PROCEEDINGS OF SCIENCE

The muon-to-electron conversion process and the Mu2e experiment at Fermilab

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The Mu2e experiment at Fermi National Accelerator Laboratory will search for the Charged Lepton Flavour Violating (CLFV) neutrino-less coherent conversion of a muon into an electron in the field of a nucleus with a single event sensitivity of $3 \cdot 10^{-17}$, which is an improvement of four order of magnitude over the existing limits. The muon conversion probes new physics at a scale that cannot be reached with direct searches at present or planned colliders and complements similar searches for CLFV performed by the MEG-II experiment at Paul Scherrer Institut. In this paper, we report on the Mu2e physics motivations, the design of the muon beamline and the detectors employed by the experiment, which include a tracking spectrometer, a calorimeter and a cosmic ray veto. Mu2e is currently being constructed at the Fermilab Muon Campus and is expected to begin data taking in 2025 (Run 1) with a reduced average beam intensity. Run 1 will continue for two years. After a shutdown for the upgrade of Fermilab accelerator complex, Mu2e data taking will be resumed at full beam intensity in 2029 (Run 2).

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1. Overview

The Mu2e experiment is part of a worldwide effort dedicated to the search for Charged Lepton Flavour Violating (CLFV) processes that, if observed, would represent a powerful smoking gun for the presence of new physics beyond the Standard Model. Most minimal extensions of the Standard Model accomodating neutrino oscillations introduce right-handed neutrinos while preserving the total lepton number and assume neutrinos are Dirac particles. In this framework, individual lepton numbers are not conserved and CLFV transitions such as $\mu^+ \to e^+\gamma$ occur through interactions of W bosons with massive neutrinos. However, due to the light neutrinos tiny masses, the associated rate is about forty orders of magnitude below the sensitivity of present day and future experiments. When introducing new particles beyond the Standard Model, branching fractions are enhanced and CLFV processes emerge as one of the distinctive features of these theories and make the search for CLFV very attractive. The experimental observation of CLFV would be an unambiguous signature of new dynamics related to a non-trivial extension of the lepton sector of the Standard Model with huge impact on establishing new models. Among the possible CLFV processes within the muon sector, the $\mu N \to eN$, where N is an atomic nucleus, is usually considered "the golden channel" due to its clear signature and its discovery potential [1]. The outcome of the $\mu N \to eN$ is a monochromatic electron with an energy slightly below the muon rest mass, E=104.97 MeV, due to the contributions from the muon binding energy and the nucleus recoil. The Mu2e goal is to improve the current best limit [2] by four orders of magnitude.

2. The Mu2e detectors

Mu2e consists of three main superconducting solenoidal systems: (i) the Production Solenoid (PS), where an 8 GeV proton beam, pulsed with a period of about 1.7 μs, strikes a tungsten target; (ii) the Transport Solenoid (TS), which allows the charged π and then selects only low-momenta μ^-; the Detector Solenoid (DS), which houses the Al Stopping Target that is used to stop the μ^-, and the detector system [3]. The whole DS and half of the TS are surrounded by a cosmic ray veto system aimed to detect the atmospheric muons that interact in the detector region. Figure 1 (Top) shows the schematic representation of the Mu2e experimental setup (the cosmic ray veto is not shown). The detector system inside the DS consists of a straw-tube tracker and a crystal calorimeter placed downstream the Stopping Target in a 1 T magnetic field region and 10^{-4} tor of vacuum. Both detectors have the inner region left un-instrumented in order to be not sensitive to the majority of low energy charged particles. The topology of a conversion electron event in this setup is represented by a helical trajectory that makes 2-3 loops in the tracking chamber and then hit the calorimeter, producing an electromagnetic shower. The R&D of the sub-detectors is mature and the production phase is progressing smoothly.

