PROCEEDINGS OF SCIENCE

# cLFV/g-2/EDM Experiments

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We review experiments of lepton cLFV searches and precise measurements of muon g-2/EDM. Both lepton cLFV searches and precise measurements of muon dipole moments are thought to be sensitive to new physics beyond the Standard Model because there is no Standard Model background for lepton cLFV processes practically and theoretical calculation of muon dipole moments are reliably precise. Sensitivities and measurement precisions are expected to improve greatly in future experiments thanks to available high-intensity proton accelerators.

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## 1. Introduction

Charged Lepton Flavor Violation (cLFV) is strictly forbidden in the framework of the Standard Model (SM) even if we take the neutrino oscillation into account; expected reaction rates of cLFV processes in the SM are smaller than $10^{-50}$ as they are suppressed with a power of the ratio of neutrino and W-boson mass ($m_\nu/m_W$). This means that there is in principle no SM background in experimental searches and thus any observation of the signal is an evidence of new physics beyond the SM without any ambiguity. The muon has been used for this research because it can be easily produced in proton nucleus interactions as a decay product of a pion and has long enough lifetime to be transported to an experiment area after removing associated background particles. There are three muon reactions used in cLFV searches; $\mu^+ \to e^+\gamma$, $\mu$-e conversion, and $\mu^+ \to e^+e^+e^-$. The experimental upper limit of these processes are all below the level of $10^{-12}$ although many new physics models predict existence of either of these just below current experimental bounds[1]. However their effects are only though a loop and/or intermediate particle exchange with a flavor violating vertex. Thus it is not possible to pin down the physics behind them only with a discovery of one of these reactions. Nevertheless comparing results of three searches will provide us precious information about possible physics; it is very important to conduct three searches with similar sensitivities.

The tau lepton is also used for cLFV searches after tau lepton pair production became available at $e^+e^-$ colliders; recent research activities at $B$ factories where large amount of tau lepton pairs can be produced have allowed us to use tau leptons to investigate cLFV. The most sensitive modes of cLFV tau lepton decays to the new physics are, similarly to muon, $\tau \to \mu\gamma$, $\tau \to e\gamma$, $\tau \to \mu\mu\mu$, and $\tau \to eee$ Tau has many other possible decay modes with hadron(s) in the final stats with lepton-flavor violation as its mass is as large as 1.8 GeV/c$^2$, which makes various kinds of cLFV searches possible.

Precise measurement of muon electric and magnetic dipole moments are thought to be sensitive to new physics. Deviation of the muon electric dipole moment measurement in the Brookhaven National Laboratory (BNL) g-2 experiment (E821) from theoretical predictions within the framework of SM[2] may indicate the existence of new physics; many theoretical attempts to interpret the deviation as new physics effect have been intensively made. Magnetic dipole moment of muon should be zero within the framework of SM. Its measurement is more difficult than electric dipole moment measurement because muon spin precession is more complicated to observe the effect. Progress of theoretical calculations of muon dipole moments is also remarkable these days taking all available information into account. Theoretical ambiguity which was difficult to solve due to complicated calculation is being clarified by carefully treating relevant experimental data[3]. Further progress is expected also in this aspect.

There are three major facilities in the world where high-intensity muon beam is available; Paul Scherrer Institute (PSI) in Switzerland, Fermi National Accelerator Laboratory (FNAL) in the U.S., and Japan Proton Accelerator Research Complex (J-PARC) in Japan.

## 2. Muon cLFV experiments

In this article we focus on recent experimental activities. A $\mu^+ \to e^+\gamma$ search at PSI, the MEG experiment, has already published the final result. A successive experiment with improved physics sensitivity, the MEG II experiment, will start physics data acquisition soon. There are two $\mu$-e conversion searches with competitive sensitivity to each other prepared at J-PARC and FNAL. An experimental search for $\mu^+ \to e^+e^+e^-$ is planned at PSI using the same beam line with MEG II.

