Advanced assessment of Beam Induced Background at a Muon Collider

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ABSTRACT: Muon collider detector design and interaction region optimization are strongly correlated by the beam-induced background that finally determines the detector performance. Therefore, it is crucial to be able to study and optimize both of them simultaneously, being able to quantify the effects of interaction region elements modification on the beam-induced background fluxes and composition. An advanced simulation tool, based on the LineBuilder and Fluka programs, has been developed to produce beam-induced background events and to study their characteristics when the interaction region active and passive elements are changed. The tool characteristics, as well as the performance against previous simulations are presented together with the feature that allows to deeply study the beam-induced background point of origin.

KEYWORDS: Accelerator Subsystems and Technologies. Detector modelling and simulations I (interaction of radiation with matter, interaction of photons with matter, interaction of hadrons with matter, etc).

Contents

1 Introduction

In the continuous endeavor to deepen our comprehension of the fundamental structure of matter, muon colliders (MC) are being considered as an alternative to the classical stable particle (pp and e^+e^-) colliders. Even though the LHC has still to deliver several years of data, it is already mandatory to explore possible new options and solutions to carry on the research on fundamental particle physics in the next decades. Despite having being first proposed in the late '60s [1, 2], and studied quite in detail by the Muon Accelerator Program (MAP) [3], the idea of a MC is receiving today a renewed interest by the scientific community, thanks to the possibility of overtaking some of the main limitations of other proposed colliders by design.

With respect to huge and powerful machines with unprecedented energies and luminosities, like those considered by the Future Circular Collider design studies [4], the fact of deploying muons would bring unpaired advantages. Since these particles are about 200 times heavier than electrons, synchrotron radiation is expected to be almost negligible for muon beams up to very high energy, allowing to reach the multi-TeV regime, whereas synchrotron radiation is usually the main intrinsic limit factor of circular e^+e^- colliders. Linear e^+e^- colliders suffer from beamstrahlung [5], which reduces the actual luminosity and generates unwanted beam-gamma interactions. Moreover, the lack of light emission in a MC does also allow to obtain a much reduced energy spread of the beam, resulting in a significantly improved energy resolution.

Compared to hadron colliders, the advantages of a possible muon collider are in the physics reach at the same center of mass (CM) energy. A complete review on this topic can be found in [6].

Besides these remarkable advantages, however, conceptual and technological challenges have hindered so far the design of such a machine. First and foremost, muon decay, happening in few μs at rest, implies that the whole chain from muon generation to their interaction must be performed very quickly. Moreover, the production scheme currently considered as baseline that has been proposed and studied by the MAP collaboration has some intrinsic challenges. The scheme, based on protons impinging on a target to generate π/K further decaying into muons, leads inevitably to muon beams with a large emittance. Muon beam cooling of several orders of magnitude is necessary and it has to be accomplished in a very short time. A new method, based on the ionizing cooling has been proposed and tested by the Muon Ionization Cooling Experiment (MICE) [7].

In this context, a novel approach to muon production [8] has been recently proposed by the LEMMA collaboration to overcome the intrinsic limitation on the muon beam emittance. In the proposed scheme, muons are directly produced by annihilation of a positron beam impinging on a fixed target, just above the threshold energy of the production process: in such a way much smaller emittances can be achieved, possibly avoiding the need for cooling. Despite being this an interesting approach, further studies are needed to address relevant showstoppers like the thermo-mechanical stability of muon production targets or the positron source.

Problems and difficulties in a muon collider are not expected to pertain only the phases of production and acceleration of muons, but also the operation of the machine and the detection of physics. In fact, muons decay all along the machine, resulting in a continuous flux of secondary and tertiary particles, the so called *"Beam-Induced Background"* (BIB), that is able to jeopardize the data taking if not properly dealt with since the initial stages of the concept of the collider.

2   The Beam-Induced Background Issue

The *"Beam-Induced Background"* can have a detrimental role in several aspects of the machine, possibly leading, for example, to magnet quenching or radiation hazard issues. It also affects the performance of the detector, that will have to deal with a massive, continuous flux of a variety of different particles at different energies.

The MAP collaboration studied in detail muon collider optics, interaction region and Machine-Detector Interface (MDI) [9], with the aim of mitigating as much as possible BIB effects. A peculiar design of the MDI, based on the presence of two cone-shaped tungsten shields called "nozzles", leads to a massive reduction of the BIB in the detector. This has been demonstrated by means of simulations performed with the MARS15 [10, 11] Monte Carlo code. A complete design of the whole machine and MDI at the CM energies of 125 GeV, 1.5 and 3 TeV has been performed by MAP collaboration, including a preliminary study at 6 TeV [12–15]. The MAP collaboration did also a preliminary study of the BIB characteristics in the presence of the nozzle [11] and the necessary mitigation strategies to be taken into account in the detector design [16].

3   Advanced approach to BIB simulations

As demonstrated by MAP results, the amount of BIB impacting the detector depends on the CM energy and on the instantaneous luminosity, key figures of the interaction region (IR) design. A

"Higgs Factory" muon collider would in fact present a BIB [17] totally different from that of multi-TeV muon colliders and a huge optimization effort is needed to have the same level of background in the detector.

In this context, in parallel with this renewed interest in a possible muon collider, the need arose of a further extended MARS15 approach - using a different Monte Carlo code, FLUKA [18, 19], to perform BIB studies, allowing to easily go from the machine optics to the Monte Carlo simulation.

A seamless transition between optics and Monte Carlo simulations is indeed a crucial point. In fact, as demonstrated by the first BIB MAP study [11], the MDI optimization is expected to be an iterative process, in which each and every change performed in the machine optics, even hundreds of meters away from the IP, can substantially change the BIB in the detector.

