



正反繆子素转化实验 (MACE) 研究进展

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繆繆论坛

2026-07-12 北京大学物理学院

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(MACE working group)

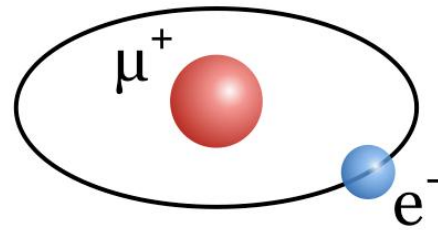
[Conceptual Design of the Muonium-to-Antimuonium Conversion Experiment \(MACE\),](#)
Nucl. Sci. and Tech. 37, 57 (2026), cover story

Muonium and muonium-to-antimuonium conversion

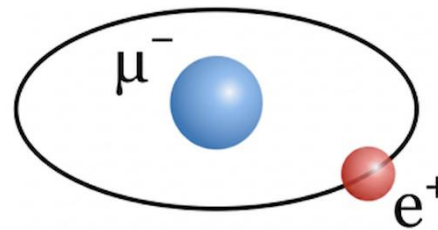
- **Muonium (M)** is a hydrogen-like exotic atom consisting of an antimuon (μ^+) and an electron (e^-).

- 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 ($\tau = 2.197 \text{ us}$).

	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



Antimuonium

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

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

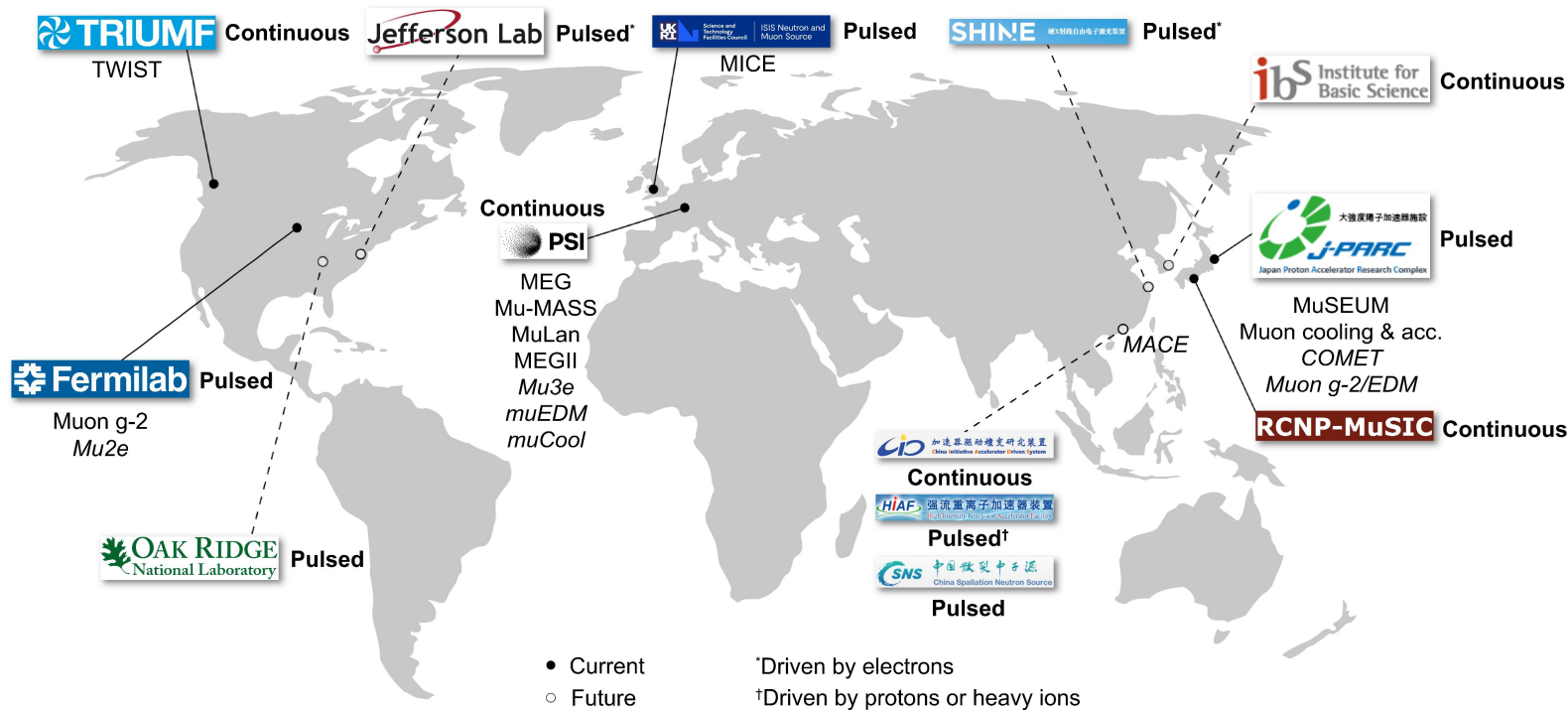
- **This process violates lepton flavor by 2 units.**
- Latest 90% C.L. bound on conversion probability (MACS 1999): L. Willmann, PRL 82 (1999), 49-52

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

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

(*The kinematics of $M \rightarrow \bar{M}$ is similar to that of $K - \bar{K}$ or $B - \bar{B}$ oscillation. However, $M - \bar{M}$ 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.)

Status of muon sources

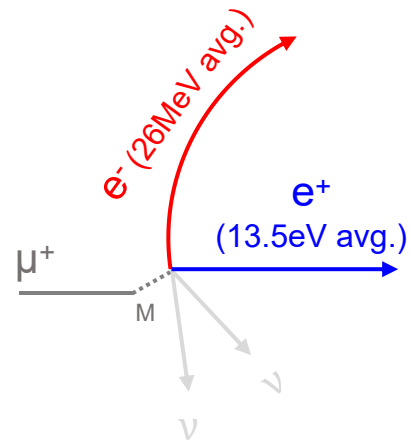


- Global facilities: PSI (Switzerland), J-PARC (Japan), ISIS (UK), TRIUMF (Canada), FNAL (USA).
- First high-intensity muon source in **China**, to be built in the Greater Bay Area: **CiADS/HIAF/CSNS**.

Signal and background

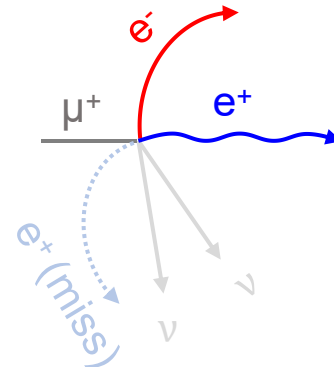
◆ Signal:

Multi-10 MeV e^- +
Multi-eV e^+



1. Muon internal conversion decay

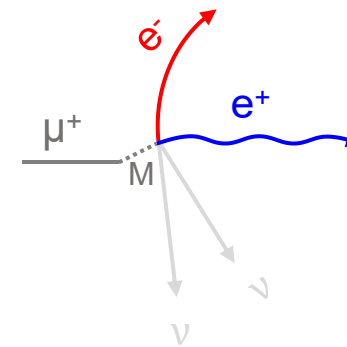
$$\mu^+ \rightarrow e^+ e^- e^+ \bar{\nu}_\mu \nu_e$$



2. Final state scattering

$$M \rightarrow e^+ \bar{\nu}_\mu \nu_e e^-$$

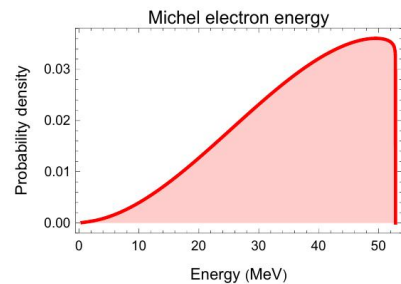
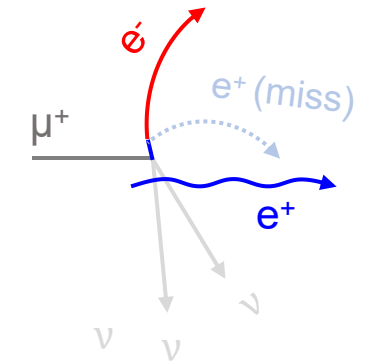
$$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e + \text{scattered } e^-$$



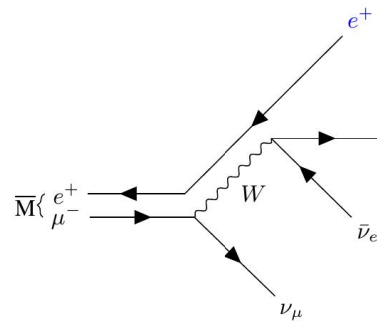
3. Accidental

$$\square \text{ Scattered } e^- + \text{low-E } e^+$$

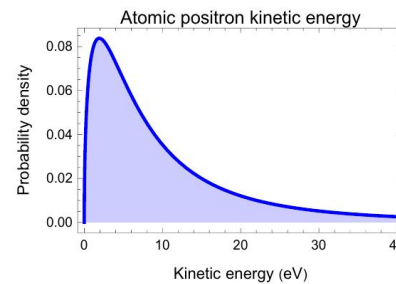
$$\square \text{ Misid. } e^- + \text{low-E } e^+$$



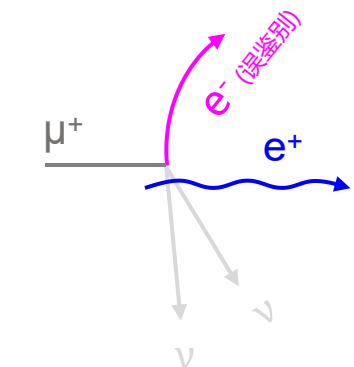
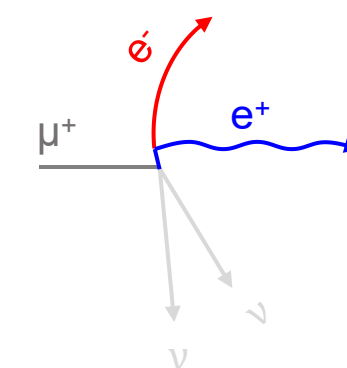
(a) e^- energy spectrum.



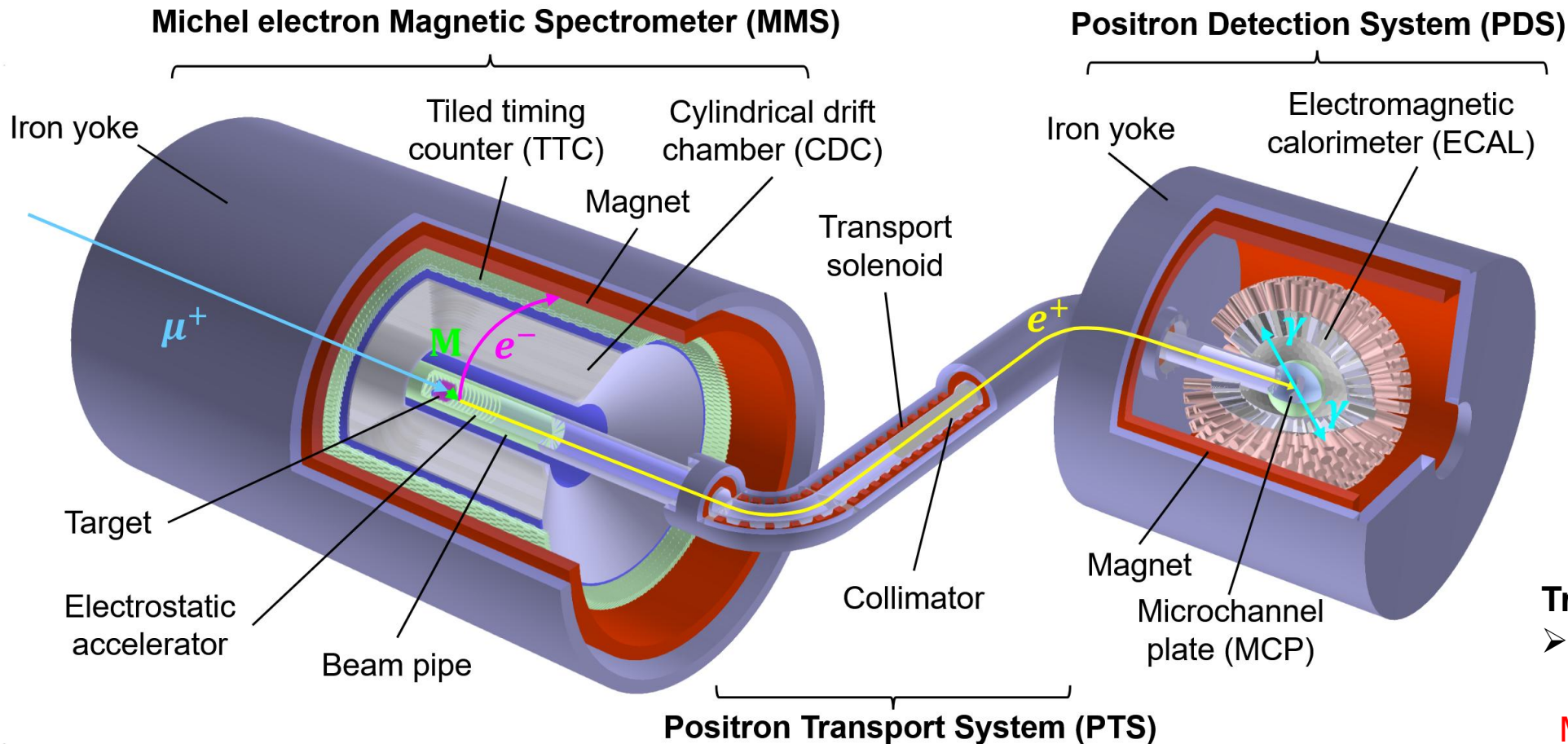
(b) Leading-order $\bar{M}$ decay.



(c) e^+ energy spectrum.



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**

↓
Michel e^- Atomic e^+

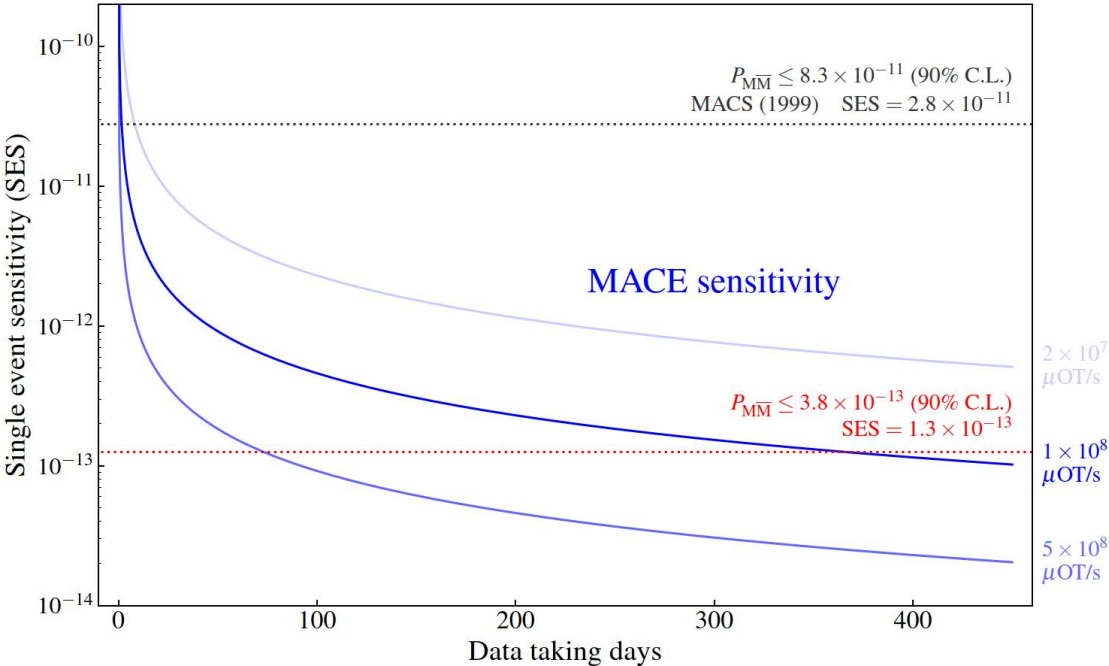
- I. Surface muon stop in target → muonium
- II. M diffuse into vacuum & convert to $\bar{M}$
- III. Decay in a vacuum: $\bar{M} \rightarrow e^+ e^- \nu_\mu \bar{\nu}_e$
- IV. CDC detects **Michel e^-** track

- 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/($10^8 \mu^+/\text{s} \cdot 1 \text{ yr}$)
Physical background	$\mu^+ \rightarrow e^+ e^- e^+ \nu_e \bar{\nu}_\mu$	0.287 ± 0.020
Accidental background	Beam positron	< 0.07
	Cosmic ray (with veto)	< 0.1
Total		< 1



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

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

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

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

(90% C.L.)

