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Charged Lepton Flavour Violation: experimental activities

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Charged lepton flavour violation processes are powerful probes to investigate new physics beyond the standard model of particle physics. There are several ongoing activities and future projects. All of them are going to achieve the levels of sensitivity which are able to explore many new physics scenarios, corresponding to higher energy scale than that is directly accessible with present particle colliders. This paper introduces the recent and present experimental efforts in this area of searches, especially focusing on MEG, MEG2, Mu3e, Mu2e and COMET.

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1. Introduction

In the standard model of particle physics (SM) with a minimal neutrino oscillation extension, rates of charged lepton flavour violating (CLFV) processes are strongly suppressed. For instance, the branching fraction of the $\mu \to e\gamma$ decay is calculated to be an $O(10^{-54})$ [1]. On the other hand, many new physics models predict significant enhancement in such processes. There are different CLFV modes and each of them is sensitive to different new physics scenarios [2, 3]. For example, the $\mu \to e\gamma$ decay is more sensitive to the radiative process with a loop, compared to the $\mu \to eee$ decay which is more sensitive to the four fermion contact processes. If any of them are discovered, others should also occur within similar orders of magnitude. And the difference of the branching fractions can provide the detailed new physics mechanism. Therefore, CLFV searches are powerful tools to test the new physics beyond the SM. The theoretical predictions can be made extremely precisely, especially for muon CLFV processes, because they do not include any hadronic products in their final states. Besides, there are several facilities that are capable to provide the high intensity muons thanks to the progress in accelerator technologies. Those motivate to improve the sensitivities in searching for the muon CLFV modes, especially for following three simplest modes, called muon CLFV golden channels; $\mu \to e\gamma$, $\mu \to eee$ and $\mu N \to eN$. In this paper, the recent experimental projects, which are searching for above golden channels, will be reviewed.

2. $\mu \to e\gamma$ decay searches

The $\mu \to e\gamma$ decay is one of the golden channels as above mentioned in which a muon decays into an electron and a gamma-ray. The search is generally done by using positive muons to avoid the capture process by nuclei. Since the $\mu \to e\gamma$ is a two body decay, the electron and the gamma-ray carry the same amount of energy, $M_\mu/2 \approx 52.8$ MeV, back-to-back at the muon rest frame. In the SM, a positive muon can also decay as $\mu^+ \to e^+\nu_e\bar{\nu}_\mu\gamma$; this is called a Radiative Muon Decay (RMD), and an intrinsic background of the $\mu^+ \to e^+\gamma$ decay. In the RMD, the visible total energy, $E_e + E_\gamma$, should be less than M_μ because of the missing energy carried by two accompanying neutrinos. Hence, the RMD background can be strongly suppressed by the precise energy and opening angle measurement of the gamma-ray and the positron. The other background is caused by an accidental overlap of the e^+ from the SM decay of muon ($\mu^+ \to e^+\nu_e\bar{\nu}_\mu$; also know as a Michel decay) and a gamma-ray from either RMD or e^+ annihilation in flight (AIF). Since this is an accidental process, the relative timing and opening angle of two particles are uniformly distribute, while the signal event must happen simultaneously with $\Theta_{e\gamma} = 180^{\rm o}$. The most stringent upper limit on the $\mu \to e\gamma$ decay is set by the MEG (Muon to Electron Gamma) experiment [4]. The details of the MEG experiment are described in the following section.

