論文の内容の要旨

The final result of $\mu^+ \to e^+\gamma$ search with the MEG experiment
(MEG 実験による$\mu^+ \to e^+\gamma$探索の最終結果)

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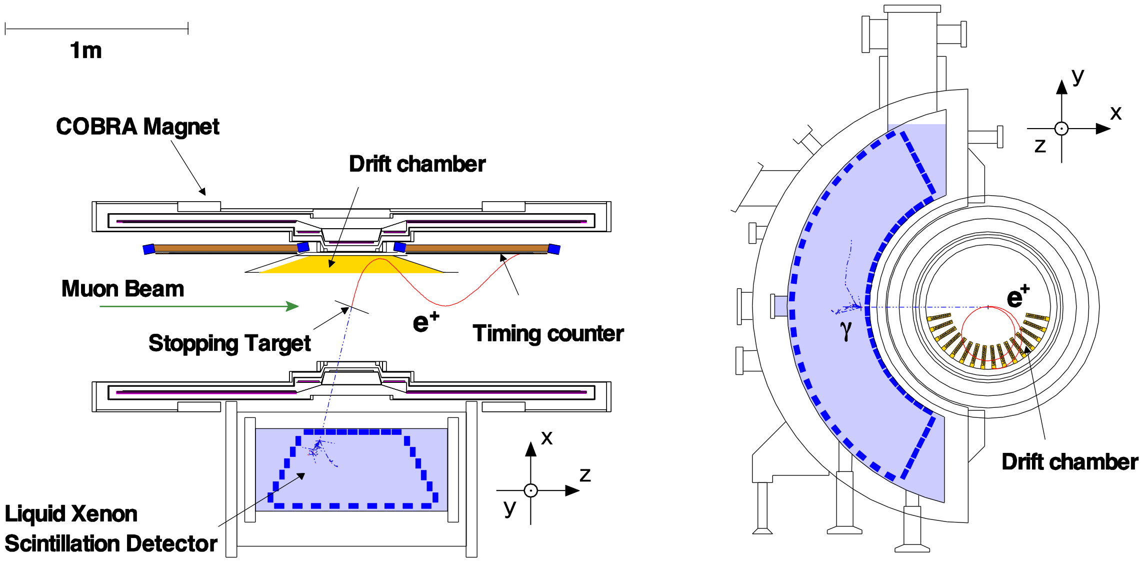
Charged lepton flavor violation (CLFV) is a phenomenon which has never been observed. $\mu^+ \to e^+\gamma$ is one of the examples. It is forbidden in Standard Model (SM), and even the neutrino oscillation is considered, the probability is too low to be found. Therefore it will be an unwavering evidence of the physics beyond the Standard Model, if it is discovered. The MEG experiment is searching for $\mu^+ \to e^+\gamma$ with sensitivity in branching ratio of order of 10^{-13}. The dominant background of the MEG experiment is accidental background, where a gamma-ray and a positon look like a real signal. In order to achieve good sensitivity, the resolution of the energy, direction, timing of gamma-ray and positron are important.

The MEG experiment is conducted at the πE5 beam line in the Paul Scherrer Institute in Switzerland where the world's most intense positive muon beam is available. An overall image of the MEG detector is shown in Figure 1. The MEG detector consist of gamma-ray detector and positron spectrometer. The gamma-ray detector adopts the liquid xenon (LXe) for its excellent features. Photo-multiplier tubes which are directly submerged in the LXe detect scintillation photons. The positron spectrometer is composed of COBRA magnet, which generates special magnetic field, ultra-low mass drift chamber as positron tracker, and timing counter.

Figure 1　Setup of the MEG detector in cross sectional view.

The energy, conversion position in LXe and timing of gamma-ray conversion are reconstructed from the LXe detector information. The positron track is reconstructed from hits in the drift chamber to estimate initial vertex position and momentum. The Kalman filter method is used for estimate positron track in the magnetic field. The



timing information is reconstructed by combining track and information from the timing counter. The relative timing and relative angle are obtained by comparing the reconstructed gamma and positron.

