PROCEEDINGS OF SCIENCE

New physics and hidden sectors at Muon Collider

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Muon colliders offer enormous potential for the exploration of the particle physics frontier, representing the unique possibility of combining the high centre-of-mass energy and luminosity of hadron colliders with very precise measurements of lepton machines. They provide an unprecedented physics reach from Standard Model (SM) processes to new physics beyond the SM.
The contribution presented will give a general overview of the latter topic, broadening from supersymmetry and dark matter to muon-specific opportunities for the study of $g-2$ and B anomalies.
In particular, the sensitivity of a 3 TeV Muon Collider to an extended dark-SUSY model, a hidden sector coupled to SM via supersymmetric neutralino portal characterized by multi muons in the final state, will be discussed along with some considerations on muon reconstruction performance.

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1. Introduction

Muon colliders offer a great opportunity to combine the advantages of both proton and electron machines. They can achieve, on the one hand, high center-of-mass energy and luminosity and, on the other hand, very precise measurements by ensuring a low level of synchrotron radiation and beamstrahlung.

However, the dare of producing bright muon beams and the muon's short lifetime make these colliders challenging to realize [1]. A review of all the recent studies concerning the design of the machine and the detector is reported in Ref. [2] together with the physics potential. Regarding this last topic, some results are discussed in Section 2 by way of examples of new physics opportunities, while Section 3 shows preliminary sensitivity of a 3 TeV Muon Collider to a specific hidden sector, the dark-SUSY model.

2. New physics potential

Muon colliders provide an extensive and unprecedented physics program broadening from direct searches to muon-specific opportunities, such as the test of lepton flavour universality, passing through high-energy measurements, e.g. Higgs self-coupling, and high-energy probes, e.g. compositeness. A few of these are discussed in the following to prove the potential of a muon collider.

2.1 Direct searches

As far as beyond Standard Model (BSM) is concerned, a 10 TeV Muon Collider with an integrated luminosity of 10 ab^{-1} can produce new particles abundantly. In fact, Figure 1 left shows the number of these pair-produced hypothetical particles computed with MadGraph [5] by considering only neutral vector boson fusion (VBF) induced by electroweak (EW) interactions.

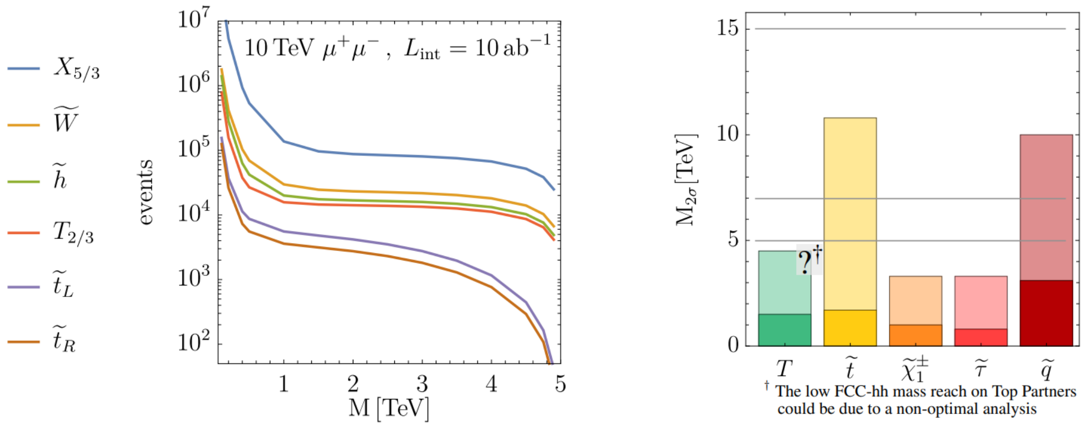

Figure 1: Left: Number of EW pair-production expected events at a 10 TeV Muon Collider, with 10 ab^{-1} integrated luminosity, for several BSM particles [3]. Right: 95% CL mass reach, from Ref. [4], for BSM particles at the HL-LHC (solid bars) and at the FCC-hh (shaded bars). The tentative discovery reach of a 10, 14 and 30 TeV Muon Collider are reported as horizontal lines.

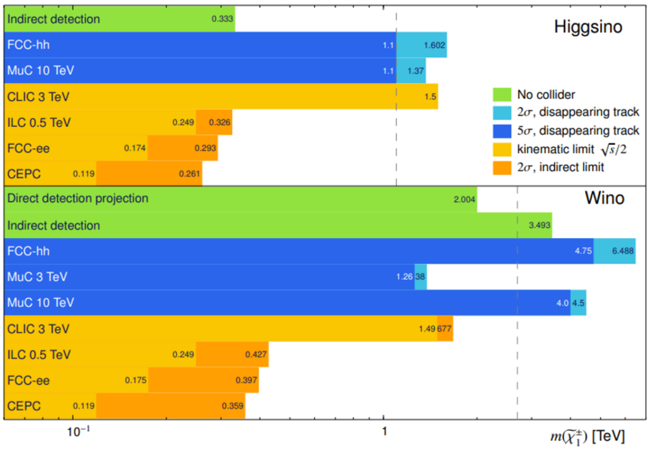

Figure 2: Summary of the exclusion and discovery mass reach on Higgsino and Wino dark matter candidates at future experimental facilities. Figure readapted from Ref. [6].