2.1 The MEG experiment

The MEG experiment collected data during 2008–2013 using the direct current (DC) muon beam at πE5 beamline in Paul Scherrer Institut (PSI), Switzerland. In MEG, muons are stopped by the thin plastic target located inside the super conducting magnet with the stopping rate of 3×10^7 μ^+/sec. The magnet provides specially graded magnetic field in order to quickly sweep out low momentum charged particles while making the radius of the signal like positrons constant

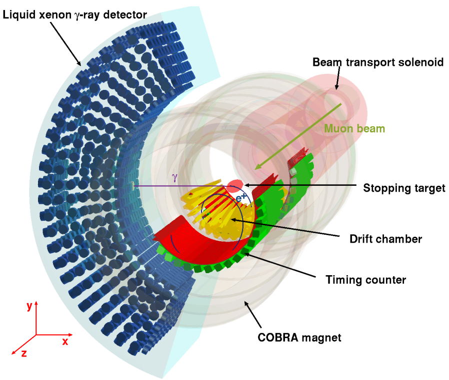

Figure 1: MEG detector apparatus

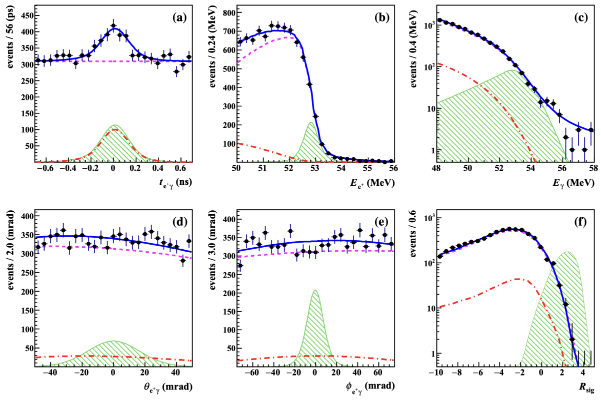

Figure 2: The distributions of the best fitted likelihood function and R_sig together with those of the full MEG data [4].

independent on their transverse momentum, therefore, it is called the COBRA (COnstant Bending RAdius) magnet. The detector system consists of the gamma-ray calorimeter and the positron spectrometer. The positron momentum is measured by ultra-light 16 drift chamber (DCH) modules radially surrounding the muon stopping target inside the COBRA magnet. Since the multiple scattering effect dominates the momentum resolution of the e^+ reconstruction, each DCH module was constructed based on 12.5 μm thin wall with the open arm light frame, filled with helium based gas mixture. The timing of the positrons is measured by the longitudinal scintillation counter bars placed at both ends of the drift chambers and scintillation lights are read by photo multiplier tubes (PMTs) attached at both ends of the each counter.

The single body, C-shaped calorimeter was filled with 900 l liquid xenon, and the scintillation light was read by 846 two-inch, VUV (vacuum ultra violet) sensitive PMTs. The experiment has published the final result in 2016. No excess events were observed in the data, and the upper limit was set as 4.2×10^{-13} at 90% C.L. [4].

2.2 The MEG 2 experiment

The MEG 2 experiment is an upgrade of the MEG experiment, aiming to improve the previous result by a factor 10 [5]. The experiment has improved the rate capability, detector resolutions and signal acceptance while keeping the same COBRA magnet and the muon beam line for the early and cost-effective realisation. For the e^+ reconstruction, the DCH was replaced with a single-body cylindrical drift chamber (CDCH), and the timing counter bars were substituted with a finer segmented 2-d tiles read by SiPMs. In addition, an additional detector called Radiative Decay Counter (RDC) has been newly introduced to identify the low momentum e^+ produced in RMD by taking a coincidence with a high energy gamma-ray in LXe. This significantly reduces the background γ rays induced by the RMD. Thanks for those improvements also summarised in Figure 3, the detector system is capable of handling the higher muon rate up to $7 \times 10^8 \mu^+$/s.

