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The "Golden" cLFV channels $\mu \rightarrow e\gamma$ and $\mu \rightarrow eee$ — the high-intensity frontier

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Abstract The muon as a laboratory for studying charged lepton-flavour violation (cLFV) has proven to be one of the most sensitive areas to probe for "New Physics", due to the muon's copious production rate and relatively long lifetime. The search at the intensity frontier with precision-type experiments is complementary to the search for new particles at the high-energy frontier of TeV colliders. Of the three "golden" muon channels: $\mu \rightarrow e\gamma$, $\mu \rightarrow 3e$ and $\mu \rightarrow e\ conversion$, an overview of the status of the coincidence experiments MEG, together with the latest results, which constitute the most stringent limit to date on this decay and the recently initiated Mu3e experiment, will be given.

Keywords Muon decay · Lepton flavour violation · MEG · Mu3e

1 Introduction

Lepton-flavour violation (LFV) is a key area of investigation in the search for "New Physics" beyond the Standard Model (SM) and is seen as a complementary approach to the direct searches at the high-energy frontier of TeV-scale colliders. Since the original experimental confirmation of flavour mixing in the neutral lepton sector, in the form of neutrino oscillations [1–3] and with it, the consequence that lepton flavour is a broken symmetry, the impetus in the charged lepton sector has also increased with next generation experiments such as MEG II ($\mu \rightarrow e\gamma$), Mu3e ($\mu \rightarrow 3e$) both at PSI in Switzerland, COMET ($\mu \rightarrow e$) at J-PARC in Japan and Mu2e ($\mu \rightarrow e$) at Fermilab in the US, all in the planning. Also, the next generation

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Table 1 Current experimental limits on LFV muon decays

Channel	Experiment	B-Limit (90 %C.L.)	Ref.
$\mu \to e\gamma$	MEG	$\leq 2.4 \cdot 10^{-12}$	[4]
$\mu \to 3e$	SINDRUM	$\leq 1.0 \cdot 10^{-12}$	[5]
$\mu Au \to eAu$	SINDRUM II	$\leq 7 \cdot 10^{-13}$	[6]

B-factories SuperKEKB + Belle II in Japan and Super-B in Italy, which will address the cLFV tau decays.

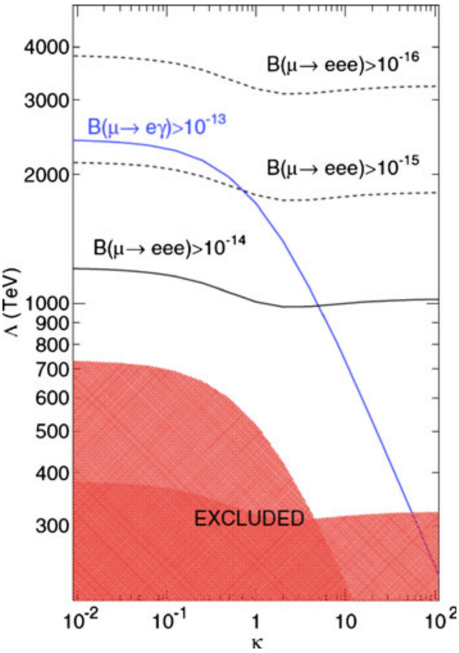
Despite the overwhelming success of the SM being one of the most tested theories of nature, there are however still recognized deficiencies, which have formed the general opinion that it be seen rather as a low-energy manifestation of a more fundamental theory at higher energies, in which mixing or flavour changing can be naturally introduced by the extra degrees of freedom given by the additional particles in the high-energy sector. In most such classes of models beyond the SM, a sizable fraction of the LFV parameter-space is predicted to be experimentally accessible to both the current and next-generation experiments.

