PROCEEDINGS OF SCIENCE

MPGD-based Hadronic calorimeter for a future experiment at Muon Collider

Luigi Longo,[a,*] Marco Buonsante,[a,b] Anna Colaleo,[a,b] Lisa Generoso,[a,b] Marcello Maggi,[a] Antonello Pellecchia,[a] Raffaella Radogna,[a,b] Federica Maria Simone,[a,b] Anna Stamerra,[a,b] Rosamaria Venditti,[a,b] Piet Verwilligen,[a] Angela Zaza,[a,b]
endorsed by the International Muon Collider Collaboration,
Michele Bianco,[c] Maryna Borysova,[d] Maria Teresa Camerlingo,[a] Mauro Iodice,[e] Luca Moleri,[d] Givi Sekhniaidze[f] and Darina Zavazieva[d]

[a] *Istituto nazionale di fisica nucleare - Sezione di Bari, Via Amendola 173, Bari, Italy*
[b] *Università degli studi di Bari Aldo Moro, Piazza Umberto I, Bari, Italy*
[c] *CERN, Esplanade des Particules 1, Meyrin, Switzerland*
[d] *Weizmann institute of science, Herzl St 234, Rehovot, Israel*
[e] *Istituto nazionale di fisica nucleare - Sezione di Roma 3, Via della Vasca Navale, 84, Roma, Italy*
[f] *Istituto nazionale di fisica nucleare - Sezione di Napoli, Via Cintia, Napoli, Italy*

E-mail: luigi.longo@ba.infn.it

The International Muon Collider Collaboration has proposed a multi-TeV muon collider as a powerful tool to investigate the Standard Model with unprecedented precision, after the High-Luminosity LHC era. However, muons are not stable particles and it is of extreme importance to develop technologies able to distinguish genuine hits, originating from particles created in collisions, from hits due to the background radiation induced by the beam itself. In this context, an innovative hadronic calorimeter (HCAL), based on Micro-Pattern Gaseous Detectors (MPGD) as active layers, has been proposed. MPGDs represent the ideal technology, featuring high rate capability, good spatial and time resolution, good response uniformity and, moreover, they are radiation hard and allow for high granularity readout ($1{\times}1\,\mathrm{cm}^2$ cell size). The response of an MPGD HCAL to the incoming particles is studied in Monte Carlo simulations and presented here. The tests performed at SPS with muons of 100 GeV, for the detector characterization, and at PS with pions of few GeV, for a HCAL cell prototype study, are also shown.

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[*] Speaker

1. Introduction

Several feasibility studies are ongoing to understand the best LHC successor, for the post High-Luminosity (HiLumi) era. In this context, the International Muon Collider Collaboration (IMCC) [1] has proposed a multi-TeV muon collider [2], as a possible future successor. Indeed, a muon collider represents a unique opportunity thanks to the possibility of having all collision energy available in the hard-scattering process, a well defined initial and, a cleaner final state. However, muons are not stable particles and an asynchronous background, induced by the beam itself, (BIB) is expected. In order to face this environment, high readout granularity and good time resolution are mandatory for the detectors of the experiment. In particular, for what concerns the hadronic calorimeter (HCAL), the readout element size should be between 1×1 and $3 \times 3\,\text{cm}^2$, to allow the use of a Particle Flow (PF) reconstruction algorithm, and the time resolution per cluster must be of the order of few ns, to distinguish between signal and BIB. Such requirements are fundamental to guarantee an HCAL energy resolution lower than $60\%/\sqrt{E}$ needed to reach a jet energy resolution of 3% for jets above 100 GeV, fundamental for discriminating W and Z boson hadronic decays [3].