### 2.1 MEG and MEG II at PSI

The MEG experiment searched for the $\mu^+ \to e^+\gamma$ decay with a better sensitivity than the previous experiment conducted at Los Alamos National Laboratory (LANL) in the U.S., the MEGA experiment [4]. The search was carried out using a continuous positive muon beam ($\geq 10^7 \mu$/sec) provided at the PiE5 beam line in PSI. The muon beam was stopped on a thin polyethylene target of 205 $\mu m$ thickness located at the center of the spectrometer magnet with gradient magnetic field. The decay positrons were measured with a positron spectrometer located in the solenoidal field; the spectrometer was composed of 16 segmented low-mass drift chambers and timing counters located both ends of the magnet. The spectrometer was optimized to detect the signal positron of 52.8 MeV. The gamma rays were measured with a liquid-xenon gamma-ray detector located beside the magnet. The scintillation light from liquid xenon was measured by photomultipliers immersed in the liquid and light distribution on them was used to evaluate the energy, position, and time of gamma rays. The gamma-ray detector was also optimized to detect the signal gamma ray of 52.8 MeV. Details of the MEG detector is described in [5]. Muon decay data corresponding to $7.5\times10^{14}$ stopped muon on target was collected in 2008-2013. Because there was no event excess in the signal region over the expected number of background, the upper limit of $4.2\times10^{-13}$ at 90% Confidence Limit (CL) has been set[6], which is the most stringent limit in muon cLFV experiments at the moment.

After the MEG experiment completed, the collaboration immediately started upgrade of the detector to realize almost 10 times better sensitivity. The positron spectrometer is upgraded by replacing the segmented drift chamber system with a single volume cylindrical drift chamber to achieve uniform acceptance and larger detection efficiency. The positron timing counter which was composed of bar plastic scintillators with photomultiplier readout in MEG is replaced pixelated tile plastic scintillators with Silicon Photomultiplier (SiPM) readout to achieve better timing resolution in MEG II. The liquid-xenon gamma-ray detector is upgraded by replacing 2-inch diameter photomultipliers used in the front surface of the detector with SiPM's sensitive to ultra-violate light and operational in liquid xenon, resulting in better detection efficiency owing to smaller amount of material and better position and timing resolutions thanks to the smaller dimension of the photo sensor. Schematic view of the experiment setup of the MEG II experiment is shown in Figure 1. The beam rate will be increased to $7\times10^7 \mu$/sec for physics data acquisition. It is expected to reach the sensitivity to $\mu^+ \to e^+\gamma$ decay of $6\times10^{-14}$ in three years data acquisition. Details of the experiment design are described in [7].

### 2.2 COMET at J-PARC

The COMET experiment at J-PARC [8] intends to search for $\mu - e$ conversion in muonic atom with a sensitivity better than $10^{-16}$, which improves the current best limit of $\mu - e$ conversion search achieved by SINDRUM II experiment ($7\times10^{-13}$) [9]. The COMET experiment plans to achieve this goal with a staged approach; in phase I a part of the experimental setup is constructed

