$\mu \to e$ conversion and the Mu2e experiment at Fermilab

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The Mu2e experiment aims to measure the charged-lepton flavour violating (CLFV) neutrinoless conversion of a negative muon into an electron in the field of a nucleus. The conversion process results in a monochromatic electron with an energy slightly below the muon rest mass (104.97 MeV). The goal of the experiment is to improve by four orders of magnitude the previous measurement and reach a single event sensitivity of 3×10^{-17}on the conversion rate with respect to the muon capture rate.
Although the SM is very well tested in many regimes, it is incomplete. In many of Beyond the Standard Model (BSM) scenarios, rates for CLFV processes are within the reach of the next generation of experiments. In particular, if SUSY particles have masses and couplings within the discovery reach of the LHC, CLFV rates may be observable at the next generation experiment. On the contrary, many CLFV searches have a sensitivity to new physics that exceeds the LHC reach bringing the reach of new mass scale up to 10^4 TeV. In this contest indirected measurements of CLFV will be crucial evidence of new physics. The experiment will use a very intense pulsed negative muon beam directed onto an Aluminium target for a total number of 10^{18} stopped muons in three years of running. Production and transport of the muons is accomplished with a complicated and sophisticated magnetic systems composed of a production, a transport and a detector solenoid, hosting a straw-tube tracker and a crystal calorimeter. The entire detector region is surrounded by a Cosmic Ray Veto system. Mu2e is under design and construction at the Muon Campus of Fermilab. In the current schedule, the installation phase will start in 2021, the commisioning in 2022 and the data taking will start in 2023.

European Physical Society Conference on High Energy Physics - EPS-HEP2019 -
10-17 July, 2019
Ghent, Belgium

*Speaker.

†This work was supported by the US Department of Energy; the Italian Istituto Nazionale di Fisica Nucleare; the US National Science Foundation; the Ministry of Education and Science of the Russian Federation; the Thousand Talents Plan of China; the Helmholtz Association of Germany; and the EU Horizon 2020 Research and Innovation Program under the Marie Sklodowska-Curie Grant Agreement No.690385. Fermilab is operated by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the US Department of Energy.

PoS(EPS-HEP2019)232

1. Charged Lepton Flavor Violation (CLFV) and muon to electron conversion

Charged Lepton Flavor Violation processes are forbidden in the Standard Model with massless neutrinos. Neutrino oscillations, in its minimal extention yield, predicted branching ratios in the muon sector smaller than 10^{-50}, unreachable by the current particle accelerators [4].
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, $\mu N \to eN$, is a 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 [1] [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].
$R_{\mu e}$ is defined as the ratio between the number of electrons from the conversion process and the number of captured muons:

$$R_{\mu e} = \frac{\mu^{-}\,{}^{27}Al \to e^{-}\,{}^{27}Al}{\mu^{-}\,{}^{27}Al \to \nu_{\mu}\,{}^{27}Mg} < 8 \times 10^{-17} \text{ (at 90\% C.L.)}, \tag{1.1}$$

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].

2. The Mu2e experimental apparatus

The Mu2e apparatus consists of three superconducting solenoid magnets, as shown in Figure 1. In the Production Solenoid (PS) a 8 GeV proton beam provided by the Fermilab accelerator hits a

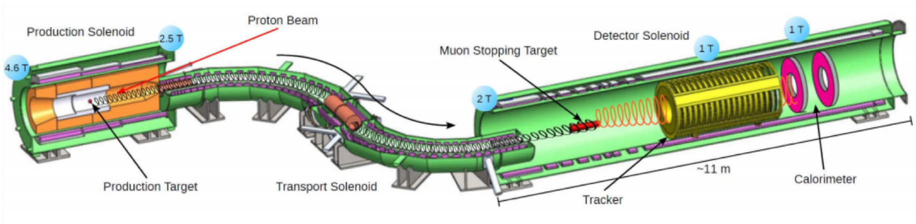

Figure 1: *Layout of the Mu2e experiment.*

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 of 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 μ-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 passes into the Electromagnetic Calorimeter, which provides independent measurements of energy, impact time and position. Both detectors operate in a 10^{-4}

Torr vacuum and in a uniform 1 T axial field.
A Cosmic Ray Veto (CRV) system covers the entire DS and half of the TS.
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. Moreover a pulsed beam structure is needed to suppress the prompt background coming from proton interactions.

