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The muon collider: A challenge for the future

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Summary. — The future of high-energy physics relies on the capability of exploring a broader energy range than current accelerators, with higher accuracy. A muon collider combines the great precision of electron-positron machines, with a low level of beamstrahlung and synchrotron radiation, and the high center-of-mass energy and luminosity of hadron colliders. For these reasons, current studies aim at designing a muon collider able to reach more than 10 TeV center-of-mass energies with luminosity higher than $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. These operational conditions open an unprecedented physics program, which ranges from precision studies of the Higgs boson to Beyond Standard Model (BSM) searches. Among the technological challenges, the ability to produce collimated beams of unstable particles, the muons, for a period sufficiently long to allow high-luminosity collisions, together with the treatment of the Beam-Induced Background (BIB) are the most critical issues for the detector design. This contribution will present the status of the detector design and will discuss the expected reach of the most representative physics processes.

1. – Introduction

Many pioneering ideas contributed to the recent programs related to a possible muon accelerator. The US MAP program [1] together with the Muon Ionization Cooling Experiment (MICE) [2] gave a big boost toward a muon collider. In June 2020 the European Strategy document reported the muon collider as a unique opportunity to reach the multi-TeV energy domain. It was recognized that the biggest challenge is the production of an intense beam of cooled muons. The International Muon Collider Collaboration was born in 2021 with the idea of taking up this challenge.

2. – Physics potential

A muon collider is a unique possibility of combining the two advantages of hadron and lepton colliders: high energy with very precise measurements and very low radiation losses. Lepton collisions at 14 TeV are comparable to 100–200 TeV proton collisions for

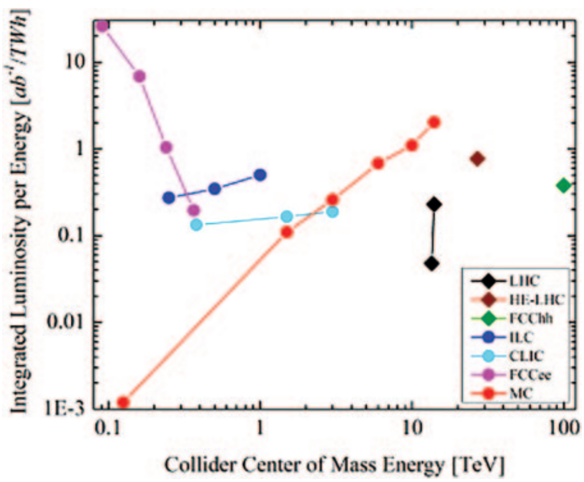

Fig. 1. – The electric power efficiency, defined as the collider annual integrated luminosity divided by the facility annual use, for different colliders [3].

production of heavy particle pairs. This makes the muon collider an excellent candidate for discovery reach.

An important advantage of a muon collider is displayed in fig. 1 where the electric power efficiency is shown. Already at 2 TeV a muon collider is the most efficient option, with obvious advantages. Moreover, the luminosity increases linearly with the center-of-mass energy and this drives a broad physics case [4].

The new International Muon Collider Collaboration is focusing on the baseline designs of a 3 TeV and a more than 10 TeV machine with instantaneous luminosities of about $2 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ and $4 \times 10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, respectively. At 3 TeV with an integrated luminosity of $1\,\mathrm{ab}^{-1}$ a high production cross-section of single Higgs is expected (about 5×10^5 single Higgs). High rates are accessible for multi-Higgs processes at 10 TeV with $10\,\mathrm{ab}^{-1}$ (expected 3×10^4 double Higgs events). A more comprehensive compendium on the physics program at the muon collider can be found in ref. [4].

3. – Challenges

A muon collider has a technically limited timeline. A development path that can address the major challenges foresees the delivery of a 3 TeV muon collider by 2045; more advanced technology and thus a longer time is needed for collisions at energies larger than 10 TeV.

