PROCEEDINGS OF SCIENCE

Search for charged lepton flavor violation in rare muon decays

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Charged lepton flavor violating processes are strongly suppressed in the Standard Model, therefore their observation would be a clear indication of new Physics. The MEG experiment at the Paul Scherrer Institute (PSI) searches for the lepton flavor violating decay $\mu^+ \to e^+\gamma$. The combined result of the data taken in 2009 and 2010 is presented. The upper limit on the branching ratio obtained (BR($\mu^+ \to e^+\gamma < 2.4 \times 10^{-12}$) [1] improves by a factor five the previous best limit and tighten constraints on new Physics models. Future prospects are also discussed. Another lepton flavor violating decay of the muon is $\mu^+ \to e^+e^-e^+$. The Mu3e Collaboration recently proposed a new experiment for searching this decay aiming at a sensitivity in the range $10^{-15} - 10^{-16}$.

The XIth International Conference on Heavy Quarks and Leptons,
June 11-15, 2012
Prague, Czech Republic

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PoS(HQL 2012)043

1. Introduction

Lepton flavor violating decays of the muon, like $\mu^+ \to e^+\gamma$ and $\mu^+ \to e^+e^-e^+$ are allowed in the Standard Model (SM), due to non-zero neutrino mass through neutrino oscillations, but at unmeasurable decay rate. On the other hand many theories of new Physics predict sizable rates. These predicted rates depend on the specific model and are in many cases accessible to present experiments, see for example [2],[3]. Due to the absence of SM background the observation of one of these decays would be an unambiguous sign of Physics beyond SM while non-observation is still important since it allows to constrain the space of the parameters of the different models. The previous best limit on $\mu^+ \to e^+\gamma$ was set by the MEGA experiment and it is BR($\mu^+ \to e^+\gamma$)<1.2×10^{-11} at 90% C.L. [4] while the current best limit on $\mu^+ \to e^+e^-e^+$ is BR($\mu^+ \to e^+e^-e^+$)<10^{-12} at 90% C.L. by the Sindrum collaboration [5]. The MEG experiment searches for the decay $\mu^+ \to e^+\gamma$ and is taking data since 2008 at the Paul Scherrer Institute (PSI) in Villigen near Zurich. The Mu3e experiment is a proposal for the search of the decay $\mu^+ \to e^+e^-e^+$ at PSI. The PSI is a multidisciplinary laboratory that provides the most intense continuous μ^+ beam in the world with a rate of about 10^8 μ^+/sec.

2. The Mu3e proposal

The Mu3e letter of intent has been submitted in February 2012 at PSI. The proposed experiment is a search of $\mu^+ \to e^+e^-e^+$ with a target sensitivity of 10^{-16}, four orders of magnitude better than the Sindrum result. This high sensitivity is obtained exploiting a very performing tracking detector based on monolithic active pixel sensors that provides high spatial resolution, and an hodoscope made of scintillating fibers and tiles that provide precise timing information. It is also necessary the increase of the muon beam rate and possible upgrades of the PSI beam line are currently under discussion. Two phases are foreseen; the first phase with a minor upgrade of the PSI beam line in the period 2014-2017 and a second phase after 2017 with a high intensity beam (about 10^9 μ^+/sec). The target sensitivities for the two phases are 10^{-15} and 10^{-16} respectively. The plan is to present a complete proposal to PSI in early 2013. This experiment is highly complementary to other lepton flavor violation searches. The ratio of expected branching ratios of $\mu^+ \to e^+\gamma$ and $\mu^+ \to e^+e^-e^+$ depends on the theoretical model; the latter decay being sensitive to additional diagrams (tree diagrams with new particles like new vector bosons).