The data taking of the MEG experiment started in year 2008 and finished in year 2013. The data taken by year 2011 have been analyzed in previous study. The search sensitivity in the previous analysis was 7.7×10^{-13}. The data amount of in year 2012 and 2013 are as much as the previously analyzed data, the total number of muon stopped on the target is 7.5×10^{14}.

In this final analysis study, deformation of the muon stopping target was found. As the initial angle on the target is reconstructed from positron track, an error in the assumed position of target makes effect on the estimation of the initial angle of positron emission, and the magnitude of an impact for angle reconstruction is not negligible especially in year 2012 and 2013. The deformation is thought to gradually progress. Careful investigations are performed and countermeasures against the issue are determined. The positron tracking is corrected with fitted target form, and remaining uncertainty is taken into account by profiling in maximum likelihood analysis. The target problem turned out to result in the largest effect for the search sensitivity.

On the other hand, several improvements are also introduced. One is the recovery of the positron track where first turn was missed. About 4% of good events which was trashed with the mistake are recovered. The reduction of one of gamma-ray background which is generated from annihilation of positron in detector is another improvement. A more detail alignment of LXe detector with 3D laser scanner is also taken into account in gamma-ray reconstruction.

Almost all reconstruction methods are updated from previous publication; hence the all data, even once analyzed old data are processed again with renewed analysis methods for this study.

The $\mu^+ \to e^+\gamma$ search analysis is based on maximum likelihood analysis, and a blind is applied on the analysis region, in order to reject any human biasing to determine analysis methods. The numbers of signal events is main fitted parameter, and numbers of radiative muon decay event and accidental background event, and parameter related to target deformation are nuisance parameter. The probability density functions (PDF) for those kinds of events are determined from data out of the analysis window (side bands), the event-by-event PDF scheme is adopted in analysis where the PDF parameters vary event-by-event according to the error in the positron track reconstruction. The confidence interval about the branching ratio is set by a frequentist approach by Feldman and Cousin with the profile likelihood-ratio ordering. The factor to convert the number of the events to the branching ratio is computed with the number of the normal and radiative muon decay.

Finally in the end of year 2015, the calibration and determination of analysis method was finalized. The data in the analysis window were opened. As the result, no significant excess of the signal events against the background was found, and the distribution of backgrounds matches well with expectation. The event distribution and the result of the maximum likelihood fit are shown in Figure 2 and 3. The confidence interval is calculated on data, and new upper limit for $\mu^+ \to e^+\gamma$ is calculated to be 4.2×10^{-13} in 90% confidence level, while 90% C.L. sensitivity is 5.3×10^{-13}. The result is examined with various methods, such as distribution in relative signal likelihood, and comparison with alternative PDF analysis. In any examination, consistent results are confirmed.

The improvement from last result is about 20%, and comparing with the record before MEG experiment: MEGA experiment, the result improved by a factor of 30. The sensitivity with all data in MEG experiment is 5.3×10^{-13}.

The search for $\mu^+ \to e^+\gamma$ in MEG has been finished and continues to MEG II.

