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Searches for lepton flavour violation

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Summary. — The search for lepton flavour violation in the charged-lepton sector is one of the main present challenges of particle physics, since an observation of such a process, strongly suppressed in the Standard Model, could represent the first unambiguous evidence of physics beyond it. I review the main experimental programs looking for LFV, in the present and in the near future.

PACS `11.30.Hv` – Flavor symmetries.
PACS `13.35.Bv` – Decays of muons.
PACS `13.35.Dx` – Decays of taus.

1. – Introduction

The search for lepton flavour violation (LFV) is a classical piece of particle physics, whose (negative) outcomes provided along the years several information about the nature and the interactions of leptons.

From the theoretical point of view, LFV is an accidental symmetry of the Standard Model (SM), not related to its gauge structure, and so naturally violated in most of its extensions. LFV has been already observed in the neutrino sector, in the form of neutrino oscillations, and can be accommodated within the SM with the introduction of a heavy right-handed neutrino lying far above the electroweak scale. The resulting contribution to LFV in the charged lepton sector, corresponding to branching ratios (BR) $\sim 10^{-50}$–10^{-54}, is experimentally inaccessible. As a consequence, an observation of LFV in the charged sector in the near future would be an unambiguous evidence of new physics (NP) beyond the SM.

Indeed, many NP models predict LFV at an observable level. In supersimmetry (SUSY), for instance, off-diagonal terms in the slepton mass matrices naturally arise from renormalization group evolution from the high-energy scale down to the electroweak scale, also in case of flavour blind SUSY at the high scale [1]. Moreover, in SUSY grand-unified theories [2], the slepton mixing matrices can be related to the CKM (quark mixing) or the PMNS (neutrino mixing) matrix, providing different sets of predictions for the different LFV effects that can be searched for at the present experimental facilities. It makes the searches in the muon and τ sectors largely complementary. In particular, the

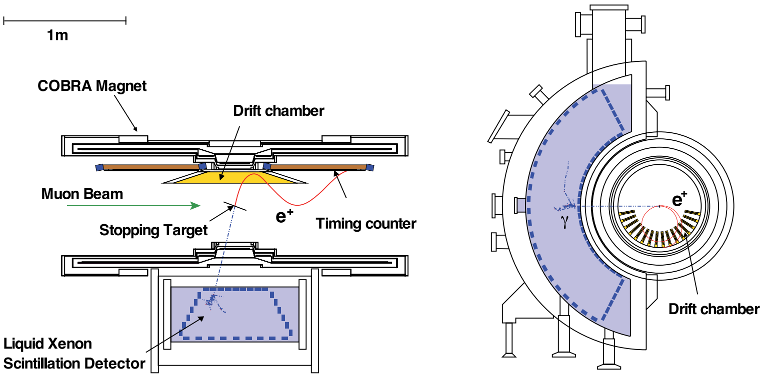

Fig. 1. – The layout of the MEG experiment.

$\mu \to e\gamma$ process tends to be enhanced in the PMNS case, but it is affected by a strong dependence on the neutrino mixing angle θ_{13}, for which only an upper limit is currently available [3]. Conversely, the $\tau \to \ell\gamma$ ($\ell = e, \mu$) decay is not affected by the value of θ_{13}, but it tends to be less favoured in the PMNS case. In summary, the relative importance of the the different channels strongly depends on the specific flavour structure of the NP, bringing us to the conclusion that the searches for them are strongly complementary and all necessary to better understand the NP if a positive signal is observed somewhere.

2. – The MEG experiment

The present limit on the BR of $\mu \to e\gamma$ has been set by the MEGA Collaboration [4] at 1.2×10^{-11}, and already excludes a large portion of the parameter space for PMNS-like SUSY [2]. The MEG experiment started taking data in October 2008, taking advantage of the most intense continuous muon beam in the world ($\sim 3 \times 10^7\ \mu/\mathrm{s}$), at the Paul Scherrer Institute in Villigen (CH). It aims at a limit at the level of 10^{-13}, in order to access also part of the parameter space for the CKM-like case.

