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Muon colliders to expand frontiers of particle physics

Muon colliders offer enormous potential for the exploration of the particle physics frontier but are challenging to realize. A new international collaboration is forming to make such a muon collider a reality.

K. R. Long, D. Lucchesi, M. A. Palmer, N. Pastrone, D. Schulte and V. Shiltsev

Future high-energy particle physics facilities have traditionally been evaluated on the basis of three criteria: (1) scientific potential, (2) technical construction and financial requirements, and (3) flexibility for further upgrades and developments[1]. The most recent update of the European Strategy for Particle Physics, which provides a roadmap for the future of the field, has added an important new requirement: next-generation facilities should meet very high ecological and environmental standards and, in particular, should be energy efficient[2].

Since colliders were developed in the 1960s, they have been built in a variety of types, shapes and sizes[3] — from the 2-m-long 0.16 GeV electron–positron collider VEP-1 in Novosibirsk, Russia, to the world's biggest Large Hadron Collider (LHC) at CERN with a circumference of 27 km and designed to operate at 14 TeV centre-of-mass energy. Today, colliders represent some of the largest and most expensive facilities for fundamental science research. The next stage of exploration in particle physics aims to push forward the frontier of knowledge to shed light onto many open questions, such as the nature of dark matter or the origin of the matter–antimatter asymmetry in the Universe. Future colliders, reaching up to the multi-TeV scales, can reveal new phenomena extending the energy frontier for direct and indirect searches[4]. At least an order of magnitude increase in collision energy could be envisaged with currently foreseen technology developments.

One path towards achieving this goal is the proposed 100-km-long Future Circular Collider (FCC-hh)[5], which will collide protons at a centre-of-mass energy of 100 TeV. As the energy of a relativistic proton is distributed among its constituent quarks and gluons, a lepton collider at a fraction of that energy would have similar discovery reach (Box 1). Traditional technologies to reach high energies in electron–positron collisions require long linear colliders due to synchrotron radiation losses that pose stringent limits on circular rings. Muons, over 200 times heavier than electrons, could reach higher energies in smaller circular colliders.

The concept of using colliding beams of oppositely charged muons dates back to the late 1960s[6,7]. The clear advantage of colliding muons is that they can be accelerated in rings without suffering from the large synchrotron radiation losses that limit the performance of electron–positron colliders. This allows a muon collider to use the traditional and well-established accelerator technologies of superconducting high-field magnets and radiofrequency cavities[8]. In addition, the electric power efficiency of muon colliders (defined as the collider's annual integrated luminosity divided by the facility's annual energy use) increases with centre-of-mass energy. Thus, above

