The Muon Collider

Input to the European Strategy for Particle Physics - 2026 update

The International Muon Collider Collaboration

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Abstract

Muons offer a unique opportunity to build a compact high-energy electroweak collider at the 10 TeV scale. A Muon Collider enables direct access to the underlying simplicity of the Standard Model and unparalleled reach beyond it. It will be a paradigm-shifting tool for particle physics representing the first collider to combine the high-energy reach of a proton collider and the high precision of an electron-positron collider, yielding a physics potential significantly greater than the sum of its individual parts. A high-energy muon collider is the natural next step in the exploration of fundamental physics after the HL-LHC and a natural complement to a future low-energy Higgs factory. Such a facility would significantly broaden the scope of particle colliders, engaging the many frontiers of the high energy community.

The last European Strategy for Particle Physics Update and later the Particle Physics Project Prioritisation Panel in the US requested a study of the muon collider, which is being carried on by the International Muon Collider Collaboration. In this comprehensive document we present the physics case, the state of the work on accelerator design and technology, and propose an R&D project that can make the muon collider a reality.

International MUON Collider Collaboration

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Introduction and Overview

The muon collider is a unique, compact, high-energy electroweak collider concept which will produce, cool, accelerate and collide two single-bunch muon beams of opposite charge. It is a paradigm-shifting tool for particle physics representing the first collider to combine the high-energy reach of a hadron collider and the high precision of a lepton collider, yielding a physics potential significantly greater than the sum of its individual parts.

The muon collider potential motivates a growing community, with substantial international interest and enthusiasm, with many calling for the scientific community to aim high and "*shoot for the muon*". The innovative nature of the muon collider in accelerator, detector and magnet technologies has attracted a vibrant community of early career researchers across all regions, many of whom are key designers of systems throughout the accelerator complex. This is an important asset for the muon collider and for the fields of accelerator and particle physics in general. This report contains the proposals and steps necessary to make the muon collider a reality, even within the next generation of high-energy particle physics facilities. Substantial improvements of the design and several enabling technologies are essential to achieve this goal. However, it is important to emphasise that no technological showstoppers have been identified in any studies of the muon collider.

1 The muon collider concept

The baseline muon collider design is a $10\,\mathrm{TeV}$ centre-of-mass collider providing an integrated luminosity of $10\,\mathrm{ab}^{-1}$ [1]. An initial stage that can be implemented by around 2050 is also considered [2].

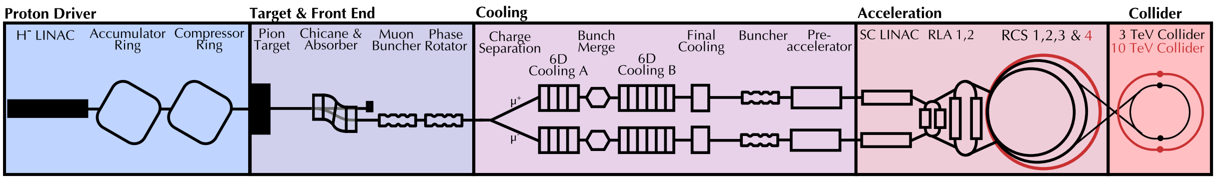

Fig. 1: Conceptual layout of the muon collider.

The design of the muon collider is based on a concept, which was developed by the U.S. Muon Accelerator Programme (MAP) until 2017 [3]. The design is now being progressed by the International Muon Collider Collaboration (IMCC) [4]. A schematic layout of the collider is shown in Figure 1 and contains the following key areas:

1. The **proton driver** (blue box in the diagram) produces a short, high-intensity proton pulse.
2. This pulse hits the **target** (indigo) and produces pions. The decay channel guides the pions and forms a beam with the resulting muons via a buncher and phase rotator system.
3. Several **cooling** stages (purple) reduce the longitudinal and transverse emittance of the beam using a sequence of absorbers and RF cavities in a high magnetic field.
4. A system of a linac and two recirculating linacs **accelerate** (light red) the beams to $63\,\mathrm{GeV}$ followed by a sequence of high-energy accelerator rings which reach $1.5\,\mathrm{TeV}$ or $5\,\mathrm{TeV}$.
5. Finally the beams are injected at full energy into the **collider** ring (red). Here, they will circulate and collide within the detectors until they decay.

Table 1 shows the key parameters for a site independent implementation of a $3\,\mathrm{TeV}$ and a $10\,\mathrm{TeV}$ centre-of-mass energy stage. These are target parameters conceived to explore the limits of each technology and design. If they can be fully met, the integrated luminosity goal could be reached within five years (or 2.5 years, with two detectors) of full luminosity operation. This provides margin for further design and technology studies and a realistic ramp-up of the luminosity.

