DEVELOPMENT OF A MPGD-BASED HADRON CALORIMETER FOR MUON COLLIDER.

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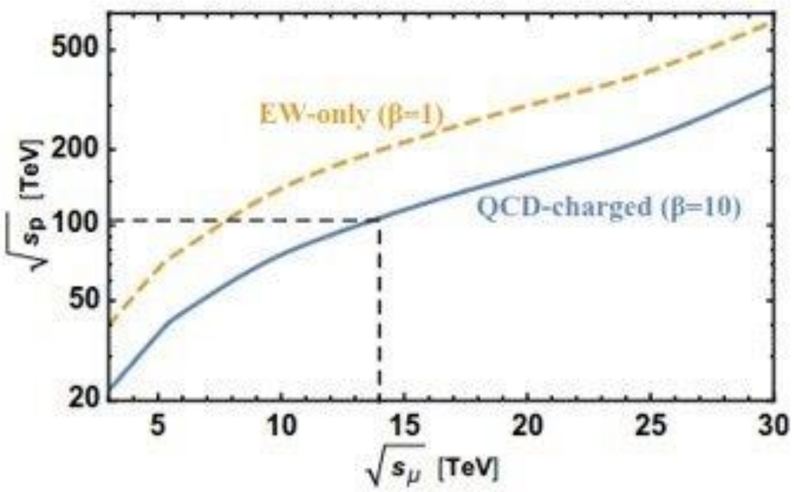
Introduction to Muon Experiment

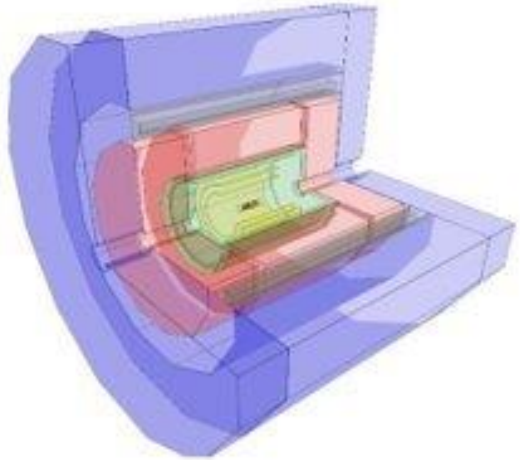
The Muon Collider is a proposed option to investigate Standard Model and beyond after HL-LHC.
Advantages:

- 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.

GOAL
For future colliders:
Jet energy resolution for Z/H separation:
σ_E /E< 3% - 4%
→ 60%/sqrt(E) for HCal



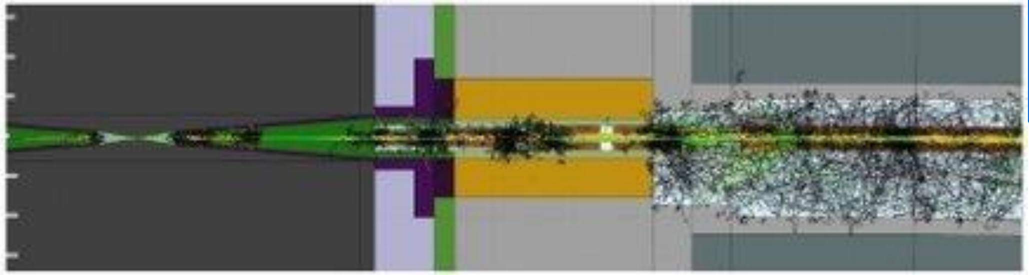
Section of the Muon Collider experiment:
- Tracking system
- ECAL
- HCAL
- Magnet return yoke + Muon System

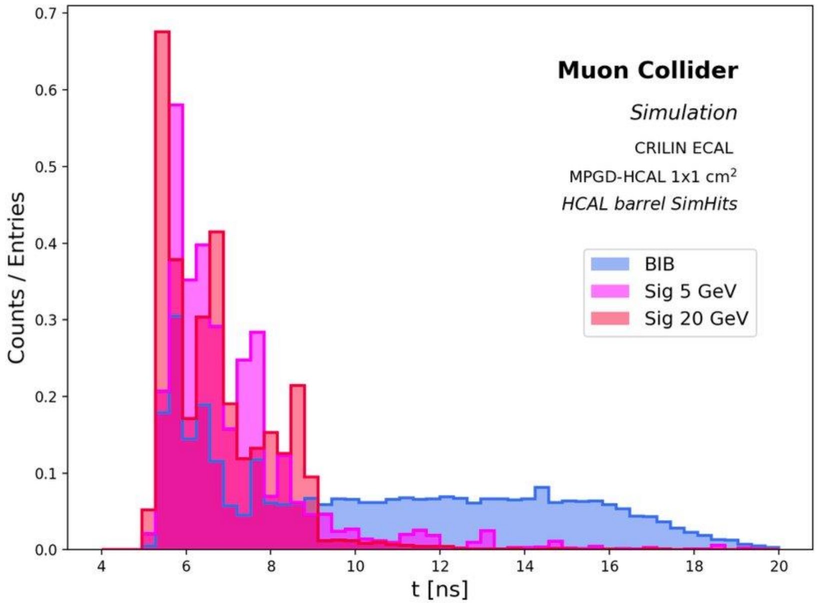


Challenges for HCal design

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 (few(ns))
- Good energy resolution
  ~ 10% / √E for ECAL
  ~ 55% / √E for HCAL
- Fine granularity (1 – 3 cm^2)
- Longitudinal segmentation
- Good response uniformity for the active layers.





