Design and optimization of a MPGD-based HCAL for a future experiment at Muon Collider

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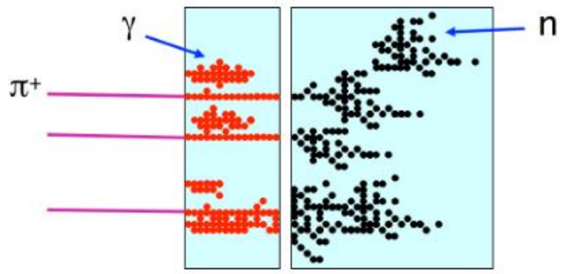
16th Topical Seminar on Innovative Particle and Radiation Detectors
Siena, 28-09-2023

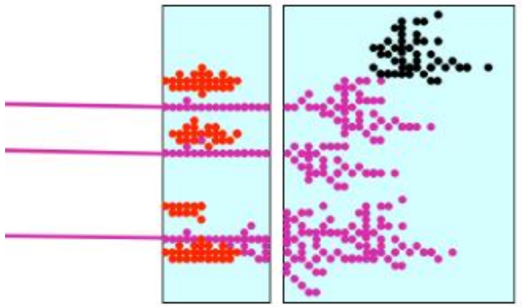
Motivation: Particle-Flow Caloriemtry



$E_{JET} = E_{ECAL} + E_{HCAL}$

Traditional approach

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



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

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

Requirements for future colliders:

- Jet energy resolution: **$\sigma_E / E < 3.5\%$**
- **High granularity**

Requirements for HCAL

- **Separate** neutral from charge hadrons -> **high transverse and longitudinal granularity**

J. Marshall, M. Thomson
arXiv:1308.4537

HCAL for Muon Collider experiment

Muon collider

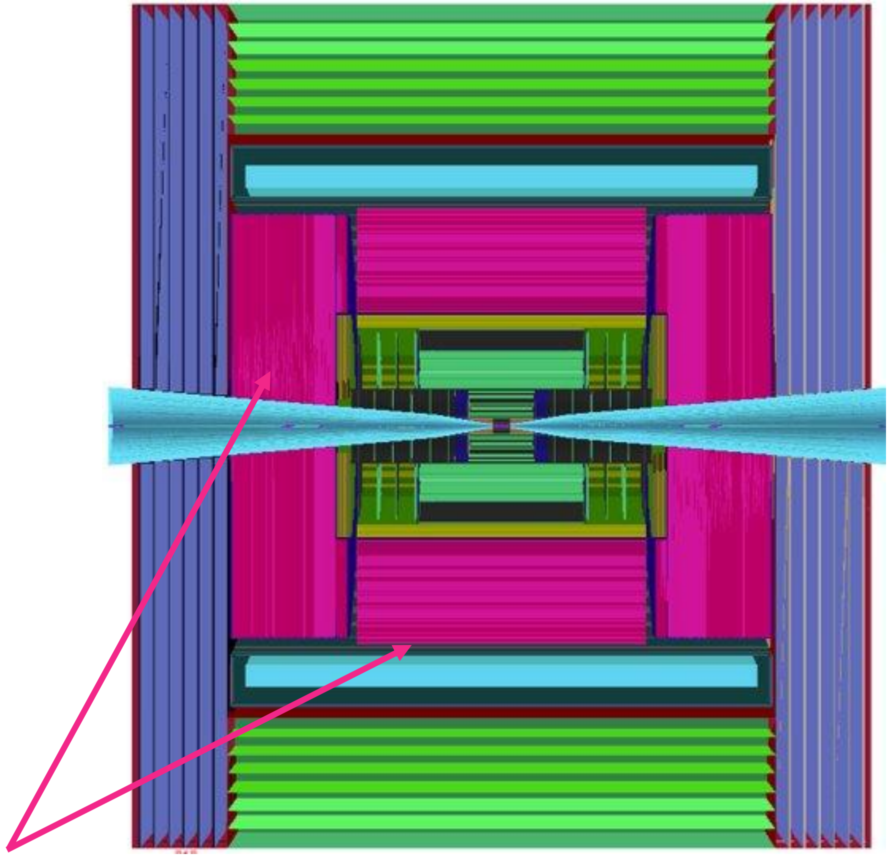
Advantages:

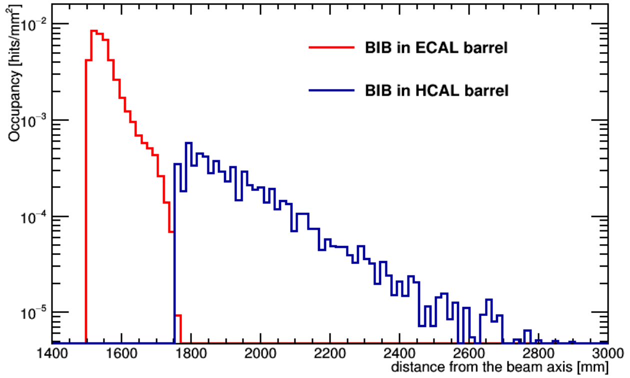
- multi-TeV energy range in **compact circular** machines;
- well **defined initial state** and **cleaner final state**;
- all **collision energy available** in the hard-scattering process.

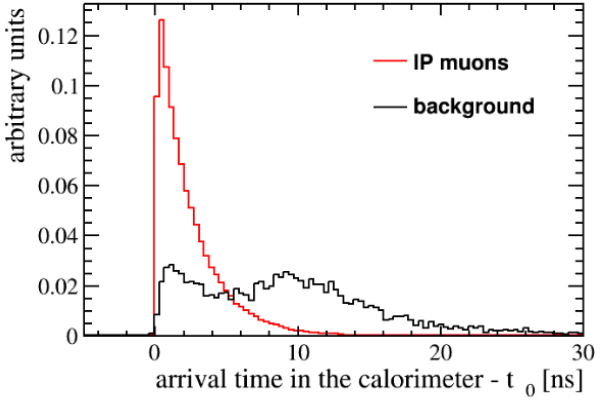
Challenges:

- 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)**.

Section of the Muon Collider experiment







Hadronic Calorimeter

Requirements for BIB suppression:

- Radiation hard technology
- Fine granularity
- High time resolution (ns)

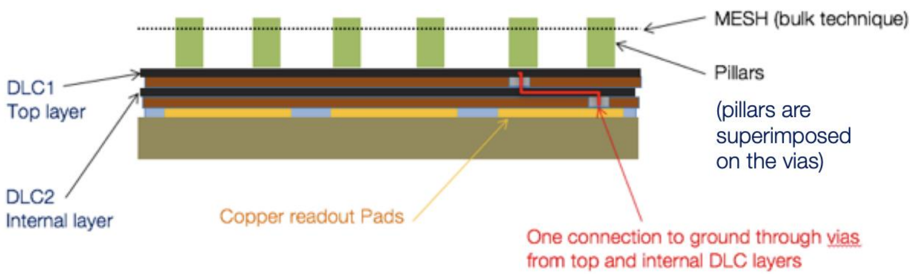
2021 JINST 15 P11009

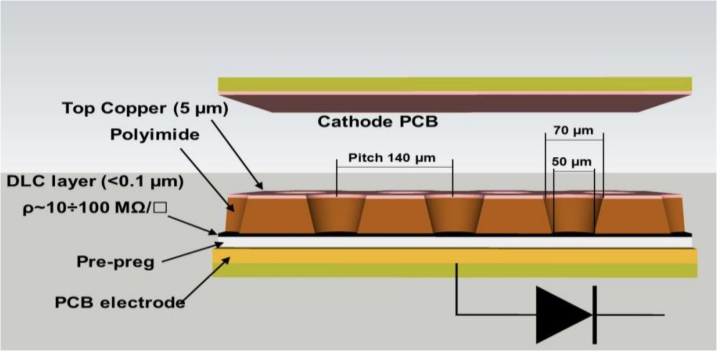
MPGD-HCAL for Muon Collider

Why MPGDs for calorimeters?

