Lepton Flavour Violation Experiments in LHC Era

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Abstract. I review the present status of Lepton Flavour Violation Experiments involving muons and taus and the future perspectives of this physics field.

1. Introduction

In the minimal standard model (from now on: SM) the lepton flavour violating (from now on: LFV) processes are not allowed at all; leptons are grouped in separated doublets and the lepton flavour conservation is built in by hand assuming vanishing neutrino masses. Nevertheless, the neutrino oscillations are now established facts (for a continuously updated review see [1]) and the neutrino masses are definitely not vanishing; then, LFV in the neutral sector is an experimental reality, while until now there are no corresponding indications in the charged sector. When massive neutrinos and neutrino oscillations are introduced in the SM, LFV decays of charged leptons are predicted, but at immeasurably small levels (branching fractions $\sim 10^{-50}$ with respect to SM decays). However, Supersymmetric and expecially GUT supersymmetric theories (from now on: SUSY and SUSY-GUT) naturally accomodate finite neutrino masses and predict relatively large (and probably measurable) branching ratios (from now on: BR) for LFV processes (see for example [2], [3], [4], [5], [6]). Therefore, sizable flavour violation processes would be strong indications in favour of new physics beyond the SM.

Even if searches for charged LFV effects have, so far, yielded no results, they had a relevant impact on the particle physics development: for example, the non observation of $\mu^+ \to e^+\gamma$ decay [7] established that the muon and the electron are two distinct leptons [8] and the stronger and stronger constraints on this process were basic arguments for introducing a second neutrino (ν_μ) [9]. At the beginning of the third millennium, the search for charged LFV reactions allows to explore SUSY mass scales up to $1000 \div 10000$ TeV (even out of LHC reach) and to give insights about large mass range, parity violation, number of generations ...

Figures 1 and 2 illustrates examples of recent theoretical predictions for charged LFV processes in the SUSY frame: on the left the $\mu^+ \to e^+\gamma$ BR is shown as a function of $M_{1/2}$ (in GeV) for three different classes of models [5], on the right the sensitivity of some present and future experiments in the plane $(m_0, M_{1/2})$ is reported [6]. A detailed review of the mechanisms which might induce LFV processes and of the relation between LFV and other signs of new physics (like Muon Anomalous Magnetic Moment) can be found in [10].

Many experiments are under way or in preparation which would test the theoretical predictions with unprecedented levels of sensitivity.
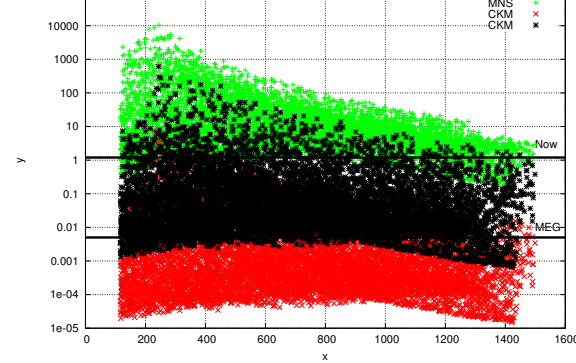
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[1] On behalf of the MEG Collaboration

Figure 1. Branching ratio of $\mu^+ \to e^+\gamma$ decay (in units of 10^{-11}) as a function of $M_{1/2}$ (GeV) for three classes of SUSY models [5]. The horizontal line labelled "NOW" is the present experimental limit: $BR(\mu^+ \to e^+\gamma) \leq 1.2 \times 10^{-11}$ [11].
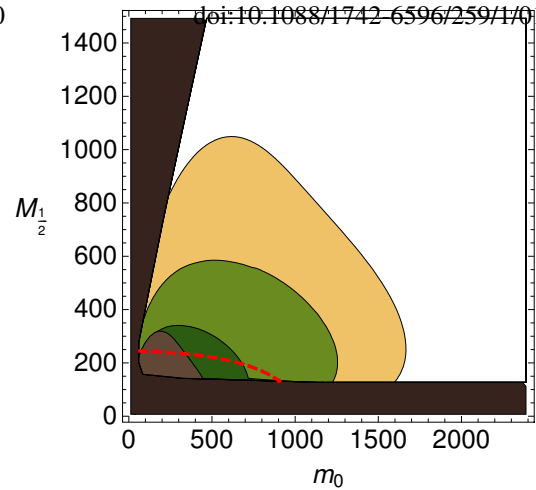

Figure 2. Sensitivity contours in the plane $(m_0, M_{1/2})$ for MEGA (Brown), BaBar + Belle (dark green), Super B (light green) and MEG (light brown). The dark brown regions are excluded by LEP data [6].
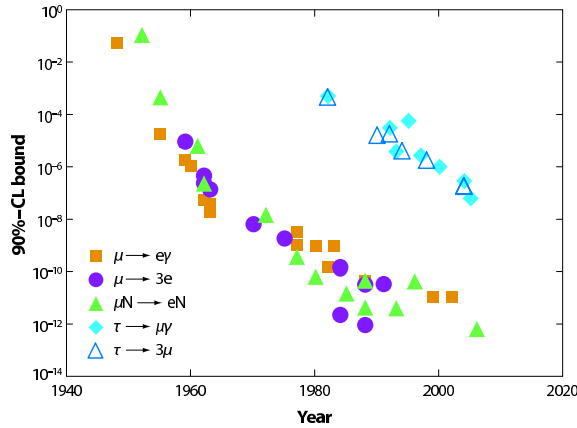

Figure 3. Improvement with time of some LFV searches (from [10]).

Note that not only positive results, but also negative results could be very significant, since they would tightly constrain the multi-dimensional SUSY parameter space. We also stress that searching for LFV processes in different channels and with different leptons is one of the most powerful tools to discriminate between different models. Figure 3 shows the improvement with time of the upper limits for some LFV processes. In this talk I discuss status and perspectives of LFV experiments involving muons and taus.

2. The muonic channel

2.1. Generalities

Muons are very sensitive probes for LFV searches since a) intense muon beams ($\sim 10^8$ μ/s) can be obtained at the meson factory machines, b) the final states are very simple, c) the LFV processes have clean signatures and d) the muon lifetime (2.2 μs) is relatively long.

