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

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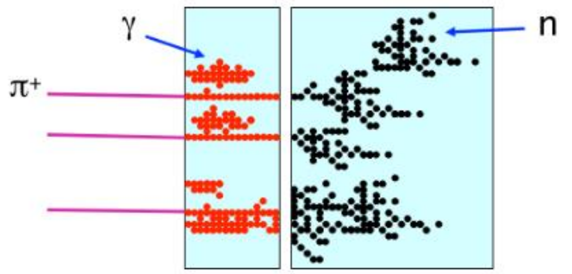
16th Topical Seminar on Innovative Particle and Radiation Detectors
Siena, 28-09-2023

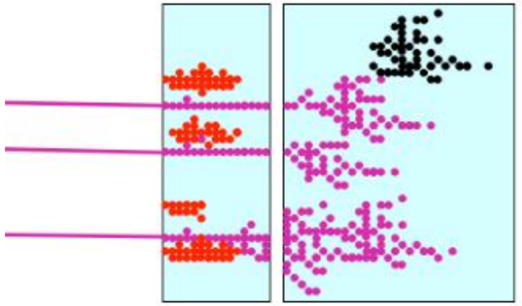
Motivation: Particle-Flow Calorimetry



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

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

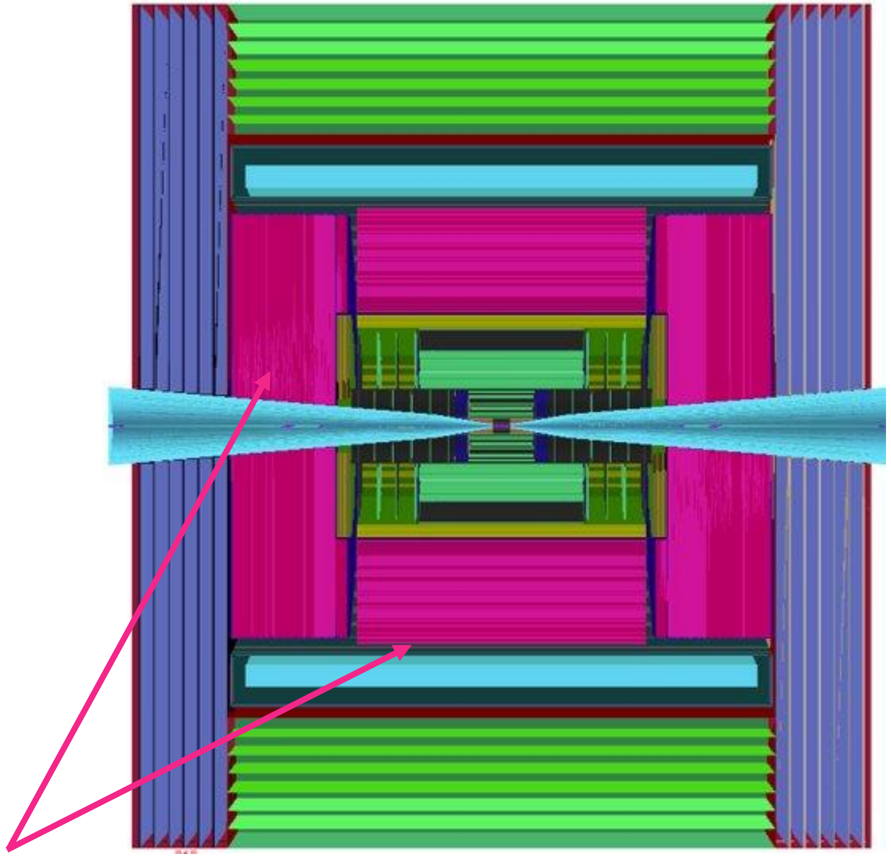
Advantages:

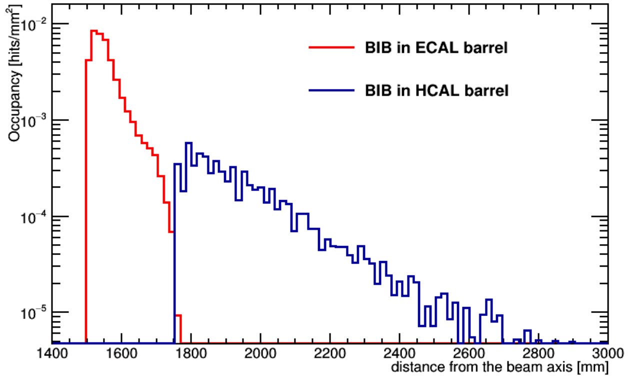
- multi-TeV energy range in **compact circular** machines;
- well **defined initial state** and **cleaner final state**;
- all **collision energy available** in the hard-scattering process.

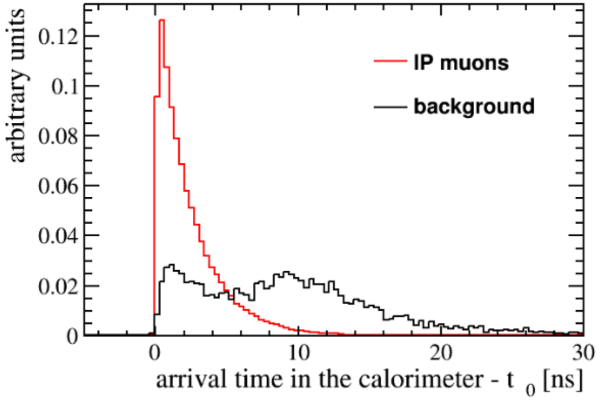
Challenges:

- 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)

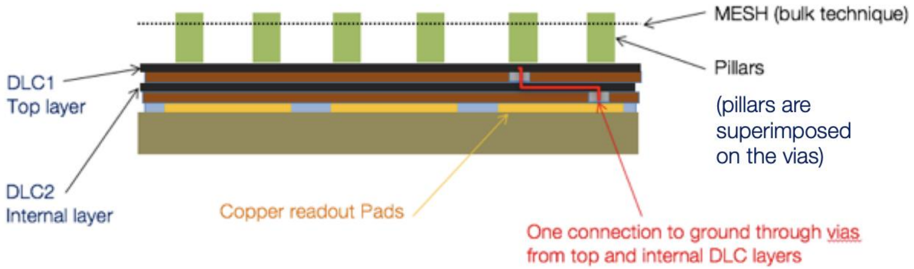
2021 JINST 15 P11009

MPGD-HCAL for Muon Collider

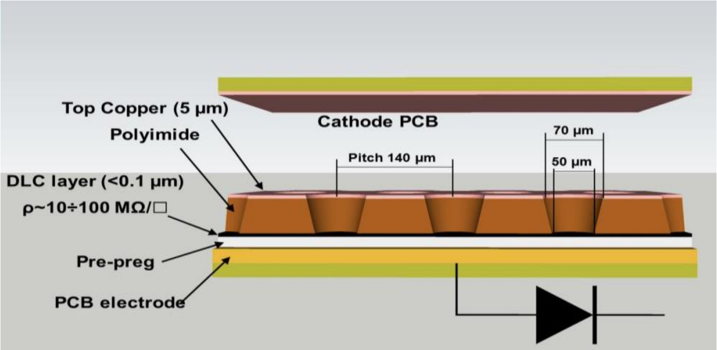
Why MPGDs for calorimeters?

