Summary of Muon Collider Study and Ask for the 2023 P5

Muon Collider Ask

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*Corresponding author, sergo@fnal.gov

1 Introduction

Muon colliders have a strong potential to get us to 10 TeV scale with sufficient luminosity to explore the next frontier of physics, the soonest, in the smallest real estate footprint, and possibly at the lowest price-point of all 10 TeV scale machines.

The energy frontier community studied the physics potential of a 10 TeV 10 ab^{-1} machine and are excited by the prospect of preparing a conceptual design of the machine and the detector, including a siting option in the USA.

Timely realization of a conceptual design for the 10-TeV muon collider and associated detector requires investment in focused R&D now. In March of 2023, following a request from the Fermilab directorate, a Muon Collider R&D group was assembled to provide input to P5. The group was asked to develop the R&D plan, budgets, and deliverables. It focused on the key elements of 10 TeV accelerator and detector design. Findings and recommendations of the group are summarized in this document.

2 Physics Case

Historically, our understanding of fundamental physics has been advanced by the complementary pursuit of energy and precision, respectively the domains of proton colliders and e^+e^- colliders. Muon colliders blur this dichotomy, enabling the simultaneous increase of energy and precision in a single accelerator complex. A muon collider's combination of energy and precision not only presents the most attractive way to reach the energy frontier, but is also ideally suited to the questions we seek to answer there.

Many of the most pressing questions of the current era involve electroweak symmetry and its spontaneous breaking. The Higgs boson discovered in 2012 is but the herald of this phenomenon, whose complete exploration calls for colliders that effectively reach the 10 TeV and above. Such colliders can address whether electroweak symmetry is realized by the known particles (or involves additional as-yet-undiscovered degrees of freedom), experimentally demonstrate the restoration of electroweak symmetry at high energies, and access the qualitatively new phenomenon of electroweak radiation. Precision measurements of the Higgs potential not only allow us to investigate the origin of electroweak symmetry breaking, but provide a window into both the past and future of our universe.

The urgency of the 10 TeV scale stems from a number of different directions, and the advantages of probing it with EW charged particles make a muon collider uniquely suitable. To truly understand electroweak symmetry and go beyond our phenomenological description vis-a-vis the Higgs potential requires measuring of the Higgs couplings in greater detail. For single Higgs couplings, e^+e^- colliders will take an important first step, but to go further requires the production of Higgs particles at higher energies. Furthermore, deviations in precision measurements imply a scale for new physics that should be accessed directly; for a 1% benchmark this roughly implies new physics up to the TeV scale in weakly coupled models. This will be probed in a variety of ways directly at the HL-LHC, therefore again more energy and precision are needed to illuminate the origins of EWSB. A muon collider is the *unique* option which allows both to be probed in the same collider and take us an order of magnitude beyond the LHC. Therefore if there is a strong case for a Higgs factory, the case for a high energy muon collider is even more urgent. Furthermore, a muon collider fully realizes its potential when analyzing the Higgs potential. Reaching the 1% threshold on the Higgs self interaction, which only a muon collider can lay claim to, allows us to answer questions about the nature of the Electroweak phase transition definitively. Finally, if the ultimate origin of EWSB is due to strongly coupled dynamics which manifests itself in an EFT parameterisation, a muon collider allows for the best probes of it through its copious and clean EW gauge boson production.

Beyond its role in breaking electroweak symmetry, the Higgs provides one of the leading portals for the Standard Model to interact with sectors beyond our own. The precision of a muon collider gives access to light particles in exotic Higgs decays, while the energy of a muon collider puts heavier particles in reach of direct production. Looking beyond the Higgs, there is also abundant motivation for additional EW charged particles in the vicinity of the TeV scale. Such particles remain one of the simplest candidates for dark matter consistent with current data, with subtle signatures that are ideal targets for the energy and precision of a muon collider.

The urgent questions of the age – the nature of electroweak symmetry and the mechanism of its breaking; the origin of the universe and its ultimate fate; the identity of dark matter; and the existence of sectors beyond our own – call for a collider that achieves unprecedented energy and precision using electroweak probes. They call for a muon collider.

