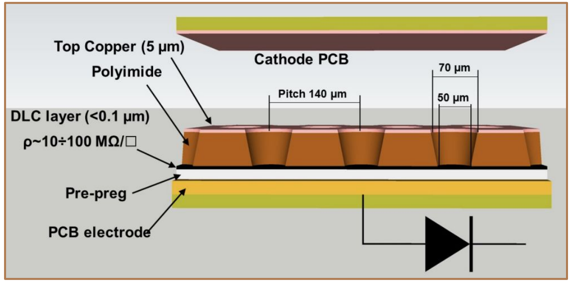
- CALICE collaboration: a sampling calorimeter using **gaseous detectors** (RPC) but also tested MicroMegas
- SCREAM collaboration: a sampling calorimeter combining RPWELL and resistive MicroMegas

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

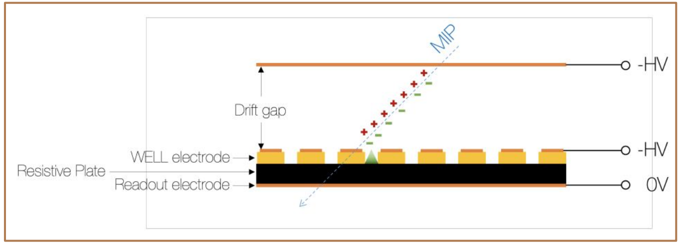
Micromegas (MM)



μRWELL



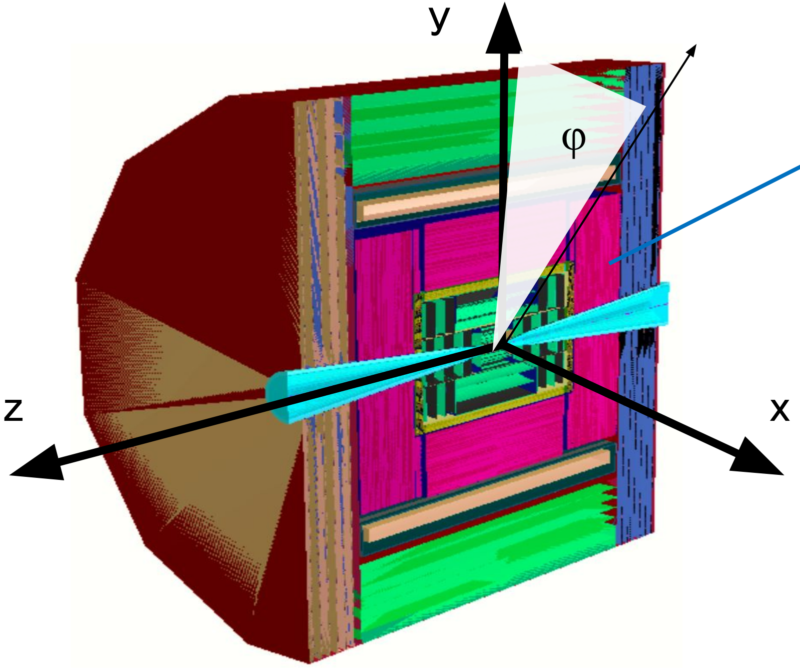
RPWELL



Simulation studies

Simulation: HCAL BIB studies

Geometry considered for the hadronic calorimeter



MPGD-based HCAL

60-layer SAMPLING CALORIMETER

Layer thickness: **2.65 cm - cell: 1 cm^2**

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

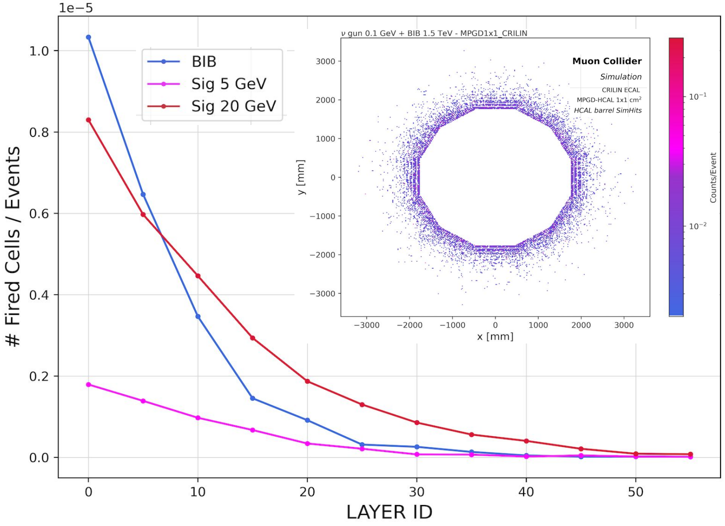
BIB simulated for a center of mass energy (ECM) of 1.5 TeV; CRILIN (more details in R. Gargiulo Talk) assumed as ECAL

Simulation: HCAL BIB studies

Preliminary

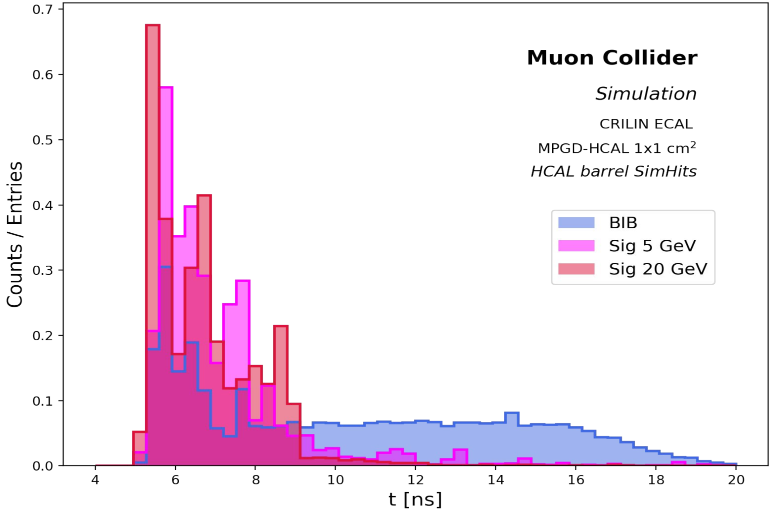
Hit Occupancy:

- **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:

