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Background studies and normalization of signal events in the Mu2e experiment

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Abstract: The Mu2e experiment is currently being constructed at Fermilab to search for the neutrino-less conversion of negative muons into electrons in the field of an aluminum nucleus. The experiment aims at a sensitivity of four orders of magnitude higher than previous related experiments, which implies highly demanding accuracy requirements both in the design and during the operation. To achieve such a goal, two important tasks should be accomplished. First, it is essential to estimate precisely the particle yields and all the backgrounds that could mimic the monoenergetic conversion electron signal. Second, it is necessary to normalize the signal events accurately. The normalization of the signal events is planned to be done using a detector system made of an HPGe detector and a Lanthanum Bromide detector, which will measure the rate of muons stopped on the aluminum target by looking at the emitted characteristic X-and γ-rays of energies up to 1809 keV. Therefore, it is essential to evaluate the detector system's performance before the start of the actual experiment. In this study, the first task was addressed by an extensive campaign of Monte Carlo simulations to investigate the relevant parameters and their impact on the experiment's sensitivity. The second task was handled by taking advantage of the Helmholtz-Zentrum Dresden-Rossendorf (HZDR) pulsed Bremsstrahlung photon beam at the ELBE facility. The detector system was tested at the ELBE facility under timing and background conditions similar to the ones expected at the Mu2e experiment. The study presents and discusses the simulation results and the detector system testing campaign.

Keywords: Radiation calculations; Simulation methods and programs; Accelerator modelling and simulations (multi-particle dynamics, single-particle dynamics); Accelerator Subsystems and Technologies

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1 Introduction

The Mu2e experiment [1, 2] will search for the conversion of negative muons into electrons in the field of an aluminum nucleus without the emission of neutrinos ($\mu^- + Al \rightarrow e^- + Al$). Such a conversion process is an example of a Charged-Lepton Flavor Violation (CLFV), an effect prohibitively too small to be observed within the Standard Model of particle physics. Therefore, its observation will be a signal of new physics.

A schematic view of the principal elements of the Mu2e experiment is shown in figure 1. The experiment starts with an 8 GeV pulsed proton beam with a time-averaged power of 7.3 kW, hitting a pion production target made of tungsten. The target is surrounded by a graded solenoidal magnetic field, which guides the produced pions towards an s-shaped transport solenoid (TS), where they decay into muons. Inside the TS, there are absorber foils that remove antiprotons and collimators that select low-momentum negatively charged muons. The selected muons then hit a stopping target made of aluminum foils, where they either decay or undergo a capture reaction on the aluminum nuclei or potentially undergo a CLFV conversion to electrons. A tracking detector and a calorimeter then detect the conversion electrons.

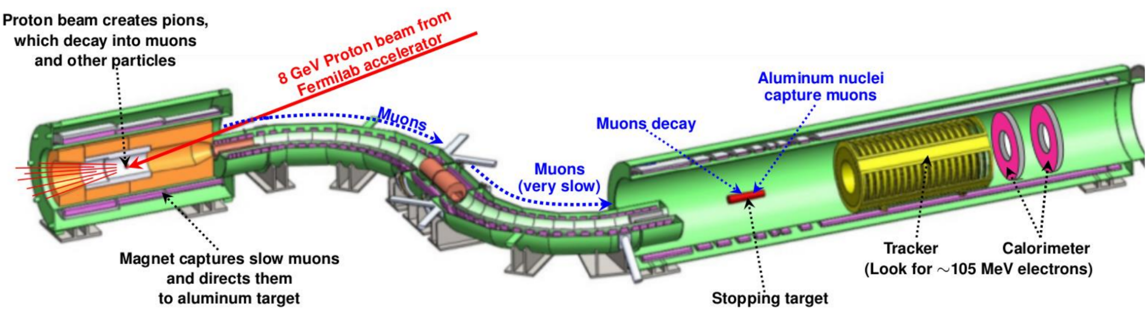

Figure 1. The Mu2e experiment.

