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

for the forming International Muon Collider Collaboration

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 extensively studied at the 1.5 TeV center of mass energy by the MAP collaboration [2] with an extension to $\sqrt{s} = 3$ and 6 TeV, the energy range above 10 TeV is an uncharted territory, offering an enormous potential for discoveries and precision measurements. Based on physics benchmarks, ranging from Higgs and SM precision measurements to searches for BSM or Dark Matter signatures, the best experiment's performance can be achieved only taking advantage of new detector R&D program and developing dedicated reconstruction tools.

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, despite the use of dedicated shielding [3]. Appropriately designed Machine Detector Interface (MDI) and two tungsten (borated polyethylene coated) cone-shaped structures (nozzles) had to be inserted in the experiment around the beam pipe, opening from the interaction point, affecting the acceptance in the forward/backward region.

The optimization of the MDI is a key element to mitigate the effect of the Beam Induced Background (BIB) on the detector while allowing good machine performance at the interaction point.
The detailed studies [3] for the 1.5 TeV center-of-mass Muon Collider showed quantitatively for the first time how severe is the background environment and how to possibly reduce it to tolerable levels.

Further MDI studies, planned at $\sqrt{s} = 3\,TeV$ [4], 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 choice to reach the desired good performance. Difficulties in reconstructing objects (e.g., tracks) due to the combinatorial not related to the collisions, and deterioration of resolutions (e.g., jet energy resolution) caused by extra background hits demand to exploit innovative solutions.

Present status

An experiment suitable for a Muon Collider environment was first designed for MAP studies [3, 5] and recently used to demonstrate [6] the reconstruction feasibility of the $H \rightarrow b\bar{b}$ decay channel in this harsh environment, with a high level of precision, competitive to other proposed machines.

Full simulation studies, which include BIB produced at $\sqrt{s} = 1.5\,TeV$, are on-going using the new common framework (Key4hep) code under development for future colliders, with a general purpose experiment layout based on the initial MAP tracker complemented by the other CLIC detectors design [7]. Since BIB products are mainly out of time with respect to the bunch crossing and not originated at the collision point, combined timing and tracking resolution, coupled with a high-granularity jet reconstruction, are the key handles to mitigate the background and enhance physics reach sensitivity.

The full simulation code, to study detector performance [9], and also used to carry on Higgs studies [10], is available to the community. Further developments are planned during the SnowMass21 process on objects and reconstruction tools, while optimizing usage of computing and software resources.

Experiment required performance

Experiment's performance requirements, also addressing $\sqrt{s}$ up to 10 TeV and above, are demanding and diverse: to select multi-jet final states with flavour-tagging and good jet energy and missing energy reconstruction, to identify high energy electrons and muons, to reconstruct bosons mass with good resolution, to identify secondary vertices and tracks not originated from the interaction region.

The rate and distribution of BIB components reaching the experiment's volume depend on the collider energy, the machine optics and lattice elements with their embodied shielding to be optimized. At the same time a new advanced detector design and more elaborated reconstruction tools will finally define the best experiment's performance parameters on a longer term plan.

The goal, during the SnowMass process, will be to establish with the improved full simulation, on a few agreed benchmark physics channels, a set of feasible performance parameters: 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 a multi-TeV Muon collider physics potential [].

Detectors and Reconstruction tools R&D

The present design is a general purpose experiment layout, full silicon tracker and high granularity calorimeter, with a solenoidal magnetic field of about 4-5 T surrounding the calorimeters and muon tracking embedded in the iron yoke to reach average momentum resolution of a few 10(^-5) GeV(^-1). Precise timing information is the most important handle to be exploited, at tracking and jet reconstruction level. Charge deposition in the tracker and shower shapes in the calorimeters together with timing could further improve background power rejection.

The proposed activities will benefit from the inputs and review during the SnowMass process:

1) evaluation of new detector R&D 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.

Quite appealing ongoing detector R&D are already considered of great interest for:

** silicon tracker: 4D tracking with sufficient radiation hardness and high occupancy capability, like the new AC-LGAD (RSD) sensors [10] and the 3D trenched [11] with 28 nm analogue and digital read-out;

** calorimeters: high granularity and timing in the inner layers and 5D imaging, exploiting new MPGD muon reconstruction and identification with unprecedented time and spatial resolution.

Assuming single-bunch beams in the collider, the time between collisions will range from 15 to 50 μs, varying with the center-of-mass energy, setting the framework to start addressing:

* the feasibility study of a trigger-less DAQ;

* the improvement of hit pattern recognition and physical objects reconstruction and identification based on new Artificial Intelligence algorithms also at detector level;

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

The goal will be to define a list of prioritized key elements to be addressed by the forming international collaboration [12,13] to finally design an optimized realistic experiment for a multi-TeV Muon Collider achieving the highest physics sensitivity reach.

AUTHORS

P. Andreetto, N. Bartosik, A. Bertolin, L. Buonincontri, A. Colaleo, M. Casarsa, F. Collamati, C. Curatolo, A. Ferrari, A. Gianelle, D. Lucchesi, B. Mansoulie, A. Mereghetti, N. Mokhov, M. Palmer, N. Pastrone, C. Riccardi, P. Sala, L. Sestini, I. Vai

➔ to be completed

REFERENCES

[1] 2020 Update of the European Strategy for Particle Physics https://home.cern/sites/home.web.cern.ch/files/2020-06/2020 Update European Strategy.pdf , see also the EPPSU "Physics briefing book", arXiv:1910.11775 (2019)

[2] The Muon Accelerator Program, https://map.fnal.gov/; see also JINST Special Issue on Muon Accelerators for Particle Physics, https://iopscience.iop.org/journal/1748-0221/page/extraproc46

[3] N.V. Mokhov and S.I. Striganov, *Detector Background at Muon Colliders*, *Phys. Procedia* **37** (2012) 2015-2022, [arXiv:1204.6721]

[4] MDI LoI

[5] V. DiBenedetto, C. Gatto, A. Mazzacane, N.V. Mokhov, S.I. Striganov and N.K. Terentiev, *A Study of Muon Collider Background Rejection Criteria in Silicon Vertex and Tracker Detectors*, 2018 *JINST* **13** P09004 [arXiv:1807.00074]

[6] N. Bartosik, et al., *Detector and Physics Performance at a Muon Collider*, JINST 15(05), P0500 (2020)

[7] CLIC collaboration, *Detector Technologies for CLIC*, YR CERN-2010-001

[8] ICHEP2020 talk M. Casarsa et al.

[9] ICHEP2020 talk L. Sestini et al.

[10] RSD

[11] 3D trenched

[12] Muon Collider Collaboration LoI

[13] Muon Collider Facility LoI