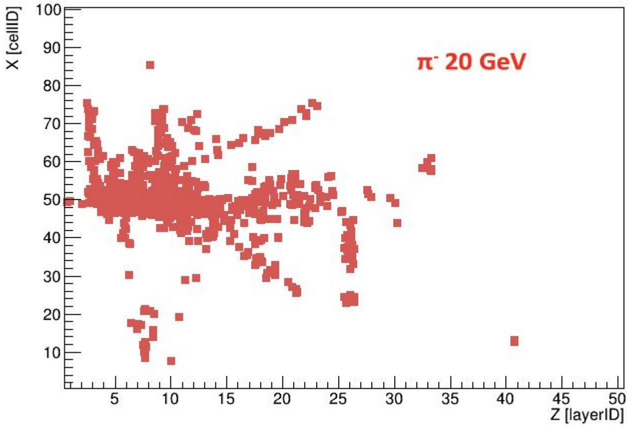
- **BIB** arrival time distribution uniform in the **range 7-20 ns;**
- **signal** arrival time peaks at **~ 6ns**;
- discrimination possible for ***t>9/10 ns*** → **achievable with MPGD detectors**



Simulation: Digital and Semi-digital HCAL

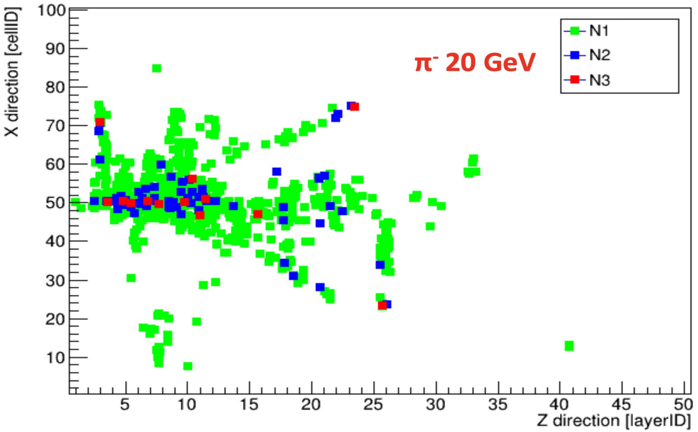
Digital Readout (Digital RO)

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

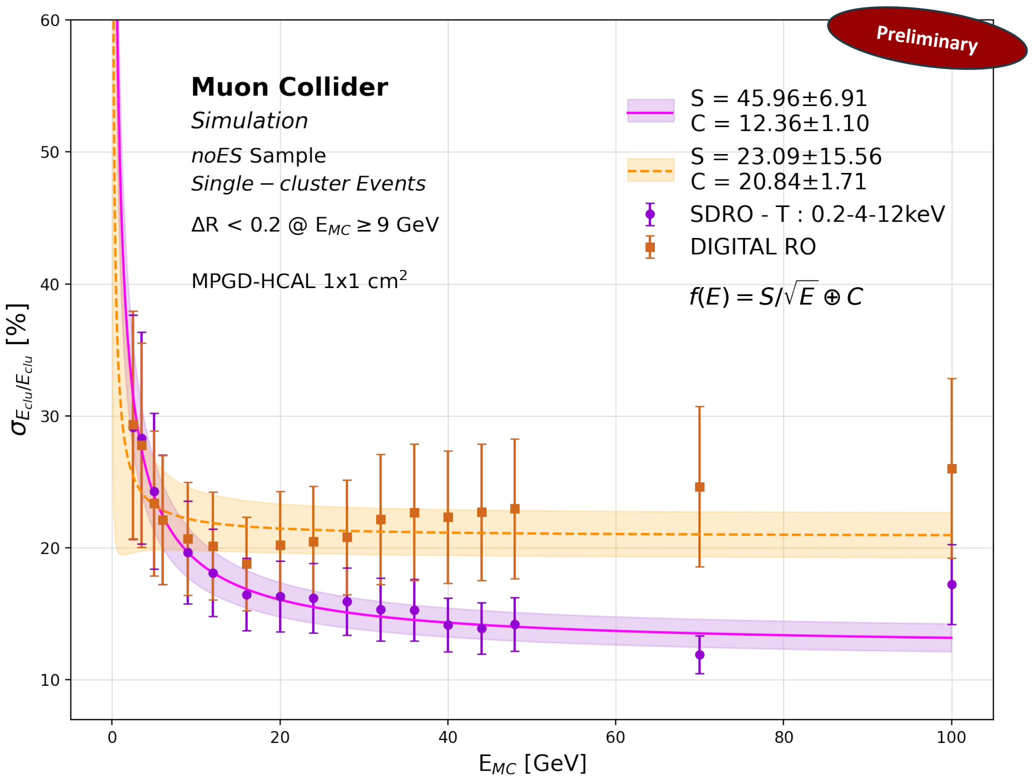


Semi-digital Readout (SDRO)

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



Simulation: Digital and Semi-digital HCAL



- $\pi^{\pm}$ guns with energy ranging from 2.5 to 100 GeV;
- **only pions not showering in ECAL**;
- reconstruction with Digital RO and SDRO:
  - Thresholds considered for SDRO: 0.2, 4, 12 keV
- 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**
  - **σ/E = 45.96%/$\sqrt{E}\oplus$12.36%**

Development of a hadronic calorimeter prototype

MPGD prototypes

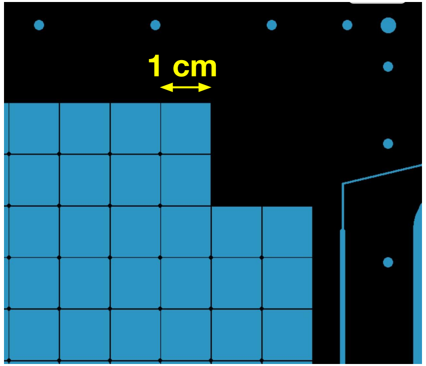
Prototypes produced and tested within **RD51 common project**:

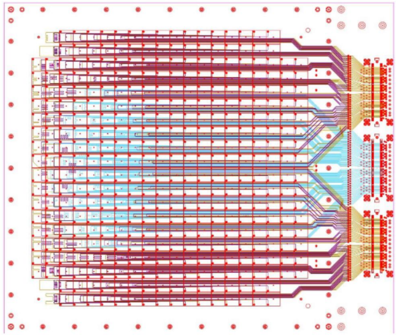
- 7 μ-RWELL
- 4 MicroMegas
- 1 RPWELL

Detector design:

