正反缪子素转化实验MACE及其新物理探究

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第十八届粒子物理、核物理和宇宙学交叉学科前沿问题研讨会

April 10th-14th, 2026

References: https://www.smooth-sysu.cn/

① Design of a CsI(Tl) calorimeter for muonium-to-antimuonium conversion experiment, e-Print: 2408.17114, **Frontier of Physics** 20 (2025) 035202.

② Conceptual Design of the Muonium-to-Antimuonium Conversion Experiment (MACE), 2410.18817, **Nucl. Sci. Tech.** 37 (2026) 4, 57. Selected as **Cover Paper**.

③ Development of portable cosmic-ray muon detector array for muography, e-Print: 2503.18800 **Journal of Applied Physics** 138, 074502 (2025) .

④ High-Precision Physics Experiments at Huizhou Large-Scale Scientific Facilities, e-Print: 2504.21050, **Chinese Physics Letter** 42 (2025) 11, 110102.

⑤ MuGrid-v2: A novel scintillator detector for multidisciplinary applications, e-Print: 2505.19777, **Journal of Applied Physics** 138, 024501 (2025).

⑥ Positron Transport System for Muonium-to-Antimuonium Conversion Experiment, e-Print: 2508.07922, **Phys. Rev. Accel. Beams** 29 (2026) 3, 031602.

⑦ Muon beams towards muonium physics: progress and prospects, e-Print: 2601.15818. Review to be submitted to **Progress in Particle and Nuclear Physics**.

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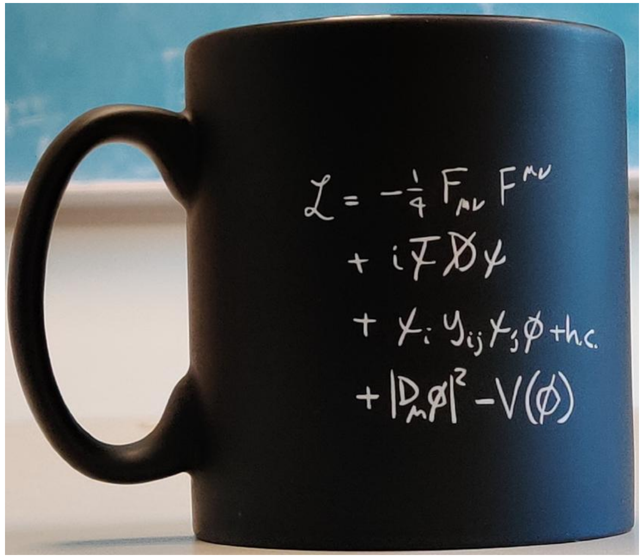
Physics beyond SM in lepton sector?

- Standard Model (SM) gauge symmetry:

$$\mathcal{G}_{\rm SM} = \underbrace{{\rm SU}(3)_{\rm C}}_{\text{QCD}} \times \underbrace{{\rm SU}(2)_{\rm L} \times {\rm U}(1)_Y}_{\text{Electroweak}}$$



- **Neutrino is massless in SM, lepton flavor is conserved,**

$$\mathcal{G}_{\rm SM}^{\rm global} = \underbrace{{\rm U}(1)_B}_{\text{Baryon number conservation}} \times \underbrace{{\rm U}(1)_{L_e} \times {\rm U}(1)_{L_\mu} \times {\rm U}(1)_{L_\tau}}_{\textbf{Lepton flavor conservation}}$$

- Neutrino oscillation → neutrino mass; charged lepton flavor violation (cLFV) is strongly suppressed in SM with Dirac neutrino.

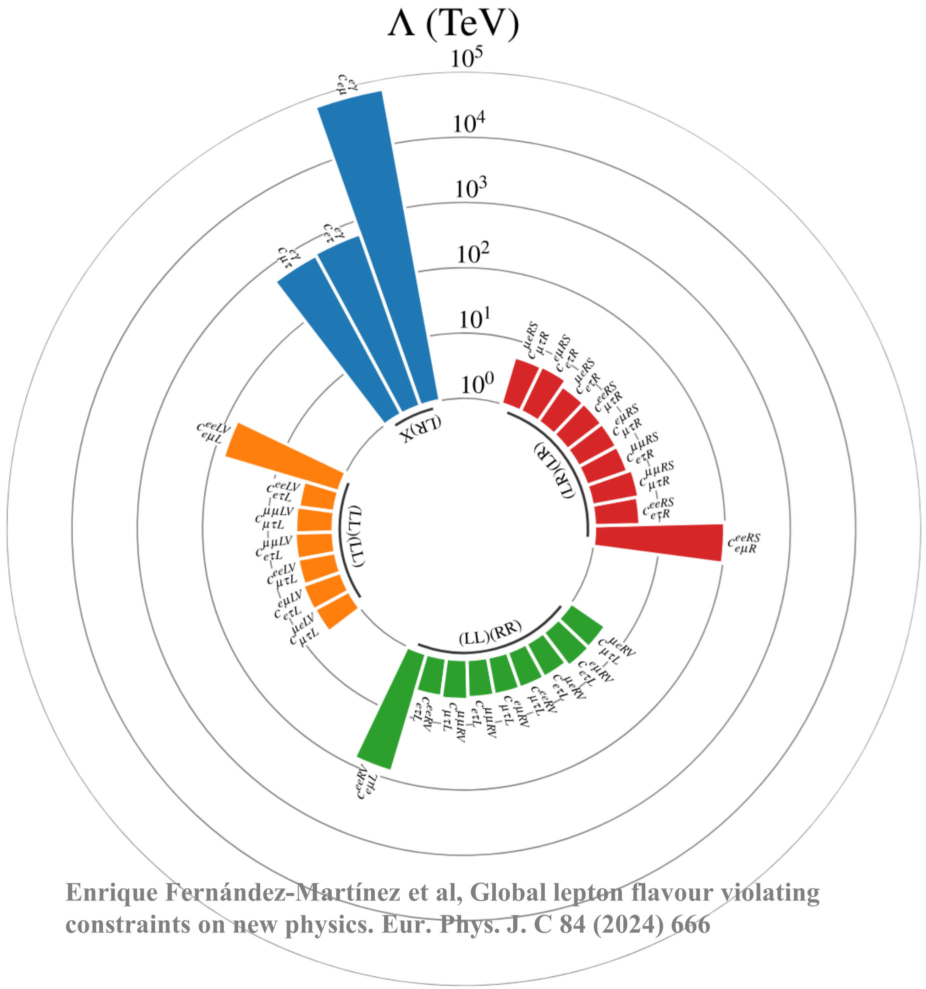
	e^- ν_e	μ^- ν_e	τ^- ν_e	e^+ $\bar{\nu}_e$	μ^+ $\bar{\nu}_e$	τ^+ $\bar{\nu}_e$
L_e	+1	0	0	-1	0	0
L_μ	0	+1	0	0	-1	0
L_τ	0	0	+1	0	0	-1

- **An excellent window to test SM and search for new physics.**

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 muon cLFV:**
  - **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, $U(1)_{B\text{-}L}$.



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

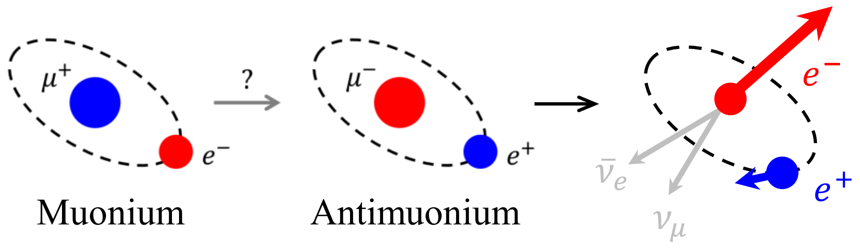
Significant cLFV signals → clear evidence for new physics;

Insignificant result → strong limit on new physics models.

Muonium conversion

Muonium ($\mathrm{M} = \mu^+ e^-$): a leptonic isotope of hydrogen

- 1957, *B. Pontecorvo* first suggested $\mathrm{M} \to \overline{\mathrm{M}}$ process.
- 1960, *V.W. Hughes* et al. first observed the muonium directly.
- 1961, *G. Feinberg* and *S. Weinberg* published a research on $\mathrm{M} \to \overline{\mathrm{M}}$.



$\mathrm{M} \to \overline{\mathrm{M}}$ ($\mu^+ e^- \to \mu^- e^+$): an $\Delta L_\ell = 2$ process

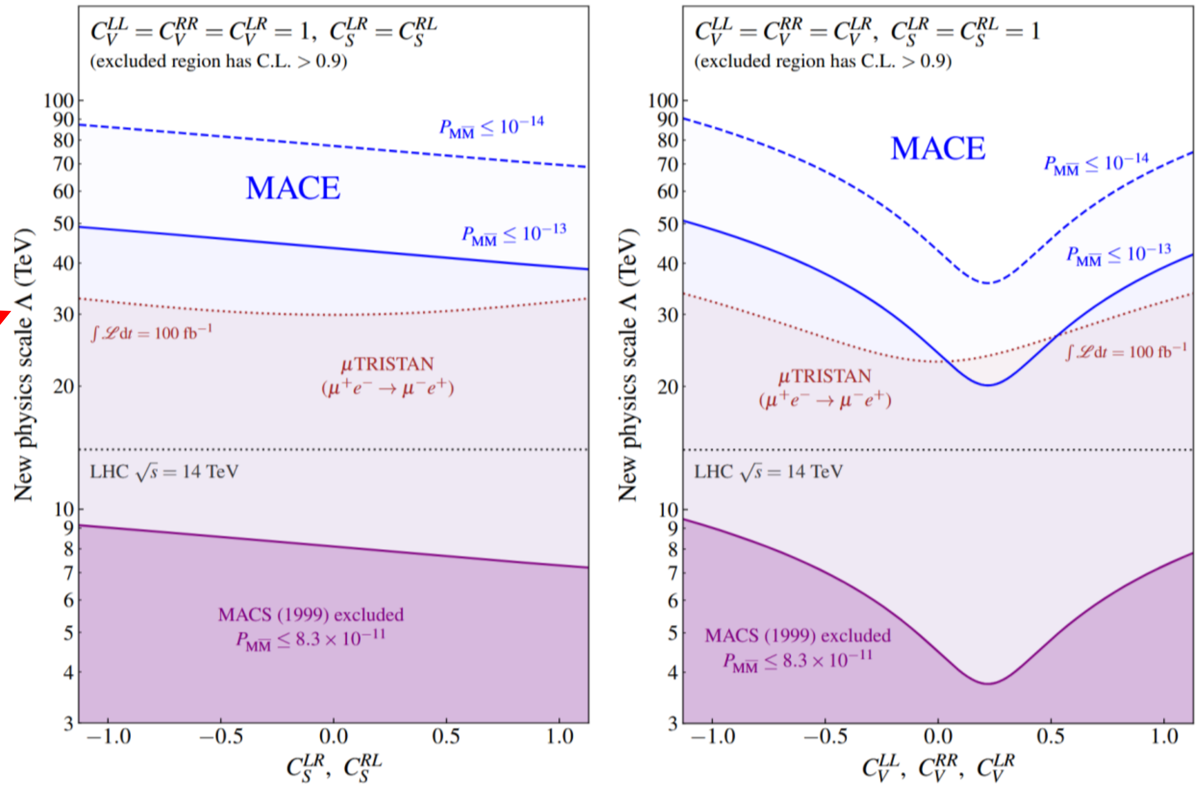
- ✓ Distinct from $\Delta L_\ell = 1$ processes ($\mu \to e\gamma$, $\mu \to eee$, $\mu N \to eN$)
- ✓ $\Delta L_\mu = -\Delta L_e = 2$ can be possible even if $\Delta L_\ell = 1$ is suppressed.
- ✓ Complementary to $\Delta L_\ell = 1$ process searches.

