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MACE and new physics

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Ai-Yu Bai, Hanjie Cai, Chang-Lin Chen, Siyuan Chen, Xurong Chen, Yu Chen, Weibin Cheng, Ling-Yun Dai, Rui-Rui Fan, Li Gong, Zihao Guo, Yuan He, Zhilong Hou, Yinyuan Huang, Huan Jia, Hao Jiang, Han-Tao Jing, Xiaoshen Kang, Kim Siang Khaw, Hai-Bo Li, Jincheng Li, Yang Li, Shulin Liu, Guihao Lu, Han Miao, Jun Kai Ng, Yunsong Ning, Jianwei Niu, Huaxing Peng, Alexey A. Petrov, Yuanshuai Qin, Mingchen Sun, Jian Tang, Jing-Yu Tang, Ye Tian, Rong Wang, Xiaodong Wang, Zhichao Wang, Chen Wu, Tian-Yu Xing, Weizhi Xiong, Yu Xu, Baojun Yan, De-Liang Yao, Tao Yu, Ye Yuan, Yi Yuan, Yao Zhang, Yongchao Zhang, Zhilv Zhang, Guang Zhao, and **Shihan Zhao**

(MACE working group)

Conceptual Design of the Muonium-to-Antimuonium Conversion Experiment (MACE),
Nucl. Sci. and Tech. 37, 57 (2026), ***cover story***

Contents

Contents

High-intensity frontier and cLFV

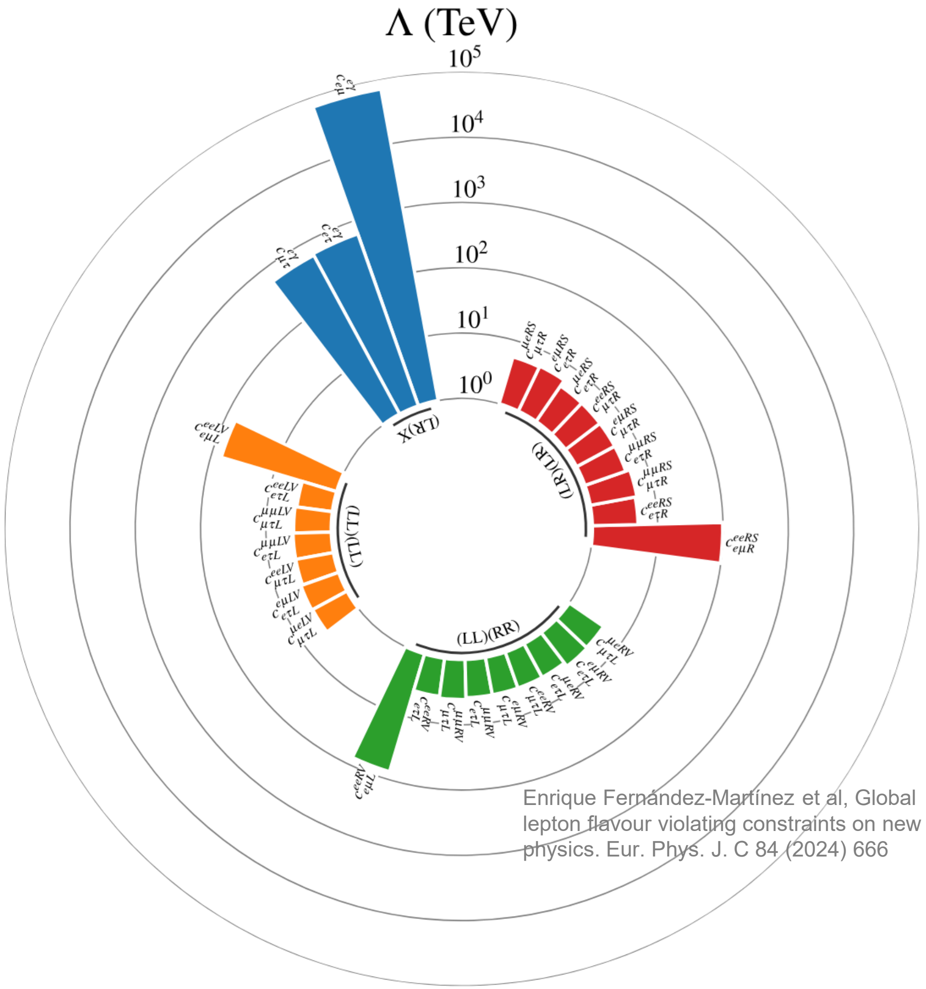
- ◆ **How to search for new physics beyond SM?**

□ High-intensity frontier:

- ➢ Provide **indirect constrains** with **precision measurement** or **search for forbidden processes**.

□ Advantages of cLFV with muon:

- ➢ **Clear signals.** cLFV is forbidden in SM, no irreducible SM backgrounds.
- ➢ **High statistics.** High-intensity muon beam → large samples within a short period.
- ➢ **Well motivated.** Scalable cLFV in new physics models including SUSY, seesaw, ALP, $U(1)_{B-L}$.



Enrique Fernández-Martínez et al, Global lepton flavour violating constraints on new physics. Eur. Phys. J. C 84 (2024) 666

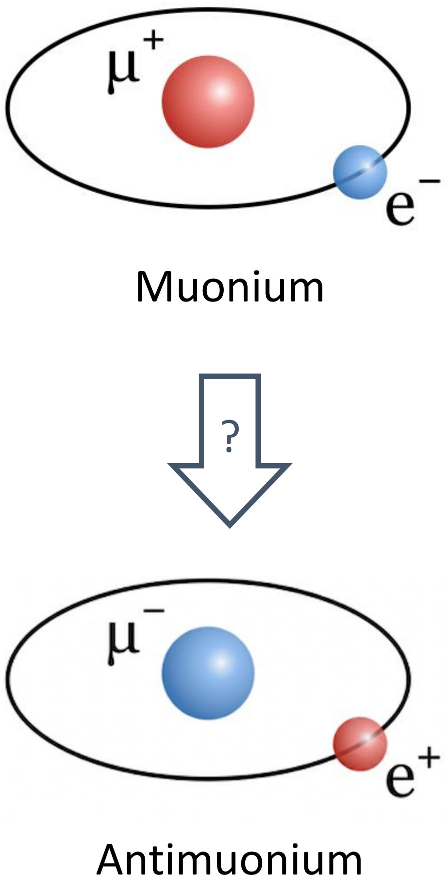
Significant cLFV signals → clear evidence for new physics;

Negative result → strong limit on new physics models.

Muonium and muonium-to-antimuonium conversion

- **Muonium (M)** is a hydrogen-like exotic atom consisting of an antimuon (μ^+) and an electron (e^-).
  - Entirely composed of point-like leptons, free from hadronic uncertainties.
  - The ideal system for testing QED and bound-state theory.
  - Lifetime practically equals to the muon lifetime ($\tau = 2.197$ us).

	Hydrogen	Muonium
Nucleus	Proton	Antimuon
Mass	938.3 MeV/c^2	106.2 MeV/c^2
Reduced mass	0.9995 m_e	0.9952 m_e
Bohr radius	52.9 pm	53.2 pm
1S energy	13.598 eV	13.540 eV
Lifetime	Stable	2.197 μs



- **Muonium-to-antimuonium conversion*** is a spontaneous conversion from muonium to its antiatom, antimuonium ($\overline{\mathrm{M}}$).

$$\mathrm{M}(\mu^+ e^-) \rightarrow \overline{\mathrm{M}}(\mu^- e^+)$$

- **This process violates lepton flavor by 2 units.**
- Latest 90% C.L. bound on conversion probability (MACS 1999): L. Willmann, PRL 82 (1999), 49-52

$$P_{\mathrm{M}\rightarrow\overline{\mathrm{M}}}^{0.1\ \mathrm{T}} < 8.3 \times 10^{-11}$$

- Muonium-to-antimuonium conversion experiment (MACE) aims to improve the limit by more than two orders of magnitude!

(*The kinematics of $\mathrm{M} \rightarrow \overline{\mathrm{M}}$ is similar to that of $K - \overline{K}$ or $B - \overline{B}$ oscillation. However, $\mathrm{M} - \overline{\mathrm{M}}$ oscillation period is constrained to O(1) second. Practically all muonium will decay before they oscillate. So, we prefer mentioning it conversion instead of oscillation.)

Muonium-to-antimuonium conversion

- $\mathrm{M} - \overline{\mathrm{M}}$ conversion is a coherent process,

$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} |\mathrm{M}(t)\rangle \\ |\overline{\mathrm{M}}(t)\rangle \end{pmatrix} = \left(M - i\frac{\Gamma}{2}\right)\begin{pmatrix} |\mathrm{M}(t)\rangle \\ |\overline{\mathrm{M}}(t)\rangle \end{pmatrix}$$

- The off-diagonal term induces the conversion,

$$\left(M - \frac{i}{2}\Gamma\right)_{12} = \frac{1}{2m}\left\langle \overline{\mathrm{M}} \middle| \mathcal{H}_{\mathrm{eff}} \middle| \mathrm{M} \right\rangle + \frac{1}{2m}\sum_n \frac{\left\langle \overline{\mathrm{M}} \middle| \mathcal{H}_{\mathrm{eff}} \middle| n \right\rangle \left\langle n \middle| \mathcal{H}_{\mathrm{eff}} \middle| \mathrm{M} \right\rangle}{m - E_n + i\epsilon}$$

Time evolution of the state and conversion probability

- Work out the time evolution: $\Gamma_{\mathrm{M}\to\bar{\mathrm{f}}}(t) \propto \mathrm{e}^{-\Gamma t}(\Gamma t)^2$,
- Normal muonium decay: $\Gamma_{\mathrm{M}\to\mathrm{f}}(t) \propto \mathrm{e}^{-\Gamma t}$.
- Define the conversion probability: $P_{\mathrm{M}\overline{\mathrm{M}}}(t) = \frac{\Gamma_{\mathrm{M}\to\bar{\mathrm{f}}}(t)}{\Gamma_{\mathrm{M}\to\mathrm{f}}(t)} \propto t^2$

- The effective Hamiltonian can be written by the combination of 5 dim-6 effective operators,

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \sum_{n>4} \frac{1}{\Lambda^{n-4}} \sum_i C_i^{(n)} Q_i^{(n)}$$

$$\begin{aligned}
Q_{\mathrm{V}}^{\mathrm{LL}} &= \left(\bar{\mu}\gamma_\alpha(1-\gamma_5)e\right)\left(\bar{\mu}\gamma^\alpha(1-\gamma_5)e\right), \\
Q_{\mathrm{V}}^{\mathrm{RR}} &= \left(\bar{\mu}\gamma_\alpha(1+\gamma_5)e\right)\left(\bar{\mu}\gamma^\alpha(1+\gamma_5)e\right), \\
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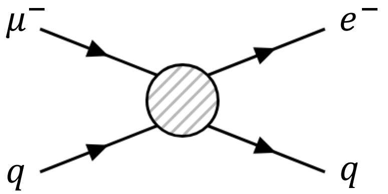
Q_{\mathrm{S}}^{\mathrm{RL}} &= \left(\bar{\mu}(1-\gamma_5)e\right)\left(\bar{\mu}(1-\gamma_5)e\right).
\end{aligned}$$

Details in e.g. R. Conlin, A. A. Petrov, Phys. Rev. D 102 (2020) 9, 095001

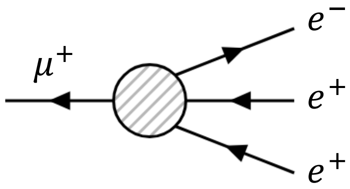
➢ **Insight:** probability evolves quadratically over time → longer travel time of muonium in vacuum leads to higher probability → **search for muonium conversion in vacuum (instead of in material).**

Muonium-to-antimuonium conversion in EFT

- **Muonium conversion can specifically probe $\mu\mu ee$ effective coupling** (which cannot be directly constrained by $\mu \to e\gamma$, $\mu \to eee$ and $\mu - e$ conversion).



$\mu - e$ conv.
μeqq contact
$|M|^2 \propto C_{\mu eqq}^2$



$\mu \to eee$
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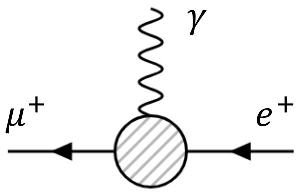
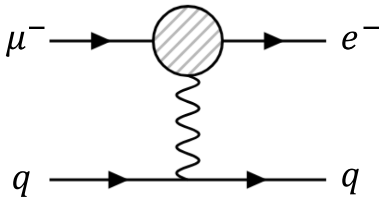
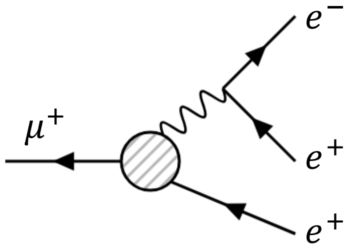


$\mu \to e\gamma$
$\mu e\gamma$ dipole
$|M|^2 \propto C_{\mu e\gamma}^2$



$\mu - e$ conv.
$\mu e\gamma$ dipole
$|M|^2 \propto \alpha C_{\mu e\gamma}^2$



$\mu \to eee$
$\mu e\gamma$ dipole
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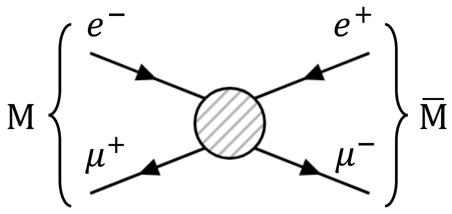

$\mathrm{M} \to \overline{\mathrm{M}}$
$\mu\mu ee$ contact
$|M|^2 \propto C_{\mu\mu ee}^2$

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$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{n>4} \frac{1}{\Lambda^{n-4}} \sum_i C_i^{(n)} Q_i^{(n)}$$

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\end{aligned}$$

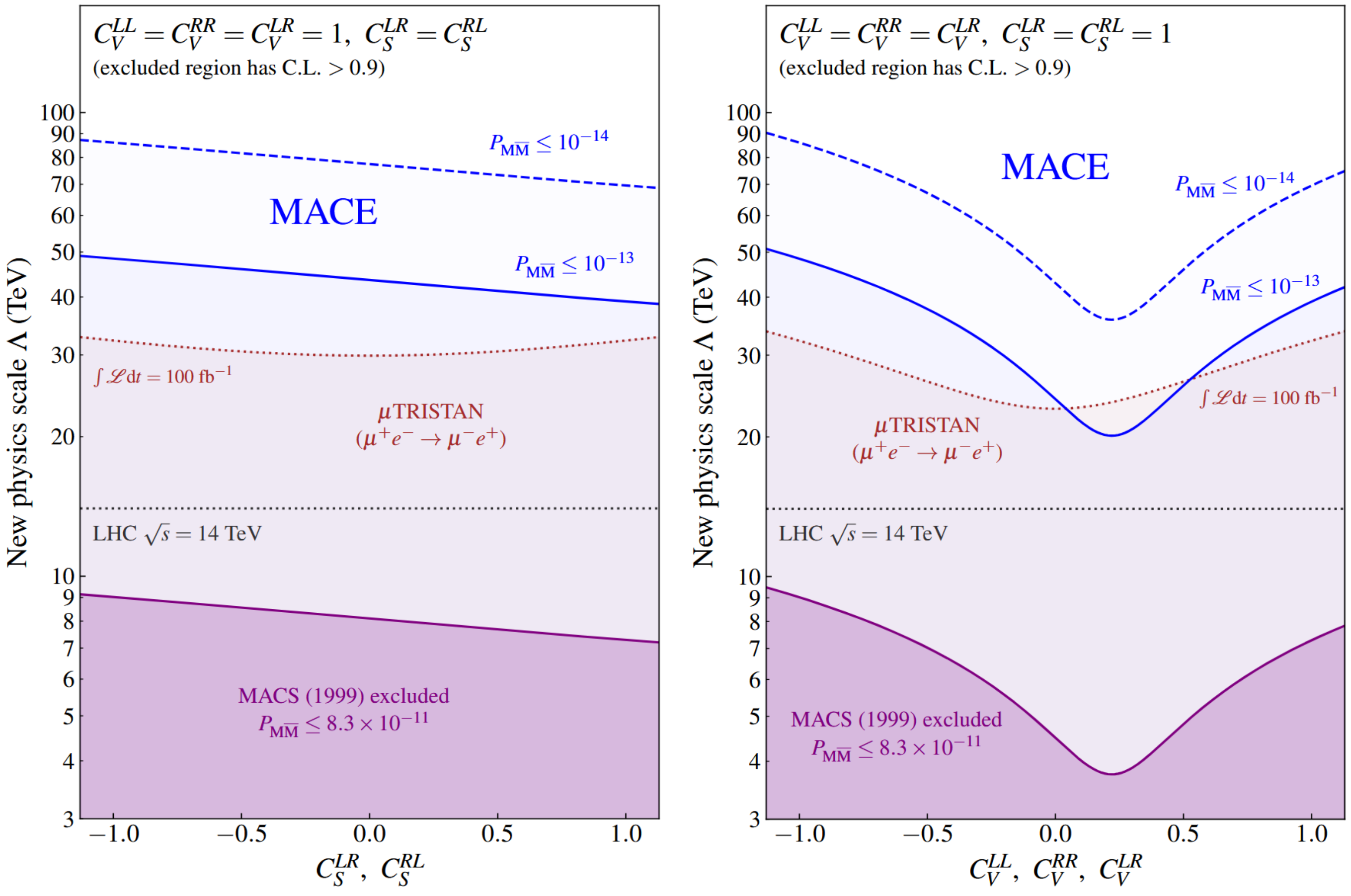
$\mu\mu ee$ contact operators

$\mu\mu ee$ contact
μeee contact
$\mu e\gamma$ dipole
μeqq contact

➢ **$M \to \overline{M}$ is the only low-energy process that can directly constrain $\mu\mu ee$ effective coupling.**

Muonium-to-antimuonium conversion in EFT

- **Muonium conversion can specifically probe $\mu\mu ee$ effective coupling** (which cannot be directly constrained by $\mu \to e\gamma$, $\mu \to eee$ and $\mu - e$ conversion).