The most studied muon LFV processes are the μ decay into and electron and a gamma or into three electrons and the muon to electron conversion. Other more exotic LFV reactions, like Muonium-Antimuonium conversion, rare K_L^0 decays, (as $K_L^0 \to e\mu$), $\mu^- A \to \mu^+ A'$, μ to τ conversion ... are not discussed here.

2.2. Search for $\mu \to e\gamma$ decay: the MEG experiment

The $\mu \to e\gamma$ decay is the historical channel where charged LFV is searched for. Positive muons (selected to avoid nuclear captures in the stopping target), coming from decay of π^+ produced in proton interactions on fixed target, are brought to stop and decay at rest, emitting

simultaneously a γ and a e^+ in back-to-back directions. Since the e^+ mass is negligible, both particles carry away the same kinetic energy: $E_{e^+} = E_\gamma = m_\mu/2 = 52.83$ MeV. The signature is very simple, but, because of the finite experimental resolution, it can be mimed by two types of background: a) the *physical* or *correlated* background, due to the radiative muon decay (from now on: RMD): $\mu^+ \to e^+\bar{\nu}_\mu\nu_e\gamma$. The BR of RMD process is (1.4 ± 0.2) % of that of usual muon Michel decay $\mu^+ \to e^+\bar{\nu}_\mu\nu_e$ for $E_\gamma > 10$ MeV; b) the *accidental* or *uncorrelated* background, due to the coincidence, within the analysis window, of a e^+ coming from the usual muon decay and a γ coming from RMD, $e^+ - e^-$ annihilation in flight, e^+ bremsstrahlung in a nuclear field ...

While signal and RMD rates are proportional to the muon stopping rate R_μ, the accidental background rate is proportional to R_μ^2, since both particles come from the beam; the accidental background is dominant and sets the limiting sensitivity of a $\mu \to e\gamma$ experiment. Then, in the search for $\mu^+ \to e^+\gamma$ decay a continuous muon beam is preferred and R_μ must be carefully chosen to optimise the signal-to-noise ratio. The number of background events depends on the sizes of the signal region, which are determined (at fixed signal detection efficiency) by the experimental resolutions: the better the resolutions, the smaller the signal window and the smaller the number of background events. Physical effects which degrade the resolution, as multiple scattering and energy loss, are reduced by using "surface" muons, i.e. muons produced by pions stopped very close to the surface of π production target, which are efficiently brought to rest in thin targets. Moreover, high resolution detectors are mandatory. Table 1 shows the figures of merit obtained by previous $\mu \to e\gamma$ experiments compared with the final goals of the MEG [12] experiment; the 90 % C.L. upper limits on $\mu \to e\gamma$ BR are also reported.

Table 1. The performances of previous $\mu \to e\gamma$ experiments compared with that expected for MEG. All the quoted resolutions are FWHM. * shows an average of the numbers given in [11].

Place	Year	$\Delta E_e/E_e$	$\Delta E_\gamma/E_\gamma$	$\Delta t_{e\gamma}$	$\Delta\theta_{e\gamma}$	Upper limit	References
SIN	1977	8.7 %	9.3 %	1.4 ns	–	$< 1.0 \times 10^{-9}$	[13]
TRIUMF	1977	10 %	8.7 %	6.7 ns	–	$< 3.6 \times 10^{-9}$	[14]
LANL	1979	8.8 %	8 %	1.9 ns	37 mrad	$< 1.7 \times 10^{-10}$	[15]
LANL	1986	8 %	8 %	1.8 ns	87 mrad	$< 4.9 \times 10^{-11}$	[16]
LANL	1999	1.2 %*	4.5 %*	1.6 ns	17 mrad	$< 1.2 \times 10^{-11}$	[11]
PSI	≈ 2013	0.8 %	4.0 %	0.15 ns	19 mrad	$< 1 \times 10^{-13}$	MEG

The MEG experiment [12] (Figure 4) uses the secondary $\pi E5$ muon beam line extracted from the PSI (Paul Scherrer Institute) proton cyclotron, the most powerful continuous hadronic machine in the world (maximum proton current $I = 2.2$ mA). A 3×10^7 μ^+/s beam is stopped in a 205 μm slanted polyethylene target. The e^+ momentum is measured by a magnetic spectrometer, composed by an almost solenoidal magnet (COBRA) with an axial gradient field and by a system of sixteen ultra-thin drift chambers (from now on: DC). The e^+ timing is measured by two double-layer arrays of plastic scintillators (Timing Counter, from now on: TC): the external layer is equipped with two sections of 15 scintillating bars each, the internal one with 512 scintillating fibres. The γ energy, direction and timing are measured in a ≈ 800 l volume liquid xenon (from now on: LXe) scintillation detector. The LXe as scintillating medium was chosen because of its large light yield (comparable with that of NaI) in the VUV region ($\lambda \approx 178$ nm), its homogeneity and the fast decay time of its scintillation light (≈ 45 ns for γ's and ≈ 22 ns for α's) [17]. The LXe volume is viewed by 846 Hamamatsu $2''$ PMTs, specially produced to be sensitive to UV light and to operate at cryogenic temperatures. Possible water or oxigen impurities in LXe are removed by circulating the liquid through a purification system.
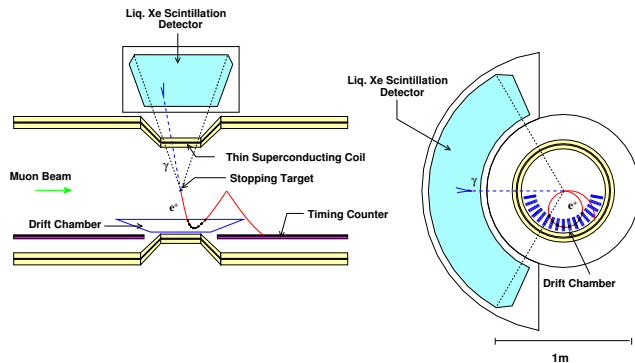
A FPGA-FADC based digital trigger system was specifically developed to perform a fast estimate of the γ energy, timing and direction and of the positron timing and direction; the whole information is then combined to select events which exhibit some similarity with the $\mu \rightarrow \mathrm{e}\gamma$ decay. The signals coming from all detectors are digitally processed by a 2 GHz custom made waveform digitizer system to identify and separate pile-up hits.