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

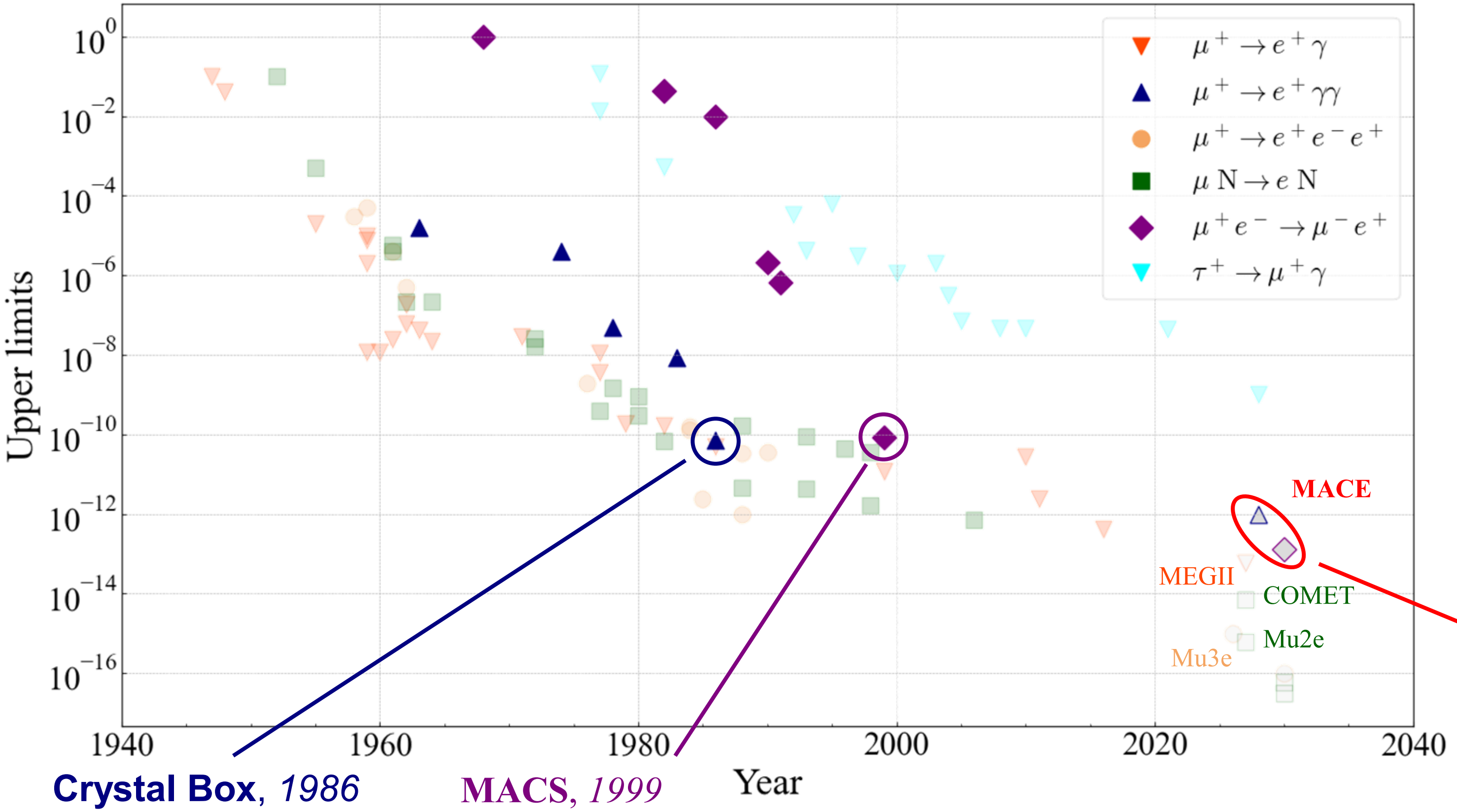
$$Q_V^{LL} = (\bar{\mu}_L \gamma_\alpha e_L)(\bar{\mu}_L \gamma^\alpha e_L),$$
$$Q_V^{RR} = (\bar{\mu}_R \gamma_\alpha e_R)(\bar{\mu}_R \gamma^\alpha e_R),$$
$$Q_V^{LR} = (\bar{\mu}_L \gamma_\alpha e_L)(\bar{\mu}_R \gamma^\alpha e_R),$$
$$Q_S^{LR} = (\bar{\mu}_L e_R)(\bar{\mu}_L e_R),$$
$$Q_S^{RL} = (\bar{\mu}_R e_L)(\bar{\mu}_R e_L).$$

Current bound (MACS):
$P_{\mathrm{M}\to\overline{\mathrm{M}}} < 8.3 \times 10^{-11}$
in 0.1T field, 90% C.L.

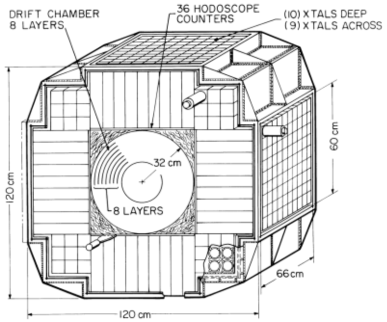
Phys. Rev. Lett. 82 (1999), 49-52.



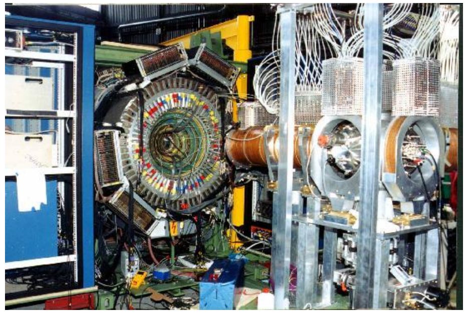
1940s till now: a cLFV odyssey



Crystal Box, *1986*
$\mathcal{BR} < 7.2 \times 10^{-11}$



MACS, *1999*
$P_{\mathrm{M}\to\overline{\mathrm{M}}} < 8.3 \times 10^{-11}$



Towards new muon cLFV experiments

- Construction of intense muon beamlines in China
- Development of particle detection technology

$\mathcal{O}(10^{-13})$ **sensitivity!**

MEGII (PSI) $\mu^+ \to e^+\gamma$

Mu3e (PSI) $\mu^+ \to e^+e^-e^+$

Mu2e (Fermilab) $\mu^-\mathrm{N} \to e^-\mathrm{N}$

COMET (J-PARC) $\mu^-\mathrm{N} \to e^-\mathrm{N}$

Muonium-to-Antimuonium Conversion Experiment

MACE (China)
$\mathrm{M} \to \overline{\mathrm{M}}$ $(\mu^+e^- \to \mu^-e^+)$

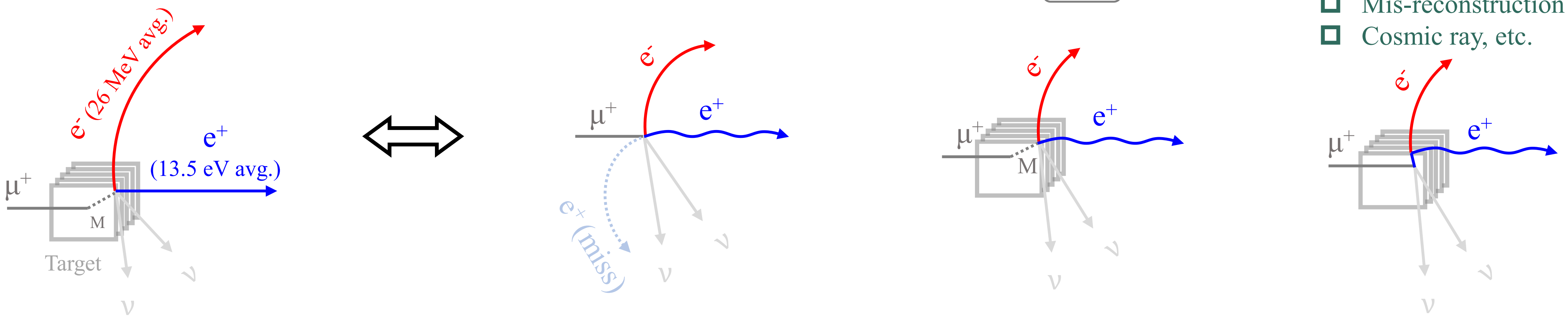
Signal and backgrounds

Signal:
fast e^- + slow e^+

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

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

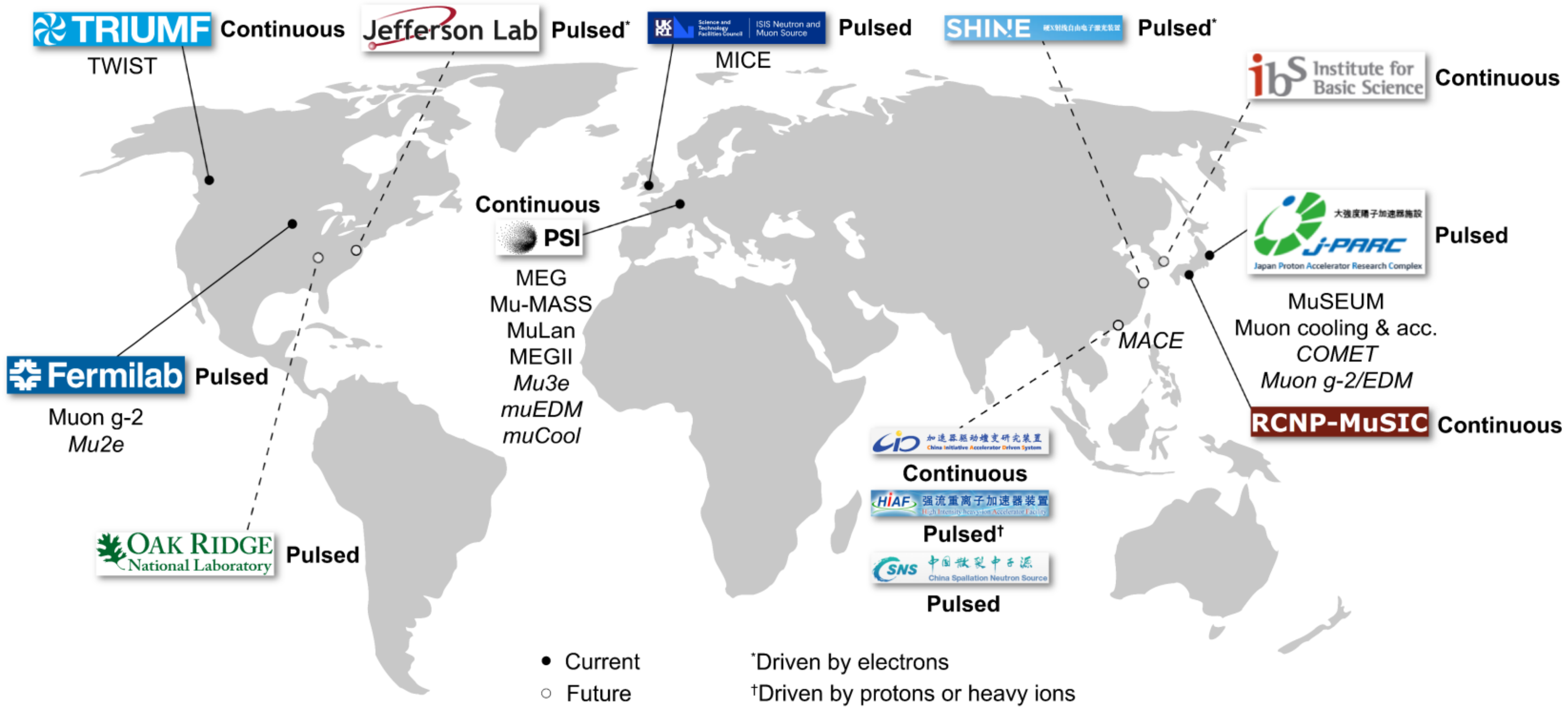
3. Accidental bkg.
- Scattering/conv. e⁻
- Mis-reconstruction
- Cosmic ray, etc.



