Presentation for the admission to third year.

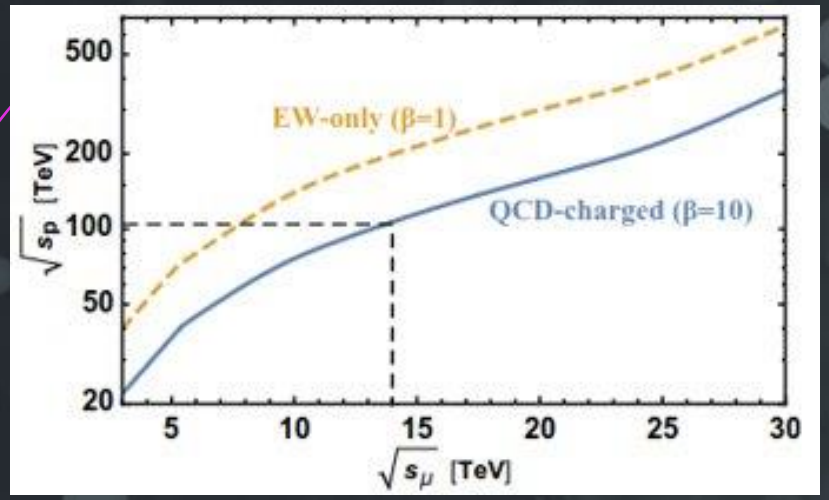
- PhD candidate: Muhammad Ali.
- TechTFPA PhD, University of Padova and INFN Bari.
- Thesis: Development of MPGD HCal for future experiment at Muon Collider.
- Supervisors: Dr. Rosamaria Venditti/ Dr. Salvatore My.

Introduction

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

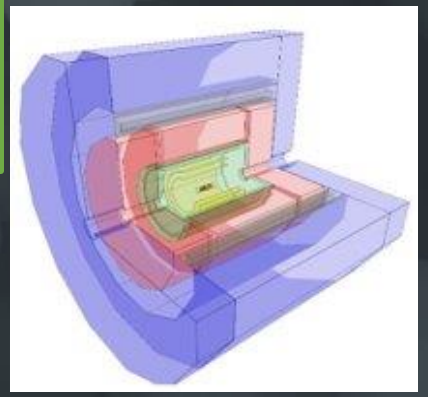
Advantages:

- 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.



Challenges:

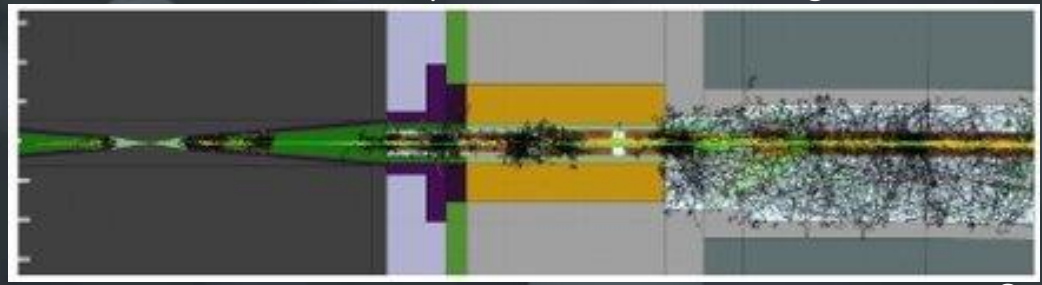
- muon is an **unstable** particle
  intense flux of background particles: **beam-induced background (BIB)**.



Section of the Muon Collider experiment:

- **Tracking system**
- **ECAL**
- **HCAL**
- **Magnet return yoke + Muon System**