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

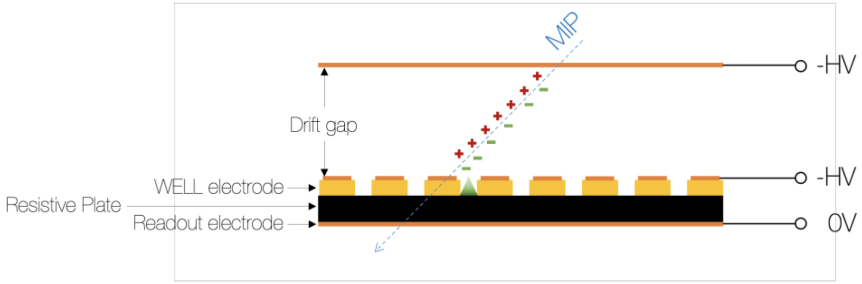
MicroMegas



µRWELL



RPWELL



GEANT4 Simulation

PRELIMINARY

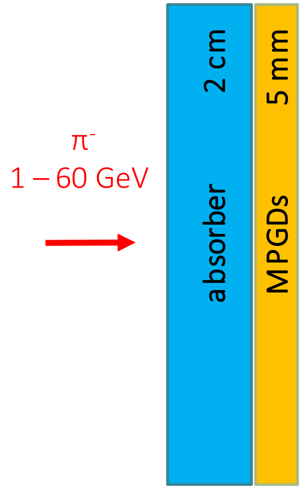
G4 Simulation – Shower containment

Implemented geometry

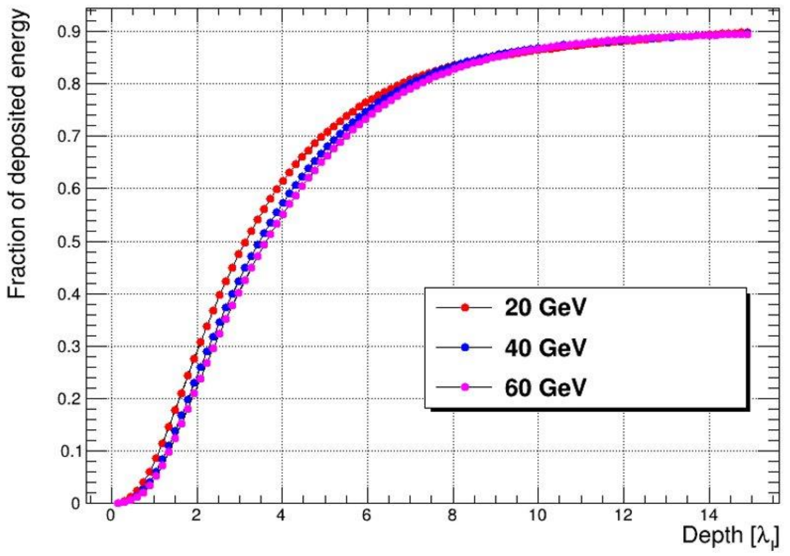
- Sampling calorimeter made of
  - 2 cm for the absorber (iron)
  - 5 mm of active layer (Ar/CO_2)
  - Cells of granularity (1x1 cm^2 and 3x3 cm^2)

Energy contained at 90% within

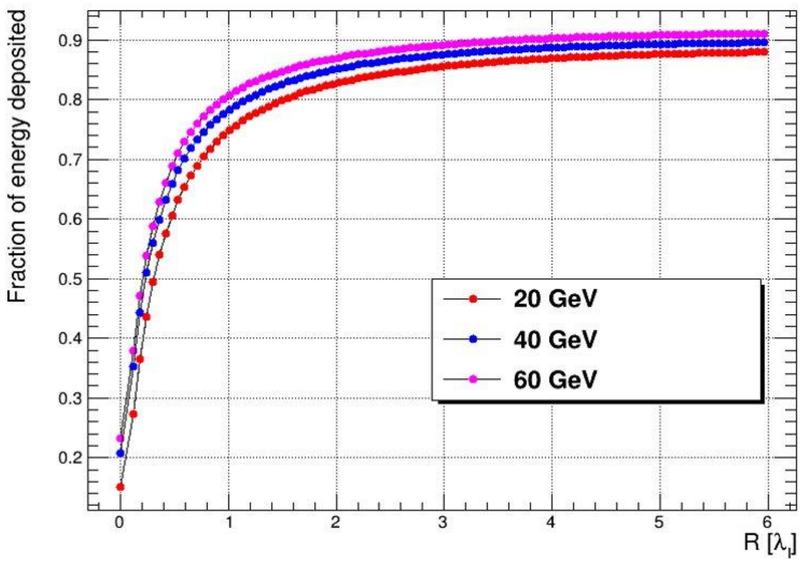
- 14 λ_N in the direction of the incoming π
- 3 λ_N in the orthogonal direction



Longitudinal shower containment



Trasversal shower containment

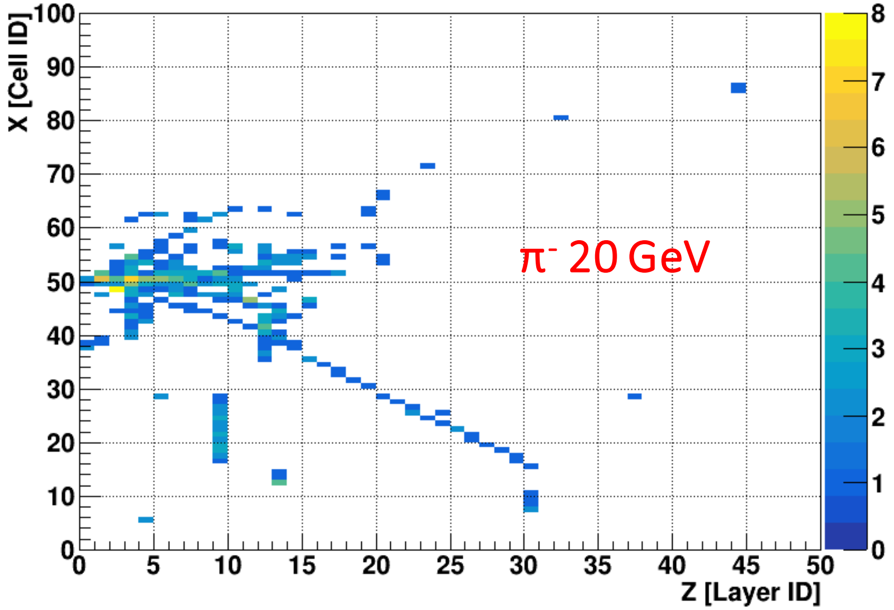


G4 Simulation – DHCAL and SDHCAL readout

DIGITAL HCAL

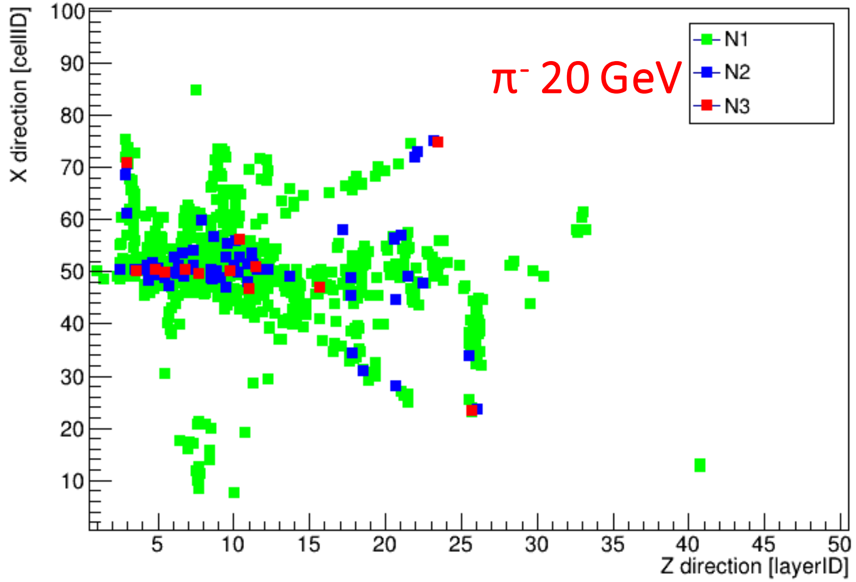
Digitization: 1 hit --> 1cell with energy deposit higher than the applied threshold

