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Simulated performance of a multi-purpose experiment at a Muon Collider

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The future of high energy physics relies on the capability of exploring a broader energy range than the one available at current colliders, with higher statistics. In this framework, the Muon Collider represents a unique possibility with the opening of an unprecedented physics program, ranging from Higgs boson studies to Beyond Standard Model (BSM) and Dark Matter searches. Studies aimed at designing a muon collider able to reach 10 TeV or higher center of mass energies with high luminosity are currently ongoing, involving unprecedented technological challenges both from the accelerator and the detector point of view. One of the detector main challenges is related to the so-called huge Beam Induced Background (BIB). The main objective of this contribution is the description of the performance in terms of different objects reconstruction in various regions of the detectors, proving that a robust track reconstruction for charged particles above 1 GeV throughout the detector acceptance can be achieved. Results of the jets reconstruction, based on a particle-flow approach and a k_T-based clustering, will be discussed: reconstruction efficiency, evaluated on samples of light, b and cjets, ranging from 82% at $p_T \approx 20$ GeV to 95% at higher p_T will be presented. Reconstruction algorithms dedicated to electrons and photons and able to cope with the BIB conditions have been developed as well, resulting in a successful reconstruction of high-p_T electrons and photons with relatively small loss of efficiency and energy resolution. Finally, the muon reconstruction algorithm, which combines the information coming from the hits in the muon system with the reconstructed hits in the tracker, will be discussed: it leads to a reconstruction efficiency in presence of BIB greater than 90% over an extended energy range.

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1. Introduction

A muon collider has a great potential for high energy physics [1]: it has the high precision of e+e- colliders and, due to the lower level of bremsstrahlung and synchrotron radiation, potentially also the high center-of-mass energy and luminosity of hadron colliders. One of the main advantages of muons is that, as they are point-like particles, the nominal center of mass collision energy E_{cm} is entirely available for the reaction, while for proton collision the relevant energy is the E_{cm} in parton collisions. In[2] the mass reach of several Beyond Standard Model (BSM) states for different colliders are compared: the muon collider reach for E_{cm} equal to 10, 14 and 30 TeV exceeds the one of the FCC-hh for several BSM candidates [2]. Dark Matter can be studied at muon colliders in several channels exploiting for example the disappearing tracks produced by charged particles involved in the process [2]. An overview of a muon collider facility can be found in [1].

2. Beam-induced background

The main challenges arise from the short muon lifetime and the harsh Beam Induced Background (BIB). BIB is due to electrons and positrons from muon decay and synchrotron photons interacting with the machine components and the surrounding environment generating secondary particles. It depends on beam energy and on the machine-detector interface (MDI). The most distinctive aspect of BIB particles at the Muon Collider is their extremely large number and low momentum: about 4×108 particles exiting the MDI in a single bunch crossing deposit energy into the detector in a diffused manner. Thanks to the tungsten nozzles, most of the BIB particles exit at a significant distance from the interaction point. Moreover, there is a substantial spread in the BIB particles arrival time with respect to the bunch crossing (Fig.1), ranging from few nanoseconds for electrons and photons to microseconds for neutrons due to their smaller velocity [3].

3. Simulated detector performance

Simulation for the Muon Collider is based on CLIC's ILCSoft software [4] and updated for the developments of the Muon Collider. The geometry currently implemented is described in Fig.2 and in Tab.1. In the following, the performance obtained for the different kinds of objects considered are presented.

Track reconstruction is complicated by the presence of a huge number of hits in the silicon sensor originating from the BIB. Applying a time window, the "BIB-hits" density can be reduced by a factor two as seen in Fig.3a [3]. Track reconstruction efficiency and transverse momentum resolution are shown in Figs.3b and 3c ([3]), where a muon is considered reconstructed if at least half of the hits associated to the track have been originated by the muon.

In Jet reconstruction, the choice of a time window allows to remove most of the BIB hits preserving the signal, as can be seen in Fig.4a. Figs4b,c show the b-jet efficiency as a function of the true b-jet η and true b-jet p_T [3].