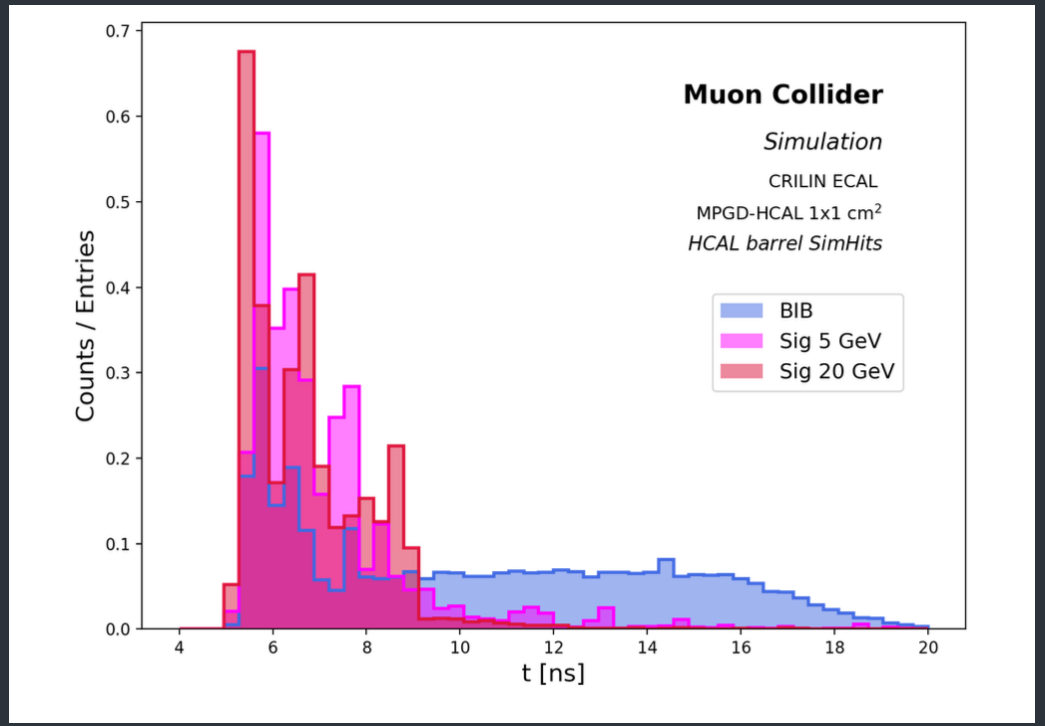
Tracks of BIB particles in interaction region



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/pdf

MPGD-HCAL R&D strategy for Muon Collider

Stand-alone simulation with GEANT4

- Design optimization, provide input parameters for full simulation and experimental data

Test on a MPGD calorimeter prototype

- Assess the performance of an active layer and within calorimeter system

GOAL of my Phd project

1. **Design the MPGD-based HCAL prototype with Geant4**
2. **Characterization of the single MPGD response to MIPs**
3. **Test the performance of resistive MPGD in a calorimeter prototypes.**

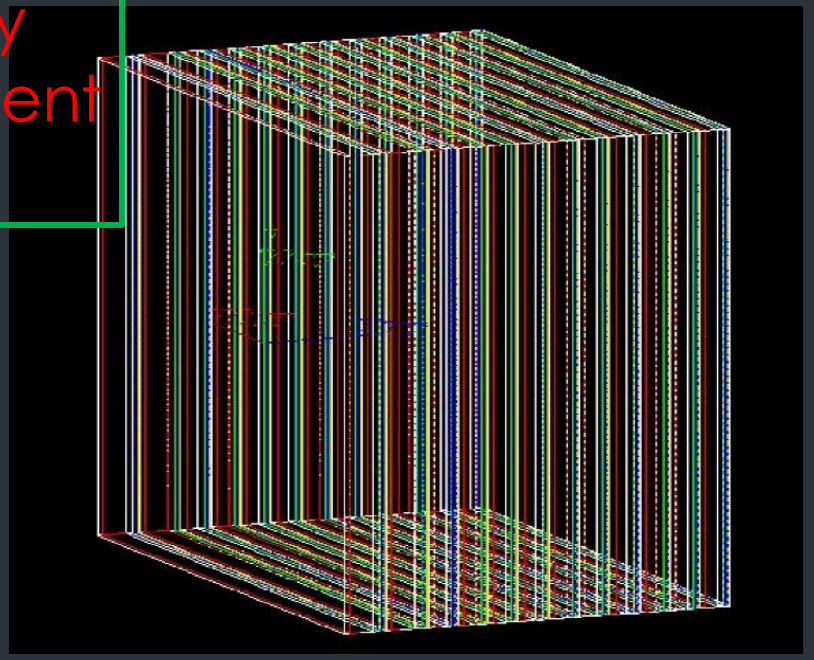
New Prototypes for HCal

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

To be tested with beam next month

- **First 8 layers:** Compact modules with 20 × 20 cm^2 active area with of 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.

