中山大學 物理学院
SUN YAT-SEN UNIVERSITY SCHOOL OF PHYSICS

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

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(MACE working group)

[arXiv:2410.18817] *Conceptual Design of the Muonium-to-Antimuonium Conversion Experiment (MACE)*, *accepted by Nuclear Science and Techniques*

Contents

- Motivations
- MACE conceptual design
- Proposal of MACE Phase-I
- Summary

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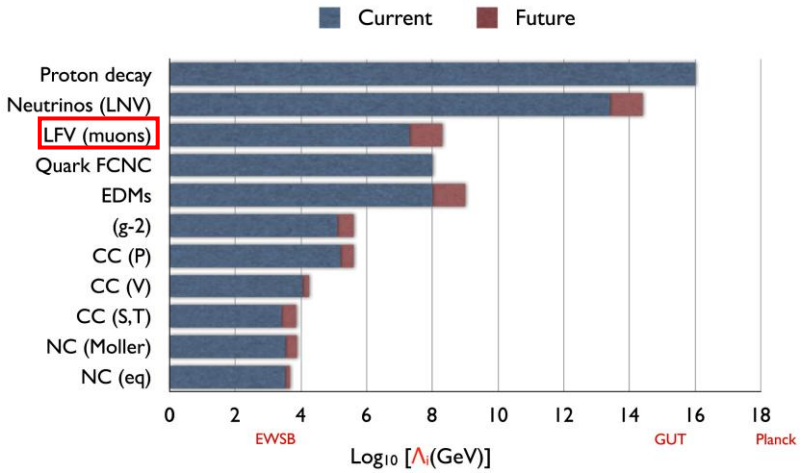
Motivations for cLFV searches

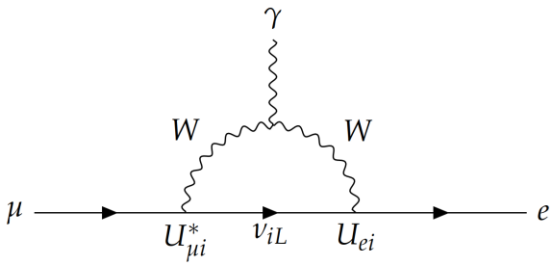
- Quark flavor mixing: CKM matrix (2008 Nobel Prize)
- Neutral lepton flavor mixing: Neutrino oscillation (2015 Nobel Prize)
- **Charged lepton: _____**



Prog.Part.Nucl.Phys. 71 (2013) 2-20

Consider tiny neutrino masses in the Standard Model

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

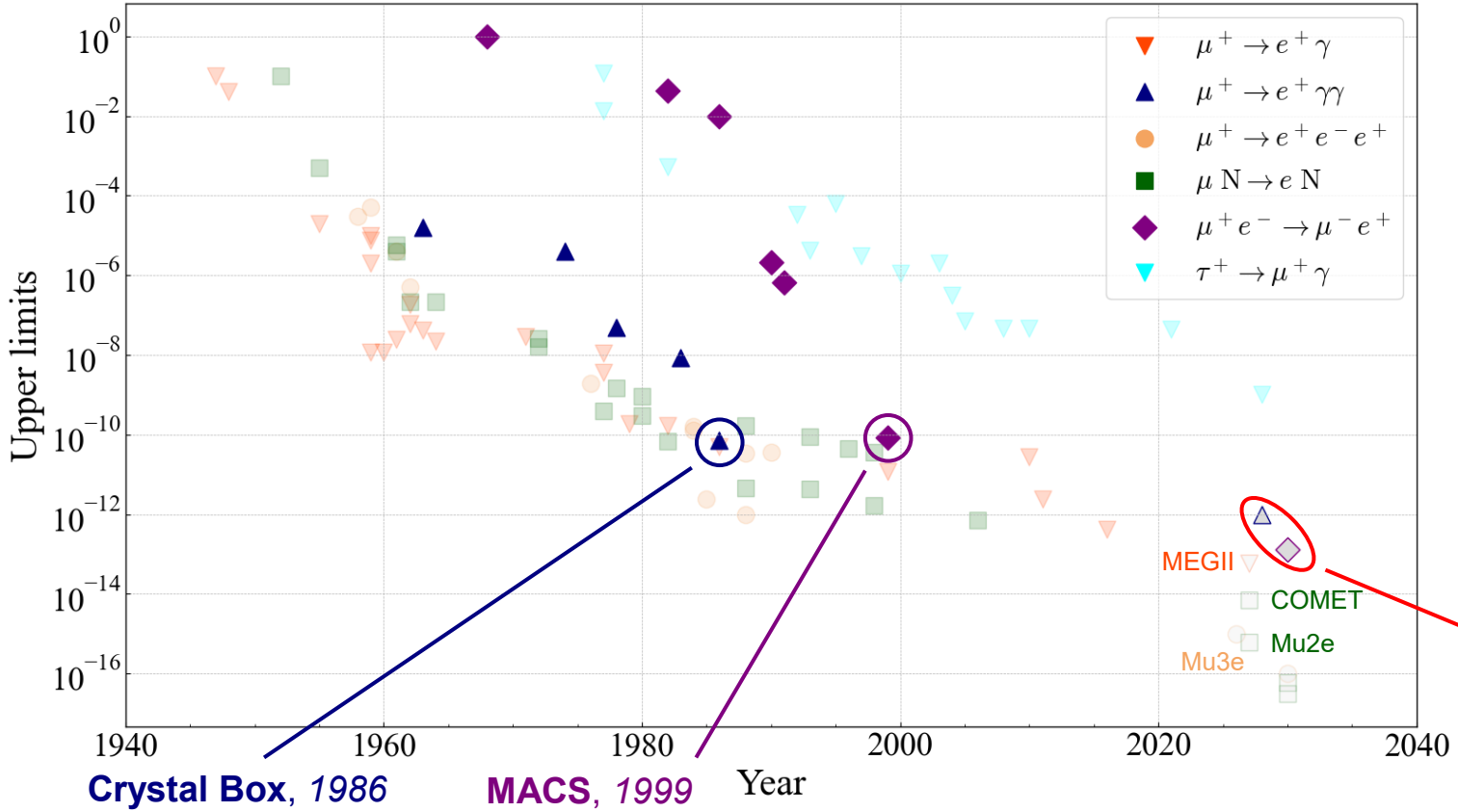


- ✓ **Forbidden in SM, free of SM background.**
- ✓ Many BSM models predict scalable cLFV
- ✓ **"Smoking gun" evidence of BSM, if observed!**
- ✓ Complementary with the high-energy frontiers.

Why muon?

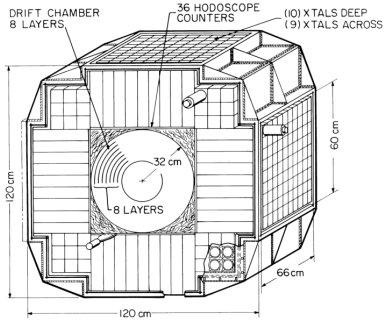
- Lightest massive unstable charged lepton.
- Reasonably long 2.2-μs lifetime.
- Almost free from QCD corrections.

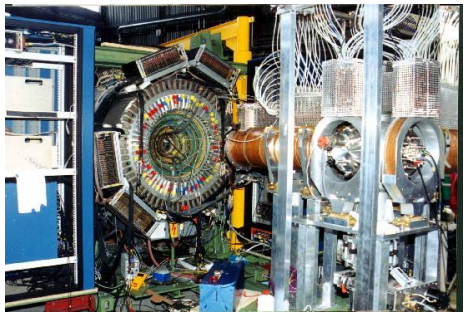
1940s till now: a cLFV odyssey



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

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





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

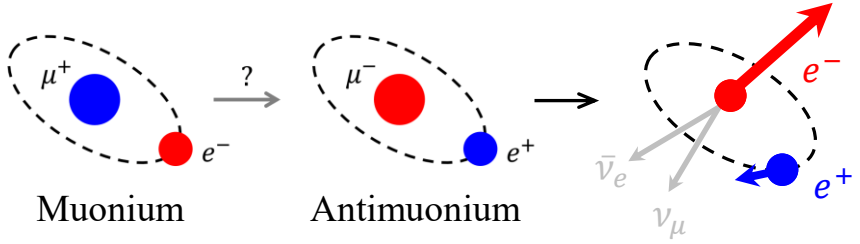
COMET (J-PARC) $\mu^-\mathrm{N} \to e^-\mathrm{N}$

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

Muonium conversion

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

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



$\mathrm{M} \to \bar{\mathrm{M}}$: an $\Delta L_\ell = 2$ process

✓ In SMEFT: operators different from $\Delta L_\ell = 1$ processes

($\mu \to e\gamma$, $\mu \to eee$, $\mu N \to eN$)

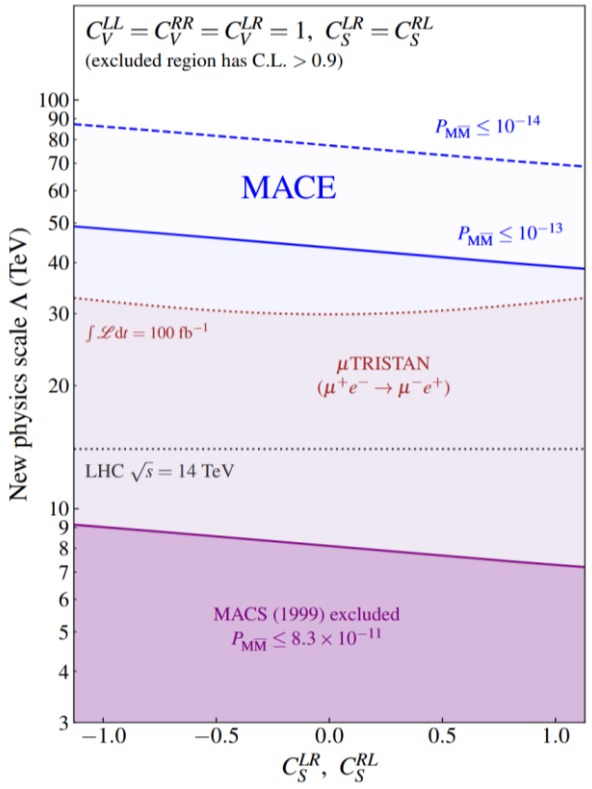
✓ $\Delta L_\mu = -\Delta L_e = 2$ can be possible even if $\Delta L_\ell = 1$ is suppressed.