3 Accelerator

This section describes a possible set of R&D and deliverables of the Muon Collider R&D program in the U.S. A goal would be to engage U.S. leaders in high-field magnets, RF, beam dynamics, targetry and instrumentation, while also choosing topics that are closely tied to a possible MC detector development effort such as MDI and backgrounds. Examples might include high-field and rapid-cycling magnets where Fermilab, LBNL and BNL are leaders. Fermilab, Jlab, and Cornell are leaders in bulk Nb and Nb3Sn SRF cavities and cryomodules. While several laboratories have expertise in normal conducting RF cavities, SLAC in particular is a leader in RF power sources and "cold" normal conducting RF components. Fermilab, LBNL, BNL, SLAC, ORNL and ANL have extensive tools for the simulation of beam dynamics, muon production and acceleration as well as instrumentation. Fermilab has a number of suitable opportunities for beam tests, while all the above national labs have a number of test facilities to develop and test accelerator hardware prototypes.

The work plan for the next 7 years would consist of design studies and technology R&D. After the end of this period, the goal is to deliver RDR design report for the final facility as well as a TDR report for a demonstrator facility including cost estimates. The details of this plan is discussed below:

3.1 Proton Driver

- Describe an upgrade to the Fermilab accelerator complex that would produce protons with the desired power and timing structure for a muon collider.
- Given the choices made to produce the desired proton beam, create a full simulation of the accumulation and compression process to produce the short bunches required for the target, a description of the hardware requires for the rings, and the resulting beam parameters.
- Proton compression and laser stripping studies at SNS and proton compression studies under extreme space-charge at IOTA.

3.2 Target

- Make a choice for how to do the target proper: material, support/delivery method. Get input from and participate in studies of target materials, perform supporting simulations for our choice. For instance, through RaDIATE collaboration study the properties of Muon Collider target candidate materials. Moreover, using the EMPHATIC spectrometer at FTBF, measure pion yield for different candidate materials.
- Design a target station and initial capture (through the chicane, though simulation further downstream may be helpful). Proton beam delivery, solenoid system, shielding, cooling, beam dump, etc.
- Provide a particle distribution for downstream simulations.

3.3 Cooling

- Find the limits of 6D cooling channels by considering improved magnet configurations, and using newer, demonstrated technologies for solenoids and RF (HTS, higher demonstrated gradients, liquid nitrogen cooling). Consult with engineers (for magnets in particular) to ensure feasibility and cost-effectiveness of design channel designs. Include collective effects, devise techniques to compensate for them, determine performance limits they create.Re-optimize the full channel using aforementioned technology improvements, limitations from engineering.

- Produce a simulation reaching the desired transverse emittances for a collider ring ("final cooling"). Include input from output of optimized rectilinear channel. Study at least 2 or three alternative methods (High-field solenoid Palmer method, PIC, emittance-exchange).
- Prepare a CDR/TDR of a cooling demonstration facility (around 12 cooling cells, muon source, diagnostics)
- Propose a RF power source (possibly alternatives) for 6D cooling RF cavities. Prepare an R&D plan for developing such power supplies.
- Prepare a design and study siting possibilities for a cooling cavity RF test facility. Describe an expanded program from what was done in MAP: additional materials: CuAg, Al; operation at 77-ish K; more flexible solenoid configurations (higher field, Helmholtz configuration to vary direction and allow a larger diameter cavity); lower frequency cavity (325-ish MHz).
- Design and construct a cooling cell prototype, including absorber, RF, and magnets, the magnets and RF will be powered, a method for heating the absorber at the rate muons would will be included. Purpose is to work out all engineering challenges, provide input to cooling channel design form engineering limitations, and demonstrate operation of hardware in complex configuration. Should be 2 cells of magnets (full central cell, half cells on both sides), and one cell of RF

3.4 Acceleration

- Design acceleration from output of final cooling up to first superconducting elliptical-cavity linac. Design acceleration from first superconducting elliptical-cavity linac through 174 GeV (top threshold; if we don't go straight to multi-TeV, this is almost certainly our first machine). Design any required longitudinal matching in transfer lines.
- Design acceleration based on pulsed (hybrid) synchrotrons to highest energy possible on Fermilab site. Design any required longitudinal matching in transfer lines.
- Perform or obtain characterization at high ramp rates of materials used for a pulsed magnet. Design and build a small prototype magnet for purposes of characterizing the magnet response over a range of pulse rates and pulsing configurations (how far one goes into saturation, etc.). At a minimum measure voltage/current/field traces.
- Design a roughly full-scale pulsed magnet and its power supply. It should operate at the desired repetition rate and have a cooling system. The emphasis is on the power supply design and performance at a production scale, we should demonstrate efficiency, control and pulse linearity, etc. Demonstrate that behavior is consistent with simulations.