To study containment only



- **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 prototypes

Standalone Geant4 simulation technology-independent

- 6mm gas (Ar/CO2).
- 4 cm (2 cm) Stainless Steel
- Readout granularity 1x1 cm2

GOAL: Investigate the energy containment and energy resolution:

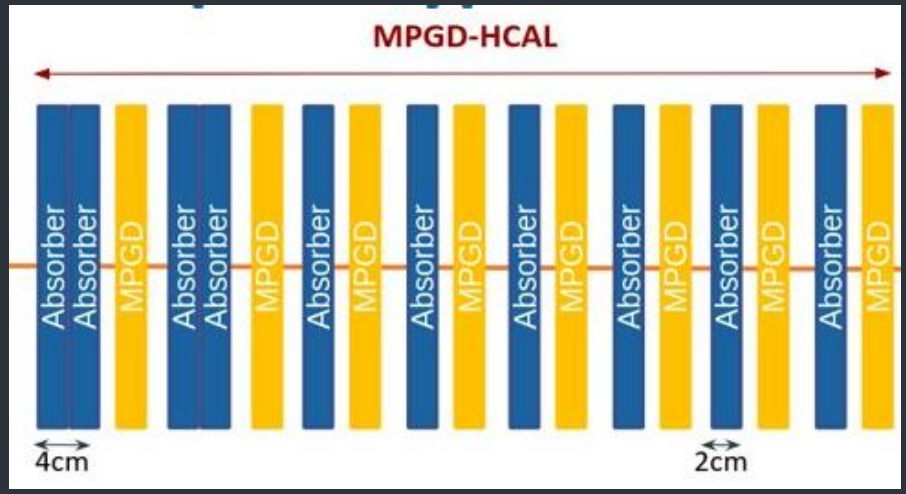
Energy containment studied for the geometry

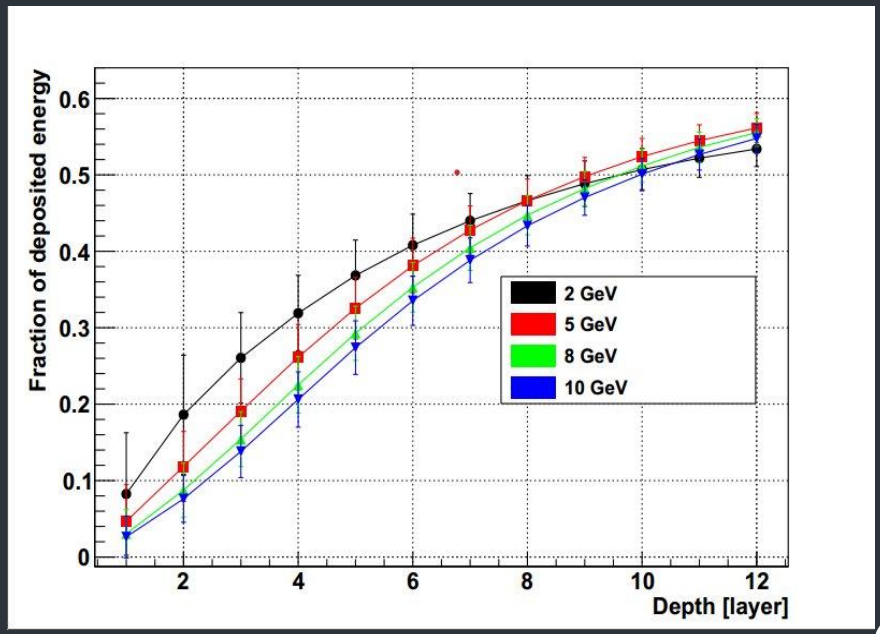
- 12 layers in longitudinal direction,
- 1x1 m2 in transverse direction

Result:

•About 58% of the total energy is contained up to layer 12 longitudinally.

•The remaining energy is attributed to invisible energy losses.





