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Challenges and synergies of a detector at high energy muon collider

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A multi-TeV muon collider offers a unique opportunity to reach high-energy lepton collisions with high luminosity. This contribution gives a short introduction to this concept, focusing on the design of a detector for this environment. Challenges and synergies with existing R&D activities for present and future colliders are highlighted.

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1. Introduction

A multi-TeV muon collider is a powerful, scalable and yet flexible experimental setup for the future of particle physics [1–3]. Such a machine can unlock answers to the most profound questions of particles physics [4] thanks to the high energy of collisions, coupled with the favorable signal cross sections as well as signal over background ratio for many of the processes of interest. Its compact design also offers the ability to scale and tune the center-of-mass energy depending on needs that might only become apparent in the next decade.

Proposals for a muon collider have been around since the 1990s; more recently the Muon Accelerator Program (MAP) initiated at Fermilab (2011-2014) had made significant progress before being terminated [5]. Nowadays, new efforts have started in Europe thanks to the International Muon Collider Collaboration [6], that has brought together scientists with a renewed enthusiasm to tackle the remaining challenges to make such a collider a reality. At the same time, the recent US Snowmass exercise [4] has captivated the interest of experimental and theoretical physicists as never before. This is both thanks to the recent advances in technology as well as due the the nature of the questions we ought to answer to make meaningful progress in our understanding of a fundamental theory of particles and interactions.

The element in between the collisions and the study of those reactions is the detector. A muon collider detector faces specific challenges due to the unusual environment it needs to operate in, with continuous muon decay products making more challenging the identification and accurate measurements of the products of the main muon-muon collisions. In this contribution we briefly review what are the main challenges for a detector operating in such environment, what technology needs to be developed with the highest importance and what performance we can expect.

While several accelerator designs have been proposed, most of the studies performed on the detector design so far focus on a center-of-mass energy of $\sqrt{s} = 1.5$ TeV and 3 TeV. A 10 TeV muon collider is the main identified target, and we will also comment on some preliminary considerations and results of studies that have started in this direction. Previous detector concepts were proposed and studied [7, 8], however they were mostly designed for different center-of-mass energies and with different technologies in mind.

2. Detector Environment

A muon collider detector has to withstand a potentially harsh environment dictated by the finite lifetime of the muons that are being accelerated. High-energy electrons produced by muon decays dominate the composition of such background, with smaller contributions from beam halo losses on collimators and incoherent e^+e^- production. These components are together defined as beam-induced background (BIB).

Dedicated shielding has been designed to shelter sensitive parts of the accelerator and detector from such high-energy electrons. A cone-shaped 10° mostly-tungsten shielding around the beampipe showers those primary electrons creating a set of mostly secondary electrons and photons via electromagnetic interaction and neutrons via nuclear photo-production. A coating of BCH_2 absorbs part of the neutrons on the outer surface of the shielding. Ref. [9] characterized in detail beam-induced backgrounds in the case of a 1.5 TeV accelerator. The particle flux is determined

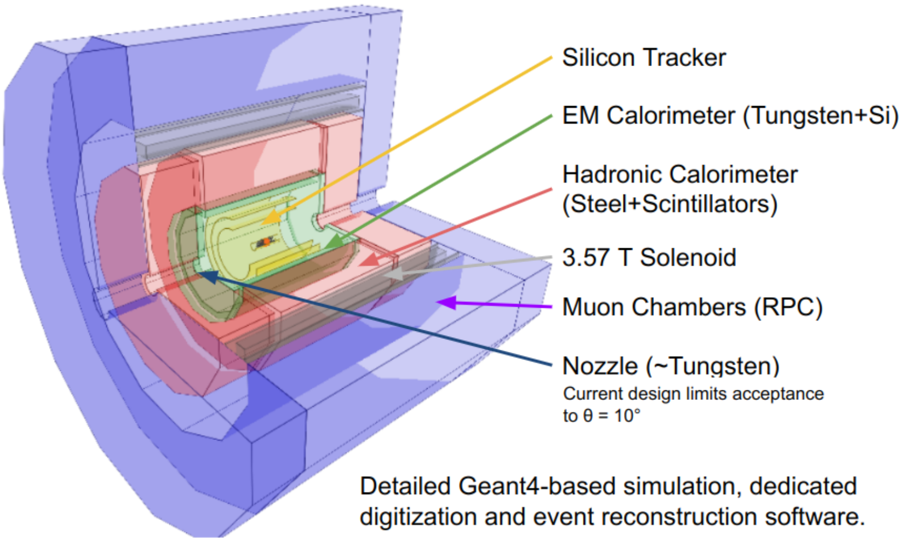


Figure 1: Cut-out view of the detector design.

using detailed simulations of the accelerator lattice configuration, and interaction of particles with matter via FLUKA.

