Searching for the Muon(ium) Rare Decays

Progress of the Muonium-to-Antimuonium Conversion Experiment (MACE)

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2024年11月8日星期五

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Muonium-to-Antimuonium Conversion Experiment

A portal of new physics-CLFV

Charged Lepton Flavor Violation (CLFV)

- CLFV = new physics beyond Standard Model (SM)

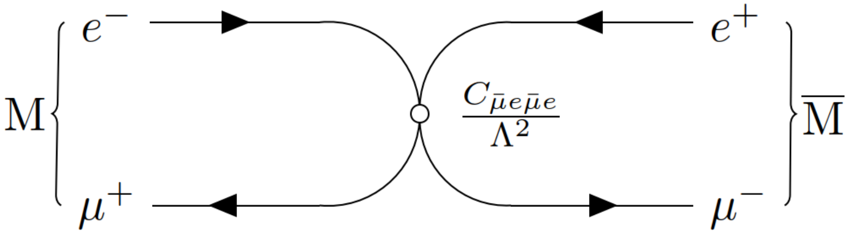
✓ **CLFV is forbidden in SM.** ⟶ $\mathrm{Br}(\mu \to e\gamma) = \frac{3\alpha}{32\pi m_W^4}\left|U_{\mu 2}U_{2e}^{\dagger}\Delta m_{21}^2 + U_{\mu 3}U_{3e}^{\dagger}\Delta m_{31}^2\right|^2 \sim 10^{-54}$

✓ **Lepton flavor is not conserved.** Neutrinos have (small) mass and mix.

Phys.Rev.Lett. 108 (2012) 171803, *J.Phys.G* 43 (2016) 3, 030401

✓ Many new physics model beyond SM predict CLFV. arXiv:1709.00294

➢ **A clear evidence of new physic if discovered!**



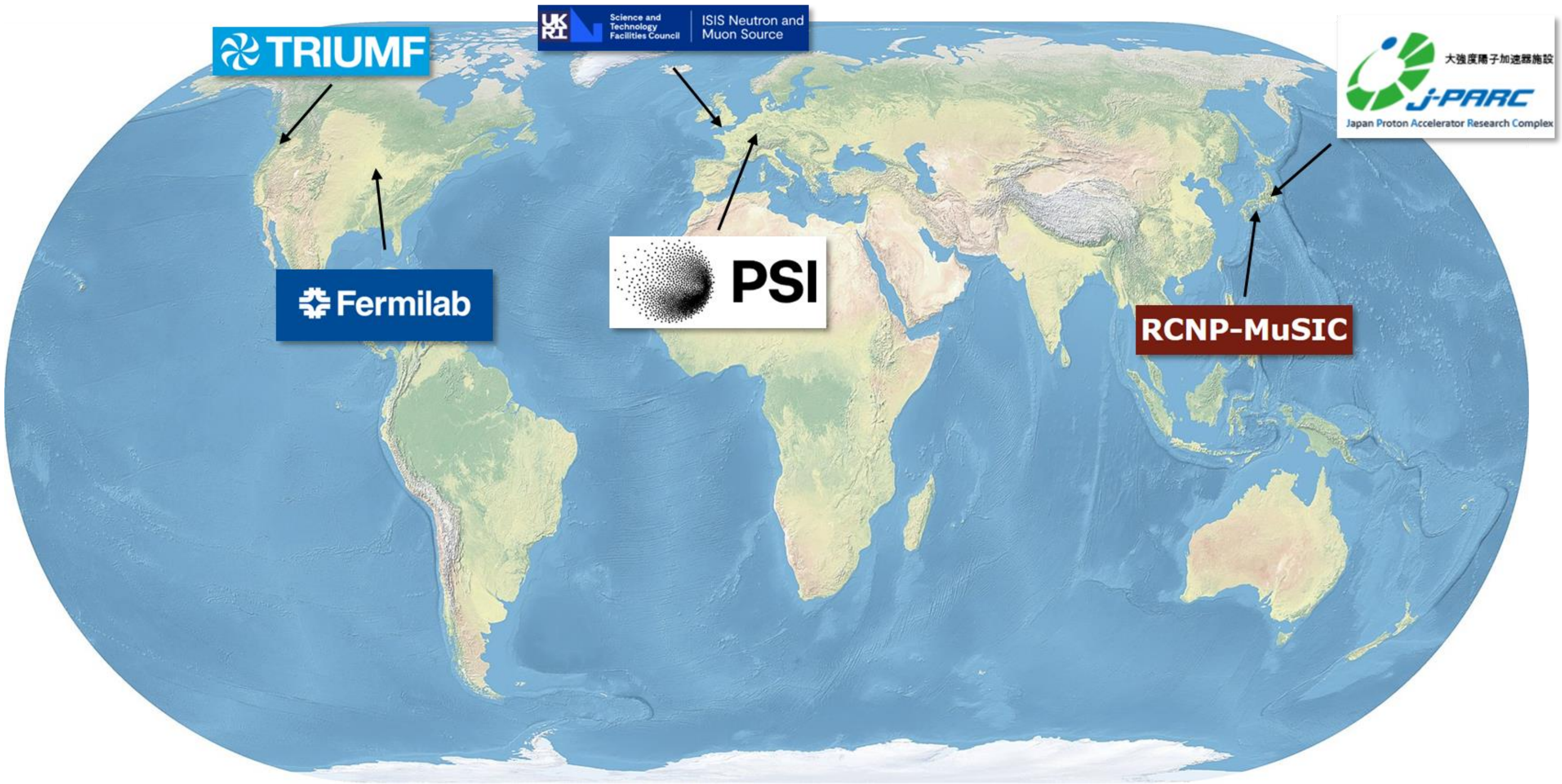
Why muon?