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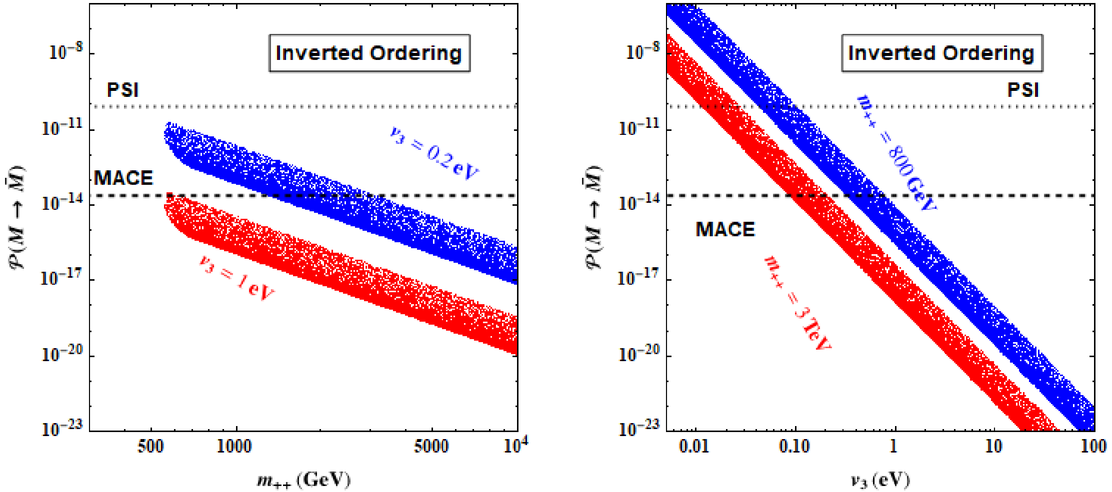
\end{aligned}\right\} \ \mu\mu ee \text{ contact operators}$$

➢ **MACE can probe TeV-scale new physics and provide unique constrain.**

See also R. Conlin, A. A. Petrov, Phys. Rev. D 102 (2020) 9, 095001

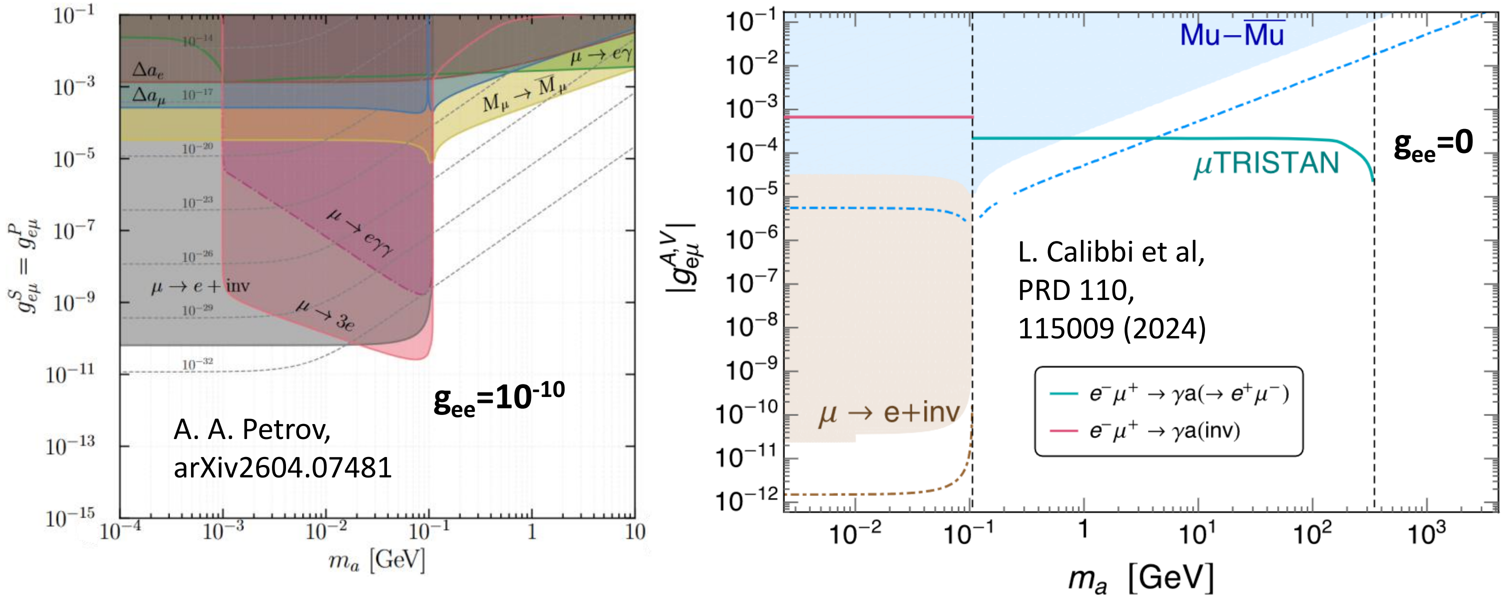
MACE physics motivation

- ✓ **Rich physics in muonium conversion.**
  - ➢ Stringent bound on maximally LFV ALP, doubly charged Higgs, bilepton, and more.
- ✓ **Muonium conversion is unique.**
  - ➢ Provide direct constrain to a set of unique EFT operators;
  - ➢ The only low-energy observable in certain flavor structure.
- ➢ **MACE is well-motivated and can complement other low-energy experiments and future colliders.**



C.C. Han et al, PRD 103, 055023 (2021)

MACE could probe doubly-charged Higgs beyond the reach of LHC



MACE could constrain LFV ALP parameter space comparable to future eμ collider

MACE physics motivation

✓ **Rich physics in muonium conversion.**

- ➢ Stringent bound on maximally LFV ALP, doubly charged Higgs, bilepton, and more.

✓ **Muonium conversion is unique.**

- ➢ Provide direct constrain to a set of unique EFT operators;
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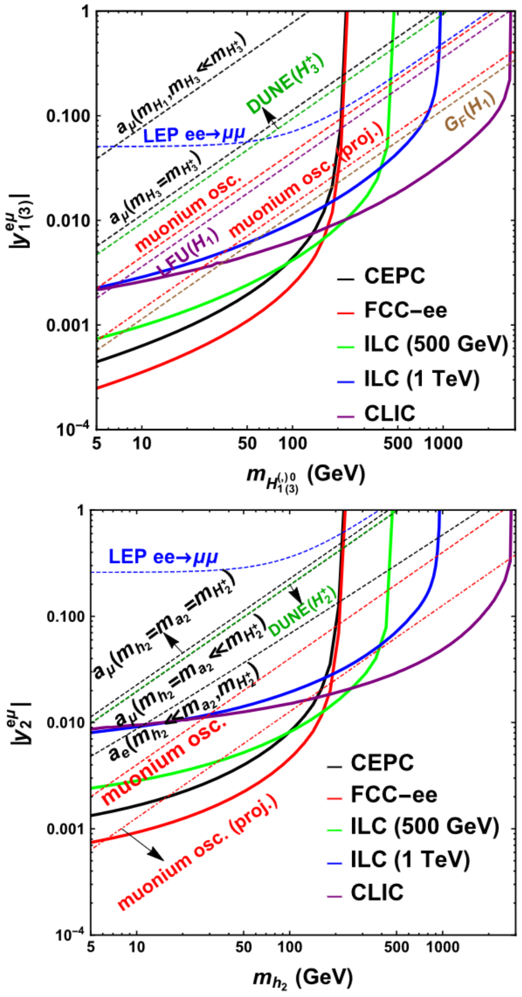
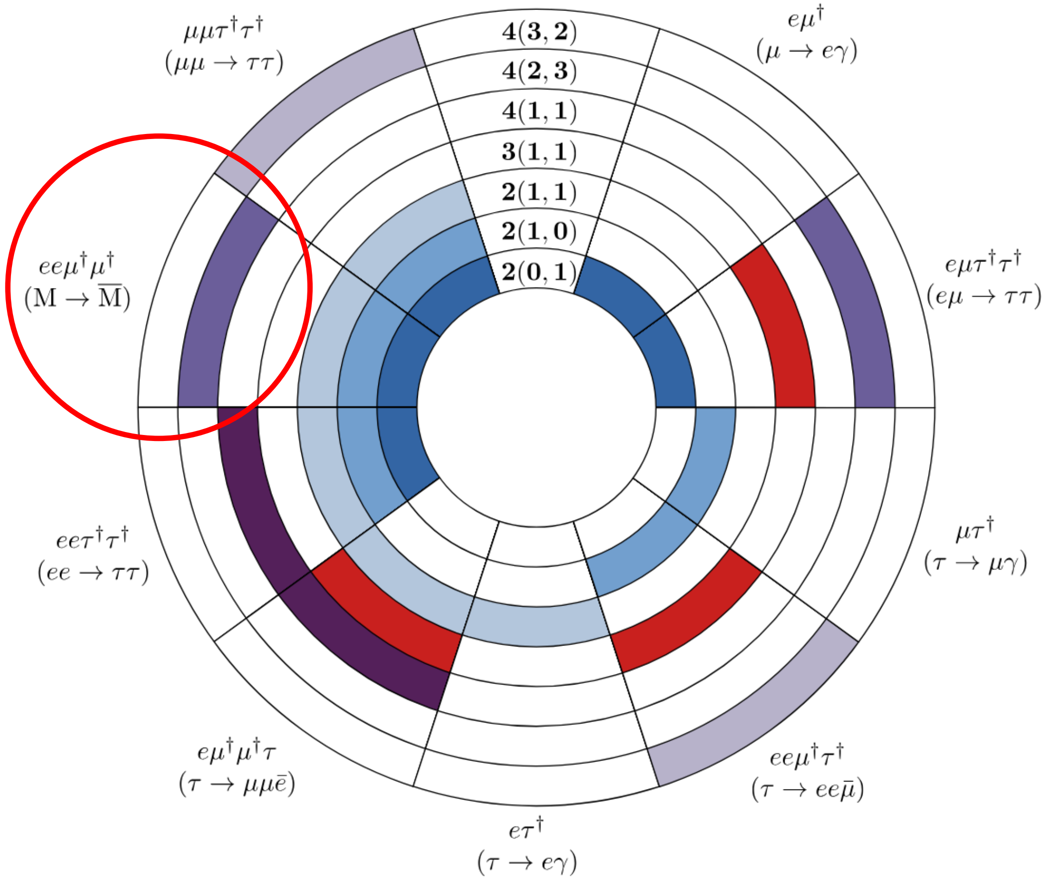


MACE can probe bileptons comparable to future colliders
(T. Li and M. Schmidt, PRD 100, 115007 (2019))



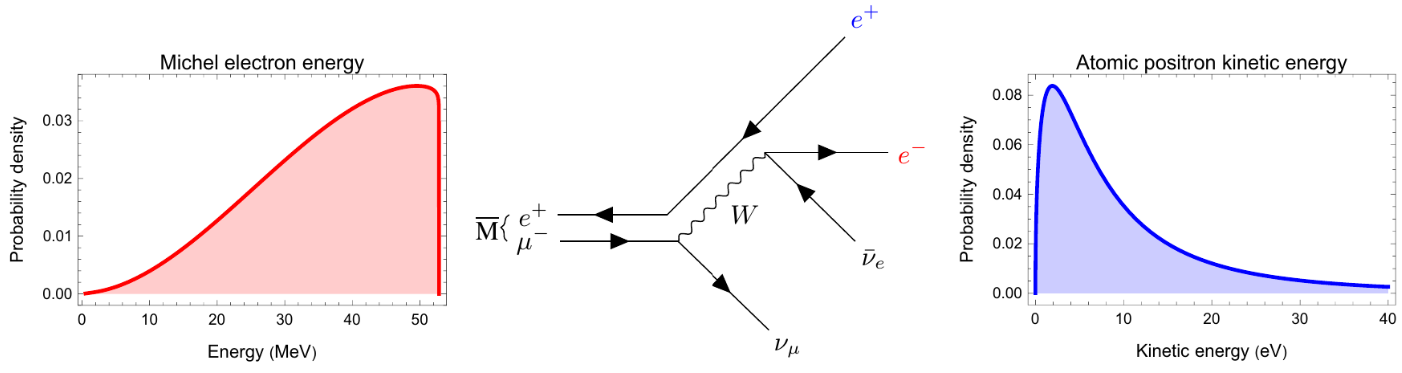
$\mathrm{M}\to\overline{\mathrm{M}}$ is even the only low-energy observable in certain flavor structure
(L. Calibbi et al, PRD 112, 075031 (2025))

Contents

How to detect muonium-to-antimuon conversion?