Figure 4. Layout of the MEG experiment.

Several calibration tools (LEDs, point-like α sources deposited on wires [18], Am-Be sources, Michel decays, through going cosmic μ's, a neutron generator, 55 MeV and 83 MeV γ's from charge exchange reaction $\pi^- \mathrm{p} \rightarrow \pi^0 \mathrm{n}$, γ-lines from nuclear reactions induced by a CW accelerator ...) are frequently used to measure and optimise the detector performances and to monitor their time stability. The experimental resolutions measured in summer of 2010 (the time of this conference) were: $\sigma_p/p = 0.75$ %, $\sigma_\phi = 8$ mrad and $\sigma_\theta = 11$ mrad for e^+'s, $\sigma_E/E = 2.1$ % and $\sigma_x = 5.5$ mm for γ's and $\sigma_{\Delta T} = 142$ ps for $\mathrm{e}^+ - \gamma$ relative timing. Significant improvements are expected in the following years, which should make these numbers closer to the Table 1 goals.

The data are analysed with a combination of blind and likelihood strategy. Events are pre-selected on the basis of loose cuts, requiring the presence of a track and $|\Delta T_{\mathrm{e}\gamma}| < 4$ ns. Preselected data are processed several times with improving calibrations and algorithms and events falling within a tight window ("blinding box", BB) in the $(E_\gamma, \Delta T_{\mathrm{e}\gamma})$ plane are hidden. The remaining pre-selected events fall in "sideband" regions and are used to optimise the analysis parameters, study the background and evaluate the experimental sensitivity under the zero signal hypothesis. When the optimisation procedure is completed, the BB is opened and a maximum likelihood fit is performed to the distributions of five kinematical variables $(E_{\mathrm{e}^+}, E_\gamma, \Delta T_{\mathrm{e}\gamma}, \theta_{\mathrm{e}\gamma}$ and $\phi_{\mathrm{e}\gamma})$, in order to extract the number of Signal (S), RMD (R) and Accidental Background (B) events. Probability Distribution Functions (PDFs) are determined by using calibration measurements and MC simulations for S, theoretical formulae folded with experimental resolution for R[1] and sideband events for B. Michel positrons are used to calculate the normalization factor needed to convert an upper limit on S into an upper limit on $BR(\mu^+ \rightarrow \mathrm{e}^+\gamma)$. The analysis procedure was applied for the first time to the data collected in 2008, with reduced statistics and not optimal apparatus performances, and a first result was published [21]: $BR(\mu \rightarrow \mathrm{e}\gamma) \leq 2.8 \times 10^{-11}$ at 90 % C.L., about twice worse than the present bound [11]. In 2009 a larger and better quality data sample was collected and the analysis procedure was repeated. 370 events fell in the BB, defined as 48 MeV $< E_\gamma <$ 58 MeV and $|\Delta T_{\mathrm{e}^+\gamma}| < 0.7$ ns. Figure 5 shows the results of the maximum likelihood fit to the five kinematical variables for 2009 data. The (preliminary !) best fit result was $S = 3.0$ and $R = 35$. The analysis was repeated by different groups varying the approach (frequentistic and bayesian), the handling of sideband information and the estimated numbers of R and B in the BB; the best fit value for S ranged between 3 and 4.5 and the corresponding 90 % C.L. interval was $(0, 15)$; then, a (preliminary !) 90 % C.L. upper limit was set: $BR(\mu \rightarrow \mathrm{e}\gamma) \leq 1.5 \times 10^{-11}$, close to the current experimental limit. The experiment is expected to run at least until the end of 2012; this will produce a huge increase in statistics and, taking into account further improvements of

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[1] In RMD events, the kinematical boundaries introduce a correlation between E_{e^+}, E_γ and positron-gamma relative angle which must be taken into account in the PDF.
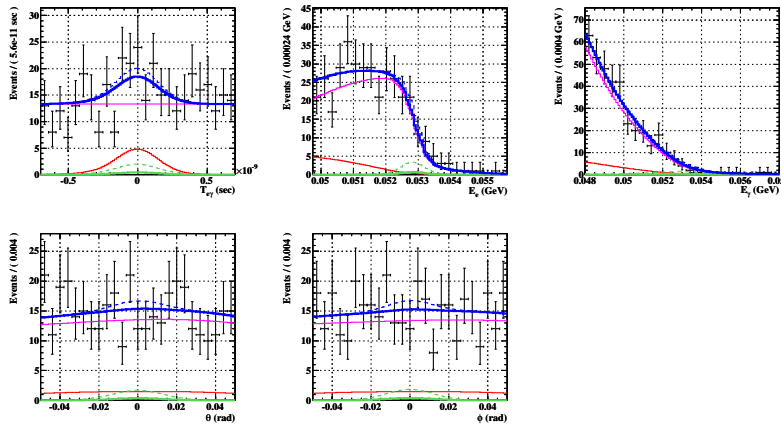
Figure 5. Results of MEG maximum likelihood analysis. From top to bottom, from left to right: $\Delta T_{e\gamma}$, E_{e^+}, E_γ, $\theta_{e\gamma}$, $\phi_{e\gamma}$. Signal PDFs are in green, RMD PDFs in red, accidental background PDFs in magenta and total PDFs in blue. The black dots represent the experimental data and the dashed lines the 90 % C.L. upper limit on the number of signal events.

detector performances, will allow to reach a sensitivity $\sim 5 \times 10^{-13}$, $(30 \div 50)$ times better than the present upper bound.

