Status of Muonium-to-Antimuonium Conversion Experiment (MACE)

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SMOOTH Lab @ SYSU & the MACE working group

SYSU MuOn and Optical TomograpHy

Muonium-to-Antimuonium Conversion Experiment

Reference: Conceptual Design of MACE, arXiv: 2410.18817, Invited review on muonium physics, to appear soon.

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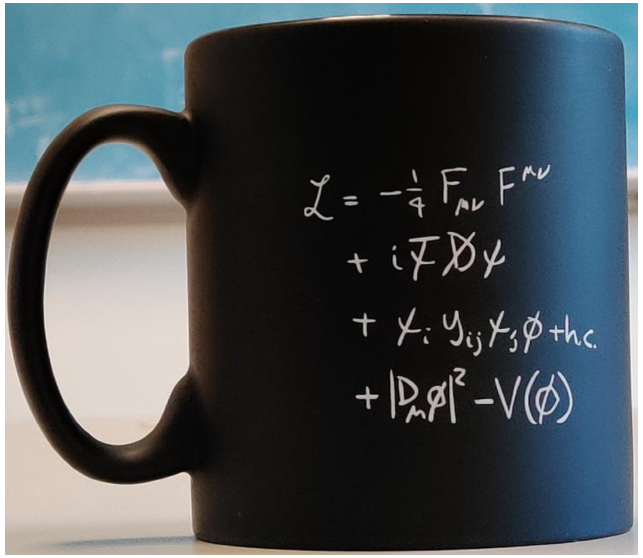
Symmetries of SM

- The Standard Model (SM) gauge symmetry:

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



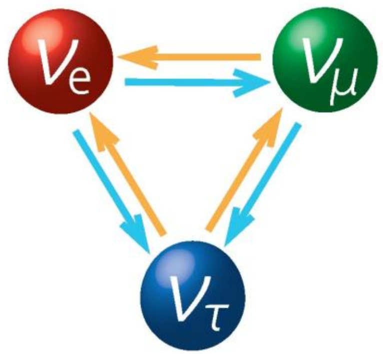
- The absence of right-handed neutrino leads to lepton flavor symmetry:

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

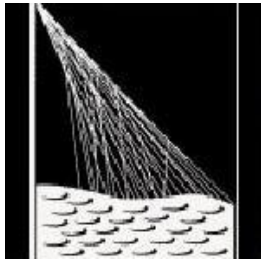
	Lepton number	Lepton family number (lepton flavor)		
		L_e	L_μ	L_τ
e^- & ν_e	1	1	0	0
μ^- & ν_μ	1	0	1	0
τ^- & ν_τ	1	0	0	1

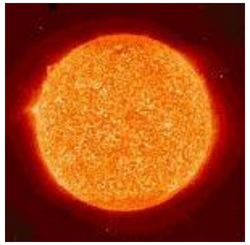
- Lepton flavor is always conserved **in the Standard Model,** however…

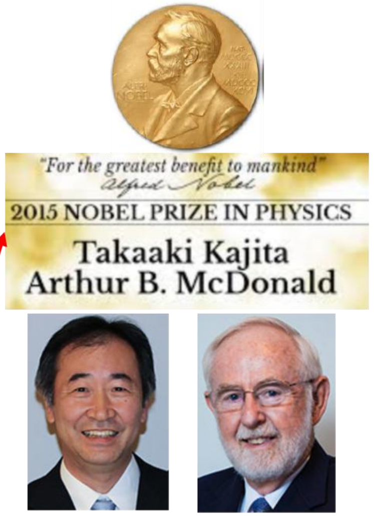
Neutral leptons oscillate!



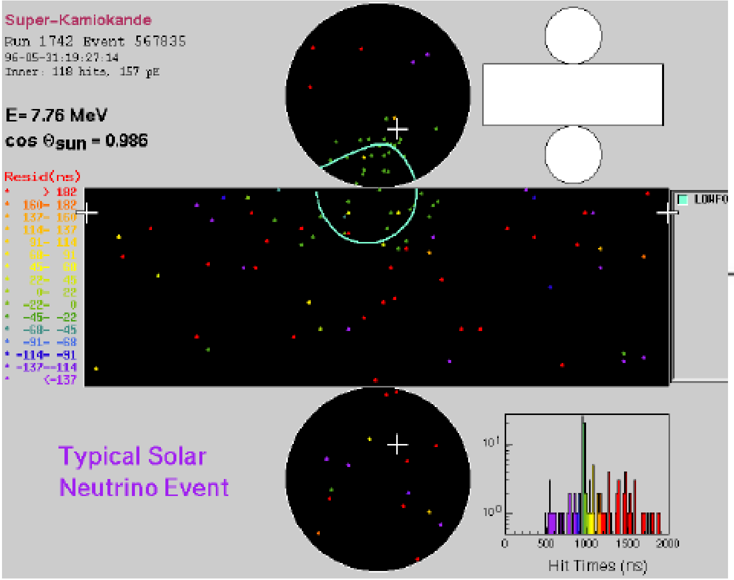
$$U_{\rm PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\, e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}\, e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} .$$

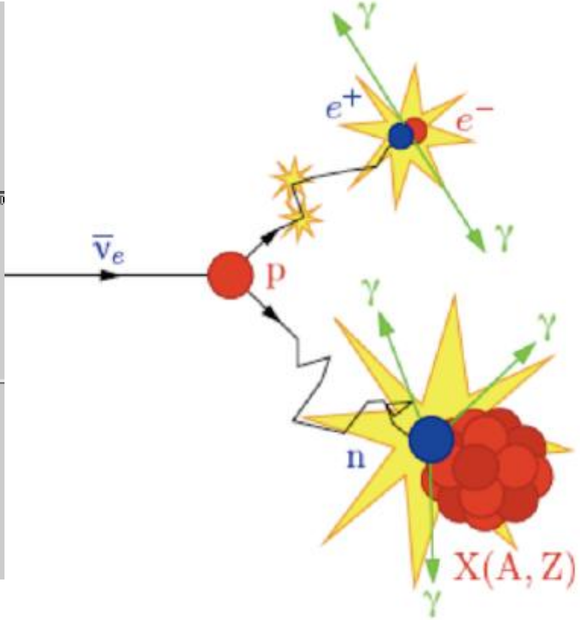
= () x (

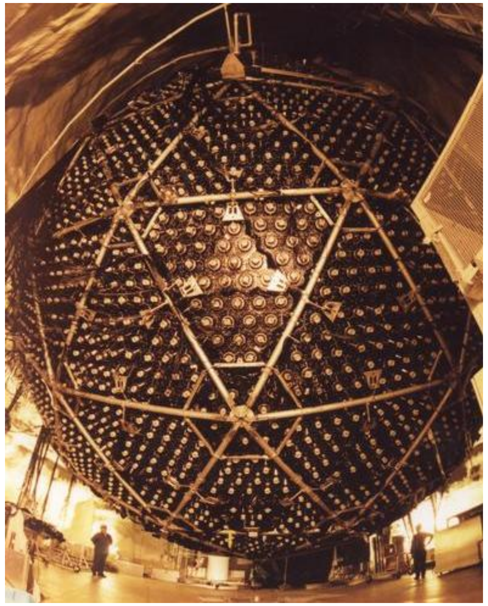
) x ()



"For the discovery of neutrino oscillations, which shows that neutrinos have mass"







cLFV: a portal of new physics

- **Lepton flavor is not conserved in the real world.**
  - Neutrino oscillation: neutrinos have mass and mixing.
  - So cLFV should exist, but it hasn't been seen yet...
- ✓ Many new physics model beyond SM predict observable cLFV.
- Charged lepton flavor violation (cLFV) → a way to new physics beyond SM.

✓ **cLFV is forbidden in SM, free of SM background.**

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

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

✓ **Provides a strong constrain to new physics models if not discovered.**

Muonium-to-Antimuonium Conversion Experiment

MEGII (PSI)	Mu3e (PSI)	Mu2e (Fermilab)	COMET (J-PARC)	**MACE in China initiative muon beamline**
$\mu^+ \to e^+\gamma$	$\mu^+ \to e^+e^-e^+$	$\mu^-\mathrm{N} \to e^-\mathrm{N}$	$\mu^-\mathrm{N} \to e^-\mathrm{N}$	$\mathrm{M} \to \overline{\mathrm{M}}$ $(\mu^+e^- \to \mu^-e^+)$

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High-intensity/-precision frontier

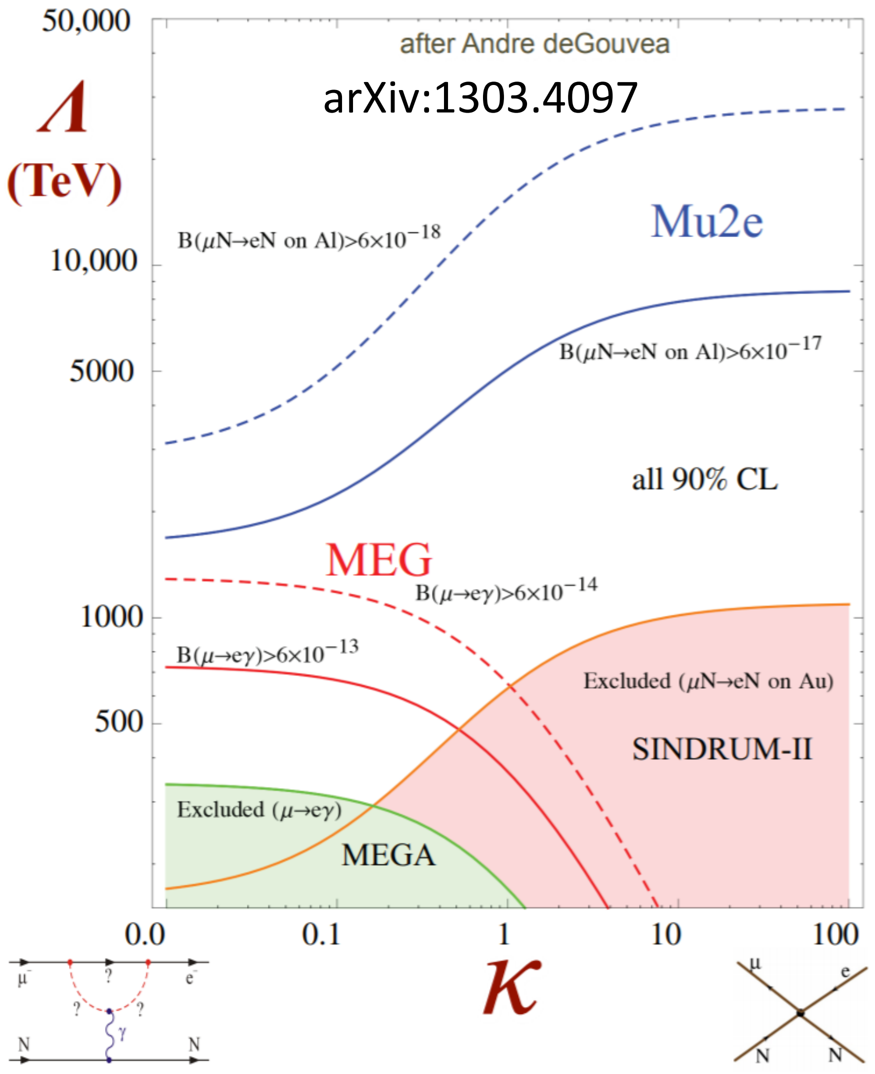
- **Experiments search for cLFV:**
  - Mu2e (Fermilab)
  - COMET (J-PARC)
  - MEG (PSI)
  - Mu3e (PSI)

$$\mu^- + \mathrm{Al} \rightarrow e^- + \mathrm{Al}$$

$$\mu^+ \rightarrow e^+\gamma$$

$$\mu^+ \rightarrow e^+e^-e^+$$

- **Precision measurements of muon properties:**
  - MuLan & FAST at PSI: Muon lifetime.
  - MuCap in PSI: Muon capture coupling constant.
  - MuSun: Muon Electroweak interactions and muon polarization.
  - TWIST at TRIUMF: Muon decay Michel parameters.
  - Fermi lab muon g-2 and J-PARC muon g-2.
  - MUSEUM: Muonium hyperfine structure.



Low-energy cLFV experiments complement high-energy frontier

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High-intensity/-precision frontier

- **Experiments search for cLFV:**
  - ➢ Mu2e (Fermilab)
  - ➢ COMET (J-PARC)

$$\mu^- + \mathrm{Al} \to e^- + \mathrm{Al}$$

  - ➢ MEG (PSI)

$$\mu^+ \to e^+\gamma$$

  - ➢ Mu3e (PSI)

$$\mu^+ \to e^+e^-e^+$$

- **Precision measurements of muon properties:**
  - ➢ MuLan & FAST at PSI: Muon lifetime.
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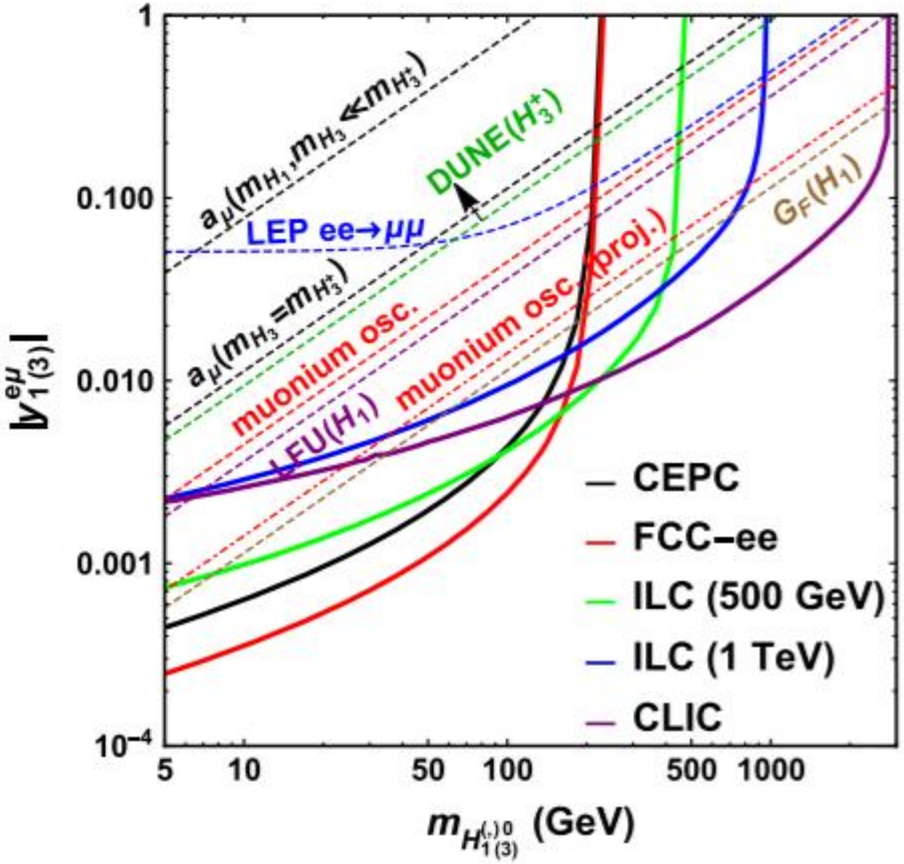
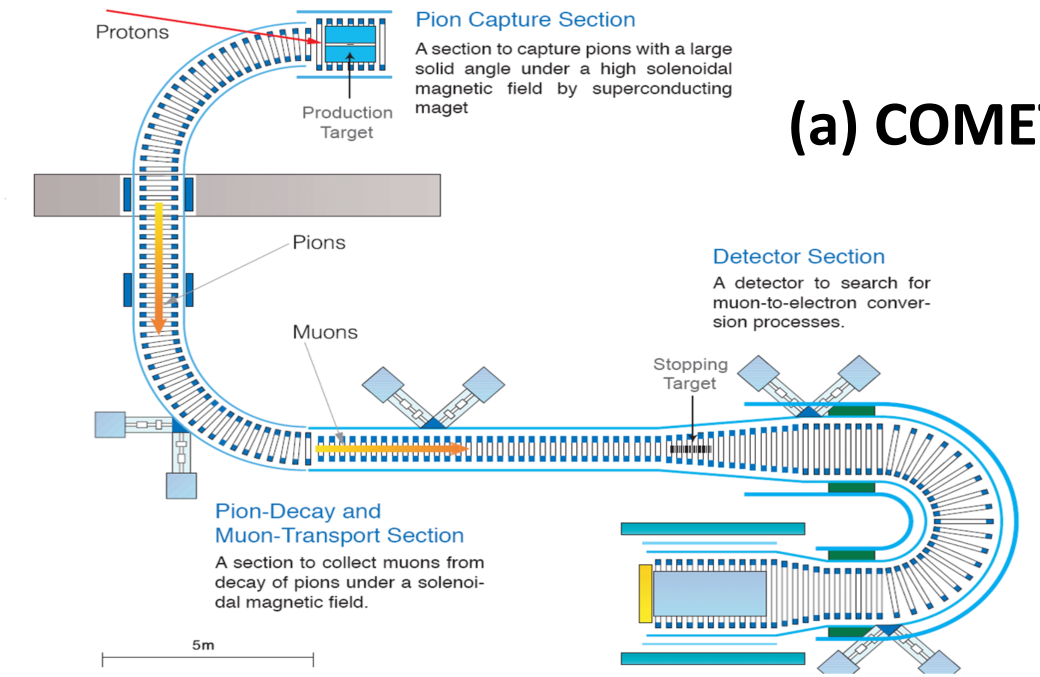


REF: *Tong Li, Michael A. Schmidt. Phys.Rev.D* 100 (2019) 11, 115007

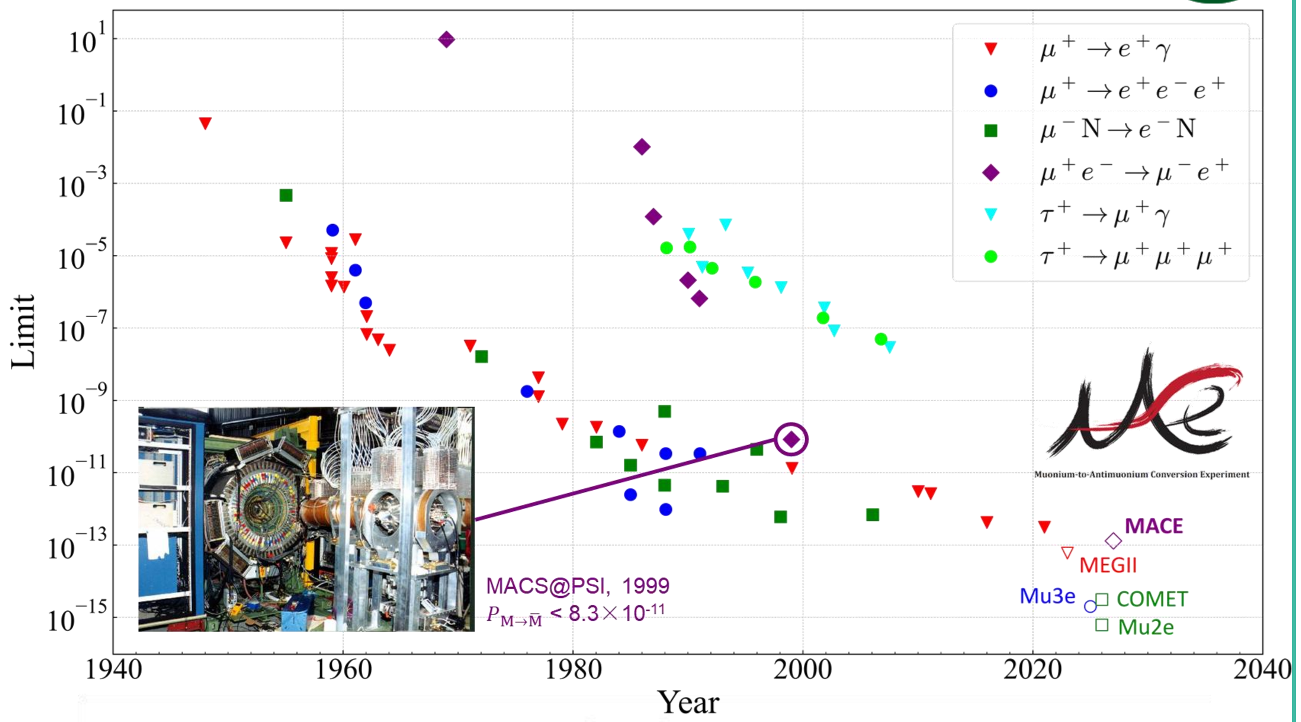
- **Low-energy cLFV experiments complement high-energy frontier**
- **cLFV complement neutrino physics**

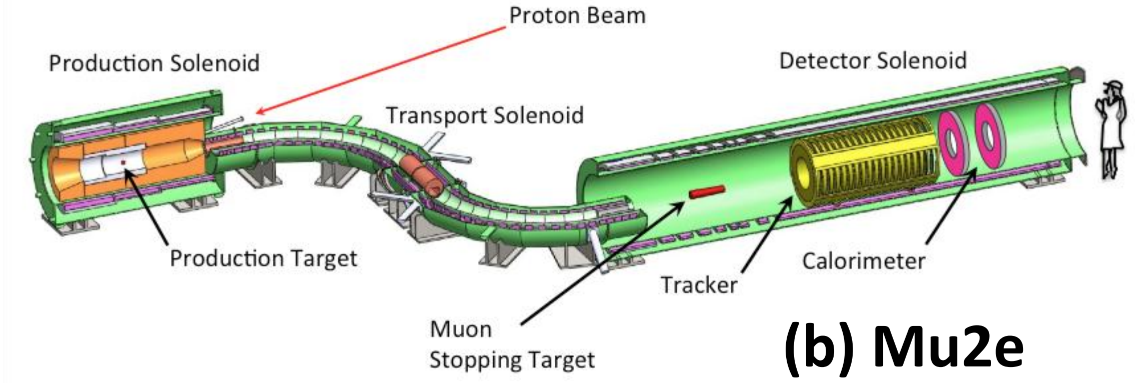
High-intensity/-precision frontier

- **Experiments search for cLFV:**
  - Mu2e (Fermilab) $\mu^- + Al \rightarrow e^- + \mathrm{Al}$
  - COMET (J-PARC)
  - MEG (PSI) $\mu^+ \rightarrow e^+\gamma$
  - Mu3e (PSI) $\mu^+ \rightarrow e^+e^-e^+$