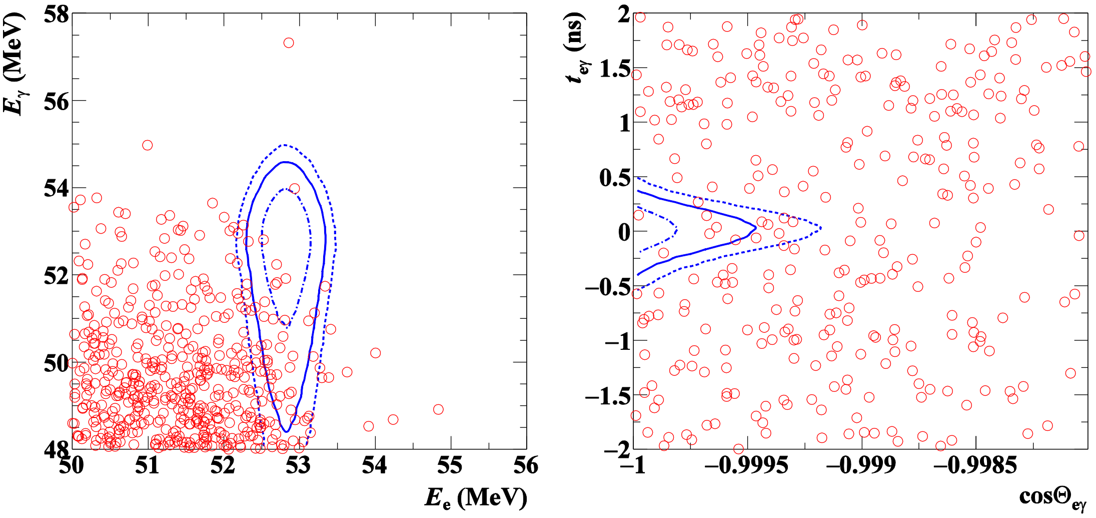


Figure 2 Observed events in analysis region. Contour shows signal PDF.
(left) Ee: energy of positron, Eγ: energy of gamma-ray (right) Θeγ: opening angle between positron and γ, teγ: time difference between positron and γ.

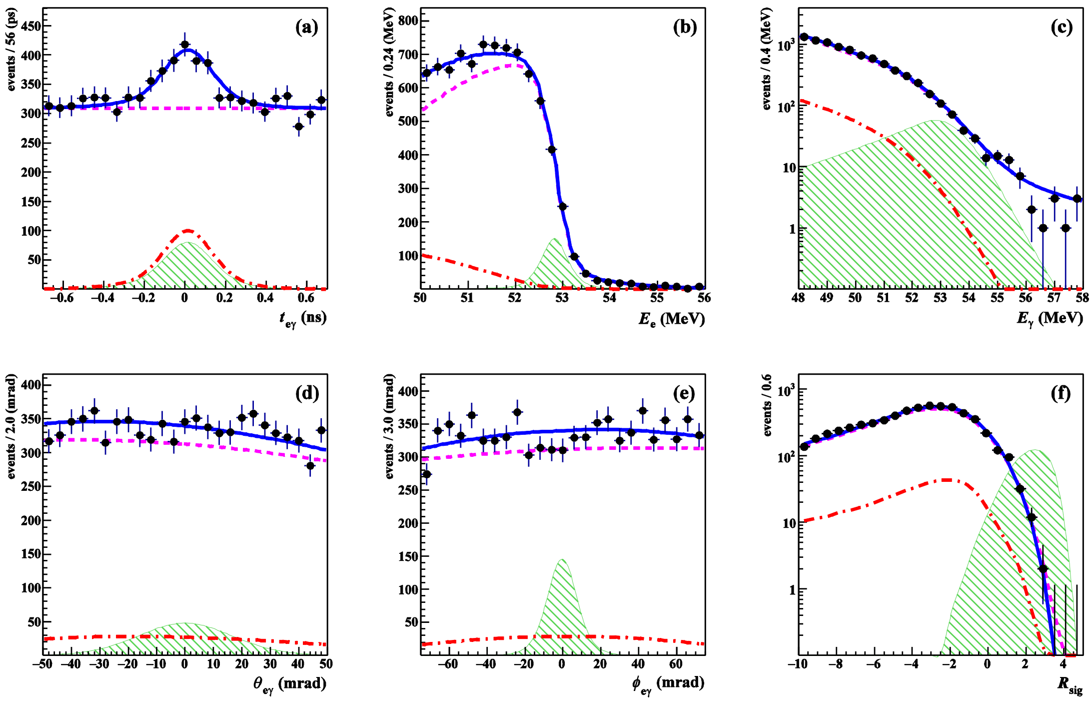


Figure 3 Result of the maximal likelihood fit. θeγ and ϕeγ means polar and azimuthal component of the stereo opening angle, respectively (0 means just back-to-back). Rsig in (f) is relative signal likelihood. Black markers show data, and blue line shows the sum of the PDFs of all kind of event types.