Simulation of new prototypes

Energy resolution using digital readout:

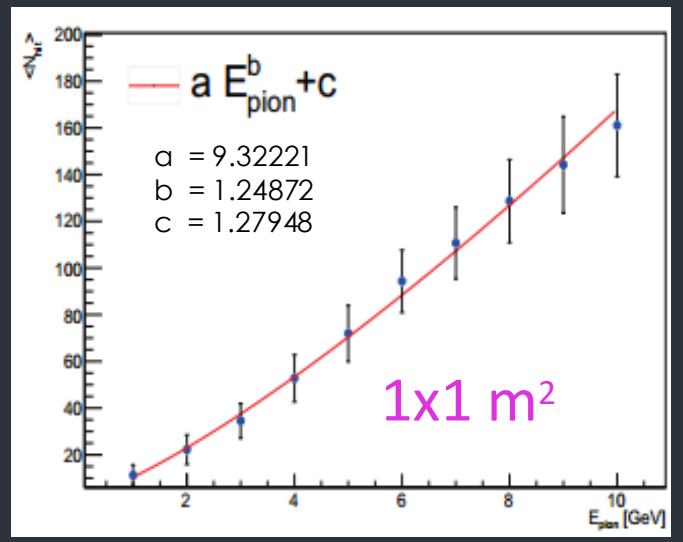
- **Method basis:** Relies on total number of hits in active layers.
- **Hit definition**: Energy deposited in a cell exceeds **0.01MIP** threshold.
- **Event selection**: Events with <4 hits per layer are excluded from analysis.

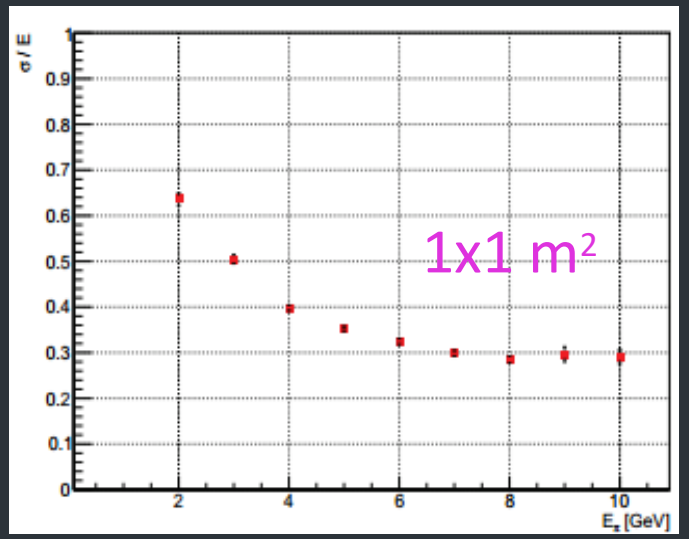
Resolution: Calculated as σ / ⟨E⟩ of the reconstructed energy distribution.

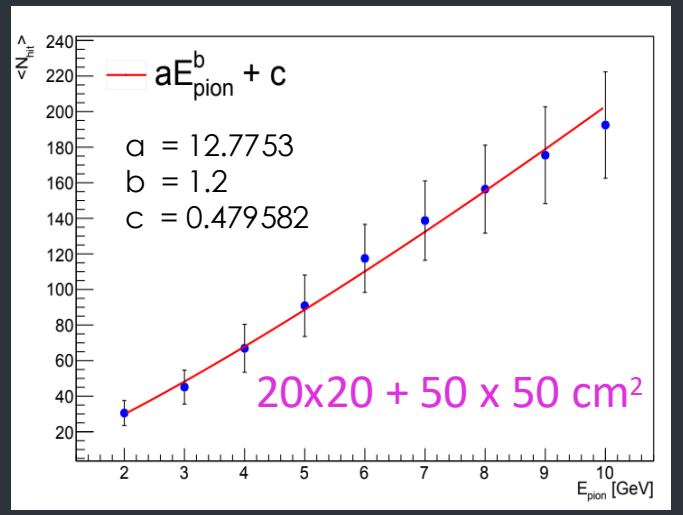
Result:

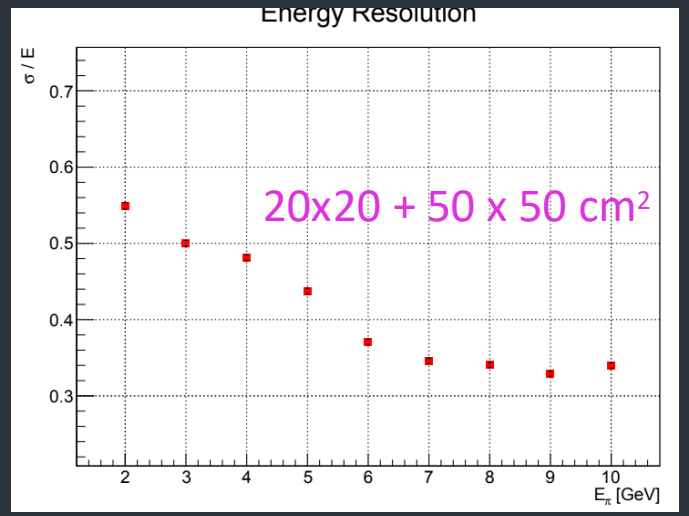
For a 10 GeV pion:

- σ / ⟨E⟩ ~ **30%** **(12 layers,** 1 x 1 m^2**)**
- σ / ⟨E⟩ ~ **35%** **(8 layers** 20x20 cm^2 + 4 layers 50x50 cm^2**)**