- Fine granularity
- Radiation hardness
- High rate-capability O(MHz/cm^2)
- Flexible space resolution (> 60 µm)
- Response uniformity
- Cheap for large area instrumentation

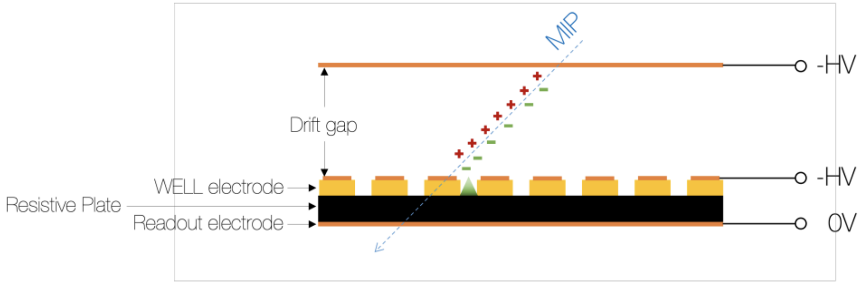
MicroMegas





µRWELL

RPWELL

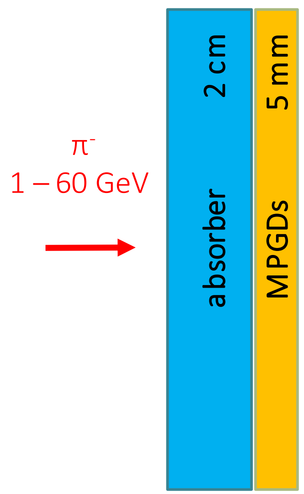


GEANT4 Simulation

G4 Simulation – Shower containment

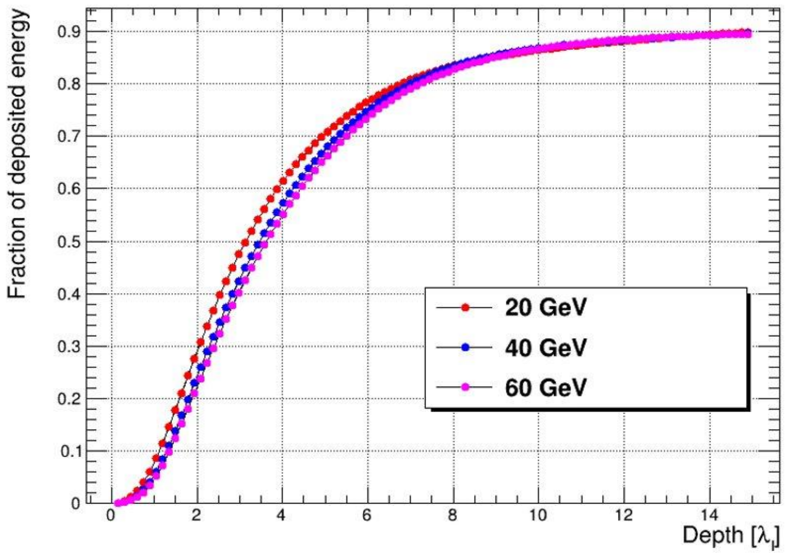
Implemented geometry
- Sampling calorimeter made of
  - 2 cm for the **absorber** (iron)
  - 5 mm of **active layer** (Ar/CO_2)
  - Cells of granularity (1x1 cm^2 and 3x3 cm^2)

Energy contained at 90% within
- 14 λ_N in the direction of the incoming π
- 3 λ_N in the orthogonal direction

