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A review of lepton flavor violation experiments

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Abstract

In the standard model of elementary particle physics, the lepton flavor violation in the charged sector (cLFV) is forbidden and cLFV have not been observed experimentally, while neutrino oscillations have been observed in many experiments. In well-motivated new theories beyond the standard model, cLFV is naturally introduced and the branching fractions are predicted in the experimental reaches. In this presentation, the status of experiments searching for cLFV is reviewed.

Keywords: LFV, flavor

1. Introduction

In the standard model of elementary particle physics (SM), flavor changing neutral currents (FCNCs) are forbidden at the tree level. They may occur beyond the tree level, but they are highly suppressed by the GIM mechanism [1]. For example, the branching fraction of $\mu \to e\gamma$ through the W-ν mediation in the SM is smaller than 10^{-54}; it is therefore impossible to experimentally detect it. On the other hand, in many new theories beyond the SM, the lepton flavor is naturally violated. For example, in the super-symmetry theories (SUSY), a μ to e transition can occur through the flavor violations of SUSY particles. Many new theories beyond the SM such as SUSY-GUT [2], SUSY Seesaw [3], Little Higgs models [4] and models with extra dimensions [5] predict the branching fraction of cLFV decay channels close to the current experimental limits. Searches for different channels are complementary to discriminate the new physics because the ratios of the branching fractions of different cLFV channels depend on the new physics models and parameters as described in [4]. As an example, one can assume the effective model-independent Lagrangian of cLFV for $\mu \to e\gamma$ and $\mu \to eee$ as

$$\begin{aligned}\mathcal{L}_{\rm cLFV} \;=\; & \frac{m_\mu}{(\kappa+1)\,\Lambda^2}\overline{\mu_R}\sigma^{\mu\nu}e_L F_{\mu\nu} + \\ & \frac{\kappa}{(\kappa+1)\,\Lambda^2}\left(\overline{\mu_L}\gamma^\mu e_L\right)\left(\overline{e_L}\gamma_\mu e_L\right) \qquad (1)\end{aligned}$$

, where for the second term the left-left vector coupling is chosen. Λ is the LFV mass scale and κ is the ratio of the coupling of the dipole (first) and the contact (second) terms. The first term directly mediates $\mu \to e\gamma$ and mediates $\mu \to eee$ at order α. The second term mediates $\mu \to eee$ at tree level. The relative strength of these decays therefore depends on the κ parameter. If the dipole contribution dominates cLFV decays, which is the case in most SUSY models, $\mathcal{B}(\mu \to e\gamma)$ is 170 times larger than $\mathcal{B}(\mu \to eee)$, and about 200~400 larger than $\mathcal{B}(\mu N \to eN)$ depending on the conversion target nuclei. The ratios of branching fractions of a LFV μ decay and a τ decay also depend on the models and parameters. For example, the SUSY Seesaw model predicts the ratio of $\mathcal{B}(\mu \to e\gamma)$ and $\mathcal{B}(\tau \to \mu\gamma)$ from $O(1)$ to $O(10^4)$ depending on θ_{13} from 0 to 10 degrees [3]. The recent measurements of θ_{13} about 9 degrees [6, 7, 8, 9, 10] favor large $\mathcal{B}(\mu \to e\gamma)$ compared to $\mathcal{B}(\tau \to \mu\gamma)$. The lepton flavor conservation has been tested in history by searching for many rare decay channels of μ, τ and K; so far no significant signals of cLFV were found. Figure 1 shows the history of LFV search experiments; the sensitivities have been improved as the technologies of the beam and the detectors develop.

