Conceptual Design of Muonium-to-Antimuonium Conversion Experiment

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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

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- Conceptual design of MACE
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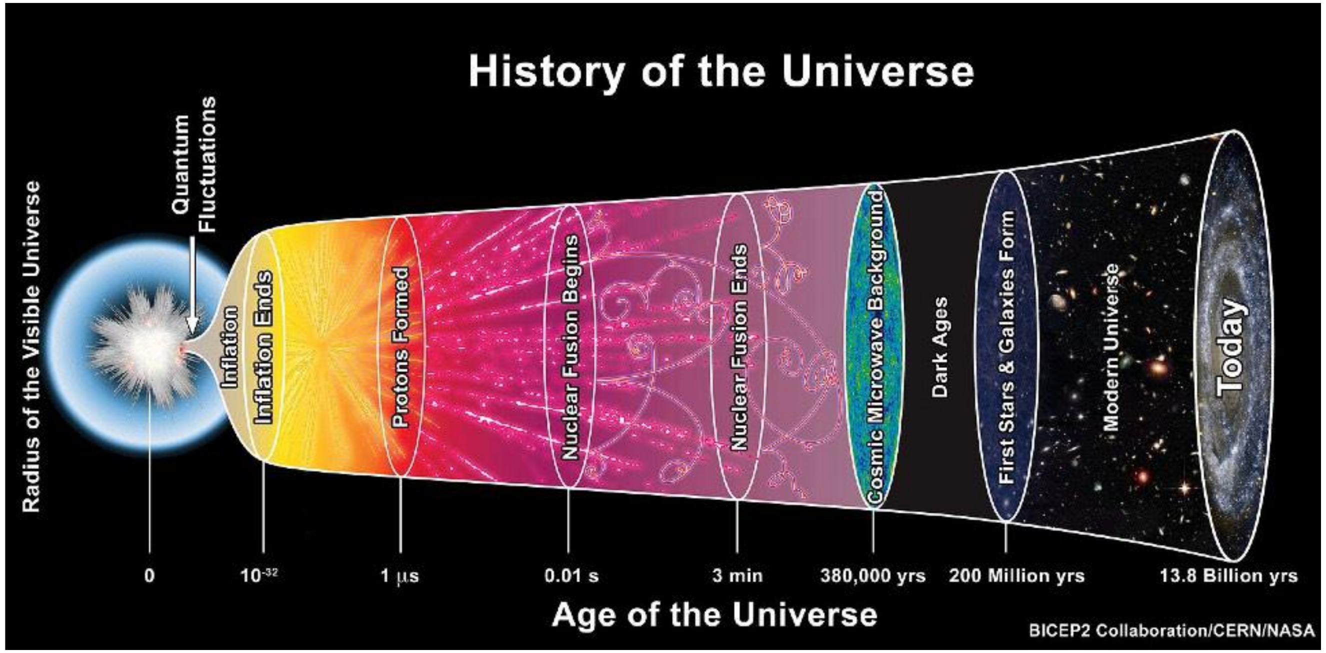
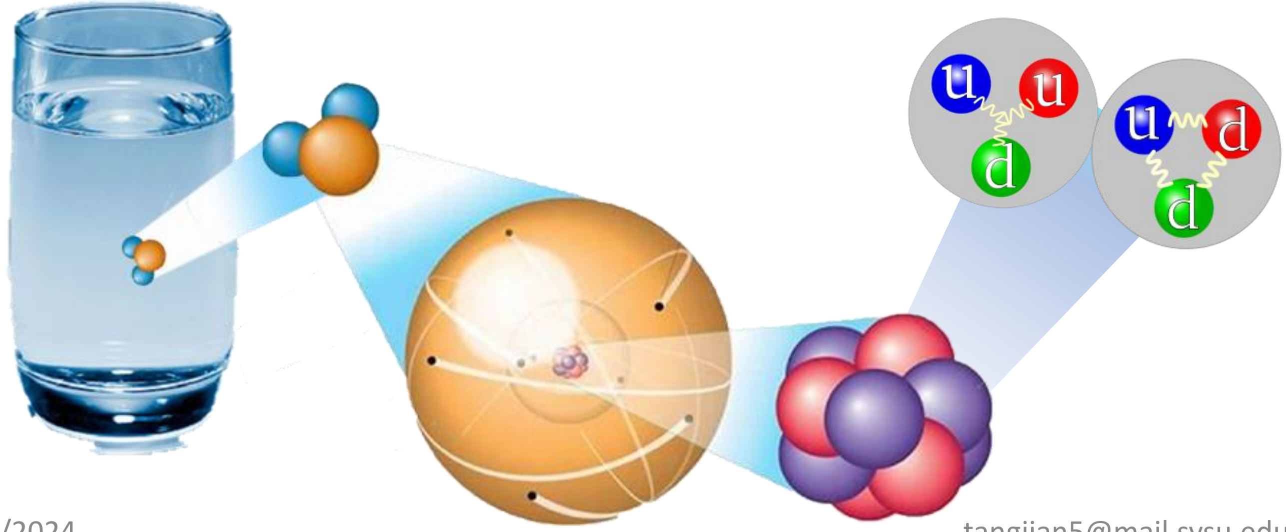
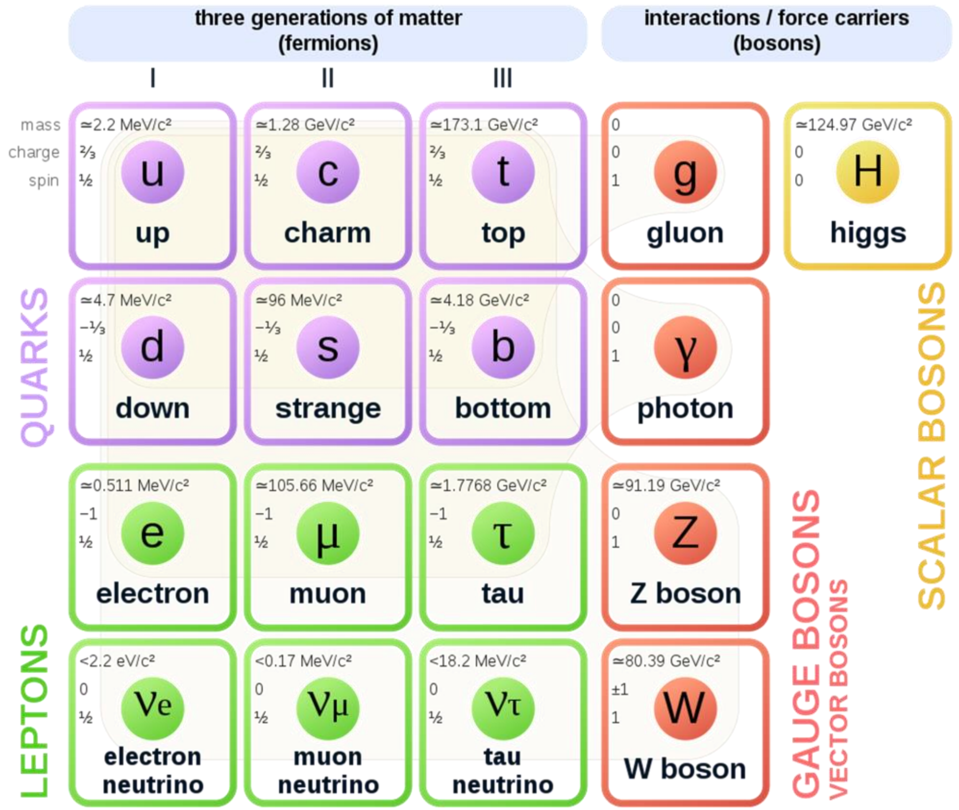
Standard Model







$$\underbrace{SU(3)_{\text{Color}}}_{\text{QCD}} \otimes \underbrace{SU(2)_{\text{Left}} \otimes U(1)_{\text{Hyper charge}}}_{\text{WEAK} \oplus \text{QED}}$$

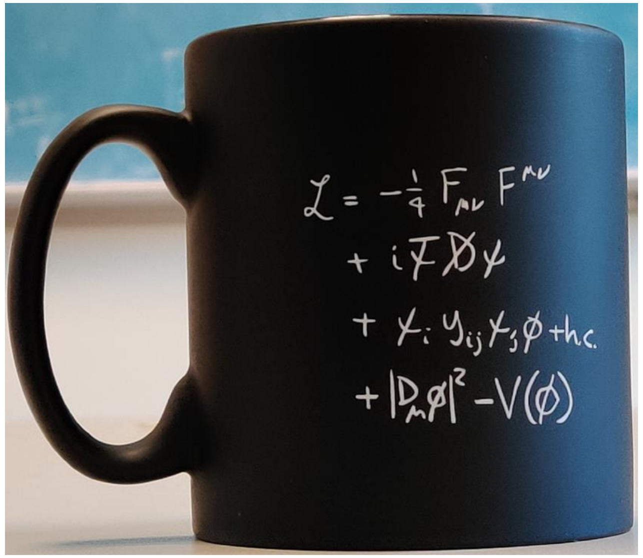
(Strong Interaction)

(Unification of Weak and Electromagnetic)

Symmetries of SM

- The Standard Model (SM) gauge symmetry:

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



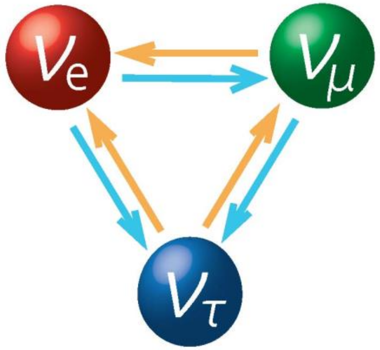
- The absence of right-handed neutrino leads to lepton flavor symmetry:

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

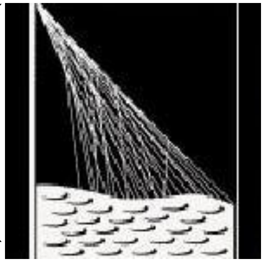
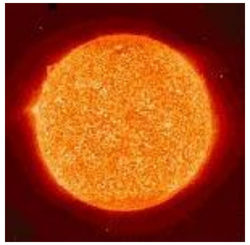
	Lepton number	Lepton family number (lepton flavor)		
		L_e	L_μ	L_τ
e^- & ν_e	1	1	0	0
μ^- & ν_μ	1	0	1	0
τ^- & ν_τ	1	0	0	1

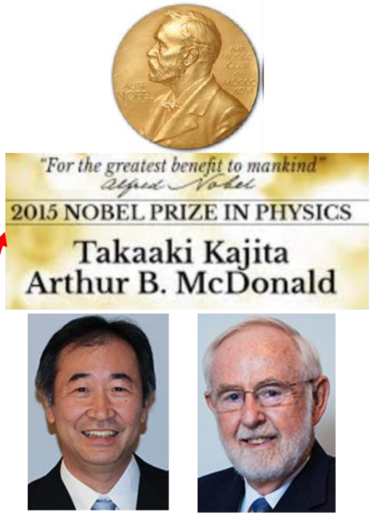
- Lepton flavor is always conserved **in the Standard Model,** however…

Neutral leptons oscillate!

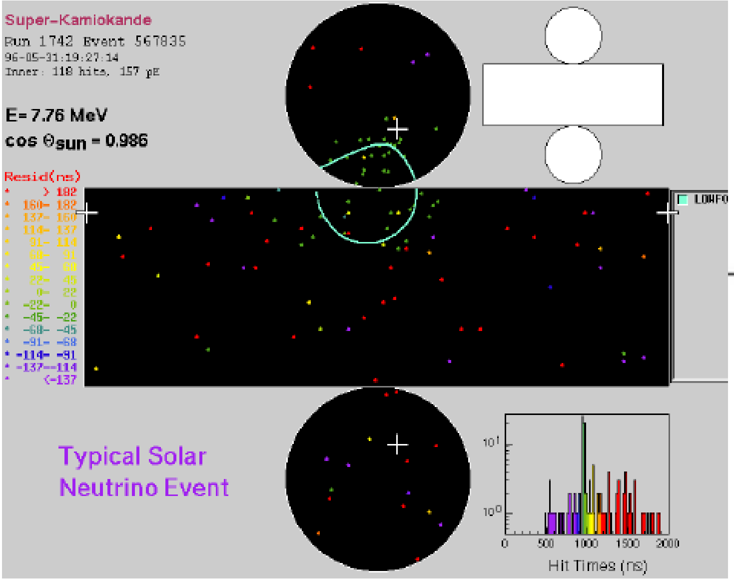


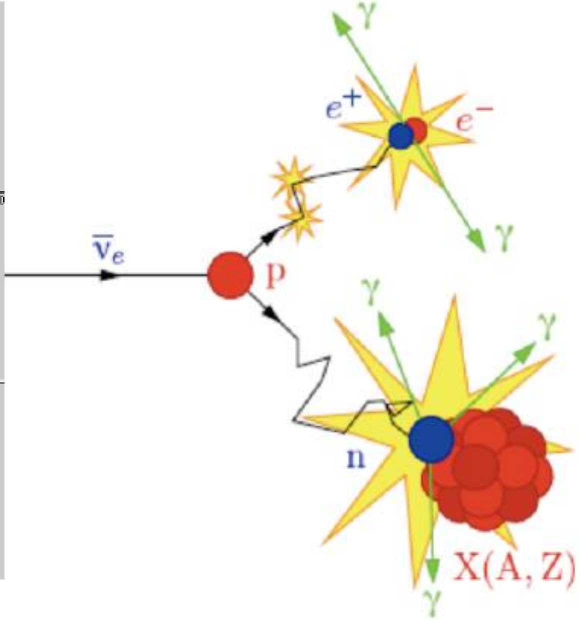
$$U_{\rm PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\, e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}\, e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

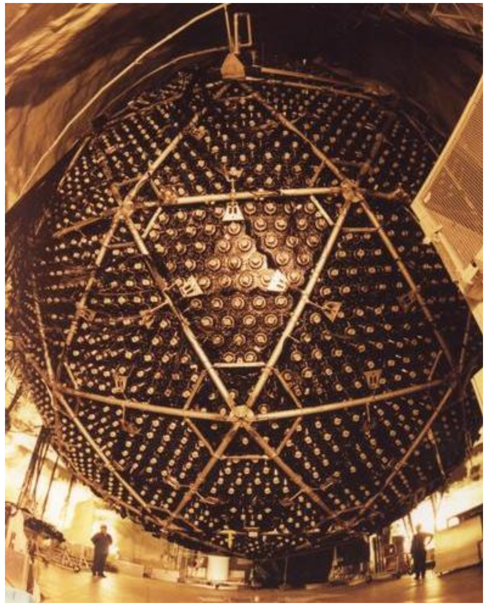
= () x () x ()



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



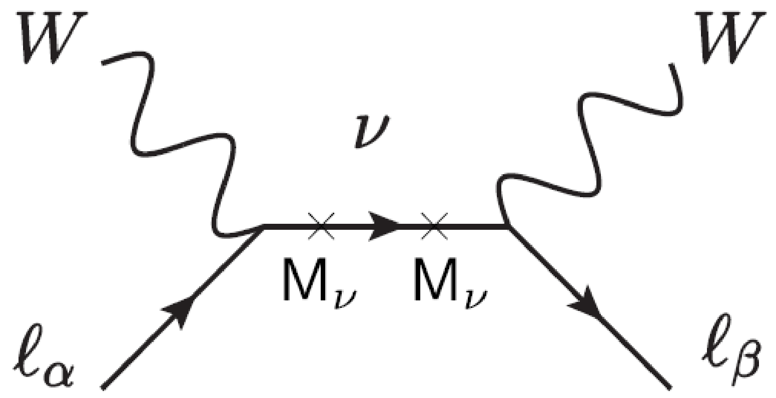




Neutrino oscillation → cLFV?