- Lightest massive unstable charged lepton
- Relatively long lifetime (2.2 μs)

Most concerned channels:

- $\mu^+ \to e^+\gamma$
- $\mu^+ \to e^+e^-e^+$ $\quad \boldsymbol{\Delta L_\mu = 1}$
- $\mu^- \mathrm{N} \to e^- \mathrm{N}$

Existing muon sources

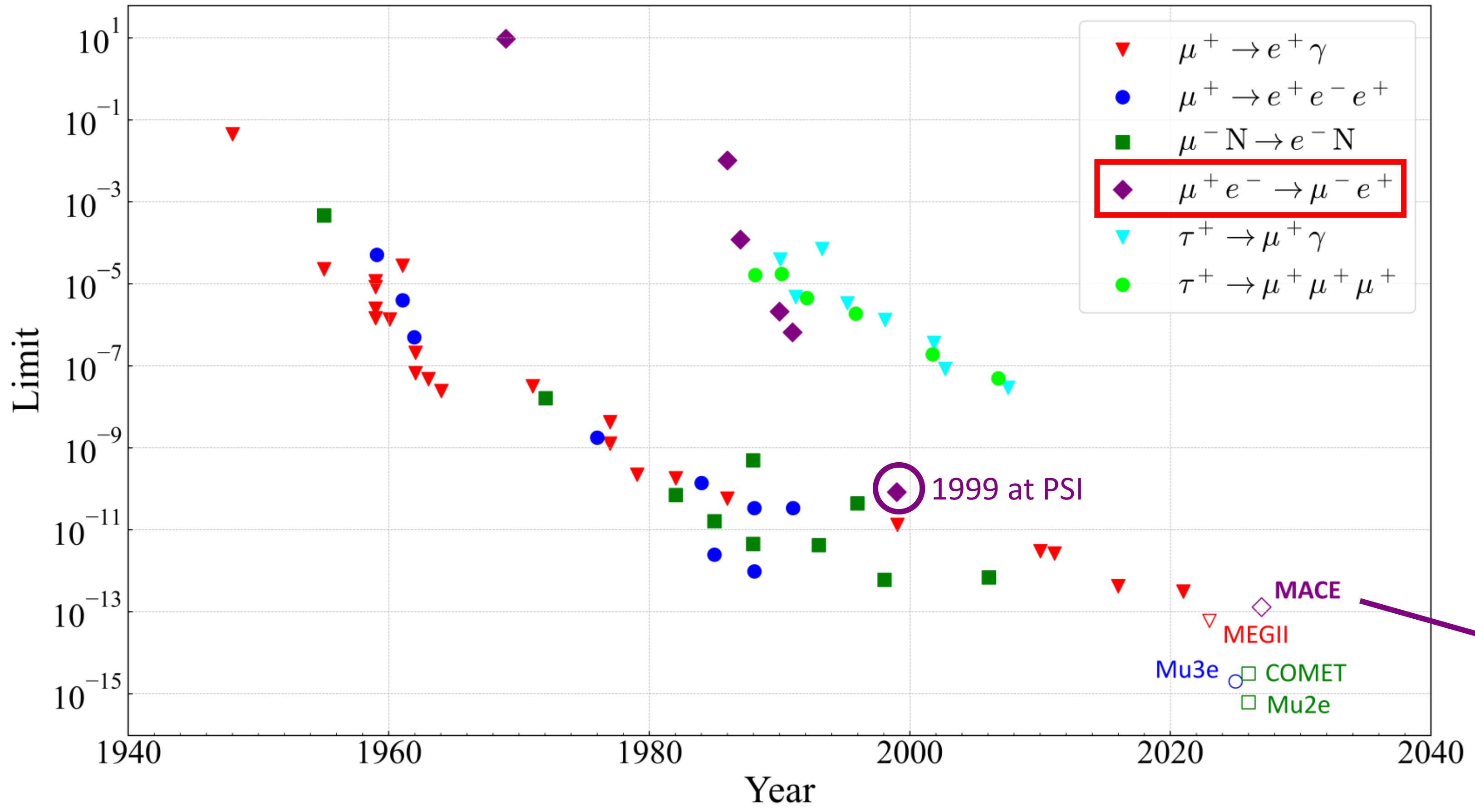


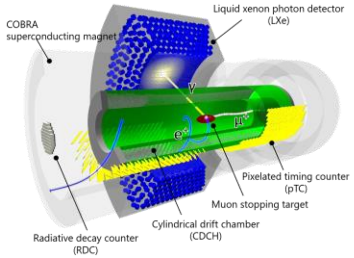
- Muon CLFV experiments emerging in 40 years taking advantage of the *accelerators*

