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Prospects of a future multi-TeV muon collider

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Abstract

A multi-TeV muon collider is a discovery machine and an invaluable tool for many new standard model precision measurements such as the shape of the Higgs boson potential. The update of the European Strategy for Particle Physics recognized the unique opportunity of a muon collider to reach the energy frontier, despite the challenges to produce intense collimated muon beams. The options of a collider at 3 TeV and a collider at 10 TeV or above are the main focus of the forming International Muon Collider Collaboration as well as of the discussion panels at the ongoing US Snowmass process.

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1 Introduction

Among the projects currently under study for the next generation of high-energy particle accelerators the muon collider represents a unique machine that has the capability to provide leptonic collisions in a multi-TeV energy range, opening the way to an unprecedented and vast Physics program.

The acceleration and collisions of muon beams offer many advantages over the traditional electron and proton colliders. Since muons are point-like fundamental particles, the four-momenta of the colliding particles are completely defined and the full energy of the collision is available in the hard-scattering process, whereas in the case of hadronic colliders the proton energy is distributed among its constituents. Fig. 1 (left) compares the center-of-mass energies at which a proton and a muon collider have an equivalent cross section for the production of a new state via the neutral current annihilation of two incoming particles. The effective energy reach of a muon collider is about a factor of five higher for electroweak processes (solid lines), while it becomes less favorable in case of stronger partonic couplings (dashed lines). The synchrotron radiation emitted by muons (∼207 times heavier than electrons) curving in magnetic fields is suppressed by a factor of $(m_\mu/m_e)^4 = 1.8 \times 10^9$ with respect to electrons. Therefore, muons can be accelerated in a circular machine to much higher energies than electrons. A

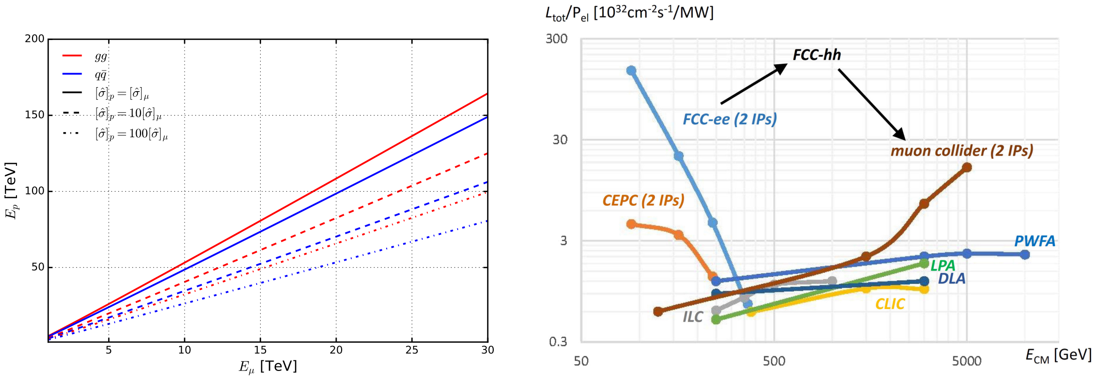

Figure 1: Left: the equivalent center-of-mass energy required at a proton-proton collider to reach the same cross section as at a $\mu^+\mu^-$ collider for the neutral-current annihilation of two incoming particles into a new state (reproduced from Ref. [1] licenced under CC-BY 4.0). Right: total instantaneous luminosity divided by the electric power consumption as a function of the center-of-mass energy for different future accelerator projects and technologies (reproduced from Ref. [2] licenced under CC BY-NC-ND 4.0).

muon collider facility can be built with a relatively small footprint and, hence, a lighter impact on the environment. In comparison with e^+e^- linear colliders, at a muon collider the beam energy spread is not severely degraded by beam-strahlung effects: an average energy spread of $\Delta E_{beam}/E_{beam} < 10^{-3}$ is expected up to $\sqrt{s} = 14$ TeV. An additional important feature of muon colliders is the operation costs: at the highest collision energies a muon collider results the most energy-efficient machine, as shown in Fig. 1 (right).

Unfortunately, such a tremendous potential is not coming for free. Muons are unstable particles that decay weakly into $e^-\nu_\mu\bar{\nu}_e$ with a mean life of 2.2 μs. This fact poses formidable technological and experimental challenges to every aspect of the design, construction and operation of the accelerator complex and the Physics detectors.

2 Physics potential

A high-energy muon collider represents both a discovery machine and an invaluable tool for precision measurements of known standard model (SM) processes, albeit in an unexplored energy regime.