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



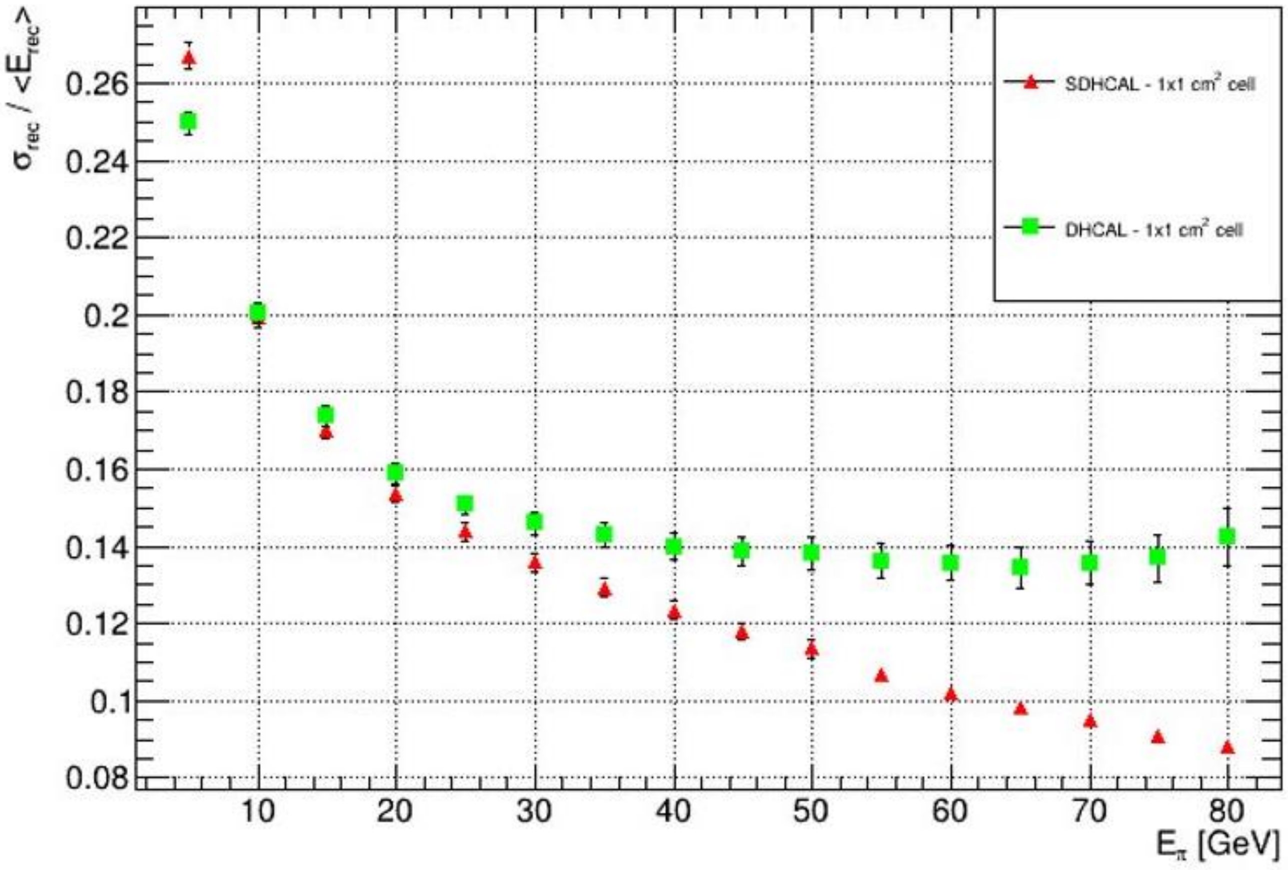
SEMI DIGITAL HCAL

- **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



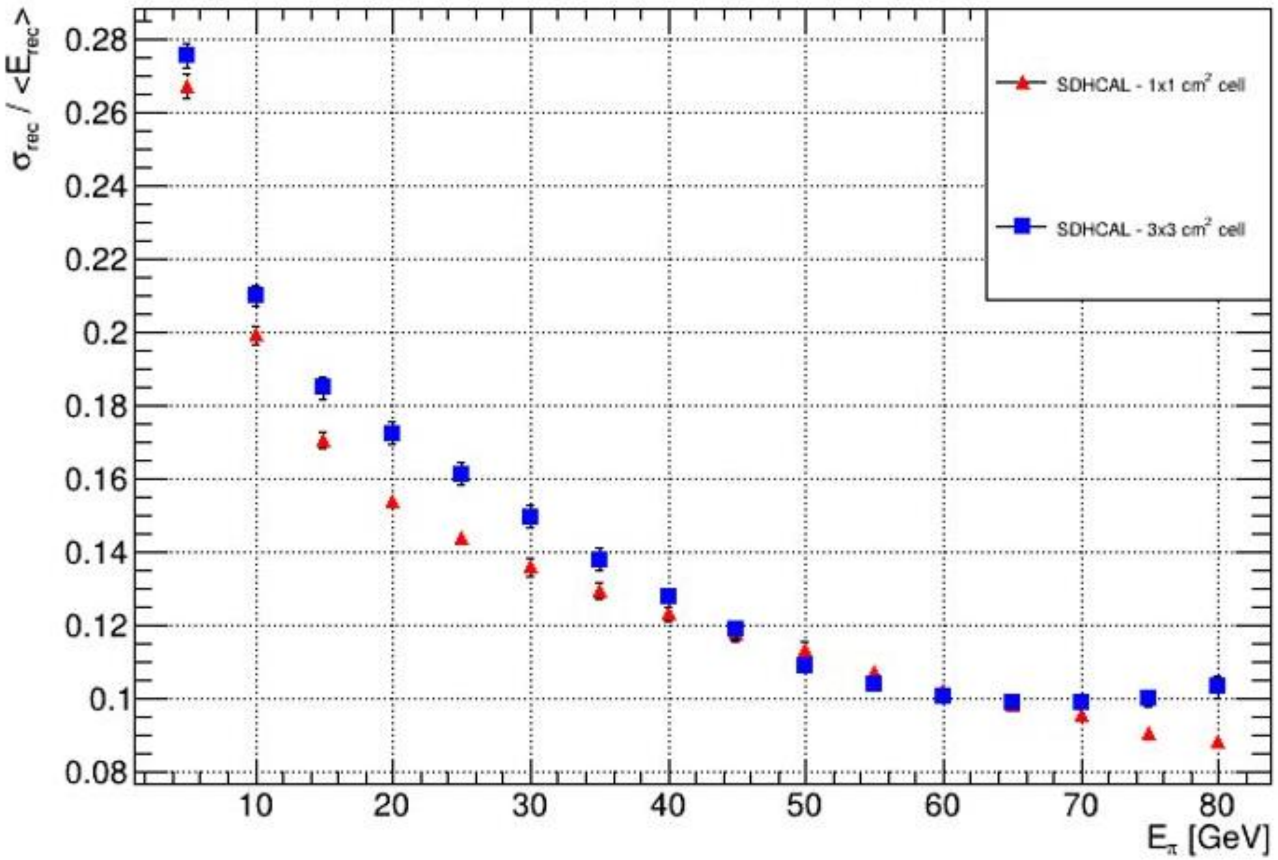
DHcal suffers from **saturation effect** of N_{hit} – the only variable used for reconstruction – for E_π > 40 GeV

At E_π= 80 GeV, the resolution

- DHcal ~ 14%
- SDHcal ~ 8%

G4 simulation - SDHcal 1x1 cm^2 – SDHcal 3x3 cm^2

PRELIMINARY



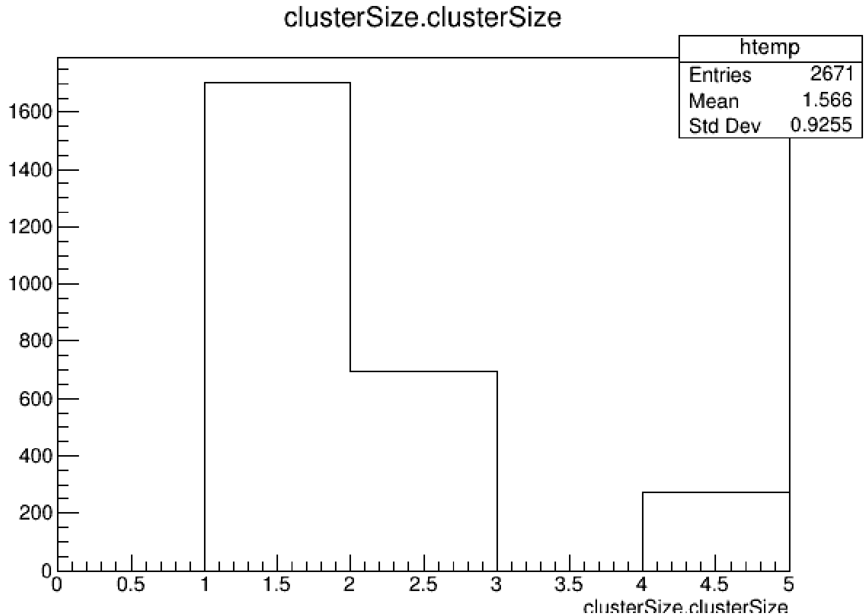
Increasing cell dimensions, the resolution saturates at 60 GeV.