The experiment has already started the physics data taking since 2020 with a lower beam rate up to $4 \times 10^8 \mu^+$/s. The expected sensitivity is calculated to be 6×10^{-14} in the 90% C.L. upper limit under the null signal hypothesis with another few years of data taking, which is one order of magnitude better than the current one as shown in Figure 4. The experiment recently published the new result from the data taken in the first physics run in 2021 [6]. No excess was observed, and the

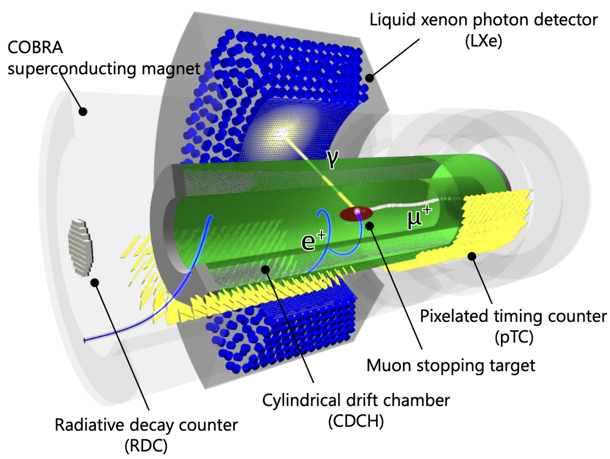

Figure 3: MEG 2 detector apparatus.

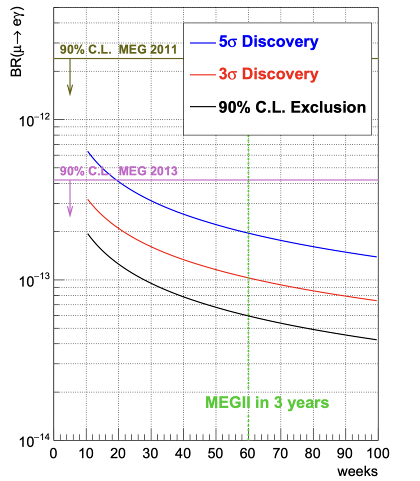

Figure 4: The expected sensitivity curve in MEG 2.

upper limit was calculated to be $B(\mu \to e\gamma) < 3.1 \times 10^{-13}$ (90% C.L.) by combining with the final MEG result.

3. $\mu \to eee$ decay searches

The $\mu \to eee$ decay is also a CLFV process which is sensitive to different BSM models/parameters. At the rest frame, total energy must equal to M_μ with $\Sigma p = 0$. An intrinsic background of the $\mu \to e\gamma$ decay is caused by RMD in which the photon internally convert to the electron-positron pair; $\mu^+ \to e^+e^+e^-\nu_e\overline{\nu}_\mu$. Due to the missing energy carried away by neutrinos, this background can be suppressed by requiring the total energy to be M_μ and the total momentum to be closer to zero. The background is caused by a Michel decay positron combined with accidentally overlapping e^+e^- pairs caused by either Bhabha scattering or gamma-rays from RMD, or charge misidentified Michel positrons.

Current upper bound is set to 1.0×10^{-12} at 90% C.L. by SINDRUM [7] in 1988. There is an experiment, called a Mu3e experiment [8], which is going to improve the sensitivity by several orders of magnitude. The details will be discussed in the following section.

3.1 The Mu3e experiment

The Mu3e experiment aims to search for the $\mu^+ \to e^+e^+e^-$ decay at the single event sensitivity of 10^{-16}, which is 10,000 times better than the current bound. The concept of the experiment is similar to that of MEG; both need to suppress the accidental backgrounds while requiring the high intensity muon beam. Thus, the Mu3e experiment will utilise the πE5 beamline at PSI as well. Compared to MEG, the vertex constraints are much more powerful in Mu3e due to containing all three charged particles inside the tracking volume. As shown in Figure 5, the $\mu \to eee$ search is done in Mu3e by using 50 μm-thick silicon pixel tracker surrounding the double hollow cone muon stopping target with almost 4π coverage, together with the fast timing detector inside the solenoidal magnetic field. This ultra thin silicon tracker is made available by using the cutting edge HV-MAPS (High Voltage Monolithic Active Pixel Sensors) technology. Based on the simulation

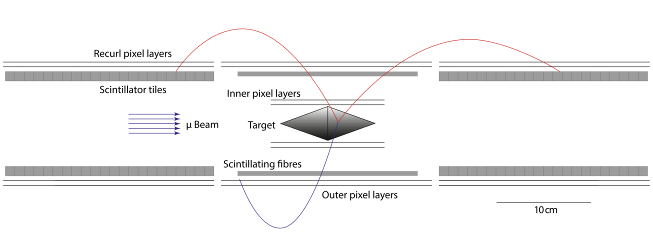

Figure 5: Mu3e experimental apparatus in its phase-I.

