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

C. Aimè[1,2], C. Riccardi[1,2], P. Salvini[1,2], I. Vai[2,3] on behalf of the International Muon Collider Collaboration
[1]Università degli Studi di Pavia, [2]INFN - Pavia, [3]Università degli Studi di Bergamo

Muon Collider

A muon collider has a great potential for high energy physics [1]. It combines the high precision of e^+e^- colliders, with low level of bremsstrahlung and synchrotron radiation, with the high center-of-mass energy and luminosity of hadron colliders.

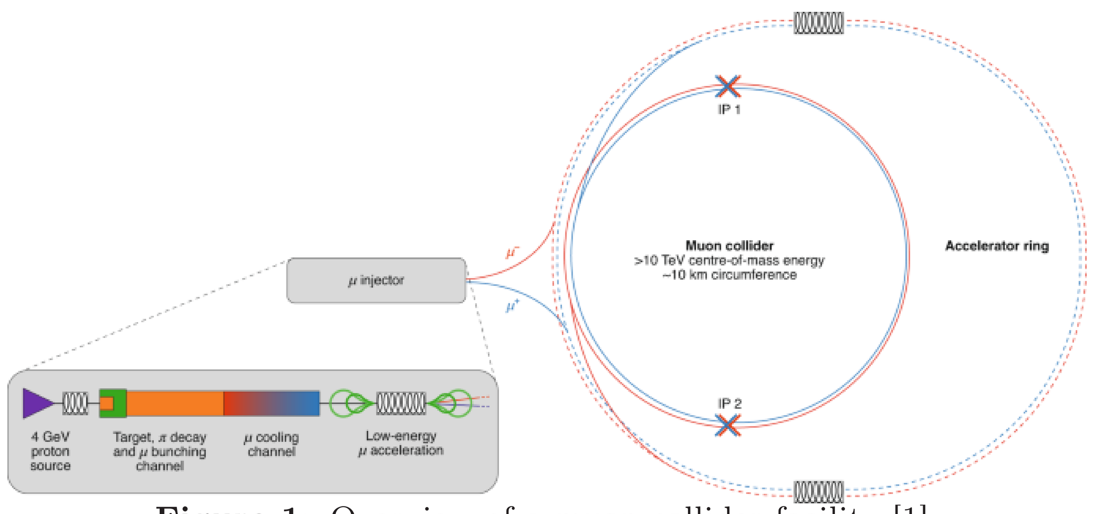


Figure 1: Overview of a muon collider facility [1].

One of the main advantages of muons is that, as they are point-like particles, the nominal center of mass collision energy is entirely available for the reaction. On the contrary, the relevant energy for proton colliders is instead the center of mass energy of the collisions between the partons that constitute the protons. Fig.2 quantify this concept, showing the center of mass energy a proton collider must possess to be equivalent to a muon collider of a given energy [2].