3. The MEG experiment

3.1 The experimental technique

The MEG experiment searches for $\mu^+ \to e^+\gamma$ where the muon decays at rest. The signal has a very clean experimental signature: the decay products appear simultaneously, have an energy of $\sim$52.8 MeV and the relative angle of their momentum vectors is 180^o. The main source of background is an accidental pile-up of a positron and a photon from two different muon decays where, for example, the photon comes from a radiative muon decay or from a positron annihilation in flight. The branching ratio for this background increases quadratically with the muon beam intensity so a compromise is needed to balance statistics and purity of the sample. The second

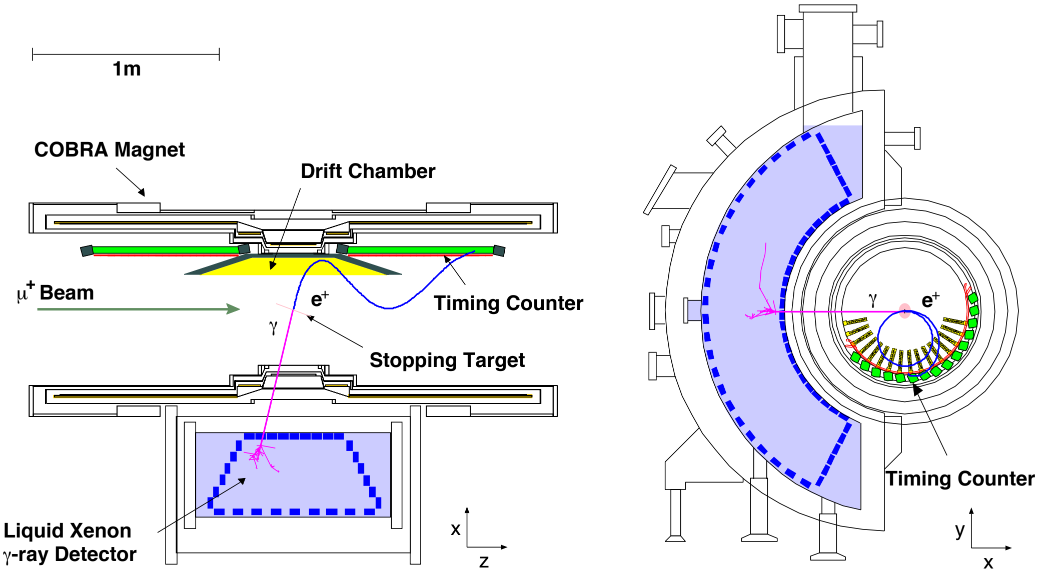

Figure 1: MEG detector

source of background, less severe, comes from radiative decays of the muons ($\mu^+ \to e^+\nu\bar{\nu}\gamma$, called physics background) that at the edge of the allowed kinematic region can mimic the signal. In order to reject the background it is crucial to have excellent experimental resolution on the discriminating quantities; the MEG design resolutions (FWHM) are : 1% for the positron energy, 4.5% for the photon energy, 150ps for the relative timing and 19mrad for the relative angle. With the above resolutions, the equivalent branching ratio in the signal region is at the level of 10^{-15} for the physics background and at the level of 10^{-14} for the accidental background.

3.2 The MEG detector

The PSI πE5 beam line is used to stop 3×10^7 positive muons per second in a thin polyethylene target. The residual polarization of the decaying muons along the beam axis was measured to be $P = -0.89 \pm 0.04$. The MEG detector, shown schematically in figure 1, covers ten percent of the solid angle and it is centered around the target. It is constituted by:

- A positron spectrometer with drift chambers placed in a non-homogeneous magnetic field. The COnstant Bending RAdius (COBRA) magnet produces a non homogeneous field with maximum at the center (1.28T) and decreasing towards the spectrometer edges. The advantages of COBRA with respect to a traditional solenoid is two-fold. First, positrons with high transverse momentum are quickly swept away from the drift chambers that can thus work at the high rate typical of the experiment and secondly, the bending radius depends approximately only on the magnitude of the positron momentum and it is thus independent on the emission angle. Positron tracks are measured with 16 low-mass, trapezoidal drift chambers aligned radially at 10^o intervals in azimuthal angle. The amount of material seen by the positron through the drift chambers is about $2{\cdot}10^{-3}$ radiation length. Each sector consists of two staggered arrays of drift cells filled with a mixture of He/Ethane (50%/50%), immersed in Helium atmosphere. The radial coordinate is obtained from the drift time on the wire

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ends where a precise measurement of the longitudinal coordinate is obtained with a Vernier cathode pattern.