MACE conceptual design report

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



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

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



MACE Phase-I

□ Muon cLFV decay modes

- ✓ $\mu^+ e^-$ annihilation: $\mu^+ e^- \rightarrow \gamma\gamma$ $\mathcal{O}(10^{-5})$, 1959
- ✓ Neutrinoless decay: $\mu^+ \rightarrow e^+ \gamma\gamma$ $\mathcal{O}(10^{-11})$, 1988
- ✓ New particles: DM, ALP, Fimilon, ... Crystal Box, MEG

PRL, 1959, 3: 288-291

PRD 38 (1988) 2077

EPJC 80 (2020) 9, 858

□ Test of the standard model

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

EPJC 76 (2016) 3, 108

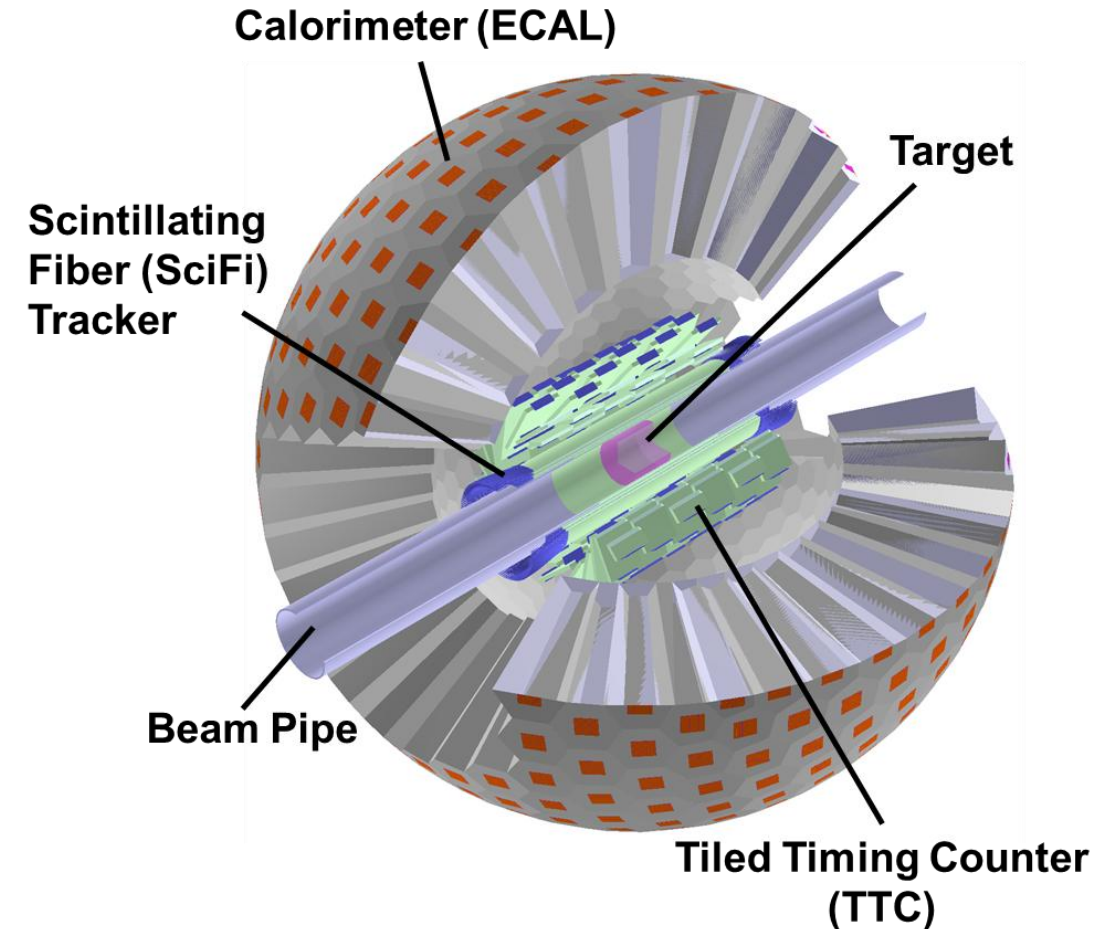
Int.J.Mod.Phys.A 20 (2005) 472-481

PRL. 115 (2015) 7, 071801

arXiv:2203.01981

PIONEER CDR, 2022

More in backup slides.



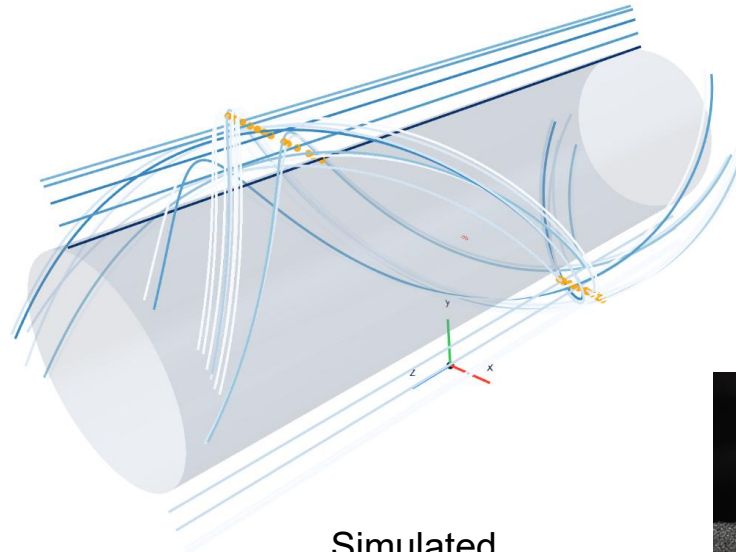
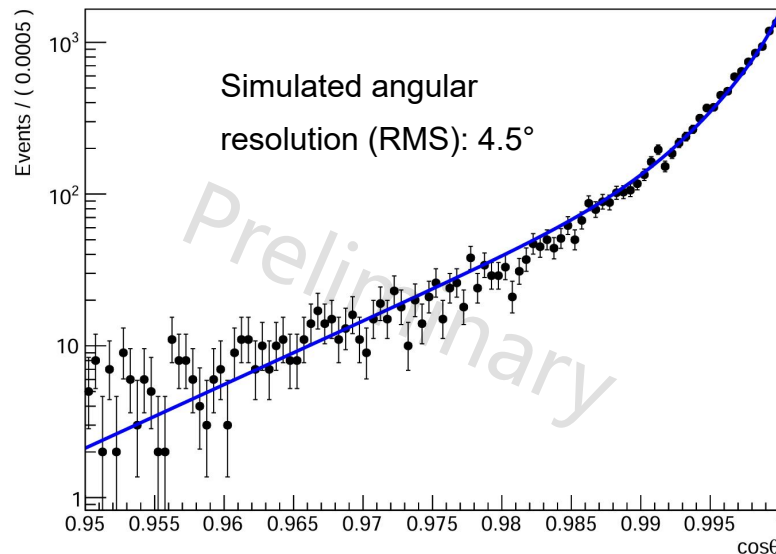
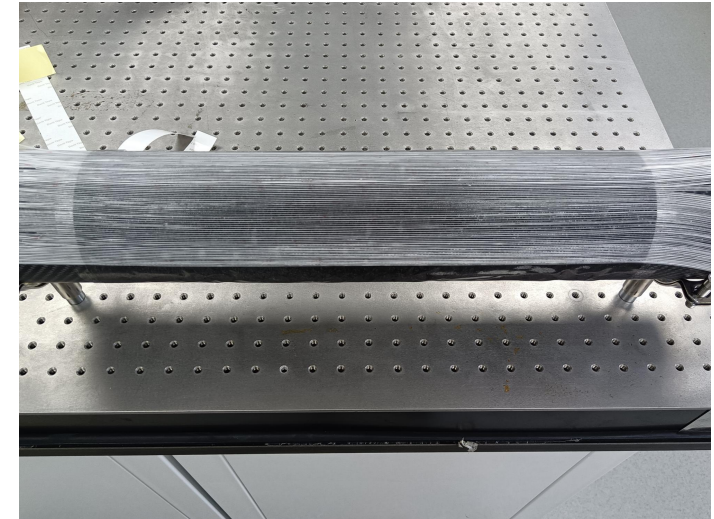
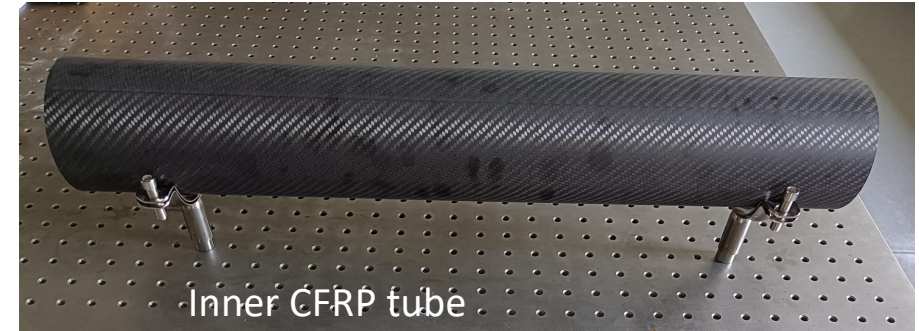
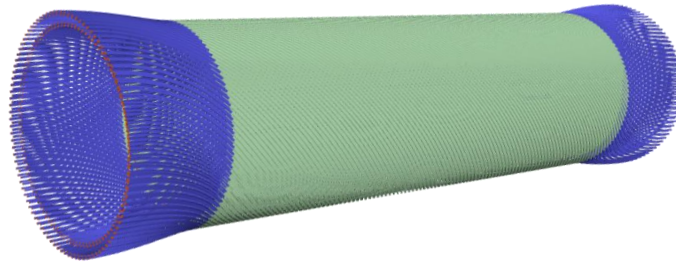
SciFi tracker in MACE phase-I

SciFi baseline design:

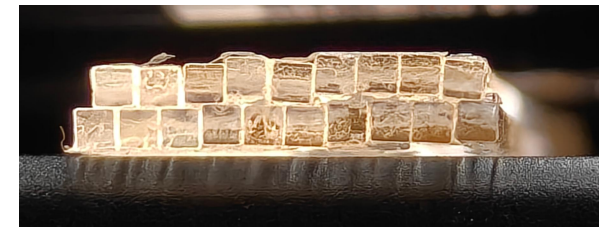
- Single-end SiPM readout
- Angular resolution $\sim 5^\circ$
- Timing resolution ~ 1 ns
- $\epsilon_{\text{Recon}} \approx 90\%$
- $\epsilon_e = 97\%$
- $\epsilon_\gamma = 2\%$

Credit: Yinyuan Huang

Design schematic



Simulated event display

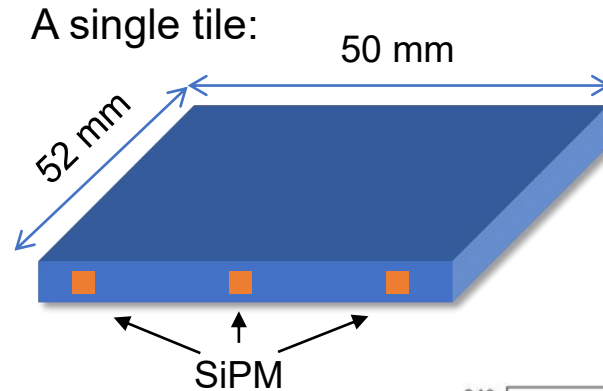


Prototype assembly in progress.

Tiled timing counter (TTC) for MACE Phase-I

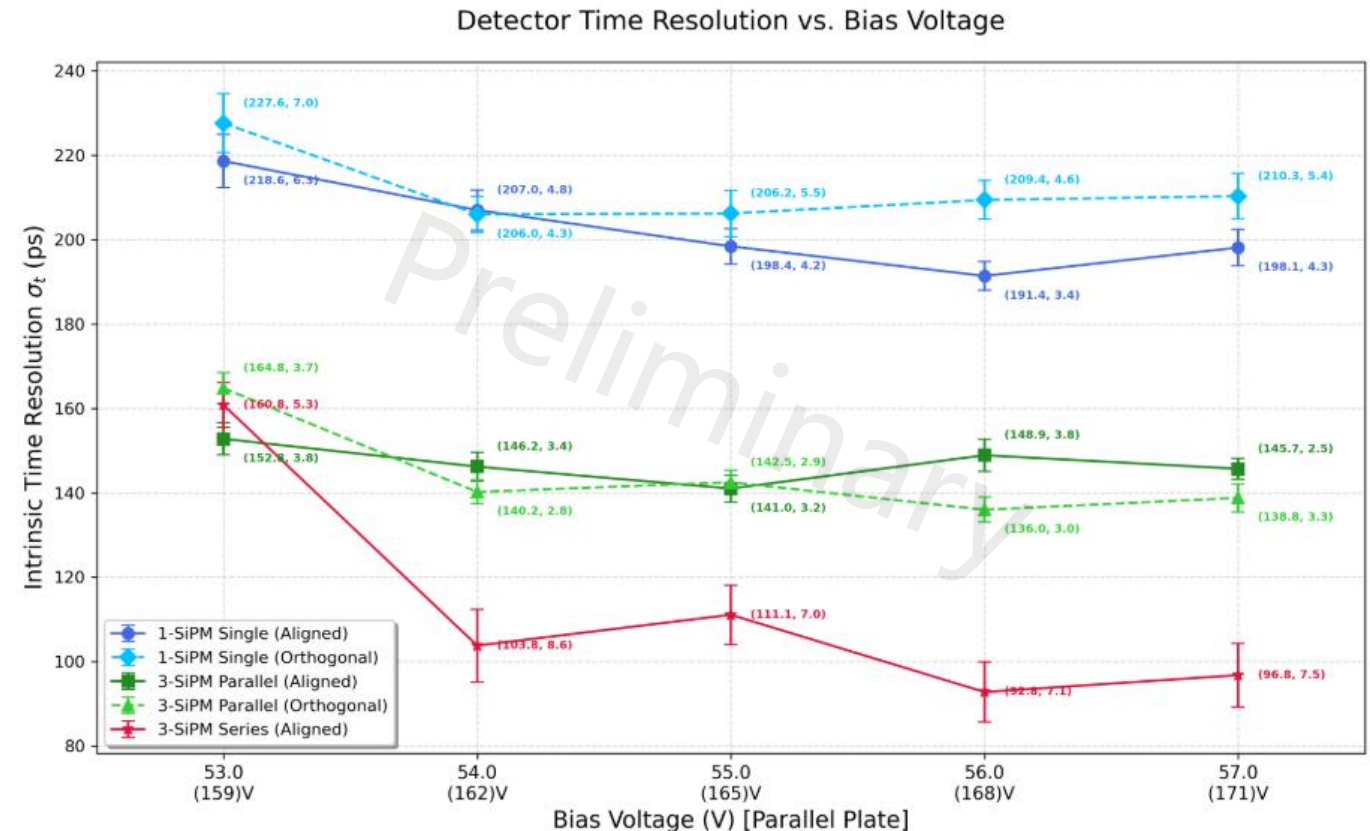
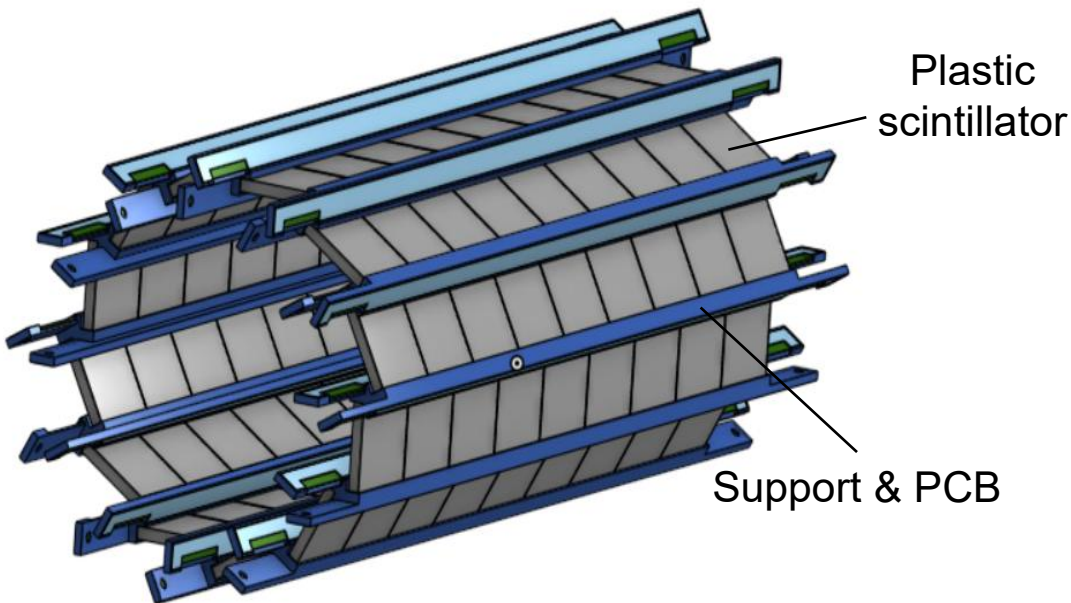
Tiled timing counter (TTC):

- Thin plastic scintillator
- Double-end SiPM readout
- 3 SiPM in series per end



Credit: Changlin Chen & Hao Jiang

- Single SiPM, 3 SiPM serial / parallel readout tested.
- Timing performance: 3-serial > 3-parallel > single.
- 100 ps time resolution achieved.