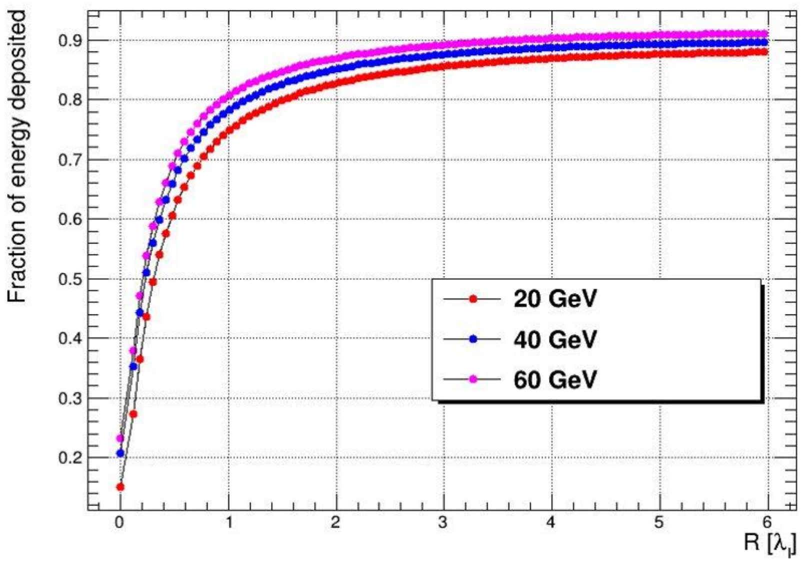


PRELIMINARY

Longitudinal shower containment



Trasversal shower containment

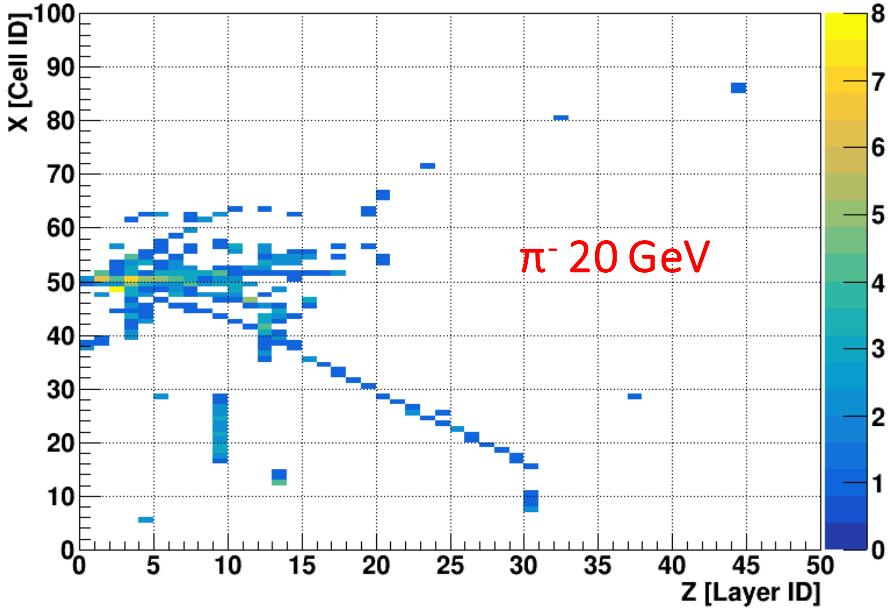


G4 Simulation – DHCAL and SDHCAL readout

DIGITAL HCAL

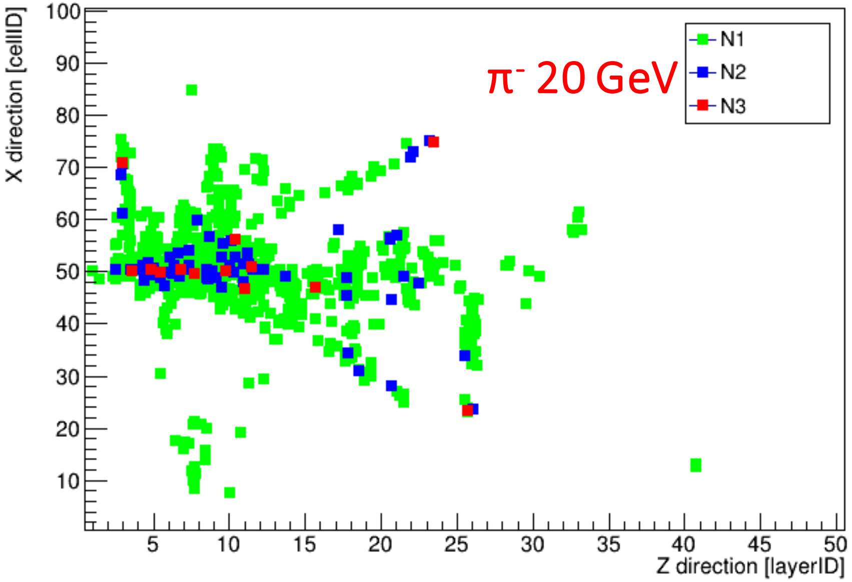
Digitization: 1 hit --> 1cell with energy deposit higher than the applied threshold

- **Calorimeter response function:** $<N_{hit}>=f(E_\pi)$
- **Reconstructed energy:** $E_\pi=f_{-1}(<N_{hit}>)$



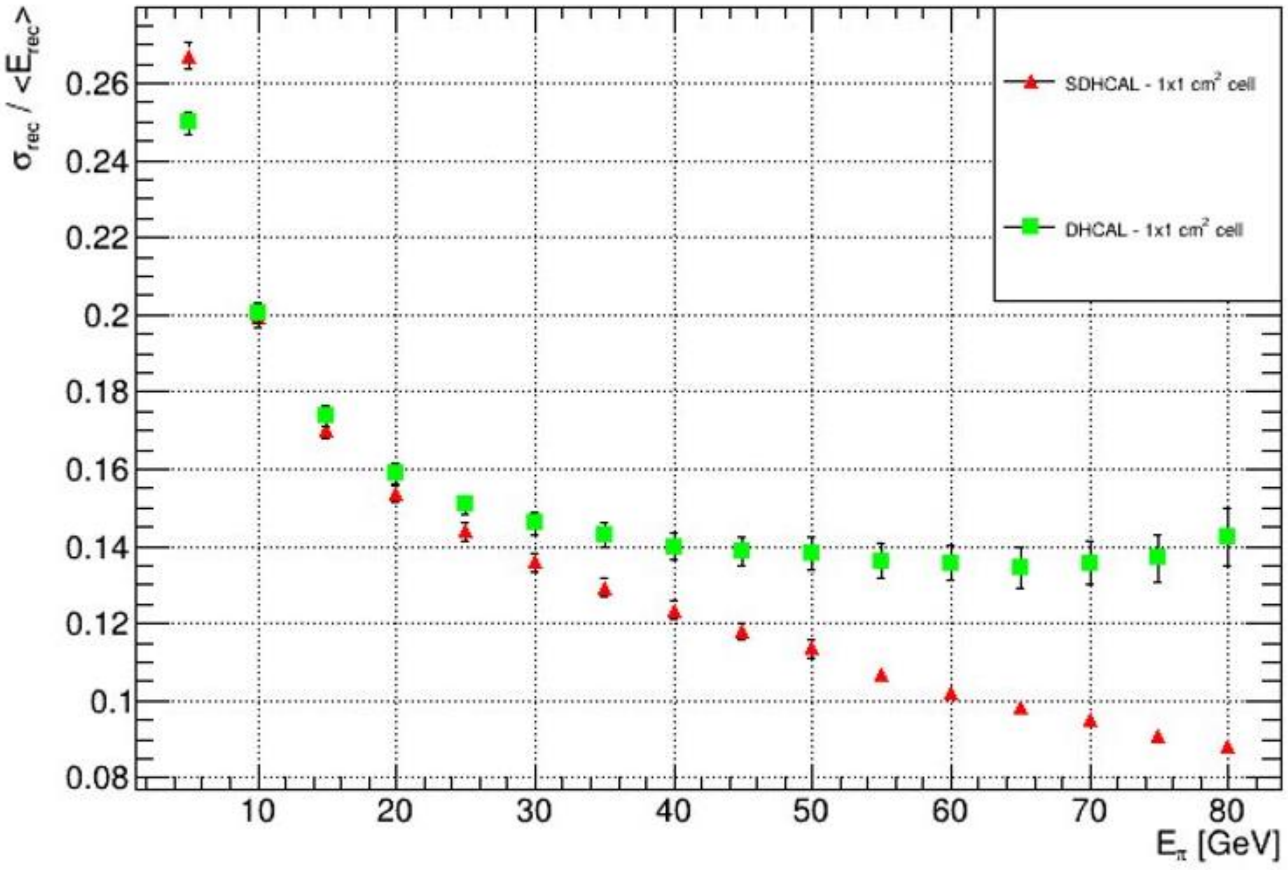
SEMI DIGITAL HCAL

- **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 resolution – DHCAL and SDHCAL comparison

PRELIMINARY



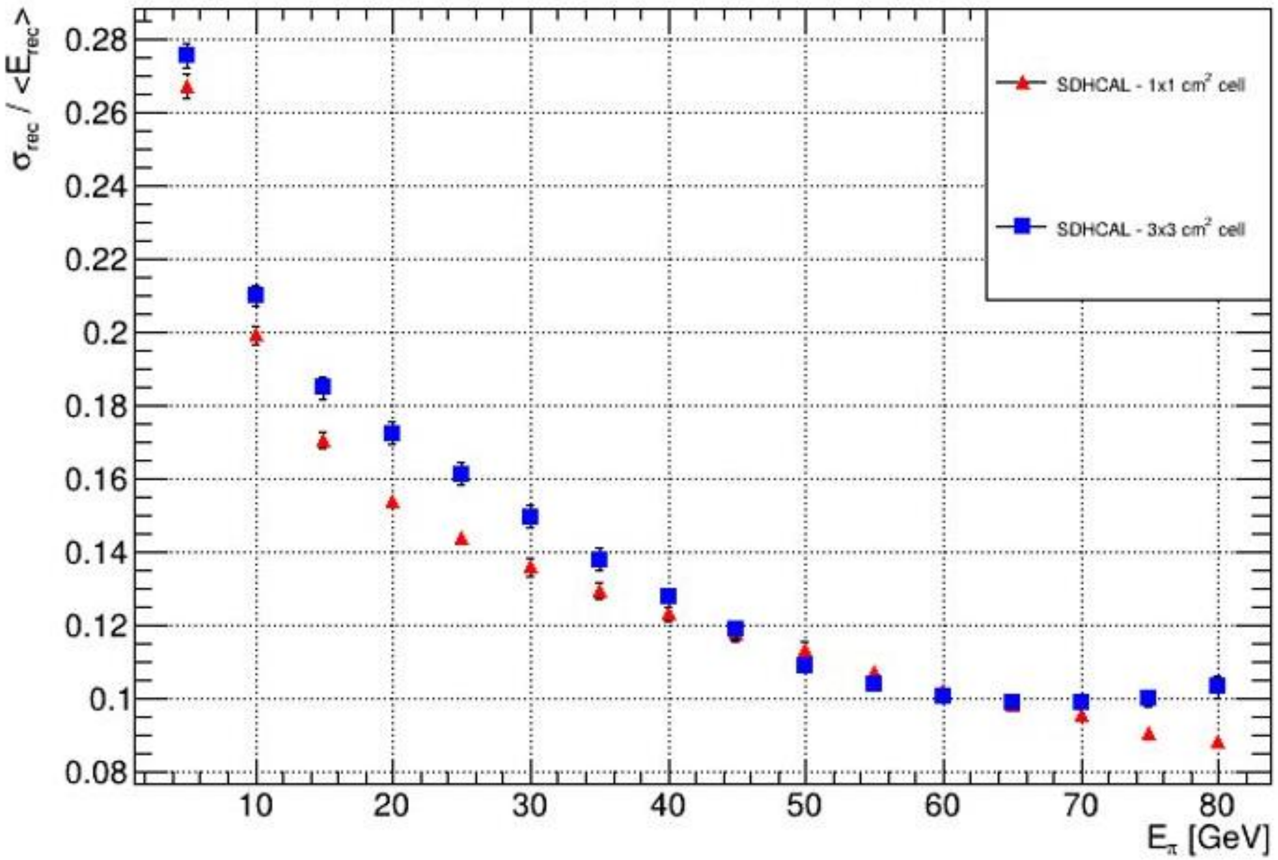
DHcal suffers from **saturation effect** of N_{hit} – the only variable used for reconstruction – for E_π > 40 GeV