- Neutrino oscillation → $M_\nu \neq 0$
- cLFV should exist, but we don't see it

$$U(1)_{L_\mu - L_\tau} \times U(1)_{L_\mu + L_\tau - 2L_e}$$



- Tiny neutrino masses → suppressed cLFV in νSM

$$\mathcal{A}(\ell_\alpha^- \to \ell_\beta^-) \propto \frac{(M_\nu M_\nu^\dagger)_{\alpha\beta}}{M_W^2} < 10^{-24}$$

Right-handed neutrino acquire a lepton number violating mass, leaving an $SU(2)_L \times U(1)$ subgroup unbroken. Consequence for the decay μ→eγ are studied. Now called Type-I seesaw model.

Peter Minkowski, Phys.Lett.B 67 (1977) 421-428

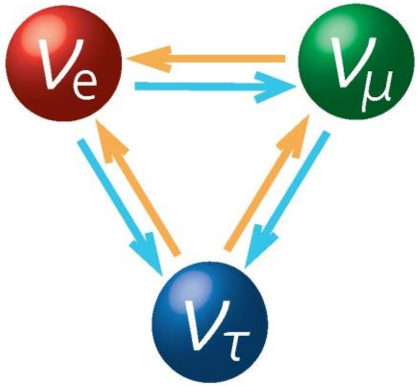
- Neutrino mass models, e.g. seesaw(Type-I, II, III), predict observable cLFV!

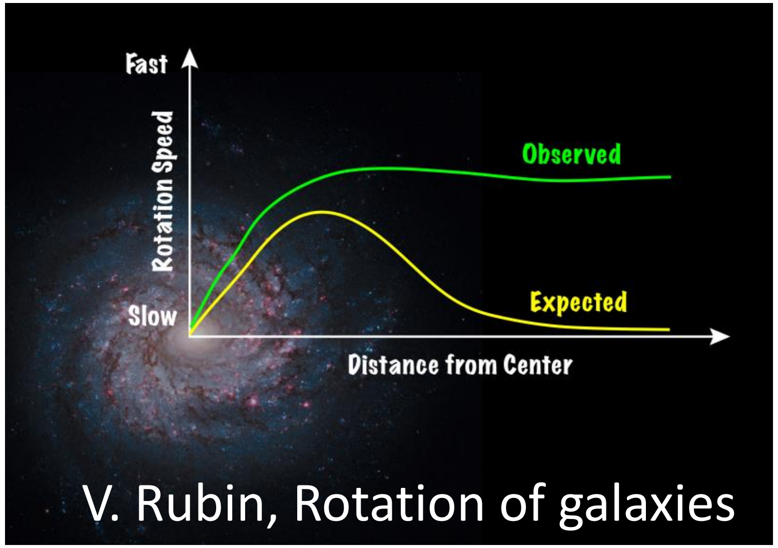
cLFV offers a probe to the origin of neutrino mass

New Physics beyond SM

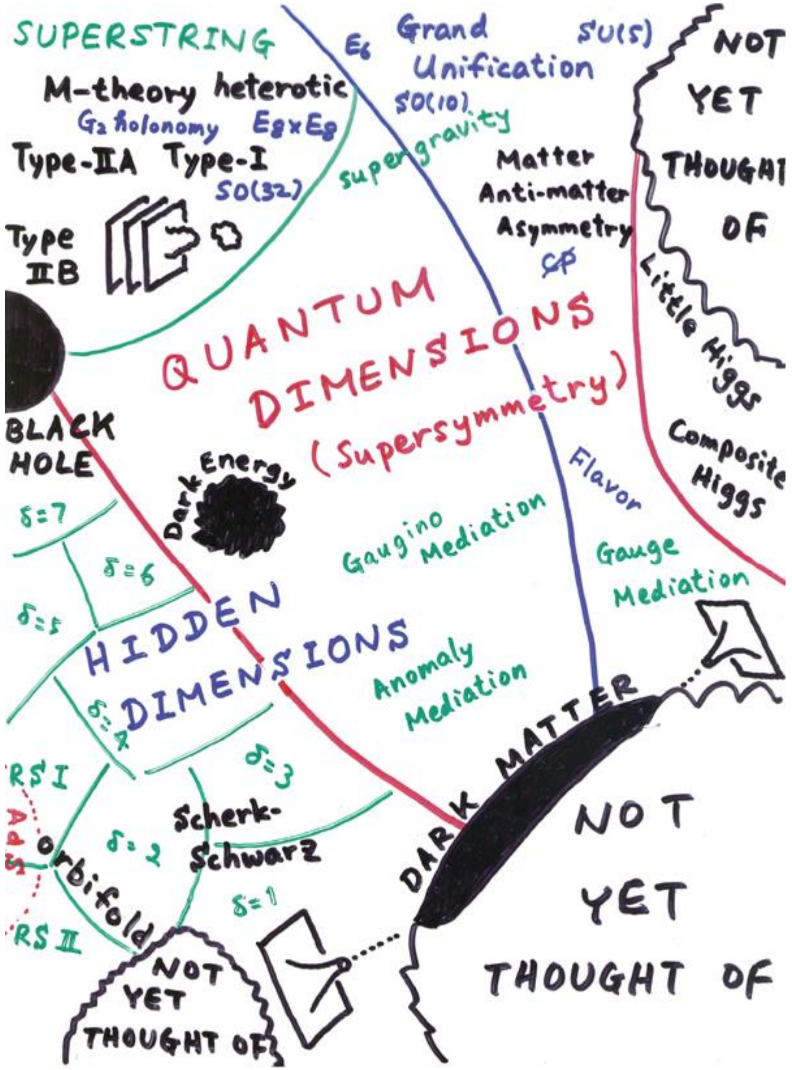
To-do lists:

- **Origin of neutrino masses?** **Non-standard interactions?**
- CP violations in the lepton sector?
- **Charged lepton flavor violations?**
- What is DM?
- Origin of matter-antimatter asymmetry? …





V. Rubin, Rotation of galaxies



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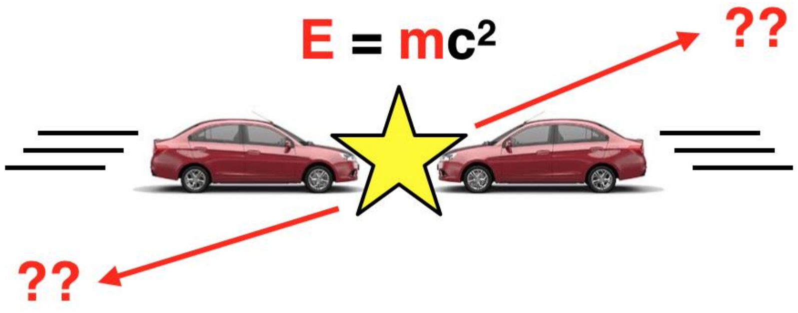
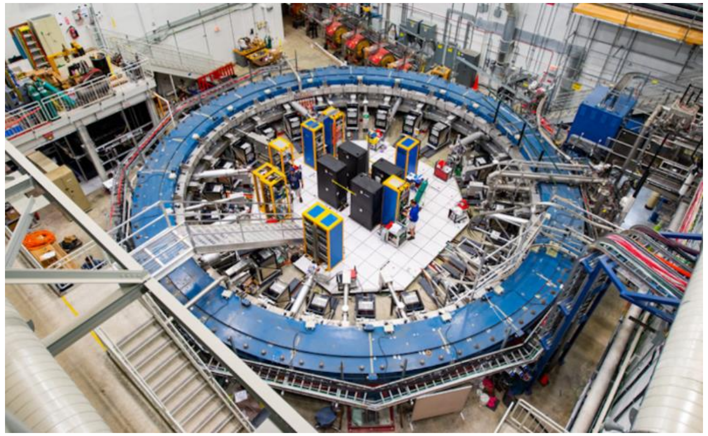
Two frontiers searching for New Physics

Energy frontiers



Complementary

Intensity frontiers



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

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High-intensity/-precision frontier

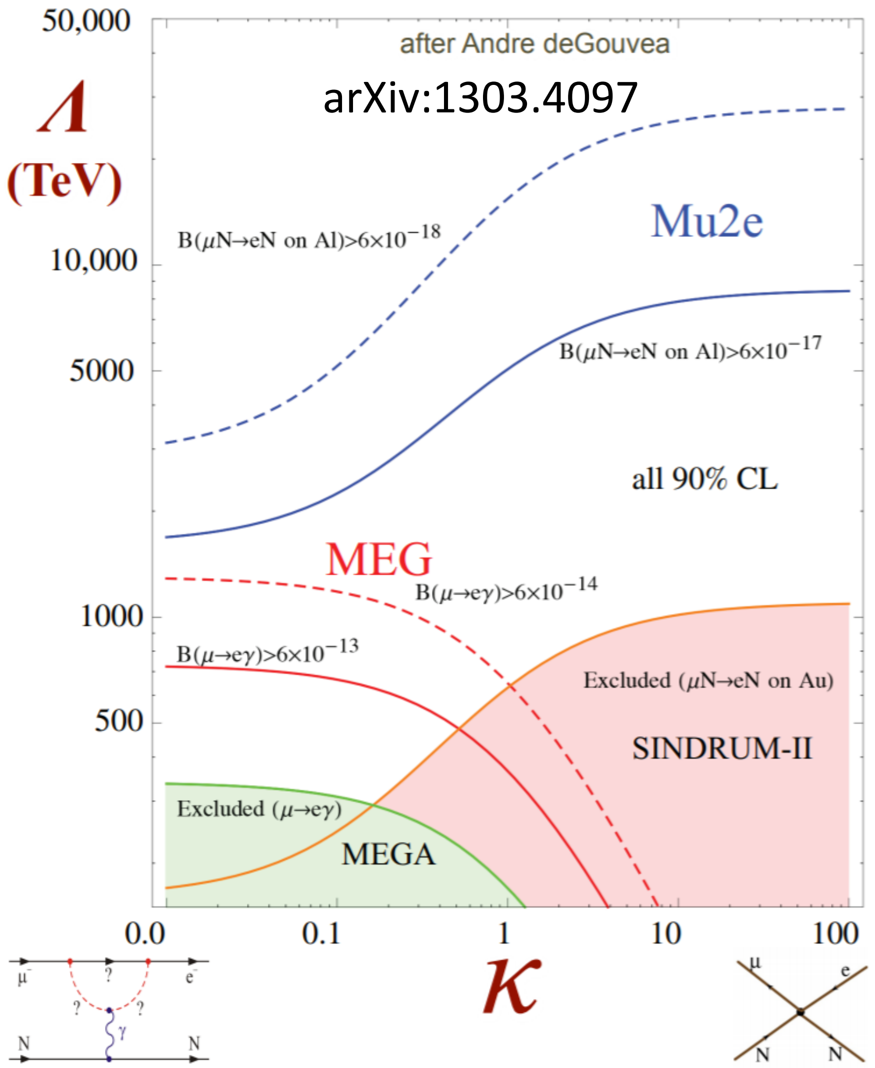
- **Experiments search for cLFV:**
  - ➢ Mu2e (Fermilab)
  - ➢ COMET (J-PARC)
  - ➢ MEG (PSI)
  - ➢ Mu3e (PSI)

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

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

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

- **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)

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

  - ➢ MEG (PSI)

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

  - ➢ Mu3e (PSI)