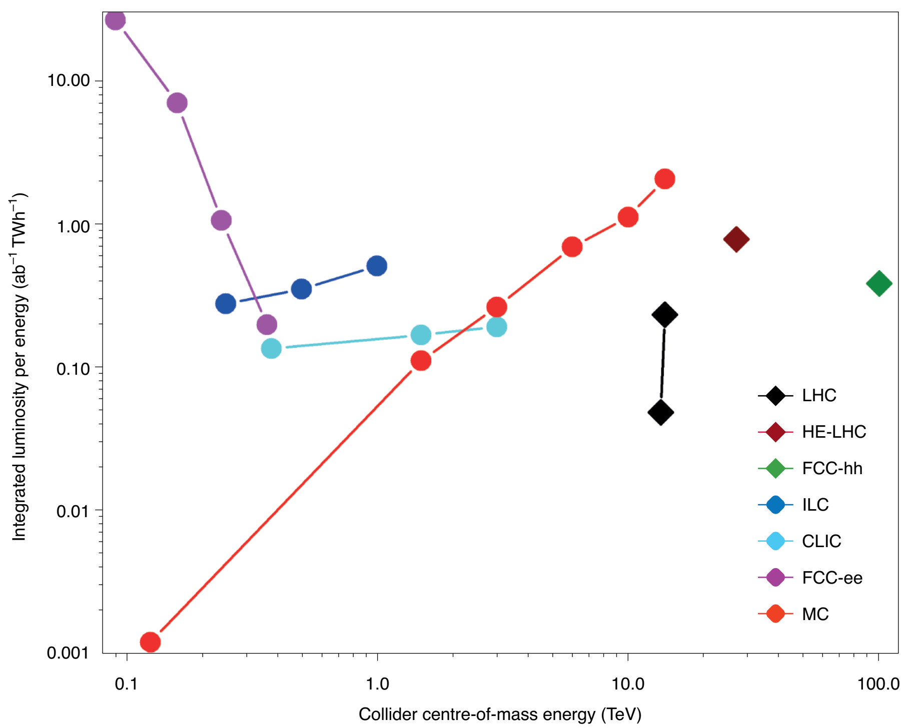

Fig. 1 | Energy efficiency of present and future colliders. Annual integrated luminosity (1 ab = 10^{-42} cm^2) per terawatt hour of electric power consumption as a function of the centre-of-mass energy. The LHC — both present and expected after its high-luminosity upgrade (black diamonds) — is contrasted with a variety of proposed particle colliders, as taken from ref. [3]: the Muon Collider (MC, red circles), the Future Circular electron–positron Collider (FCC-ee, purple circles) assuming experiments at two collision points, the International Linear Collider (ILC, dark blue circles), the Compact Linear Collider (CLIC, light blue circles), the High Energy LHC (HE-LHC, brown diamond) and the Future Circular proton–proton Collider (FCC-hh, green diamond). The effective energy reach of hadron colliders (LHC, HE-LHC and FCC-hh) is approximately a factor of seven lower than that of a lepton collider operating at the same energy per beam.

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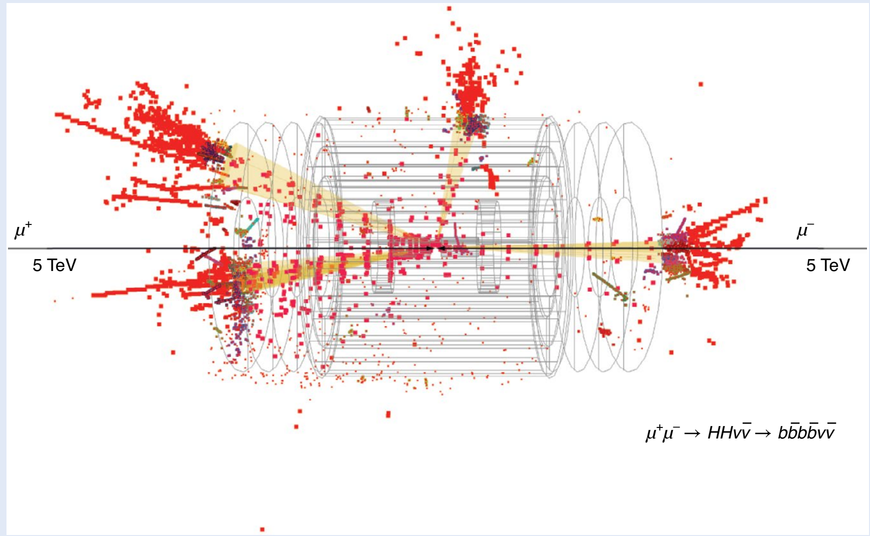
Box 1 | Physics at a multi-TeV muon collider



Muons (μ), like electrons, are fundamental particles, which release their full energy when they collide. In contrast, protons are composed of quark and gluons, which actually collide carrying only a fraction of the proton energy.

Therefore, muons can probe much higher energy scales than protons colliding with the same beam energy. Thus, a muon collider operating at energies above 10 TeV would enable direct searches for new particles over a wide range of unexplored masses[18]. This type of collider with sufficiently high luminosity would provide similar discovery potential to a 100 TeV proton–proton collider, such as the proposed FCC-hh[19]. Physics beyond the standard model, such as supersymmetry or dark matter, could also be probed at a high-energy muon machine. At energies greater than a few TeV, the dominant production process in muon collisions is electroweak vector boson fusion or scattering, which could be exploited for the detailed study of standard model processes[20]. Substantial deviations from the standard model expectations would provide a precision probe for new physics[21]. Furthermore, detailed study of the properties of the Higgs boson[22] would be possible, enabling a unique and precise determination of the shape of the Higgs potential. According to the standard model, the Higgs mechanism took place when the Universe cooled to a temperature corresponding to an energy of 160 GeV. The precision measurements of the Higgs self-couplings are crucial elements to understand the nature of the electroweak phase transition in the early Universe. In the figure, a typical double-Higgs event in an example detector is shown, where both Higgs bosons decay to bottom and antibottom quark jet pairs.