At E_π= 80 GeV, the resolution

- DHcal ~ 14%
- SDHcal ~ 8%

G4 simulation - SDHcal 1x1 cm² – SDHcal 3x3 cm²

PRELIMINARY



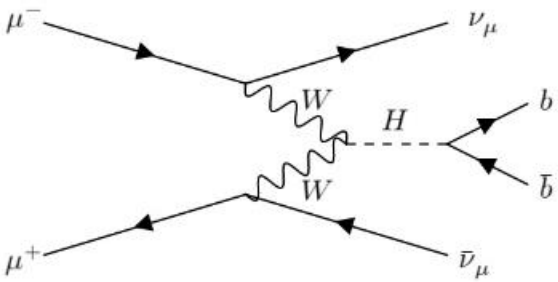
Increasing cell dimensions, the resolution saturates at 60 GeV.

At E_π= 80 GeV, the resolution

- SDHcal 3x3 cm² ~ 10%
- SDHcal 1x1 cm² ~ 8%

Simulation in Muon Collider framework

MPGD-HCAL at Muon Collider



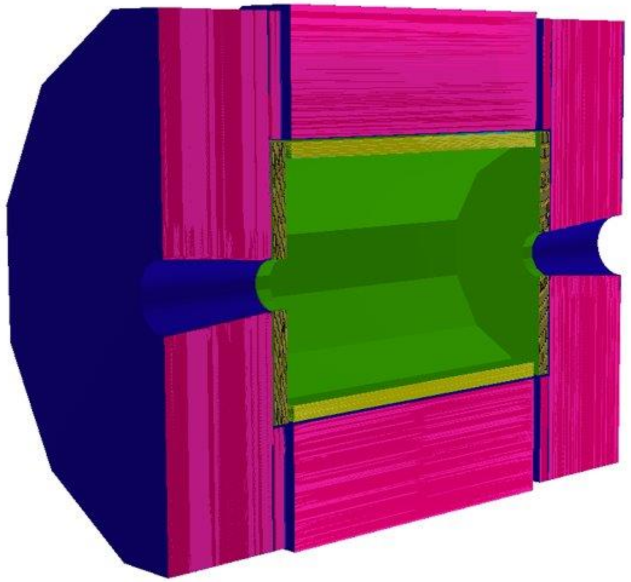
Benchmark process: $\mu^+\mu^- \rightarrow H\nu_\mu\overline{\nu_\mu} \rightarrow b\bar{b}\nu_\mu\overline{\nu_\mu}$

at center of mass energy of 1.5 TeV

Implemented geometry in MuCol Software

- Sampling calorimeter made of
  - 2 cm thick **absorber**
  - 3 mm thick **active layer**
- Granularity given by cells of size 3x3 cm^2 - Digital RO
- **BASELINE**: Scintillator (Polystirene) + Steel
- **MPGD Hcal**: Gaseous argon + Iron

- 10k events produced with Pythia
- 100 BIB events
- Signal events simulated in the whole apparatus with BIB superimposed
- Entire event reconstructed
  - For both geometries