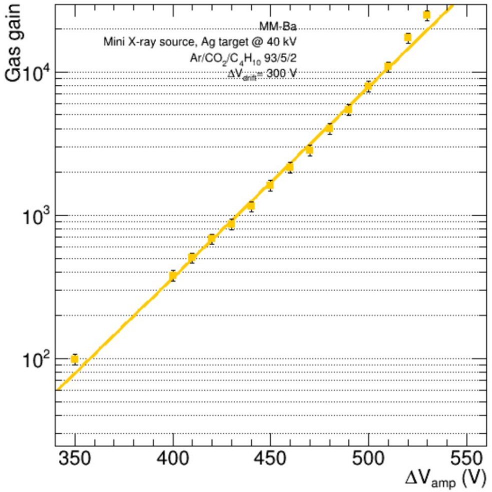
- Active area 20×20 cm^2, pad size 1×1 cm^2
- **Common readout** board

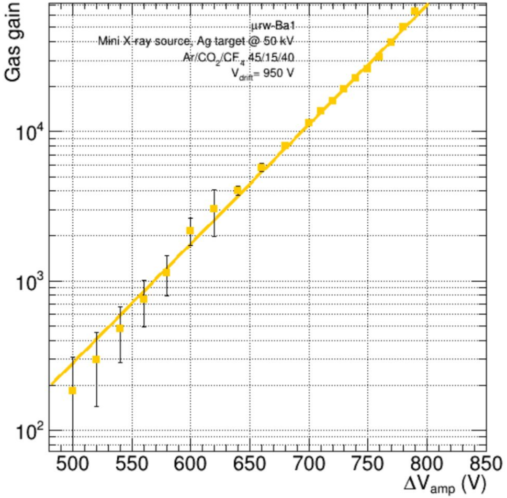
Prototypes characterization performed in different laboratories (Bari, Frascati, Naples, Rome3,Weizmann)





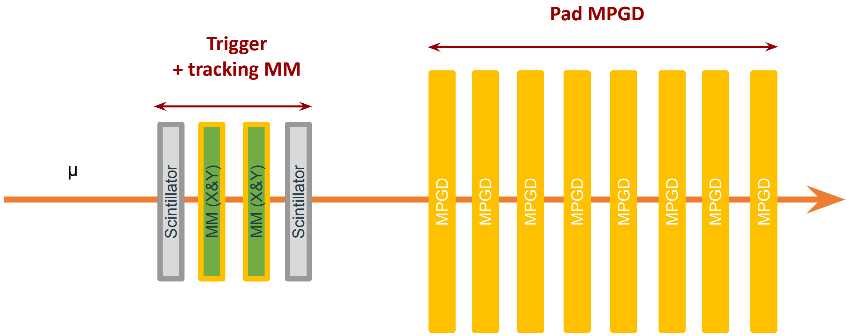
MicroMegas:
G = 10^4 at
E_a = 50 kV/cm
in $Ar/CO_2/C_4H_{10}$



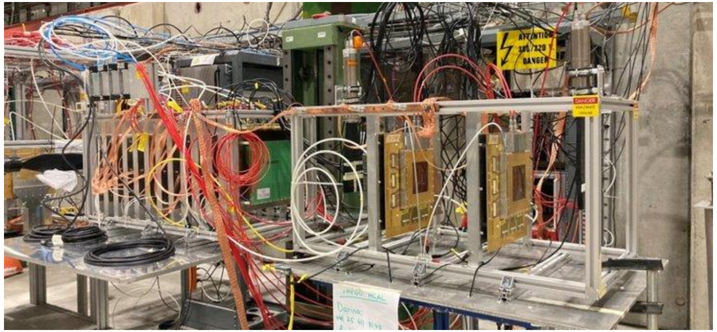


μ-RWELL:
G = 10^4 at
E_a = 140 kV/cm
in $Ar/CO_2/CF_4$

MPGD performance at SPS test beam



Test beam setup at SPS



Readout layers operated in **test beam at SPS** (July 2023):

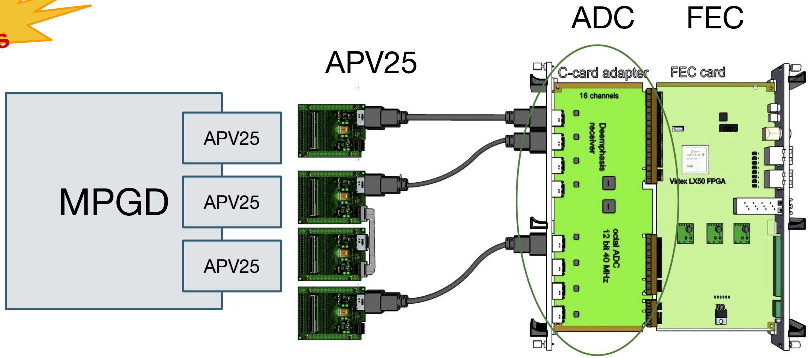
- Tracking: 2 MicroMegas (256 μm-strip)
- Under test: 12 MPGD prototypes

  Gas: **$Ar{:}CO_2{:}C_4H_{10}$(93:5:2)** (MicroMegas & RPWELL), **$Ar{:}CO_2{:}CF_4$ (45:15:40)** (μ-RWELL)
- Particle: O(100) GeV/c **muons**

No absorbers

Readout **electronics**:

- **APV25** front-end chip (analog readout + time information)
- **SRS** back-end



Readout electronics based on the APV25 SRS

Goal: **validating** the readout detectors **with MIPs** and **compare** the three **technologies**

Detector performance

Test beam **analysis workflow**:

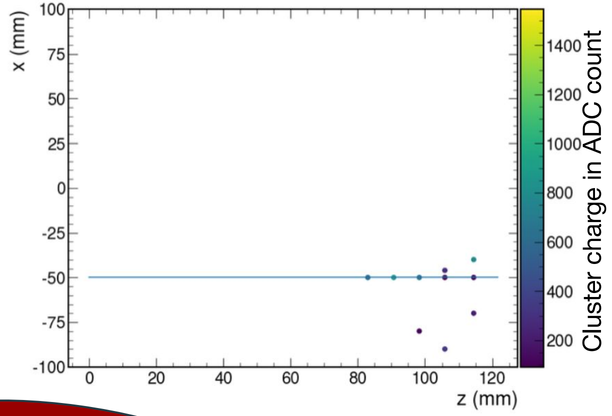
- **Tracking detectors unused** in reconstruction for the moment (high noise → possible to recover the tracker offline, currently ongoing). **Tracks built using MPGDs** under test (5 out of 6 at a time)

Track residuals:

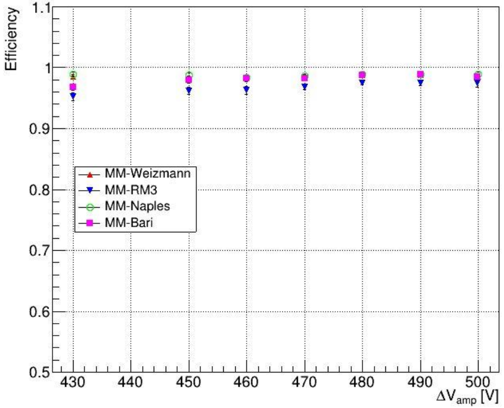
- Observed high probability of **cross-talk** between pads *due to routing of readout vias from pads to front-end*
- Patched **offline** by clustering pads based on charge sharing fraction