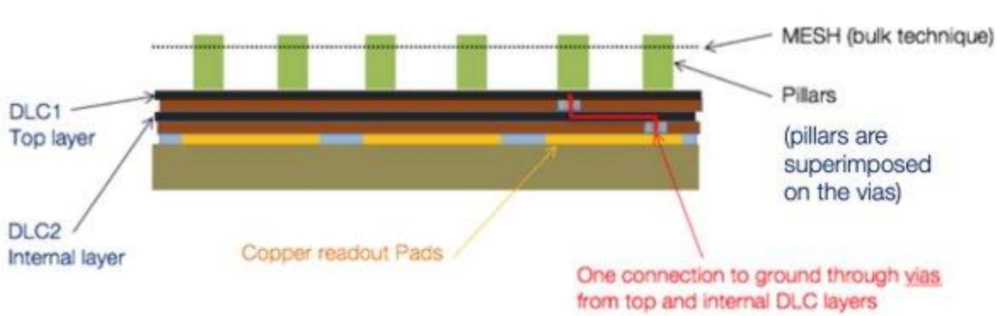
https://pos.sissa.it/476/1082/pd

MPGD-based HCAL for Muon Collider

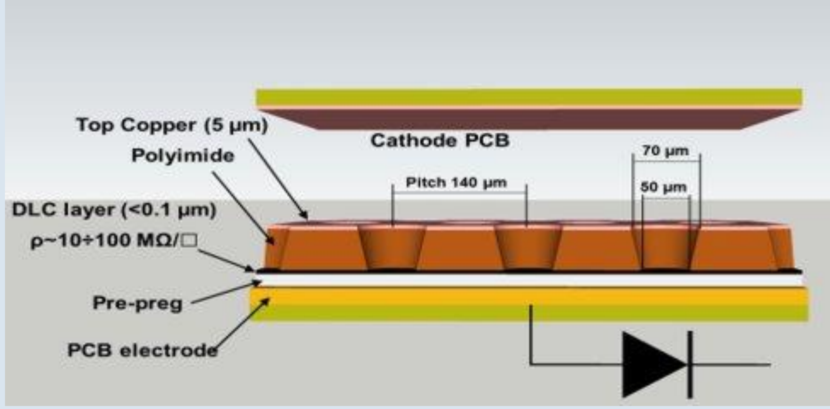
Why resistive MPGDs for calorimeters?
Cost-effective for large area instrumentation
Radiation hardness (up to few C/cm^2)
High rate-capability O(MHz3232/cm^2)
Readout granularity at-will (~cm^2 or less)
Space resolution O(100μm) ⟶ Low pad multiplicity
Response uniformity
Operational stability (low discharge rate)
Time resolution with MIPs of few ns
Large community developing these detectors

2 MPGD technologies studied in this project

RμMegas



μ-RWELL

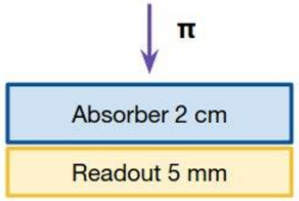


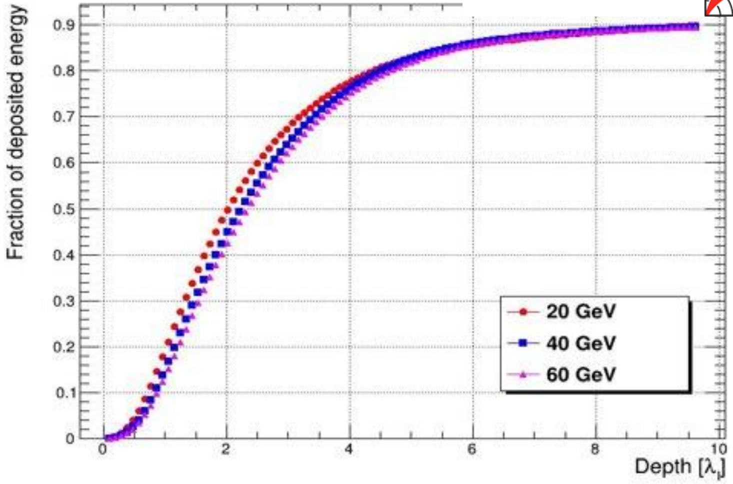
HCal standalone simulation

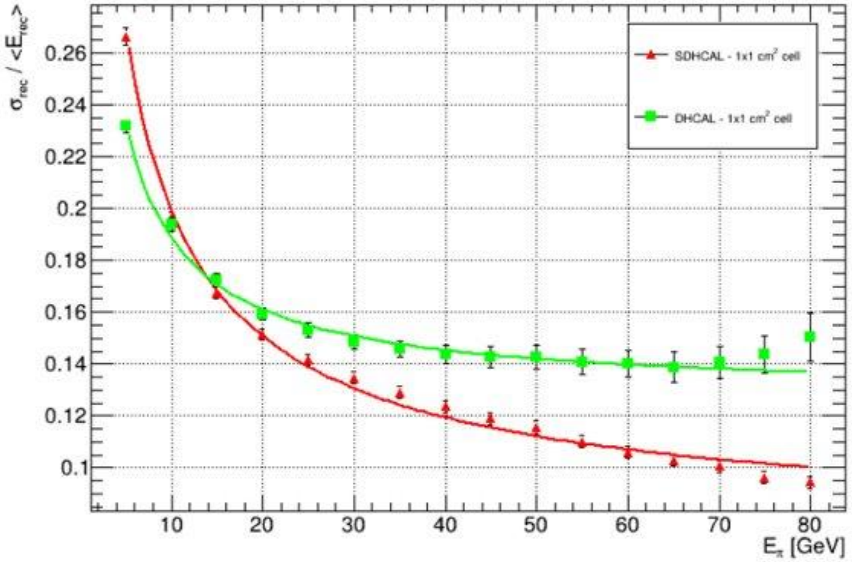
Standalone Geant4 simulation technology-independent (8 layers 20x20 cm^2)

- Geometry of single layer:
  - 2 cm of iron for absorbers
  - 5 mm gas (Ar/CO_2)
- Readout granularity 1x1 cm^2

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







Energy resolution simulated in two scenarios:

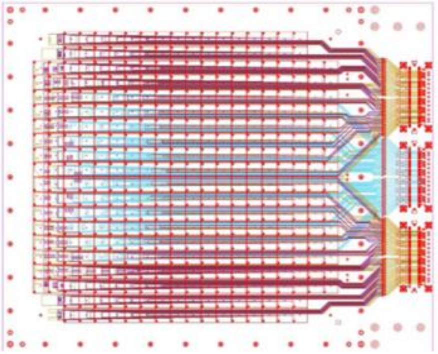
- **Digital** calorimeter: shower energy proportional to total number of hits
- **Semi-digital** calorimeter: hits are weighted based on three thresholds (using CALICE thresholds) $E_\pi = \alpha N_1 + \beta N_2 + \gamma N_3$

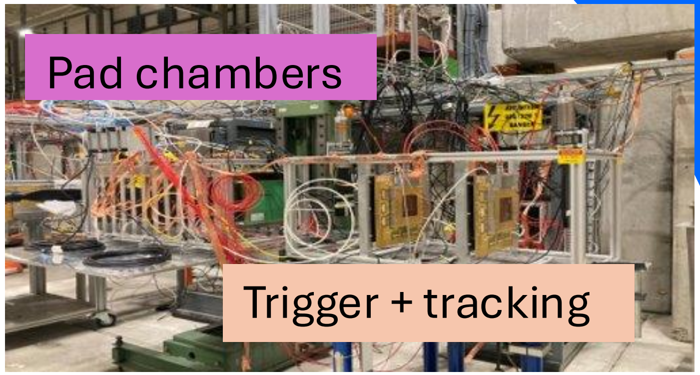
Result:

- resolution at **8%** for E_π ~ 80 GeV with semi-digital readout
- resolution **saturates** at **14%** for E_π ~ 30 GeV for digital readout.