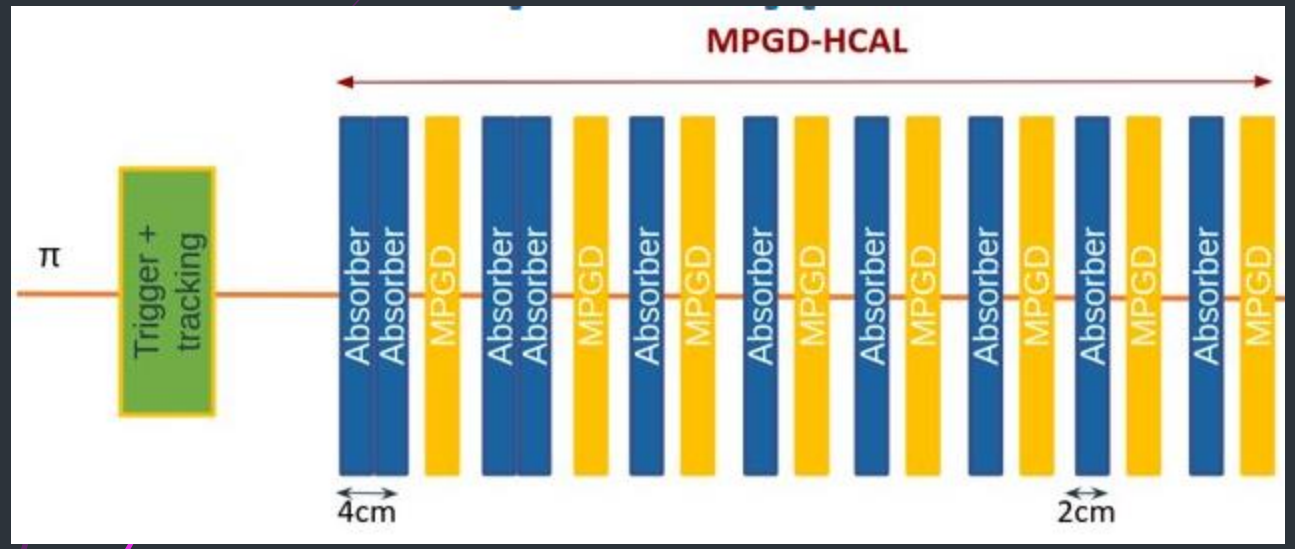


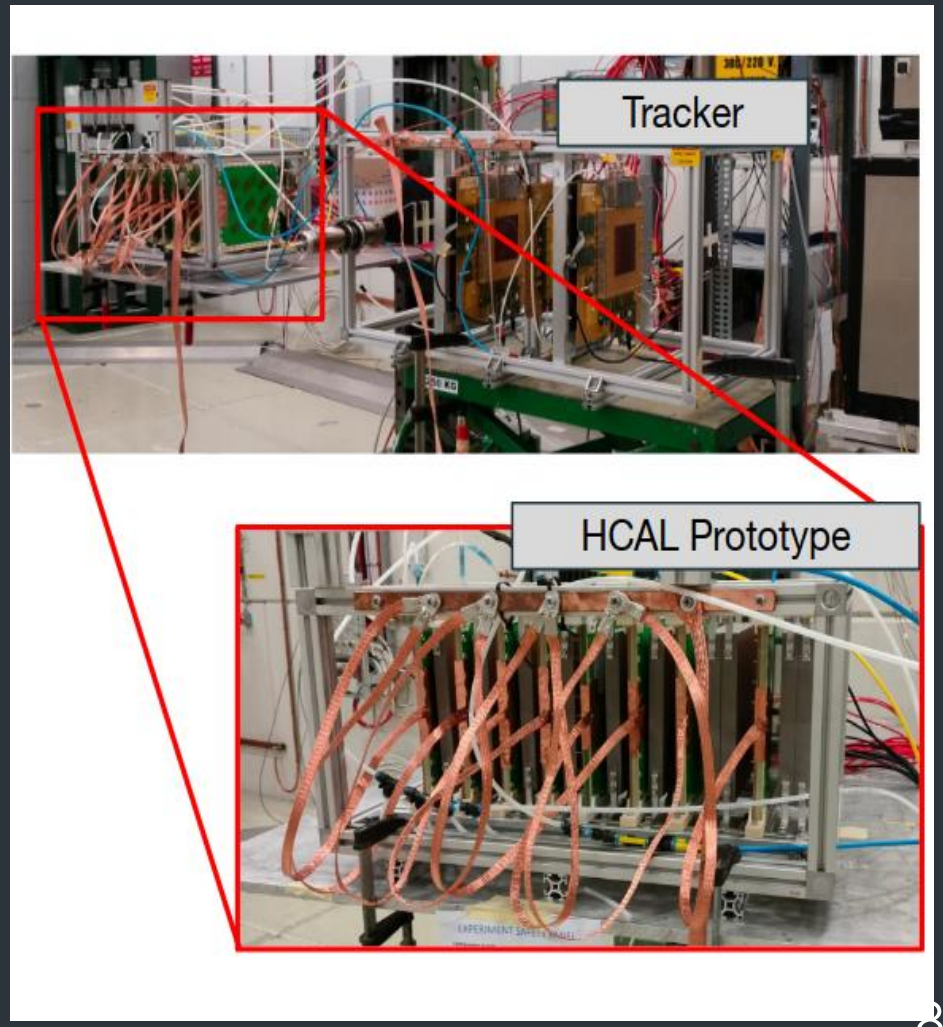




MPGD- HCal prototype

With absorbers

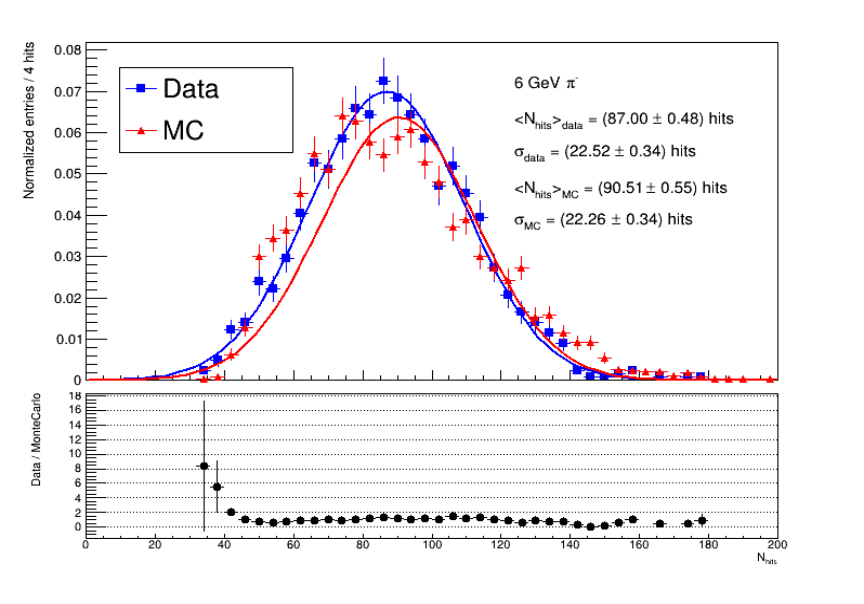




MPGD-HCAL prototype tested under pion beam at CERN PS

- Pion energy range: 3-10 GeV
- MPGD HCAL geometry:
  - 8layers, 20x20 cm^2
  - 5 µRWELL + 3 resistive RµMegas
  - Analog readout