2.3. Search for $\mu \to 3e$ decay

In the $\mu \to 3e$ decay the final state is composed by charged particles only. In many models, for instance SUSY-GUT, its BR is related to the $\mu \to e\gamma$ BR by a factor α, since the e^+e^- pair originates from a virtual photon; then, a sensitivity of $\sim 10^{-15}$ is needed to be competitive with a $\sim 10^{-13}$ sensitivity for $\mu \to e\gamma$. The search for the $\mu \to 3e$ process is based on kinematical criteria: all possible triplets of electron tracks are formed and $\mu \to 3e$ candidate events are selected requiring a zero total momentum, an invariant mass equal to m_μ and three simultaneous tracks originating from a common vertex. The present limit $BR(\mu^+ \to e^+e^-e^+) < 10^{-12}$ at 90 % C.L. [19] dates back by 25 years, but no new $\mu \to 3e$ experiment is presently planned. However, one can ask whether this limit could be significantly improved by using the presently available beam intensity $> 10^8 \mu/s$. As for $\mu \to e\gamma$, the background for $\mu \to 3e$ decay is dominated by accidental events, coming from the coincidence of a Michel e^+ and a e^+e^- pair produced by a γ conversion in the detector or a Bhabha scattering of an other Michel e^+; the accidental event rate is proportional to R_μ^2. Since only charged particles must be detected, an electromagnetic calorimeter, with its limited resolution, is not needed and the apparatus can be based on a magnetic spectrometer only, which, however, must have a large acceptance and a relatively low momentum threshold. Morever, with intense μ beams a very high hit rate is expected in the tracking system, which causes problems of dead time, trigger and pattern recognition. With the present detector technologies a significant improvement of the limit [19] is not easy to foresee.

2.4. Search for $\mu \to e$ conversion: Mu2E and COMET/PRISM experiments

The $\mu \to e$ conversion is a LFV process which might take place when negative muons are captured by matter. The typical destiny of a stopped μ^- is to form a muonic atom with a nucleus; then, it can be absorbed by the nucleus or decay in orbit according to the usual Michel process. However, if the leptonic number can be violated, the muon can experience a coherent flavour change in the nuclear field, with the final state formed by a single electron only; this process is usually named $\mu \to e$ conversion. The theoretical predictions for $\mu \to e$ conversion range by some orders of magnitude, depending on the process-mediating mechanism: in SUSY frames this transition is dominated by the exchange of a virtual photon and $BR(\mu \to e) \sim 10^{-(2 \div 3)} BR(\mu \to e\gamma)$, but in other models more exotic schemes, like Leptoquarks, Heavy Neutrinos, a second Higgs doublet etc. are invoked. Note that some of these mechanisms can contribute to the $\mu \to e\gamma$ decay too,

but some others not; therefore, the search for $\mu \to e\gamma$ decay and for $\mu \to e$ conversion provide complementary information. The present upper limit for $\mu \to e$ conversion in Au was obtained by the SINDRUM II experiment [20]: $BR\,(\mu \to e) \le 7 \times 10^{-13}$ at 90 % C.L.

In $\mu \to e$ conversion experiments a pulsed negative muon beam is formed from the decay of pions produced in proton collisions on fixed target and brought to stop in a layer of thin targets, where muon captures take place. The signal is a single monochromatic electron, with energy $E_e = m_\mu - E_B - E_R$ where m_μ is the muon mass, E_B is the muonic atom binding energy and E_R is the nucleus recoil energy. Since E_B and E_R depend on the capturing nucleus (as a first approximation, $E_B \propto Z^2$ and $E_R \propto A^{-1}$), the E_e value is ≈ 105 MeV for Al and 104.3 MeV for Ti. Note that the $\mu \to e$ conversion experimental sensitivity is not limited by the accidental background, because there is only one particle in the final state. Electrons in the signal energy window can originate from a couple of beam-related sources, the muon decay in orbit (MDIO) and the radiative muon (RMC, $\mu^- A \to \nu_\mu \gamma A$) and pion (RPC, $\pi^- A \to \gamma X$) captures. The RPC background can be taken under control by reducing the π contamination in the beam ("beam purity") by means of collimators inserted within the beam line and appropriate transport systems and the MDIO by selecting a muon beam with momentum $p_\mu < 70$ MeV/c, in order to reduce the Lorentz boost of decaying electrons. Moreover, since the lifetime of muonic atoms is some hundreds of ns (for instance 860 ns in Al), one can use a pulsed beam with very short buckets (~ 100 ns), leave pions decay and search for $\mu \to e$ conversion in a delayed time window. This requires, however, that the fraction of protons arriving on the pion production target between two separate bunches is as small as possible ($\sim 10^{-9}$): this "extinction factor" is one of the key parameters in determining the final sensitivity of a $\mu \to e$ conversion experiment.

Presently there are two projects of $\mu \to e$ conversion experiments, Mu2E at Fermilab (Illinois) and COMET/PRISM at J-PARC (Japan), the latter one scheduled in two distinct stages.

Mu2E [22] (Figure 6) is derived from the original MECO project [23], which was cancelled by budget reasons in 2005. The experiment will use a 8 GeV proton beam, with 100 ns bunches, to produce a π/μ beam; then, secondary particles will be transported through a curved solenoid, arranged to single out μ^- and reject antiprotons and positive and neutral particles.
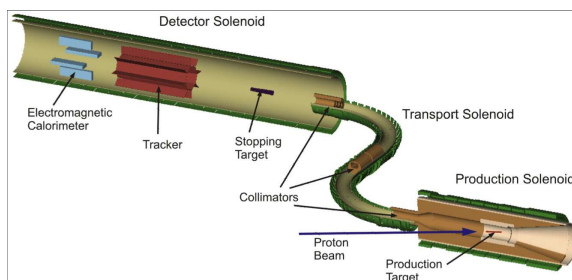

Figure 6. Layout of the Mu2E experiment.

Selected negative muons will be brought to stop in thin Al foils and electrons from muon decay or capture will be looked for by using a high resolution (900 keV FWHM at 105 MeV/c) spectrometer, with a graded magnetic field, and an electromagnetic calorimeter. The magnetic field configuration would allow to select high energy ($p > 90$ MeV/c) and recover backward going electrons.

A total number of stopped muons $N_\mu \approx 10^{18}$ is foreseen in two years of data taking; assuming $BR\,(\mu \to e) = 10^{-15}$ and a 10^{-9} extinction factor, a 40 events signal is expected, with an estimated background < 0.5 events. On the other hand, in case of no signal Mu2E would set an upper limit: $BR\,(\mu \to e) \le 6 \times 10^{-17}$.