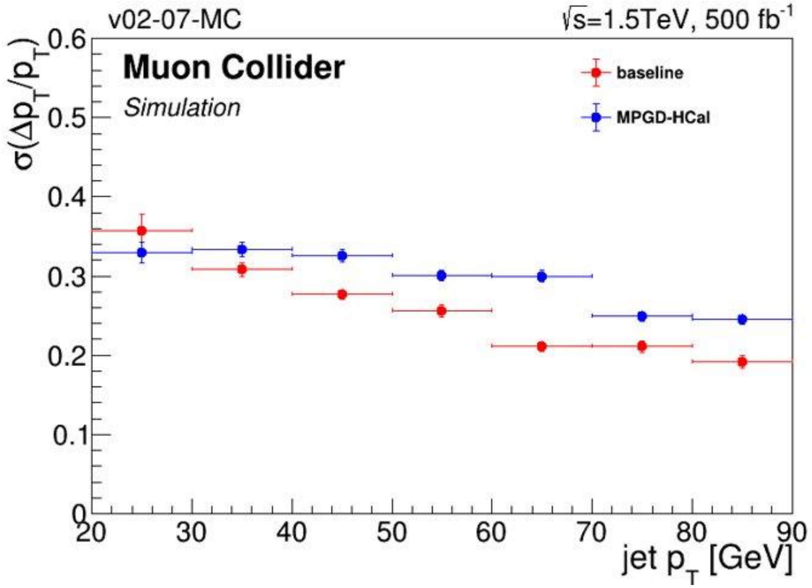


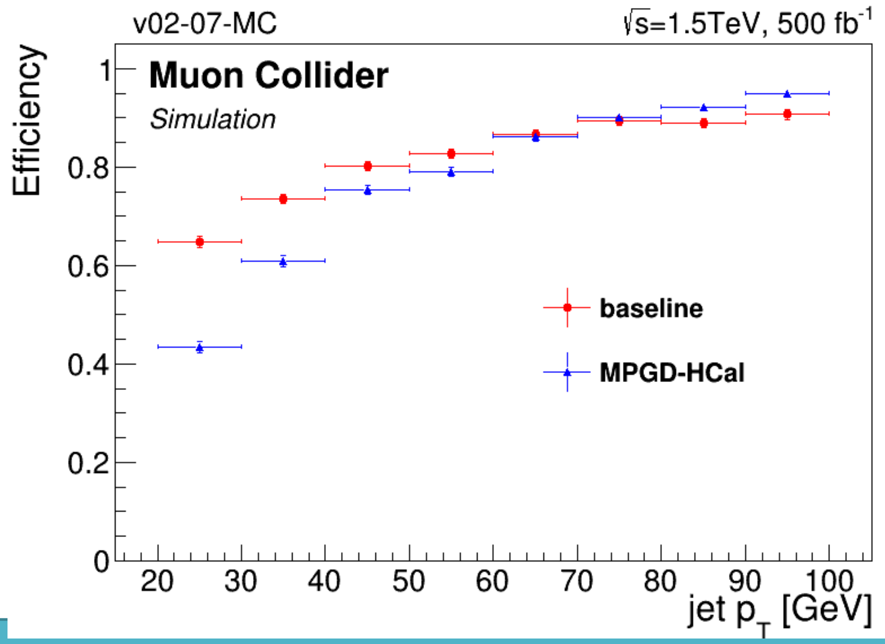
MPGD-HCAL at Muon Collider

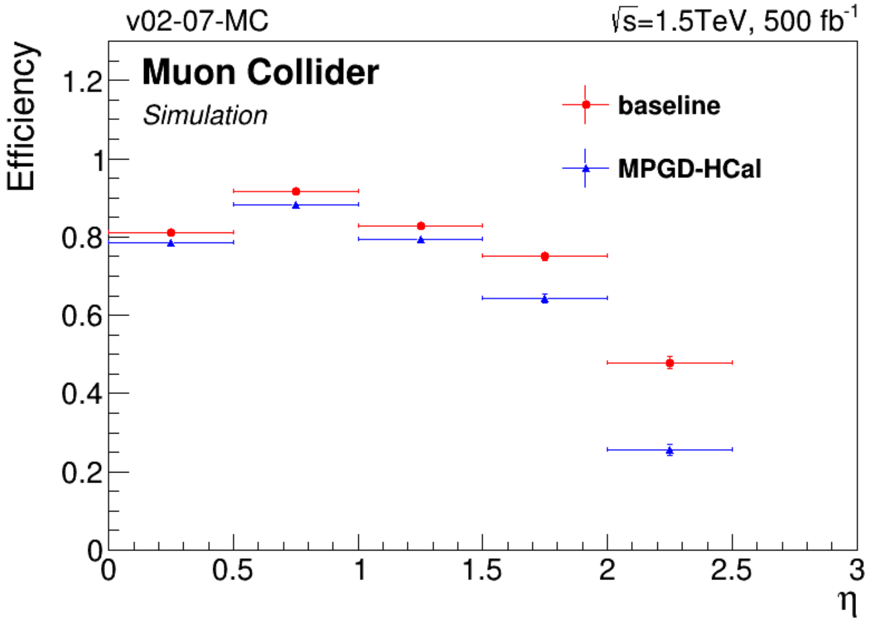
Performances of **MPGD-HCal geometry** in terms of
- Reconstruction efficiency
- Resolution on jet p_T

are **comparable** with the **baseline** (scintillator + steel).

Studies to be repeated also with cell granularity of 1 cm2







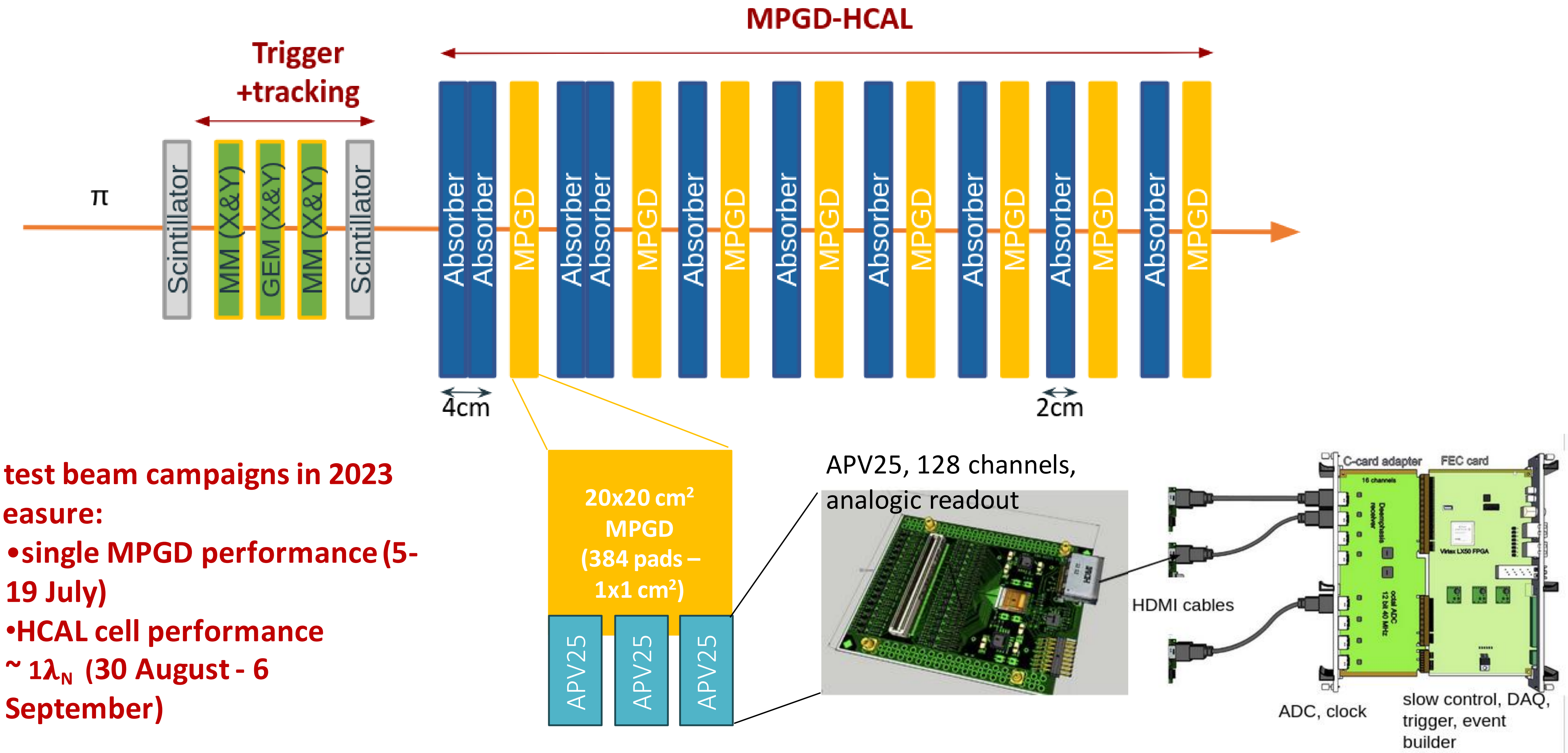
To be understood:
Drop at low pT, high eta with MPGD based geometry

MPGD-HCAL prototype

In collaboration with

- INFN Roma 3
- INFN Napoli
- INFN Frascati
- Weizman Institute of Science

MPGD-HCAL prototype

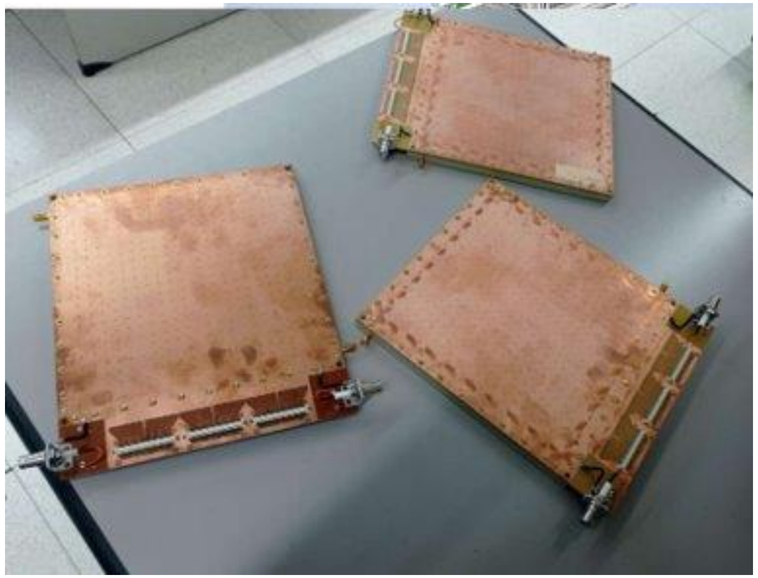


Two test beam campaigns in 2023 to measure:

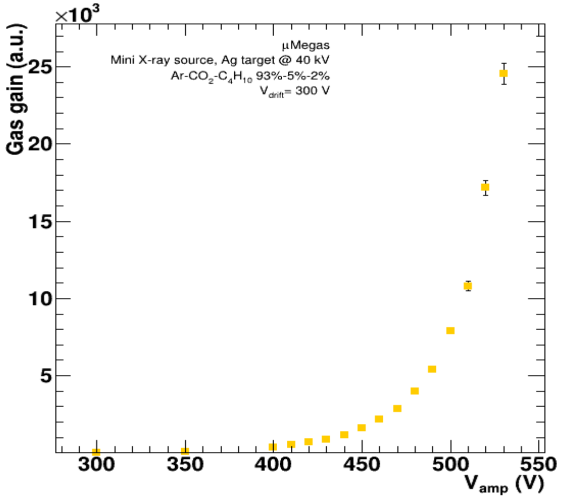
- **single MPGD performance (5-19 July)**
- **HCAL cell performance ~ 1λ_N (30 August - 6 September)**

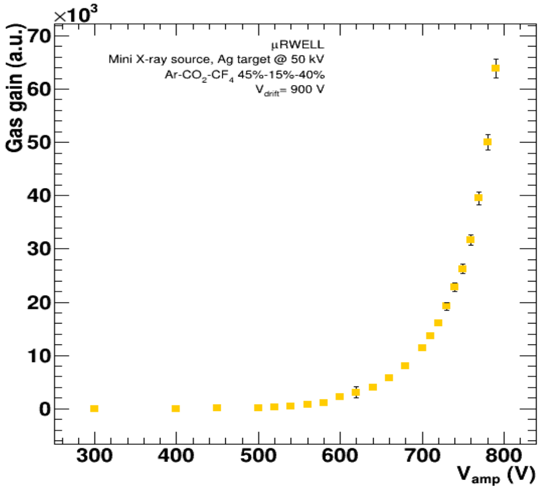
MPGD-HCAL prototype

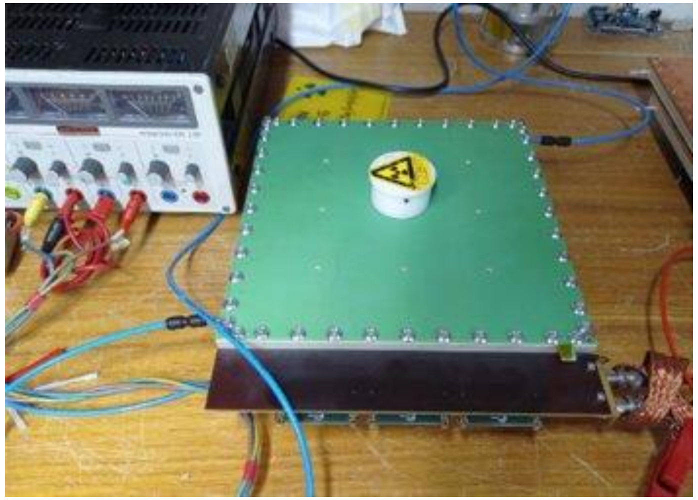
- **MPGD total production batch**:
  - 7 uRWELL
  - 4 MicroMegas
  - 1 RPWELL
- detector size: 20x20 cm^2
- pad size: 1cm^2 pad→ 384 pads
- Common readout board



First characterizations (HV stability & effective gain) performed in all the labs involved in the project







MPGD-HCAL prototype - July test beam 2023

Preliminary test beam on single detectors at SPS with μ beam at 150 GeV to measure:

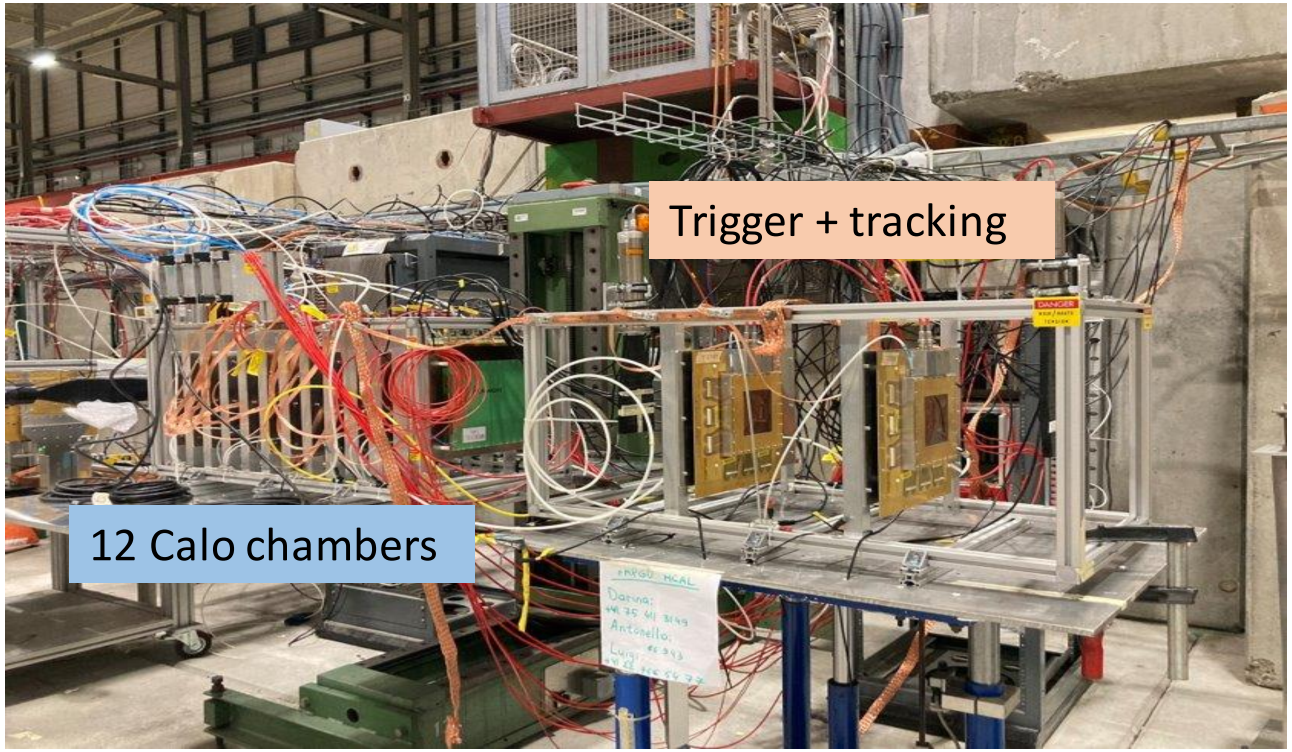
- **Efficiency**
- **Response uniformity**
- **Space resolution**

Data taking

- APVs + SRS (2 FECs) for the DAQ
  - Read 6 chambers + Tmms at a time
- HV scan, XY position scan

Reconstruction

- Tmms temporarily excluded
- Track reconstruction with hits from 5 pad calo-chambers, excluding the one under test



Calo-chambers

12 detectors with 1 cm^2 RO PADs

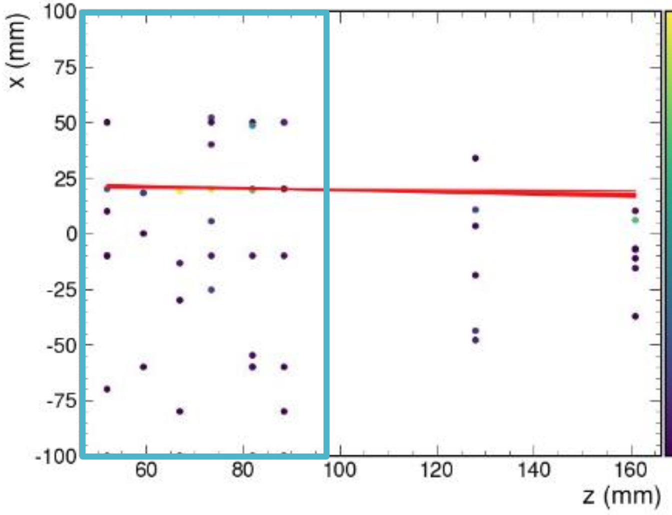
- 4 Resistive MicroMegas
- 7 μ-RWELL
- 1 RPWELL