To this aim, in this paper a flexible and powerful approach to BIB simulation is presented, based on the FLUKA Monte Carlo code, and results for the 1.5 TeV CM energy case are shown.

4   Simulation of 1.5 TeV BIB

4.1   Simulation Setup

The core of the software needed to perform BIB studies is represented by the simulation of primary muons decay and the interaction of their decay products with collider and detector components. This is a task commonly performed by Monte Carlo codes, one of the most used being FLUKA. FLUKA is a general purpose Monte Carlo code, used in a variety of applications ranging from medical physics to astroparticles. In particular, FLUKA is for example the golden standard in radioprotection and shielding studies.

FLUKA does natively support very complicated geometries, thus in principle allowing to accurately model the full accelerator complex in the simulation. However, the manual construction of such complex geometries can be both difficult and error prone, and, above all, it is definitely not compatible with the flexibility required by this particular application.

For an MDI-based optimization of the IR design of a MC, it is necessary to tightly couple traditional codes for optics and lattice design like MAD-X [20] to the estimation of the BIB by Monte Carlo simulations. In fact, it is essential to characterize the machine lattice and optics design in terms of expected BIB at the detector in order to proceed with a sensible machine optimization.

The possibility to model in the FLUKA geometry the lattice and optics optimized with MAD-X, a possibility similar to that deployed by the MARS15 studies of the 1.5 TeV MC as well as the Higgs Factory MC, is offered by the FLUKA *LineBuilder* [21] (LB). The LB is a Python program aimed at automatizing the construction of complex FLUKA geometries of accelerators synchronized with the optics. In particular, *LineBuilder* uses the output of a code for lattice design (e.g. MAD/MAD-X) to assemble the beam line geometry with the accelerator elements modelled in the *Fluka Elements Database* (FEDB). The FEDB stores the FLUKA geometry of each family of accelerator elements, such as dipoles, quadrupoles, collimators, etc. . . required to properly model the beam line. The *LineBuilder* automatically constructs the accelerator geometry according to the optics, placing each needed element at the correct position with the correct orientation and magnetic fields.

In this work, we present BIB results computed with FLUKA for the 1.5 TeV CM energy machine configuration, assembled with the LB. This case has a two-fold motivation: firstly, this IR

configuration is one of the best optimized; secondly, a BIB sample generated with MARS15 Monte Carlo is available, giving thus the opportunity to use it as reference for benchmarking.
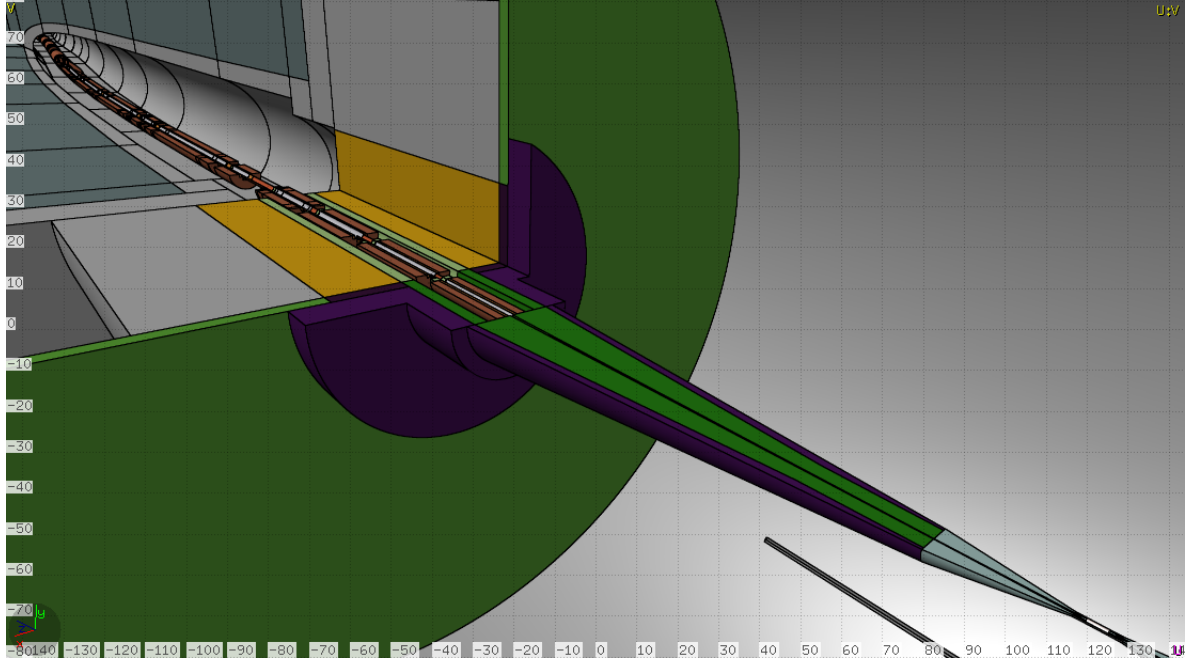
4.2 Implementation

Figure 1. 3D Visualization of the FLUKA geometry produced by LineBuilder by means of FLAIR [22].

Figure 1 shows a 3D rendering of the FLUKA geometry assembled with the LB; the interaction region with the "nozzle" (see later) and the first magnets around the interaction point are shown. The optics file, in MAD8 format, provided by the MAP collaboration is used. Families of accelerator elements have been defined in FEDB based on information contained in this file and based on what reported in MAP publications [9, 10]. The models are as accurate as possible, in particular regarding the inner aperture and outer radius, since all these aspects play a significant role in the BIB generation and propagation. The list of the parameters of the magnetic elements close to the interaction point are reported in Table 1.