At J-PARC accelerator facility a two stage search for $\mu \to e$ conversion is planned: the goal of the first phase is to reach a sensitivity on $BR\,(\mu \to e) < 10^{-16}$ in the COMET experiment, that of the second phase is to improve this sensitivity by two orders of magnitude in the PRISM/PRIME experiment. COMET (COherent Muon to Electron Transition, Figure 7) will use a 8 GeV pulsed proton beam with $\approx 1\ \mu$s bunch separation for two years, with a total number of stopped

muons $N_\mu = 1.5 \times 10^{18}$. The experiment is conceptually similar to Mu2E, with two main differences: a) a C-shape instead of the Mu2E S-shape transport solenoid and b) a curved solenoidal spectrometer instead of the Mu2E straight solenoidal spectrometer. The C-shaped solenoid was chosen to optimise the μ momentum selection by coupling it with a suitable vertical magnetic field and the curved spectrometer to reduce the single chamber tracking rate. With an estimated background of 0.4 events, COMET would be sensitive to $\mu \to e$ $BR \geq 3 \times 10^{-17}$. In the second stage the π decay and μ transport sections of the COMET experiment will be modified and coupled with a very intense μ beam source, PRISM (Phase Rotation Intense Slow Muon source, Figure 8) [25]. A beam intensity of $10^{11 \div 12}$ μ/s is aimed, with a central momentum of 68 MeV/c. The π/μ beam will be passed through a μ storage ring, equipped with a FFAG (Fixed Field Alternating Gradient) synchrotron, where the survived pions will decay and the momentum spread will be reduced from the original ± 30 % to ± 3 %. A so small energy spread would allow to stop enough muons in very thin foils, minimising the resolution worsening due to electron interactions in the target. A final momentum resolution of 350 keV FWHM at 105 MeV/c is envisaged. The combined effect of the increased resolution and of the intense μ beam would allow to be sensitive to a $\mu \to e$ BR $< 10^{-18}$. The experimental demonstration of the phase rotation in the PRISM-FFAG ring is underway.

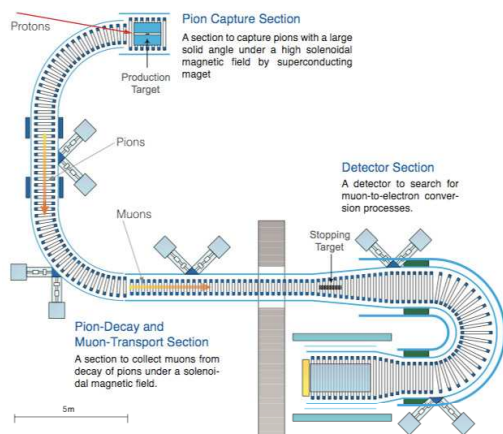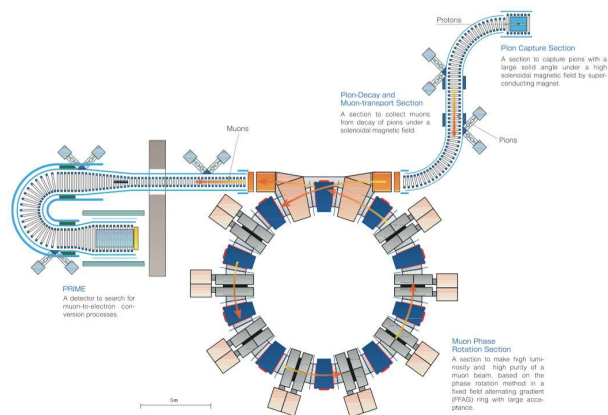**Figure 7.** Layout of the COMET experiment.

Figure 8. Layout of the PRISM/PRIME experiment.

3. The tauonic channel

3.1. Generalities

The τ lepton is in principle a very promising source of LFV decays. Thanks to the large τ mass ($m_\tau \approx 1.78$ GeV ≈ 18 m_μ) many LFV channels are open: $\tau \to \mu\gamma$, $\tau \to e\gamma$, $\tau \to 3$ leptons (from now on $\tau \to 3\,\ell$), $\tau \to$ lepton + hadron(s) (from now on $\tau \to \ell + h(s)$) .. and in many SUSY and SUSY-GUT schemes the BRs are enhanced with respect to the muon LFV decays by a factor $(m_\tau/m_\mu)^\alpha$, $\alpha \geq 3$. Therefore one expects ([26], [27]): $BR(\tau \to \mu\gamma)/BR(\mu \to e\gamma) \approx 10^{(3 \div 5)}$ and experiments searching for $\tau \to \mu\gamma$ must reach a sensitivity $\sim 10^{-(9 \div 10)}$ to be competitive with dedicated μ LFV decay experiments. The BR of other τ LFV processes are generally expected to be lower than that of $\tau \to \mu\gamma$: for instance, $\tau \to e\gamma$ is usually disfavoured because of the small coupling between first and third generation and $\tau \to 3\,\ell$ is suppressed by a factor α due to an intermediate virtual photon. However, in models with heavy Dirac neutrinos or inverted slepton hierarchy values of $BR(\tau \to e\gamma) > BR(\tau \to \mu\gamma)$ are predicted. We remind again that the complementarity between the various LFV channels is essential in the search for new physics and for a profound understanding of the flavour structure.

