PROCEEDINGS OF SCIENCE

A Geant4-based simulation study of a preliminary setup of the MUonE experiment

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MUonE is a proposed experiment which aims at an independent and precise determination of the leading hadronic contribution to the muon $g-2$, based on the measurement of the hadronic running of the electromagnetic coupling in the space-like region. This can be achieved by measuring with extremely high accuracy the shape of the differential cross section of the μe elastic scattering, using a 160 GeV muon beam available at CERN, off atomic electrons of a light target. Geant4 simulations are required in order to estimate the backgrounds in the proposed experiment. For this reason, the MUonE setup has been simulated with the recent Geant4 versions containing relevant updates, mostly regarding the correct estimation of the angular distribution of the e^+e^- production from muon interactions. In this work, two related studies utilizing the most accurate Geant4 physics list are presented, one involving standalone simulation tests and another one employing simulation and reconstruction using the new FairRoot release. In both cases, the latest Geant4 version has been validated comparing it with a previous version.

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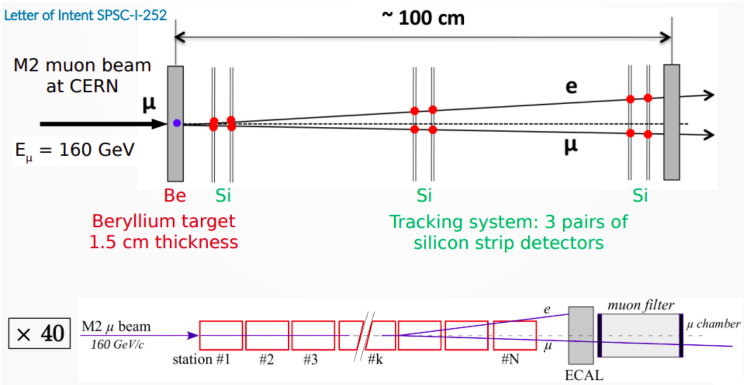

Figure 1: Preliminary MUonE setup scheme where the locations of the tracking stations, ECAL, and muon chamber are indicated. (Not-to-scale.)

1. The MUonE experiment - Introduction

The new experimental average of the recent FNAL Muon $g - 2$ measurement of the positive muon magnetic anomaly a_μ [1] combined with the previous measurement increases the tension between experimental and theoretical SM value to 4.2 standard deviations. It is known that hadronic contributions are responsible for almost all of the theoretical uncertainty. The leading hadronic contribution is due to hadronic vacuum polarization [2]. However, it should be noted that a recent Lattice QCD result [3] is closer to the experimental data, in tension with the usual dispersive calculation.

MUonE is an experiment aiming at an independent determination of the leading hadronic contribution to a_μ with a new method, from a precise measurement of $\Delta\alpha(t)$, the hadronic contribution to the running of the fine-structure constant, in $\mu e \to \mu e$ elastic scattering, by using the CERN muon beam ($E = 160$ GeV) on a fixed target [4, 5]. The experiment is planned to consist of 40 tracking stations with a thin (in order to limit multiple scattering) low-Z target and 6 silicon microstrip detectors using the same 2S modules developed for the upgrade of the CMS outer tracker [6]. After the tracking stations, an electromagnetic calorimeter (ECAL) and a muon filter will complete the apparatus to help with the identification and the selection (Figure 1). The signal from elastic scattering will produce two-track events, with the emission of a high-energy atomic electron (δ-ray), while all the other processes (e^+e^- pair production, Bremsstrahlung, nuclear interactions) will contribute to the background with pair production constituting the main background.

2. MUonESim and standalone Geant4 tests

Standalone Geant4 [7] tests were performed with an application called MUonESim in order to determine the appropriate physics lists, models and Geant4 versions to be used in the simulation of the MUonE setup before including the reconstruction stage. MUonESim was used for the estimation of contributions of different interaction processes to the total energy loss for the relevant materials composing the MUonE detector. The application calculates the transferred energy ε from the incoming muon at every step. Furthermore, it calculates the macroscopic differential cross section $d\sigma/d\varepsilon$, where the macroscopic cross section σ is related to the microscopic atomic cross section

