Detector performance for low- and high-momentum particles in $\sqrt{s}$ = 10 TeV muon collisions

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A 10 TeV muon collider is the ideal machine to explore the energy frontier. In addition to producing large samples of Standard Model particles, it has the potential to create new, possibly massive states, enabling a broad physics program that includes direct and indirect searches for new physics, precise Standard Model measurements in an unexplored energy regime, and significant advancements in the Higgs sector. The fulfillment of such physics potential lies in the detector's ability to reconstruct physics objects and measure their properties over a wide range of momenta at high levels of machine-induced background. At 10 TeV collisions, the transverse momenta of Standard Model particles are relatively low, while new heavy states are expected to decay into high-momentum central physics objects. This contribution outlines two detector concepts that are currently under development and presents the first studies on the reconstruction performance of tracks and photons using a detailed detector simulation, including the beam-induced background.

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1. Introduction

A muon collider can provide leptonic collisions at a center-of-mass energy of several TeV [1, 2], enabling a broad physics program that includes direct and indirect searches for new physics, precise Standard Model measurements in an unexplored energy regime, and significant advancements in the Higgs sector [3].

The fulfillment of such physics potential lies in the detector's capability to reconstruct efficiently and accurately the events produced in the collisions [4]. The main driving factors for the detector specifications are physics, constraints from the machine design, and the machine background conditions. The requirements from physics are similar to those of other multi-TeV machines to reconstruct physics objects over a wide momentum range: boosted low-p_T physics objects from Standard Model processes and central energetic physics objects from decays of possible new massive states. Moreover, the detector should be sensitive to the experimental signatures of exotic theoretical models, such as disappearing tracks, heavy stable charged particles, displaced leptons, photons or jets, and other less conventional event topologies. The machine design requires the magnets to be placed at ±6 m from the interaction point, thereby determining the length of the detector.

Ultimately, the detector design, the technological choices, and the development of the event reconstruction algorithms will be driven by the high levels of machine-induced background expected in the detector.

2. Machine background conditions

The primary sources of machine-induced background in the detector are the decay products of the muons circulating in the beams and the incoherent production of electron-positron pairs at bunch crossings [5].

The beam-induced background (BIB) is produced by the muon decay products interacting with the machine components. It has been extensively studied with the simulation package FLUKA [6], which implements a detailed model of the collider around the interaction point (IP). The BIB consists of particles with generally soft momenta, most of which arrive at the detector out of time with respect to the bunch crossing: $\sim 10^8$ photons, $\sim 10^7$ neutrons, $\sim 10^5$ electrons and positrons, $\sim 10^4$ charged hadrons, and $\sim 10^3$ Bethe-Heitler muons. Figure 1 (left) shows the FLUKA energy spectra of BIB particles entering the detector at every bunch crossing in the window [-1, 15] ns with respect to the bunch crossing time.

Another significant source of background expected in the detector arises from incoherent e^+e^- pairs, which are generated during bunch crossings and enter the detector at the IP in time with the bunch crossing. The composition and kinematical characteristics of this background are studied with the Guinea-Pig software [7]. It is composed of $\sim 10^6$ photons, $\sim 10^5$ neutrons, and $\sim 10^5$ electrons and positrons. The e^+e^- energy spectrum presents a tail up to ~ 100 GeV, as shown in the right panel of Fig. 1. The detector solenoidal B field confines most of the pair-produced electrons and positrons to the innermost region of the detector near the beam pipe, primarily affecting the vertex detector and the inner tracker layers.