- **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)**

- A "clean" data taking duration
  - Pulsed muon beam
- Excellent vertex resolution
  - e^+/e^- spatial resolution
  - Precise e^+ transport in EM field
- Excellent time resolution
  - e^+/e^- time resolution

Status of muon sources around the world

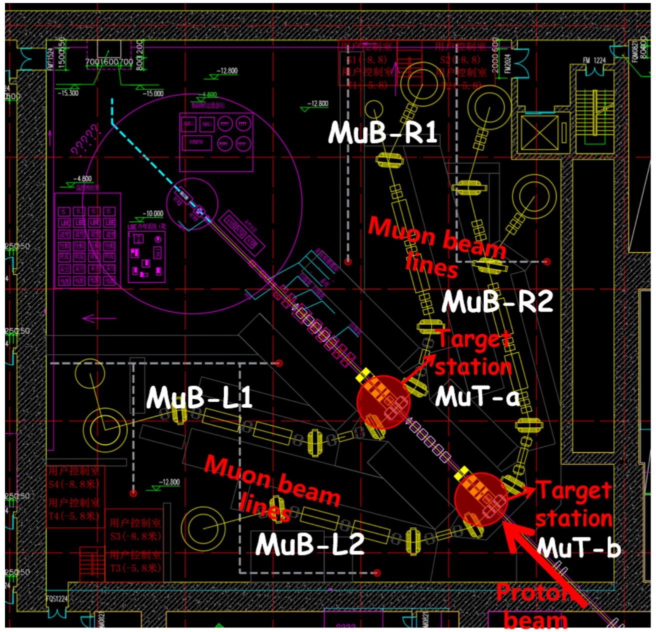


- Global facilities: PSI (Switzerland), J-PARC (Japan), ISIS (UK), TRIUMF (Canada), FNAL (USA).
- Various high-intensity muon sources in China, to be built soon: **CiADS/CSNS/HIAF/SHINE**.

Muon beamline of CiADS

- A surface muon beamline is under way at **China Initiative Accelerator Driven System** (CiADS)
- Exploring cutting-edge research with high muon flux?

Credit: Han-Jie Cai



Beam power	Target	Target	Intensity（s^{-1}）	Spin pol.	background
300 kW	Graphite	Full-solenoid	**$> 5 \times 10^{8}$**	~94%	<0.1%
		Mixing	$> 5 \times 10^{7}$	>99%	
3 MW	Lithium jet	Full-solenoid	**$> 1 \times 10^{10}$**	~94%	
		Mixing	$> 1 \times 10^{9}$	>99%	

H. -J Cai et al. PRAB 27 (2024) 2, 023403

2025～2026

25 kW: 500MeV & 50μA

- Accelerator construction
- Proton beam commissioning

2026～2027

250 kW: 500MeV & 500μA

- Beam stability test
- Muon beam commissioning
- One target station, two beamlines

2027~2030

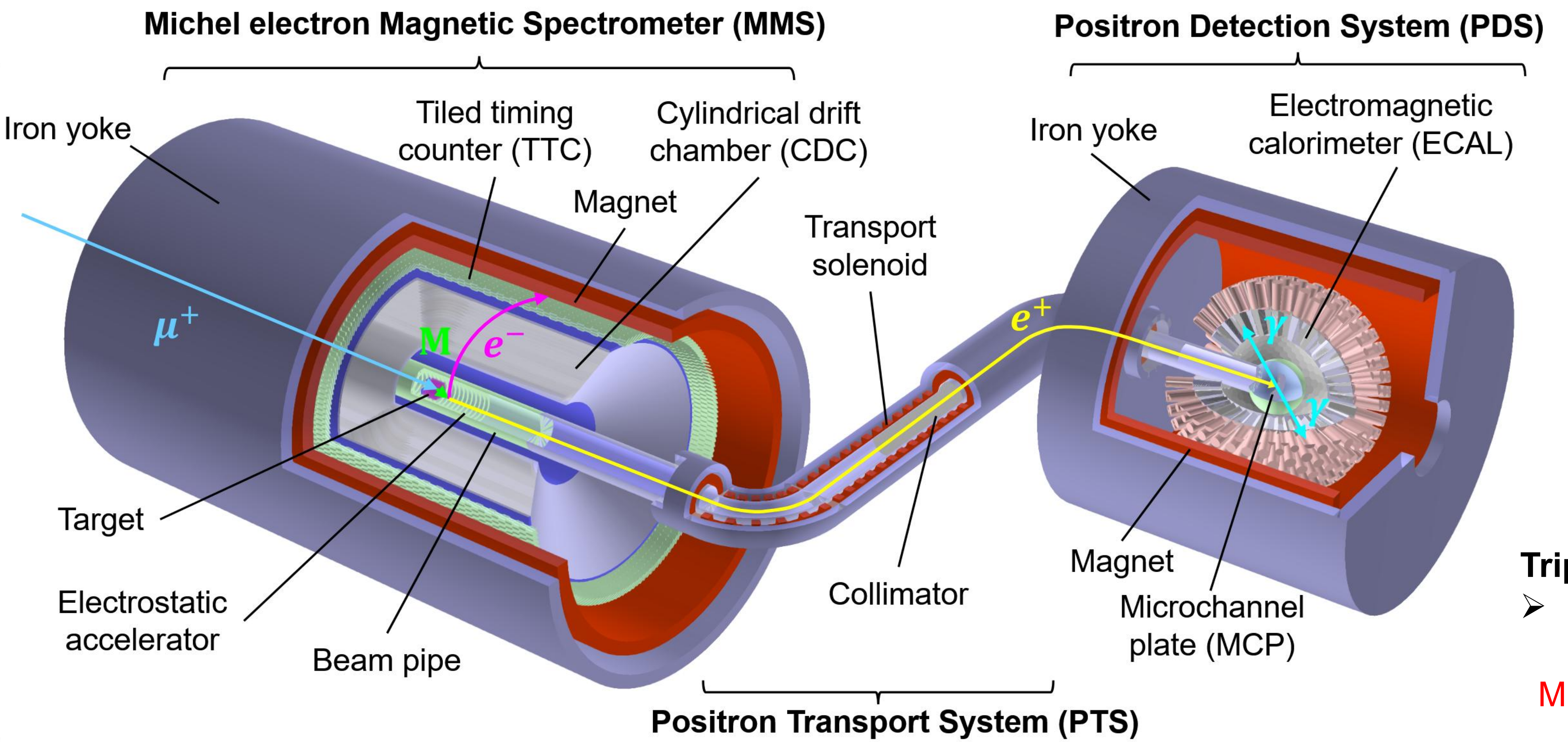
3 MW: 600MeV & 5mA

- 2.5 MW commissioning
- 2.5 MW long-term run
- Two target station, four beamlines
- Muon physics and applications

Muonium-Antimuonium Conversion Experiment (MACE)

- ☐ Physics motivations
- ☐ **MACE conceptual design**
- ☐ Progress of MACE Phase-I
- ☐ Summary

Conceptual design of MACE detector system



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^+

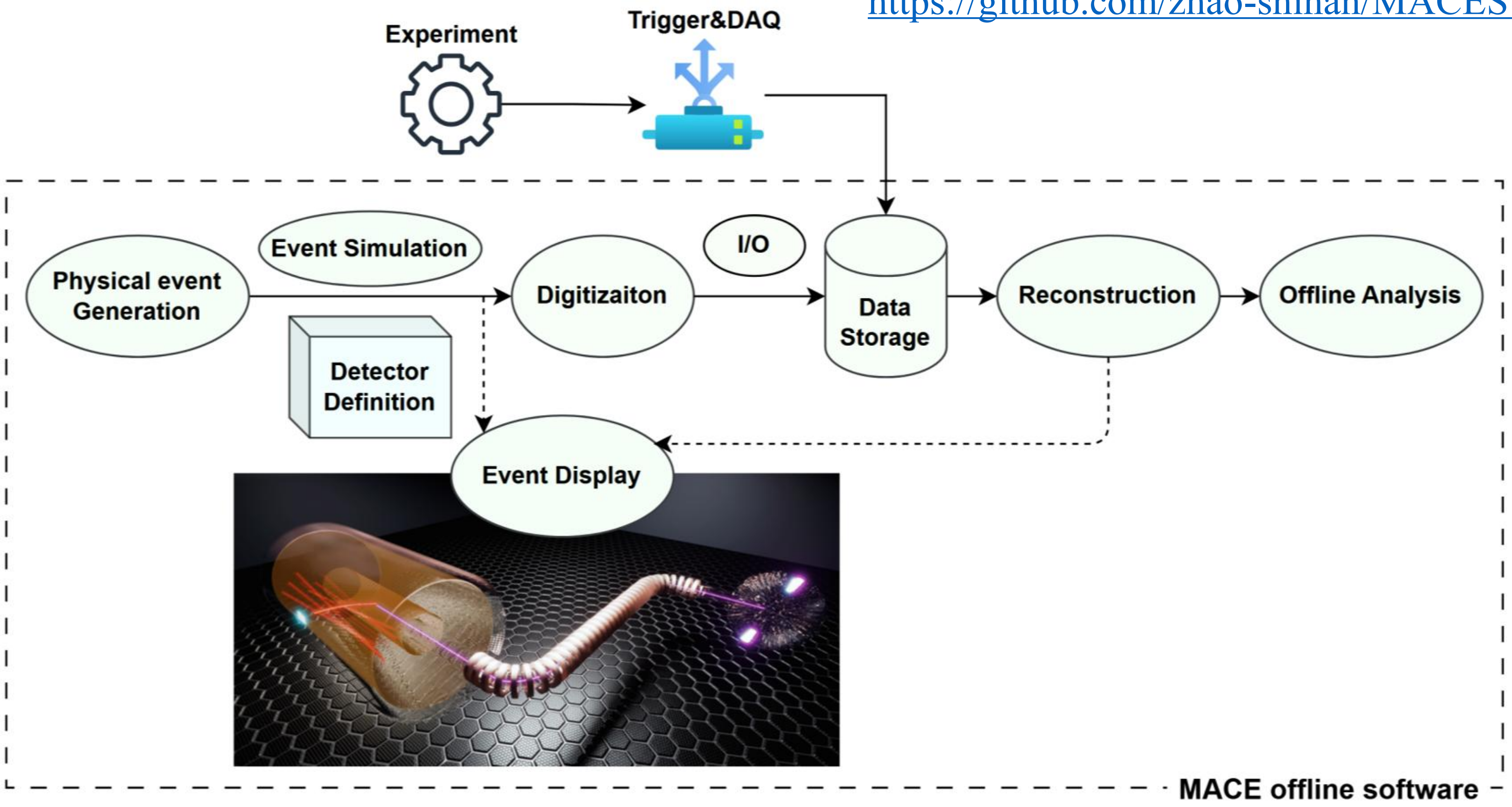
I. Surface muon stop in target → muonium
II. M diffuse into vacuum & convert to $\overline{\mathrm{M}}$
III. Decay in a vacuum: $\overline{\mathrm{M}} \to e^+e^-\nu_\mu\bar{\nu}_e$
IV. CDC detects Michel e^- track

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

Development of Monte Carlo Simulation 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…