An implementation at CERN is under consideration and could reuse the existing SPS and LHC tunnels to accelerate the muon beam. This design could reach a centre-of-mass collision energy of up to 7.6 TeV and a practical initial energy stage could reach up to 3.2 TeV, depending on the layout. The significant reduction of civil engineering and associated environmental impact may justify the slight reduction in physics scope.

Example parameters for a CERN implementation are shown assuming that a single collider ring tunnel is constructed and used for both energy stages, which is consistent with the use of Nb_3Sn magnets at full energy. If two independent collider rings at CERN are used with Nb_3Sn dipoles for the 3.2 TeV and high-temperature superconductors (HTS) for the 7.6 TeV stage, the luminosities would increase to $2 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and $10.1 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, respectively. Use of fast-ramping HTS magnets in the muon acceleration might enable increase of the final energy stage to close to 10 TeV; R&D is required to verify that such an option is practical.

Table 1: Tentative target parameters for a muon collider at different energies. The site independent scenario uses Nb_3Sn technology in the collider ring that is consistent with a project implementation by 2050. The CERN scenario reuses the SPS and LHC tunnels and assumes a 11 km collider tunnel, while the initial studies assumed 10 km. The estimated luminosity refers to the value that can be reached if all target specifications can be reached, including beam-beam effects.

Parameter	Symbol	unit	Site independent		CERN	
			Stage 1	Stage 2	Stage 1	Stage 2
Centre-of-mass energy	E_{cm}	TeV	3	10	3.2	7.6
Target integrated luminosity	$\int \mathcal{L}_{\mathrm{target}}$	ab^{-1}	1	10	1	10
Estimated luminosity	$\mathcal{L}_{\mathrm{estimated}}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.8	17.5	0.9	7.9
Collider circumference	C_{coll}	km	4.5	11.4	11	11
Collider arc peak field	B_{arc}	T	11	14	4.8	11
Collider dipole technology			Nb_3Sn	HTS	NbTi	Nb_3Sn or HTS

2 Physics Case

A muon collider is a high-energy electroweak collider. It can access directly and precisely the underlying simplicity of the Standard Model (SM) in its high-energy regime of "unbroken" electroweak symmetry. This makes it an ideal and unique machine to investigate fundamental questions about our universe – both long-held ones and more recent ones sparked by the LHC. Simultaneously, it is a paradigm-shifting tool for particle physics representing the first high-energy, high-precision compact collider. It combines the precision of a lepton collider with the energy reach of a hadron collider, yielding a physics potential significantly greater than the sum of its individual parts. This enables unparalleled exploration of the Electroweak-Higgs Unification era that we have entered since the discovery of the Higgs. We can now hope to answer the question of why electroweak symmetry breaking (EWSB) occurs by directly probing the transition between the "broken" and "unbroken" symmetry regimes. Furthermore, we can address the phase diagram of EWSB and quantitatively investigate the earliest moments in our universe and its ultimate fate. With high-energy EW collisions we can also search for physics beyond the SM directly using a muon collider as an unrivaled EW discovery machine. These same high-energy high precision collisions allow us also to probe new physics to scales far beyond the collider's energy and study the Standard Model in new domains where new phenomena emerge.

For example, a muon collider can make exquisite measurements of TeV-scale vector boson scattering. This is due to the inherently quantum and relativistic effect of abundant effective vector bosons contained in a high-energy muon, which gives rise to large collision rates with low backgrounds. Such measurements enable the first precision experimental tests of the "unitarization" of massive gauge boson scattering, arguably the foremost prediction of Electroweak symmetry breaking. High-energy, high-precision studies of the Higgs and vector bosons also give the first detailed probes of the "Electroweak symmetry restoration" realm within the SM. The high-energy nature of the muon collider also enables new insights into, and tests of, the "quantum compositeness" of particles. This is ideally studied in Electroweak processes due to their perturbative and thus in principle calculable nature (unlike the strong interactions), and the physical mass gap that makes "particles" fully well defined as asymptotic states unlike in Quantum Electrodynamics (QED). Finally, the intrinsic nature of a high-energy muon collider provides the most abundant and best characterized source of high-energy neutrino-target collisions conceived thus far. The neutrino physics program at a muon collider provides a high-energy complement to current and future long-baseline neutrino experiments.