(CA, CH, JP, UK, US)

- Future muon beamline in **China**:
  - CiADS
  - HIAF
  - CSNS (MELODY)
  - SHINE

New-Generation experiments





PSI

J-PARC

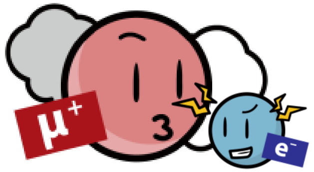
Fermilab

Muonium-to-Antimuonium Conversion Experiment

China

Progress of MACE

How about the **Muonium** (μ^+e^-)?



- Similar to the H atom
- Pure QED bound state
- $\mu^+e^- \to \mu^-e^+$, $\Delta L_\mu = 2$

Conceptual Design of the Muonium-to-Antimuonium Conversi[on]

Experiment (MACE)

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(Dated: October 25, 2024)

Abstract

The spontaneous conversion of muonium to antimuonium is one of the interesting charged lepton flavor violation phenomena, offering a sensitive probe of potential new physics and serving as a tool to constrain the parameter space beyond the Standard Model. Utilizing a high-intensity muon beam, a Michel electron magnetic spectrometer and a positron transport solenoid together with a positron detection system, MACE aims to discover or constrain this rare process at the conversion probability beyond the level of 10^{-13}. This report provides an overview of the theoretical framework and detailed experimental design in the search for the muonium-to-antimuonium conversion.

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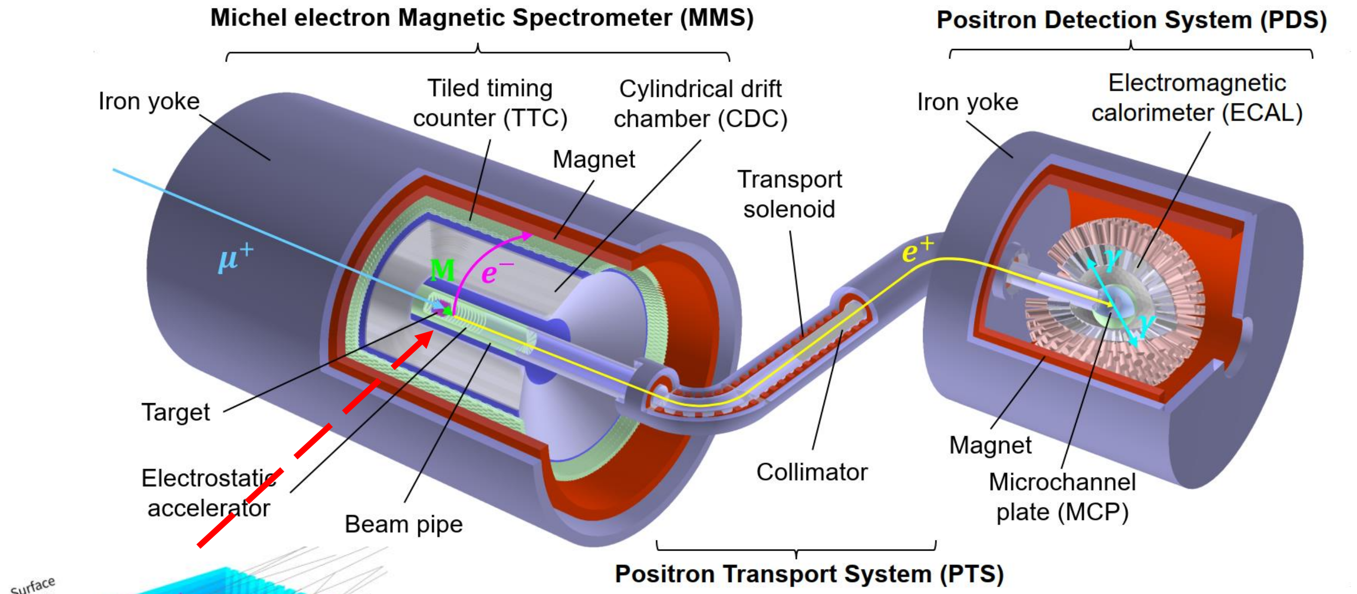
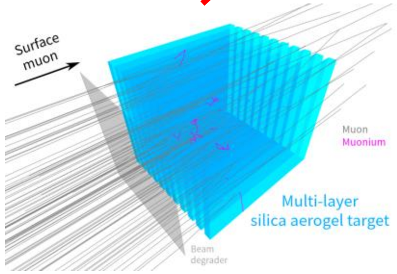
arXiv:2410.18817v1 [hep-ex] 24 Oct 2024

Conceptual Design Report, arXiv:2410.18817





Multi-layer target

- **4.94%** (vacuum)
- 3.45 times larger than single
- 0.5% (vacuum) in 1999

Triple coincidence:

- **MMS + MCP + ECAL**

Michel e^- Atomic e^+

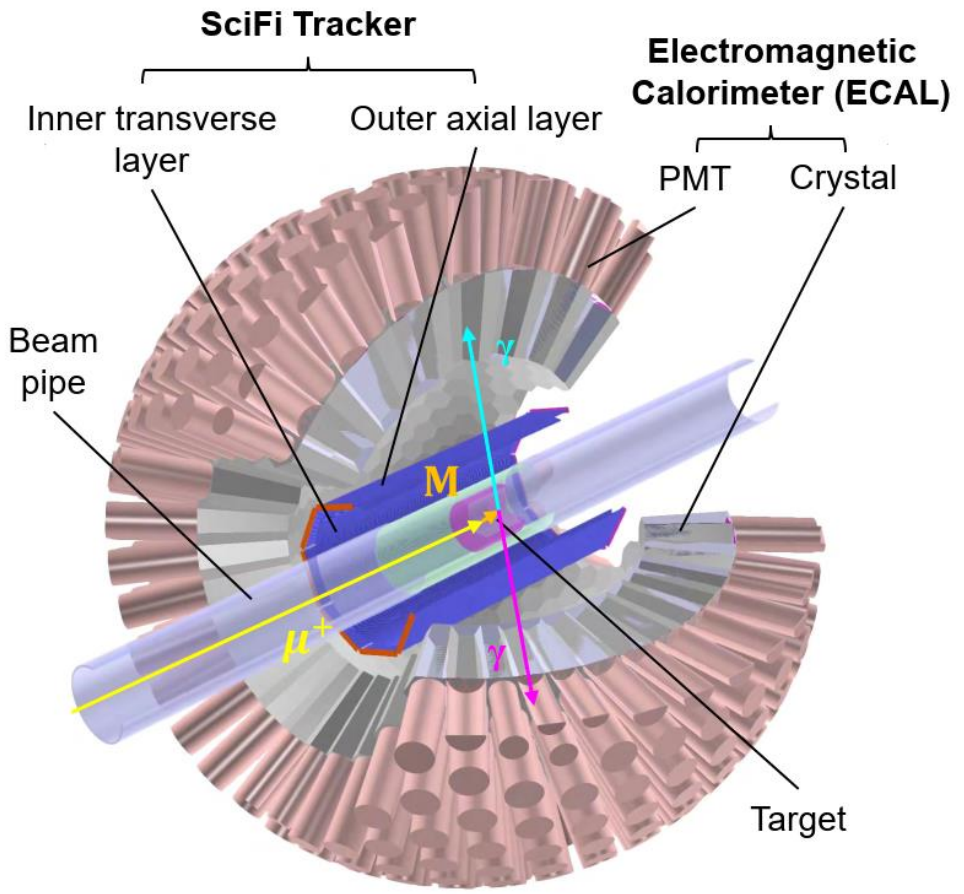
Nucl.Instrum.Meth.A 1042 (2022) 167443

$\text{SES} = 1.3 \times 10^{-13}$ for the M-to-$\overline{\text{M}}$ conversion

Two orders of magnitude improvement than the 1990s!

MACE Phase-I concept

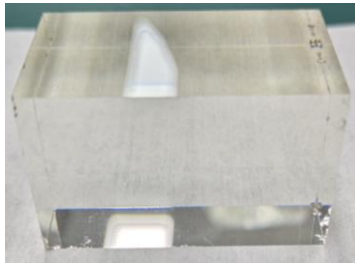
- Searching for the neutrinoless double radiative decay of muon(ium), i.e.
  - $\mathrm{M} \to \gamma\gamma$ (unsearched)
  - $\mu^+ \to e^+\gamma\gamma$ (no experimental progress since the 1986)*
- Beamline: $1 \times 10^7\ \mu^+$/s, CW
- Detector:
  - BGO calorimeter
  - Scintillating fiber tracker
- A sensitivity of $\mathcal{O}(10^{-12})$ expected!