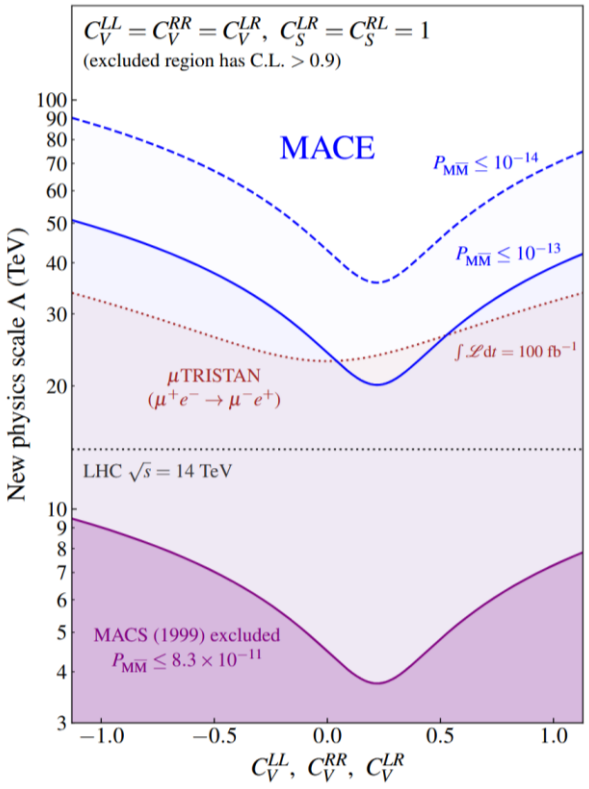
✓ Complementary to $\Delta L_\ell = 1$ process searches.

Phys.Lett.B 852 (2024) 138621
Phys.Rev.D 105 (2022) 1, 015026

Current bound:
$P_{\mathrm{M}\to\bar{\mathrm{M}}} < 8.3\times10^{-11}$
in 0.1T field, 90% C.L.

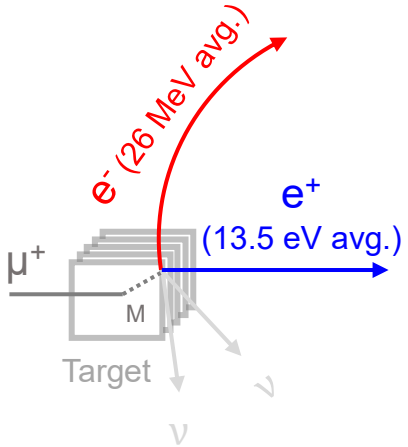
Phys. Rev. Lett. 82 (1999), 49-52.



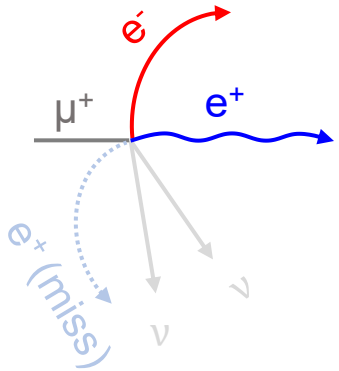


Signal and backgrounds

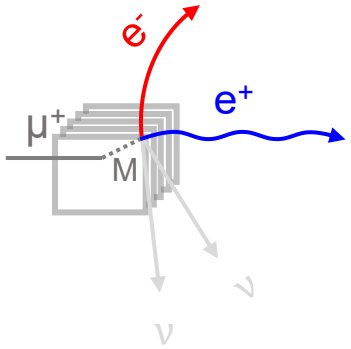
Signal:
fast e^- + slow e^+



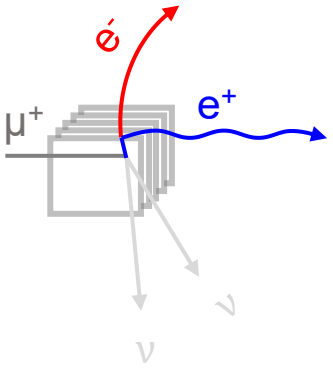
1. Internal conv. (IC) decay
- $\mu^+ \to e^+ e^- e^+ \bar{\nu}_\mu \nu_e$



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



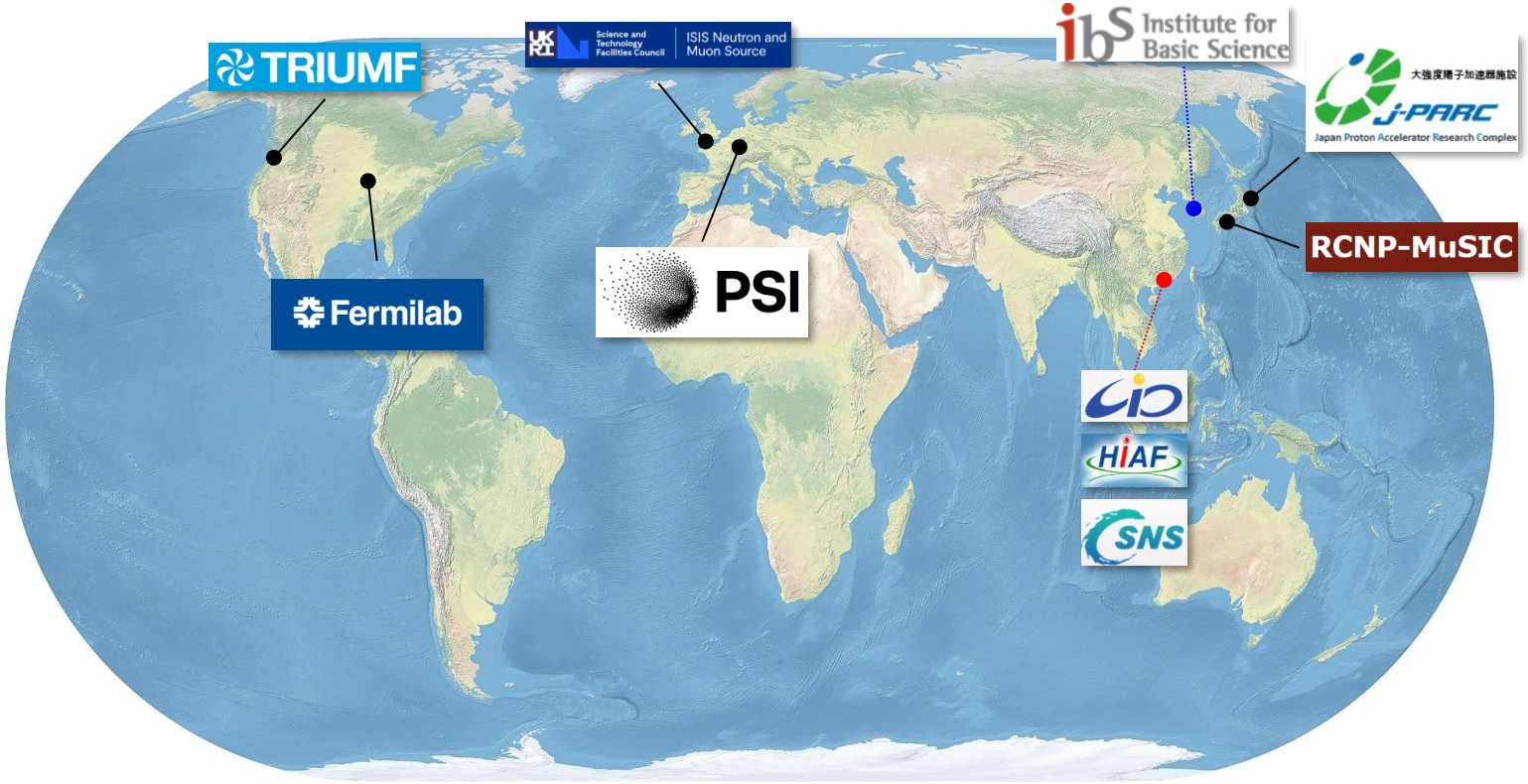
3. Accidental bkg.
- Scattering/conv. e⁻
- Mis-reconstruction
- Cosmic ray, etc.



- **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

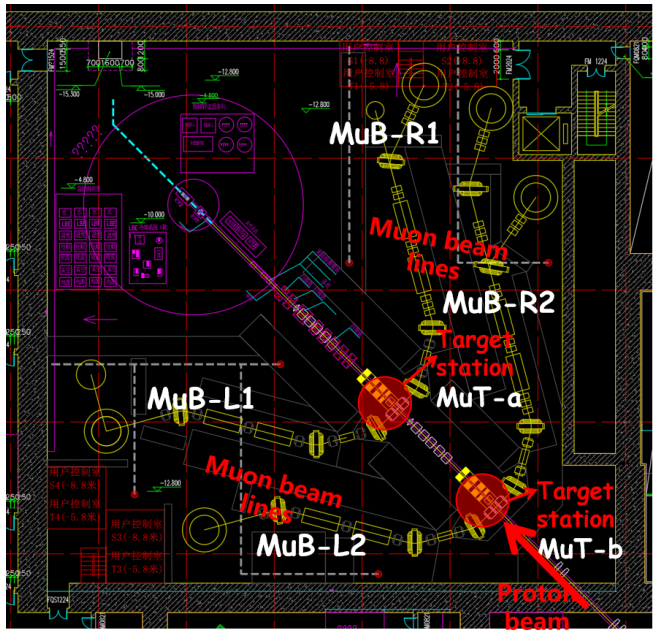


- Global facilities: PSI (Switzerland), J-PARC (Japan), ISIS (UK), TRIUMF (Canada), FNAL (USA).
- First high-intensity muon source in **China**, to be built in the Greater Bay Area: **CSNS/CiADS/HIAF**.

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?