3.5 Collider Ring

- Design of a collider ring compatible with the aforementioned maximum acceleration energy. Should include considerations of shielding & cooling, longitudinal dynamics.
- Give details of a plan for limiting neutrino radiation exposure. Give engineering details of any required systems, prepare a CDR/TDR for a demonstrator/prototype if needed.
- Make detailed designs of the most challenging magnets in the collider ring. Choose magnets to be prototyped (in particular IR magnets), create designs for those prototypes, and prepare a prototyping program (timelines, etc.)

4 Detectors

The unstable nature of muons poses unique challenges for particle detectors at a muon collider. It is impossible to study muon collisions without being exposed to muon decay products from the beam. This section describes how the unique collision environment at a muon collider influences detector design, and outlines specific needs for simulation, design, and technology progress.

4.1 Collision Environment

Dedicated shielding is used to prevent high-energy electrons produced by the decaying beam are prevented from entering into the detector region. The properties of the resulting beam-induced-background (BIB) and overall detector occupancy depend on the details of beam focusing and shielding design. An iterative co-design process integrating both accelerator and experimental expertise is crucial to optimize the machine detector interface.

Current designs use tungsten nozzles to shield the detector [1]. High-energy electrons shower inside the nozzle resulting in large multiplicities of diffuse low-energy particles, the majority of which are photons, neutrons, electrons, and positrons. To date, the BIB for a $\sqrt{s} = 1.5$ TeV collider is the most thoroughly studied scenario. However, preliminary studies have demonstrated that BIB properties do not dramatically change with increasing beam energy. For example, doubling the beam energy without any nozzle re-optimization results in a $0-35\%$ increase in fluence for different particle species.

The total ionising dose and neutron equivalent fluence is comparable to the HL-LHC in simulation. However, the per-event occupancy is expected to be higher, particularly in the inner layers of the tracker, calling for highly granular detectors with precision timing capabilities. To enable detector readout, it is necessary to differentiate signal hits from BIB particles emerging from these nozzles. Module-level precision timing and angular determination have been shown to be effective tools for this task.

4.2 Current status

A $\sqrt{s} = 3$ TeV detector design has been optimized incorporating detailed studies of BIB from 750 GeV beams. This scenario was considered due to the early availability of BIB samples at this beam energy, and an initial detector design for $\sqrt{s} = 3$ TeV collisions at CLIC. To test that precision measurements are possible in the busy environment of a muon collider, key physics benchmarks have been assessed with and without the presence of BIB. These studies demonstrated that with near-term detector technologies even challenging signatures like secondary vertices from b-jets and disappearing tracks from long-lived particles could be reconstructed in the presence of beam backgrounds Additional details can be found in the Snowmass Muon Collider Forum Report [2]. More recently, higher energies have been studied, including a preliminary design for a $\sqrt{s} = 10$ TeV collisions, Efforts to characterize performance and refine detector design at these higher energies are ongoing.

From these studies, key design requirements for each subsystem have been identified:

- **Tracker:** In order to suppress BIB, the ability to reject non-pointing and out-of-time particles is key. 4D silicon sensors with temporal resolution on the order of 10s of picoseconds are required in all layers. Background occupancy in the innermost layers of the tracker additionally require granularity on the order of 25×25 μm^2. Local pointing measurements can further reduce backgrounds, and low power on-chip intelligence is crucial for the implementation of any rejection algorithm. Any technology used must be radiation hard, though this requirement is similar to that of the HL-LHC detectors.
- **Calorimeters:** Low energy particles from the BIB are almost entirely absorbed by the first few layers of the Electromagnetic Calorimeter. For these innermost layers 5×5 mm^2 spatial granularity, $\mathcal{O}(100)$ ps temporal resolution, and longitudinal segmentation are all required to accurately extract signal particle energies from the BIB pedestal. In the Hadronic Calorimeter, and potentially the outer layers of the EM Calorimeter, LHC-like designs would suffice. Expected radiation is similar to HL-LHC.
- **Muon Spectrometer:** The majority of the muon system is shielded from BIB by the calorimeter, and gaseous detector technologies used at the HL-LHC will suffice. In the forward region, BIB particles can reach the system without traversing the calorimeter, resulting in higher rates. As with the other systems, pointing and timing information can improve

performance. A major challenge for the muon spectrometer will be identifying low global warming potential gas mixtures that also satisfy performance requirements.

