Searching for a lepton flavour violating muon decay mediated by a new light particle with the MEG I full datasets
Introduction (1/2)

- There is no clear evidence of new physics to date (except for some anomalies).
- Therefore it is important to search any possibility of BSM using existing experimental setups.
  - Displaced vertex/long-lived particles search in ATLAS/CMS, FCC.
  - LHC + X facilities (Codex-b, MATHUSLA, MilliQan, SHiP, FASER)
  - Long-lived particles search in KOTO.
  - Dark sector search in Belle2 (B2TiP).
  - ……
  - MEG can do the similar thing!
The MEG experiment

- The MEG experiment searched for charged lepton flavour violating muon decay ($\mu^+ \rightarrow e^+ \gamma$).

- Physics data taking: 2009–2013
  - $7.5 \times 10^{14}$ stopped muons

- No excess was found and the most stringent upper limit, $4.2 \times 10^{-13}$ (90% C.L.) was set on $\text{Br}(\mu^+ \rightarrow e^+ \gamma)$ in 2016.

At Paul Scherrer Institut in Switzerland

Introduction (2/2)

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- We have started studying a search for $\mu^+ \rightarrow e^+ X$, $X \rightarrow \gamma \gamma$ using the MEG full datasets.
Physics motivation

- **Main motivation:** LFV is one of the key tools to search for BSM.
- However, we have not yet observed LFV mediated by heavy particles.
- LFV mediated by *new light particle* $X \sim O(10^{-100})$ MeV might be left undiscovered as a loophole.

- A possible search in MEG: $\mu \rightarrow eX$, $X \rightarrow \gamma\gamma$ (hereafter we call it “MEx2G”)
  - $X$ is generated via LFV coupling and the on-shell $X$ decays back into SM particles.
  - In this search, we assume decay width is narrow and $X$ is long-lived.

- A possible mechanism of the light mass: Nambu-Goldstone boson generated via spontaneously symmetry breaking of approximate global symmetry (i.e. relatively light mass of $\pi$)

- Possible candidates of $X$: axion-like particle, majoron, familon, flaxion, and strongly interacting DM (SIDM)
Previous studies

- Crystalbox (1988): $\mu \rightarrow e\gamma\gamma$ decay search
  - This upper limits are converted into MEx2G taking into account the difference of the detector efficiency (solid line in left plot).
- H. Natori (2012): $\mu \rightarrow eX$, $X \rightarrow \gamma\gamma$ decay search using the MEG 2009/2010 datasets
  - the first in the world, available in a Ph.D thesis (not published yet).
- SN1987A/beam dumps: “$>1$ cm or <20 MeV” is excluded (right plot).
  - Target parameter space should be “$<1$ cm and $>20$ MeV”.

10 ps ~ a few mm

Ph.D. thesis by H. Natori (UTokyo, 2012)
Today’s topic

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Today’s topic

• We have started studying a search for $\mu^+ \rightarrow e^+X$, $X \rightarrow \gamma\gamma$ using the MEG full datasets.
  focusing on
    ‣ expected Br sensitivity
    ‣ possible updates
    ‣ schedule

※The physics results will not be presented today.
Signal reconstruction & BG

1. $e^+$ reconstruction

2. $\gamma$ reconstruction

3. $2\gamma$ event selection

4. $2\gamma$ reconstruction

5. $X$ vertex reconstruction assuming $m_X$.

- Signal $e^+, X$:
  - back-to-back
  - the same momentum
  - coincidence in time

- Possible BG:
  - $e^+$ is accidental
  - one of $\gamma$ is accidental
  - $e^+, \gamma, \gamma$ is accidental

- BG is estimated with time sideband.
Updates from the previous study

- ~5 times larger statistics
- Refined reconstruction methods
  - $e^+$ events
    - ✓ noise subtraction, refined tracking
  - $2\gamma$ event selection
    - ✓ A better algorithm to select $2\gamma$ events.
  - $2\gamma$ event reconstruction
    - ✓ rejection of biases, additional corrections.
  - $X$ vertex reconstruction

- Corrections/modifications on the estimation of efficiencies
  - Additional corrections (trigger, $e^+$ efficiency).
  - Taking additional correlations b/w variables into account.
  - More data-driven estimation.
Expected Br sensitivity

- The purpose of this study is to estimate expected Br sensitivity with the MEG full datasets.

- Updates included in this calculation:
  - ~5 times larger statistics.
  - Analysis updates (mainly on the positron side).
  - A change of trigger conditions after 2010.

