Status and perspectives of Lepton Flavour Violation experiments with muons.

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Abstract. Lepton Flavour Violation effects are predicted in several extensions of the Standard Model at a measurable level. Since the Standard Model background, even including ν oscillations and mixing, is completely negligible, the observation of such effects would be a strong evidence for New Physics beyond the Standard Model, while a non observation with high precision experiments would put severe constraints on possible Standard Model extensions. In this talk I review the present status and the future perspectives of the Lepton Flavour Violation experiments involving μ’s and discuss the sensitivity improvements which could be obtained from new high intensity machines coupled with high resolution detectors.

1. Generalities
In the minimal Standard Model of particle physics, processes where the leptonic flavour is not conserved are not allowed, while if ν oscillations and mixing effects are included in the model such processes become possible, but at an extremely low rate (∼ 10^{-54}) [1]. On the other hand, Standard Model extensions within supersymmetric and grand unified schemes predict the possibility of charged Lepton Flavour Violating processes at a measurable level: for example the predicted rate of μ → eγ decay is ∼ 10^{-(12\div15)} with respect to the standard μ decay μ → eνν̅ ([2], [3] and references therein). Since the Standard Model background is negligible, the observation of a Lepton Flavour Violation process would be a clear evidence for New Physics, while a non observation in high sensitivity experiments would constitute a strong constraint for several New Physics theories. In the search for Lepton Flavour Violation μ’s are a very sensitive tool, since high intensity μ beams can be obtained at meson factories or high energy accelerators, the μ life time (2.2 μs) is much higher than that of all other unstable particles and the final states of reactions involving μ’s are simple and easy to detect. The main Lepton Flavour Violation processes involving μ’s are μ anomalous decays (μ → eγ and μ → eee) and μ to e conversion (μ → e) in a nuclear field. In many models these reactions are related to other New Physics processes, like τ anomalous decays, μ magnetic anomaly, lepton universality violation etc. [3], [4]. Note that different types of experiments are sensitive to different regions of the New Physics parameter space; then, a network of experiments based on independent approaches is crucial for Lepton Flavour Violation physics. The search for Lepton Flavour Violation with μ’s dates back by more than 70 years and in this time interval the sensitivity improved by 12 orders of magnitude as shown in figure 1. This search marked important milestones in the history of particle physics, such as the presence of two different ν’s, the existence of leptonic families and doublets and the leptonic number symmetry. Several reviews of Lepton Flavour Violation searches can be found in literature; see for instance [3].

1 On behalf of the MEG II Collaboration
2. The historical channel: $\mu^+ \rightarrow e^+\gamma$

In this process a $\mu^+$ (chosen to avoid the nuclear capture of negative $\mu^-$) is stopped in matter and decays emitting a $e^+$ and a $\gamma$, simultaneously and back-to-back, both with energy equal to half of the $\mu$ mass: $E = m_\mu/2 = 52.83$ MeV. This anomalous decay can be mimed by two types of noise: the correlated background due to the $\mu$ radiative decay $\mu^+ \rightarrow e^+\nu\bar{\nu}\gamma$ (RMD), an usual $\mu$ decay accompanied by the emission of a $\gamma$ by inner bremsstrahlung, and the accidental background, due to the random coincidence of a $e^+$ from the normal $\mu$ decay and a $\gamma$ from RMD, $e^+e^-$ annihilation in matter etc. In the correlated background the particles are emitted simultaneously, but their energies and relative angle are phase-space limited by the presence of $\nu$'s; in the accidental background $e^+$ and $\gamma$ come from independent processes, without phase space limitations. Therefore the accidental background rate is proportional to the square of the $\mu$ stopping rate $R_\mu$ and is the dominant one. Note that the identification of a copious sample of RMD events is fundamental to calibrate the relative timing between $e^+$ and $\gamma$ detectors.

2.1. The MEG and MEG II experiments

The MEG experiment [5] at Paul Scherrer Institut (PSI [6]) consisted of 

(a) a $e^+$ spectrometer, immersed in a graded magnetic field and formed by 16 segmented drift chambers (DCH) for the measurement of $e^+$ momentum vector and 2 arrays of scintillator bars for the measurement of $e^+$ timing (Timing Counter, TC), and 

(b) of a liquid xenon (LXe) $\gamma$ detector for the measurement of $\gamma$ energy, arrival time and impinging point. With a data sample of $7.5 \times 10^{14}$ $\mu^+$'s stopped on target ($R_\mu \approx 3 \times 10^7/s$) the experiment established the present most sensitive upper limit (UL) on the branching ratio ($BR$) of Lepton Flavour Violation reactions: $BR(\mu^+ \rightarrow e^+\gamma) < 4.2 \times 10^{-13}$ at 90 % C.L. with respect to $\mu \rightarrow e\nu\bar{\nu}$ [7], 30 times more stringent than that of previous experiments [8].