A simulated double Higgs boson (H) event at a centre-of-mass energy of 10 TeV is shown in the figure. Two oppositely charged muon beams with an energy of 5 TeV each collide at the centre of a detector. The detector must be capable of distinguishing the reactions of interest from the background of particles originating from the interactions between the decay products of the muons and the machine elements. The two produced Higgs bosons are each identified by their decay to a bottom (b) and antibottom ($\bar{b}$) quark jet pair, whereas the neutrino (ν) and antineutrino ($\bar{\nu}$) cannot be directly detected. Solid lines show the volume of the tracking detectors that allow the reconstruction of the trajectories of charged particles. To reduce the sensitivity to background[23], tracking timing resolution needs to be a few tens of picoseconds, which exceeds the present state of the art. The yellow cones highlight the charged particles produced by each of the bottom quarks in an object called a b-jet. The red dots represent the energy deposition of these jets inside the calorimeters in the outer region of the detector.

approximately a centre-of-mass energy of 2 TeV, a muon collider is expected to be the most energy-efficient choice for exploring new physics at the highest possible collision energies, as shown in Fig. 1. Despite these advantages, the challenge of producing bright muon beams and the short lifetime of the muon have hindered the realization of a muon collider.

Technological challenges

Rapid acceleration to high energies increases the lifetime of muons in proportion to their energy — a lifetime of 21 ms is reached at 1 TeV. To achieve this, high-gradient normal and superconducting radiofrequency systems are required to accelerate the beams before they decay into an electron or positron accompanied by a neutrino and an antineutrino. Another related issue is that the muon decay dissipates the beam. To maximize the number of muon collisions before this happens, superconducting dipole magnets capable of providing 10 T to 15 T magnetic fields are required to keep the collider ring as small as possible.

The generation and acceleration of muon beams is schematically illustrated in Fig. 2 for a centre-of-mass energy of 6–14 TeV and a luminosity of the order of 10^{35} cm^{-2} s^{-1}. A high-power proton driver produces a dense beam that is further compressed in an accumulator and a compressor ring. The proton beam is then directed onto a target, where positive and negative pions are produced that subsequently decay into positive and negative muons accompanied by neutrinos and antineutrinos. The oppositely charged muons are separated into two beams that are then cooled using the ionization-cooling technique[9] and afterwards accelerated in several stages before they are injected into the collider ring. The cooling system is essential to reduce the large initial phase space by a factor of more than five orders of magnitude to that needed for a practical collider. Without such cooling, the luminosity would be several orders of magnitude too small.

As muons rapidly decay, the cooling step has to be very fast. The ionization-cooling technique applies uniquely to muons because of their minimal interaction with matter. The muon beam is passed many times through an absorber material, for example, liquid hydrogen, in which the muons lose energy via ionization, which reduces both transverse and longitudinal momentum. The longitudinal component of the momentum is restored by acceleration in radiofrequency cavities. The combination of energy loss and re-acceleration causes a reduction in the transverse momentum of