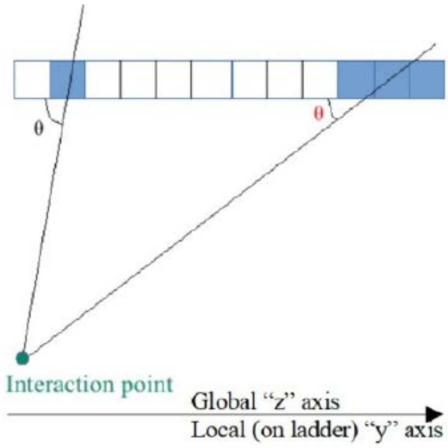
A comparison of the expected radiation environment at the innermost tracking layer and at the entrance of the calorimeter with the one expected at the HL-LHC shows that the expected fluence and doses are around a similar order of magnitude.

3. Detector Design Highlights

An overview of the current conceptual detector design is shown in Figure 1. It consists of a silicon-based tracker, electromagnetic (EM) and hadronic calorimeters and muon chambers. The tracking and EM calorimeter are immersed in a 3.57 T magnetic field.

There are several unique challenges that BIB poses to the detector design in each system, to data acquisition, and offline reconstruction algorithms. For a comprehensive overview of the expected performance see Refs. [10, 11].

One of the most challenging aspects is the large multiplicity of energy deposits (hits) in the inner tracking system. It challenges the bandwidth needed to readout the detector as well as the offline reconstruction of charged particle trajectories. There are several handles that can be used to reduce the multiplicity of hits from BIB. Among the most important ones it is the requirement for a time resolution of the order of $O(50)$ ps, together with a granularity as low as $25x25\mu\text{m}^2$ in the innermost layer; such requirements ensure the occupancy to be below about 1%. Given the nature of BIB, any directional information can further discriminate hits produced by BIB and by particles originating near the nominal collision points. To mention one recent development, Figure 2 (left) shows how the shape of the cluster of pixel hits produced by prompt particles can be used to discriminate against BIB. Table 2 (right) shows the effect of a simple selection on the number of pixels accepted for a given module position in the innermost layers of the tracking system. Such a selection can be applied offline before track reconstruction, or be implemented already in



Cut Efficiency	Loose	Tight
prompt particle	99.3%	99.1%
BIB	37.4%	30.7%

Figure 2: (left) Cartoon illustrating particles from the nominal interaction point leaving a hit in multiple contiguous pixels. BIB particles originate mostly away from the nominal interaction point and produce on average a different number of pixels with a signal. (right) Efficiency of simple selection on the number of contiguous hits for a prompt (originating at the nominal interaction point) particle and for BIB.

the Front-End detector readout logic to reduce the bandwidth needs. From a technological point of view, producing tracking detector with a high granularity and such a good timing resolution is a challenge. Several lines of research are being pursued, ranging from the most mainstream hybrid pixel detectors, to CMOS integrated sensors and front-end designs, to Low-Gain-Avalanche detectors (LGAD). The investigation of 28 ns technology for ASIC development is also seen as crucial to get the needed logic that allows decoding and filtering based on what pixels have received a signal in real-time. More information on each solution and needs can be found in Refs [10, 12].

Calorimeters also offers challenges, especially for electromagnetic calorimeters. Key characteristics of a successful calorimeter for a muon collider detector include:

- short integration time ($<$ 100 ns);
- good time of arrival resolution ($<$ 100 ps);
- longitudinal segmentation;
- good radiation hardness (similar to HL-LHC);
- good energy resolution.

Ref. [10] shows promising technologies that are being pursued to achieve these requirements.