Pion shower studies with test beam data



- **Digital Readout Emulation**: Counted all calorimeter pads with induced charge > 80 ADC counts (~2.5 fC) per showering pion event
- **Showering Event Selection**:

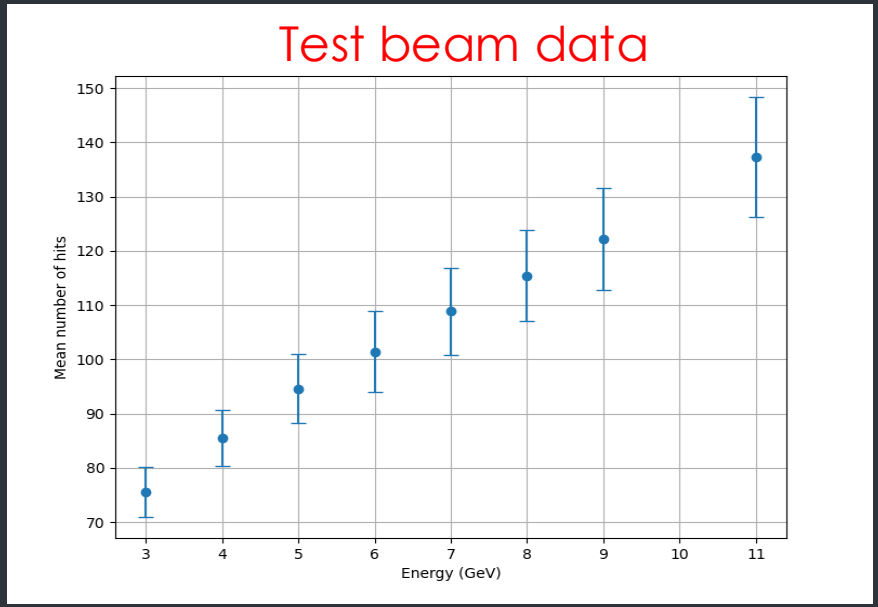
i. Rejected MIP-like and late-starting showers.

ii. Required ≥4 firing pads per active layer.

- **Simulation Support**: Used **GEANT4** to simulate the experimental prototype.

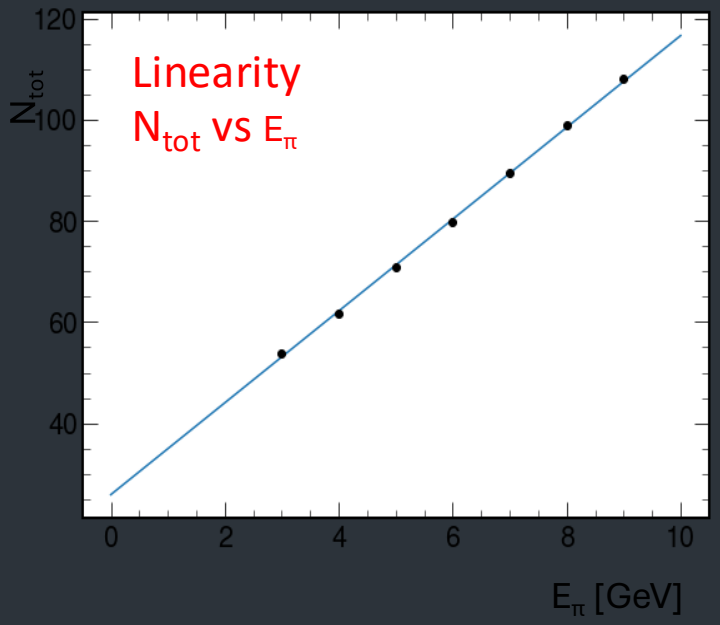
Results:

- Good match found between data and Monte Carlo in the total number of hits distribution.
- The mean number of hits increased with increasing pion energy.
- Loss of linearity in calorimeter response observed at higher pion energies due to partial shower containment.



