Muon Collider: solidifying the physics case.

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Abstract: Muon Colliders present a highly attractive future collider option due to their small size, high efficiency, and the potential to reach very high energies. In this Letter of Interest, we propose to benchmark performance of physics objects reconstruction in the Muon Collider environment using realistic beam and detector simulations. As part of the development, we propose to improve and advance the existing simulation tools in order to make them more accurate, efficient, and accessible for an average HEP user. We will then measure and parametrize properties (efficiency, resolutions, etc) of reconstructed leptons, jets, and missing energy, as well as heavy flavor tagging performance. This will be done taking into account the overwhelming beam induced backgrounds (BIB) present at the muon colliders, which is a necessary step to establish accuracy of phenomenological studies that have so far mostly ignored the BIB. The proposed work will be carried out with European collaborators and will lay the foundation for specific studies in the areas of precision Higgs/Standard Model (SM) measurements and direct searches for physics beyond the SM (BSM), for which separate LOIs will be submitted.

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Motivation: Collider physics is rich, diverse, and versatile. It offers amazing opportunities at the Energy Frontier. Over the last several decades, colliders have played a central role in experimental establishment of the SM, from discovery of the charm quark in 1974 to the Higgs boson discovery in 2012. Since the Higgs boson discovery, the hunt for new physics in the collider environment has essentially taken two approaches: (1) direct searches for new physics with higher masses or smaller couplings, or (2) precision measurements of the SM parameters, including detailed characterization of the Higgs boson, that can access new physics in an indirect way. The full LHC dataset will provide great opportunities for studies of the SM and will greatly extend the sensitivity for new physics.

However, it is plausible that new colliders are necessary to shed light on the existence and nature of new physics. A number of e+e- machines have been proposed globally as Higgs factories in order to achieve unprecedented accuracy of the Higgs properties measurements. However, their energy reach is limited to a few TeV at best. Very large proton-proton colliders are thus envisioned to follow e+e- runs, extending the direct reach for new physics up to the ~10 TeV scale. In light of these considerations, the muon collider is extremely appealing because such a machine can be very compact and yet potentially capable of providing both precision measurements in the electroweak sector and direct access to particles with masses of up to 10 TeV [1]. It also offers unique synergies with the neutrino physics community (e.g. nuSTORM). The size of a muon collider varies from a few kilometers (which could easily fit on the Fermilab site) to approximately LHC size for 10 TeV or more. The muon collider option is particularly attractive for the US HEP community, which possesses unique expertise based on the experience with MAP and, more recently, close collaboration with the European proponents. Finally, acceleration of muons appears to be the only option for pushing the energy horizon beyond 100 TeV, which is the maximum for the future proton machines.

Challenges: For the purpose of event reconstruction, the challenge that separates mu+mu- colliders with the e+e- counterparts is the BIB. Because muons are unstable, they decay in flight, producing electrons that further interact with the accelerator and detector components. This creates very large multiplicities of mostly soft secondary particles, some of which end up in the detector. It should be noted that the amount of background reduces as the energy of the collider grows because of the increased lifetime of higher energy muons. The hits produced by the secondary particles in the tracker lead to a huge combinatorial challenge for the track reconstruction, while their energy deposits lead to the reconstruction of unphysical jets in the calorimeters. This in turn results in stringent requirements on the granularity, resolution, and timing properties of the muon collider detectors. Phenomenological studies of the muon collider physics performed so far largely ignore the issue of the BIB and assume high efficiency of physics object reconstruction. Limited studies in the presence of BIB exist. However, full simulation studies are necessary for thorough benchmarks of reconstruction performance that can translate into physics projections.

Proposal: Future e+e- and pp machines benefit from large communities and years of studies to establish their physics program. The Muon Collider physics studies are less comprehensive, however now is a natural time to fully understand the physics reach of such a machine and consider it as a realistic option.

A framework for Muon Collider simulations has been recently developed by physicists from INFN [2] based on the CLIC/ILC simulation framework ILCSoft [3]. This framework allows for beam induced background simulation generated using MARS [4] to be overlayed onto simulated collision events. We propose to collaborate with European partners to measure and parametrize reconstruction and tagging efficiencies and resolutions for leptons (electrons and muons), jets (potentially including boosted hadronically decaying top quarks and bosons), flavor tagging of jets, and missing momentum. Reconstruction of these objects is necessary for a wide range of physics measurements, e.g. Higgs boson couplings to the vector bosons (k_V), fermions (k_b, k_c, k_μ), self-coupling strength (k_3/k_4), and searches for new physics such as new resonances, Dark Matter production, or electroweak/RPV supersymmetry. We aim to evaluate the object reconstruction parameters for different center-of-mass energies (and hence background configurations) of 1.5 and 3 TeV and extrapolate to higher energies of up to 30 TeV. We will also attempt to study the 125 GeV Higgs factory scenario, which amongst other benefits could provide incredible precision on the total Higgs width and mass.

There are several challenges that need to be overcome in the current framework. Due to the BIB, tracking and clustering are currently memory- and CPU-intensive, prohibiting the framework from running on the grid infrastructure and limiting simulations to a few high-end machines. The authors will work on improving the detector design and the reconstruction algorithms to suppress the BIB and reduce resource consumption of the framework. Different approaches to simulating, digitizing, and reconstructing the BIB will be explored in order to reduce the resource consumption of the framework.

The outcome:

1. The derived parametrizations will be used for creating DELPHES cards necessary to benchmark physics scenarios in time for Snowmass. LOIs for physics studies of the processes of interest at the Muon Collider are being submitted in parallel.
2. By comparing object performance at $\mu^+\mu^-$ with those at the e^+e^- and pp machines and by folding in corresponding energies (cross section) and luminosities, we should be able to obtain at least qualitative comparisons for many more physics scenarios.
3. The studies will help to develop improved detector design concepts, reconstruction algorithms, and allow corner specifications for the future muon collider detectors.
4. The proposed work will help to improve performance of the current full simulation tools, to the point where they can be used for developing the Muon Collider Physics Technical Design Report.

References:

[1] https://arxiv.org/pdf/2005.10289.pdf
[2] https://github.com/MuonColliderSoft
[3] https://ilcsoft.desy.de/portal
[4] https://mars.fnal.gov/