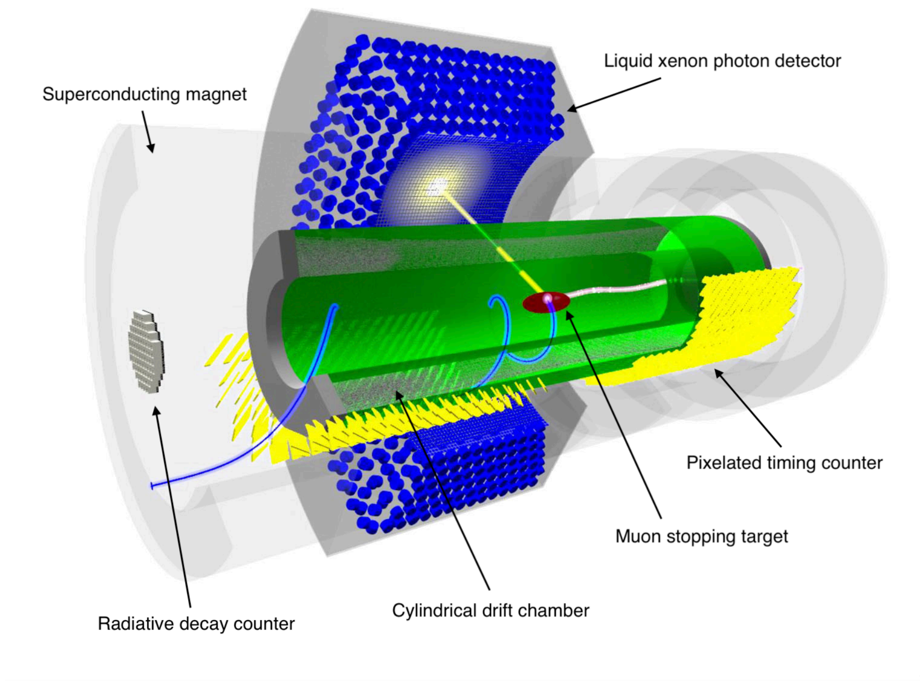


**Figure 1:** Schematic view of the MEG II experiment at PSI.

as described below and physics data acquisition will be conducted using 8 GeV proton beam of 3.2kW from the J-PARC Main Ring (MR) accelerator with a target sensitivity better than $10^{-14}$, and in phase II the setup is extended to accept 56 kW proton beam from MR to reach the final sensitivity better than $10^{-16}$.

The experiment needs intense muon beam to be stopped on an array of thin target disks where muonic atoms are formed; an electron spectrometer observes the signal electron from $\mu - e$ conversion with a characteristic energy. The COMET experiment uses aluminium as a muon stopping target material; the muon has 860 nseconds lifetime in muonic aluminum. The muon beam should have a time structure in order to fit this lifetime and to remove efficiently prompt background caused by pions arriving at the muon stopping target. The data acquisition system is activated after a few hundred nano seconds after secondary particles produced by proton beam arrive at the muon stopping target. The pulsed proton beam for the COMET experiment has a pulse-to-pulse width of 1.2 $\mu$seconds. Time window selection described above enables to eliminate possible background caused by pions in secondary beam, resulting in clean background condition for the measurement.

Figure 2 shows experimental setups for COMET phase I (left) and phase II (right). In phase I, a graphite rod will be used as a pion production target located in a solenoid magnet (Pion Capture Solenoid) with gradient magnetic field (5 T at the target position and 3 T at the exit). The muon stopping target disks, located after a curved solenoid magnet with a 90-degree bend (Muon Transport Solenoid), are surrounded by a Cylindrical Drift Chamber (CDC) to measure the signal electron momentum in another solenoid magnet (Detector Solenoid). Two sets of timing counter composed of plastic scintillators and Lucite Cherenkov counters are located at both ends of Detector Solenoid for time measurement. In COMET Phase II, a tungsten alloy rod will be used as a pion production target. Thanks to high density of tungsten alloy, the pion production beam image can be minimized and thus muon transport efficiency to the experiment area will be much improved. The Muon Transport Solenoid is extended to 180 degree in Phase II, which enables better beam background suppression. An electron spectrometer composed of a straw-tube tracker and LYSO crystal calorimeter will be located after another curved solenoid with a 180-degree bend. This curved solenoid will help to reduce detector hit rate even in 17 times higher proton beam rate in Phase II.

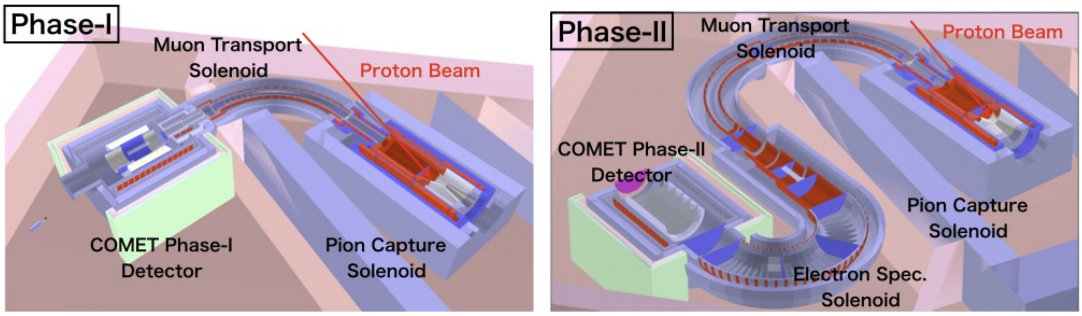


**Figure 2:** Schematic view of the COMET experiment setups for Phase I (left) and Phase II (right)

A new proton transport line from the J-PARC accelerator to the COMET experiment hall is in construction and to be completed in early 2020s. Construction of the magnet system including a dedicated cryogenics facility will also be completed in a similar time scale. Detector preparation is intensively ongoing by the collaboration to be ready to investigate the cosmic-ray background well before the start of physics data acquisition.