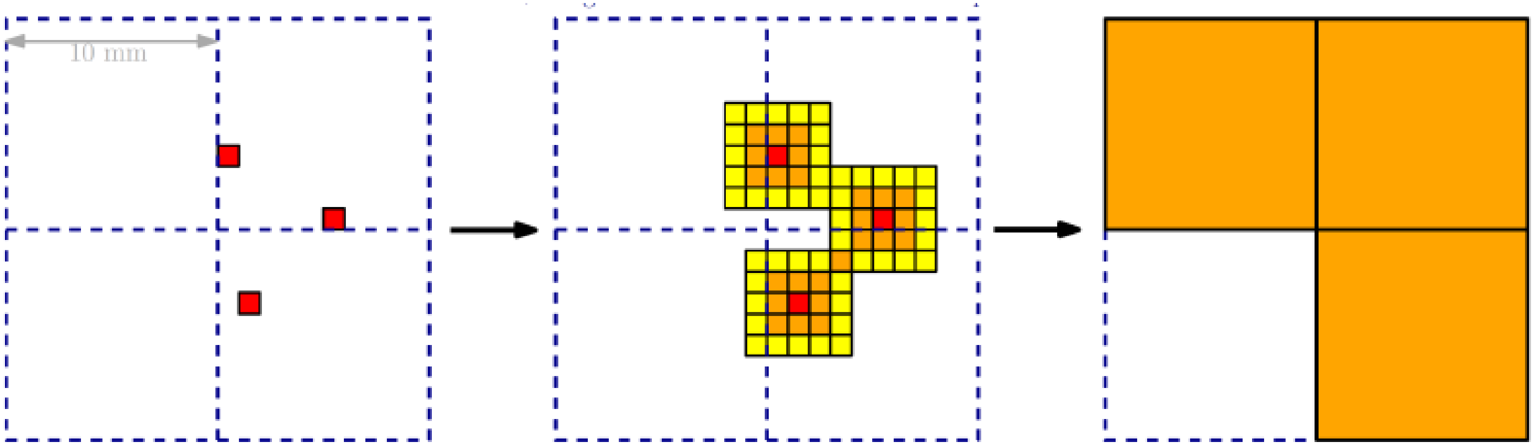
At E_π= 80 GeV, the resolution

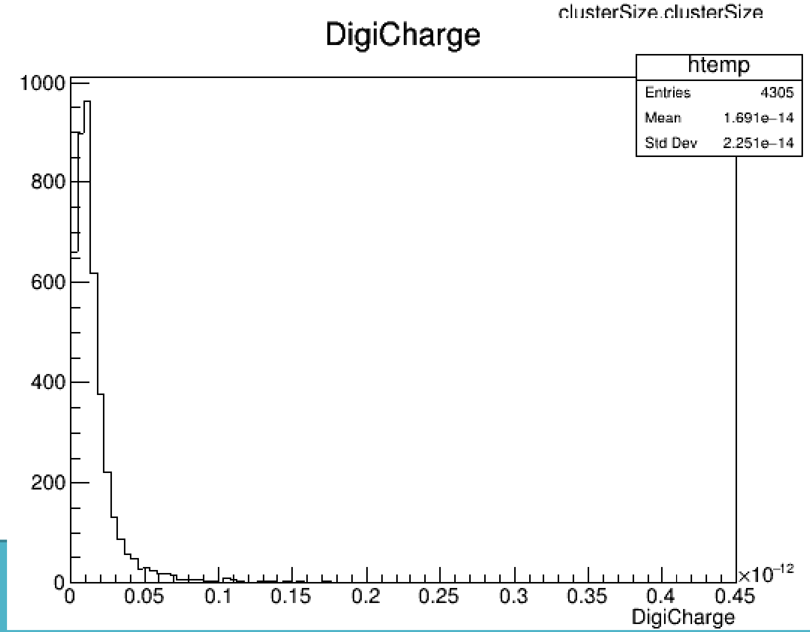
- SDHcal 3x3 cm^2 ~ 10%
- SDHcal 1x1 cm^2 ~ 8%

G4 simulation – Digitization: charge spreading

- Digitalization: simulate detector response in terms of **cluster size** and **efficiency** of the detector
- from (x,y) position of track in the active layer, define a gaussian distribution centered in (x,y) and with sigma related to the measured pad multiplicity
- 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

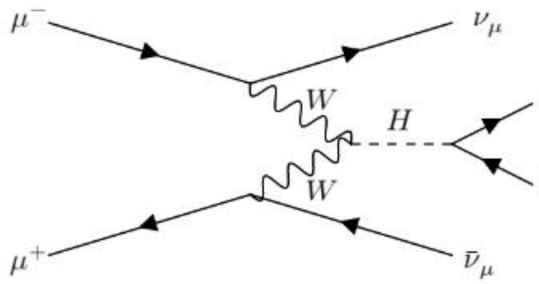






Simulation in Muon Collider framework

MPGD-HCAL at Muon Collider

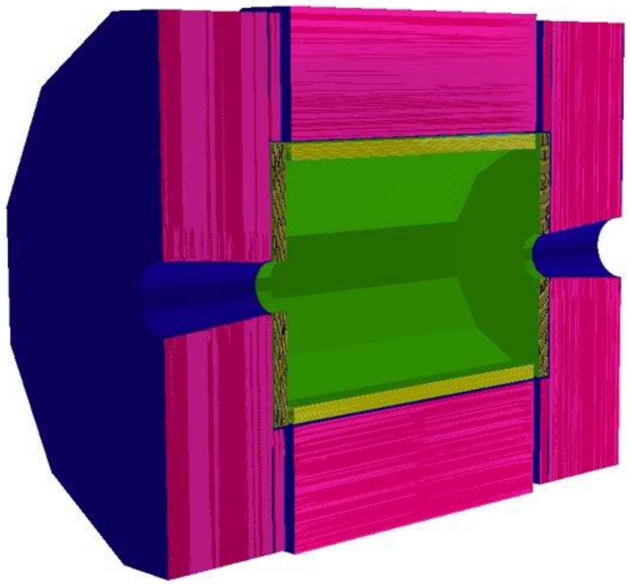


Benchmark process: $\mu^+\mu^- \to H\nu_\mu\overline{\nu_\mu} \to b\bar{b}\nu_\mu\overline{\nu_\mu}$
at center of mass energy of 1.5 TeV