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

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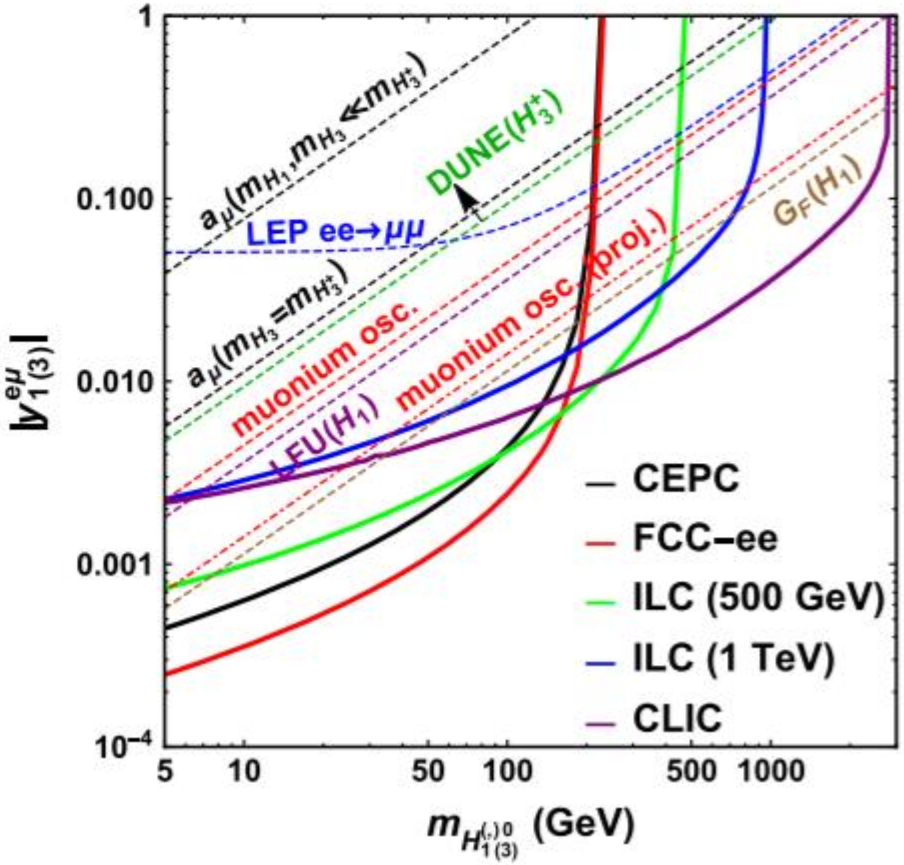
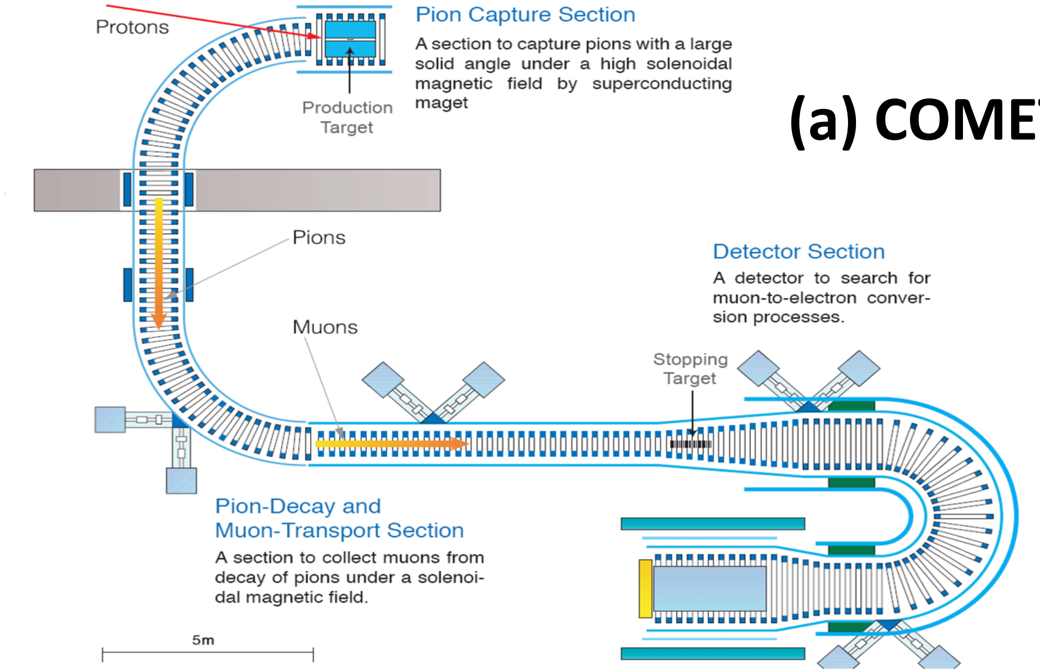


REF: Tong Li, Michael A. Schmidt. Phys.Rev.D 100 (2019) 11, 115007

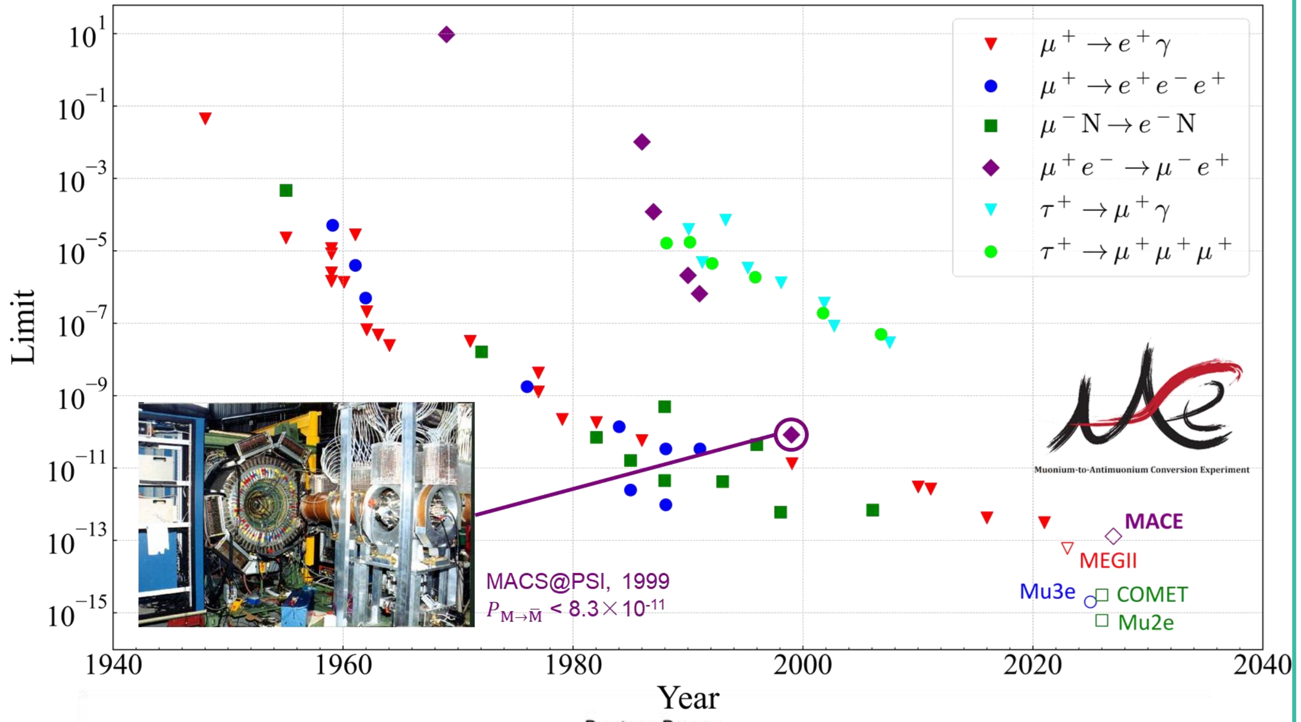
- **Low-energy cLFV experiments complement high-energy frontier**
- **cLFV complement neutrino physics**

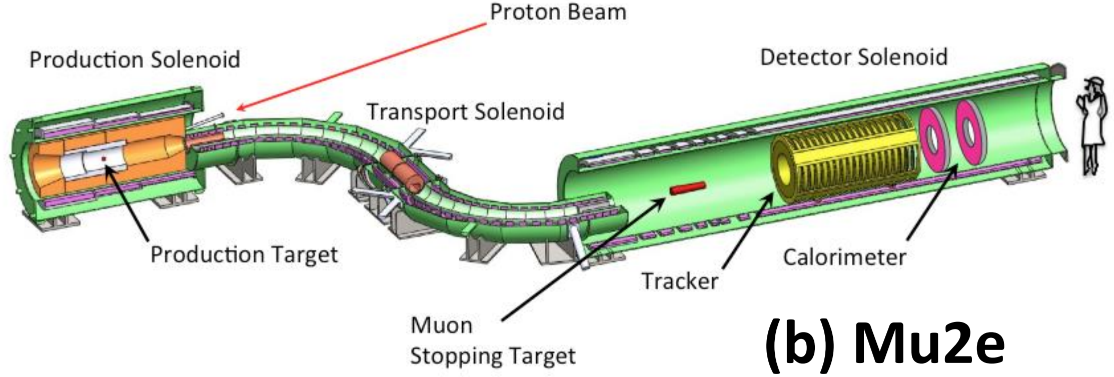
High-intensity/-precision frontier

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



(a) COMET





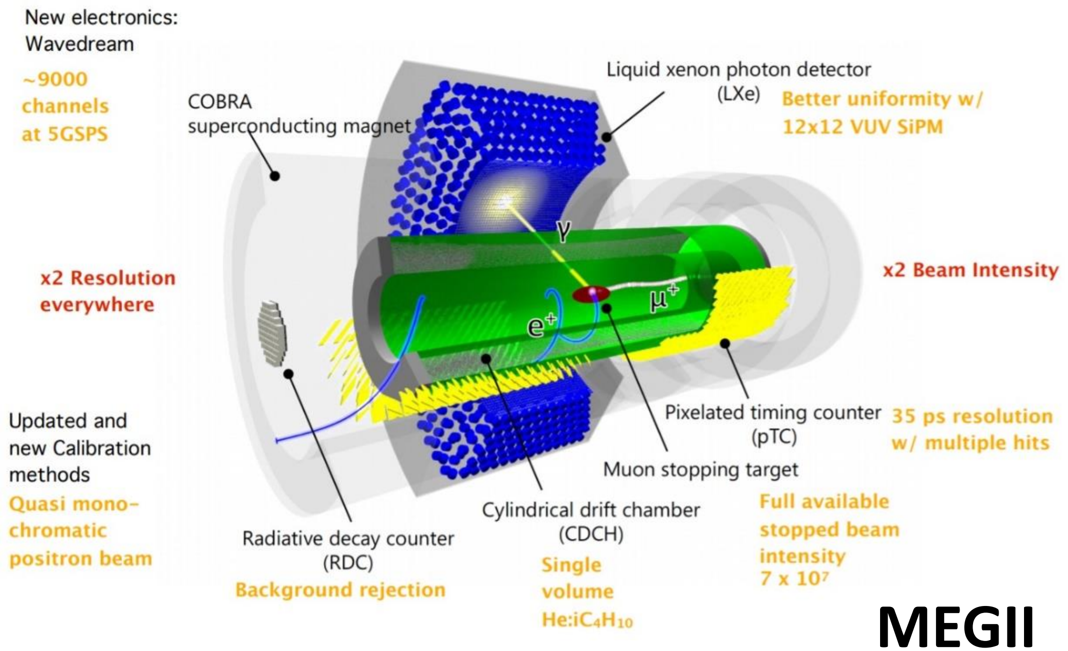
(b) Mu2e

High-intensity/-precision frontier

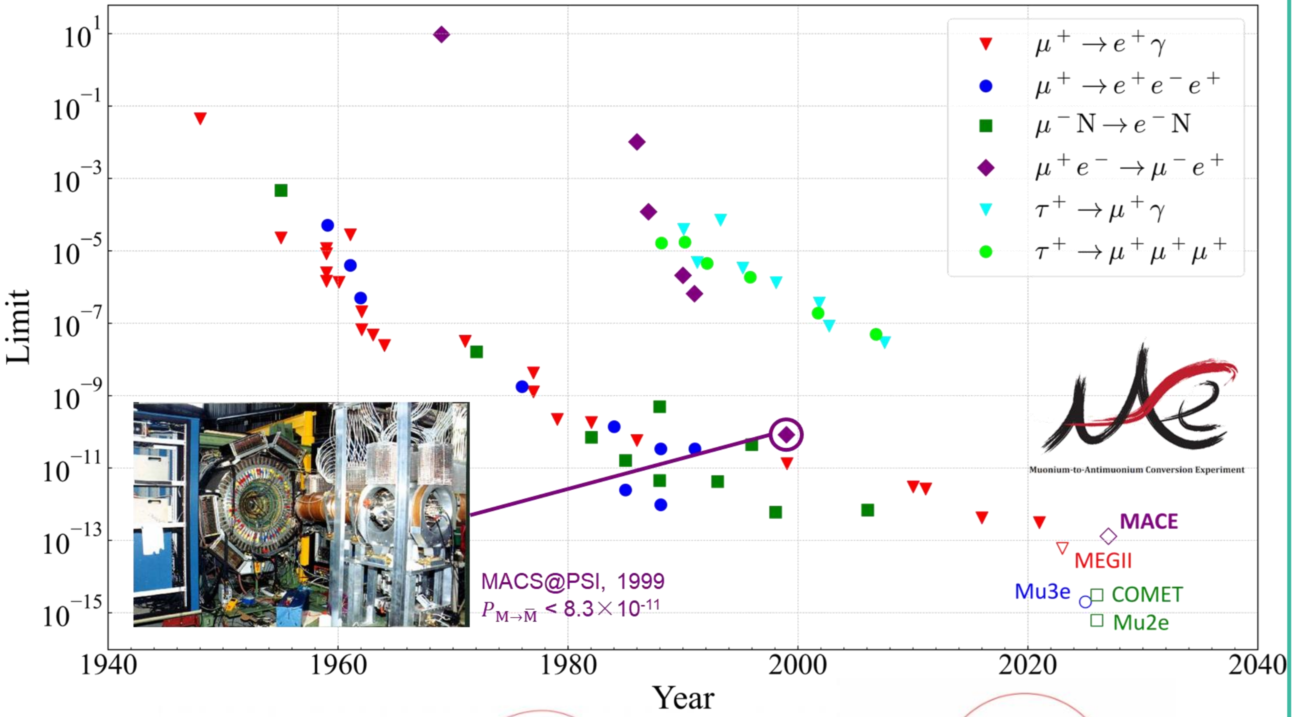
- **Experiments search for cLFV:**
  - ➢ Mu2e (Fermi lab)
  - ➢ COMET (J-PARC)

