Letter of Interest: Muon Collider Physics Potential

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On behalf of the forming muon collider international collaboration [1]

We describe the plan for muon collider physics studies in order to provide inputs to the Snowmass process. The goal is a first assessment of the muon collider physics potential. The target accelerator design center of mass energies are 3 and 10 TeV or more [2]. Our study will consider energies $E_{\mathrm{CM}} = 3, 10, 14$, and the more speculative $E_{\mathrm{CM}} = 30$ TeV, with reference integrated luminosities $\mathcal{L} = (E_{\mathrm{CM}}/10\ \mathrm{TeV})^2 \times 10\,\mathrm{ab}^{-1}$ [3]. Variations around the reference values are encouraged, aiming at an assessment of the required luminosity of the project based on physics performances. Recently, the physics potentials of several future collider options have been studied systematically [4], which provide reference points for comparison for our studies.

1 Physics study topics

Among the many possible directions, we plan to first focus on the following ones.

Reach of the direct search for heavy new physics particles. This will be a main strength of the muon collider running at multi-TeV energies. Selected study topics include:
1) SUSY. The reaches for the stop, other sfermions, and EW-inos will be estimated, possibly including R-parity-violating signatures. Scenarios with well separated to compressed particle spectra will be considered, which will require significantly different strategies and challenge the detector performances (see below). The lessons learned from SUSY benchmarks will be also useful for the study of other new physics scenarios.
2) Minimal WIMP dark matter scenarios. Many of the simplest WIMP dark matter scenarios put its mass in the multi-TeV range, within the reach of a high energy muon collider. They often feature a highly compressed spectrum. Direct reach can be based on stub-tracks, as well as more inclusive search channels, such as the mono-X. Indirect searches can also be sensitive [5]. Possible benchmarks include the Minimal DM [6] in which the dark matter resides in an electroweak multiplet, as well as the Coannihilation [7] and well-tempered [8] scenarios. See also [9, 10]
3) Heavy particle production in Vector Boson Fusion (VBF), including $\gamma\gamma$ initial state. VBF is instrumental at a high energy muon collider. Its potential in the singlet searches has been demonstrated [11,12]. An assessment of the VBF opportunities for direct new physics searches, by extending and refining Ref. [13], will be performed. This might impact the studies in "1" and "2".
High energy measurements. Cross-sections at the highest available energies offer tremendous indirect sensitivity to very heavy new physics. This will be substantiated by the following study.
4) Effective Field Theory (EFT) sensitivity of high energy di-boson/di-fermion production cross-section, with interpretation in Composite Higgs (and Top) and simple Z' models. The interplay with direct searches will also be explored. Low-energy (e.g., Higgs couplings) and intermediate-energy (e.g., VBF double-Higgs at TeV energies [14]) probes will be also exploited.
The precision measurement of the Higgs couplings. The muon collider with the baseline energies and luminosities will produce a large number of Higgs bosons, from 10^5 at 3 TeV to more than 10^7 at 10 TeV and above. We will study how to fully take advantage of this opportunity.The main targets of the study are:
5) Projections of the precision of single Higgs coupling measurements, with EFT interpretation for a comparison of the sensitivity with other probes such as those at point "4". Unlike the other proposed (e^+e^-) Higgs factories running at lower energies, the main Higgs production mode would be vector boson fusion instead of higgsstrahlung. The implications of this difference will be carefully investigated. The possible complementarity with low-energy Higgs factories, probably constructed before the muon collider, will be investigated.

6) Higgs self-coupling measurements. The muon collider at 10 TeV would produce 3×10^4 double Higgs events, which offers a golden opportunity for Higgs trilinear coupling measurements [16]. The quadrilinear Higgs coupling could also be measured in triple-Higgs events [15]. We aim at realistic sensitivity projections including differential analysis, Higgs decays and backgrounds. We will interpret the findings in concrete new physics scenarios. We will also assess the interplay with direct searches for the degrees of freedom responsible for the self-coupling modifications, which are very effective at the muon collider due to the high mass-reach.

More exotic possibilities. We will study several scenarios of new physics with unique signals. The goal here is to showcase the rich physics program we could have at a muon collider, and to offer additional targets for detector studies.

7) Higgs exotic decay. Lepton colliders such as the e^+e^- Higgs factories can have good sensitive to a variety of Higgs exotic decay channels [16]. A muon collider running at high energies will produce one to two orders of magnitude more Higgs bosons. It has the potential of significantly enhancing the sensitivity. Higgs decays to Long-lived particles, which are ubiquitous in dark sector models, will be also considered. A common benchmark is the Higgs portal decay $h \to XX$ with X being long lived. With 10^7 to 10^8 Higgs bosons, the muon collider could be competitive with other projects.

2 Physics simulations

Standard tools such as WHIZARD [17] and MadGraph5_aMC@NLO [18] are already available for signal and (physics) background simulations at the muon collider. Work is ongoing to include in MadGraph5_aMC@NLO the generation of Initial State Radiation and (when available) the Beam Energy Spectrum. Notice that both effects are reduced in comparison with high-energy e^+e^- colliders, with potential advantages on some aspects of the physics reach. ISR-based (i.e., from radiative return) $2 \to 1$ BSM production should be also studied [19].

On the other hand, computation of cross sections and simulations of VBF processes at such high energies pose new challenges. Potentially large electroweak logarithms $\log(s/m_W^2)$ (and QED $\log(s/m_\mu^2)$ logs) may be generated, making on the one hand the fixed order simulations hard to converge, and on the other hand possibly affecting the accuracy of the predictions at fixed order. The implementation of the equivalent W, Z, γ approximations are available both in WHIZARD and MadGraph5_aMC@NLO. A systematic comparison of the reliability of these approximations is planned. In addition, the effects of the resummation of the large logarithms at high energy have started to be explored [20], and their impact on the accuracy of the total cross section will be studied.

A parametric modeling of the detector response, in terms of high-level objects efficiencies and reconstruction performances, is needed for a realistic assessment of the physics potential including physics backgrounds (as opposite to Beam-Induced Backgrounds (BIB)). This will be provided by a Delphes [21] card, which we will prepare and maintain. The first version of the card will incorporate "target" performances of high level objects (tracking, lepton and photon identification, jet reconstruction and heavy flavour tagging), that are comparable with those of present detectors and of future projects, and supposedly sufficient to achieve the physics goals.

The "target" detector is expected to provide realistic results for the majority of the studies described in Section 1. However, the BIB might pose significant challenges on the reconstruction and identification (heavy-flavour tagging for example) of low pT objects produced in the compressed decay regime of item "1" and the Higgs decay products (e.g., the bottom quarks, for which BIB-aware studies exist [22], see also [23]) in items "5" and "6". Forward- or backward-produced particles could be also difficult to see because of the reduced angular acceptance of the detector due to the radiation-absorbing nozzles in the current designs. Finally, BIB is definitely crucial for certain aspects of the physics potential, such as the study of disappearing tracks in item "2", and of long-lived particles in item "7". The impact on the physics reach of these aspects will be monitored, also by progressively updating the Delphes card as the detector studies proceed [24], in order to link the design of the machine and the detectors to the physics goals.

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