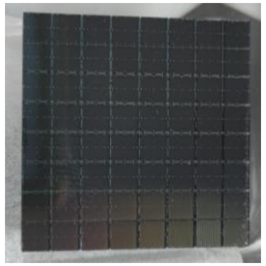


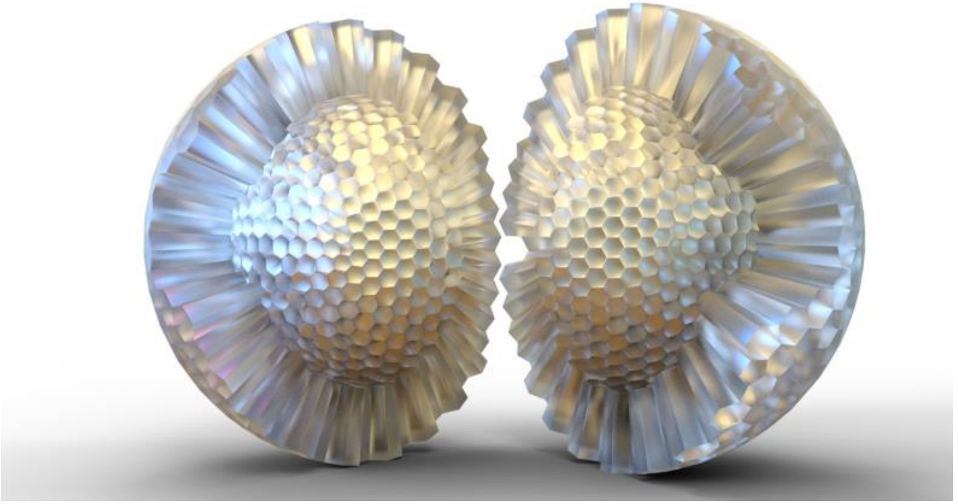
*$\mathcal{BR} < 7.2 \times 10^{-11}$ 90% C. L. *Phys.Rev.D* 38 (1988) 2077

BGO calorimeter

- For stopping photons up to ~50 MeV
- Properties of BGO:
  - **High density**
  - **non-deliquescent**
  - Relatively short decay time (300 ns)
- Geometry: Class I GP(8,0) Goldberg polyhedron, $\mathbf{11X_0}$
- Sensor: SiPM arrays (**50%** PDE at max.)
- Baseline performance:
  - An energy resolution of **~3%** at 50 MeV
  - A timing resolution of **~1 ns**







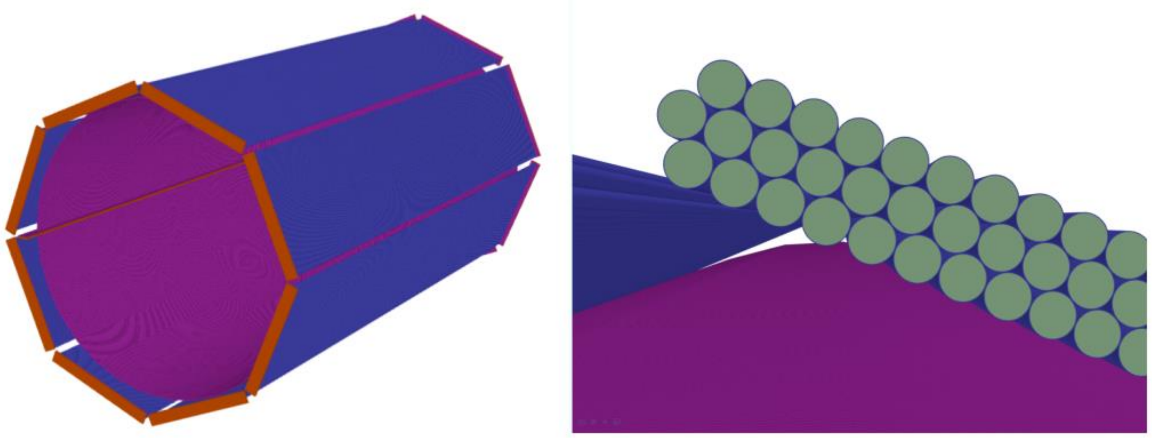
Phase-I: 528 modules, **82%** coverage
Phase-II: 622 modules, 97% coverage

Event selection criteria for $\mathrm{M} \to \gamma\gamma$:

- $E_{seed} > 15$ MeV
- $\theta_{12} > 160°$
- $\Delta E_{rec} < 10$ MeV

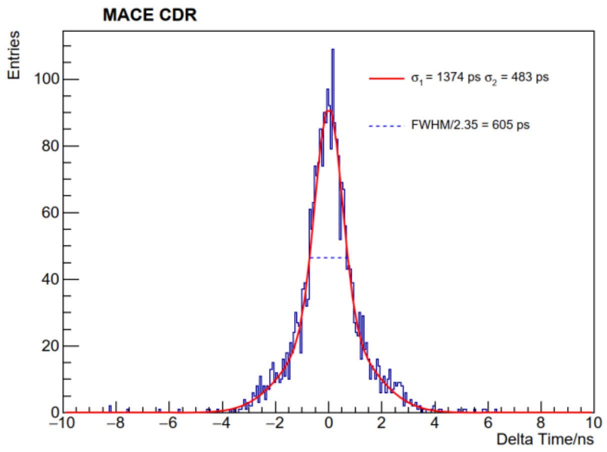
Scintillating fiber Tracker

- For charged particles timing and tracking
- Consisting of axial layer and transverse layer
- **324 mm** length, **85 mm** radius, **6656 channels** in total
- Baseline performance:
  - A timing resolution of **605 ps**
  - A detection efficiency of **94%** if fully covered
- Reconstruction: Neural Network (*in progress*)