However, since τ lifetime is only 2.9×10^{-13} s, τ beams can not be realized and large τ samples must be obtained in intense electron or proton accelerators, operating in an energy range where the τ production cross section is large and coupled with refined detectors, able to select and reconstruct rare events. The first experiments to satisfy these requirements are that based on B factory machines, BaBar [28] at SLAC (USA) and Belle [29] at KEKB (Japan). Both experiments operate at a total Center of Mass (CM) energy at the peak of the $Y(4S)$ resonance ($\sqrt{s} = 10.54$ GeV); at this energy $\sigma\,(\mathrm{e^+e^-} \to \tau^+\tau^-) \approx 0.9\,\sigma\,(\mathrm{e^+e^-} \to b\bar{b})$ so that the B factories are τ factories too. Moreover, in $\mathrm{e^+e^-}$ colliders the initial state is very well known and high resolution detector technologies are employed. Belle and BaBar are large central detectors, equipped with a combination of tracking devices, particle identification (PID) systems, vertex detectors and calorimeters. The main difference is related to the PID technique, based on a threshold Čerenkov counter, the time-of-flight and the tracker dE/dx for Belle and on a RICH and dE/dx in the trackers for BaBar. Several LFV decays are searched for: the gamma-leptonic $\tau \to \ell\gamma$ ($\ell = \mu, \mathrm{e}$), the purely leptonic $\tau \to 3\,\ell$ and the leptonic-hadronic ones $\tau \to \ell + h(s)$.

3.2. Search for LFV τ decays with Belle and BaBar

The Belle and BaBar upper limits on τ LFV decays continuously improved since 2004, according to the increase of the collected and analysed data samples. In all these searches the event world is divided in two hemispheres, defined by the thrust axis: the "tag side" and the "signal side". Events with $\tau^+\tau^-$ pairs are selected by identifying in the tag side a standard SM τ decay, while possible LFV decays are searched for in the signal side. The tagging is based on the purely leptonic $\tau \to \ell\nu\bar{\nu}$ decay or on decays involving a ν and at least one prong. In the signal side LFV candidates are preselected according to the expected topology of the process under study: for $\tau \to \ell\gamma$ one single muon or electron and at least one γ; for $\tau \to 3\,\ell$ all possible triplets of charged leptons and for $\tau \to \ell + h(s)$ an isolated lepton plus the combination of tracks expected for the selected hadron(s) (for instance, for $\tau \to \ell + K_S^0$ a lepton and a $\pi^+\pi^-$ pair). Preliminary topological cuts are applied and then a blind strategy is used: the signal region is hidden and sideband data and MC simulations are used to estimate the background and optimise the selection criteria. The efficiency for LFV searches is usually $\sim 3 \div 10$ %.

In the $\tau \to \ell\gamma$ searches the main background comes from the coincidence of a γ from initial (ISR) or final state radiation and an isolated lepton from the usual τ decay. Radiative processes like $\mathrm{e^+e^-} \to \mu^+\mu^-\gamma$ or $c\bar{c}$ pairs are also relevant background sources. It is important to note that the ISR represents an irreducible and unavoidable noise, which limits the sensitivity of these experiments to $\tau \to \ell\gamma$ decays. We will discuss later this point. The BaBar data sample analysed for $\tau \to \ell\gamma$ search corresponds to a total luminosity $\int \mathcal{L}dt > 500$ fb^{-1}; the calculated number of τ decays is $(963 \pm 7) \times 10^6$. After applying all preliminary selections, the $\tau \to \mu\gamma$ and $\tau \to \mathrm{e}\gamma$ candidate events are studied in the $(\Delta E, M_{\ell\gamma})$ plane, where ΔE is the difference between the total energy of the $(\ell + \gamma)$ pair and the beam energy in the CM frame and $M_{\ell\gamma}$ is the $(\ell + \gamma)$ pair invariant mass. For a LFV τ decay, $\Delta E = 0$ and $M_{\ell\gamma} = M_\tau$, but because of the finite resolution one must consider a two-dimensional region. Events in a $3\,\sigma$ window are blinded and the expected background is evaluated; then, the blinded region is opened and one looks at the events observed in the 2 and $3\,\sigma$ windows around the nominal values. Figure 9 shows the distribution of selected events in the $(\Delta E, M_{\ell\gamma})$ plane for $\tau \to \mu\gamma$ (left) and $\tau \to \mathrm{e}\gamma$ (right): the red dots are experimental points, the black ellipses are the $2\,\sigma$ contours and the yellow and green regions contain 90 % and 50 % of MC signal events. Since the number of measured events is in agreement with the expected background, the following limits are set: $BR\,(\tau \to \mu\gamma) \le 4.4 \times 10^{-8}$ and $BR\,(\tau \to \mathrm{e}\gamma) \le 3.3 \times 10^{-8}$ [30] at 90 % C.L. The Belle data sample for this search is almost equivalent (954×10^6 τ decays) and the strategy is quite similar. Figure 10 shows the distributions of Belle events in the $(M_{\ell\gamma}, \Delta E)$ plane for $\tau \to \mu\gamma$ (left) and $\tau \to \mathrm{e}\gamma$ (right). The dashed and dotted-dashed ellipses represent the $3\,\sigma$ and $2\,\sigma$ contours,
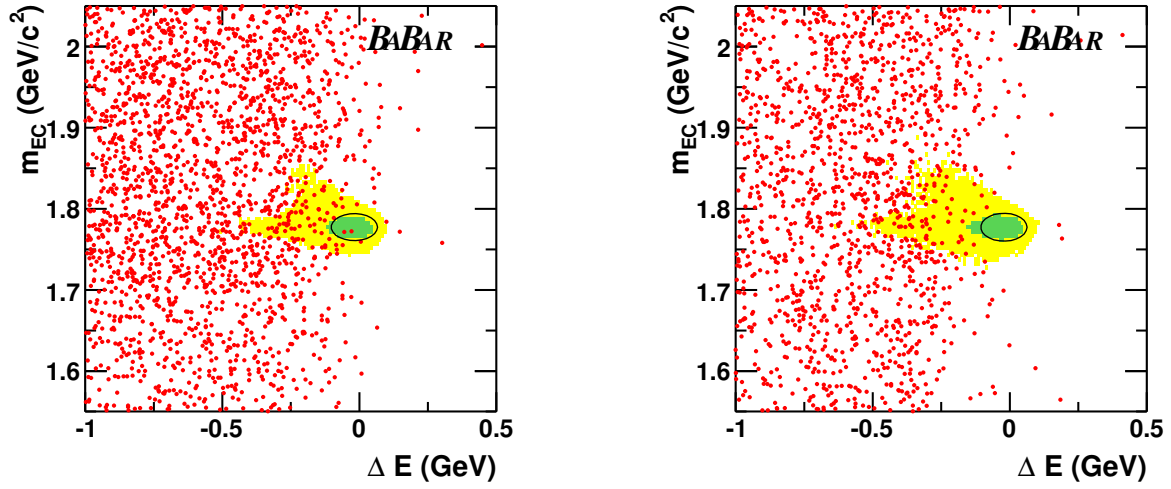
Figure 9. Results of the BaBar search for $\tau \to \mu\gamma$ (left) and $\tau \to e\gamma$ (right) LFV decays.