See talk by 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

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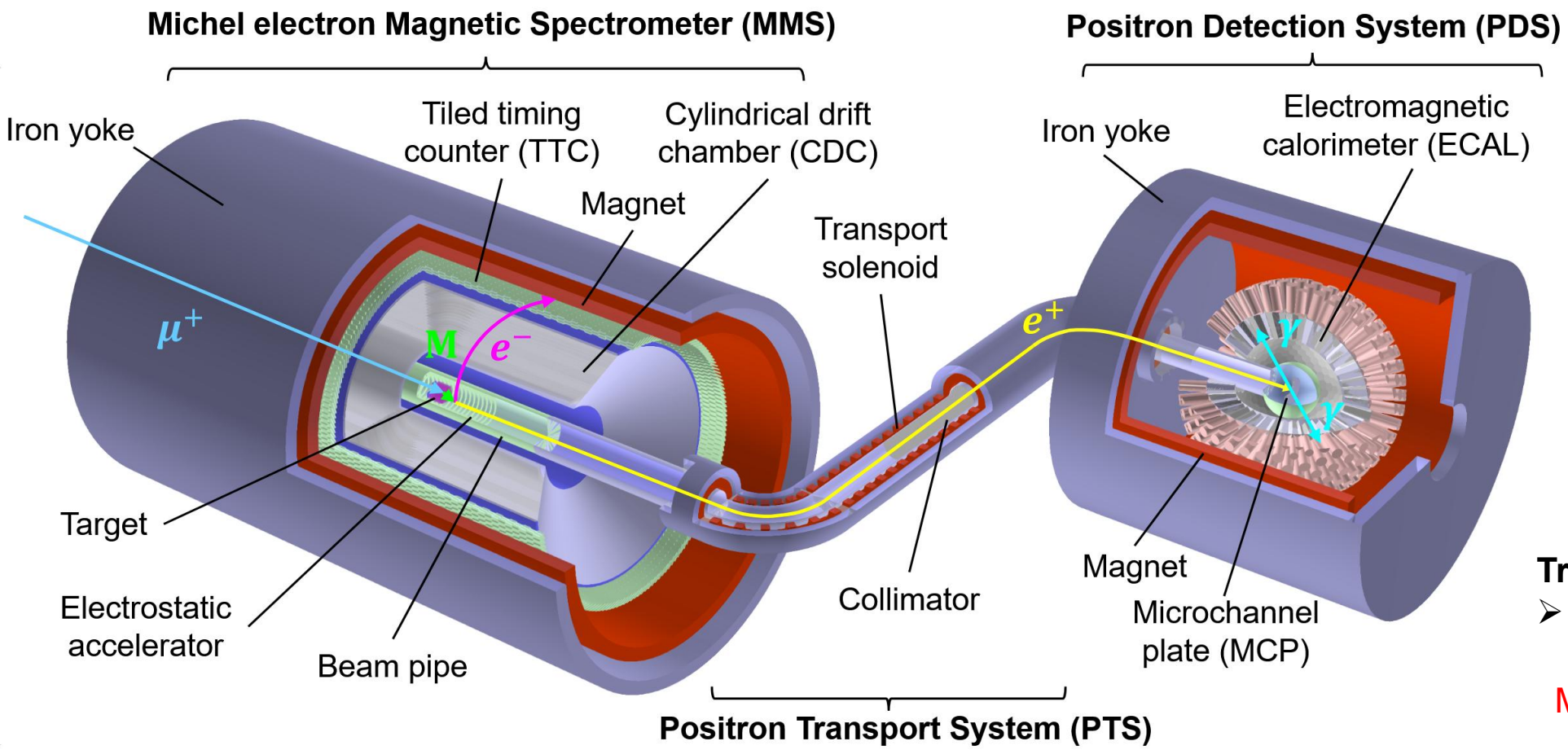
Conceptual design of MACE detector system



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**

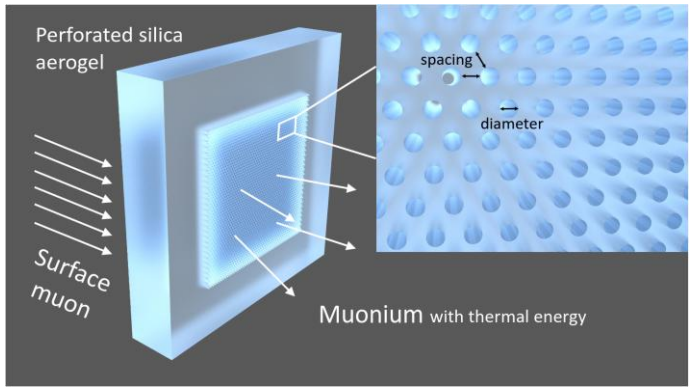
Michel e^- Atomic e^+

I. Surface muons stop in target → muonium
II. M diffuses into vacuum & converts to $\bar{\mathrm{M}}$
III. Decay in a vacuum: $\bar{\mathrm{M}} \rightarrow e^+ e^- \nu_\mu \bar{\nu}_e$
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

Muonium production target

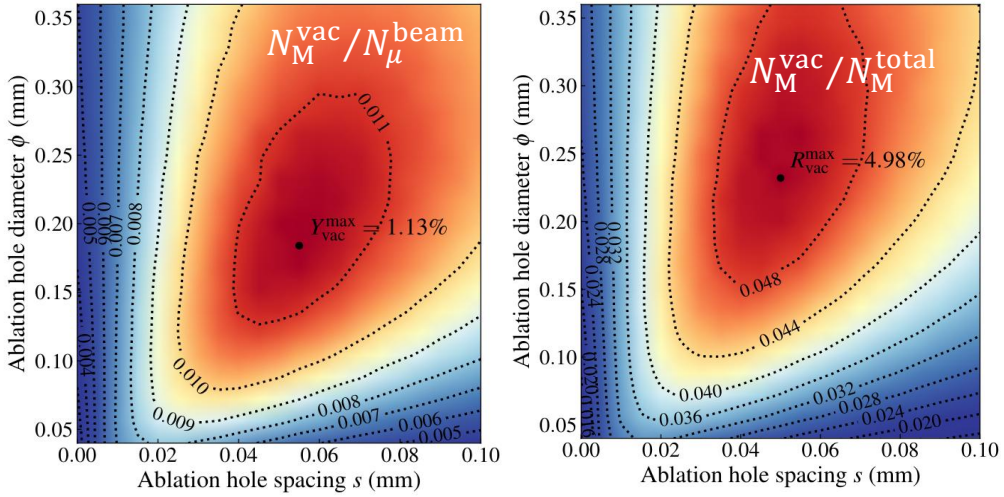
- Intensity of in-vacuum muonium source: $I_{\mathrm{M}}^{\mathrm{vac}} = I_{\mathrm{beam}} Y_{\mu\to\mathrm{M}}$
- $Y_{\mu\to\mathrm{M}}$ can be improved by utilizing porous materials, ideally perforated silica aerogel.
- A simulation method is developed to accurately simulate muonium production and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



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

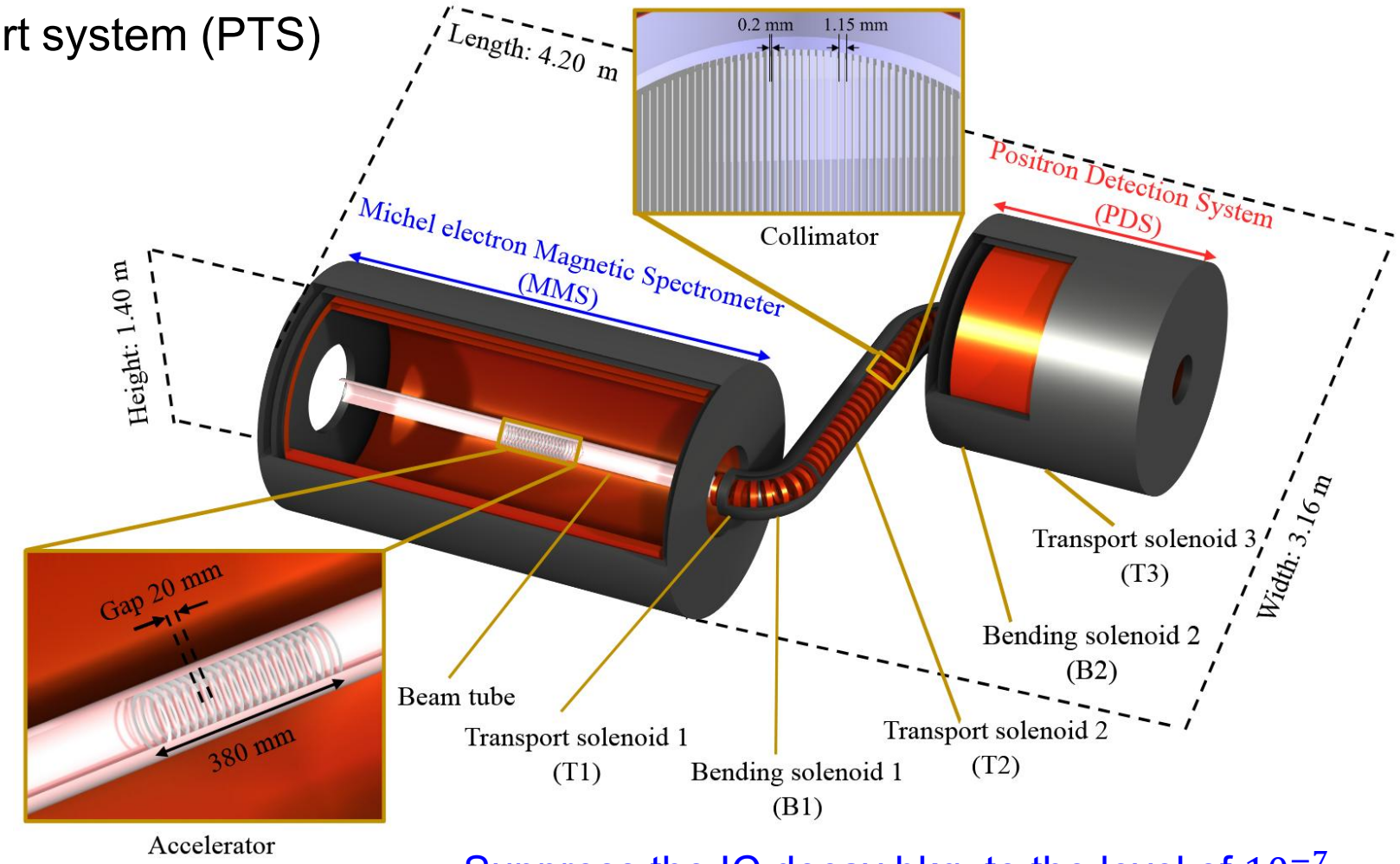
- The simulation is validated by muonium yield data measured in TRIUMF. J. Beare et al., PTEP. 2020, 123C01 (2020)
- Optimize $Y_{\mu\to\mathrm{M}}$ in perforated bulk target by scanning parameters, it can achieve
  - ✓ Max $Y_{\mu\to\mathrm{M}} = N_{\mathrm{M}}^{\mathrm{vac}}/N_{\mu}^{\mathrm{total}}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