### 2.3 Mu2e at FNAL

The Mu2e experiment also searches for the $\mu - e$ conversion with a target sensitivity better than $10^{-16}$ at FNAL [10]. The Mu2e uses proton beam provided by the FNAL accelerator chain; the proton beam is optimized for $\mu - e$ conversion search as in the case of the COMET experiment. The Mu2e experiment realizes necessary beam pulsing by RF re-bunching in Delivery Ring and extract it to the experiment area in the slow extraction mode.

A pion production primary target is located in a pion collection solenoid magnet with a gradient magnetic field, 4.6 T at one end and 2.5 T at the other end, realizing collection efficiency as high as possible. The pions and their decay products, muons, produced in the backward direction are transported to muon stopping target disks made of aluminium through two curved solenoid magnets with opposite curvatures forming an S-shape transport solenoid magnet as shown in Figure 3. A collimator is located at the center of the S-shape, and remove positive particles and higher momentum particles.

The Mu2e detector to identify the $\mu - e$ conversion signal electron is composed of two detectors; a straw-tube tracking detector and CsI calorimeter located in the large solenoid magnet containing the muon stopping target. The straw-tube tracker measures precisely the momentum of electrons from the muon stopping target, and the CsI calorimeter measures the electron energy.

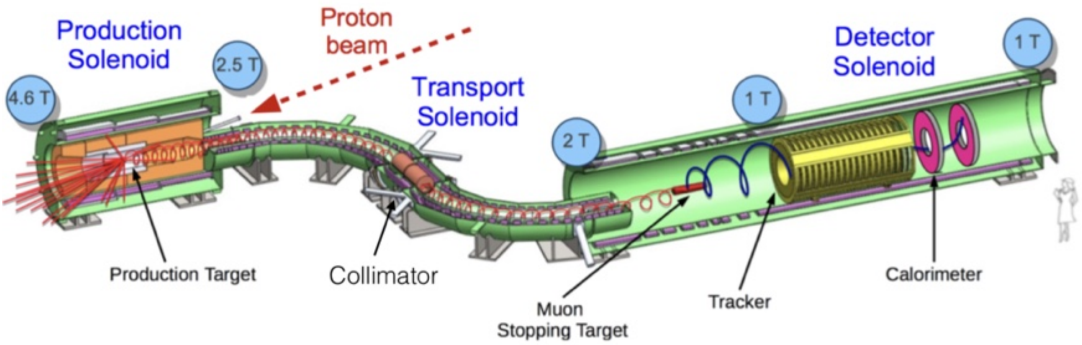


**Figure 3:** Experimental setup of the Mu2e experiment.

Facility construction and detector preparation is in progress to start the engineering run in 2022, followed by physics data acquisition for three years to achieve the target sensitivity better than $10^{-16}$. A schematic view of the Mu2e experiment setup is shown in Figure 3.

### 2.4 Mu3e at PSI

The Mu3e experiment aims at achieving a physics sensitivity to $\mu^+ \to e^+e^+e^-$ of $10^{-16}$ with a staged approach [11]. A schematic view of the Mu3e setup is shown in Figure 4. The Mu3e experiment uses a DC muon beam provided at PiE5 beam line at PSI. A muon stopping target consisting of double hollow cones is located at the center of the spectrometer. The expected muon stop rate at the target is about $10^8\mu$/s. The signal is identified by requiring two positrons and one electron with momentum valance and time coincidence along with the invariant mass equal to the muon mass. The major physics background for the search comes from $\mu^+ \to e^+e^+e^-\bar{\nu}_\mu\nu_e$ decays when two neutrinos in the final start carry tiny amount of energy. It is indispensable to achieve good momentum resolutions for low energy electrons in high rate environment to distinguish the signal from this background. A new tracking device has been developed with extremely small material budget (50$\mu$m thick) for this purpose [12]. Two different types of time measuring detectors will be install; one is a tile plastic scintillation detector with 70 pseconds time resolution expected located at both ends of the spectrometer magnet and the other is a fibre hodoscope detector surrounding the muon stopping target around the central region with a time resolution better than 500 pseconds expected. As the beam stop rate is so high in the Mu3e experiment that a farm of Graphical Processor Units will be used for online tracking. This is mandatory to achieve the target sensitivity better than the current experiment bound by the SINDRUM experiment ($7 \times 10^{-13}$ at 90% CL) [13].