The schematic layout of a 10 TeV-class muon collider is shown in fig. 2. A proton-driven production is used as a baseline for muon beams. The muon injector systems are the most critical parts of the design and include the proton driver, a high-power target system with capture solenoid for the pions generated by the proton interactions with the target, a pion decay channel where muons are collected and subsequently bunched together, a muon ionization cooling channel that provides cooling for both positive and negative muon beams by more than 5 orders of magnitude, and a low-energy muon accelerator stage that would deliver beams with energies up to 100 GeV. From the injector, each species of muon beam is transferred into a

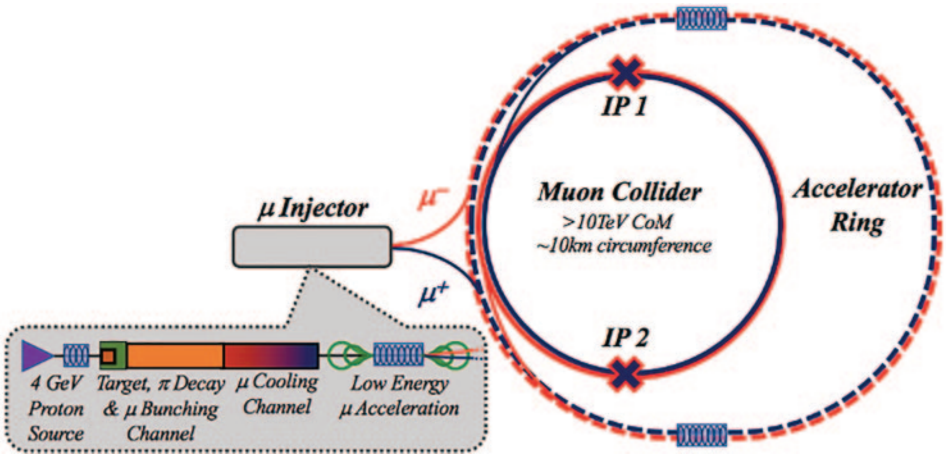

Fig. 2. – Schematic layout of a 10 TeV-class muon collider complex [5].

high-energy accelerator complex that can take the beams to the required multi-TeV energies. Finally, the beams will be transferred to a smaller collider ring whose circumference is optimized for luminosity performance. A 10 TeV-class collider ring is anticipated to support at least two detector interaction regions for the physics program.

A high-quality beam production is one of the main key challenge areas. The high-energy systems after the cooling and high-quality muon beam production together with the full accelerator chain represent a crucial challenge areas for the realisation of the muon collider. The ambitious R&D program planned for the muon collider and the progress made in other accelerator facilities, *e.g.*, LBNF, T2HK, J-PARC, will prove mutually beneficial.

Other key challenge areas concern the impact of muon decay products on the environment. The neutrino flux and its impact on the site must be mitigated, as shown by simulations performed with FLUKA Monte Carlo particle transport code [6, 7].

On the other hand, electrons interact with the machine's components by producing secondary particles (called Beam-Induced Background). The BIB has an impact on the detector, can degrade its performance, and can limit the scope of the physics.

BIB particles are characterized by an extremely large number, low momentum, and asynchronous time of arrival to the detector with respect to the bunch crossing. They are mostly photons ($\sim 10^7$), neutrons ($\sim 10^7$), electrons/positrons ($\sim 10^6$), charged hadrons ($\sim 10^4$), and muons ($\sim 10^3$)(1). The preliminary results suggest that the increased lifetime of the primary muons in the beam with higher energy is naturally compensated by the longer decay length, leading to a BIB intensity of the same order of magnitude as in the $\sqrt{s} = 1.5$ TeV case. A careful optimization of both the machine lattice and the machine detector interface is expected to further suppress BIB in the detector region. The detector concept and technologies to design experiments are crucial for the physics potential evaluation.

(1) The numbers refer to a single bunch crossing with $2 \cdot 10^{12}$ muons.

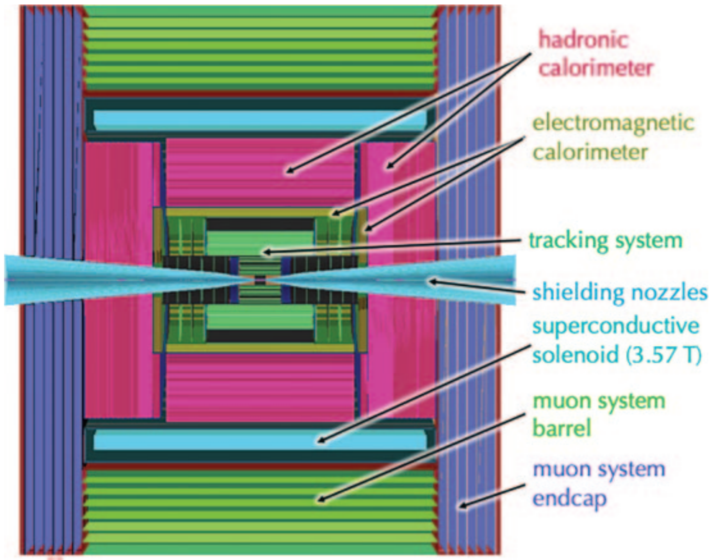

Fig. 3. – Detector layout.