(a) COMET





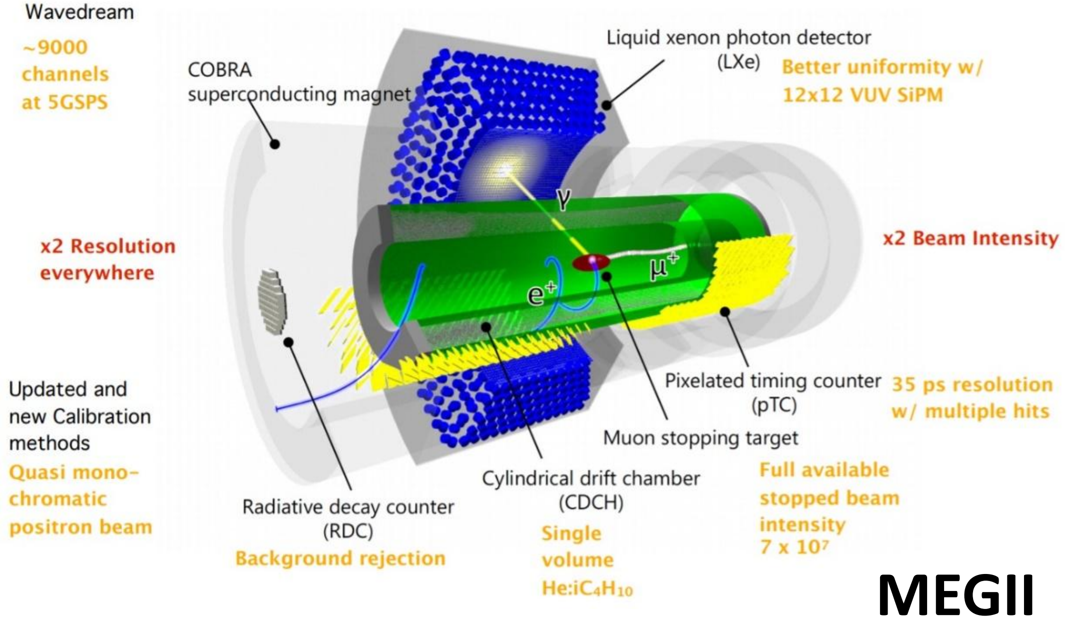
(b) Mu2e

High-intensity/-precision frontier

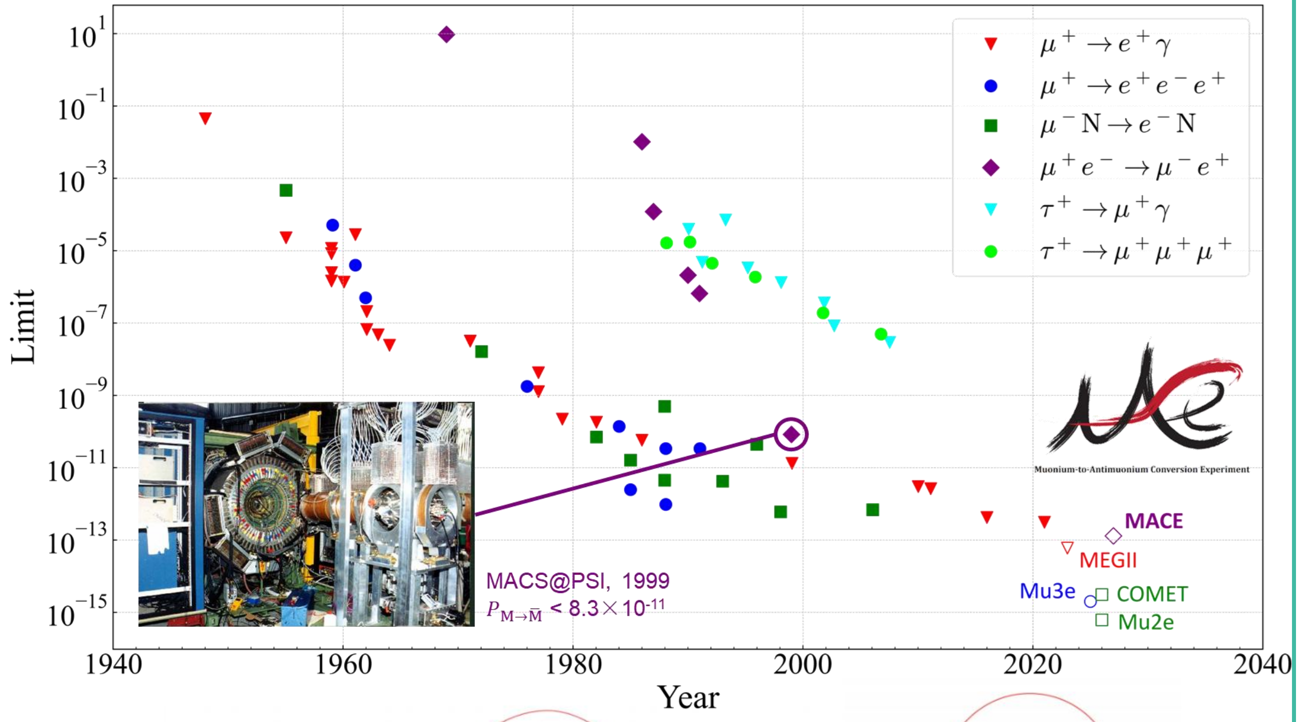
- **Experiments search for cLFV:**
  - Mu2e (Fermi lab)
  - COMET (J-PARC)

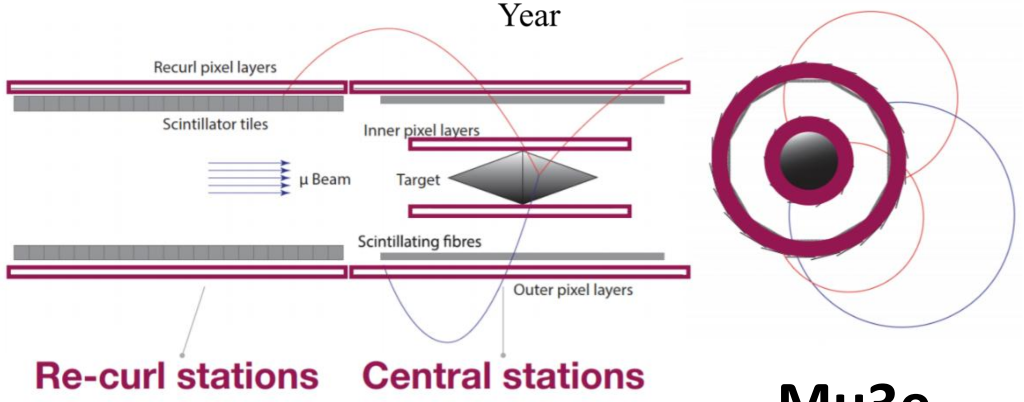
$$\mu^- + Al \rightarrow e^- + Al$$

  - MEG (PSI) $\boldsymbol{\mu^+ \rightarrow e^+\gamma}$
  - Mu3e (PSI) $\boldsymbol{\mu^+ \rightarrow e^+e^-e^+}$



MEGII

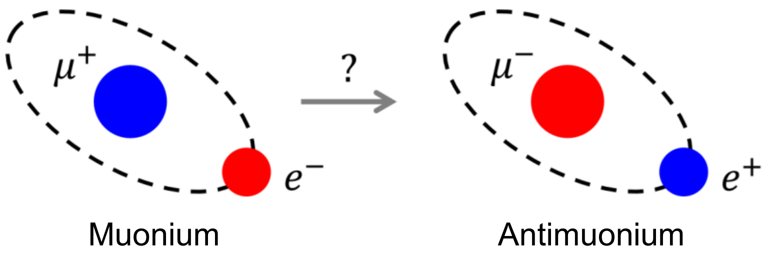




Mu3e

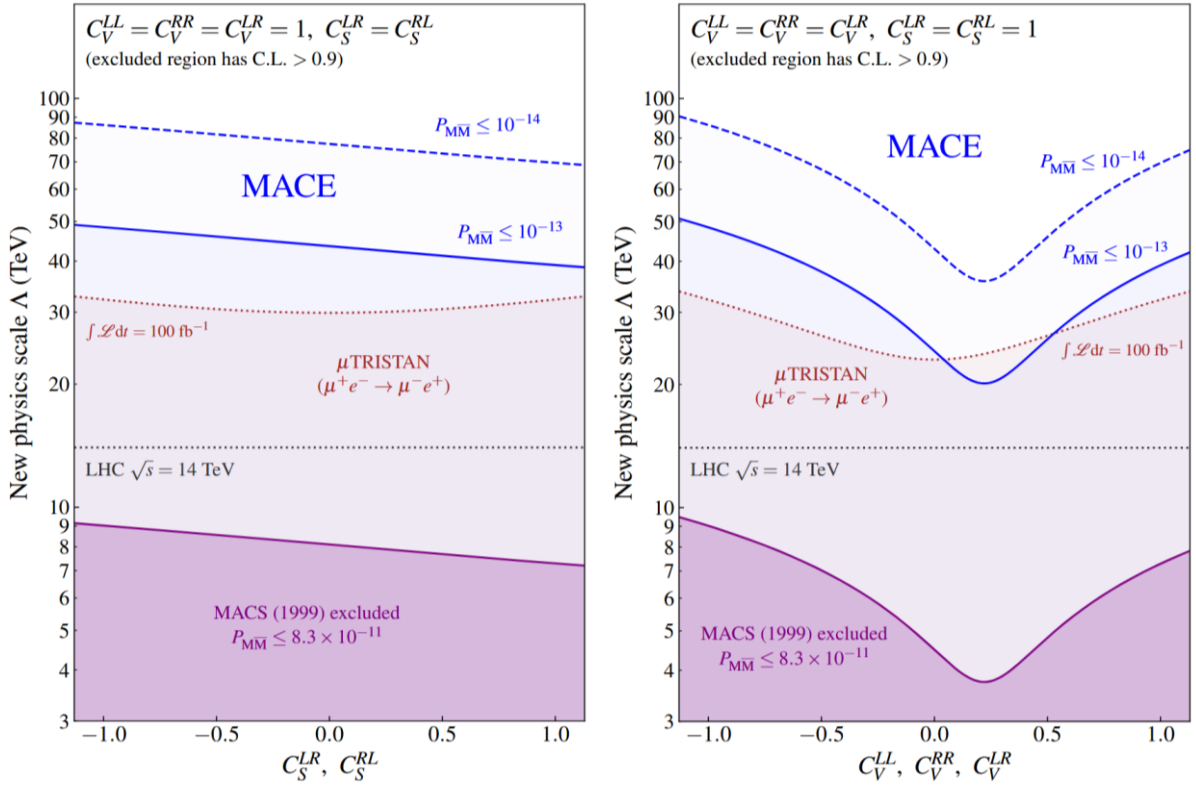
Muonium conversion: a cLFV process

- Muonium ($\mathrm{M} = \mu^+ e^-$): a leptonic hydrogen isotope.
- **M-to-$\overline{\mathrm{M}}$ conversion**: $\mathrm{M} \to \overline{\mathrm{M}}$ $(\mu^+ e^- \to \mu^- e^+)$

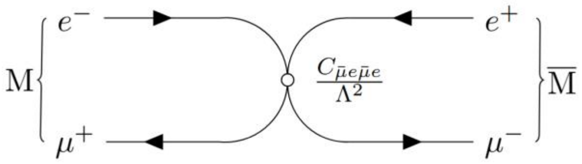


Current bound:
$P_{\mathrm{M}\to\overline{\mathrm{M}}}$ < 8.3×10^-11
(in 0.1T field, 90% C.L.)

L. Willmann et al.,
Phys. Rev. Lett. *82 (1999), 49-52.*



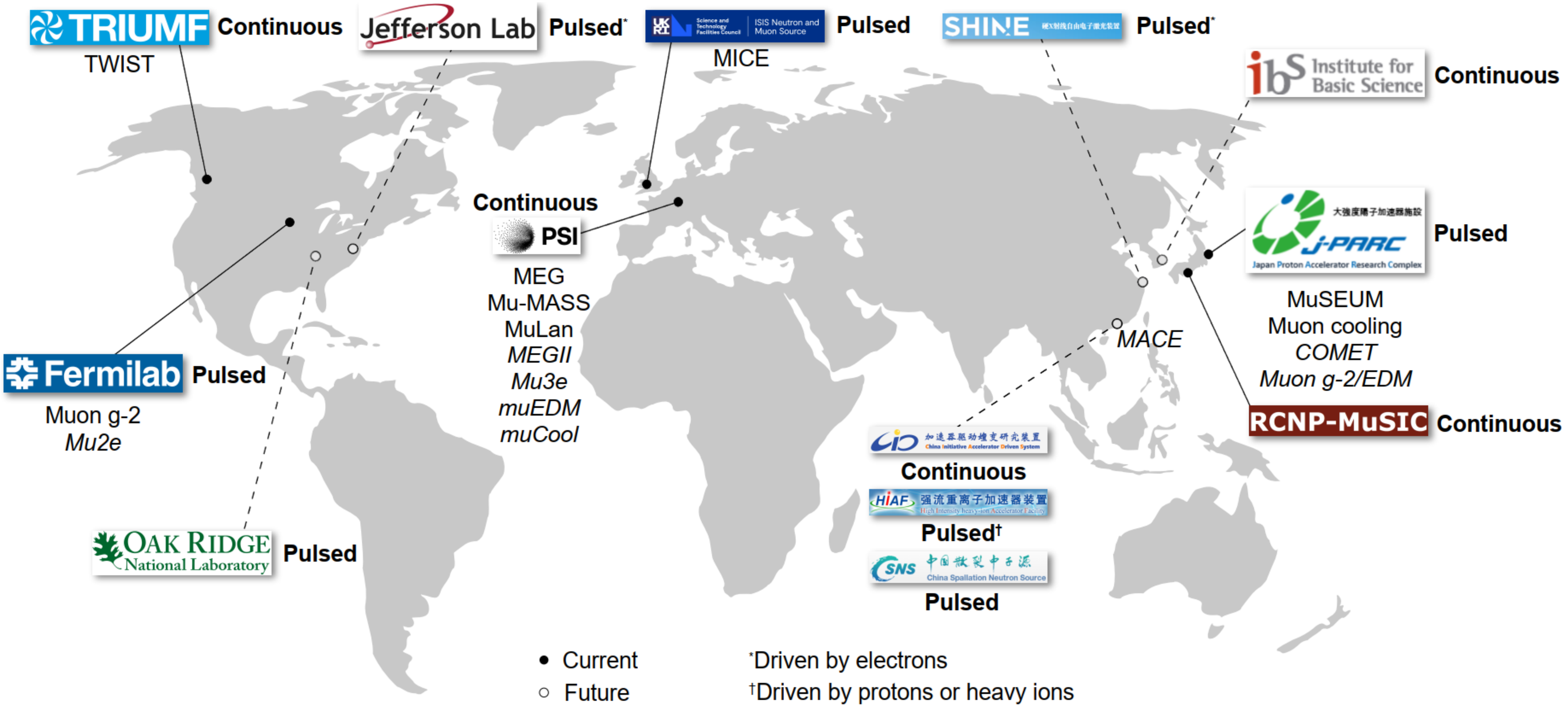
- $\mathrm{M} \to \overline{\mathrm{M}}$: an $\Delta L_\mu = -\Delta L_e = 2$ process.
  - ✓ Different EFT operators from $\Delta L_\mu = -\Delta L_e = 1$ proc. ($\mu \to e\gamma$, $\mu \to eee$, $\mu N \to eN$).
  - ✓ $\Delta L_\mu = -\Delta L_e = 2$ can be possible even if $\Delta L_\mu = -\Delta L_e = 1$ is suppressed or not exist.
  - ✓ Complementary to $\Delta L_\mu = -\Delta L_e = 1$ process searches.



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

Julian Heeck and Mikheil Sokhashvili. Lepton flavor violation by two units. ***Phys. Lett. B****, 852:138621, 2024.*

Worldwide accelerator muon sources



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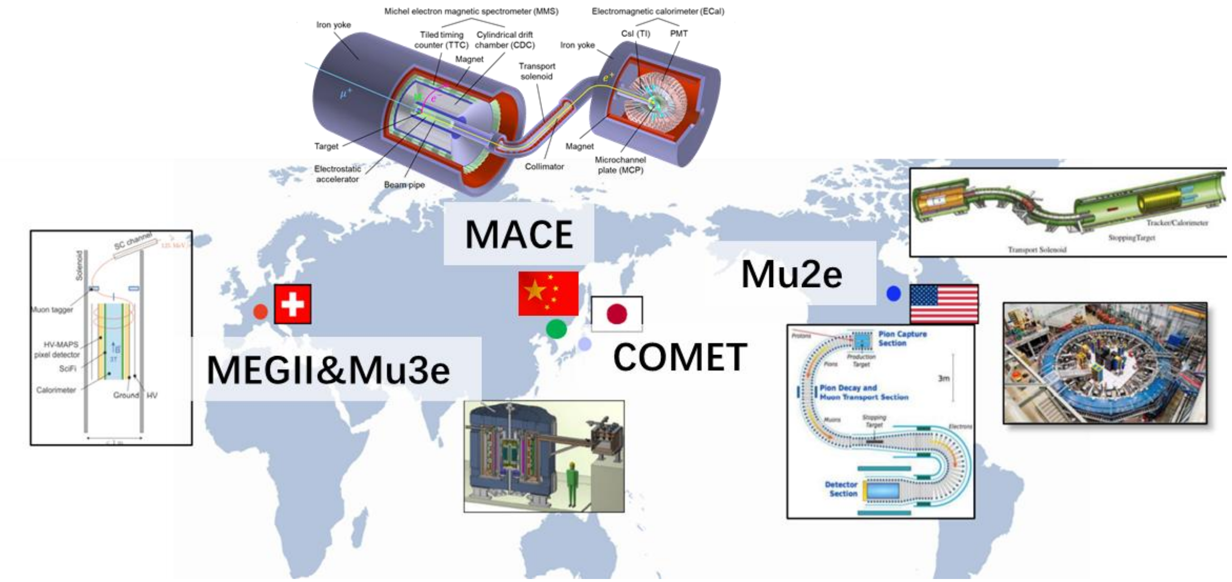
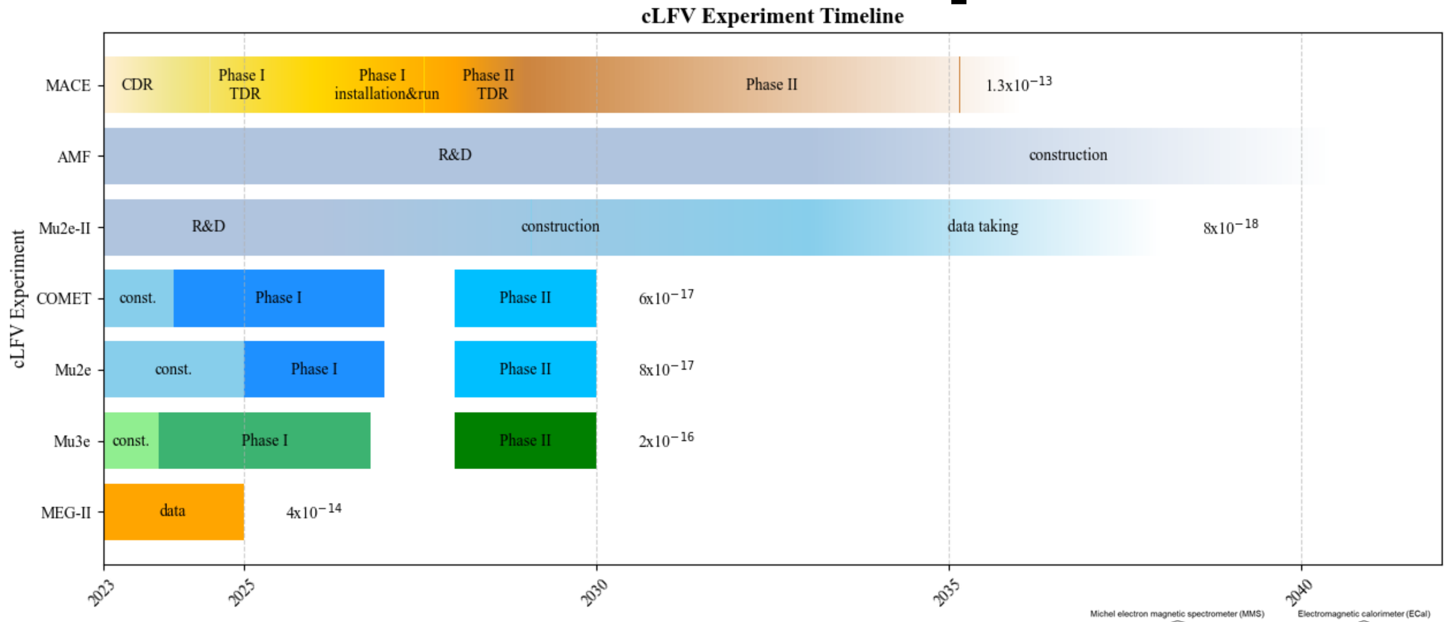
Worldwide cLFV experiments

Experiment	Facility	Process	Progress
MEGII	PSI (Switzerland)	$\mu^+ \to e^+\gamma$	Data taking
Mu2e	Fermilab (US)	$\mu^-\mathrm{Al} \to e^-\mathrm{Al}$	Construction
COMET	J-PARC (Japan)	$\mu^-\mathrm{Al} \to e^-\mathrm{Al}$	Construction
Mu3e	PSI (Switzerland)	$\mu^+ \to e^+e^-e^+$	Commissioning
MACS	PSI (Switzerland)	$\mathrm{M} \to \overline{\mathrm{M}}$	Finished (1999)

- Muonium conversion is a key cLFV process.
- After PSI set the bound $P < 8.3 \times 10^{-11}$ in 1999, no new experiments were proposed for 20 years.
- With enhanced beam intensity and advances in detector technology, breakthroughs in this field are anticipated.



Worldwide cLFV experiments



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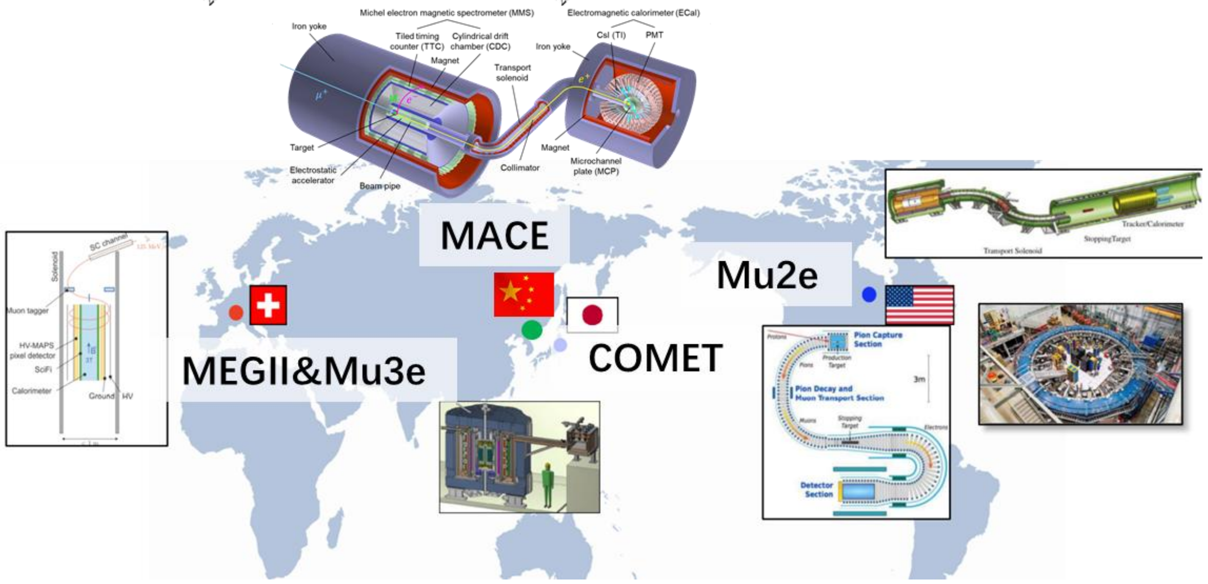
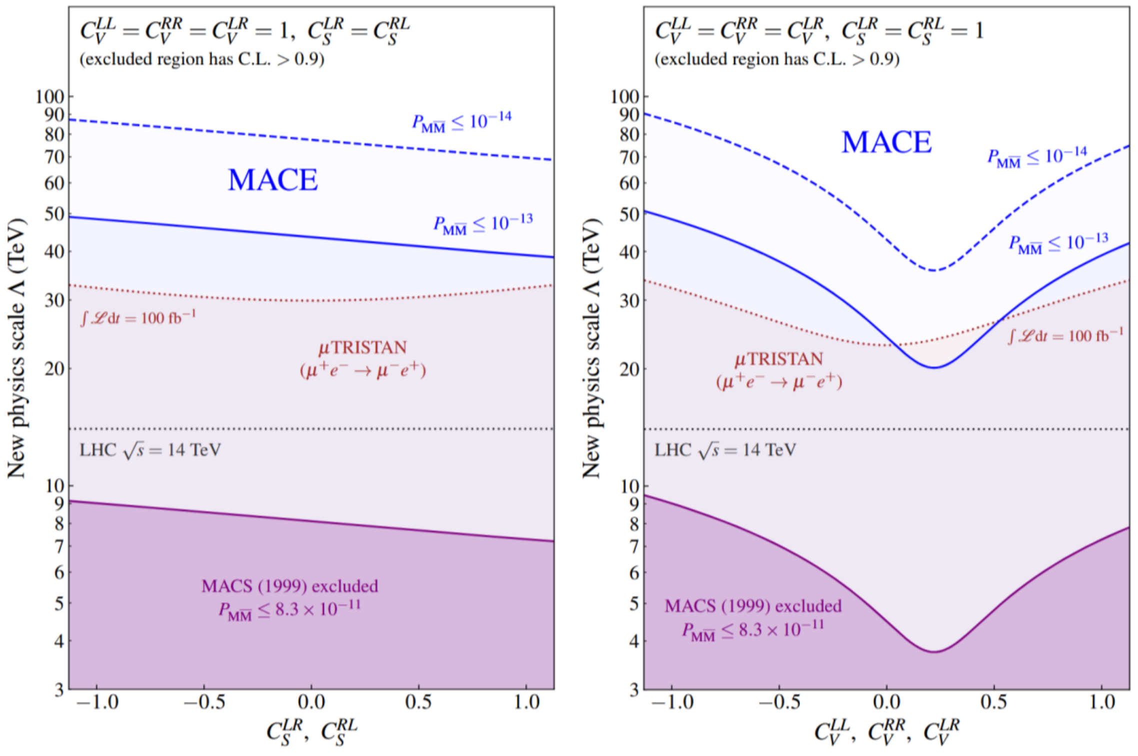