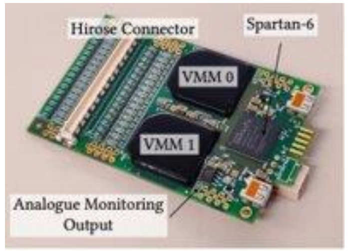
Characterization in test beams at SPS

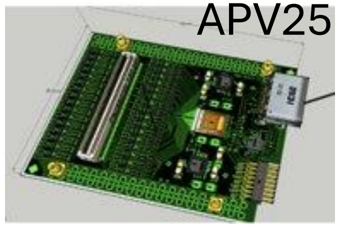
MPGD technologies:
- 5 μRWELL
- 3 resistive RμMegas
- Detector **layout**: 20x20 cm^2
- ~6 mm drift gap
- **Common readout** board: 1x1cm^2 pad



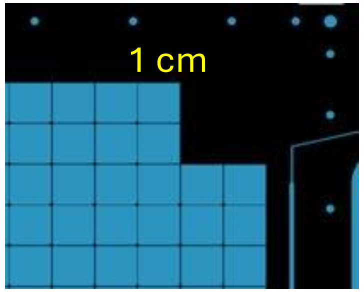


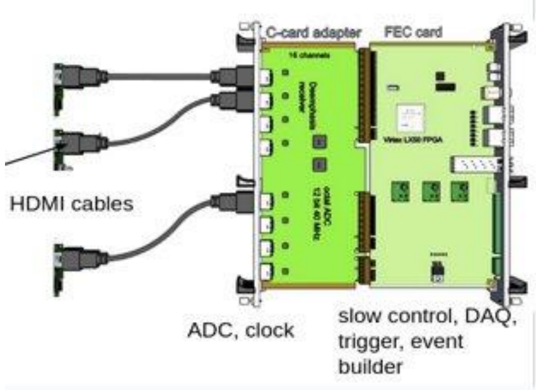
- Pad chambers under test (RμMegas, μ-RWELL)
- $Ar/CO_2/CF_4$: μRWELL - $Ar/CO_2/iC_4H_{10}$: RμMegas.
- Particles O(100GeV) μ beam



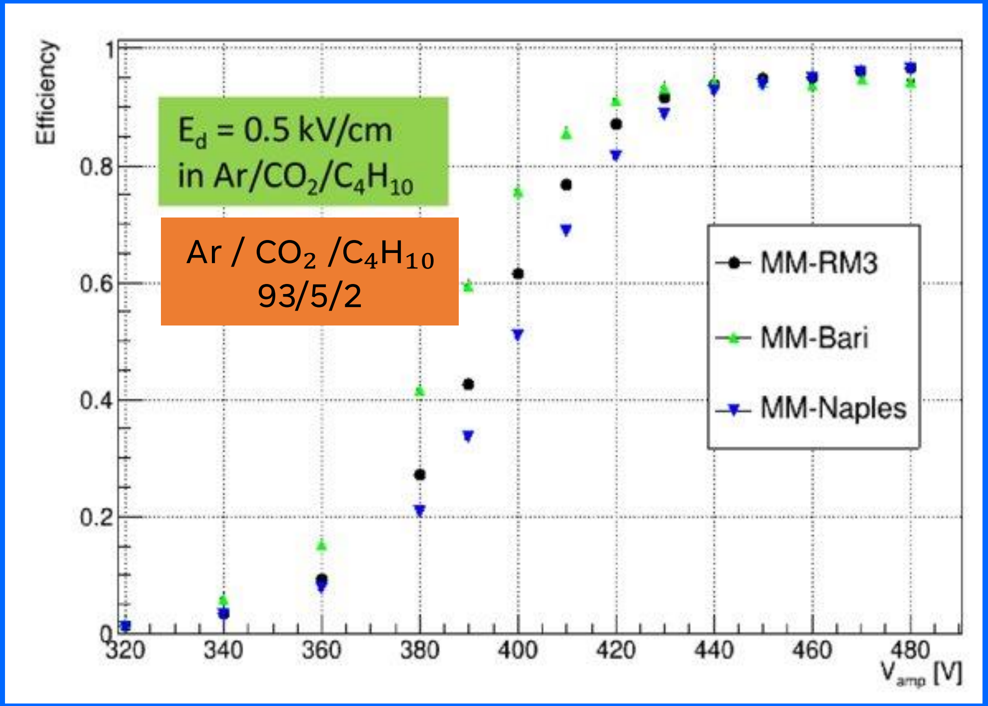


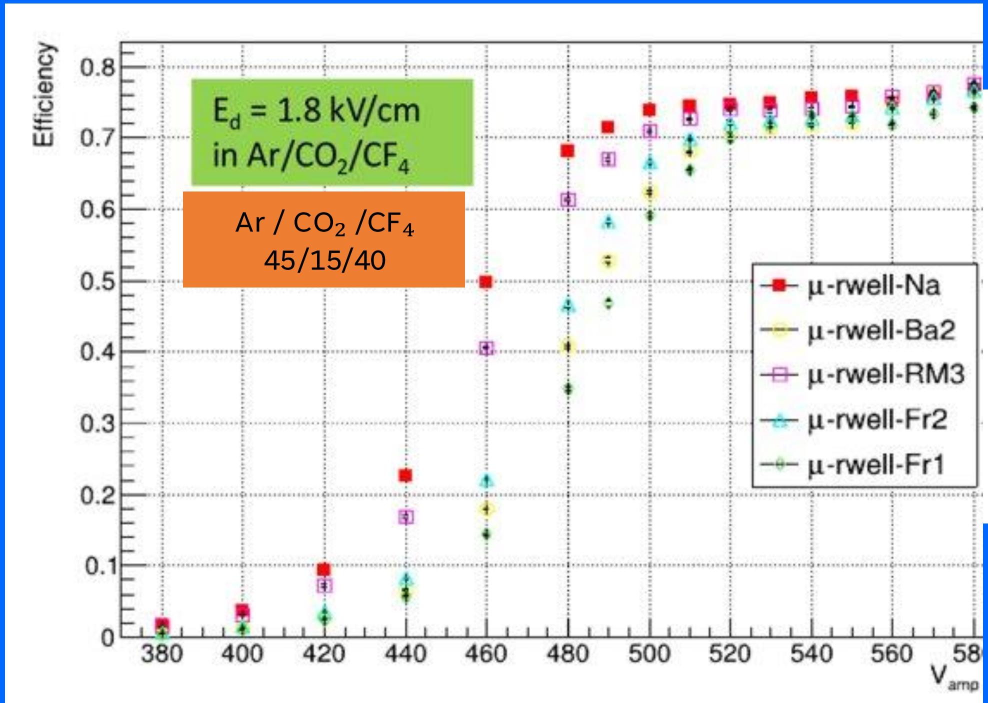
2 different hybrids tested with SRS back-end:
- APV25
- VMM hybrids tested in 1 μ-RWELL in a different test beam (thanks to DRD1 collaboration)