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



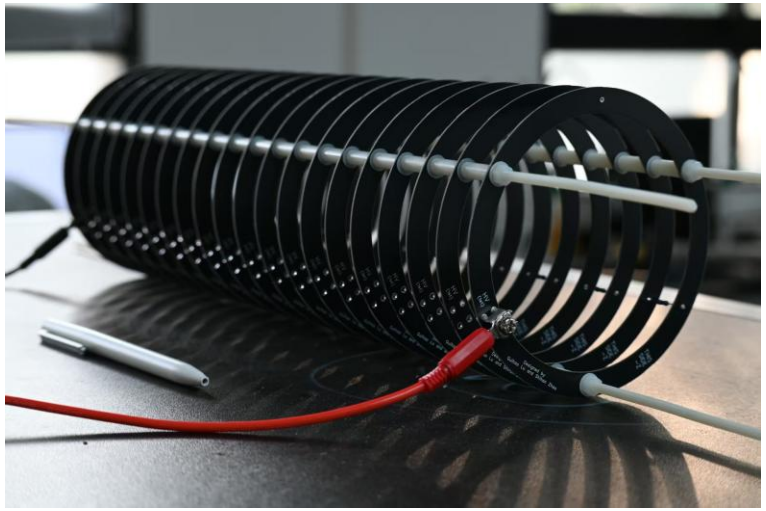
Suppress the IC decay bkg. to the level of 10^{-7}

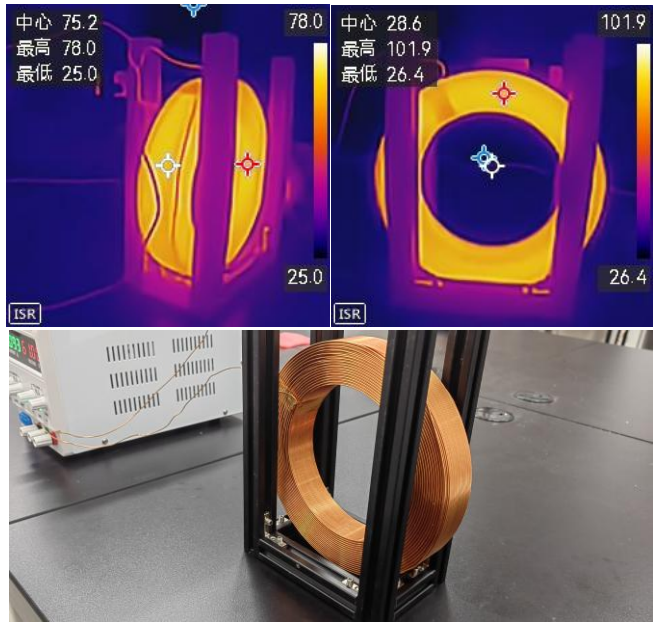
Lu, Guihao, et al. "Positron Transport System for Muonium-to-Antimuonium Conversion Experiment." *arXiv preprint arXiv:2508.07922* (2025).

PTS prototyping progress

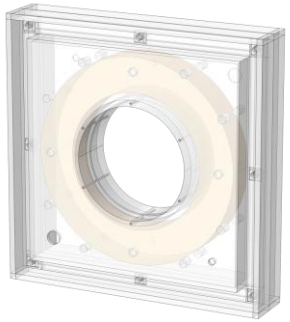
- **PTS validation**

  Testing with TS solenoids and accelerator module





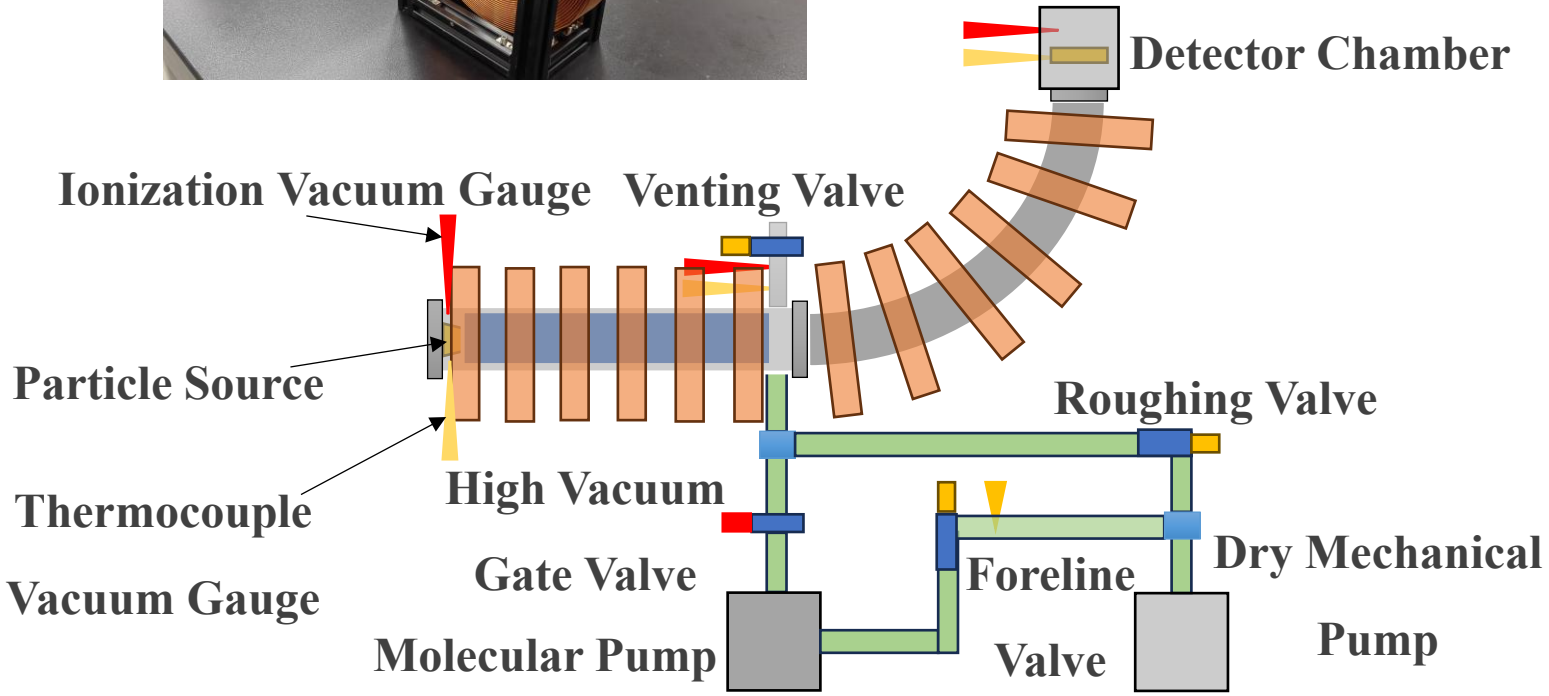
Credit: Guihao Lu



- Accelerator module prototype

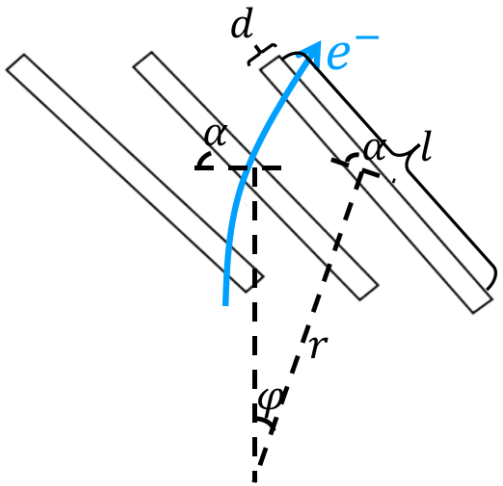
  Multi-layer PCB

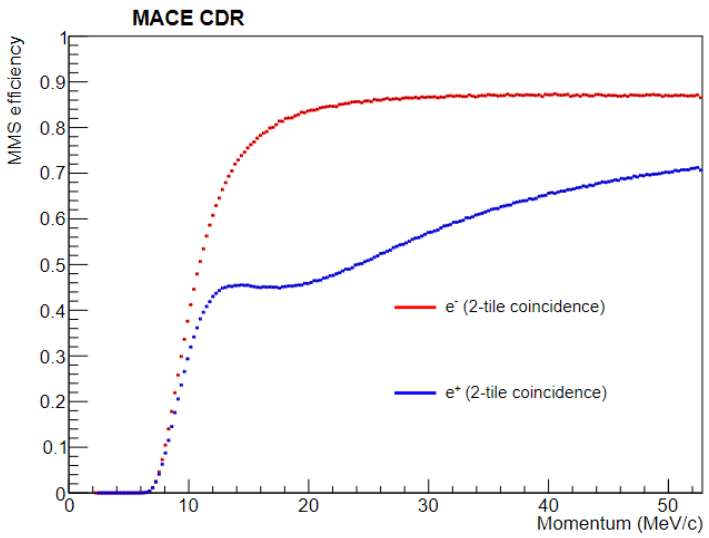
  High voltage > 2 kV

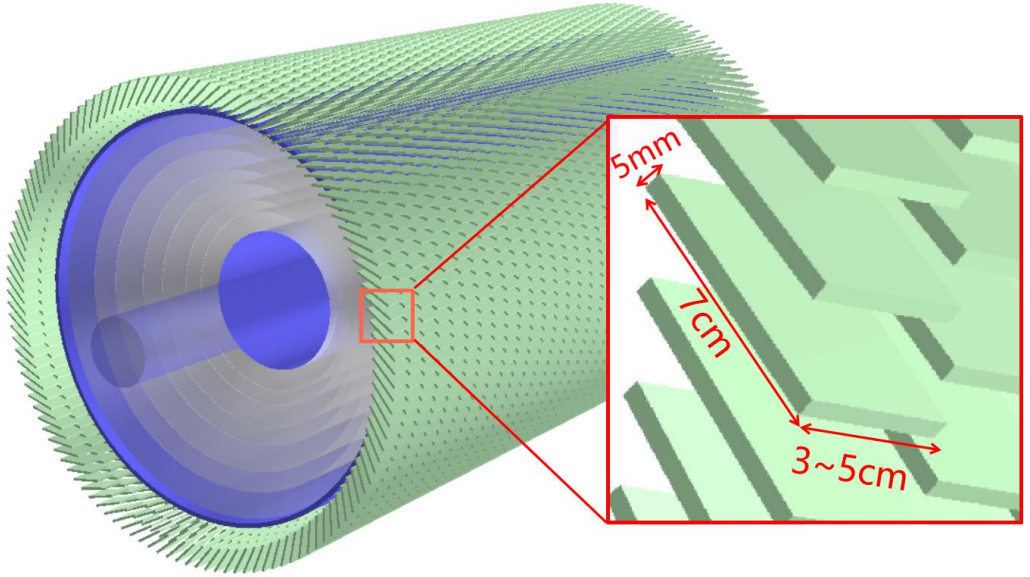


Tiled timing counter

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

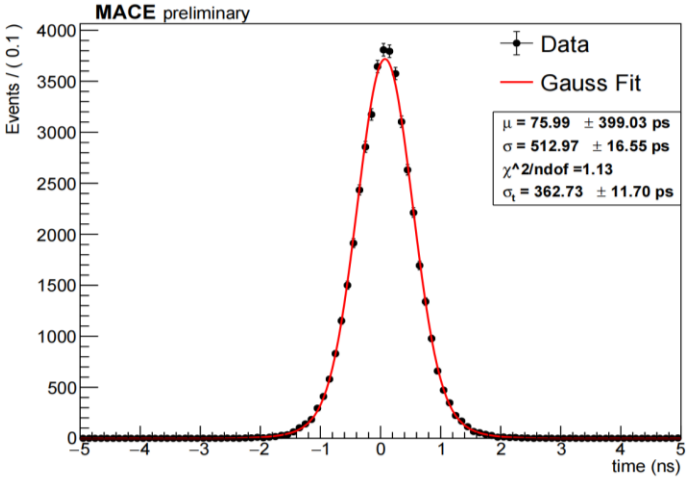






Test with cosmic-ray muons:

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

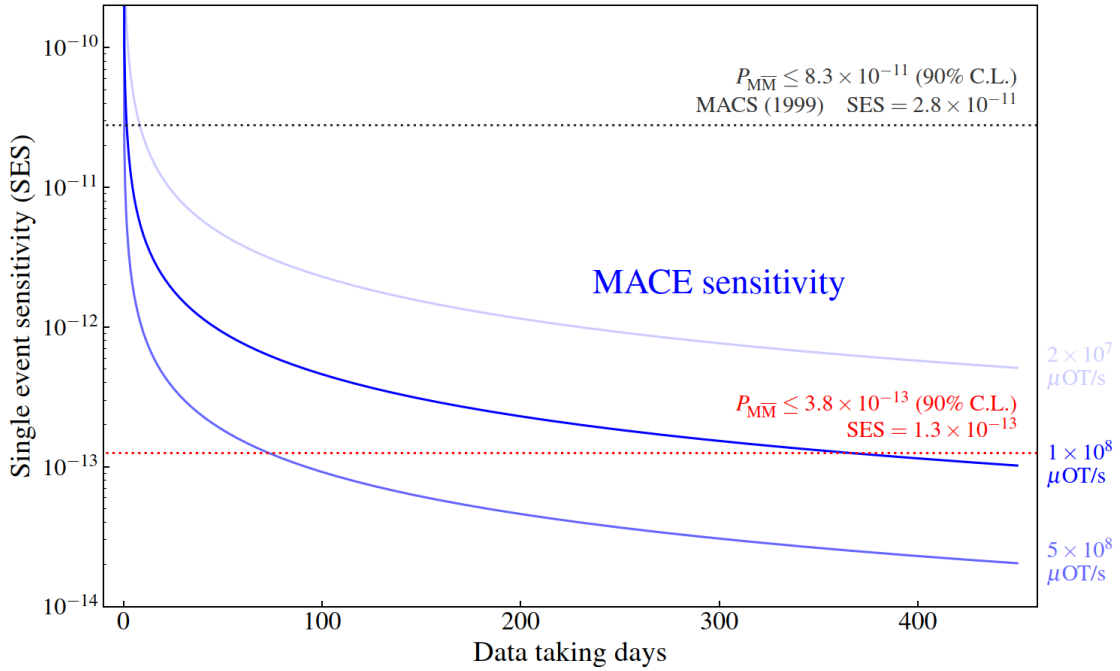


Credit: Hao Jiang

Sensitivity estimation

- Summary of current 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 ($\varepsilon^{\mathrm{geom}}_{\mathrm{MMS}}$)	84.6%
	Reconstruction efficiency ($\varepsilon^{\mathrm{recon}}_{\mathrm{MMS}}$)	$\sim 80\%$
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 $\varepsilon^{\mathrm{In}}_{\mathrm{ECAL}}$	63.4%
	Geometric efficiency $\varepsilon^{\mathrm{Geom}}_{\mathrm{ECAL}}$	95.3%
	Reconstruction efficiency $\varepsilon^{\mathrm{Recon}}_{\mathrm{ECAL}}$	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:

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

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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

☐ Test of the Standard Model

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

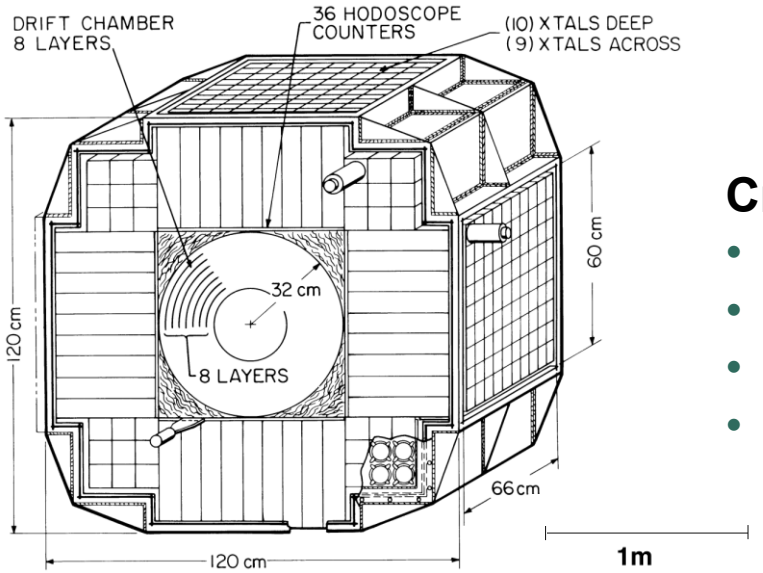
EPJC 76 (2016) 3, 108

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

PRL. 115 (2015) 7, 071801

arXiv:2203.01981

PIONEER CDR, 2022

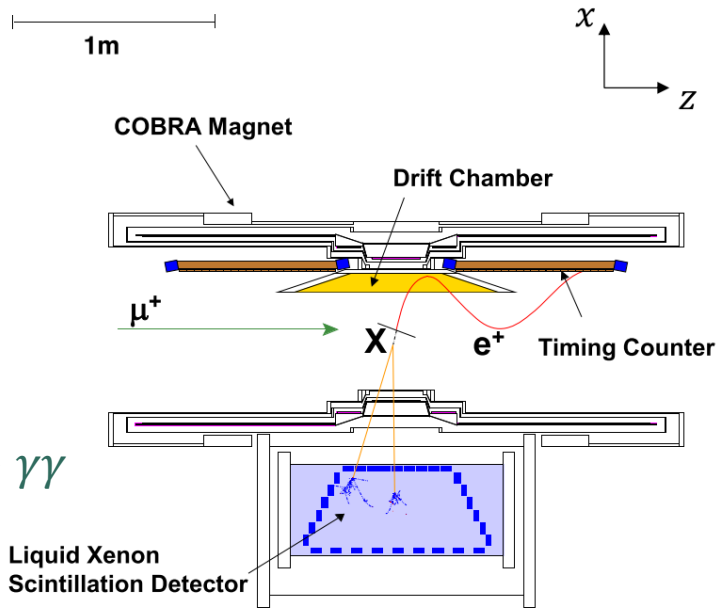


Crystal Box:

- $\mu^+ \to e^+\gamma\gamma$
- $\mu^+ \to e^+X, X \to \gamma\gamma$
- $\mu^+ \to e^+\gamma f$
- …

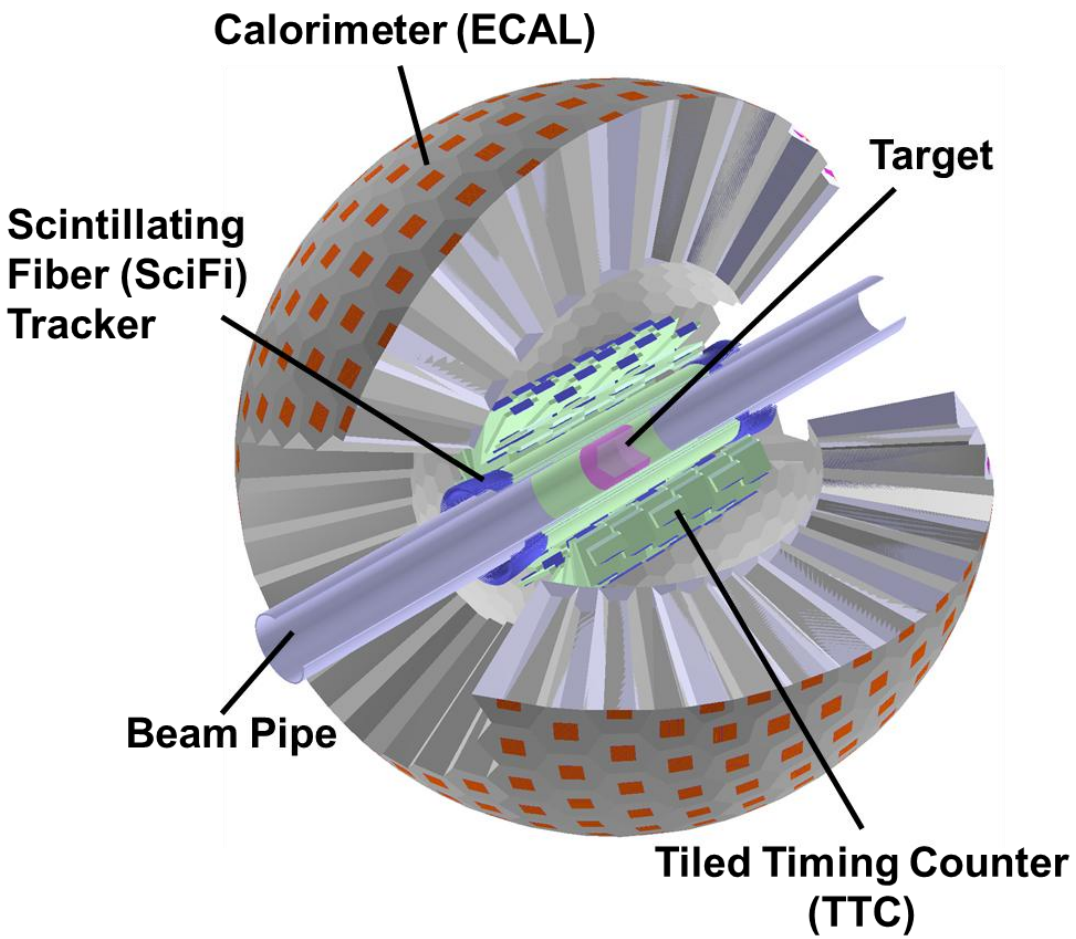
MEG:

- $\mu^+ \to e^+\gamma$
- $\mu^+ \to e^+\gamma\nu\nu$
- $\mu^+ \to e^+X, X \to \gamma\gamma$



How to improve the sensitivity?