On the basis of the MEG experience the collaboration designed an upgrade of the experiment, MEG II [9], shown in figure 2, with the goal of gaining a further order of magnitude in sensitivity. This requires significant modifications in the subdetectors in order to handle a more than doubled $R_\mu \sim 7 \times 10^7/s$ without worsening the signal to noise ratio. The 16 segmented DCHs are replaced by a single volume, 2 m long, DCH, filled with a $85 : 15$ He/iC$_4$H$_{10}$ mixture and equipped with 1792 anodic sense wires and $> 10^4$ cathodic and guard wires; the TC scintillator bars are replaced by 512 plastic tiles read by SiPMs, arranged to have on average $\sim 9$ tiles hit by a 52.83 MeV $e^+$, with a corresponding timing resolution of 30 ps; the LXe detector acceptance is enlarged by $\sim 7\%$ and the 216 photomultipliers in the $\gamma$ entrance face are replaced by 4092 UV-sensitive SiPMs to have a more uniform response of the detector as a function of the depth of $\gamma$ impinging point and a better energy and position resolution;
finally a new detector, the Radiative Decay Counter, has been added to reduce the RMD background, and a new trigger/DAQ system has been developed to handle the increased number of channels. All subdetector resolutions are expected to improve by a factor 2 at least, as verified in engineering runs; the envisaged sensitivity on $\mu^+ \rightarrow e^+\gamma$ process is $6 \times 10^{-14}$ at 90% C.L. in three years of data taking.

3. $\mu^+ \rightarrow e^+e^-e^+$

As for $\mu \rightarrow e\gamma$ this process is searched for with $\mu^+ \rightarrow e^+e^-e^+$ all products are charged particles, which can be efficiently detected with a magnetic spectrometer, formed by tracking and time measuring detectors. Since no $\gamma$'s are present in the final state an electromagnetic calorimeter, with its limited resolution, is not needed; however, the three charged particles are emitted isotropically with a broad energy spectrum, so that the spectrometer must have a low momentum threshold and an almost full solid angle coverage. Then, for a high intensity $\mu$ beam the tracking environment is crowded by hundreds of tracks, with major issues related to the dead time and pattern recognition, among others. In dipole-dominated models $BR(\mu^+ \rightarrow e^+e^-e^+) \sim \alpha BR(\mu^+ \rightarrow e^+\gamma)$ but in models with more complex interactions the rates of the two decays become comparable. The signal is given by three simultaneous tracks, with total charge equal to one, a common vertex, total energy equal to $m_\mu$ and zero total momentum; the momentum of any track cannot exceed $m_\mu/2$. The background has, as for $\mu^+ \rightarrow e^+\gamma$, a correlated component, given by a RMD process where the $\gamma$ converts internally in a Dalitz pair, and a random component, coming from the superimposition of an isolated $e^+$ with a Dalitz pair or of two $e^+$'s with one isolated $e^-$. Again the accidental component dominates for high $R_\mu$. The present UL on this process was established in 1988 by the Sindrum experiment [10]: $BR(\mu^+ \rightarrow e^+e^-e^+) < 1.0 \times 10^{-12}$ at 90% C.L., limited by the $\mu$ beam intensity.

3.1. The Mu3e experiment

The Mu3e experiment [11] at PSI, shown schematically in figure 3, aims to improve the sensitivity on $\mu^+ \rightarrow e^+e^-e^+$ down to $10^{-16}$, four orders of magnitude better than that of Sindrum. The experiment is organized in three phases (IA, IB e II), with increasing sensitivity goals, corresponding to the development stages of the apparatus. Since $> 10^{10}$ stopped $\mu$'s are needed to explore a $BR \sim 10^{-16}$, Mu3e people plan to use in phases IA and IB the existing $\pi E5$ [12] beam, with $R_\mu \approx 10^8$/s, and in phase II the High intensity Muon Beam (HiMB, [13]), a new muonic line (in project) which would reach $R_\mu \approx 1.3 \times 10^{10}$/s by means of a very efficient transport scheme. Refined detector techniques with excellent momentum, vertex and timing resolutions are mandatory to distinguish signal from background. In phase IA the detector will be formed by a hollow, double cone shaped mylar target, a central pixel tracker and a fiber hodoscope, immersed in a 1 T magnetic field and surrounding the target. In phase (IB) two cylindrical stations, constituted by recurl pixel trackers and scintillation tile counters, will be added on front and on rear of the central detector. Two other identical stations will be
4. $\mu^- \rightarrow e^-$ conversion in nuclei