Table 1. Parameters describing the magnets close to the interaction point. Q_1, Q_2, Q_3, Q_4, Q_5 are quadrupoles, whereas B_1 is a dipole. The copper coils are delimited by the inner and outer radius, Rc_{int} and Rc_{out} respectively, and the whole magnet is delimited by the outer radius of the iron yoke Ri_{out}.

Name	Q_1	Q_2	Q_3, Q_4	Q_5	B_1
Rc_{int} (cm)	4	5.5	8	8	8
Rc_{out} (cm)	8	9.5	12	12	12
Ri_{out} (cm)	20	25	30	30	30
Length (m)	1.5	1.76	1.7	1	6

The interaction region is characterised by the presence of two tungsten nozzles, i.e. passive elements present around the beam pipe; the outer shell of the detector has been also included, based on the available sources of information of the MARS15 studies. This is one of the key elements in determining the BIB fluxes at the detector surface. The representation of the interaction region and the materials of the various components are reported in Fig. 2, while the nozzle geometry is shown in Fig. 3.
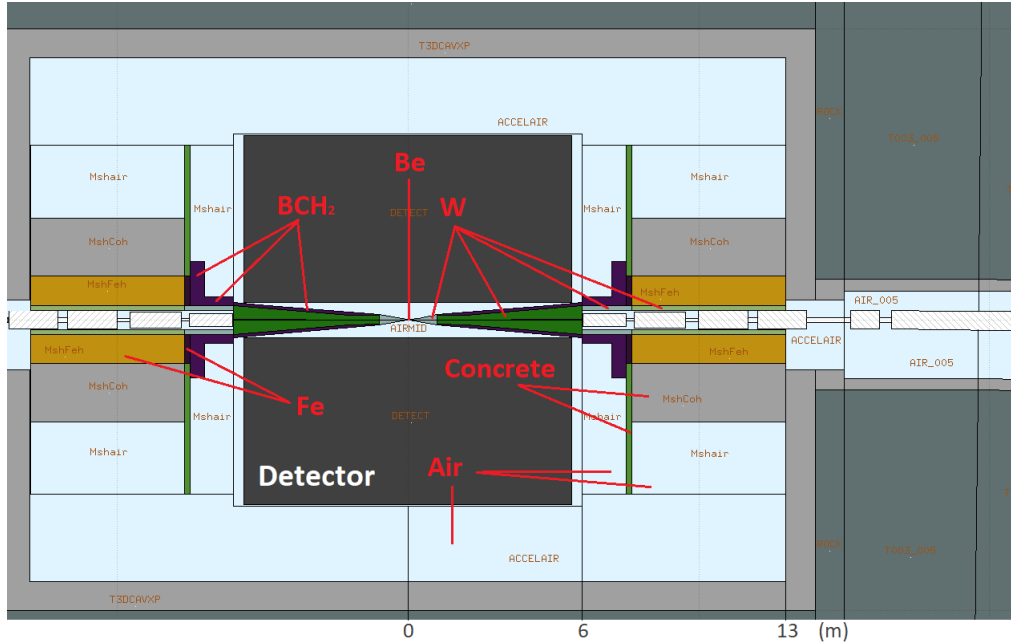

Figure 2. Interaction region. The passive elements, the nozzles and the pipe around the interaction point are constituted by iron (Fe), borated polyethylene (BCH_2), berillium (Be), tungsten (W) and concrete. The detector volume is a 11.28 m long cilinder of 6.3 m outer radius with an inner hole of 60 cm radius. The bunker is a 9 m radius and 26 m long cilinder.
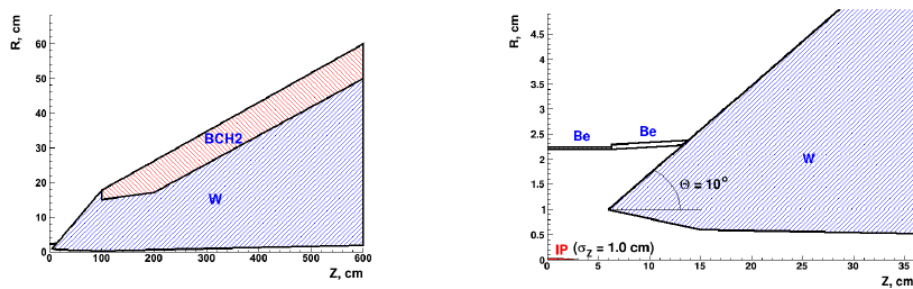

Figure 3. Detailed geometry and material description of the nozzle from [16].

As far as the detector is concerned, only its external shell has been considered in this simulation setup, as a first approximation. It fact, the relevant quantity of interest for this study is the flux of particles that enters the detector; the detailed study of what happens inside the detector is

then performed by a separate simulation, starting from flux distribution and taking care of all the experimental issues [23].

The primary muon beam at 750 GeV energy is simulated starting from the point opposite to the interaction point considered for the flux estimation; therefore, it travels half ring reaching the IP from the right side looking at the machine from up. The realistic beam, i.e. taking into account emittance and energy spread, is used. Only half of the machine is modelled, considering its symmetry and the simmetry of μ^+/μ^-. In order to have a reasonable statistics the muon decay can be biased in the simulation. The decay probability of muons is increased in the section of the ring next to the interaction point, and a weight is assigned to the decay products to compensate. Decay products are further transported in the geometry, with accurate description of electromagnatic and hadronic processes. Hadrons (mostly neutrons) are generated through electronuclear and photonuclear interactions.