MACE Phase-I detector



Phase-I requirements：

- High-intensity muon beam —— improvement of statistics
- Detectors with fast response —— “pileup” rejection
- e^+ tracking and timing, e^+/γ discrimination
- High acceptance and granularity, good resolution

Challenge： No applied magnetic field, high background rate.

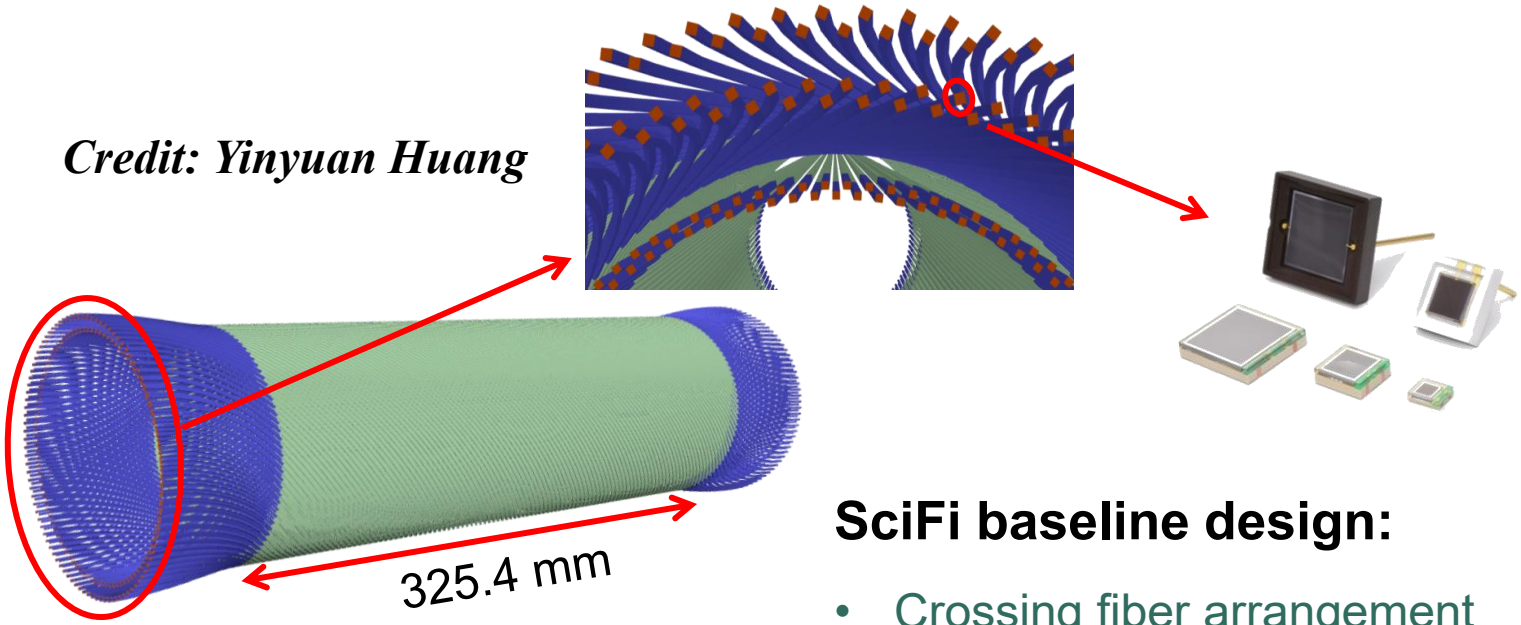
Tracker System

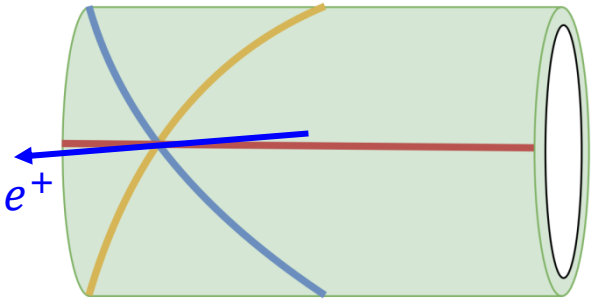
- Precise timing and tracking ability
- Low material budget
- Low cost
- e^+/γ discrimination
  - High active area
  - High e^+ detection efficiency
  - Low γ detection efficiency

⇩

Plastic scintillators!

Credit: Yinyuan Huang



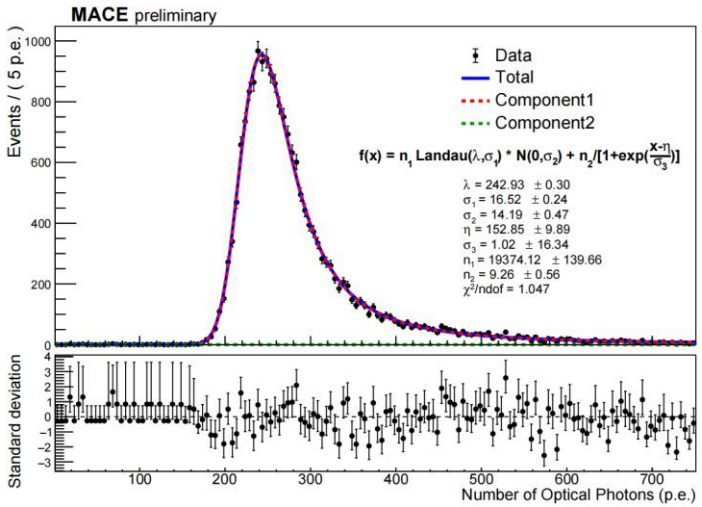


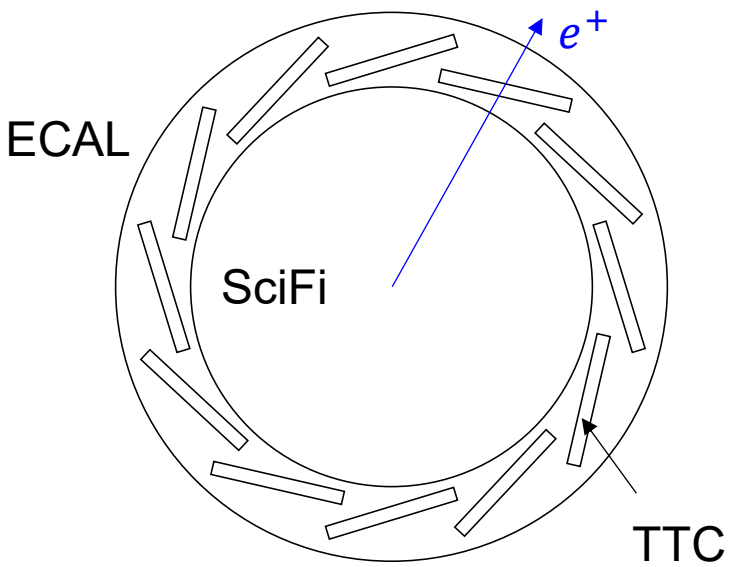
SciFi baseline design:

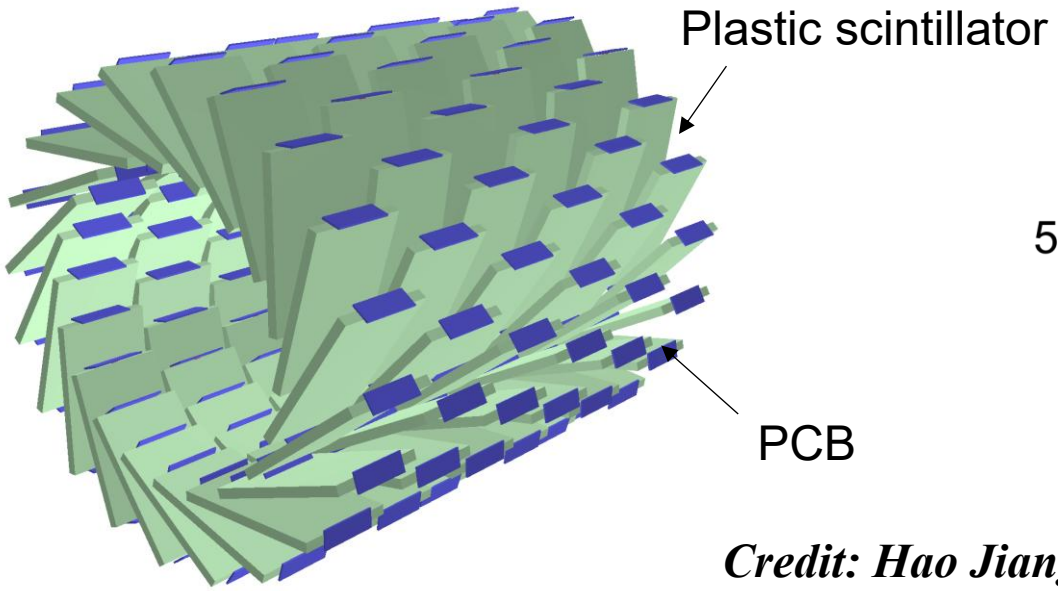
- Crossing fiber arrangement
- 2360 channels
- Single-end readout by SiPM
- Spatial resolution ~1 mm
- Timing resolution ~800 ps
- $\varepsilon_{\mathrm{Recon}} \approx 80\%$
- $\varepsilon_e = 96\%$
- $\varepsilon_\gamma = 3\%$

