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A novel MPGD-based Hadronic Calorimeter for Muon Collider experiments(*)

A. Stamerra(1)(2) on behalf of the Muon Collider Physics and Detector Group

(1) *INFN, Sezione di Bari - Bari, Italy*
(2) *Dipartimento di Fisica, Università di Bari - Bari, Italy*

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Summary. — The Multi-TeV Muon Collider is proposed as a promising tool for advancement in understanding the Standard Model within the European particle physics strategy. The Muon Collider physics program focuses on precise measurements in the Higgs boson sector and exploring new physics at the TeV scale. Achieving these goals requires accurate full-event reconstruction, with the Particle Flow (PF) algorithm as a suitable approach. This algorithm utilizes information from tracking, calorimeter, and muon detectors for particle identification and momentum/energy measurements. The challenge lies in discriminating $\mu\mu$ collision products from the intense beam-induced background (BIB) due to the unstable nature of muons. To address this, an innovative hadronic calorimeter (HCAL) based on Micro Pattern Gas Detectors (MPGDs) is proposed. MPGDs offer robust technology for high radiation environments and high granularity for precise spatial measurements. Dedicated studies are needed to assess and optimize the performance of the MPGD-based HCAL, including developing prototypes as proof of concept. Monte Carlo simulations using Geant4 evaluate the HCAL's response to incoming particles, comparing digital and semi-digital readouts with energy resolution as the key metric. The simulated geometry is integrated into the Muon Collider software to analyze its impact on jet reconstruction amid the full apparatus and in the presence of BIB. Validation involves testing a small-size calorimeter cell equipped with resistive MPGD technologies like MicroMegas, μRWELL, and RP-WELL.

1. – Introduction

In particle physics, two main strategies for exploring new physics are possible: one involves colliding electrons/positrons for precise measurements, and the other uses high-energy colliders like proton-proton machines for direct discoveries. Muon colliders [1], however, offer a unique advantage by combining the benefits of both approaches in a single machine. The high mass of muons allows for multiple ring passages and repeated collisions, mitigating synchrotron radiation emission. While protons can achieve high energy, their composite nature limits the available energy for short-distance physics.

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Operating a muon collider poses a challenge due to the instability of muons. Their decay products generate intense radiation known as "Beam Induced Background" (BIB) [2], contaminating the collision environment. BIB is characterized by low-energy particles arriving at a broad range of times. Designing a detector for a muon collider focuses on managing and mitigating the effects of BIB, requiring the ability to endure long-term radiation exposure and high-granularity measurements in space, time, and energy to distinguish between beam collision products and BIB particles.

The muon collider focuses on measuring physics processes at the energy frontier, demanding excellent resolution in both energy and spatial dimensions for collimated high-energy jets, especially those above 100 GeV, with a required jet energy resolution of 3-4%. Understanding the distribution and rates of BIB in the calorimeter system is crucial for assessing radiation levels and optimizing detector design to achieve the necessary jet energy resolution.

BIB in the calorimeter region is primarily composed of photons (96%) and neutrons (4%). Simulations [3] indicate a photon flux of approximately 7.5 kHz/cm^2 at the surface of the hadronic calorimeter at 15 kHz bunch crossing. Radiation dose estimates for the muon collider detector suggest a neutron-equivalent fluence of about $10^{13}, cm^{-2}$ per year in the HCAL, with a steep radial decrease. The expected total ionizing dose in the HCAL is around 10^3 kRad per year.

Mitigating the effects of BIB while maintaining good physics performance requires careful technology and calorimeter design choices. High granularity is essential to reduce BIB overlap in the same calorimeter cell. A time resolution on the order of nanoseconds would reject most out-of-time components of BIB. Longitudinal calorimeter segmentation aids in distinguishing between signal and fake showers produced by BIB. These requirements align with the high granularity particle flow algorithm approach [4], aiming to create an image of showers induced by jet fragments for accurate identification and energy measurement of neutral hadron-induced showers.

The CALICE Collaboration [5] played a key role in advancing calorimeter concepts for highly granular detectors in particle flow applications. Their focus centered on gaseous detectors as the active element, providing higher granularity and cost competitiveness compared to traditional scintillator-based calorimeters. While Resistive Plate Chambers (RPCs) have been historically considered for their digital nature and excellent time resolution, recent proposals involve Micro Pattern Gas Detectors (MPGDs) like resistive Micromegas, as well as newer technologies such as μrwell and RP-WELL, for semi-digital calorimeters. These advancements are expected to outperform RPCs in terms of rate capability, energy resolution, stability, uniformity, and pad multiplicity.