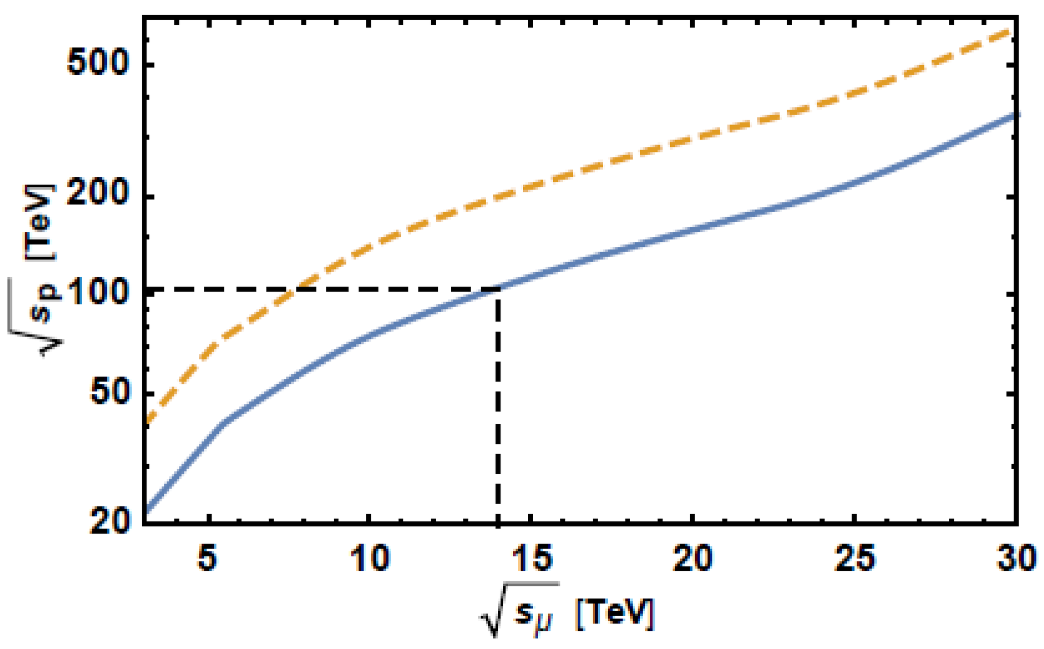
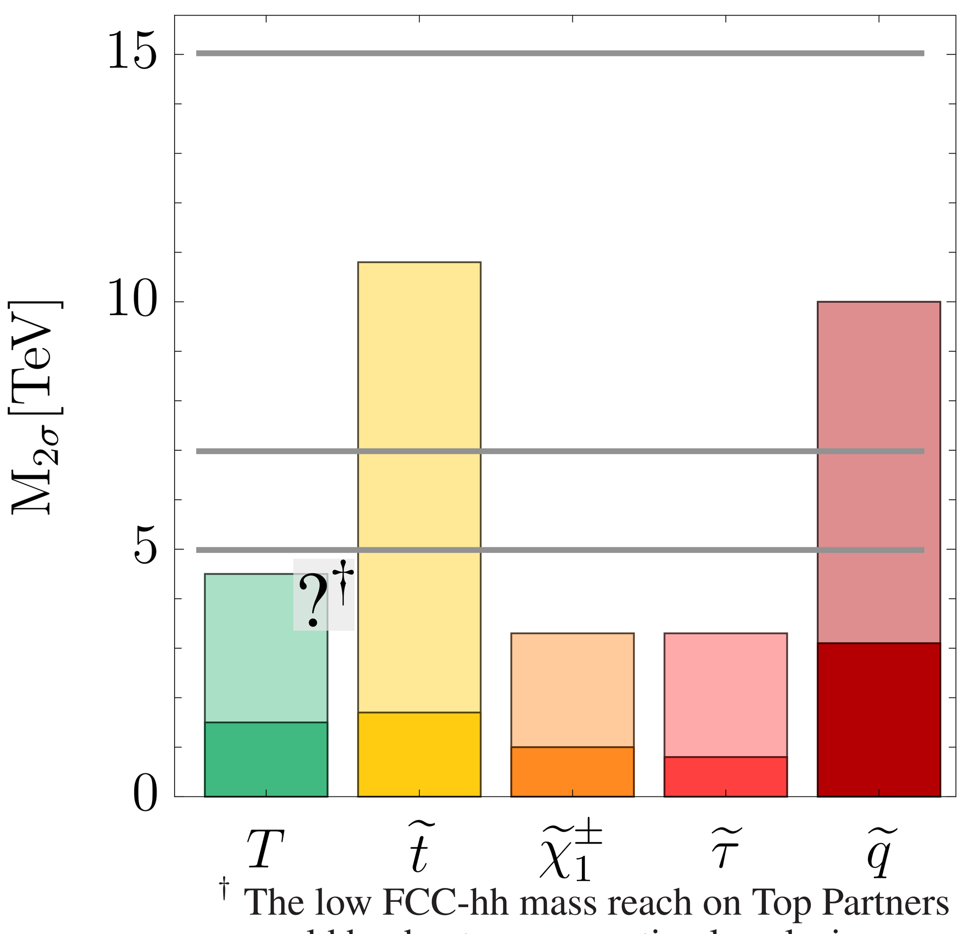


Figure 2: Equivalent proton collider energy [2].