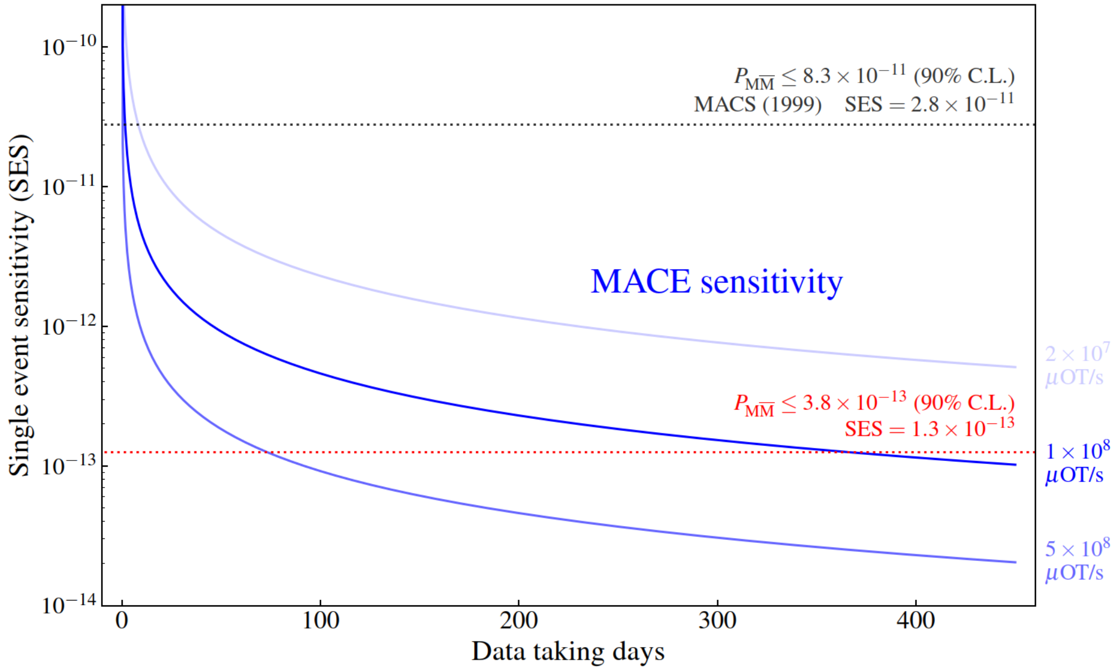
Software quality control:

- Framework and architecture
- Continuous integration
- Validation

Physics sensitivity of MACE

- 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 ($\varepsilon^{\text{geom}}_{\text{MMS}}$)	84.6%
	Reconstruction efficiency ($\varepsilon^{\text{recon}}_{\text{MMS}}$)	$\sim$ 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 $\varepsilon^{\text{In}}_{\text{ECAL}}$	63.4%
	Geometric efficiency $\varepsilon^{\text{Geom}}_{\text{ECAL}}$	95.3%
	Reconstruction efficiency $\varepsilon^{\text{Recon}}_{\text{ECAL}}$	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:

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

MACE CDR is released!

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

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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. The Muonium-to-Antimuonium Conversion Experiment (MACE) is 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 as well as a detailed description of the experimental design for the search for muonium-to-antimuonium conversion.

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

arXiv 2410.18817

Nucl. Sci. Tech. 37 (2026) 4, 57

- ☐ Physics motivations
- ☐ MACE conceptual design
- ☐ Progress of MACE Phase-I
- ☐ Summary

Proposal of MACE Phase-I

Muon cLFV decay modes

- ✓ **$\mu^+ e^-$ 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

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

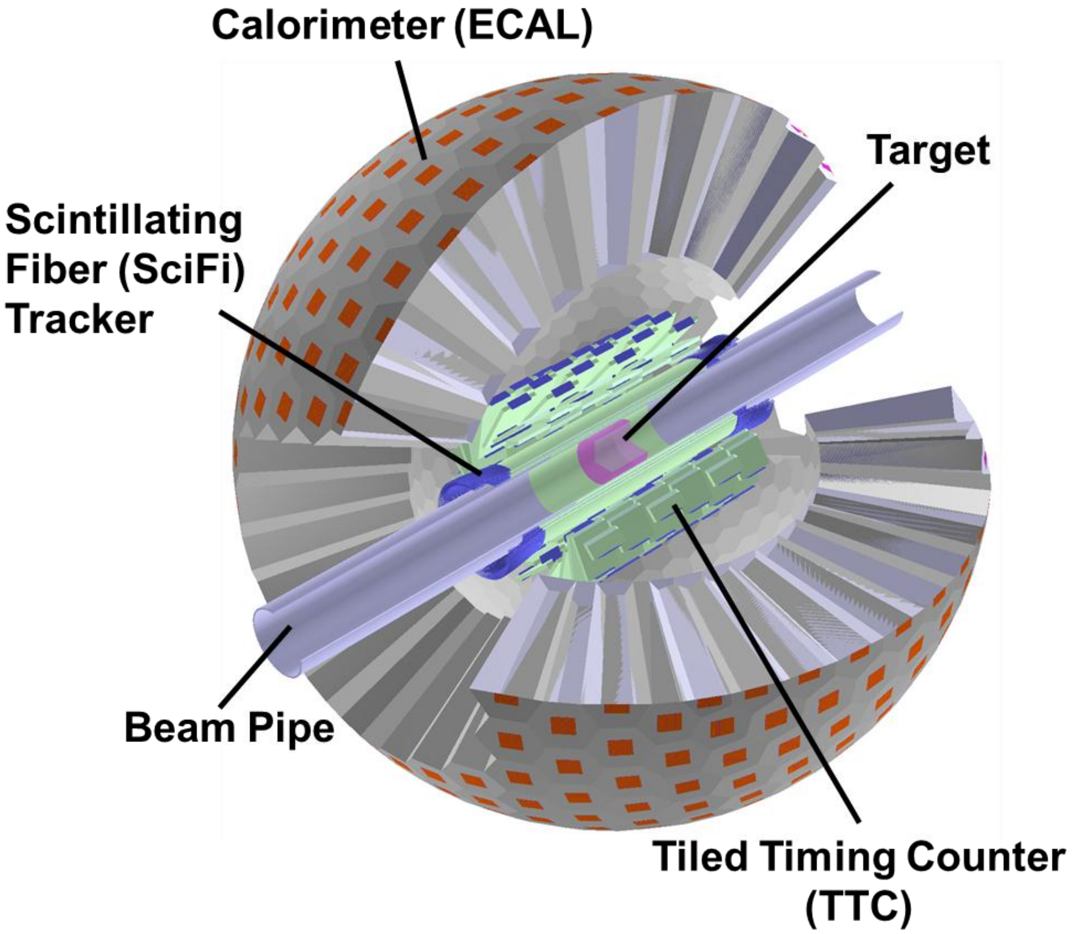
EPJC 76 (2016) 3, 108

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

PRL. 115 (2015) 7, 071801

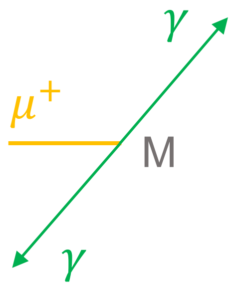
arXiv:2203.01981

PIONEER CDR, 2022



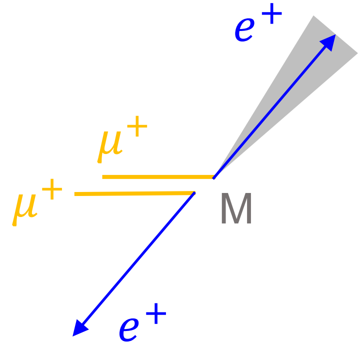
Sensitivity estimation of $\mathrm{M} \to \gamma\gamma$

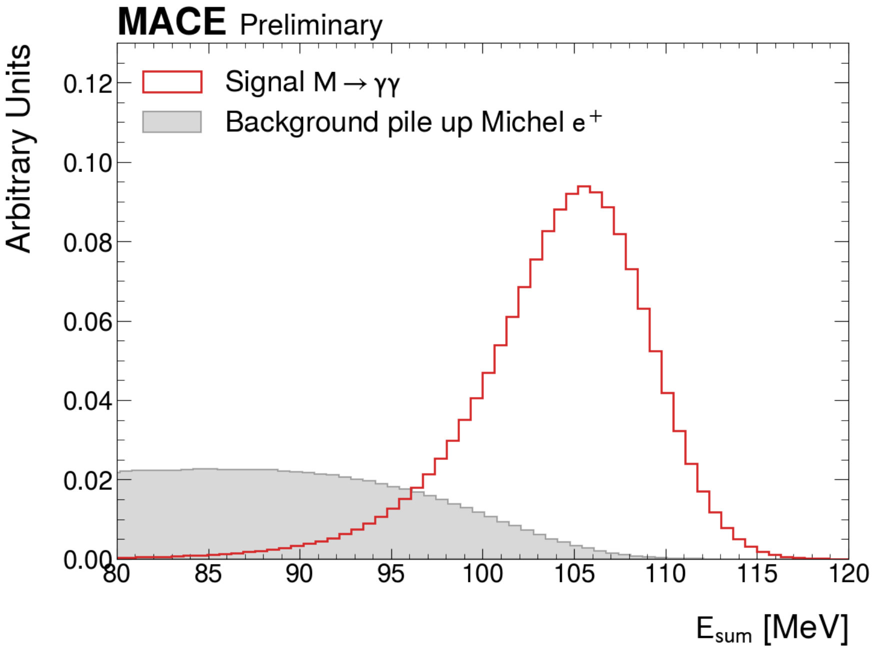
Signal: Double collinear 53 MeV gamma-rays.

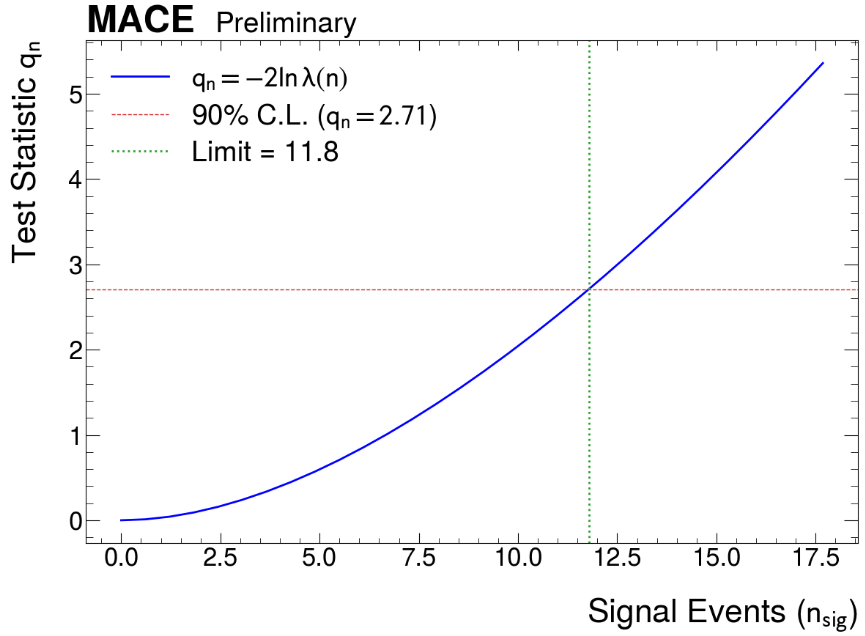


- No response in Tracker
- Double tracks reconstructed by ECAL

Background: Accidental coincidence of "pileup" positrons.







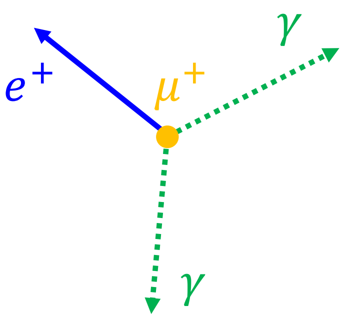
- Asimov dataset (signal & bkg)
- Profile likelihood ratio test
- 5% systematics error included

Upper limit of BR: 5.11×10^{-13} (90% C.L.)

