PhD course of National Interest in Technologies for Fundamental Research in Physics and Astrophysics

Annual report

Name and surname: Muhammad Ali
Cycle and a.a.: 39th cycle
Supervisor: Dr. Rosamaria Venditti/Dr. Salvatore My

- **Research activity carried out during the year**

I am working on Micro-Pattern Gas Detectors (MPGDs) within the CMS and Muon Collider teams at INFN-Bari. Our research focuses on developing a hadron calorimeter (HCal) using MPGD technology as the active layer for a future experimental facility of muon collider. This machine aims to explore the Standard Model with unprecedented precision.

A major challenge in the experiment design is the muon beam-induced background (BIB), which impacts detector performance and imposes strict radiation-hardness requirements. The physics goals of the Muon Collider include precision measurements of Higgs boson couplings, requiring excellent discrimination between Z and Higgs events, even in hadronic decay channels. This demands accurate identification and four-momentum reconstruction of neutral and charged hadrons, as well as efficient jet clustering, which depends on correctly assigning calorimeter hits to reconstructed particles. Achieving this requires high-granularity calorimetry integrated with precise tracking.

The proposed MPGD-based HCal employs a sampling structure of absorber material and resistive MPGDs as active layers, offering:

- High rate capability (up to MHz/cm²)
- Flexible spatial granularity and good time resolution (~1 ns)
- Uniform response (~30%)
- Cost-effective large-area instrumentation

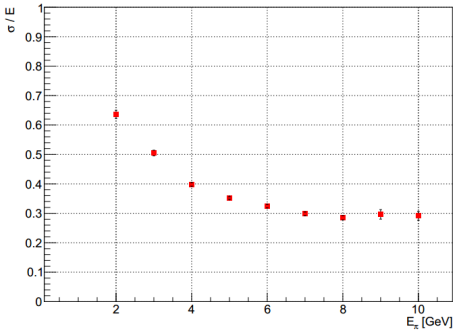
This design aims to meet the requirements for future collider experiments, ensuring robustness against backgrounds while enabling precision measurements. During the second year, I mainly focused on geometrical modeling and simulation studies of the HCal in GEANT4. During last year, new MPGD (2micromegas and 2 micro r well) with and active surface of 50x50 cm² and 1.1x1.1 cm² pitch have been developed by Bari INFN and university and are now in production in the MPGD workshop at CERN. The plan is to extend the present MPGD HCAL prototype, which consists of 8 layers of 20×20 cm² MPGD, by adding 4 additional layers with extended active area. My goal is to optimize the design of the HCAL prototype (in terms of the width of the absorber layers and position of the 50x50 cm² active layers within the HCAL cell) and predict its performance, in terms of shower containment and energy resolution. The simulation predictions will be compared with the data we will collect in a test beam campaign in October 2025. Also, I took part in the analysis of data collected during the test beam performed on the previous version of the prototype (8 layers of 20×20 cm²).

Furthermore, I contributed to the testing of VFAT3 ASICs in the MPGD Bari lab, which will be installed in GEM detectors for the CMS muon system upgrade.

Simulation studies of MPGD-HCal with GEANT4:

I developed the GEANT4 simulation of the new MPGD-HCAL prototype with 12 layers including the 50x50 cm² MPGD that is going to be tested with pion beams at CERN SPS in October 2025. I studied the performance of the new 12 layers prototype using pion beams with energies ranging from 1 to 10 GeV. I quantitatively evaluated the energy containment in both the longitudinal and lateral directions. For energy reconstruction, I employed a digital readout approach with a threshold of 0.01 MIP, and analyzed the energy resolution to assess the overall performance of the calorimeter. The energy resolution obtained is showed in Fig. 1.

Fig.1: Energy resolution of the 12 layers MPGD HCAL prototype obtained with G4 simulation, for the energy range expected in the next test beam.



At a pion energy of 10 GeV, the resolution reaches 30%, characterized by the standard deviation of the distribution relative to the mean value.
Future plans: evaluate the energy resolution using semi digital readout and compare the outcome of the simulation with the test beam data.

Analysis of 2023/2024 test beam data (resistive MPGD & HCal prototype).

I contributed to the data analysis of a small-size (~1λ) calorimeter prototype built with eight MPGD layers (3 resistive MicroMegas and 5 μ-RWELLs) alternated with iron absorbers. The setup, read out through a common DAQ chain based on APV25 and SRS, was tested with negative pion beams up to 11 GeV at CERN East Area. I implemented a digital readout emulation by counting pads above an 80 ADC threshold (~2.5 fC) for each event and energy point, applying selection criteria to reject MIP-like events.

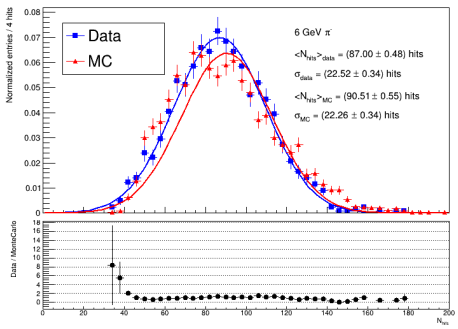


Fig.2: Number of hits recorded in MPGD-HCAL in MC (red) and test beam data (blue) after selection criteria.

The analysis was compared with a dedicated GEANT4 simulation, showing good agreement in hit distributions (Fig. 2) and energy dependence, despite some non-linearity at higher energies due to limited shower containment.

I will participate in the upcoming test beam campaigns (Oct/Nov 2025 and 2026) for evaluating a new HCal prototype (20 × 20 cm²) with the last four layers (50 × 50 cm²) integrated at CERN .

My work includes characterizing the 50 × 50 cm² MPGD which are expected to be ready by mid-September 2025, using cosmic muons to measure efficiency, time resolution, and response uniformity. Additionally, I will conduct pion beam tests on MPGD HCal at CERN to study shower development, energy response, and resolution. I will be involved in test beam operations, detailed data analysis, and comprehensive comparison with GEANT4 simulations to validate the experimental results.

*I have completed all coursework and passed the examinations. Additionally, I attended two workshop schools and two international conferences. I presented a conference paper at **IWASI 2025** in Manfredonia and a poster at **IWORID 2025** in Bratislava.*

- **List of attended courses and passed exams**

1. Gaseous detectors for experimental particle physics. (Passed)
2. Machine learning programming in physics. (Passed)
3. Design of readout integrated circuits for particle physics. (Passed).
4. DRD1 Detector School at CERN. (Awarded 4 CFU)

- **List of attended conferences, workshops and schools, with mention of the presented talks**

1. DRD1 Gaseous Detectors School November27, 2024 to December 6, 2024 CERN, Switzerland. https://indico.cern.ch/eYent/1384298.
2. First steps with GEANT4. (19-23, May). https://indico.cern.ch/event/1410347/.
3. National TECH-FPA, L'Aquilla. https://agenda.infn.it/event/43840/ (Poster presentation).
4. 10th IEEE International Workshop on Advances in Sensors and Interfaces. https://pbl.ee.ethz.ch/iwasi2025.html. (Oral presentation).
5. IWORID 2025. https://indico.cern.ch/event/1428808/overview. (Poster presentation).
6. 111 Congresso Nazionale Societa' Italiana di Fisica. https://www.sif.it/ (Oral Presentation)

- **List of published papers/proceedings**

1. 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.

2. Resistive MPGD-based HCAL for future colliders. (Conference paper).

- **Thesis title (even temporary)**

  Hadron Calorimeter MPGD-based development for future muon collider experiment.

Date, 16/09/2025 **Signature..**

Seen, the supervisor

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