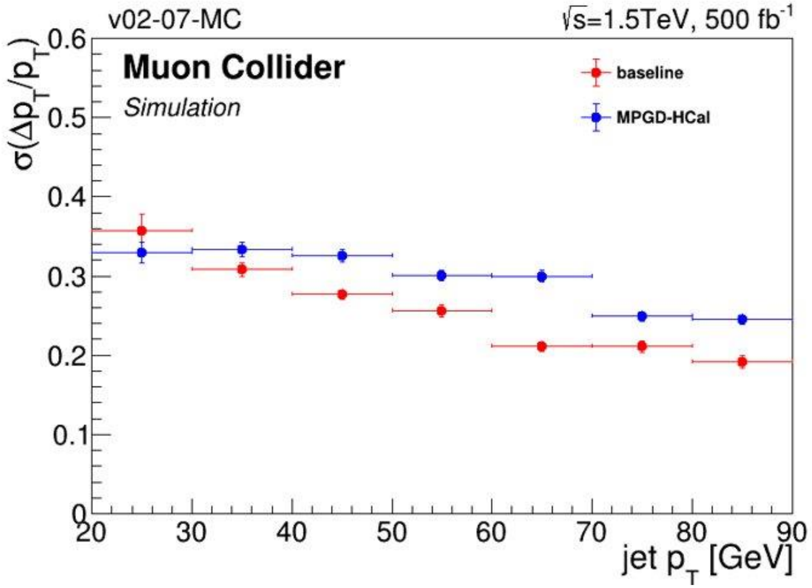
Implemented geometry in MuCol Software

- 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

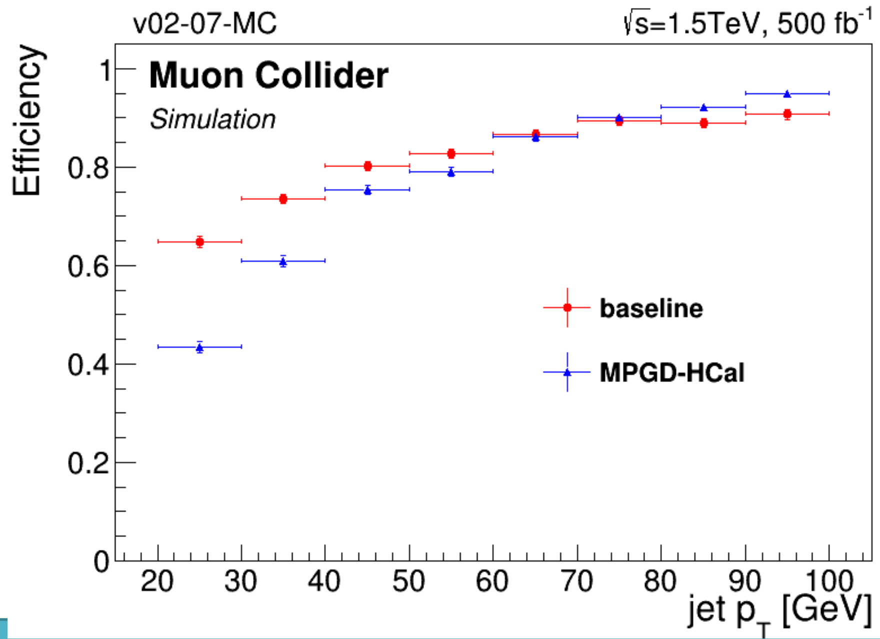


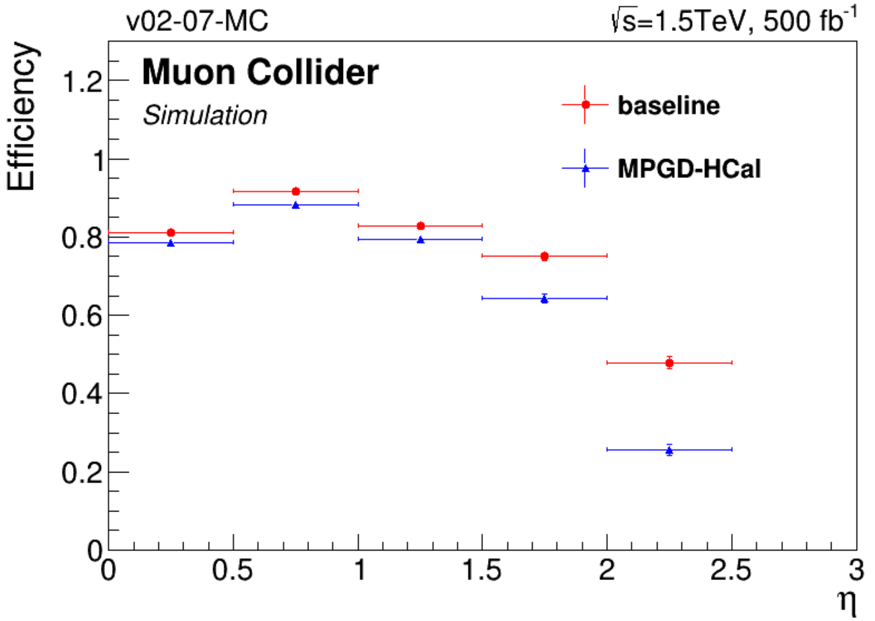
Performances of **MPGD-HCal geometry** in terms of

- 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





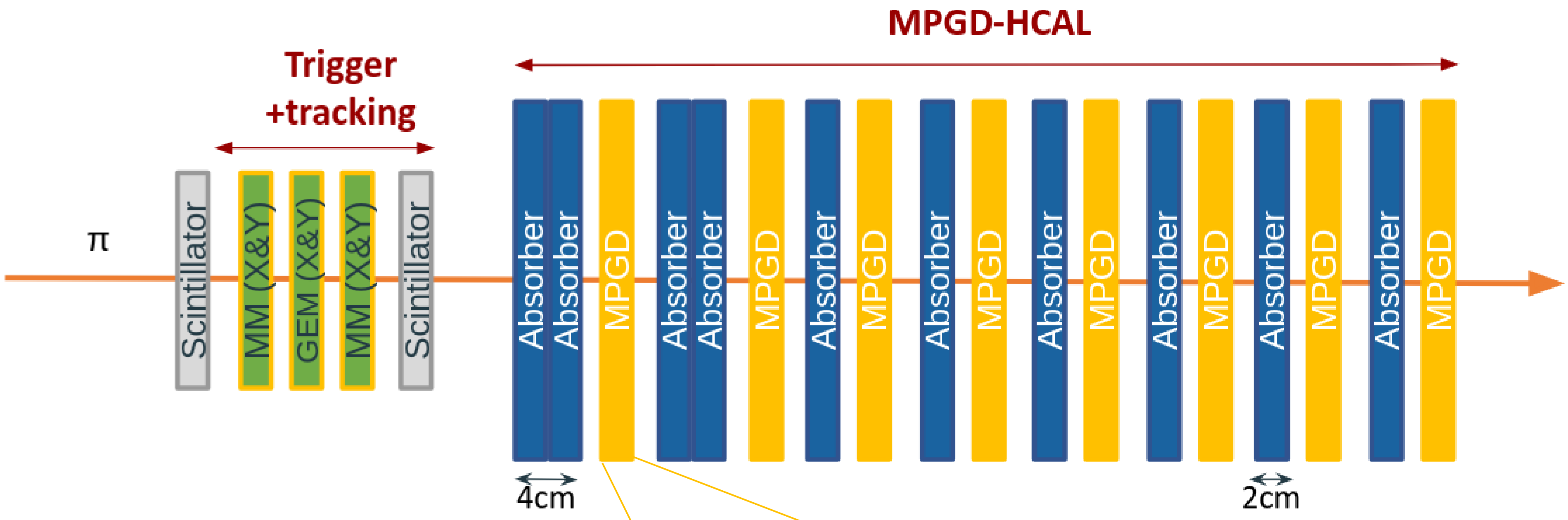
To be understood:
Drop at low pT, high eta with MPGD based geometry

MPGD-HCAL prototype

In collaboration with

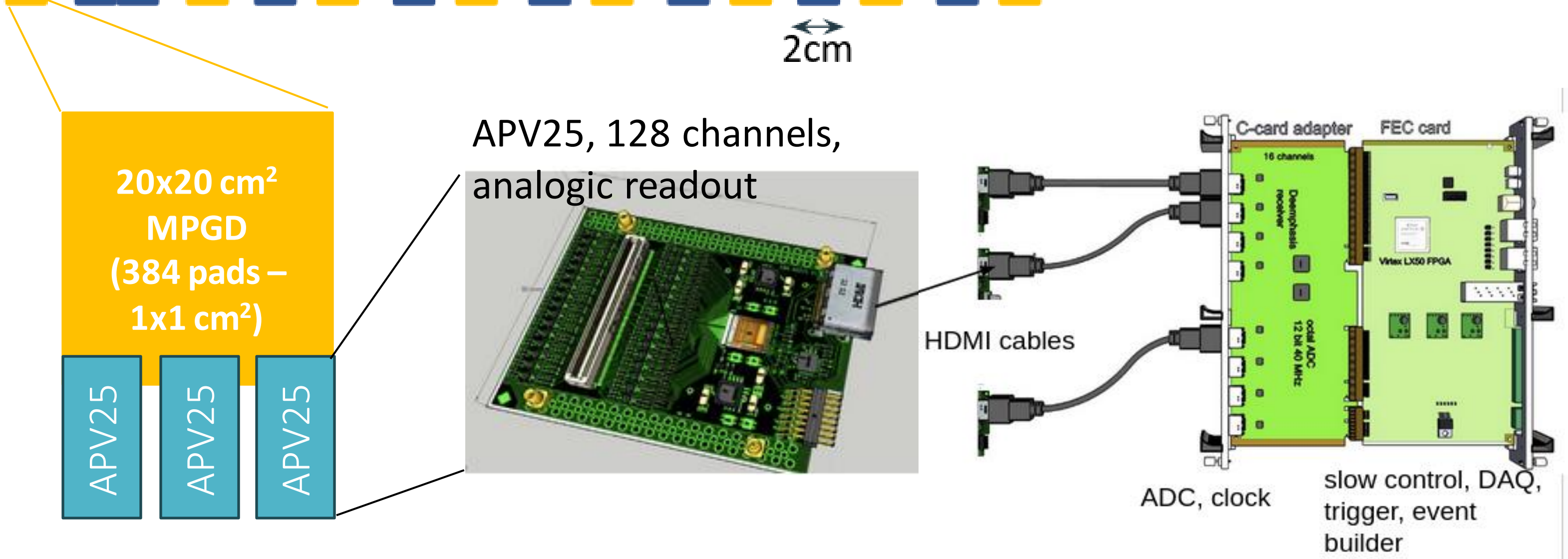
- INFN Roma 3
- INFN Napoli
- INFN Frascati
- Weizman Institute of Science

MPGD-HCAL prototype



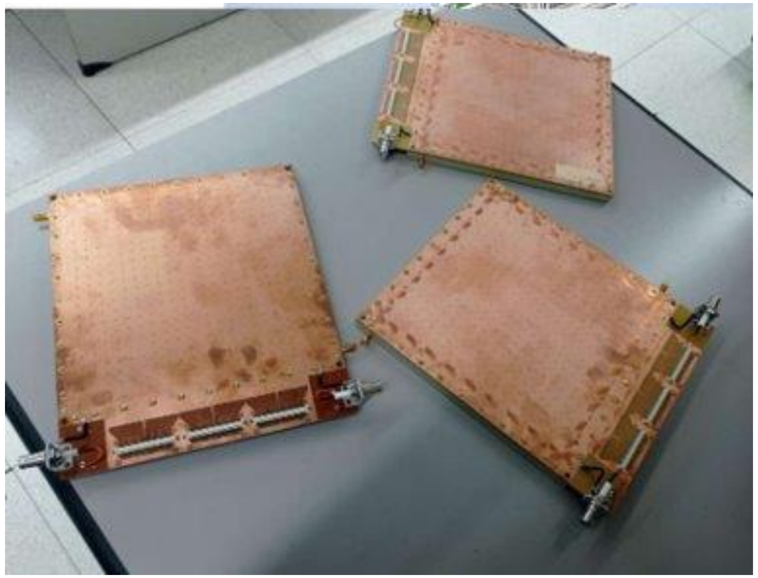
Two test beam campaigns in 2023 to measure:

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

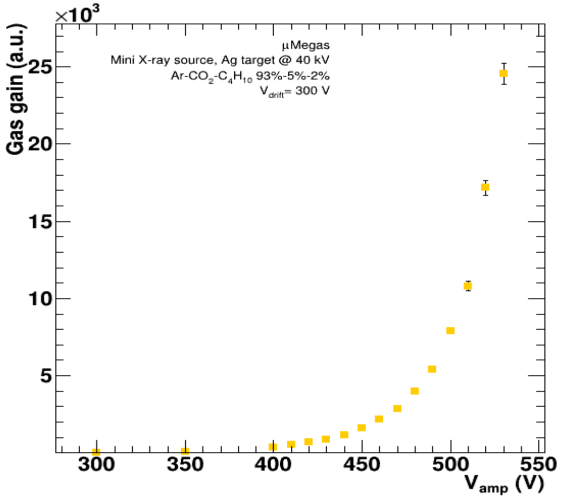


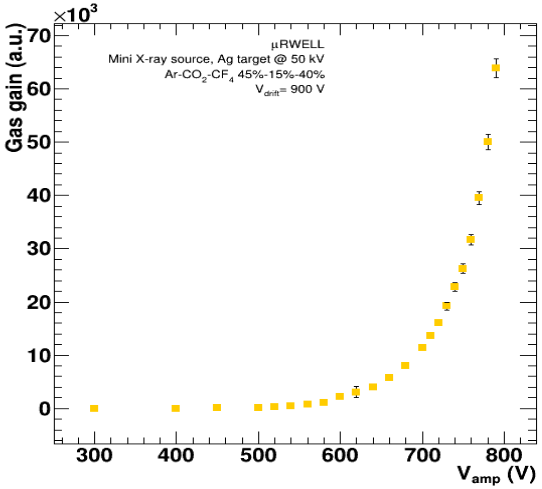
MPGD-HCAL prototype

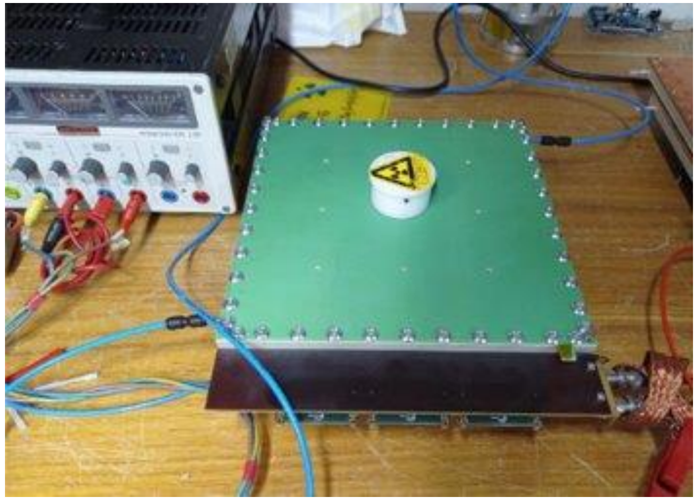
- **MPGD total production batch**:
  - 7 uRWELL
  - 4 MicroMegas
  - 1 RPWELL
- detector size: 20x20 cm^2
- pad size: 1cm^2 pad→ 384 pads
- Common readout board



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:

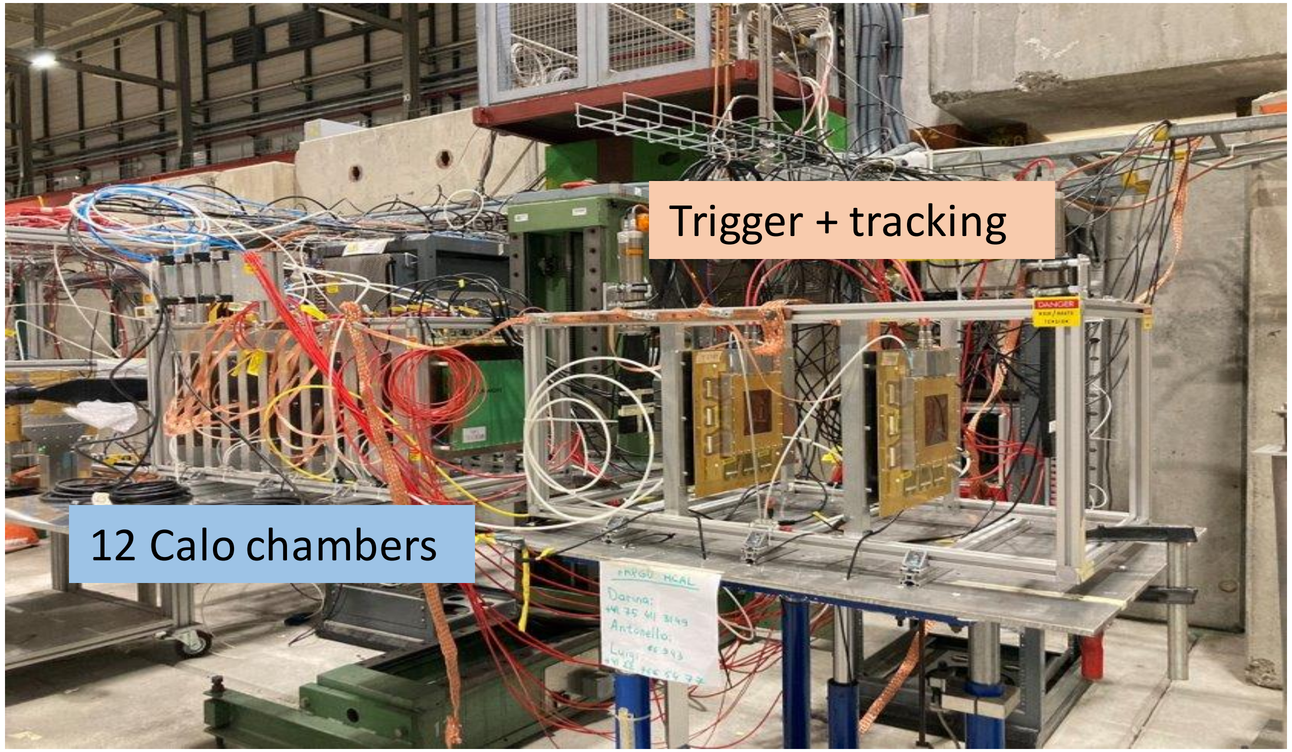
- **Efficiency**
- **Response uniformity**
- **Space resolution**

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

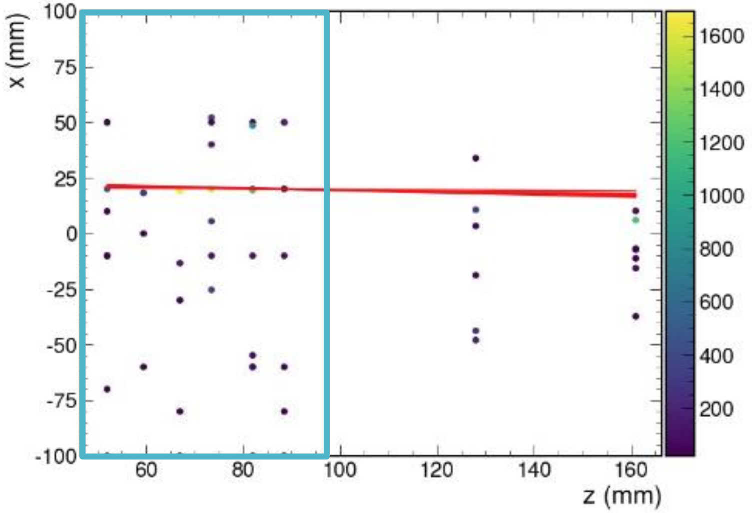
- 4 Resistive MicroMegas
- 7 μ-RWELL
- 1 RPWELL