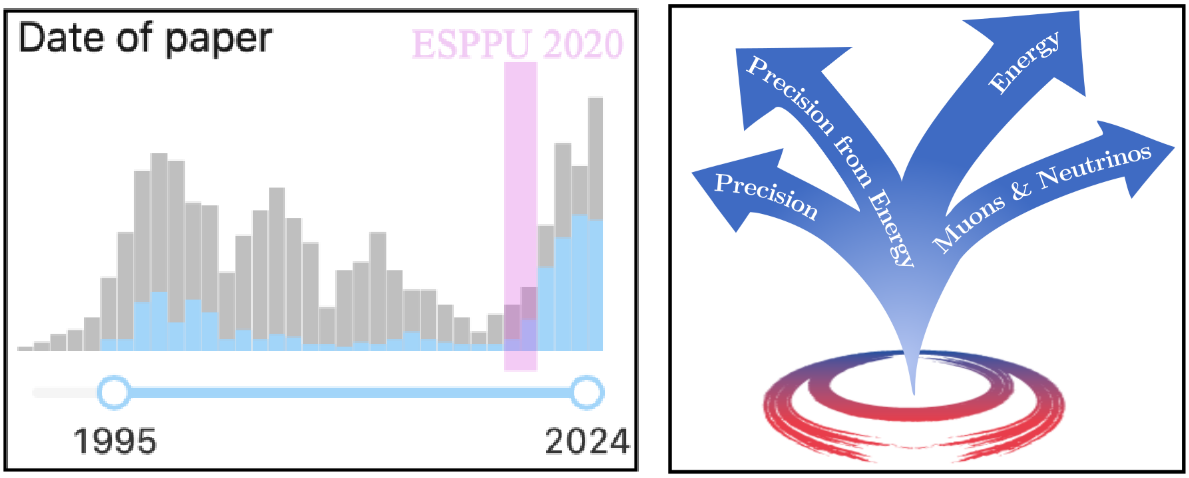

Fig. 2: The ground-breaking nature of the muon collider physics perspectives and its contemporary pertinence in the particle physics landscape after the LHC is well represented by the enthusiastic reaction of the theory community to the muon collider study plans initiated by the 2020 ESPPU. The number of papers on muon colliders in the hep-ph category is reported in blue on the left panel. The right panel summarises the core directions of the physics case.

A muon collider simultaneously offers numerous pathways to searching for Beyond Standard Model (BSM) physics by utilizing the energy reach, precision measurement capabilities, and the combination thereof. The same abundant vector boson scattering that enables exploration of new SM phenomena also furnishes a next-generation Higgs factory. In certain channels this allows an order of magnitude or more improvement in the understanding of Higgs properties, including its potential. This allows one to experimentally probe BSM contributions that could change the nature of the EW phase transition and baryogenesis, the ultimate fate of our vacuum and the "Higgs portal" to hidden sectors. Furthermore the energy reach of a muon collider allows one to test the origin of any deviation from SM properties found in a precision measurement at the same collider, and by extension any previous Higgs Factory. The combination of precision and energy also allows one to probe BSM possibilities such as "Higgs compositeness" up to the $\mathcal{O}(100)$ TeV scale, far beyond the reach of any other proposed collider. Reaching the 10 TeV scale directly also enables unmatched probes of new EW particles such as those responsible for the simplest dark matter paradigms, or alternatively probing the possibility of new gauge forces in many cases to unrivaled scales. The combination of energy and precision also revolutionises flavor physics by enabling direct tests of fermions interactions, with a new physics scale reach that is comparable or superior to the one attainable by traditional studies of meson or leptons decays. This includes neutral current flavor tests sensitive to mediators at the 100 TeV scale, while also enabling new windows into

SM flavor in the Higgs sector and potential explanations of neutrino masses with Heavy Neutral Lepton searches.

The impressive physics potential of a muon collider is enabled by both its energy reach as well as its high luminosity. The luminosity goal of 10 TeV with 10 ab^{-1} is naturally consistent with the emittance targets from cooling and the inherent increase of luminosity power efficiency at high-energy. While most studies have been performed for these parameters, it's important to note that the bulk of the physics potential is only mildly affected by a slight change in energy or an order of magnitude change in luminosity. Furthermore, a muon collider is an innately stageable project in both luminosity and energy given a common front end for muon production and cooling. With a staged approach, considerable technical and financial risk could be retired and physics progress can be achieved along the path to the highest energies. Low energy stages could provide direct measurements of the Higgs width or experimentally and theoretically precise measurements of the top mass. Such low-energy muon colliders could be also considered as an independent satellite project at the muon collider complex. A 3 or 3.2 TeV stage can offer the first significant step beyond the HL-LHC in understanding the Higgs potential as well as testing certain Dark Matter (DM) candidates. A 7.6 TeV stage at CERN would extend our understanding of EWSB even further allowing a differential test of EW restoration, especially relevant if luminosity goals are relaxed in the pursuit of the highest energies. Furthermore, while 10 TeV is the ultimate goal of this study, it is not the final goal of particle colliders nor the highest conceivable energy of a muon collider in the far future.

