Muon Collider experiment: requirements for new detector R&D and reconstruction tools

for the forming International Muon Collider Collaboration

Abstract

The update of the European Particle Physics Strategy [1] recommended to pursue the design of a feasible multi-TeV Muon Collider facility. While the machine has been studied in details at a centre of mass energy of 1.5 TeV by the MAP collaboration [2] with an extension to $\sqrt{s} = 3$ and 6 TeV, the energy range above 10 TeV is uncharted territory, offering an enormous potential for discoveries and precision measurements [3].

The optimization of the Machine Detector Interface (MDI) is a key element to improve machine performance at the interaction point, while mitigating the effect of the Beam Induced Background (BIB) on the detector performance. The unprecedented constraints, posed by the BIB components, require to further develop the state-of-the-art detector technologies and reconstruction tools to design experiments able to achieve the best performance at a muon collider facility.

During the SnowMass process, the goal will be to validate feasible performance parameters of newly designed experiments on a few agreed benchmark physics channels.

Present status

In a muon collider, the interaction of the muon decay products with machine elements causes enormous fluxes of secondary and tertiary particles that reach the experiment and could degrade its performances. In addition to an appropriately designed Machine Detector Interface (MDI), two tungsten (borated polyethylene coated) cone-shaped structures (nozzles) need to be inserted in the experiment around the beam pipe, opening from the interaction point, affecting the acceptance in the forward/backward region.

The detailed studies [4] for the 1.5 TeV center-of-mass Muon Collider showed quantitatively how severe is the background environment but also how to possibly reduce it to tolerable levels. Further MDI studies, planned at $\sqrt{s} = 3\ TeV$ [5], are crucial to optimize the experiment performance towards higher energies up to 10 TeV and above.

The BIB causes high occupancy levels and detector radiation aging, setting stringent constraints on the technology choices to reach the target performance. Difficulties in reconstructing objects (e.g. tracks), due to combinatorics not related to the collisions, and deterioration of resolutions (e.g. jet energy resolution), caused by extra background hits, demand to exploit innovative solutions.

An experiment suitable for a Muon Collider environment was first designed for MAP studies [4, 6] and its feasibility to reconstruct $H \rightarrow b\bar{b}$ decays with high precision, even in a very harsh environment, with a high level of precision has recently been demonstrated [7]. The study indicated that such an experiment is competitive to those at other proposed machines.

Full simulation studies, which include BIB produced at $\sqrt{s} = 1.5\ TeV$, are using the new common framework (Key4hep) code under development for future colliders. The experiment layout is based on the initial MAP tracker complemented by the other CLIC detectors design [8].

Since BIB products are mainly out of time with respect to the bunch crossing and do not originate at the collision point, combined timing and tracking resolution, coupled with a high-granularity jet reconstruction, are key handles to mitigate this background and enhance physics reach sensitivity.

The full simulation code, used for initial performance evaluation [9] and physics studies, is available to the community [10].

Experiment required performance

Physics benchmarks channels range from Higgs and Standard Model (SM) precision measurements to searches for Beyond SM (BSM) or Dark Matter signatures. The experiment's performance must satisfy demanding requirements: select multi-jet final states with flavour-tagging, reconstruct energetic leptons, boosted Higgs and gauge bosons, measure jets and missing energy with a superb energy resolution, identify secondary vertices and tracks not originated from the interaction region. Different collision energies, assumed to range between $\sqrt{s}$=3 TeV up to 10 TeV and above, could impact experiment performance and detector design.

The rate and distribution of BIB components reaching the experiment also depend on the beam energy, the machine optics and lattice elements with their embodied shielding which need to be optimized.

The goal, during the SnowMass process, will be to evaluate a set of performance parameters for several benchmark processes, using the improved full simulation [11]. The key performance parameters are: jet reconstruction efficiency and jet energy resolution, tracking efficiency and momentum resolution, impact parameter resolution, flavour tagging performance, lepton and photon identification. This will allow to validate an improved DELPHES card to better establish the multi-TeV Muon collider physics potential.

Detectors and Reconstruction tools R&D

The present design of a muon collider experiment layout includes a full silicon tracker and a high granularity calorimeter, with a solenoidal magnetic field of 4 T surrounding the calorimeters and muon tracking embedded in the iron yoke to reach average momentum resolution of a few $10^{-5}\ GeV^{-1}$.

Precision timing is one of the most important handles and needs to be available at detector level. Together with charge deposition in the tracker and shower shapes in the calorimeters one could further improve the background rejection power.

The following studies are proposed, during the SnowMass process:

1) evaluation of new detector R&Ds to join future programs, addressing dedicated developments;
2) assessment of new detector technologies to design an optimized experiment;
3) implementation and test of new reconstruction tools to mitigate backgrounds;
4) improvement and optimization of full simulation (with BIB) code assuming agreed benchmarks.

Several on-going detector R&D projects are of great interest for a muon collider experiment design:

** for silicon trackers: 4D tracking with sufficient radiation hardness and high occupancy capability, such as the AC-LGAD (RSD) sensors [12] and the 3D trenched [13] with 28 nm analogue and digital read-out;

** for calorimeters: high granularity [14] and timing in the inner layers and 5D imaging, also exploiting MPGDs [15] with unprecedented time and spatial resolution as active layers of a sampling calorimeter or muon detectors.

Assuming single-bunch beams in the collider, with time between collisions ranging from 15 to 50 μs, according to the centre-of-mass energy, the proposal is to study:

* the feasibility of a trigger-less DAQ;

* the improvement of hit pattern recognition and physical objects reconstruction and identification based on new Machine Learning (ML) algorithms also at detector level, exploiting FPGA and ASICs in heterogeneous platforms [16];

* the development of reconstruction software for heterogeneous computing resources (GPU, CPU).

Further developments are planned during the SnowMass 2021 process on objects and reconstruction tools, while optimizing usage of computing and software resources.

Parallel execution of critical parts of the tracking software may be achieved by leveraging GPUs, and modern machine learning techniques may be critical to achieve the needed reconstruction performance.

The final goal is to design an experiment for a multi-TeV Muon Collider achieving the highest physics sensitivity under realistic assumption, at different energy regime: $\sqrt{s} = 3$ and 10 TeV or above.

The new forming international collaboration [17, 18] aims to finally identify the prioritized lists of R&D projects needed for realizing such an experiment.

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