The scoring is performed by simply saving in a dump file tracks exiting the machine, either from the tungsten nozzle or from the "world" volume. In particular, these quantities are registered: *particle type, energy, momentum, statistical weight, position, time, position of the decaying muon, region of the machine where the first interaction of secondary particles occurs and exit region of BIB from the machine*. Energy, momentum and direction are given at the machine exit surface. Time is defined with respect to the interaction time at the IP.

A software framework based on python has been developed to analyze the simulation output and to study BIB properties before the interaction with the detector. This is an important element in view of the flexibility imposed by the studied case, since the iterative task of MDI optimization will rely on a prompt interpretation of the Monte Carlo simulation output, for example when the effect of a single modification in the lattice must be evaluated.

5   Comparison between FLUKA and MARS Results

The results we obtained are benchmarked against the ones provided by the MAP collaboration. The comparison between MARS15 and FLUKA results considering only primary muons decaying within 25 m from the IP is discussed in the following, together with a further analysis of the FLUKA simulated BIB taking into account muons that decay up to 250 m from the IP. In all cases the BIB is generated assuming a 2×10^{12} μ^- beam. The energy threshold cuts are set as stated in [11]: 200 keV for γ, e^+/e^-, 100 keV for neutron and 1 MeV for charged hadron (proton, π^+/π^-, K^+/K^-), μ^+/μ^- for both FLUKA and MARS15 Monte Carlo data-sets. The lower thresholds optimization will be performed by looking at the events arriving into the detector, before generating high statistics BIB samples for physics studies. Table 2 reports the total number of particles produced by the primary muons' decay that enter the detector hall, divided by particle type; the energy and the time distributions are shown in Figs. 4, 5.

The major contributors to BIB are photons, neutrons and electrons/positrons, as confirmed by both simulation programs. The kinetic energy and time distribution of all particles types have similar shapes. The observed discrepancies on the total number of particles types are within a factor of 3. Several studies have been performed to understand these differences without finding a unique effect. The most probable reason should stay in the evenience that the two simulation are not using exactly the same IR configuration, due to the difficulties in retrieving in detail such
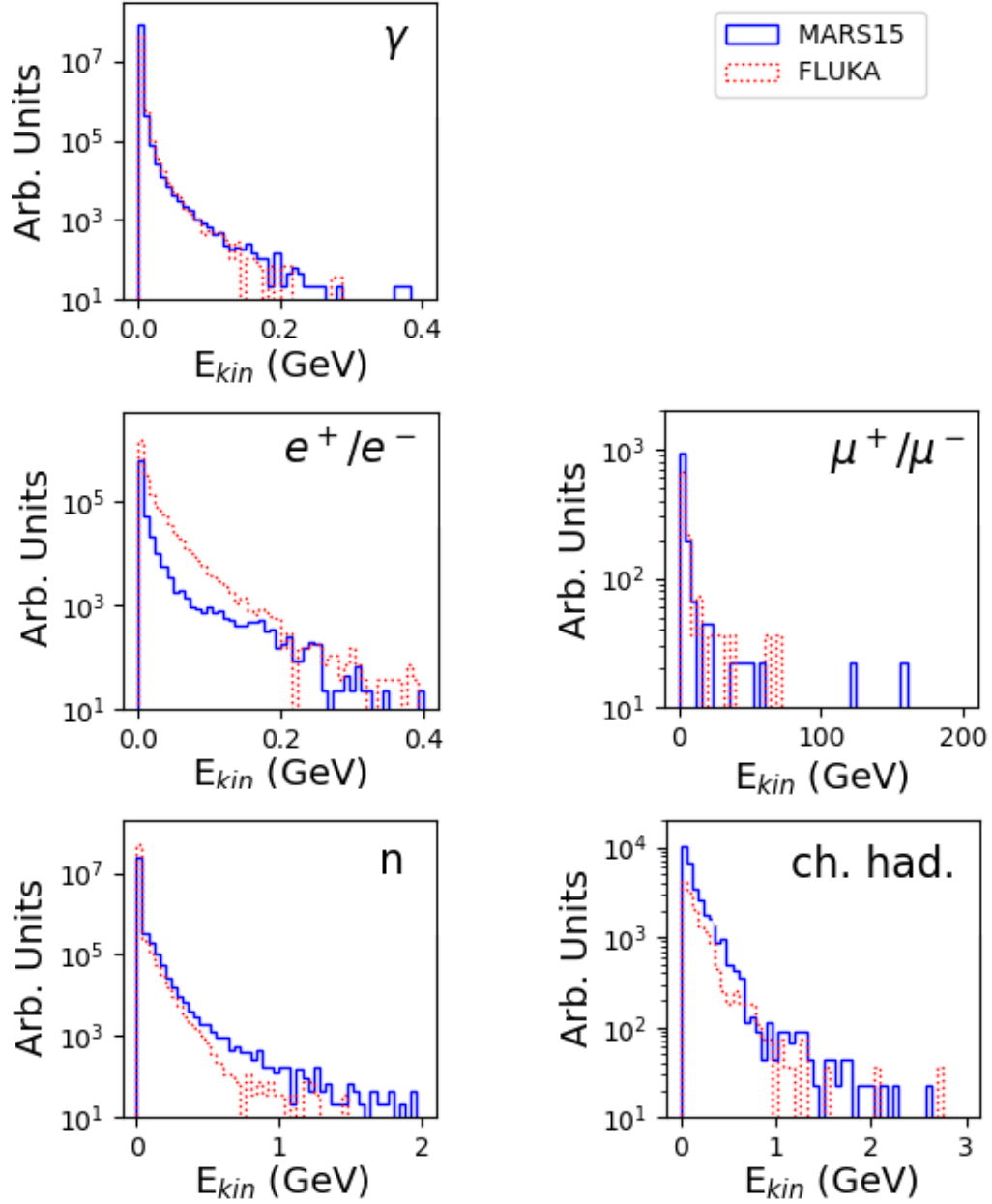
Figure 4. Energy distribution of BIB particles obtained with MARS15 code in solid blue line and the FLUKA program in dotted red line considering muon decays within 25 m from IP.