MACE offline software and Mustard framework

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

◆ MACE offline software

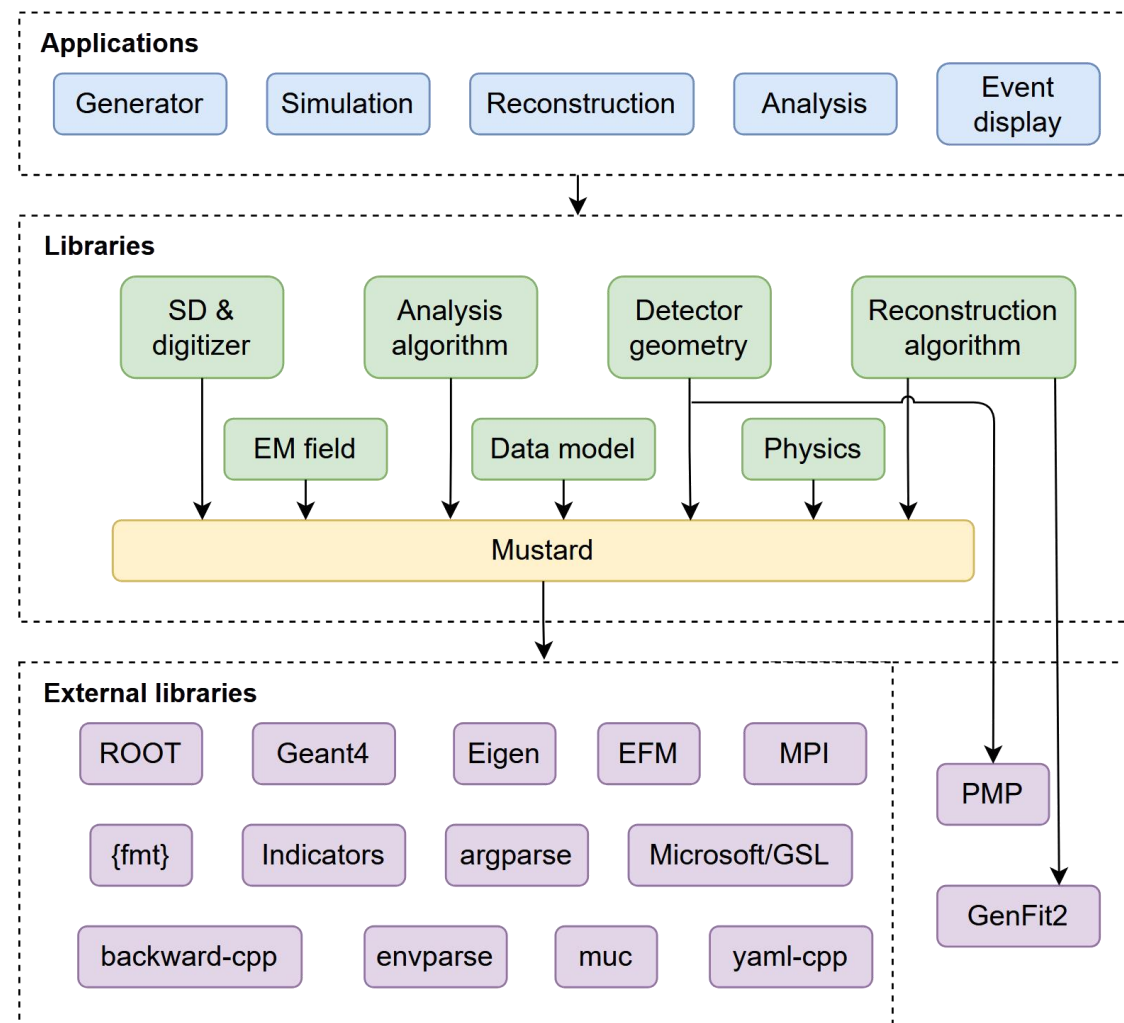
- Event generation, detector simulation, offline reconstruction and data analysis framework.
- Based on Mustard framework and HEP toolkits.

◆ Mustard framework

- A modern, high-performance offline software framework for non-collider experiment.
- Natively support large scale distributed computing.
- Framework for data model definition, event generation, detector geometry management, application interface and other utilities.
- Applications: MACESW, MusAirS (an air shower simulation tool), CRMuSR offline software, muon tomography simulation and analysis software.

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

More in backup slides.



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- $\bar{M}$ 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!**



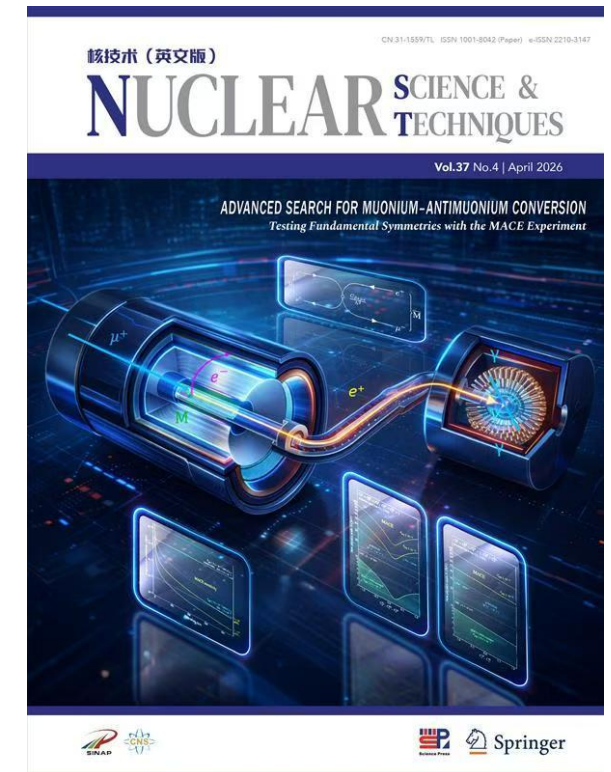
Muonium-to-Antimuonium Conversion Experiment

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

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

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Thank you!

Backup

High-intensity frontier and cLFV

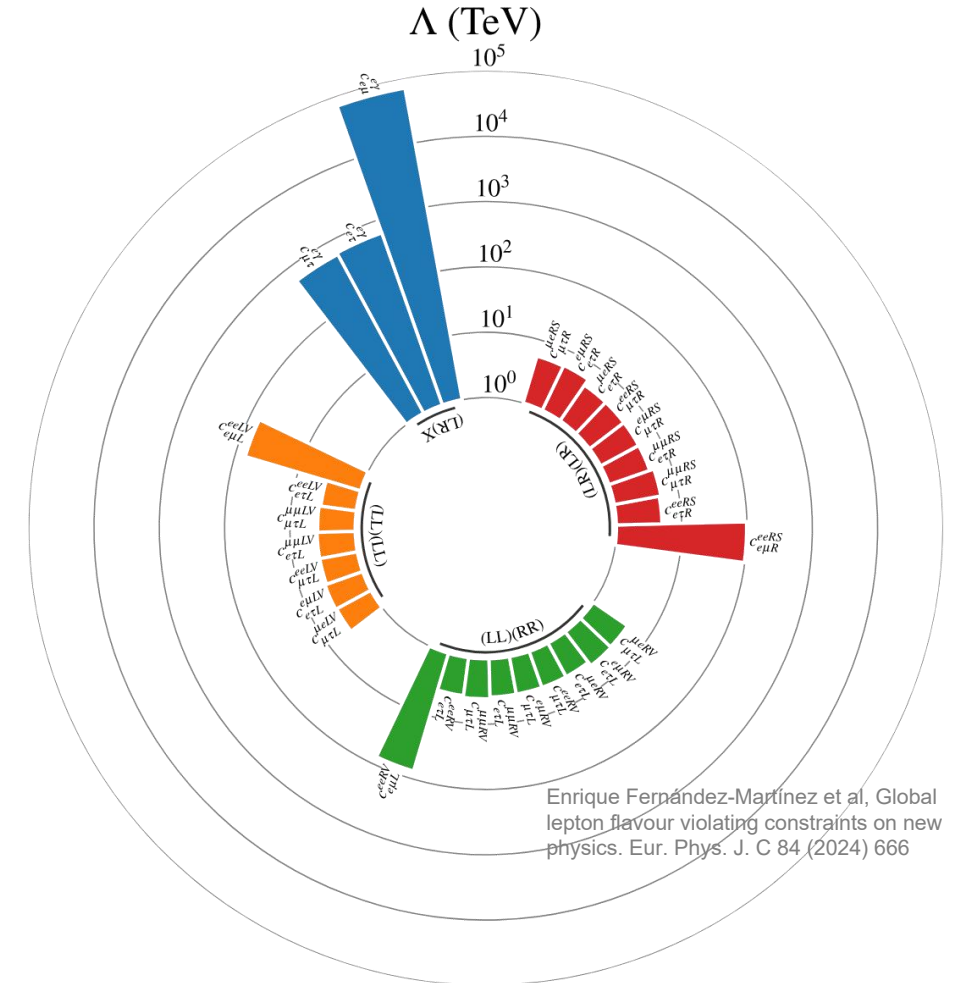
◆ How to search for new physics beyond SM?

□ High-intensity frontier:

- Provide **indirect constraints** 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, $U(1)_{B-L}$.



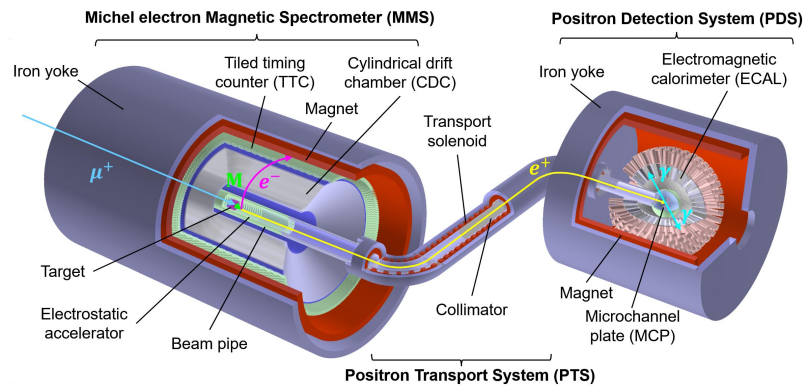
Significant cLFV signals → clear evidence for new physics;

Negative result → strong limit on new physics models.

Muonium science and application

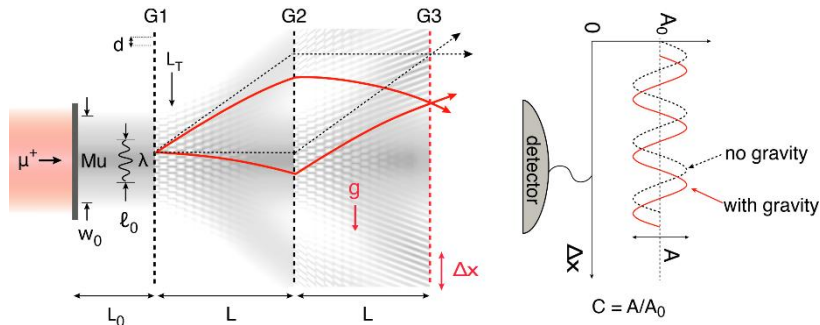
◆ 缪子素

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。



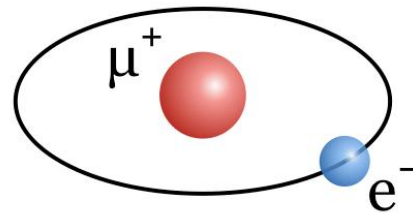
正反缪子素转化实验

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

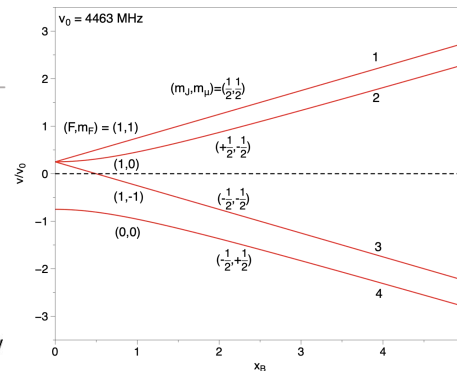


缪子素重力测量实验

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



缪子素示意图



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

Muonium-to-antimuonium conversion

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

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

- The off-diagonal term induces the conversion,

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

Time evolution of the state and conversion probability

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

➤ **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).**

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

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

$$Q_V^{\text{LL}} = (\bar{\mu} \gamma_\alpha (1 - \gamma_5) e) (\bar{\mu} \gamma^\alpha (1 - \gamma_5) e),$$

$$Q_V^{\text{RR}} = (\bar{\mu} \gamma_\alpha (1 + \gamma_5) e) (\bar{\mu} \gamma^\alpha (1 + \gamma_5) e),$$

$$Q_V^{\text{LR}} = (\bar{\mu} \gamma_\alpha (1 - \gamma_5) e) (\bar{\mu} \gamma^\alpha (1 + \gamma_5) e),$$

$$Q_S^{\text{LR}} = (\bar{\mu} (1 + \gamma_5) e) (\bar{\mu} (1 + \gamma_5) e),$$

$$Q_S^{\text{RL}} = (\bar{\mu} (1 - \gamma_5) e) (\bar{\mu} (1 - \gamma_5) e).$$

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

Muonium-to-antimuonium conversion in EFT

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

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

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

$$Q_V^{\text{LL}} = (\bar{\mu}\gamma_\alpha(1 - \gamma_5)e)(\bar{\mu}\gamma^\alpha(1 - \gamma_5)e),$$

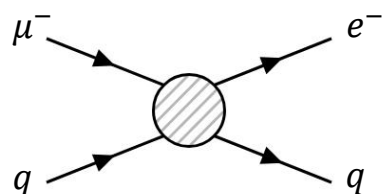
$$Q_V^{\text{RR}} = (\bar{\mu}\gamma_\alpha(1 + \gamma_5)e)(\bar{\mu}\gamma^\alpha(1 + \gamma_5)e),$$

$$Q_V^{\text{LR}} = (\bar{\mu}\gamma_\alpha(1 - \gamma_5)e)(\bar{\mu}\gamma^\alpha(1 + \gamma_5)e),$$

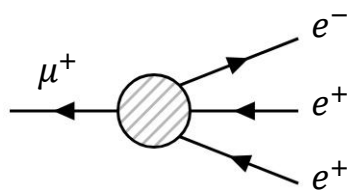
$$Q_S^{\text{LR}} = (\bar{\mu}(1 + \gamma_5)e)(\bar{\mu}(1 + \gamma_5)e),$$

$$Q_S^{\text{RL}} = (\bar{\mu}(1 - \gamma_5)e)(\bar{\mu}(1 - \gamma_5)e).$$

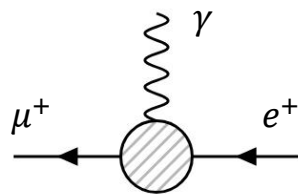
**$\mu\mu ee$
contact
operators**



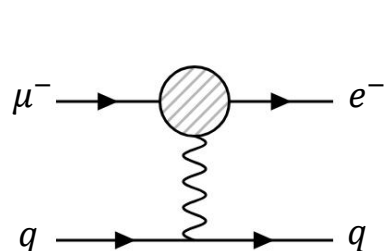
$\mu - e$ conv.
 $\mu e q q$ contact
 $|M|^2 \propto C_{\mu e q q}^2$



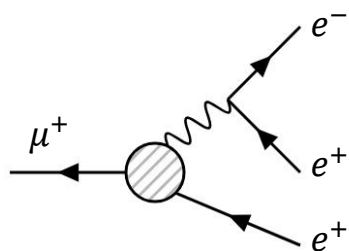
$\mu \rightarrow eee$
 $\mu e e e$ contact
 $|M|^2 \propto C_{\mu e e e}^2$



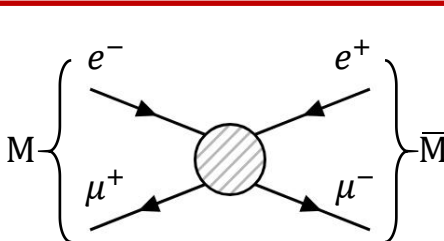
$\mu \rightarrow e\gamma$
 $\mu e \gamma$ dipole
 $|M|^2 \propto C_{\mu e \gamma}^2$



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



$\mu \rightarrow eee$
 $\mu e \gamma$ dipole
 $|M|^2 \propto \alpha C_{\mu e \gamma}^2$



$M \rightarrow \bar{M}$
 $\mu\mu ee$ contact
 $|M|^2 \propto C_{\mu\mu ee}^2$

$\mu\mu ee$ contact

$\mu e e e$ contact

$\mu e \gamma$ dipole

$\mu e q q$ contact

➤ $M \rightarrow \bar{M}$ is the only low-energy process that can directly constrain $\mu\mu ee$ effective coupling.