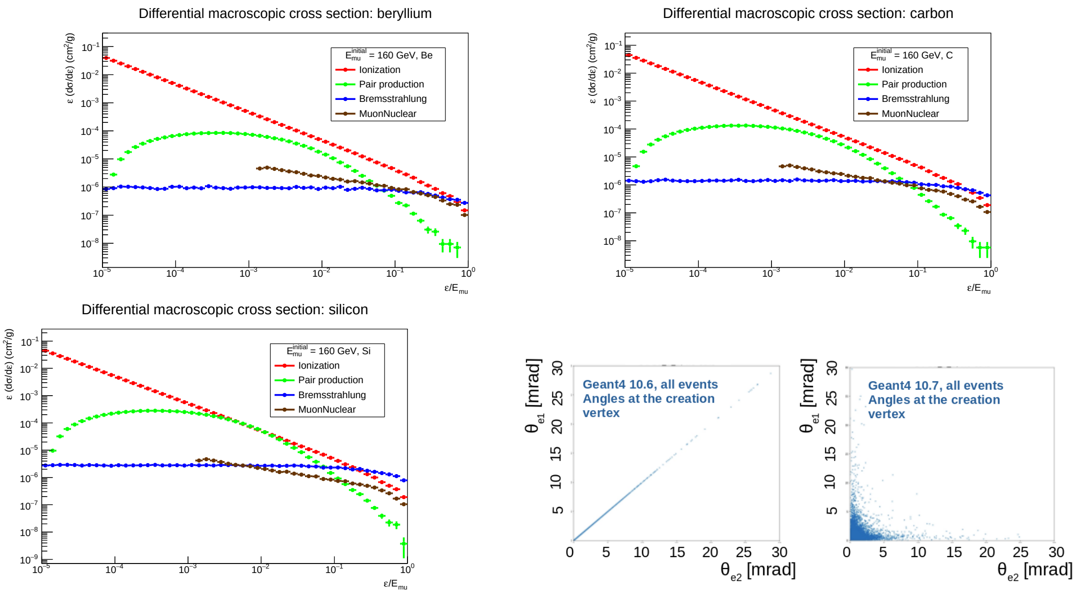

Figure 2: Geant4 (version 11.0) differential macroscopic cross section for muon interaction processes in beryllium (top left), carbon (top right) and silicon (bottom left) for production of δ-electrons, e^+e^- pairs, bremsstrahlung and nuclear interactions. Comparison of electron-positron pair angles with respect to the incoming muon in Geant4 10.6 (bottom middle) and 10.7 (bottom right).

σ_A by $\sigma = \sigma_A n_A/\rho_A$, where n_A is the density of atoms per unit volume and ρ_A is the material density. Tests were done for candidate target materials (beryllium or carbon) as well as for silicon, which is the main material in the tracking modules (Figure 2 top and bottom left, respectively). It was observed through simulations, that the optimal physics list for MUonE should contain the Geant4 lists: FTFP-BERT, electromagnetic option 4 (containing the most accurate standard and low-energy models) and the default model for muon nuclear interactions. (Option4 EM physics mainly affects the simulation of secondary particles produced by muons, and in addition is more accurate for δ-electrons and photons.) MUonESim was also used for the estimation of angular correlations. In particular, it was shown that the latest Geant4 versions (from 10.7 and onward) [8] introduce an improved simulation of the angular distribution of e^+e^- pairs. In previous versions, the e^+ and e^- were simply generated at a common outgoing direction. The recent versions have an improved angular distribution, and the two exit angles show a reasonable distribution, as visible in Figure 2 bottom right.

3. Simulation using FairMUonE

FairMUonE is the official MUonE software (using the FairRoot framework [9]) which was developed for generation, simulation and offline reconstruction of events. It interfaces with the MESMER Monte Carlo generator [10, 11] and allows for the production of LO and NLO signal samples of elastic collisions with an accurate beam profile. The interaction with the detector material is simulated using Geant4 and the full tracker digitization is already implemented. After the reconstruction of individual tracks within each tracking station from compatible hit patterns, event vertices are searched for based on a linear χ^2 fit of one incoming and two outgoing tracks