Tracking system

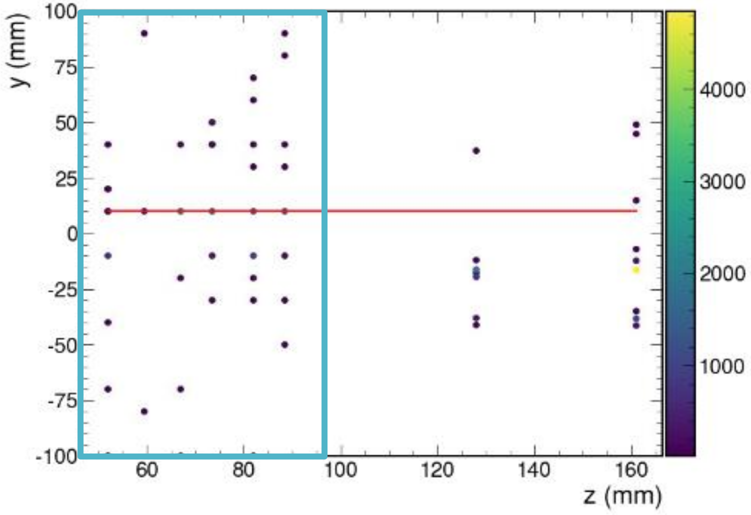
- 2 10x10 cm^2 Tmms

MPGD-HCAL prototype - July test beam 2023

Calo chambers



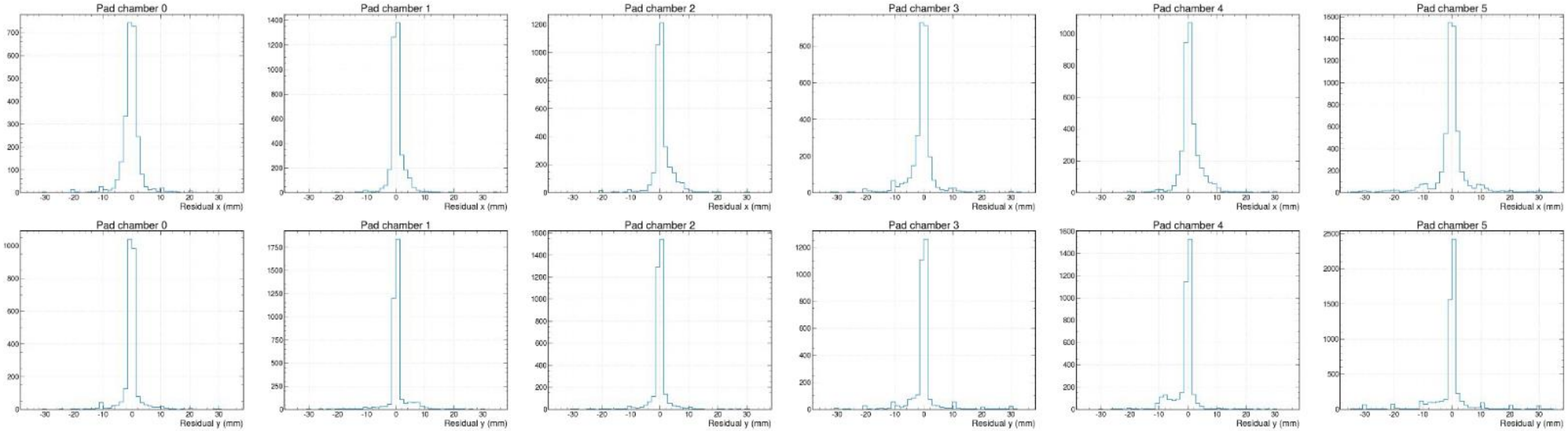
Calo chambers



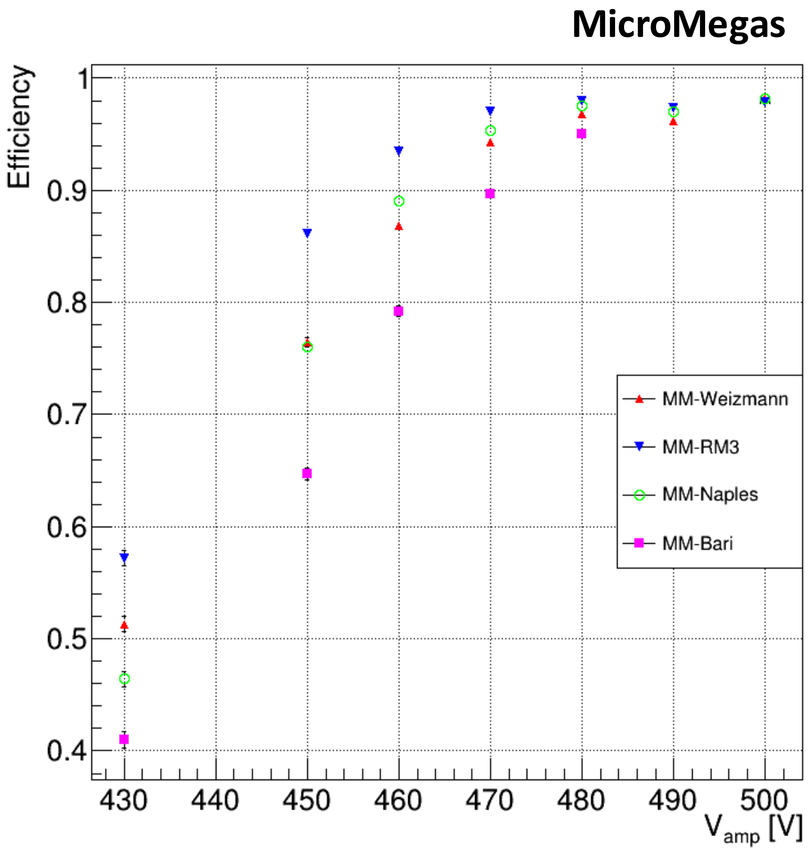
PRELIMINARY

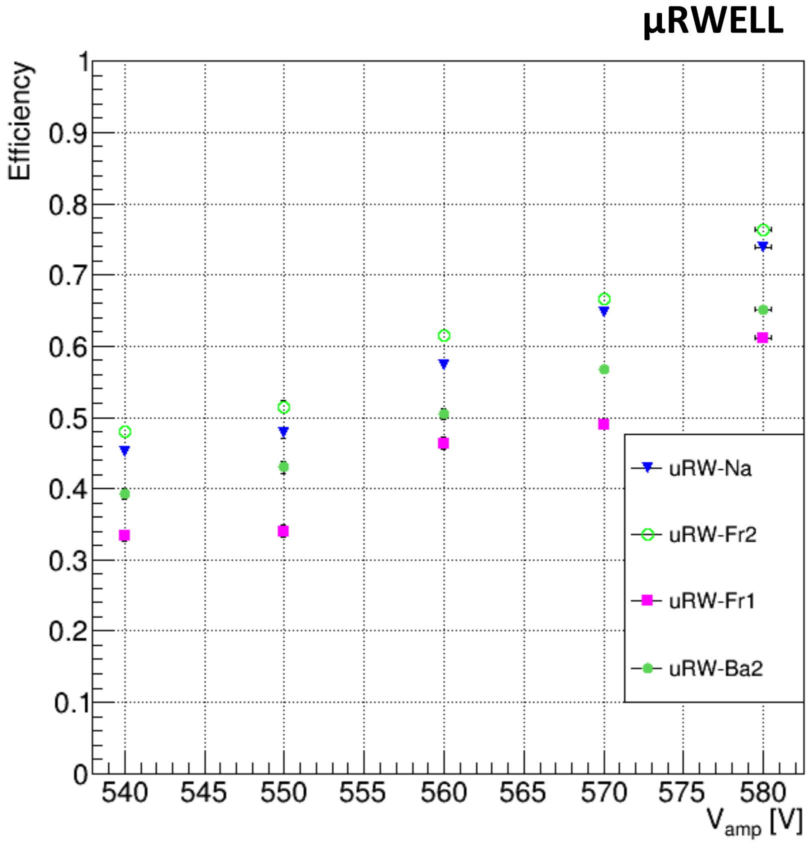
Narrow residuals, in agreement with detector granularity