Fig. 2 shows the production cross sections for some representative SM processes as a function of the $\mu^+\mu^-$ collision energy. Two concurrent production modes are evident: the s-channel annihilation mode, that scales as $\sim 1/s$ as the collision energy increases, and the electroweak vector boson fusion (VBF) mode, that increases as powers of $\log(s)$ with the collider energy. Above the energy of a few TeV, the VBF modes become eventually dominant for all channels, ultimately making the muon collider a vector-boson collider. A muon collider will produce abundant samples of W and Z electroweak bosons, Higgs bosons, and $t\bar{t}$ pairs, enabling a rich program of high-precision SM measurements [1,3]. For example, a 14 TeV collider with an integrated luminosity of 20 ab^{-1} would produce huge samples of multi-bosons and top quarks: 1.1×10^7 WW, 5.2×10^6 ZZ, 1.1×10^6 WWZ, 2.4×10^5 ZZZ, and 4.4×10^5 $t\bar{t}$. In particular, samples of $\mathcal{O}(10^8)$ Higgs bosons will allow to improve the precision on the Higgs boson properties, like the Higgs couplings to fermions and electroweak bosons. Samples of $\mathcal{O}(10^5)$ HH and $\mathcal{O}(10^2)$ HHH will provide direct access to the trilinear and quartic self-couplings of the

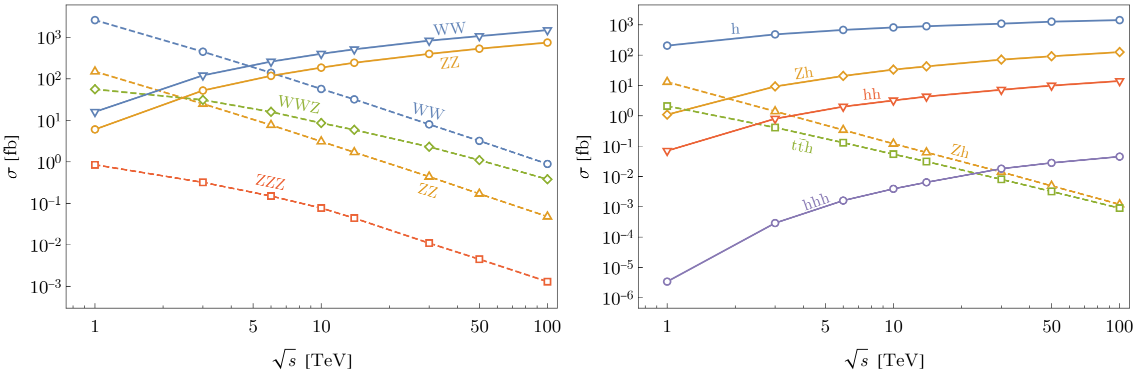

Figure 2: Cross sections for some representative annihilation (dashed) and VBF (solid) standard model processes as a function of the $\mu^+\mu^-$ collision energy $\sqrt{s}$ (reproduced from Ref. [3] licenced under CC-BY 4.0).

Higgs boson [4], and hence to a measurement of the shape of the Higgs boson potential.

Moreover, a muon collider will offer the opportunity to probe a wide range of models of Physics scenarios beyond the SM both via indirect and direct searches. Indirect searches rely on precision measurements of electroweak processes and look for significant deviations from the SM predictions, as could occur with the trilinear and quartic Higgs self-couplings [5]. Direct searches aim at detecting and directly reconstructing new unknown particles: for example, a muon collider could produce pairs of new heavier states with masses up to half the collider center-of-mass energy [6].

3 Experimental challenges

The new International Muon Collider Collaboration, as well as the discussion panels at the ongoing US Snowmass process, is focusing on two muon collider conceptual designs: a 3-TeV collider providing an instantaneous luminosity of a few 10^{34} cm^{-2} s^{-1} and a machine at $\sqrt{s} = 10$ TeV or above with an instantaneous luminosity of a few 10^{35} cm^{-2} s^{-1}.

A schematic layout of a muon collider facility with a center-of-mass energy of 10 TeV or higher may be seen in Fig. 2 of Ref. [7]. The main components of the accelerator complex are the muon beam injector, the accelerator and the collider rings. The muon injector system represents the key element of such a facility and is going to encompass the most advanced and novel technologies for magnets and accelerating resonant cavities to produce, collimate and manipulate bright μ^+ and μ^- beams. The muon production scheme currently under consideration was proposed by the US Muon Accelerator Program (MAP) [8] and is based on a high-power proton driver: muons are produced as tertiary particles from the decay of pions created by an intense proton beam impinging on a target. Before being collected in bunches, accelerated and put into collision, muons must be cooled down, i.e. their phase space must by reduced by more than five orders of magnitude. Muon beams are then quickly accelerated in order to take as soon as possible advantage of the relativistic time dilation: for instance, the mean life of 5-TeV muons extends to 105 ms in the laboratory reference frame. First, a low-energy acceleration stage brings the energy of the muon beams to ∼100 GeV, subsequently the beams are accelerated to the nominal multi-TeV collision energy and, finally, injected into a collider ring, which will be designed as small as possible to increase the collision frequency and optimized to maximize the delivered luminosity. At every stage of the beam life-cycle, the heat load caused by the electrons from muon decays strains all the machine elements, which require to be properly shielded: a 750-GeV beam with 2×10^{12} muons is expected to radiate on average 0.5 kW/m. A promising alternative method has been proposed that exploits a 45-GeV positron beam on a target to produce $\mu^+\mu^-$ pairs via electron–positron annihilation. In this case, a smaller muon phase space could allow the same luminosity with less intense beams.