- A scintillating detector, the timing counter, that provides the timing of the positrons at the end of their path through the drift chambers. The timing counter consists of two sections placed upstream and downstream of the target. Each section is made of 30 scintillating bars aligned along the beam direction, read by PMTs, that measure the time and the azimuthal coordinate, and of 256 scintillating fibers placed perpendicular to the bars. The fibers measure the z coordinate of the impinging positron.

- A C-shaped liquid Xenon calorimeter. Xenon is liquid at a comparatively high temperature (165K), has a small radiation length (2.7cm) and has a high light yield, comparable to that of the sodium iodide, but with a significantly lower emission time, of the order of tens of ns. The calorimeter is made of 900l of liquid Xenon and is read out by 846 PMTs with quartz window, since the peak emission wave length is in the vacuum UV.

The MEG trigger utilizes a 100MHz waveform digitizer on VME boards and applies requirement on the photon energy, the positron-photon time coincidence, and the positron-photon collinearity. The waveforms from the electronic channels of all the detectors are digitized with a custom chip designed at PSI, the Domino Ring Sampling (DRS). The DRS has been designed in order to allow pile-up rejection within waveforms close in time as much as possible. The MEG detector response, resolutions and stability are constantly monitored and calibrated with a wide set of calibration tools that include LEDs and alpha sources for the calorimeter's phototube, photons from nuclear reactions induced on appropriate targets from a Cockroft Walton accelerator, and photons from a Am/Be radioactive source. Moreover, every year a special charge exchange (CEX) run is taken where a pion beam impinged on a liquid hydrogen target producing $\pi^0 \to \gamma\gamma$ events where photons with energy close to that of the signal can be studied. Detector performances are quoted in the next subsection.

3.3 Analysis and results

The results presented here are based on data collected in 2009 and 2010 for a total of 1.8×10^{14} μ^+ decays in the target. The 2008 data are not used in this analysis because of the limited statistics and unstable detector performances. The collaboration has chosen a blind analysis strategy where the variables used to blind the region where the signal is expected to be (signal box) are the photon energy and the photon-positron relative time. The signal box was opened once all the calibration procedures and the selection criteria were finalized. A maximum likelihood analysis has been performed, based on 5 discriminating variables: the photon and the positron momentum, the photon-positron relative angle polar and azimuthal projections and the photon-positron relative time. The likelihood function has three components: one component for signal events, one for the radiative decay background and one for accidental background. The detector resolutions are used to parametrize the signal probability density functions (PDFs). They are determined from data by means of the calibration samples, mainly photons from the CEX run, positrons from normal muon decay and radiative decays. The photon energy response function depends on the photon conversion position, especially on the depth from the entrance surface (w). The resolution σ_R (the spread of the response function at the high energy side) is measured from CEX data to be 1.9%(w > 2 cm) and 2.4%(w < 2 cm) for signal photon of 52.8 MeV. The position resolution also depends on the position on the LXe detector and is measured to be 5 and 6 mm on the entrance surface and along the depth, respectively. The positron energy response function has been measured by fitting the kinematic edge of the Michel spectrum and it is well described with three Gaussian functions with a resolution (fraction) of the core component of 0.31 MeV (80%) and 0.32 MeV (79%) for 2009 and 2010, respectively. The resolution of the positron direction is estimated by exploiting tracks with two full turns in the drift chambers. Each turn is treated as an independent track and the resolutions are extracted from the difference between the two reconstructed segments. The polar and azimuthal angle resolutions are measured to be 6.7 (7.2) and 9.4 (11.0) mrad for 2009 (2010). The vertex resolutions are estimated to be 1.5 (2.0) mm along the beam axis and 1.1 (1.1) mm in the vertical direction for 2009 (2010). Combining the photon and positron angular and vertex resolutions gives the resolution on the relative angles; azimuthal of 14.5 (17.1) and polar of 13.1 (14.0) mrad for 2009 (2010). The relative photon-positron time resolution has been measured from radiative decay data in the photon energy sidebands and it is 146 (122) ps for 2009 (2010).

