Lepton Flavor Violation perspectives beyond MEG

Paolo Walter Cattaneo[a]

[a]INFN Pavia
Via Bassi 6, Pavia, I-27100, Italy
Email: Paolo.Cattaneo@pv.infn.it

MEG will test Lepton Flavor Violation in the $\mu \to e^+\gamma$ down to an unprecedendet sensitivity.
After an introduction to various scenarios of physics beyond the Standard Model suggesting the possibility of LFV processes at a measurable level, the possibility of future experiments more sensitive to new physics is discussed in the following.

1. Theoretical motivations

The Lepton number is a quantum number associate to a class of elementary particles not experiencing strong interation. These particles are: e, μ, τ and their corresponding $\nu_{e\mu\tau}$. There is very strong experimental indication that the total lepton number L is conserved.
There is also evidence that the separate lepton numbers $L_{e\mu\tau}$ are conserved.
With Lepton Flavor Violation (LFV) we mean processes conserving L but changing one of $L_{e\mu\tau}$.
In the Standard Model with massless ν LFV processes are strictly forbidden.
In the Standard Model with massive ν, where the Δm^2_ν masses are deduced from the oscillation experiments, we have

$$BR(\mu \to e\gamma) = \frac{3\alpha}{32\pi}|\Sigma_{i=2,3}U^*_{\mu i}U_{ei}\frac{\Delta m^2_{1i}}{M^2_W}|^2 < 10^{-54} \quad (1)$$

that is an experimentally unaccessible level.
Other LFV processes, like $BR(\tau \to \mu\gamma)$, are allowed at a level that can be several order of magnitude higher but still experimentally unreachable. That makes the detection of such decays an unambiguous sign of new physics.

1.1. LFV processes

The LFV processes that can be tested experimentally are mainly

- $\mu \to e\gamma$
- $\mu \to eee$
- $\mu A \to eA$ (conversion)
- $\tau \to l\gamma$
- $\tau \to lll$

As a general rule the BR of processes involving μ and e are related to the corresponding processes involving τ and μ by a factor $(m_\tau/m_\mu)^\alpha$ with $\alpha \approx 3$ that is 3-4 order of magnitude.
Within the same lepton generation, the approximate relations $L \to l\gamma \approx 100L \to lll$ and $LA \to lA \approx L \to lll$. Other processes are possible like $\mu A \to tauA$ [9]-[10] or $\mu^- A \to \mu^+ A$ (muonium-antimuonium conversion) [11] but they are extremely difficult to test experimentally and will not discussed any further.

1.2. Beyond the Standard Model

Many of the models beyond the Standard Model predict much higher LFV branching ratios.
The work that marked a renewed interest in LFV violating process is [1].
Many other works have attempted to calculate the BR of LFV in various models beyond the SM.
Some of the models for which BR LFV processes have been calculated are

- SM + ν mixing [2]
- SM + heavy Majorana ν_R [3]
- Non-universal Z′ [4]
- SUSY SO(10) [5]

- mSUGRA+seesaw [6]
- SUSY Higgs [7]

The calculations are often plagued by uncertainties in model parameters. Nevertheless some estimation of the order of magnitude of the BR upper limits in any given model are possible. Details are discussed in the references but in many cases the existing limits provides already constraints on the model parameters and improvements will further constraint the models.

2. Muonic channels

3. $\mu \to e\gamma$

The $\mu \to e\gamma$ decay is in most of the models the most sensitive to new physics.

3.1. Status

The kinematic of the signal is depicted in Fig.1 and is very simple. In the rest frame of the μ a e and a γ are emitted back to back with a monochromatic energy very close to $m_\mu/2$ in time coincidence.
An experimental setup for searching this decay consists of a high intensity μ^+ beam (to prevent absorption) brought in a thin target (to limit multiple scattering) to a stop (to exploit monochromaticity). A calorimeter or a converter followed by a tracker measures the photon energy while a spectrometer based on tracking chambers measure the e^+ momentum. Both detectors must implement an excellent time and position/angular resolution [12]-[15].
Part of the background is prompt, shown in Fig.1, coming from Radiative Decay events with vanishing E_ν energy; it is independent from the rate and cannot be separated from signal with the help of time measurement. In [15] it is shown that for past and present experiment it is negligible.
The rest of the background comes from accidental where e^+ is from Michel decay and γ is either from Radiative Decay or from external bremstrahlung or from annihilation in flight of Michel e^+. This background increases with rate and can be reduced exploiting the timing property of the detectors.