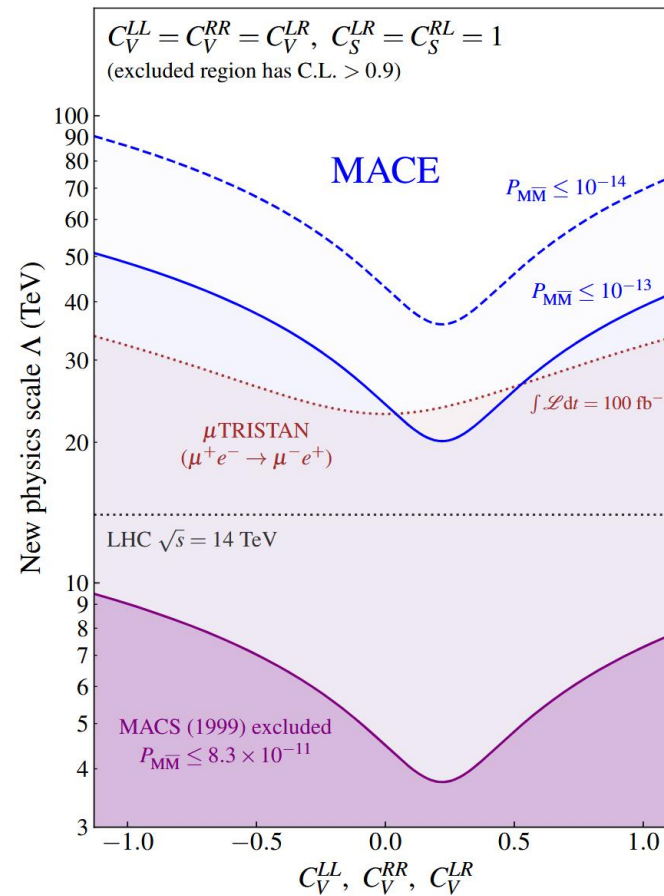
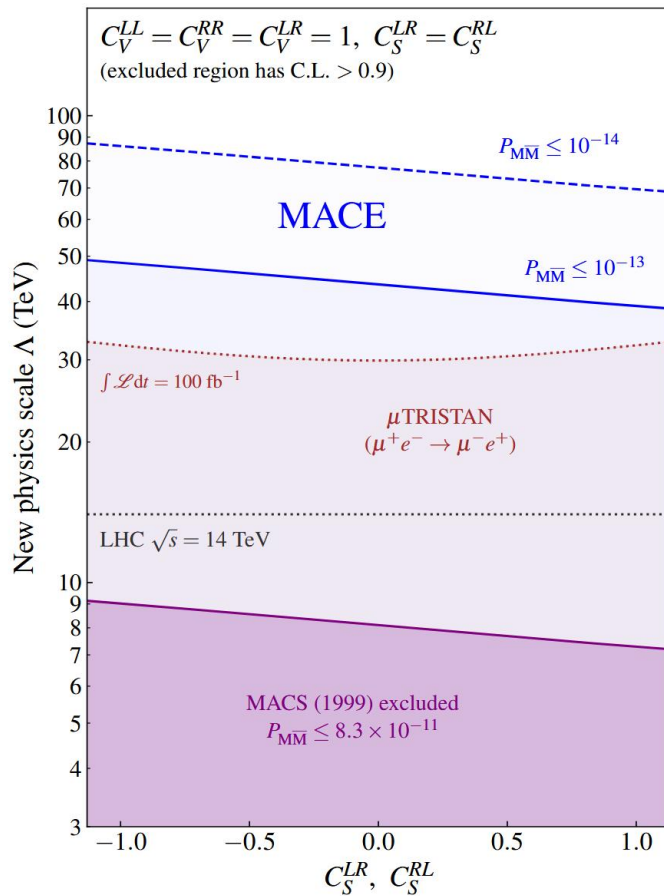
Muonium-to-antimuonium conversion in EFT

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$$\left. \begin{aligned} Q_V^{LL} &= (\bar{\mu}\gamma_\alpha(1-\gamma_5)e)(\bar{\mu}\gamma^\alpha(1-\gamma_5)e), \\ Q_V^{RR} &= (\bar{\mu}\gamma_\alpha(1+\gamma_5)e)(\bar{\mu}\gamma^\alpha(1+\gamma_5)e), \\ Q_V^{LR} &= (\bar{\mu}\gamma_\alpha(1-\gamma_5)e)(\bar{\mu}\gamma^\alpha(1+\gamma_5)e), \\ Q_S^{LR} &= (\bar{\mu}(1+\gamma_5)e)(\bar{\mu}(1+\gamma_5)e), \\ Q_S^{RL} &= (\bar{\mu}(1-\gamma_5)e)(\bar{\mu}(1-\gamma_5)e). \end{aligned} \right\} \mu\mu ee \text{ contact operators}$$



- **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

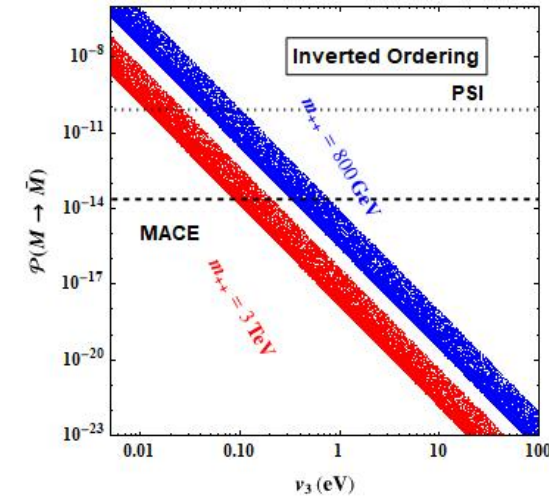
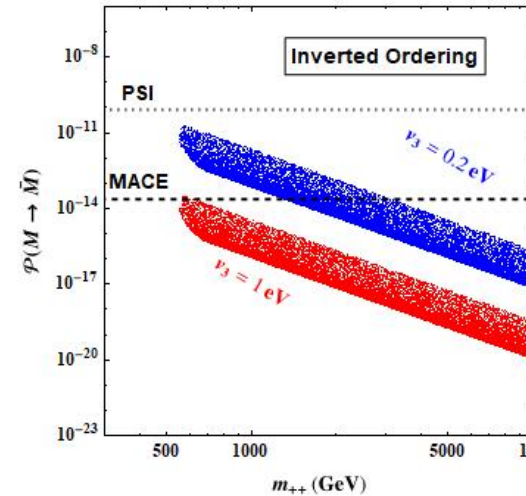
✓ Rich physics in muonium conversion.

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

✓ Muonium conversion is unique.

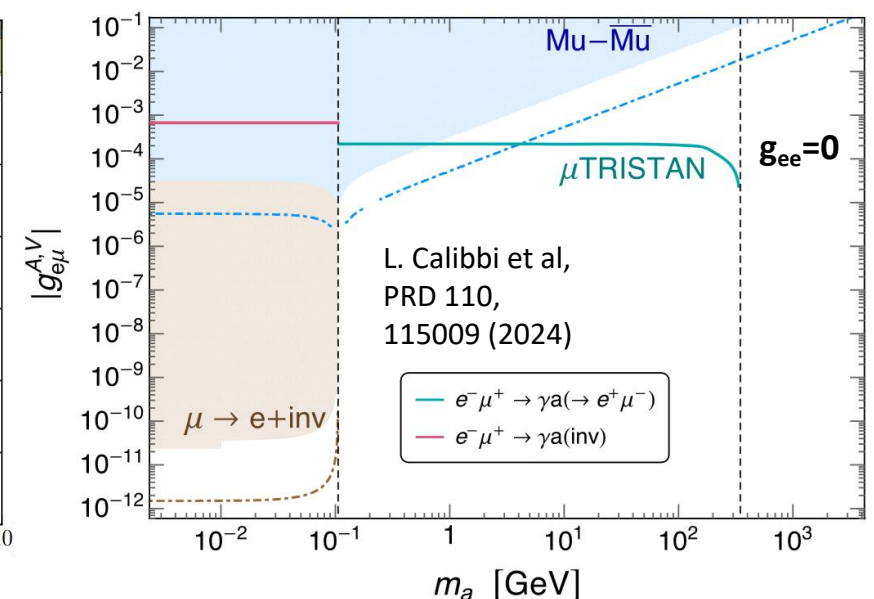
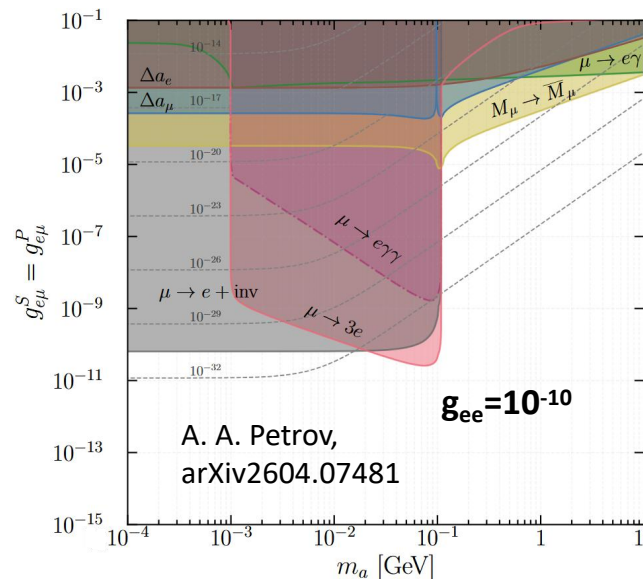
- Provide direct constrain to a set of
unique EFT operators;
- The only low-energy observable in
certain flavor structure.

➤ 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 $e\mu$ collider

MACE physics motivation

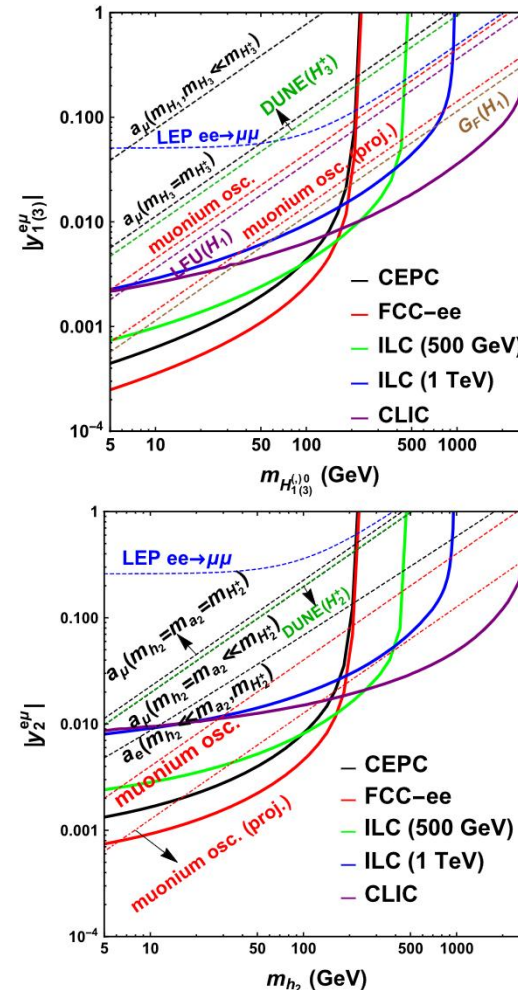
✓ Rich physics in muonium conversion.

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

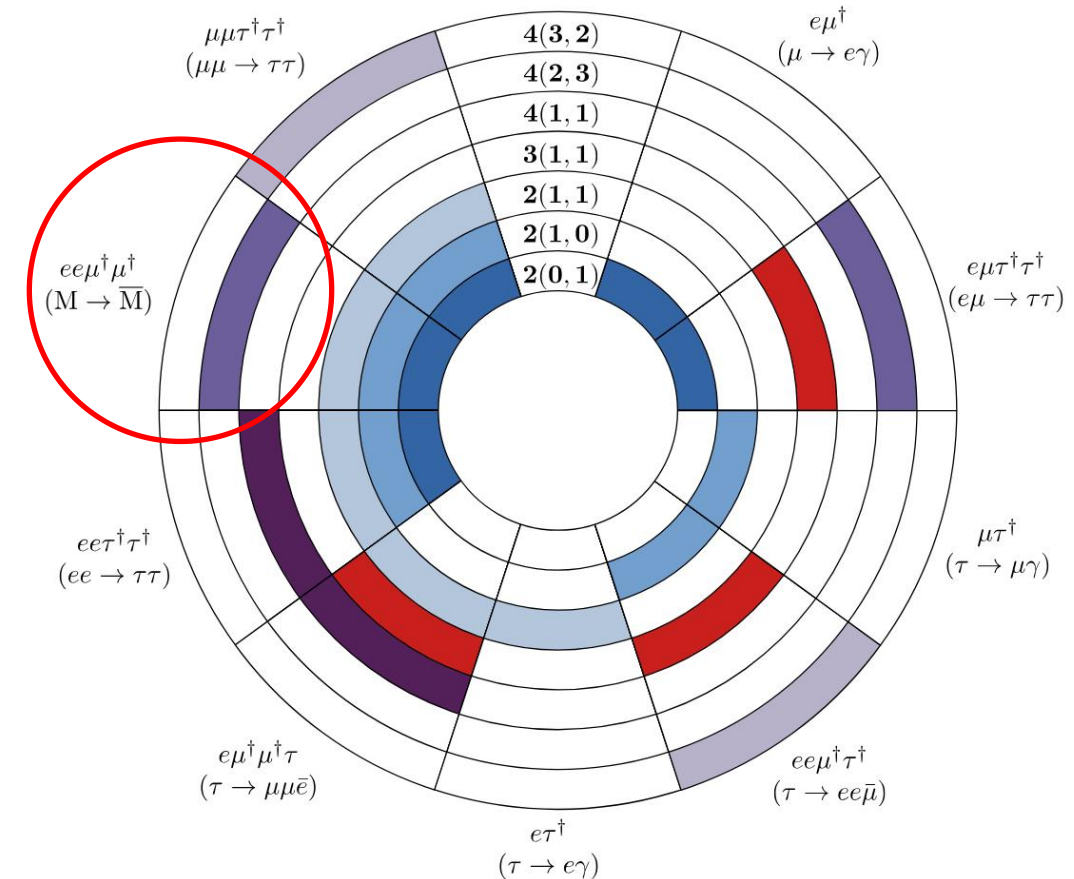
✓ Muonium conversion is unique.

- Provide direct constrain to a set of unique EFT operators;
- The only low-energy observable in certain flavor structure.