Successfully building a muon collider allows us to reset the collider landscape with this paradigm shifting tool. Muon collider investment now lays the groundwork for coming generations to explore nature *directly* at even shorter distances, in likely the only sustainable and technically practical way for the future of High-Energy Physics (HEP).

3 Detector

The design of dedicated experiments to take data at the collider interaction points has sparked a lively environment that allowed the community to make fast progress in just a few years. The detector design is still in its infancy, but it is already possible to make substantive statements about the technological requirements, expected performance, and opportunities for further improvement.

Requirements were spelled out in terms of detector acceptance, particle detection and identification efficiency, as well as to resolutions on the various particle properties inferred by the instrumental measurements. They were outlined in terms of "baseline" and "aspirational" targets, corresponding, respectively, to the requirements to fully exploit the physics potential of the machine and a more ambitious set of performances comparable to those targeted by Higgs/Top/Electroweak-factories. These targets are summarised in Table 2.

An initial detector, optimised for operation at a $\sqrt{s} = 3$ TeV muon collider, was extensively studied and demonstrated the feasibility of the physics programme. Recent work focused on developing the first detector designs for a $\sqrt{s} = 10$ TeV machine. Two distinct detector concepts have been developed: MUSIC (MUon System for Interesting Collisions) and MAIA (Muon Accelerator Instrumented Apparatus). Both designs, shown in Figure 3, envision a multi-purpose detector sharing a similar structure: a cylinder 11.4 m long with a diameter of 12.8 m. They comprise typical collider detector instrumentation, such as an all-silicon tracking system, an electromagnetic calorimeter (ECAL), a hadron calorimeter (HCAL), and a muon sub-detector. Superconducting solenoids are used to provide bending power for the measurement of charged particle momenta within the tracking system. The design work follows the concept already developed for $\sqrt{s} = 3$ TeV, with modifications to account for the higher energy. The main differences between the two detector concepts lie in the placement of the solenoid (after the tracker in MAIA and between ECAL and the HCAL in MUSIC) and the technologies selected for the ECAL (Si-W for MAIA and semihomogeneous crystals for MUSIC).

Table 2: Preliminary summary of the "baseline" and "aspirational" targets for selected key metrics for a 10 TeV muon collider.

Requirement	**Baseline**	**Aspirational**
Angular acceptance $\eta = -\log(\tan(\theta/2))$	$\|\eta\| < 2.5$	$\|\eta\| < 4$
Minimum tracking distance [cm]	~ 3	< 3
Forward muons ($\eta > 5$)	tag	$\sigma_p/p \sim 10\%$
Track σ_{p_T}/p_T^2 [GeV^{-1}]	4×10^{-5}	1×10^{-5}
Photon energy resolution	$0.2/\sqrt{E}$	$0.1/\sqrt{E}$
Neutral hadron energy resolution	$0.4/\sqrt{E}$	$0.2/\sqrt{E}$
Timing resolution (tracker) [ps]	$\sim 30 - 60$	$\sim 10 - 30$
Timing resolution (calorimeters) [ps]	100	10
Timing resolution (muon system) [ps]	~ 50 for $\|\eta\| > 2.5$	< 50 for $\|\eta\| > 2.5$
Flavour tagging	b vs c	b vs c, s-tagging
Boosted hadronic resonance identification	h vs W/Z	W vs Z

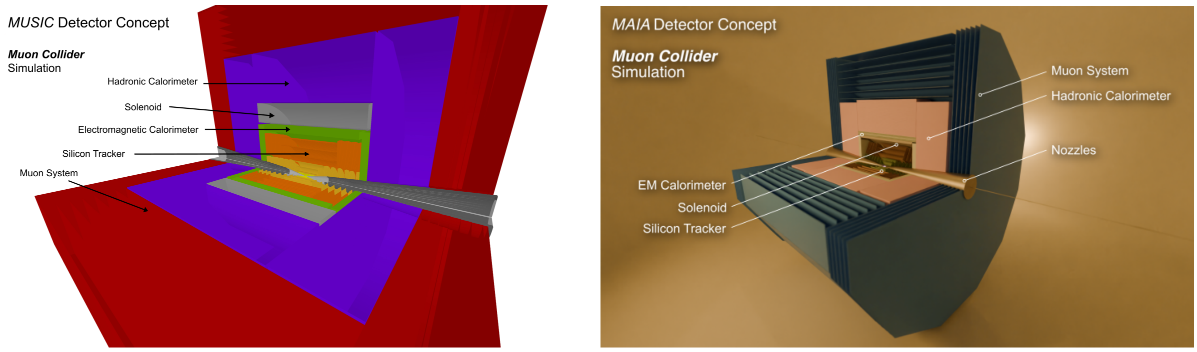

Fig. 3: Layout of the MUSIC (left) and MAIA (right) detector concepts

High levels of beam-induced background in the detector pose unprecedented challenges for the reconstruction and identification of particles produced in muon collisions. Studies based on detailed simulations of the MAIA and MUSIC detector concepts were carried out. These studies used state-of-the-art FLUKA simulations to account for the beam backgrounds produced by the decays in the latest accelerator lattice, and GUINEA-PIG predictions to study the effects of incoherent pair production at the interaction point. The detector response was studied to develop initial background-mitigation measures. In both cases, the results indicate that the background effects on the detector response can be minimised to a degree that approaches the aspirational goals.

