THE MU2E EXPERIMENT AT FERMILAB: R&D, DESIGN AND STATUS

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Abstract

The Mu2e Experiment at Fermilab \(^1\) will search for coherent, neutrinoless conversion of negative muons into electrons in the field of an aluminum nucleus, \(\mu^- + N(A, Z) \rightarrow e^- + N(A, Z)\). This is an example of Charged Lepton Flavour Violation (CLFV) never observed experimentally. The dynamics of such a process is well modelled by a two-body decay, resulting in a mono-energetic electron with an energy slightly below the muon rest mass (~104.967 MeV).

If no events are observed in three years of running, Mu2e will set an upper limit on the ratio between conversion and capture rate \(R_{e} \leq 6 \times 10^{-17}\) (at 90% C.L.). This will improve the current limit of a factor of \(10^4\) over previous experiments.

The experiment complements and extends the current/planned searches (\(\mu \rightarrow e\gamma\) decay at MEG, \(\mu 3e\)) as well as the direct searches for new physics at the LHC. Indeed, such CLFV searches in the muon sector probe new physics at a mass scale inaccessible with direct searches at either present or planned high-energy colliders.

To detect the muon conversion process, a very intense pulsed beam of negative muons is produced by means of a S-shape Superconducting Solenoid Magnet System that is organized into three sub-systems: the Production Solenoid, the Transport Solenoid and the Detector Solenoid. The beam is stopped at 10 GHz on an Aluminum target inside the Detector Solenoid.

The Mu2e detectors, also installed inside the Detector Solenoid, are a high-precision tracker made on ~20000 straw tubes, and a calorimeter composed of ~1500 pure CsI crystals organized in two disks and readout by two large area UV-extended Silicon Photomultipliers (SiPMs). The Detector Solenoid region is surrounded by a Cosmic Ray Veto based on scintillators readout by SiPMs.
1 Charged Lepton Flavor Violation and muon to electron conversion

Within the Standard Model (SM), transitions in the lepton sector between charged and neutral particles preserve flavor, since the neutrinos are considered massless. Even considering the discovery of neutrino oscillations, in the minimal extension of SM, the predicted branching ratios of Charged Lepton Flavor Violation (CLFV) processes in the muon sector are smaller than $10^{-50}$, unreachable by the current particle accelerators.

Any experimental observation of CLFV processes would be a clear signature of New Physics (NP). The coherent muon conversion in the electric field of a nucleus, $\mu N \rightarrow eN$, is an example process that can probe CLFV. This process has a very clear experimental signature: a monoenergetic electron with energy slightly below the muon rest mass ($\sim 104.96$ MeV).

The Mu2e experiment \(^2\) is designed to improve by 4 orders of magnitude the current limit on the conversion rate, $R_{\mu e}$, set by the SINDRUM II experiment \(^3\). The $R_{\mu e}$ rate is defined as the ratio between the number of electrons from the conversion process and the number of captured muons:

$$R_{\mu e} = \frac{\mu^- N(Z, A) \rightarrow e^- N(Z, A)}{\mu^- N(Z, A) \rightarrow \nu_\mu N(Z - 1, A)} < 6 \times 10^{-17} \text{ (at 90\% C.L.)},$$

(1)

where, in the Mu2e case, $N(Z,A)$ is an aluminum nucleus.

Many NP scenarios, like SUSY, Leptoquarks, Heavy Neutrinos, GUT, Extra Dimensions or Little Higgs, predict significantly enhanced values for $R_{\mu e}$, at a level accessible by the Mu2e sensitivity \(^4\).

A model-independent description of the CLFV transitions, for NP models, is provided by an effective Lagrangian \(^5\) where the different processes are divided in dipole amplitudes and contact-term operators. While the $\mu \rightarrow e\gamma$ decay is mainly sensitive to the dipole amplitude, $\mu \rightarrow e$ conversion and $\mu \rightarrow 3e$ receive contributions also from the contact interactions. It is possible to parametrise the interpolation between the two amplitudes by means of two parameters \(^5\): $\Lambda$, which sets the mass scale, and $\kappa$, which governs the ratio of the four-fermion to the dipole amplitude. For $\kappa \ll 1(\gg 1)$ the dipole-type (contact) operator dominates. Figure 1 summarises the power of different searches to explore this parameter space \(^6\).

Present experimental limits already excluded the energy scale up to $\Lambda < 700$ TeV, setting serious constraints on SM extensions. The interpretation of a eventual direct observation of NP at LHC will have to take into account precise measurements (or constraints) from MEG \(^7\) and Mu2e: the comparison between these determinations will help pin down the underlying theory.

2 The Mu2e experimental apparatus

The Mu2e apparatus consists of three superconductive solenoid magnets, as shown in Figure 2.