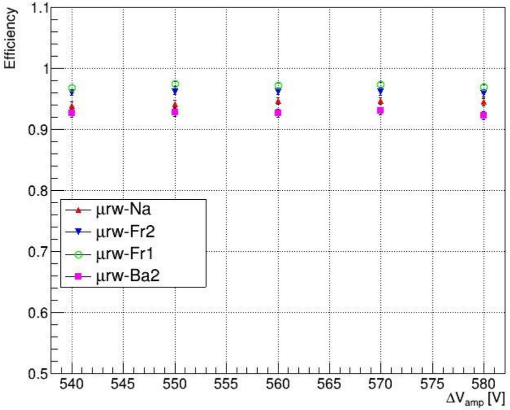
High average **efficiency** (detectors always operated at plateau)

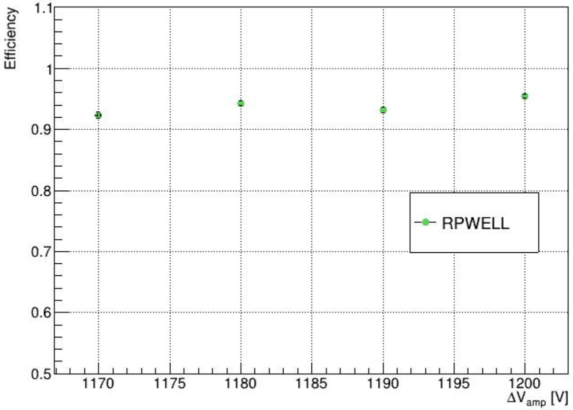
Track reconstructed using 4 detectors out of 5



Preliminary







Detector uniformity

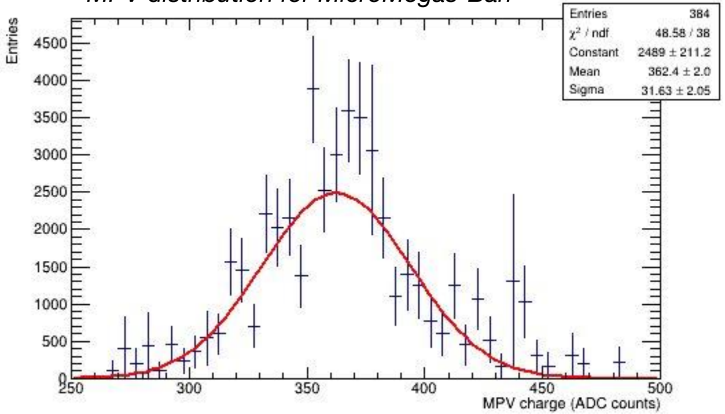
Preliminary

Response uniformity measured using clusters matching muon tracks

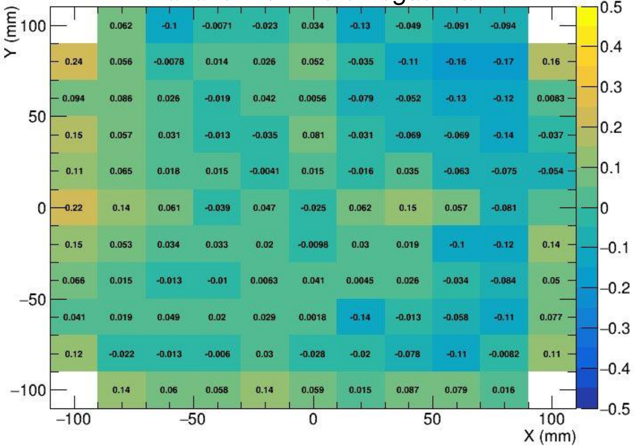
- Good uniformity for **MicroMegas** (~10%)
- Regions of non-uniformity observed on some **µ-RWELLs** → under investigation in lab
- Slightly worse uniformity for **RPWELL**

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	$(16.3 \pm 1.1)\%$

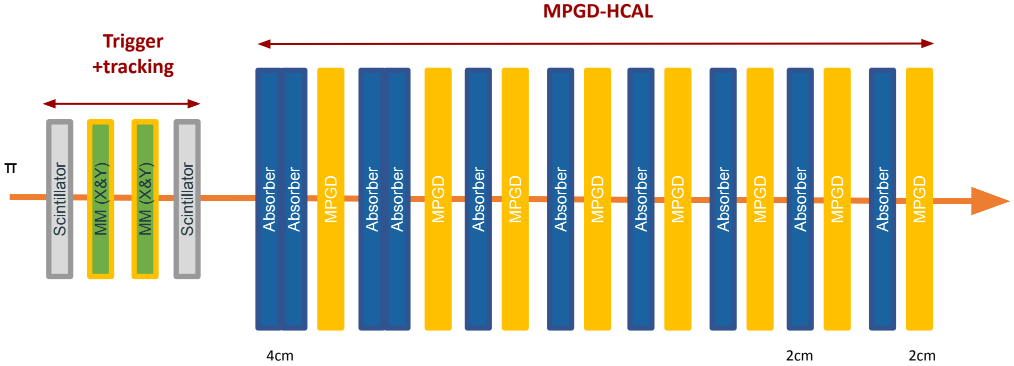
MPV distribution for MicroMegas-Bari

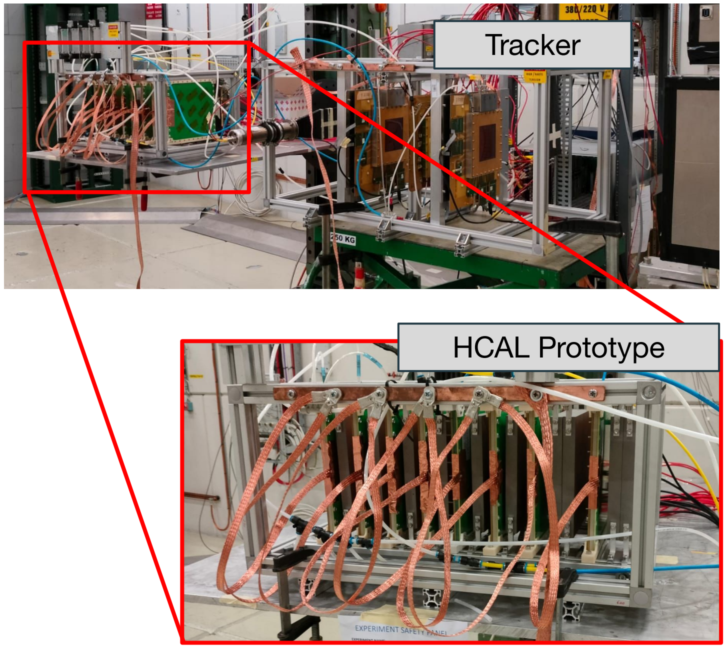


2D-MPV variation for MicroMegas-Bari



Calorimeter prototype at PS test beam





Test beam at PS with calorimeter prototype (August-September 2023):

