PROCEEDINGS OF SCIENCE

Experimental status of muon lepton flavor violations

Paolo Walter Cattaneo*INFN Pavia

E-mail: paolo.cattaneo@pv.infn.it

The experimental status and future perspectives of charged lepton flavor violation searches with muons is reviewed, with particular emphasis on the following three searches: $\mu^+ \to e^+\gamma$, $\mu^- \to e^-$ and $\mu^+ \to 3e$. The prospect for future improvements are presented.

9th International Workshop on the CKM Unitarity Triangle
28 November - 3 December 2016
Tata Institute for Fundamental Research (TIFR), Mumbai, India

*Speaker.

PoS(CKM2016)068

1. Introduction

Charged lepton flavor violating (CLFV) transitions are forbidden in the Standard Model with massless neutrinos. The introduction of neutrino masses and mixing induces flavor transitions at the loop level, but the expected branching ratio for $\mu \to e\gamma$ is $\sim 10^{-51}$. Therefore the observation of charged lepton flavor transitions is a background free signal of physics beyond the Standard Model at variance with the quark sector where signals of new physics would emerge from deviations from expected branching ratios, whose precise values are often marred by non perturbative QCD calculations. In the following the status and perspectives of CLFV experiments are reviewed: $\mu^+ \to e^+\gamma$, $\mu^- \to e^-$ and $\mu^+ \to 3e$.

2. Charged Lepton Flavor Violation: a theoretical point of view

After having established that a positive detection of CLFV processes is a sure sign of BSM physics, we attempt to define frameworks to compare in a model independent approach the different CLFV transitions [1]. A first approach assumes that the CLFV is mediated by effective operators of dimension five and six as follows

$$\mathscr{L}_{CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\overline{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + h.c. + \tag{2.1}$$

$$\frac{\kappa}{(\kappa+1)\Lambda^2}\overline{\mu}_L\gamma_\mu e_L(\overline{u}_L\gamma^\mu u_L + \overline{d}_L\gamma_\mu d_L) + h.c. \tag{2.2}$$

The subscripts L,R indicate the chirality of the fermion fields, F is the photon field strength and m_μ is the muon mass. The relative weights of the two operators are parametrized by two constants: Λ (with dimension of mass), which represents the effective mass scale of the new interaction, and the dimensionless κ, which regulates the relative strength of the two operators. The magnetic moment type operator in the first addendum of Eq. 2.1 mediates directly $\mu \to e\gamma$ while mediating $\mu^+ \to 3e$ and $\mu^- \to e^-$ conversion in nuclei at order α. The four-fermion dimension-six operators in the second addendum of Eq. 2.1, on the other hand, mediate $\mu^- \to e^-$ at the leading order and $\mu \to e\gamma$ and $\mu^+ \to 3e$ at one-loop level, order α. For $\kappa \ll 1$, the dipole-type operator dominates CLFV phenomena, while for $\kappa \gg 1$ the four-fermion operator is dominant.
A second approach assumes the following Lagrangian

$$\mathscr{L}_{CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\overline{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + h.c. + \tag{2.3}$$

$$\frac{\kappa}{(\kappa+1)\Lambda^2}\overline{\mu}_L\gamma_\mu e_L(\overline{e}\gamma^\mu e) + h.c. \tag{2.4}$$

In this case the dimension-six operators in Eq.2.3 mediates $\mu^+ \to 3e$ at the tree level and $\mu \to e\gamma$, $\mu^- \to e^-$ at the one-loop level, order α.

3. The muon CLFV decays

The most relevant CLFV transitions involving muons are $\mu \to e\gamma$, $\mu^+ \to 3e$ and $\mu^- \to e^-$ conversion on nuclei. Those processes have been searched for in the last seven decades with increasing precisions as shown in Fig. 1 (see [2] and references therein). The history can be broadly