The experimental signature of $\mu^+ \to e^+\gamma$ for muons at rest is given by one positron and one photon, produced back-to-back with a momentum of $(m_\mu^2 - m_e^2)/2m_\mu \sim m_\mu/2$ each. A physical background is due to the radiative muon decay (RD) $\mu \to e\nu\bar{\nu}\gamma$, but at high muon rate the most important source of background is found to be the accidental coincidence of a positron and a photon produced by two different muon decays. The reduction of this contribution requires a very precise reconstruction of the positron and photon energies $E_{e(\gamma)}$, the relative $e\gamma$ timing $T_{e\gamma}$ and their relative angle $\Theta_{e\gamma}$. A picture of the MEG layout can be found in fig. 1.

The positron momentum is measured by a set of 16 low-mass drift chambers in a graded magnetic field of $\sim 1.2\,\mathrm{T}$ at the target and $\sim 0.6\,\mathrm{T}$ at $\sim 1\,\mathrm{m}$ from it upstream and downstream. This configuration produces tracks whose bending radius is independent on the emission angle. Moreover, also the positrons emitted almost in the transverse plane are expelled from the spectrometer after at most three turns inside it, strongly reducing the pileup. The propagation of the positron track to the target also allows to determine the muon decay point with a precision of 2–3 mm.

After exiting the spectrometer, the positron impacts one or more of the 30 scintillating bars (the *Timing Counter*) that are used to fire the trigger and provide a precise measurement of the positron timing, with a goal resolution of $\sim 45\,\text{ps}$. A system of scintillating fibers, not yet operational in the first data taking, is expected to provide longitudinal position information, to be also used in the trigger system.

The photon is detected by a 800 liter liquid xenon (LXe) calorimeter, that provides accurate energy, time and conversion point position measurements. The latter measurement is combined with the muon decay point measured by the positron spectrometer, in order to estimate the photon direction. The LXe, as a scintillation device, is characterized by a fast time constant (45 ns for photons, 4 ns for α particles) and a good light yield ($\sim 75\%$ of NaI(Tl)). Resolution of 800 keV in energy, 2–4 mm in position and 65 ps in time are expected for the signal. In order to reach this level of accuracy, a careful and redundant set of calibrations is needed. Among them, the charge exchange (CEX) reaction $\pi^- + p \to \pi^0(\gamma\gamma) + n$ is used to provide almost monochromatic signal-like photons for energy calibration on a yearly basis. A dedicated Cockroft-Walton accelerator for protons is used to induce nuclear reactions on a lithium tetra-borate target and get low-energy photons (up to 17.6 MeV) for monitoring the stability of the detector on a weekly basis.

The experiment exploits a fully digital trigger system that is able to reconstruct on-line the photon energy and the relative time. Moreover, position information from the TC and the calorimeter are used to apply an approximate back-to-back requirement, also at the trigger level. It allows to reduce the trigger rate down to 5–10 Hz, corresponding to a live time of $\sim 84\%$ during the 2008 run. The data acquisition exploits the performances of a custom digitization chip, the *Domino Ring Sampler* (DRS), characterized by a sampling frequency of 0.5 to 4.5 GHz.

In the first physics run in 2008, the MEG experiment collected more than 9×10^{13} muon decays. Severe detector instabilities affected the drift chamber system, resulting in an efficiency at the level of 12% for signal positrons and resolutions far above the goal. This problem strongly limited the MEG sensitivity, but it has been solved and the chambers have been successfully operated during the 2009 run.

