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cLFV searches using DC muon beam at PSI

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Search for lepton-flavor violation in the charged lepton sector (cLFV) is a clue to new physics beyond the Standard Model. MEG experiment at PSI in Switzerland has set the world's most stringent limit in the search of $\mu^+ \to e^+\gamma$ decay in 2013. Analysis of further data taken in 2012 and 2013 is in progress with refined detector calibrations. Detector upgrade for the next stage of the experiment, MEG II, is also in progress toward improving the sensitivity of the experiment. Another experimental approach to address the muon cLFV through the process of $\mu^+ \to e^+e^+e^-$ is in preparation utilizing an innovative tracking detector being developed by the Mu3e collaboration. We report the status and prospect of MEG, MEG II, and Mu3e in this presentation.

Flavor Physics & CP Violation 2015,
May 25-29, 2015
Nagoya, Japan

[∗]Speaker.
[†]Thanks to MEG, MEG II and Mu3e collaborations for providing material for this presentation

PoS(FPCP2015)033

1. Introduction

No sign of new physics beyond the Standard Model has been observed so far in high-energy frontier experiments although the Higgs boson was discovered and is being confirmed to be Standard Model like. However many suggestions have been made indicating that new physics beyond the Standard Model should exist. These do not necessarily assume specific physics models but are based on extrapolation of the physics observed already. One good example is unification of forces and matter particles; force unification looks natural at high energy around $10^{14-17} GeV$ based on results of measurements of coupling constants up to around 100 GeV. Matter particle unification also provides a simple view of particle configurations ever observed. These are indicating existence of a unification theory beyond the Standard Model. Neutrino mass, which has been confirmed to be non-zero thanks to many excellent neutrino oscillation experiments, needs additional theory to the Standard Model where the neutrino mass is supposed to be zero. Dark matter and dark energy, which are confirmed to exist in the universe, have to be explained in theories including candidates of these. The Standard Model can not address these problems at all.

In this situation quest of new physics beyond the Standard Model will be continued by high-energy frontier experiments. Those experiments aims at directly detecting new particles produced at high energy. On the other hand, search for lepton-flavor violation in the charged lepton sector (cLFV) tries to detect a sign of new physics by observing forbidden process in the Standard Model. This is because many of new physics models explaining the incompleteness of the Standard Model predict existence of cLFV through a loop diagram composed of new particles [1]. Such new particles are heavier than Standard Model particles and have not yet been observed directly. However as long as they have a coupling to the Standard Model particles and flavor violation among them exist, cLFV processes can be induced at a level where an experimental sensitivity may reach.

Among three charged leptons, muon is thought to be most suitable for cLFV searches because of the following reasons; it is easy to produce as a decay product of pion that can be produced in large numbers with a high-power proton machine. The lifetime of the muon, 2.2-μsec, enables us to transport muons from the pion production part to an experiment area where a dedicated spectrometer can be constructed. Tau lepton, which is thought to be more sensitive to new physics, requires higher energy to produce and its decay is more complicated with shorter lifetime, thus the sensitivity of a tau experiment would be limited compared to muon experiments.

There are three muon processes, $\mu^+ \to e^+\gamma$ (Figure 1(left)), $\mu - e$ conversion (center), and $\mu^+ \to e^+e^+e^-$ (right) violating the conservation of the lepton flavor. These are predicted by many new theoretical model to exist barely below the current upper limit of the branching ratios [1]. The DC muon beam is suitable for searching $\mu^+ \to e^+\gamma$ and $\mu^+ \to e^+e^+e^-$ because more than one particles are to be observed in the final states of these processes and thus accidental overlaps of particles from different processes could dominate the background. On the other hand, the pulsed-muon beam is suitable to search for $\mu - e$ conversion because any kind of background coming from the environment such as cosmic rays can be reduced by applying a timing selection in the final state. The time structure of muon beam depends on the time structure of the primary proton beam producing mother particles of muons, namely, pions. The time structure of the proton beam equivalent to the pion lifetime can produce DC muon beam while longer time structure can produced pulsed muon beam.