When $\mu^-$'s are stopped in nuclear matter, they form muonic atoms in the ground state: $\mu^- + (A,Z) \rightarrow \mu^- (A,Z)_{1S}^+$. The bound $\mu$ is then captured by the nucleus: $\mu^- (A,Z)_{1S}^+ \rightarrow (A,Z - 1) + \nu_\mu$ or decay in orbit into an $e^-$ and two $\nu$'s: $\mu^- (A,Z)_{1S}^+ \rightarrow (A,Z) + e^- + \nu_\mu + \nu_\gamma$. If Lepton Flavour Violation is allowed $\mu^-$ may also converts into an $e^-$: $\mu^- (A,Z)_{1S}^+ \rightarrow (A,Z) + e^-$ process known as $\mu^- \rightarrow e^-$ conversion. For captures in the ground state the energy $E_{\mu e}$ of outgoing $e^-$ is monochromatic: $E_{\mu e} = m_\mu - E_R (A,Z) - E_K (A,Z)$ where $E_R (A,Z)$ and $E_K (A,Z)$ are the nucleus binding and recoil energy; $E_{\mu e} \approx 105$ MeV for Al, $\approx 104.3$ MeV for Ti. The theoretical predictions for $\mu^- \rightarrow e^-$ conversion rate (CR) range by some orders of magnitude: in New Physics schemes with dipole-mediated transitions $CR (\mu \rightarrow e) \sim 10^{-2+3} BR (\mu \rightarrow e\gamma)$, while in models with more exotic schemes predictions can be much higher. In $\mu^- \rightarrow e$ conversion experiments a $\mu^-$ beam is formed from the decay of $\pi^-$'s produced in $p$ collisions on fixed target and stopped in thin targets, where $\mu$'s are captured. The signal is given by a single $e^-$ with energy $E_{\mu e}$. Background $e^-$'s in the signal energy window can originate from $\mu$'s decaying in orbit (MDIO), radiative $\mu$ (RMC) and $\pi$ (RPC) captures, $\mu$'s decaying in flight (MDIF) and cosmic rays. The energy spectrum of MDIO $e^-$'s can reach $E_{\mu e}$ if $\nu$'s carry away very little energy and the recoiling nucleus ensures energy-momentum conservation; close to the end point $E_{\mu e}$ the energy spectrum is proportional to $(E - E_{\mu e})^4$. The RPC background can be reduced by inserting $\pi$ moderators within the beam line and the MDIF one by selecting a low momentum $\mu$ beam: $p_\mu < 70$ MeV/c. Moreover, since the lifetime of muonic atoms is several hundreds of ns ($\tau_\mu$ Al $= 860$ ns and $\tau_\mu$ Ti $= 329$ ns), one can use a pulsed $p$ beam with buckets $\sim 100$ ns, separated by $> 1 \mu$s, let $\pi$'s decay and search for $\mu^- \rightarrow e^-$ process in a delayed time window. This requires, however, a fraction of “out-of-time” $\nu$'s, arriving on the $\pi$ production target between two bunches, $< 10^{-9+10}$, the so-called “extinction factor”. Finally, the spill-in of MDIO $e^-$'s into the signal window is reduced by a high resolution tracking detector and the cosmic ray induced events are rejected by veto counters and external shieldings and by identifying their signals in tracking devices and calorimeters. The present ULs on $\mu^- \rightarrow e^- CR$ were set by the Sindrum II experiment [14] on Au and Ti targets: $CR (\mu^- \rightarrow e^-) < \text{few} \times 10^{-13}$, primarily limited by the $\mu$ beam intensity. Two new experiments, Mu2e [15] at Fermilab [16] and COMET [17] at J-PARC [18], plan to improve these limits by four orders of magnitude. Both experiments will use a triple solenoid $\mu$ transport and detection system which can increase the $\mu$ beam intensity by a factor $\sim 10000$.

4.1. The Mu2e, COMET and DeeMe experiments

The Mu2e experiment will use a 8 GeV, 25 kWatt $p$ beam with 250 ns bunches, separated by 1.7 $\mu$s, to produce secondary particles which will be captured by a large acceptance capture solenoid surrounding the $p$ target and driven through a S-shaped transport solenoid, arranged to single out $\mu^-$'s and reject $\bar{p}$ and positive and neutral particles. The needed extinction factor will be obtained by means of a system added in phase II.

Figure 4. The Mu2e experiment. 