- **Forward systems:** Luminosity measurements are crucial in all machines, and in a muon collider in particular, forward muon tagging enables precision measurement of VBF processes. Depending on placement, these systems can be shielded by tungsten nozzles or focusing magnet systems, but are expected to experience high rates regardless. Studies on these systems are in their early stages, but can benefit from work already done to understand the tracker environment.
- **Detector magnets:** Current designs make use of a 3.6 T solenoid surrounding the calorimeter, with an iron return yoke extending through the muon spectrometer. This design has not been thoroughly optimized, but the technology is similar to what is used in the current LHC detectors. Detectors at higher center of mass energies will require a larger tracker and calorimeter. For these scenarios alternate magnet strategies are being considered, including a separate toroidal system for the muon spectrometer.
- **Data acquisition:** Because a muon collider only would only circulate two bunches at a time, its event rate would be $\mathcal{O}(10^3)$ smaller than the LHC's. This makes readout of every event a possibility if packet size can be kept small enough. On-chip intelligence separating signal information from BIB is the key technology needed to enable triggerless operations.

Detector readiness for a multi-TeV muon collider has benefited substantially from R&D for the HL-LHC. There are also strong overlaps with technology needs for other proposed future colliders. Needs most specific to a muon collider detector include integrated precision timing and on-chip intelligence, which are both essential for BIB rejection.

4.3 Simulation, Design, and Technology Needs

While foundational studies have demonstrated that precision physics is possible in a muon collider environment with near-term technologies, much more development is needed. Nearly all optimization performed so far has focused on $\sqrt{s}$ = 1.5 TeV BIB, though signal processes have been simulated at higher energies in many key studies. A preliminary design for a $\sqrt{s}$ = 10 TeV detector is still in progress. Additional designs are needed at other energies to access the physics performance of possible intermediate staging options.

Given the long timescales necessary to achieve technical readiness, it is crucial that development begins now. We've identified three main thrusts to ensure further design and technology progress.

- **Software and computing:** Software to generate key processes and simulate the detector response is critical for further design progress, performance studies, and physics case development. Generating and simulating BIB samples with packages such as MARS, Fluka, and GEANT is CPU-intensive and currently a major bottleneck for future studies. These packages require development, and possible improvements from hardware acceleration (eg. GPUs) should be investigated. Software for digitization, reconstruction, and analysis should be also modernized and supported, identifying any synergies with other future collider proposals. Dedicated disk space (500-1000 TB) is crucial to store samples.
- **Detector design:** All detector systems require person power for further design optimization. For example, the location and number of layers in a given subsystem, assumptions about available technology, digitization, and reconstruction all require investigation. High priority areas for further study include full-simulation studies at $\sqrt{s}$ = 10 TeV, nozzle design and optimization, and forward detector design. These studies require frequent iteration between experimentalists, theorists, and accelerator physicists. The detector should be designed to maximize the physics case in the face of realistic constraints due to the unique beam induced background.
- **Detector technology:** Dedicated detector R&D must proceed in parallel to establish technology feasibility. There is substantial overlap with technology needs for other proposed future colliders, motivating a robust generic detector R&D program. However, there are several needs specific to muon collider detectors that require dedicated R&D. In particular

the need for ASICs with precision timing and on-chip intelligence will not be met with a single design iteration. For example, ASIC development for the HL-LHC pixel upgrades required multiple iterations over 20 years as well as two steps forward in CMOS technology with respect to the original detectors. Given this experience, it is crucial key detector and technology development begins now.

5 The ASK

We are asking for support of a Muon Collider accelerator and detector R&D program with the ultimate goal of establishing technical feasibility for a high energy Muon Collider, compatible with US siting.