The Muon system, being situated the farthest from the beamline, is subject to an already greatly reduced flux of BIB particles, although the most forward region, between 8° and 12°, will need to sustain rates as high as 60 kHz/cm^2. A position resolution of the order of 100 μm and time resolution of the order of 1 ns would ensure the detector can withstand the expected background, while offline reconstruction is able to easily cope with the resulting measurements multiplicity. Promising technologies being investigated include sub-ns timing MicroMegas detectors and research towards eco-friendly gas mixtures. Approaches using cherenkov radiation, instead of the primary ionization, to achieve sub-ns timing resolution are being investigated as rather promising [13].

The online software processing is expected to have to handle an event rate of about 100 kHz. Despite the potentially large multiplicity of measurements recorded due to BIB effects, this results in about 60 Tb/s of data, which is not very far from the technology being developed for HL-LHC.

Many more detector components are being developed and new solutions being proposed. A special mention goes to the development of very forward detectors that can identify muons scattered at angles of the order of 10 mrad, as expected for most neutral-current vector-boson-scattering/fusion processes with Q^2 values of interest. Such developments can be in synergy with very forward detector developments for HL-LHC, since some of the challenges are in common.

4. Design for a $\sqrt{s} = 10$ TeV collider

The physics case for a high-energy muon collider [1–3] calls for a center-of-mass energy as high as 10 TeV. The detector design will also have to evolve accordingly. Preliminary simulations of the expected BIB indicate that the flux of particles produced remains in the same order of magnitude: the effect of a longer laboratory-frame muon lifetime roughly balances the higher-energy electrons from muon decays.

The main technological challenges for the detector therefore remain qualitatively similar. Initial experimental designs of alternative detector layouts are being performed; they include studies of the needed solenoidal magnetic field, inner tracker and calorimeter dimensions and material budget and alternative inner tracker layers' configurations. More results on this developments are expected to mature in the next few years.

5. Timeline and Synergies

The expected timeline for the construction of a high-energy muon collider facility spans at least two decades [1], including R&D and a demonstrator program in the short term. For this reason it is of paramount importance to take advantage of synergies in the R&D with other fields to foster innovation and possibly take advantage of developments towards a muon collider detector in applications in other fields.

Two broad initiatives in detector R&D are being setup in the framework of CERN European efforts as well as in the US, in addition to existing similar frameworks elsewhere in the world. The European ECFA initiative [14] and the US-based CPAD panel [15] are calling for broad involvement in detector R&D for particle physics, including long-term developments for future colliders. Table 1 shows the groups, with a loose mapping between the two initiatives, most relevant for R&D items for a muon collider detector and where they would most naturally fit.

6. Conclusions

To extract the exciting physics behind multi-TeV muon-muon collisions, an outstanding detector is needed to disentangle beam-induced backgrounds.

An initial detector design has been simulated in detail proving that such a task can be accomplished and identifying key technological developments that are needed.

Given the long timescale involved, it is extremely beneficial to identify synergies that connect generic detector R&D and project-specific developments. Synergies with HL-LHC and other future high-energy colliders are more apparent, but identifying connections with other experiments might provide a huge boost to such developments.

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ECFA	CAPD	Topic	Muon Collider Detector Topics
DRD3	RDC3	Solid-State Detectors	Radiation-hard silicon detectors with O(10 ps) timing resolution; Integrated or hybrid design.
DRD6	RDC9	Calorimetry	High-granularity (transverse and longitudinal); good radiation hardness; good timing resolution and low integration time (esp. ECAL); Scintillator or Silicon-based sampling; Crilin: semi-homogeneous w/ SiPMs.
DRD1	RDC6	Gaseous Detectors	Micromegas, GEM, and similar with focus on good timing resolution and sustainable gas mixtures.
DRD4	RDC2	Photon-Detectors and PID	Less explored, but PID can offer additional physics opportunities
DRD7	RDC4	Electronics	Radiation-hard ASIC design; Small feature size for more complex on-chip processing.
DRD7	RDC5	Trigger& DAQ	Trigger-less readout requires large real-time data rate handling.
	RDC10	Mechanics	Lightweight structures; nozzle support design.

Table 1: List of the subset of ECFA and CAPD R&D groups with their most natural connection to the required detector technology for a high-energy muon collider detector.

7. Acknowledgments

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