The 2008 data have been used to set the first MEG limit on the $\mu \to e\gamma$ BR [5]. A maximum-likelihood analysis has been performed, based on five discriminating observables: the photon and positron momentum, their relative time and the polar ($\theta_{e\gamma}$) and azimuthal ($\phi_{e\gamma}$) projections of their relative angle. These observables are statistically independent for the signal and the accidental background, and the corresponding probability distribution functions (PDF) are simply multiplied. Conversely, a four-dimensional (E_γ, E_e, $\theta_{e\gamma}$, $\phi_{e\gamma}$) PDF is used for the radiative decay (*RD*), in order to take into account the kinematical properties of this process, multiplied by a $T_{e\gamma}$ PDF identical to the signal one. The detector resolutions are used to parametrize the signal PDFs. They are determined from data by means of calibration samples, mainly photons from the CEX reaction and positrons from the normal muon decay. The accidental background PDFs are estimated by fitting the spectra of the data lying on the sidebands of a signal box in the $(T_{e\gamma}, E_\gamma)$ plane. The four-dimensional *RD* PDF is obtained by combining the theoretical spectrum with the resolution and acceptances measured on data. The result of the maximum-likelihood fit is shown in fig. 2. The Feldman-Cousins approach [6] has been used to set an upper limit on the number of observed signal events, $N_s < 14.7$, where systematic uncertainties are included with a Bayesian approach. A limit on the $\mu \to e\gamma$ BR has been obtained by normalizing the number of signal events to the number of the observed normal muon decays, taking into account the correction factors related to the differences in the kinematical properties and in the trigger efficiencies. A 90% CL limit of $\text{BR}(\mu \to e\gamma) < 2.8 \times 10^{-11}$ has been set, although simulated experiments predicted

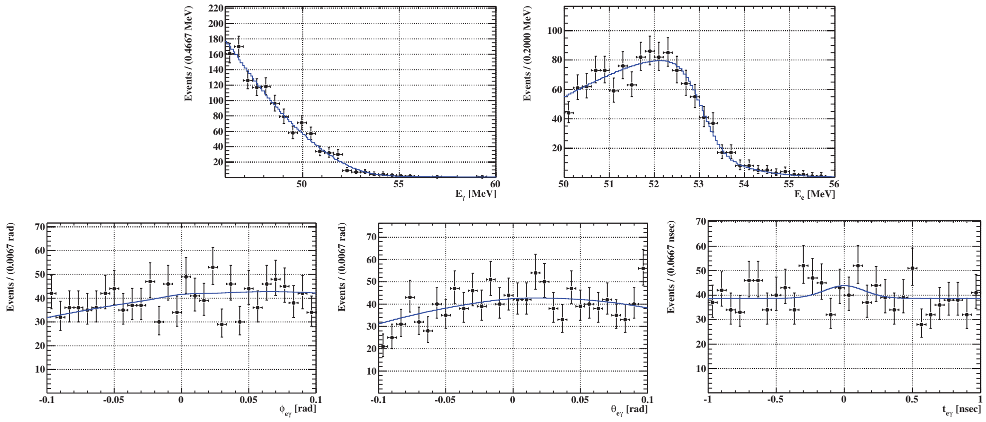

Fig. 2. – The result of the fit of the 2009 data. From top right, the distributions of E_γ, E_e, $\phi_{e\gamma}$, $\theta_{e\gamma}$ and $T_{e\gamma}$ are shown. Signal would appear at $E_\gamma = 52.8\,\text{MeV}$, $E_e = 52.8\,\text{MeV}$, $\phi_{e\gamma} = \theta_{e\gamma} = 0$ and $T_{e\gamma} = 0$.

an expected limit of about 1.3×10^{-11} and a probability of a few percent of getting such a large limit.

The MEG experiment will continue to take data in 2010 and 2011. Hardware and analysis improvements are on going and will allow to reach a sensitivity of $\sim 5 \times 10^{-12}$ for the 2009 data and to the goal level of about 10^{-13} with the final statistics.

3. – LFV in the τ sector

The B-Factories PEP-II and KEKB, e^+e^- colliders mainly operating at a center-of-mass (CM) energy of about 10.58 GeV for the production of a large amount of B-mesons, can be also considered good τ-Factories, being the $e^+e^- \to \tau^+\tau^-$ cross section, at this energy, of the same order of the $e^+e^- \to b\bar{b}$ one ($\sim 1\,\text{nb}$). Several LFV channels can be searched for in the clean environment provided by e^+e^- colliders. In particular, recent results have been published by the BaBar and Belle experiments, for the $\tau \to \ell\gamma$ and $\tau \to \ell\ell\ell$ decays ($\ell = e, \mu$).

