Muon collider: A window to new physics

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Abstract *We propose to study the physics potential of a future muon collider at center-of-mass energies ($\sqrt{s}$) of 1.5, and 3 TeV, and provide extrapolations to even higher energies up to 30 TeV. The studies should include realistic reconstruction efficiencies to take into account limitations such as those from the beam induced background (BIB). In this Letter of Interest (LoI), we discuss studies for new physics searches. A second LoI has been written for studying standard model (SM) precision measurements of the electroweak sector, and a third one for studies on the reconstruction and simulation of a muon collider experiment.*

Motivation High energy particle colliders are powerful tools for studying the SM and searching for physics beyond the SM (BSM). While the SM provides the best known description of the universe, open questions remain, for example the origin of dark matter (DM). The LHC has shown no hints of new physics thus far, suggesting that new particles could be lurking at higher energies. A new collider that can produce multi-TeV collisions is the only way to conclusively test what lies beyond the SM.

Two types of machines have been used over the last century. Electron-positron colliders excel in precision studies, however have limited reach in energy: proposed circular colliders might reach energies up to the $t\bar{t}$ production threshold, while linear colliders reach energies of "only" a few TeV. Proposed proton-proton colliders might reach $\mathcal{O}(100\,\text{TeV})$ collisions. However, these ring machines will have to be enormous in footprint, with circumferences of $\mathcal{O}(100\,\text{km})$, and cost. Also, protons are not fundamental particles, so the effective energy is considerably smaller. Future muon colliders are unique machines. They are appealing because they could reach high energies while still being compact. A multi-TeV muon collider could, for example, fit on the Fermilab site [1]. A muon collider similar in size to the LHC could reach $\sqrt{s} > 10\,\text{TeV}$. Therefore, its discovery reach is expected to significantly exceed that of proposed future circular proton-proton colliders for new electroweak physics [2].

Proposed Studies In this LoI, we propose several benchmark studies for BSM physics at a muon collider with $\sqrt{s}$ in the multi-TeV range. These benchmark studies will take into account the realistic challenges posed by the overwhelming BIB at a muon collider. A separate LoI which focuses on examining reconstruction efficiency and resolution of standard physics objects at a muon collider experiment is being submitted. If possible, we will use Delphes cards from the studies presented in that LoI to obtain realistic efficiencies. Else, we will use dedicated full-detector simulations.

Our focus here is to study BSM signatures that could be significantly impacted by BIB. For example, it is important to keep resolution effects to a minimum for DM searches which utilize missing momentum.

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Several BSM signatures also require the reconstruction of soft leptons and tracks with a low mistag rate, or good separation between photon showers and those of electrons or jets.

In the following sections we discuss several possible benchmark models, for which we believe a muon collider experiment might give unprecedented insights into our understanding of particle physics.

Resonances and Dark Matter The presence of DM in the universe is one of the biggest puzzles in particle physics, as no particle candidate for DM has been discovered. We propose to perform two studies in this aspect. First, one can look for the production of DM at a collider in a model-independent way. One typical signature is tagging the DM interaction through events containing an initial-state-radiated (ISR) photon which is balanced by missing momentum [3]. Especially for heavy mediators, the sensitivity for DM surpasses that of direct DM detection experiments. Second, we can search directly for the mediator, which could be heavy gauge or Higgs bosons [4, 5]. Some models have reduced couplings to quarks [6–8], and the direct search for such a resonance at highest energies of a muon collider should yield exceptional sensitivities. Precise measurement of the high energy distributions could also reveal indirect evidence of the mediators with mass beyond the reach of the direct searches. For wide resonances performing an $\sqrt{s}$ scan should quickly reveal the existence of these new particle states. Otherwise, we can look for them using an ISR photon as above [9], or - if the mediator couples to electroweak bosons - using the vector boson fusion (VBF) signature.

Electroweakino searches Searching for electroweak BSM physics at hadron colliders is usually difficult because the signal is small and the background is overwhelmingly large. A search for electroweakinos, the partners of the gauge and Higgs bosons in supersymmetry (SUSY), is highly motivated, inter alia by naturalness [10]. They can be interesting dark matter candidates as well. Depending on the electroweakino mass and $\sqrt{s}$, either the annihilation of two muons or the VBF process will dominate the sensitivity of the search [11]. An interesting observation is that for the VBF process, the electroweakino production cross section grows steadily with $\sqrt{s}$. For example for a mass of $400\,\text{GeV}$ and $\sqrt{s} = 1\,\text{TeV}$, the cross section is 4 orders of magnitude smaller than that of the $125\,\text{GeV}$ Higgs boson. But for $\sqrt{s} \geq 10\,\text{TeV}$, the electroweakino cross section grows by more than two orders of magnitude, while the Higgs boson cross section grows by about a factor 4. Of particular interest in electroweak SUSY searches is the compressed spectrum between different electroweakino states (of $\Delta\text{M} \lesssim 1\,\text{GeV}$) as proton-proton collider experiments are not sensitive to them [12, 13]. For this signal to yield a high sensitivity, a good reconstruction of soft leptons and tracks is needed as mentioned above.

Another interesting signature is search for electroweakinos in R-parity violating (RPV) scenarios, particularly baryon-number violating scenarios. Such models can give rise to all-hadronic final states. Due to low production cross-section and large backgrounds, searches for such signatures are extremely difficult at hadron colliders. A muon collider experiment could probe new phase space in these scenarios for the first time since LEP.

Long-lived particles Most searches for new physics assume that a new BSM particle would decay almost immediately, or is invisible and escapes the detector. However, several particles in the SM already break this assumption, and new long-lived particles are predicted in a diverse array of BSM models, including models which address the hierarchy problem and provide a dark matter candidate [14, 15]. The resulting long-lived particle signatures pose unique challenges in terms of reconstruction and non-standard backgrounds.

We propose to study sensitivity to heavy meta-stable charged particles. These new particles could be reconstructed as prompt tracks, which are slowly moving or highly ionizing. The track's time of flight and dE/dx measurements can be used to infer the mass of the LLP. Sensitivity depends on the number of detector layers providing timing or dE/dx information, as well as the resolution of each measurement. One important question is what is the minimum number of hits that could be required per track in the presence of a large BIB, in order to retain sensitivity to shorter lifetimes. We are also interested in studying how track pointing or hit timing requirements designed to reject BIB would impact sensitivity to displaced or delayed jets. We plan to use these studies to demonstrate if a muon collider experiment is sensitive to LLP scenarios, and possibly inform detector design.

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This LoI proposed studies related to following subgroups:

– **Energy frontier** (primary frontier):

- EF08: BSM: Model specific explorations
- EF09: BSM: More general explorations
- EF10: BSM: Dark Matter at colliders

– **Accelerator frontier** (related frontier):

- AF04: Multi-TeV Colliders