

Full simulation study of a hadronic calorimeter for a future muon collider

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Summary. — In the context of the European Particle Physics Strategy and the US P5, a multi-TeV Muon Collider is proposed to study the Standard Model with unprecedented precision after the HL-LHC. A major challenge is the Beam-Induced Background (BIB), which imposes strict constraints on detector performance and radiation hardness. Achieving sub-percent precision in Higgs hadronic decays requires a jet energy resolution of 3–4% for jets above 100 GeV. This demands a hadronic calorimeter with millimeter-scale position resolution, nanosecond timing for BIB rejection, and at least $60\%/\sqrt{E}$ energy resolution. This contribution explores an innovative calorimeter design using a sampling structure with absorber material and resistive micro-pattern gaseous detectors as active layers. Performance is optimized through full simulations, adapting the Particle Flow algorithm to the proposed layout and characterizing the energy resolution with simulated monochromatic hadron beams.

1. – Introduction

The Standard Model has proven highly predictive, with numerous experimental validations culminating in the Higgs boson discovery. This has intensified efforts to explore Higgs properties, particularly its unmeasured self-coupling constants. The European Strategy for Particle Physics [1] and the US P5 [2] identify a multi-TeV Muon Collider as the ideal tool for a consistent jump ahead in the investigation of fundamental particles and interactions [3]. Such a collider combines the benefits of hadron and electron-positron machines. Unlike protons, muons are elementary, granting full center-of-mass energy for fundamental interactions. Their higher mass, compared to that of electrons, also minimizes synchrotron radiation, allowing acceleration to higher energies and probing smaller scales. The effective energy reach of a muon collider is thus comparable to a much higher-energy proton collider, achieving TeV-scale collisions in a cleaner environment with reduced QCD background. A muon collider with a center of mass energy of

10 TeV offers unprecedented potential for producing Higgs pairs via Vector Boson Fusion (VBF), generating ten million Higgs bosons in five years —ten times more than future e^+e^- facilities. This enables precise measurements of the Higgs trilinear and possibly quadrilinear couplings [4].

Despite the advantages, such a machine has to cope with an intense flux of secondary and tertiary particles originating from the decay of muon beams, defined as Beam-Induced Background (BIB). Addressing this challenge requires innovative solutions in detector technology, such as nanosecond time resolution to discard asynchronous BIB, and sophisticated pattern recognition algorithms to mitigate the impact of the background particles on the experimental environment and allow for accurate event reconstruction [5].

A Particle Flow (PF) approach is envisioned to conduct precision measurements of Higgs boson couplings and explore potential new physics phenomena at the TeV scale, requiring exceptional Z/W separation [6]. To this end, the hadronic calorimeter (HCAL) must deliver a single-hadron energy resolution of approximately $\sim 60\%/\sqrt{E}$ to better ensure a jet energy resolution of 3–4% for jets with energies above 100 GeV. Integrating Micro Pattern Gaseous Detectors (MPGDs) into the HCAL design provides significant performance and cost advantages. MPGDs are well-suited for large-area instrumentation, offering fine granularity ($1 \times 1 \text{ cm}^2$), high radiation hardness, and affordability. Their high rate capability (0.1–1 MHz/cm²) makes them ideal for muon collider environments. MPGDs deliver robust energy resolution ($\sim 20\%$), precise timing, stability, and low pad multiplicity [7, 8].

This study presents the first performance optimization of a newly proposed MPGD-based hadronic calorimeter within a comprehensive simulation of the 3 TeV Muon Collider environment. The analysis focuses on energy reconstruction for calorimetric clusters, utilizing monochromatic π^\pm beams generated at the interaction point (IP) and propagated through the entire detector, traversing the Trackers and the Electromagnetic Calorimeter, to finally reach the HCAL. Detector functionality and performance were characterized through energy resolution studies, both in the absence and presence of BIB, including a comparison between the digital (DRO) and semi-digital readout (SDRO) approaches.

2. – Simulation methodology and analysis strategy

The study is carried out in the comprehensive simulation framework provided by the iLCSoft software [9], where the geometry of the calorimeter system was implemented. The Electromagnetic Calorimeter (ECAL) follows the CRILIN design [10], a semi-homogeneous calorimeter with a total depth of 0.9 hadronic interaction lengths (λ_I). The HCAL configuration consists of 60 alternating layers, each comprising a 3 mm argon gas layer as the active material and a 22 mm thick iron layer as the absorber, corresponding to an equivalent depth of 5.9 λ_I . The read-out cells have an area of $1 \times 1 \text{ cm}^2$, ensuring high granularity for precise spatial resolution.