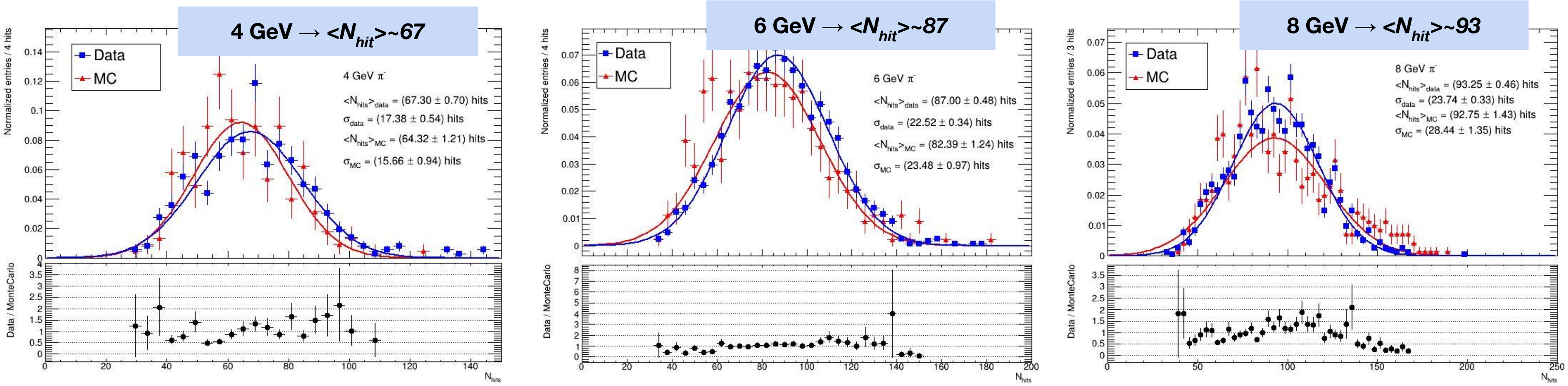
- Goal: **measuring** the energy resolution of a 1 λ calorimeter prototype with 1-10 GeV pions beam
- Developed **G4 simulation** for the **small prototype**, including a **digitization algorithm** to account for charge-sharing among adjacent pads and detector efficiency
- **Issue:** problematic electronics for the first 2 MPGD layers → taken into account for data/MC comparison

Calorimeter prototype at PS test beam

Event selection: events where pions start showering from the third layer

Preliminary

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



- **Good data/MC comparison**
- **Total number of hits increases as expected as a function of the energy**
- Ongoing studies to fully exploit all the data collected

Conclusion and next steps

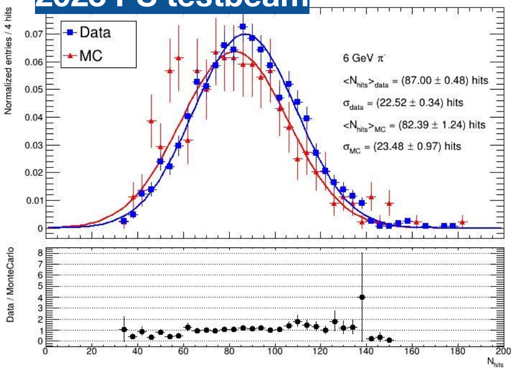
Developments of MPGD-HCAL ongoing in **simulations** and **hardware**

- Preliminary results on BIB studies show MPGD technologies are good candidates for BIB rejection in the context of the hadronic calorimeter at 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
- All MPGD detectors show good efficiency

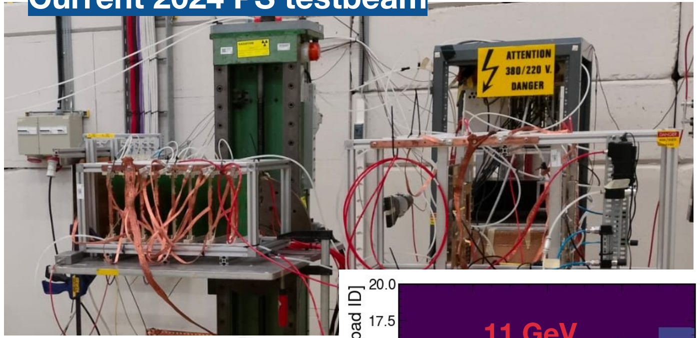
Plans for 2024-2025

- Consolidating results with present prototypes in two test beams in 2024:
  - SPS (done):
    - full efficiency Vs HV curve,
    - response uniformity,
    - timing
  - PS (on-going): test of a fully equipped 8 MPGD layers Prototype with pions beam
- 4 **large detectors** (50×50 cm^2) to be built in 2024/2025:
  - Design **optimization** to exclude cross-talk and simplify manufacturing

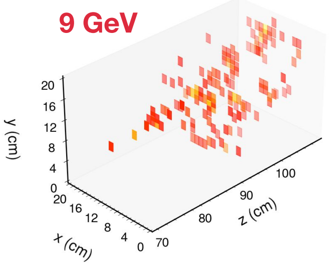
2023 PS testbeam

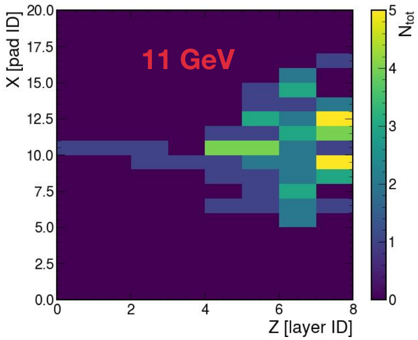


Current 2024 PS testbeam



Shower events (2024)