Research and development over the next decade must focus on developing the necessary technologies, tools, and crucial expertise to design and construct state-of-the-art detectors for this future machine. At the muon collider, most detector components must simultaneously optimize position resolution, timing capability, radiation hardness, data transmission, and on-detector background rejection, all while maintaining low-mass and low-power consumption. Many of these technical challenges align with ongoing research in other initiatives, such as the LHC and Higgs/Top/EW-factory R&D programs. However, the development effort must also address challenges unique to the muon collider, including its harsh radiation environment, the need to suppress significant beam-induced backgrounds, and the requirements for high-precision calorimetry to measure significantly higher energy physics objects.

The R&D program is organised around three main areas: simulation and performance, technology and computing. In technological R&D, multiple technologies will be investigated in the first phase of the work. The choices are expected to consolidate after the first four to six years and resources will transfer to the identified technologies needed for the chosen detectors designs. Coverage across areas for items relevant for the same sub-detectors is also ensured. Among all tasks that have been identified, ASICs and detector magnets have been identified as critical components requiring extended development timelines and should therefore be prioritized to ensure readiness for detector construction.

4 Readiness and muon collider challenges

The IMCC, the Muon Beam Panel of the Laboratory Directors Group (LDG) and the Snowmass process in the U.S. have all assessed the muon collider challenges with the support of the global community [5, 6]. Key conclusions are that, although the muon collider concept is less mature than several linear collider concepts, no insurmountable obstacles have been identified, and that important design and technical challenges have to be addressed with a coherent international effort. Furthermore, past work, in particular within the U.S. Muon Accelerator Programme (MAP) [3], has demonstrated several key technologies and concepts, and gives confidence that the overall Muon Collider concept is viable. Since then further component designs and technologies have been developed that provide increased confidence that one can cool the initially diffuse beam and accelerate it to multi-TeV energy on a time scale compatible with the muon lifetime. However, a fully integrated design has yet to be developed and full demonstrations of technology are required.

Following the last European Strategy, the IMCC has been formed with the goal to establish whether the investment into an important R&D programme on the muon collider is justified. A prioritised work programme has been developed by the LDG with this goal and is being implemented by IMCC. Resources have been made by the 58 member institutions, several other partners and the European Union. Following discussions with DoE representatives, an addendum to the CERN-DoE agreement is prepared and currently being reviewed by DoE. At this point, progress in several areas is limited by resources and additional resources are being sought across the collaboration, in parallel with the processes to include new partners. The R&D programme thus addresses priority challenges.

The IMCC programme prepares the way towards a conceptual design report (CDR) and a demonstration programme for a muon collider. The IMCC studies physics potential, detector design, accelerator design and performance studies. Studies assess technology maturity and develop critical designs to understand key challenges.

Parameters for the **proton driver** were developed based on existing facilities and simulations of key systems for a high-intensity 5 GeV or 10 GeV beam. Heat and radiation load in the **target** area was assessed for 2 MW proton beam power; a target and shielding design was developed that adequately protects the capture solenoid and limits damage to the graphite target rod. Extraction of the spent proton beam at the target has been identified as a potential technical issue.

The **muon cooling** system reduces the 6D beam size (emittance) to improve luminosity, and has been optimised from previous designs. The system delivers transverse and longitudinal emittances of $22.5\,\mu\mathrm{m}$ and $7\,\mathrm{meV\,s}$ respectively. The longitudinal emittance is almost a factor 3 better than the target parameters but the transmission is 20 % lower than target. Optimisation continues by matching between cooling stages, integrating components within the cooling cell and improving the longitudinal beam capture section. Beam-loading and heat-load on the hydrogen absorbers have been identified as technical issues.

Low-energy **acceleration** solutions have been found for the LINAC and the second recirculating linear accelerator. Simulation of the high-energy acceleration has been performed including single-turn and multi-turn wakefields and with counter-rotating beams.The lattice exceeds the target values for transmission. Suitable emittance control has been demonstrated in the absence of errors. Lattice errors may impact the beam quality and this is a focus of ongoing studies.