➢ **(Anti)muonium decay kinematics:**

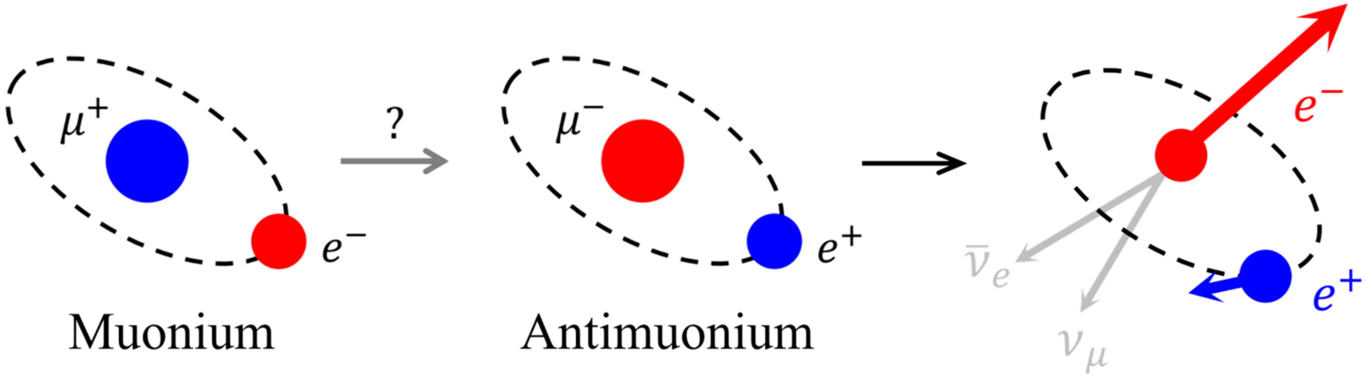
- Muonium: a bound state, $\mathrm{M} = \mu^+ e^-$
- Muonium decay: $\mathrm{M} \rightarrow e^+(\mathrm{fast})e^-(\mathrm{slow})\bar{\nu}_\mu \nu_e$
- Antimuonium decay: $\overline{\mathrm{M}} \rightarrow e^-(\mathrm{fast})e^+(\mathrm{slow})\nu_\mu \bar{\nu}_e$



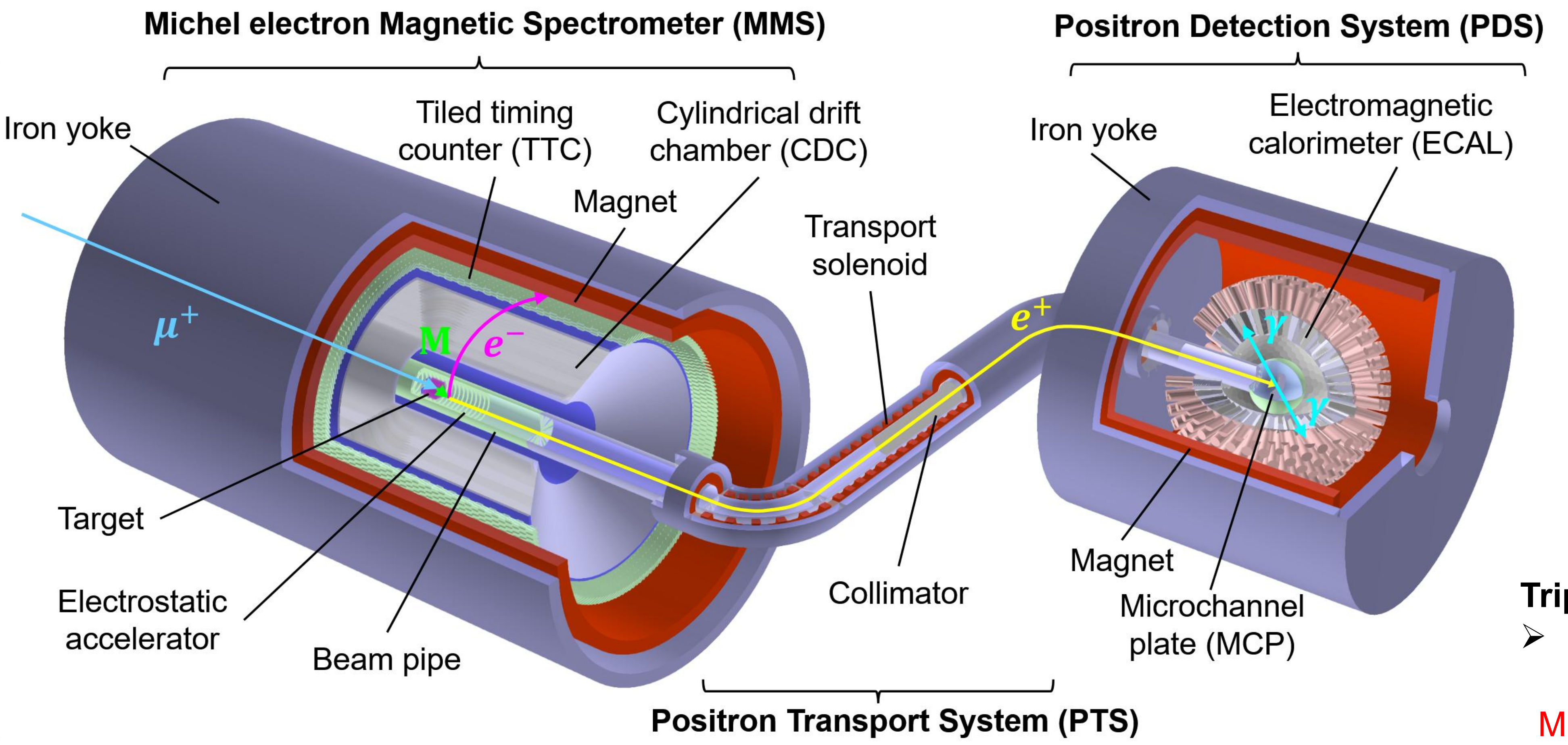
(a) e^- energy spectrum. (b) Leading-order $\overline{\mathrm{M}}$ decay. (c) e^+ energy spectrum.

➢ **Roughly three steps:**

1. Produce **muonium in vacuum** as many as possible;
2. If there are muonium-mixing, **some M will decay as anti-M**;
3. Find a **MeV e^-** and an **eV e^+** in the detector to search for muonium conversion.



Conceptual design of MACE detector system



More details in backup slides.

MMS:
- CDC: e^- tracking
- TTC: Trigger, timing

PTS:
- Accelerate and transport atomic e^+

PDS:
- MCP: atomic e^+ transverse position
- ECAL: e^+ identification

Triple coincidence:
- **MMS + MCP + ECAL**

MMS → Michel e^-; MCP + ECAL → Atomic e^+

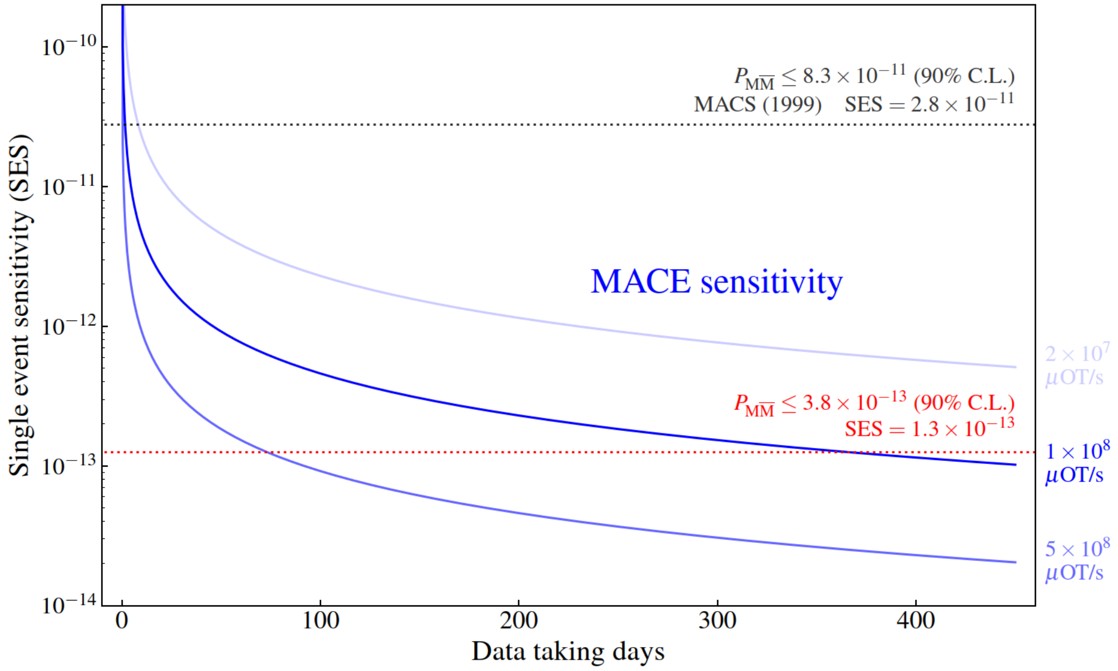
I. Surface muon stop in target → muonium
II. M diffuse into vacuum & convert to $\overline{\mathrm{M}}$
III. Decay in a vacuum: $\overline{\mathrm{M}} \rightarrow e^+e^-\nu_\mu\bar{\nu}_e$
IV. CDC detects Michel e^- track

I. Transport atomic e^+ to MCP (conserving transverse position)
II. MCP detects e^+ position
III. e^+ annihilates on MCP
IV. ECAL detects 2 back-to-back annihilation γ

Experimental sensitivity

- Summary of simulation results:

Background type		Counts/(10^8 μ^+/s · 1 yr)
Physical background	$\mu^+ \to e^+e^-e^+\nu_e\bar{\nu}_\mu$	0.287 ± 0.020
Accidental background	Beam postiron	< 0.07
	Cosmic ray (with veto)	< 0.1
Total		< 1



Detector, component or analysis	Efficiency type	Efficiency value
Magnetic spectrometer (MMS)	Geometric efficiency ($\varepsilon_{\mathrm{MMS}}^{\mathrm{geom}}$)	84.6%
	Reconstruction efficiency ($\varepsilon_{\mathrm{MMS}}^{\mathrm{recon}}$)	$\sim$ 80%
Positron transport system (PTS)	Transmission efficiency ($\varepsilon_{\mathrm{PTS}}$)	65.8%
Microchannel plate (MCP)	Detection efficiency ($\varepsilon_{\mathrm{MCP}}$)	32.6%
Electromagnetic calorimeter (ECAL)	Incident efficiency $\varepsilon_{\mathrm{ECAL}}^{\mathrm{In}}$	63.4%
	Geometric efficiency $\varepsilon_{\mathrm{ECAL}}^{\mathrm{Geom}}$	95.3%
	Reconstruction efficiency $\varepsilon_{\mathrm{ECAL}}^{\mathrm{Recon}}$	94.0%
Total detection efficiency		8.25%
Analysis	Signal efficiency ($\varepsilon_{\mathrm{Cut}}$)	$\sim$ 80%
Total signal efficiency		6.6%

$\mathcal{O}(10^{-13})$ single event sensitivity is expected:

$$\mathrm{SES} = \frac{1}{\varepsilon_{\mathrm{MMS}}^{\mathrm{geom}}\varepsilon_{\mathrm{MMS}}^{\mathrm{recon}}\varepsilon_{\mathrm{PTS}}\varepsilon_{\mathrm{MCP}}\varepsilon_{\mathrm{ECAL}}^{\mathrm{In}}\varepsilon_{\mathrm{ECAL}}^{\mathrm{Geom}}\varepsilon_{\mathrm{ECAL}}^{\mathrm{Recon}}\varepsilon_{\mathrm{Cut}}N_{\mathrm{M}}^{\mathrm{vac}}} = 1.3 \times 10^{-13} .$$

$$P(\mathrm{M} \to \overline{\mathrm{M}}) \lesssim \left(\frac{1}{2}F_{\chi^2}^{-1}\left(1-\alpha; 2(n_{\mathrm{obs}}+1)\right) - b\right) \times \mathrm{SES} = 3.8 \times 10^{-13} .$$

(90% C.L.)

MACE conceptual design report

*Nucl. Sci. and Tech. 37, 57 (2026), **cover story***

Nuclear Science and Techniques (2026) 37:57
https://doi.org/10.1007/s41365-025-01876-0

Check for updates

Conceptual design of the muonium-to-antimuonium conversion experiment (MACE)

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Abstract
The spontaneous conversion of muonium to antimuonium is an interesting charged lepton flavor violation phenomenon that offers a sensitive probe for potential new physics and serves as a tool to constrain the parameter space beyond the Standard Model. The Muonium-to-Antimuonium Conversion Experiment (MACE) was designed to utilize a high-intensity muon beam, a Michel electron magnetic spectrometer, a positron transport system, and a positron detection system to either discover or constrain this rare process with a conversion probability of $\mathcal{O}(10^{-13})$. This article presents an overview of the theoretical framework and a detailed description of the experimental design for muonium-to-antimuonium conversion.

Keywords Muonium · Lepton flavor violation · Muon beam · Drift chamber · Microchannel plate · Electromagnetic calorimeter

Contents

- Physics motivations
- MACE conceptual design
- Progress of MACE Phase-I
- Offline software system
- Summary

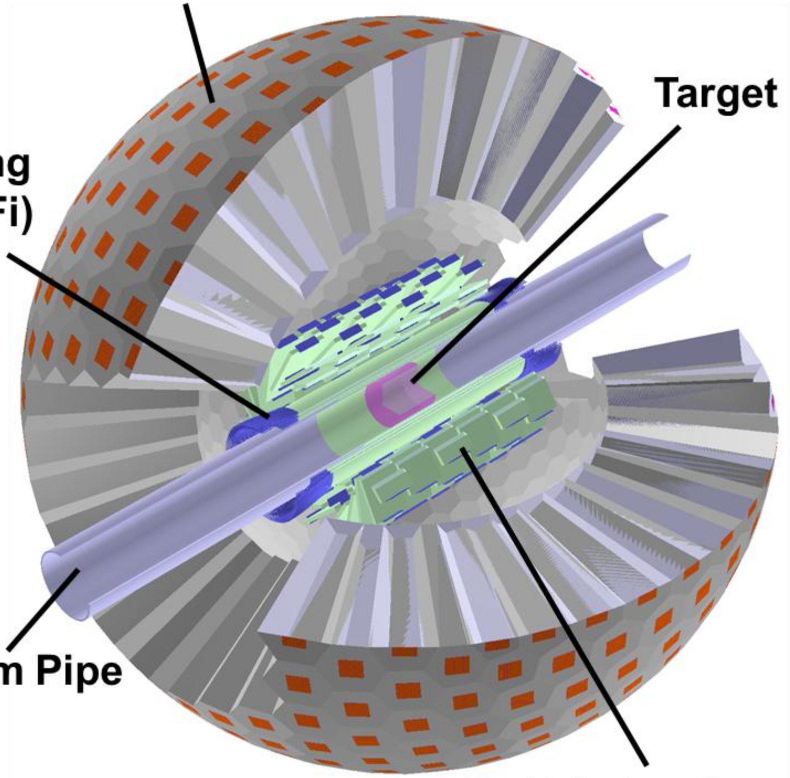
Proposal of MACE Phase-I

Muon cLFV decay modes

- ✓ **μ^+e^- annihilation:** $\mu^+e^- \to \gamma\gamma$ $\mathcal{O}(10^{-5})$, **1959**
- ✓ **Neutrinoless decay:** $\mu^+ \to e^+\gamma\gamma$ $\mathcal{O}(10^{-11})$, **1988**
- ✓ **New particles:** DM, ALP, Familon, … Crystal Box、MEG

PRL, 1959, 3: 288-291
PRD 38 (1988) 2077
EPJC 80 (2020) 9, 858

More details in backup slides.