Particles are labelled according to the composite Higgs model ($X_{5/3}$ and $T_{2/3}$ are top quarks heavy partners with exotic charge) and supersymmetry nomenclature, but the results are model-independent. Moreover, the Muon Collider's reach exceeds the one of the High-Luminosity Large Hadron Collider (HL-LHC) and of the hadronic Future Circular Collider (FCC-hh) for many BSM particles (see Fig. 1 right).

Dark matter is the most fascinating evidence of physics BSM, and a 10 TeV Muon Collider could help shed light on its nature. Figure 2 shows the sensitivity of future accelerators to minimal models with pure Higgsino (top) and Wino (bottom), respectively. For the Muon Collider, the case of disappearing tracks is investigated, and it turns out to be one of the most promising proposed machines, excluding FCC-hh. Besides, the Muon Collider reaches the thermal mass (dashed grey vertical line in Fig. 2) for which the observed relic abundance is obtained by thermal freeze-out.

Finally, a muon collider is extremely sensitive to VBF production. A simple benchmark model foresees only a new particle, a real scalar singlet, that mixes with the physical Higgs boson. The trilinear coupling is $SH^\dagger H$, and γ is the mixing angle. The singlet is directly produced by VBF $VV \to S$. Figure 3 left shows the exclusion contour in the mass-mixing angle plane. Already a 3 TeV Muon Collider improves the HL-LHC sensitivity by a factor of three. Moreover, at tens of TeV centre-of-mass energy, a sensitivity $s_\gamma^2 \lesssim 10^{-4}$ or lower can be reached, corresponding to a deviation in the Higgs coupling of $O(10^{-4})$, which is beyond the limit of any present and future machine.

2.2 Muon-specific opportunities

A muon machine also offers muon-specific opportunities. It is the only machine able to probe new physics (NP) in the muon $g-2$ in a completely model-independent way in the assumption of very heavy NP ($\Lambda \gg 1$ TeV). The dipole operator that generates Δa_μ induces, for example, NP contributions to $\mu^+\mu^- \to h\gamma$. The reach of a muon collider as a function of the centre-of-mass energy is reported in Figure 3 right for this process (black curve) together with $\mu^+\mu^- \to hZ$ (blue curve), $\mu^+\mu^- \to c\bar{c}$ (orange curve), and $\mu^+\mu^- \to t\bar{t}$ (red curve). If the g-2 anomaly arises at

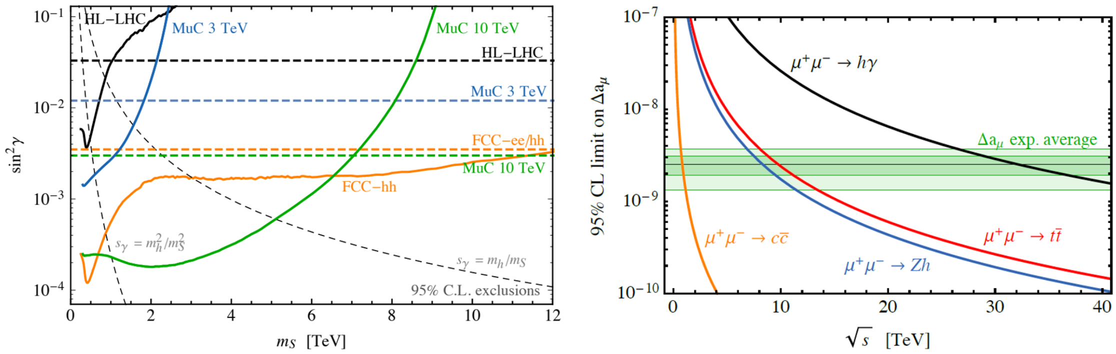

Figure 3: Left: Exclusions on the mixing angle of a generic scalar singlet ($\sin^2\gamma$) as a function of the singlet mass for the various collider benchmarks. The thin dashed lines indicate the two possible scalings of the mixing angle with singlet mass [7]. Right: 95% CL reach on the muon anomalous magnetic moment as a function of the collider center-of-mass energy [8].

loop-level from quark interactions, a few TeV collider could already probe it with a threshold of 1 TeV for charm and 10 TeV for top quarks, respectively.

