Development of calibration methods for MEG II positron timing counter

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On behalf of MEG II Collaboration
Inter-generational mixing have not been observed only for charged lepton sector.

Too small branching ratio is predicted in the framework of the standard model + neutrino mass.

Beyond the standard model (SUSY GUT etc) predicts that charged lepton should also mix at experimentally observable rate: $O(10^{-11}) \sim O(10^{-15})$

The discovery of cLFV is clear evidence for new physics.
MEG II Experiment

- Search for cLFV ($\mu^+ \rightarrow e^+ \gamma$) with unprecedented sensitivity: $4 \times 10^{-14}$
- $x10$ improvement from MEG ($4.2 \times 10^{-13}$, 2016)

- Signal ($e^+, \gamma$)
  - Simultaneously emitted
  - back-to-back
  - same energy

- All detectors will be ready in 2018

- Improve every resolution by factor 2
MEG II Detector

At Paul Scherrer Institut in Switzerland

Intro

Liquid Xenon Gamma-ray Detector

Cylindrical Drift Chamber

pixelated Timing Counter

Radiative Decay Counter

-13aU33-1 (中尾)
-13aU33-2 (宇佐見)
-14aS36-7 (中尾)

-13aU33-3 (恩田)
-13aU33-7 (家城)
-13aU33-9 (小川)
-13aU33-10 (松澤)

-14pS35-8 (家城)

JPS Autumn Meeting 2017 (13aU33-1)

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We have completed our detector and ready for installation into experimental site.
Key Concept

- Improve time resolution by averaging the signal time of multiple hits.

- Averaged hit multiplicity for signal $e^+$s: 9 (MC)

- The total time resolution is expected to improve with $\frac{1}{\sqrt{N_{hit}}}$ and $\sim 35$ ps can be achieved at 9 hits.

Mathematical expression:

$$\sigma_{all}(N_{hit}) = \sqrt{\sigma^2_{intrinsic} + \frac{\sigma^2_{inter-pixel}}{N_{hit}} + \sigma^2_{MS}(N_{hit}) + \sigma^2_{const}}$$

- Intrinsic resolution: $70 \sim 80$ ps
- Multiple scattering: $\sim 4$ ps at 9 hits

512 pixels
53 MeV $e^+$ (helical trajectory)

Stopping Target

$\phi$

$\mu^+$ beam

z

Number of hit pixels

Probability

Mean: 9

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pTC (2): Pixel

- Upstream (256 pixels) + Downstream (256 pixels) = 512 pixels
- Fast plastic scintillator (BC422, 40 (50) x 120 x 5 mm³)
- Readout by 6 SiPMs* with series connection (in total 6144 SiPMs) at each of both sides.
- Time calibration accuracy among pixels: < 30 ps

*AdvanSiD, ASD-NUV3S-P High-Gain, 3x3 mm², 50x50 μm², $V_{\text{breakdown}} \sim 24$ V
Time Calibration

- We have to know time offset of all 512 counters with the accuracy of 30 ps.
- Radiative Muon Decay ($\mu \rightarrow e\gamma\nu\nu$) is used for absolute calibration for relative timing b/w $e^+$ and gamma.
- We have two complementary methods to calibrate time offset b/w counters: laser-based method and track-based method.
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What we did so far

- We performed beam test using $1/4$ of pTC under the MEG II beam.
- We checked the consistency b/w 2 calibration methods under a limited situation:
  - Laser-based method: laser system was installed into 40 counters.
  - Track-based method: w/o Drift Chamber.