Motivations of MACE

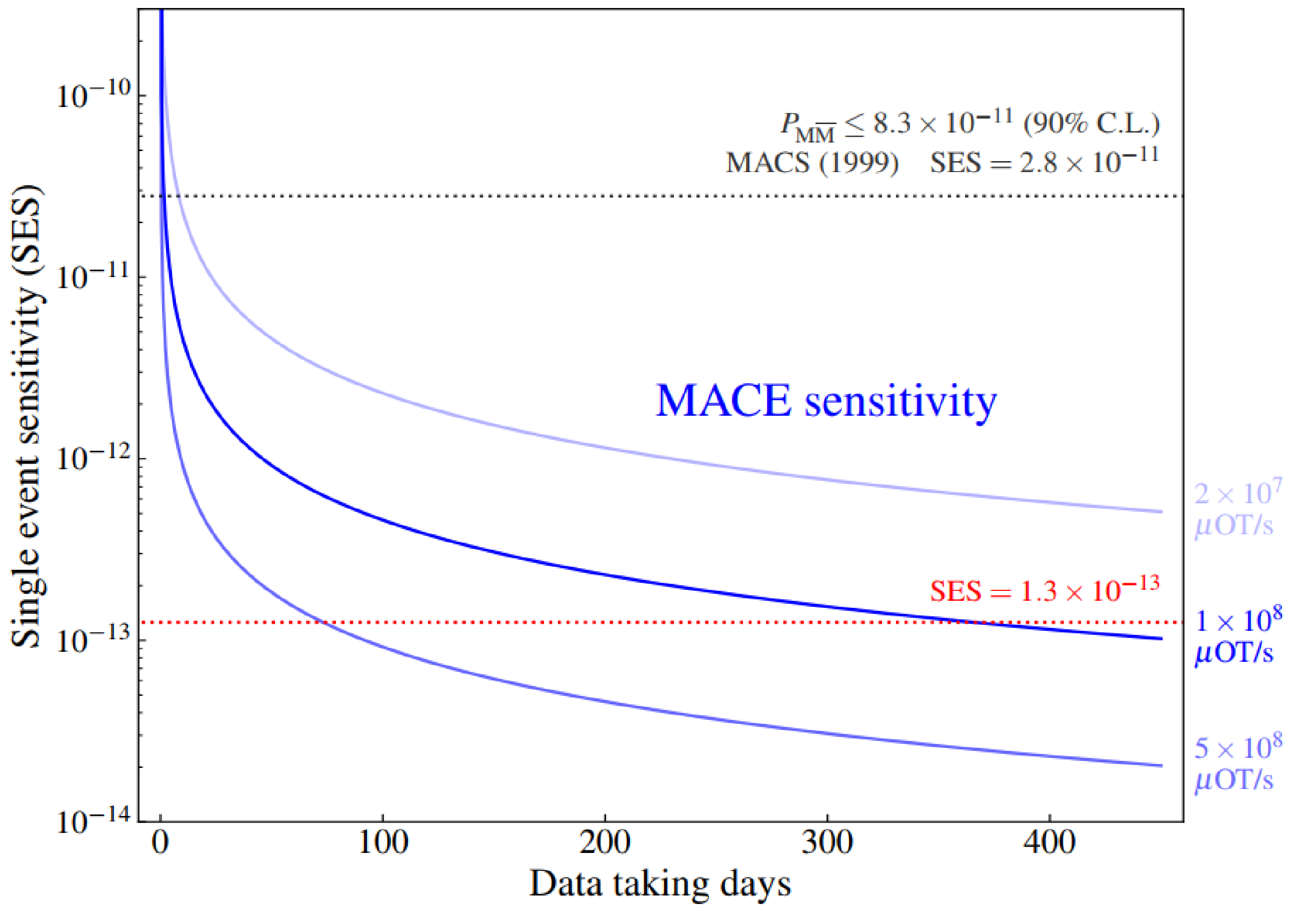
- Neutrinos are in oscillation; charged leptons?
- Demand for cutting-edge research:
  - cLFV selects neutrino mass generation mechanism.
  - Charged leptons and neutrinos share Yukawa couplings,

  → cLFV complementing neutrino physics.
  - Lepton cLFV ←→ quark flavor physics.
  - Low-energy cLFV experiments → high-energy frontiers.
  - Muonium conversion experiments have stalled for decades,

    → both opportunities and challenges.
- Opportunities in China initiative accelerator facilities:
  - China is set to build several high-intensity muon sources.
  - What type of muon physics deserves further exploration?
  - An innovative approach: MACE!



Breakthrough in fundamental science?



- The latest result was obtained by MACS in 1999, with a muon flux of $8 \times 10^{6}\mu^{+}/s$.
- Requirement: China domestic accelerator muon source to provide $10^{8}\mu^{+}/s$, surface muon.
- Over 20 years, significant advances in detector technology.
- China's accelerator and particle detection technology have made great strides.
- Currently, there are no ongoing muonium conversion experiments internationally.
- The new generation of experiments is expected to improve sensitivity by over two orders of magnitude compared to the 1999 PSI results!
- MACE is expected to be at the forefront of global research!

MACE: Muonium to Antimuonium Conversion Experiment.

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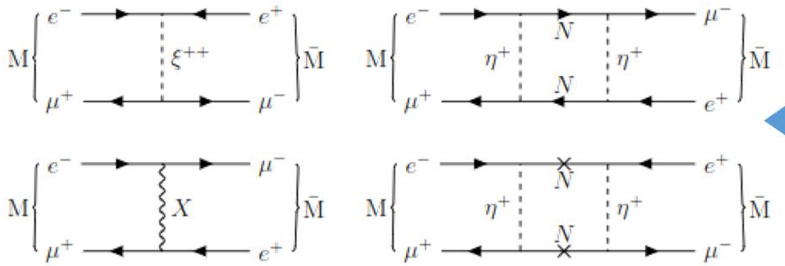
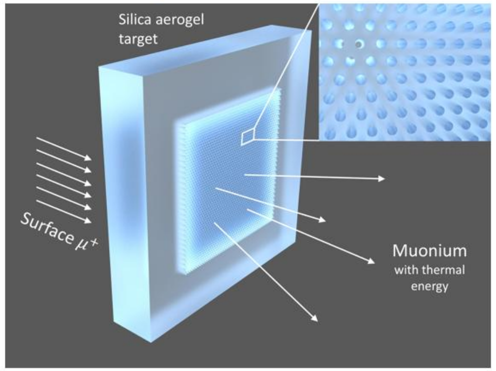
Challenges and solutions for MACE

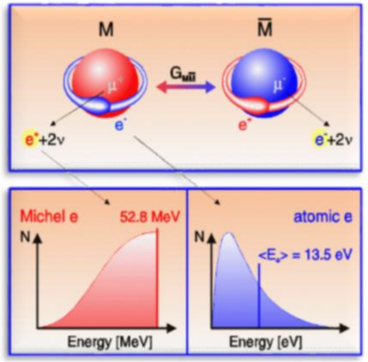
Muonium-to-Antimuonium Conversion Experiment

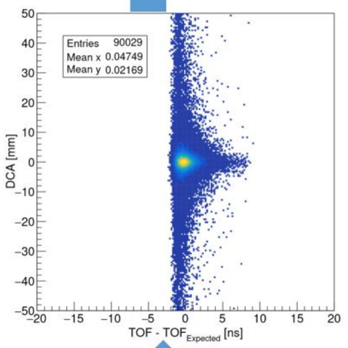
High-efficiency muonium production?

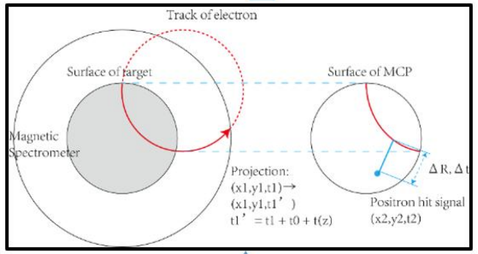


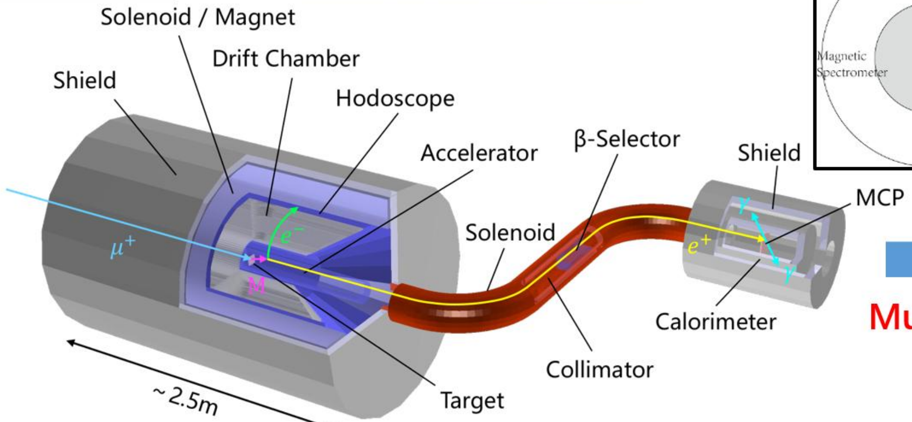
High signal/noise ratio











High-resolution spectrometer

Multiple coincidence?

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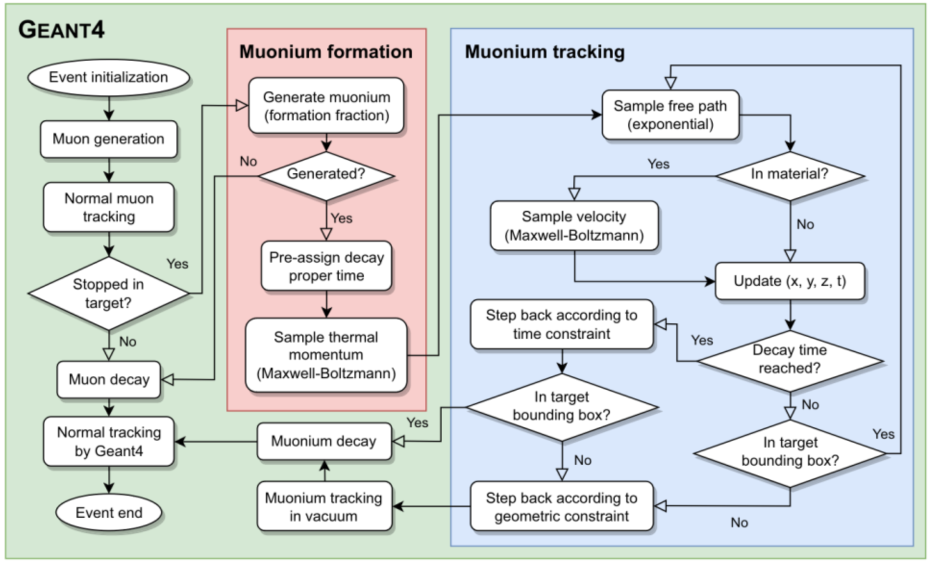
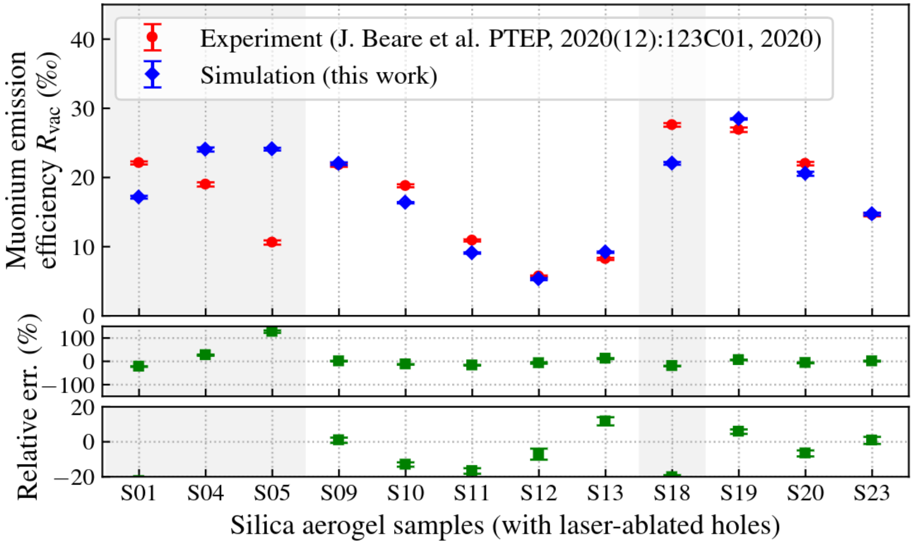
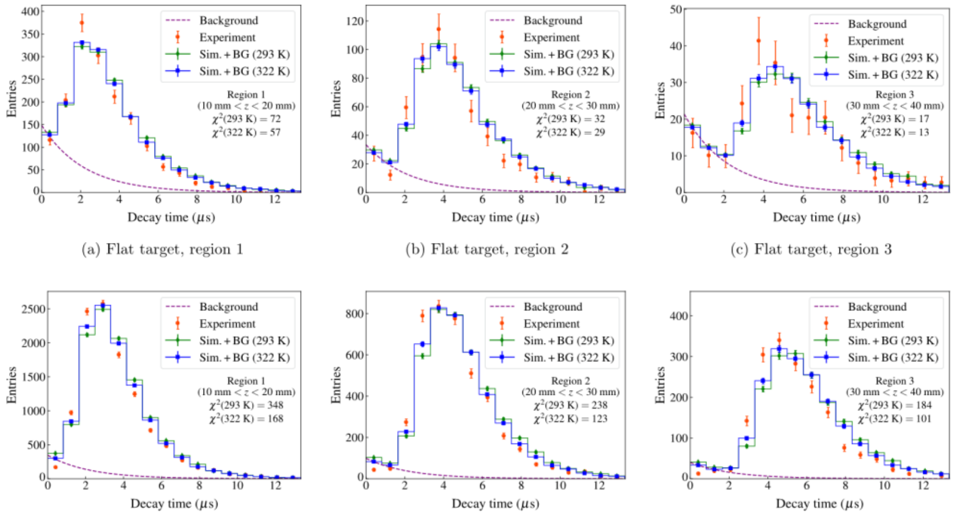
Optimization of muonium yield in perforated silica aerogel

Shihan Zhao and Jian Tang, Optimization of muonium yield in perforated silica aerogel, **Phys. Rev. D** 109, 072012. arXiv 2401.00222

- 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**.
- The simulation is **validated** by muonium yield data measured in TRIUMF and J-PARC.





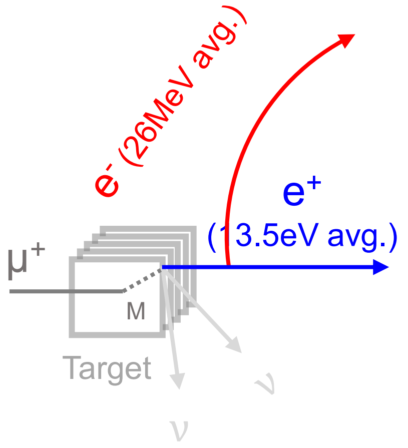


(a) Flat target, region 1 (b) Flat target, region 2 (c) Flat target, region 3

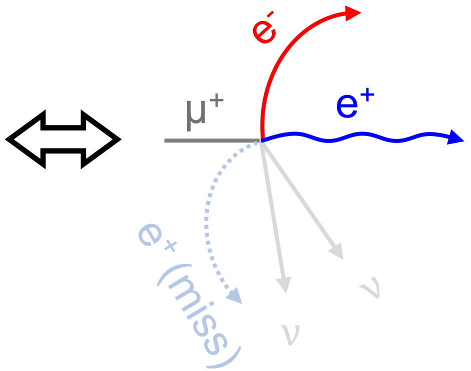
(d) Perforated target, region 1 (e) Perforated target, region 2 (f) Perforated target, region 3

MACE signal and background

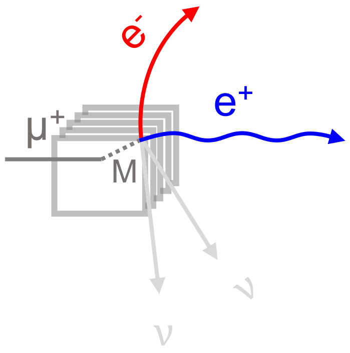
Signal:
fast e^- + slow e^+



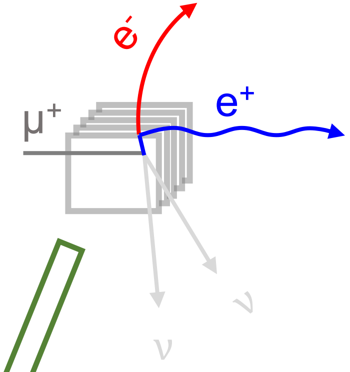
1. Internal conv. (IC) decay
- ☐ $\mu^+ \to e^+ e^- e^+ \bar{\nu}_\mu \nu_e$



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



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



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

- ➢ 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

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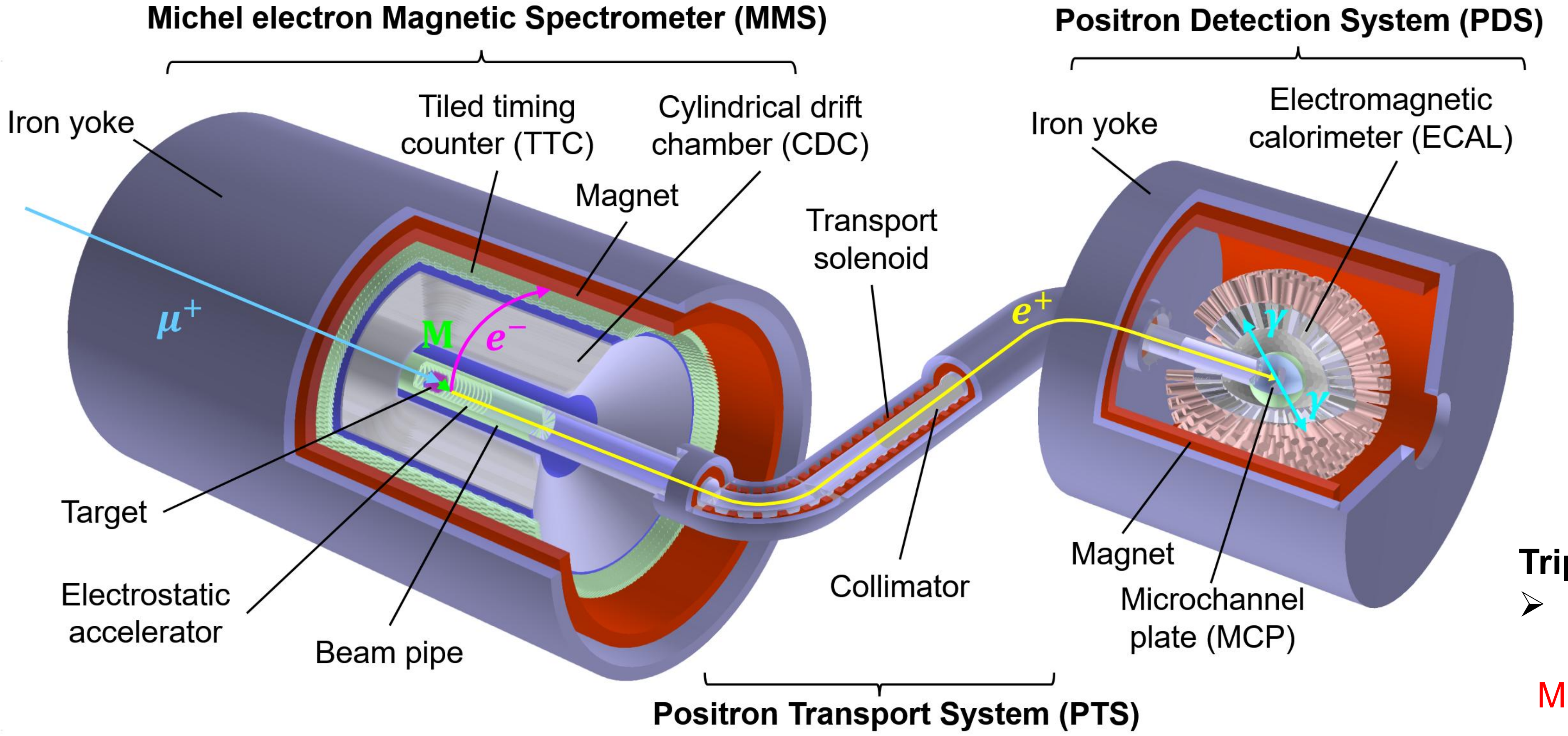
MACE baseline design v1



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^- (MMS) Atomic e^+ (MCP + ECAL)

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

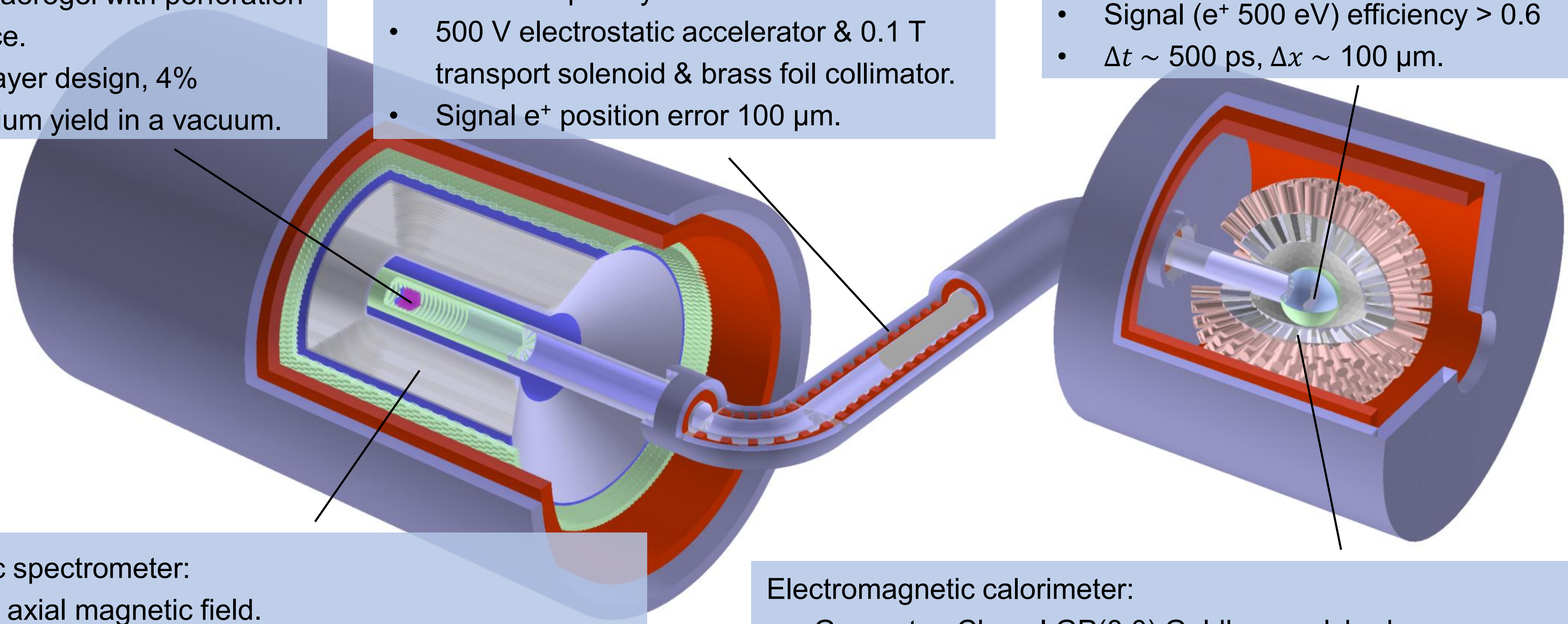
I. Transport atomic e^+ to MCP (conserving transverse position)
II. MCP detects e^+ position
III. e^+ annihilates on MCP
IV. ECAL detects 2 back-to-back annihilation γ

MACE baseline design v1

Muonium target:
- Silica aerogel with perforation surface.
- Multilayer design, 4% muonium yield in a vacuum.