2 The "Golden" muon channels and "New Physics"

The muon is considered as one of the most sensitive probes for studying cLFV due to its copious production rate and relatively long lifetime, nevertheless for the next generation experiments stopping rates in excess of the world's most intense muon beams (Order 10^8 muons/s) at the Paul Scherrer Institut PSI are required. The inclusion of finite but tiny neutrino masses into the SM gives predictions for cLFV muon channels which are far beyond the experimental reach of $O(10^{-54})$. Hence any signal seen by these experiments would be a clear and unambiguous sign of New Physics beyond the SM. Of the three so-called "Golden" Channels: $\mu \to e\gamma$, $\mu \to eee$ and $\mu \to e$ *conversion* predicted to have branching ratios within the reach of either next-generation experiments or as in the case of $\mu \to e\gamma$, seen in many classes of models to have the highest sensitivity to "New Physics", to be within the reach of the currently running MEG experiment at PSI, the first two are coincidence-type experiments. They are best probed using continuous (DC) muon beams, owing to the limiting combinatorial backgrounds, whereas in the $\mu \to e$ *conversion* experiments where a single high-energy electron is sought, high-intensity pulsed beams can be used. The current most stringent limits on these decays are summarized in Table 1.

In order to unravel the complex nature of lepton mixing and neutrino masses and to distinguish between the different beyond the SM-predictions for cLFV, all of the "Golden Channels" need to be investigated, as they are all subject to possible different forms of mediation in the interaction. Concentrating here on the coincidence channels $\mu \to e\gamma$ and $\mu \to eee$, a comparison of the physics potential, based on an effective model [7] is shown in Fig. 1. Both the sensitivity to and mass-reach attainability for "New Physics" mediating mass scales Λ are compared in terms of the dimensionless parameter κ, which represents the relative strength of either the photonic loop contributions, dipole couplings ($\kappa \ll 1$) or the 4-fermion couplings ($\kappa \gg 1$) of the interaction. Also shown are the projected branching ratio sensitivities, and exclusion zones from previous experiments (MEGA and SINDRUM).

Fig. 1 Shows the sensitivity of the two "coincidence experiments" to the mass-scale of "New Physics" Λ mediating those reactions (see text, figure taken from [7])



For small values of κ (dominant dipole contribution) the MEG experiment is clearly seen to be more sensitive by order $1/\alpha_{em}$(fine structure constant) and therefore any next-generation $\mu \rightarrow eee$ experiment must aim at a sensitivity better than 10^{-15} to be competitive over the whole range of κ. The current MEG-limit excludes mass-scales below approximately 1,000 TeV for small κ.

3 MEG experiment search for $\mu \rightarrow e\gamma$

The MEG experiment, located at the $\pi E5$ channel of the 590 MeV, 1.3 MW proton cyclotron facility of the Paul Scherrer Institut PSI in Switzerland, has been searching for the LFV-decay $\mu \rightarrow e\gamma$ since the end of 2008. The event signature from the stopped muon decay is a simple 2-body topology with a back-to-back photon and positron in the final state, coincident in time with each acquiring half the muon rest mass (52.8 MeV). The experiment employs one of the world's highest intensity surface muon beams capable of more than 10^8 muons per sec. together with a liquid xenon (LXe) scintillation detector and gradient-field superconducting positron spectrometer, incorporating ultra-thin tracking detectors and ultra-fast scintillation timing detectors to detect the photon and positron from the decay respectively, as shown in Fig. 2. A more detailed description is given in [8].

The five observables to be extracted from the detector information are: photon energy (E_γ), positron energy (E_e), azimuthal ($\phi_{e\gamma}$) and polar ($\theta_{e\gamma}$) relative angles and the relative time ($t_{e\gamma}$) between the positron and the photon. The photon energy, position and timing are precisely determined through information received from