The **collider** ring at 10 TeV centre-of-mass energy and β^*=1.5 mm must deliver a short bunch with a large energy spread to avoid luminosity dilution from the hour-glass effect. Challenges arise from controlling chromatic aberration in the ring despite the 0.1% RMS momentum spread. The current β^* lattice has a reduction in energy acceptance compared to the target parameters. Magnet misalignments may reduce performance further, especially as the magnets will be periodically moved ± 1 mrad, to dilute the neutrino flux. Designs are ongoing to improve energy acceptance. The potential improvement in longitudinal cooling may alleviate the shortfall.

The **magnet team** has developed conceptual designs for critical magnet systems, including: a 1.2 m bore and 20 T *target solenoid*; *cooling solenoids* with achievable values for radial and hoop stress, stored energy, current density and fields up to 40 T; *rapidly pulsed normal-conducting* ± 1.8 T magnets for the accelerator system with high-efficiency power converters that require acceptable wall-plug power and; *high-field dipoles*, quadrupoles and combined-function magnets including appropriate shielding from muon decay electrons. A resource-loaded programme for magnet hardware development, which is on the muon collider facility critical path, has been assessed and is discussed below.

The **RF team** has developed 352 and 704 MHz normal conducting RF cavity designs for the cooling system. The *cooling RF cavities* are challenging owing to tight integration with the solenoids and up to 32 MV/m required electric field. Power couplers have been developed to minimise interference with neighbouring equipment. *High-energy acceleration cavities* have been developed assuming 1.3 GHz RF structures. The required layout of RF stations and impact on the beam quality has been assessed. It has been integrated within the overall lattice.

A **Muon Cooling Demonstration** programme has been proposed based on a typical section of the cooling channel. An integrated engineering design has been developed. Candidate sites at CERN, Fermilab and other laboratories have been identified. Concepts for layout and beam optics design of the beam transport sections have been assessed. The programme, including magnet and RF cavity R&D, has been developed into a resource-loaded timeline. The Demonstrator is also on the muon collider facility critical path and implementation is discussed below.

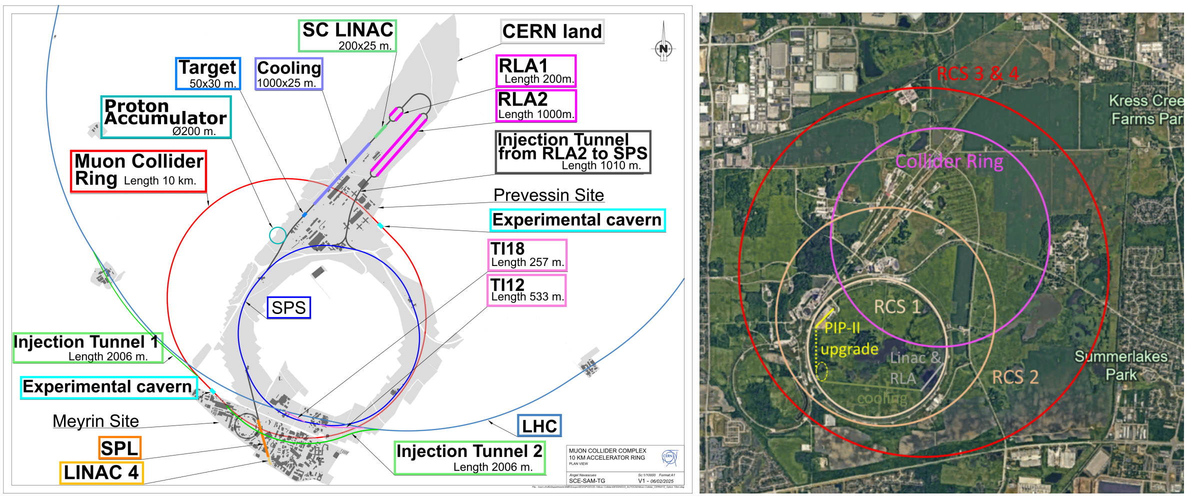

Fig. 4: Conceptual layout of the muon collider at CERN (left) and Fermilab (right).

Civil engineering studies at CERN indicate that the surface installations of the accelerator facility could be constructed fully on CERN land and that **the SPS and LHC tunnels could be reused** to host the accelerator rings, thus minimising the overall civil engineering. The proton complex would be located on the Meyrin site. Figure 4 (left) shows a layout. The beam would be transported through the SPS tunnel to the Prevessin site where the cooling and initial linacs would be located in cut-and-cover tunnels. The beam is injected into the SPS then the LHC and finally into a new 10 km long collider ring. It may be possible to maintain the current SPS in parallel to the muon collider. A similar siting study, including investigation of how the existing and planned infrastructure can be used, is underway for Fermilab and the preliminary layout, constrained within the boundaries of the Fermilab site, is shown in Figure 4 (right). The exact parameters of the collider sited at Fermilab are to be refined taking into account findings from the study.