Test of the Standard Model

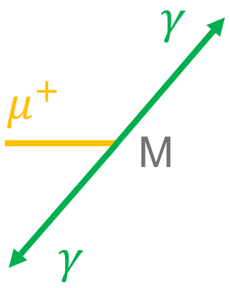
- ✓ $\boldsymbol{\mathcal{B}(\mu^+ \to e^+\gamma\nu\nu)}$ $\mathcal{O}(10^{-8}), E_e > 45, E_\gamma > 40$ MeV, **2016**
- ✓ $\mathcal{B}(\pi^+ \to \pi^0 e^+\nu_e)$ $\mathcal{O}(10^{-8})$, 2004
- ✓ $\mathcal{B}(\pi^+ \to e^+\nu_e)/\mathcal{B}(\pi^+ \to \mu^+\nu_\mu)$ $\mathcal{O}(10^{-4})$, 2015

EPJC 76 (2016) 3, 108
Int.J.Mod.Phys.A 20 (2005) 472-481
PRL. 115 (2015) 7, 071801
arXiv:2203.01981

PIONEER CDR, 2022

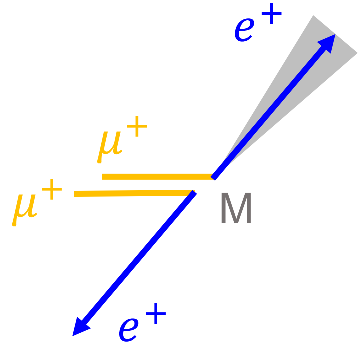
MACE Phase-I sensitivity to $\mathrm{M} \to \gamma\gamma$

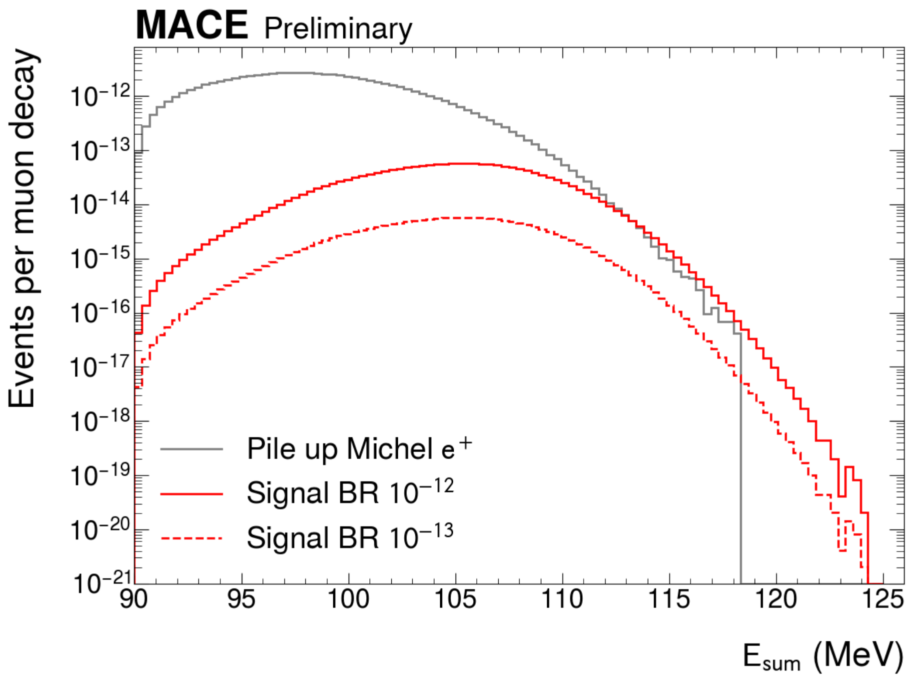
Signal: Double collinear 53 MeV gamma-rays.

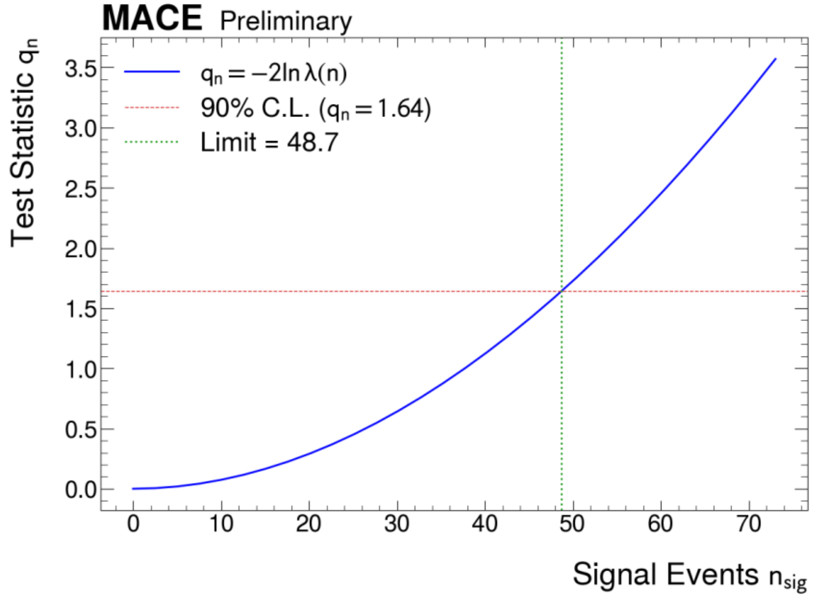


- Non-response in tracker
- Double tracks reconstructed by ECAL

Background: Accidental coincidence of “pileup” positrons.







- Asimov dataset (signal & bkg)
- Profile likelihood ratio test
- 5% systematics error included

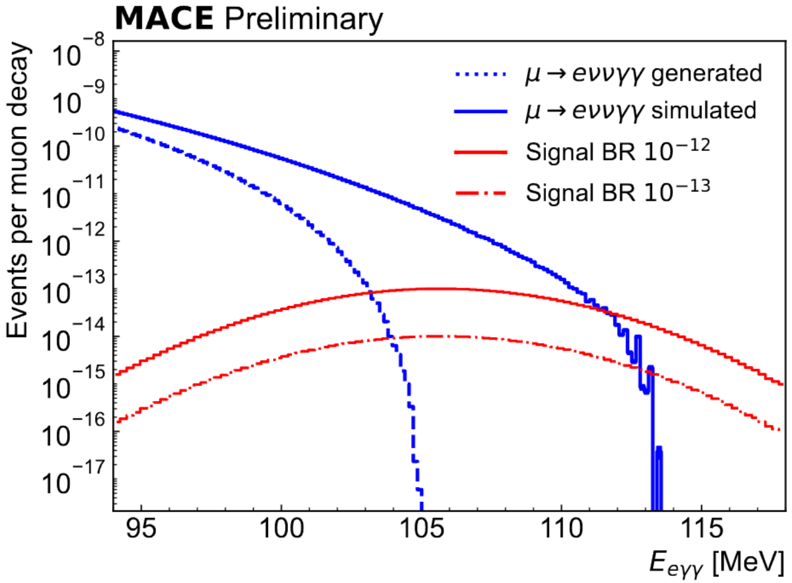
Upper limit of BR: 5.2×10^{-13} (90% C.L.)

$\mathcal{O}(10^{-5})$ in *1959* PRL, 1959, 3: 288-291

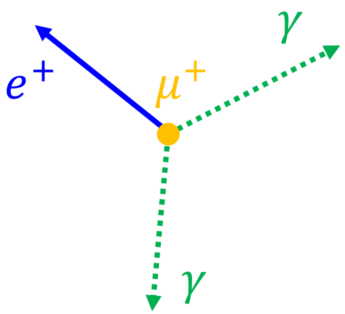
MACE Phase-I sensitivity to $\mu^+ \to e^+\gamma\gamma$

Event selection criteria:

- Time coincidence
- Single track in Tracker, Triple tracks in ECAL
- Energy-momentum conserved

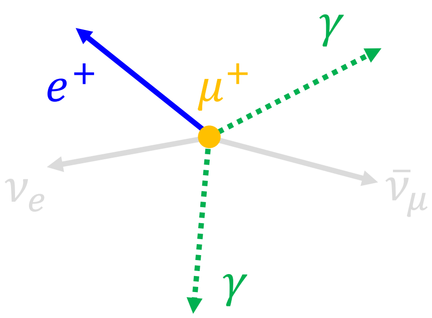


Signal:
Triple coplanar tracks
e^+ and two γs



Background:
Double radiative muon decay

SciPost Phys. 9, 027 (2020)



$$s_{up} = \frac{1}{2} F^{-1}_{\chi^2}[1-\alpha, 2(n_{obs}+1)] - b$$

$$n_{obs} = b$$

$$\mathcal{BR}(\mu^+ \to e\gamma\gamma) = \frac{s_{up}}{\varepsilon_{signal}\Phi_\mu T}$$

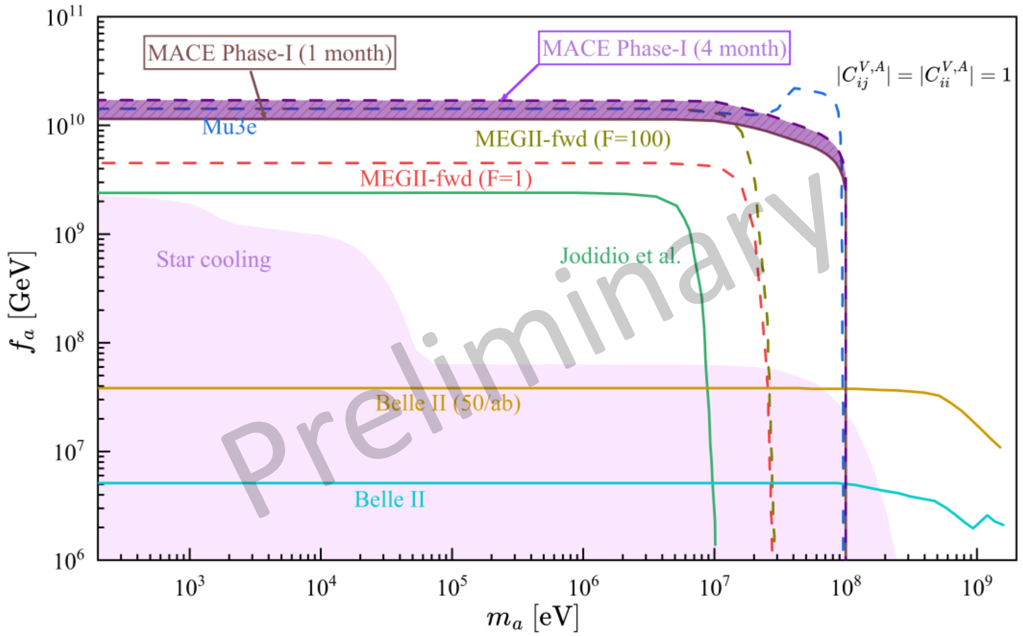
Upper limit of BR: 3.5×10^{-13} (90% C.L.)

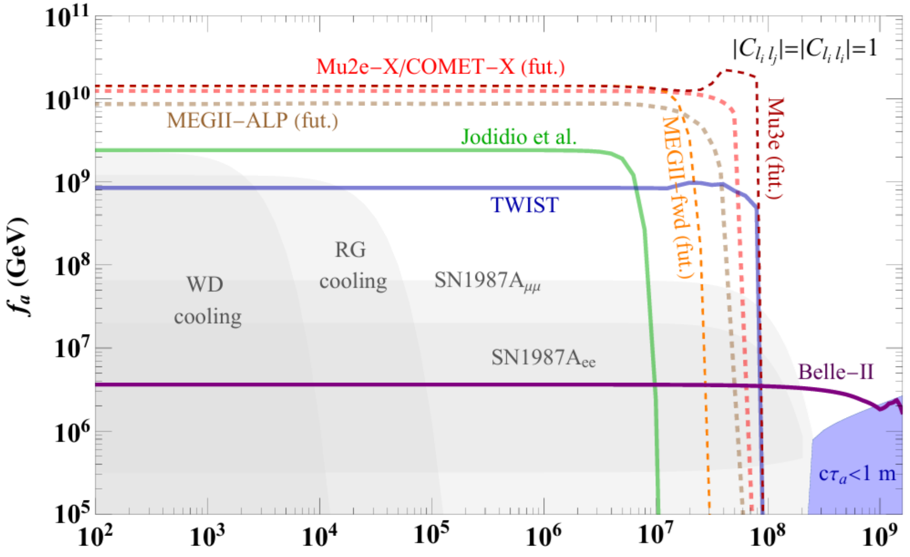
$\mathcal{O}(10^{-11})$ in *1988* PRD 38 (1988) 2077

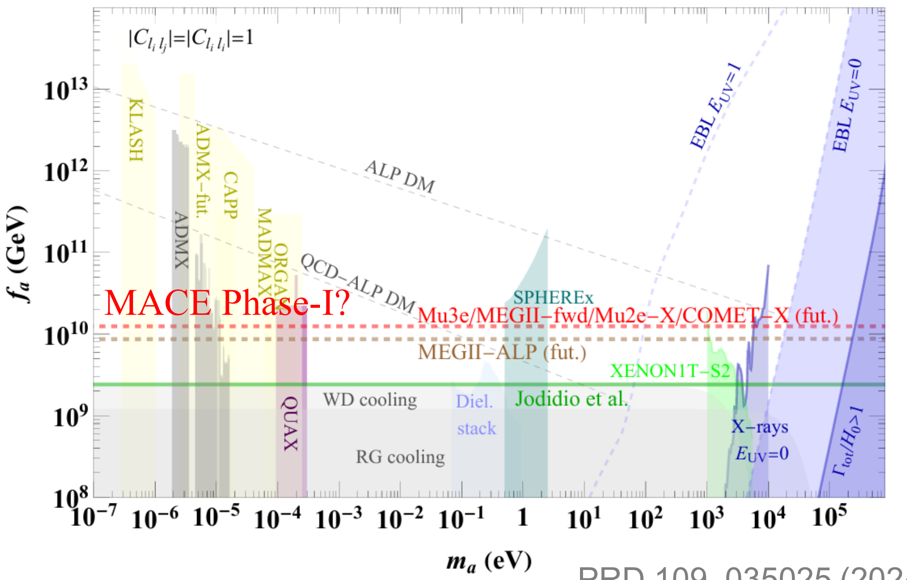
More solid simulations and refined data analyses to be updated!

MACE Phase-I sensitivity to $\mu^+ \to e^+ a$

- Background: normal muon decays
- Beam time of approximately 28 days
- Comparable to **Mu3e** and **MEGII-fwd**
- Extending the running time to 120 days would provide a clear sensitivity advantage $\sim\mathcal{O}(10^{-8})$
- **MACE Phase-I is sensitive to ALPs!**







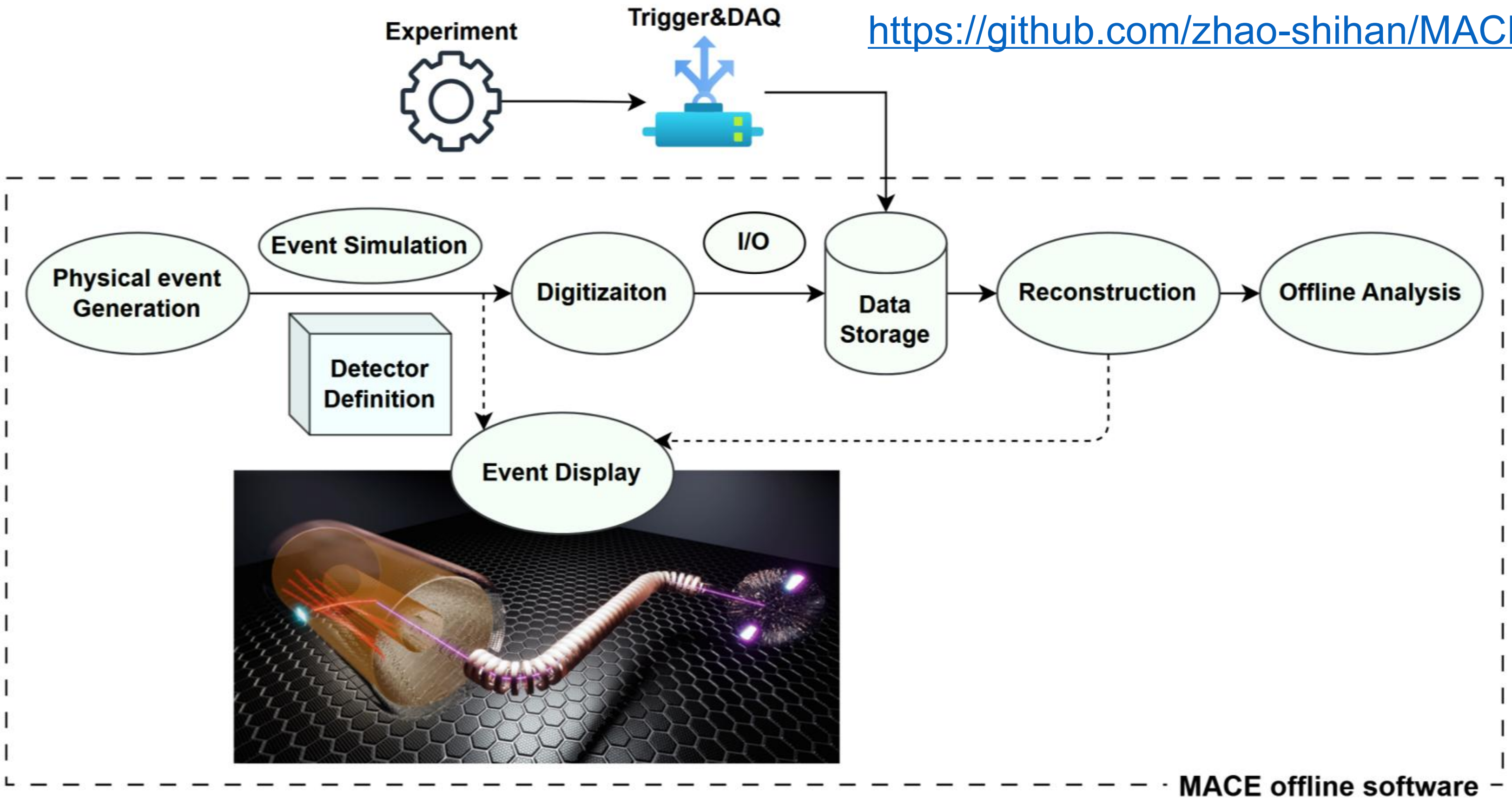
PRD 109, 035025 (2024)