The physics reach of a muon collider is extremely interesting and it vastly and generically exceeds the sensitivity of the High-Luminosity LHC (HL-LHC). Fig.3 for example compares the mass reach of several Beyond Standard Model (BSM) states for different colliders. The 95% CL exclusion is reported, instead of the discovery, as quantification of the physics reach. Solid bars represent the projected HL-LHC mass reach, while the reach of a 100 TeV proton-proton collider (FCC-hh) is shown as shaded bars. The muon collider reach, displayed as horizontal lines for $E_{cm} = 10$, 14 and 30 TeV, exceeds the one of the FCC-hh for several BSM candidates and in particular, as expected, for purely electroweak charged states [2].



† The low FCC-hh mass reach on Top Partners could be due to a non-optimal analysis

Figure 3: 95% CL mass reach, at the HL-LHC (solid bars) and at the FCC-hh (shaded bars). The tentative discovery reach of a 10, 14 and 30 TeV muon collider are reported as horizontal lines [2].

Dark Matter can also be studied at muon colliders in several channels exploiting for example the disappearing tracks produced by charged particles involved in the process [2].

References

[1] K.R. Long et al.: *Muon colliders to expand frontiers of particle physics*, Nat. Phys. **17**, 289-292 (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`

ICHEP 2022, 6 - 13 July 2022
Contact: paola.salvini@pv.infn.it

Beam-Induced-Background

The main challenges, that impact both the machine and detector design, 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 machine-detector interface (MDI).

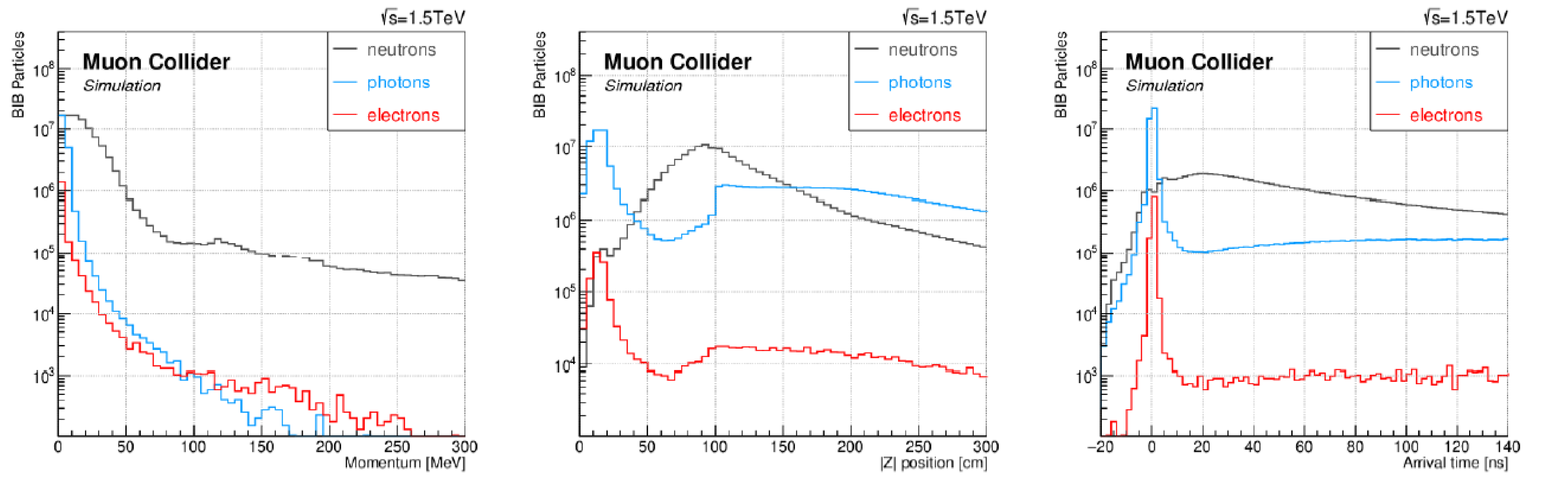
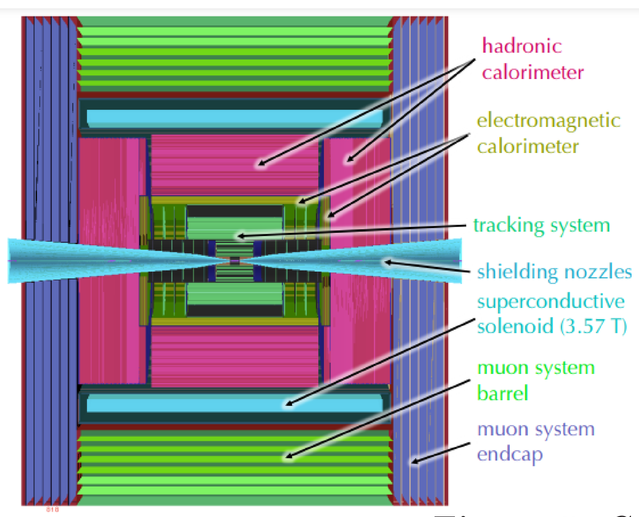