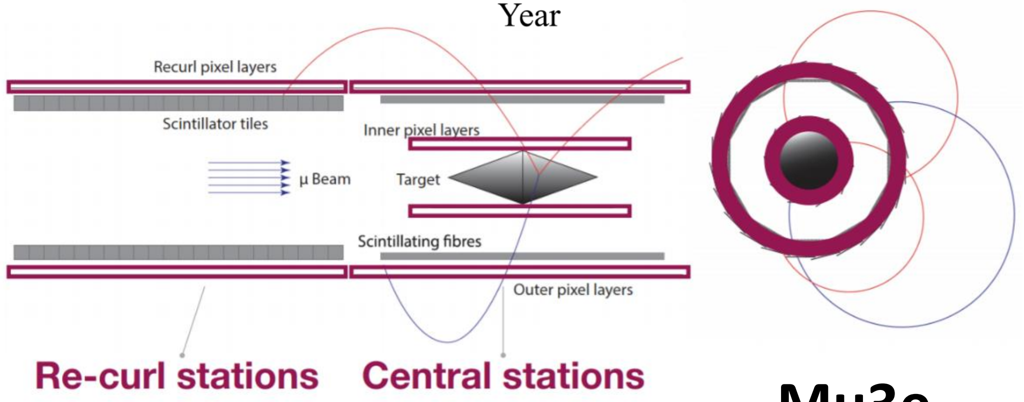
$$\mu^- + Al \rightarrow e^- + Al$$

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



MEGII





Mu3e

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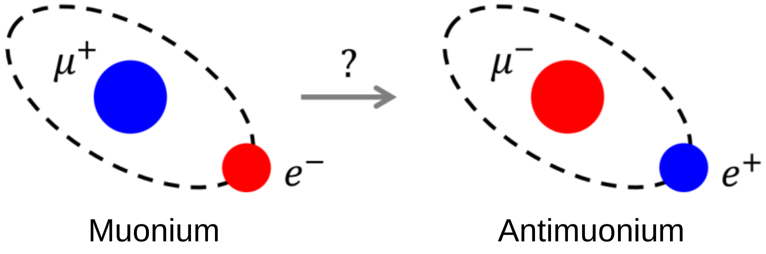
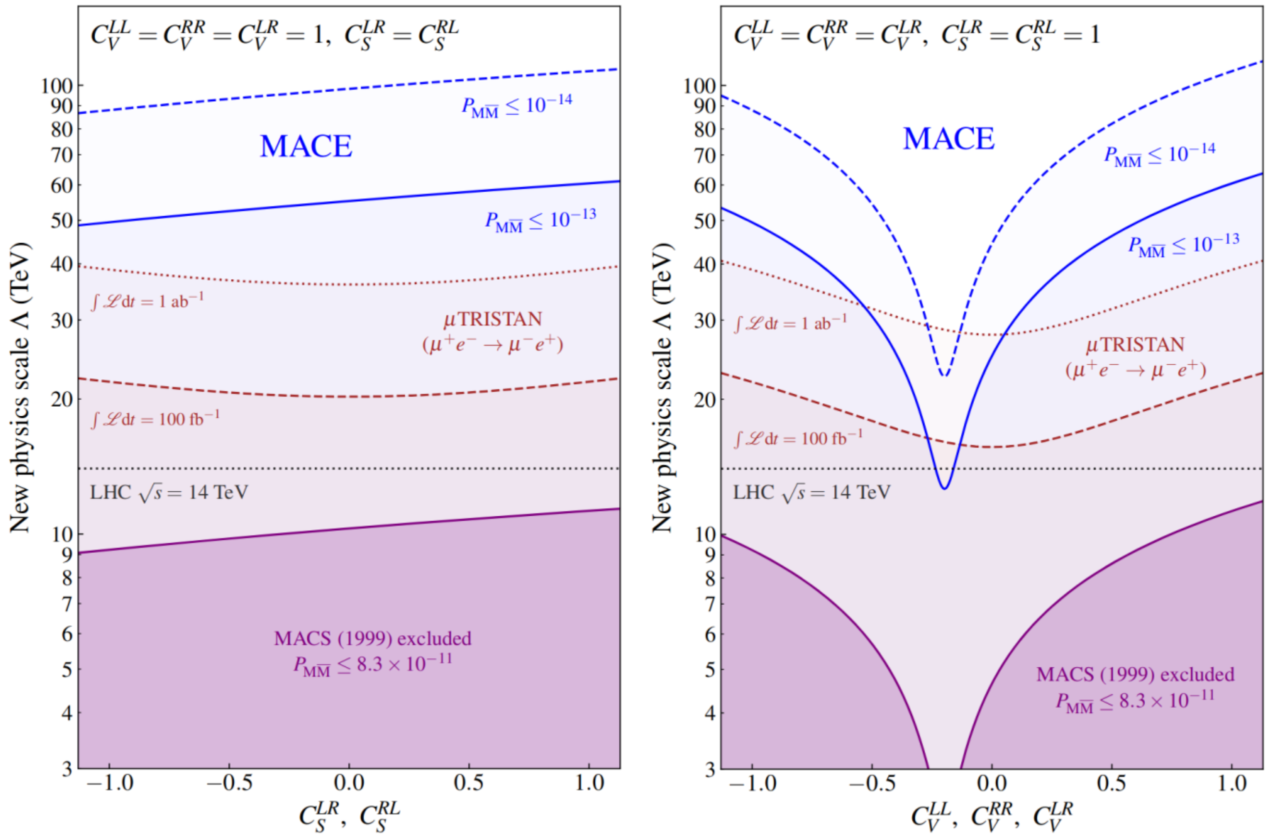
Muonium conversion: a cLFV process

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

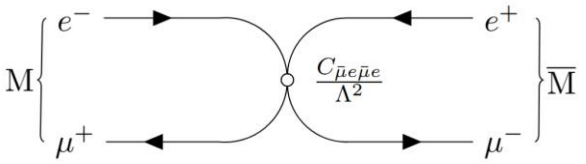


Current bound:
$P_{\mathrm{M}\to\overline{\mathrm{M}}} < 8.3\times10^{-11}$
(in 0.1T field, 90% C.L.)

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



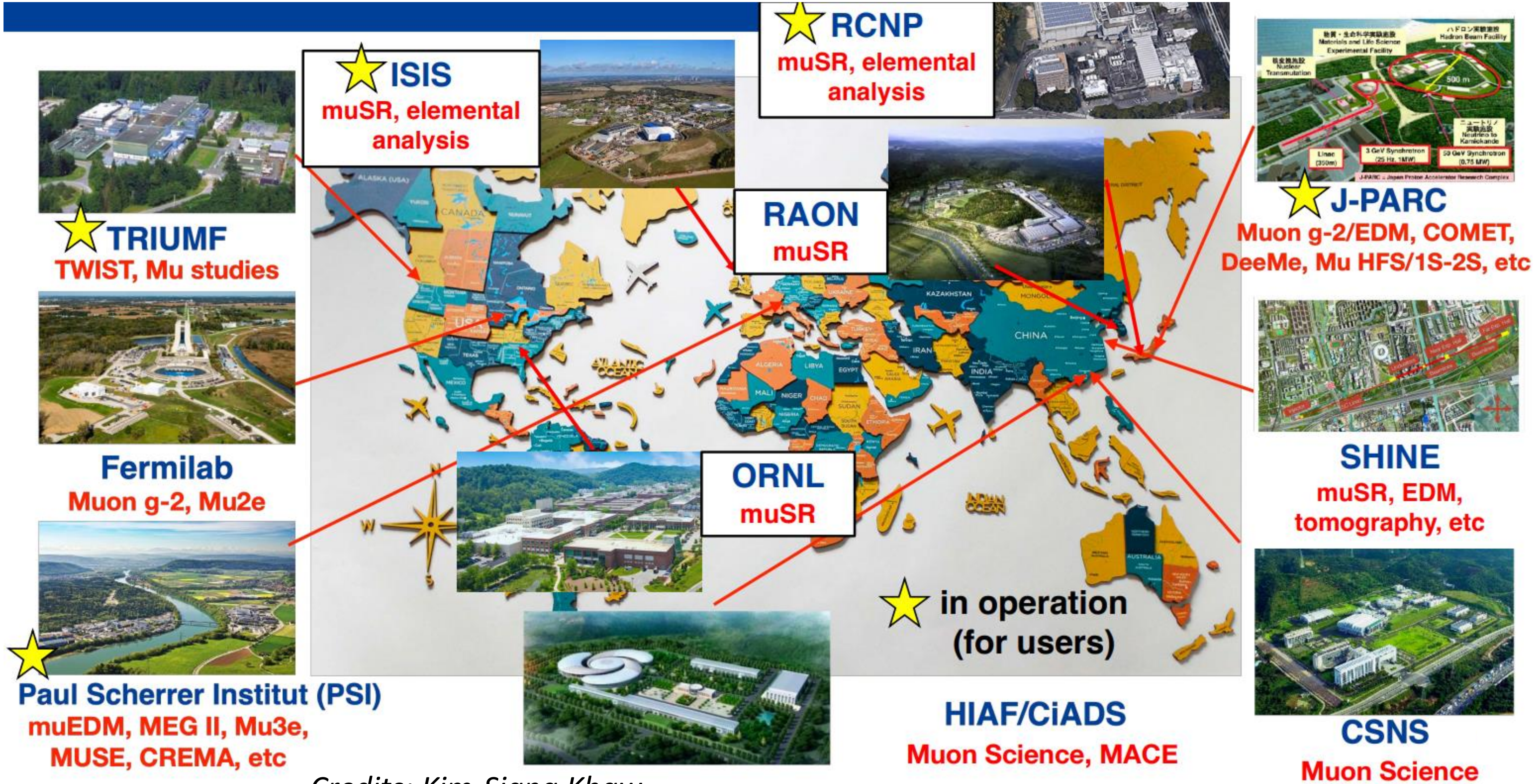
- $\mathrm{M} \to \overline{\mathrm{M}}$: an $\Delta L_\mu = -\Delta L_e = 2$ process.
  - ✓ Different EFT operators from $\Delta L_\mu = -\Delta L_e = 1$ proc. ($\mu \to e\gamma$, $\mu \to eee$, $\mu N \to eN$).
  - ✓ $\Delta L_\mu = -\Delta L_e = 2$ can be possible even if $\Delta L_\mu = -\Delta L_e = 1$ 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

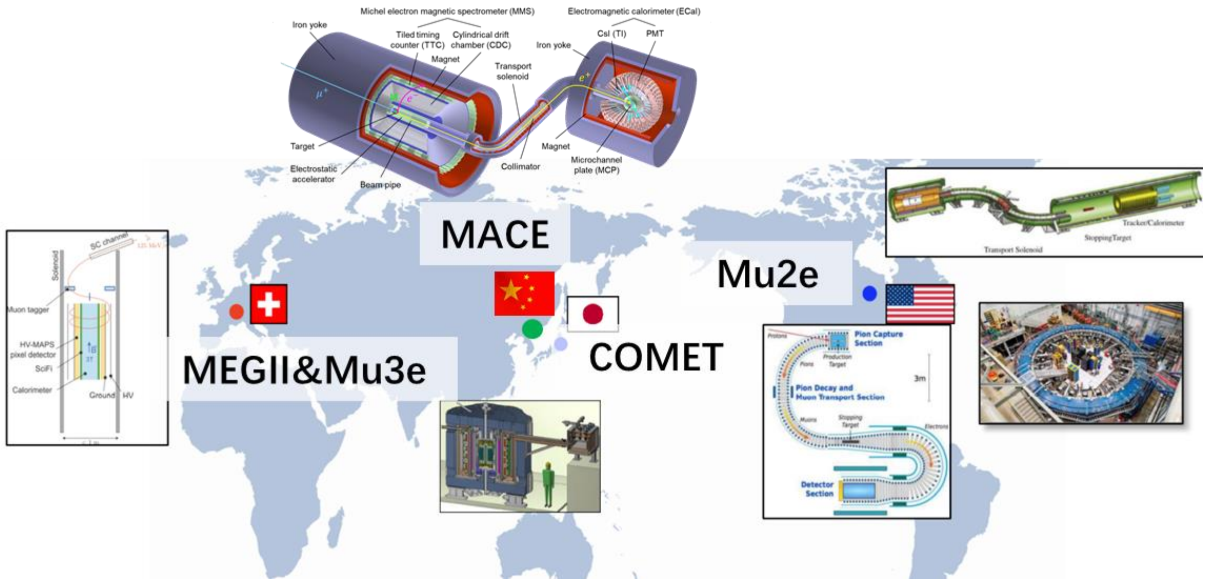


Credits: Kim-Siang Khaw

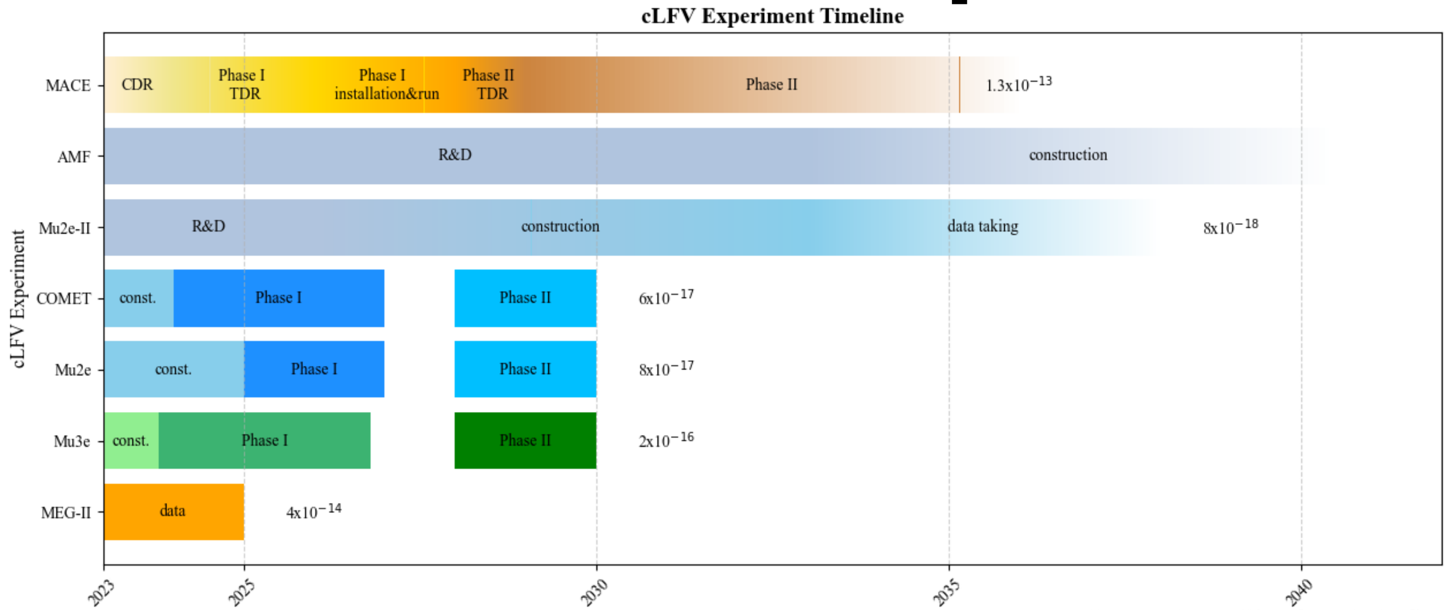
Worldwide cLFV experiments

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)