Contents

MACE offline software

- ➢ Experiment design stage: simulation-guided detector design optimization.
- ➢ Engineering stage: detector alignment and detector-response simulation.
- ➢ Data-taking stage: bridges experimental data to physics results.

https://github.com/zhao-shihan/MACESW



Tasks:

- Event generation
- Simulation: detector, DAQ…
- Reconstruction & analysis
- Visualization: event, track, detector geometry…

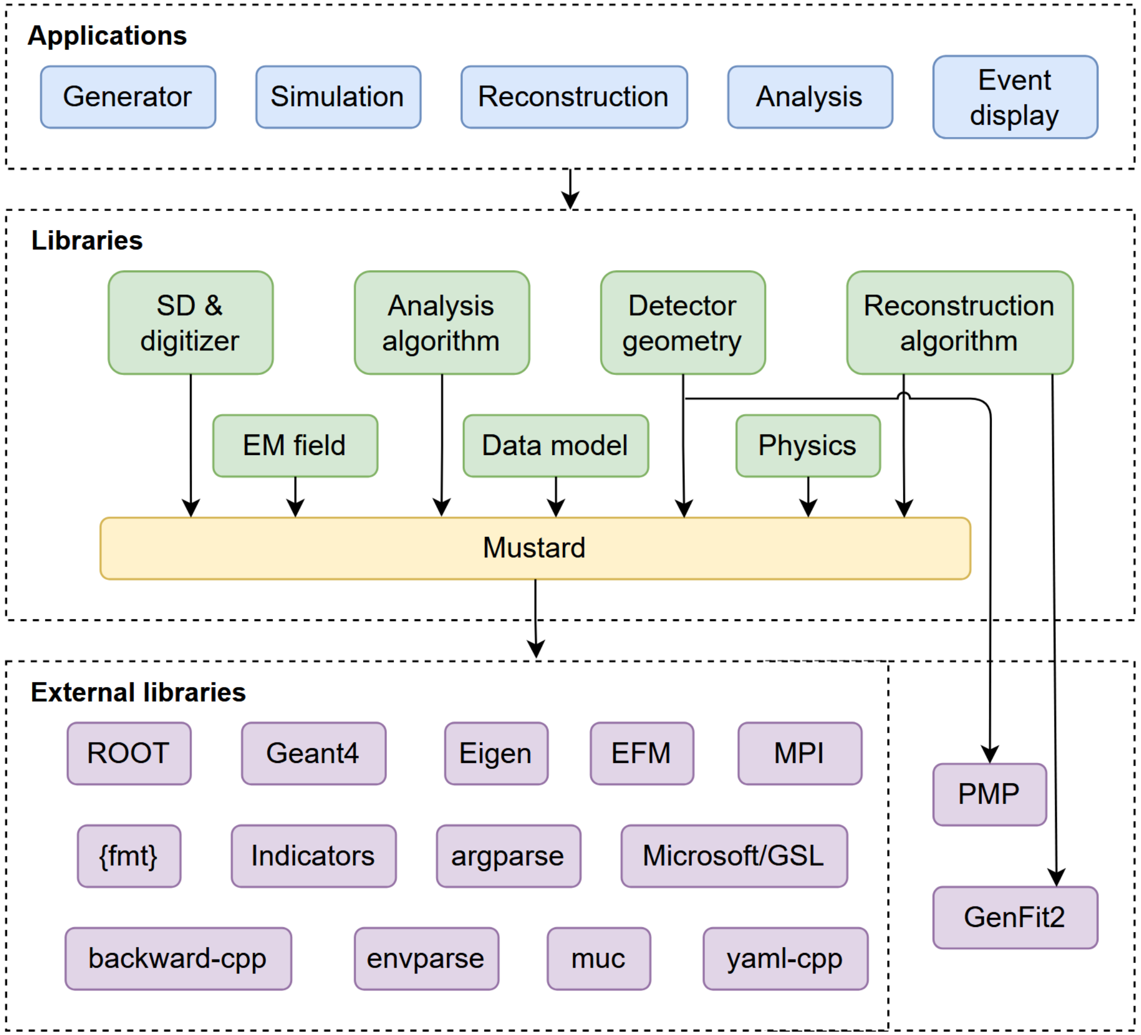
Software quality control:

- Framework and architecture
- Continuous integration
- Validation

Software framework

- **Mustard framework:**
  - ➢ A modern, distributed, high-performance architecture
- **High-performance design:**
  - ➢ Distributed executor for simulation and analysis.
  - ➢ Follows zero-overhead abstraction principle.
- **Key components:**
  - ➢ Distributed computing framework
  - ➢ Unified geometry interfaces
  - ➢ High-level data model abstractions and IO
  - ➢ Utilities for simulation, reconstruction, analysis...

https://github.com/zhao-shihan/Mustard



Contents

Summary

- Rich new physics in muonium-to-antimuonium conversion!
- Next-generation muon cLFV experiment — MACE aims at two orders of magnitude improvement in M-to-$\overline{\mathrm{M}}$ conversion probability. MACE Phase-I: Forerunner of MACE. A search for batches of muon(ium) cLFV decay, also aiming at **broader physics programs**.
- $\mathcal{O}(10^{-13})$ sensitivities are expected.
- **Welcome to joining the high-intensity muon physics experiment MACE!**

Muonium-to-Antimuonium Conversion Experiment

Contact person:
Prof. Jian Tang (tangjian5@mail.sysu.edu.cn)

Conceptual Design of the Muonium-to-Antimuonium Conversion Experiment (MACE)

Ai-Yu Bai,[1,2] Hanjie Cai,[3,4] Chang-Lin Chen,[5] Siyuan Chen,[1,2] Xurong Chen,[3,4,6] Yu Chen,[1,2] Weibin Cheng,[7] Ling-Yun Dai,[5,8] Rui-Rui Fan,[9,10,11] Li Gong,[7] Zihao Guo,[12] Yuan He,[3,4] Zhilong Hou,[9] Yinyuan Huang,[1,2] Huan Jia,[3,4] Hao Jiang,[1,2] Han-Tao Jing,[9] Xiaoshen Kang,[7] Hai-Bo Li,[9,4] Jincheng Li,[3,4] Yang Li,[9] Daming Liu,[13] Shulin Liu,[9,4,14] Guihao Lu,[1,2] Han Miao,[9,4] Yunsong Ning,[1,2] Jianwei Niu,[3,15] Huaxing Peng,[9,4,14] Alexey A. Petrov,[16] Yuanshuai Qin,[3] Mingchen Sun,[1,2] Jian Tang,[1,2,*] Jing-Yu Tang,[17] Ye Tian,[3] Rong Wang,[3,4] Xiaodong Wang,[18,19] Yi Wang,[13] Zhichao Wang,[1,2] Chen Wu,[9,10] Tian-Yu Xing,[20,21] Weizhi Xiong,[22] Yu Xu,[23] Baojun Yan,[9,14] De-Liang Yao,[5,8] Tao Yu,[1,2] Ye Yuan,[9,4] Yi Yuan,[1,2] Yao Zhang,[9] Yongchao Zhang,[12] Zhilv Zhang,[3] Guang Zhao,[9] and Shihan Zhao[1,2]

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[19] *Key Laboratory of Advanced Nuclear Energy Design and Safety (MOE), University of South China, Hengyang 421001, China*
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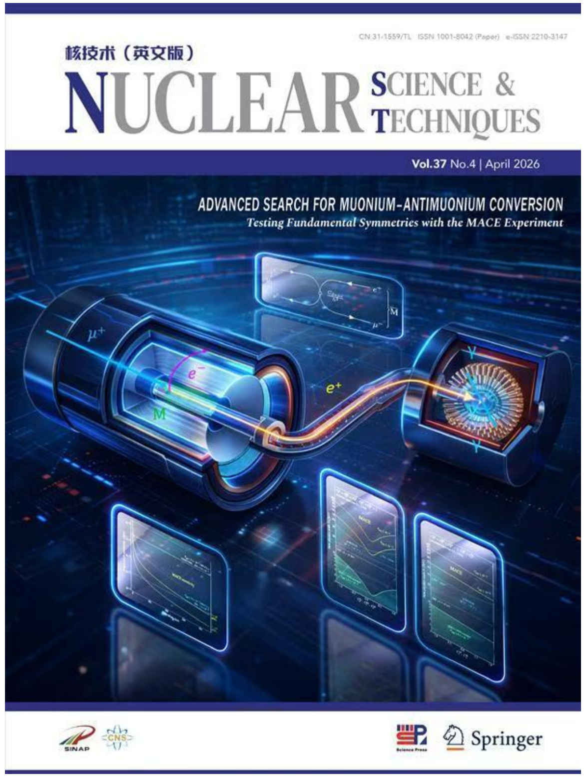


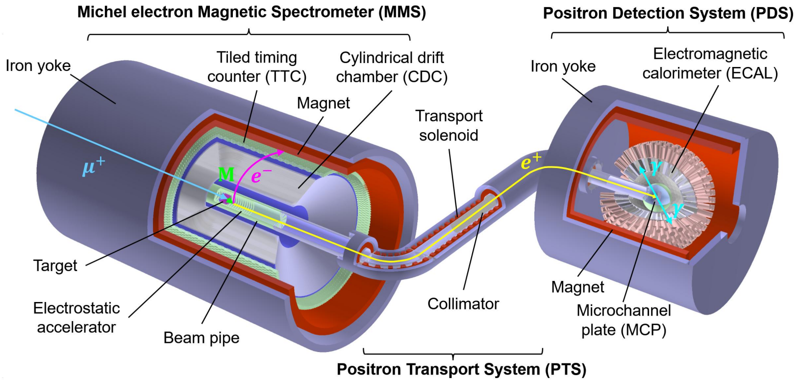
Thank you!

Backup

Muonium science and application

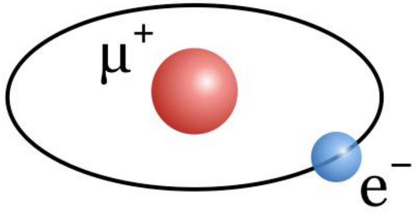
◆ 缪子素

由正缪子（μ^+）和电子（e^-）组成的原子，基本性质类似氢原子，但质量较轻且会自发衰变。

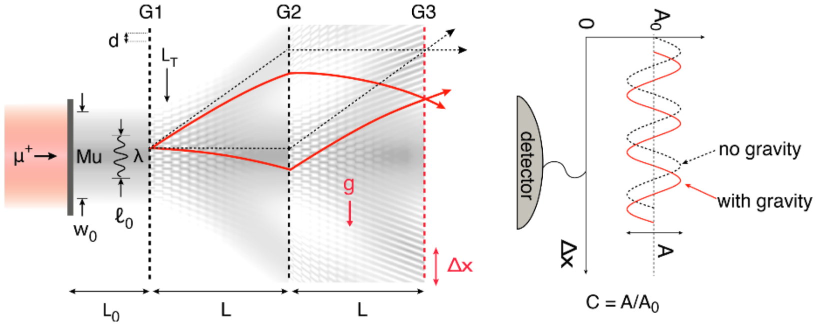


正反缪子素转化实验

Ai-Yu Bai et al (MACE working group). Conceptual Design of the Muonium-to-Antimuonium Conversion Experiment (MACE). arXiv: 2410.18817, 2024.

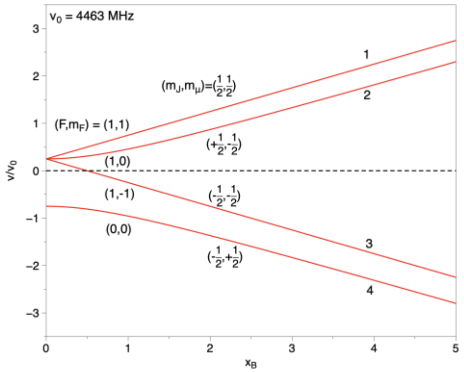


缪子素示意图



缪子素重力测量实验

Anna Soter and Andreas Knecht, Development of a cold atomic muonium beam for next generation atomic physics and gravity experiments, SciPost Phys.Proc. 5, 031, 2021



缪子素 1S 态的 Breit-Rabi 能级

Tanaka K S, Iwasaki M, Kamigaito O, et al. PTEP, 2021, 2021(5): 053C01.

◆ 缪子素在前沿科学研究中有重要价值

- ➢ 缪子素是精确检验**基础物理定律**的重要体系
  - ✓ 精确测量缪子素能级 → **精确检验量子电动力学**
  - ✓ 寻找正反缪子素转化过程 → **寻找超越标准模型的新物理**
  - ✓ 测量缪子素重力 → 研究**反物质重力**及**检验广义相对论**
- ➢ 缪子素是**交叉学科前沿**的重要窗口
  - ✓ 缪子素自旋谱学 → **研究材料内禀磁学性质**
  - ✓ 缪子素化学 → **研究化学反应机理**

缪子素研究铁氢酶催化机理

Joseph A. Wright. Muonium Chemistry at Diiron Subsite Analogues of [FeFe]-Hydrogenase. Angewandte Chemie International Edition, 55, 47, 14471, 2016

➢ **缪子素是前沿科学研究的理想对象**

Muon beam

From Hanjie Cai
(MIP2026)

Timetable of the Linac

2025～2026

25 kW:
500MeV & 50μA

- Assembly
- Commissioning

2026～2027

250 kW:
500MeV & 500μA

- Accelerator stability study
- Beam to the subcritical reactor and other terminals

2027～2030

3 MW:
600MeV & 5mA

- 3 MW Commissioning
- Normal operation with MW-level proton beam

Beam time of the linac

- 3 months for the subcritical reactor
- 8–9 months for other terminals, including the muon source