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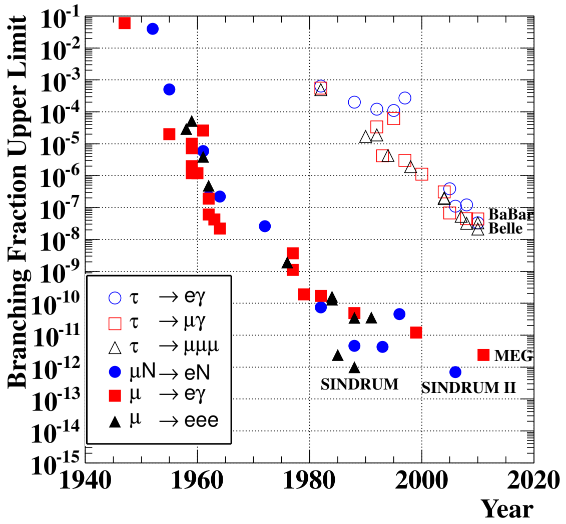

Figure 1: Upper limits of branching fractions of lepton flavor violating decays in charged sector

2. $\mu^+ \to e^+\gamma$

A muon rare decay $\mu^+ \to e^+\gamma$ is one of the most sensitive channels for the new physics because of the relatively large branching fraction predicted by new theories. The previous upper limit of 1.2×10^{-11} [11] was set by the MEGA experiment in 1999. MEG is currently in operation at Paul Scherrer Institut (PSI) in Switzerland to search for the decay. The signature of the signal is a two-body decay of a positron and a γ ray emitted back-to-back, each with energy of 52.8 MeV. The main background is the accidental coincidence of a Michel positron and a γ-ray from the radiative muon decay (RMD) or annihilation in flight of a positron. The second background is the RMD where little energy is carried by neutrinos, and the rate is about 1/10 of the total backgrounds. To suppress the backgrounds, excellent resolutions of the detector are needed.

Figure 2 shows a schematic view of the MEG detector. The most intense muon beam, $3 \times 10^7 \mu/\mathrm{s}$ during the measurement, is transported through a Wien filter and a superconducting transport solenoid. During the transportation, positron contaminations are separated and a pure muon beam is provided. The momentum of the muon beam is controlled by a degrader to efficiently stop muons in a thin (205μm thick) target located at the center of the detector. The positron spectrometer consists of the COnstant Bending RAdius (COBRA) magnet, the drift chambers (DC) and the timing counters (TC). A special gradient magnetic field is formed by COBRA so that the bending radii of the positrons emitted from muon decays are almost independent of the emission angle and high-rate background positrons are quickly swept out not to make the occupancy of DC channels too high. The trajectories of positrons are reconstructed using the hits recorded in 16 modules of DC system and extrapolated to the target and to TC. The time of positrons is measured by TC which consists of plastic scintillators. Hit positions of TC are used for matching with the reconstructed trajectories using DC hits. The largest liquid xenon detector is located outside of COBRA to measure the position, time and energy of γ-rays. In the γ-ray detector, 846 PMTs are submerged in 900 litters of liquid xenon. The PMT is specially developed to efficiently detect the vacuum ultraviolet light from the scintillation of the liquid xenon. The readout system is triggered with about 99% signal efficiency and waveforms of the detector channels are digitized by in-house designed waveform digitizers (DRS) [12]. The online and offline data analysis are done with a common analyzer based on a framework-generator ROME [13].