Figure 4: Kinematic properties of BIB particles entering the detector region: momentum (left), position along the beamline (middle) and arrival time with respect to the bunch crossing (right) [3].

The most distinctive aspect of BIB particles at the Muon Collider is their extremely large number and low momentum: about 4×10^8 particles exiting the MDI in a single bunch crossing depositing energy to 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 arrival time of the BIB particles with respect to the bunch crossing, ranging from a few nanoseconds for electrons and photons to microseconds for neutrons due to their smaller velocity [3].

Simulated detector performance

Simulation for the Muon Collider is based on CLIC's ILCSoft software [4]. The geometry currently implemented is described in Fig.5. Below, the performance obtained for the different kinds of objects considered are presented.



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

Figure 5: Geometry of the simulated detector [3].

Track reconstruction at the Muon Collider is complicated by the presence of a huge number of hits in the silicon sensor originating from the BIB. The "BIB-hits" are out-of-time with hard collision hits: applying a time window, the hit density can be reduced by a factor of two as seen in Fig.6 left [3].

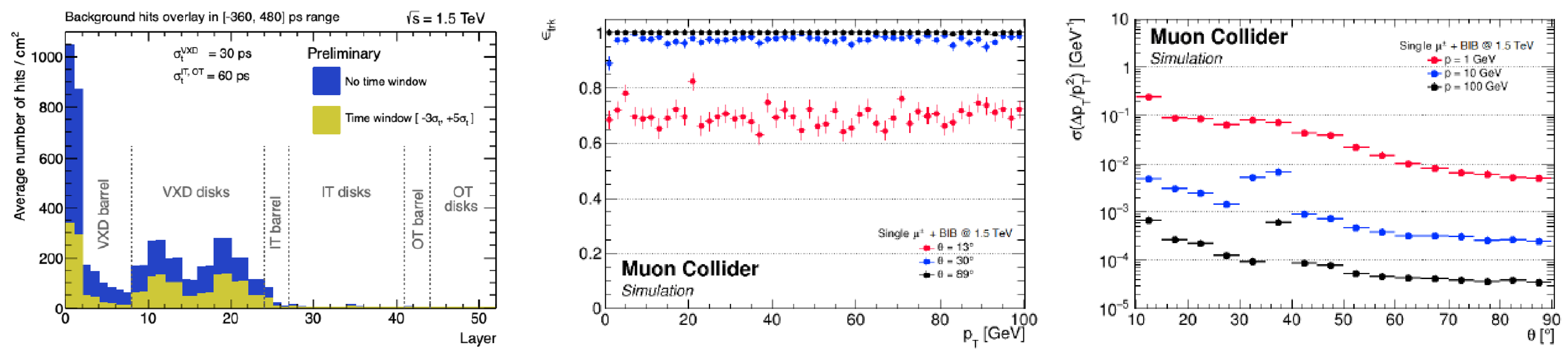


Figure 6: Hit density in the different layers of the tracking detectors in a single event with full BIB overlay. The density before (blue) and after (yellow) applying the timing cut is shown (right). Tracking performance for single-muon events overlaid with BIB, as a function of p_T (center). Momentum resolution Δp_T is shown divided by the p_T^2 as a function of θ [3].