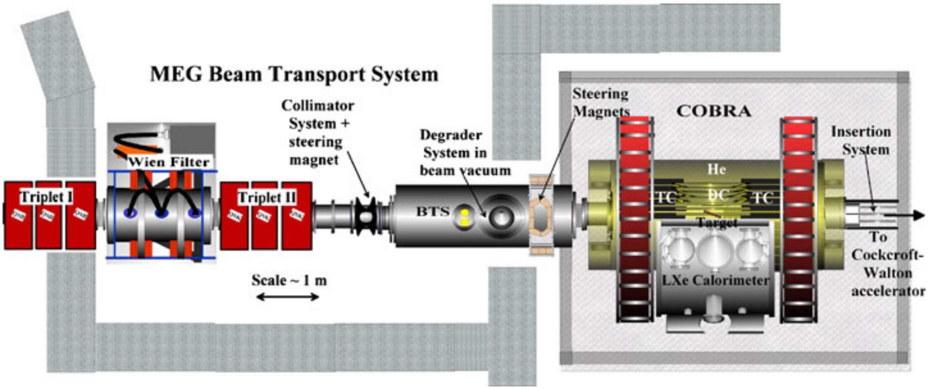
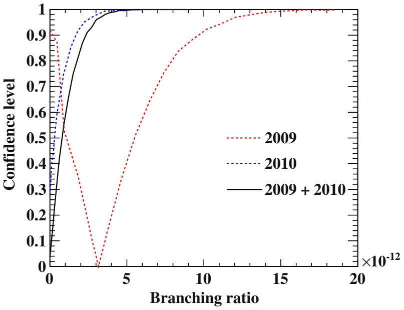


Fig. 2 Schematic of the MEG experiment, showing the beam elements: Wien-filter, collimator system and BTS superconducting transport solenoid and central degrader system. Coupled to these are the He-filled COBRA superconducting spectrometer, consisting of a gradient-field magnet and central target system. A set of radial drift chambers (DC) and two sets of fast scintillation counter arrays for timing and trigger purposes (TC) complete the positron tracking and detection side. The 900 l C-shaped liquid xenon (LXe) photon detector is also shown and the downstream insertion system allowing the remote insertion of our Cockcroft-Walton beam pipe, for calibration purposes

the 846 photomultiplier tubes (PMTs) immersed in the 900 litre volume of the LXe detector. A depth-dependent energy resolution of 1.9 % (depth>2 cm) and 2.4 % (depth<2 cm) respectively for signal photons of 52.8 MeV was measured using photons of 55 MeV from the pion charge-exchange reaction, while a positional resolution of 5 mm over the front-face and 6 mm in the depth was measured. On the positron side, the energy resolution is extracted from the kinematic edge of the Michel decay ($\mu^+ \rightarrow e^+ \nu \bar{\nu}$), while the response function is described by a triple Gaussian function with a resolution (core fraction) of 310 keV (80 %) and 320 keV (79 %) respectively for the 2009 and 2010 data samples. The respective angular and vertex resolutions, determined by a double-turn reconstruction, treating each turn as a separate track and comparing their differences at a common point of closest approach to the beam-axis, were found to be 6.7 (7.2) mrad in ϕ and 9.4 (11.0) mrad in θ respectively for 2009 (2010). The target vertex resolutions were 1.5 (2.0) mm along the beam-axis and 1.1 (1.1) mm vertically for 2009 (2010) data. The combining of both the positron and photon positional and angular resolutions results in a final angular resolution on the relative angle of 13.1 (14.0) mrad in $\phi_{e\gamma}$ and 14.5 (17.1) mrad in $\theta_{e\gamma}$ respectively for the 2009 (2010) data samples. The relative timing resolution $t_{e\gamma}$, determined from the simultaneously measured radiative decay muons in the E_γ side-band yields 146 (122) ps for the 2009 (2010) data.

3.1 Combined analysis of 2009 and 2010 data

The presented combined 2009+2010 results constitute a total of $1.8 \cdot 10^{14}$ stopped muons and include improvements to several aspects: the relative detector alignment, magnetic field map, treating of positron variable correlations and improved likelihood tools and methods. The number of $\mu \rightarrow e\gamma$ events as well as radiative muon



Data set	$\mathcal{B}_{\mathrm{fit}}$	LL	UL
2009	3.2×10^{-12}	1.7×10^{-13}	9.6×10^{-12}
2010	-9.9×10^{-13}	–	1.7×10^{-12}
2009 + 2010	-1.5×10^{-13}	–	2.4×10^{-12}