➤ **MACE is well-motivated and can complement other low-energy experiments and future colliders.**



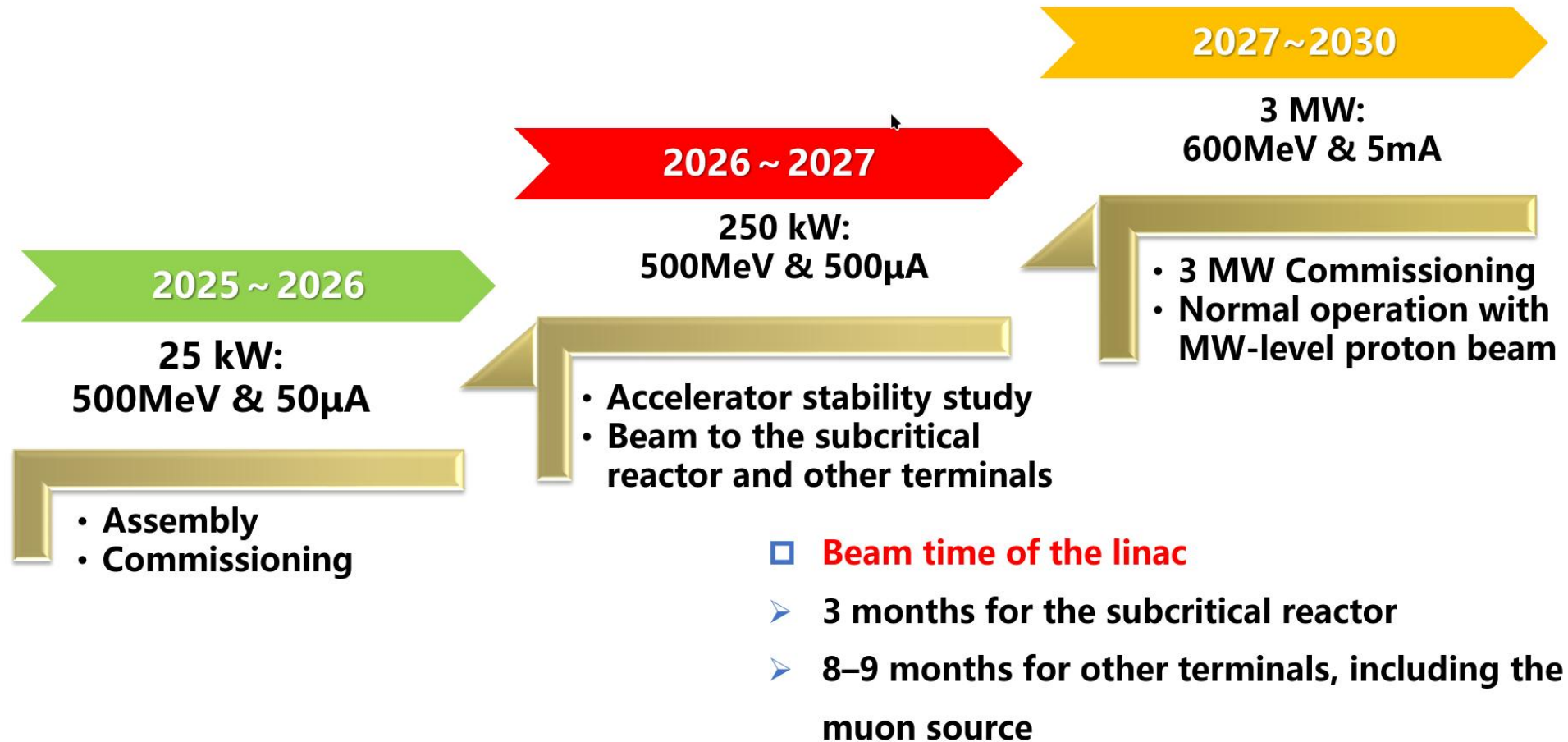
MACE can probe bileptons
comparable to future colliders
(T. Li and M. Schmidt, PRD 100, 115007 (2019))



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



Timetable of the Linac





Layout and Plan of MuST-CiADS

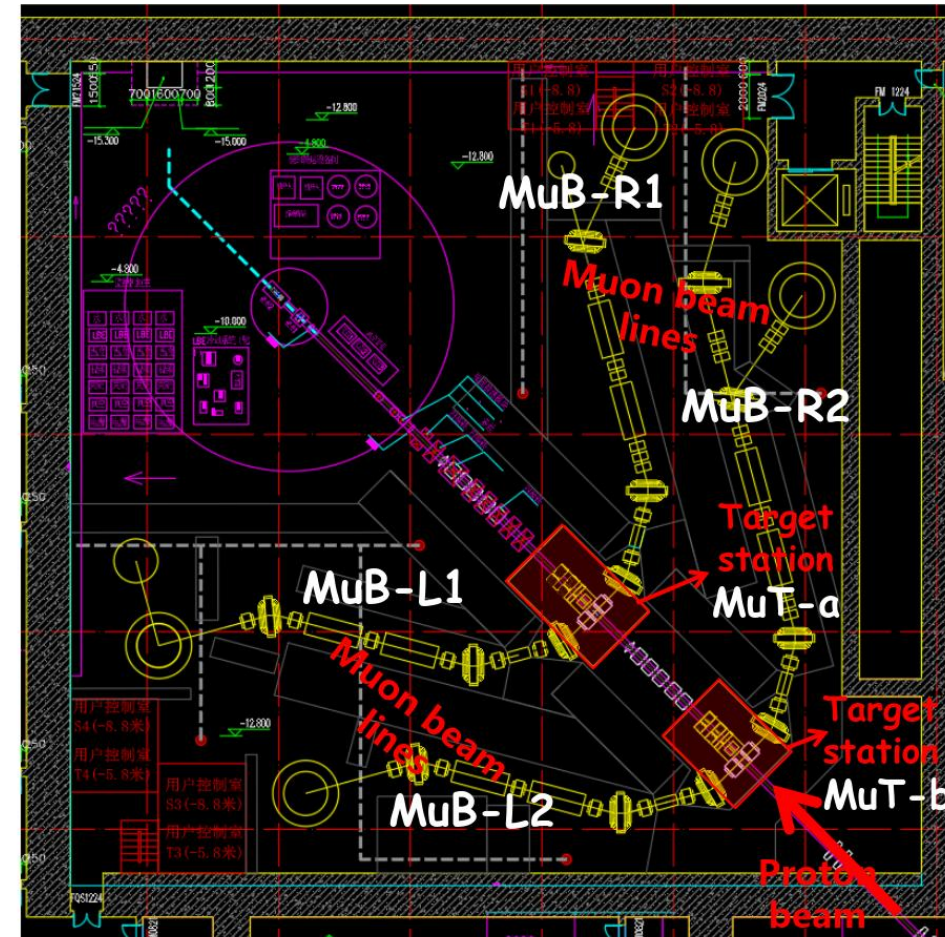


□ Conceptual Layout:

- 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 $10^7/s \sim 10^{10}/s$

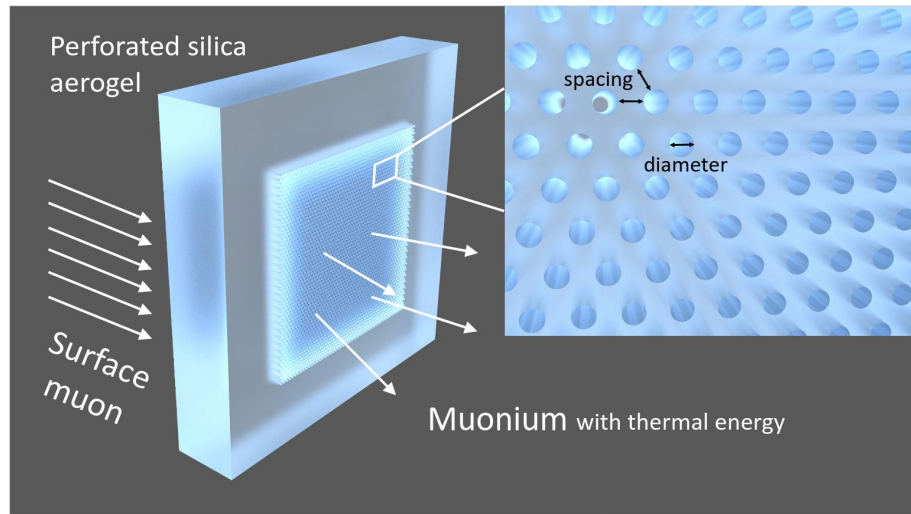
□ Plan with two phases:

Phase	Target	Muon beamlines	Applications
Phase I 2025~2029	Tgt a (MuT-a)	$\Phi 300$ up to $10^8 \mu/s$ @0.5mA	R1: $\sim 30 \text{ MeV/c}$ $\mu\text{SR/MACE}$
			L1: to 90 MeV/c MIXE/ μCF
Phase II 2029~2032	Tgt b (MuT-b)	$\Phi 500$ up to $10^{10} \mu/s$ @5mA	R2: to 90 MeV/c $\mu\text{SR/MACE}$
			L2: to 120 MeV/c Muography/MI XE



Muonium production target

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

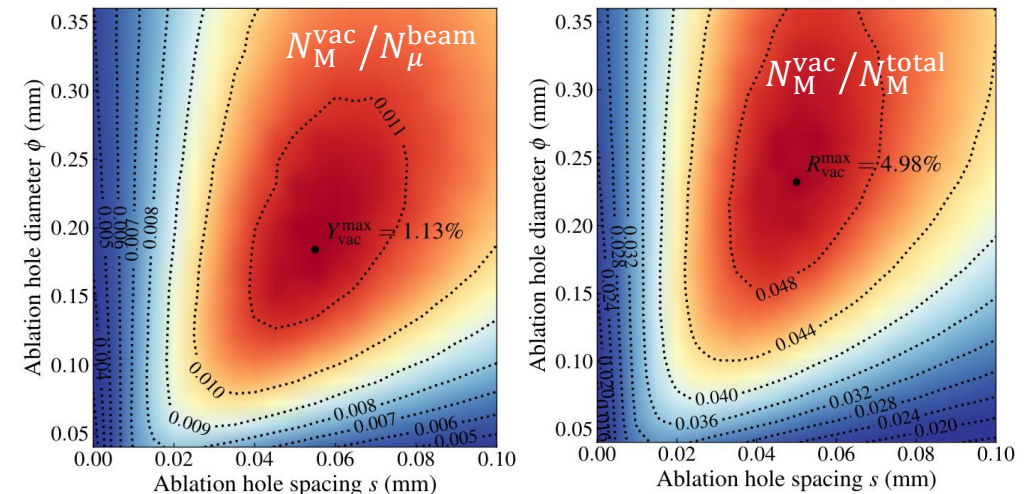


Zhao, Shihan, and Jian Tang. "Optimization of muonium yield in perforated silica aerogel." *Physical Review D* 109.7 (2024): 072012.

- The simulation is validated by muonium yield data measured in TRIUMF. J. Beare et al., PTEP. 2020, 123C01 (2020)
- Optimize $Y_{\mu \rightarrow M}$ in perforated bulk target by scanning parameters, it can achieve
 - ✓ Max $Y_{\mu \rightarrow M} = N_M^{\text{vac}} / N_{\mu}^{\text{total}} = 1.134\%$, with 2mm hole

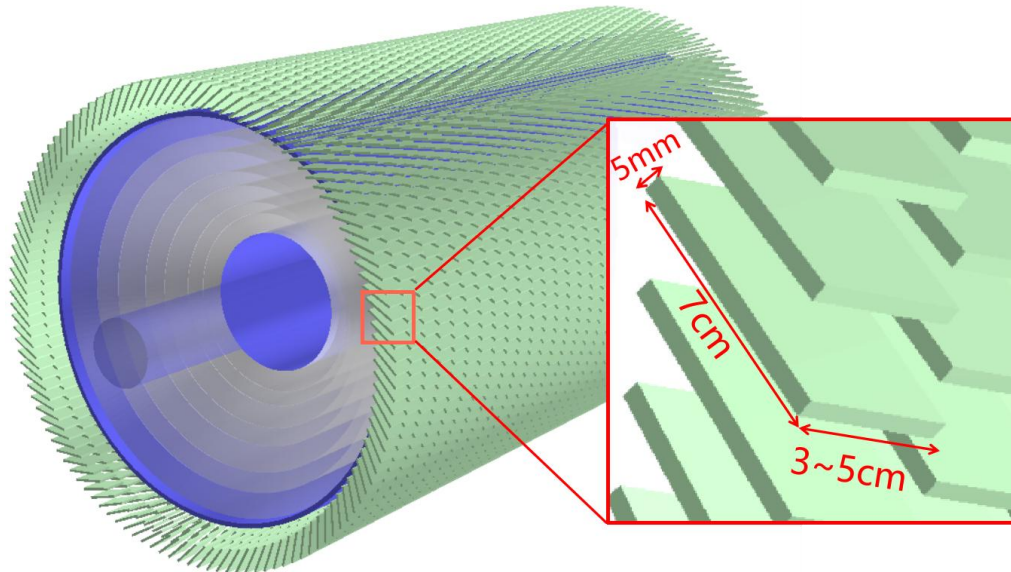
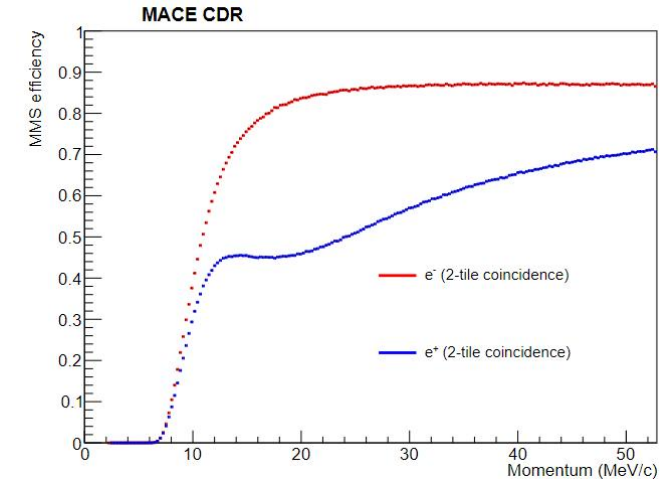
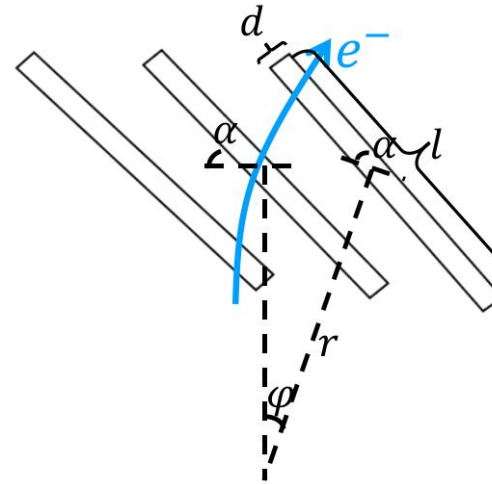
depth, $p_{\text{beam}} = 28 \text{ MeV}/c$ and $\frac{\sigma_{p_{\text{beam}}}}{p_{\text{beam}}} = 2.5\%$.