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

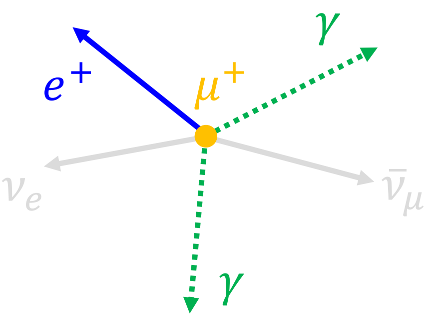
Sensitivity estimation of $\mu^+ \to e^+\gamma\gamma$

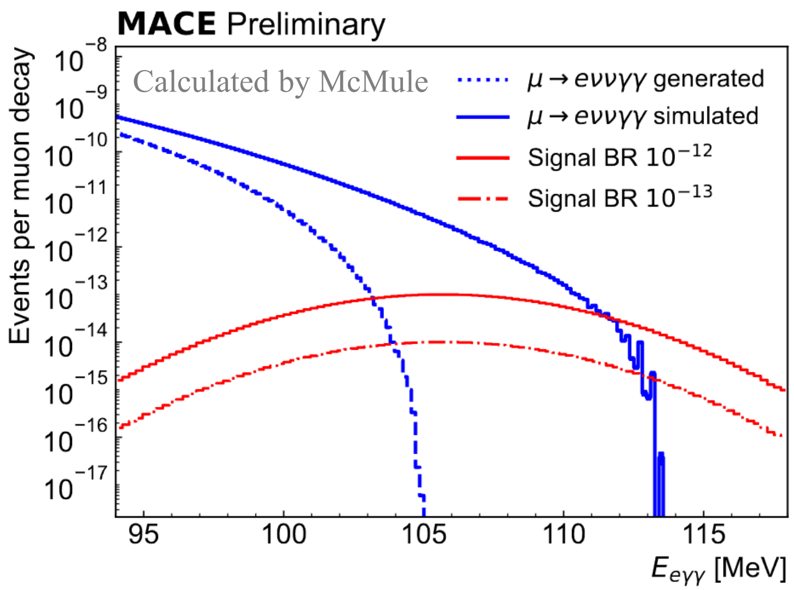
Signal:
Triple coplanar tracks
e^+ and two γs



Background:
Double radiative muon decay

SciPost Phys. 9, 027 (2020)





Event selection criteria:

- Time coincidence
- One track in Tracker, Two tracks in ECAL
- Energy-momentum conserved

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

$$n_{obs} = b$$

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

Upper limit of BR: 3.53×10^{-13} (90% C.L.)

More solid simulations and refined data analyses to be updated!

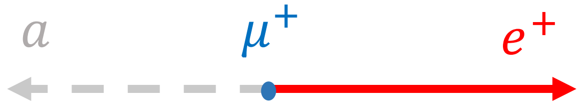
$\mathcal{O}(10^{-11})$ in *1988* PRD 38 (1988) 2077

Searching for ALPs

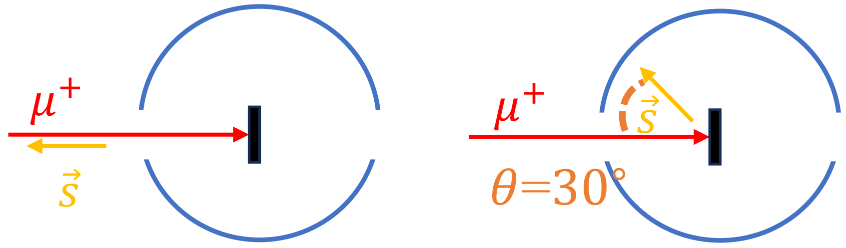
ALPs (Axion-like particles)

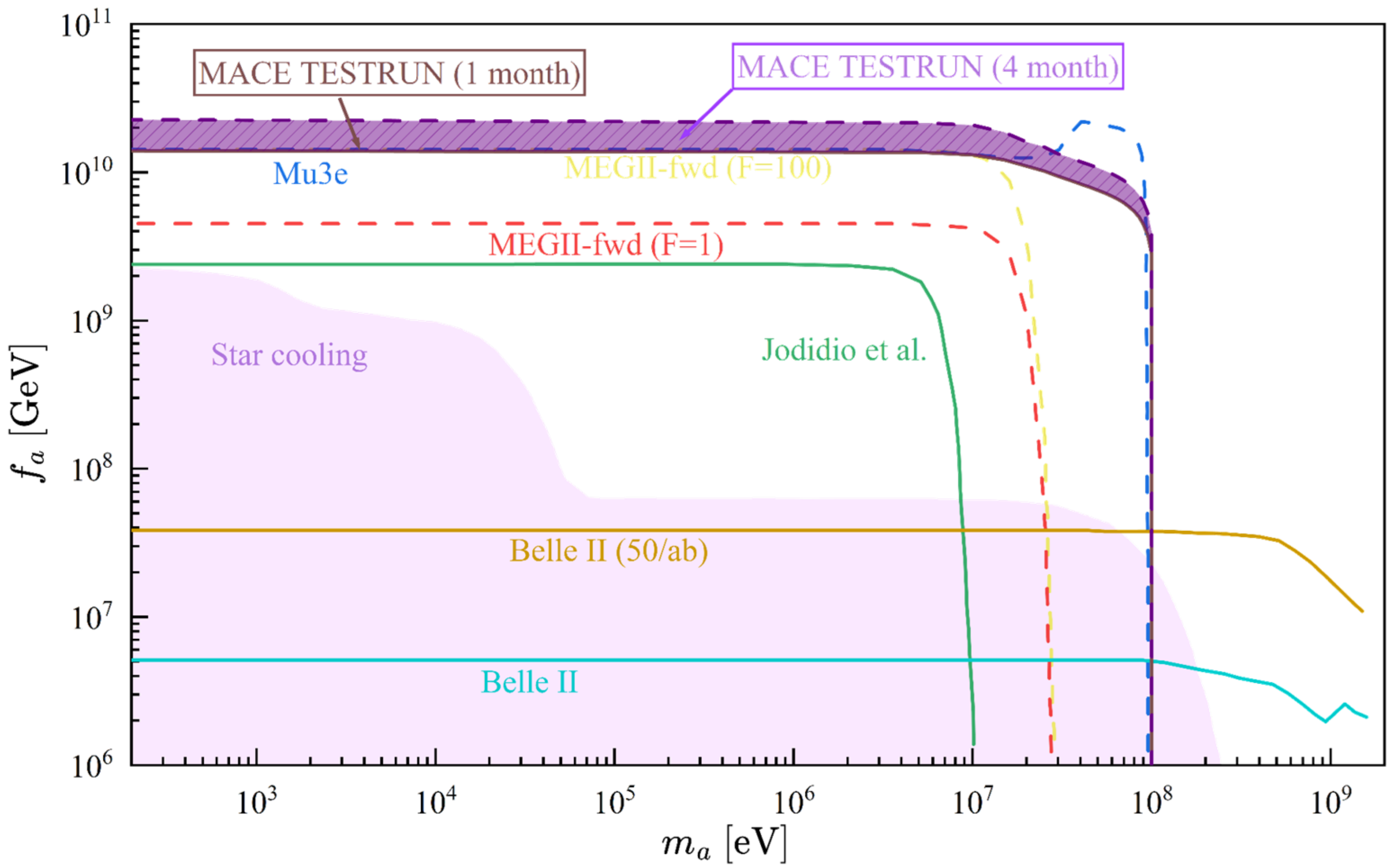
$$\mathcal{L}_{a\mu\mu} = \frac{\partial^\mu a}{2f_a}\left(C^V \bar{\mu}\gamma_\mu \mu + C^A \bar{\mu}\gamma_\mu\gamma_5\mu\right)$$

$$\boldsymbol{\mu^+ \rightarrow e^+ + a}$$



- Within ~1 month of beam time, we can search for ALP processes and reach a world-leading sensitivity.





Muonium-Antimuonium Conversion Experiment (MACE)

- Physics motivations
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- **Summary**

Technical Design of MACE

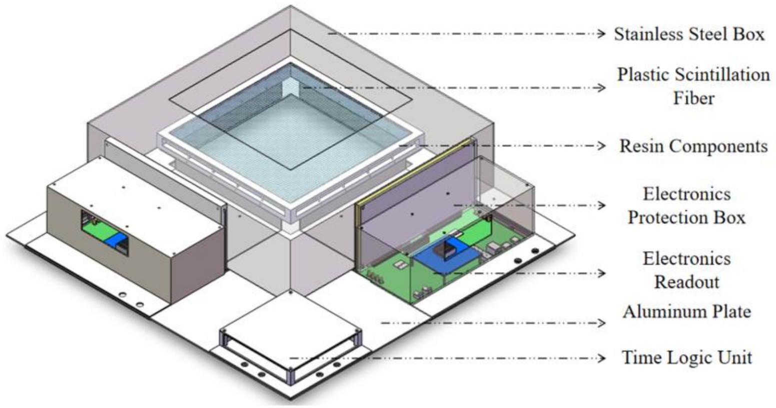
CONTENTS

Welcome to joining our efforts!

Progress of various muon detector development

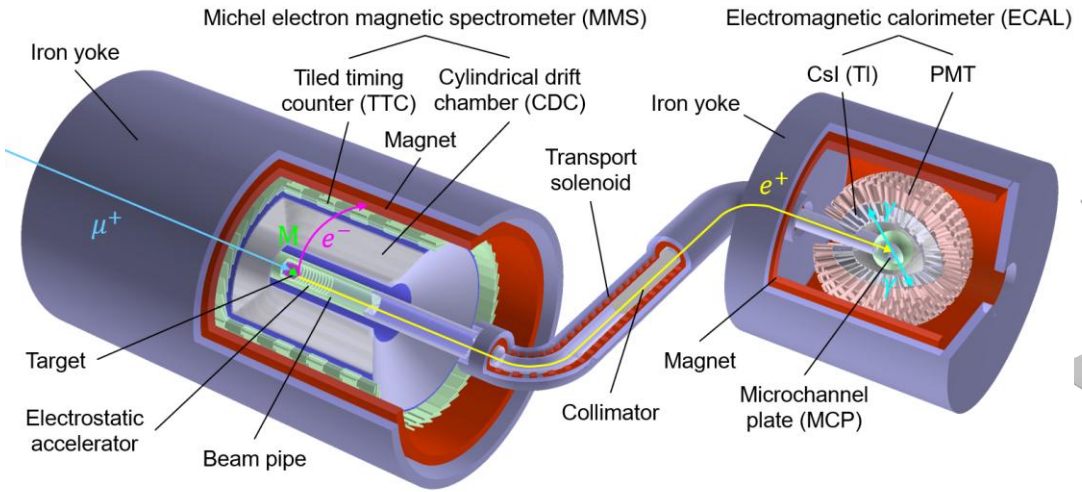
COMET muon beam monitor

Yu Xu et al, Nucl.Sci.Tech. 35 (2024) 4, 79



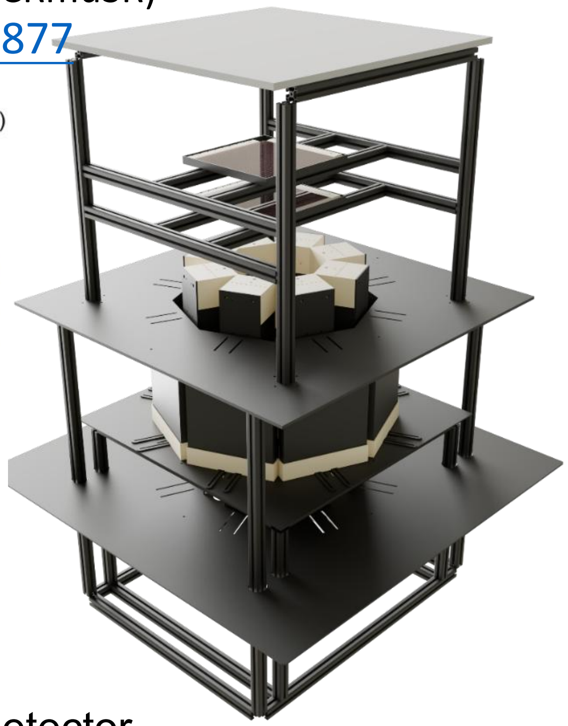
Conceptual Design Report of **MACE**

arXiv: 2410.18817 [hep-ex]