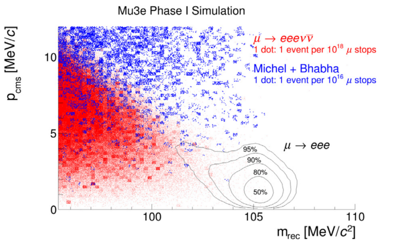

Figure 6: Scatter plot of the simulated backgrounds and signal contours.

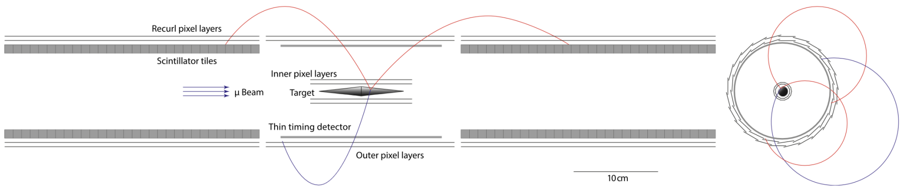

Figure 7: An upgraded Mu3 detectors in phase-II.

and measured detector performance, the momentum sum resolution is calculated to be better than 1 MeV/c, which is sufficient to suppress the backgrounds at the target sensitivity of 10^{-15} in the phase-I measurement. In phase-I, timing will be measured by the three layers of 250 μm scintillating fibre detectors and the outer region scintillator tiles to achieve the timing resolution of 100 ps. The experiment adopted the staging approach, starting with an intermediate sensitivity of 2×10^{-15} with the current πE5 beamline in parallel with the MEG 2 experiment. Then upgrade the detectors and use the 10 times more intense muons that will be available after the beamline upgrade. The details of the upgrade plan have not been fixed yet, however, the several ideas are shown in Figure 7, by extending the outer silicon tracker, smaller target to improve the vertex resolutions, further thin down the silicon tracker, and use a lighter inner timing detector, or measure the timing with new silicon sensor with the better timing resolution. The beamline upgrade called High Intensity Muon Beam (HiMB) has been proposed and already been approved in PSI [9] to build the world's most intense continuous muon beam at the rate of 10^{10} Hz at most.

4. $\mu N \to eN$ process searches

The neutrinoless transition of a muon to an electron conversion in a muonic atom, called a mu-e conversion. is another type of CLFV processes of muons. In comparison with other two muon CLFV modes, the mu-e conversion is more sensitive to the new physics models which include the new interaction between quarks and leptons, such as a Leptoquark, due to having a nucleus field.

The latest upper limit is 3.0×10^{-13} at 90% C.L. set by SINDRUM II [10]. The experiment used the continuous muon beam at PSI, and it was found that there are potential background electrons produced by the decay of pions. Since the decay lifetime of pions is much shorter than that of the muons, next generation experiments adopted the delayed timing window scheme by using the pulsed muon beam. In this scheme, the measurement is performed several hundreds nanoseconds after the main pulse arrival time to avoid almost all decay products of pions. There are three experimental