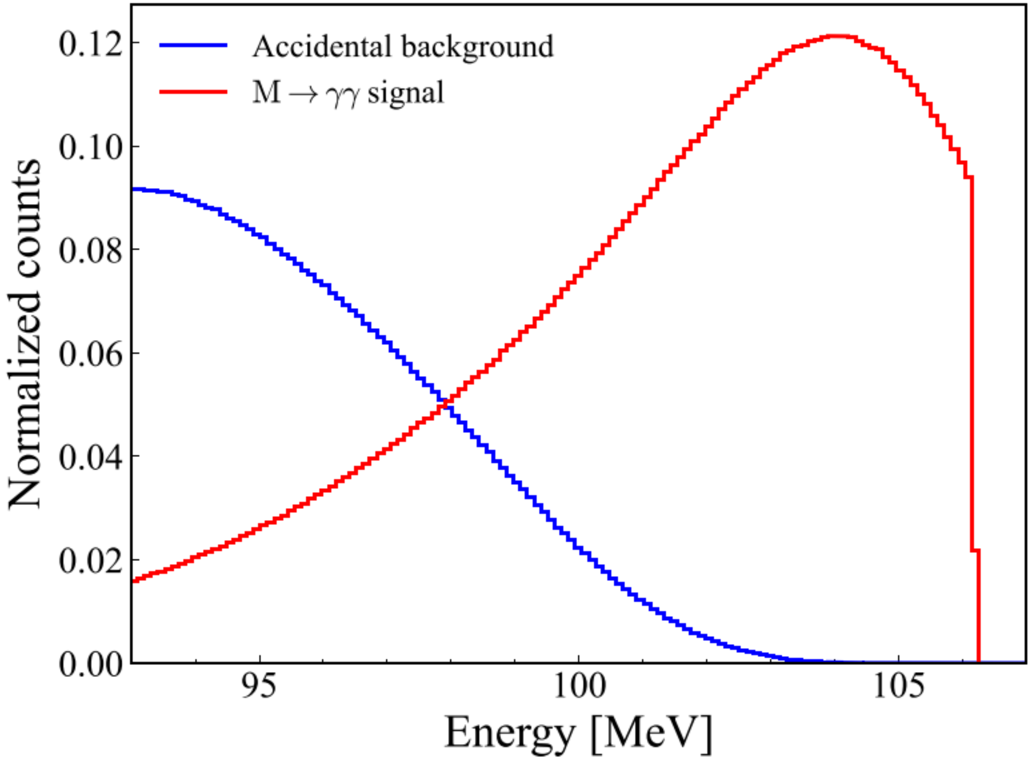
(a) Overall view of SciFi Tracker (b) SciFi arrangement

Goals based on Mu3e:
- $\Delta T = 449$ ps
- $\sigma_s = 100$ μm
- $\eta = 96\%$



Sensitivity estimation

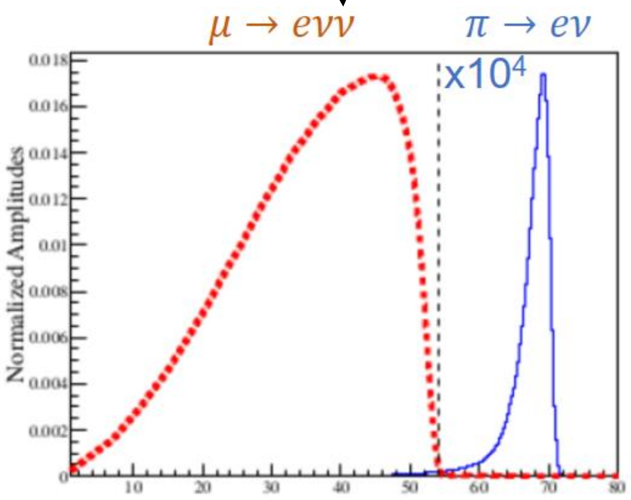
- Dominant background: **accidental coincidence** of two μ^+ decay produced e^+
- Fast simulation:
  - 4-layer SciFi tracker
  - Energy cut based on an optimum signal/noise ratio analysis
  - 80.1 BKGs/1 year
  - $\mathcal{BR}(\mathrm{M} \to \gamma\gamma) \lesssim 9.87 \times 10^{-13}$ (90% C.L.)
- $\mu^+ \to e^+\gamma\gamma$ simulation *in progress*



Events with energy greater than the mass of muonium (106.16 MeV) are discarded.

Potential goals with Phase-I detector

- **Probing new particle or interaction, e.g.**
  - $\mu^+ \to e^+ X, X \to \gamma\gamma$
- **Lepton Flavor Universality, e.g.**
  - $\pi^+ \to e^+ \nu_e$ (***if pion beamline available***)
- Polarization measurement
- ……



https://indico.fnal.gov/event/59896/contributions/280027/

Process	Beamline	Goal
$\mathrm{M} \to \gamma\gamma$	Surface Muon	New physics beyond Standard Model
$\mathrm{M} \to e^+e^-$		
$\mu^+ \to e^+\gamma$		
$\mu^+ \to e^+\gamma\gamma$		
$\mu^+ \to e^+X$		New particle or interaction
$\mathrm{M} \to \phi^*\gamma$		
$\mathrm{M} \to \nu_e\,\bar{\nu}_\mu$		Precision tests of Standard Model
$\mu^+ \to e^+\nu_e\,\bar{\nu}_\mu$		
$\mu^+ \to e^+\nu_e\,\bar{\nu}_\mu\gamma$		
Muon lifetime		
Muonium gravity		Gravity measurement of antimatter
$^7\mathrm{Li}(p,\mathrm{X}(17))\ ^8\mathrm{Be}$	Proton	New particle or interaction
$\pi^+ \to e^+\nu_e$	Pion	Precision tests of Standard Model