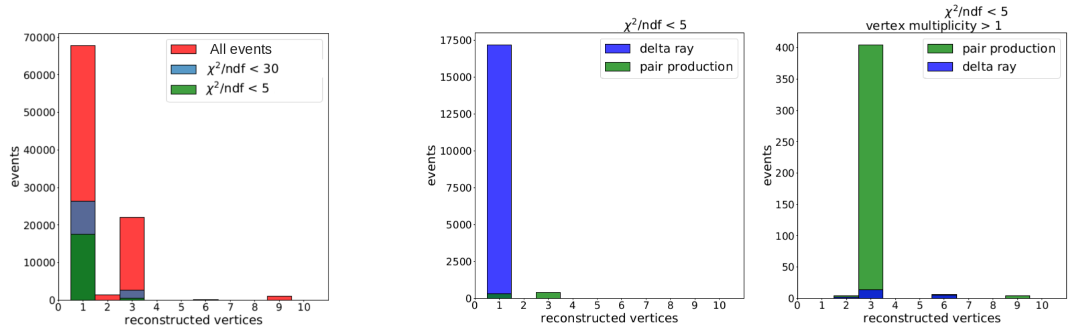

Figure 3: Left: Number of reconstructed vertices in simulated events for different requirements on χ^2/ndf. Middle: Number of reconstructed vertices selected with a good χ^2/ndf, showing the contribution of the signal (delta ray) and the pair production background. Right: The same, but selecting events with more than one vertex.

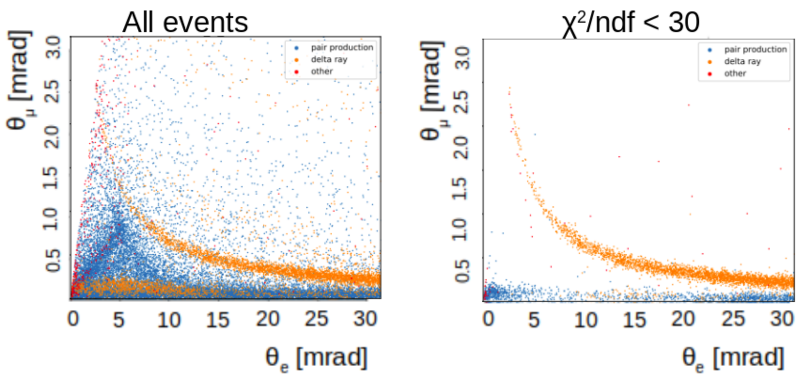

Figure 4: Kinematic correlation between the reconstructed angles of the outgoing candidate muon and electron tracks without (left) and with (right) selection criteria for signal (δ-ray), pair production and other background processes.

constrained to a common vertex position. Selection requirements are imposed on the best vertex in an event, corresponding to the lowest χ^2/ndf. From simulation runs it was observed that a significant fraction of pair production events has 3 vertices (3 combinations of outgoing μ and e^+e^- pair tracks), as shown in Figure 3 left, and that a requirement of a single reconstructed vertex with a relatively low χ^2/ndf provides an effective veto against the most important background (Figure 3 middle and right). The effect of a selection cut on the vertex χ^2 has been studied. Without any identification of the two outgoing tracks the one at the lowest scattering angle is assumed to be the outgoing muon. The correlation plot of the two tracks angles is shown for all the reconstructed events (Figure 4 left), and for the selected events (Figure 4 right), with truth matching of the event source from either signal or background. The physical origin of an event is taken to be the process that created the Monte Carlo track linked to the candidate electron. The effect of the assumption on the particle identity is visible on the left side of the plots. This will be mitigated by introducing muon chambers and ECAL in the future.

4. Conclusions and future plans

The MUonESim application was developed for the validation of different Geant4 versions and physics configurations, and in particular for the estimation of the multiplicity of secondary particles due to different muon processes, the energy loss and the angular distribution of the outgoing particles. Additionally, FairMUonE was introduced as the official software for the MUonE experiment, which is currently ready for the full simulation and reconstruction for both the upcoming Test Run and the final detector configuration. Several ideas for related future studies have been considered so far by the MUonE Collaboration: the development of an improved generator of pair production events to better estimate background contributions; the creation of a custom MUonE physics list for Geant4; the study of the data collected during the Test Run in 2022-23 using simulated events from the MC signal and background samples.

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