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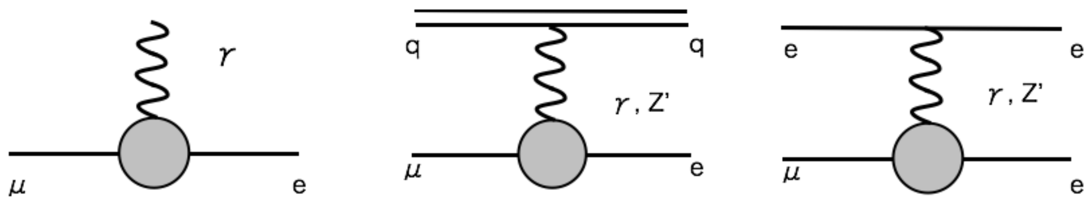

Figure 1: Three muon processes violating the lepton-flavor conservation. $\mu^+ \to e^+\gamma$ (left), $\mu - e$ conversion (center), and $\mu^+ \to e^+e^+e^-$ (right).

2. DC muon beam at PSI

The cyclotron proton accelerator at Paul Scherrer Institute (PSI) in Switzerland accelerate protons to 590-*MeV* with a maximum proton current of 2.2-*mA* corresponding to 1.3-*MW* beam power. The accelerator frequency is 50.63-*MHz*, providing the time between two proton pulses of 19.75-*nsec*. This is as long as the pion lifetime at rest, 26-*nsec*, and is suitable to produce DC muon beam. The proton beam extracted from the accelerator is injected to a graphite target on a rotating wheel to produce pions. The rotating wheel structure is employed for the purpose of radiation cooling. A part of positive pions produced at the target are stopped on the surface of the target before decaying to a muon and a muon neutrino. Such muons produced on the target surface, called surface muons, has a typical momentum of 28-MeV/c thanks to the pion decay at rest and are transported to experimental areas through beam line apparatus.

3. MEG and MEG II experiments

MEG is an experiment searching for $\mu^+ \to e^+\gamma$ with a dedicated setup composed of a liquid xenon photon detector and a positron spectrometer. The apparatus was installed in the PiE5 beam line area at PSI. The PiE5 beam line, viewing the primary proton target backward, is capable to transport the surface muon beam more than 10^8-muons/sec. The positron contamination in the beam is efficiently removed by a Wien filter installed at the end of the beam line.

Figure 2 shows the MEG detector setup [2]. The surface muon beam transported through the PiE5 beam line is stopped on a muon stopping target of 18-mg/cm^2 thick polyethylene located at the center of the magnet. The target is surrounded by a low-mass drift chamber system measuring positron momentum [3]. Positron timing is measured by plastic scintillation counters with fine-mesh photomultipliers readout [4] located both ends of the spectrometer magnet. The spectrometer magnet has a gradient magnetic field to sweep low momentum positrons quickly and keep the bending radius of signal positrons almost constant independently of their emission angle. The photon energy, its time, and position are measured by a 900-ℓ liquid xenon calorimeter. The scintillation light from liquid xenon is observed by 846 photomultipliers submersed in the liquid [5]. Signals from all detectors are digitized by a multi-GHz domino ring sampler [6]. The setup is optimized to maximize the signal detection efficiency while efficiently reducing background events dominated by radiative muon decays with two neutrinos carrying only small amount of energy and accidental overlaps of energetic photons and positrons from different processes. During data acquisition pe-