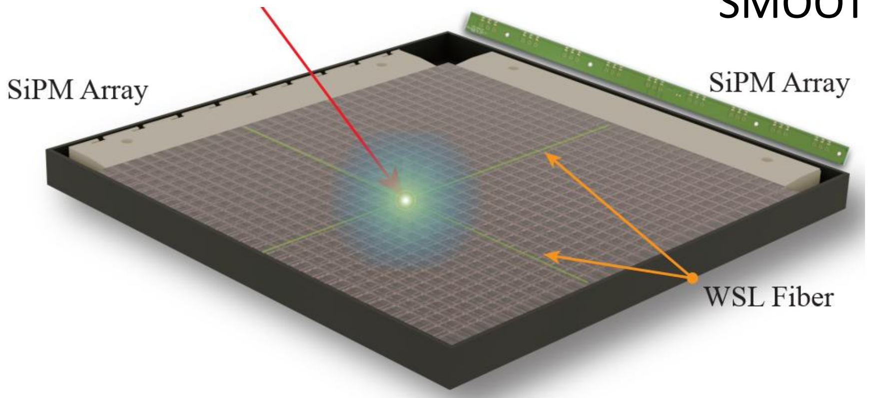


Cosmic-Ray muSR(CRmuSR)

e-Print: 2505.13877

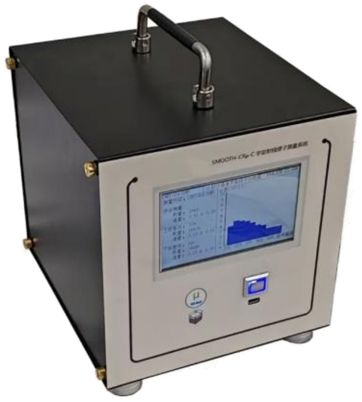


MuGrid-v2 for muography



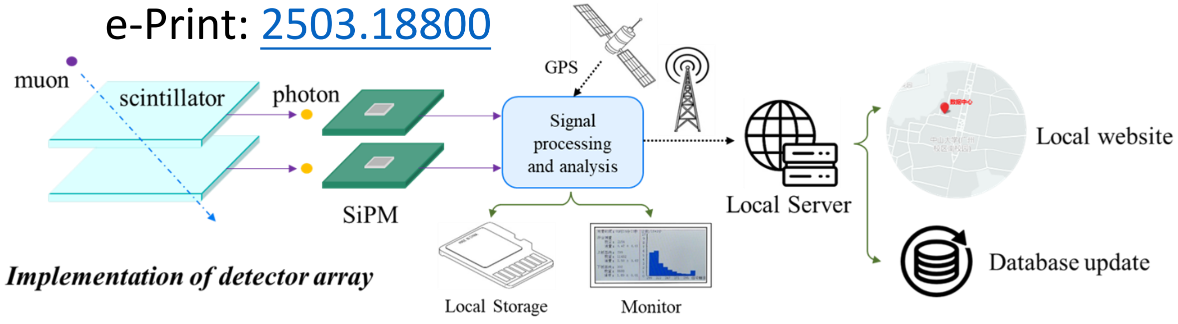
e-Print: 2505.19777

SMOOTH实验室主页 https://www.smooth-sysu.cn

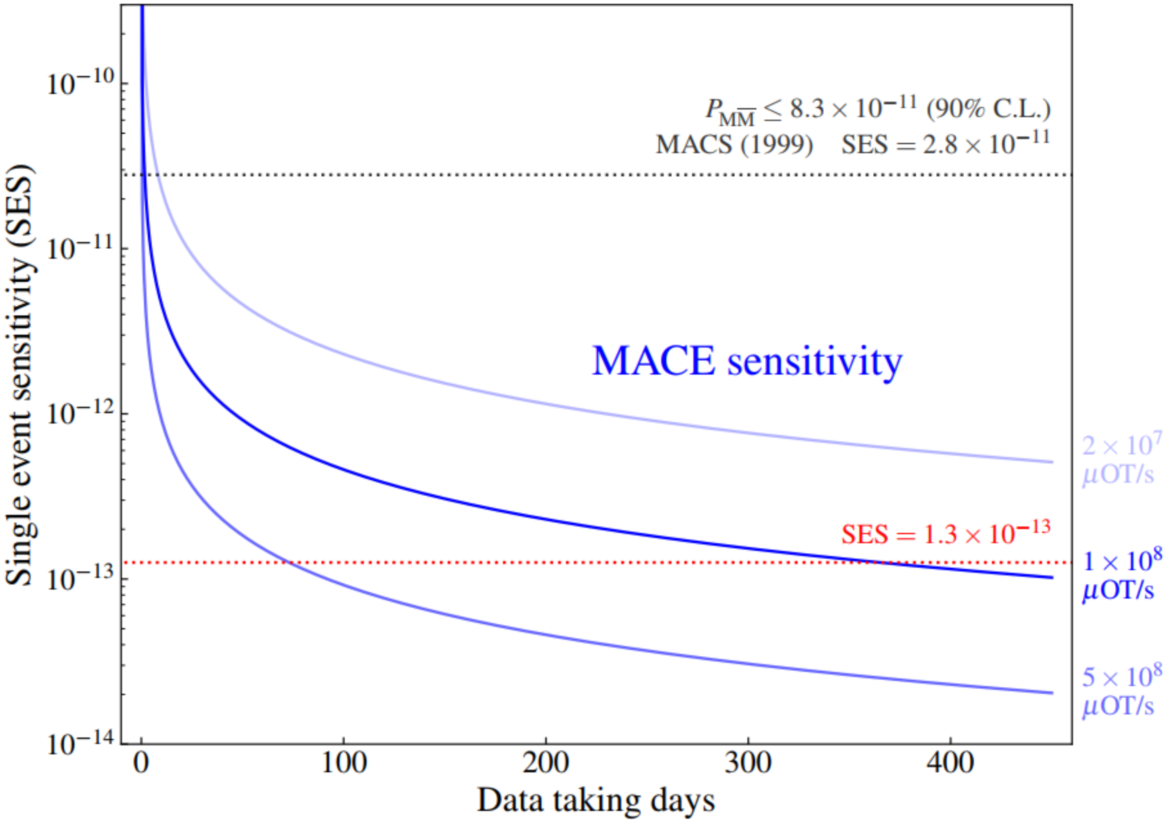


Portable cosmic-ray muon detector

e-Print: 2503.18800



Summary



- Next-generation muon cLFV experiment —— MACE aims at two orders of magnitude improvement.
- MACE Phase-I: forerunner of MACE. A search for batches of muon(ium) cLFV decay modes → **broader physics programs**.
- $\mathcal{O}(10^{-13})$ sensitivities are expected.
- **Welcome to joining the muon physics experiment MACE!**

□ **Check out our new muonium physics review:**

Muon beams towards muonium physics: progress and prospects

arXiv:2601.15818 ***Comments are welcome!***

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, 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, Jian Zhang, Yao Zhang, Yongchao Zhang, Zhilv Zhang, Guang Zhao, Shihan Zhao

(MACE working group)

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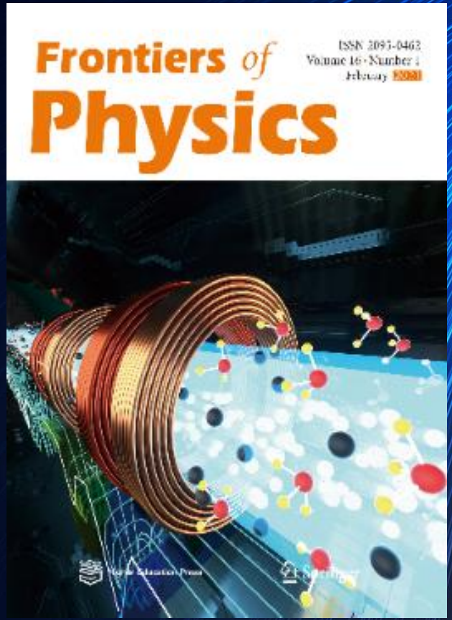

最新IF：5.3，JCR Q1 区；
CiteScore 11.2，SCOPUS Q1区

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- 文章类型：Review, Research Article, ...
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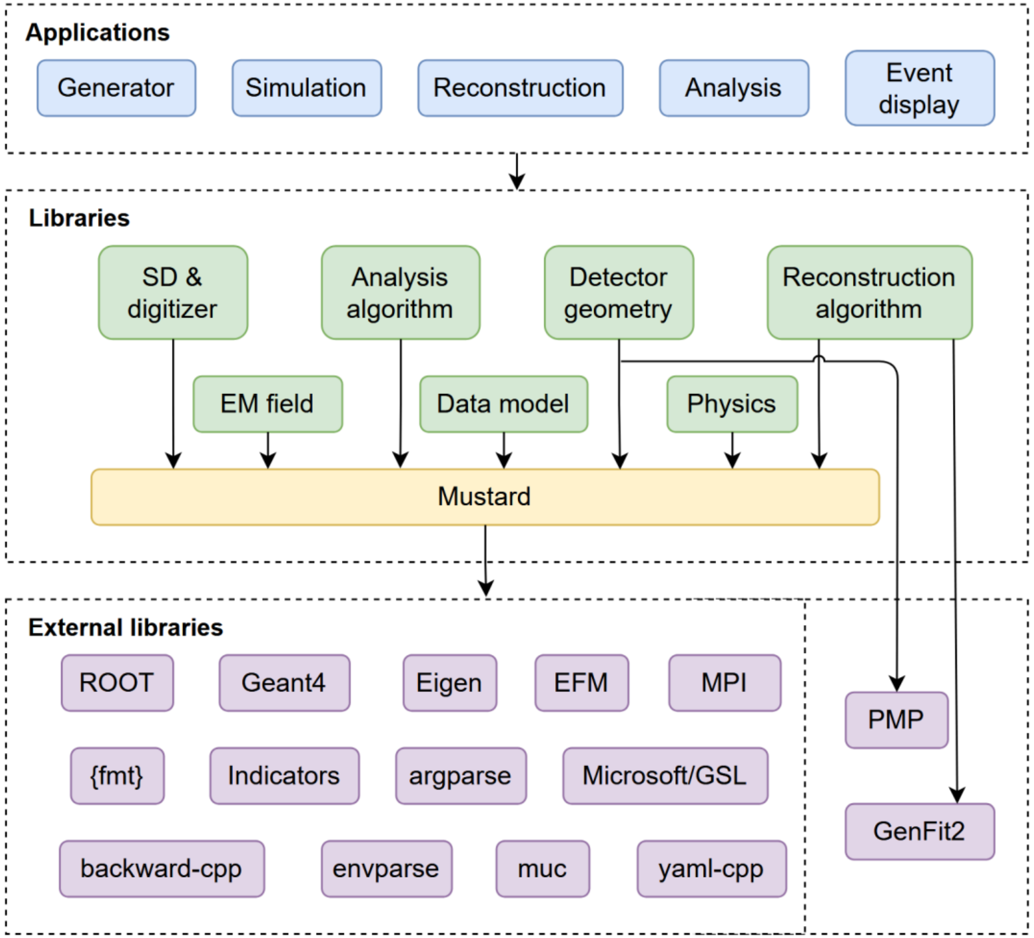
欢迎投稿
感谢引用

THANK YOU

MACE Software framework

●Mustard framework:

- A modern, distributed, high-performance architecture for particle physics experiments.