Tracking system

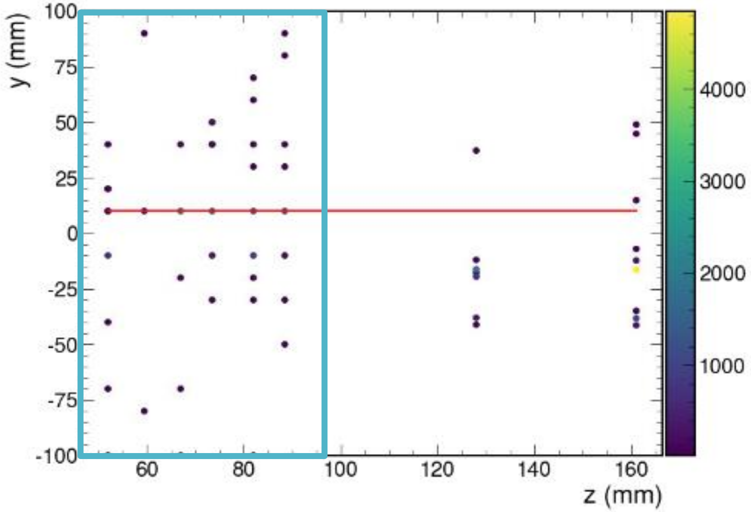
- 2 10x10 cm^2 Tmms

MPGD-HCAL prototype - July test beam 2023

Calo chambers



Calo chambers



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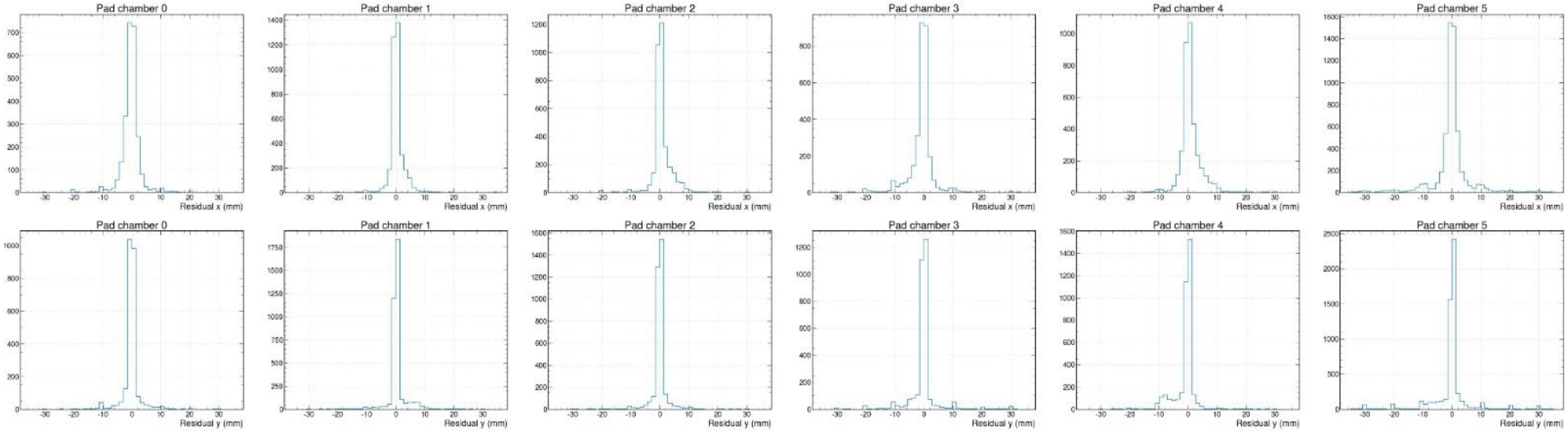
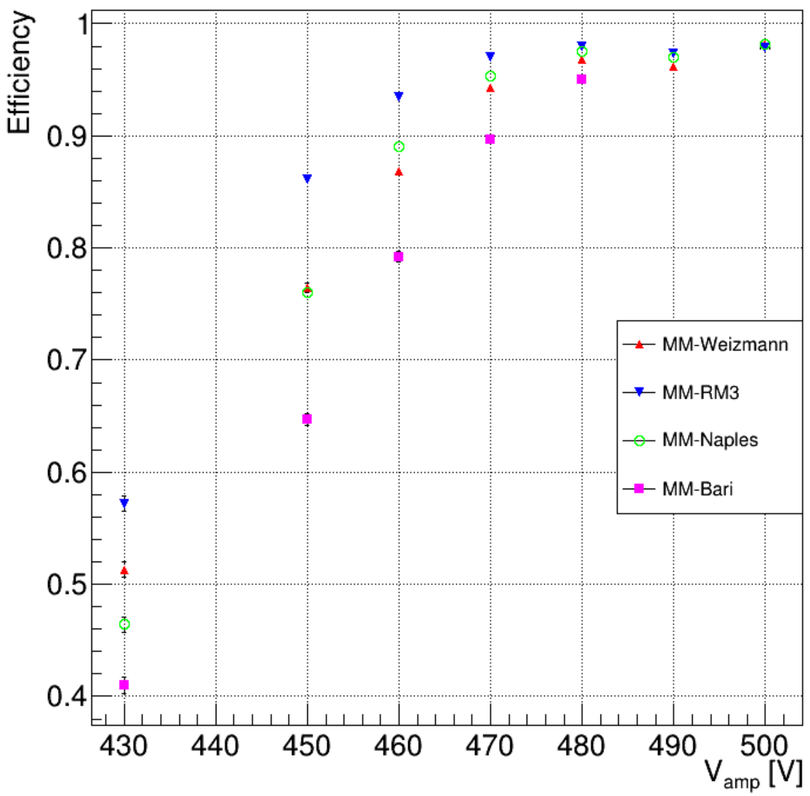
Narrow residuals, in agreement with detector granularity