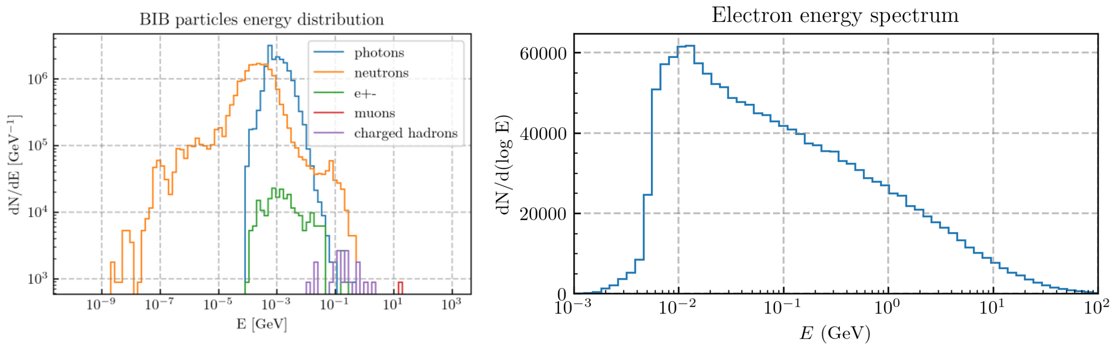

Figure 1: Left: Energy spectra of BIB particles entering the detector at every bunch crossing in the time window [-1, 15] ns. Right: energy spectrum of electrons and positrons from the incoherent pair production.

3. Detector concepts for a $\sqrt{s}$ = 10 TeV muon collider

The design of a detector for a 10 TeV muon collider is based on long experience with studies at $\sqrt{s}$ = 3 TeV with a GEANT4 [8] detailed detector simulation including the beam-induced background [1]. Since the muon collider can accommodate two interaction points, two detector concepts are currently under development for $\mu^+\mu^-$ collisions at 10 TeV.

The two detector concepts share common features derived from machine and machine-detector interface constraints. The length of the detectors is dictated by the position of the machine's final focusing magnets at ±6 m from the IP. Moreover, two conical tungsten shields are installed inside both the detectors along the beam line to mitigate the BIB effects.

In contrast, the overall layout of the subdetectors in the two cases is based on two distinct approaches, which are detailed below. The two detector concepts, named MUSIC and MAIA, are illustrated in Fig. 2. The following sections briefly outline the main features of their tracking and calorimetric systems, while a technological choice for the muon detectors has yet to be made. Additionally, preliminary performance studies are presented.

3.1 The MUSIC detector

The MUSIC (MUon System for Interesting Collisions) detector concept includes an all-silicon tracking system and an electromagnetic calorimeter (ECAL), both housed within a superconducting solenoid with a 2-meter inner radius that generates a 5-Tesla magnetic field and is surrounded by a hadronic calorimeter (HCAL) and muon detectors.

The tracking system consists of a vertex detector (VXD), an inner tracker (IT), and an outer tracker (OT). The VXD is a 25×25 µm^2 silicon pixel detector with hit spatial and time resolutions of 5 µm × 5 µm and 30 ps, respectively. The inner and outer trackers feature 50 µm × 1 mm macropixels with 7 µm × 90 µm hit spatial resolution and 60 ps hit time resolution.

The ECAL is a semi-homogeneous electromagnetic crystal calorimeter with longitudinal segmentation (CRILIN) [9]. It consists of $10 \times 10 \times 45$-mm^3 lead-fluorite crystals arranged in six layers for a total of 26.5 radiation lengths. The HCAL is an iron-scintillator sampling calorimeter comprising 70 layers of 20-mm iron absorber and 30×30 mm^2 scintillator pads, for a total of