A sampling hadronic calorimeter based on resistive Micro-Pattern gaseous detectors (MPGD) can meet these requirements. Moreover, MPGDs are able to withstand integrated charges of several C/cm^2 [4] and, compared to other gaseous detector technologies, such as RPCs, have a better rate capability [5] and spatial resolution [6], thus allowing better performance in presence of BIB. In this context, dedicated MPGD-based calorimeter simulations have been developed and three different technologies MicroMegas [7], μ-RWELL [8] and RPWELL[9] are under studies, as possible active layer, with tests performed at SPS with muons of 100 GeV, for their characterization, and at PS with pions of few GeV, for a HCAL cell prototype study.

2. Calorimeter simulation

The performance of a MPGD-HCAL has been assessed within the muon collider software framework [10] implementing a sampled calorimeter of 60 layers, mainly made of 20 mm of iron (absorber) and 3 mm of argon (active material), with a readout element size of $1\,\text{cm}^2$. Two different approaches were considered for energy reconstruction: the digital readout (RO), where the reconstructed energy is assumed to be a function of the total number of hits in the calorimeter, and the semi-digital readout (SDRO), where instead the energy is estimated as a linear combination of the number of hits above three different thresholds [11]. As shown in Fig. 1, digital RO and SDRO show comparable performance below 6 GeV but SDRO has better performance at higher energy, reaching $\sigma/E = 46\%/\sqrt{E} \oplus 12\%$ (well below the requirement of $60\%/\sqrt{E}$), and not showing any saturation at high energy, as instead for the digital RO where larger fluctuations, observed on the total number of hits, affects the energy resolution.

The impact of BIB was also evaluated in terms of occupancy and arrival time in the MPGD-HCAL, in the case of a centre of mass energy of 1.5 TeV. As shown in Fig. 2a, BIB is present mostly in the first 20 layers of the hadronic calorimeter but shows a higher probability to occupy the calorimeter cell than the signal one, especially for low energetic particles. However, the BIB arrival time shows a flat distribution between 8 and 16 ns, with a tail up to 20 ns, against a signal arrival time peaking at ~ 6 ns and almost totally contained in 10 ns (Fig. 2b). This allows the rejection

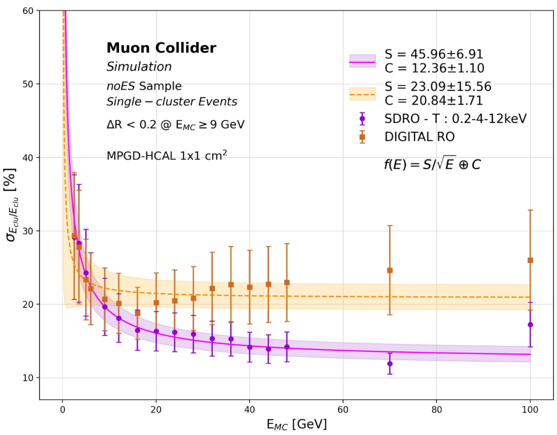
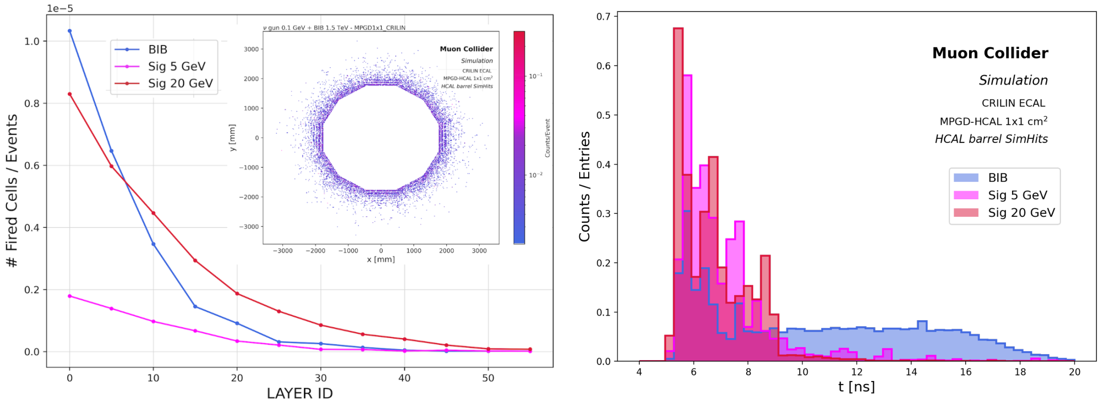


Figure 1: Energy resolution for digital readout (RO), in orange, and semi-digital RO (SDRO), in violet, as a function of the energy of the impinging particle. For SDRO, the following thresholds were assumed: 0.2, 4 and 12 keV. Only particle not showering in the electromagnetic calorimeter were considered. Both sets of data were fitted against $S/\sqrt{E} + C$.