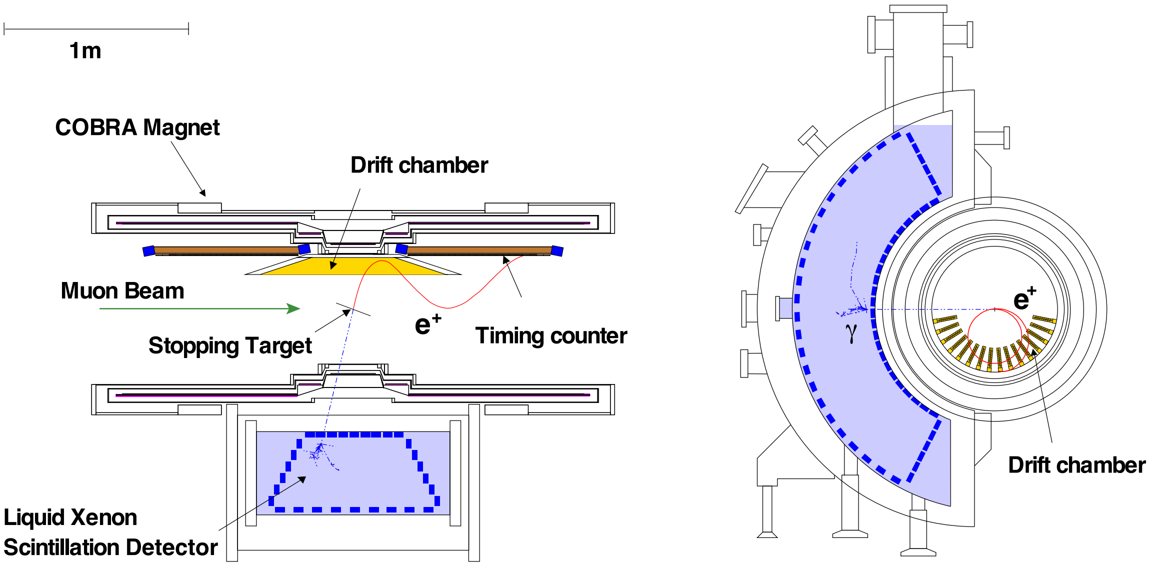

Figure 2: Top (left) and front (right) views of the MEG detector.

riod great care was taken to keep the detector stable and to obtain calibration data to achieve the best performance of the experiment [7].

In the years 2009-2010 MEG collected 3.7×10^{14} muons stopped on target and set the upper limit of 2.4×10^{-12} at 90% C.L. on the branching ratio of $\mu^+ \to e^+\gamma$ [8]. The analysis was conducted by employing the so-called blind analysis method; the data samples around the signal region on the E_γ (photon energy) - $T_{e\gamma}$ (relative timing between positron and photon) plane was blinded, which corresponds to 0.2% of the whole data sample. The side band data (16% of the whole sample) was used to study the background and to evaluate the detector responses. Then the numbers of signal, radiative-muon decay, and accidental background events were determined in a maximum likelihood method. Data distributions of $T_{e\gamma}$, E_γ, E_e (positron energy), θ and ϕ (relative opening angles between photon and positron) were carefully checked and found to have no excess over the background. Accordingly the upper limit of the branching ratio is set by taking into account the normalization factor, the effective number of muons stopped on the target. By adding data samples obtained in 2011 the MEG experiment succeeded to further improve the upper limit of the $\mu^+ \to e^+\gamma$ decay branching ratio at 90% C.L. down to 5.7×10^{-13} with a normalization fact of 7.77×10^{12} [9]. There is more data taken in the year 2012-2013 which is not analyzed yet. The amount of this data sample is equivalent to that already analyzed for publication. The new result with almost doubled statistics will be released soon from the collaboration.

In parallel the collaboration is preparing the detector upgrade to further improve the sensitivity of the experiment (MEG II) [10]. The target sensitivity of MEG II is 5×10^{-14} at 90% C.L. with 75 weeks data acquisition period. The upgraded performance will be realized by increased beam intensity ($7 \times 10^7 \mu^+$/sec), a thinner (140 μm) or active muon stopping target, an enlarged cylindrical single-volume drift chamber and pixelated timing counter [11] for positron measurement, enlarged liquid-xenon volume and finer segmentation of liquid-xenon scintillation photon readout by silicon photomultipliers [12], and new high-bandwidth data acquisition boards. Radiative muon decay counters to be located both ends of the spectrometer magnet are also considered. Intensive R&D work of components necessary for this upgrade is ongoing in the collaboration. Data acquisition of MEG II is anticipated in 2016.

4. Mu3e experiment

Another attempt is being made at PSI to search for a cLFV process using muons, $\mu^+ \to e^+e^+e^-$. The current best list of this decay mode was obtained at 1.0×10^{-12} at 90% C.L. by SINDRUM collaboration [13]. The new experiment, Mu3e experiment, aims at improving the sensitivity by four orders of magnitudes in three steps by measuring all electron tracks very precisely. The most severe background comes from the decay of $\mu^+ \to e^+e^+e^-\bar{\nu}\nu$. An ultimate energy resolution of about 1.3-*MeV* is required to reject this background and reach the sensitivity of 10^{-16}. The detector technology employed in the Mu3e experiment utilizes the method developed for high-voltage monolithic active pixel sensors [14]. This technology enables to thin the detector below 50-μm and implement the logic circuit on the chip for zero suppression. By now Mu3e has developed 5 generations of the prototype. The current one will be the final model implementing all features required for the experiment.

Design of the supporting structure of the silicon sensor is also developed using 25-μm thick kapton. Signal readout form the silicon sensor is carried out through 25-μm thick kapton flexible print circuit with aluminum traces. The material budget will be 1% radiation length per layer with this configuration. Another important issue for the silicon tracker is cooling of the sensor during operation. The Mu3e group plans to conduct this using helium gas circulation taking 2-*kW* heat generation away from the chips. Timing measurement will play another important role in background reduction. Mu3e aims at achieving 1-*nsec* time resolution with scintillating fiber counters and 100-*psec* time resolution with scintillating tiles. These are expected to reduce the background tracks and help to simplify the tracking algorithm in the early stage of data analysis.