2 times larger than the yield in 1999



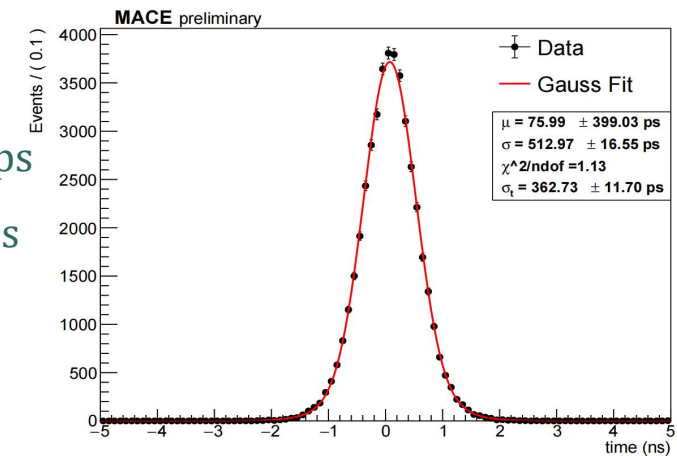
Tiled timing counter (TTC)

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



Test with cosmic-ray muons:

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



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

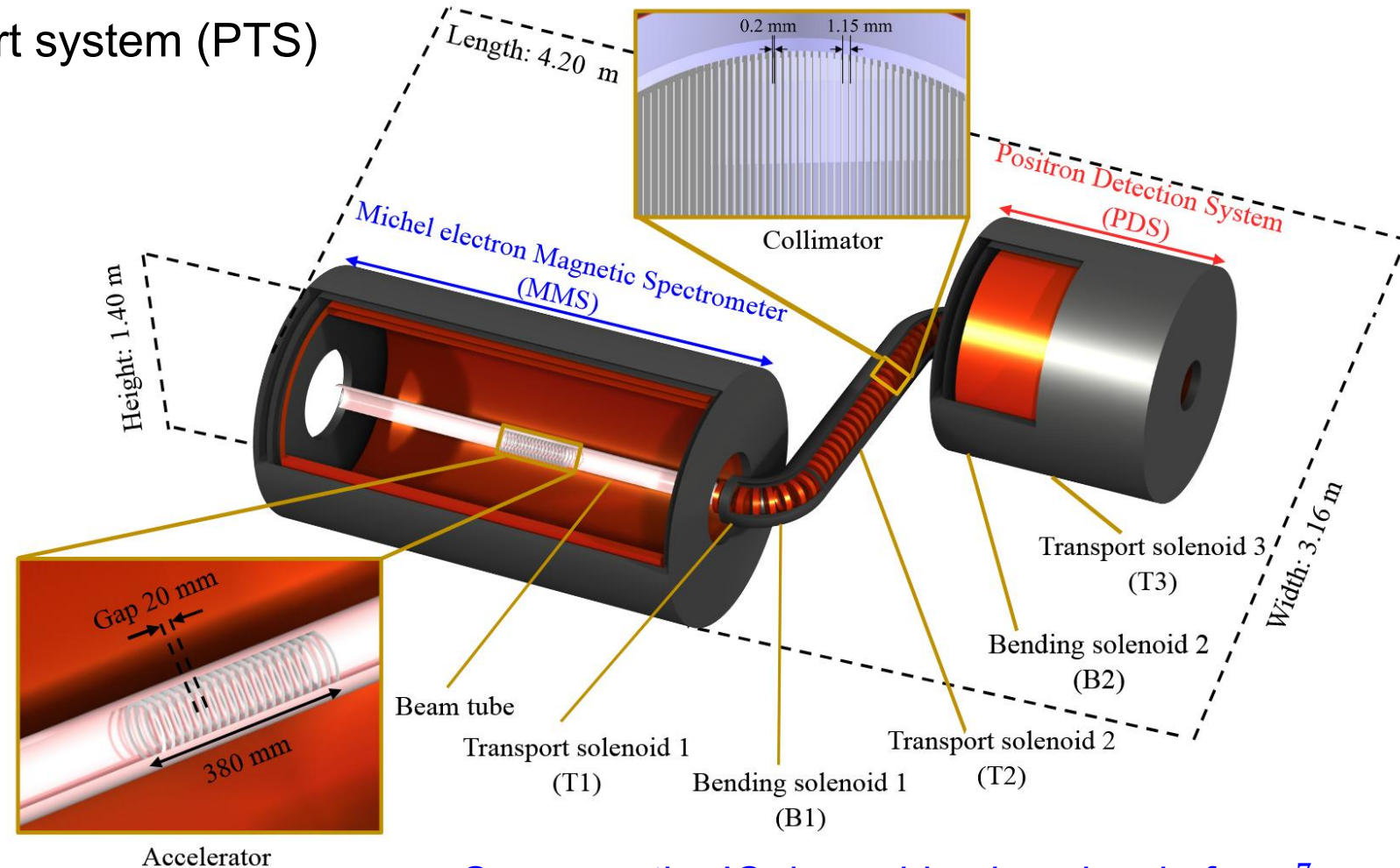
- PTS performance

- I. Transmission efficiency: 65.8%.

- II. Flight time: 322 ns.

- III. Flight time FWHM: 6.9 ns.

- IV. Spatial resolution: $0.088 \text{ mm} \times 0.102 \text{ mm}$



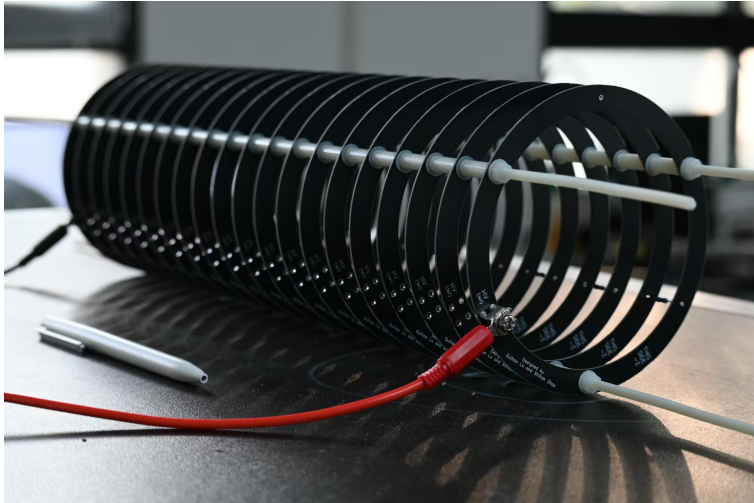
Suppress the IC decay bkg. by a level of 10^{-7}

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

PTS prototyping progress

- **PTS validation**

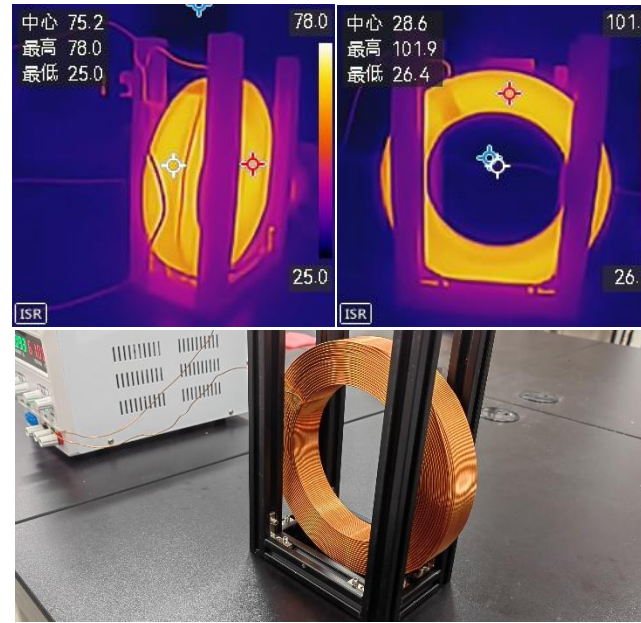
Testing with TS solenoids and accelerator module



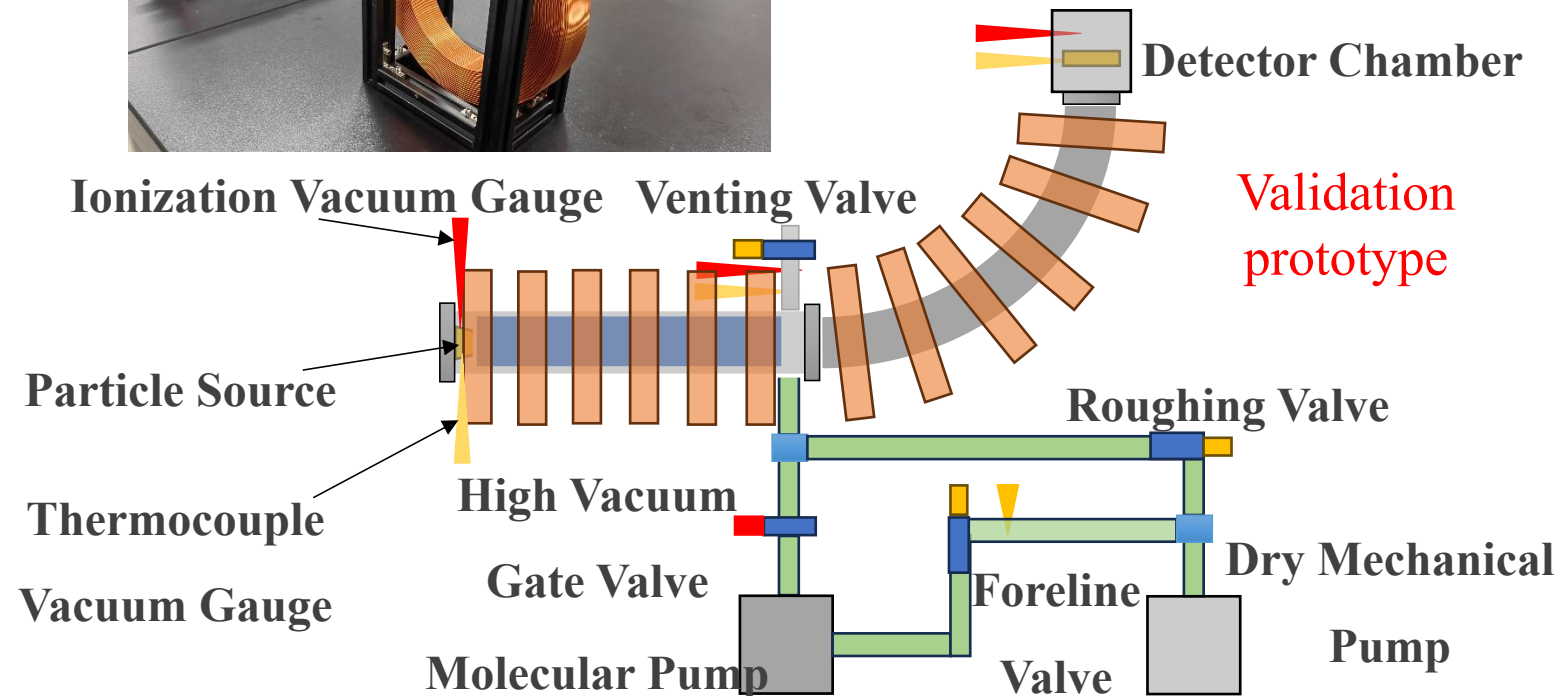
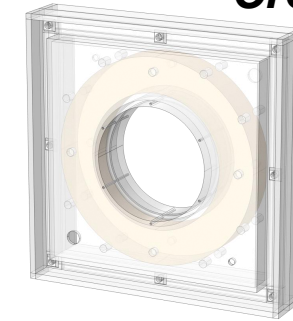
- **Accelerator module prototype**

Multi-layer PCB

High voltage > 2 kV



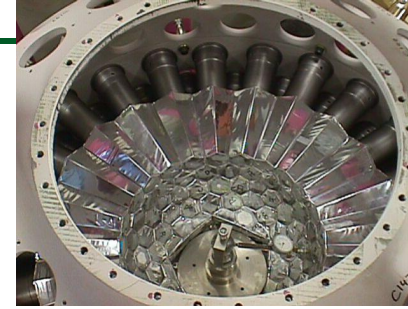
Credit: Guihao Lu



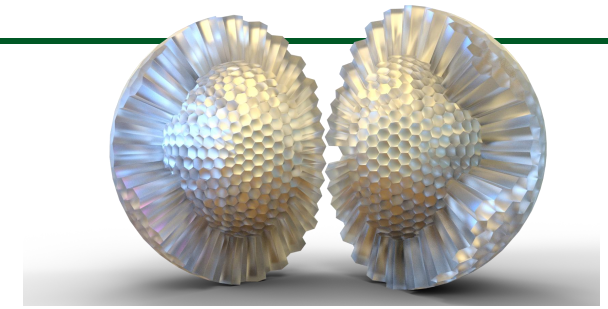
Electromagnetic Calorimeter

Design scheme:

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



PEN detector
pCsl + PMT



MACE ECAL
pCsl + SiPM

LYSO

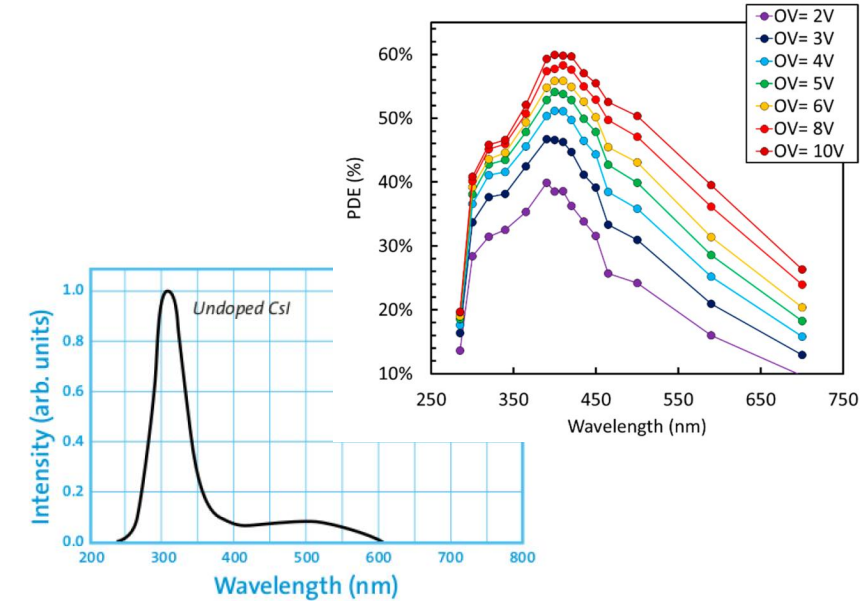
- 30000 ph/MeV
- **40 ns**
- Radiation hard
- Not hygroscopic
- Emits at 420 nm
- CNY ¥ 300/cm³

BGO

- 8000 ph/MeV
- 300 ns
- Not hygroscopic
- Emits at 480 nm
- CNY ¥ 100/cm³

Pure Csl ✓ Baseline design

- 3500 ph/MeV
- **40 ns**
- Slight hygroscopic
- Emits at 310 nm
- Adopted by **Mu2e** and **PIBETA**
- **CNY ¥ 30/cm³**



NUV SiPM readout

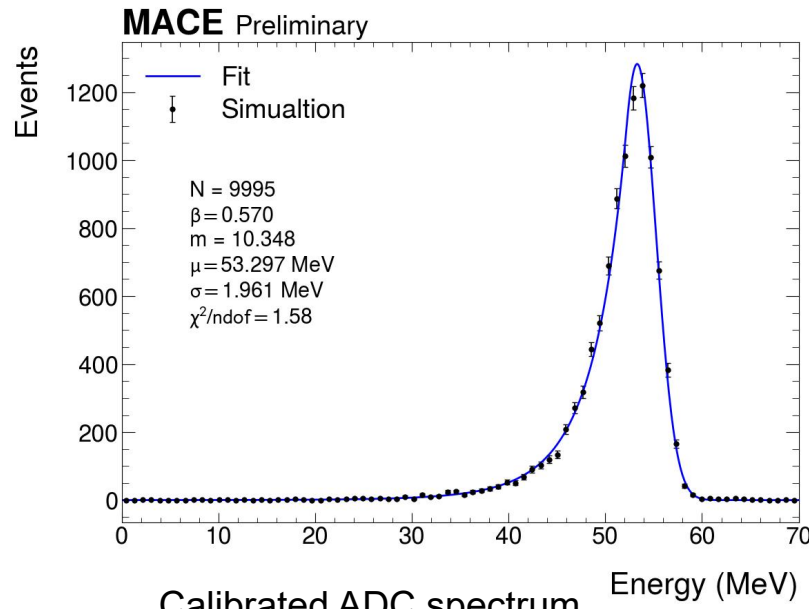
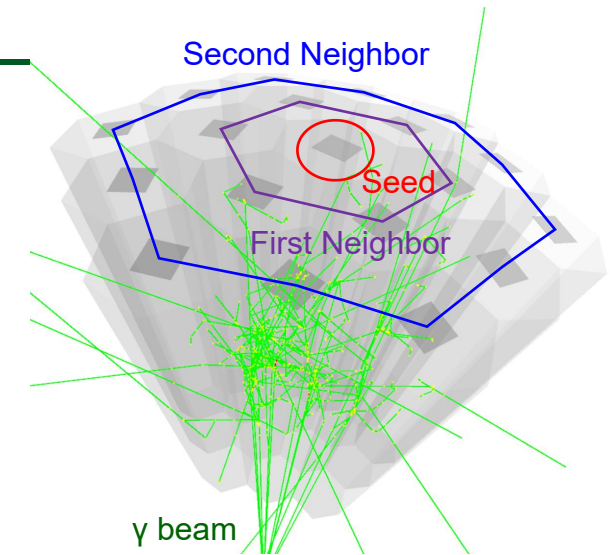
Sensors 19 (2019) 2, 308