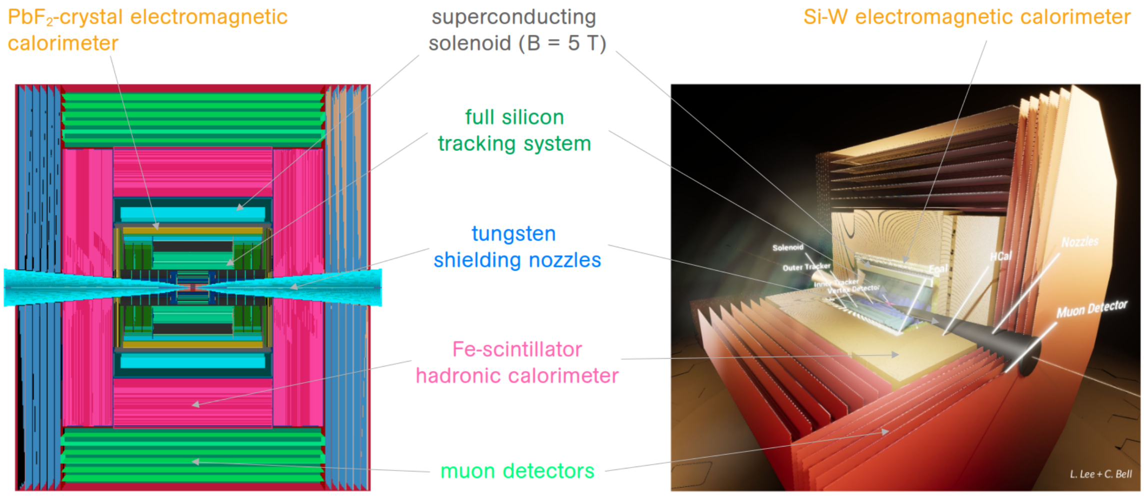

Figure 2: Layouts of the MUSIC (left) and MAIA (right) detector concepts.

approximately seven nuclear interaction lengths. Additionally, the iron absorber serves as a return yoke for the magnetic field flux.

3.2 The MAIA detector

The MAIA (Muon Accelerator Instrumented Apparatus) detector concept [10] employs an alternative approach to subdetector layout. It features a 5-Tesla superconducting solenoid that encompasses only the tracking system, while both the calorimeters and the muon detectors are positioned outside.

The tracking system comprises three components: a vertex detector (VXD), an inner tracker (IT), and an outer tracker (OT). The VXD is a 25×25 μm^2 silicon pixel detector with a hit spatial resolution of 5 μm × 5 μm and a hit time resolution of 30 ps. Its innermost barrel layer and closest endcap disks are equipped with double-layer silicon sensors. The IT and OT modules are segmented into 50 μm × 1 mm and 50 μm × 10 mm megapixels, respectively, with a hit spatial resolution of 7 μm × 90 μm and a hit time resolution of 60 ps. The solenoid has an inner radius of 1.5 m and a total thickness corresponding to approximately four radiation lengths.

The ECAL and HCAL are sampling calorimeters. The ECAL consists of 50 layers of 2.2-mm tungsten absorber and 5×5 mm^2 silicon pads, totaling 28 radiation lengths. The HCAL is an iron-scintillator calorimeter with 100 alternating layers of 20 mm absorber and 10 mm scintillator. The iron in the HCAL also serves to close the magnetic field flux.

3.3 Preliminary performance studies

The primary challenge for a detector at a muon collider is to manage the overwhelming machine-induced background while maintaining high reconstruction efficiency for physics objects and ensuring high accuracy in measuring their properties.

A sample of BIB particles generated with FLUKA at $\sqrt{s}$ = 10 TeV was used to assess the effects of the BIB on the tracking system and the electromagnetic calorimeter, the subdetectors expected to be most affected. The impact of BIB on the tracking system is similar for both detector concepts,

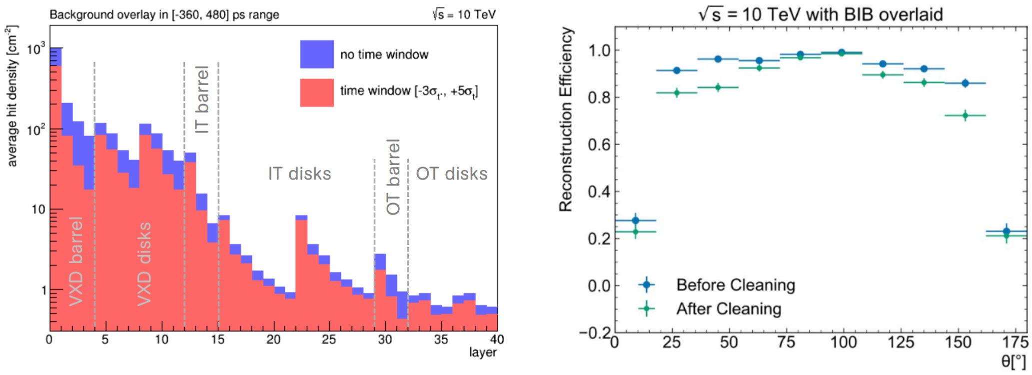

Figure 3: Left: average density of the BIB hits in the tracking-system layers of the MUSIC detector. Right: track reconstruction efficiency for muons as a function of the polar angle θ for the MAIA detector; the cleaning selection requires $p_T > 1$ GeV, $|d_0| < 0.1$ mm, and $N_{\text{hits}} > 5$.