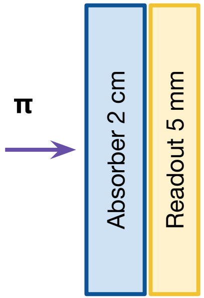


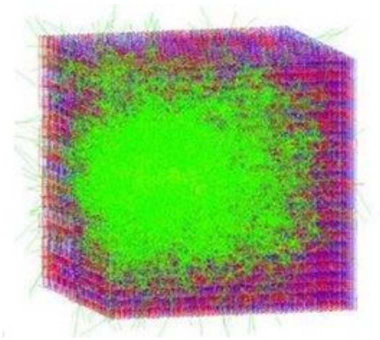


Backup

Simulation: shower containment studies

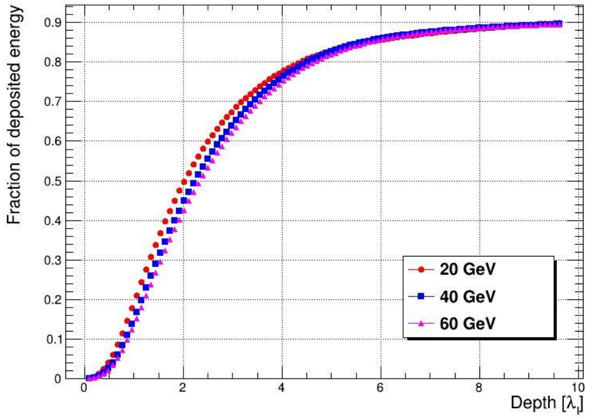
Geant4 simulation of a 100 layers calorimeter



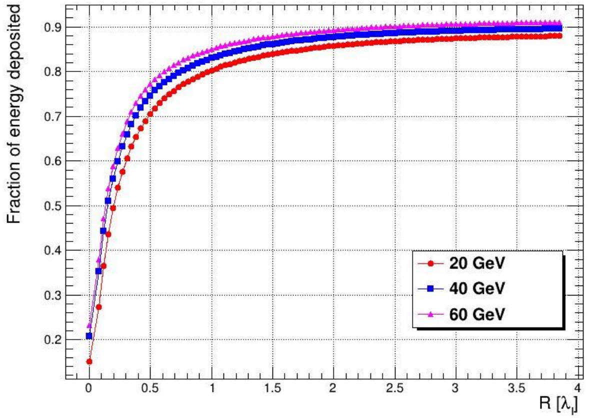


- Geometry: 2 cm iron, 5 mm gas (Ar/CO_2)
- Readout granularity → cell size of
  - 1×1 cm^2
  - 3×3 cm^2
- Pion guns of different energies
- **Result:** longitudinal containment in ~10 λ_I, transversal in ~2 λ_I