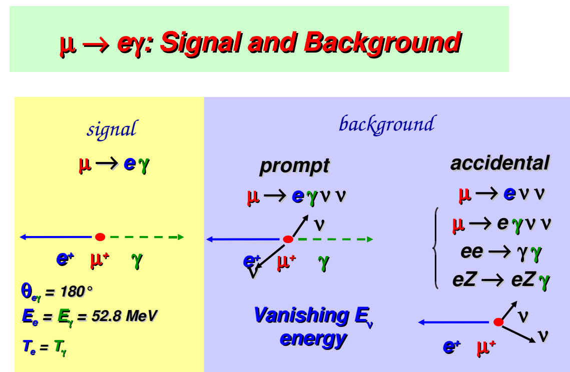

Figure 1. $\mu \to e\gamma$ signal and background

3.2. Perspectives

It can be proved that the optimal rate for given detector resolutions is

$$R_\mu^{opt} \propto \frac{1}{\sqrt{T \times \frac{\Omega}{4}\epsilon_e \epsilon_{sel} \epsilon_\gamma \Delta E_e \Delta t_{e\gamma}}} \frac{1}{(\Delta E_\gamma \Delta\theta_{e\gamma})}$$

where T is the data taking time, Ω the angular acceptance ΔE_e the e^+ energy resolution (FWHM), ΔE_γ the γ energy resolution, $\Delta t_{e\gamma}$ the relative time resolution, $\Delta\theta_{e\gamma}$ the angular resolution, $\epsilon_e, \epsilon_\gamma, \epsilon_{sel}$ are the efficiencies for detecting e^+, γ and for selection respectively.
The optimal sensitivity goes as

$$SES^{opt} \propto (\Delta E_\gamma \Delta\theta_{e\gamma})\sqrt{\frac{\Delta E_e \Delta_{te}}{T \times \frac{\Omega}{4}\epsilon_e \epsilon_{sel} \epsilon_\gamma}}$$

It is evident that gaining an order of magnitude compared to MEG design parameter [15] requires either a major improvement in ΔE_γ or $\Delta\theta_{e\gamma}$ or improvements of factors 1.5-2.0 for all the resolution parameters.
Both approaches appear very challenging.

4. $\mu \to eee$

The limit on $\mu^+ \to e^+e^+e^-$ is 20 years old [13]. Ths signal consists of 3 $e^\pm$ lying on the same plane

and coincident in time, such that $\Sigma E_e = m_\mu$.
In this experiment the rate $R_\mu \approx 5 \times 10^6\, Hz$ is limited by accidental background. The accidental background is the random overlapping in time of a Michel e^+ and a $e^\pm$ pair from Bhabha scattering in the target. The prompt background where the $e^\pm$ pair comes from μ Dalitz decay is negligible.
The advantage of this decay is the absence of γ, so that no calorimeter is required. However the full Michel spectrum must be measured and that implies high rate in the tracking system.

4.1. Perspectives

To be competitive with MEG measurement of $BR(\mu \to e\gamma) \approx 10^{-13}$ the goal should be $BR(\mu \to eee) \approx 10^{-15}$.
The efficiency in [13] is 15% cannot be improved significantly.
Match the BR goal through R_μ requires an increase by 10^3, but the accidental rate would increase by 10^6. A factor of 10 can be obtained using the timing system developed for MEG.
It seems out of reach improve of another factor 10^5 through tracking resolution.