Table 2. Results for a 2×10^{12} μ^- beam. Number of BIB particles obtained by using MARS15 and FLUKA programs. Muon dacays within 25 m and 250 m from the IP are analysed with FLUKA. For each particle type the threshold energy is also reported.

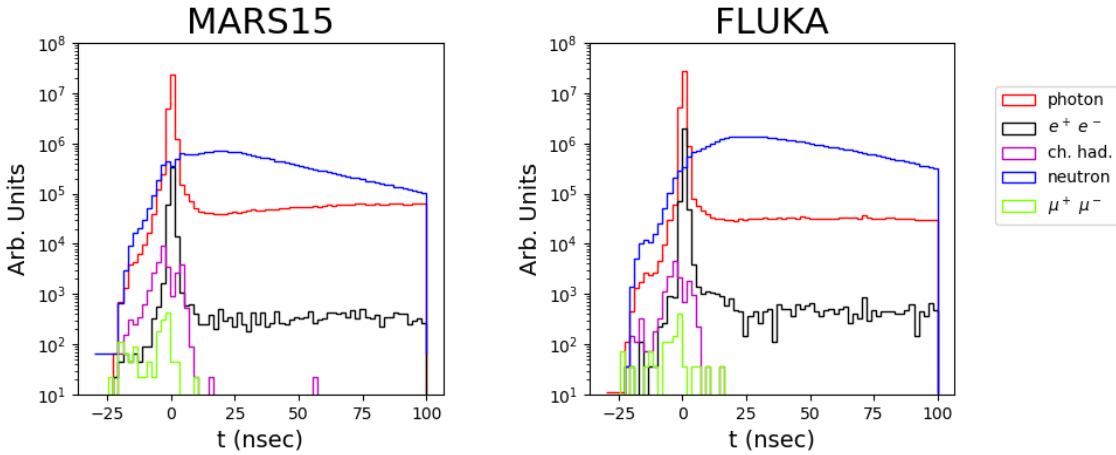| Particle (E_{th}, MeV)	MARS15 25 m	FLUKA 25 m	FLUKA 250 m
Photon (0.2)	$8.3 \, 10^7$	$4.3 \, 10^7$	$5.1 \, 10^7$
Neutron (0.1)	$2.4 \, 10^7$	$5.4 \, 10^7$	$5.9 \, 10^7$
Electron/positron (0.2)	$7.2 \, 10^5$	$2.2 \, 10^6$	$2.3 \, 10^6$
Ch. Hadron (1)	$3.1 \, 10^4$	$1.5 \, 10^4$	$2 \, 10^4$
Muon (1)	$1.5 \, 10^3$	$1.2 \, 10^3$	$3.4 \, 10^3$

Figure 5. Time distribution up to 100 nsec of BIB particles simulated with MARS15 (left plot) and with FLUKA (right plot) considering muon decays within 25 m from IP.

information. In particular, it is possible that the passive elements are not exactly the same between the two simulation. This seems confirmed by the distributions of the particles entering the detector as a function of longitudinal primary muon decay coordinate in Fig. 6 where dissimilarities are evident.

A previous comparison [24] performed by MAP of BIB generated at 125 GeV CM energy with MARS15 and FLUKA had highlighted an agreement between the two at the level of factor two, which is very similar to the result presented here.