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°**

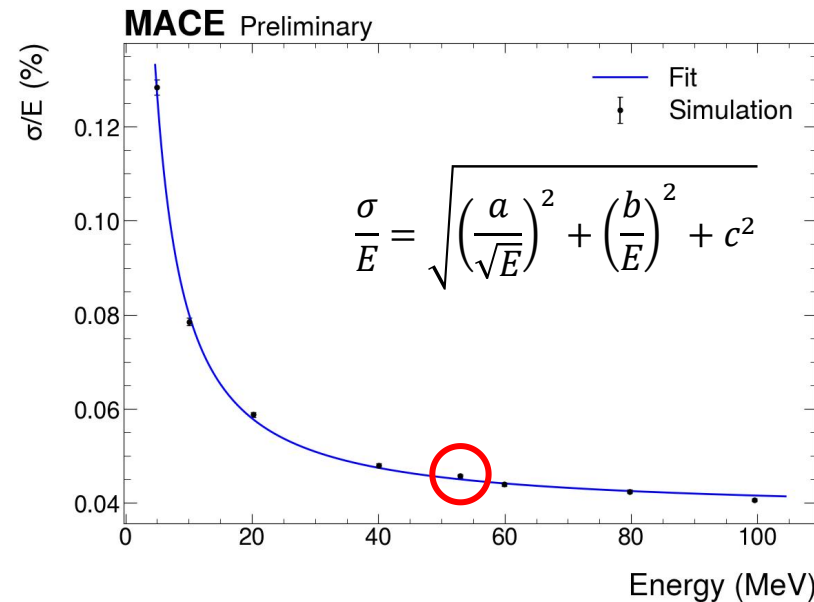
Energy-weighted clustering

Credit: Siyuan Chen



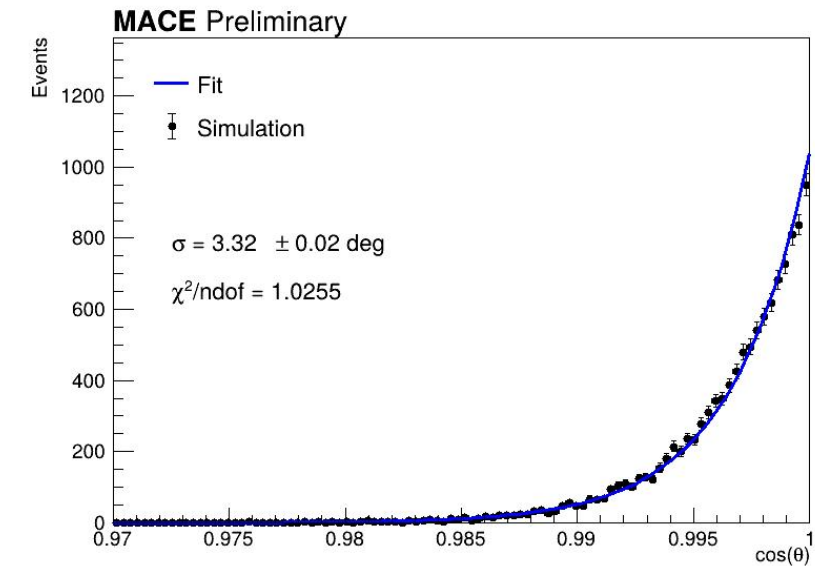
Calibrated ADC spectrum
fitted by Crystal Ball function

O(50) p.e. electronic noise considered



Energy resolution

1.5% nonlinear correction considered



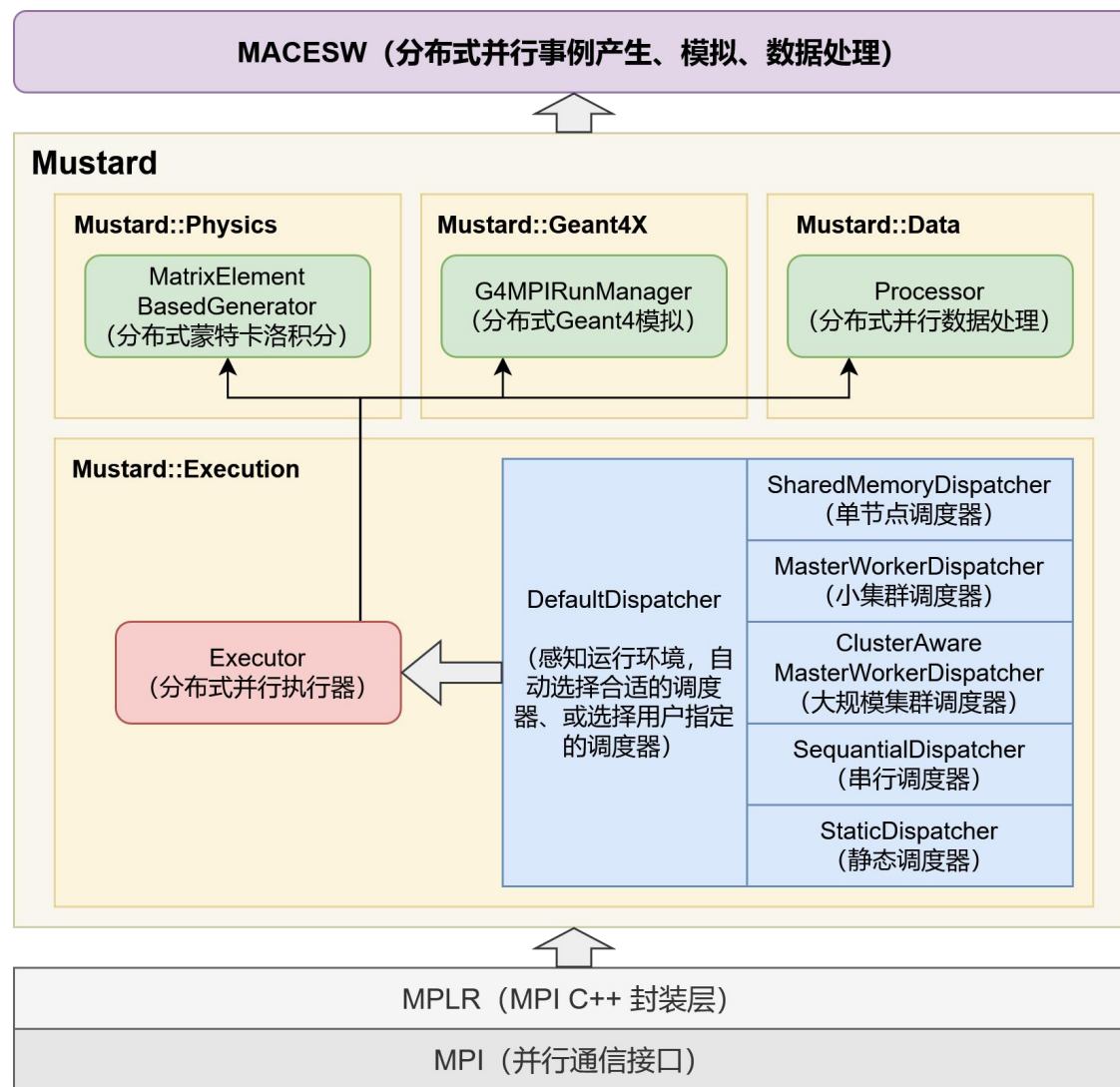
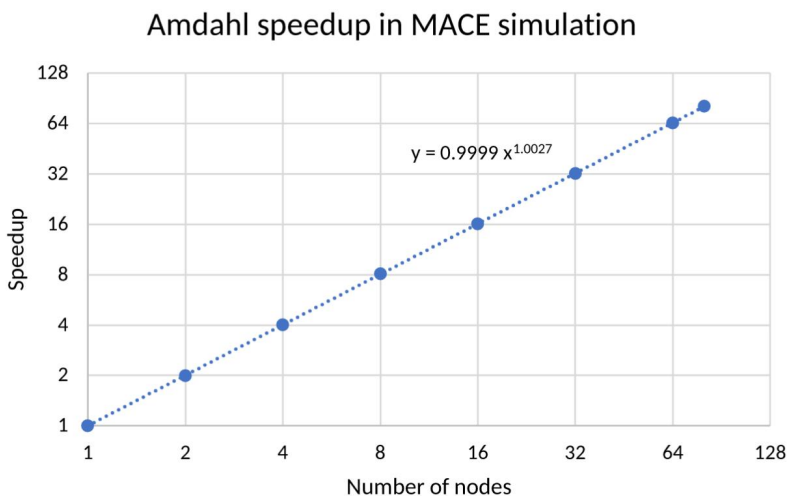
Angular resolution

Events isotopically emitted from the target

并行计算架构研发进展

◆ 分布式并行计算框架

- Mustard 原生支持**基于 MPI 的分布式并行计算**，基于 Mustard 开发的软件可在超级计算机（HPC）或高通量计算机（HTC）上开展大规模并行计算。
- 基于统一的执行器架构实现并行事例生成、模拟和数据处理。
- 框架可感知运行情况和环境，**自动优化并行效率**。
- 设计为最大化计算与通信的重叠，可获得最优并行效率。
- 先前在“天河二号”超算上开展了千核规模加速比测试，实现了**线性加速比**，可满足目前需求，且远未触及性能边界。
- 后续可在新一代超算上开展万核规模的测试。



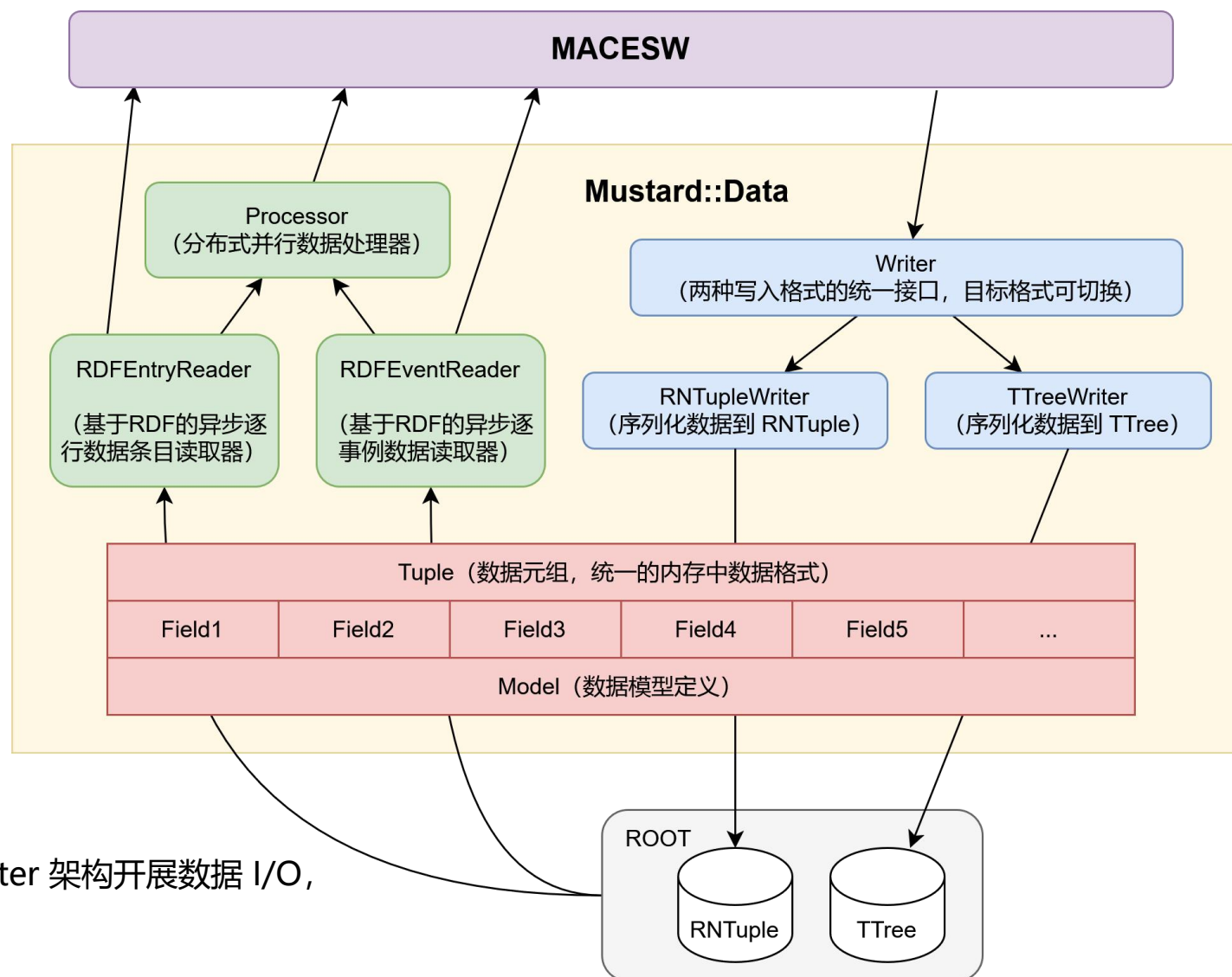
数据 I/O 与管理框架研发进展

◆ 数据模型框架

- 已在 Mustard 中实现了统一的数据模型定义和管理框架。
- 除提供一部分预定义模型外，可根据实验需求定义所需的模拟。
- 数据模型采用**展平结构**以提高兼容性和改善 I/O 性能。该架构下产生的数据**不依赖于字典**，可在外部开展独立分析，有利于开放数据的使用。

◆ 数据 I/O 框架

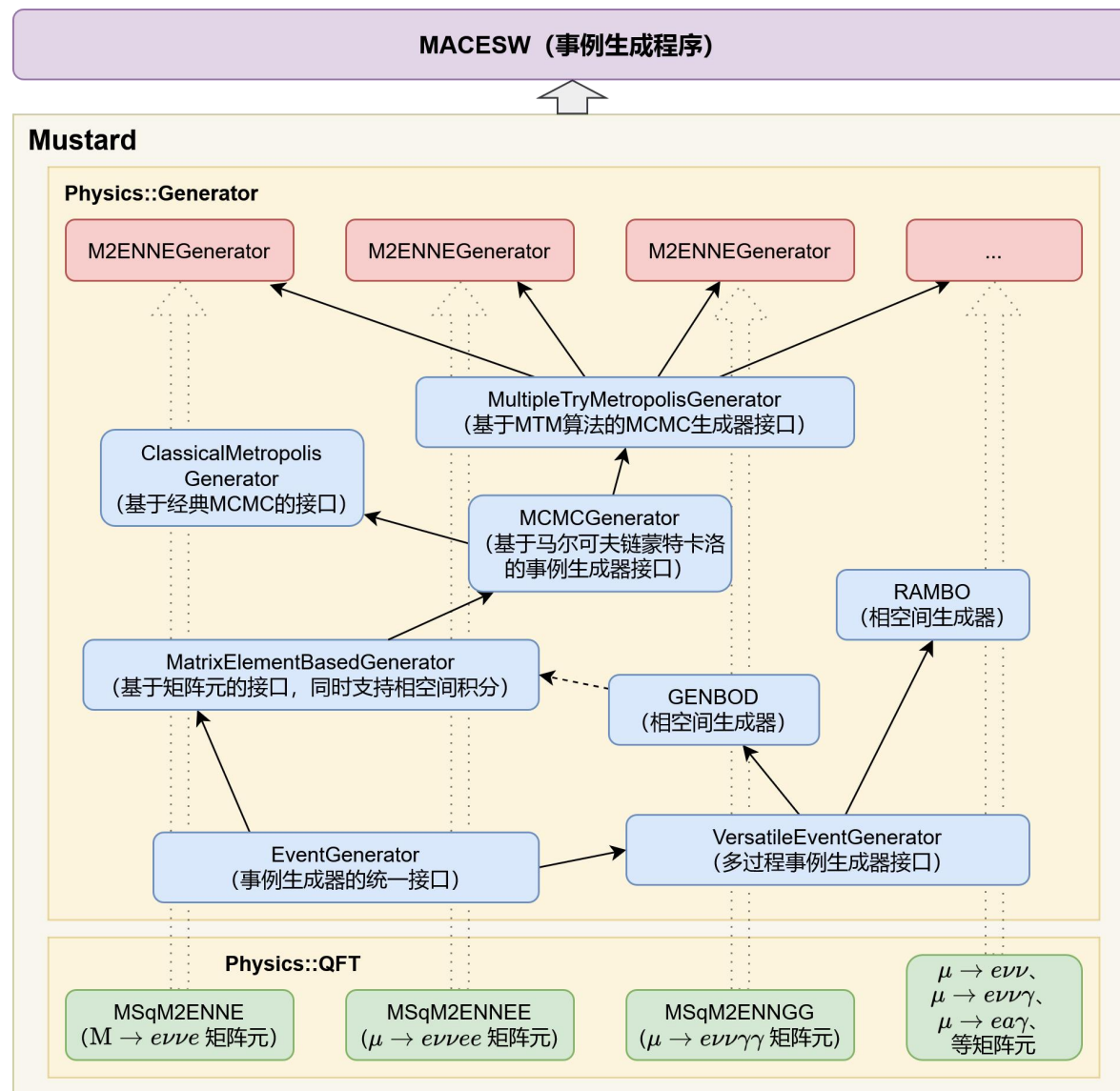
- Mustard 原生支持为 HL-LHC 升级而开发的 RNTuple（接替 TTree 作为新一代数据格式）。**数据大小减小~30%，读取速度提升~50%。**
- Mustard 基于一套统一的 Reader / Writer 架构开展数据 I/O，后端数据格式可无缝切换，保障兼容性。