Longitudinal shower containment

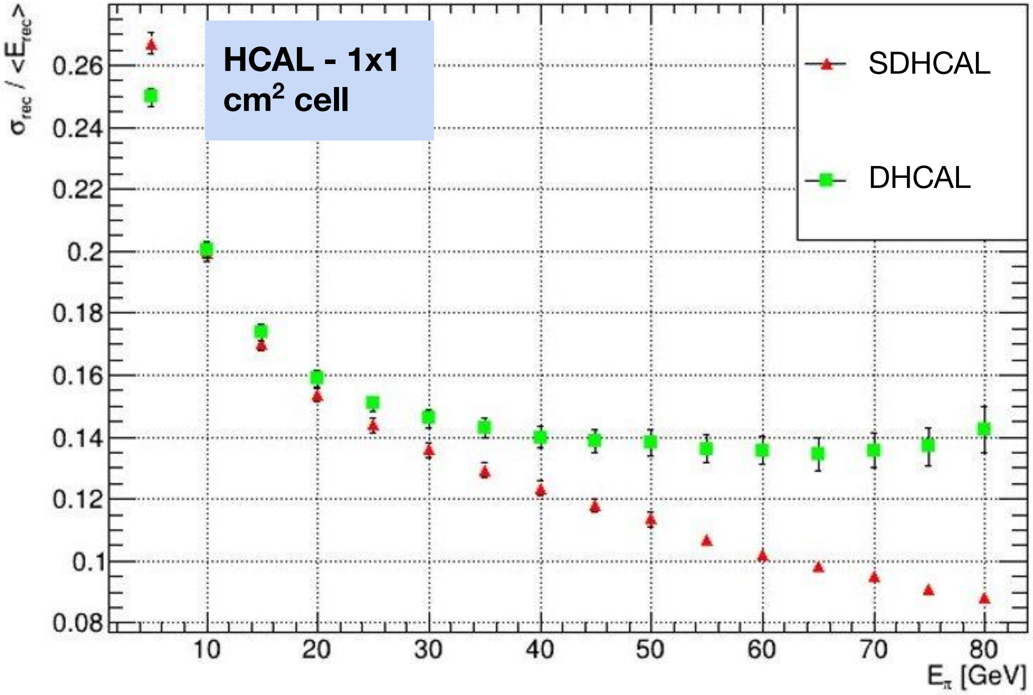


Transversal shower containment



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

Simulation: Digital and Semi-digital HCAL



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

At $E_\pi = 80$ GeV, the resolution

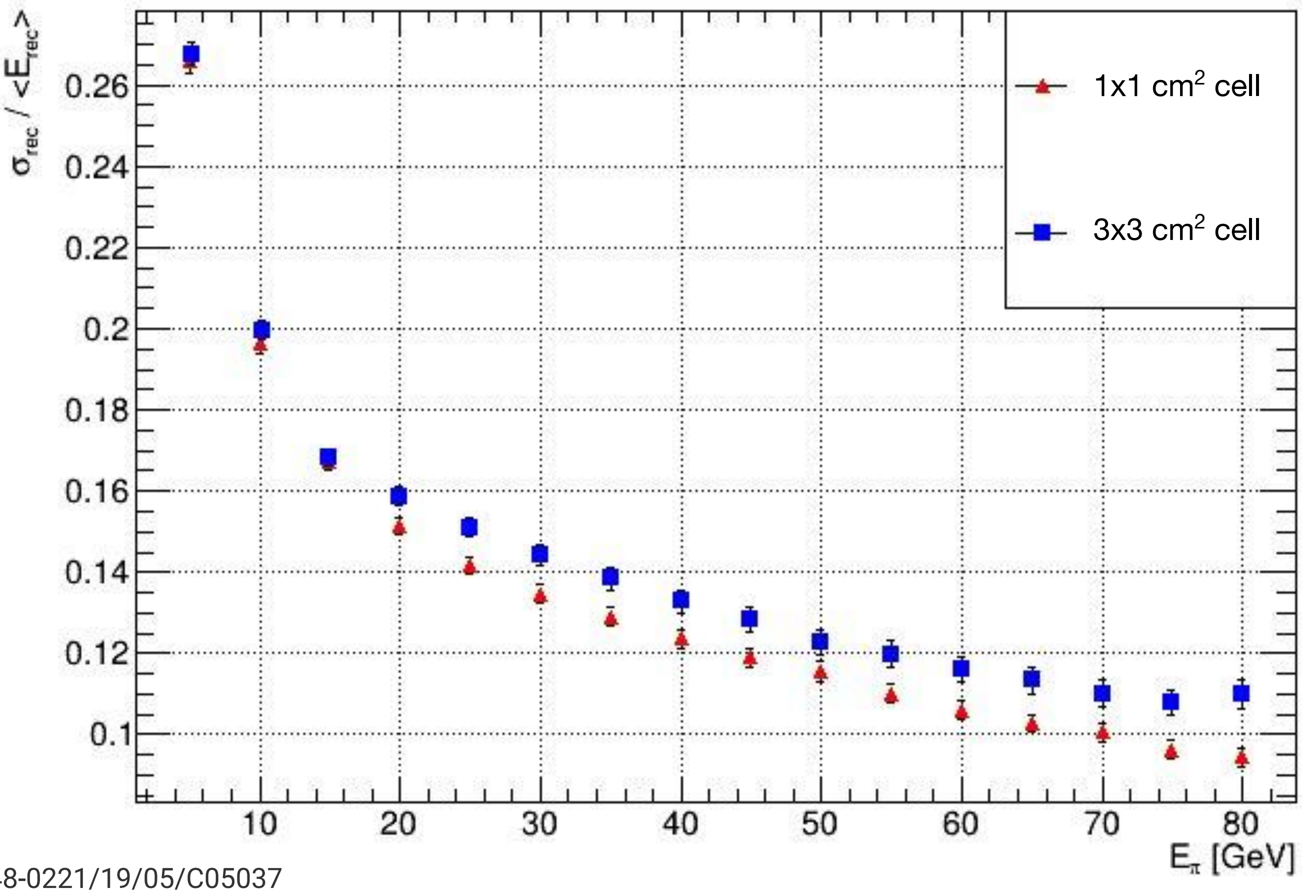
- DHcal ~ 14%
- SDHcal ~ 8%

DHCAL suffers from **saturation effect** for $E_\pi > 40$ 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

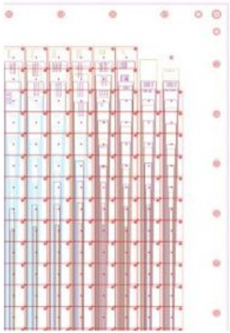
Simulation: Semi-Digital readout

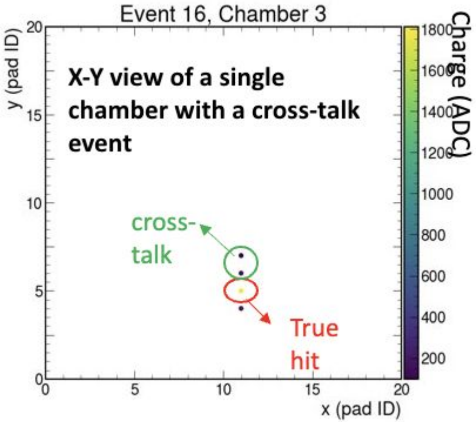


DOI 10.1088/1748-0221/19/05/C05037

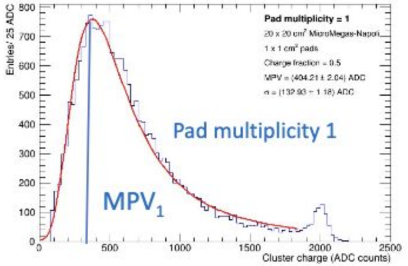
Cluster reconstruction

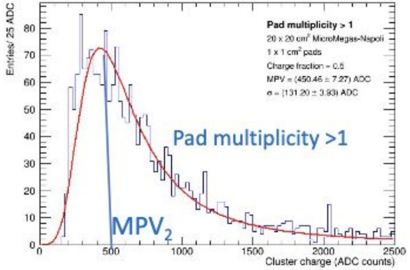
Preliminary

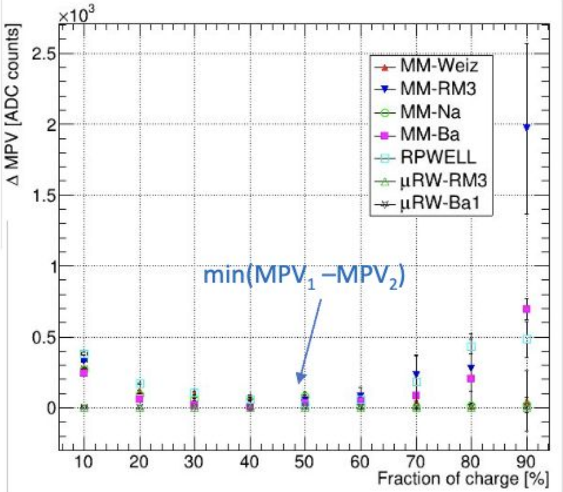




High probability of **cross-talk** effect observed among adjacent pads due to routing of the vias connecting pads to the connectors