the diagonal dashed lines define the 2 σ band of the shorter ellipse axis and the shaded boxes indicate the signal MC events. The number of signal events was extracted by a maximum

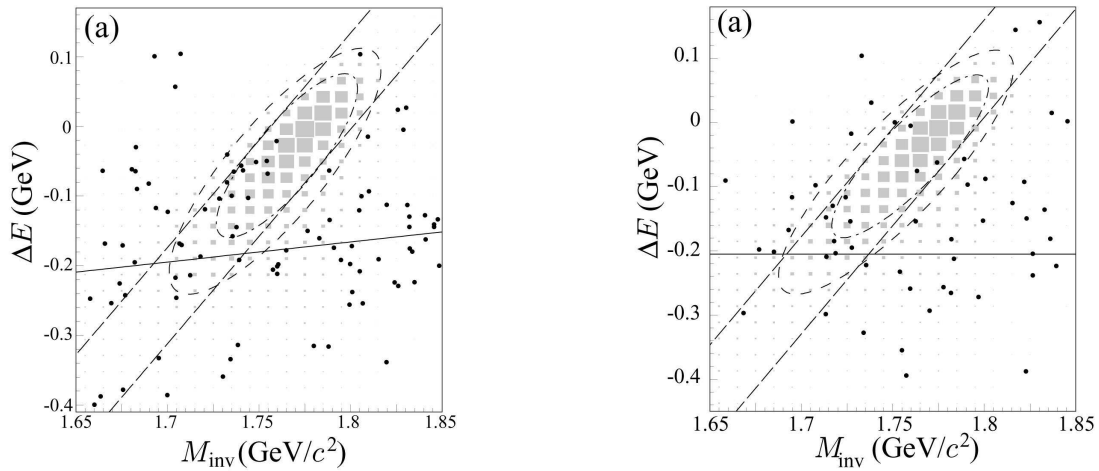**Figure 10.** Results of the Belle search for $\tau \to \mu\gamma$ (left) and $\tau \to e\gamma$ (right) LFV decays.

likelihood fit obtaining $-3.9^{+3.6}_{-3.2}$ for $\tau \to \mu\gamma$ and $-0.14^{+2.18}_{-2.45}$ for $\tau \to e\gamma$; the corresponding limits are $BR(\tau \to \mu\gamma) \leq 4.5 \times 10^{-8}$ and $BR(\tau \to e\gamma) \leq 1.2 \times 10^{-7}$ [31] at 90 % C.L.

The search for $\tau \to 3\,\ell$ decay is potentially more interesting from the experimental point of view since with only charged particles in the final state the mass resolution is excellent and there are no irreducible sources of noise. The search strategy for both experiments is based on the distribution of events in the $(M_{3\ell}, \Delta E)$ plane, where $M_{3\ell}$ is the invariant mass of each possible 3-leptons combination having the required sign of charge. The main background comes from $q\bar{q}$ and Bhabha pairs, but since these events can be efficiently rejected by appropriate cuts, the residual noise in the signal region ($M_{3\ell} \approx M_\tau$ and $\Delta E \approx 0$) is very low. Table 2 shows the results of the BaBar (468 fb^{-1} data sample) [32] and Belle (782 fb^{-1} data sample) [33] searches for $\tau \to 3\,\ell$ LFV decays[2]. The 90 % C.L. upper limits on LFV decay BRs range from 1.8 to

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[2] Results are shown for τ^-, but charge conjugation is implied: then, for instance $\tau^- \to e^- e^+ e^-$ includes

Table 2. Efficiencies, number of expected background and observed events and 90 % C.L. BR upper limits for $\tau \to 3\,\ell$ LFV searches for BaBar and Belle (adapted from [32] and [33]).

Mode	BaBar				Belle			
	$\epsilon\,(\%)$	$N_{\rm bkg}$	$N_{\rm obs}$	BR^{90}	$\epsilon\,(\%)$	$N_{\rm bkg}$	$N_{\rm obs}$	BR^{90}
$e^-e^+e^-$	8.6 ± 0.2	0.12 ± 0.02	0	2.9×10^{-8}	6.0	0.21 ± 0.15	0	2.7×10^{-8}
$\mu^-e^+e^-$	8.8 ± 0.5	0.64 ± 0.19	0	2.2×10^{-8}	9.3	0.04 ± 0.04	0	1.8×10^{-8}
$\mu^+e^-e^-$	12.7 ± 0.7	0.34 ± 0.12	0	1.8×10^{-8}	11.5	0.01 ± 0.01	0	1.5×10^{-8}
$e^+\mu^-\mu^-$	10.2 ± 0.6	0.03 ± 0.02	0	2.6×10^{-8}	10.1	0.02 ± 0.02	0	1.7×10^{-8}
$e^-\mu^+\mu^-$	6.4 ± 0.4	0.54 ± 0.14	0	3.2×10^{-8}	6.1	0.10 ± 0.04	0	2.7×10^{-8}
$\mu^-\mu^+\mu^-$	6.6 ± 0.6	0.44 ± 0.17	0	3.3×10^{-8}	7.6	0.13 ± 0.06	0	2.1×10^{-8}

3.3×10^{-8} for BaBar and from 1.5 to 2.7×10^{-8} for Belle, depending on the individual channel. Finally, both Belle and BaBar searched for LFV $\tau \to \ell + h(s)$ decays, where a charged lepton of the same sign of the τ is emitted together with a combination of pseudo-scalar or vector hadrons (e.g. $\tau \to \ell\pi^0$, $\tau \to \ell\omega$, $\tau \to \ell\pi^+\pi^-$...). Many of these channels are very clean, without irreducible backgrounds. No evidence for LFV decays was found and the 90 % C.L. upper limits on BRs lie between 2 and 20×10^{-8} (for summaries see [34] and [35]).