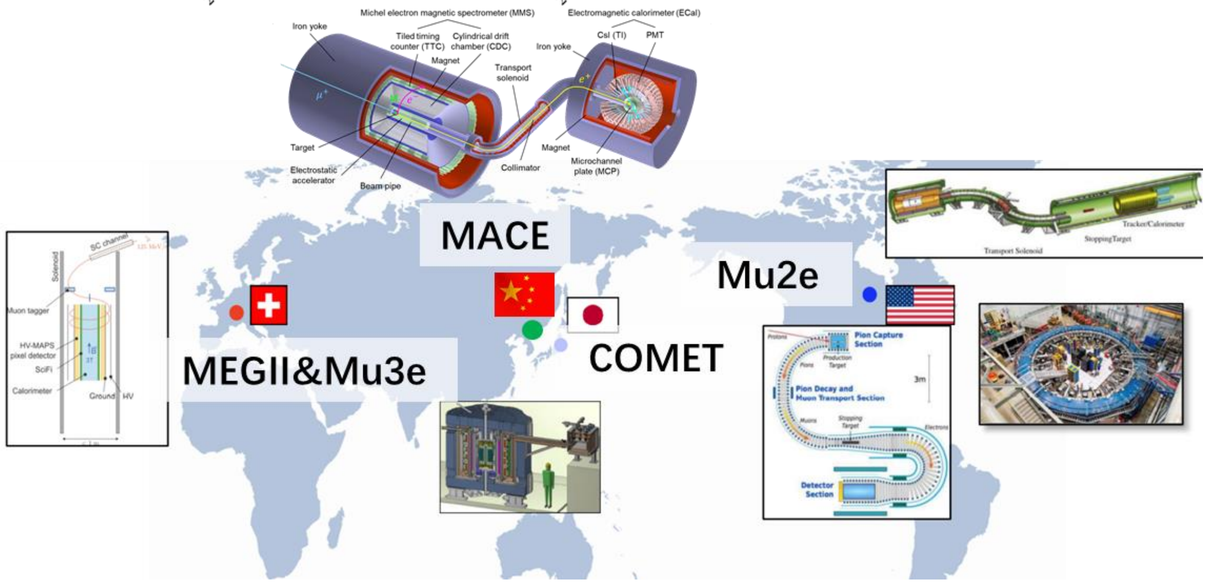
- Muonium conversion is a key cLFV process.
- After PSI set the bound $P < 8.3 \times 10^{-11}$ in 1999, no new experiments were proposed since then.
- With enhanced beam intensity and advances in detector technology, breakthroughs in this field are anticipated.



Worldwide cLFV experiments



- 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.

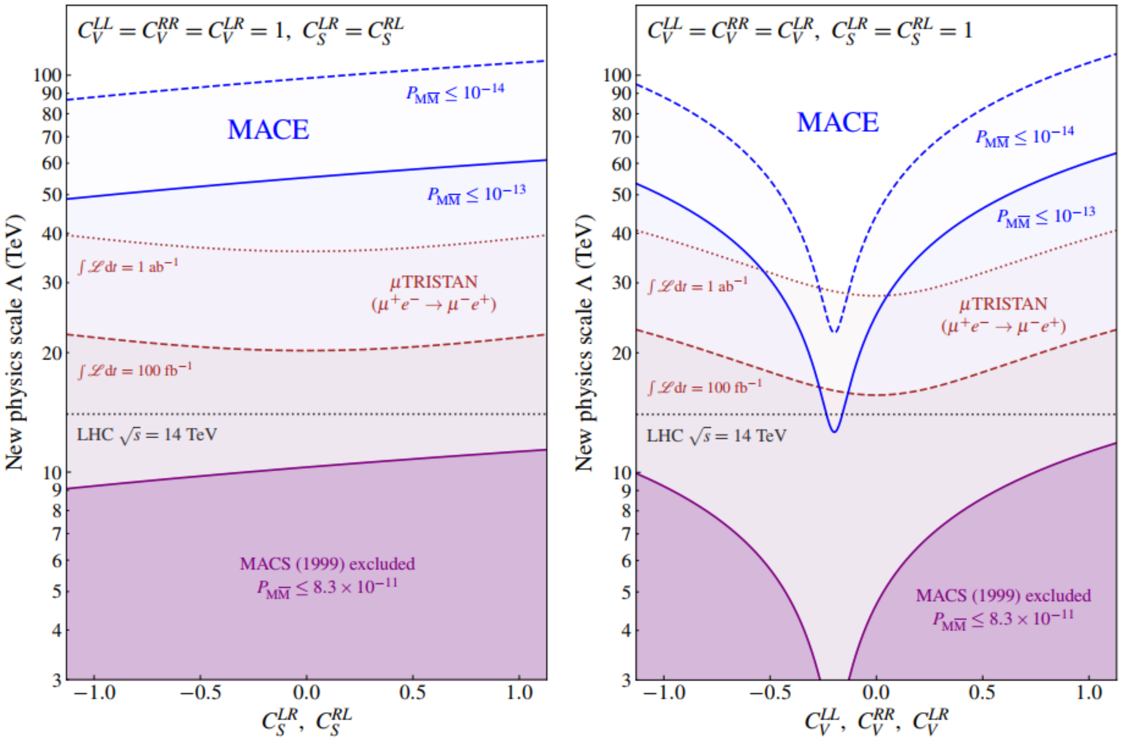


Motivations of MACE

- 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!



Snowmass2021 - Letter of Interest

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

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

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

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

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

Snowmass2021 - Letter of Interest

RF5-RF0-126

Search for Muonium to Antimuonium Conversion

RF Topical Groups: (check all that apply □/■)

□ (RF1) Weak decays of b and c quarks
□ (RF2) Weak decays of strange and light quarks
□ (RF3) Fundamental Physics in Small Experiments
□ (RF4) Baryon and Lepton Number Violating Processes
■ (RF5) Charged Lepton Flavor Violation (electrons, muons and taus)
□ (RF6) Dark Sector Studies at High Intensities
□ (RF7) Hadron Spectroscopy
□ (Other) *[Please specify frontier/topical group(s)]*

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Collaboration: MACE working group
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Abstract: It is puzzling whether there is any charged lepton flavor violation phenomenon beyond standard model. The upcoming Muonium (bound state of μ^+e^-) to Antimuonium (μ^-e^+) Conversion Experiment (MACE) will serve as a complementary experiment to search for charged lepton flavor violation processes, compared with other on-going experiments like Mu3e ($\mu^+ \to e^+e^-e^-$), MEG-II ($\mu^+ \to e^+\gamma$) and Mu2e/COMET ($\mu^-N \to e^-N$). MACE aims at a sensitivity of P($\mu^+e^- \to \mu^-e^+$) $\sim \mathcal{O}(10^{-13})$, about three orders of magnitude better than the best limit published two decades ago. It is desirable to optimize the slow and ultra-pure μ^+ beam, select high-efficiency muonium formation materials, develop Monte-Carlo simulation tools and design a new magnetic spectrometer to increase S/B.

Yu Chen, Yu-Zhe Mao, Jian Tang, School of Physics, Sun Yat-sen University, China.
Yu Bao, Yu-Kai Chen, Rui-Rui Fan, Zhi-Long Hou, Han-Tao Jing, Hai-Bo Li, Yang Li, Han Miao, Ying-Peng Song, Jing-Yu Tang, Nikolaos Vassilopoulos, Tian-Yu Xing, Ye Yuan, Yao Zhang, Guang Zhao, Luping Zhou, Institute of High-Energy Physics, Beijing, China.
Chen Wu, Research Center of Nuclear Physics (RCNP), Osaka University, Japan.

Probing the doubly charged Higgs boson with a muonium to antimuonium conversion experiment

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[5]*Institutes of Physical Science and Information Technology, Anhui University, Hefei 230601, China*
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PHYSICAL REVIEW D **103,** 055023 (2021)

Snowmass2021 whitepaper

March 23, 2022

arXiv: 2203.11406

Muonium to antimuonium conversion: Contributed paper for Snowmass 21

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The spontaneous muonium to antimuonium conversion is one of the interesting charged lepton flavor violation processes. It serves as a clear indication of new physics and plays an important role in constraining the parameter space beyond Standard Model. MACE is a proposed experiment to probe such a phenomenon and expected to enhance the sensitivity to the conversion probability by more than two orders of magnitude from the current best upper constraint obtained by the PSI experiment two decades ago. Recent developments in the theoretical and experimental aspects to search for such a rare process are summari…

20 citations so far based on inspirehep.net

Feedbacks after Snowmass LOI

A New Charged Lepton Flavor Violation Program at Fermilab

Bertrand Echenard – Caltech

with Robert Bernstein (FNAL) and Jaroslav Pasternak (ICL/RAL SCTF)

Potential Fermilab Muon Campus & Storage Ring Experiments Workshop
May 2021

Snowmass process and contributed papers

Frontier for Rare Processes and Precision Measurements

Alexey A. Petrov
Wayne State University

This effort is part of a global muon program under study within Snowmass

- Muon decays (MEG and Mu3e)
- Muon conversion (Mu2e / COMET and Mu2e II)
- ΔL=2 processes $\mu^-N \to e^+N$
- Muonium – antimuonium (MACE)
- General Low Energy Muon Facility (FNAL)
- Light new physics in muon decays (MEG-Fwd)

Bertrand lists MACE as a key next-generation cLFV experiment proposal

A large community committed to muon physics at FNAL and around the world

- Theoretical Letter of Intent

Physics of muonium and muonium oscillations

Alexey A. Petrov[1]
[1] *Department of Physics and Astronomy*
Wayne State University, Detroit, MI 48201, USA

Precision studies of a muonium, the bound state of a muon and an electron, provide access to physics beyond the Standard Model. We propose that extensive theoretical and experimental studies of atomic physics of a muonium, its decays and muonium-antimuonium oscillations could provide an impact on indirect searches for new physics.

- Experimental Letter of Intent

Search for Muonium to Antimuonium Conversion

RF Topical Groups: (check all that apply □/■)

□ (RF1) Weak decays of b and c quarks
□ (RF2) Weak decays of strange and light quarks
□ (RF3) Fundamental Physics in Small Experiments
□ (RF4) Baryon and Lepton Number Violating Processes
■ (RF5) Charged Lepton Flavor Violation (electrons, muons and taus)
□ (RF6) Dark Sector Studies at High Intensities
□ (RF7) Hadron Spectroscopy
□ (Other) *[Please specify frontier/topical group(s)]*

Contact Information:(authors listed after the text)
Name and Institution: Jian Tang/Sun Yat-sen University
Collaboration: MACE working group
Contact Email: tangjian5@mail.sysu.edu.cn

Abstract: It is puzzling whether there is any charged lepton flavor violation phenomenon beyond standard model. The upcoming Muonium (bound state of μ^+e^-) to Antimuonium (μ^-e^+) Conversion Experiment (MACE) will serve as a complementary experiment to search for charged lepton flavor violation processes, compared with other on-going experiments like Mu3e ($\mu^+ \to e^+e^-e^-$), MEG-II ($\mu^+ \to e^+\gamma$) and Mu2e/COMET ($\mu^-N \to e^-N$). MACE aims at a sensitivity of $P(\mu^+e^- \to \mu^-e^+) \sim \mathcal{O}(10^{-13})$, about three orders of magnitude better than the best limit published two decades ago. It is desirable to optimize the slow and ultra-pure μ^+ beam, select high-efficiency muonium formation materials, develop Monte-Carlo simulation tools and design a new magnetic spectrometer to increase S/B.

Alexey A Petrov (WSU) 2 Muon Campus Experiments, 24-27 May 2021

Feedbacks after Snowmass LOI

Detectors and concepts for future CLFV experiments

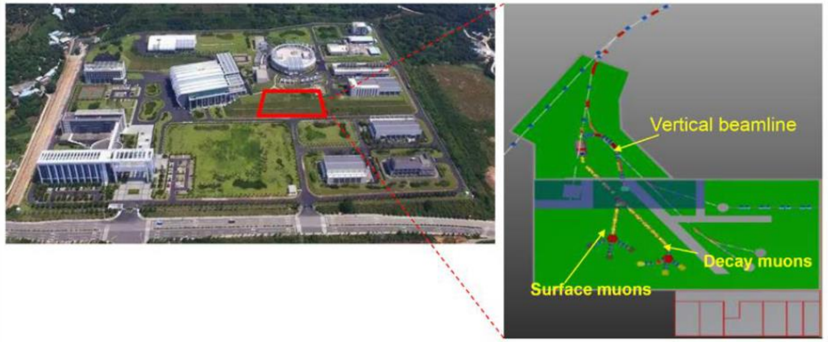
Bertrand Echenard
Caltech

NuFact 2021
Cagliari - September 2021

MACE at EMuS

EMuS – new muon facility in China

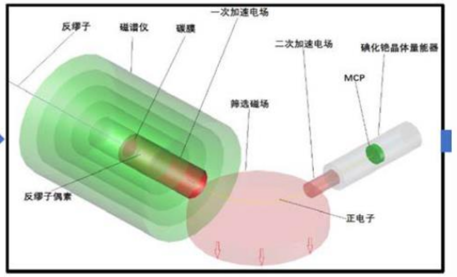
Jian Tang
(Snowmass 2021 RPP meeting)

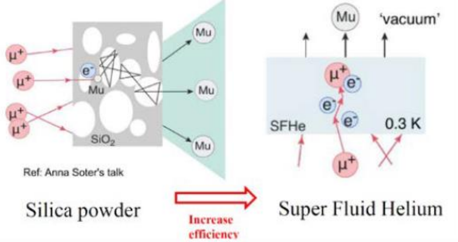


	Proton driver [MW]	Surface muons			Decay muons		
		Intensity [1E6/s]	Polarization [%]	Spread [%]	energy [MeV/c]	Intensity [1E6/s]	Spread [%]
PSI	1.3	420	90	10	85-125	240	3
ISIS	0.16	1.5	95	<15	20-120	0.4	10
RIKEN/RAL	0.16	0.8	95	<15	65-120	1	10
JPARC	1	100	95	15	33-250	10	15
TRIUMF	0.075	1.4	90	7	20-100	0.0014	10
EMuS	0.005	83	50	10	50-450	16	10
Baby EMuS	0.005	1.2	95	10			

