Electroweak multiplets at the Muon Collider

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1 Introduction

The lack of a Dark Matter (DM) candidate in the Standard Model (SM) is one of the most compelling arguments to seek for its extension. Among the various possibilities, Weakly Interacting Massive Particles (WIMP) are a well-motivated option to obtain the correct relic abundance through the freeze-out mechanism, and they are ubiquitous in BSM models. Higgsino- and Wino-like states, the supersymmetric partners of the Higgs and W fields respectively, are a notable model-specific example of a WIMP. Minimalistic bottom-up SM extensions [1, 2] propose to add new multiplets to the SM such that the lightest neutral component is stable and provides a DM candidate. Depending on the mass hierarchy and differences between the particles in the multiplets, striking experimental signatures can be obtained, with either charged states with a long enough lifetime to be observed directly as charged tracks, or production of displaced charged particles [3, 4, 5, 6, 7, 8]. The investigation of either of these scenarios is particularly challenging at hadron colliders. Future lepton colliders, such as a high-energy muon collider could greatly extend the reach of the current hadronic machines (LHC and HL-LHC) [9]. In particular, for the muon collider case, it has been shown in Ref. [10] that it can discover the new physics behind the g-2 anomaly, assuming that the current running experiment at Fermilab establish the g-2 excess.

While this LoI focuses on EW multiplets as WIMP DM, it is true that they have a larger scope and appear in other contexts, e.g: FIMP DM [11], Seesaw type-III [12], or explanations for the muon (g-2) anomaly [13, 14]. We leave the exploration of such new physics scenarios as a possible research direction.

2 Experimental setup(s)

The main experimental facility considered in this study is a future muon collider able to operate at the center of mass energies $\sqrt{s} = 3$, 10, and 30 TeV. For each $\sqrt{s}$ configuration, an integrated luminosity of $L = (\sqrt{s}/10\,\text{TeV}) \times 2 \times 10\ \text{ab}^{-1}$ is assumed to be collected. Compared to hadron machines, lepton colliders utilize the full $\sqrt{s}$, enabling the exploration of BSM physics at unprecedented energy scales. The muon collider sensitivity will be compared, when available, with the recent HL-LHC prospects [15, 16] . The studies assumed an integrated luminosity of 3 ab^{-1} collected with centre-of-mass energy $\sqrt{s} = 14$ TeV proton-proton collisions at the High-Luminosity Large Hadron Collider (HL-LHC). If time allows, a comparison with other alternatives is also foreseen.

3 Simulation and reconstruction

Monte Carlo samples will be used to predict the expected backgrounds from SM processes and to model the signal scenarios under consideration. Signal and background processes will be generated with standard programs like WHIZARD and MadGraph5_aMC@NLO. The detector response will be modeled with parameterised response functions for the high-level objects reconstruction and identification efficiencies with the Delphes [17] program. Dedicated response functions will be derived for track-based quantities from full simulation. This is particularly important to realistically assess the impact of the beam-induced-backgrounds [18, 19, 20, 21] on the reconstruction of short "disappearing" tracks, the reconstruction of potential low-energy secondary particles (e.g. charged pions) and the respective fake rates. This work will be pursued within the newly forming International Muon Collider collaboration.

4 Goals

We plan to investigate the sensitivity of a future muon collider to new electroweak multiplets that could address the DM problem. Compressed sub-GeV mass spectra will be the target of the investigation, and experimental signatures such as the "disappearing" tracks or the production of displaced charged particles will be considered.

Discovery and exclusion lines will be presented as a function of the next-to-lightest particle in the electroweak multiplet and its lifetime. We will also explore the potential to directly extract the masses, mass splittings and lifetimes, which are particularly challenging to reconstruct at a hadron collider. A comparison with the available future collider prospects will be provided. If time allows, a comparison with other alternatives, such as electron-positron colliders, will be presented. In this scenario, although the absolute reach will be limited by the lower centre of mass energy, the beam induced backgrounds are expected to have a significantly lower impact, and constitute an optimal scenario comparison for the refinement of the tracking methods at the muon collider.

The findings of this study will greatly contribute to the physics case of the muon collider, allowing to directly probe the phase space favoured by minimalistic SM extensions aimed at solving the DM problem.

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