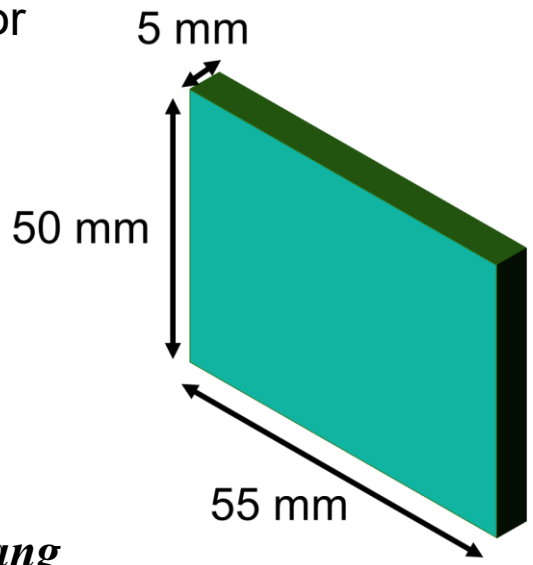
Tracker System

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







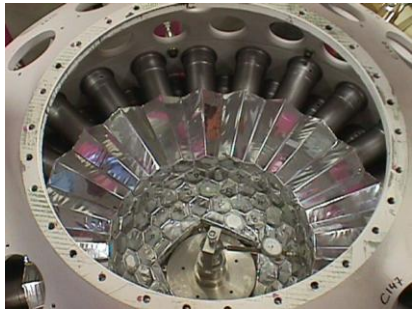


Credit: Hao Jiang

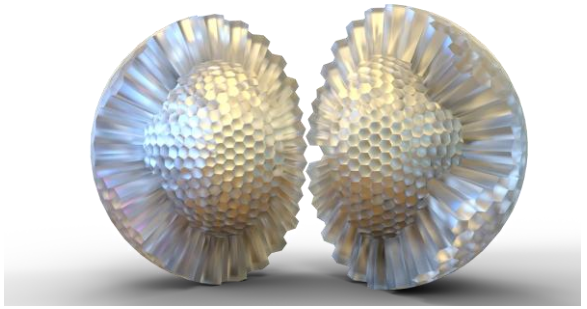
Electromagnetic Calorimeter

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

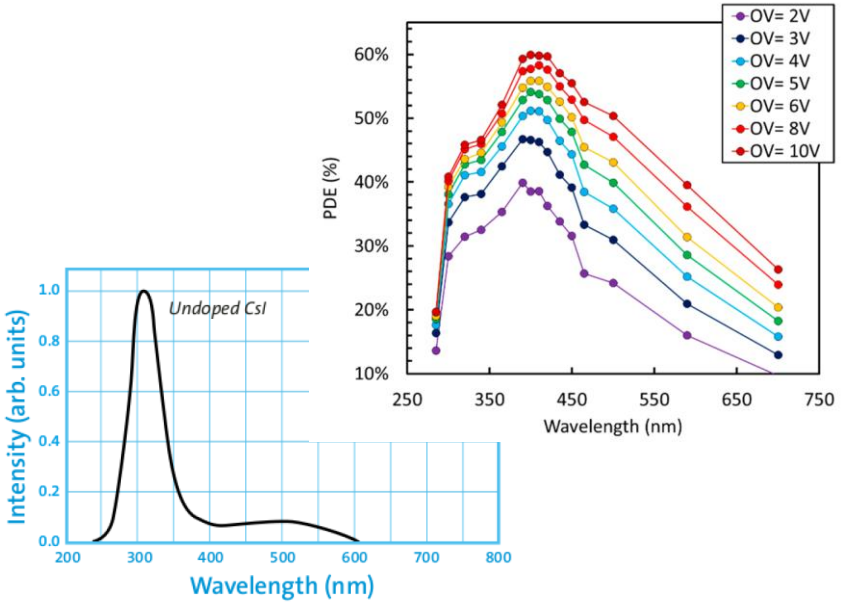
- 30000 ph/MeV
- **40 ns**
- Radiation hard
- Not hygroscopic
- Emits at 420 nm
- CNY ￥300/cm^3

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**

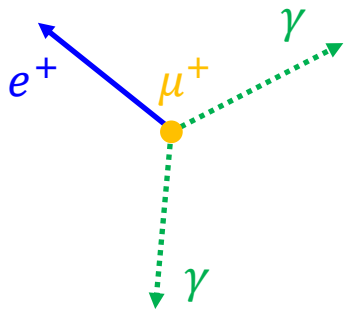


NUV SiPM readout

Sensors 19 (2019) 2, 308

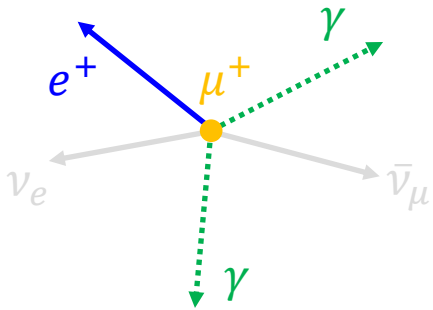
Sensitivity estimation of $\mu^+ \to e^+\gamma\gamma$

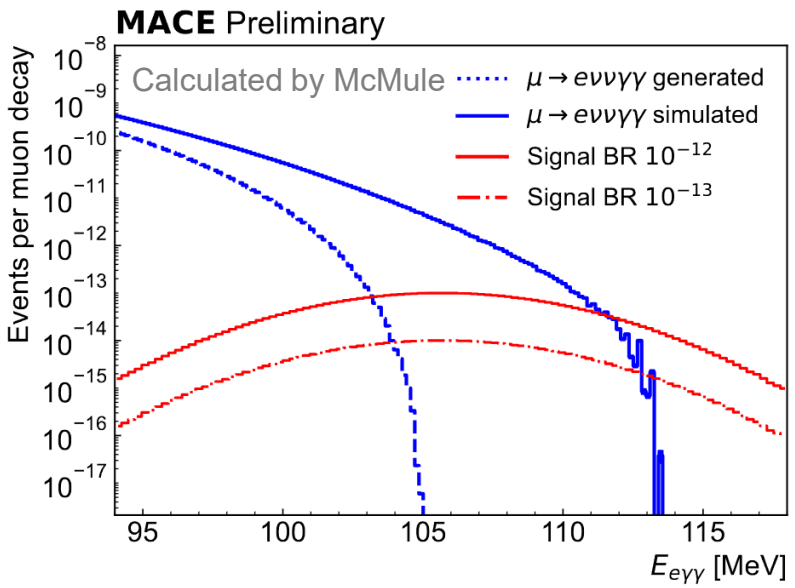
Signal:
Triple coplanar tracks
e^+ and two γs



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

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

$$n_{obs} = b$$

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

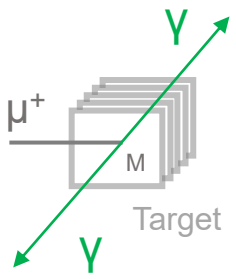
Total energy cut: 107.5 MeV

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

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

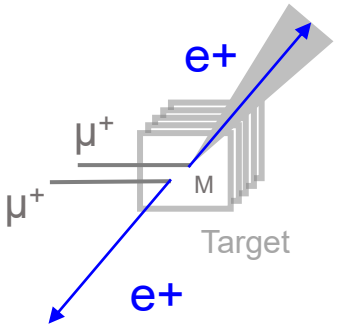
Sensitivity estimation of $M \to \gamma\gamma$

Signal: Double collinear 53 MeV gamma-rays



- No response in Tracker
- Double tracks reconstructed by ECAL

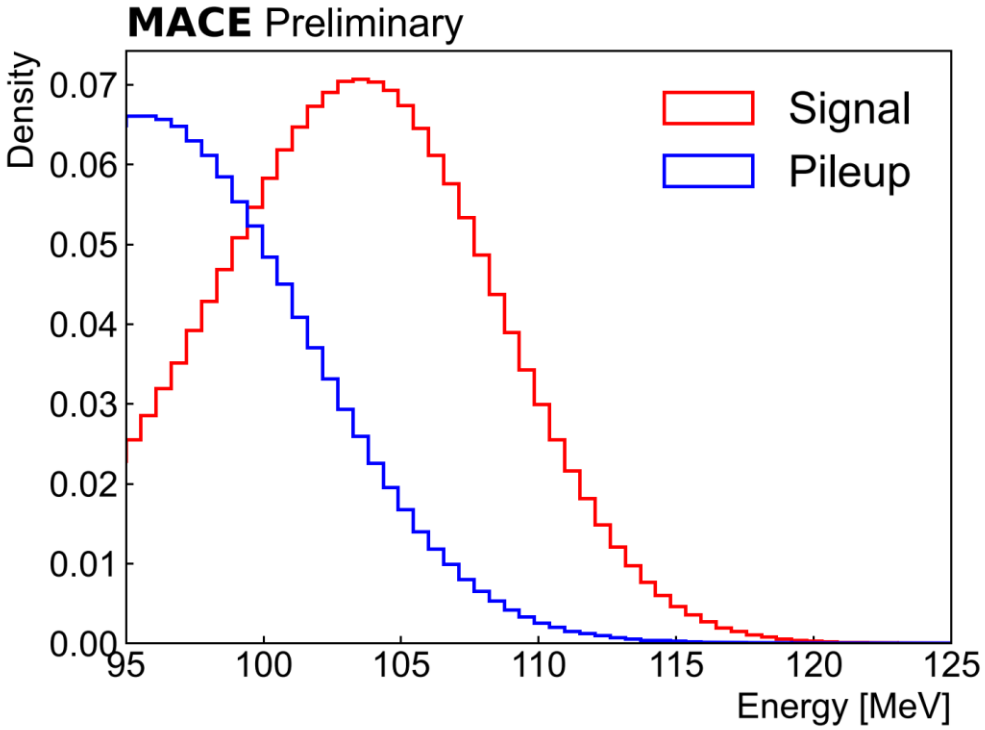
Background: Accidental coincidence of "pileup" positrons



Importance biasing simulation

- Energy and angular biasing
- Speeding up by $\sim 10^6$

More background simulations and refined data analyses to be updated!



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

$$n_{obs} = b$$

$$\mathcal{BR}(M \to \gamma\gamma) = \frac{s_{up}}{\varepsilon_{signal} Y_M \Phi_\mu T}$$

Upper limit of BR: 1.55×10^{-13} (90% C.L.)

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

Contents

- Motivations
- MACE conceptual design
- Proposal of MACE Phase-I
- Summary

Summary

- 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 other muon(ium) cLFV decay modes could be forthcoming, 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

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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Thank you!