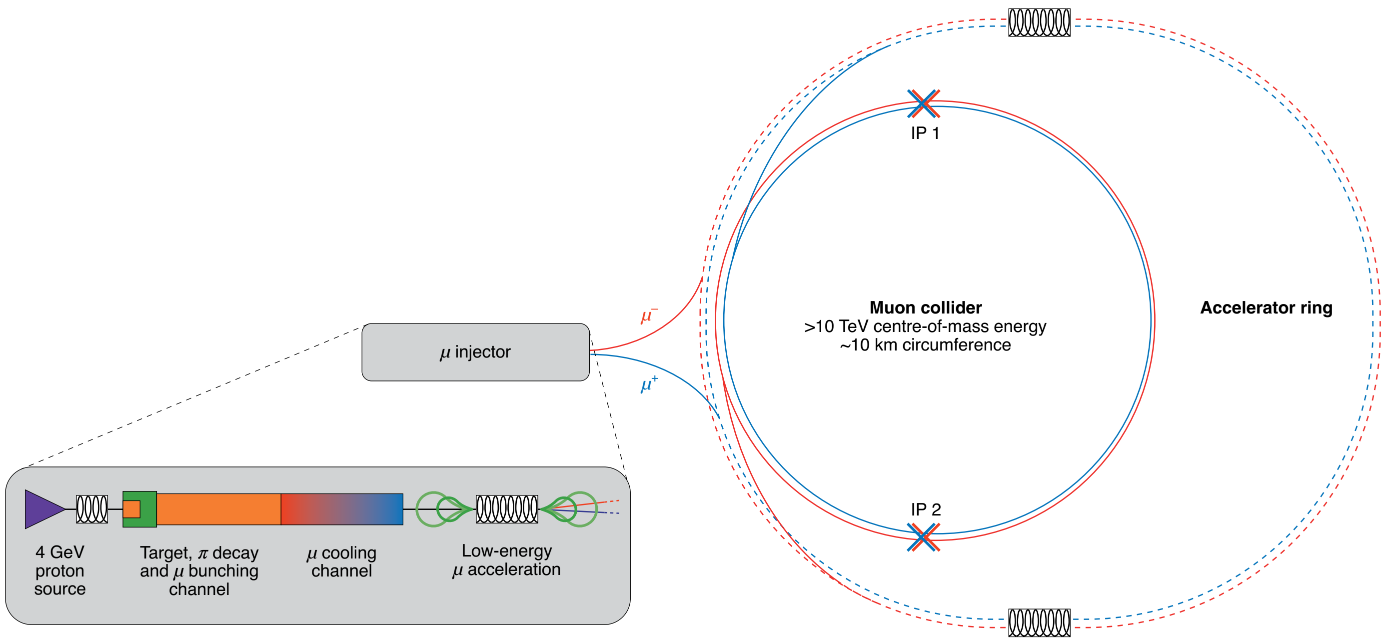


Fig. 2 | Schematic layout of a 10-TeV-class muon collider complex. The muon injector systems include the proton driver, a high-power target system with a capture solenoid for the pions generated by the proton interactions with the target, a pion decay channel, where muons are collected and subsequently bunched together, a muon ionization cooling channel that provides cooling for both positive and negative muon beams by more than five 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 high-energy accelerator complex that can increase the beam energy to the multi-TeV range. Finally, the beams will be injected into a smaller collider ring, whose bending and focusing magnets are optimized to reach the best luminosity performance. A 10-TeV-class collider ring is anticipated to support two detector interaction regions (IP, interaction point) for the physics programme.

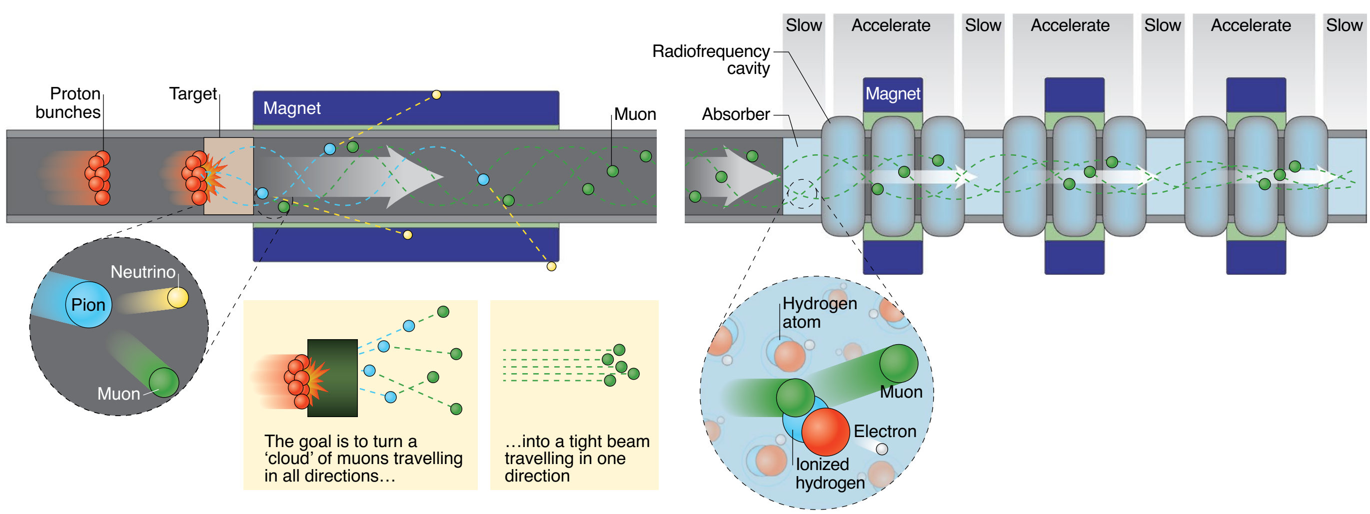


Fig. 3 | Ionization cooling-channel scheme. Proton bunches are accelerated into a solid target that is made of a dense material such as tungsten. Pions are emitted, which are unstable and quickly decay into a muon and a neutrino. Superconducting solenoid magnets steer the charged muons into a cooling channel, where the beam is radially focused at lithium hydride absorbers. As the muons pass through the absorber, they lose energy by ionizing hydrogen atoms and thus slow down. Magnetic fields guide the muons into radiofrequency cavities, where the lost energy is restored in the longitudinal direction. The muon beams pass through several absorption and acceleration stages, leading to a tightly focused muon beam that is ready for injection into the main accelerator.

the beam and hence has a cooling effect. The repetitive process (Fig. 3) results in a large cooling factor.