Fig. 3 *Left* Confidence intervals for the $\mu \to e\gamma$ branching ratio $\mathcal{B}$ versus data sets analyzed, *right* fit results—best estimates and cofindence intervals at 90 % C.L. of $\mathcal{B}(\mu \to e\gamma)$

decay (RMD) and background events in the 5-D central analysis region, defined by $48 \leq E_\gamma \leq 58$ MeV, $50 \leq E_e \leq 56$ MeV, $|t_{e\gamma}| \leq 0.7$ ns, $|\theta_{e\gamma}| \leq 50$ mrad, $|\phi_{e\gamma}| \leq 50$ mrad, is determined from a maximum likelihood analysis. The probability density functions (PDFs) used are predominantly based on measured response functions from data. The use of side-band data in estimating the number of RMD and background events is valid since the expected background in the central analysis region is also dominated by accidentals. Such issues as the photon resolution position dependence or positron track-quality are taken into account on an event-by-event basis. The confidence intervals on the number of signal events is calculated by a frequentist method with profile likelihood-ratio ordering. Finally, the sensitivity of the experiment with a null signal hypothesis was determined by toy Monte-Carlo experiments to be $3.3{\cdot}10^{-12}$ (2009), $2.2{\cdot}10^{-12}$ (2010) and $1.6{\cdot}10^{-12}$ (2009+2010), consistent with the branching ratio upper limit derived from the side-bands.

The results of the likelihood fit to the central region, post optimization of the analysis procedure, background study and unblinding are given in the table of Fig. 3, together with plots of the confidence intervals for the $\mu \to e\gamma$ branching ratio $\mathcal{B}$. The final result of $\mathcal{B}(\mu \to e\gamma) \leq 2.4{\cdot}10^{-12}$ at 90 % C.L. constitutes the most stringent limit on this decay to date and improves the previous limit by a factor of five.

The 2011 run was also successfully completed doubling the total data statistics, with the analysis currently being pursued. The MEG experiment is expected to continue until the end of 2012 or early 2013 enabling one to explore the 10^{-13} B-region. R&D efforts are also underway for MEG II aiming at an order of magnitude improvement in the sensitivity reach.

4 Mu3e experiment $\mu \to eee$

The next-generation $\mu \to eee$ search is in the planning; a Letter-of-Intent was submitted to the PSI PAC in 2012 and is to be followed by a proposal in 2013. The ambitious goal of reaching a sensitivity of 10^{-16} at 95 % C.L. [9] is to be sought after in a staged approach, with the initial stage I experiment, aiming at a sensitivity of 10^{-15}, foreseen to be undertaken at PSI's $\pi E5$ channel, while for the final goal, a muon beam rate in the GHz-range is required. The novel idea of using the SINQ spallation neutron source target window as a source for a high-intensity surface muon beam (HiMB) is currently under study at PSI and initial results look promising. The ultimate goal constitutes an improvement of four orders of magnitude over the previous best limit attained by the SINDRUM experiment [5] and will allow models involving new particles, such as Supersymmetry, extended Higgs models with new scalar bosons or models with extra dimensions, to be tested with unprecedented sensitivity as demonstrated in Fig. 1. Despite the lower sensitivity compared to the MEG experiment in the lower κ-range (c.f. Fig. 1) the search for the $\mu \rightarrow eee$ decay is considered experimentally easier than that of $\mu \rightarrow e\gamma$, due to the reduction of the combinatorial background by the presence of three particles required in the final state.

4.1 Experimental signature, backgrounds and experimental considerations

The decay signature for a positive muon is three charged particles in the final state, two positrons and an electron, showing opposite curvature in a magnetic field. These must be coincident in time, be derived from the same vertex and the topology should be co-planar. Furthermore, the vectorial sum of the momenta must vanish, while the total energy must sum to the muon mass and the individual energies should range between 0 and 53 MeV.

The main sources of background are two-fold, so-called physics background coming from radiative muon decay with either internal $\mu \rightarrow e\nu\bar{\nu}ee$ or external $\mu \rightarrow e\nu\bar{\nu}\gamma$ conversion, its suppression depending strongly on the granularity and resolution of the detectors, or accidental background which scales with the square of the beam intensity. The radiative decays are the most serious form of background since they can produce oppositely charged leptons from the same vertex, if conversion occurs in the target or surrounding detector materials. The accidentals are combinatorials from Michel or radiative decays with e.g. positrons undergoing Bhabha scattering or mistaken back-curl events. Finally, certain pion decays can potentially contribute as background such as $\pi \rightarrow eee\nu$ or $\pi \rightarrow \mu\nu\gamma$ with subsequent photon conversion. However, these are considered negligible due to the high suppression factor of the beam line $O(10^{-12})$. Therefore, in order to distinguish $\mu \rightarrow eee$ decays from background processes efficiently at a level of 10^{-16}, a combination of excellent energy and momentum resolutions for the detectors as well as a precise vertexing and TOF-measurements combined with kinematic constraints are required.