The signal for muon-to-electron conversion would give a single monoenergetic electron with an energy close to the muon mass $E_e = 104.973$ MeV [3]. The number of signal conversion-electron candidates will be normalized to the number of muons captured on aluminum in the same running period. The experiment aims to reach a single event sensitivity of 3×10^{-17} on the conversion

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ratio. That is four orders of magnitude higher than previous related experiments. To reach such sensitivity, two essential tasks should be accomplished: (1) all backgrounds that could mimic the conversion signal should be controlled; (2) the signal events should be normalized accurately. The study presented in this paper addresses these tasks. Section 2 presents the Monte Carlo simulations performed to investigate the beam-related and cosmic rays-related backgrounds and their impact on the experiment's sensitivity. Section 3 describes the testing campaign performed at the ELBE facility in HZDR to evaluate the performance of the detector system used for the signal events normalization. Section 4 then summarizes the study.

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2 Background studies

The beam-related and cosmic rays-related backgrounds were investigated via Monte Carlo simulations. As controlling the potential backgrounds drives the overall design of the Mu2e experiment, their predictions should be as accurate and reliable as possible. Therefore, the simulations were performed using the FLUKA2021 [4], MCNP6 [5], MARS15 [6], and GEANT4 [7] codes. Each code uses a different hadronic model: FLUKA2021 uses the default PEANUT package, MCNP6 and MARS15 use the LAQGSM03.03 model, and the GEANT4 data are produced with the ShieldingM physics list. As a result of the different hadronic models and other features, the codes have different predictions. Therefore, the investigation was performed with a focus on code-to-code comparison. An example of beam-related and cosmic rays-related backgrounds investigation are presented in the following sub-sections.

2.1 Antiprotons beam-related background

One of the possible beam-related backgrounds comes from antiprotons. In that case, background electrons can be produced via two mechanisms: (1) the proton beam hitting the tungsten target produces antiprotons that can reach the aluminum-stopping target, annihilate and produce electrons; (2) pions created in the TS by antiproton interactions can produce electrons via radiative pion capture. A part of the background electrons produced via this mechanism can be, however, rejected by a cut on the signal time window. To control the antiprotons beam-related background, it is critical to evaluate correctly the number of antiprotons initially forward-produced and then backscattered towards the TS.

Table 1. Antiproton yields.

$\overline{p}$ beam momentum of 1.9 GeV/c

θ	Geant4	MCNP6	Δ	FLUKA	Δ	MARS15	Δ
$0° - 10°$	3.11	3.23	3.7%	3.38	8.5%	3.19	2.4%
$10° - 45°$	$5.38{\cdot}10^{-2}$	$2.28{\cdot}10^{-2}$	-57.5%	$2.52{\cdot}10^{-2}$	-53.2%	$1.47{\cdot}10^{-2}$	-72.6%
$45° - 90°$	$4.43{\cdot}10^{-3}$	$7.34{\cdot}10^{-4}$	-83.4%	$1.47{\cdot}10^{-3}$	-66.9%	$6.42{\cdot}10^{-4}$	-85.5%
$90° - 135°$	$7.87{\cdot}10^{-5}$	$3.13{\cdot}10^{-5}$	-60.3%	$5.47{\cdot}10^{-5}$	-30.4%	$3.28{\cdot}10^{-5}$	-58.3%
$135° - 180°$	$8.26{\cdot}10^{-6}$	$4.57{\cdot}10^{-6}$	-44.7%	$1.71{\cdot}10^{-6}$	-79.3%	$6.02{\cdot}10^{-6}$	-27.1%

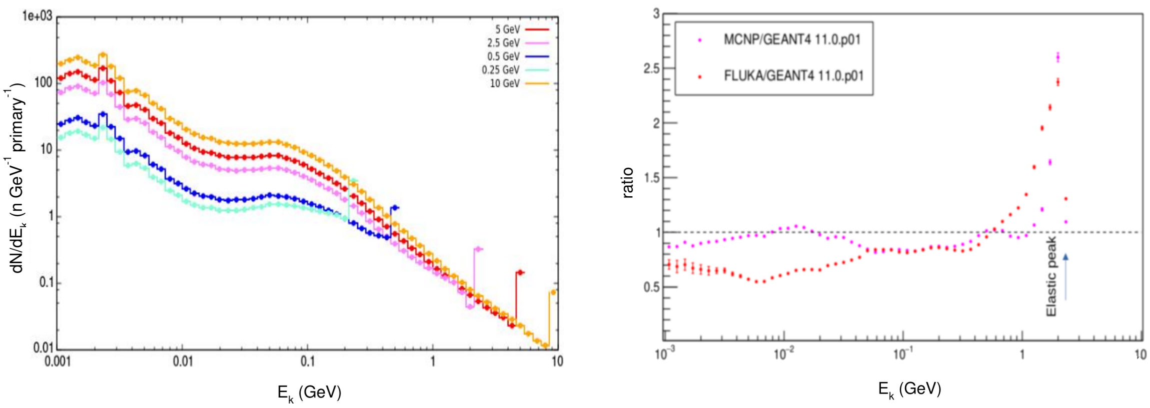
$\overline{p}$ beam momentum of 2.1 GeV/c