PoS(CKM2016)068

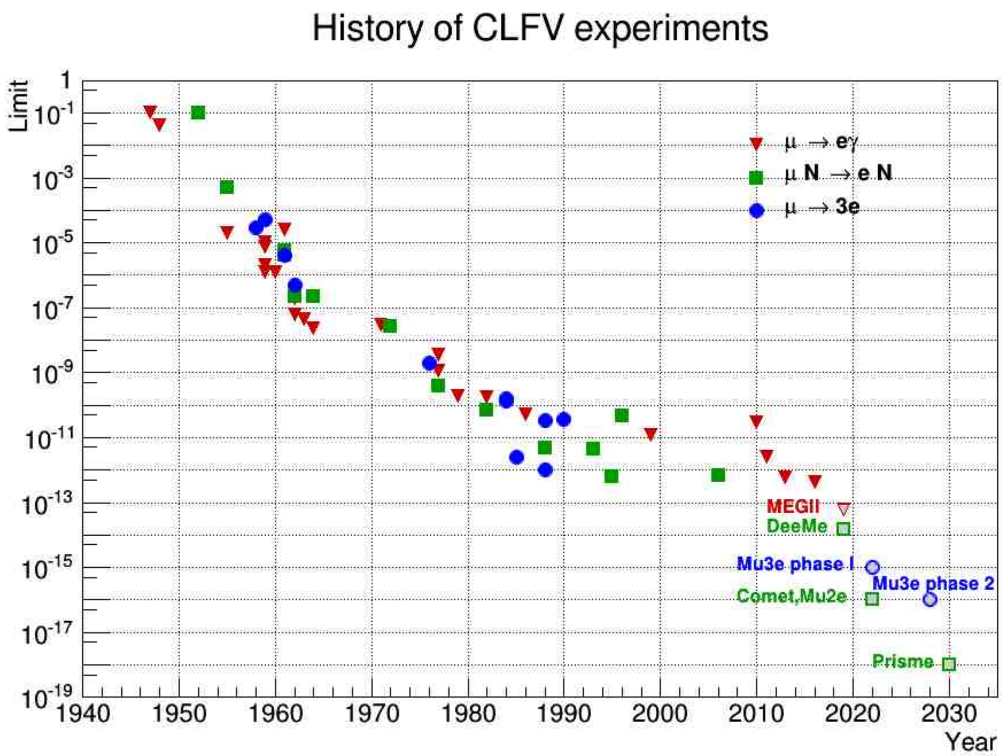

Figure 1: The history of CLFV search in processes involving muons.

divided into three groups: cosmic-ray muons (up to 1952), stopped pion beams (until mid-60s) and stopped muon beams (1970s onward). A combined progress in beam or detector technologies brought steady improvements in the limits up to the 90s after which little improvements have taken place.

At the current level of precision, each transitions requires a dedicated experimental setup in terms both of beam and detector to be competitive. The $\mu \to e\gamma$ decay is a two body decay where the daughter particles are monoenergetic (52.83 MeV) and emitted simultaneously back-to-back in the muon rest frame. That requires a high intensity beam of positive muons, to prevent nuclear capture, stopped in a thin target, to reduce multiple scattering. The background consists mainly of two processes: a muon radiative decay $\mu^+ \to e^+\gamma\nu\bar{\nu}$ in which the two neutrino carry little energy and an accidental coincidence between a positron from muon decay (Michel positron) and a high energy photon from a radiative decay, bremsstrahlung or positron annihilation in flight with both positron and photon close to their kinematic limits. It is shown in [7] that for current resolutions the dominant background is the accidental one. Therefore a continuous muon beam is preferred, in order to minimize the probability of random coincidences from different muons. This search requires a photon detector with excellent energy resolution and a low-mass spectrometer with excellent momentum resolution and angular resolution; both particles need also precise time measurements.

The search for $\mu^+ \to 3e$ decay relies again on a high intensity beam of positive muons stopped in a thin target; the three electrons, emitted simultaneously, share the muon rest energy, and are emitted on a plane with the additional constraint of zero total momentum. Also in this process the back-

ground from radiative decays with negligible neutrino's energy is less important than the accidental coincidence of three particles from different muons, hence the need of a continuous muon beam. This search requires a low-mass spectrometer with large acceptance with excellent momentum resolution, angular and timing resolution.
In the $\mu^- \to \mathrm{e}^-$ process a muon first form a muonic atom and then monoenergetic electrons are emitted against the nucleus, with energy equal to the muon rest mass minus the muon binding energy so that a single particle is present in the final state. The main background comes from muon decay in orbit (DIO) or from decay of residual particles in the primary muon beam. A beam of negative muons is required, and the suppression of beam-related background is obtained using pulsed beams and restricting the search in the intrapulse interval. In this interval the relative number of particles (extinction factor) must be minimized.

4. Status and future prospects of the search for muon CLFV decays

The most stringent limit on $\mu \to \mathrm{e}\gamma$ is due to the MEG experiment [3] $BR(\mu \to \mathrm{e}\gamma) < 4.2\,10^{-13}$ [5]. MEG took data between 2008 and 2013 improving the previous limit by a factor ~ 30. MEG consisted of a large liquid Xenon γ-ray detector and of a a gradient field spectrometer including a set of drift chambers for momentum and direction measurement and of a set of plastic scintillator counters for time measurement. A surface μ^+ beam stopped in a thin plastic target with rate 3×10^7/s.
The only prospect for an improved measurement of $\mu \to \mathrm{e}\gamma$ is the upgrade MEGII [6], that is under construction. The liquid Xenon detector upgrade consists in a higher granularity on the front face relying on SiPM rather than PMT, while the tracking system will be replaced by a new low-mass, single volume, high granularity chamber complemented by a highly segmented, fast timing counter system. This configuration is expected to handle a higher rate 7×10^7/s, that should bring the sensitivity down to $\sim 6\,10^{-14}$.
The $\mu^+ \to 3\mathrm{e}$ process has seen no new result since 1988 [8]. Recently, a proposal with the ambitious goal of improving the limit of almost four order of magnitude down to 10^{-16} was presented [9] to be achieved in two stages with an upgrade of the muon beam line to higher rate in between. It consists of a magnetic spectrometer based on thin silicon pixel detectors close to the muon decay target complemented at larger distance with scintillating fibers and tiles. The spectrometer is designed to achieve excellent momentum, timing and vertex resolutions.
There are on the other hand several proposal for improving the sensitivity to $\mu^- \to \mathrm{e}^-$ now ten years old [10]. They are based on the next generation high luminosity accelerator complexes (KEK, Fermilab) able to deliver much higher rate in pulsed mode compared to the existing ones (TRUMP,PSI). The most critical section of those experiments is the beam line delivering the muon beam from the detector. The detector requires high momentum resolution at high rate to detect e^- at energy equal to the muon mas minus the binding energy.
An approach, less ambitious but with a shorter time scale, DeeMe [11], relies on muonic atoms produced in the primary target of the proton beam, followed by a spectrometer for momentum selection and by chambers for momentum measurement.
The more demanding and with a longer time scale experiments Mu2e [12, 13] at Fermilab and