Positron transport system:
- 500 V electrostatic accelerator & 0.1 T transport solenoid & brass foil collimator.
- Signal e^+ position error 100 μm.

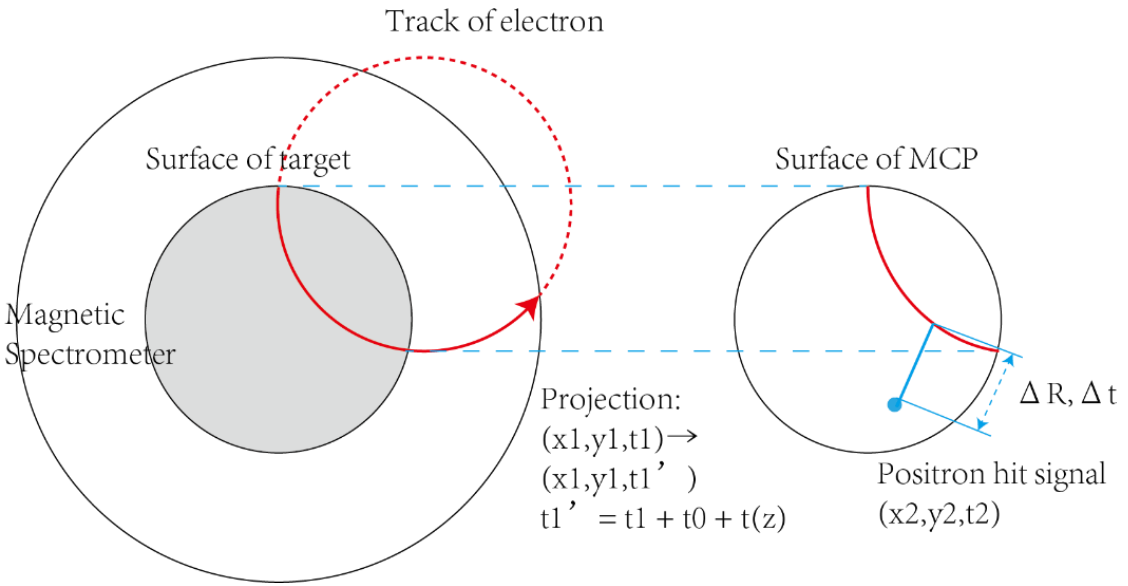
Microchannel plate (MCP) specifications:
- Signal (e^+ 500 eV) efficiency > 0.6
- $\Delta t \sim$ 500 ps, $\Delta x \sim$ 100 μm.

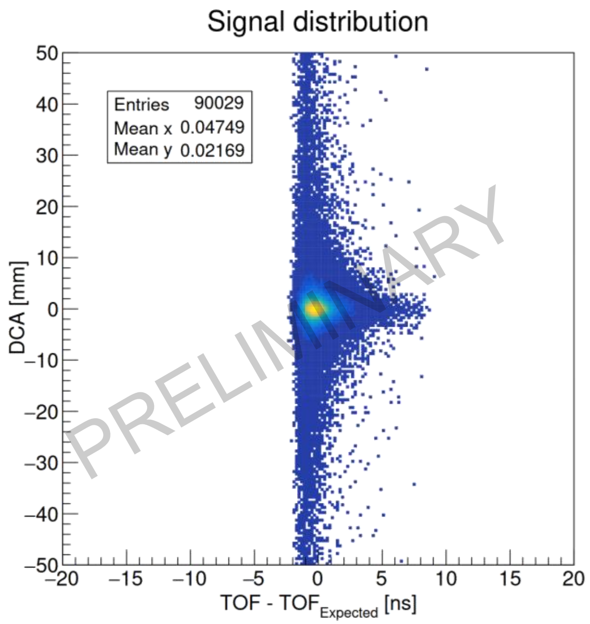


Magnetic spectrometer:
- 0.1 T axial magnetic field.
- CDC: $He(C_4H_{10})$ gas, 21 layers, 3540 cells. 89% geometry acceptance, $\Delta p \approx$ 500 keV.
- TTC: 5124 fast scintillators with SiPM readout, slant 46 deg, $\Delta t \sim$ 100 ps.

Electromagnetic calorimeter:
- Geometry: Class-I GP(8,0) Goldberg polyhedron.
- 622 CsI(Tl) crystals with 10 cm length, SiPM readout.
- 93.6% geoemtry acceptance, $\Delta E/E =$ 10% (signal 2γ event), 78.3% signal efficiency.

Simulation: muonium conversion signal

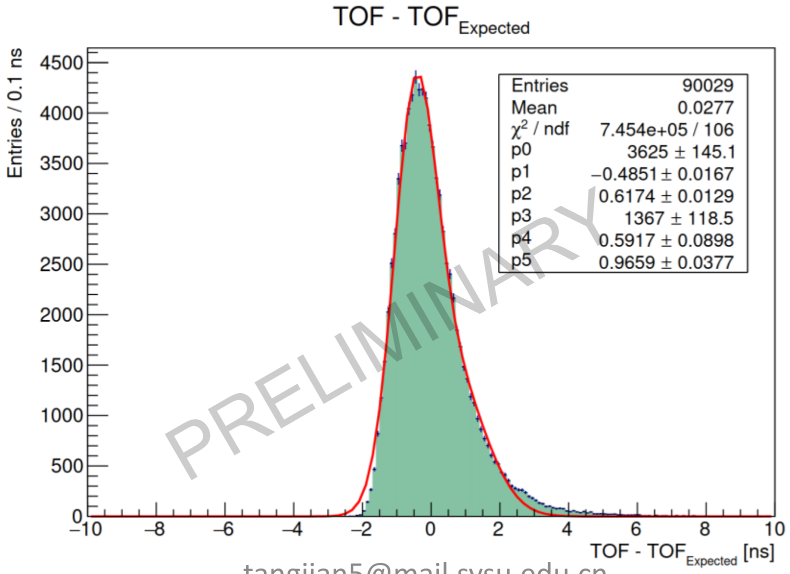


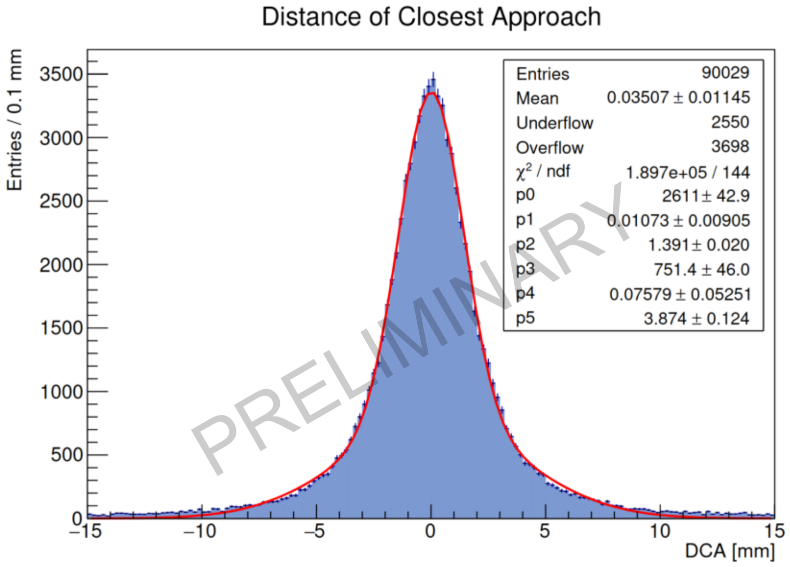


- Elliptical 3σ signal region:

$$\left(\frac{\mathrm{TOF}-\mathrm{TOF_E}}{3\sigma_{\mathrm{TOF}}}\right)^2+\left(\frac{\mathrm{DCA}}{3\sigma_{\mathrm{DCA}}}\right)^2<1$$

- $\varepsilon_{\text{signal region cut}} = 0.987$





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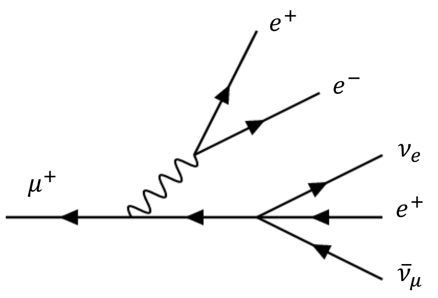
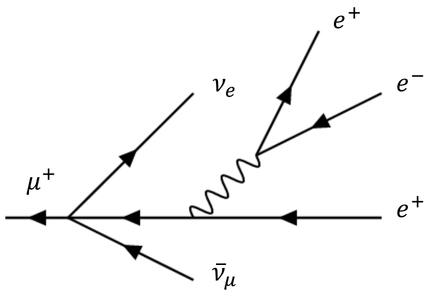
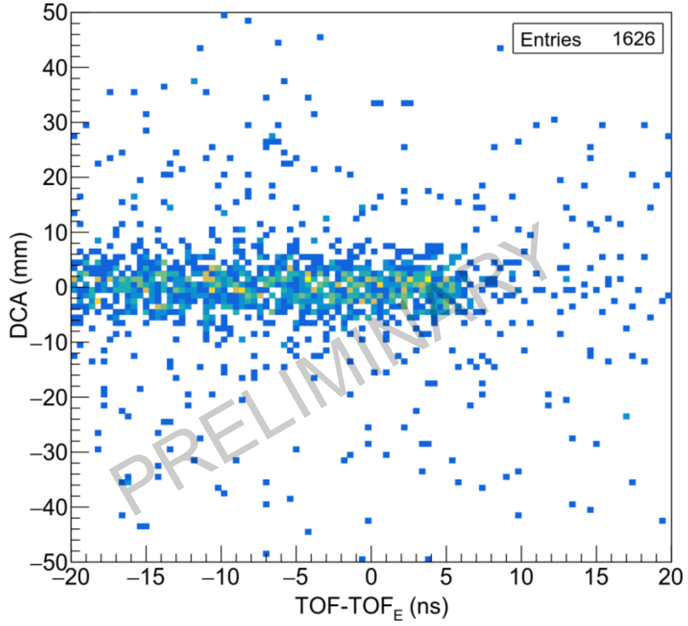
Simulation: muon internal conversion decay



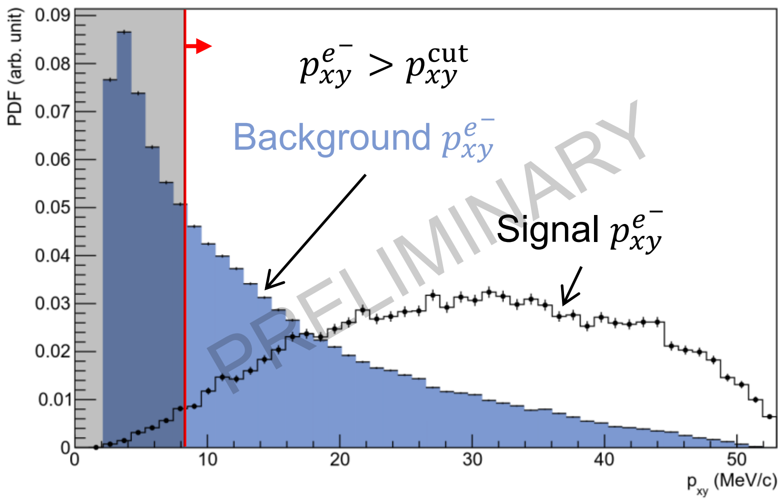




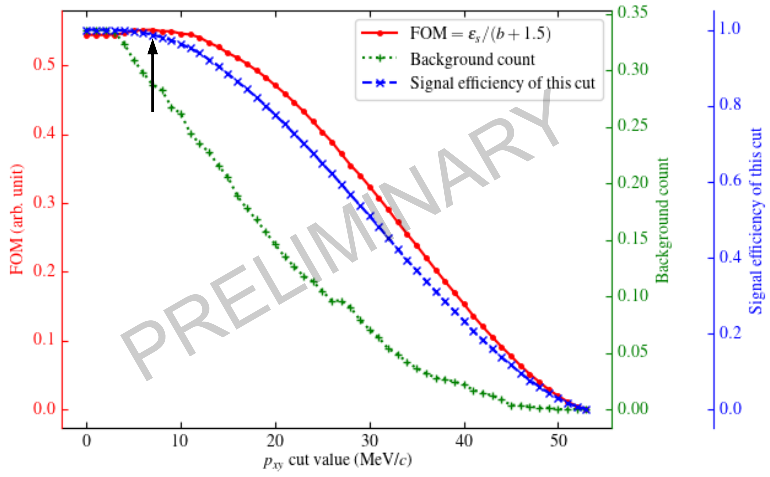
$\mu^+ \to e^+e^-e^+\bar{\nu}_\mu\nu_e$ simulation:

- Event selection:
  - 3σ signal region cut
  - $p_{xy} > 7$ MeV/c
- $\varepsilon_{\text{pxy cut}} = 0.926$
- $\varepsilon_{\text{all cut}} = 0.914$
- $N_{\text{bkg}} = 0.287 \pm 0.020$

(in 10^8 μ/s × 365 d)



$$\text{FOM} = \frac{\varepsilon_s}{b + 1.5}$$



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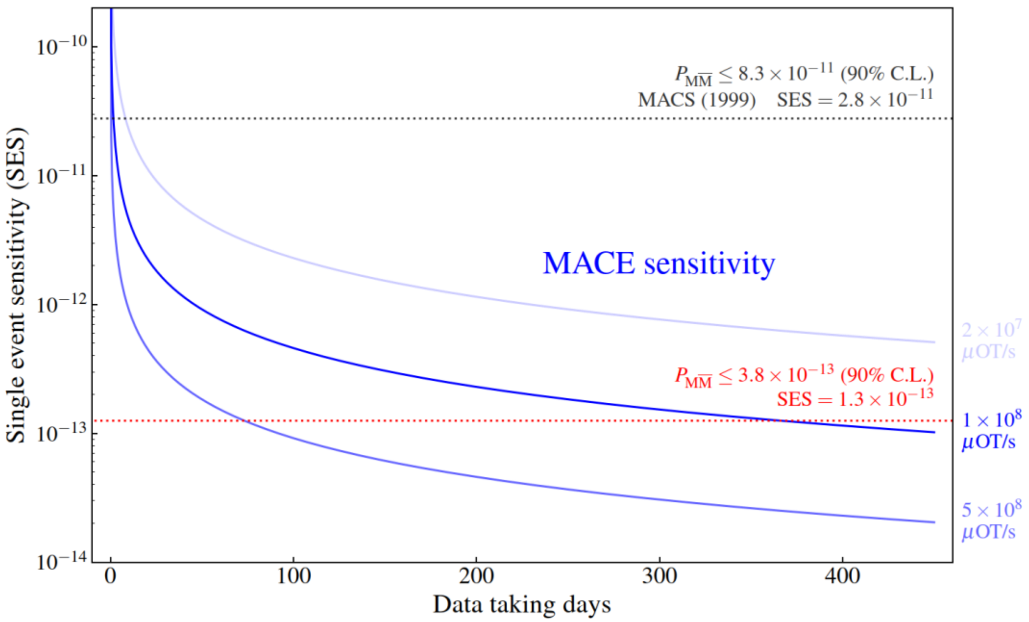
MACE sensitivity

- Summary of current full 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

Credits: Shihan Zhao

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%



✓ O(10^{-13}) single event sensitivity is expected:

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

- More **staging** scenarios to match the muon beamlines!
- More simulations and refined data analyses to be **validated with prototypes**!

Plan and timeline

Conceptual design	Phase-I Technical design & prototype	Phase-I installation	Phase-I Physics run	Phase-II Technical design	MACE Phase-II prototype	MACE Phase-II
2024	2025	2026	2027	2028	2029	2030

- Phase-I: O(10^{-11}) sensitivity for rare muonium decay (e.g. M→ee)
- Data taking duration: 1 year
- Beam specifications:
  - Surface muon, $10^6 \sim 10^7$ μ^+ OT /s
  - Momentum spreading: $\Delta p/p \sim 10\%$
  - Beam spot size ~ 50 mm

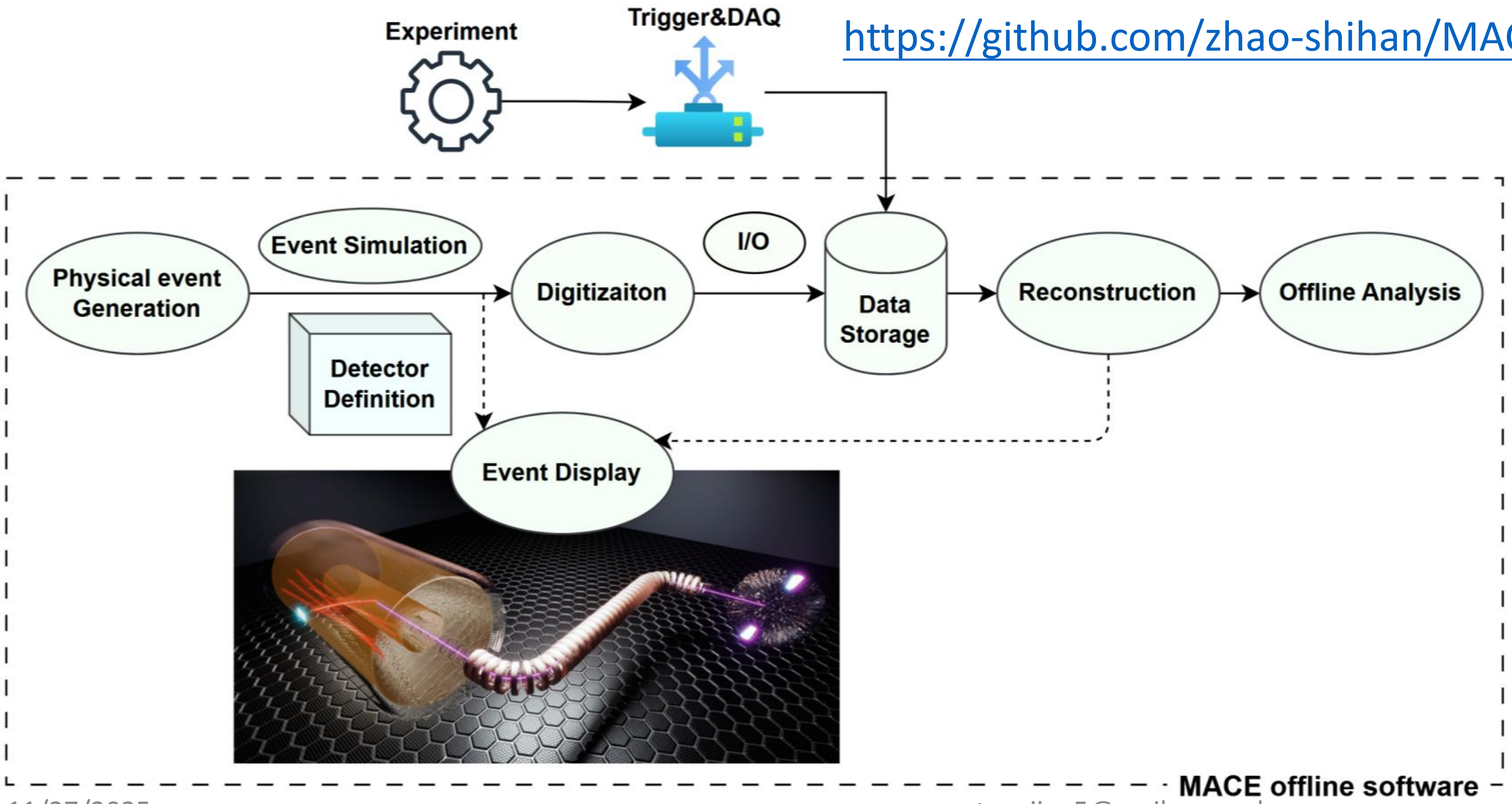
- Phase-II: O(10^{-13}) sensitivity for muonium conversion
- Data taking duration: 1 year
- Beam specifications:
  - Surface muon, 10^8 μ^+ OT /s
  - Momentum spreading: $\Delta p/p \sim 5\%$
  - Beam spot size ~ 50 mm

- Domestic muon beams in the near future: Melody, CiADS, HIAF, SHINE

MACE offline software

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

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



Tasks:

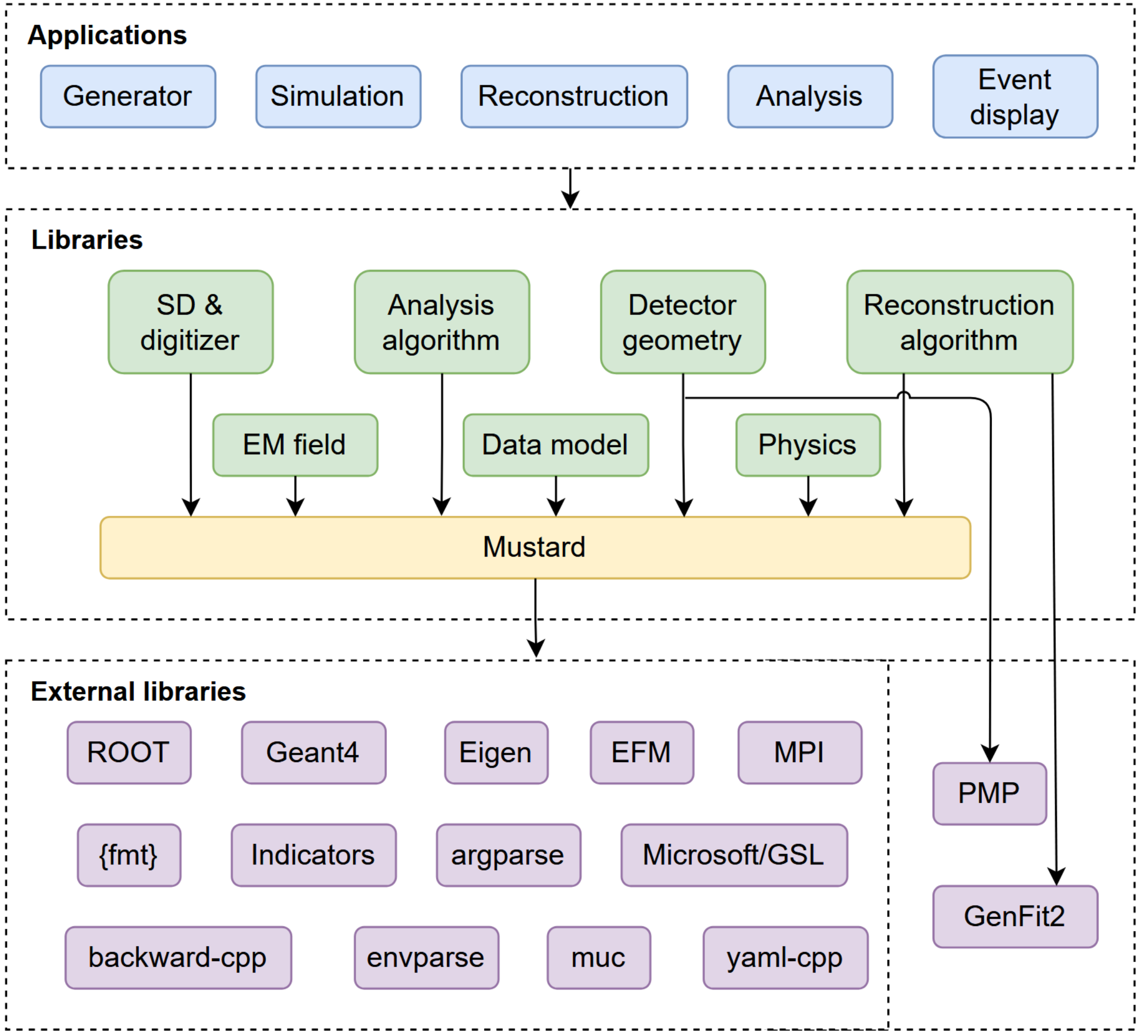
- Event generation
- Simulation: detector, DAQ…
- Reconstruction & analysis
- Visualization: event, track, detector geometry…

Quality control:

- Framework and architecture
- Continuous integration
- Regression test

Software framework

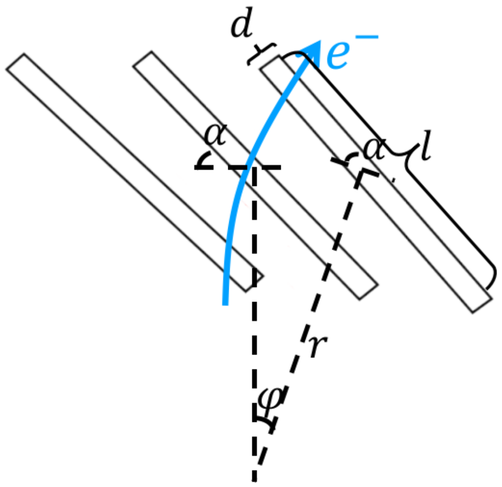
- **Mustard framework:**
  - ➢ A modern, distributed, high-performance architecture for particle physics experiments.
- **High-performance design:**
  - ➢ Distributed executor for simulation and analysis.
  - ➢ Follows zero-overhead abstraction principle.
- **Key components:**
  - ➢ Distributed computing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

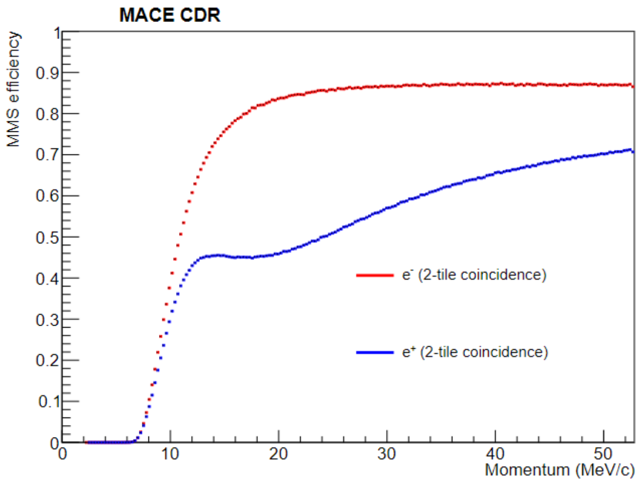


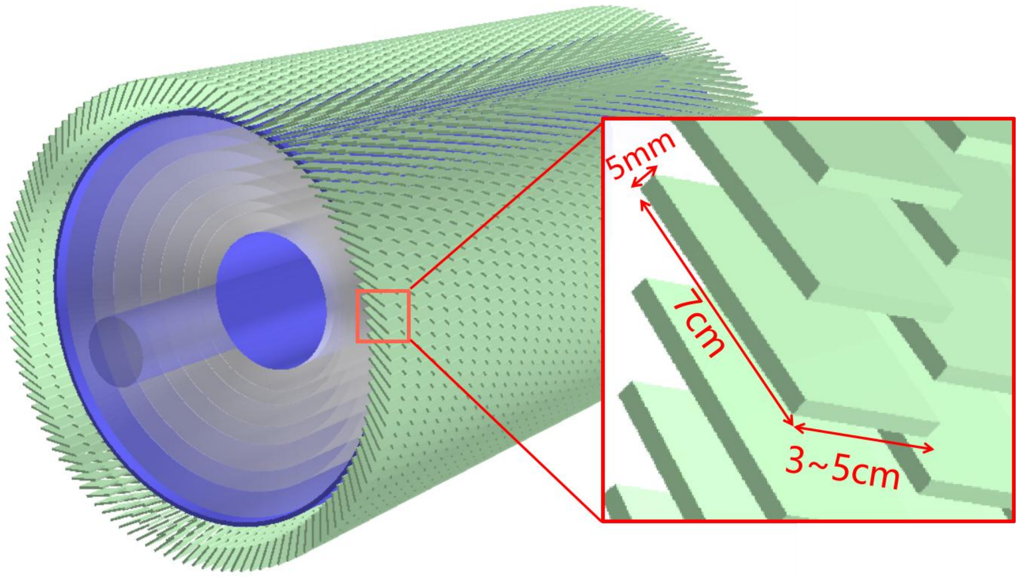
https://github.com/zhao-shihan/Mustard

Tiled timing counter (TTC)

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

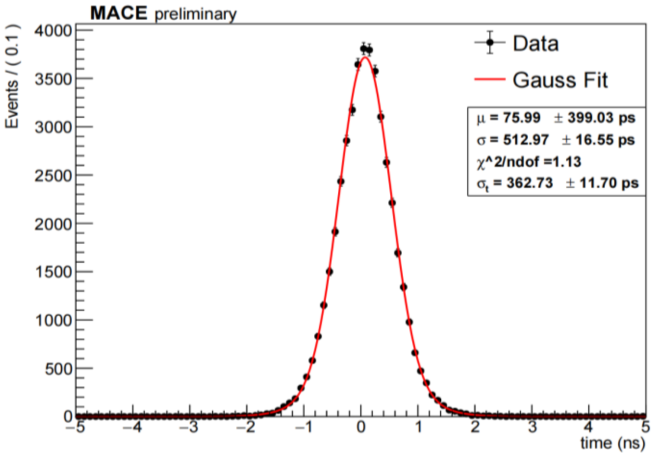






Test with cosmic-ray muons:

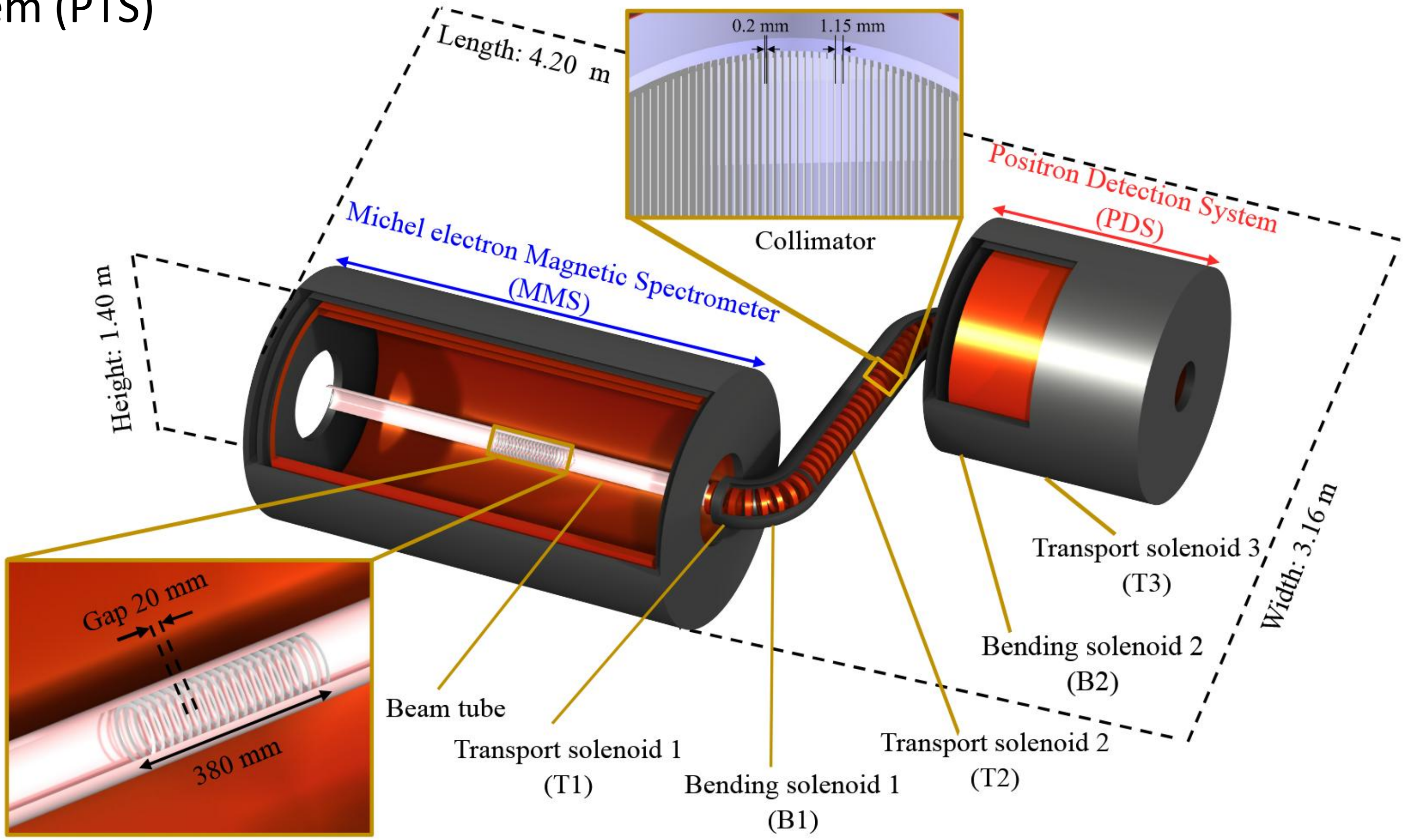
- Fitted time resolution:
  - Double-tile: $\sigma_t = (513 \pm 17)$ ps
  - Single-tile: $\sigma_t = (362 \pm 12)$ ps



Credit: Hao Jiang

Positron transport system (PTS)

- 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. at a level of 10^{-7}

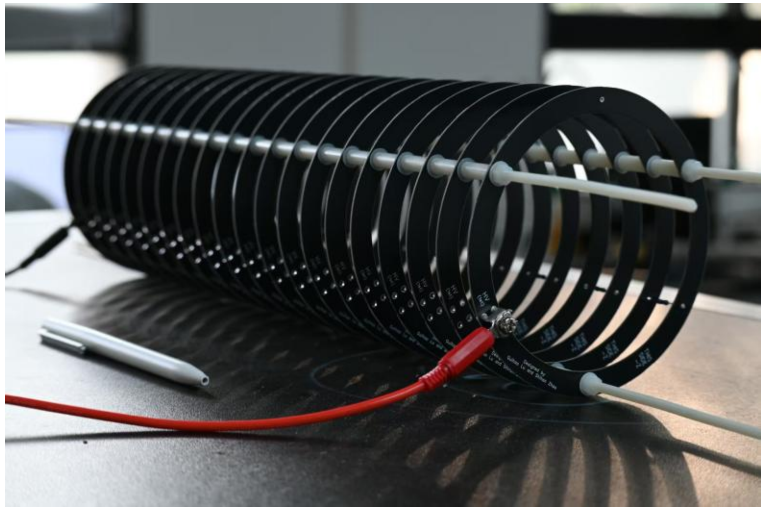
Lu, Guihao, et al. "Positron Transport System for Muonium-to-Antimuonium Conversion Experiment." *arXiv preprint arXiv:2508.07922* (2025).

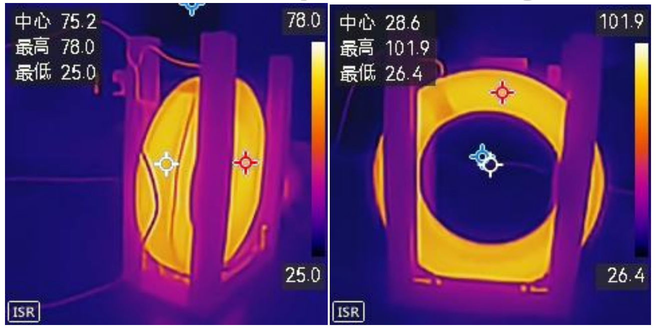
PTS prototyping

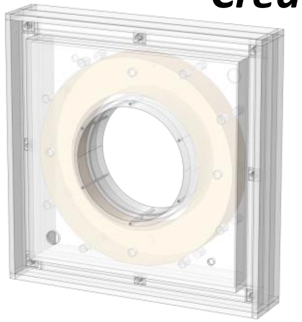
Credit: Guihao Lu

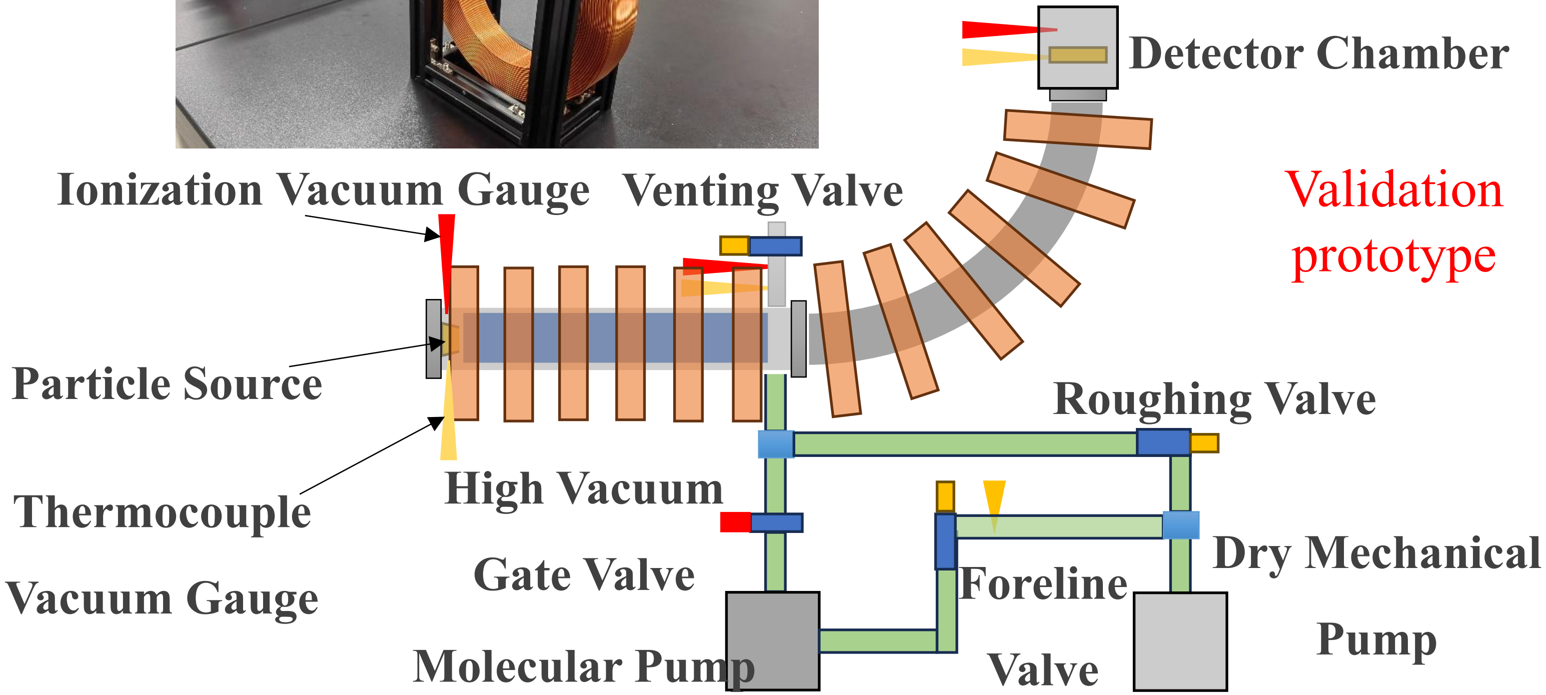
- **PTS validation**

  Testing with TS solenoids and accelerator module









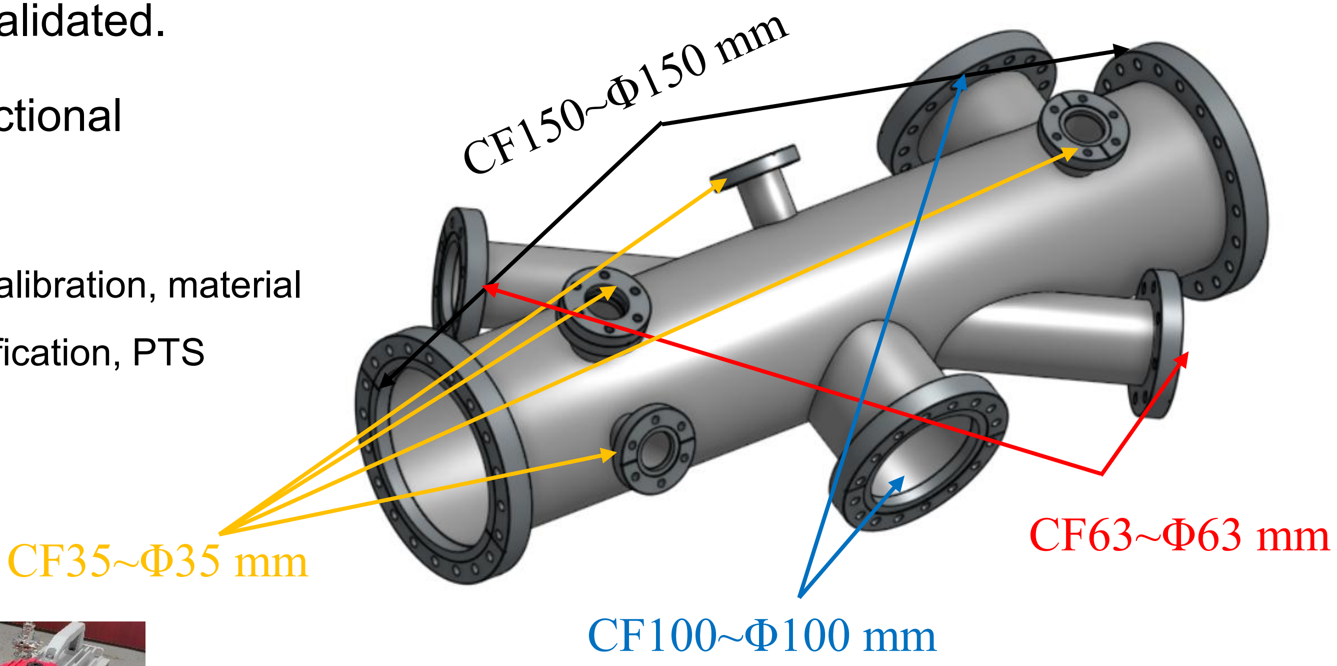
- Accelerator module prototype

  Multi-layer PCB

  High voltage > 2 kV

PTS prototyping

- The electromagnetic components have been validated.
- Developing a multifunctional platform, Multifunctional Accelerator Platform (MAP), with the PTS?
    - high-precision electron source platform, detector calibration, material measurement, plasma accelerator technology verification, PTS validation, and positron source development.



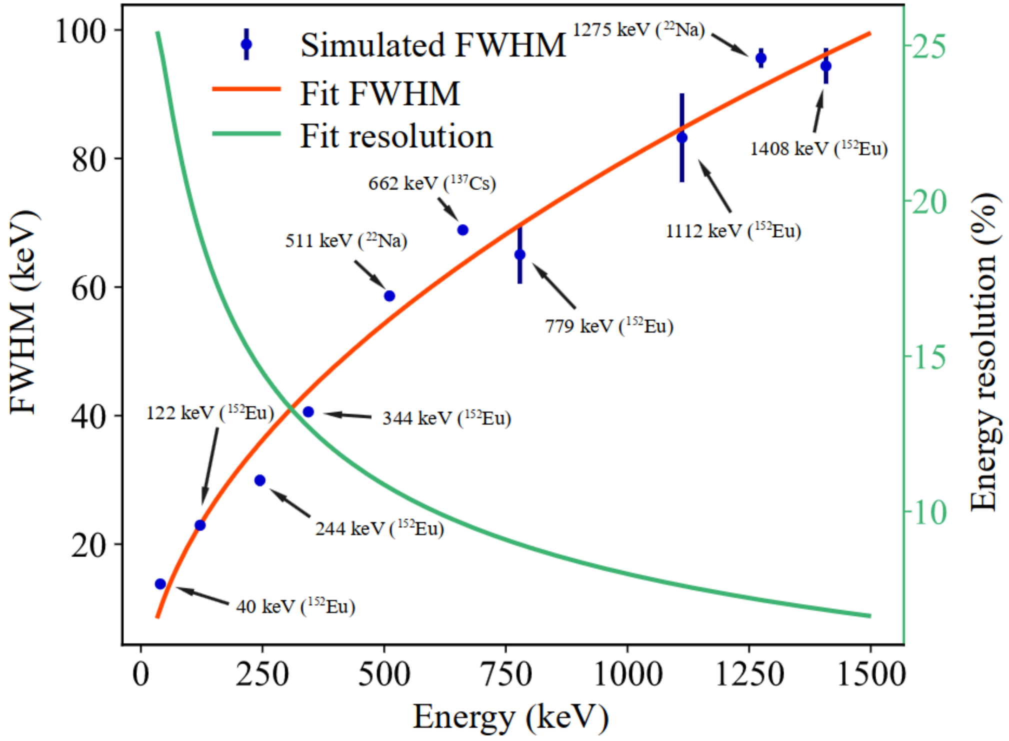
Design of calorimeter

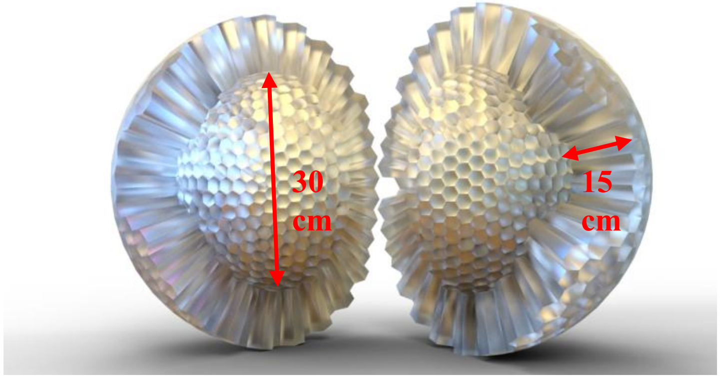
- Signal and Background

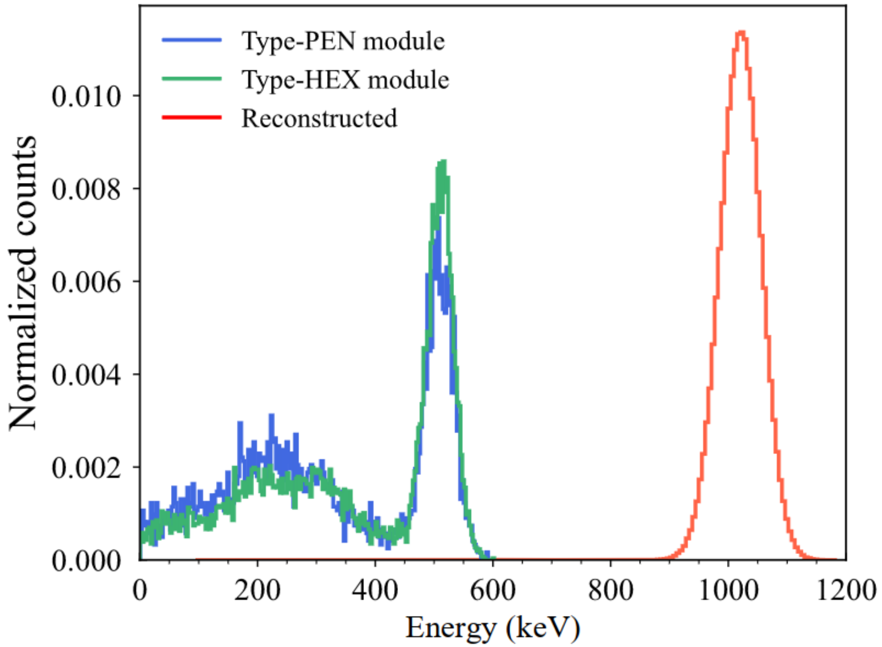
https://arxiv.org/abs/2408.17114 ***Frontier of Physics*** *20 (2025), 035202.*

Credits: Siyuan Chen

  - Energy resolution: 10.8% at 0.511 MeV
  - 78.3% signal efficiency







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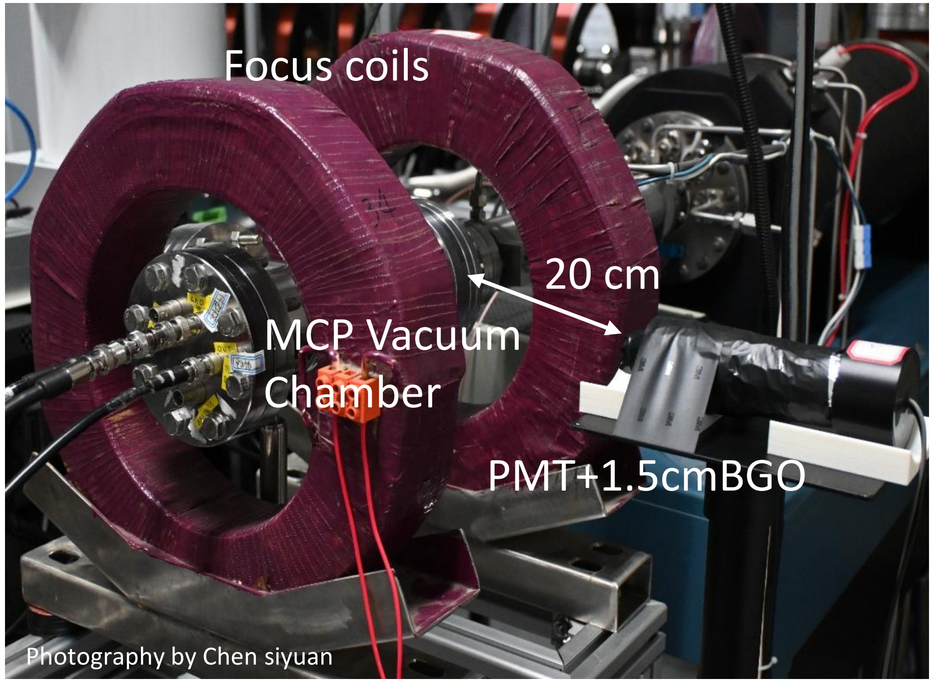
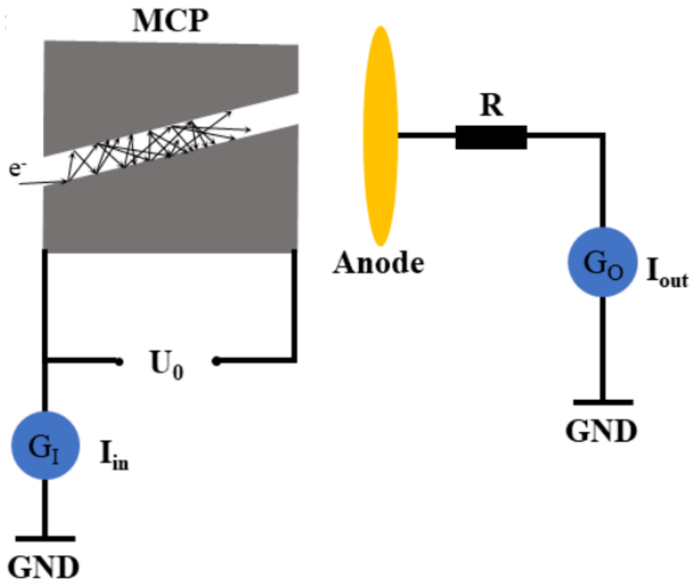
MCP+ECAL: prototype tests with a positron beam

- Beam source:
  - IHEP slow e^+ beam
  - Positron in CW/Pulse
  - $3 \times 10^4\ e^+/s$

Credits: Siyuan Chen



- Currently MCP efficiency 25 ~ 30%
  - Can reach 50% efficiency through MgO/C thin layer



- Data analysis in progress...