In the $\tau \to \ell\gamma$ analysis, the event is divided in two hemispheres: in the *signal* hemisphere, only one track, identified as a lepton, has to be present. In the *tag* hemisphere, one or three tracks are required, coming from the decay of the other τ. Finally, a photon with energy larger than 1 GeV in the CM frame is searched for in the signal hemisphere, and the lepton-photon pair is required to be consistent with a $\tau \to e\gamma$ decay. Two variables are exploited: the beam-energy constrained mass $m_{EC} = \sqrt{E^{*2}_{beam} - |\boldsymbol{p}^*_\tau|^2}$ and energy difference $\Delta E = E_{e\gamma} - E^*_{beam}$, where E^*_{beam} and p^*_τ are the beam energy and the τ 4-momentum in the CM frame.

The sensitivity is limited by the large irreducible background due to $e^+e^- \to \tau^+\tau^-$ events with a radiation photon emitted in the initial state and one of the two τ decaying leptonically. The best limits currently available, set by the BaBar Collaboration [7], are $\text{BR}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$ and $\text{BR}(\tau \to e\gamma) < 3.3 \times 10^{-8}$, obtained from a maximum likelihood fit on the (m_{EC}, ΔE) plane.

A similar analysis is performed in the search for the $\tau \to \ell\ell\ell$ process, where each lepton can be a (anti-)muon or an electron (positron). The 1-3 topology is exploited (one track in the *tag* hemisphere and three in the signal one). A relatively small background is present, mainly composed by $q\overline{q}$ events ($q = u, d, s, c$), QCD $e^+e^- \to \ell^+\ell^-$ processes and other τ decays.

Recent BaBar [8] and Belle [9] analyses set the best limits currently available, at a level of $(2\text{–}3) \times 10^{-8}$ depending on the specific channel. In these works, a signal region is defined in the (m_{EC}, ΔE) plane, and the number of observed events is compared with the expected rates of background events (in a range of 0.1–0.6 for all channels in both experiments).

4. – Future perspectives and conclusions

Future experiments have been proposed, that would be able to largely improve our sensitivity to LFV effects, in both the muon and τ sector. In particular, plans for e^+e^- colliders running at 100 times higher luminosity with respect to the present B-Factories, the SuperB [10] and SuperKEKB [11] projects, would provide an unprecedented sensitivity to LFV in the τ decays, also due to the possibility of running at a CM energy just above the $\tau^+\tau^-$ threshold. A conservative estimate of the sensitivity for LFV searches can be extrapolated with a statistical scaling of the present results. Limits of the order of $(2\text{–}3) \times 10^{-9}$ for $\tau \to \ell\gamma$ and $(2\text{–}8) \times 10^{-10}$ for $\tau \to \ell\ell\ell$ are expected for the SuperB project with $75\,\text{ab}^{-1}$ of integrated luminosity.

In the muon sector, the best sensitivity to new physics scenarios is expected from two proposed experiments, COMET [12] and Mu2e [13], devoted to the search for the LFV $\mu \to e$ conversion process in the interaction with nuclei. When a negative muon is stopped in a target it can be captured in a close orbit by a nucleus. The muon will decay usually in the $e\nu\overline{\nu}$ final state, but if LFV can occur, it can exchange a photon with the nucleus and convert to an electron, $\mu N \to eN$. In this case, a monochromatic electron of about 105 MeV is produced, at the end point for the electron production by the $\mu \to e\nu\overline{\nu}$ decay in orbit. The most important issue for this kind of experiments is the production of a very clean muon beam, to avoid a large background from beam electrons. Sensitivities at the level of 10^{-17}–10^{-19} are expected, comparable (for most of the NP models) to a sensitivity of 10^{-15}–10^{-17} in the $\mu \to e\gamma$ search.

In conclusion, the search for LFV in the charged lepton sector is one of the main topics of high-energy physics in these years, since most of the NP models predict it at an observable level, an a discovery in this field would represent an unambiguous evidence of physics beyond the SM. Complementary information are obtained from experiment that can access LFV in the muon or τ sector. Moreover, these searches are complementary with respect to the LHC program, since they will help to determine the flavour structure of the NP if it is discovered at the LHC and will provide indirect sensitivity to larger energy scales that cannot be directly explored.

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