Purpose of This Study

- Laser-based method: extend to full laser system.
- Track-based method: develop w/ Drift Chamber.
Laser-based Method: Concept

- PLP-10 (Hamamatsu) is used as a light source.
  - Wavelength 405 nm
  - Wavelength FWHM < 10 nm
  - Pulse duration typ. (max) 60 (100) ps

- Pulse laser is divided into each pixel simultaneously.
- Time offset of each pixel is measured relative to laser-synchronized pulse.
- Calibration accuracy is estimated as 24 ps by testing all parts of laser calibration system.
Test Installation (1)

Laser Hut (Cavern)

- By hand (now)
- > Optical Switch

Laser Box

Splitter Box

Detector Hut

10 m fiber*4 in a tube

Splitter Box

x 4

Splitter 1x8

x 32

Splitter 1x8

pTC (DS)

WaveDAQ

Laser Head

Mode Scrambler

Photodiode

Laser Controller

Laser Sync.
Test Installation (2)

Laser Hut (Cavern)

Detector Hut

Splitter Box

- Splitter 1×8 (x 4)
- Splitter 1×8 (x 32)

pTC (DS)

fiber*4 in a tube

Temperature sensor
in 2016

- A part of DS system was tested under the $\mu$ beam.
- Consistency w/ track-based calibration was checked.

in 2017

- DS was checked using laser system.
- Dead/bad channels were fixed.
Track-based Method: Concept

- Positron tracks from Michel decay ($\mu^+ \rightarrow e^+\nu\bar{\nu}$) are used for calibration.

1. Calculate TOF values b/w adjacent counters.
2. Define $\chi^2$ as the difference b/w measured time and expected time.
3. Minimize $\chi^2$ using Millepede II.
4. Find $\Delta T_j$.

$$\chi^2 = \sum_{i}^{N_{ev}} \sum_{j}^{N_{hit}} \left( \frac{(T_{ij} - (T_{0i} + TOF_{ij} + \Delta T_j))/\sigma)^2}{\sum_{i}^{N_{ev}} \sum_{j}^{N_{hit}} \left( (T_{ij} - (T_{0i} + TOF_{ij} + \Delta T_j))/\sigma)^2 \right)} \right.$$
**MC Setup**
- Generated from $\mu^+$ beam mixed at $7 \times 10^7$.
- Time offset was set by randomly ($\approx$ Gaus(0, 100 ps)).
- Evaluate the performance with the difference b/w calculated time offset and original time offset.
- Number of events: 260k.

**Event Selection**
- Hit reconstruction → Clustering → Matching → Propagating → TOF Estimation
- First 5 hits in a cluster which has more than 7 hits are used.
- Used for calibration
- Selection is not applied here in this study.
- There is room for improvements
First results w/ Drift Chamber.

- Bias depending on counter position was observed.
  - TOF calculation in propagation.
  - Position dependence of statistics.

- Accuracy of < ~22 ps was achieved.
  - Needs further improvements.

\[\text{Calculated time offset} - \text{true time offset} / \text{its position dependence}\]
Prospects

Key months

Nov. 2017

- **Pilot Run 2017**
  - pixelated Timing Counter, Liquid Xenon Gamma-ray Detector, Radiative Decay Counter will be installed.
  - ~7 weeks of combined detector DAQ is planned under the MEG II environment.
  - Laser-based and track-based calibration will be applied for full pTC.
  - Performance check of full pTC using μ beam is planned.

- **Installation of all detectors**
  - Including Drift Chamber.

- **Engineering Run**
  - 6 months of performance data-taking.
  - This run may evolve into physics run if things get ready.
  - Inter-detector calibrations.

- **Physics Run**
  - Start searching for $\mu^+ \rightarrow e^+\gamma$ with unprecedented sensitivity.

Jul. 2018
Consistency Check b/w 2 Methods

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Key months
- Nov. 2017
- Jul. 2018

Consistency b/w Time Calibration Methods
- Time-offset difference b/w laser-based method and track-based method (left) and its stability (right).

- The variation of time-offset difference is $\sigma = 39$ ps.
  - Including systematic uncertainty of laser-based and track-based methods.
- Time-offset difference is stable in time (~ 6 ps).
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Jul. 2018
We have developed and constructed 2 complementary methods for time calibration.

Laser-based method:
- extended to full laser system.

Track-based method:
- first results w/ Drift Chamber was presented.
- accuracy of 22 ps was achieved, but have some bias.
- it needs improvements at each step of analysis chain.

Beam test w/pTC, LXe and RDC is planned from Nov. 2017 (Pilot Run 2017).