In the Production Solenoid (PS) a 8 GeV proton beam provided by the Fermilab accelerator enters the PS and hits a tungsten target producing mostly pions. The gradient field in the PS increases from 2.5 to 4.6 T in the same direction of the incoming beam and opposite to the outgoing muon beam direction. This gradient field works as a magnetic lens to focus charged particles into the transport channel. The focused beam is constituted by muons, pions and a small number of protons and antiprotons. When the beam passes through the S-shaped Transport Solenoid (TS), low momentum negative charged particles are selected and delivered to the aluminum stopping target foils in the Detector Solenoid (DS). Electrons from the $\mu$-conversion (CE) in the stopping target are captured by the magnetic field in the DS and transported through the Straw Tube Tracker, which reconstructs the CE trajectory and its momentum. The CE then impinges the Electromagnetic Calorimeter, which provides independent measurements of energy, impact time and position. Both detectors operate in a $10^{-4}$ Torr vacuum and in an uniform 1 T
Figure 1: Sensitivity of $\mu \rightarrow e\gamma$, $\mu \rightarrow e$ transition and $\mu \rightarrow 3e$ to the scale of new physics $\Lambda$ as a function of the parameter $\kappa$. The shaded areas are excluded by the present limits.

axial field.

A Cosmic Ray Veto (CRV) system covers the entire DS and half of the TS. The measurement of the total number of captured muons is provided by a high purity germanium detector, via the observation of the X-rays resulting from the nuclear capture.

To reach the sensitivity goal $R_{\mu e} < 8.4 \times 10^{-17}$ at 90% C.L., about $10^{20}$ protons on target are needed; this corresponds to about $10^{18}$ stopped muons are needed. Moreover a pulsed beam structure is needed to suppress the prompt background coming from the proton interactions; Fermilab accelerator complex provides a sequence of 200 ns wide micro-bunches separated by 1.7 $\mu$s. The beam period is roughly twice the muon mean lifetime in Al nucleus, $\tau_{Al} = 864$ ns. This particular beam structure, as shown in Figure 3, allows Mu2e to use a delayed selection windows.

3 Mu2e Detectors

3.1 Tracker

The Mu2e tracker will measure the electron trajectory in order to calculate their momentum. The main aims of Mu2e tracker are: i) minimize multiple Coulomb scattering and energy loss to obtain a good momentum resolution, ii) provide sufficient numbers of hits to find and fit tracks with high efficiency, iii) have segmentation and/or multi-hit capability to operate at the expected rates, iv) provide redundancy to protect against mis-reconstructions and non-Gaussian tails.

The tracker total length is $\sim 3$ m and its diameter is 1.6 m; its active area’s radius extends from 40 to 70 cm, so that, as shown in Figure 4, particles with a very low momentum do not reach at all the active
Figure 2: *Layout of the Mu2e experiment.*

Figure 3: *The Mu2e spill cycle for the proton on target pulse (POT) and the delayed selection window that allows an effective elimination of the background from RPC*

area or just leave too few hits for a track to be reconstructed. The detector is made of 20736 drift straw tubes placed transverse to the axis of the DS. Current choice for drift gas is 80:20 Argon: CO₂.

Groups of 96 straws are assembled into panels, 6 panels (three per side rotated by 120°) are assembled into planes. A pair of planes made a station, each station is separated by 46 mm. This two planes are identical but the second plane is rotated of 180° around the vertical axis with respect to the first plane. The Mu2e experiment is composed of 18 stations.

Figure 4: *Left: longitudinal view of the Mu2e tracker. Right: Cross view of Mu2e tracker with trajectories of a 105 MeV/c momentum conversion electron (green circle), 53 MeV/c Michel electron (bottom right circle) and electron with energy small than 53 MeV (bottom left circle).*
3.2 Calorimeter

The Mu2e calorimeter\(^8\) must operate in a high-rate, high-radiation environment. This motivates a fast response, an excellent time resolution and good radiation hardness requirements. The Mu2e calorimeter has to: i) provide the means to implement an independent trigger based on the sum and pattern of energy deposition; ii) provide a “seed” to improve tracker pattern recognition and reconstruction efficiency; iii) provide shower shape, energy, and timing information that, in combination with information from the tracker, can distinguish electrons from muons and pions; iv) have large acceptance for signal electrons within the acceptance of the tracker. After a long R&D phase, the best compromise between costs and properties has been selected: the calorimeter design consists in 1346 undoped CsI crystals located downstream of the tracker, arranged in two disks and positioned at a distance of half wavelength of a typical conversion electron (Figure 5).

![Figure 5: CAD model of the Mu2e electromagnetic calorimeter.](image)

The crystals have squared faces with dimensions of \((34 \times 34)\) mm\(^2\) and are 200 mm long. Each crystal is read by two \(2 \times 3\) array of individual \(6 \times 6\) mm\(^2\) UV-extended Silicon Photomultipliers (SiPMs). The solid-state photodetectors are necessary due to the presence of the high magnetic field. FEE, HV, slow controls and digitizer electronics are mounted behind each disk and must then work adequately in a high vacuum (to reduce multiple scattering), high magnetic field and high radiation environment. Equalization of the crystal response will be provided through a circulating radioactive source (Fluorinert\(^\text{TM}\), C8F18), already experimented by the BaBar EMC\(^9\) while a laser flasher system will be used for relative calibration and gain monitoring. Usage of cosmic ray events for the calibration along running is also planned.