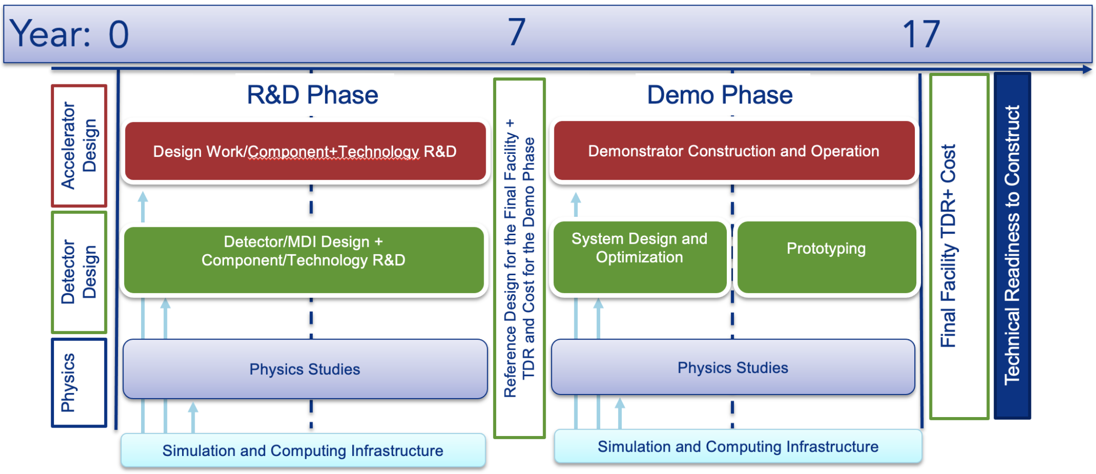

Figure 1: A sketch of the proposed Muon Collider R&D timeline, along with main activities, milestones, and deliverables.

The proposed Muon Collider R&D timeline is shown in Fig. 1. With this timeline we aim to deliver Technical Design Report for the collider in under 20 years. The program is divided into two major periods, referred to as the *R&D Phase* and the *Demo Phase*. In the *R&D Phase*, which is expected to last for about 7 years, the accelerator effort will primarily focus on the development of an end-to-end reference design using simulation. Some smaller-scale accelerator component studies will also be conducted during this period. In parallel, the detector group will proceed with optimization of 3 TeV and development of 10 TeV detector and MDI designs. Some detector component and technology R&D will also take place during this period. By the end of the *R&D Phase*, we expect to deliver: (a) a Reference Design Report (RDR) for the collider facility, including preliminary 3 and 10 TeV detector designs and (b) a TDR with detailed cost estimate for the demonstration facility, including description of physics that can be pursued at the demonstration facility. FTE and M&S needs for the *R&D Phase* of the program have been evaluated using a combination of bottom-up and top-down (where bottom-up estimate is impossible at the current stage) approaches and assuming that approximately 50% of the scope will be taken by the United States, while the remaining scope will be done by IMCC partners. The FTE and M&S profiles, separated into accelerator and detector efforts, are shown in Figs. 2 and Figs. 3. We anticipate a required ramp up to approximately 50 FTE/y for the accelerator and 40 FTE/y for the detector during the *R&D Phase*. The peak M&S needs during this phase are 5 M$ and 1.5 M$ per year, for the accelerator and the detector, respectively. No escalation is included in these estimates. Development of simulation tools and support of computing infrastructure are crucial for achieving our goals and we expect these efforts to stretch over the entire duration of the program. Support for simulation and computing work is included in the estimates above.

The *Demo Phase* starts around Year 7 and lasts for ten years. The primary goal of this phase is to demonstrate principle risk mitigation. The accelerator effort will focus on the construction and operation of various demonstrators, with the largest one being the ionization cooling demonstration facility. The detector effort will address system level design aspects, explore different design options

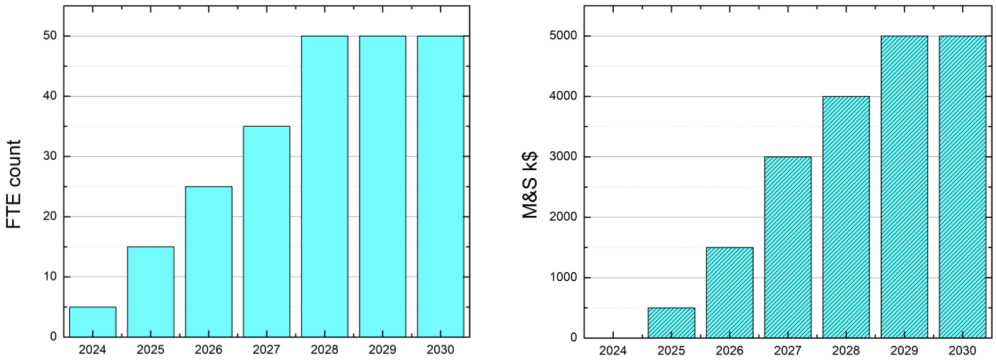

Figure 2: FTE and M&S needs for accelerator R&D corresponding to the first phase of the program.