4. – Detector performances

The detector design adopted for the following studies is based on the CLIC geometry with a new tracker design and two tungsten cone-shaped shields (nozzles) to address the BIB mitigation. The detector layout is shown in fig. 3.

The tracker system is the closest detector to the impact point and the most affected by BIB. Its structure includes silicon pixels and strips. Different track reconstruction algorithms have been tested from conformal tracking up to a Combinatorial Kalman Filter (CKF). A double layer filter technique has been exploited in the vertex region to reduce the high BIB hits multiplicity.

The jet reconstruction is mainly performed using tracks reconstructed with CKF and filtered, calorimeter hits selected with the hit time and hit energy, and finally particles reconstructed with the PandoraPFA algorithm are clustered into jets by the k_T algorithm. A detailed description of the all reconstruction algorithms used in the full simulation can be found in ref. [4].

The efficiency of jet selection as a function of truth-level jet θ is greater than 85% for the polar angle $\theta > 0.5$ rad.

Jet selection efficiency as a function of jet p_T for b-jets, c-jets and light jets in the central region $0.44 < \theta < 2.70$ is shown in fig. 4 (left). The differences between the jet flavours are mainly due to different jet θ distributions in the three samples.

Dijet invariant mass distributions for $H \to bb$ (top left) and $Z \to bb$ (top right) are shown. Distributions are normalized to the same area and are fitted with double Gaussian functions. The shapes are compared in the bottom plot. A relative width, defined as the standard deviation divided by the average value of the mass distribution of 27%(29%) for $H \to bb(Z \to bb)$ is found.

Promising results for photons, electrons and muons reconstruction show a high efficiency also with BIB, which is actually very low in the muon system.

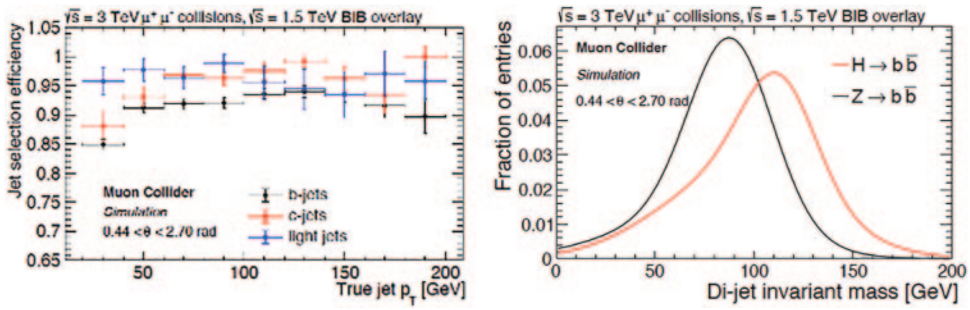

Fig. 4. – Left: jet selection efficiency as a function of jet p_T for b-jets, c-jets and light jets in the central region $0.44 < \theta < 2.70$. Right: dijet invariant mass distributions for $\mathrm{H} \rightarrow \mathrm{bb}$ and $\mathrm{Z} \rightarrow \mathrm{bb}$.

5. – Conclusions

A muon collider is a unique possibility for the future of high-energy physics, offering a novel unprecedented physics program. The biggest challenges are related to the beam quality and the impact on the environment. Among these, beam-induced background represents the most demanding task in designing the detector. Therefore, studies on the technologies, performance and the physics reach of a 3 TeV and a 10 TeV muon collider are ongoing.

REFERENCES

[1] Neuffer D. *et al.*, *Muon Sources for Particle Physics*, *Accomplishments of the Muon Accelerator Program*, in *8th International Particle Accelerator Conference* (JACoW) 2017.
[2] MICE Collaboration, *Nature*, **578** (2020), 53, arXiv:1907.08562.
[3] Gourlay S., Raubenheimer T. and Shiltsev V., *Front. Phys.*, **10** (2022) 920520.
[4] Accettura C. *et al.*, *Eur. Phys. J. C*, **83** (2023) 864.
[5] Stratakis D. *et al.*, *A muon collider facility for physics discovery*, arXiv:2203.08033 (2022).
[6] Ahdida C. *et al.*, *Front. Phys.*, **9** (2022) 788253.
[7] Battistoni G. *et al.*, *Ann. Nucl. Energy*, **82** (2015) 10.
[8] Linssen L. *et al.*, *Physics and Detectors at CLIC: CLIC Conceptual Design Report*, arXiv:1202.5940v1 (2012).