2. – Design strategy for HCAL

The study consists of the simulation of a calorimeter cell using Geant4 [6] to evaluate its response and shower containment under a pion beam irradiation. The calorimeter consists of layers with 2 cm of iron as the absorber and 5 mm of pure argon simulating the Micro Pattern Gas Detector (MPGD). Pion beams with energies of 20 GeV, 40 GeV, and 60 GeV are used for the simulation. The shower containment in both transversal and longitudinal directions relative to the pion beam line is studied. The longitudinal shower containment, expressed as a fraction of deposited energy, is studied as a function of depth in units of nuclear interaction length λ_I. Around 90% of the energy is contained within approximately 14 λ_I, corresponding to 100 layers in the geometry.

In the transverse plane, the shower containment is evaluated in terms of the fraction

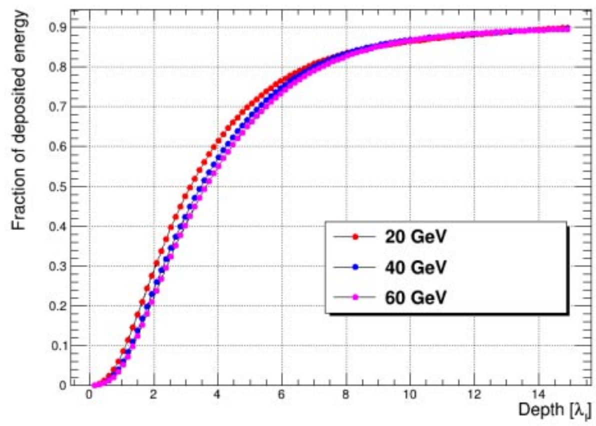

Fig. 1. – Longitudinal shower containment, expressed in terms of fraction of deposited energy, as a function of the depth in unit of nuclear interaction length λ_I, for three different values of the π^- energy. This plot is obtained with lateral surface dimension of 1×1 m^2.

of energy deposited inside cylinders of increasing radius aligned with the pion direction. About 90% of the energy is contained within a cylinder of radius approximately 3 λ_I. The study provides insights into the behavior of the calorimeter under different pion beam energies and configurations.

To account for experimental constraints, energy resolution studies use a calorimeter cell with 50 layers of alternating iron and gaseous argon, corresponding to approximately 7 λ_I, and a lateral surface area of 1×1 m^2. Pion beams with energies ranging from 5 GeV to 80 GeV are simulated, with around 80% of the energy expected to be released in the calorimeter cell.

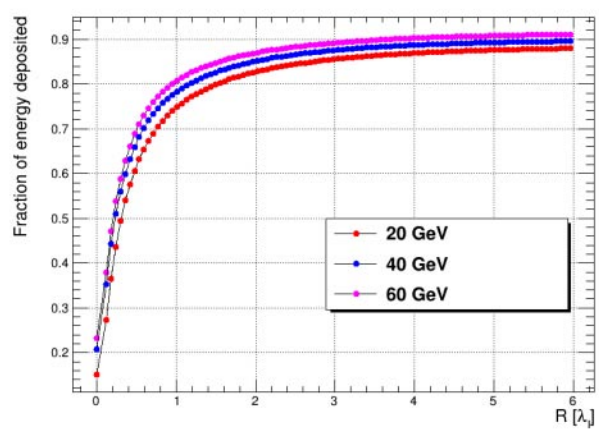

Fig. 2. – Lateral shower containment, expressed in terms of fraction of deposited energy, as a function of the cylinder radius in unit of nuclear interaction length λ_I, for three different values of the π^- energy. This plot is obtained with 100 layers.

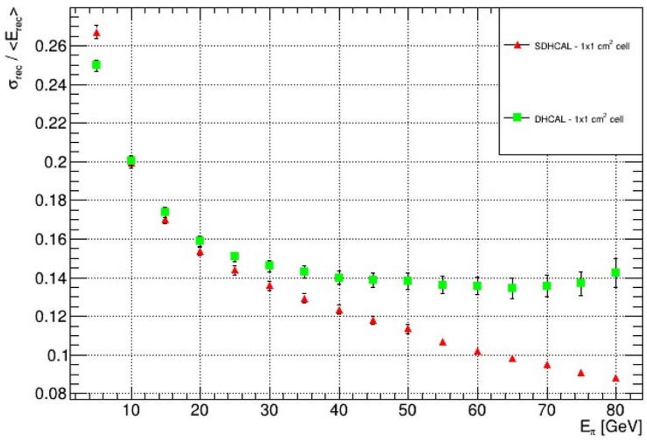

Fig. 3. – Comparison between energy resolutions obtained in the case of the digital readout, in green, and the semi-digital one, in red.

The active layer is divided into 1 cm^2 cells for high granularity. Two readout methods, digital and semi-digital, are simulated for pion energy reconstruction, comparing their performance in terms of energy resolution. Both methods rely on the total number of hits in the active layers, with a 'hit' defined based on the energy deposited in each cell.