(a) Occupancy

(b) Arrival Time

Figure 2: (a) Occupancy as a function of the MPGD-HCAL layer for BIB and Pions ($\pi^{\pm}$) of 5 and 20 GeV together with a 2D plot showing the BIB distribution in the $X - Y$ plane. (b) Arrival time in the MPGD-HCAL for BIB and 5 and 20 GeV $\pi^{\pm}$.

of the asynchronous background requiring an arrival time within a 10 ns time window, which lets MPGD detectors be a suitable solution for the hadronic calorimeter at muon collider.

3. Performance of a calorimeter prototype

Twelve MPGD detectors have been produced: 7 μ-RWELL, 4 resistive MicroMegas and 1 RPWELL. All of them have an active area of $20 \times 20\,\text{cm}^2$, a drift gap of thickness 6 mm and same readout made of 384 $1 \times 1\,\text{cm}^2$ pads. They were tested with muons of $O(100\,\text{GeV})$ and some of them were used to build a MPGD-HCAL prototype of a length of 1 nuclear interaction length (λ_I), assembled alternating 8 layers of iron absorbers and 8 layers of MPGD detectors. The prototype was characterized with pion beam in the energy range [1, 11] GeV.

3.1 Performance of MPGDs under muon beam

All the twelve MPGD prototypes were tested with $O(100\,\mathrm{GeV})$ muons at the CERN North Area in 2023 to measure their detector efficiency, spatial resolution and gain uniformity. The detectors were operated with the state-of-the-art gas mixture for each technology (Ar:CO_2:C_4H_{10} 93%:5%:2% for the MicroMegas and RPWELL, Ar:CO_2:CF_4 45%:15%:40% for the μ-RWELL); as front-end electronics, the APV25 [12] ASIC[1] read out by the RD51 scalable readout system (SRS) was used [13].

Efficiency and spatial resolution were measured for each pad detector using as reference tracks the segments reconstructed in turn by all the other detectors; all MPGDs under test were found to have a good spatial resolution, smaller than the readout pad pitch, and an efficiency close or above the 90% for all the detector technologies. The response uniformity is measured as ratio between standard deviation and mean of the charge distribution of all the readout clusters matching a muon track. Both MicroMegas and μ-RWELL have an excellent response uniformity of at most 16%; however, some pattern in the uniformity was observed for μ-RWELL and more detailed studies are ongoing. Instead, the RPWELL prototype shows a slightly larger response uniformity ($\sim 23\%$).

It was also observed high probability of cross-talk between pads, due to routing of readout vias. This effect was patched offline by clustering pads under the assumption that clusters bigger than four pads are not expected, due to geometry constraints, and considering the pad with the highest charge as seed. Then, a dedicated clustering algorithm based on charge sharing fraction was developed to associate the pad to the correct cluster seed.

3.2 Performance of calorimeter prototype with pions

The one λ_I calorimeter prototype was tested with negative pion beams in the CERN East Area in 2023. As already mentioned, the prototype was made of 8 layers of iron absorbers and readout MPGDs; however, the thickness of the absorbers was 4 cm for the first two layers and 2 cm for the subsequent ones to anticipate the starting point of the shower. The data were analyzed in a digital readout approach, i.e. counting the total number of hits over a fixed threshold event by event. A dedicated simulation in Geant4 [14] was implemented, taking into account the efficiency of each readout layer[2] and the effect of the cross-talk. The data to Monte Carlo comparison shows good agreement for the different pion energies, as shown in Fig. 3; the difference in the mean value between the data and simulation is under further investigation and it could be related to the presence of remnant effects of the cross-talk. A refinement of the analysis to obtain a comparison to the semi-digital readout approach and a full energy calibration is ongoing, including also the new data collected in a new test beam campaign in 2024 .