Performance to MIPs



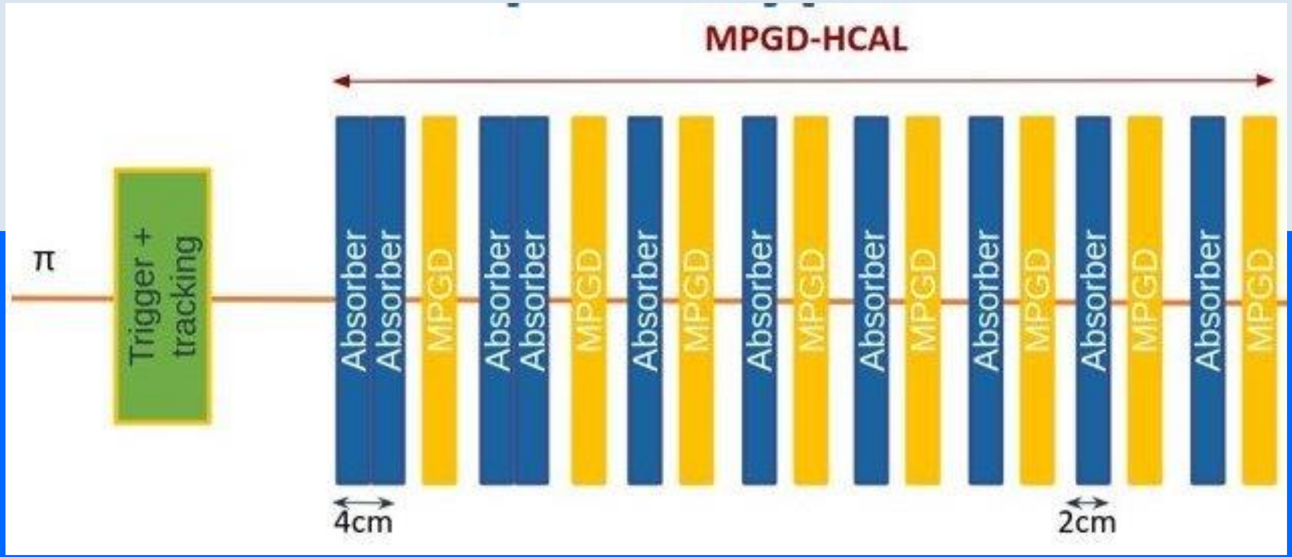


Detector	Uniformity (%)
MM-RM3	$(12.3 \pm 0.8)\%$
MM-Na	$(11.6 \pm 0.8)\%$
MM-Ba	$(8.0 \pm 0.5)\%$
RPWELL	$(22.6 \pm 4.7)\%$
μrw-Na	$(11.3 \pm 1.0)\%$
μrw-Fr2	$(16.2 \pm 1.7)\%$
μrw-Fr1	$(16.3 \pm 1.1)\%$

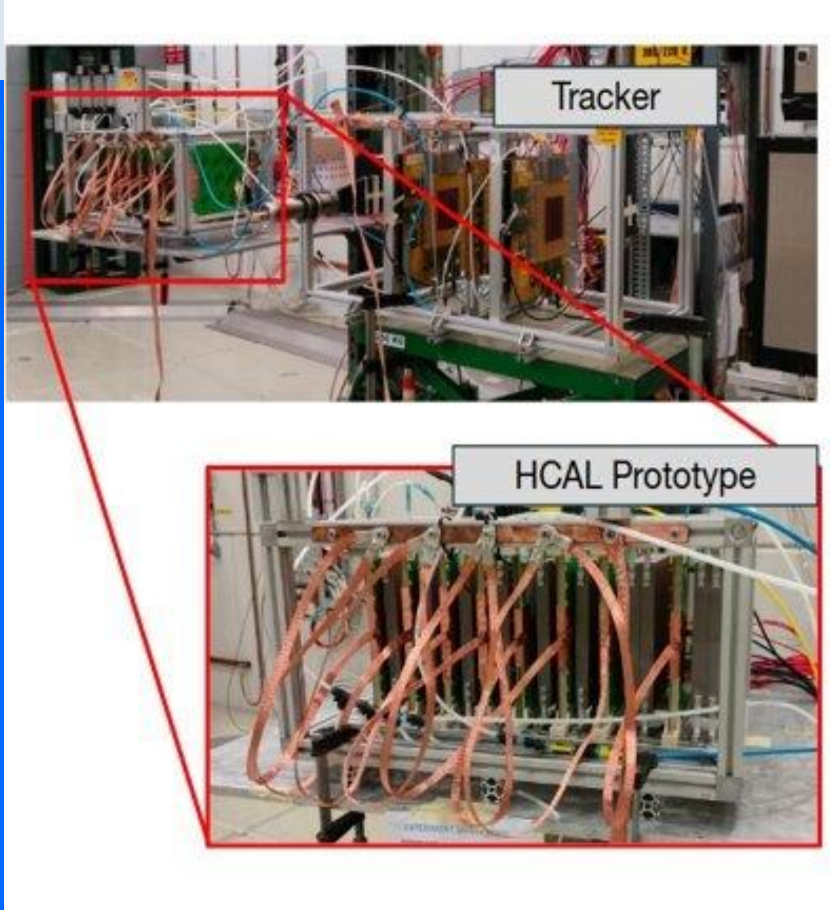
Plateau Efficiency: about **95% for µMegas, 75% for µ-RWELL.**

Response Uniformity: 10% RµMegas, 16% µ-RWELL

MPGD-HCAL prototype



With absorbers



HCAL prototype ~ 1 λ_I (8 active layers) tested under pion beam at PS.

Data taking based on analog FE (APV25 + SRS)

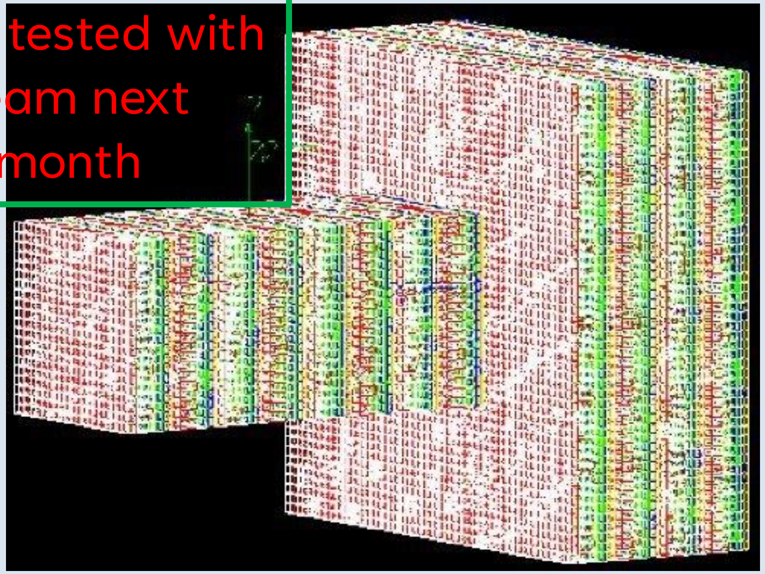
Runs at different π^- energy (up to 11 GeV)

- Two TB campaigns: August 2023, July 2024
- Data analysis **ongoing**
- Developed G4 simulation for comparison with TB prototype.