Summary

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- Next generation muon CLFV experiment MACE aims at two orders of magnitude improvement in M-to-$\overline{\mathrm{M}}$ conversion probability to provide unique information on Charged Lepton Flavor Violation.
- **MACE Phase-I**: *Forerunner* of MACE. With a calorimeter and a novel scintillating fiber tracker, a search for muon(ium) rare decay could be forthcoming, also aiming at more physical goals (e.g. pion rare decays).
- **Future works:** Full simulation, prototype R&D, etc..

Acknowledgements:
We express our gratitude to Yoshitaka Kuno, Kim-Siang Khaw, Klaus Jungmann, Lorenzo Calibbi, Ce Zhang, Tsutomu Mibe, Yuichi Uesaka, Yu Bao, Ningqiang Song and many other colleagues for their insights and expertise during discussions. We also appreciate the professional and constructive comments provided by Xin Chen, Kim-Siang Khaw, Teng Li, Yi Liao, Yong Liu and Xiang Xiao in reviewing the MACE conceptual design report.

SMOOTH Lab gallery

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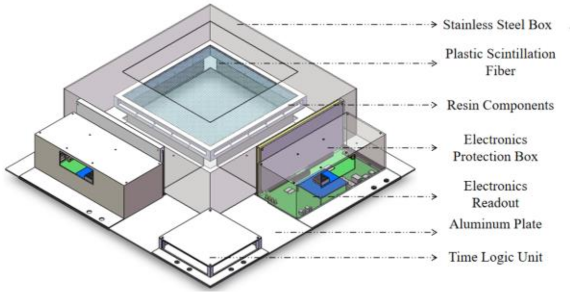
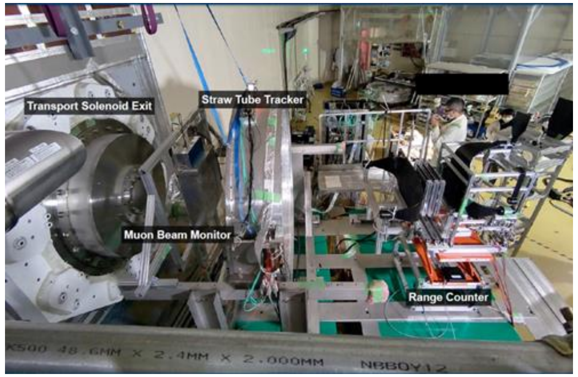
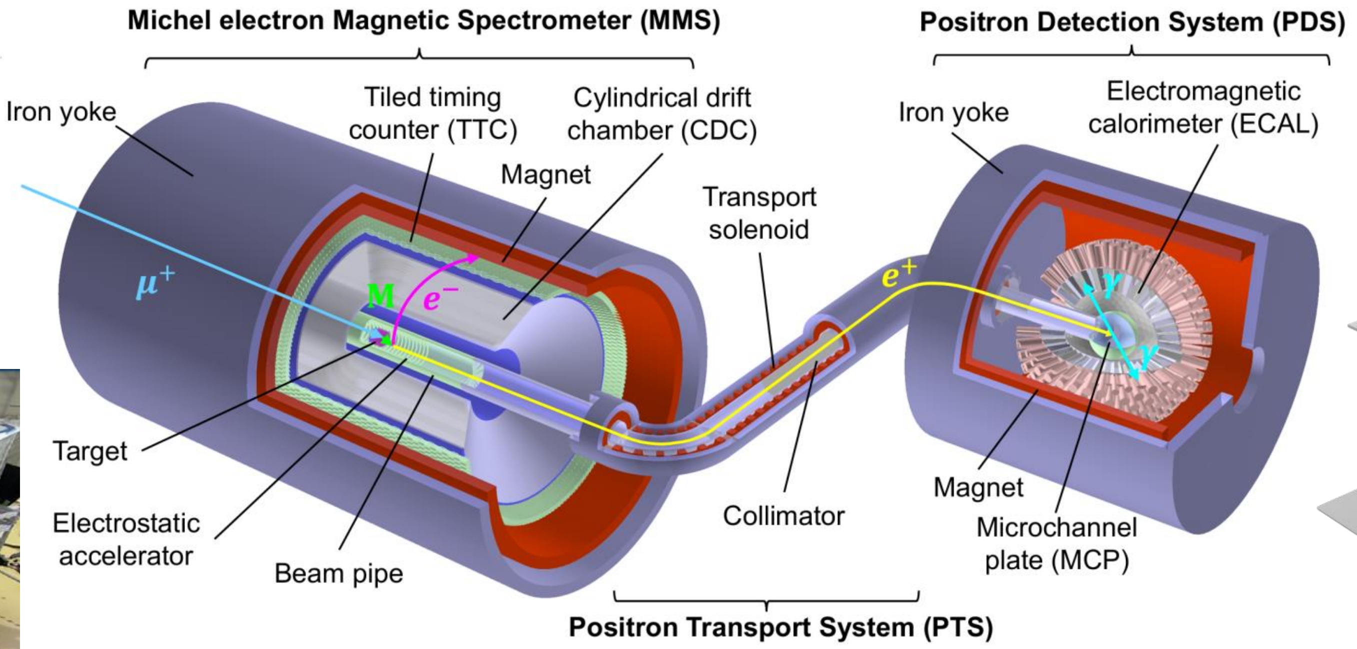
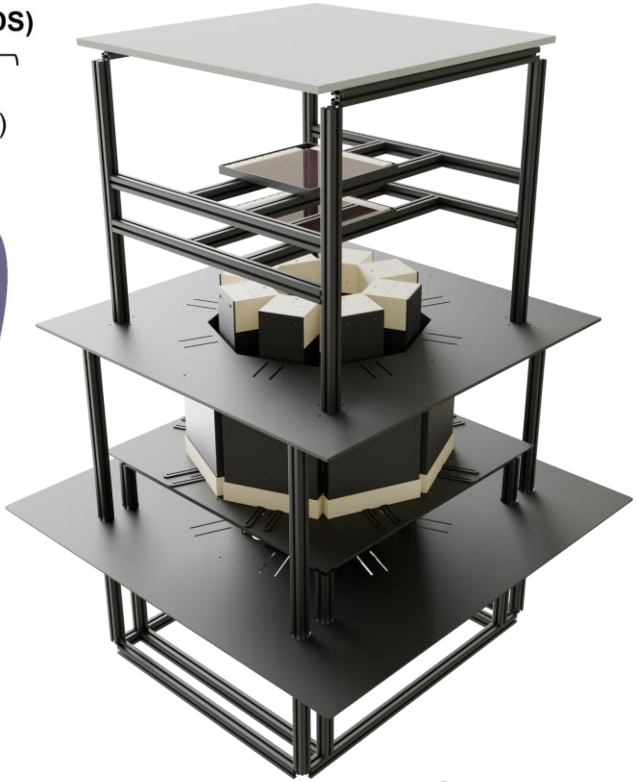
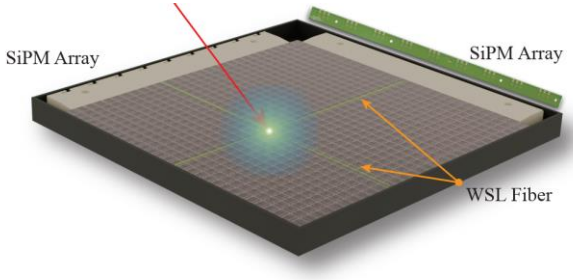
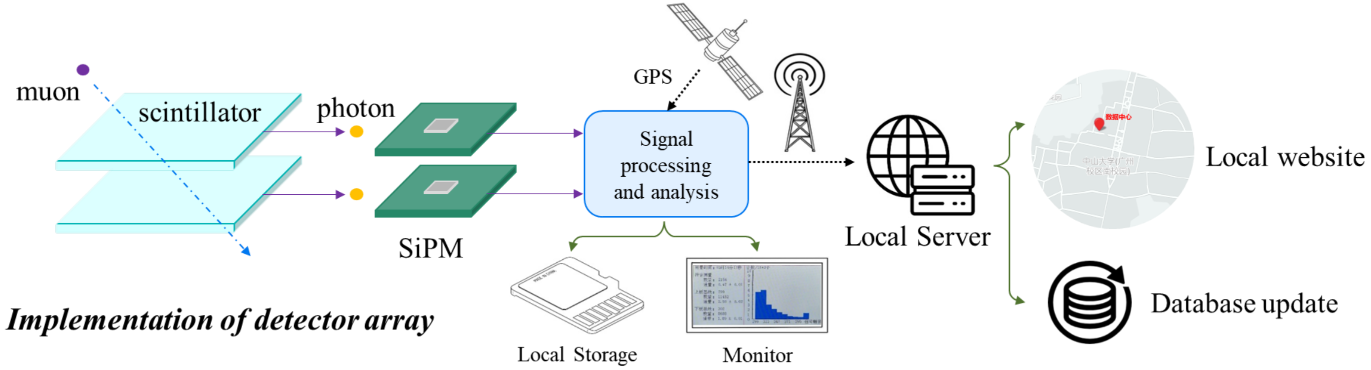




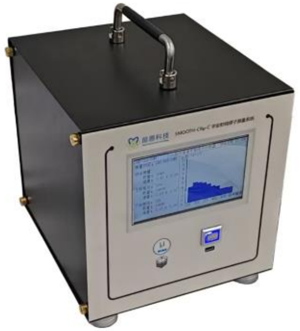








Implementation of detector array



Thank you for your attention!

Questions?

Backup

New physics scale of MACE