●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

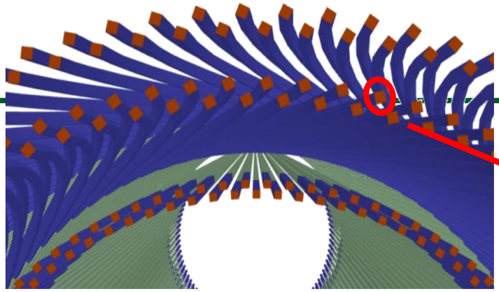
Tracking System

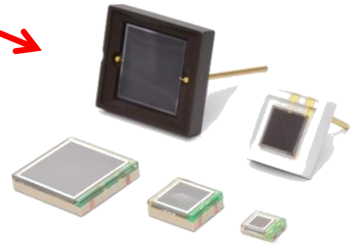
- Precise timing ability
- Low material budget
- Low cost
- e^+/γ discrimination
  - High active area
  - High e^+ detection efficiency
  - Low γ detection efficiency

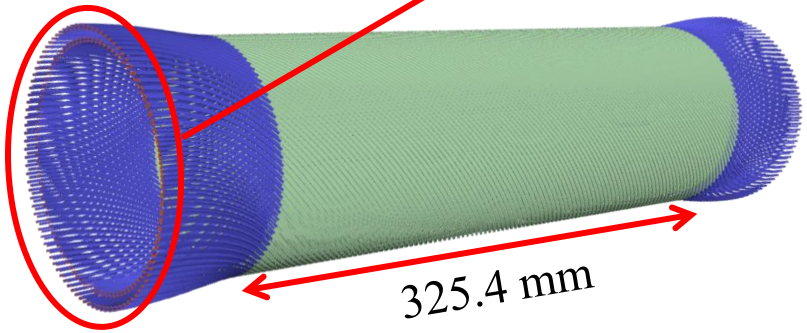
⇩

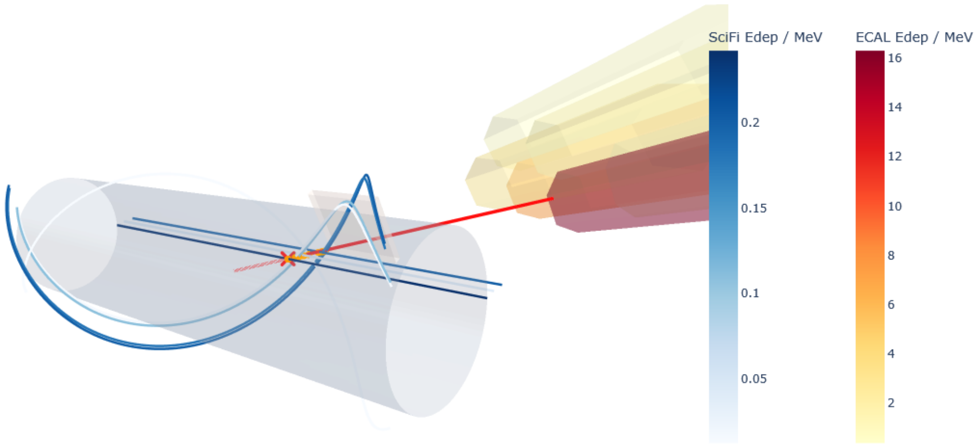
Plastic scintillators!

Credit: Yinyuan Huang









Event display

SciFi baseline design:

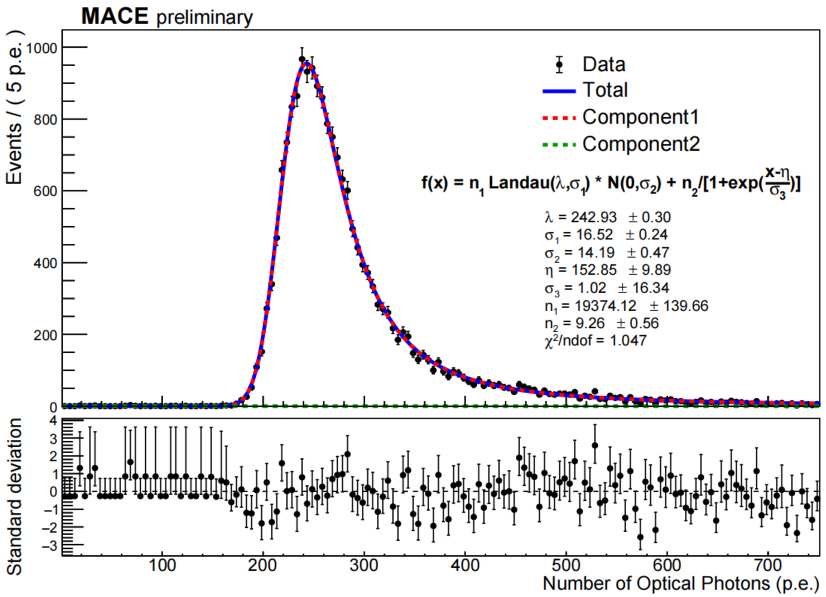
- Crossing fiber arrangement
- 2360 channels
- Single-end readout by SiPM
- Angular resolution ~5°
- Timing resolution ~1 ns
- $\varepsilon_{\text{Recon}} \approx 90\%$
- $\varepsilon_e = 97\%$
- $\varepsilon_\gamma = 2\%$