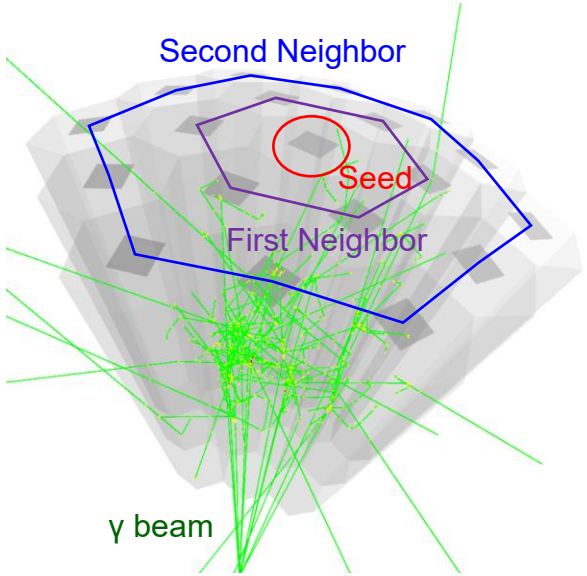
Contact person:
Prof. Jian Tang (tangjian5@mail.sysu.edu.cn)

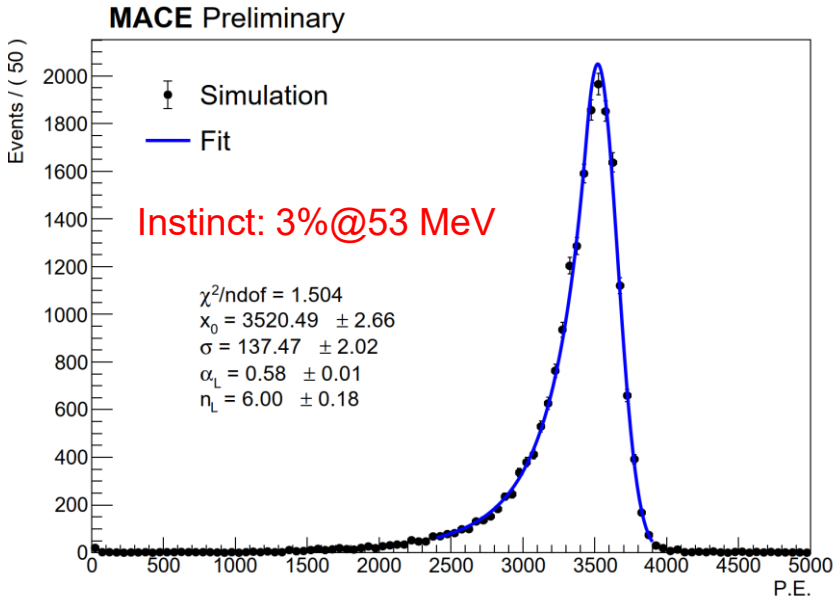
Backup slides

ECAL performance

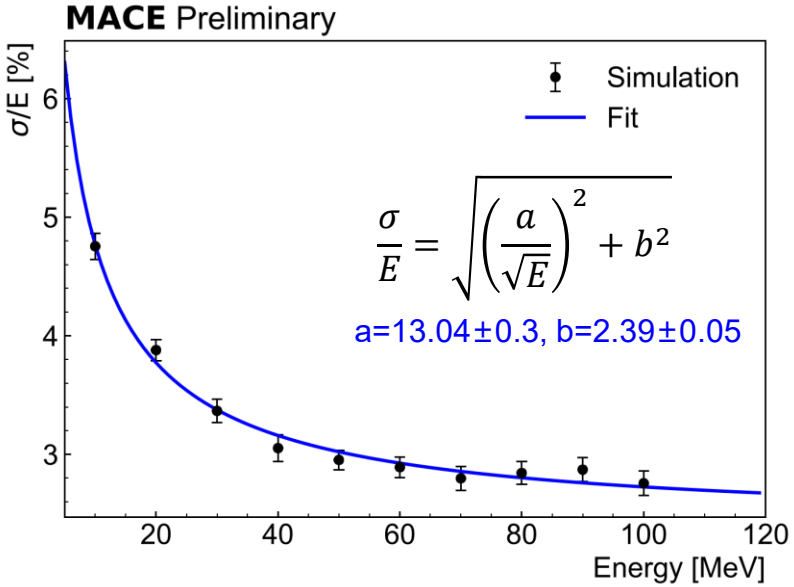
- Baseline requirement based on full simulation:
  - Coincidence timing resolution better than **200 ps**
  - Energy resolution better than **6% @ 53 MeV**
  - Angular resolution better than **10°**

Energy-weighted clustering

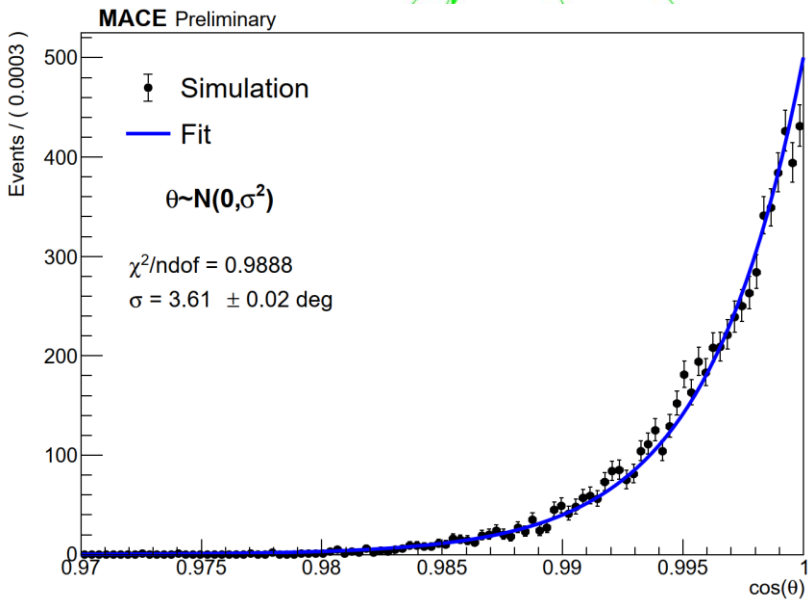




Simulated QDC value
fitted by Crystal Ball function



Energy resolution curve

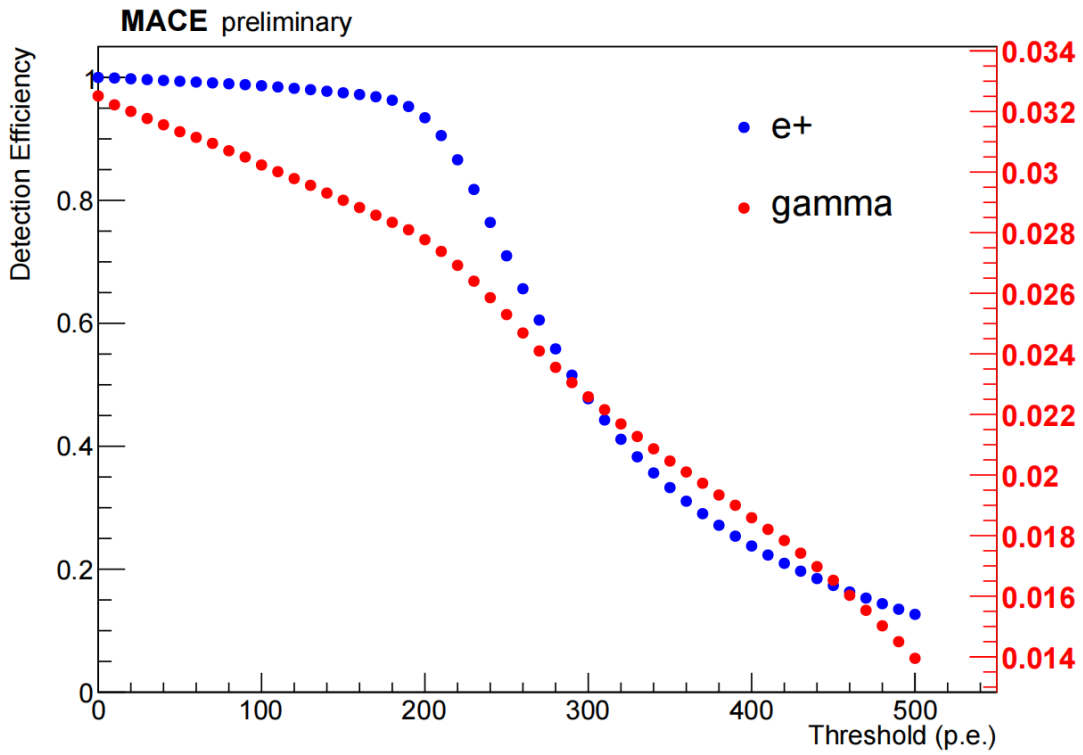


Angular resolution

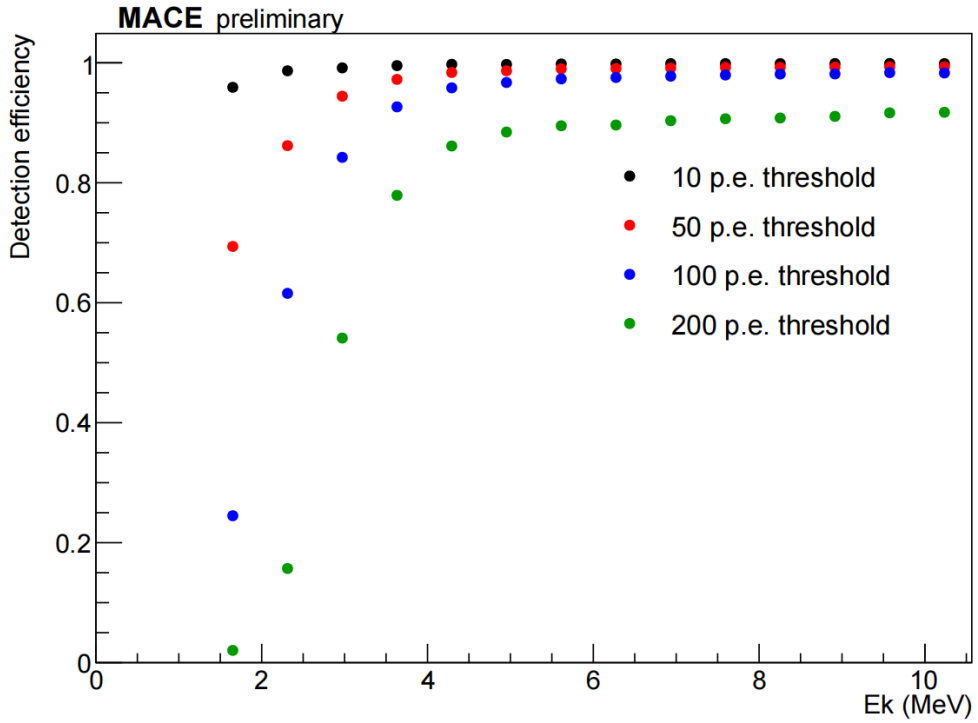
TTC efficiency in Phase-I

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

✓ $\varepsilon_e = 99\%$ $\varepsilon_\gamma = 3\%$ with 10 p.e. threshold



53 MeV, Threshold vs. Efficiency



e^+, Energy vs. Efficiency