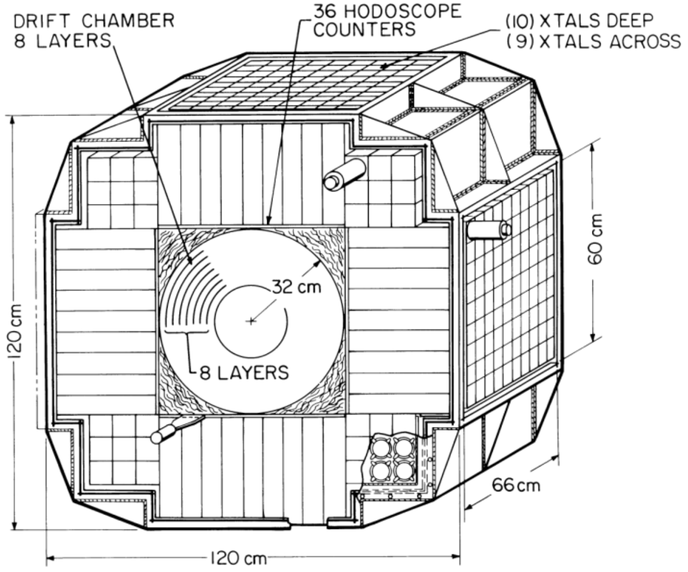
Acknowledgement: Baoyi Wang, Peng Zhang, Xiaotian Yu, and all IHEP slow e^+ beam colleagues.

Proposal of MACE Phase-I

Muon cLFV decay modes

- ✓ **μ^+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, Familon, … Crystal Box、MEG

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



Crystal Box:

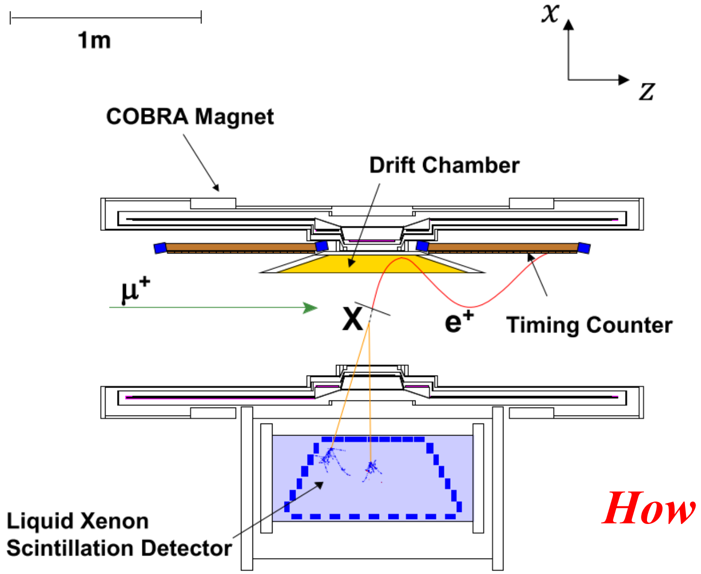
- $\mu^+ \rightarrow e^+\gamma\gamma$
- $\mu^+ \rightarrow e^+X, X \rightarrow \gamma\gamma$
- $\mu^+ \rightarrow e^+\gamma f$
- …

Test of the Standard Model

- ✓ $\boldsymbol{\mathcal{B}(\mu^+ \rightarrow e^+\gamma\nu\nu)}$ $\mathcal{O}(10^{-8}), E_e > 45, E_\gamma > 40$ 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

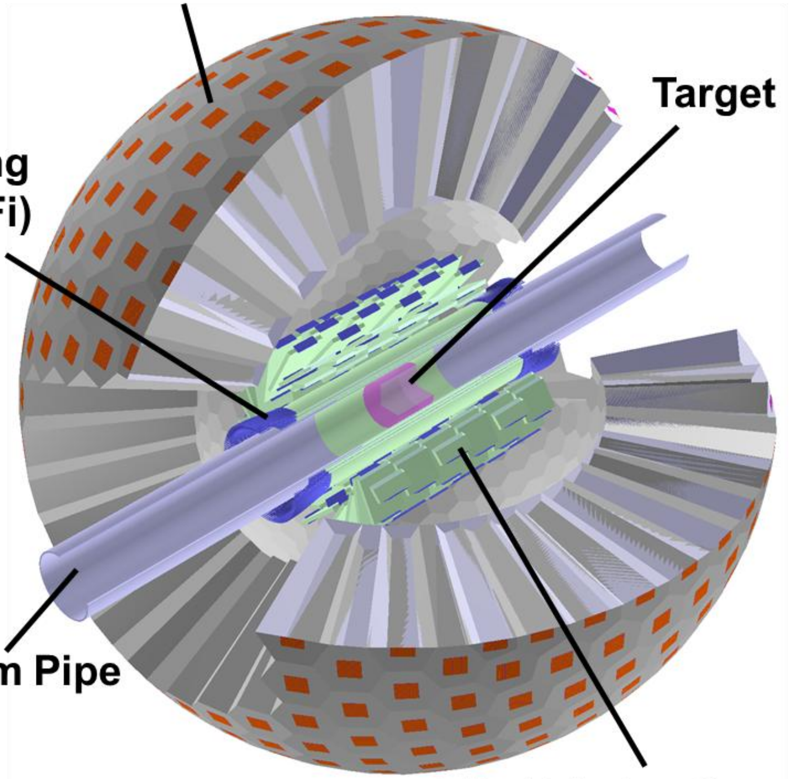


MEG:

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

How to improve the sensitivity?

Proposal of MACE Phase-I



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 magnetic field applied.
- High background rates.

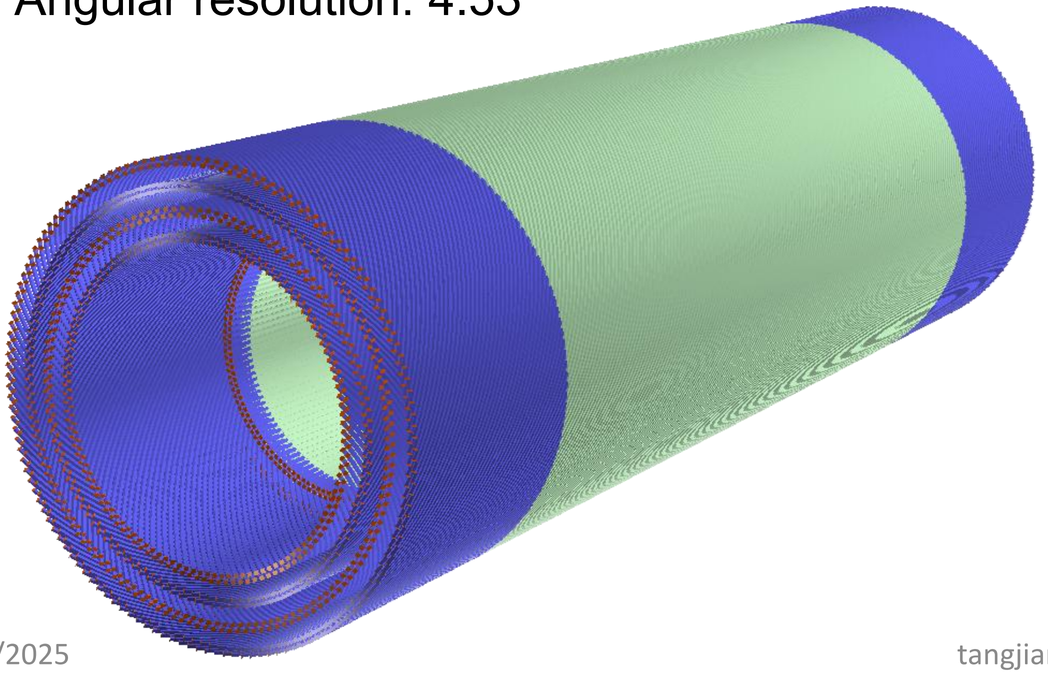
MACE Phase-I tracker

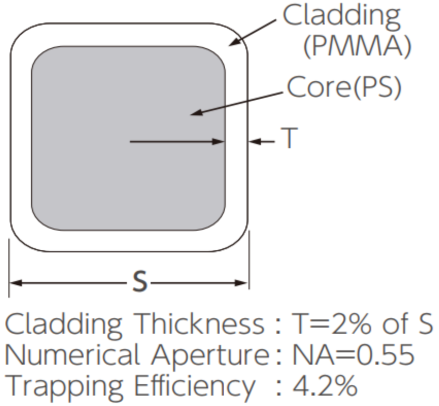
Scintillating fiber (SciFi) tracker

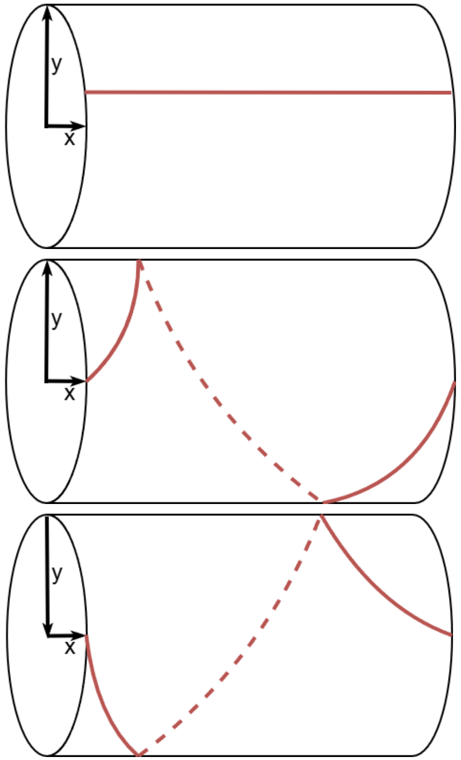
- 16 SciFi layers, 8 super layers
- 3 fiber types: Axial; Left-handed helix; Right-handed helix

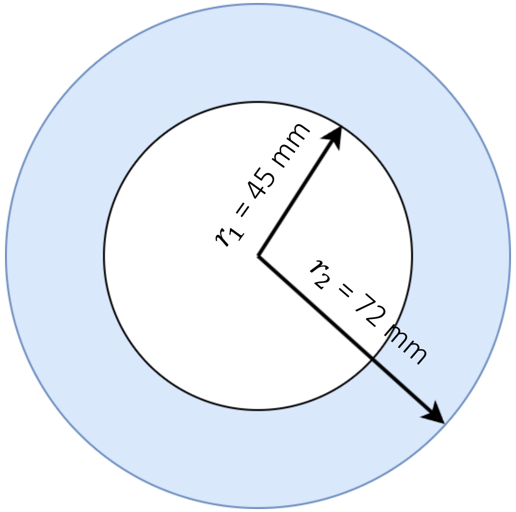
Performance (preliminary):

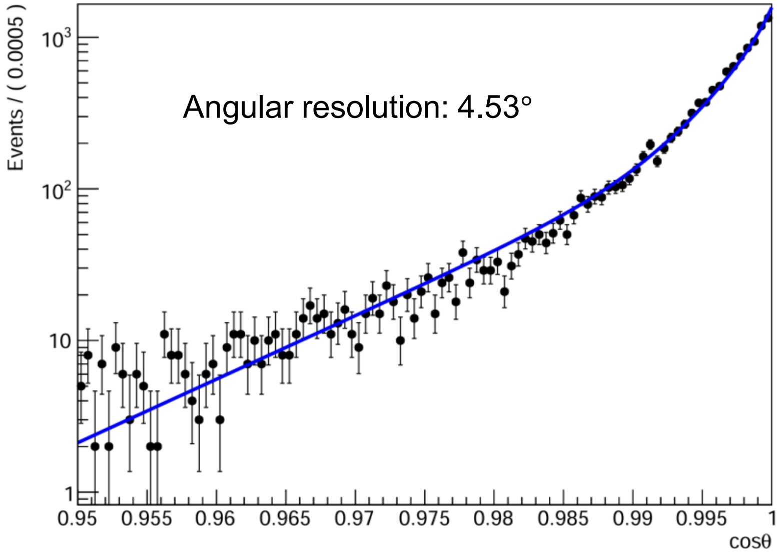
- Detector efficiency: 98.9%
- Reconstruction efficiency: 75%
- Angular resolution: 4.53°











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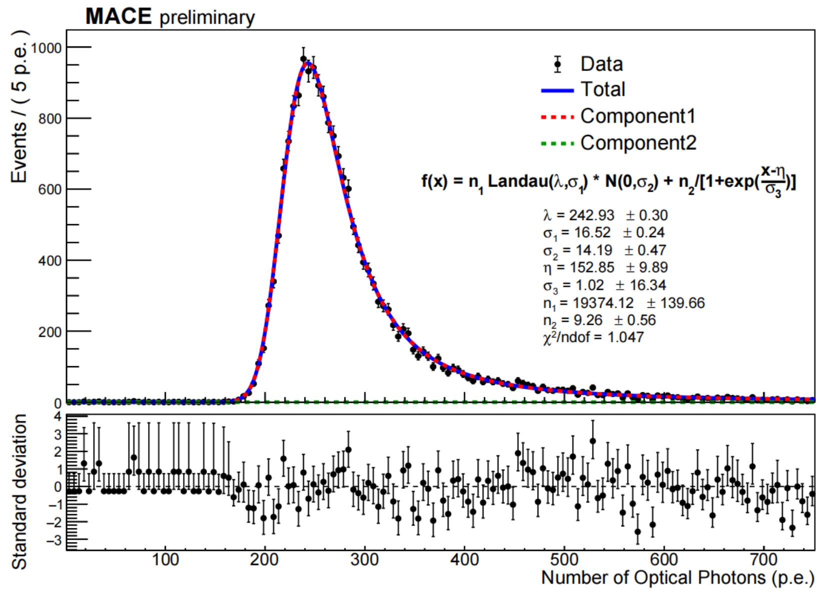
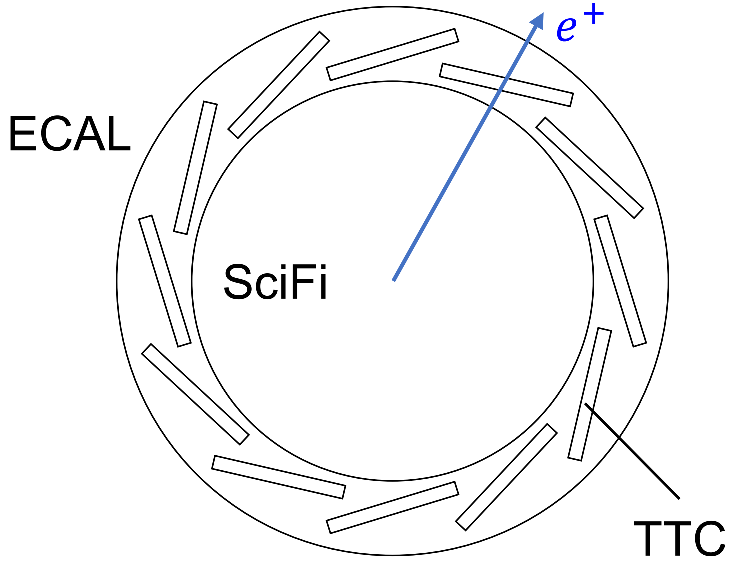
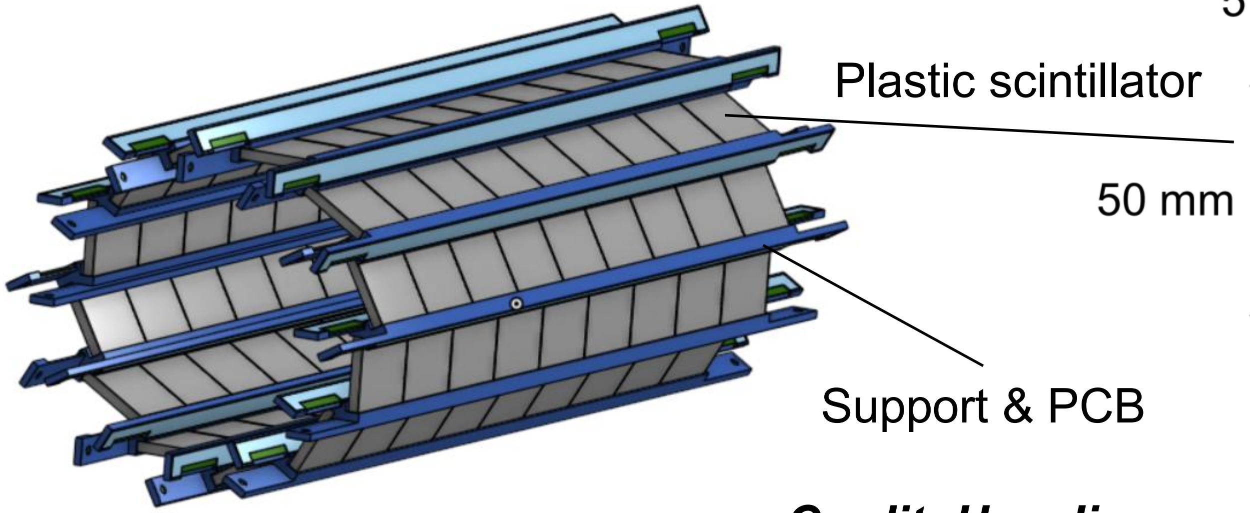
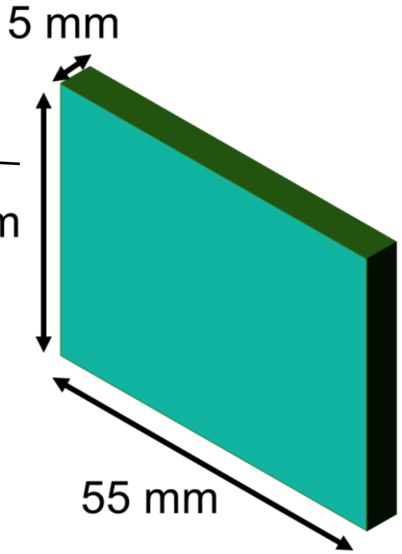
Tiled timing counter (TTC) for MACE Phase-I

- 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







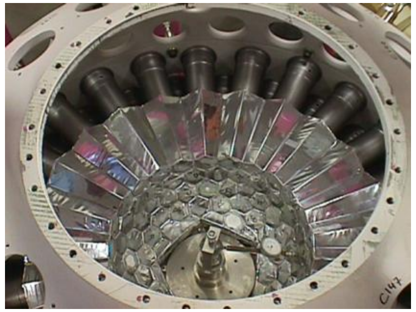


Credit: Hao Jiang

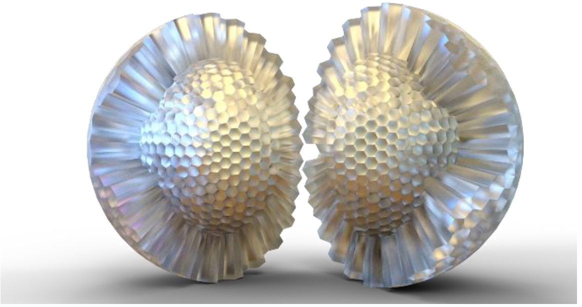
ECAL for MACE Phase-I

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/cm³

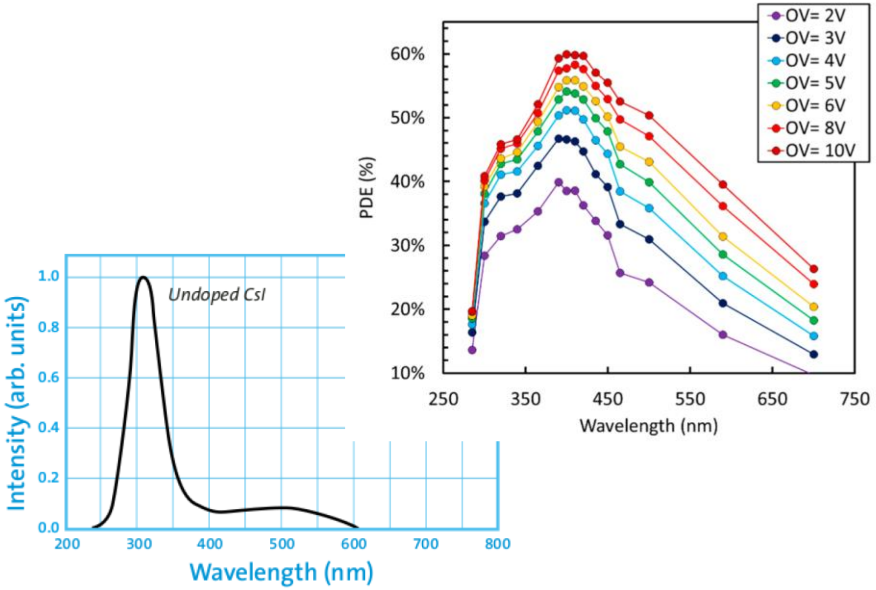
BGO

- 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**

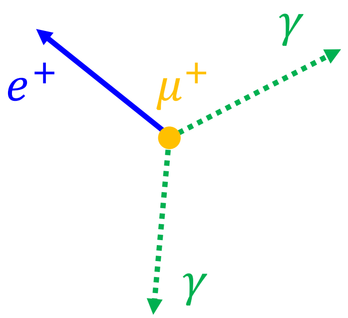


NUV SiPM readout

Sensors 19 (2019) 2, 308

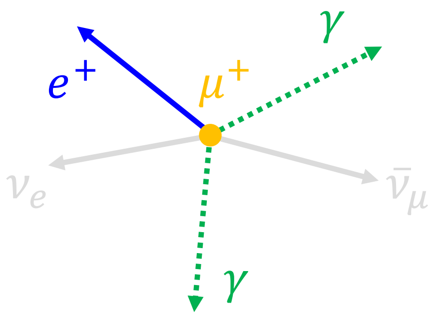
Sensitivity estimation of $\mu^+ \to e^+\gamma\gamma$

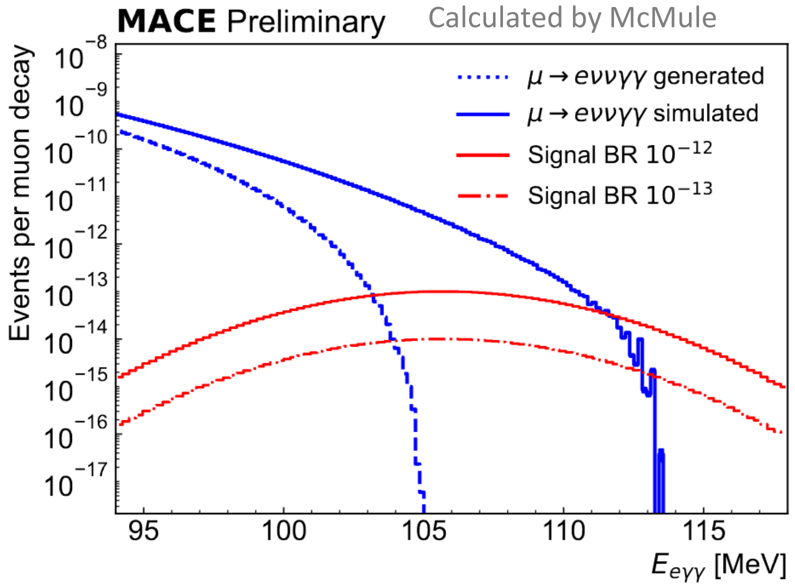
Signal:
Triple coplanar tracks
e^+ and two γs



Background:
Double radiative muon decay

SciPost Phys. 9, 027 (2020)





Event selection criteria:

- Time coincidence
- One track in tracker, two tracks in ECAL
- Select missing energy

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

$$n_{obs} = b$$

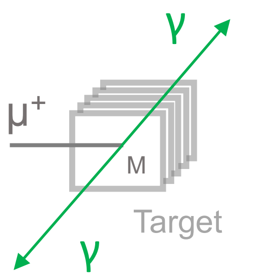
$$\mathcal{B}(\mu \to e\gamma\gamma) < \frac{s_{up}}{\varepsilon_{signal}\Phi_\mu T}$$

BR upper limit estimation: 4×10^{-13} (90% C.L.)