Figure 5. The COMET experiment.
of resonant AC dipoles. The charge and momentum selection will be operated by using the shift of the centre of the helicoidal trajectory of a charged particle in the direction perpendicular to the solenoid plane and by placing appropriate collimators. Selected $\mu^-$’s will be stopped in Al foils and $e^-$’s from $\mu$ decay or capture will be looked for by using a high resolution ($\approx 900$ keV FWHM at 105 MeV/$c$) spectrometer and an electromagnetic calorimeter. The magnetic field configuration would allow to select $p > 90$ MeV/$c$ and recover backward going $e^-$’s. Mu2e is expected to be sensitive to $CR(\mu^- \rightarrow e^-) > 2 \times 10^{-16}$, while in case of no signal it should put an UL of $2 \times 10^{-17}$ in two years of data taking.

The COMET experiment is a two stage program to search for $\mu^- \rightarrow e^-$ conversion. The goal of the first phase is to reach a sensitivity on $CR(\mu^- \rightarrow e^-) < 3 \times 10^{-15}$ with an apparatus based on a half-C $\pi$ capture solenoid, a prototype tracking detector and an electromagnetic calorimeter. In the second phase an improvement of two orders of magnitude in sensitivity is expected by doubling the $\pi$ capture solenoid, inserting a $\mu$ transport section and a 180° $e^-$ spectrometer, followed by more refined tracking devices and calorimeters. COMET will use a 8 GeV, 56 kWatt pulsed $p$ beam with $\sim 100$ ns bunches separated by $\approx 1$ $\mu$s. COMET is conceptually similar to Mu2e, with two main differences: $a)$ the transport solenoid has a C-shape in COMET and a S-shape in Mu2e; $b)$ the solenoidal spectrometer is curved in COMET and straight in Mu2e. The COMET arrangement ensures a better $\mu$ momentum selection at the expense of a 30 % lower $\mu$ beam intensity. For both experiments extinction factors $< 10^{-10}$ seem feasible.

The DecMe experiment [19] is a less ambitious, but of shorter time scale experiment for $\mu^- \rightarrow e^-$ conversion with an expected sensitivity of $10^{-14}$, 20 times better than SINDRUM II. Electrons from $\mu^- \rightarrow e^-$ conversion will be got directly from production target without need of $\mu$ and $\pi$ transport sections. The experiment will operate at J-PARC Material and Life Science facility, an intense $\mu$ beam source extracted from a 3 GeV, Rapid Cycling Synchrotron. Muons will be produced and stopped in a SiC target and subsequent $e^-$’s will be transported by a beam line composed of focusing solenoids, prompt kickers and bending magnets to an $e^-$ spectrometer, with a resolution $\sigma_P \approx 0.5$ MeV/$c$ at 100 MeV, adequate to control the MDIO background.

Figure 6. Expected time schedule of future muon Lepton Flavour Violation experiments.

5. Perspectives with high intensity accelerators

Muon beams of intensity up to $10^{14}$ $\mu$/s could be available in few years at future high intensity accelerators, as PiP-II [20] at Fermilab, HiMB at PSI and MuSIC [21] in Japan; then, one can ask whether Lepton Flavour Violation searches can take benefit from these high intensity machines. Unfortunately experiments searching for $\mu^+ \rightarrow e^+ \gamma$ or $\mu^+ \rightarrow e^+e^-e^+$ are unavoidably faced with the bottle neck due to accidental background, which scales with $R_{\mu}^2$; then a simple increase of $R_{\mu}$ does not improve the sensitivity. In order to go beyond the sensitivity expected for MEG II substantial progresses in experimental techniques are needed as, for example, the use of higher quality calorimeters or high resolution pair spectrometers for the $\gamma$ detection and of finely segmented or active targets; for a discussion see [22]. On the other hand $\mu^- \rightarrow e^-$ conversion experiments, whose signal is an isolated $e^-$, are not rate limited but their sensitivity is determined by beam purity (extinction factor) and background control.
For instance, PiP-II at Fermilab is expected to provide at least ten times more $\mu$'s to Mu2e (a Mu2e-II proposal has been already submitted [23]) and the major challenge for the collaboration will be to maintain the background at a level $< 1$ event. Other main concerns are the target radiation heating (with risk of melting) and the beam spread, which could take advantage from the FFAG (Fixed Field Alternating Gradient) technology under study in the PRISM project [24]. A beam spread reduction from 30% to 3% would allow to stop many $\mu$'s in very thin foils, minimising the resolution worsening due to $e^-$ interactions in the target. A final momentum resolution of 350 keV FWHM at 105 MeV/c is envisaged, which could make possible to reach a sensitivity $\sim 10^{-18}$ on $CR(\mu^- \rightarrow e^-)$. The time scale of future muon Lepton Flavour Violation experiments is shown in Figure 6 [25].

6. Conclusions
Several experiments searching for Lepton Flavour Violation with $\mu$'s are starting their data taking in the next years. They form a complementary network of detectors, sensitive to a large variety of New Physics schemes and parameter regions. A bright future for New Physics is probably on the horizon!

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