The structure of the pulsed proton beam is shown in Figure 1 (Bottom). The time interval between two proton spills is 1.7 μs and well matches the muonic Al lifetime (864 ns). A delayed analysis window starting from 700 ns is used to suppress the prompt background

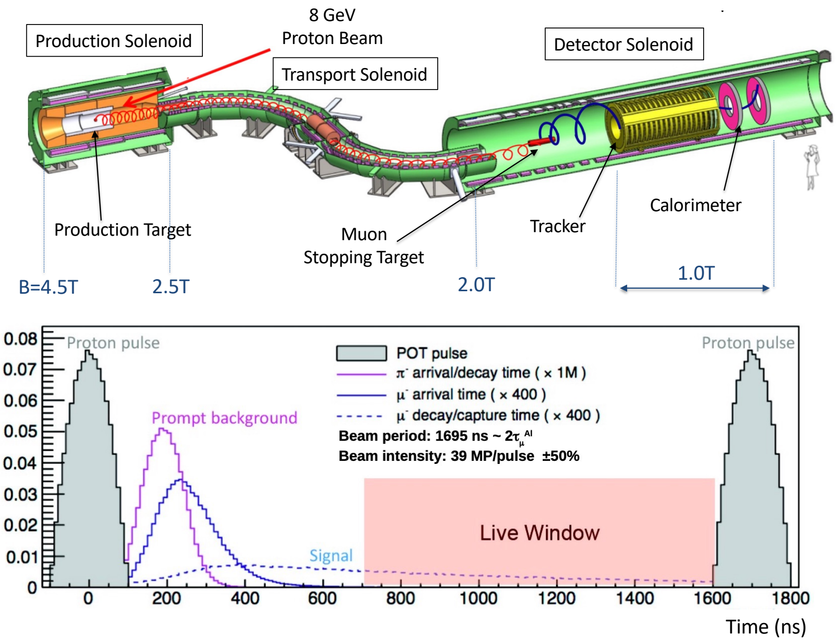

Figure 1: (Top) Schematic representation of the Mu2e experimental setup (the Cosmic Ray Veto surrounding the Detector Solenoid and half the Transport Solenoid are not shown); (Bottom) Mu2e pulsed proton beam structure.

while keeping a good efficiency on the muon conversions. The fraction of protons out of spill is expected to be lower than 10^{-10} and will be monitored by a detector observing the particles scattered from the production target.

The Al Stopping Target has a segmented structure (37 disks 100 μm thick) to minimize the energy losses. A central hole reduces the amount of bremsstrahlung radiation reaching the detectors. The tracker is made of 21,000 straw tubes, with a diameter of 5 mm and a thin wall of 15 μm of mylar, filled with a 80%-20% Ar-CO_2 gas mixture. The anode is a 15 μm tungsten wire at 1450 V read by ADCs and TDCs at both ends. Straw tubes of variable length are assembled in a double-layer 120^o circular segment (panel) covering a radius from 380 mm to 700 mm (Figure 2, Top Right). Three panels rotated with steps of 120^o form a plane. Two planes rotated by 60^o form a station. There are 18 stations placed along the beam axis, for a total tracker length of 3.3 m. The central hole makes the tracker insensitive to particles produced in the stopping target with a momentum lower than about 80 MeV/c2 and to the remnant beam (Figure 2, Top Left). The hit coordinate resolutions measured on a panel prototype (280 μm in the transverse direction and 43.4 mm along the wire) are in agreement with Monte Carlo expectations. The reconstructed conversion electron momentum distribution obtained with the simulation is nearly gaussian with a FWHM of 0.96 MeV/c and a small low momentum tail mainly due to energy losses.