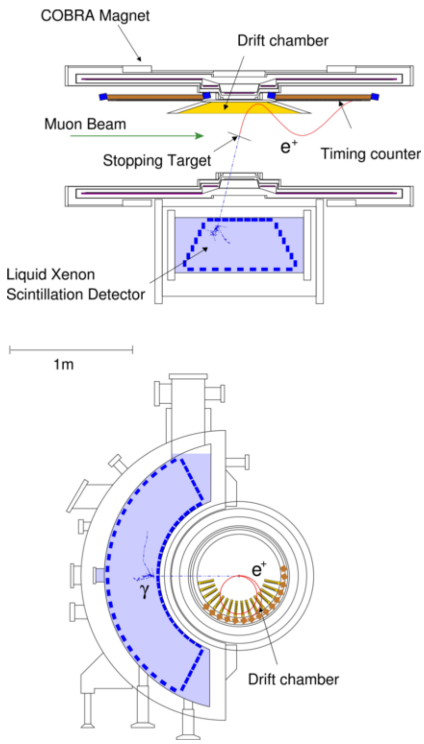

Figure 2: Schematic view of the MEG detector

The physics data taking of MEG has been done since

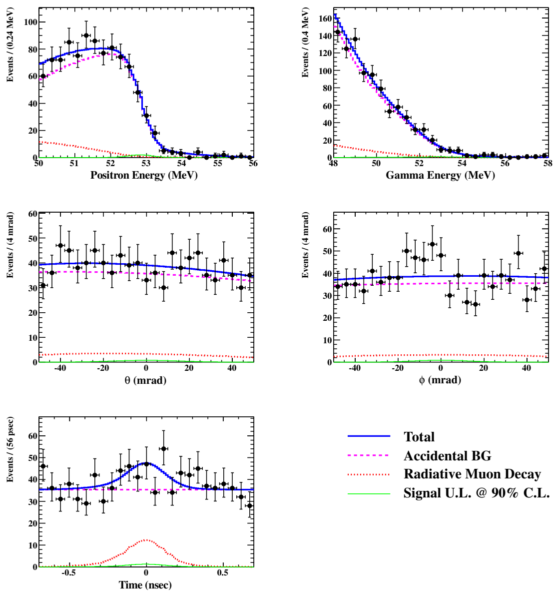

Figure 3: Fitting result of MEG 2009 and 2010 data. The best fits of RMD background (dotted line), accidental background (dashed line) and the total (thick solid line) are shown. The line for the best fit of the signal is not visible because the best fit is about zero. The thin solid line corresponds to the upper limit of the number of the signal. The peaks of the signal PDF of time and angles are at 0, and those for energies are at 52.8 MeV.

2008. At this moment, the physics result using 2009 and 2010 data was published [14]. The branching fraction and its limits are extracted using a likelihood analysis where five kinematic observables, the energies of a positron and a γ ray, the time difference of the two particles, the azimuthal and the polar opening angles, are used. The sensitivity of the experiment with the dataset is 1.6×10^{-12}. Figure 3 shows 2009 and 2010 data in the analysis box and the fitting results. No significant excess was found in the dataset; and the upper limit of the branching fraction was set to be 2.4×10^{-12} at 90% confidence level (C.L.). The upper limit is about 5 times tighter than the previous limit and the new physics are constrained stringently.

The data taking using the present detector will be finished in 2013 because the improvement of the sensitivity is going to be slower due to the backgrounds. The final sensitivity could be $\sim 6\times10^{-13}$.

An upgrade of the experiment is considered to improve the sensitivity by one order of magnitude. The main differences from the present configuration is the 2-3 times higher beam rate, the new positron tracker with a single large tracking volume and the new γ-ray detector where the inner face PMTs are replaced by smaller photo-sensors such as silicon photo-multipliers. The development of the new detectors will be done in two years, and about 3 years of the physics data taking is considered.

3. μ-e conversion

A negative muon stopped on a target forms a muonic atom. In the SM, a muon in a muonic atom can decay to an electron and two neutrinos, or be captured by a nucleus. On the other hand, new physics beyond the SM predict a muon decays to an electron in the field of nucleus without emitting neutrinos. The lifetimes of the muonic atoms are the order of hundreds of nanoseconds. The branching fraction of μ-e conversion depends on the target nuclei [15]; it is therefore interesting to measure the branching fractions with several target materials once the signal is discovered. The signal of μ-e conversion is a mono energetic (about 105 MeV) electron. The backgrounds are high-energy positrons from the muon decays in orbit, radiative pion captures, muon decays in flight in the beam and cosmic rays. In the proposed experiments, to suppress the beam-related prompt backgrounds, pulsed muon beams and delayed timing windows for the data acquisition are used. The present upper limits, $\mathcal{B}(\mu^- + \mathrm{Pb} \to e^- + \mathrm{Pb}) < 4.6 \times 10^{-11}$ [16], $\mathcal{B}(\mu^- + \mathrm{Ti} \to e^- + \mathrm{Ti}) < 4.3 \times 10^{-12}$ [17] and $\mathcal{B}(\mu^- + \mathrm{Au} \to e^- + \mathrm{Au}) < 7.0 \times 10^{-13}$ [18] are set by the SINDRUM II experiment.