The PDFs for accidental background events are determined from data outside the blind box (sidebands) while the PDFs for radiative decay events are determined from the theoretical distribution convoluted with the detector resolution. Correlations between analysis variables are taken into account where necessary, for example a correlation exists between the positron energy and angle variables due to the kinematic constraints given by the almost bidimensional target. After the likelihood fit is performed, a frequentistic method with a profile likelihood ordering is used to calculate the confidence interval on the number of signal events. The sensitivity, which is defined as a 90% confidence level upper limit of the branching ratio averaged over an ensemble of toy Monte Carlo experiments with a background-only hypothesis, is calculated to be 3.3×10^{-12} , 2.2×10^{-12} and 1.6×10^{-12} for the data 2009 and 2010 and the combined data sample, respectively. The sensitivity is consistent with the branching ratio upper limits observed at the side-bands. The resulting upper limit at 90% C.L. is 2.4×10^{-12} which constitutes the most stringent limit on the existence of the $\mu^+ \to e^+\gamma$ decay, superseding the previous limit by factor 5. Figure 2 shows the confidence intervals obtained. The largest contributions to the systematic uncertainty come from the uncertainties of the relative angle center, the correlations of the positron observables and the normalization factor (obtained from Michel decays).

3.4 The future of MEG and the upgrade proposal

The MEG experiment took data also during 2011 (the sample corresponds to about the same statistics of 2009 and 2010) and the analysis is on-going. Another run is started and will last until the end of 2012. It is foreseen that the final sensitivity of the MEG experiment will be $6-7 \times 10^{-13}$. The collaboration is also studying the case of an upgrade of the experiment that aims at a sensitivity of 5×10^{-14}. Several improvements are under study:

- a new tracking drift chamber, capable of operations at high rate, with improved efficiency, momentum and angular resolution .This will be a cylindrical chamber possibly with cluster timing capabilities

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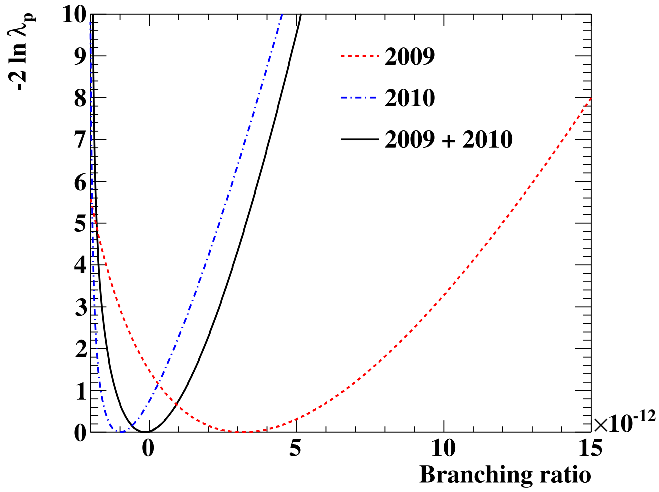

Figure 2: Confidence interval of the $\mu^+ \to e^+\gamma$ branching ratio.

- an upgrade of the electromagnetic calorimeter to improve the photon energy and position resolution by using a larger number of smaller diameter sensitive devices
- an active target that improves angular resolution by providing a measurement of the track at the production point
- a new timing counter detector made of scintillating tiles instead of bars

The time scale of the project, if approved, would be of two years of R&D activity followed by three years of running.

4. Conclusion

The lepton flavor violating decays $\mu^+ \to e^+\gamma$ and $\mu^+ \to e^+e^-e^+$ are unmeasurably small in the SM and are sensitive probes for new Physics. The Mu3e collaboration proposes an experiment to search the $\mu^+ \to e^+e^-e^+$ decay with a target sensitivity of 10^{-16}. The MEG experiment searches for the $\mu^+ \to e^+\gamma$; the result of the analysis on the data from run 2009 and 2010 is recently published. No evidence of signal is found and the most stringent upper limit on the branching ratio of 2.4×10^{-12} at 90% C.L., improving the previous limit by a factor of five, is set instead. The run of 2011 is successfully completed and the total data statistics is then doubled with this data sample. The analysis on the data 2011 is going smoothly and hopefully the data will be unblinded soon. The MEG experiment will be continuing the data-taking until 2012 to explore $6-7\times10^{-13}$ branching ratio region. An R&D work on detector upgrade has also started in parallel aiming at improving the sensitivity by another order of magnitude.

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