The electromagnetic calorimeter is made of 2 disks of pure CsI crystals (Figure 2, Bottom Left). The disks have an annular shape, with an inner radius of 374 mm and an outer radius of 660 mm. The disks are spaced by 700 mm to allow the second disk to detect the electrons passing through the hole of the first one. Each disk contains 674 crystals of equal dimensions ($34\times34\times200$ mm^3). Each crystal is read by 2 arrays of 6 SiPMs. Preamplifier boards sit just on the back of the SiPMs while the slow control and data acquisition electronics are hosted in crates mounted all around the disks. Test beam results have shown an energy resolution of 7% and a single sensor time resolution of 230 ps on 100 MeV electrons with a 50^o impact angle. A particle identification neural network classifier using the particle time of flight from the tracker to the calorimeter and the ratio between the energy measured by the calorimeter and the momentum measured by the tracker is able to suppress the muons by a factor > 100 while introducing a negligible inefficiency for the conversion electron signal. About 1 cosmic ray event per day will mimic a 105 MeV/c electron. The main part of this background will be rejected by the Cosmic Ray Veto system (Figure 2, Bottom Right). Four layers of scintillator counters surround the DS and the last part of the TS. Each fibre is read at both ends by SiPMs. The Cosmic Ray Veto is expected to recognize 99.99 % of the charged cosmic particles crossing it. This challenging performance will be monitored by exploiting a large amount of data acquired with beam off during normal runs.

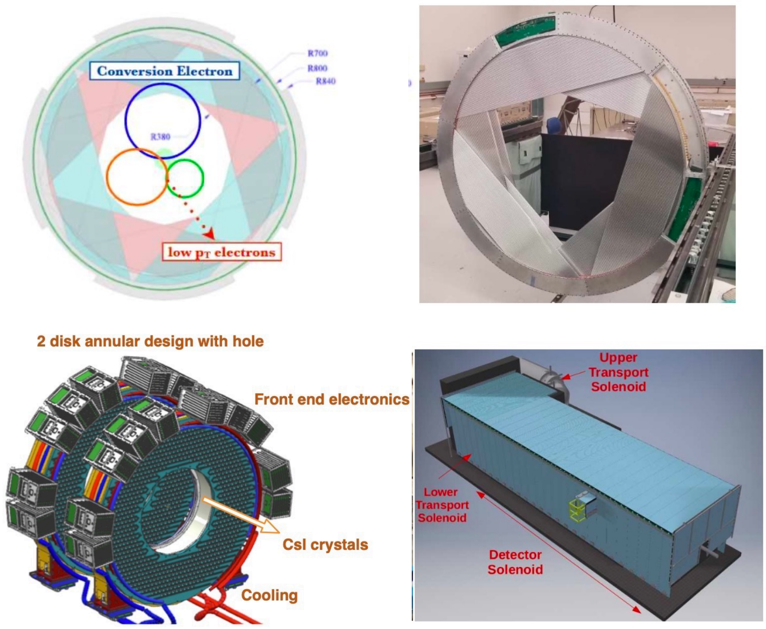

Figure 2: (Top Left) Pictorial representation of the conversion and low momentum electron trajectories in the transverse plane; (Top Right) Photograph of one produced straw-tracker plane; (Bottom Left) Pictorial view of the electromagnetic calorimeter; (Bottom Right) Pictorial view of the Cosmic Ray Veto surrounding the Detector Solenoid and half of the Transport Solenoid.

3. Physics Backgrounds and Expected Sensitiviy

The Mu2e experimental setup has been designed to minimise and/or keep under control the expected sources of background. The main source is due to cosmic muons mostly entering from regions of the Transport Solenoid not covered by the Cosmic Ray Veto and producing electrons through the interaction with the Transport Solenoid material. The second largest source is due to muon Decays in Orbit in the Al Stopping Target which can generate electrons with the same energy as the conversion electrons. Antiprotons and Radiative Pion Captures provide an additional but lower contribution to the background. The Monte Carlo simulation shows that with the expected backgrounds (0.107 ± 0.032 events) for the first two years of data-taking (Run 1), Mu2e will improve the limit on the ratio between the muon conversion and the muon nuclear captures of three orders of magnitude. With the statistics expected for Run 2, this limit will be further improved of one order of magnitude to reach the unprecedented single event sensitivity of $3 \cdot 10^{-17}$.

4. Conclusions

The construction of the Mu2e experiment at Fermilab is well under way. The Mu2e Collaboration is planning for a Run 1 in 2025-2026 which will allow to improve the world's best limit on the muon conversion rate of three orders of magnitude, and a Run 2 in 2029 and beyond to further improve the limit by one order of magnitude.

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