事例生成框架研发进展

◆ 事例生成框架

- Mustard 提供一套易用的事例生成框架，用于计算相空间积分和生成树图阶事例。
- 针对新物理实验对**高效抽样稀有事例**的需求，设计为**可自由施加重要性抽样分布**并可快速采样稀有事例，**可高效生成非加权事例**。
- 为满足该设计，底层使用马尔科夫链蒙特卡洛 (MCMC) 实现，基于迭代式相空间生成器和多次尝试 Metropolis 算法采样。
- 实现了**全同粒子对称化提议分布**，解决了 MCMC 导致末态全同粒子分布不一致的问题。
- 为克服 MCMC 固有的样本自相关问题，实现了对**样本自相关时间的计算**以及一套**自适应去关联算法**，从而获取近独立样本。
- 框架中已提供几种缪子衰变过程。接口定义友好，只要计算出矩阵元即可新增新的过程。



Continuous Integration

● Challenges in Parallel Development

- ❑ Merge conflicts
- ❑ Tedious code review
- ❑ Hidden risks

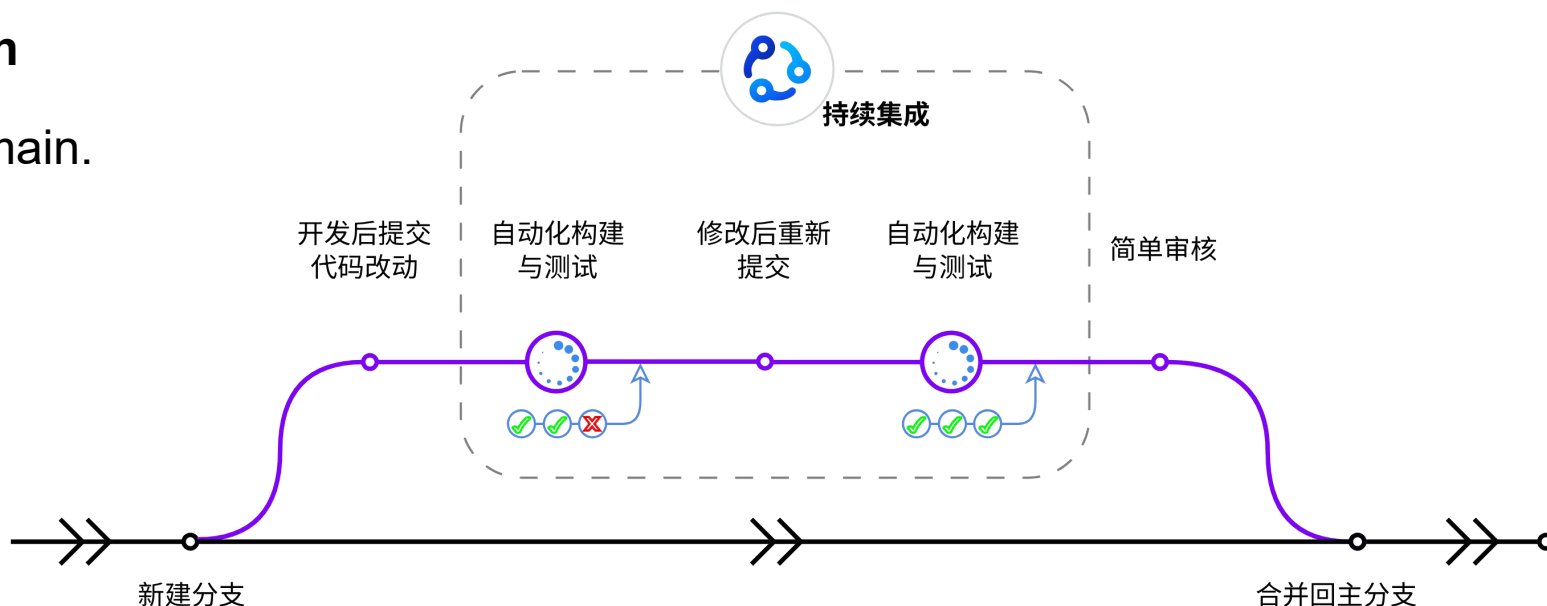
● Practice of Continuous Integration

- Frequently integrate code into main.
- Automated builds and tests.

● CI/CD

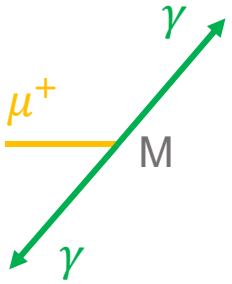
- Configure pipeline via config file.
- Runners execute automated test scripts.
- Regression tests.

Credit: Zhichao Wang



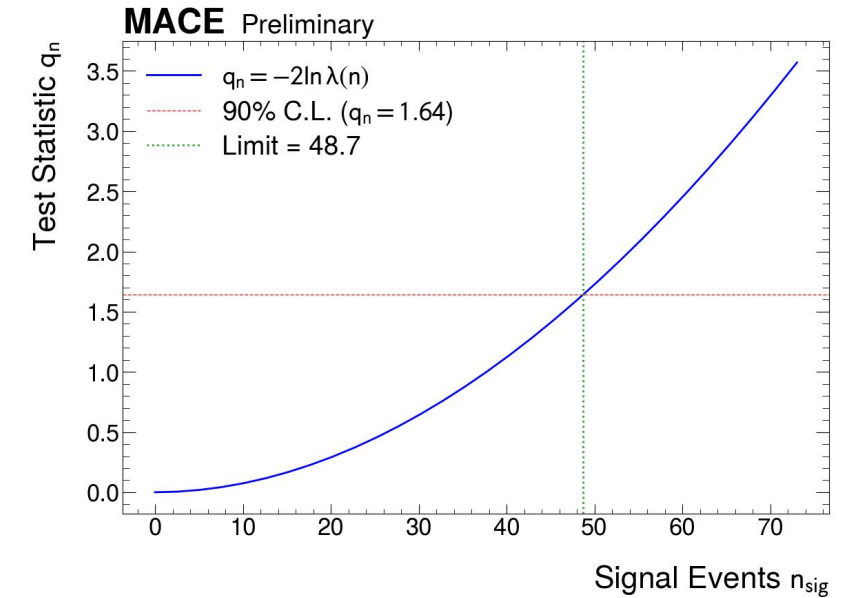
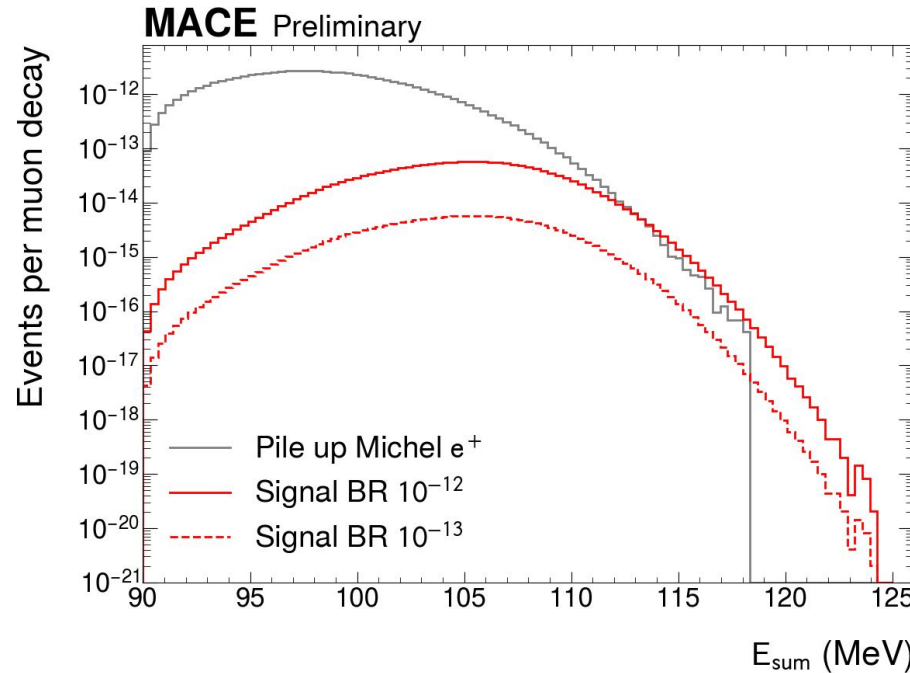
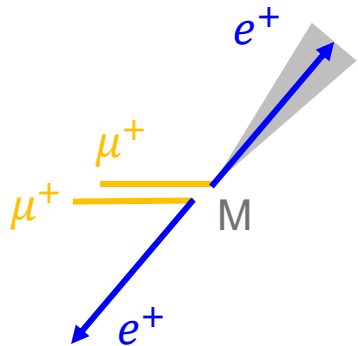
MACE Phase-I sensitivity to $M \rightarrow \gamma\gamma$

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.)

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

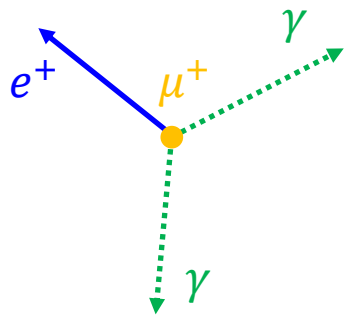
MACE Phase-I sensitivity to $\mu^+ \rightarrow e^+ \gamma \gamma$

Event selection criteria:

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

Signal:

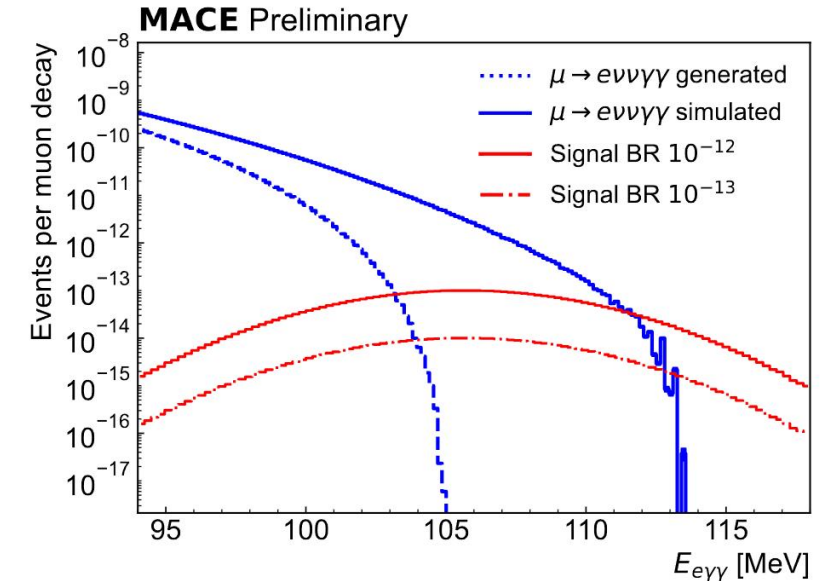
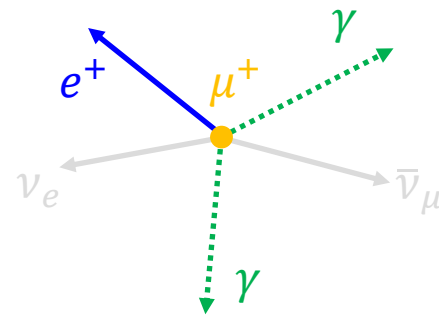
Triple coplanar tracks
 e^+ and two γ s



Background:

Double radiative muon decay

SciPost Phys. 9, 027 (2020)



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

$$n_{obs} = b$$

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

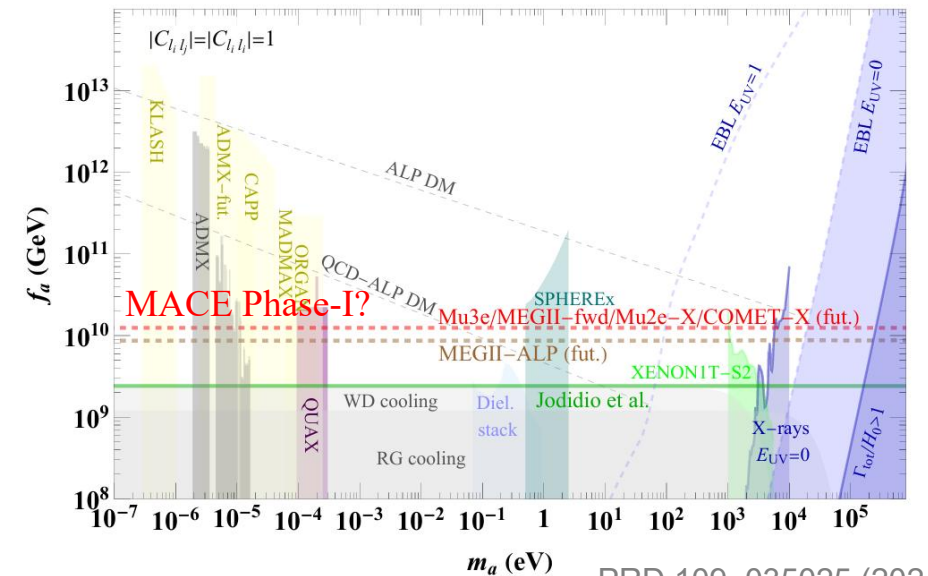
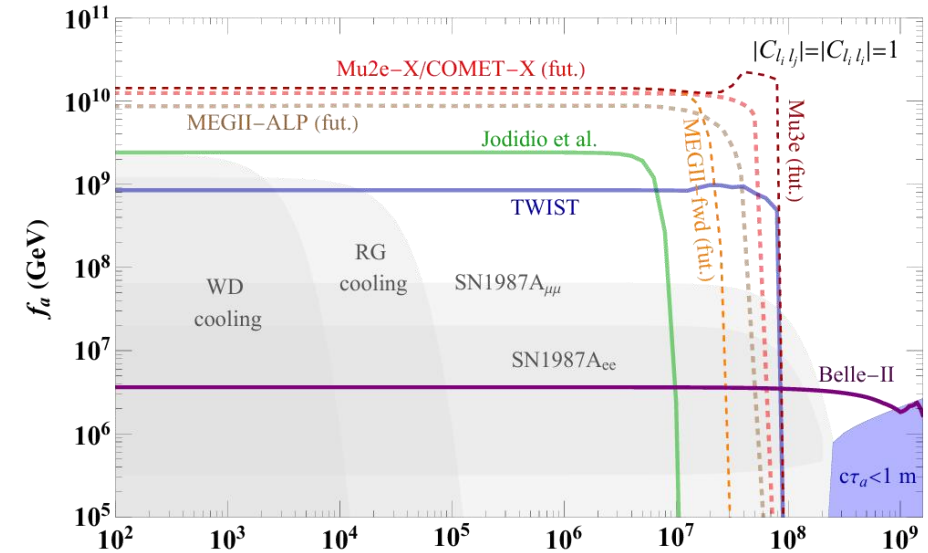
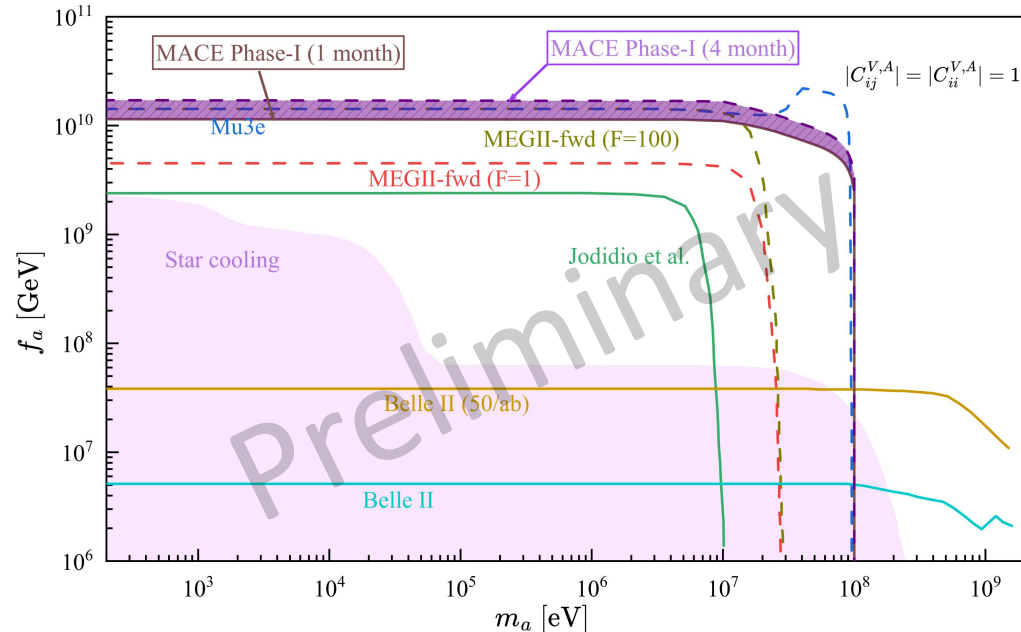
Upper limit of BR: 3.5×10^{-13} (90% C.L.)

More solid simulations and refined data analyses to be updated!

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

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

- 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)