θ	Geant4	MCNP6	Δ	FLUKA	Δ	MARS15	Δ
$0° - 10°$	3.01	3.04	1.0%	3.22	7.1%	3.01	0.1%
$10° - 45°$	$5.03{\cdot}10^{-2}$	$2.27{\cdot}10^{-2}$	-55.0%	$3.30{\cdot}10^{-2}$	-34.4%	$1.46{\cdot}10^{-2}$	-70.9%
$45° - 90°$	$4.12{\cdot}10^{-3}$	$7.80{\cdot}10^{-4}$	-81.1%	$1.78{\cdot}10^{-3}$	-56.8%	$7.09{\cdot}10^{-4}$	-82.8%
$90° - 135°$	$2.35{\cdot}10^{-4}$	$3.17{\cdot}10^{-5}$	-86.5%	$6.70{\cdot}10^{-5}$	-71.5%	$3.53{\cdot}10^{-5}$	-84.9%
$135° - 180°$	$3.06{\cdot}10^{-5}$	$4.20{\cdot}10^{-6}$	-86.3%	$2.24{\cdot}10^{-6}$	-92.7%	$6.23{\cdot}10^{-6}$	-79.7%

To investigate the antiproton beam-related background, Monte Carlo simulations were performed to evaluate the antiproton yields from a 1.9 GeV/c and a 2.1 GeV/c antiproton pencil beam hitting a tungsten cylindrical target ($R = 0.315$ cm, $L = 16$ cm). Table 1 presents the antiproton yields in several angle intervals obtained from the different codes for the antiproton beam momentum of 1.9 GeV/c and 2.1 GeV/c. The table also shows the difference between the results obtained from the different codes with respect to GEANT4 (which is the official simulation tool of the Mu2e experiment). As can be noted, quite a good agreement is obtained between the code in the most forward direction (angle interval of 0°–10°). However, in the backward direction, while MCNP6, FLUKA2021, and MARS15 have a good agreement, GEANT4 overestimates the yield. Since GEANT4 gives very different results than the other codes, discussions with the GEANT4 developers have started to understand whether the GEANT4 code antiproton evaluation can be improved. If one trusts the other Monte Carlo results and neglects the Geant4 one, it would be possible to reduce the antiproton absorber thickness and to recover some muon, but the increase of stopped muon yield would be marginal, so the absorber thickness has not be changed.

2.2 Cosmic rays-related background

One of the possible cosmic rays-related background comes from neutrons. The experiment has a cosmic ray veto (CRV) system, suppressing the background due to the cosmic rays that could hit the stopping target. The CRV system is shielded by 1 m of (standard) concrete. The concrete absorbs cosmic neutrons, forming an additional possible background source. To investigate this background, Monte Carlo simulations were performed to evaluate the transmission of cosmic neutrons in a 10×10×1 m^3 concrete block. Monoenergetic neutron pencil beams with energy of 0.25 GeV, 0.5 GeV, 2.5 GeV, 5.0 GeV, and 10 GeV were considered in the simulations.



(a) Neutron transmission FLUKA2021 results

(b) Neutron transmission (2.5 GeV n-beam) MCNP6 and FLUKA2021 vs. GEANT4

Figure 2. Neutron transmission.