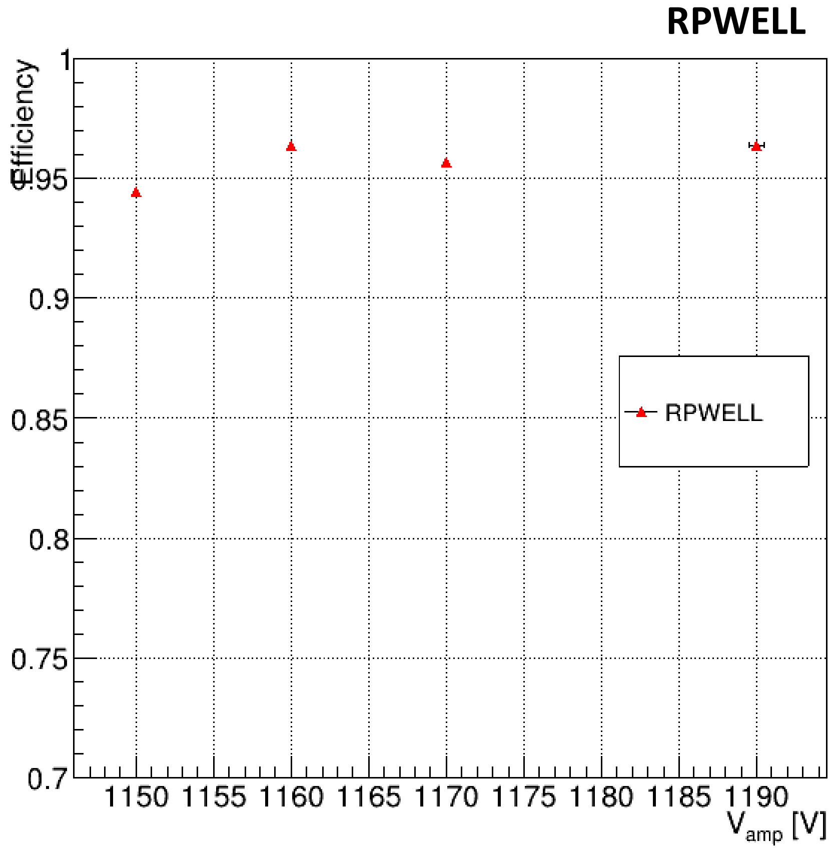
Residuals



MPGD-HCAL prototype – July test beam 2023







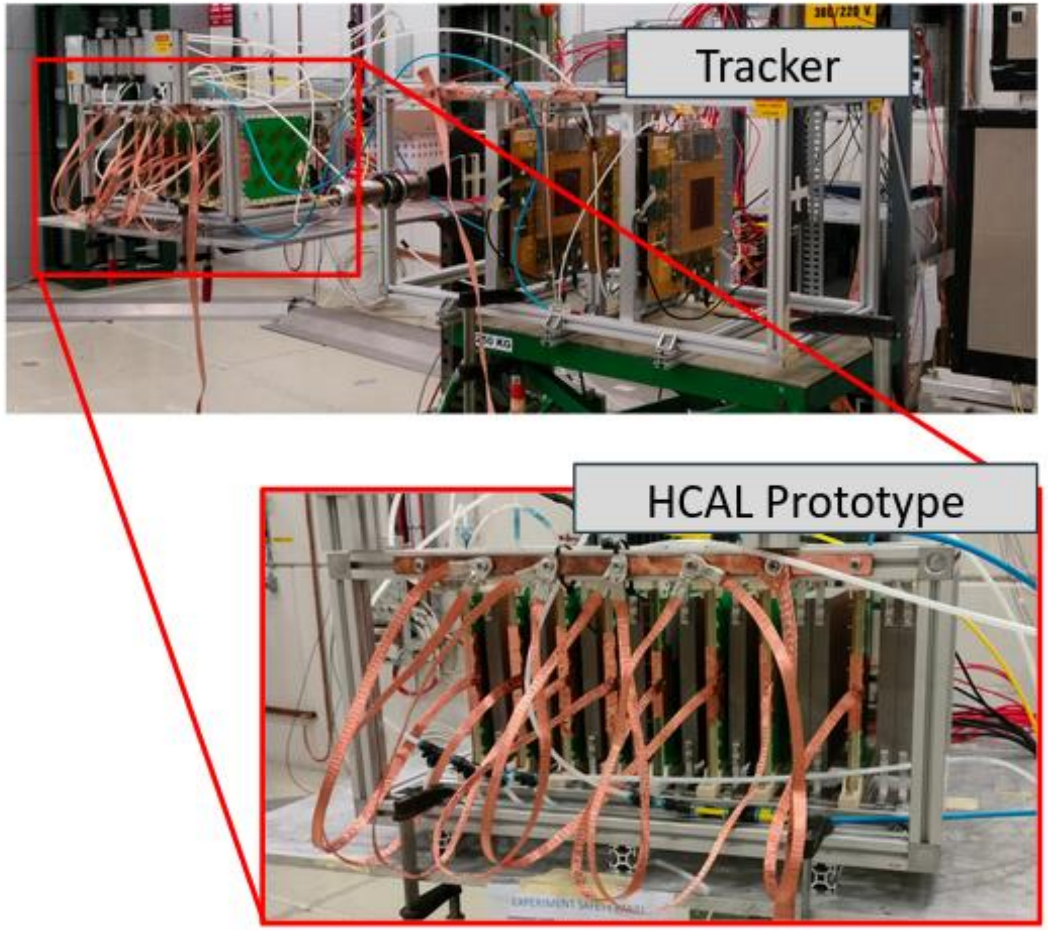
PRELIMINARY

MPGD-HCAL prototype – August test beam 2023

Full prototype test beam campaign at PS
- pure negative pion beams
- beam size of ~1cm^2
- monochromatic E=2, 4, 6,7,9,10 GeV

First operation of the full system!

Scientific program
- without absorbers: response to an X&Y scan
  - at 11 GeV, highly collimated and pure beam
- with absorbers: energy and energy resolution measurement with monochromatic beam
  - Cherenkov detectors used to veto electrons and muons contamination
- Define thresholds for semi-digital readout using per-pad charge distribution obtained with the analog readout



Conclusions

MPGD-HCal simulation in G4– response to single π:

- Energy resolution improves of a factor 2 using **semi-digital RO** for cells of 1x1 cm^2

Muon Collider framework – (very preliminary results)

- Comparable jet reconstruction performance using MPGD or Scintillators as active layers
    - Future plans: Study the reconstrunction performance as a function of granularity also for the case of semi-digital readout

Test on MPGD prototype :

- All technologies have been characterized with MIPs with and without absorbers
    - Excellent MIP efficiency for MM and RPWELL, results on μrwell still to be understood
- Test beam data analysis in progress: data from PS test beam to be fully analyzed and compared with GEANT4 simulation