Fig. 7 shows a color-map of the exit point in the x,z plane of the particles, again for one beam coming from the right side. Most of them exit the beam-pipe in the nozzles closer to the IP, as is particularly visible in the bottom row with an higher zoom in. The beam reaching the nozzle from the right side is channeled towards the left tip of the nozzle where a high number of interactions occurs. This behaviour suggested to investigate in detail the origin of the BIB in the IR elements, which is possible with the presented tool.
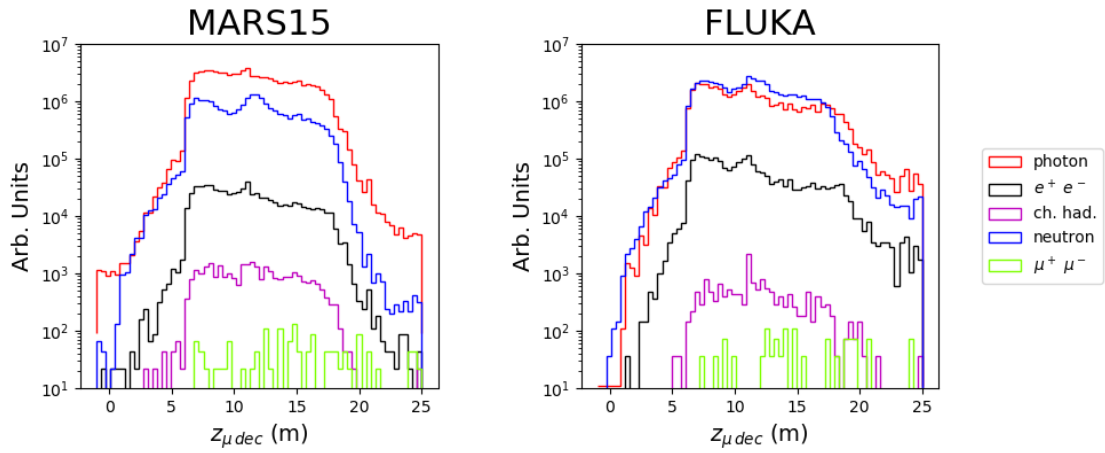
Figure 6. Distribution of the particles type entering the detector as a function of z_μ, the longitudinal coordinate of the primary muon decay.
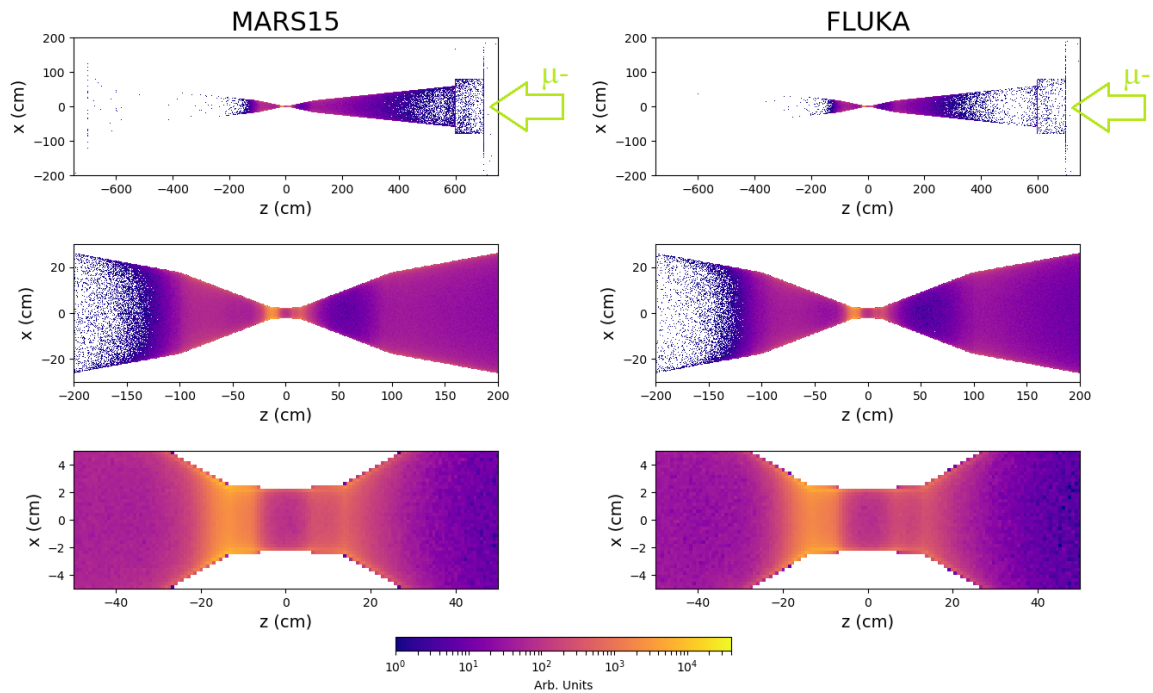

Figure 7. Colormap of the particles entering the detector represented in the x,z plane. From top to bottom a zoom in around the IP is shown.

6   Study of the BIB origin

In order to perform a detailed study of the BIB origin and its interaction with the IR elements, FLUKA simulation is used taking into account muons decaying within 250 meters from the IP. As reported in Table 2, the only relative valuable difference between 25 m and 250 m is represented by the number of Bethe-Heitler muons entering the detector hall. Fig. 8 shows in fact that, in order to have a correct estimate of the secondary muon particle number, it is necessary to consider primary muons decay at least up to 150 meters, after that point the contribution to the BIB becomes almost negligible. To better understand the history of particles that are entering the detector, information
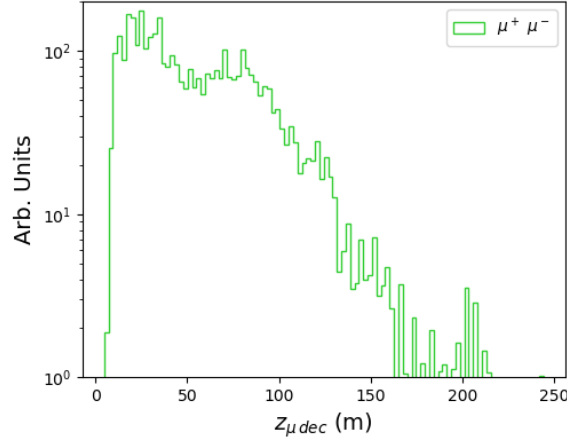

Figure 8. Distribution of primary muon dacays generating Bethe-Heitler muons finally entering the detector.

regarding first interaction region has been extracted from the simulation. In particular, Fig. 9 top-left reports regions where the first interactions corresponding to the BIB particles entering the detector occur. As expected, the majority of them happens in the right nozzle, but a not negligible number is also on the left nozzle.

The pie on the right of Fig. 9 represents the elements from which the BIB particles exit just before entering the detector. Many elements are present, but the left nozzle is the second more important element. The sketch at the bottom of Fig. 9 displays the elements names with the primary beam arriving from the right. These three graphs together demonstrate that the first interactions occur mainly in the right inner part of the nozzle that, together with the right tip, acts as a "funnel", and on the opposite nozzle tip, that operates as a "target", from where 31.7% of BIB exits to enter the detector.