resulting in a large number of spurious hits that make track finding very difficult. An example of the average hit occupancy expected per square centimeter in the layers of the MUSIC tracking system is shown in Fig. 3 (left). A comparable result is obtained for the MAIA detector. For the MUSIC electromagnetic calorimeter, a flux of about 300 particles per cm^2 has been estimated through the ECAL surface at each bunch crossing. This flux consists of approximately 96% photons with an average energy of a few MeV and about 4% neutrons. In the case of the MAIA detector, the calorimeter is partially shielded by the magnet material, resulting in the energy deposited by the BIB in the ECAL being about three to ten times lower, depending on the polar angle. The majority of the particles reaching the inner surface of the calorimeter are photons.

The reconstruction performance of the tracking systems and the electromagnetic calorimeters was evaluated on single muon and single photon samples overlaid with the BIB. A track reconstruction efficiency exceeding 95% is achieved in the central region of the MAIA tracker, as shown in Fig. 3 (right). Similar performance is expected for the MUSIC detector. Figure 4 (left) shows the energy resolution of photons reconstructed in the ECAL barrel of the MUSIC detector as a function of the photon energy, both with and without the BIB overlaid. The resolution degradation due to the BIB is less than 1% for high-energy photons, although no tuning of the ECAL configuration and reconstruction algorithms has been performed yet. Figure 4 (right) shows the photon reconstruction efficiency as a function of the photon energy for the MAIA detector, with finely calibrated energy thresholds for the ECAL hits.

4. Summary

The success of the muon collider physics program hinges on the detector's ability to efficiently reconstruct the collision products and precisely measure their properties across a wide range of momenta, even in the presence of high levels of machine-induced background. Two detector concepts for a 10 TeV muon collider, named MAIA and MUSIC, are currently under development and are well advanced. Preliminary studies, based on detailed detector simulations that include the beam-induced background, demonstrate that the effects of the background on the tracking system and electromagnetic calorimeter can be mitigated, preserving detector performance.

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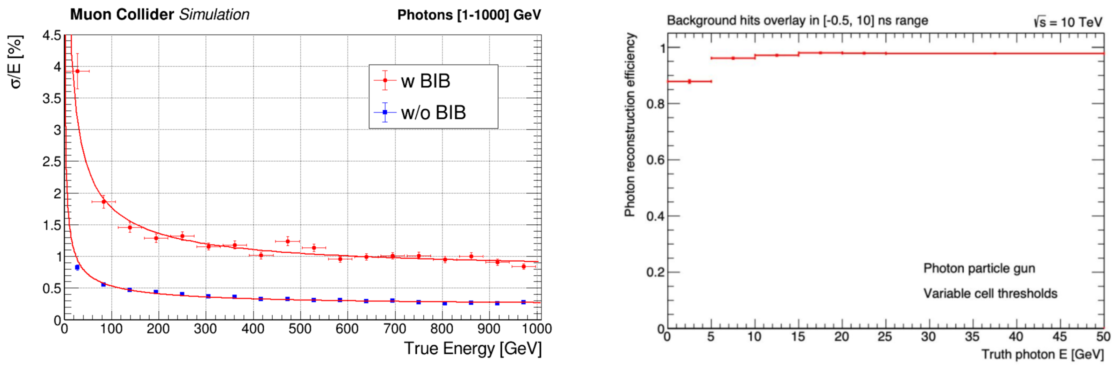

Figure 4: Left: comparison of the photon energy resolutions in the ECAL barrel of the MUSIC detector as a function of the photon energy, with and without the BIB overlaid. Right: photon reconstruction efficiency as a function of the photon energy for the MAIA detector.

Acknowledgments

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