Figure 2a presents the neutron transmission obtained from the FLUKA2021 code for the different neutron incident beams. Figure 2b shows the difference between the results obtained from MCNP6 and FLUKA2021 with respect to GEANT4 for the 2.5 GeV neutron incident beam. As can be noted, the spectra of neutrons after 1 m concrete generally differs by less than a factor of two. However,

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at the elastic peak, GEANT4 is about 2.5 lower than MCNP6 and FLUKA2021. In any case, the Mu2e collaboration has chosen to wait for the results of Run 1 before modifying the cosmic neutron shielding. The shielding upgrade will be performed before Mu2e Run 2 during the two years shut down for the PIP-II (Proton Improvement Plan II) accelerator upgrade.

3 Normalization of signal events

The normalization of the signal events is planned to be done using a system made of an HPGe detector and a Lanthanum Bromide ($LaBr_3$) detector. The system will measure the rate of muons stopped on the aluminum target by looking at the emitted characteristic X-and γ-rays of energies between 347 keV (the 2p$\rightarrow$1s Al radiative transition) up to 1809 keV. While high-purity germanium crystals are optimal for measuring X-rays with the known superior energy resolution at the few keV levels in the MeV region, their performance can be challenged by the high background photon rates expected at Mu2e (up to several tens of kHz/cm^2, depending on the geometry and position of the HPGe). On the other hand, the $LaBr_3$ detector has ~7 times greater rate handling capability and better radiation resistance despite its worse energy resolution.

(a) HPGe test (b) $LaBr_3$ test

Figure 3. Test of the detector system at the gELBE facility (HZDR).

The detector system was tested at the gELBE facility in HZDR. The gELBE produces bremsstrahlung from an electron beam impinging on niobium radiator foils. Using the gELBE pulsed bremsstrahlung spectrum and calibration sources (^{137}Cs, ^{60}Co, ^{88}Y) allows simulating the Mu2e conditions. Three irradiation campaigns were carried out to test the detector system: the HPGe test was performed in 2017, the $LaBr_3$ test was completed in 2021, and the test of the FPGA-based data acquisition system of the two detectors took place in 2022.

The HPGe test aimed to measure the detector performance in terms of energy resolution and radiation damage and to understand the best detector geometry and position in the final experimental setup, and at the same time, to exercise and test reconstruction algorithms. It was concluded that it is possible to reconstruct single spectral lines over a high-rate bremsstrahlung background with high average photon energy. The test showed resolutions between 3 and 6 keV depending on the reconstruction algorithm, with no degradation as a function of the photon rate, which varied between 32 kHz/cm^2 and 75 kHz/cm^2. Moreover, the test showed no radiation damage after an estimated

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energy deposit of 3×10^{10} MeV. To minimize the photon rate and the average deposited energy, a geometrical configuration at 45° with respect to the beam has been chosen for the final design since it guarantees a satisfactory level of 37 kHz/cm^2, with an average deposited energy of 1.8 MeV.

The $LaBr_3$ test aimed to test whether the detector could deal with the rate fluctuations anticipated at the Mu2e experiment. A calibration source, including the ^{88}Y line at 1836 keV, was used to mimic the muon capture on aluminum emission at 1809 keV. The idea was to determine energy resolution for the 1836 keV line over the Bremsstrahlung spectrum at increasing levels of gELBE electron current. "Nominal" expected Mu2e conditions were found at a pulse frequency of 813 kHz and 1.1 μA electron current, corresponding to an averaged deposited photon energy of 3.8 MeV. The test showed satisfactory and stable energy resolutions, going from 11.9 keV to 12.5 keV ($\sigma_E/E < 0.7\%$) when increasing the photon rate from 44 kHz up to 150 kHz, with the latter rate matching well the nominal rate expected at Mu2e (141 kHz). Moreover, the detector system could handle data at twice the nominal photon rate, with an energy resolution of 13.4 keV.

4 Summary

Two tasks for supporting the Mu2e experiment design were performed: (1) investigation of the backgrounds via MC simulations and (2) testing of the detector system for the signal events normalization. The Monte Carlo simulations were performed using GEANT4, FLUKA2021, MCNP6, and MARS15 codes to evaluate the prediction credibility of the codes and tune the simulation setup. The detector system was tested successfully at the gELBE in HZDR. It has been ensured that both subsystems can fulfill the requirements in terms of expected gamma rates (the strong point of the $LaBr_3$ detector) and energy resolution (the strong point of the HPGe detector). The detector system is currently being set up in the Mu2e building at Fermilab.

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