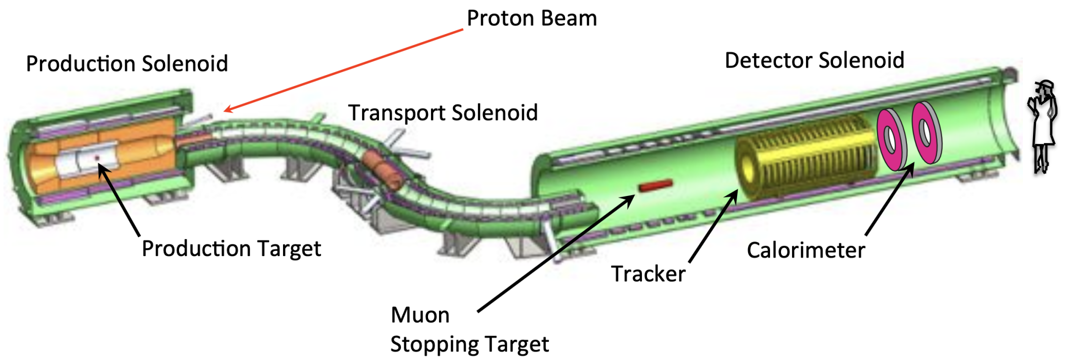

Figure 8: The conception design of the Mu2e experiment [12].

projects aiming to search for the mu-e conversion, DeeMe, Mu2e and COMET. In this paper latter two experiments are introduced while the details of the DeeMe experiment is summarised in [11].

4.1 The Mu2e experiment

The Mu2e experiment searches for the $\mu^- N \to e^- N$ process with the target sensitivity of 10^{-16} at the Fermilab in the US. Figure 8 shows the schematic of the experiment. In the experiment, 8 GeV proton beam is accelerated by the Booster, and two batches for Mu2e are injected into the Recycler Ring (RR) with approximately 1.4 s main injector cycle. The RR transform one batches into four 2.5 MHz bunches with 48 ms intervals, and each bunch is extracted from RR and injected into the Delivery Ring (DR) at once in every bunch period. Individual bunch is kept inside the DR and slowly extracted towards the Mu2e experimental area via the electrostatic septum. One cycle of DR forms the ideal bunch separation time of 1.6 μs. In order to suppress any unwanted beam particles between bunches, an AC dipole magnet is used. After the proton beam delivery, the proton beam is impinged into the tungsten target located at the centre of the Production Solenoid (PS). The pions are produced in p-W interaction and captured in the maximum 4.6 T magnetic field produced by the PS.

Due to the graded field of the PS getting weaker towards backward direction as can be seen in Figure 8, back scattered pions as well as mirrored pions are directed toward the S-shaped Transport Solenoid (TS). This S-shaped TS also has a decreasing field from 2.5 T to 2.0 T from the entrance to exit, and contains the collimator in the middle to reduce the high momentum charged particles above 100 MeV/c, while adjusting the vertical position of low momentum muons at the centre of the TS at the end. After the TS, a series of aluminium disks are at the beginning of the detector solenoid to stop the muon and form the muonic aluminium. The detector system located the downstream of the detector solenoid consists of 36 planes of the straw tube tracker and two sets of the pure CsI electron calorimeter. Both detectors have holes at the centre in order to avoid most of DIO electrons having momentum less than 70 MeV/c. To suppress the background induced by the cosmic ray muons, entire detector solenoid as well as the second part of TS are fully covered by the cosmic ray veto detector which is composed of the staggered four layers of plastic scintillation bars read by wavelength shifting fibres and silicon SiPMs. The magnet components are almost ready and the detector construction and assembly are underway to start the Run-I data taking in

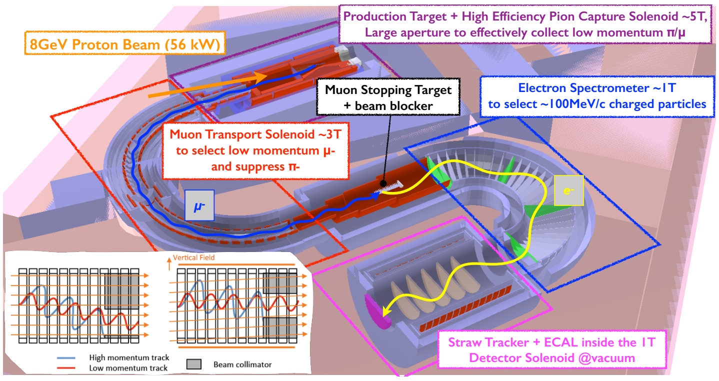

Figure 9: The experimental apparatus for the COMET Phase-II experiment.