3.3 Cosmic Ray Veto (CRV)

Cosmic muons are one of the major sources of background for the Mu2e experiment: they can produce 105 MeV electrons through interaction with the apparatus or with a decay-in-flight.

The CRV system provides both a passive shielding (thick layer of concrete surrounding the DS) and an active veto, with a system of four layers of long scintillator strips, with an aluminum layer between them, covering all the DS and the last part of the TS (Figure 6). The strips are 2 cm thick, providing ample light yield to allow a low enough light threshold to be set to suppress most of the backgrounds.
Figure 6: *Left:* 3D view of the cosmic ray veto. *Right:* detail of a single CRV module with 4 scintillator strips.

<table>
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<tr>
<th>Category</th>
<th>Background process</th>
<th>Estimated Yield (events)</th>
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<tbody>
<tr>
<td>Intrinsic</td>
<td>Decay in orbit (DIO)</td>
<td>$0.199 \pm 0.092$</td>
</tr>
<tr>
<td></td>
<td>Muon Capture (RMC)</td>
<td>$0.000 \pm 0.004$</td>
</tr>
<tr>
<td>Late Arriving</td>
<td>Pion Capture (RPC)</td>
<td>$0.023 \pm 0.006$</td>
</tr>
<tr>
<td></td>
<td>Muon decay in flight</td>
<td>$&lt; 0.003$</td>
</tr>
<tr>
<td></td>
<td>Pion decay in flight</td>
<td>$0.001 \pm 0.001$</td>
</tr>
<tr>
<td></td>
<td>Beam electrons</td>
<td>$0.003 \pm 0.001$</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>Antiproton induced</td>
<td>$0.047 \pm 0.024$</td>
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<tr>
<td></td>
<td>Cosmic rays</td>
<td>$0.092 \pm 0.020$</td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td><strong>$0.37 \pm 0.10$</strong></td>
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Table 1: *Expected background list as evaluated by full simulation.*

Aluminum absorbers between the layers are designed to suppress punch through from electrons. The scintillation light is then captured by optical fibers and then read out by means of SiPMs.

4 Expected background

When negative muons stop in the aluminum target, they are captured in an atomic excited state. The resultant muonic atoms persist with a lifetime of 864 ns, decaying in orbit (DIO) 39% of the time while capturing on the nucleus the other 61% of the time. Low-energy photons, neutrons and protons are emitted in the nuclear capture process and constitute an environmental background that produces an ionization dose and a neutron fluency on the detection systems as well as an accidental occupancy for the reconstruction program. The kinematic limit for the muon decay in vacuum is at about 54 MeV, but the nucleus recoil generates a long tail that has the endpoint exactly at the conversion electron energy. For this reason, DIO electrons are an irreducible background that have to be distinguished by the mono-energetic CE. The finite tracking resolution and the positive reconstruction tail has a large effect on the falling spectrum of the DIO background that translates in a residual contamination in the signal region. Estimates of other backgrounds are presented in Table 1 for a total background contribution of 0.37 events.

5 Conversion Electron reconstruction

At the CE energy the momentum resolution is dominated by fluctuations in the energy loss in the target, multiple scattering and bremsstrahlung in the tracker. By performing a full simulation of the tracker, a pattern recognition and a Kalman fitter for the tracking we obtain: a CE reconstruction efficiency of 9% for good quality tracks and at least 25 hits/track. The resolution is well parametrised by a Crystal Ball
function with a negative bremsstahlung tail, a Gaussian core of 116 keV and a long exponential positive resolution tail.

Figure 7 shows the signal and background distributions as seen by a full simulation of the experiment (pileup included) in the following conditions: (i) $3.6 \times 10^{20}$ proton on target, (ii) $6 \times 10^{17}$ stopped muons and (iii) a $R_{\mu e}$ of $10^{-16}$. After maximising signal over background, the best selection corresponds to counting events in a momentum window between 103.75 and 105 MeV/c. A DIO contribution of 0.199 events is estimated and 3.5 candidates are observed. This counting corresponds to setting a limit on $R_{\mu e}$ below $6 \times 10^{-17}$ at 90 % C.L., in good agreement with the experimental goal.

![Figure 7: Full simulation of DIO and CE events for an assumed $R_{\mu e}$ of $10^{-16}$.](image-url)

References

3. W. Bertl et al.; A search for $\mu - e$ conversion in muonic gold, The European Physical Journal C - Particles and Fields 47(2)2006 337-346
7. A.M. Baldini et al; Search for the lepton flavour violating decay $\mu^+ \rightarrow e^+\gamma$ with the full dataset of the MEG experiment. The European Physical Journal C, 2016, Volume 76, Number 8, Page 1