A muon collider facility is an intense source of electron and muon neutrinos. On one hand, this is going to promote fruitful synergies between the muon collider and the neutrino Physics communities, but on the other hand it may also represent a severe ionization radiation hazard for the population living nearby and the surrounding environment [9]. Neutrinos from the accelerator curved sections fan out in a disk in the plane of the collider ring, while the machine straight sections produce highly collimated ν beams with a characteristic opening half angle of $\vartheta_\nu \simeq 10^{-4}/E_\mu\,[\text{TeV}]$. Emerging on the earth surface even far away from the muon collider complex, the neutrinos interact with the material they cross and develop showers of ionizing charged particles that are estimated to deliver to an exposed person an average whole-body radiation dose proportional to the intensity of the muon beam and E_μ^3/D^2, where D is the depth of the accelerator. Preliminary studies by MAP indicate that the neutrino radiation of a 3-TeV machine is below the safety levels (the European legal limit is 0.1 mSv/year), while an appropriate site has to be chosen and suitable mitigation measures have to be adopted in the case of a 10-TeV collider.

The products of the muon decays represent a dominant source of machine background also for the experimental apparatus: the electrons originating from muons decayed even tens of meters upstream the interaction point, and the photons radiated by them, interact with the machine elements producing a pervasive flux of secondary and tertiary particles that eventually reach the detector. The amount and characteristics of this beam-induced background (BIB) depend on the collider energy, the machine lattice elements and optics, and the design of the machine-detector interface. A preliminary study on a 1.5-TeV collider with 2×10^{12} muons per bunch estimates that at every bunch crossing $\mathcal{O}(10^8)$ BIB particles enter the detector: 4×10^7 photons with $E_\gamma > 0.2$ MeV, 5×10^7 neutrons with $E_n > 0.1$ MeV, 2×10^6 electrons and positrons with $E_e > 0.2$ MeV, and 2×10^4 charged hadrons with $E_h > 1$ MeV. The BIB particles are characterized by relatively soft momenta (on average, a few MeV for the electromagnetic component and ∼500 MeV for the hadronic one) and a time of arrival to the detector asynchronous with respect to the bunch crossing [11]. The BIB could severely degrade the detector performance and jeopardize the full muon collider Physics program. Full simulation studies are currently underway to assess the impact of the BIB on the detector response. The assumed detector model consists of a full-silicon vertex detector and central tracker, a tungsten-silicon sampling electromagnetic calorimeter and a steel-plastic scintillator sampling hadronic calorimeter, all immersed in a solenoidal magnetic field and surrounded by muon chambers. A well-designed detector and the exploitation of state-of-the-art detector technologies and novel reconstruction and analysis techniques can effectively mitigate the BIB effects [12]: the main features of a muon collider detector will be internal shielding, high granularity, and high-precision timing.

Full simulation studies are also ongoing to assess the Physics reach of a muon collider in the presence of the beam-induced background and to demonstrate that competitive Physics measurements are possible in such a harsh environment. In Ref. [13] the relative precision for a measurement of the Higgs boson coupling to $b\bar{b}$ is estimated to be 1.9%, 1%, and 0.91% for $\sqrt{s} = 1.5$, 3, and 10 TeV, respectively. Ref. [14] reports a preliminary estimate of 33% for the uncertainty on the HH production cross section in the final state with two $b\bar{b}$ pairs with an integrated luminosity of 1.3 ab^{-1} at $\sqrt{s} = 3$ TeV.

4 Conclusion

The design and construction of a muon collider is going to present novel technological and experimental challenges along the way, but the final reward will be an extraordinary harvest of high-precision standard model measurements and an unprecedented discovery potential.

An International Muon Collider Collaboration is been formed with the objective of assessing the potential of a muon collider and identifying an R&D path to demonstrate the feasibility of such a collider for the next update of the European Strategy for Particle Physics. The design study will identify the key issues, the risks, and an R&D priority plan in order to provide a baseline concept for a muon collider facility (machine, experiment and machine detector interface) with well-supported performance expectations to ensure the overwhelming scientific merits.

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