DeeMe at J-PARC is a proposed experiment aiming a moderate sensitivity in a timely fashion for a low-cost. Signal electrons are directly extracted from the proton target and the momentum is measured by a spectrometer. The collaboration is aiming the first physics result in 2015, and the expected single event sensitivity (S.E.S.) is 2×10^{-14}.

Another experiment COMET is proposed to J-PARC. Figure 4 shows the apparatus of COMET phase-II. Pions produced in the proton target are extracted and transported through a C-shaped magnet, where muons from the decay of pions are selected. Electrons produced in the stopping target are transported through another C-shaped solenoid to select high momentum electrons. The electrons are detected and the energy is measured by a spectrometer and a calorimeter. The target S.E.S. of COMET phase-II is 2.6×10^{-17} and the expected U.L. at 90% C.L. is 6.0×10^{-17}. Mainly to study potential background sources for phase-II and to measure the extinction directly, COMET phase-I is proposed. At the phase-I, a part of the pion and muon transport solenoid for the phase-II is used and the detector is

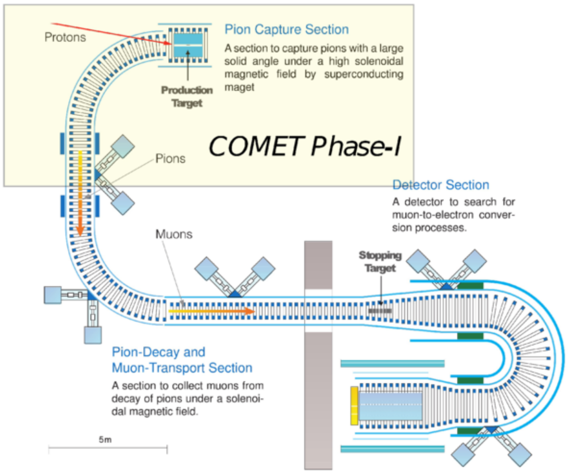

Figure 4: Schematic layout of COMET and COMET Phase-I

located around the stopping target. A physics data will be also taken in the phase-I and the expected U.L. sensitivity is 7.2×10^{-15}. The phase-I experiment is supposed to be carried out in 2017. The construction of the phase-II will be started in 2018 and the physics data taking will be started in 2021.

The Mu2e experiment at Fermilab is proposed with a similar sensitivity to that of COMET. The target S.E.S. of Mu2e is 2×10^{-17} and the U.L. sensitivity is 6.0×10^{-17}. The apparatus of Mu2e consists of the pion production magnet, an S-shaped transport magnet, a stopping target and the detector. Unlike COMET, the target and the detector are located in a straight magnet. In order to detect only high momentum electrons, the detector measure particles with large bending radii. The physics run of Mu2e is supposed to start in 2020.

For the further future, PRISM/PRIME [19] at J-PARC and Project-X at Fermilab are being designed for the sensitivity of $O(10^{-18})$.