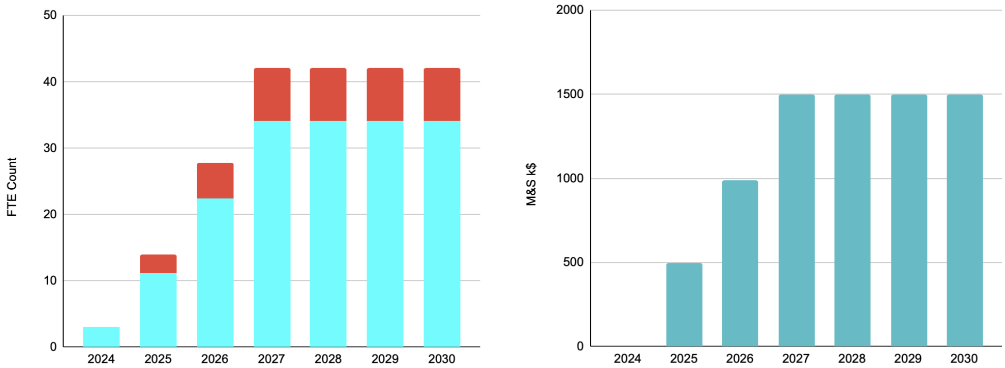

Figure 3: FTE and M&S needs for detector R&D corresponding to the first phase of the program. The FTE counts are separated into physicist (cyan) and engineer labor (red).

for the two interaction points, and perform some initial prototyping, including construction of a small-scale detector slice to demonstrate the necessary background rejection capability with beam. The amount of required funding for the *Demo Phase* depends on specifications of the demonstrators, their siting, and the scope taken by the US. The budget profile for the accelerator demonstrators during the *Demo Phase* will be evaluated at the end of the *R&D Phase*, but we estimate it to be 100+ M$ per year during the demonstrator construction; this is a top-down estimate based on experience with more mature future collider concepts (e.g. ILC, CLIC). The detector R&D budgets will also need undergo a growth in this period by approximately a factor of 1.5–2.0 with respect to the *R&D Phase*. The deliverable of the *Demo Phase* is a Technical Design Report for the collider facility and the associated detectors, including a detailed cost estimate.

We believe that the most fruitful path forward towards the development of design of the Muon Collider and associated detector in the USA, will involve coordination with the IMCC efforts. A US Muon Collider Collaboration (US-MCC) needs to be formed with a goal towards preparing a proposal for the US funding agencies, assuming identification of the Muon Collider as an important path forward for the US energy frontier community. Given the necessity of a strong coupling of the Muon Collider accelerator and detector communities, it seems most suitable to follow the IMCC model with a unified US-MCC, rather than work individually at various institutes. We anticipate that individual US institutions joining the IMCC will also be members of a new US-MCC, elect its leadership and represent the combined interest of the US muon collider community to the US funding agencies.

We also ask that DOE and NSF recognize muon collider work within the AF and EF base program proposals (including support for software and simulations), to enable DOE National Labs and US University community to efficiently contribute to the effort. In order to gauge interest of the US LHC community in the physics and detector part of the program, we conducted a quick survey asking PIs to identify areas of interest and resources they could allocate to this effort, assuming that funding was available. We received an expression of interest from 31 PIs from 24 institutions (not including theorists and accelerator physicists) with a wide range of interests from the core simulation framework development to detector technology and design studies.

Work on physics studies will proceed through both phases of the program. These studies would allow to further refine the physics goals and influence both the accelerator and the detector designs. While the FTE numbers above do not include theorists, we advocate for a strong support of the theory community to allow for a strong collaboration between theorists, accelerator physicists, and experimentalists. Such a collaboration has been shown to be very fruitful during the Snowmass process and in preparation of the P5 input.

References

[1] C. Accettura et al. *Towards a Muon Collider*. 2023. arXiv: 2303.08533 [physics.acc-ph].
[2] K. M. Black et al. *Muon Collider Forum Report*. 2023. arXiv: 2209.01318 [hep-ex].