To reach an acceptable luminosity for a collider, the phase-space volume occupied by the initial muon beam needs to be reduced rapidly and sufficiently. This is expected to be achievable by ionization cooling as shown in theoretical studies and numerical simulations[10,11] with realistic hardware parameters. A complete cooling channel would consist of a series of tens of cooling stages, each reducing the six-dimensional phase-space volume by roughly a factor of two (Fig. 3).

The practical implementation of ionization cooling is challenging but has recently been demonstrated[9] by the international Muon Ionization Cooling Experiment (MICE) at the Rutherford Appleton Laboratory (United Kingdom). As expected, it achieved a reduction of the transverse phase-space volume (emittance) of the order of 10% of muons with a momentum of 140 MeV c^{-1} passing through a prototype ionization cooling-channel cell. In the final stages of a cooling channel for a collider, relatively small aperture solenoid magnets with fields of tens of tesla, similar to those already developed in leading high-field superconducting magnet laboratories, are required to deliver beams of the quality required for a multi-TeV collider.

In addition to the rapid decay of the muons and the required high brightness, the intense neutrino flux originating from the muon decays poses another challenge — the need to minimize the environmental impact. The collider complex is usually located underground and when the produced neutrinos emerge at the surface, a small fraction interacts with the rock (and other material) and produces ionizing radiation[12]. The neutrino interaction rate in the vicinity of the surface rises linearly with energy. The impact of this neutrino-induced radiation can be mitigated, for example, by continually adjusting the orbits of the beams to spread them out on a wider area. A further reduction in the neutrino-induced radiation would be obtained if the emittance of the muon beam was reduced so that the required luminosity could be obtained using a substantially smaller number of muons. A novel muon production scheme, the low emittance muon accelerator (LEMMA), has recently been proposed, in which muon pairs are produced through electron–positron annihilation just above the production threshold when a 45 GeV positron beam strikes a solid target[13]. This scheme might allow beams to be produced with much lower current, which corresponds to the number of muons, but much higher phase-space density, thus delivering the same luminosity but with substantially reduced neutrino-induced radiation due to fewer muons decaying.

The development of an energy-frontier muon collider has elements that have great synergy with other efforts in the field. For instance, the need for the development of high-field magnets parallels the ongoing research and development programme for very-high-energy proton–proton colliders[14]. The development of a high-brightness muon source would also benefit other scientific endeavours. In particular, muons from a proton driver-based source would provide high-purity and precisely characterized neutrino beams for long- and short-baseline neutrino experiments[15–17].

Towards a muon collider at the energy frontier

The high-luminosity upgrade of the LHC will extend the physics programme at the world's highest energy collider to about 2040. It is possible to envision a path towards an energy-frontier muon collider in Europe by the mid- to late 2040s. The plan starts with an initial four-year development phase to establish baseline designs for a 3 TeV collider with a luminosity of around 2×10^{34} cm^{-2} s^{-1} and a collider operating at a centre-of-mass energy above 10 TeV with a luminosity of about 4×10^{35} cm^{-2} s^{-1}. The discovery potential of the latter machine could be similar to other proposed energy frontier collider options.

The resulting baseline designs will allow the evaluation of the cost scale and risks of a muon collider and define the muon production, cooling and acceleration test facility (or facilities) as a basis to decide on the future of the project. The initial phase of the programme would be followed by a second phase of roughly six years to construct and operate the test facility, during which the collider design would be optimized. The results of this second phase would lay the foundations for a decision to move forward into the third four-year phase to develop a full technical design. The construction of the muon collider itself is estimated to require a further ten years.

The focus of the technical development towards successful implementation of a muon collider will be on key systems that can reduce the cost of the collider and to increase its power efficiency and performance. Laboratories from around the world with sufficient expertise to deliver elements of the programme are joining together to form the international collaboration required to explore the various options and to develop an integrated design concept that encompasses the physics, the detectors and the accelerator. ❐

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Competing interests

The authors declare no competing interests.