4. $\mu^+ \to e^+e^-e^+$

The current upper limits of $\mathcal{B}(\mu^+ \to e^+e^-e^+)$ was set by the SINDRUM experiment to be 1.0×10^{-12} [20] in 1988. In 2011, a letter of intent for the Mu3e experiment [21], which searches for $\mu^+ \to e^+e^-e^+$ decay, was submitted to PSI. The phase-I of the experiment is expected to be carried out from 2014 to 2017 at an existing beam line at PSI, and the phase-II is supposed to be conducted after 2017. The target U.L. sensitivities at the phase-I and at the phase-II are $O(10^{-15})$ and $O(10^{-16})$, respectively. As well as $\mu^+ \to e^+\gamma$ experiments, the detector resolutions are important to get rid of backgrounds. The detector consists of monolithic active pixel sensors and hodoscopes using scintillating fibers and tiles as show in Fig. 5. A key technology of the experiment is silicon pixel detectors based on High Voltage Monolithic Active Pixel Sensors (HV-MAPS). The sensor can be thinned down to about 50 μm, and its logic is directly implemented in its silicon layer. This technology allows one to reduce multiple scattering of positrons and electrons and to measure hit positions precisely. The time information is improved by scintillation counters with silicon photo-multipliers. For the phase-II of Mu3e, upgrades providing muon intensities higher than 10^9 muons per second are required. Upgrades of the existing beam line or the installation of a new beam line are currently under discussion.

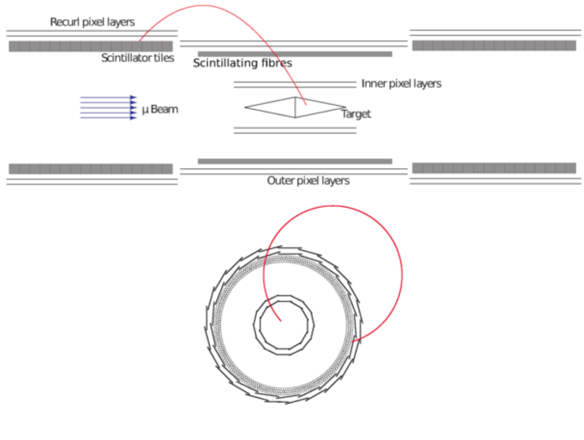

Figure 5: Schematic view of the Mu3e detector.

5. τ LFV

The current experimental upper limits of the branching fractions of τ LFV processes are four orders of magnitude larger than those of μ LFV processes. In general, predicted branching fractions of τ LFV decays are higher than μ LFV because of the large mass of τ decreases GIM suppression. For example, typically the predicted $\tau \to e\gamma$ or $\mu\gamma$ is $\geq$500 times larger than that of $\mu \to e\gamma$. The predicted ratios between μ and τ processes depends on the details of the new physics models; it is therefore complementary to search for μ and τ LFV. In the case of μ LFV, there are only three major search channels. On the other hand, in the case of τ LFV, one can search for many decay channels, such as two $\tau \to l\gamma$ channels, six $\tau \to lll$ channels, many $\tau \to lhh$ channels