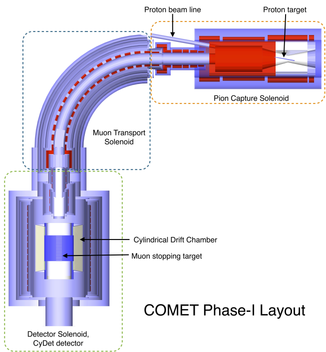

Figure 10: Layout of the COMET Phase-I.

2026, before the accelerator long shutdown, followed by the main physics data taking (Run-II) after the shutdown. With the Run-I data, Mu2e is expected to give a three orders of magnitude better sensitivity compared to the current best limit with a 5σ discovery sensitivity of 1.2×10^{-15}, while the Run-II is expected to improve the sensitivity by another order of magnitude.

4.2 The COMET experiment

The COMET experiment will utilise the 8 GeV proton beam provided by the main ring synchrotron (MR) accelerator of J-PARC (Japan Proton Accelerator Complex) in Japan. The nominal bunch separation at the MR is $\approx$600 ns in the MR with nine buckets structure. To make the bunch intervals longer than the lifetime of muons in muonic aluminium, only one of two buckets in the rapid cycle synchrotron will be filled in the COMET beam operation, and injected into the MR with 180^{o} shifted kicker timing to completely block the empty bucket which may include residual protons. The beam in the MR is slowly extracted towards the hadron experiments facility where the COMET hall locates. The experimental concept of COMET is similar to the Mu2e's one, however, there are few difference as follows; (1) C-shaped muon transport solenoid with additional dipole field to optimise the vertical position of low momentum muons. (2) C-shaped electron spectrometer after the muon stopping target to filter the low momentum DIO electrons. (3) Two stage approach to conduct the intermediate physics measurement and the beam measurement at the end of the first 90^{o} of curved TS. In Phase-I, the physics measurement will be done by using the Cylindrical Detector surrounding the muon stopping target as shown in Figure 10, to prevent remaining beam particles and the majority of DIO electrons less than 70 MeV/c [13]. The Phase-I program also includes the beam background measurement by using the straw tube trackers and LYSO electron calorimeter, which are the prototype detectors of the Phase-II physics measurement.

The preparations for the COMET Phase-I experiment is ongoing and the data taking is expected to start in the coming few years. The detailed simulation study based on the measured performance of detectors has demonstrated that an expected single event sensitivity is to be 3×10^{-15} with 150 days of the data acquisition time, which is 100 times better than the present upper limit. For Phase-II, simulation and detector R&Ds are still ongoing. The latest study has shown that a single event sensitivity of $O(10^{-17})$ is achievable with possible improvements [14].

5. Summary

In the field of muon CLFV, there are several complementary searches ongoing. Recently, the MEG 2 experiment has begun the physics data taking and the sensitivity is expected to be improved their previous result in MEG by an order of magnitude thanks to their detector improvement in everywhere. At PSI, the Mu3e experiment is being prepared for the first physics measurement in coming years at the same beam line, πE5, to conduct the $\mu \to eee$ search with 1,000 times better sensitivity than the current upper limit. After the upgrade of the muon beam line, the Mu3e phase-II has already been planned with another order of magnitude better sensitivity by improving the detector apparatus. In searching for a muon to electron conversion, there are two major experiments, Mu2e and COMET, are going to start the data taking in a few years with the sensitivity improvements by 2–3 orders of magnitude. In conclusion, many new results are expected in a coming decade in this area.

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