In order to further understand the phenomenology of BIB events, FLUKA capability of visualizing tracks has been exploited. Fig. 10 shows BIB tracks along the ring and at the IR. The top picture shows all particles except neutrons: it is thus possible to identify the elements along the beam pipe where particles originate. The middle picture includes the neutrons that bounce all around releasing a lot of energy given their low momentum. Fig. 10, bottom, illustrates a zoom in around the IP relative to a single muon decay.
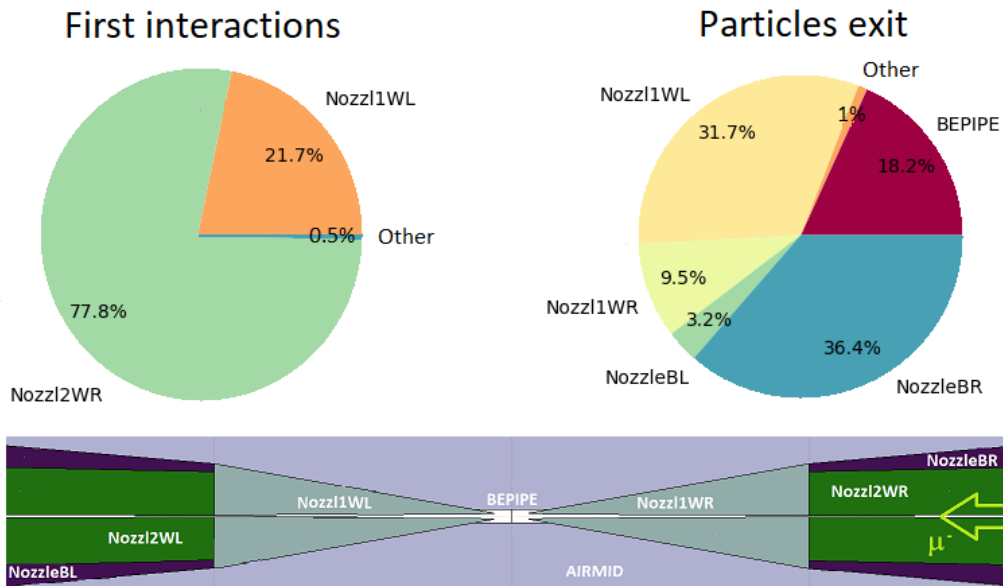
Figure 9. The pie graph on the left shows the elements of the IR where the first interactions occur after the primary muon decay. The pie on the right represents the elements from which the BIB particles exit the IR to enter the detector. At the bottom a sketch of the IR with the relevant regions names is reported.

7 BIB characteristics without the nozzle absorber

The remarkable flexibility allowed by the advanced approach to BIB simulations described in this paper, based on FLUKA and LineBuilder, allows to easily investigate the possibility of changing the nozzle structure, for example by implementing an asymmetric structure or even completely modify the interaction region. In order to propose something new, the characteristics of the BIB without the nozzle have to be understood. The comparison between the "with nozzle" (Y) and "without nozzle" (N) cases is reported in Fig. 11. As expected, a major increase in particle fluxes is observed when removing the nozzle for photons and e^+e^-. A milder increase is observed for charged hadrons and muon flux. On the contrary, the nozzle insertion yields to an increase in the neutron flux. Besides fluxes, the most important thing to highlight it is the energy spectrum of the particles which is very similar to the one of the particles produced in the muons primary interaction. This huge amount of high energy BIB particles would completely jeopardize the physics measurements. As shown in Fig. 11, the nozzle play a crucial role in suppressing high energy component, any other structure need to have the same performance or better.

8 Conclusion

Among the challenges presented by a muon collider, a prominent role is played by the BIB, as illustrated in this paper.

A massive reduction of the BIB can be obtained by means of a careful optimization of the Machine Detector Interface, for which an advanced approach to its simulation is presented, based on the combination of LineBuilder and FLUKA. Such a software combination allows a seamless
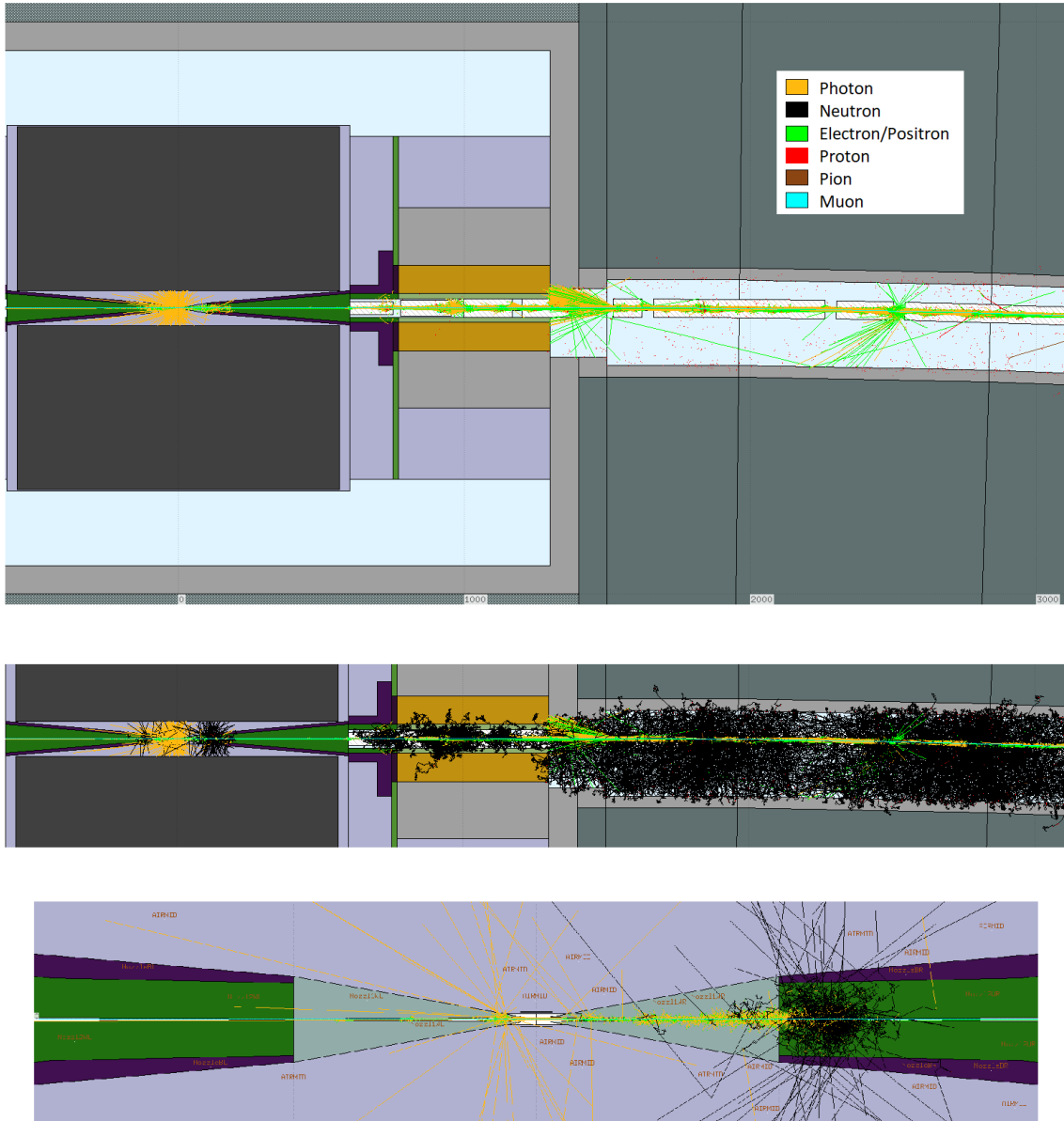
Figure 10. BIB particle tracks along the ring and at the IR. Top: All particles but neutrons; middle: all particles including neutrons, tracks shown are relative to a reduced number of muon decays. Bottom: zoom in around the IP, tracks shown are relative to a single muon decay.