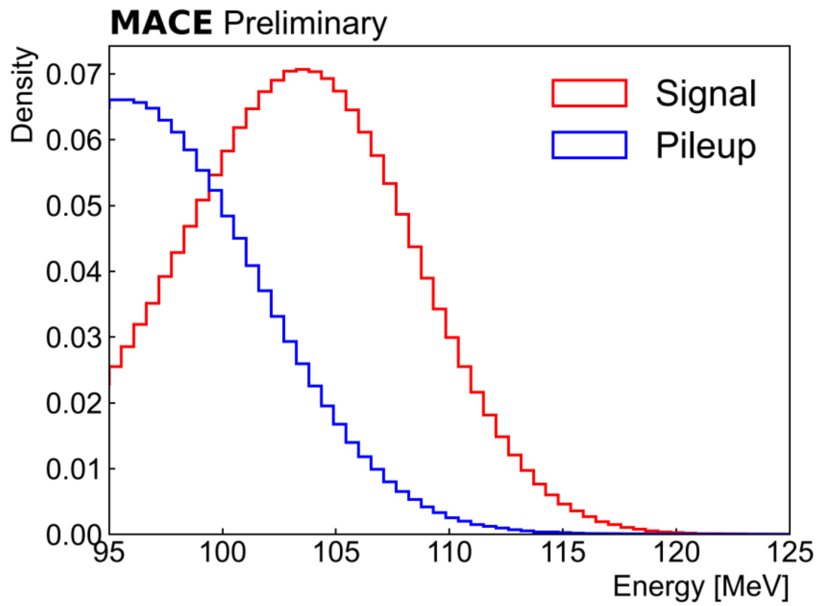
$\mathcal{O}(10^{-11})$ in *1988* PRD 38 (1988) 2077

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

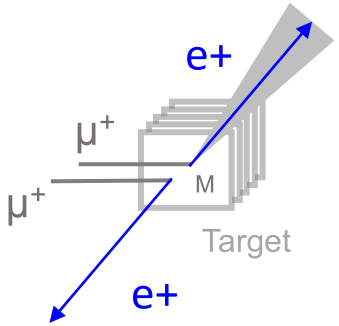
Signal: Double collinear 53 MeV gamma-rays



- No response in Tracker
- Double tracks reconstructed by ECAL



Background: Accidental coincidence of “pileup” positrons



- Positron → gamma misidentification
- Two accidental coincidence misidentified tracks at same vertex

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

$$n_{obs} = b$$

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

BR upper limit estimation: 2×10^{-13} (90% C.L.)

More background simulations and refined data analyses to be updated!

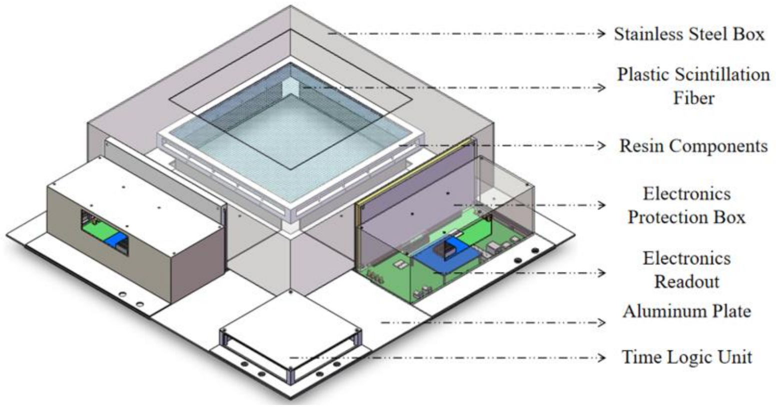
$\mathcal{O}(10^{-5})$ in *1959* PRL, 1959, 3: 288-291

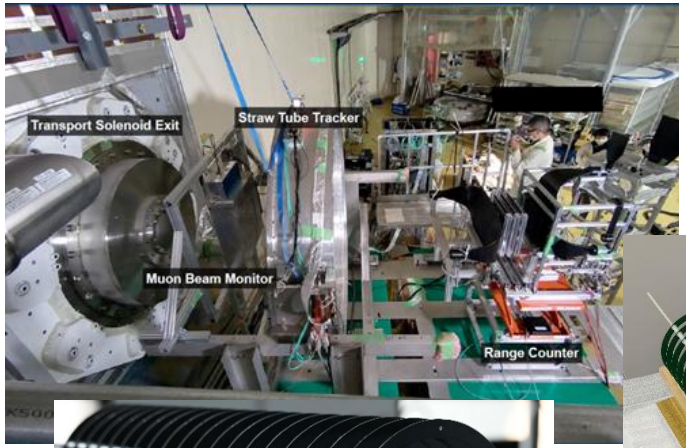
Table of contents

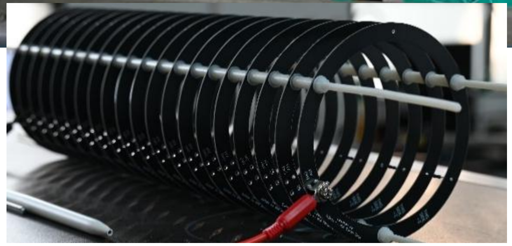
Gallery of the local lab

COMET muon beam monitor

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

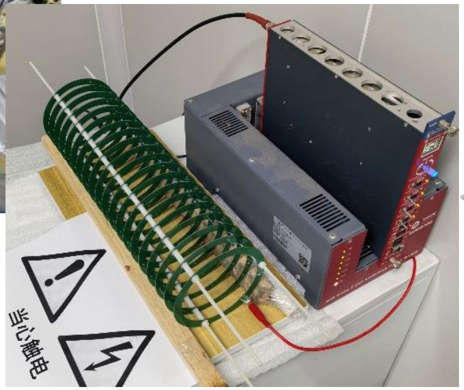




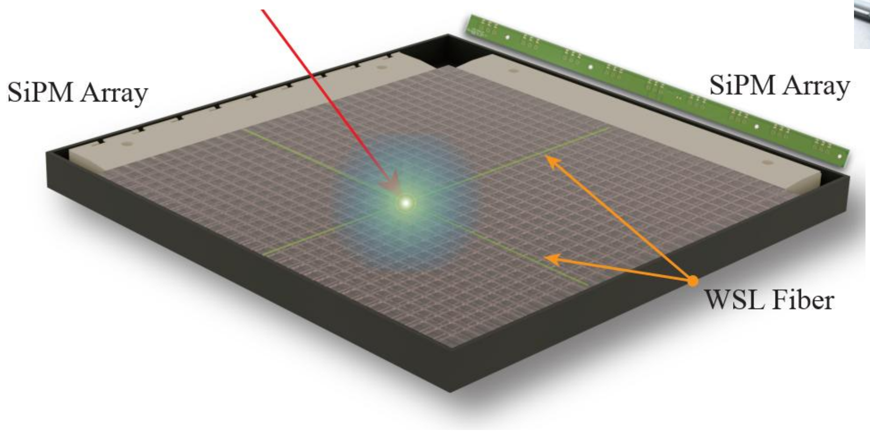


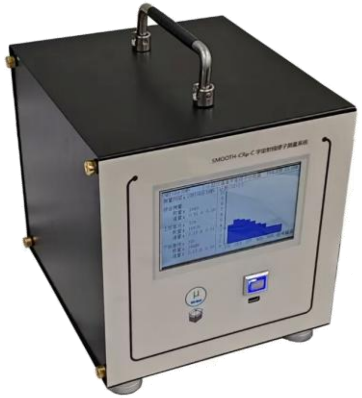
Cosmic-ray muSR (CRmuSR)

[M.-C. Sun, HHIF2024](#)