3. Mu2e Detectors

3.1 Tracker

The Mu2e tracker will measure the electron trajectory in order to calculate its 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 2, particles with a very low momentum do not reach the active area or leave too few hits for a track to be reconstructed. The detector is made of 20736 drift straw

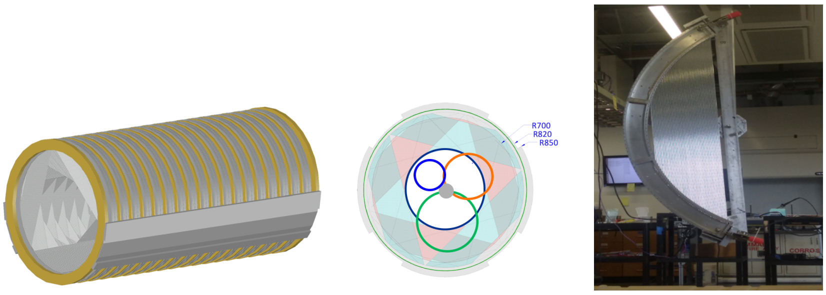

Figure 2: *Left: longitudinal view of the Mu2e tracker. Center: Cross view of Mu2e tracker with trajectories of a 105 MeV/c momentum conversion electron (green circle), 53 MeV/c Michel electron (bottom right circle) and electron with energy small than 53 MeV (bottom left circle). Right: A production panel during its assembly.*

tubes (with 5 μm diameter and 15 μm mylar thickness tubes, each with a 25 μm tungsten wire) placed transverse to the axis of the DS. The current choice for drift gas is 80:20 Argon: CO_2 .
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 180° around the vertical axis with respect to the first plane. The Mu2e experiment is composed of 18 stations.
At the moment of writing 15 panels have already been assembled (see Figure2 right). The panel production is expected to be completed in May 2020. First tests of the assembled modules are undergoing with cosmic rays and a good agreement between experimental data and MC has been shown.

3.2 Calorimeter

The main role of the Mu2e calorimeter is particle identification. The Mu2e calorimeter[8] must operate in a high-rate, high-radiation environment. This requires a fast response, excellent time resolution and good radiation hardness requirements. The Mu2e calorimeter has to: i)provide shower shape, energy, and timing information that, in combination with information from the tracker, can distinguish electrons from muons and pions; ii) provide a "seed" to improve tracker pattern recognition and reconstruction efficiency; iii) provide the means to implement an independent trigger based on the sum and pattern of energy deposition; 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 wavelenght of a typical conversion electron (Figure 3). The crystals have square faces with dimensions