In the first stage of the experiment Mu3e aims at achieving the sensitivity around 10^{-14} in about 100 days data acquisition with a minimum setup surrounding the muon stopping target (Figure 3 (top)). In the next stage the setup will be extended to reach the sensitivity around 10^{-15} in 300 days data acquisition. The ultimate goal of the sensitivity of 10^{-16} requires additional extension of the setup and 400 days data acquisition. Necessary muon beam intensities for these are 10^8 muons/sec for 1st and 2nd stages, and 2×10^9 muons/sec for the 3rd.

5. Summary

cLFV searches using DC muon beam are reviewed in this presentation. The MEG experiment at PSI is a leading experiment in this field and has set the most stringent limit on the branching ratio of $\mu^+ \to e^+\gamma$ at 5.7×10^{-13} [9]. Further improvement is expected based on more data samples collected in the year 2012-2013. The upgrade of the experiment, MEG II, is in preparation in order to reach the sensitivity of the order of 10^{-14} [10]. Mu3e, a search for $\mu^+ \to e^+e^+e^-$, is in preparation at PSI [15]. The Mu3e experiment aims at improving the sensitivity by four orders of magnitude than the current limit (1.0×10^{-12} at 90% C.L. [13]) in three steps. Extensive R&D to realize ultra-thin tracking silicon detector is in progress. These experiments will certainly provide

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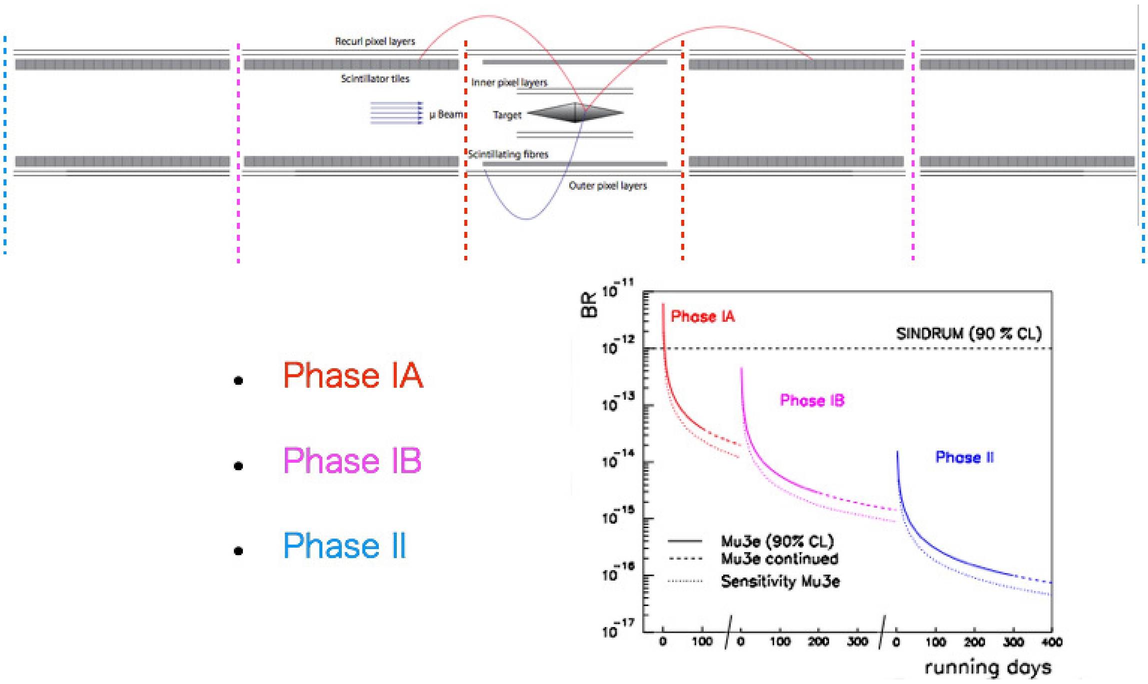

Figure 3: Schematic view of the Mu3e experiment setup (top). The setup will be extended to improve the sensitivity in three steps. Muons are stopped on a cone-shape muon stopping target located at the center of the solenoid magnet. The bottom graph shows the sensitivity curves as a function of data acquisition period [15].

complementary information on new physics beyond the Standard Model to the high-energy frontier experiments along with similar searches using pulsed muon beam [16].

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