×5 CSNS-II upgrade

MACE concept





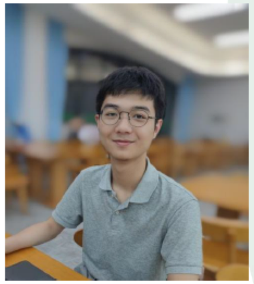
On-going physics studies and detector R&D

Bertrand Echenard - Caltech   p. 27

Feedbacks after Snowmass LOI

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

Workshop on a Future Muon Program at Fermilab



2023-03-28

Shihan Zhao

zhaoshh7@mail2.sysu.edu.cn

Muonium-to-Antimuonium Conversion Experiment

MACE working group: Ai-Yu Bai,[1] Yu Chen,[1] Yukai Chen,[2] Rui-Rui Fan,[2] Zhilong Hou,[2] Han-Tao Jing,[2] Hai-Bo Li,[2] Yang Li,[2] Han Miao,[2] Huaxing Peng,[2] Ying-Peng Song,[2] Jian Tang,[1] Jing-Yu Tang,[2] Nikolaos Vassilopoulos,[2] Chen Wu,[3] Tian-Yu Xing,[2] Yu Xu,[1] Ye Yuan,[2] Yao Zhang,[2] Guang Zhao,[2] Shihan Zhao,[1] and Luping Zhou[2]

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[2]*Institute of High Energy Physics, Chinese Academy of Science, China*

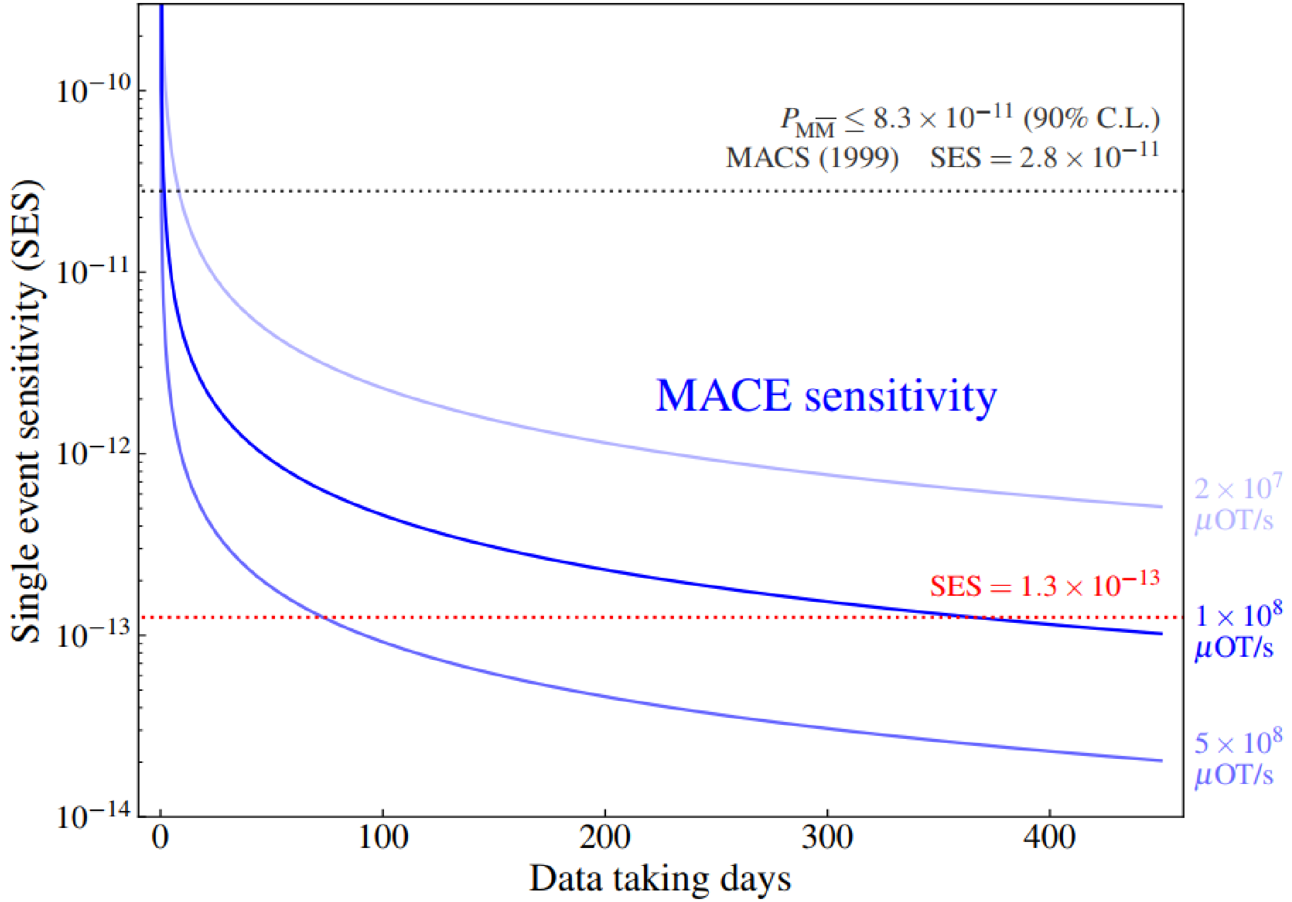
[3]*Research Center of Nuclear Physics, Osaka University, Japan*

Reference: Snowmass2021 Whitepaper: Muonium to antimuonium conversion, arXiv:2203.11406

- **Invited talks at ICHEP and Fermilab workshop, see also conference proceedings https://arxiv.org/abs/2309.05933**
- **International Advisory Committee at NuFact**

Plenary talk at CLFV2023, Heidelberg University

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 initiative accelerator muon source to provide $10^8 \mu^+/s$, surface muon.
- Over 20 years, significant advances in detector technology.
- No other muonium conversion experiments since 1999.
- The new generation of experiments is expected to improve sensitivity by over two orders of magnitude!
- MACE is going to make a breakthrough.

MACE: Muonium to Antimuonium Conversion Experiment.

MACE conceptual design report

https://indico.impcas.ac.cn/event/63/overview

CDR review - 8/26

https://arxiv.org/abs/2410.18817

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

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(Dated: October 25, 2024)

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- Conceptual design of MACE
- Local laboratory: SMOOTH

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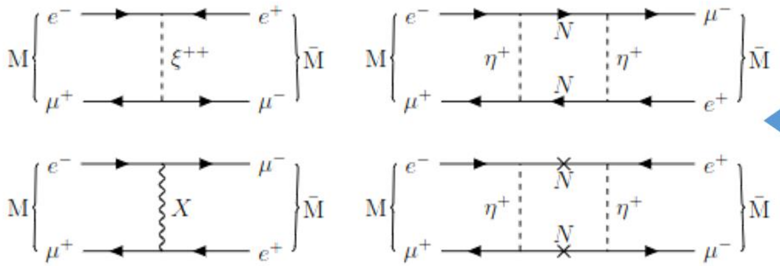
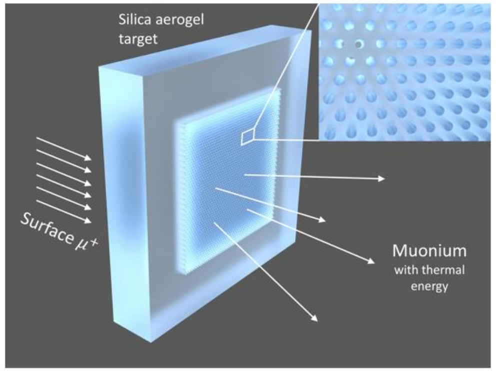
Challenges and solutions for MACE

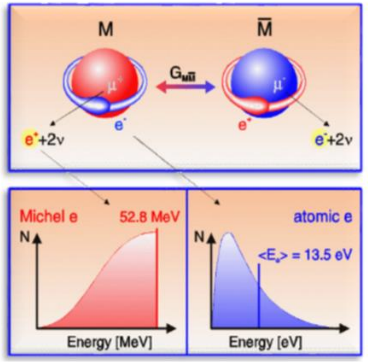
Muonium-to-Antimuonium Conversion Experiment

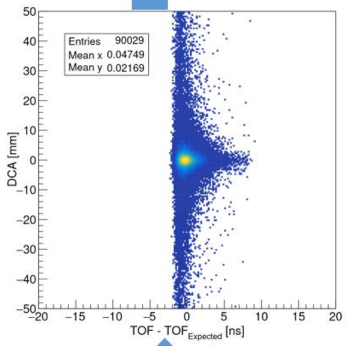
High-efficiency muonium production?

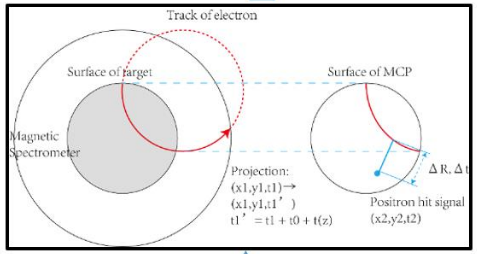


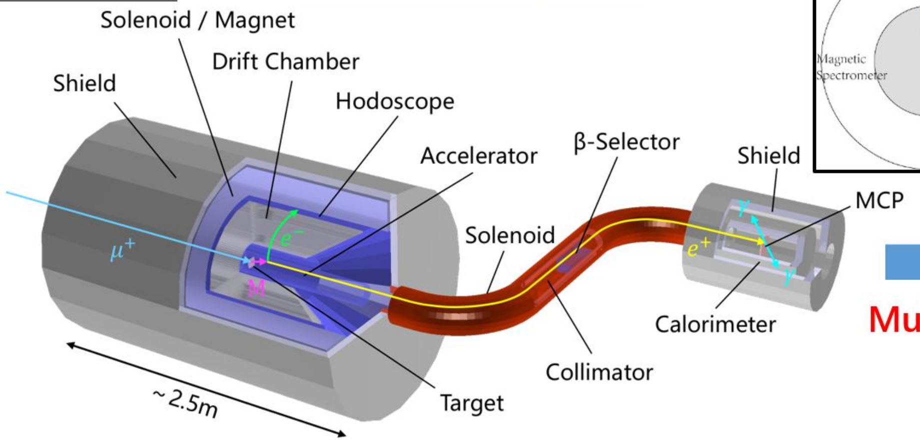
High signal/noise ratio











High-resolution spectrometer

Multiple coincidence?

Muonium production in silica aerogel

μ^+ (~1MeV) scattering

↓

Electron capture (~1keV)

↓

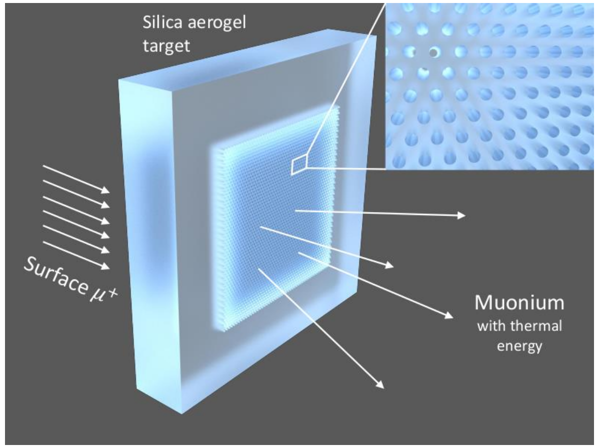
Muonium (~100eV)
Epithermal scattering

↓

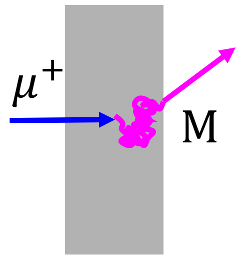
Random walk (room temp.)

↓

Emission to vacuum



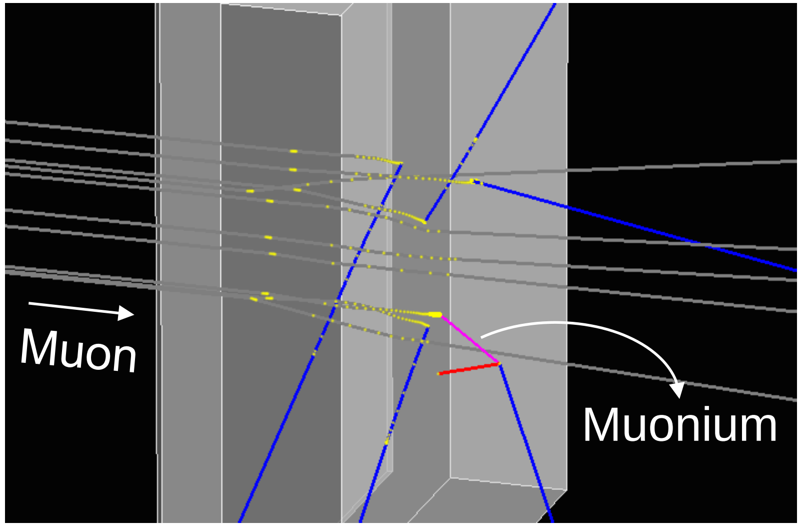
MC simulation for muonium transport has been developed under the MACE offline software framework.



① Geant4 low-energy EM process.

② Geant4 AtRest process, modeled phenomenologically.

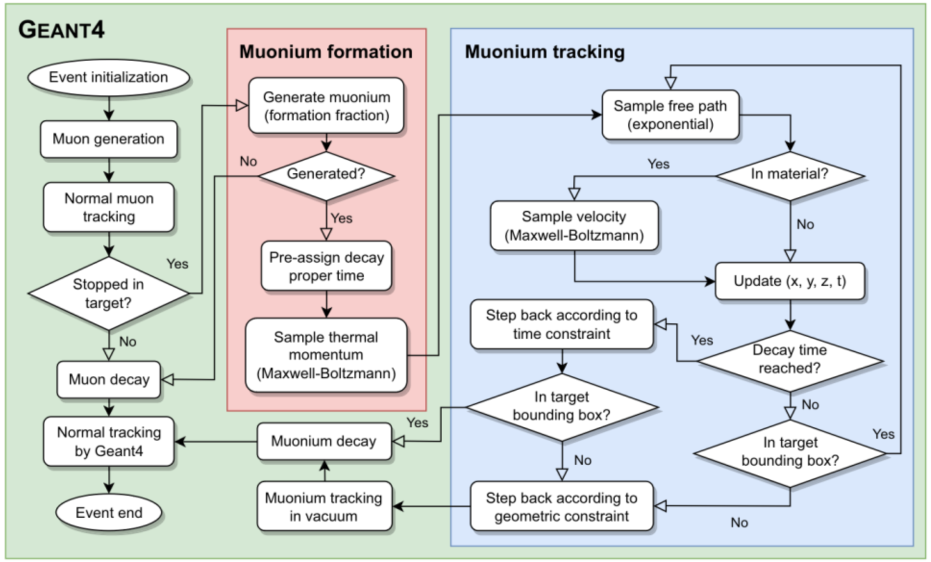
③ Random walk approach to thermal muonium tracking.