A preliminary analysis of particle species interacting with the calorimeter system at a 3 TeV Muon Collider used the VBF $H \rightarrow b\bar{b}$ process as a benchmark. This channel served to study particle types, energy distributions, and jet multiplicities. A thousand events were produced by the Monte Carlo (MC) event generator WHIZARD [11], then jet clustering was performed using the k_t algorithm [12] on stable particles post b-quark hadronization. The analysis at the generator level of di-jet events reveals that most identified particles are photons and charged pions, followed by charged and neutral kaons. On average, 48 particles are generated per event, with half being hadrons. The high particle multiplicity in the hadronization process implies that 95% of generated particle

have energies below 20 GeV. The performances of the HCAL were, then, probed using primarily low energy pions. Monochromatic π^\pm samples, of approximately 30000 events each, were generated at the IP with fixed momenta in the range of 0.5–100 GeV/c and simulated throughout the entire Muon Collider Detector using the *DD4hep* package.

Particles traversing the calorimeter system deposit energy as *hits* in the detector volume. Events can be classified by shower origin: *noES* for showers starting in the HCAL after MIP-like behavior in the ECAL, and *EH* for showers beginning in the ECAL and extending into the HCAL. The *noES* samples were analyzed to focus on HCAL shower properties independently of ECAL contributions.

At this stage of the simulation, the Pandora Particle Flow Algorithm (PandoraPFA) was employed to cluster ECAL and HCAL hits using a cone-based, forward-projective approach [6]. Cluster energy was calculated by summing contributions from both ECAL and HCAL, according to the readout method. The ECAL employed an analog readout, summing individual ECAL hit energies. Concerning the HCAL, the prototype under analysis is designed to implement digital read-out technology. With this approach, the deposited energy is a function of the number of HCAL hits exceeding a predefined energy. The digital improves energy resolution by suppressing high-energy Landau fluctuations typical of the analog approach. On the other hand, it suffers from saturation at higher energies when multiple shower particles deposit energy in the same cell within a time smaller than the readout integration time, leading to underestimation. The SDRO, combining digital and analog features, mitigates these limitations by introducing multiple thresholds. The final energy is a weighted sum of the number of hits in each threshold range. This allows distinguishing among small, medium and large energy deposits, which in principle should reduce high-energy saturation effects [13].

In the presented study, both digital and semi-digital approaches are pursued and compared in terms of energy resolution. The SDRO was implemented through a three-level digitization. The lowest threshold is set by the readout electronics and the ionization potential of argon. The second and third thresholds were determined with a threshold scan based on the energy distribution of hits of the simulated pions at different momenta. The ultimate criterion for evaluating the effectiveness of the chosen thresholds was the resulting energy resolution. The optimal values, which were then used for the semi-digital reconstruction, were found to be 0.2, 4, and 12 keV.

3. – Results and discussion

3.1. Energy resolution. – The intrinsic energy resolution of the MPGD-based HCAL was evaluated using *noES* sample clusters reconstructed with DRO and SDRO. For each pion gun energy, the reconstructed mean energy was 10–30% lower than the true MC pion energy (E_{MC}) due to invisible calorimetric deposits in hadronic showers. A linear calibration was applied to re-scale the cluster energy spectra and address this underestimation. Energy resolution curves were derived by fitting calibrated energy distributions with Gaussian functions to extract the peak parameters μ and σ . The resolution at each pion energy was calculated as σ/μ from the fit. A comparative plot on the left of fig. 1 shows the energy resolution *versus* the MC energy for the two readout approaches together with the fitting function accounting for the stochastic term (S) and the constant term (C).