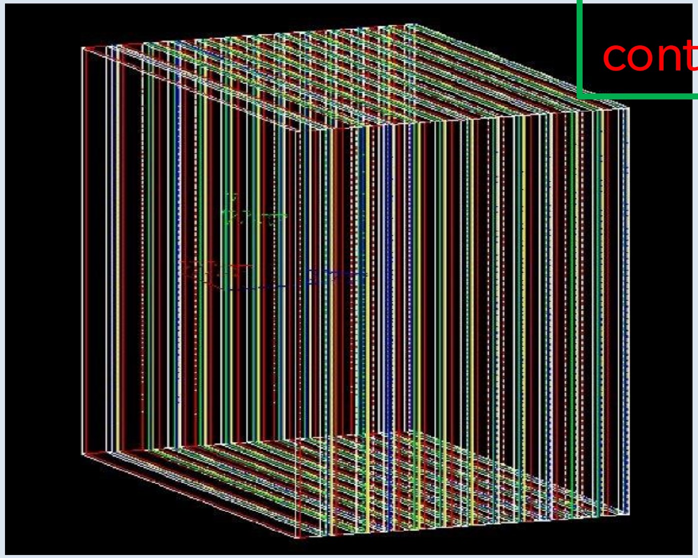
New Prototypes for HCal

- Two HCal Geometries Under Study:
- Analyzing Energy Containment, Resolution & Shower Profiles in GEANT4.

To be tested with beam next month



To study containment only



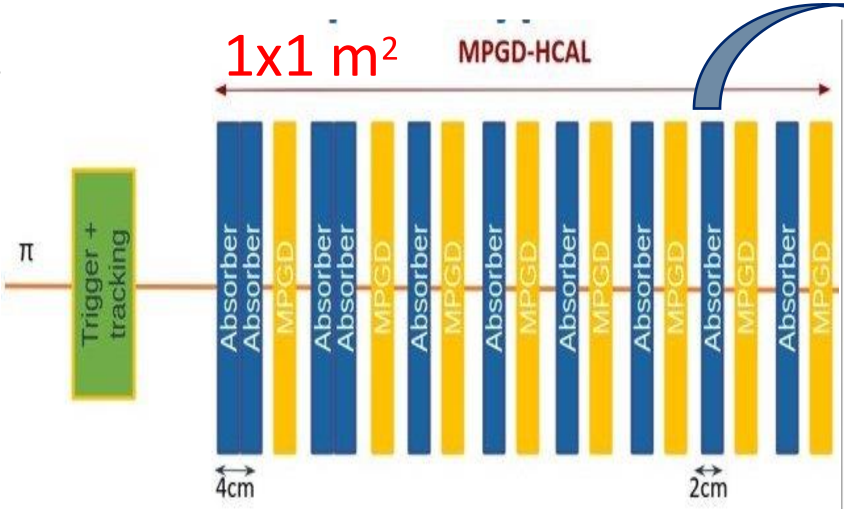
- **First 8 layers:** Compact modules with 20 × 20 cm^2 active area with of 4cm(2 cm) absorber.
- **Last 4 layers:** Large modules with 50 × 50 cm active area and 2 cm absorber.
- **Active gap:** 6 mm spacing between layers.

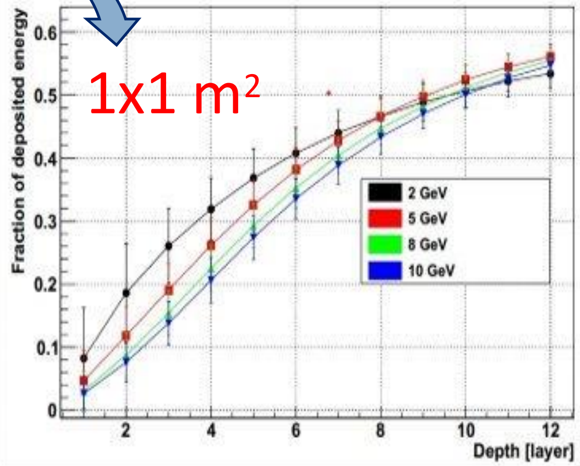
- **First 2 layers:** Steel absorbers with 4 cm thickness. (1x1 m^2)
- **Remaining 10 layers:** Steel absorbers with 2 cm thickness.
- **Active gap:** 6 mm spacing between layers.

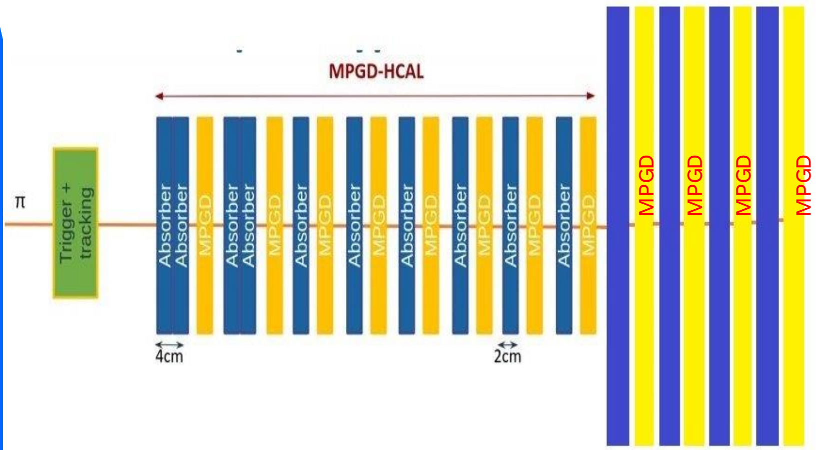
Simulation of new Prototype

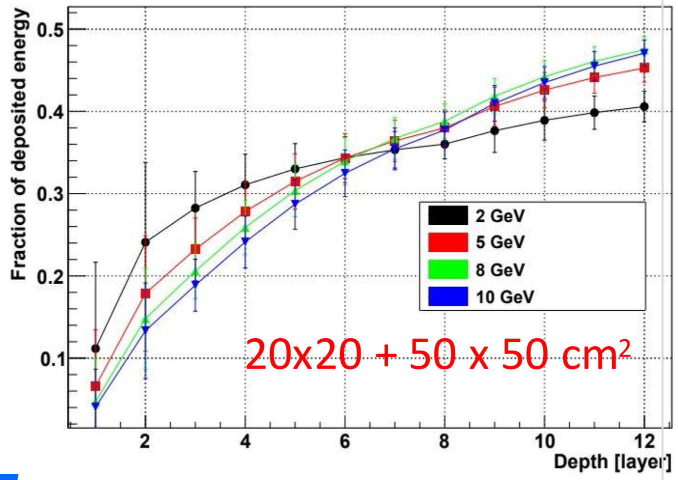
Standalone Geant4 simulation technology-independent

- Different configurations of layers are tested in this analysis:
  - 20 x 20 cm^2 + 50 x 50 cm^2 and 1 x 1 m^2
  - 4cm (2cm) Stainless steel.
  - 6mm gas (Ar/CO_2).
  - Readout granularity 1x1 cm^2









Energy containment studied for the geometries:

Two 12-layer geometries are analyzed longitudinally:

i. 1×1 m^2 transverse for all 12 layers,

ii. First 8 layers: 20×20 cm^2; last 4 layers: 50×50 cm^2

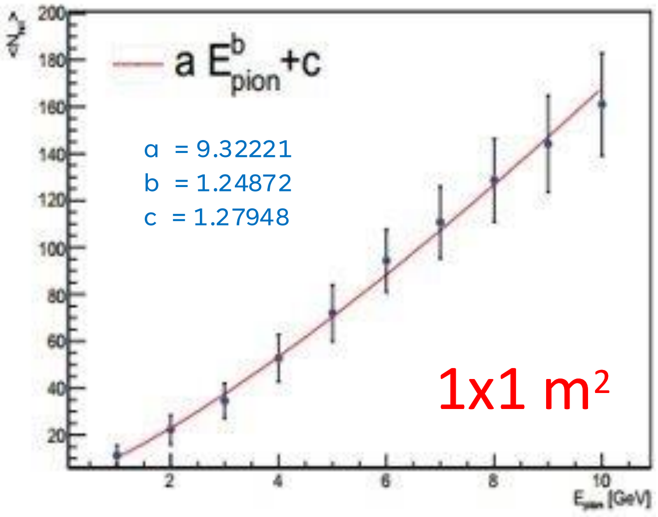
Result:

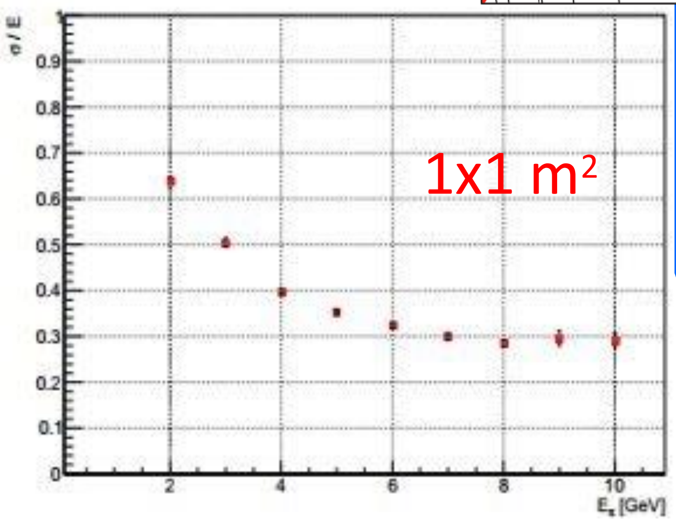
- About 58% of the total energy is contained up to layer 12 longitudinally for 1x1 m^2.
- For the geometry 20x20 + 50x50 cm^2, the energy containment is around 48%.
- The remaining energy is attributed to invisible energy losses.

Simulation of new Prototype

Energy reconstruction using Digital readout:

- **Method basis:** Relies on total number of hits in active layers.
- **Hit definition**: Energy deposited in a cell exceeds **0.01 MIP** threshold..
- **Event selection**: Events with < 4 hits per layer are excluded from analysis.



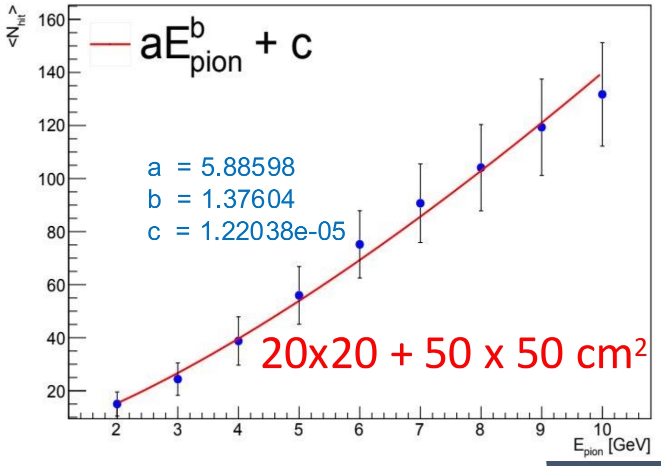


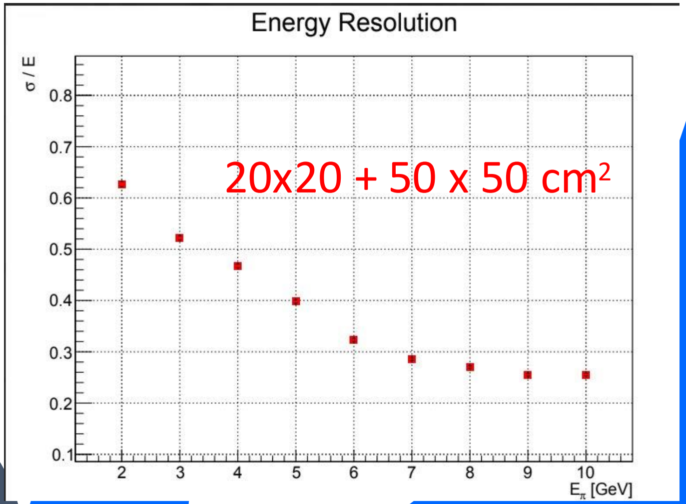
Energy resolution:

- Calculated as σ / ⟨E⟩ of the reconstructed energy distribution.

For a 10 GeV pion:

- σ / ⟨E⟩ ~ **30%** **(12 layers,** 1 x 1 m^2**)**
- σ / ⟨E⟩ ~ 25% **(8 layers** 20x20 cm^2 + 4 layers 50x50 cm^2**)**





CONCLUSIONS

Calorimeter Test: An 8-layer MPGD calorimeter (3 Micromegas + 5 μ-RWELL, 20×20 cm²) was tested with pion beams at CERN.

Detector Upgrade: Updated geometries, including larger MPGDs, are under production.

Energy Resolution: Semi-Digital readout provides better performance at high energies.

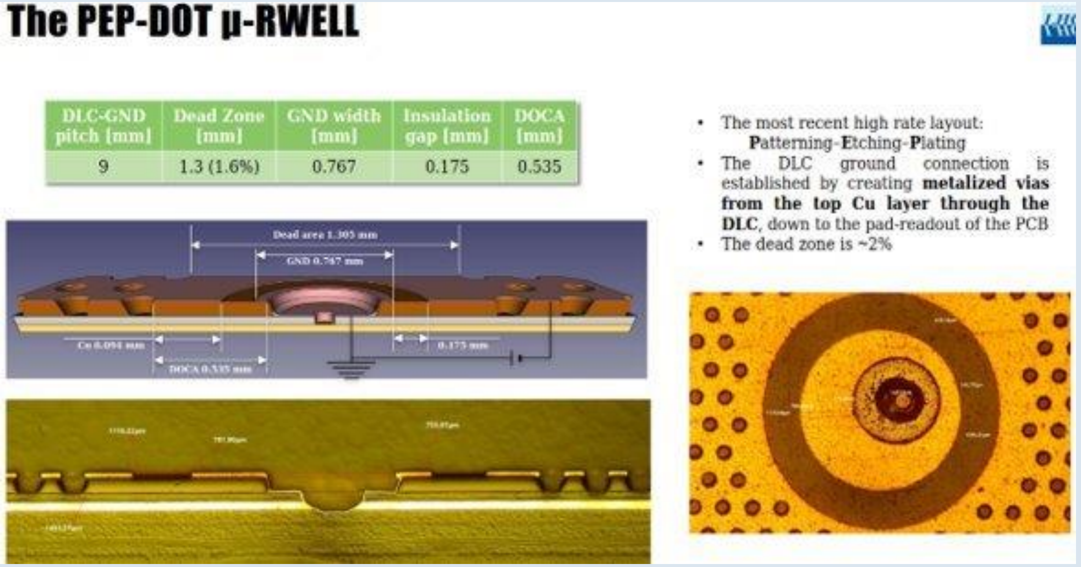
Containment Studies: Tests on a 1×1 m² and 20x20 + 50 x 50 cm² setup showed 58% and 48% containment.