Photon reconstruction and identification performances were assessed in a sample of 10^6 events with a single photon per event, 4×10^4 events were also reconstructed with the BIB overlaid [3]: efficiency for photons is shown in Fig.5a. Electrons are identified through an angular matching of

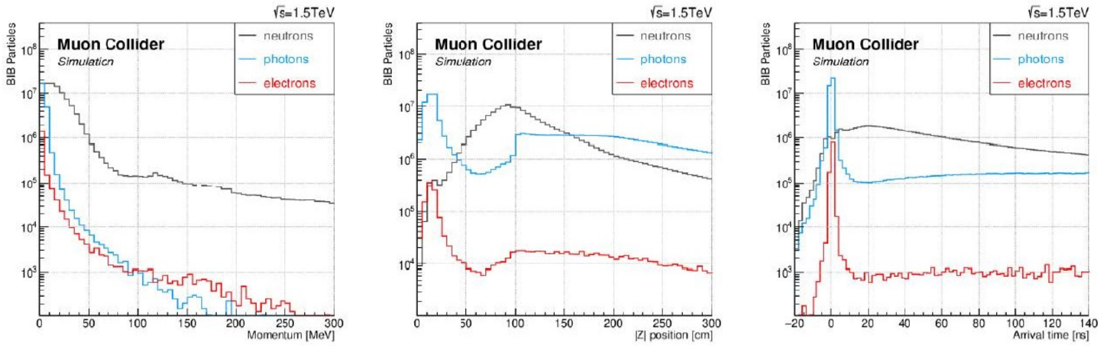

Figure 1: Kinematic properties of BIB particles entering the detector region: momentum (left), position along the beamline (middle) and arrival time with respect to the bunch crossing (right) [3].

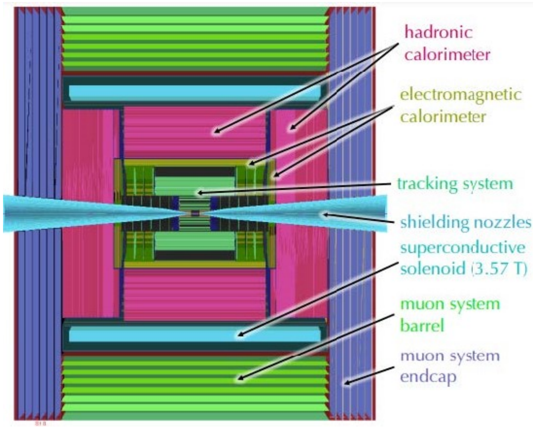

Figure 2: Geometry of the simulated detector [4].

Subsystem	Region	R dimensions [cm]	|Z| dimensions [cm]	Material
Vertex Detector	Barrel	3.0 – 10.4	65.0	Si
	Endcap	2.5 – 11.2	8.0 – 28.2	Si
Inner Tracker	Barrel	12.7 – 55.4	48.2 – 69.2	Si
	Endcap	40.5 – 55.5	52.4 – 219.0	Si
Outer Tracker	Barrel	81.9 – 148.6	124.9	Si
	Endcap	61.8 – 143.0	131.0 – 219.0	Si
ECAL	Barrel	150.0 – 170.2	221.0	W + Si
	Endcap	31.0 – 170.0	230.7 – 250.9	W + Si
HCAL	Barrel	174.0 – 333.0	221.0	Fe + PS
	Endcap	307.0 – 324.6	235.4 – 412.9	Fe + PS
Solenoid	Barrel	348.3 – 429.0	412.9	Al
Muon Detector	Barrel	446.1 – 645.0	417.9	Fe + RPC
	Endcap	57.5 – 645.0	417.9 – 563.8	Fe + RPC

Table 1: Boundary dimensions of individual subsystems of the Muon Collider Detector concept as defined in the geometry `MuColl_v1`.

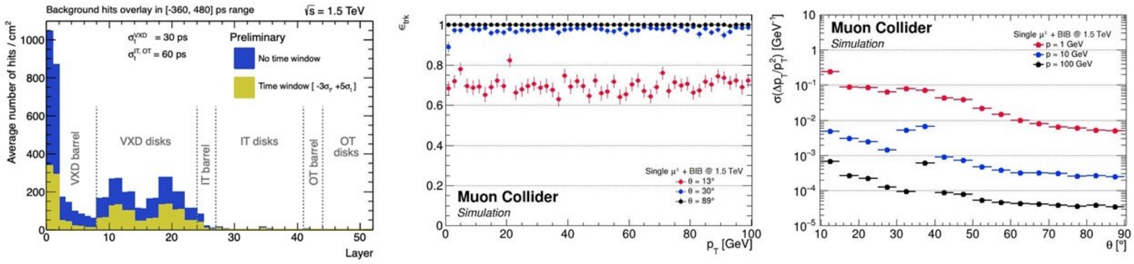

Figure 3: Tracking detectors hit density in a single event with full BIB overlay before (blue) and after (yellow) applying the timing cut (a). Tracking performance for single-muon events overlaid with BIB, as a function of p_T (b). Momentum resolution $\triangle p_T$ divided by p_T^2 as a function of θ (c) [3].