Muon decays produce neutrinos that will exit the earth's surface far from the accelerator facility. These neutrinos will enable a unique experimental programme that goes far beyond current state-of-the-art programmes such as FASERν. In this case neutrino detectors would be installed on the surface where the neutrino beam emerges. A suitable implementation has been identified at CERN. The neutrinos arising from the rest of the facility must be diluted so that there is negligible radiation outside the CERN site, comparable to the impact of the LHC. A system of movers are required in collider arcs to displace the magnets vertically to achieve this. Tentative studies indicate that it is possible to have a negligible impact on the environment. Further optimisation and expansion of the studies to the full complex are required.

The overall facility design has progressed well given the available resources. The transmission and beam emittance has been estimated across the facility. Further development of the lattice design may reveal new issues, but also make possible a global optimisation for cost, power and performance. Some technical issues have been uncovered. None of the issues have impacted the concept feasibility although in some areas the performance relative to target parameters may be degraded. Innovative approaches have enabled the IMCC to exceed target parameters in other areas. **Overall we are convinced that the target luminosity is achievable.** If the target luminosity can be met **IMCC considers that we have a significant contingency in luminosity in hand.**

The power consumption for CERN implementations at 3.2 and 7.6 TeV and the 10 TeV site-independent design are about 117 MW, 182 MW, and 201 MW, respectively.

5 Timeline and R&D plan

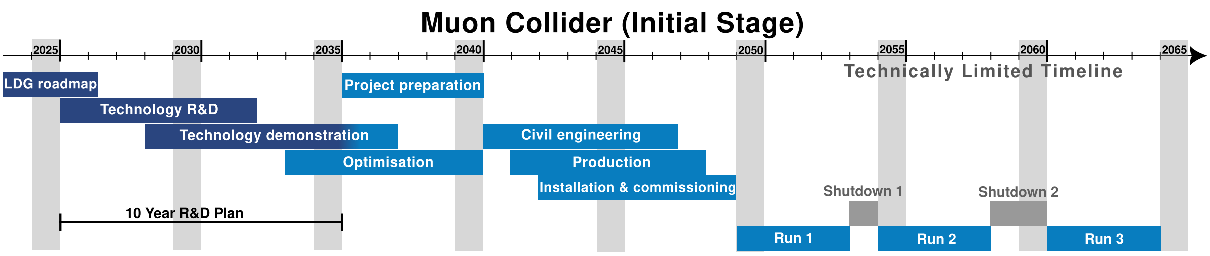

Fig. 5: Technically limited timeline for the initial muon collider stage, assuming a firm commitment to implement the project as soon as possible after the High-Luminosity LHC. The timeline of the project phases beyond the planned 10 years of R&D are affected by the siting choice and detailed planning by the host laboratory.

A roadmap towards a muon collider must remain flexible, and is an important part of a diverse international research programme in particle physics. New results, from the HL-LHC or non-accelerator based experiments, and potentially also lower energy experiments, might change the desired parameters for a future muon collider. Societal changes and priorities might also influence resource availability and hence timelines for investments in basic science as needed for future colliders. The potential of a muon collider to reach around 10 TeV parton-parton collisions with high luminosity makes it an exciting opportunity for the near and more distant future.

IMCC proposes a comprehensive R&D programme to reach the maturity required to initiate the approval process. The programme requires approximately 300 MCHF material budget and about 1800 FTEy of personnel for the accelerator and about 20 MCHF and 900 FTEy for detectors. With timely funding, the programme spans about 10 years. This would enable a first muon collider stage with a start of operation around 2050. Its could thus be the next flagship project in Europe in case no Higgs factory is realised at CERN. A slightly longer timescale is envisaged for an implementation in the U.S. taking into account budget constraints.

The first phase of the R&D programme contains completion of a start-to-end facility design. It also includes hardware development of components that drive the overall timeline for the collider such as the superconducting magnets and the muon cooling technology. After this phase a ramp-up of resources will enable a more detailed facility design to prepare for the start of the decision process. This process could start in 2036 and allow investing into industrialisation of the components before project construction approval. The proposed technically limited timeline, shown in Figure 5, is feasible, contingent on the strong commitment from the community and the funding agencies to realise a muon collider at the earliest possible time.