Fig.6 center shows the reconstruction efficiency as a function of p_T; a muon is considered reconstructed if at least half of the hits associated to the track have been originated by the muon. Fig. 6 right shows transverse momentum resolution as a function of polar angle [3].

Jet reconstruction is one of the most difficult reconstruction tasks, since almost all sub-systems are involved, and the impact of the BIB is significant in all of them. Also in this case applying a time window allows to remove most of the BIB hits but preserving the signal, as can be seen in Fig.7 left [3].

Fig.7 center shows the b-jet efficiency as a function of the true b-jet η. Fig.7 right displays b-jet efficiency as a function of the true b-jet p_T [3].

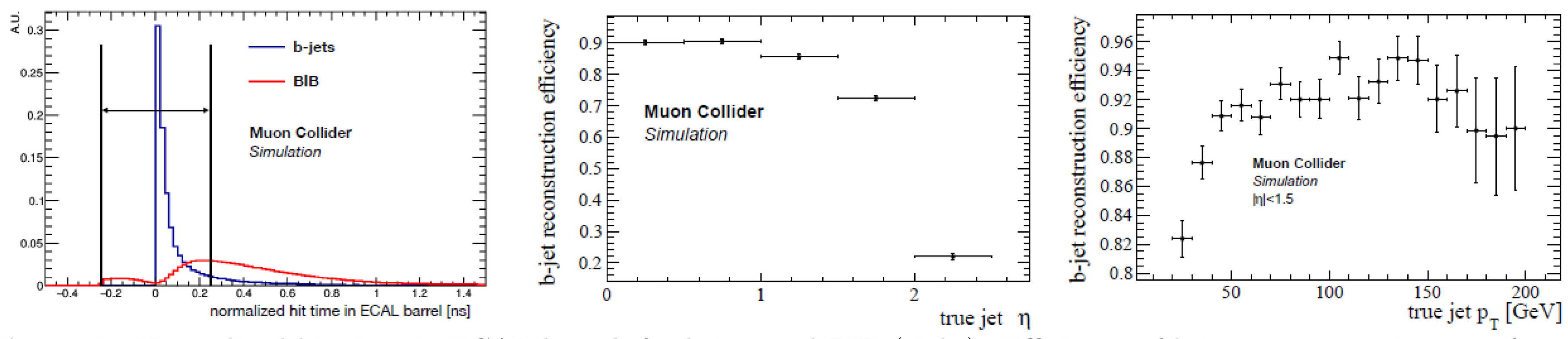
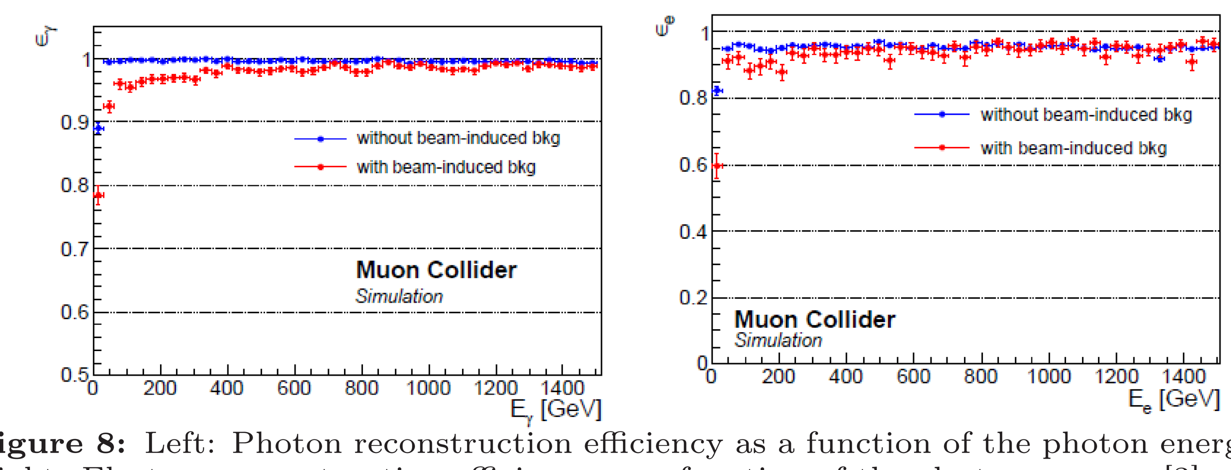