3. Hidden sectors

Hidden sectors are collections of particles (dark bosons, fermions, and scalars) that are not directly charged under SM strong, weak and electromagnetic forces, proposed to explain easily the known gaps of the SM such as the nature and abundance of dark matter, the naturalness, and the baryon asymmetry. These new particles interact with ordinary matter through a mediator, and, according to the mediator spin and parity, different portals can be distinguished.

The dark-SUSY is a vector portal hidden sector that adds to the minimal SUSY model the gauge symmetry group $U(1)_D$, spontaneously broken at the GeV scale, that gives rise to a light dark photon [9]. The simplest way to generate dark photon mass is through a dark Higgs mechanism [10]. Thus, a self-consistent hidden sector contains also a dark Higgs in addition to the dark photon. Figure 4 left shows the Feynman diagram of the extended dark-SUSY channel investigated: the lightest supersymmetric neutralino $\widetilde{N}_1$ decays through a dark Higgs boson H_d in two dark photons (γ_d). A muon pair, with kinematics driven by the photon mass, is then expected from each dark photon, giving final states characterized by eight muons. A dark neutralino (n_d) is also produced, resulting in missing energy. The total cross section is

$$\sigma(\mu^-\mu^+ \to \widetilde{N}_1\widetilde{N}_1) \times \mathcal{B}^2(\widetilde{N}_1 \to n_d H_d) \times \mathcal{B}^2(H_d \to \gamma_d\gamma_d) \times \mathcal{B}^4(\gamma_d \to \mu^+\mu^-),$$

but the branching ratio $\mathcal{B}(H_d \to \gamma_d\gamma_d)$ is supposed equal to 1, and the same holds for the branching ratio of the neutralino in a dark Higgs and a dark neutralino. The neutralino mass is set to 96.69 GeV, the default Minimal Supersymmetric Standard Model value, corresponding to a neutralino pair production cross section of 13.36 fb at 3 TeV centre-of-mass energy, while the mass of the dark neutralino is fixed to 1 GeV. The event generator MadGraph [5] is used to simulate the process under consideration at leading order. The full simulation is performed without the overlay

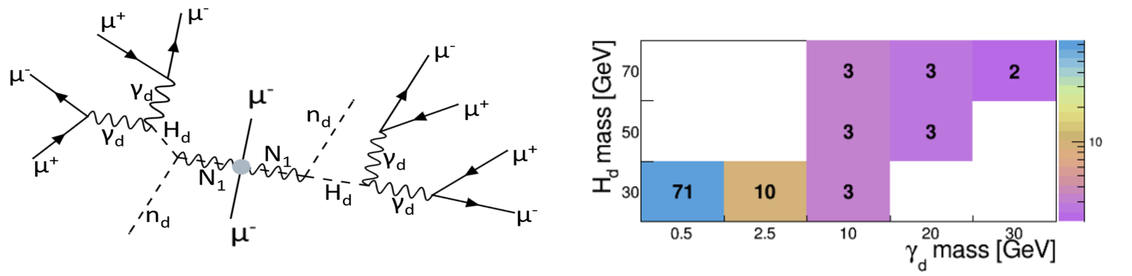

Figure 4: Left: Feynman diagram of the extended dark-SUSY channel. Right: Signal yield at 3 TeV Muon Collider with an integrated luminosity of 1 ab^{-1}.

of the beam-induced background with ILCSoft [11]. The contribution of EW and double-Higgs background is negligible.

Given the high multiplicity of muons in the final state, a great deal of effort has been put into their reconstruction. The conformal tracking algorithm [12] with PandoraPFA-New software [13] has been used to reconstruct muon tracks. Results for the reconstruction performance are presented in Ref. [14]. The signal selection algorithm is designed to pair muons and dark photons by exploiting the symmetry of the event. As expected, the efficiency is reduced at smaller masses because the muon transverse momentum and, therefore, the resolution on invariant mass decreases. The event yield is evaluated assuming an integrated luminosity of 1 ab^{-1}. The higher cross section at smaller masses compensates for the loss in efficiency. The results are obtained neglecting possible systematic uncertainties. This preliminary study highlights the importance of physics object reconstruction for new physics channels.

4. Conclusions

The Muon Collider pushes to face the technological challenges, mainly arising from the dare of producing bright muon beams and the muon's short lifetime, to reach an unprecedented physics potential.

It is extremely sensitive to VBF production, and a 10 TeV machine can produce BSM particles abundantly, exceeding the reach of FCC-hh for most of them. Moreover, as far as dark matter is concerned, a collider with this centre-of-mass energy can arrive at the thermal mass. On the other hand, 3 TeV centre-of-mass energy is enough to provide hints on muon $g-2$ anomaly. Finally, hidden sector searches can benefit from this new machine and the dark-SUSY channel presented here as a benchmark highlights that physics objects reconstruction is the first challenge to meet to exploit all the opportunities offered by a muon collider that represents a unique and promising possibility for the future of high energy physics.

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