The proposed R&D plan will achieve the following:

– Further development of the **detector** will optimise the performance and minimise the impact of beam induced background.
– The **muon cooling technology** demonstration programme will develop this novel technology. It will develop the components such as the HTS solenoids, the cavities and the absorbers. Test of a full cooling cell with RF power will allow verification of the integrated performance. The demonstrator facility will test several of the cooling cells with beam to demonstrate the technology.
– An intense programme will establish the **superconducting magnet** performance through the construction and test of models and protoypes. It will focus in particular on HTS solenoids for the muon production target and the muon cooling. These have strong synergy with applications in society such as fusion reactors. A model of the collider ring dipoles will also be constructed and establish the field at large aperture.
– A **start-to-end model** of the collider. The completion of the lattice design along the whole complex and its optimisation will guide the component development. The development of simulation tools that include the relevant beam physics, such as collective effects and imperfections as well as the relevant mitigation techniques, will enable robust luminosity predictions. A study of the machine availability will establish the integrated luminosity performance and guide component and accelerator design.
– Experiments in combination with further design work will verify the **target** robustness.
– Conceptual designs of the superconducting and normal-conducting **cavities** along the whole complex. Experimental verification of the performance limits will allow to optimise the complex design. In particular, the construction of an infrastructure to test RF in a high magnet field will enable experimental optimisation and verification of the normal-conducting muon cooling RF.
– The development of high-power, high-efficiency **klystrons** will be instrumental for the muon cooling cell test and enable cost effective design.
– The performance of the **fast-ramping magnet systems and power converter** for the Rapid-Cycling Synchrotrons (RCS) will be demonstrated.
– **Site and environmental impact studies**, including civil engineering, will allow optimisation for power consumption and material usage as well as minimising the impact of the machine for the local environment.
– An **overall optimisation** of the complex for cost, power consumption and risk will be performed and is particularly essential since we cannot base ourselves on experience with previous similar projects. This optimisation will also cross the boundaries between the different systems.

It will also be important to explore promising alternatives to the current baseline, e.g. the use of a Fixed-Field Accelerator (FFA) in the proton complex to reduce the linac energy and cost.

6 Synergies

Particle physics and the associated accelerator and detector development have made important contributions to society; both in training of young people and in developing technologies.

Many young people have developed their scientific and technical skills in the field; they also learned to work in fully international collaborations. Because the muon collider is a novel concept it opens opportunities for young researchers to make original contributions to the development that are much harder to make in long-established design approaches.

The muon collider needs technologies in several areas that differ from other colliders. High-field solenoids are a prime example. In the past low-temperature superconductors such as the very mature NbTi and still developing Nb_3Sn were the technologies of choice for accelerators and most other applications. Now HTS are becoming an important technology. In particular, they are of interest for fusion reactors, that have similar requirements to the one for the muon collider target solenoid. Highly-efficient superconducting motors and power generators, e.g., for off-shore windmills, also have strong synergy. Other relevant areas are life and material sciences; in particular, applications exist for nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI). In addition synergy exists with magnets for neutron spectroscopy, physics detectors and magnets for other particle colliders, such as hadron colliders.

The muon production target is synergetic with neutron spallation sources targets and neutrino targets, in particular the alternative liquid metal concept.

The muon collider RF power sources have synergy with other developments of high-efficiency klystrons and superconducting cavities. Some RF systems need to work in high magnetic fields, an issue that also exists in some fusion reactor designs.

The test facility and the collider itself require a high power proton source to produce muon beams of unprecedented intensity and brightness and experimental conditions not available in any other facility. This allows sharing technology and potentially even facilities. Neutron spallation sources such as SNS and ESS are major examples; other examples are neutrino facilities, such as NuSTORM, lepton flavour violation experiments, such as mu2e and COMET and low-energy muon beam facilities used for materials science.

7 Conclusion

The formation of IMCC has enabled important progress on the muon collider design and technologies, greatly increasing confidence in the concept. Investment in an experimental programme for the technologies is now essential for further progress. Demonstrating key technologies for muon cooling—such as HTS solenoids, RF cavities, klystrons, absorbers and their integration into cooling cells—will advance the novel aspects of the design. Additionally, the development of other critical technologies, including fast-ramping magnet systems, high-field superconducting dipoles, high-power target and superconducting RF technology, will optimise collider performance. The technology development has strong synergies with other projects, such as FCC-hh, as well as applications with significant societal impact, such as fusion reactors. Increasing effort on the start-to-end design will enable robust predictions of luminosity performance and availability of the collider, optimise cost, power consumption, and risk, and guide the continued development of technologies.

Global interest in the muon collider as a path to 10 TeV parton-parton collisions is growing, with CERN and Fermilab currently being considered as potential sites. Initial exploration indicates that a muon collider could be implemented at CERN, reusing the SPS and LHC tunnels. The corresponding technically limited timeline indicates that a first collider stage could be available by around 2050. Following HL-LHC or a potential fast Higgs factory, the muon collider could thus become Europe's next flagship project.

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