link between the code used for lattice and optics design (e.g. MAD-X) of the Muon Collider and the Monte Carlo simulation used to assess the BIB impact on the detector. First results for the 1.5 TeV CM energy case have been shown, also compared to those obtained by the MARS15 simulations. A good agreement has been found, and the residual differences are most probably due to the imperfect reproduction of some parts of the machine (i.e. passive absorbing materials between magnetic elements). The tool allows to investigate the origin of the BIB in the machine elements, opening to the possibility to improve the configuration for further BIB reduction. Results shown in this paper
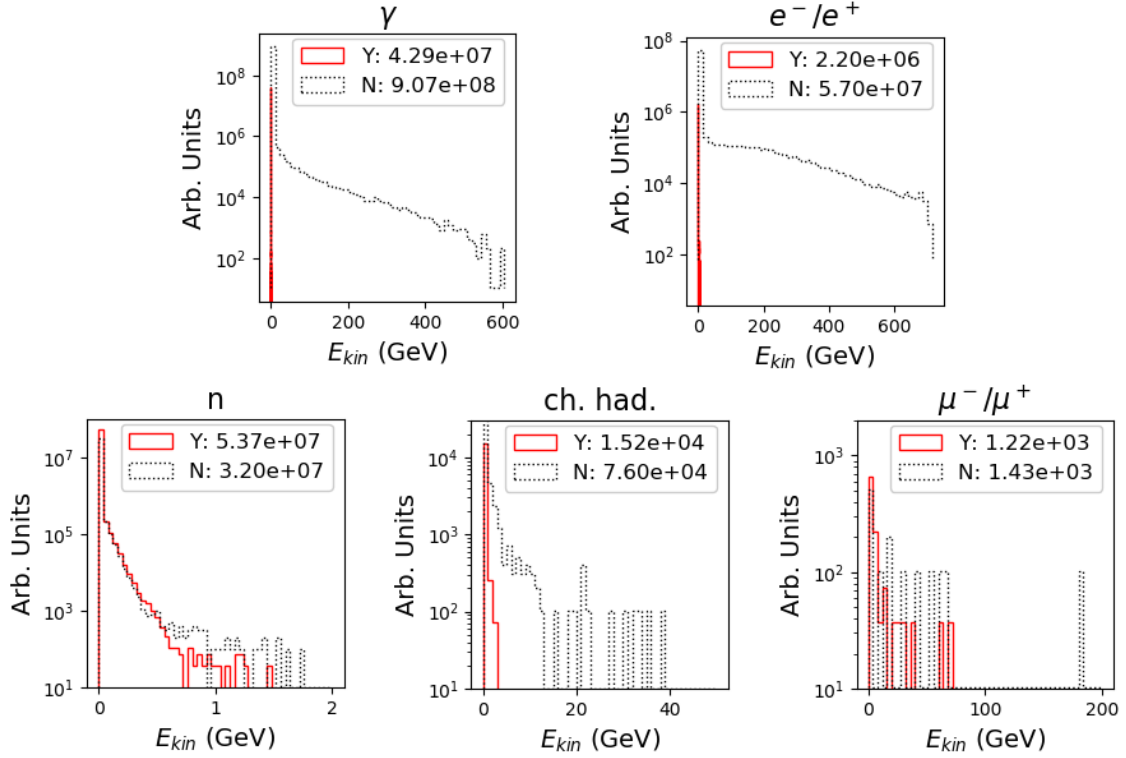
Figure 11. Number and energy spectrum of the particles divided by type in the two cases: with nozzle (Y) in solid red line and without nozzle (N) in dotted black line.

suggest that this tool has the required characteristics in terms of flexibility and accuracy, and can thus be fundamental to perform the MDI optimization needed in a Muon Collider.

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