4. Conclusions and outlook

Sampling hadronic calorimeters with MPGD active layers are a promising technology for experiments at future colliders, such as the Muon Collider. The performance of a digital and semi-digital MPGD calorimeter shows an energy resolution below $60\%/\sqrt{E}$, needed to reach a jet

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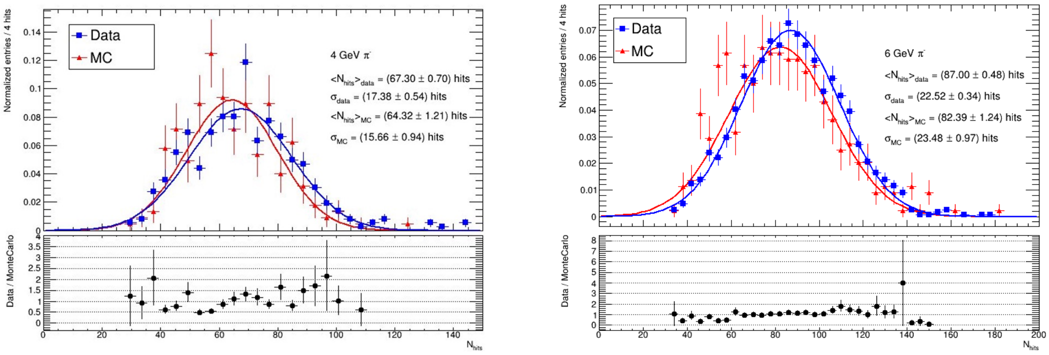
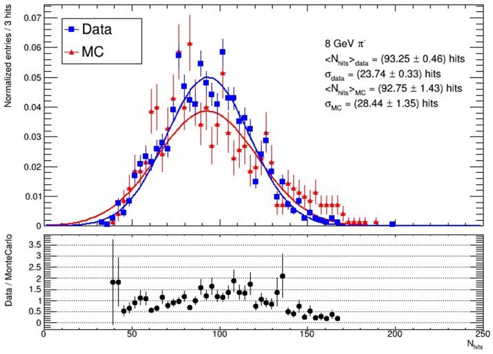
[1] An analog chip providing charge, arrival time and signal shape for each readout channel.

[2] Including both intrinsic detector efficiency and electronics effects, such as dead readout channels.



(a) 4 GeV π^- **(b)** 6 GeV π^-



(c) 8 GeV π^-

Figure 3: Distribution of the total number of hits in the calorimeter prototype tested at the CERN PS East Area for a 4, 6, and 8 GeV pion beam, compared with the results of a Geant4 simulation, implementing the calorimeter prototype under test.

energy resolution of 3% for jets above 100 GeV in a Particle Flow approach. The majority of BIB contribution can be rejected requiring a signal arrival time within a 10 ns time window, which is a performance target achievable by MPGDs.

All the three MPGD technologies under test have shown good efficiency, good spatial resolution and good uniformity, even if additional studies are ongoing to understand the pattern observed in the response uniformity for some μ-RWELL detectors. The cross-talk was understood and partially patched with an offline solution. New detectors are going to be produced and the distance between pads and readout vias has been increased to reduce this effect. Studies on the timing performance of the three technologies are also ongoing.

Finally, the calorimeter prototype made of eight layers of iron absorbers and MPGDs has shown good agreement between data and Monte Carlo in the digital readout approach. New test beam campaign was conducted in 2024 to consolidate the results with the present prototype and in view of extending the current prototype to a 2 λ_I calorimeter, once included 4 layers of $50 \times 50\,\mathrm{cm}^2$ MPGD prototypes.

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