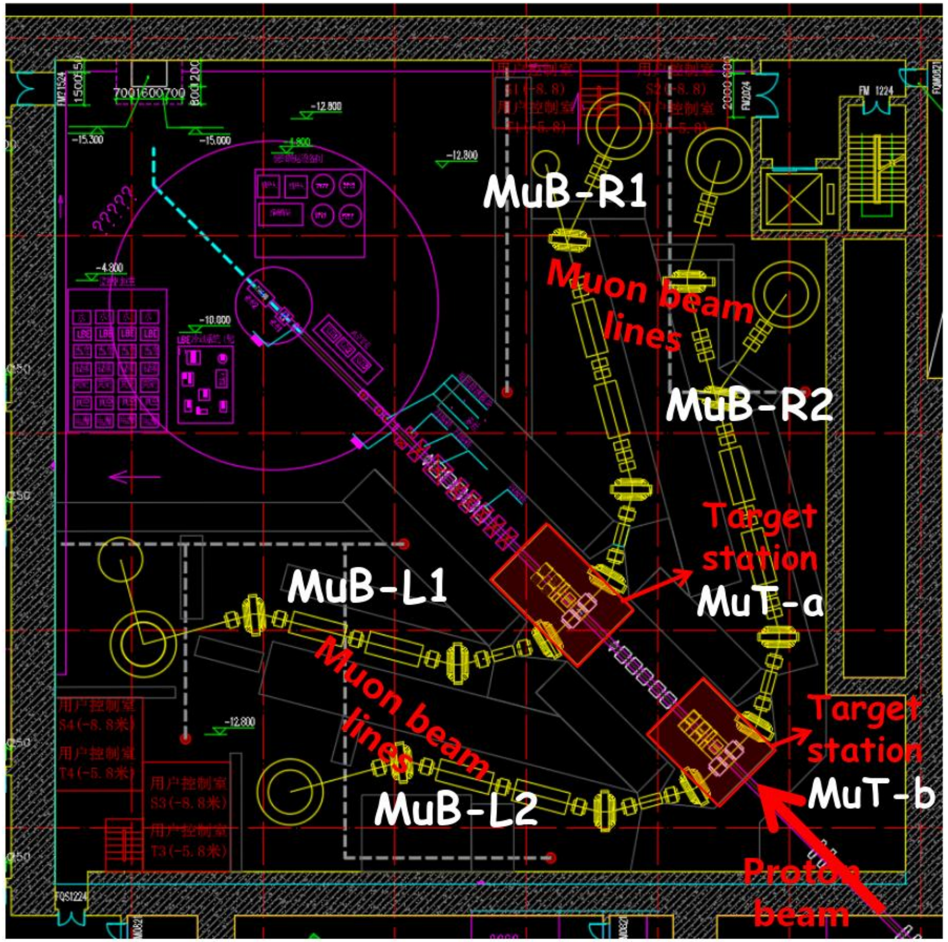
Muon beam

From Hanjie Cai
(MIP2026)

Layout and Plan of MuST-CiADS

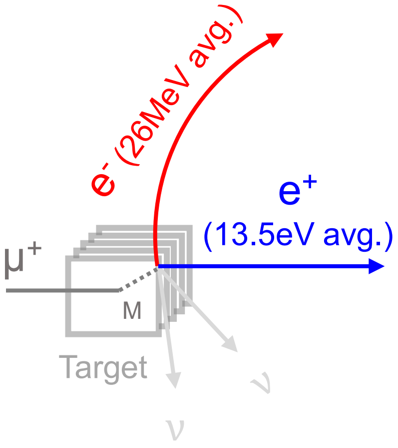
- **Conceptual Layout:**
  - Each of the two tandem target feeds two muon beamlines, approximately mirror-symmetric to each other
  - To deliver muon beams to 5 terminals, with the intensity varies from 10^7/s~10^{10}/s
- **Plan with two phases:**

Phase	Target	Muon beamlines		Applications
Phase I 2025~2029	**Tgt a** (MuT-a)	**Φ300 up to 10^8μ/s @0.5mA**	R1: ~30MeV/c	μSR/MACE
			L1: to 90MeV/c	MIXE/μCF
Phase II 2029~2032	**Tgt b** (MuT-b)	**Φ500 up to 10^{10}μ/s@ 5mA**	R2: to 90MeV/c	μSR/MACE
			L2: to 120MeV/c	Muography/MIXE

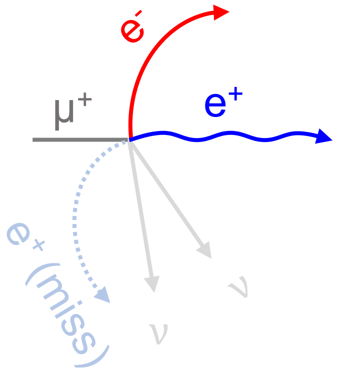


Signal and background

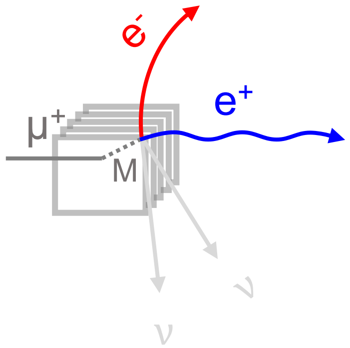
Signal:
fast e^- + slow e^+



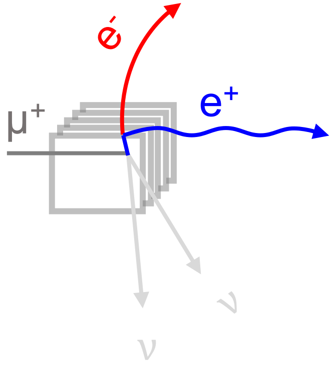
1. Internal conv. (IC) decay
- ☐ $\mu^+ \rightarrow e^+ e^- e^+ \bar{\nu}_\mu \nu_e$



2. Final state scattering
- ☐ $\mathrm{M} \rightarrow e^+ \bar{\nu}_\mu \nu_e e^-$



3. Accidental bkg.
- ☐ Scattering/conv. e-
- ☐ Misreconstruction
- ☐ Cosmic ray, etc.

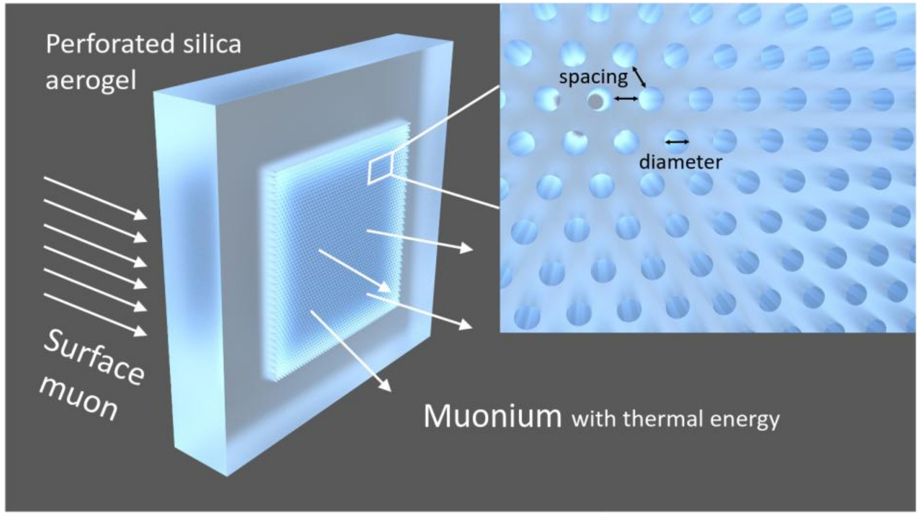


- ☐ **Coincidence of a fast e^- and a slow e^+**
- ☐ **Common vertex (by selecting e+/e- track DCA)**
  - ✓ Select p_{xy} of e+
  - ✓ Reject accidental e-
- ☐ **Time coincidence (by selecting e+ TOF)**
  - ✓ Select p_z of e+
  - ✓ Reject e+ from IC decay or Bhabha scattering
- ☐ **Charge identification (by e- track & e+ annihilation)**

- ➢ Excellent vertex resolution
  - ☐ e+/e- spatial resolution
  - ☐ Precise e+ transport in EM field
- ➢ Excellent time resolution
  - ☐ e+/e- time resolution

Muonium production target

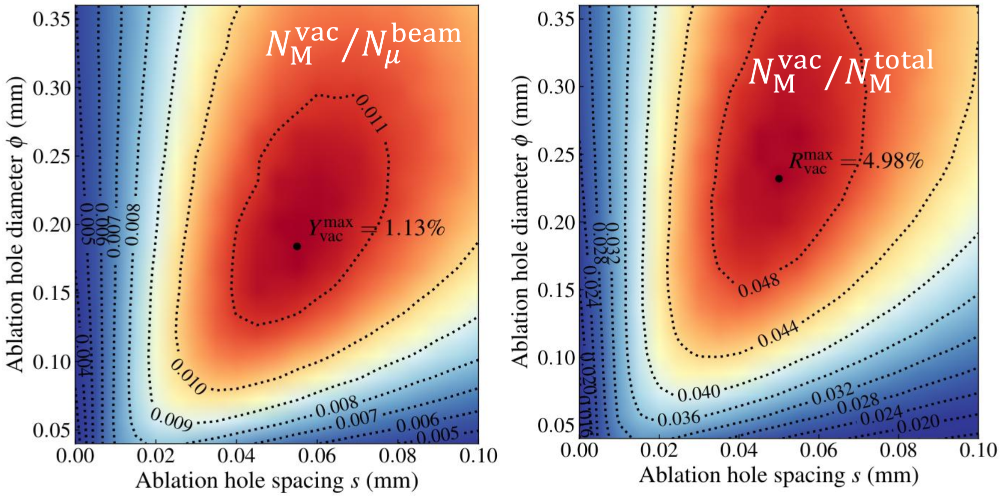
- Intensity of in-vacuum muonium source: $I_{\mathrm{M}}^{\mathrm{vac}} = I_{\mathrm{beam}} Y_{\mu\to\mathrm{M}}$
- $Y_{\mu\to\mathrm{M}}$ can be improved by utilizing porous materials, ideally perforated silica aerogel.
- A simulation method is developed to accurately simulate muonium production and diffusion.



Zhao, Shihan, and Jian Tang. "Optimization of muonium yield in perforated silica aerogel." *Physical Review D* 109.7 (2024): 072012.

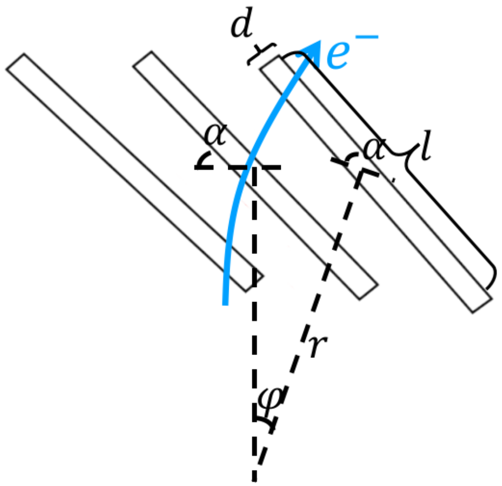
- The simulation is validated by muonium yield data measured in TRIUMF. J. Beare et al., PTEP. 2020, 123C01 (2020)
- Optimize $Y_{\mu\to\mathrm{M}}$ in perforated bulk target by scanning parameters, it can achieve
  - ✓ Max $Y_{\mu\to\mathrm{M}} = N_{\mathrm{M}}^{\mathrm{vac}}/N_{\mu}^{\mathrm{total}} = 1.134\%$, with 2mm hole depth, $p_{\mathrm{beam}} = 28\ \mathrm{MeV}/c$ and $\frac{\sigma_{p_{\mathrm{beam}}}}{p_{\mathrm{beam}}} = 2.5\%$.

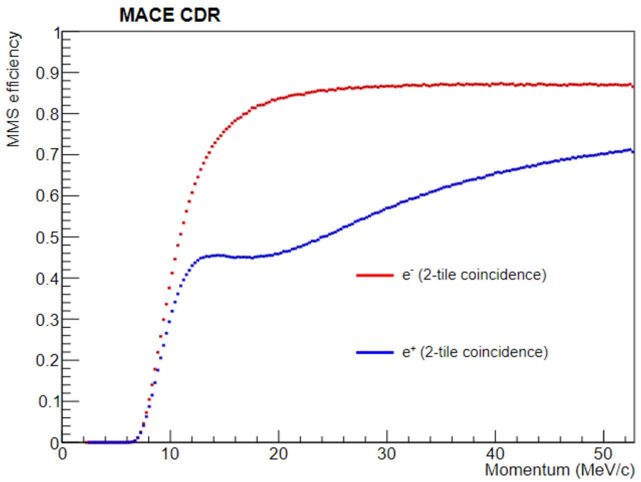
2 times larger than the yield in 1999

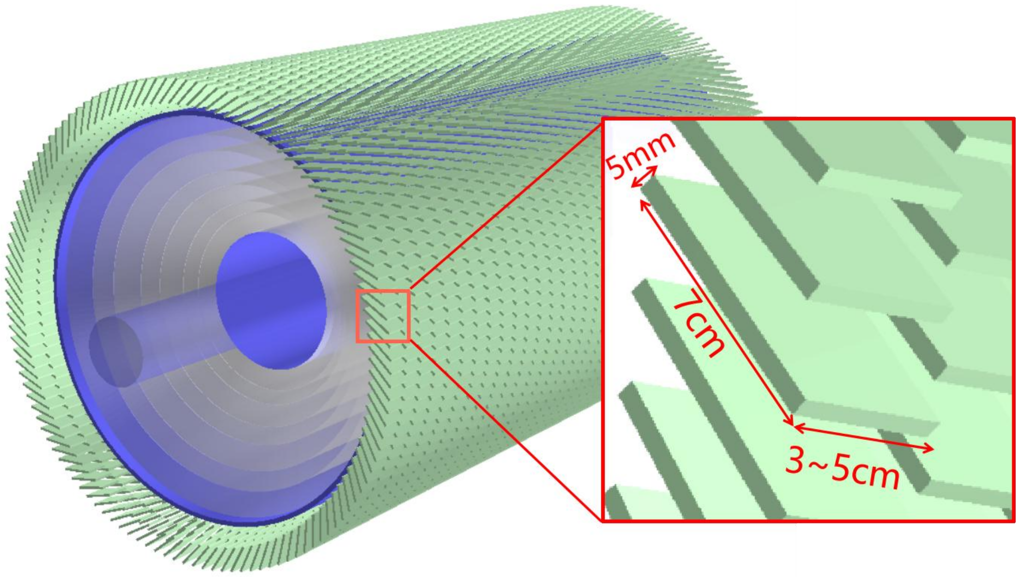


Tiled timing counter (TTC)

- Tilt design, signal track hits 2-3 scintillator tiles.
- Azimuth spacing $\varphi = 2.951°$, tilt angle $\alpha = 46°$.
- Full simulation result:
  - Geometry efficiency: $\varepsilon_{\mathrm{geom}} = 83.7\%$
  - Detection efficiency (amp. > 3 p.e.): $\varepsilon_{\mathrm{thr}} = 99.6\%$

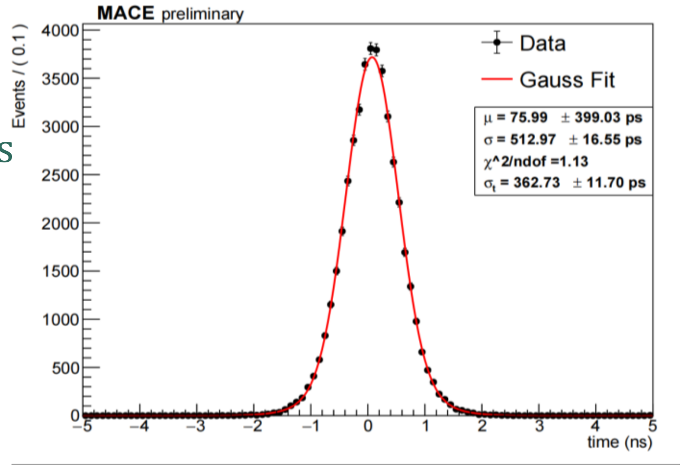






Test with cosmic-ray muons:

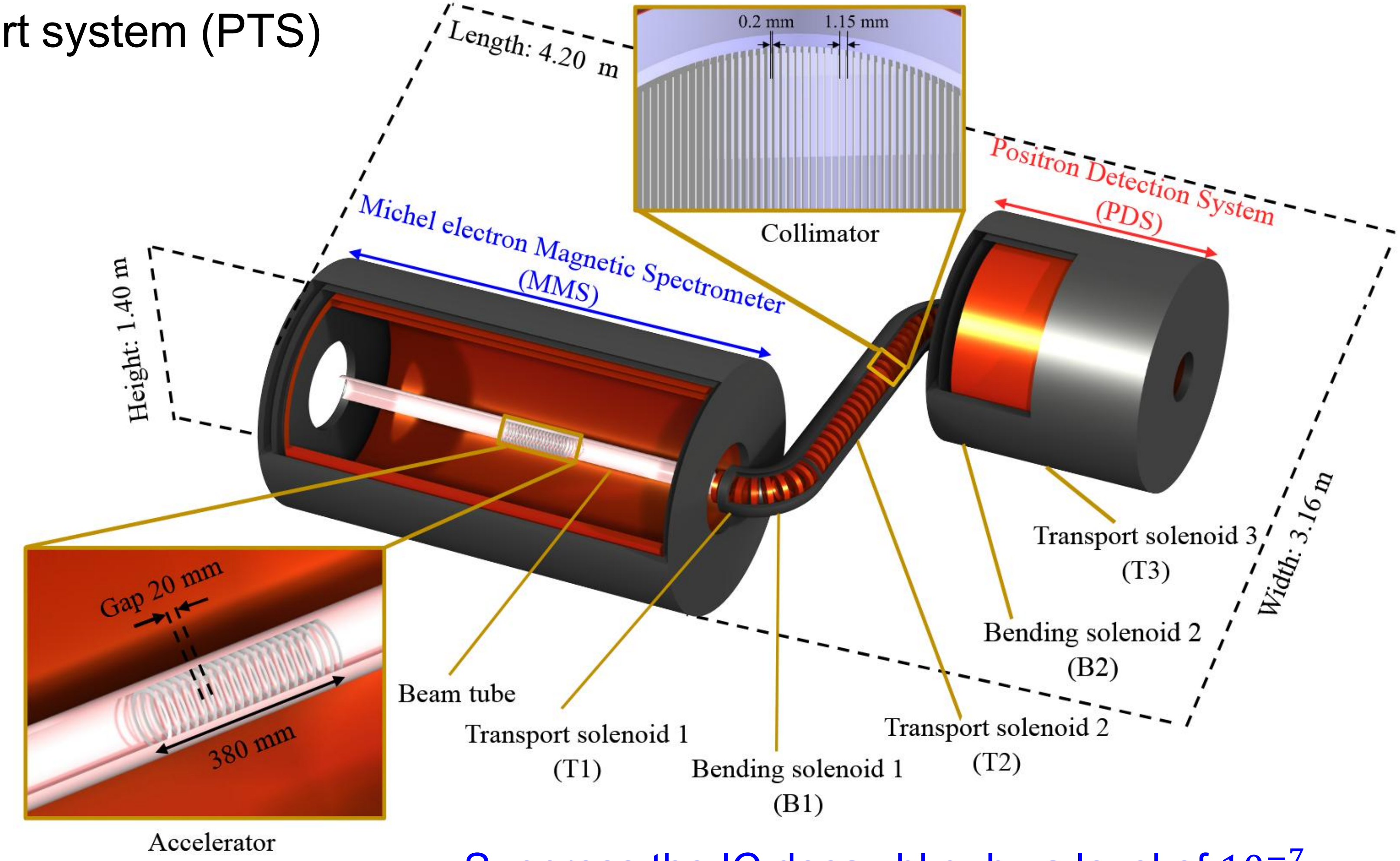
- Fitted time resolution:
  - Double-tile: $\sigma_t = (513 \pm 17)$ ps
  - Single-tile: $\sigma_t = (362 \pm 12)$ ps



Credit: Hao Jiang

Positron transport system

- The component of positron transport system (PTS)
  - I. Electrostatic accelerator
  - II. Solenoid system
    - 1. MMS solenoid
    - 2. TS solenoid
    - 3. ECAL solenoid
- PTS performance
  - I. Transmission efficiency: 65.8%.
  - II. Flight time: 322 ns.
  - III. Flight time FWHM: 6.9 ns.
  - IV. Spatial resolution: 0.088 mm × 0.102 mm



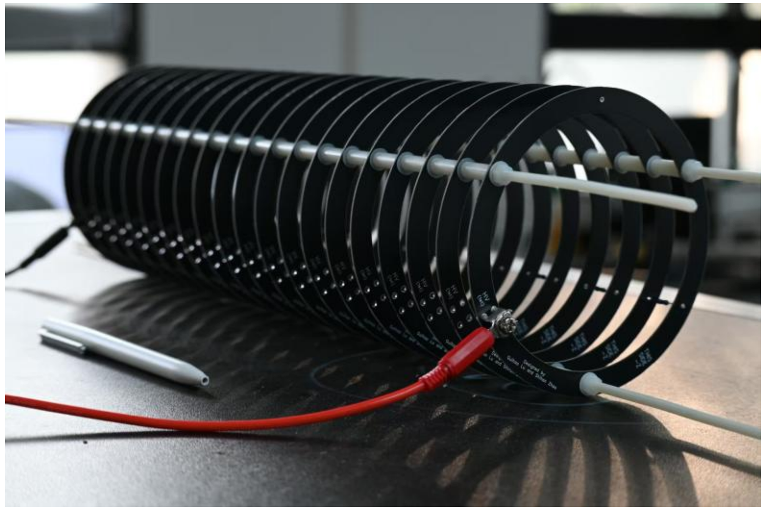
Suppress the IC decay bkg. by a level of 10^{-7}

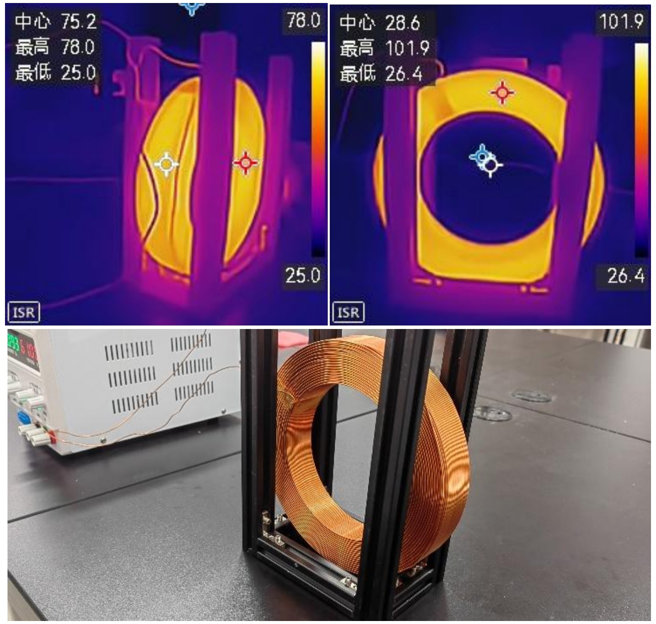
Lu, Guihao, et al. "Positron Transport System for Muonium-to-Antimuonium Conversion Experiment." *arXiv preprint arXiv:2508.07922* (2025).

PTS prototyping progress

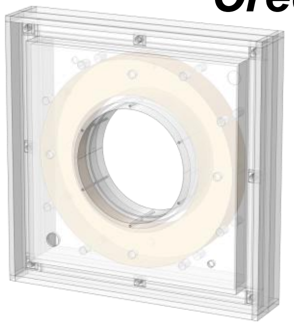
- **PTS validation**

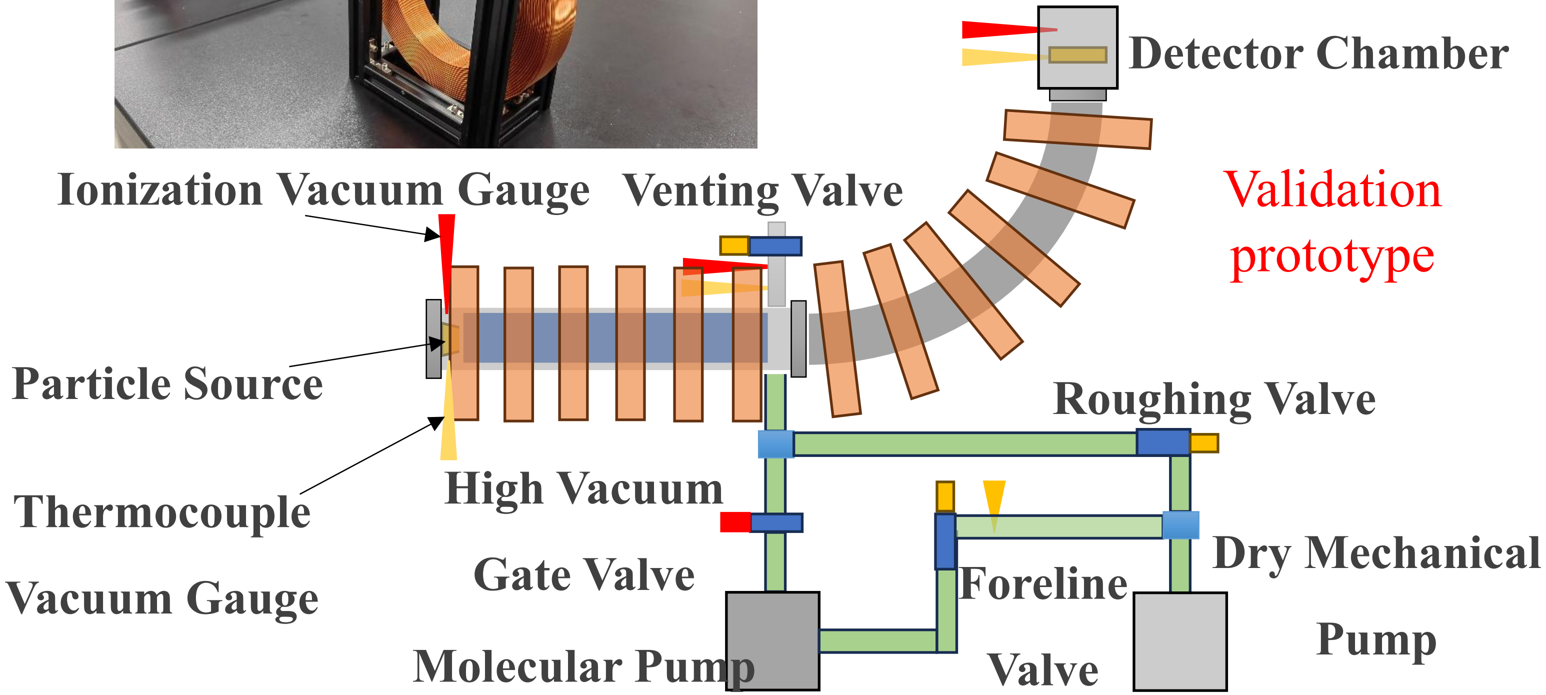
  Testing with TS solenoids and accelerator module





Credit: Guihao Lu





- Accelerator module prototype

  Multi-layer PCB

  High voltage > 2 kV

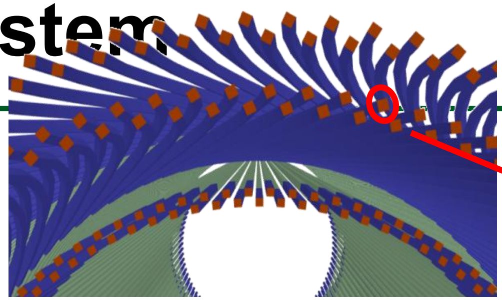
Tracking System

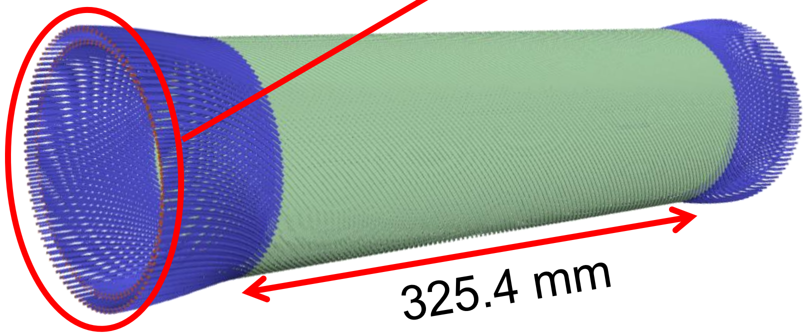
Credit: Yinyuan Huang

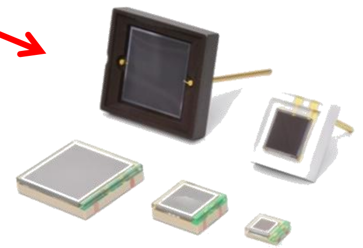
- Precise timing ability
- Low material budget
- Low cost
- e^+/γ discrimination
  - High active area
  - High e^+ detection efficiency
  - Low γ detection efficiency

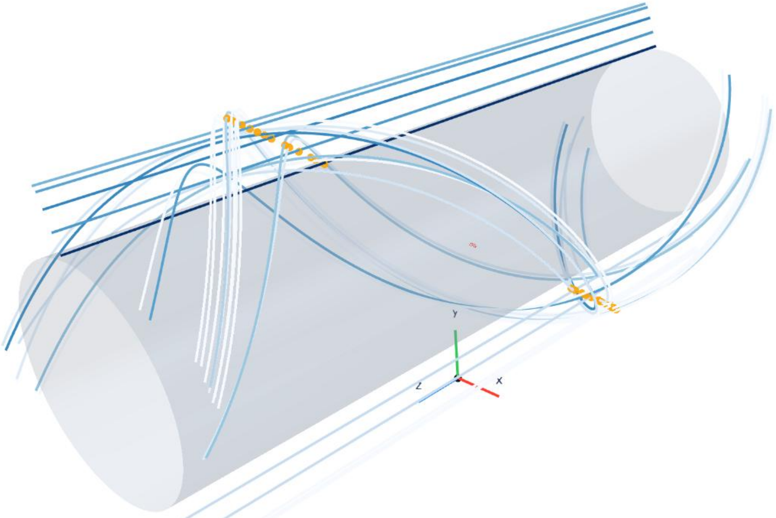
⇩

Plastic scintillators!









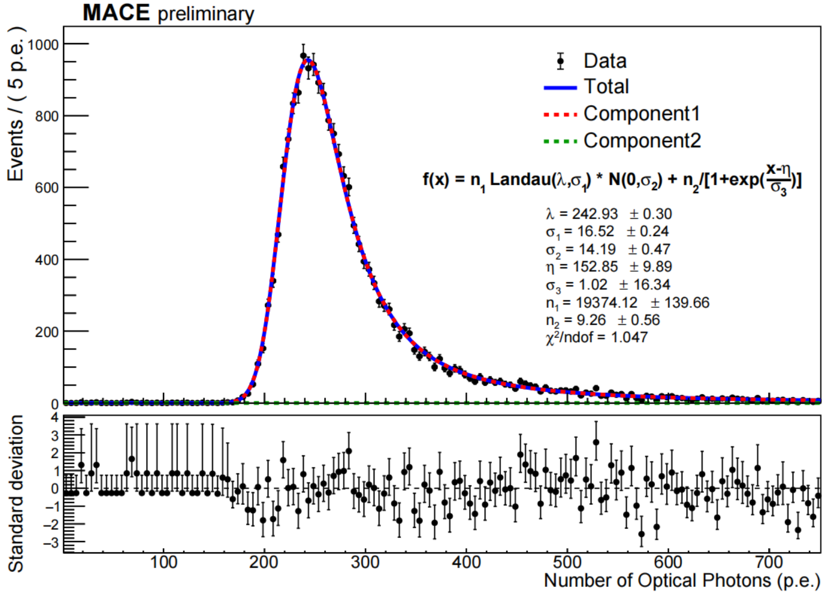
Event display

SciFi baseline design:

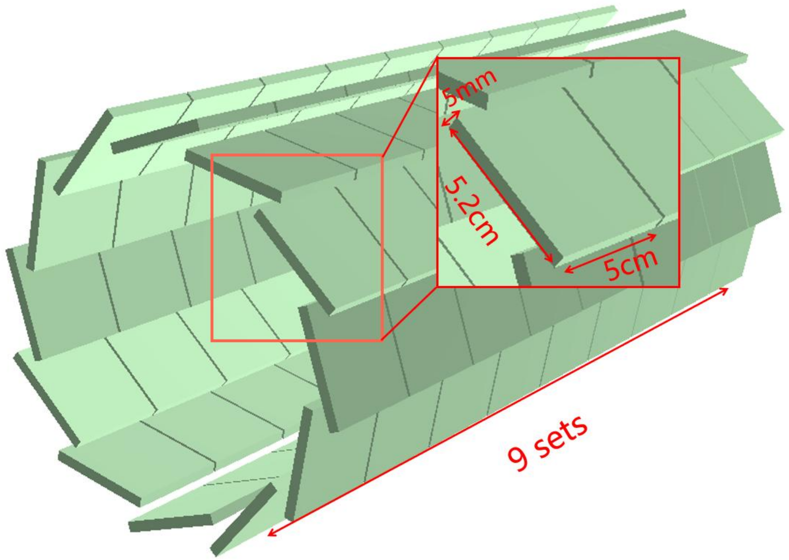
- Crossing fiber arrangement
- 2360 channels
- Single-end readout by SiPM
- Angular resolution ~5°
- Timing resolution ~1 ns
- $\varepsilon_{\mathrm{Recon}} \approx 90\%$
- $\varepsilon_e = 97\%$
- $\varepsilon_\gamma = 2\%$

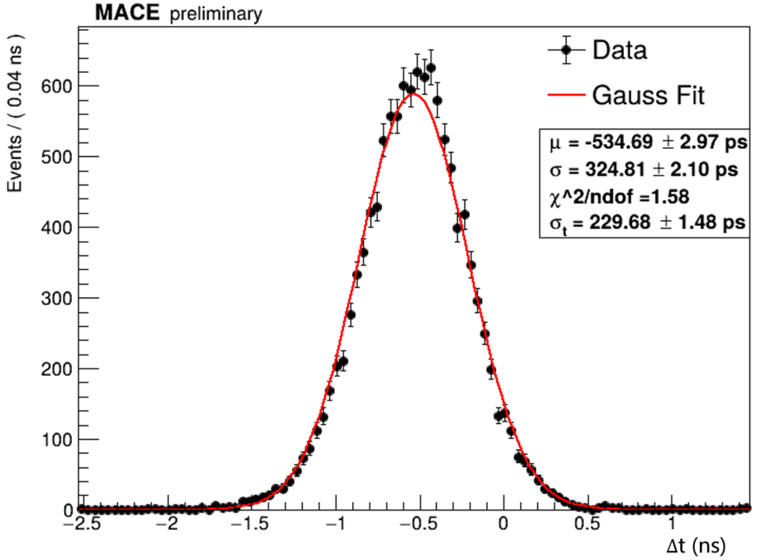
Tracking System

- **Tiled timing counter (TTC)** ***Credit: Hao Jiang***
  - 108 tiles of plastic scintillator in total
  - Double-end readout by SiPM arrays
  - Good timing resolution, ~$\mathcal{O}(100)$ ps
  - Providing timing information to ECAL, e/γ discrimination



Prototype readout by single SiPM each end reaches 230 ps.

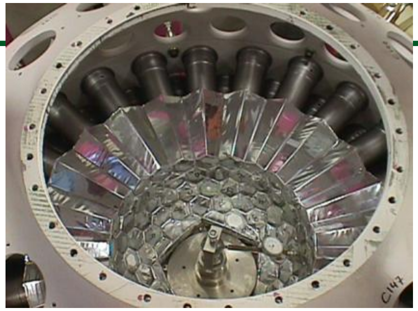




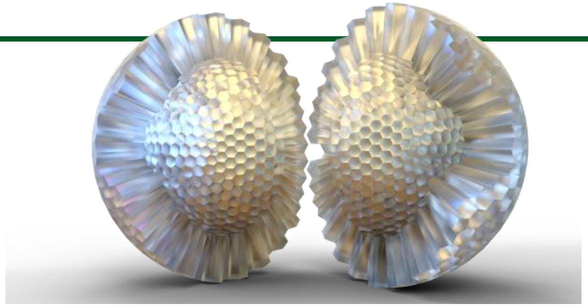
Electromagnetic Calorimeter

Design scheme：

- High acceptance and granularity
- Symmetrical structure
- Class-I GP(8,0) Goldberg polyhedron
- Crystal scintillators coupled with SiPM arrays



PEN detector
pCsI + PMT



MACE ECAL
pCsI + SiPM

LYSO

- 30000 ph/MeV
- **40 ns**
- Radiation hard
- Not hygroscopic
- Emits at 420 nm
- CNY ￥300/cm^3

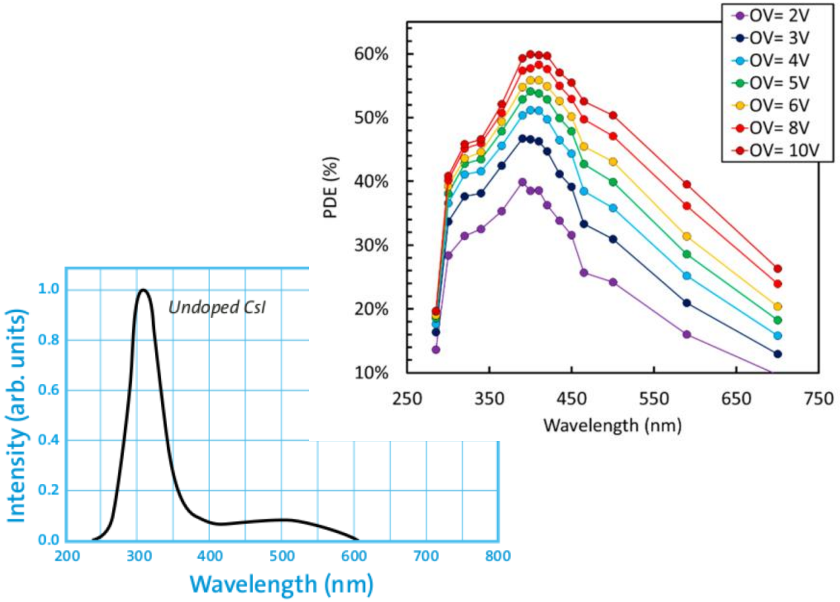
BGO

- 8000 ph/MeV
- 300 ns
- Not hygroscopic
- Emits at 480 nm
- CNY ￥100/cm^3

Pure CsI

✓ Baseline design

- 3500 ph/MeV
- **40 ns**
- Slight hygroscopic
- Emits at 310 nm
- Adopted by **Mu2e** and **PIBETA**
- **CNY ￥30/cm^3**



NUV SiPM readout

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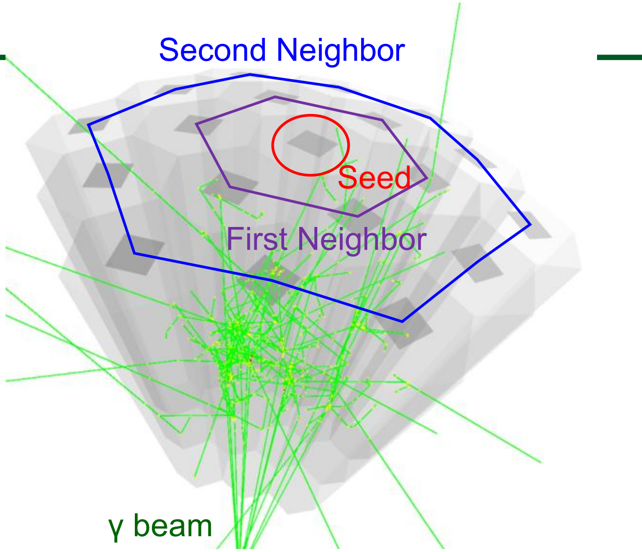
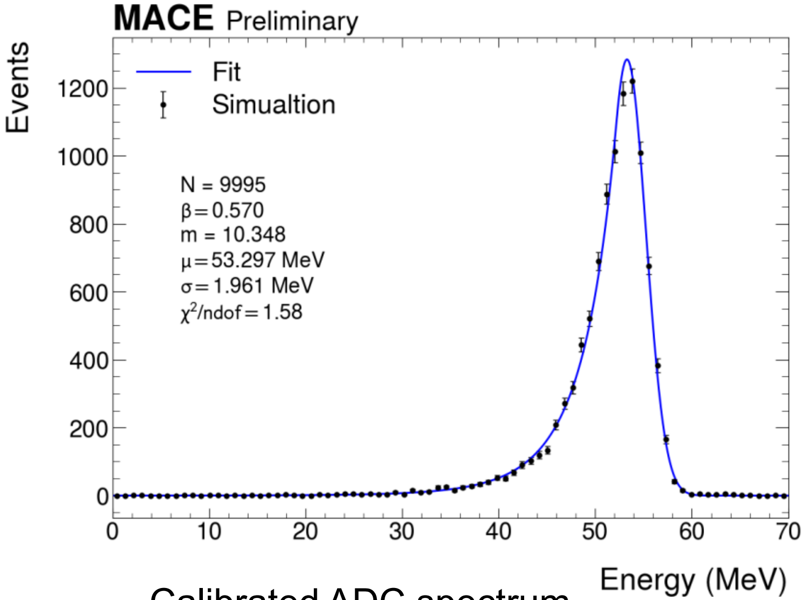
Phase-I ECAL performance

- Baseline requirement based on full simulation:
  - Full optical physics: scintillation, transportation, collection
  - Coincidence timing resolution better than **200 ps**
  - Energy resolution better than **5% @ 53 MeV**
  - Angular resolution better than **5°**

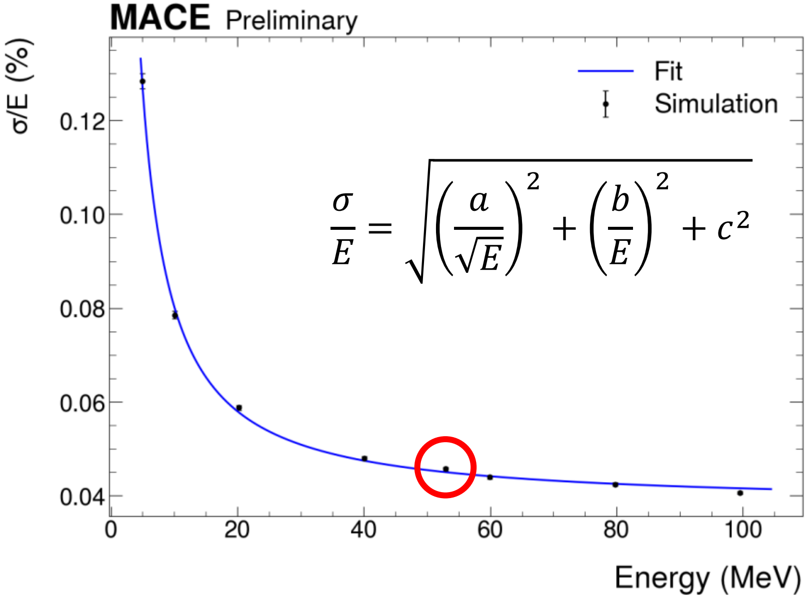
Energy-weighted clustering



Credit: Siyuan Chen

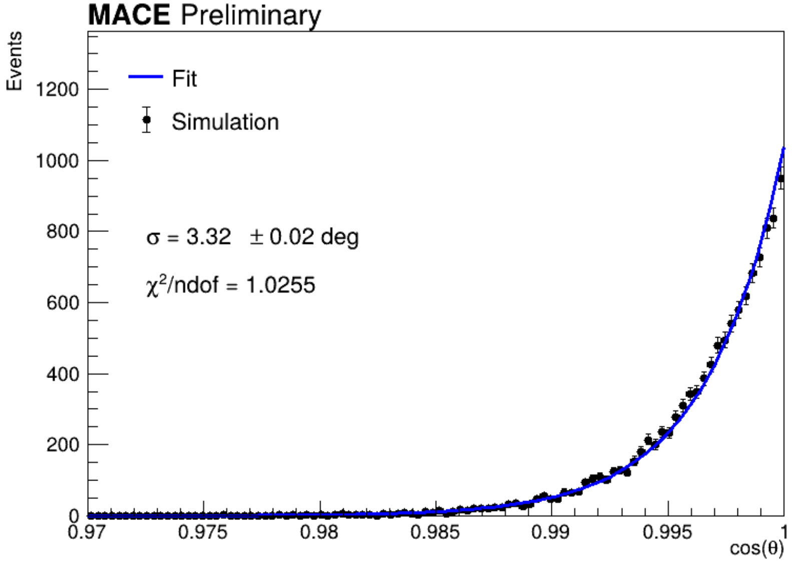


Calibrated ADC spectrum fitted by Crystal Ball function
$\mathcal{O}(50)$ p.e. **electronic noise** considered



$$\frac{\sigma}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + \left(\frac{b}{E}\right)^2 + c^2}$$

Energy resolution
1.5% nonlinear correction considered

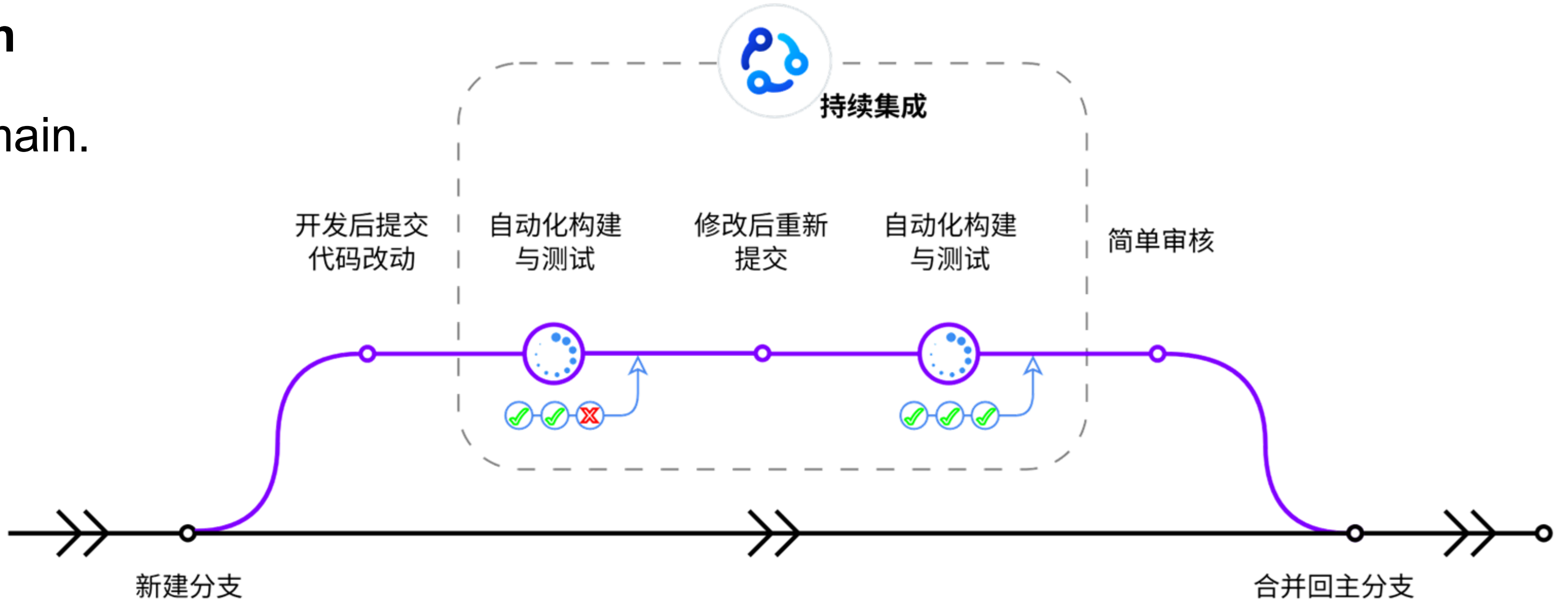


Angular resolution
Events isotopically emitted from the target

Continuous Integration

- **Challenges in Parallel Development**
  - Merge conflicts
  - Tedious code review
  - Hidden risks
- **Practice of Continuous Integration**
  - Frequently integrate code into main.
  - Automated builds and tests.

- **CI/CD**
  - Configure pipeline via config file.
  - Runners execute automated test scripts.
  - Regression tests.



Credit: Zhichao Wang