Figure 7: Normalized hit time in ECAL barrel, for b-jets and BIB (right). Efficiency of b-jet reconstruction as a function of truth-level jet η (center) and as a function of the truth-level jet pT (right, for $|\eta| < 1.5$) [3].

The photon reconstruction and identification performance were assessed in a sample of 100000 events with a single photon per event. 40000 events were also reconstructed with the beam-induced background overlaid [3].



The results in terms of efficiency for photons are shown in Fig.8 left. Electrons are identified through an angular matching of the electromagnetic clusters with a reconstructed track. The electron reconstruction and identification efficiency as a function of the electron generated energy is shown in Fig.8 right [3].

Figure 8: Left: Photon reconstruction efficiency as a function of the photon energy.
Right: Electron reconstruction efficiency as a function of the electron energy [3].

In the muon system, BIB hits are concentrated in the endcaps around the beam axis, thus a simple geometrical cut allows to get rid of almost all the BIB hits. This suggests using standalone muon objects to seed the global muon track reconstruction.

Fig.9 shows an efficiency greater than 85% for transverse momentum higher than 80 GeV for single muons without BIB (left) and with BIB (right). The drop of the curve at low p_T is due to known effects currently under study, that mostly concern the inefficiency of reconstruction of muons in the region between barrel and endcap and tracks with a high curvature [3].

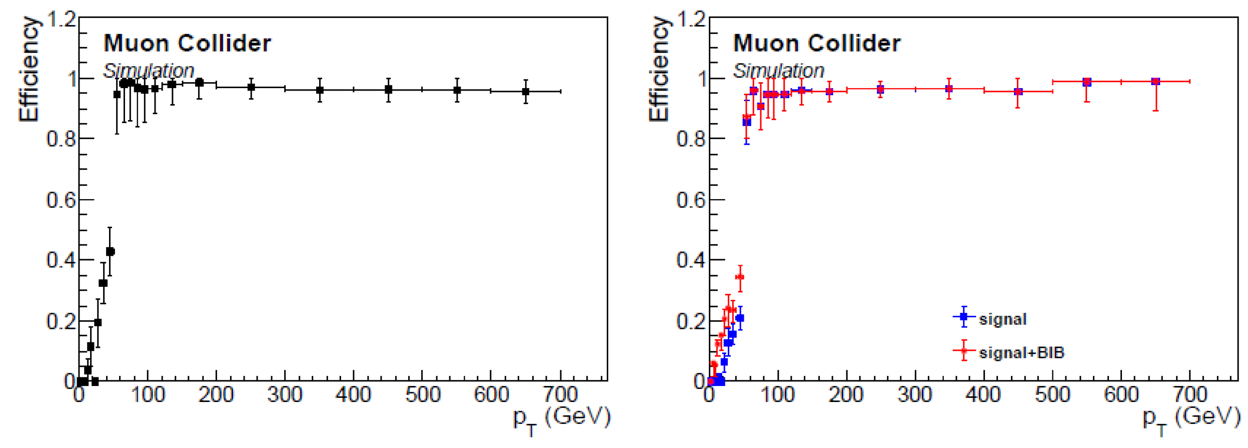


Figure 9: Muon reconstruction efficiency as a function of transverse momentum in a sample of single muons with no BIB overlaid (left) and in a sample with multi-muons in the final state both with and without BIB (right) [3].