- $\langle N_{BG} \rangle$ is calculated based on the analysis in 2012 (using 2009/2010 data), assuming it is proportional to the statistics ($=k$)

- The expected Br sensitivity is calculated using the Feldman-Cousins (FC) approach*.

- Br sensitivity: $B = \frac{1}{k} \times N_{\text{sensitivity}}$
  - $k$: normalisation
  - $1/k$: single event sensitivity
  - $N_{\text{sensitivity}}$: expected $N_{\text{signal}}$ upper limit when no signal is assumed

To get the relative normalisation, Michel events (Br(\(\mu^+ \rightarrow e^+ \nu \bar\nu\)) \approx 100\%) are used.

\[ \mu^+ \rightarrow e^+ \nu \bar\nu : \text{Michel decay, Br \sim 100\%} \]
\[ \mu^+ \rightarrow e^+ X, X \rightarrow \gamma \gamma : \text{MEx2G signal} \]

\[
\mathcal{B}_{\text{Signal}} = \frac{1}{k} \times N_{\text{Signal}}
\]

\[
\frac{1}{k} = \frac{1}{N_{\text{Michel}}} \times \frac{\text{ratio of e\(\)\#}}{\text{efficiency}} \times \frac{1}{\gamma \text{ efficiency}} \times \frac{\text{ratio of trigger}}{\epsilon_{\text{Michel}}} \times \frac{\epsilon_{\text{Signal}}}{\epsilon_{\text{Michel}}} \epsilon_{\text{Signal}}
\]

The number of Michel events \sim 1

Efficiency of \(\gamma \gamma\) events. 0.1\%–9\% depending on the assumed \(m_X\) and \(\tau\). 

Efficiency of analysis cut on energy, time, vertex quality, momentum conservation. 20\%–40\% depending on the assumed \(m_X\) and \(\tau\).

By using Michel positrons as a normalisation, the estimation is independent of beam rate (stopped muons), and insensitive to absolute positron detection efficiency.
Single event sensitivity

- S.E.S.: Single Event Sensitivity = 1/k
  - $k_{\text{Natori2012}} = k_{2009a} + k_{2009b} + k_{2010a} + k_{2010b}$
  - $k_{\text{This study}} = k_{\text{new 2009a}} + k_{\text{new 2009b}} + k_{\text{new 2010a}} + k_{\text{new 2010b}} + k_{2011} + k_{2012/2013}$

- **Blue**: S.E.S. estimated in the previous analysis in 2012.
- **Red**: updated results with more statistics ($\times 4.7–5.3$).

![Graph showing S.E.S. (100 ps) vs. Assumed $m_X$ (MeV) in vertex reconstruction](image)
1. N_{BG} in the previous study is shown in blue:

2. Assume N_{BG} is proportional to the statistics*, then we get expected N_{BG} in the full datasets (see the next):
   - expected N_{BG} = previous N_{BG} * k_{This study} / k_{Natori2012}
   - 4.7–5.3 times larger statistics than the previous results.

3. Calculate the sensitivity (see the next).  

*In the final analysis, it will be estimated using sideband data.
Sensitivity

- Sensitivity is defined as the average upper limit that would be obtained by an ensemble of experiments with the expected background and no true signal.
- Sensitivity is calculated using estimated $N_{BG}$ and Feldman-Cousins approach.
- Sensitivity at 90% C.L. is shown in right plot together with expected $N_{BG}$.
Br sensitivity

- We can get Br sensitivity with $\mathcal{B} = \frac{1}{k} \times N_{\text{sensitivity}}$
- Br sensitivity is expected to be improved by a factor of $3.2$–$5.0$.
- Lower mass: $N_{BG}$ is larger and it should be decreased to get the better sensitivity.
- Higher mass: new analysis can update crystal box results, which cannot be updated in Natori2012.

Worse sensitivity in the higher mass region due to
- Cut efficiency
- Trigger efficiency
- Gamma acceptance
Summary & Prospects

- Recently, it is important to search any possibility of BSM with existing experimental setups.

- We have started thinking the search for $\mu^+ \to e^+ X, X \to \gamma\gamma$ using the MEG I full datasets.

- Br sensitivity is expected to be improved by a factor of $3.2 - 5.0$ from the previous study in 2012.

- It will be updated with refined analyses.

- Updates on reconstruction tools: on going

- Physics results: this year

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### Br Sensitivity ($\tau = 100$ ps)

![Graph showing Br sensitivity vs. assumed $m_X$ (MeV)]