For pion energies below 9 GeV, both readout approaches perform similarly. However, at higher pion energies, the resolution curves diverge. The SDRO shows a decrease in resolution staying below 20%. In contrast, the digital readout exhibits an increasing

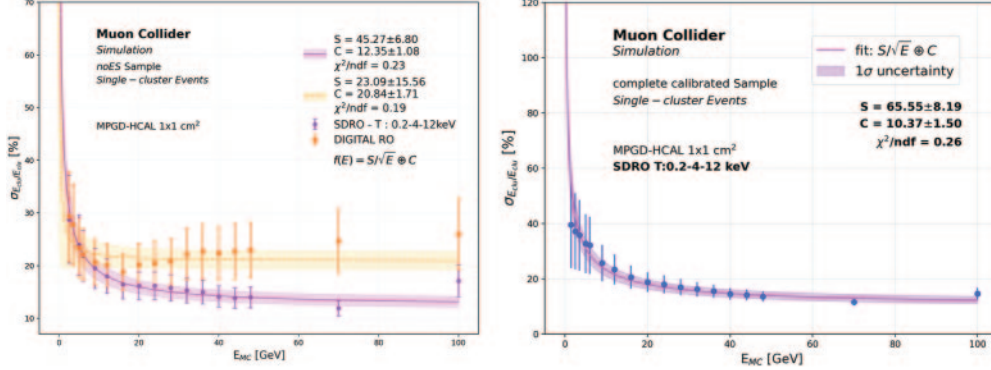


Fig. 1. – Left: intrinsic energy resolution as a function of the MC energy for the MPGD-HCAL obtained with semi-digital (bullet marker) and digital (square marker) read-out. The fit curves are represented by the solid line (SDRO), and the dashed line (DRO). The shaded bands are the 1σ uncertainties of the fit. Right: energy resolution as a function of the MC energy for the Muon Collider calorimeter system with the ECAL CRILIN and the MPGD-HCAL. The fit curve is represented by the pink solid line, while the purple shaded band stands for the 1σ uncertainty of the fit function.

trend, reaching a resolution of 25%. The constant term C in the fitting function is smaller for SDRO ($\sim 12.35\%$), indicating that the semi-digital approach may be superior for the MPGD-HCAL. Additional studies are required to further decrease C . Additionally, the stochastic term S is equal to 45.27% in the semi-digital reconstruction, meeting the target requirements of being less than 60%.

To assess the energy resolution of the entire calorimetric apparatus, the complete collection of events was taken into account, including pions from the EH samples. In this comprehensive approach, the performances of both ECAL and the HCAL impact the energy measurement and reconstruction. Since the energy responses of ECAL and HCAL were still not perfectly tuned, an *ad hoc* calibration of the energy spectra was needed to equalize the two different contributions. Then, the resolution of the whole calorimeter system was derived as before and depicted on the right of fig. 1.

Compared to the intrinsic resolution of the HCAL, the fit function for the entire calorimeter system exhibits a larger S of about 65% and a slightly smaller C around 10%. The 20% increase in the stochastic term is symptomatic of the deterioration of the resolution for $E_{MC} < 20$ GeV. Below this energy, the ECAL contribution becomes important due to the higher probability of pions starting a shower already in ECAL. A more accurate calibration is, therefore, needed to restore the target performance.

3.2. BIB studies. – The BIB characterization was carried out by simulating the two decaying μ^\pm beams within the full Muon Collider environment for a center-of-mass energy of 1.5 TeV. The plot on the left of fig. 2 illustrates the spatial distribution of BIB hits in the x - y plane, orthogonal to the beam. The energy deposits are mostly contained within the first 20 layers of the HCAL barrel and have energies of a few keVs.

The plot on the right of fig. 2 shows the probability of a cell being fired by a BIB or signal hit in the HCAL barrel. BIB hits outnumber signal hits in the first seven layers before decreasing sharply, becoming negligible for the 20 GeV signal and comparable to the 5 GeV signal. The largest discrepancy is in the first layer, where BIB hits are more likely ($\sim 1.0 \times 10^{-5}$) compared to signal hits (0.2×10^{-5} at 5 GeV and 0.8×10^{-5} at 20 GeV).