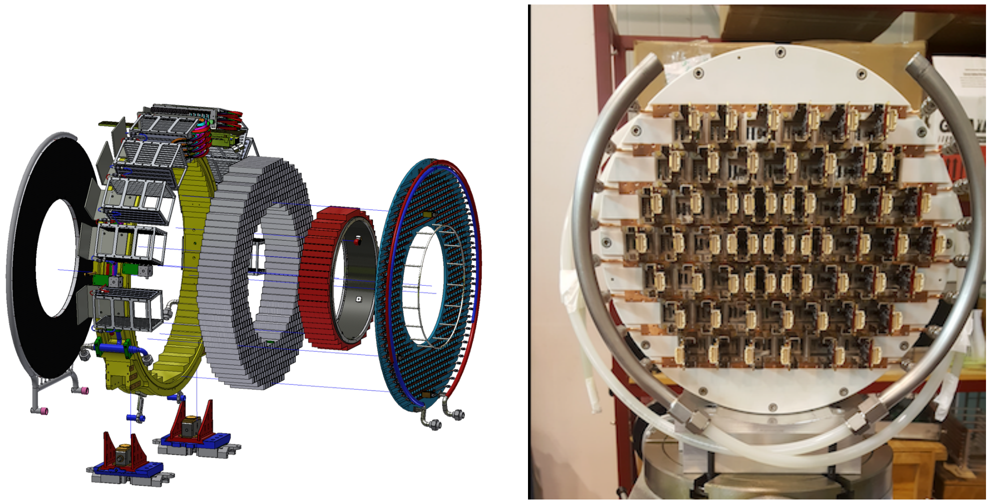

Figure 3: *Left:CAD model of the Mu2e electromagnetic calorimeter. Right: back view of the large size prototype tested in 2017 at the BTF facility of the National Laboratories of Frascati*

of (34×34) mm^2 and are 200 mm long. Each crystal is read by two 2×3 array of individual 6×6 mm ^{2} UV-extended Silicon Photomultipliers (SiPMs). 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.
A measurement of the crystal response will be provided using a circulating radioactive source (FluorinertTM, C8F18), already experimented by the BaBar EMC [9] while a laser flasher system will be used for relative calibration and gain monitoring. Cosmic ray events will be used for calibration along the running period. In 2017 a Test Beam with electrons was performed at the Beam Test Facility of the National Laboratories of Frascati obtaining very good results in terms of energy and time resolution. At the beginning of 2018 the production of crystals and SiPMs began; in May 2019 all the SiPMs were tested and the crystal production is expected to finish by the end of 2019. During the fall 2019 SiPMs will be glued on the electronic FEE. The assembly of the first disk of the calorimeter is expected to be completed by the beginning of the summer 2020.

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 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 4). The strips are 2 cm thick,

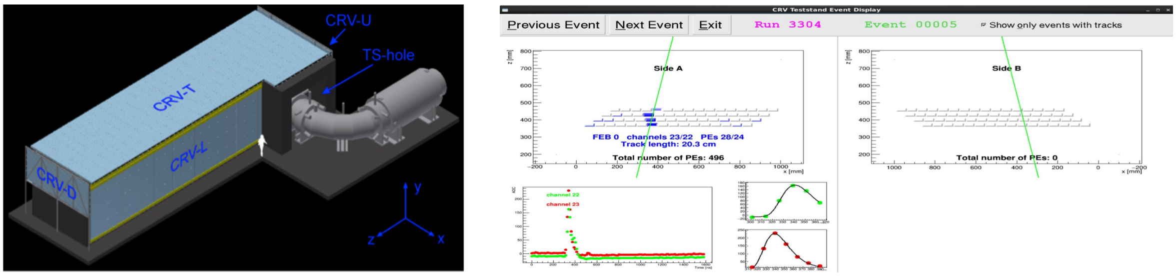

Figure 4: *Left: 3D view of the of the cosmic ray veto. Right: Example of the screen of the first CRV modules tested with cosmic rays*

providing ample light yield to allow a low enough light threshold to be set to suppress most of the backgrounds. Aluminum absorbers between the layers are designed to suppress punch through from electrons. The scintillation light is then captured by WLS optical fibers and then read out by means of SiPMs. The module production started during the summer 2018 and one year later half of the production was completed and is now under test acquiring cosmic ray events

4. Expected background

When negative muons stop in the aluminum target, they are captured in an atomic excited state. The resultant muonic atoms decay 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 fluence on the detection systems as well as an accidental occupancy for the reconstruction program.

The kinematic limit for the muon decay is 52.8 MeV, but in a bound state nuclear recoil generates a long tail that has the endpoint exactly at the conversion electron energy. 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.