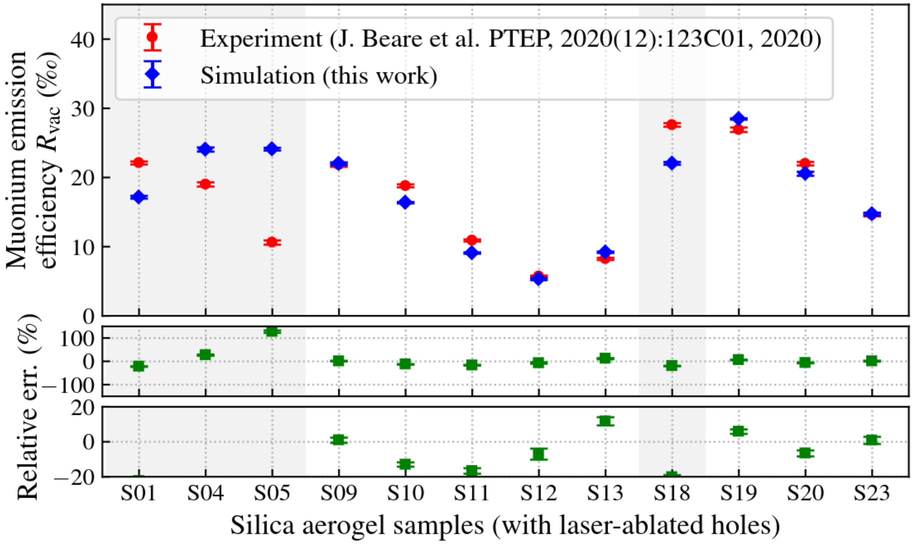


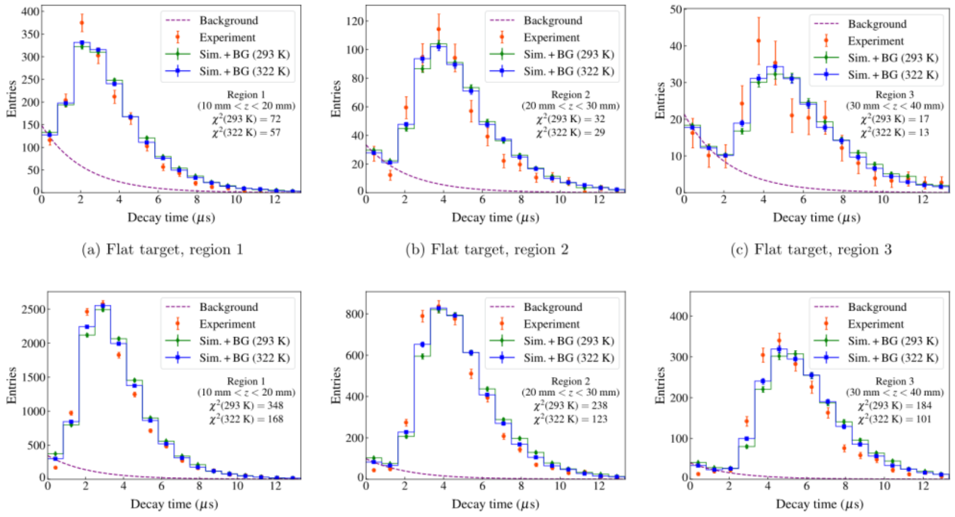
Optimization of muonium yield in perforated silica aerogel

- 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.
- An 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.

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



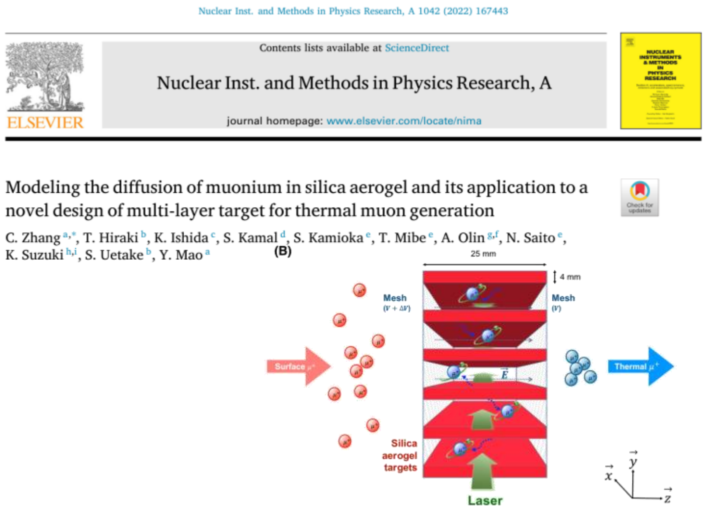




(a) Flat target, region 1 (b) Flat target, region 2 (c) Flat target, region 3
(d) Perforated target, region 1 (e) Perforated target, region 2 (f) Perforated target, region 3

Optimization of muonium yield in perforated silica aerogel

- A novel multi-layer design is expected considerably increase muonium yields in a vacuum (Ce Zhang et al.).
- The simulation result achieves
  - ✓ $Y_{\mu\to\mathrm{M}} = N_{\mathrm{M}}^{\mathrm{vac}}/N_{\mu}^{\mathrm{total}} = 4.08\%$
  - ✓ Nearly an order of magnitude improvement on $N_{\mathrm{M}}^{\mathrm{vac}}/N_{\mu}^{\mathrm{total}}$.
  - ➢ Still room for further optimization.
- Multi-layer target + intensive muon beam → intensive in-vacuum muonium source:
  - ✓ $I_{\mathrm{M}}^{\mathrm{vac}} = I_{\mathrm{beam}} Y_{\mu\to\mathrm{M}} = 4 \times 10^{6}/\mathrm{s}$, assuming $I_{\mathrm{beam}} = 10^{8}/\mathrm{s}$
  - ➢ For comparsion, MACS 1990s: $I_{\mathrm{M}}^{\mathrm{vac}} = 4 \times 10^{4}/\mathrm{s}$
  - ➢ Expected two orders of magnitude improvements in in-vacuum muonium source intensity!


Nuclear Inst. and Methods in Physics Research, A 1042 (2022) 167443

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

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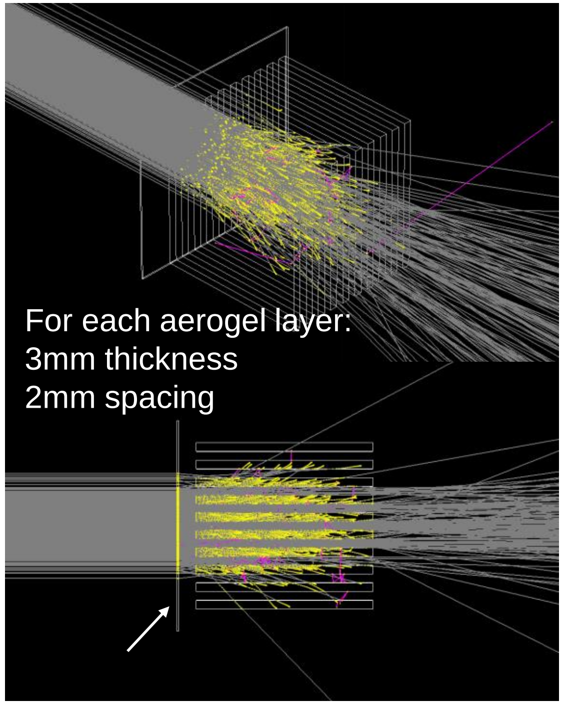
Modeling the diffusion of muonium in silica aerogel and its application to a novel design of multi-layer target for thermal muon generation

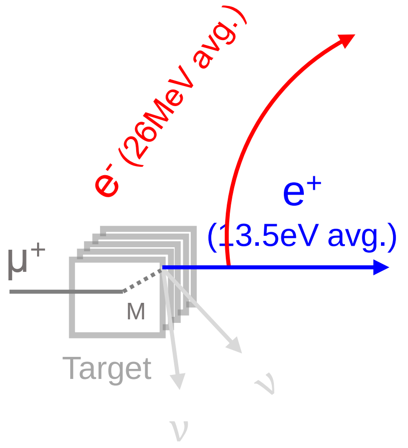
C. Zhang, T. Hiraki, K. Ishida, S. Kamal, S. Kamioka, T. Mibe, A. Olin, N. Saito, K. Suzuki, S. Uetake, Y. Mao



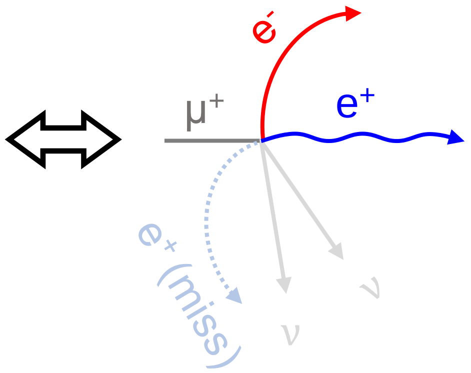
Shihan Zhao and Jian Tang, Optimization of muonium yield in perforated silica aerogel, **Phys. Rev. D** 109, 072012

MACE signal and background

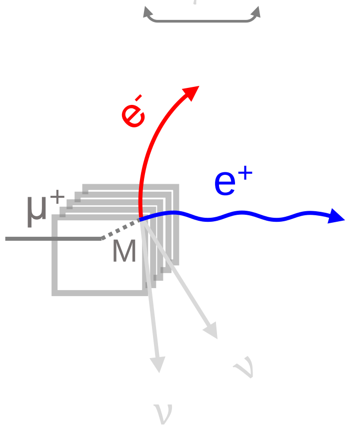
Signal:
fast e^- + slow e^+



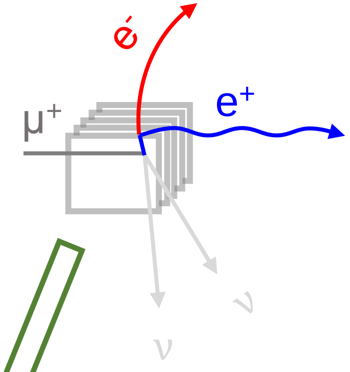
1. Internal conv. (IC) decay
- ☐ $\mu^+ \to e^+ e^- e^+ \bar{\nu}_\mu \nu_e$



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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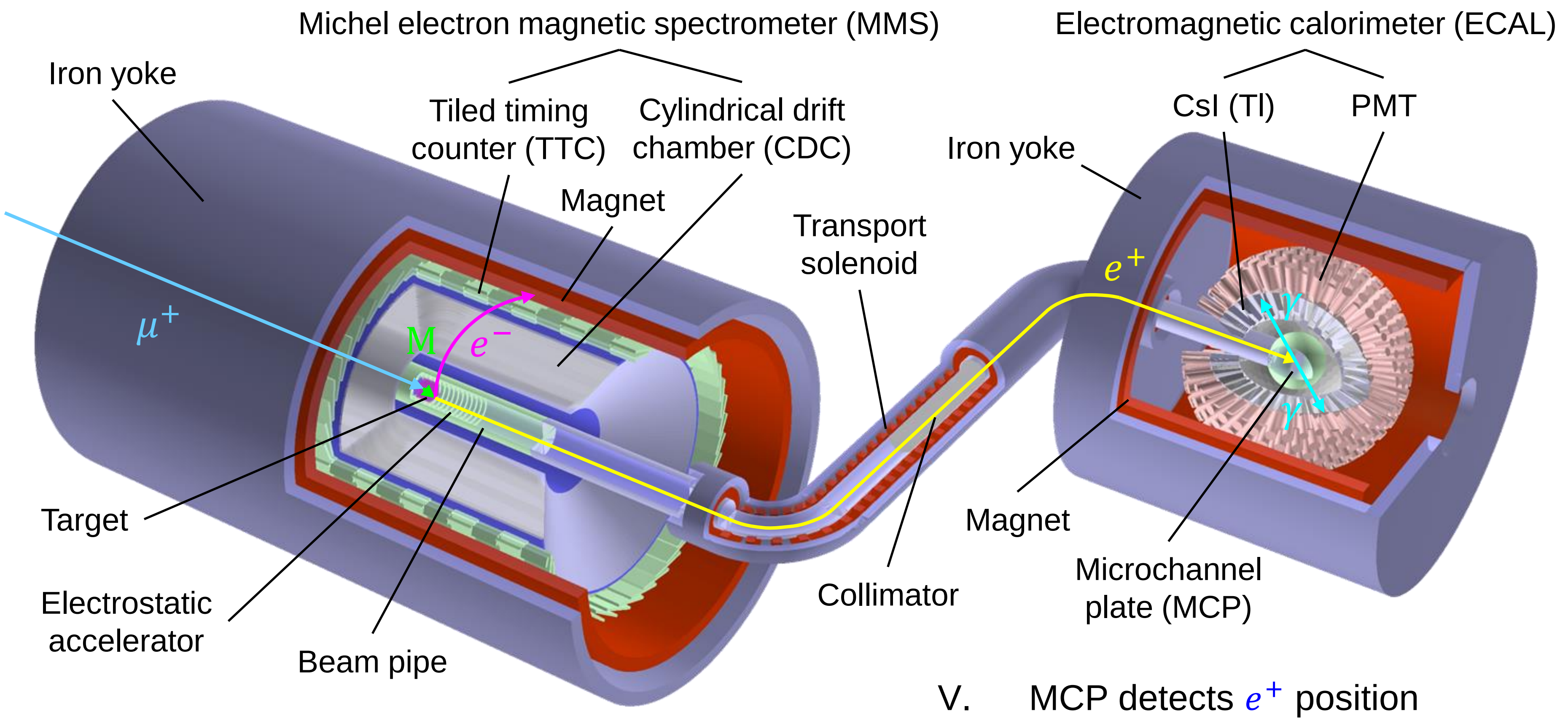
MACE baseline design v1



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
V. Transport atomic e^+ to MCP (conserving transverse position)