## 3. Muon g-2/EDM experiments

There are two experiments to measure the muon magnetic/electric dipole moments more precisely than the previous experiment conducted at BNL. One is FNAL muon g-2 experiment and the other is J-PARC muon g-2/EDM measurement.



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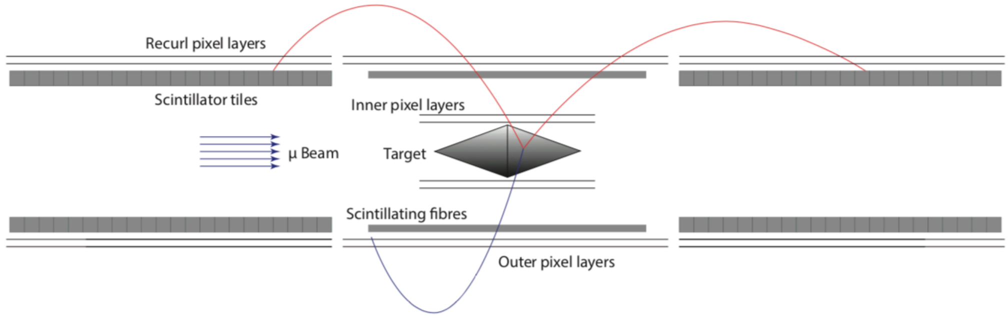


**Figure 4:** Experimental setup of the Mu3e experiment.

### 3.1 FNAL muon g-2 experiment

The FNAL muon g-2 experiment intends to improve the measurement accuracy by one order of magnitude ( $< 0.1$ ppm ) using higher intensity muon beam provided at FNAL [14]. The muon storage ring used in the BNL E821 experiment has been transported to FNAL and recycled for the experiment. Precise measurement of the magnetic field distribution has been carried out after careful shimming along the ring, resulting in significant reduction of the systematic error compared to the BNL-E821 experiment result. New detector system to measure decay electrons are developed and installed to cope with higher muon yield injected into the ring. The experiment method is same with that of the BNL-E821 experiment; muons with momentum of 3.09 GeV/c, so-called magic momentum, are injected into the storage ring and spin precession is measured by detecting decay electrons. The muon precession vector is simplified as,

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right] \tag{3.1}$$

where $a_\mu$ and $\eta$ are muon anomalous magnetic dipole moment and electric dipole moments respectively. It can be naturally assumed that $\eta$ is small enough to eliminate the second term. Thus the muon spin precession frequency, $\vec{\omega}$ is related linearly to the muon anomalous magnetic dipole moment, $a_\mu$. Physics data acquisition has already started and almost same amount of statistics with the previous experiment has already been accumulated until Summer 2018. First outcome of the measurement is expected in summer 2019.

### 3.2 J-PARC g-2/EDM measurement

The J-PARC g-2/EDM experiment takes a different approach [15] to achieve the g-2 measurement precision of 0.1 ppm from that of the FNAL muon g-2 experiment. The experiment will prepare extremely cold muon beam, namely muon beam with very small emittance. This enables to store the muon beam in a storage ring without using electric field. Then the muon precession vector is further simplified as,

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right] \tag{3.2}$$

where $\vec{\beta}$ shows the velocity of the muon. This indicates that the muon spin precesses in the perpendicular plane to the magnetic field in proportion to the muon anomalous magnetic dipole moment $a_\mu$ and also in the plane parallel to the magnetic field. The latter precession appears as an up-down symmetry in proportion to the electric dipole moment $\eta$. Thus the experiment can be sensitive also to $\eta$ with an expected sensitivity of $10^{-21}$e·cm.

Development of the ultra-cold muon beam for the experiment is in progress. Surface muons produced at J-PARC Muon Facility, MUSE, are stopped on a silica aerogel plate with laser-ablated holes, producing muoniums ($\mu^+e^-$). The muoniums moving out of the aerogel are ionized to generate ultra-cold positive muons that are accelerated by a series of linear accelerators to 300 MeV/c. Then positive muons are injected into a muon storage ring of 3 T with a diameter of 66 cm. Magnetic field of the storage ring is precisely controlled within a local precision of 1 ppm. First test of muon acceleration using a radio-frequency accelerator was successfully carried out at J-PARC[16], where muons were successfully accelerated up to 89 keV. Further studies to achieve the design muon intensity of $10^6$ $\mu$/sec is ongoing both in ultra-cold muon source development and muon acceleration including injection scheme to the storage ring. The experiment setup overview is illustrated in Figure 5.