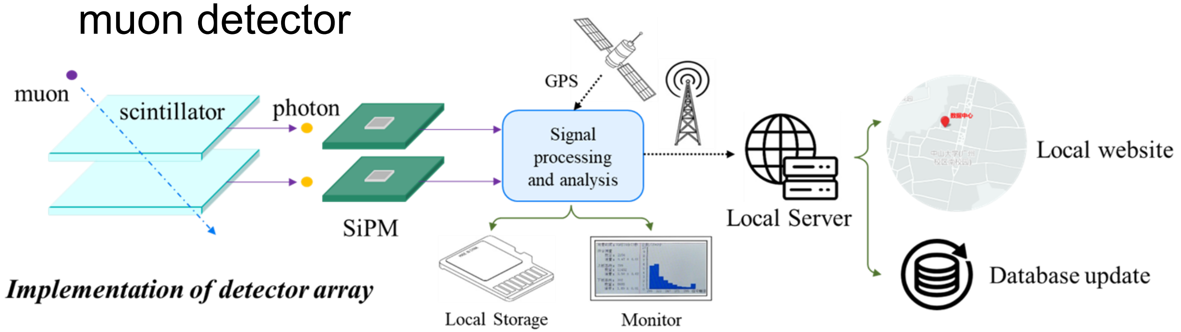


MuGrid-v2 for muography

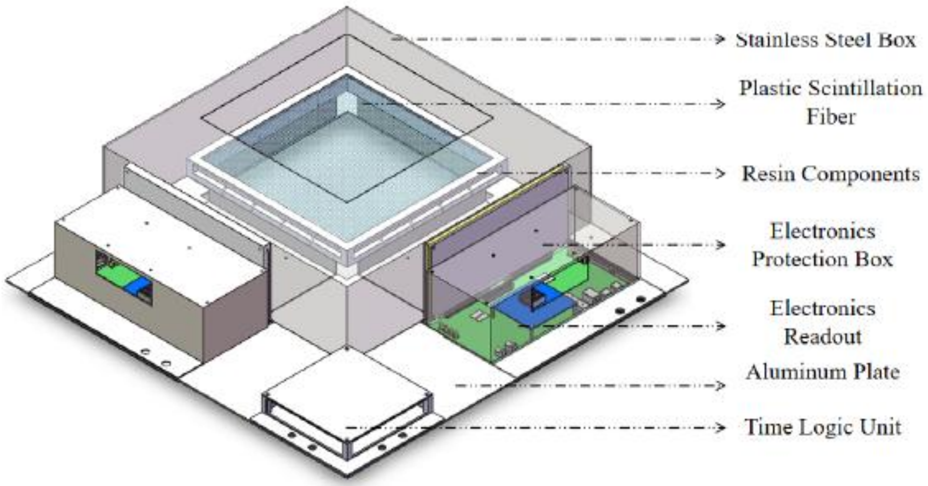


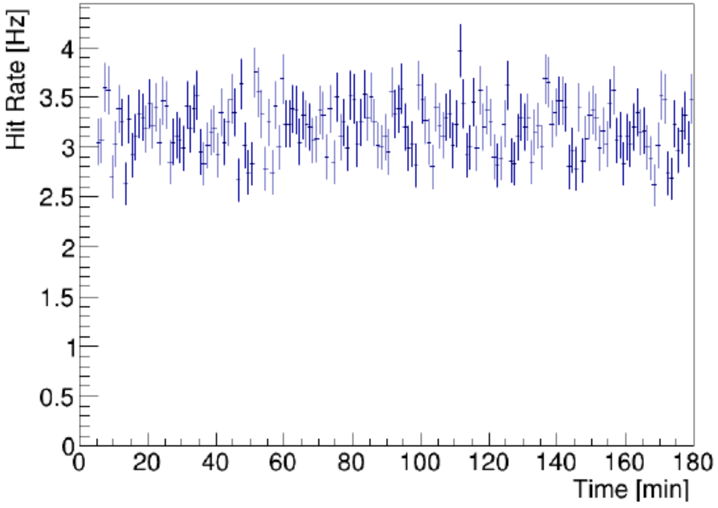


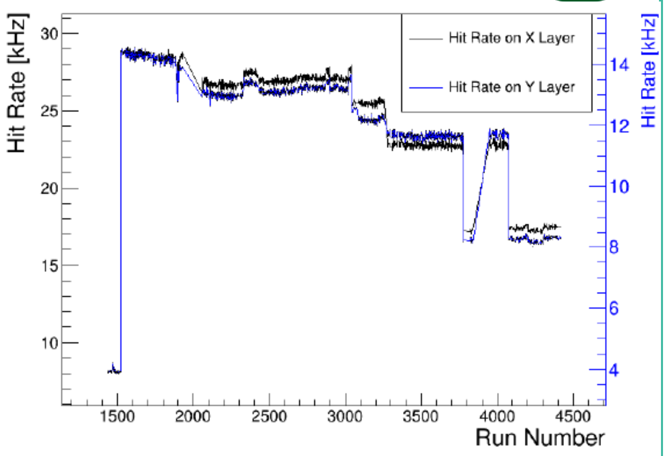
Portable cosmic-ray muon detector

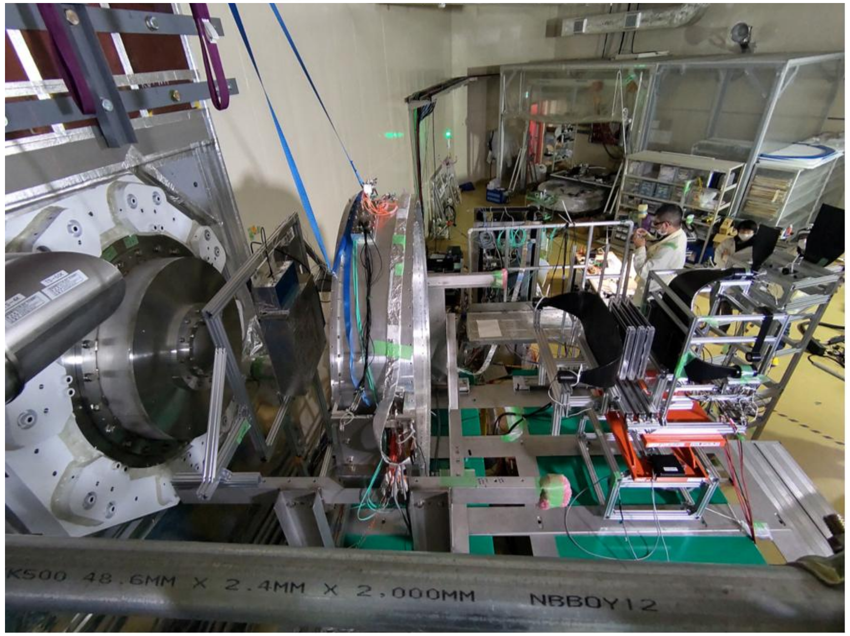


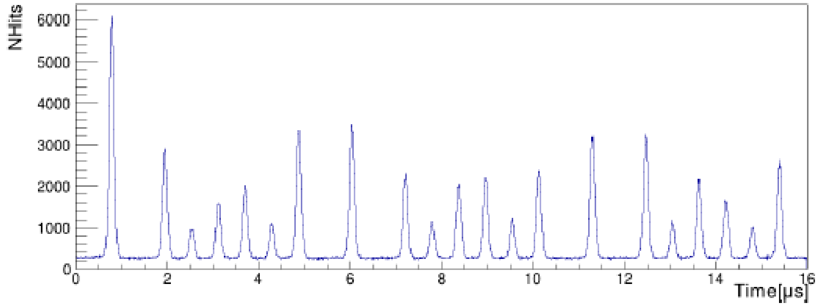
Muon beam monitor for COMET

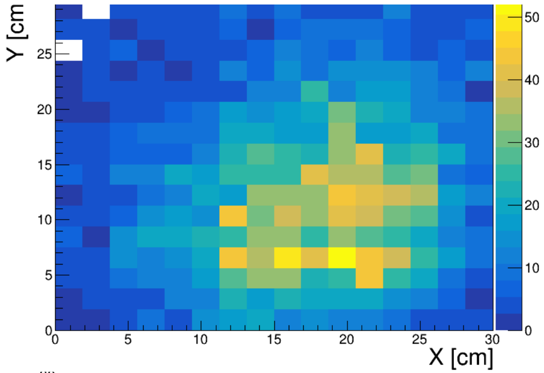


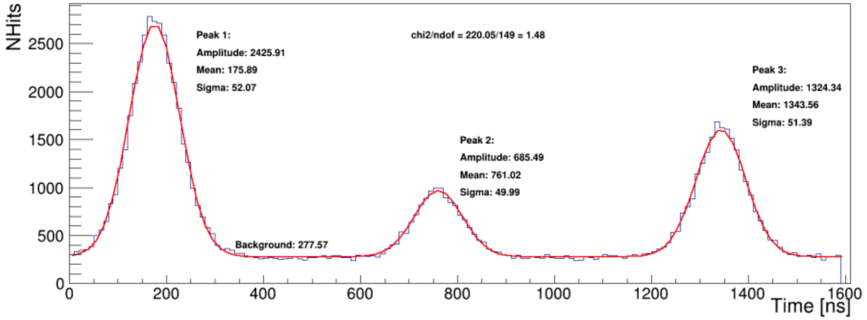


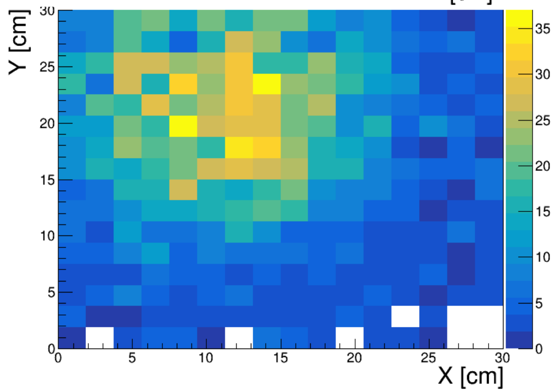




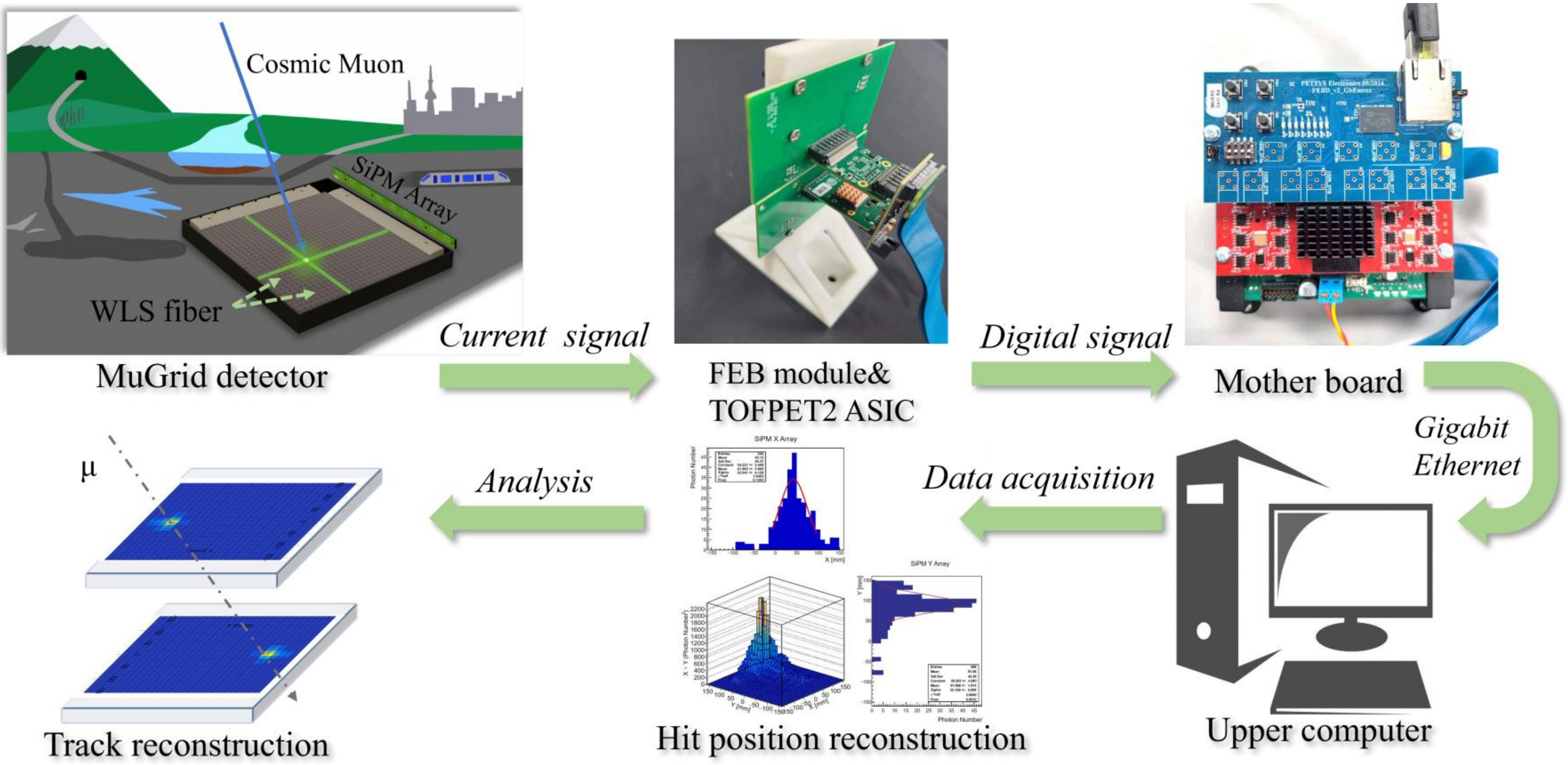






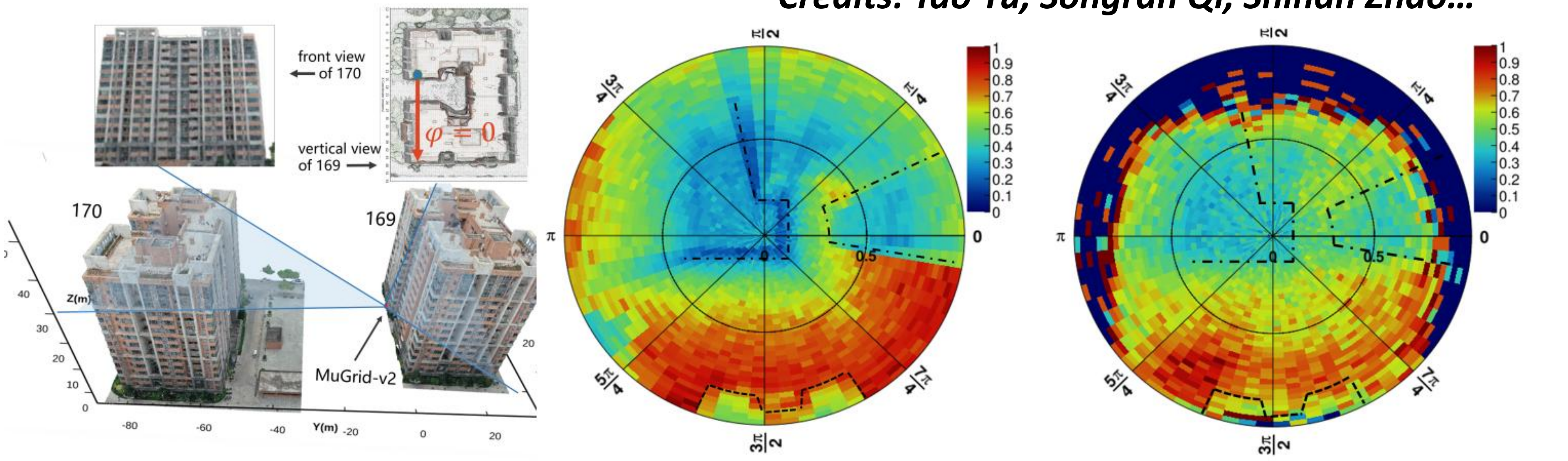


Muography: MuGrid-v2

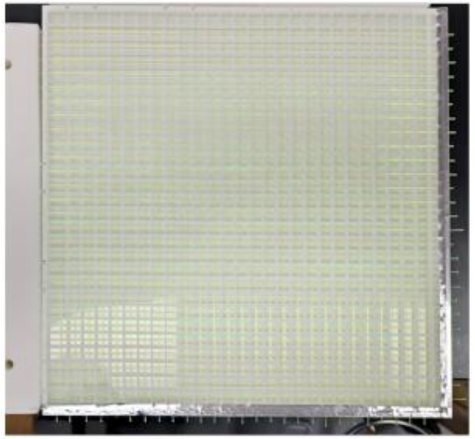


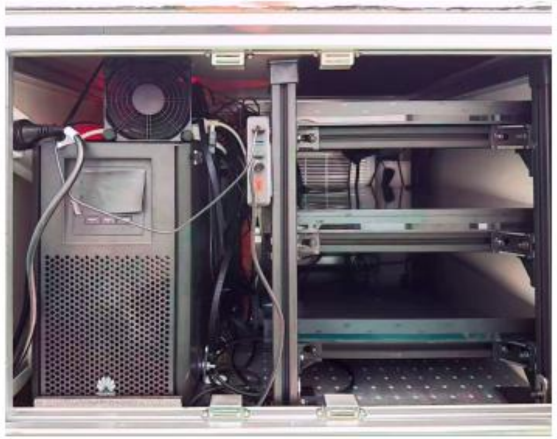
Muography : MuGrid-v2

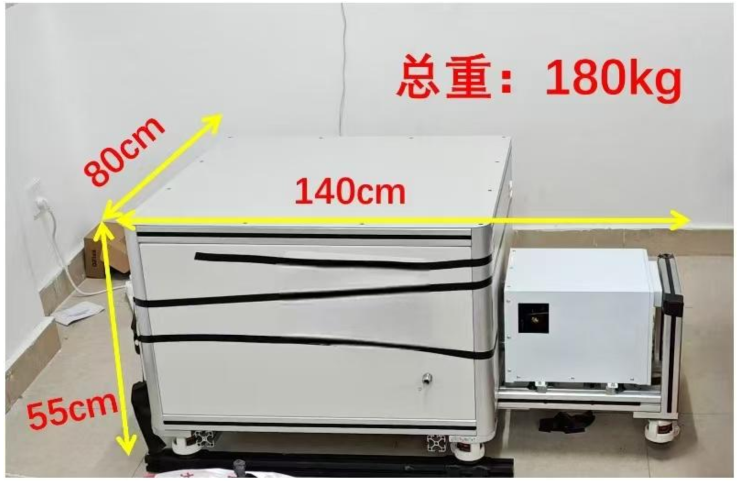
Credits: Tao Yu, Songran Qi, Shihan Zhao…



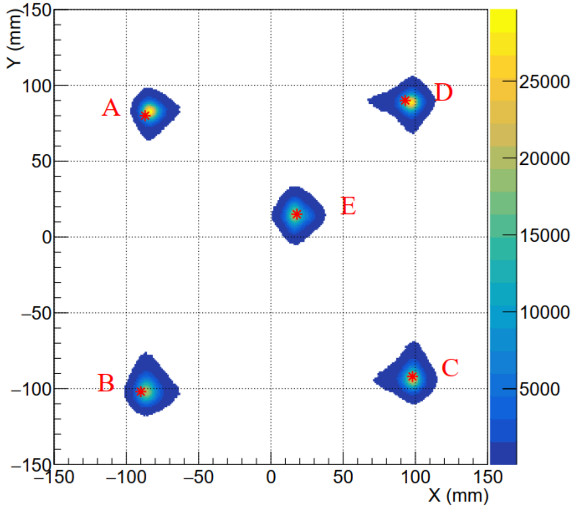
(a) An illustration of experimental setup. (b) Muon survival ratio in simulation. (c) Muon survival ratio in experiment.





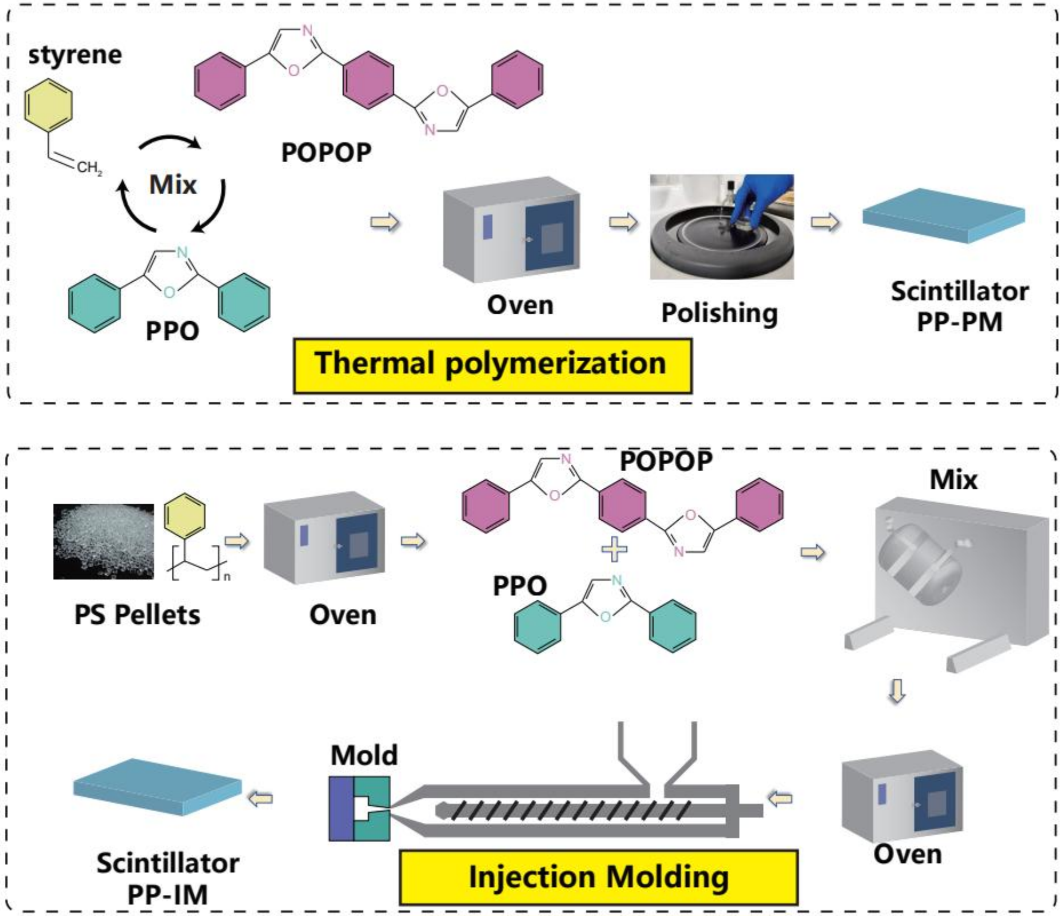


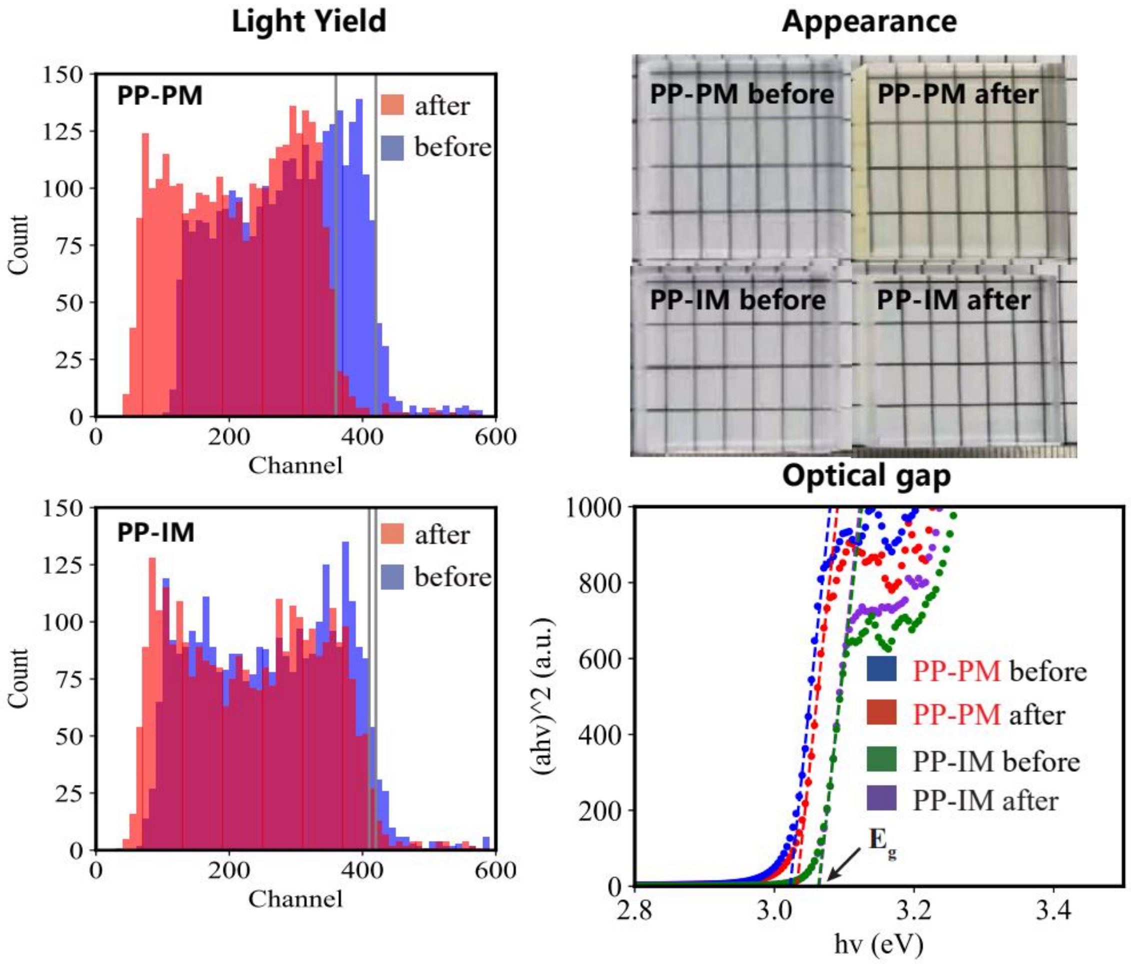
The detector MuGrid-v2 after assembly.



Calibrations with the energy and timestamp information.

R&D of new plastic scintillators for muon detections



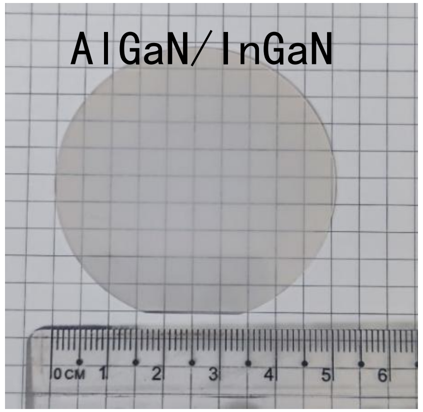


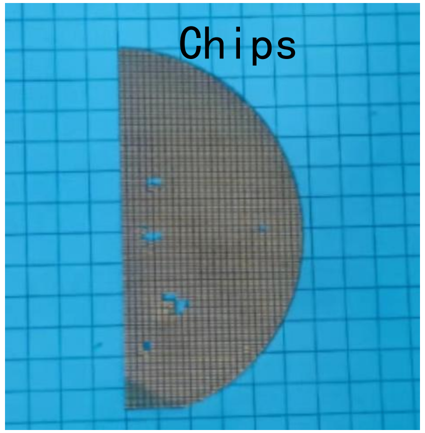
Enhancing plastic scintillator performance through advanced injection molding techniques

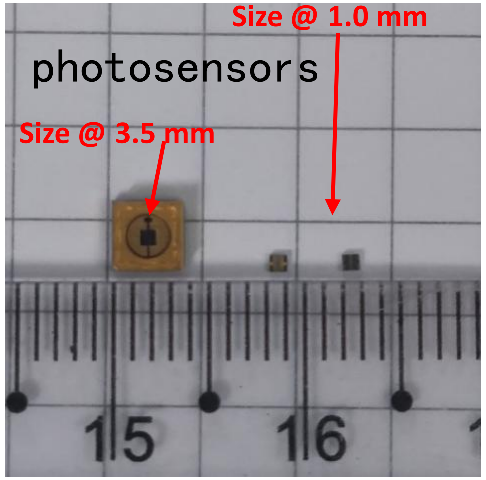
Credits: Jiahao Zhong, Nouman, Jian Zhou, ***Jian Tang***
Radiation Physics and Chemistry *226 (2025) 112193*

R&D of new photosensors for muon detections

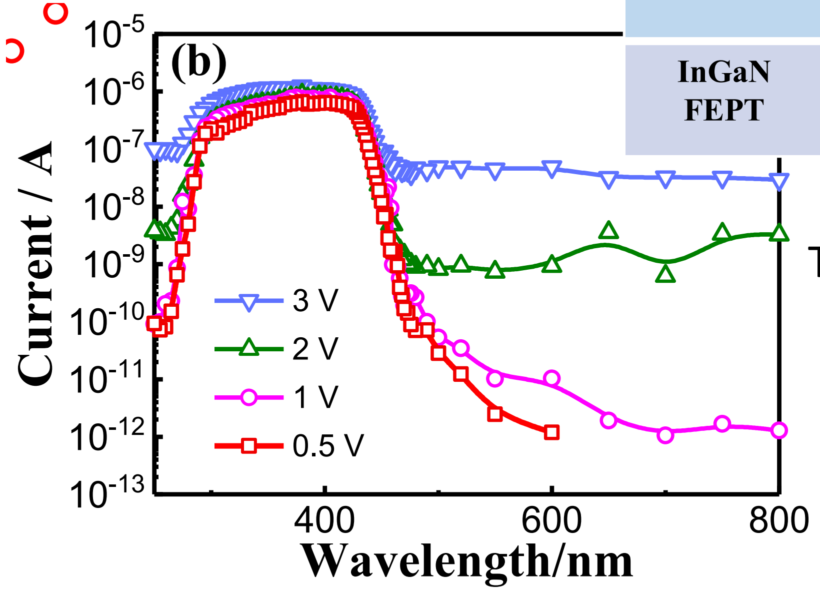
- Wavelength: 280~450 nm
- Low cost, low power consumption
- To replace SiPM/MPPC?





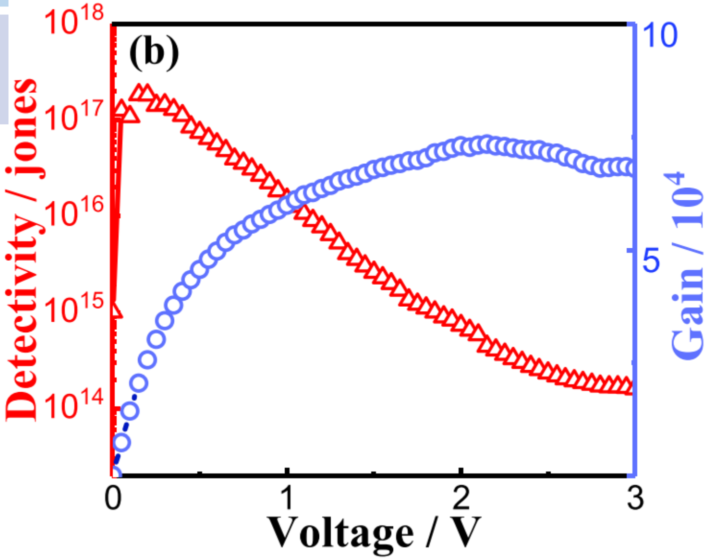


Structure	Working voltage	Dark counts	Sensitivity	Gain	Risetime/ fall time
InGaN FEPT	1.0 V	0.2 pA @ 1 V	2×10^4 A/W @6.8μW/cm^2	6.2×10^4	15 / 160 ns



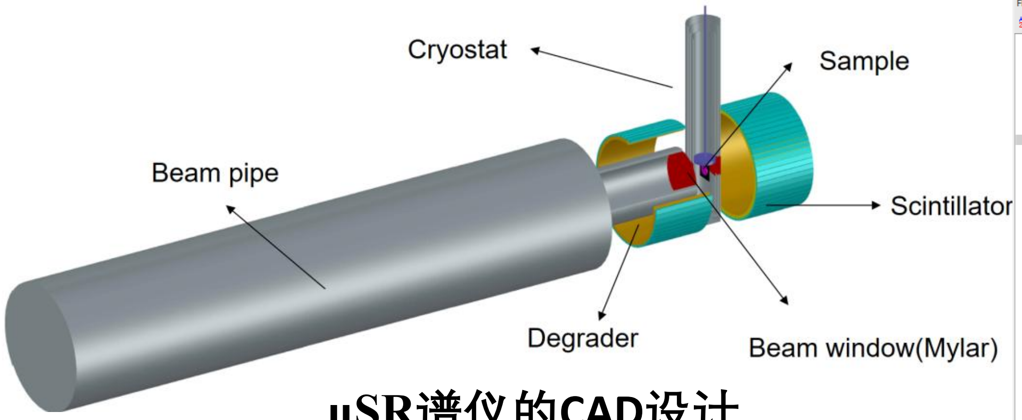
To collaborate with my previous students!

Credits: Zhesheng Lv

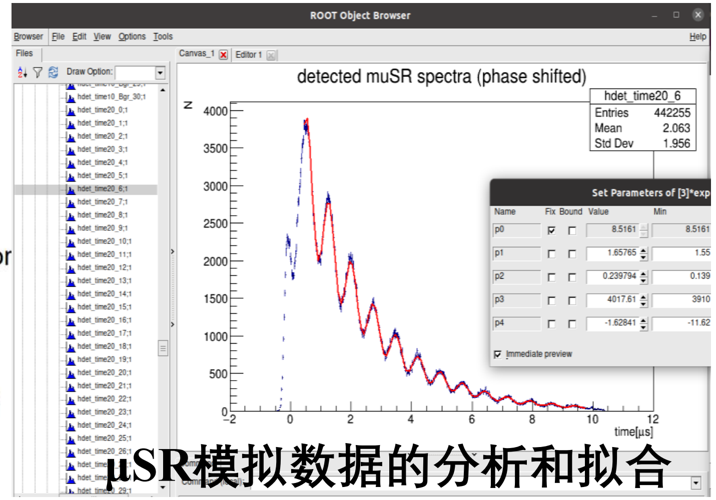


Appl. Phys. Lett. 125, 191104 (2024); *Appl. Phys. Lett.* 123, 051103 (2023)

R&D of μSR prototype: CRμSR

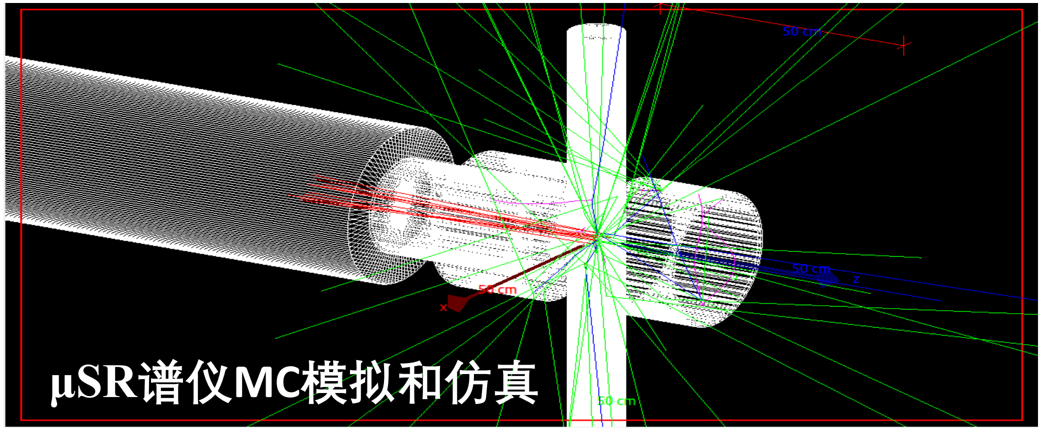


μSR谱仪的CAD设计



μSR模拟数据的分析和拟合

μSR谱仪样机安装



μSR谱仪MC模拟和仿真

μSR谱仪样机设计

μSR谱仪样机测试

Summary of recent progress

1. Positron Transport System for Muonium-to-Antimuonium Conversion Experiment, e-Print: 2508.07922 [hep-ex]
2. MuGrid-v2: A novel scintillator detector for multidisciplinary applications, e-Print: 2505.19777 [physics.ins-det], **Journal of Applied Physics** 138, 024501 (2025)
3. Cosmic Ray Muon Polarization to Facilitate Atmospheric Neutrino Physics, e-Print: 2505.13877 [hep-ex]
4. Development of portable cosmic-ray muon detector array for muography, e-Print: 2503.18800 [physics.ins-det] **Journal of Applied Physics** 138, 074502 (2025) .
5. High-Precision Physics Experiments at Huizhou Large-Scale Scientific Facilities, e-Print: 2504.21050 [hep-ph], **Chinese Physics Letters** 42 (2025) 11, 110102.
6. Tensor interaction in coherent elastic neutrino-nucleus scattering, e-Print: 2502.10702 [hep-ph], **Physical Review D** 112 (2025), 035036.
7. Conceptual Design of the Muonium-to-Antimuonium Conversion Experiment (MACE), e-Print: 2410.18817 [hep-ex], accepted by **Nuclear Science and Techniques**.

Summary

- Muon physics is a hot topic, enabling precise tests of QED theory and probe of new physics beyond SM.
- MACE experiment will make a breakthrough in muon physics.
- Significant progress has been made in experiment design, muonium target design, and offline software development.
- Ongoing development of sub-detectors (MBM, EMCal, etc.) and reconstruction algorithms.
- Local muon lab SMOOTH: cosmic muon detector, muon beam monitoring detector, μSR prototype
- MACE Conceptual Design Report completed; Cutting-edge science will drive technological applications; looking forward to multidisciplinary applications after a development of SMOOTH-μSR prototype.
- Great potential in muon physics — small sparks can ignite a bush fire!
- Welcome to joining MACE and looking forward to fruitful results!

Thanks!

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

(MACE working group)

NSFC