Category	Background process	Estimated Yield (events)
Intrinsic	Decay in orbit (DIO)	0.144 ± 0.028
	Muon Capture (RMC)	0.000 ± 0.004
Late Arriving	Pion Capture (RPC)	0.021 ± 0.003
	Muon decay in flight	< 0.003
	Pion decay in flight	$0.001 \pm < 0.001$
	Beam electrons	$(2.1 \pm 1.0) \times 10^{-4}$
Miscellaneous	Antiproton induced	0.040 ± 0.024
	Cosmic rays	0.209 ± 0.022
	Total	0.41 ± 0.13

Table 1: *Expected background list as evaluated by full simulation.*

Figure 5 shows the signal and background distributions as seen by a full simulation of the experiment in the following conditions: (i) 3.6×10^{20} proton on target, (ii) 6×10^{17} stopped muons and (iii) a $R_{\mu e}$ of 2×10^{-16}. After maximising signal over background, the best selection corresponds to counting events in a momentum window between 103.75 and 105 MeV/c. The expected signal events in this region are 7.2 . This counting corresponds to setting a limit on $R_{\mu e}$ below $8\times\ 10^{-17}$ at 90 % C.L., in good agreement with the experimental goal.

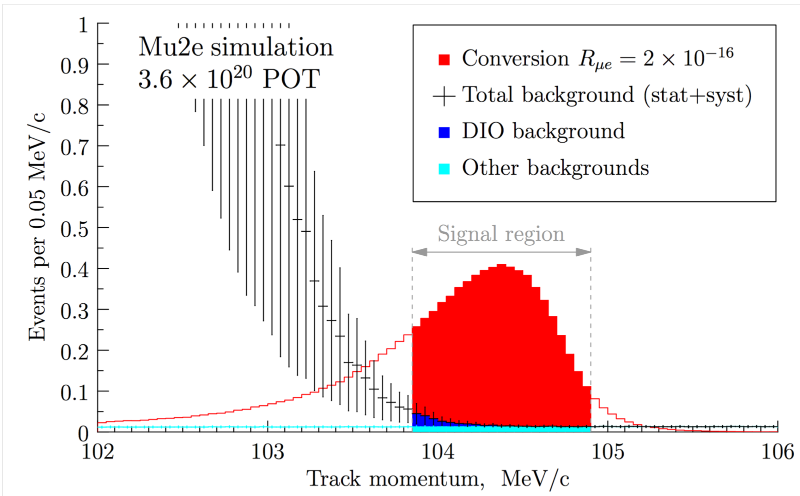

Figure 5: *Full simulation of DIO and CE events for an assumed $R_{\mu e}$ of 2×10^{-16}.*

References

[1] L. Bartoszek, et al., Mu2e Technical Design Report [arXiv:1501.05241]

[2] R. Bernstein.The Mu2e Experiment. Front. Phys., 28 January 2019 | https://doi.org/10.3389/fphy.2019.00001 [arXiv:1901.11099]

[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

[4] Marciano, Mori, and Roney, Flavour physics of leptons and dipole moments, Ann. Rev. Nucl. Sci. 58 ;doi:58.110707.171126 2008 [arXiv:0801.1826]

[5] A. De Gouvea et al. Lepton Flavor and Number Conservation, and Physics Beyond the Standard Model; Prog. Part. Nucl. Phys 71,75-92 doi:10.1016/j.ppnp.2013.03.006, 2013 [arXiv:1303.4097]

[6] R. Bernstein and P. Cooper, Charged Lepton Flavor Violation: An Experimenter's Guide, FERMILAB-PUB-13-259-PPD,doi:10.1016/j.physrep.2013.07.002 2013[arXiv:1307.5787]

[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

[8] N. Atanov et al; The Mu2e undoped CsI crystal calorimeter; JINST 13 (2018) C02037 [arXiv:1801.02237]

[9] J.M. Bauer; The BaBar Electromagnetic Calorimeter: Status and Performance Improvements; IEEENucl.Sci.Symp.Conf.Rec.2:1038-1042, 2006 [arXiv:physics/0601138]

[10] BTF website `http://www.lnf.infn.it/acceleratori/btf`