Future Plans: The next test beam is planned for October 2025 at CERN PS to validate results for 50x50 cm² .

Thank you !

Back up

PEP grooves

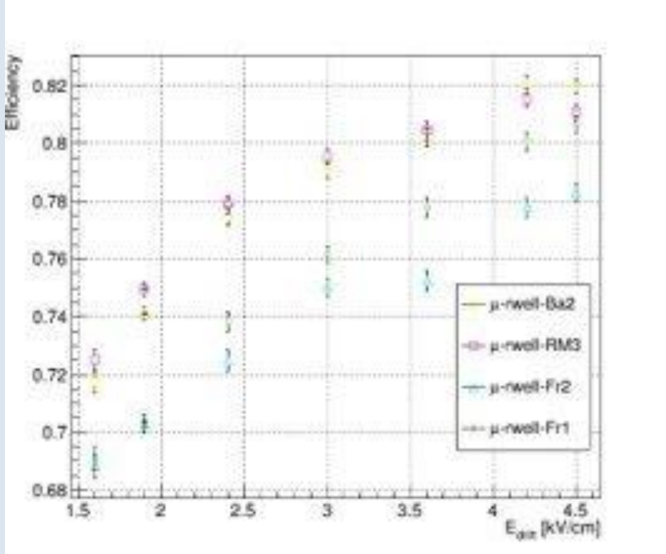


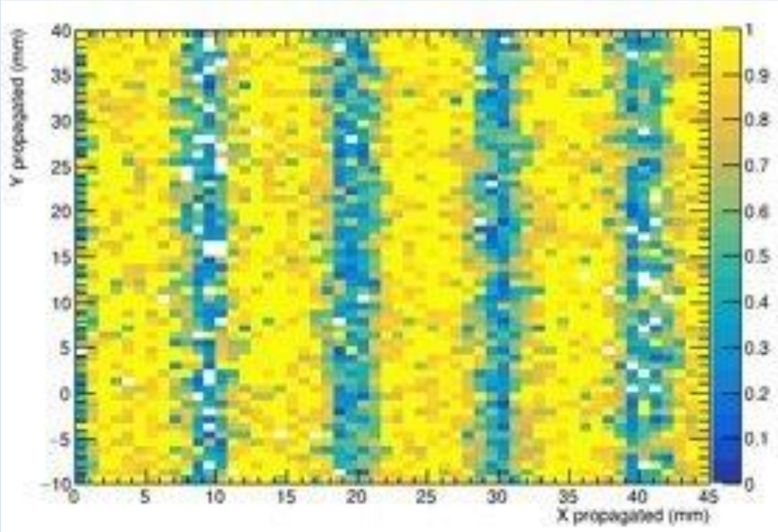
The PEP-DOT µ-RWELL

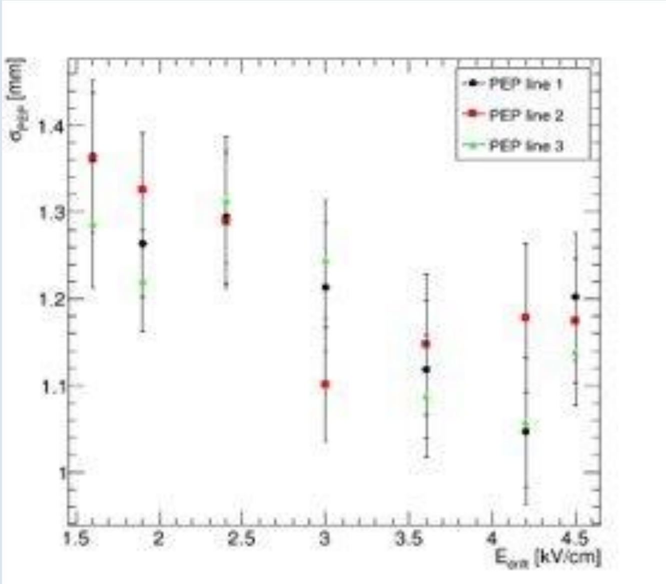
DLC-GND pitch [mm]	Dead Zone [mm]	GND width [mm]	Insulation gap [mm]	DOCA [mm]
9	1.3 (1.6%)	0.767	0.175	0.535

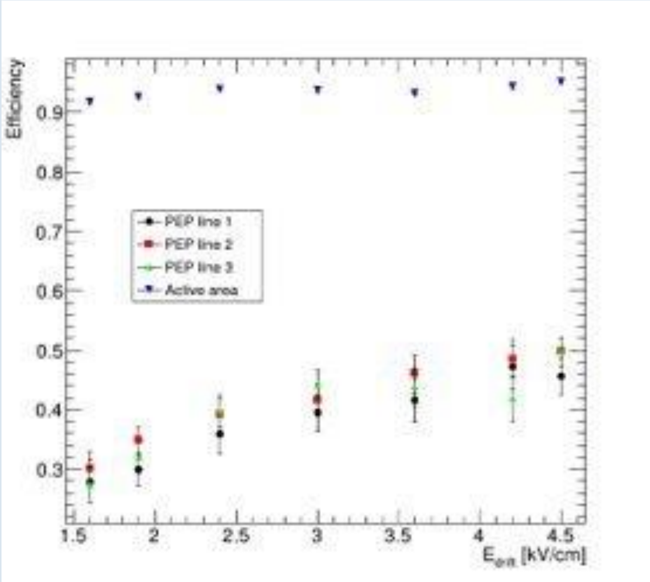
- The most recent high rate layout: **P**atterning-**E**tching-**P**lating
- The DLC ground connection is established by creating **metalized vias from the top Cu layer through the DLC**, down to the pad-readout of the PCB
- The dead zone is ~2%

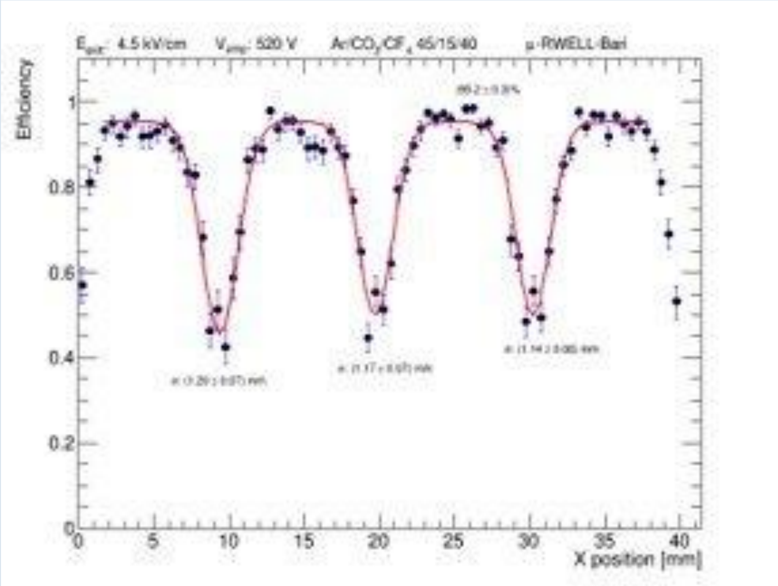
INEFFICIENCY OF INEFFICIENCY OF MRWELLDD