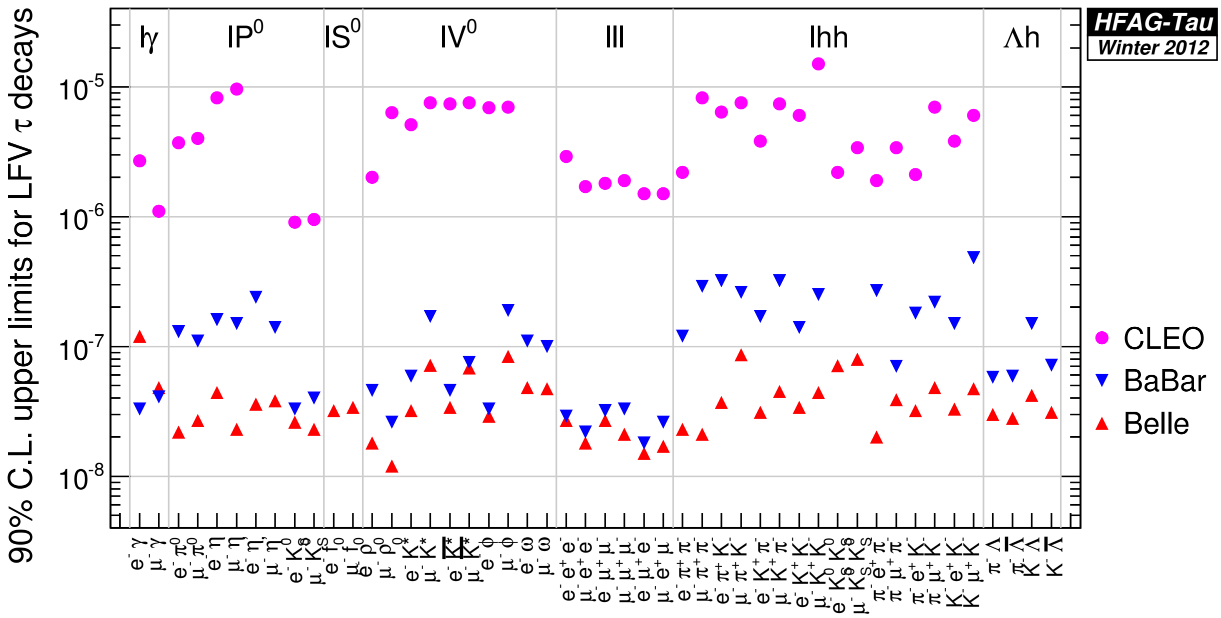

Figure 6: Upper limits of τ LFV decays. [22]

and so on in a single experiment. This feature is an advantage to discriminate the new physics models from the correlations among channels.

Two B-factories, namely Belle at KEK and BaBar at SLAC greatly improved the upper limits of the τ LFV channels by two orders of magnitude from the previous limits. The present upper limits of τ LFV channels are $O(10^{-8})$ as shown in Fig. 6. Expected sensitivities of future B-factories, Belle-II at KEK and SuperB at the Cabbibo Laboratory, depend on the background level of a channel. For example, the expected sensitivity for $\mathcal{B}(\tau \to l\gamma)$ is $O(10^{-9})$ and that for $\mathcal{B}(\tau \to lll)$ is $O(10^{-10})$ due to the different background level.

6. cLFV searches at LHC

At LHC, LFV τ decays can be searched for, and the sensitivity for $\tau \to \mu\mu\mu$ can become comparable to the current limits. But the limits of τ LFV are not expected to be improved dramatically. An LFV signature at LHC via new particles is $pp \to l_i^+ l_j^- + X$. It can occur in the decay of the second lightest neutralino and the slepton. LFV searches at LHC could be competitive to the low-energy experiments if the mediating heavy new particles beyond the SM can be produced.

7. Conclusion

In the standard model, the lepton flavor violating transitions are forbidden in the charged sector, and the probabilities of such transitions through neutrino oscillations are too small to experimentally detect. An observation of LFV in the charged sector will be therefore unambiguous evidence of new physics beyond the standard model. Searches for cLFV of different particles or different channels are complementary to discriminate the new physics. The current upper limits of μ LFV channels, $\mu^+ \to e^+\gamma$, μ-e conversion and $\mu^+ \to e^+e^-e^+$ are about 10^{-12}. Currently, MEG is running for a remaining couple of years to improve the sensitivity to $O(10^{-13})$. The upgrade of MEG is considered to improve the sensitivity by one order of magnitude. Two large-scale experiments (COMET and Mu2e) and one smaller experiment (DeeMe) are proposed to search for μ-e conversion. The target sensitivity of COMET and Mu2e is $O(10^{-17})$. A new letter of intent of an experiment to search for $\mu^+ \to e^+e^-e^+$ was presented to Paul Scherrer Institut by Mue3 collaboration. The target sensitivity of the Mu3e phase-I is $O(10^{-15})$ and that of the phase-II is $O(10^{-16})$. The latest upper limits of lepton flavor violating τ decays are set by B-factories (Belle and BaBar) to be $O(10^{-8})$. The sensitivities of the future B-factories are expected to be $O(10^{-9})$ to $O(10^{-10})$

depending on the decay channels. LFV search experiments play important roles as well as the high-energy frontier experiments to explore new physics beyond the standard model.

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