For digital readout, a hit is defined using a single threshold on the energy deposited in each cell, and the primary pion's energy is reconstructed by counting the number of hits. The calorimeter response function is established through simulation, providing an analytic relationship between the energy of the showering pion and the mean total number of hits.

Semi-digital readout involves applying three thresholds to each cell in MIP units, defining three hit regions. The energy is reconstructed through an empirical formula, and parameters are determined by minimizing the χ^2 function for each pion energy value.

The energy resolution curves for both digital and semi-digital readouts are compared, showing that the resolution saturates at approximately 40 GeV for the digital readout due to the loss of proportionality in the response function at high energy. For an 80 GeV pion, the resolution is approximately 8% for semi-digital and 14% for digital readout.

3. – Test of the active layers

As a proof of concept, a real prototype of a calorimeter cell was built and tested in August 2023 at the CERN PS facility, with a pion beam of energy ranging from 3 GeV to 10 GeV. The prototype consisted of 8 layers with alternating stainless steel absorber and MPGD, reaching a depth of approximately 1 λ_I. The active layers have been instrumented with resistive MicroMegas [7, 8], μrwell [9], and RP-WELL [10]. A preliminary test beam with a muon beam of 150 GeV was conducted at CERN SPS in July 2023 on the detectors alone to assess their performance. All these technologies have been built according to the latest developments for the high-rate layouts, using one (for the μrwell) or two (for the MM) DLC layers for discharge suppression. The readout board, common to all the detectors, consists of arrays of 1×1 cm^2 pads mounted on

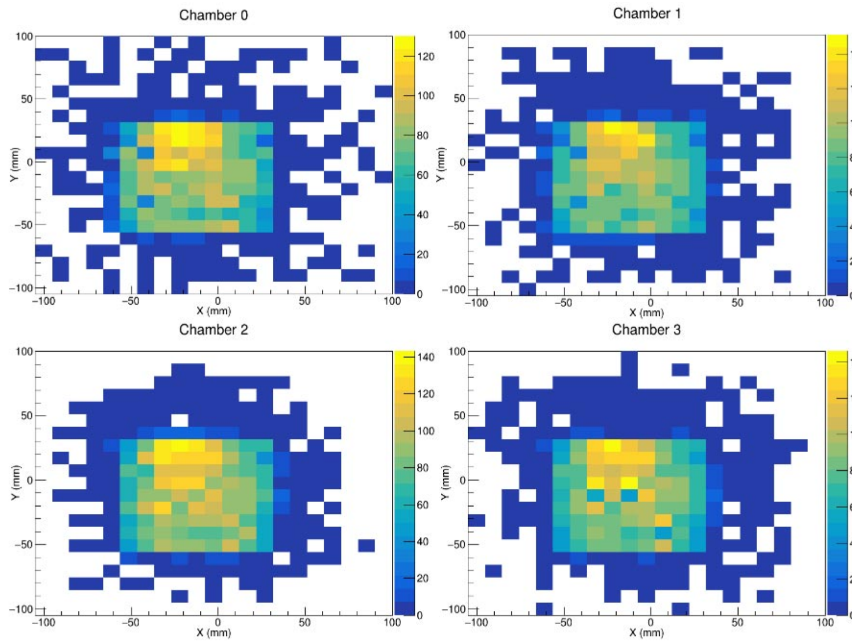

Fig. 4. – Occupancy plots for the four resistive MicroMegas tested under muon beam at the SPS in July 2023. The beam (large about 8 cm in xy direction) hit the central area of the chambers.

the PCB, covering a total active area of approximately 20×20 cm^2. The setup at the SPS counted 12 detectors in total, including 4 resistive MicroMegas, 1 RP-WELL, and 7 μrwell. They have been read through APV25 connected to the ADC and the Front-End Card in the SRS architecture via HDMI cables. Figure 4 shows an occupancy plot obtained for the MicroMegas, where the area hit by the beam is visible.

4. – Conclusions

This contribution presented initial results regarding the simulated performance of an HCAL based on Micro Pattern Gas Detectors (MPGDs), focusing on shower containment and energy resolution. More realistic enhancements will be implemented incorporating hit detection efficiency and the impact of charge spreading among adjacent cells. To provide a more accurate depiction of the muon collider environment, the simulation will include the BIB contribution, accounting for neutron and photon flux. The geometry will be integrated into the Muon Collider software to examine its impact on jet energy reconstruction within the entire apparatus.

Additionally, a comparison between simulation results and experimental data from the PS test beam on the calorimeter cell will be conducted. A preliminary test beam using a 150 GeV muon beam was conducted at CERN's SPS in July 2023, focusing on the detectors alone to evaluate their performance. As of the conference, the analysis of the test beam data is still ongoing, and the experimental results will complement the simulation studies presented in this contribution.

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