5. $\mu A \to eA$ conversion

The process involves μ^- stopping in material foils (Al or Ti) forming muonic atoms.
Three possible fates:

- Nuclear capture
- Three body decay in orbit
- Coherent LFV decay (factor Z in rates)

Signal is a single monochromatic electron

$E_e = m_\mu - E_{rec} - E_{bind}$

$\tau_\mu = 0.35\mu s$ in Ti and $\tau_\mu = 0.90\mu s$ in Al

One of the most dangerous background is the RPC (Fig.2), because E_γ upper limit is above the signal. The reduction is achievable with a pulsed beam with a pulse duration shorter than the τ_μ and exploiting the shorter τ_π. After the pulse, the π are left to decay and the signal measurement are done in a delayed window.
High rate capability electron detectors in a 1 T field are required.
The lack of γ detection and of coincidence due to accidentals allows to exploit very high rate.
Two proposals exist to improve existing limit [14]: MECO/Mu2e to be done at Fermilab [17] and Comet [16] at JPARC with the goal of exploring conversion probability down to 10^{-16}.
In the future this channel could profit from the PRISM project at JPARC and from the beam developed for ν factories producing another order of magnitude improvement.

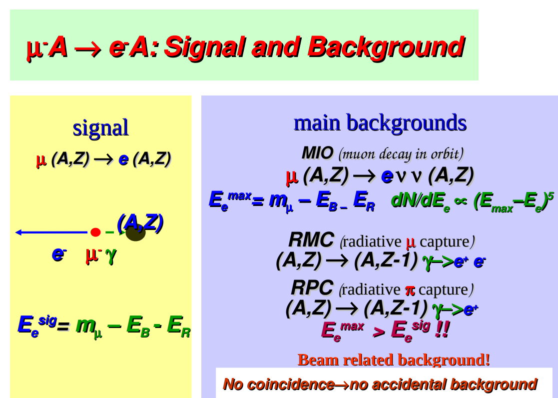

Figure 2. $\mu A \to eA$ signal and background

6. Tauonic channels

The main problem for these channels is the production of large τ samples.
New physics sensitivity comparable to the dedicated experiment in the muonic channels is expected for Branching Ratios around $10^{-(8-9)}$.

6.1. Status

These channels could profit of the B factories that are also τ factories: Belle and BaBar.
The existing limits on LFV Brs are $10^{-(7-8)}$, a region already marginally sensitive to new physics.

The signals have a simple topology requiring three leptons or a lepton with a γ with invariant mass equal to the τ mass.

6.2. Perspectives

The best possibility for improving the existing limits relies on the Super B Factory that could deliver an integrated luminosity of $50ab^{-1}$ compared to $\approx 1ab^{-1}$ of today.
The most promising measurement is $BR(\tau \rightarrow \mu\mu\mu)$ that is not background limited and could achieve down to 10^{-9}.
It is a value interesting for the class of models most sensitive to second generation mixing but it is less sensitive that dedicated muonic channels otherwise.

REFERENCES

1. R. Barbieri et al., Physics Letters B 338 (1994) 341
2. X. Pham, EPJ C8 (1999) 513
3. G. Cvetic et al., Physical Review D 66 (2002) 034008
4. C. Yue et al., Physics Letters B 547(2002) 252
5. T. Fukuyama et al., Physical Review D 68 (2003) 033012
6. J. Ellis et al., Physical Review D 66 (2002) 115013
7. A. Brignole and A. Rossi, Physics Letters B 566 (2003) 217
8. L. Calibbi et al., hep-ph/0605139v2
9. M. Sher and Ismail Turan, Physical Review D 69 (2004) 017302
10. S. Gninenko et al., Mod. Phys. Lett. A 17 (2002) 1407
11. M. Aoki, Nuclear Instrument and Methods in Phys. Res. A 503 (2003) 258
12. M. Brooks et al., Physical Review Lett. 83 (1999) 1521
13. U. Bellgardt et al., Nuclear Physics B299 (1988) 1
14. C. Dohmen et al., Physics Letters B317 (1993) 631
15. Web page http://meg.web.psi.ch/
16. Web page http://comet.phys.sci.osaka-u.ac.jp/
17. Web page http://mu2e.fnal.gov