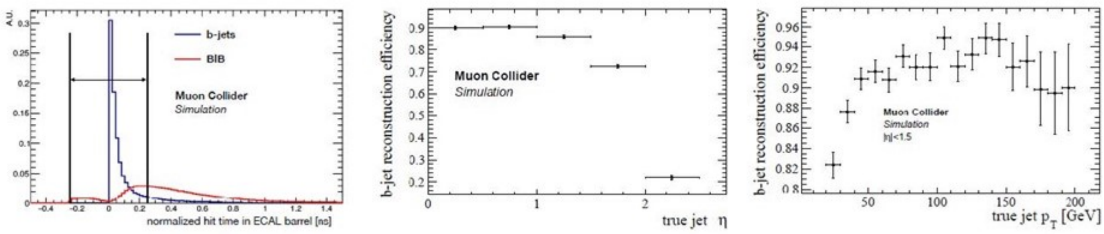

Figure 4: Normalized hit time in ECAL barrel, for b-jets and BIB (a). Efficiency of b-jet reconstruction as a function of truth-level jet η (b) and as a function of the truth-level jet p_T (c), for $|\eta| < 1.5$ [3].

the electromagnetic clusters with a reconstructed track. The e^- reconstruction and identification efficiency as a function of the e^- generated energy is shown in Fig.5b.

In the muon system, BIB hits are concentrated in the endcaps around the beam axis, thus a geometrical cut allows to exclude almost all the BIB hits. This suggests using standalone muon objects to seed the global muon track reconstruction. Fig.6 shows an efficiency greater than 85% for transverse momentum higher than 80 GeV for single muons without (left) and with BIB (right). The drop of the curve at low p_T, currently under study, appears to be mostly due to muon reconstruction inefficiency in the region between barrel and endcap and tracks with a high curvature [3].

References

[1] K.R.Long et al.: Muon colliders to expand frontiers of particle physics, Nat.Phys.17, 289(2021)

[2] C. Aimè et al.: Muon Collider Physics Summary, arXiv:2203.07256v1

[3] C. Aimè et al.: Simulated Detector Performance at the Muon Collider,arXiv:2203.07964v1

[4] ILCSoft, http://ilcsoft.desy.de/portal

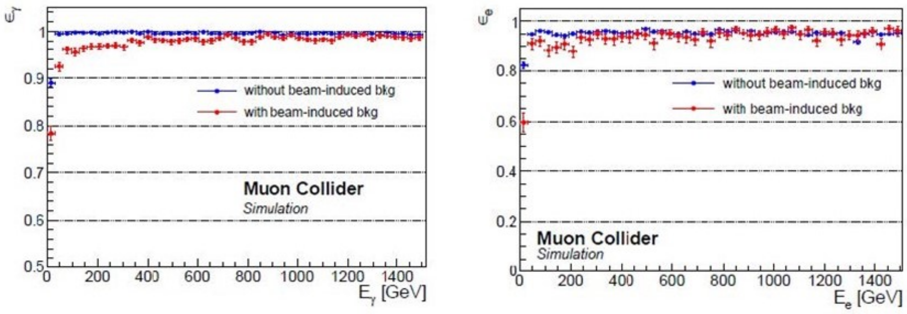

Figure 5: (a)Photon reconstruction efficiency as a function of the photon energy.(b)Electron reconstruction efficiency as a function of the electron energy [3].

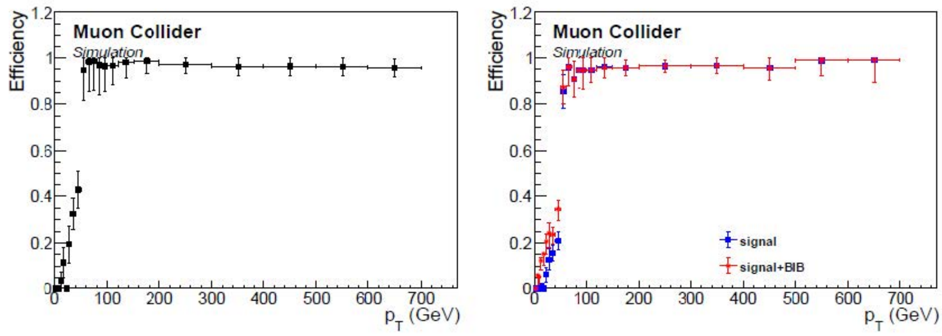

Figure 6: Muon reconstruction efficiency as a function of p_T in a sample of single muons with no BIB overlaid (a) and in a sample with multi-muons in the final state both with and without BIB (b) [3].