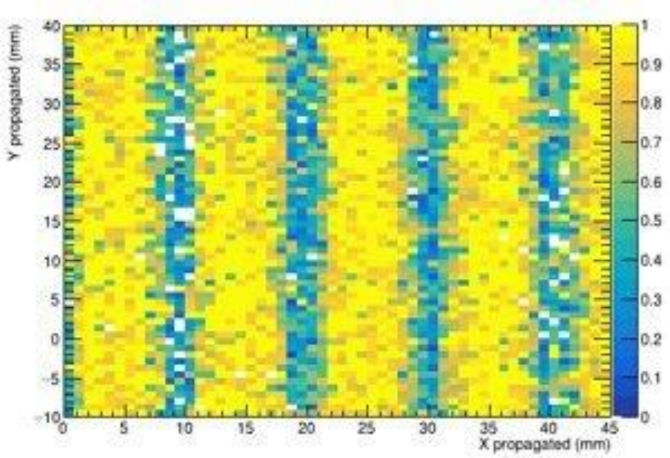
Investigation on inefficiency of μRWELL

Inefficiency of μ-RWELL due to PEP-Groove introducing dead areas

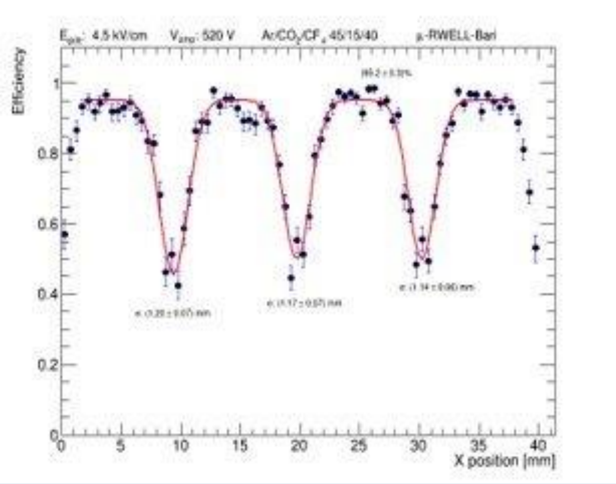
- **Locally very high** efficiency
- PEP lines introduce a **region of ~ 1 mm with ~50% efficiency drop**
- At **increasing drift** field, efficiency drop region **gets thinner and smaller**

Excluding PEP areas, the efficiency is up to 95%

→ **Optimization of drift field** to be repeated



New prototypes will follow <u>DOT grounding scheme</u>



Response uniformity

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	$(22.6 \pm 4.7)\%$
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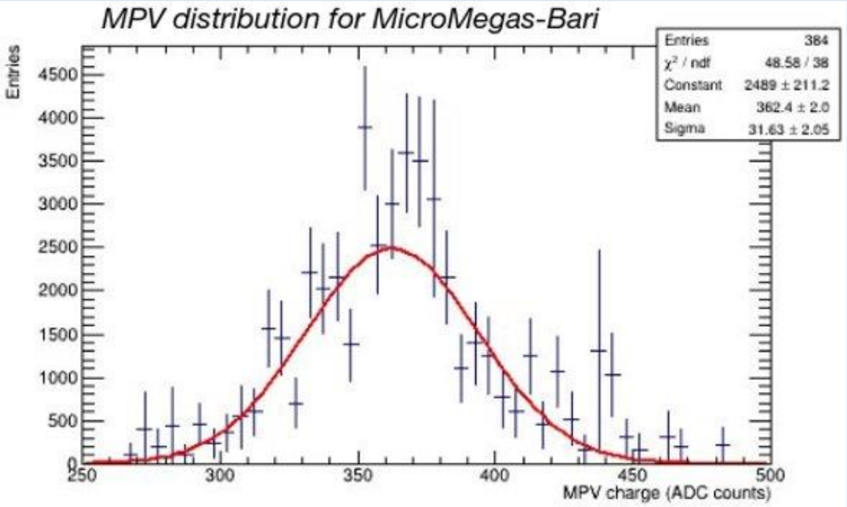
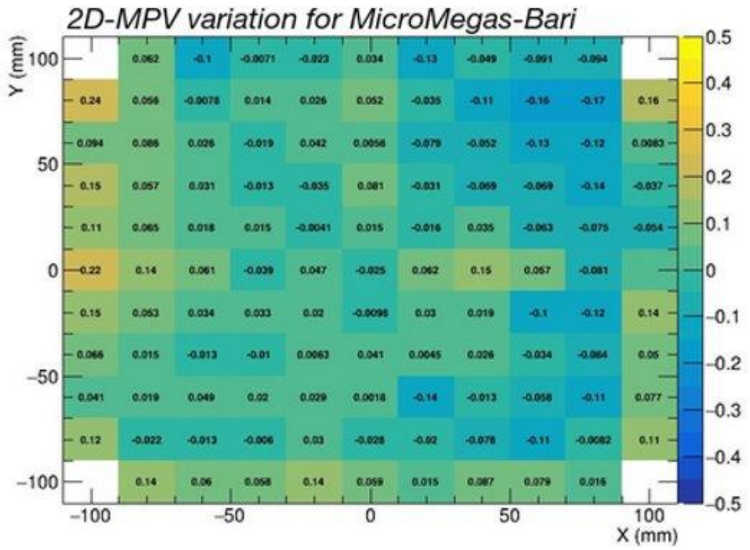
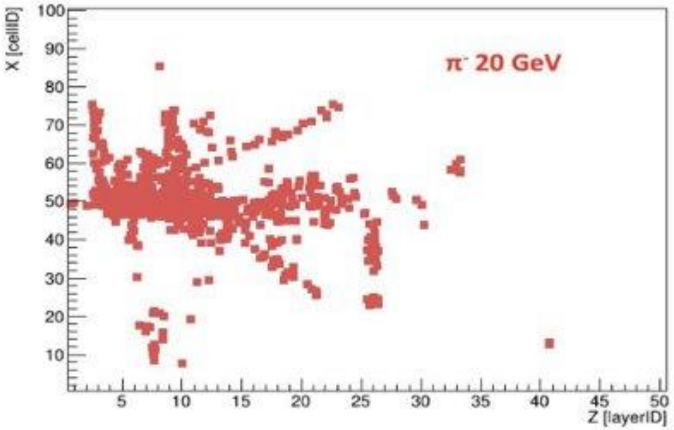




Digital vs Semi digital readout

Digital Readout (Digital RO)

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



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