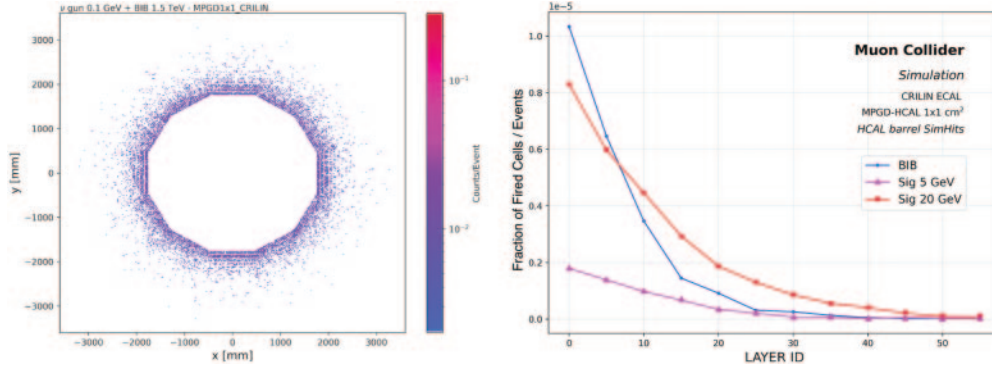


Fig. 2. – Left: distribution of BIB hits in the transversal x - y plane normalized to the number of events. Right: fraction of fired cells per event with respect to the HCAL barrel layers for the pure signal samples at 5 GeV (pink) and 20 GeV (red) and BIB (blue).

The timing coordinates of energy deposits are the key observable to selectively discard BIB hits. As shown on the left plot of fig. 3, most signal hits arrive between 5 and 10 ns, consistently with relativistic pions reaching the first HCAL layers. In contrast, BIB hits have a time distribution ranging from 5 to 20 ns. Applying a cut at $t > 10$ ns would exclude 49.53% of BIB hits while affecting only a small fraction of the signal.

To assess the energy resolution in the presence of BIB, the background samples were overlaid on signal in the digitization step. The study was carried out with the *noES* samples of pions, whose clusters were reconstructed with SDRO. A comparison of the energy resolution evaluated with and without BIB is shown on the right plot of fig. 3. With the overlay of BIB, the resolution curves, and consequently the fit parameters, are compatible within uncertainties, due to the low probability to match a BIB hit to a signal cluster.

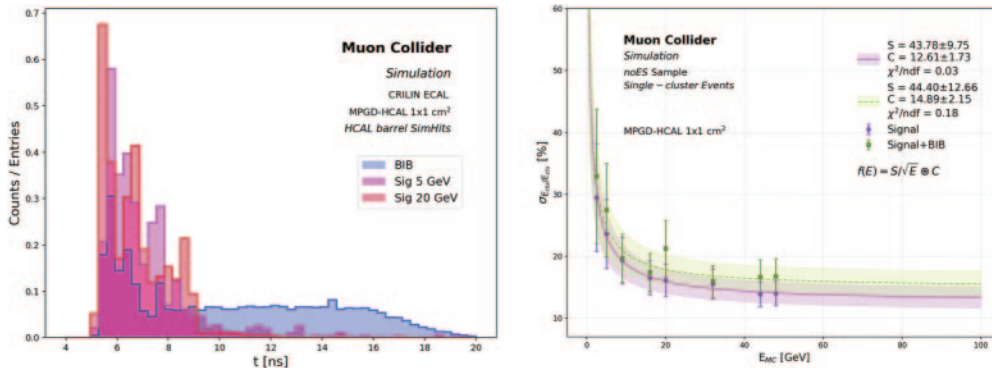


Fig. 3. – Left: arrival time distributions of hits from signal events at 5 GeV (pink) and 20 GeV (red) and BIB events (blue). Right: intrinsic energy resolution MC energy of the MPGD-HCAL markers and signal with SDRO for pure signal (purple bullet markers) and signal with BIB overlay (green squared markers). The fit curves are represented by the solid pink line for signal, and the dashed green line for signal with BIB overlay. The shaded bands are the 1σ uncertainties of the fit.

4. – Conclusions

The proposed MPGD-based HCAL proves to be a suitable design choice for a Particle Flow reconstruction due to its fine granularity (1 cm^2) and good intrinsic energy resolution. The semi-digital readout, optimized with thresholds of 0.2 keV, 4 keV, and 12 keV, outperforms the traditional digital approach, achieving an energy resolution characterized by a stochastic term S of about $45\%/\sqrt{E}$, even in the presence of BIB. The BIB characterization highlights low occupancy in the HCAL and identifies its distinguishing feature: longer arrival times compared to signal hits. BIB can be, then, mitigated by implementing arrival-time cuts. Importantly, the stochastic term of the energy resolution remains consistent within uncertainties between scenarios with and without BIB, staying below 60%. These results demonstrate the detector’s capability to meet the requirement for a precise jet energy resolution (3–4% above 100 GeV) in a PF approach, enabling the study of the Higgs boson with sub-percent precision.

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