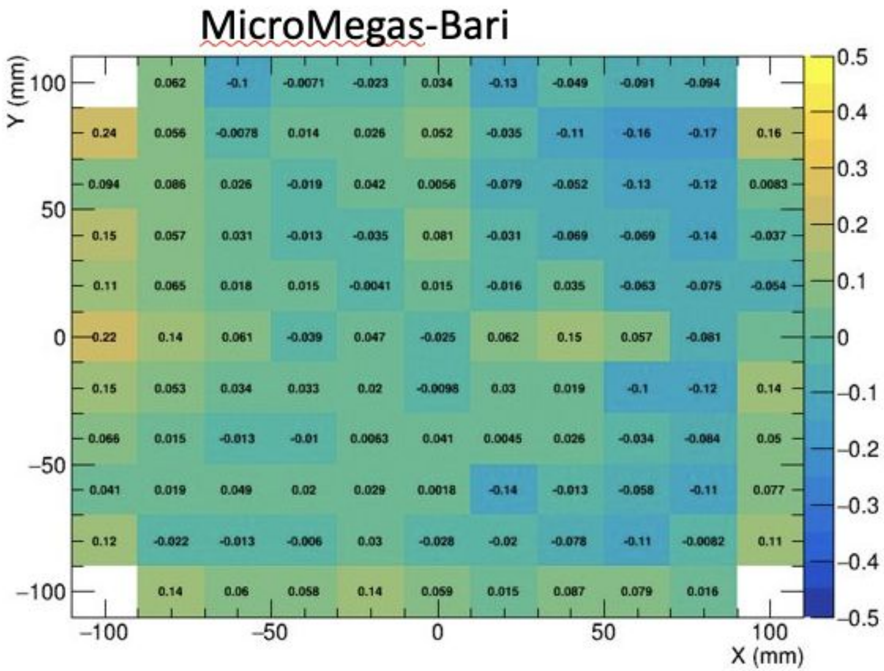


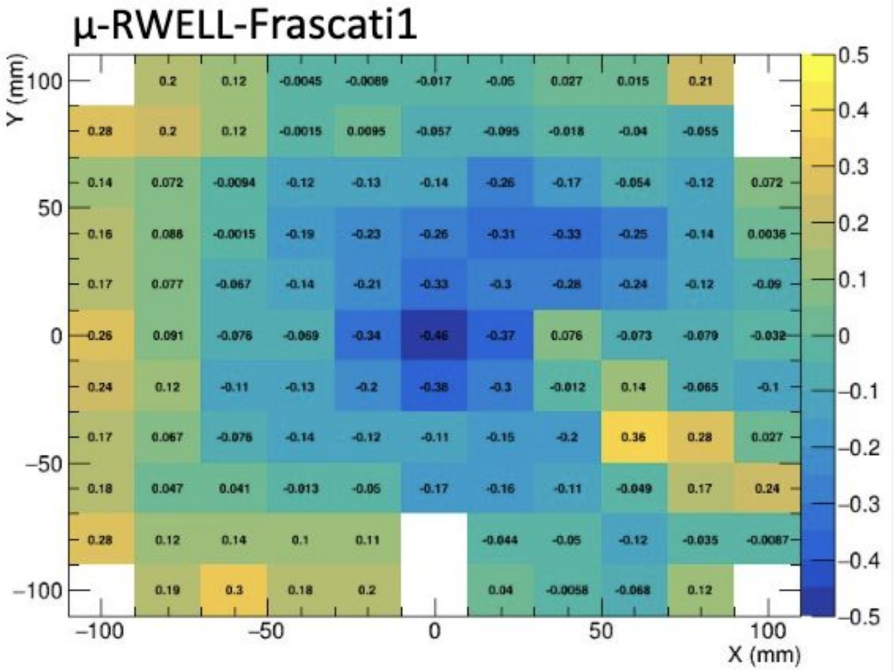
Developed ad-hoc **clustering algorithm** based on charge sharing criterium

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

Response uniformity

Preliminary

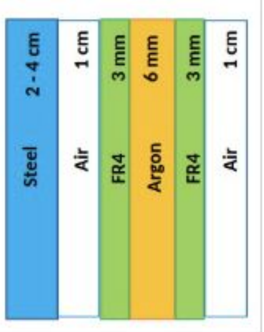




G4 simulation: small prototype

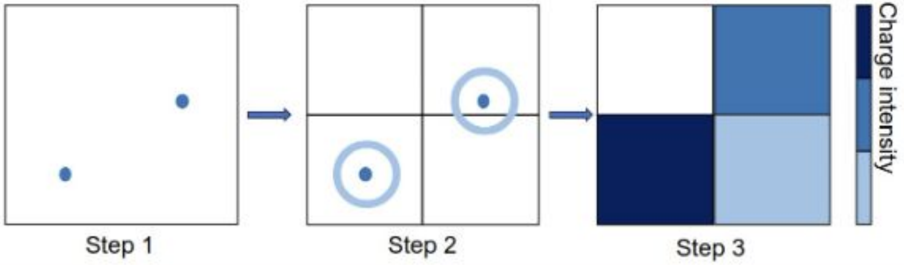
Preliminary

- 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)

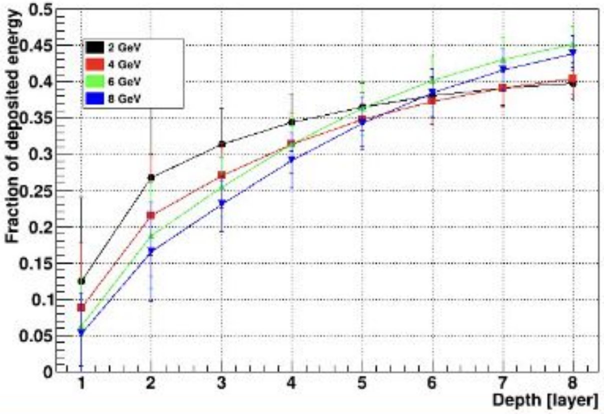


- **Digitization algorithm** implemented to account for charge-sharing among adjacent pads and detector efficiency

Digitization algorithm



Shower containment

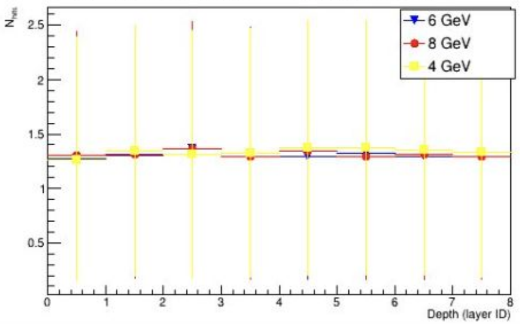


PS data / G4Sim prototype - event selection

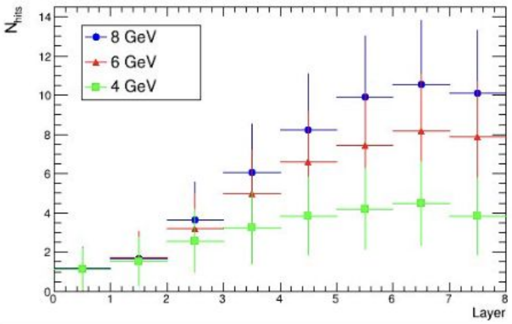
Preliminary

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

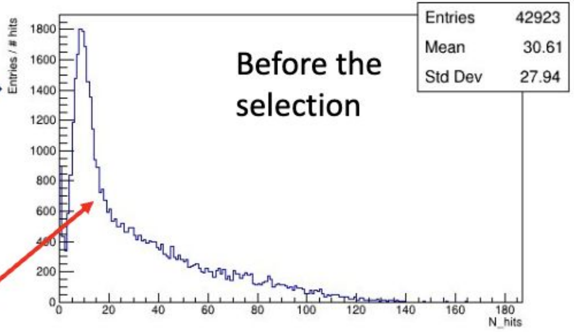


Shower events - simulation



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