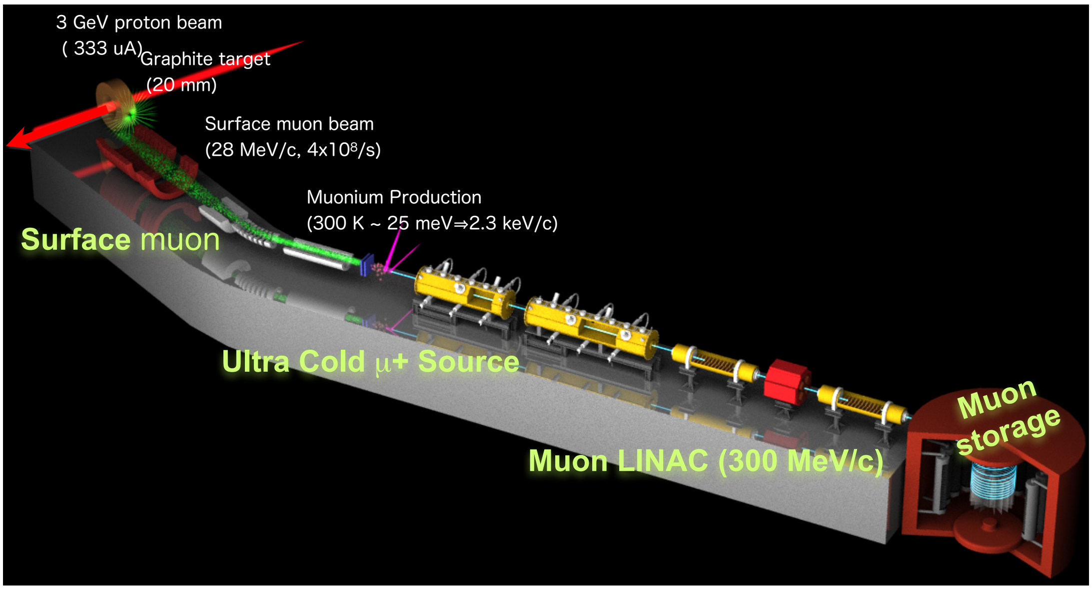


**Figure 5:** Experimental setup of the J-PARC muon g-2/EDM experiment.

## 4. Tau cLFV experiments

Intensive studies of tau lepton-flavor violating decays have been carried out at $e^+e^-$ $B$ factory experiments, Belle and BarBar. Total amount of tau production exceeds $10^9$, which enables to perform lepton-flavor violating tau decay searches with sensitivities better than $10^{-7}$. Both Belle and BarBar experiments have set the stringent limits of tau lepton-flavor violating decays as described in [17, 18, 19]. A new $e^+e^-$ $B$ factory experiment, Belle II, at KEK is starting with 40

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times larger luminosity. As many flavor-violating tau decay searches are limited in statistics at the moment, significant improvements in these studies are expected once the Belle II starts physics data acquisition.

## 5. Summary and Outlook

cLFV searches are powerful tool to investigate new physics beyond the Standard Model in a complementary way to high-energy frontier experiments. The MEG experiment reported its final result using full data set; the limit ( $4.2 \times 10^{-13}$ at 90% CL ) is most stringent among muon cLFV search experiments at the moment. New experimental attempts to improve sensitivities further in muon decay/reaction modes are intensively ongoing at J-PARC (COMET), PSI (MEG II & Mu3e), and FNAL (Mu2e). These experiments will start within a few years from 2019, providing precision information about the possibility of new physics. Precise measurements of muon dipole moments are also suitable to check the Standard Model and prove new physics; any deviation of measured values from the Standard Model prediction naturally indicates an existence of new physics. The BNL-E821 experiment has reported a deviation of the muon magnetic dipole moment from the Standard Model prediction with a significance larger than $3\sigma$. New experimental efforts to measure the value with larger statistics are in progress at J-PARC and FNAL. More tau lepton cLFV decay data is expected in Belle II where 40 times higher luminosity is anticipated; the data will significantly improve sensitivities of tau lepton cLFV searches.

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