Combined analyses were also performed to obtain global Belle+BaBar 90 % C.L. upper limits on LFV decays, both in bayesian and frequentistic framework. For a 2-years ago review see [10].

4. Future perspectives
4.1. Introduction
Future accelerators, like NUFACT [36] or Project X [37], are expected to deliver high intense ($\sim 10^{15}$ p/s) proton beams with energy of tens of GeV or higher; then, secondary muon beams up to $\sim 10^{14}$ μ/s could be available in the future. Moreover, two Super B projects, one in Italy [38] and one in Japan [39], which would reach luminosities $\sim 10^{35 \div 36}$ cm^2 s^{-1}, are under study and are expected to be on-line in some years. Since in both the muonic and tauonic channel one can expect very large improvements in data statistics, a spontaneous question arises: can the LFV searches take benefit from future high intensity machines ? If yes, at which level ?

4.2. Possible improvements in the muonic channel
As discussed before, the sensitivity of a $\mu \to e\gamma$ experiment is limited by the accidental background, whose rate is proportional to R_μ^2. Then, an increase in R_μ does not represent by itself an advantage, since it can cause a worsening of the signal-to-noise ratio. The $\sim 10^{-13}$ MEG projected sensitivity is a tough experimental challenge, since the required detector resolutions (Table 1) are at the limits of present technologies. Important detector improvements are needed to put the sensitivity to the $\mu \to e\gamma$ BR significantly below the MEG one. R&D studies are under way to gain an order of magnitude, taking advantage from the maximum beam intensity available at PSI ($\sim 10^8$ μ/s, possibly enhanced in the future) coupled with detector upgrades. Some proposed ideas are, for example, the use of high-resolution β spectrometers and of finely segmented targets. However, further improvements in sensitivity below 10^{-14} seem presently rather unlike. Similar considerations are valid for $\mu \to 3e$. In the $\mu \to e$ channel the situation is more promising, since the signal is an isolated electron, not affected by accidental background; then, the sensitivity is expected to increase significantly when high intensity machines will be

$\tau^+ \to e^+e^+e^-$ too.

on-line. However, very intense beams are also sources of problems, like high levels of radiation, large momentum spread etc. and several technical remarks must be taken into account. Detailed discussions of the potentialities of high intensity machines in the LFV muon decay searches and of the needed experimental solutions can be found in [40] and [41].

4.3. Potentialities of the SuperB projects

The Super B machines are projects of very intense e^+e^- machines, which would reach integrated luminosities $\int \mathcal{L}dt \approx (50 \div 75)$ ab^{-1}, ~ 50 times larger than the combined Belle+Babar data sample. With such a big increase in luminosity one could expect a sensitivity improvement on the LFV searches by two orders of magnitude. However, it is necessary to remind that the sensitivity scales as $1/\int \mathcal{L}dt$ only for a background-free experiment; otherwise, it scales only as $1/\sqrt{\int \mathcal{L}dt}$ and the expected improvement is much less significant. In the BaBar and Belle searches, the "golden" channel $\tau \to \ell\gamma$ is affected by a small, but not negligible background and the ISR represents an irreducible noise. Extrapolating the present limits on the basis of the increasing luminosity only, one obtains a predicted sensitivity on $\tau \to \ell\gamma$ decays of $\sim 2 \times 10^{-9}$, not completely satisfactory. A factor two improvement is expected by the use of polarized beams and of appropriate analysis selections and refinements in detector technologies are foreseen [42]. On the other hand, the purely leptonic channel $\tau \to 3\,\ell$ is potentially more promising, since background-free searches seem feasible; no background events were observed by Belle and BaBar and the expected number of noise events was $N_{\mathrm{bkg}} < 1$ (Table 2). Super B projects aim to reach a sensitivity $\sim 2 \times 10^{-10}$ on $\tau \to 3\,\ell$ LFV decays. Finally, the $\tau \to \ell + h(s)$ decays represent an intermediate situation, since they are almost background free but the efficiencies are largely different from channel to channel. The predicted sensitivities are in the range $(2 \div 6) \times 10^{-10}$.

4.4. LHC

τ leptons are also copiously produced in the LHC accelerator, mainly via B and D decays and, to a much lesser extent, via W and Z^0 decays. Detailed studies of possible detection of $\tau \to \mu\gamma$ decay in CMS and ATLAS were performed ([43], [44]): because of the unavoidable background, the sensitivity to this channel is not competitive with that of B factory experiments. The $\tau \to 3\mu$ channel looks more promising [45], even if only τ's from W or Z^0 decays could produce LFV processes acceptable by the trigger schemes of LHC experiments. (Dedicated trigger algorithms with improved efficiency for muons from decay of τ's originating from B or D mesons are under study.) Assuming that the backgrounds can be effectively suppressed by appropriate selection criteria, one obtains 95 % C.L. upper limits $(3.8 \div 7) \times 10^{-8}$ for an integrated luminosity of $(10 \div 30)$ fb^{-1}, comparable with the sensitivity levels reached by B factory experiments.

5. Summary and conclusions

It's an exciting era for LFV searches: a) the MEG experiment obtained a new limit on $BR\,(\mu^+ \to e^+\gamma)$ and is now starting a long term stable data taking to reach a projected sensitivity $\sim 5 \times 10^{-13}$; b) two $\mu \to e$ conversion experiments (Mu2E and COMET) are expected to go on-line around 2016, with expected sensitivities $\leq 10^{-16}$; c) B factory based experiments (Belle and BaBar) set first significant limits on LFV τ decay BRs, at level of few $\times10^{-8}$; d) a factor $(10 \div 100)$ improvement in sensitivity on these searches is expected from SuperB projects.

Even more significant results could be obtained if projected high intensity accelerators will become a reality and detector technologies will be upgraded. In any case, since several theoretical predictions of LFV processes are within the reach of present or near future experiments, the discovery of LFV in the charged sector is not a dream, but a realistic hope.

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