Ongoing studies

- Different **event selection** criteria are under investigation in test beam data analysis:
  - Shower events selected requiring at least 4 hits in each active layer
  - Cut on Q = std of cluster size x cluster charge (Q is expected to be high for shower events)
- Plans to further improve shower selection
  → initial data-cleaning using tracking system for MIPs identification
  → further rejection of non-contained showers.
- Semidigital readout emulation: reconstruct the energy using 3 thresholds

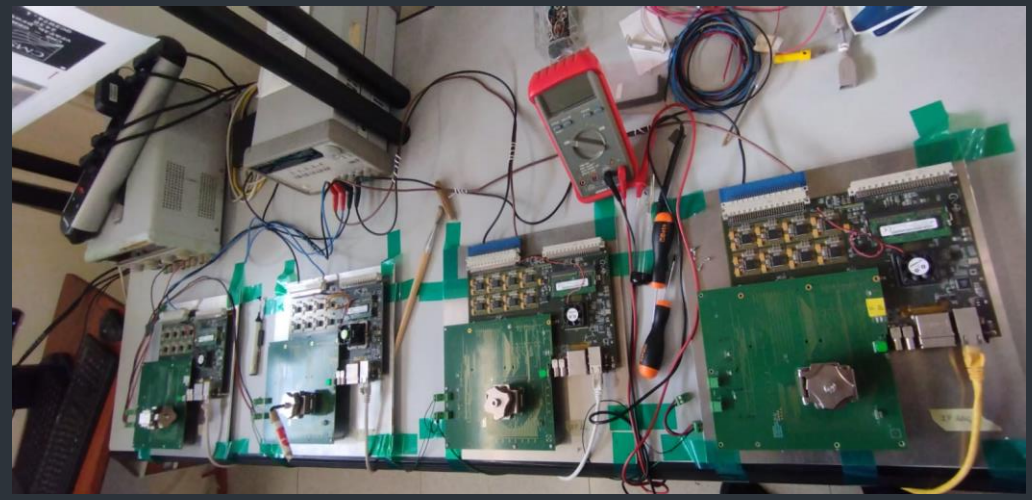


Future plans

- Participate to the MPGD HCAL test beam operation in 2025 and 2026 at PS.
- Detailed analysis of the data and comparison with G4 simulation.
- Thesis submission.

VFAT ASICs test in Bari Lab:

- I contributed in testing of VFAT3 ASICs for the CMS upgrade.
- VFAT3 ASICs consists of 128 channels digital readout.
- It will be used for triple GEM readout.



Chips checked	Good chips	Rate	DAC Error	ADC Error	Dead Channels	Communication Error	Total Errors
2711	2001	73.81%	172	359	12	20	710

Subjects and Schools

Subjects

- Gaseous detectors for experimental particle physics. (Passed)
- Machine learning programming in physics. (Passed)
- Design of readout integrated circuits for particle physics. (Passed)
- DRD1 Detector School CERN. (4 CFU awarded)

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Schools

- DRD1 Gaseous Detectors School November 27, 2024 to December 6, 2024 CERN, Switzerland. https://indico.cern.ch/event/1384298/
- First steps with GEANT4. (19-23, May). https://indico.cern.ch/event/1410347/.
- XXXV Edition of the International School "Francesco Romano" on Nuclear, Subnuclear and Astroparticle Physics - Monopoli (Italy) - 28 September-06 October 2025. https://agenda.infn.it/event/40753/.

Conferences and Proceedings

- **Attended three conferences**:
- **Oral presentation** of the conference paper *"Resistive MPGD-based HCAL for Future Colliders"* at the International Workshop on Advanced Signal Processing (IWASI), Manfredonia.
- **Participation in** National TECH FPA, L'Aquilla
- **Poster presentation** at an IWORID conference in Bratislava.
- **Abstract accepted** for presentation at the *Società Italiana di Fisica*.

Proceedings:

- Performance of resistive MPGDs for hadron calorimeter at a Muon Collider experiment.

2025-06-01 | Journal article
DOI: 10.1088/1748-0221/20/06/C06019.
CONTRIBUTORS: Anna Stamerra; **Muhammad Ali**; Marco Buonsante; Anna Colaleo; Lisa Generoso; Luigi Longo; Marcello Maggi; Antonello Pellecchia; Raffaella Radogna; Federica Maria Simone et al.

Thank you

Semidigital readout