4.2 Detector concept

In order to achieve the sensitivity goal and suppress the main backgrounds excellent vertex and timing resolutions are required to cope with a stopping rate of more than 10^9 particles s^{-1}. Furthermore, a precise determination of the momenta is necessary in order to apply the kinematic constraints. The reconstruction of candidate tracks is mainly limited by multiple scattering in the target and detector materials. Consequently a strict materials budget must be adhered to, requiring the detectors be operated in a He-environment inside the solenoidal magnetic field of about 1–1.5 T (Fig. 4).

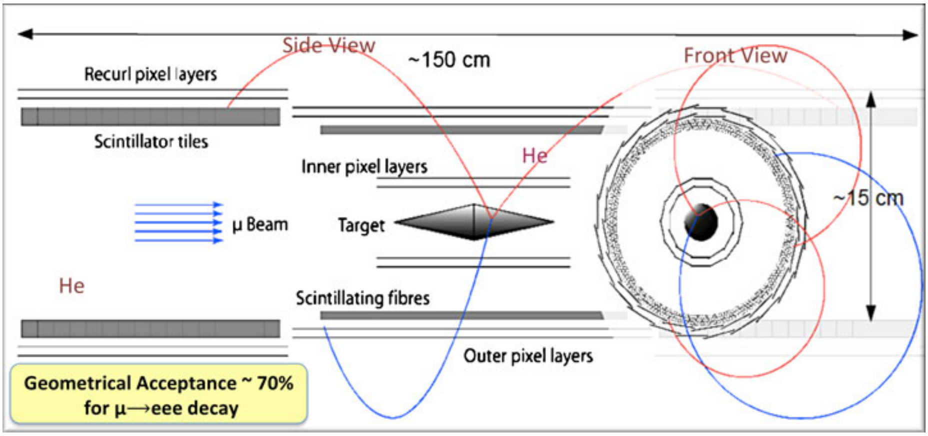


Fig. 4 Schematic of the Mu3e detector concept, showing the central extended target and inner and outer-layer silicon pixel trackers together with a scintillating-fibre tracker. On both the upstream and downstream sides fast scintillating tile “recurling stations” with outer Si-pixel layers are implemented

Due to the high stopping rate and track multiplicity a high granularity Si-based tracking detector solution has been chosen, so-called HV-MAPS, a high-voltage version of “Monolithic Active Pixel Sensors”, with the great advantage that it enables implementation of the pixel readout circuit directly in the silicon layer [10], with the added possibility of “thinning-down” to a total thickness of between 30–50 μm. A total of two double-layered central-barrel detectors are planned with additional US/DS double-layered “recurling stations”. A total of 250 million pixels for a granularity of 80×80 μm. The “recurling stations” not only increase the detector acceptance but also contribute significantly to the momentum resolution, due to the superior resolution of a 180° spectrometer concept.

The scintillating-fibre hodoscope in the central region, consisting of five layers of fibres totaling 4,000 channels, is readout using SiPMs at each end and 5 GSs^{-1}waveform digitizers. This provides a timing resolution of 1 ns for all particles. For the ultimate timing resolution of recurling tracks, two scintillating-tile hodoscopes, each with 3,000 channels complement the “recurling stations” with a timing resolution of between 50–100 ps. This is expected to reduce the accidental background by 2–3 orders of magnitude.

The readout of the experiment is based on FPGA and GPU technology which continuously (no trigger) outputs the fully digitized, zero-suppressed raw data at about 150 GBs^{-1}, while also implementing on-line track reconstruction.

5 Conclusion

cLFV searches have gained much impetus in recent years with next-generation experiments planned for all the “Golden Channels” in the muon sector. Significant progress is expected especially from the PSI experiments, with hopefully first signal events seen after a search spanning more than sixty years.

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