Residuals

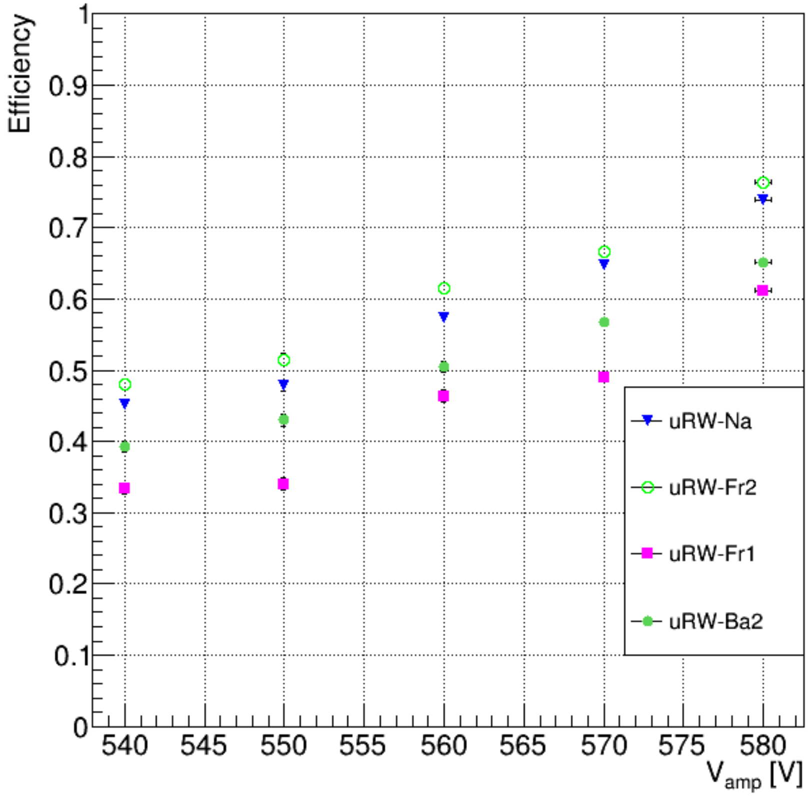


MPGD-HCAL prototype – July test beam 2023

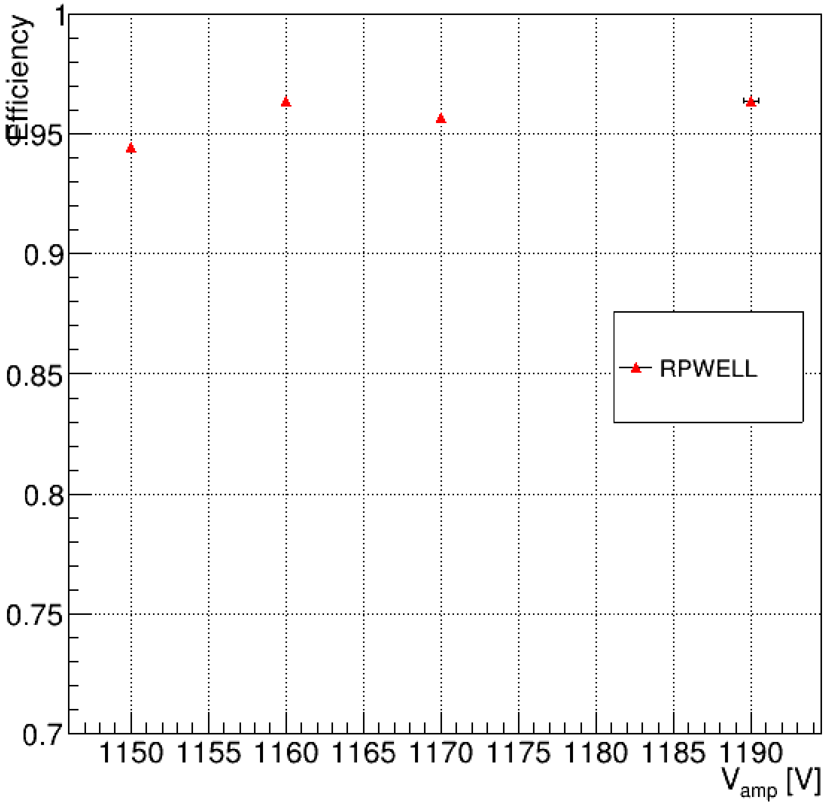
MicroMegas



µRWELL



RPWELL



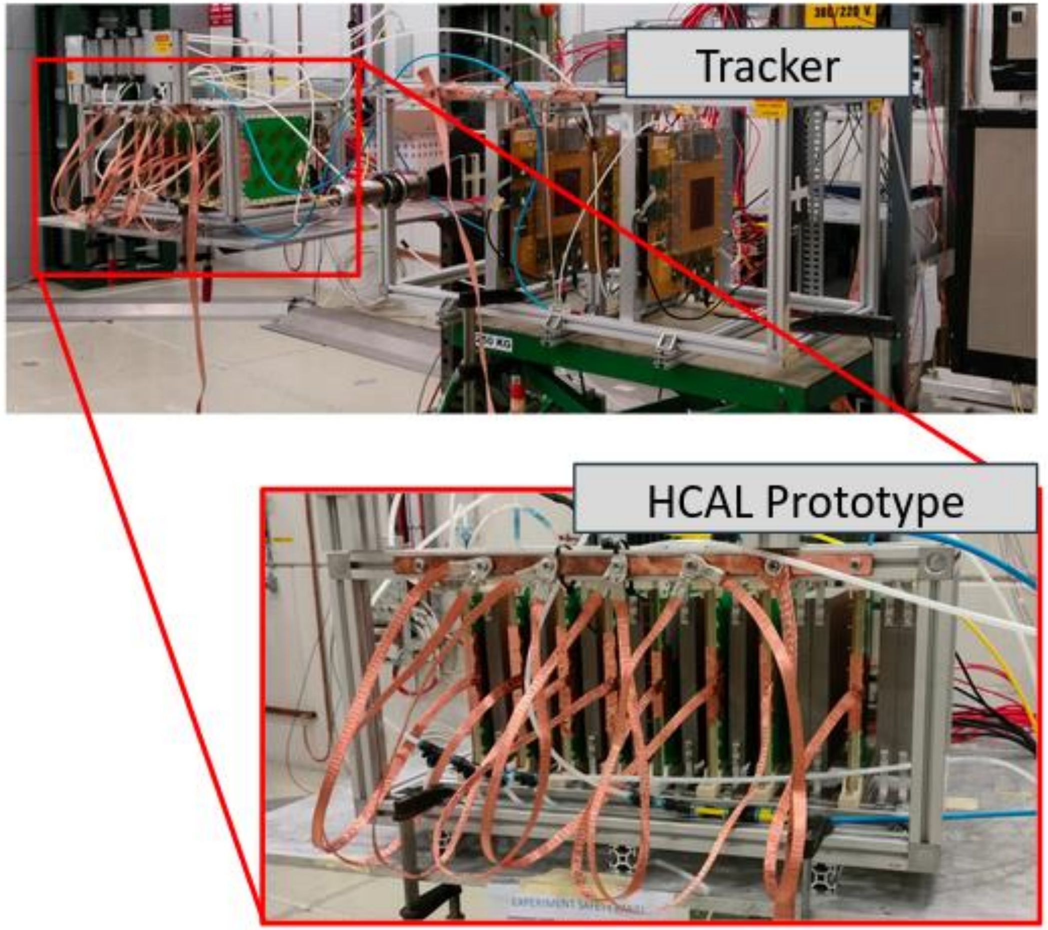
PRELIMINARY

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



Plans for 2023

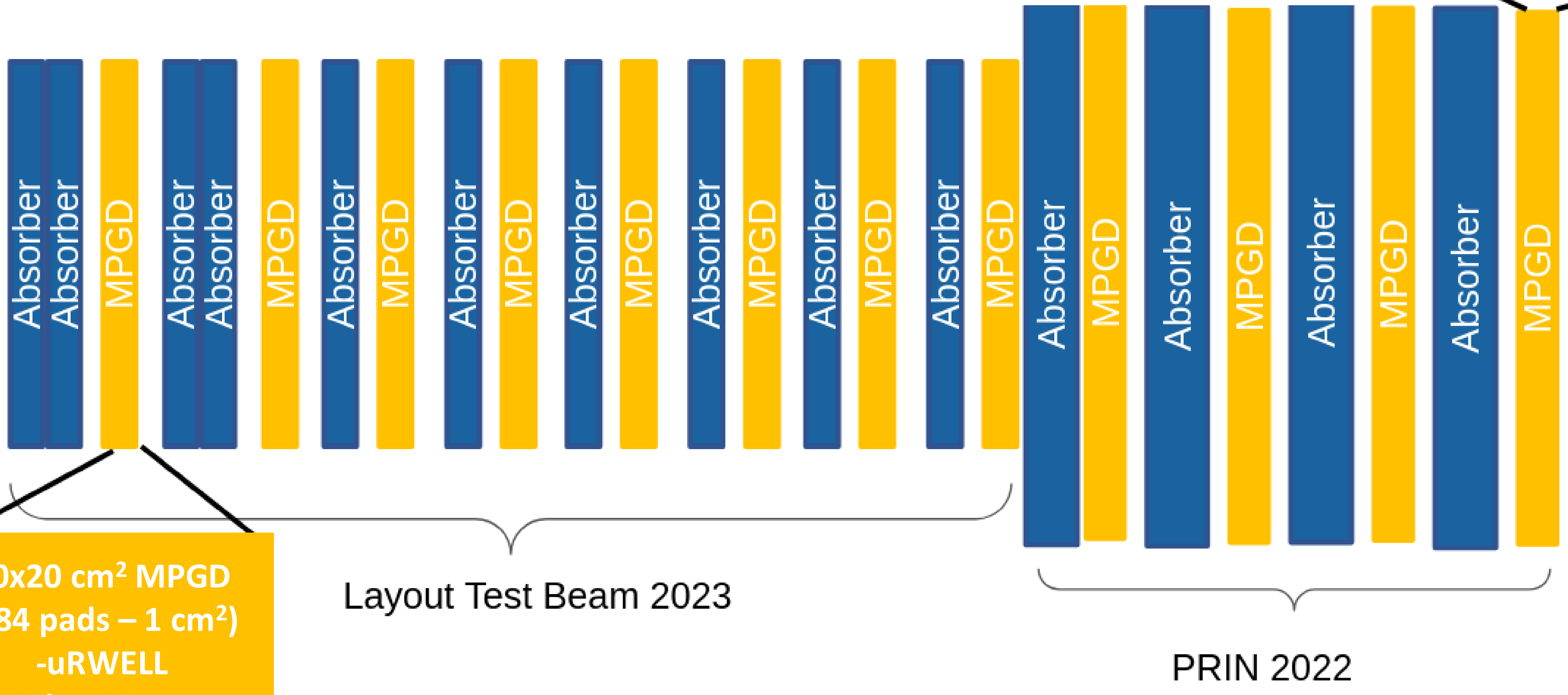
Test on MPGD prototype (both TB data analysis still ongoing)

Performance of single active layers (TB at SPS and PS)
- Measure space resolution
- Efficiency vs HV (for each detector)
- Efficiency maps to determine uniformity response
- MIP charge distribution for muon and pion

Performance of the calorimeter prototype
- Pad charge distributions for threshold optimization for semi-digital readout
- Energy reconstruction and resolution
- Comparison with G4 data for validation of the simulation

Towards 10 layer prototype (PRIN Activity)

50x50 cm² MPGD
Segmentation and technology to be defined



20x20 cm² MPGD
(384 pads – 1 cm²)
-uRWELL
-MicroMegas

Plans for 2024 – prototype development

1. **Construction of 50x50 cm^2 MPGD prototype**

- Choice of the technology – MicroMegas or uRWELL(following results of TB data analysis)
- Design definition
- Baseline 20x20 available, discuss with Rui for improvements
- Construction of first 2 modules
- First test in labs and test beam (?)

2. **Definition/design front end electronic chips**

- Study of charge distribution (simulation validation with TB data)
- First characterization of chip on detector (VMM, FATIC, GEMROC)
- Choice for electronic

1. **Design a modular mechanical structure for 10 layer prototype**

Plans for 2024 – Simulation

1. G4 studies:

- Optimization of sampling fraction and layout of 10 layer prototype
- Study of f_em/f_had vs pion energy
- Add BIB to standalone MuCol simulation
- Study on the absorber

2. Muon collider full sim

- Realistic digitization
- Pion gun with std geometry vs MPGD → efficiency, energy resolution
- Pion gun with std vs MPGD with bib→ efficiency, energy resolution, time resolution
- Repeat study with neutral hadron
- Study jet composition