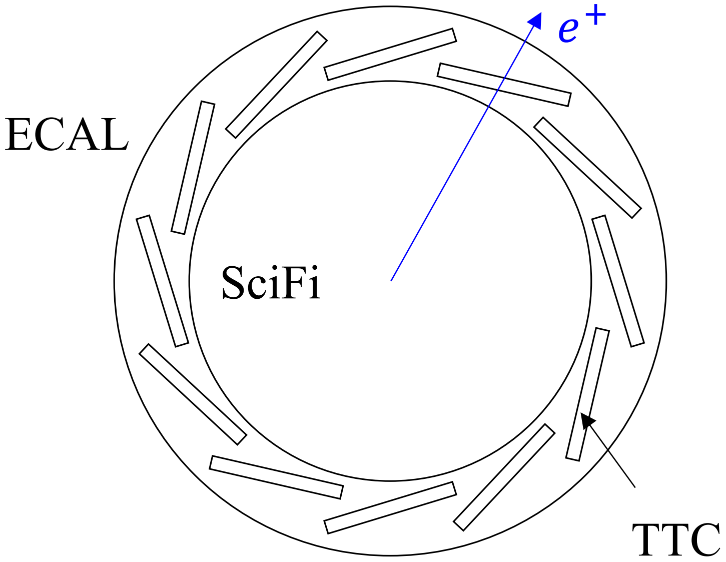
Tracking System

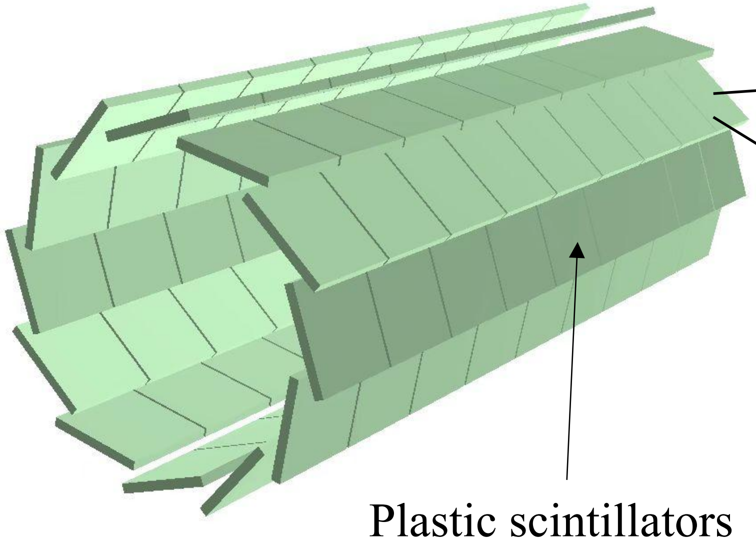
- **Tiled timing counter (TTC)**

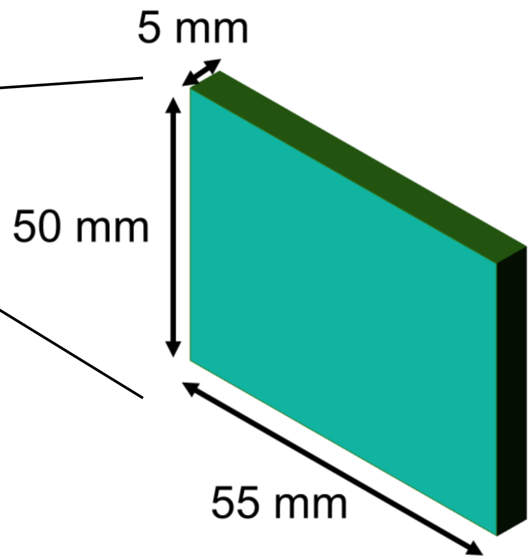
Credit: Hao Jiang

  - 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





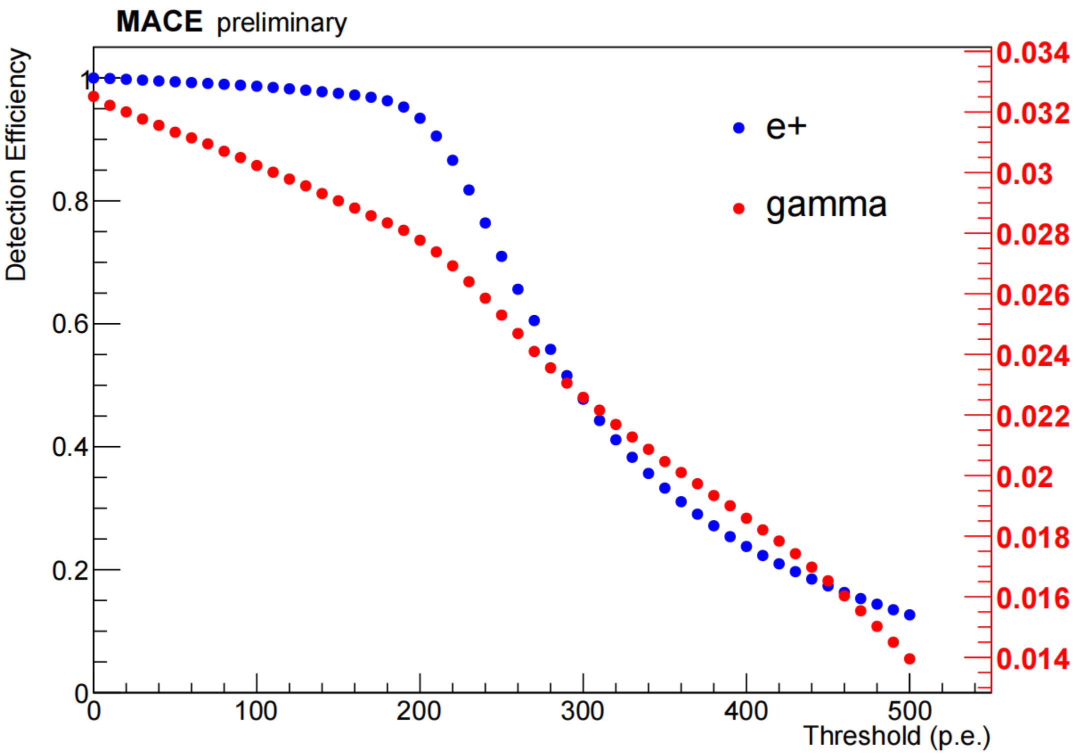




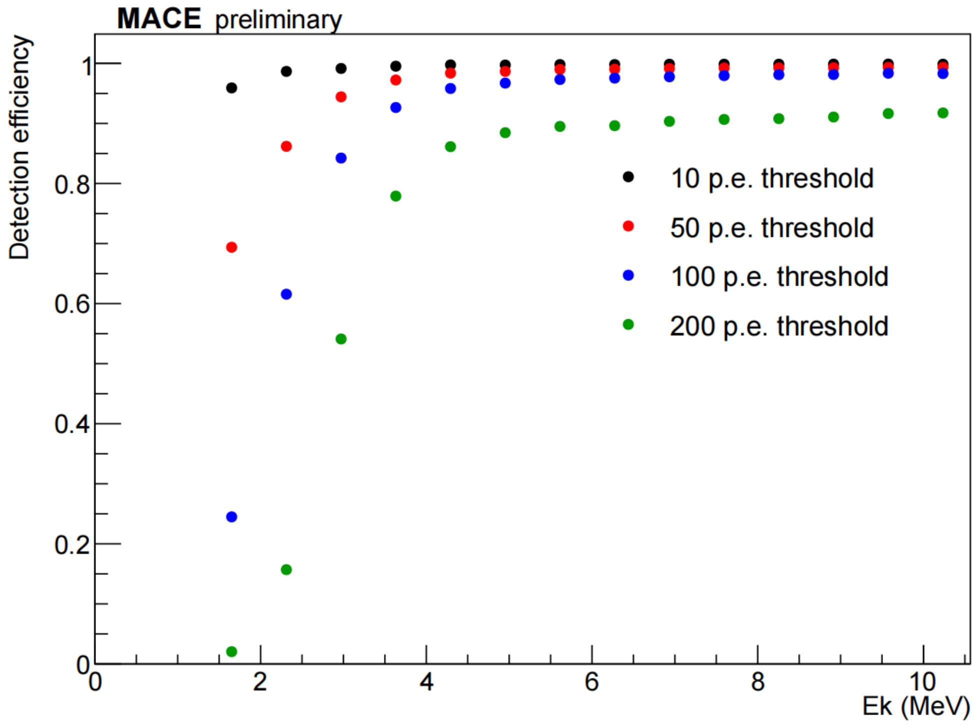
Phase-I TTC performance

- Full simulation result to investigate TTC efficiency curve and QDC threshold

✓ $\varepsilon_e = 99\%$ $\varepsilon_\gamma = 5\%$

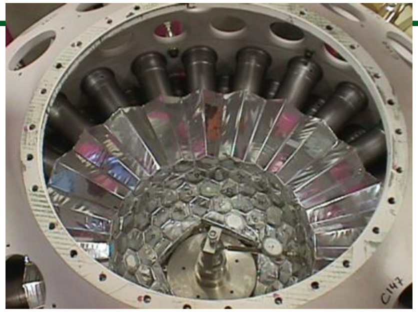


53 MeV, Threshold vs. Efficiency

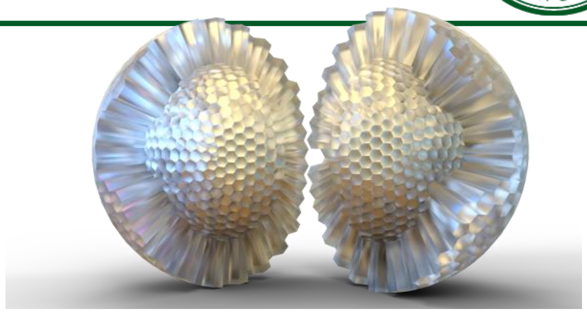


e^+, Energy vs. Efficiency

Electromagnetic Calorimeter (ECAL)



PEN detector
pCsI + PMT



MACE ECAL
pCsI + SiPM

Design scheme：

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

LYSO

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

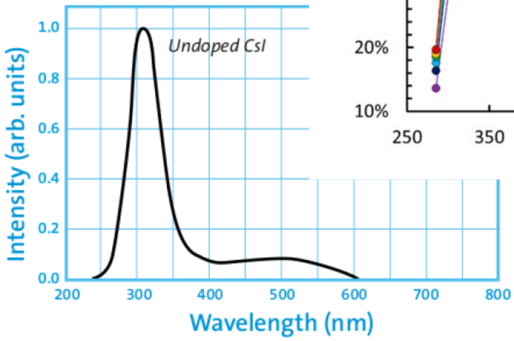
BGO

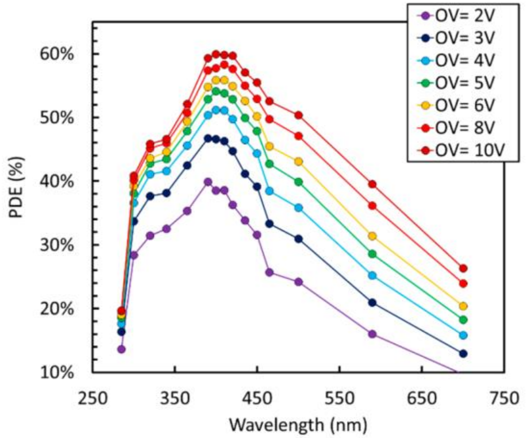
- 8000 ph/MeV
- 300 ns
- Not hygroscopic
- Emits at 480 nm
- CNY ￥100/cm³

Pure CsI

✓ Baseline design

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





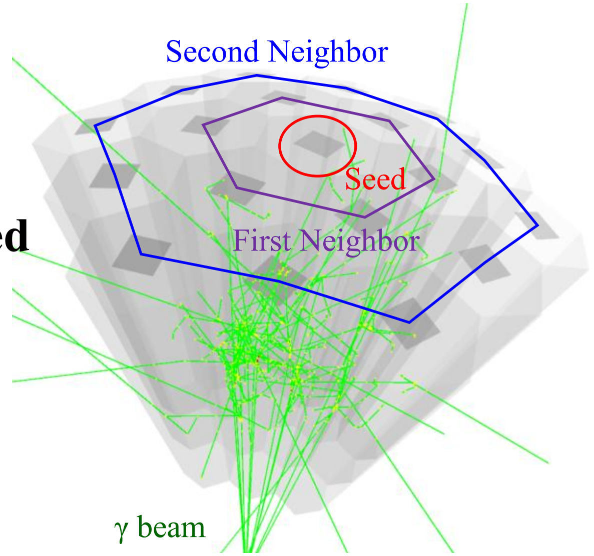
NUV SiPM readout

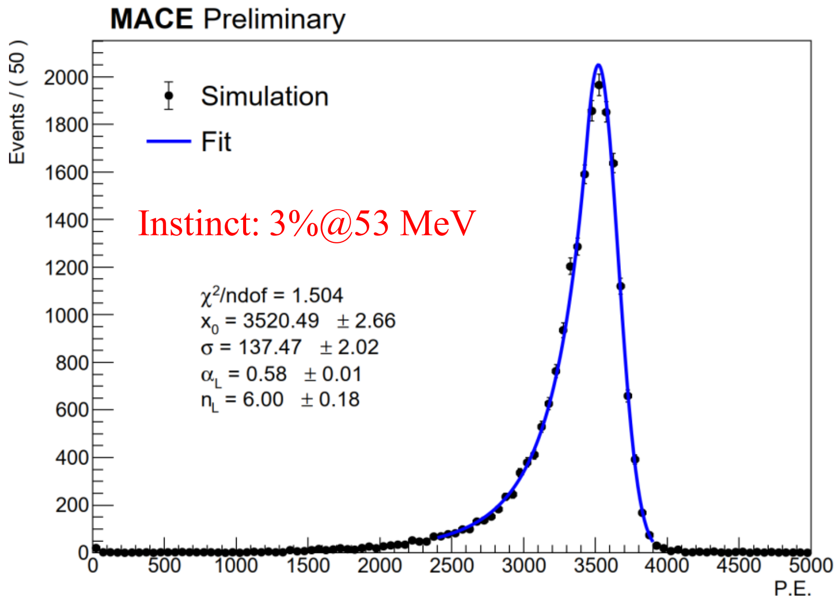
Sensors 19 (2019) 2, 308

Phase-I ECAL performance

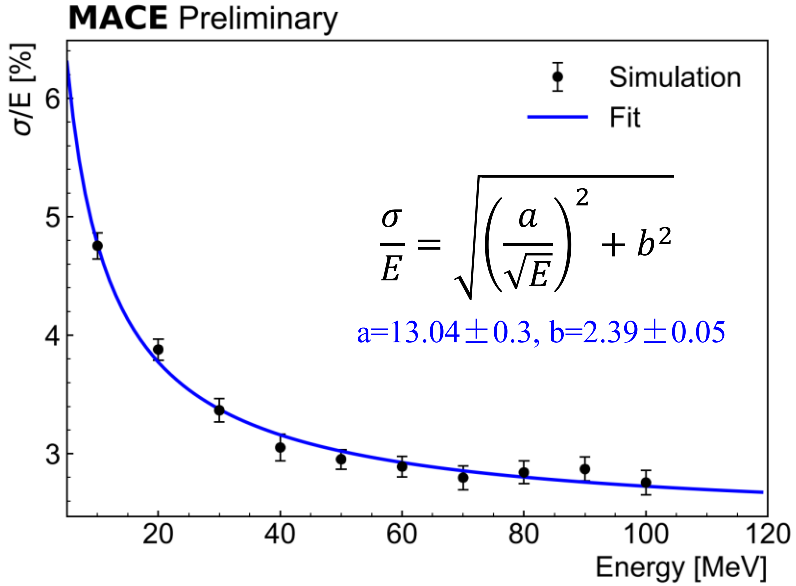
- Baseline requirement based on full simulation:
  - Optical physics, scintillation, collection
  - $\mathcal{O}(50)$ p.e. electronic noise, nonlinear correction
  - Coincidence timing resolution better than **200 ps**
  - Energy resolution better than **6% @ 53 MeV**
  - Angular resolution better than **10°**

Energy-weighted clustering

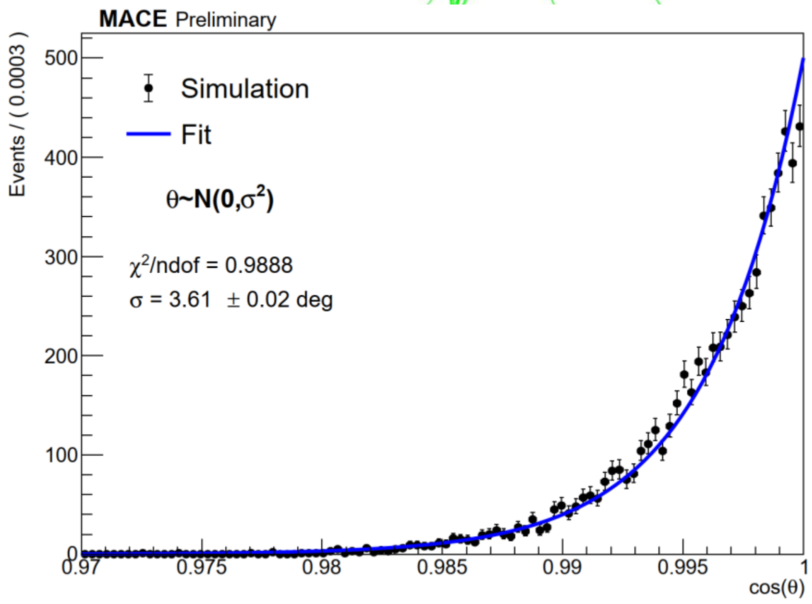




Simulated PE spectrum
fitted by Crystal Ball function



Energy resolution curve



Angular resolution