COMET [14, 15, 16] at KEK relies on a long superconducting solenoid beam line to bring a momentum selected muon beam to the detector and should provide a large improvement in sensitivity.

References

[1] A. de Gouvea and P. Vogel, Lepton Flavor and Number Conservation, and Physics Beyond the Standard Model, Prog.Part.Nucl.Phys. 75, (2013) 201801, arXiv:1303.4097 [hep-ex].

[2] R.H.Bernstein and P.S. Cooper, Charged Lepton Flavor Violation: An Experimenter's Guide, Phys. Rep. 532 (2), (2013) 27, arXiv:1303.5787 [hep-ex].

[3] J. Adam *et al.*, The MEG detector for $\mu^+ \to e + \gamma$ decay search, Eur. Phys. J. C, 73 (2013) 2365, arXiv:1303.2348 [physics.ins-det].

[4] J. Adam *et al.*, New constraints on the existence of the $\mu^+ \to e + \gamma$ decay, Phys. Rev. Lett. (2013) 201801, doi:10.1103/PhysRevLett.110.201801, arXiv:1303.0754 [hep-ex].

[5] A. Baldini *et al.*, Search for the Lepton Flavor Violating Decay $\mu^+ \to \mathrm{e}^+\gamma$ with the Full Dataset of the MEG Experiment, Eur. Phys. J. C, 76(8), (2016) 1, http://arxiv.org/abs/1605.05081.

[6] A. Baldini *et al.*, MEG Upgrade Proposal, 2013, arXiv:1301.7225 [physics.ins-det].

[7] Y. Kuno and Y. Okada, Muon decay and physics beyond the standard model, Rev. Mod. Phys. 73 (2001) 151.

[8] U. Bellgardt *et al.* (SINDRUM collaboration), Search for the decay $\mu^+ \to \mathrm{e}^+\mathrm{e}^+\mathrm{e}^-$ Nucl. Phys. B, 299(1) (1988) 1.

[9] A. Blondel *et al.* (Mu3e collaboration), Research Proposal for an Experiment to Search for the Decay $\mu \to eee$ http://www.physi.uniheidelberg.de/Forschung/he/mu3e/documents/LOI, (2013) 27, arXiv:1301.6113 [hep-ex].

[10] W. Bertl *et al.* (SINDRUM II collaboration), A search for μ-e conversion in muonic gold, (2006). Eur. Phys. J. C 47, 337

[11] M. Kinsho *et al.* (DeeMe collaboration), Proposal of an Experimental Search for μ-e Conversion in Nuclear Field at Sensitivity of 10^{-14} with Pulsed Proton Beam from RCS, KEK J-PARC Proposal (2011).

[12] R.M. Carey *et al.* (Mu2e collaboration), Proposal to search for $\mu^- N \to eN$ with a single event sensitivity below 10^{-16}, Fermilab proposal 0973, (2008), http://mu2e.fnal.gov.

[13] R.J.Abrams *et al.*, Mu2E Conceptual Design Report, Fermilab-TM-2545, (2012), arXiv:1211.7019.

[14] D. Bryman *et al.* (COMET collaboration), An Experimental Search for Lepton Flavor Violating $\mu^- \to \mathrm{e}^-$ Conversion at Sensitivity of 10^{-16} with a Slow-Extracted Bunched Proton Beam, http://comet.kek.jp/Documents_files/main-proposal.pdf, (2007).

[15] R. Akhmetshin *et al.*, Letter of Intent for Phase-I of the COMET Experiment at J-PARC, KEK/J-PARC-PAC 2, http://comet.kek.jp/Documents_files/PhaseI-LoI-draft-v1.1.pdf, (2012).

[16] R. Akhmetshin *et al.* , COMET Phase-1 Technical Design Report, http://comet.kek.jp/Documents_files/PAC-TDR-2014/PAC-Review-20141110.pdf (2014)