V. MCP detects e^+ position
VI. e^+ annihilates on MCP
VII. ECal detects 2 back-to-back annihilation γ

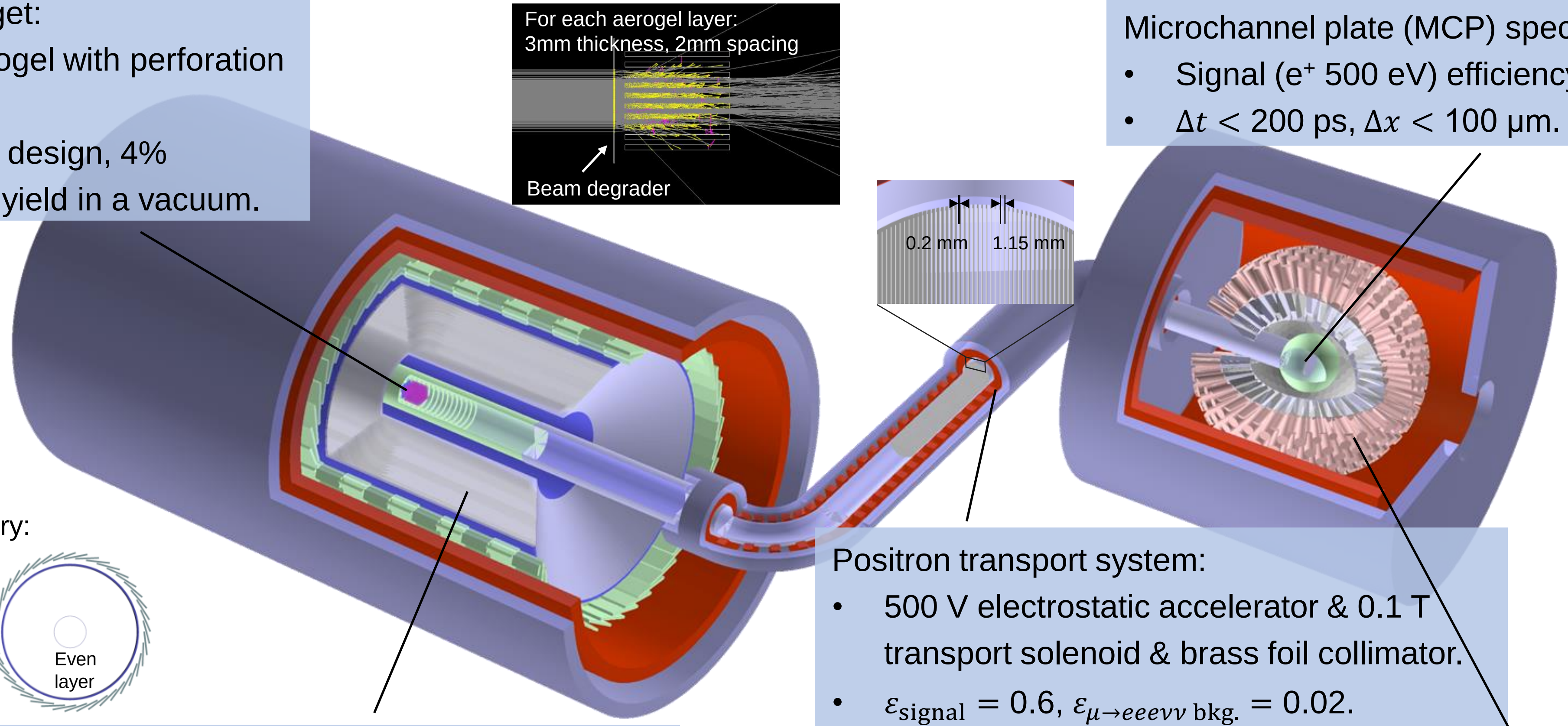
Triple coincidence:

➢ **MMS + MCP + ECal**

Michel e^- Atomic e^+

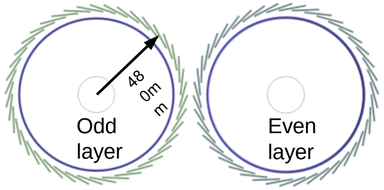
MACE baseline design v1

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



Microchannel plate (MCP) specifications:
- Signal (e^+ 500 eV) efficiency > 0.7
- $\Delta t < 200$ ps, $\Delta x < 100$ µm.

TTC geometry:



Positron transport system:
- 500 V electrostatic accelerator & 0.1 T transport solenoid & brass foil collimator.
- $\varepsilon_{\text{signal}} = 0.6$, $\varepsilon_{\mu\to eee\nu\nu\ \text{bkg.}} = 0.02$.
- Signal e^+ position error 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: 756 fast scintillators with SiPM

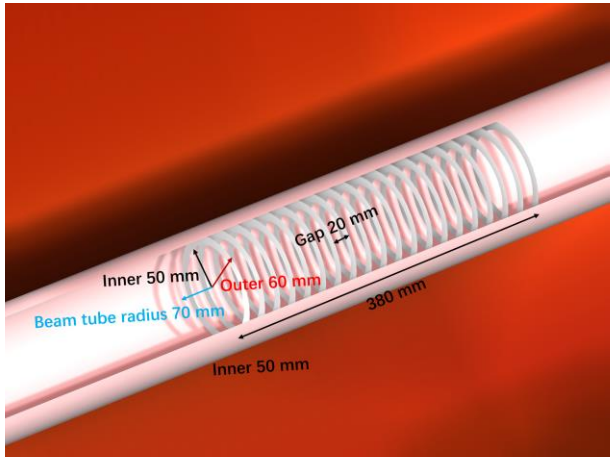
readout, slant ± 15 deg, $\Delta t < 100$ ps.

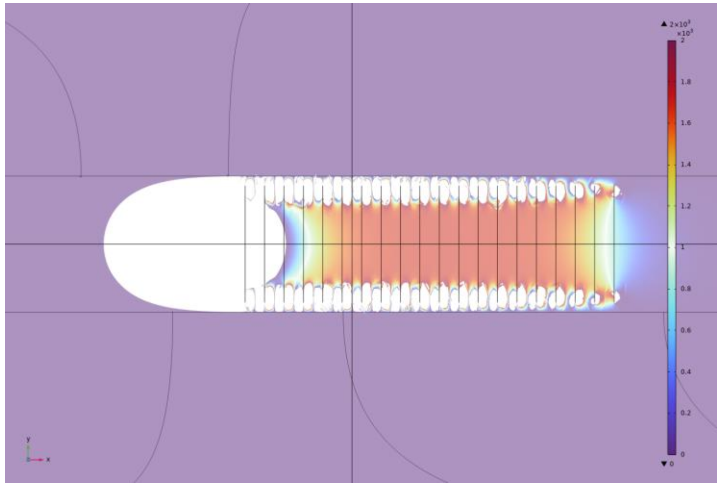
Electromagnetic calorimeter:
- Geometry: Class-I GP(4,0) Goldberg polyhedron.
- 622 CsI(Tl) crystals with 10 cm length, PMT readout.
- 97% geoemtry acceptance, $\Delta E/E = 7.5\%$ (signal 2γ event), 67.5% signal efficiency.

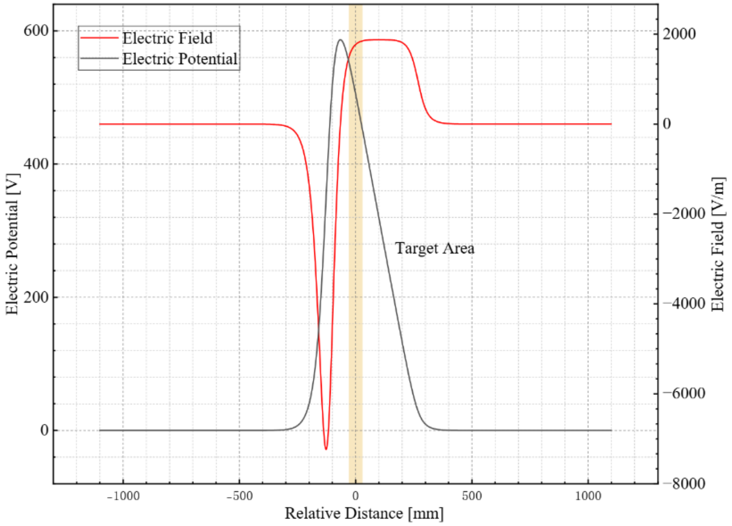
Positron transport system

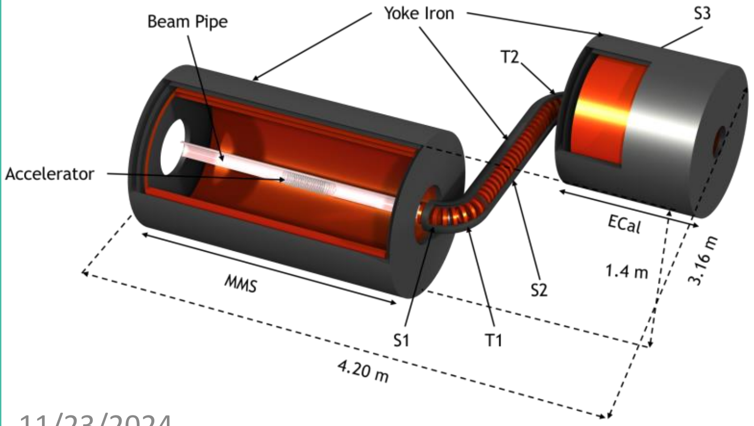
See Guihao Lu's poster (MIP2024)

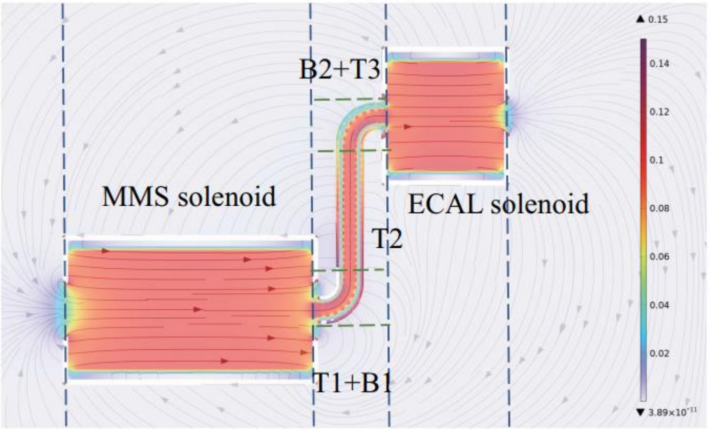
- Near-stationary signal positron should be accelerated and transport to MCP with transverse position preserved.
- Components: electrostatic accelerator & solenoid.

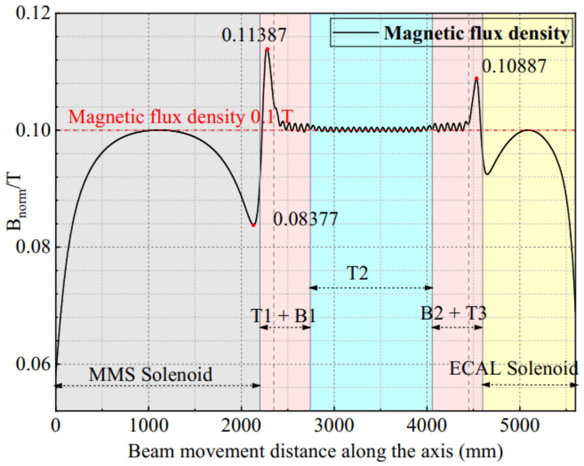












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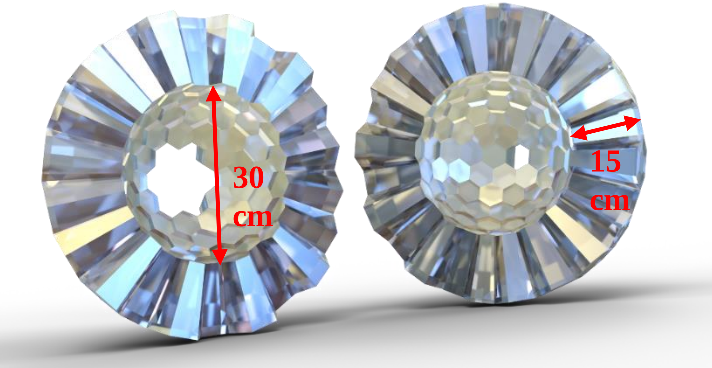
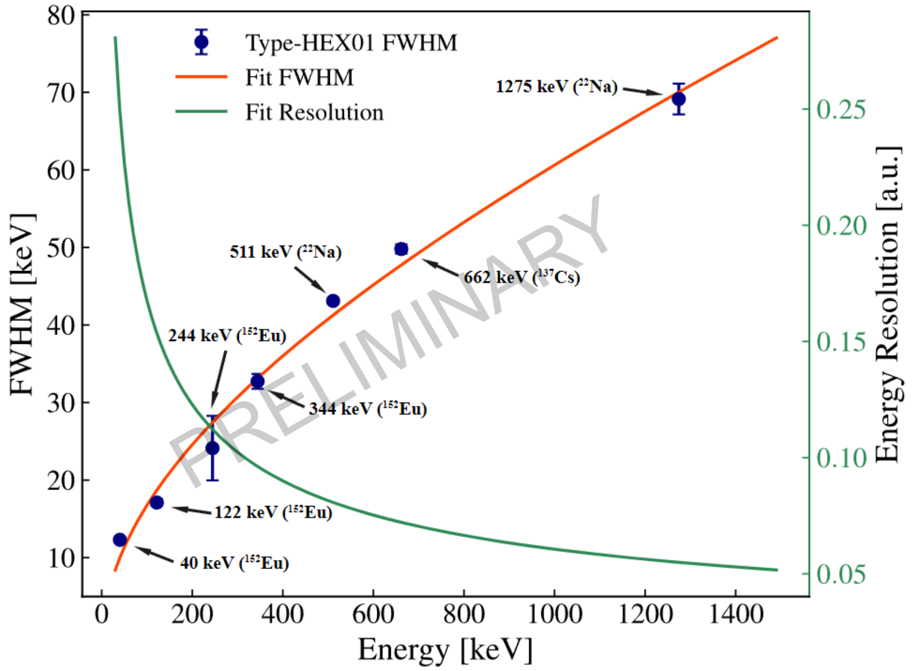
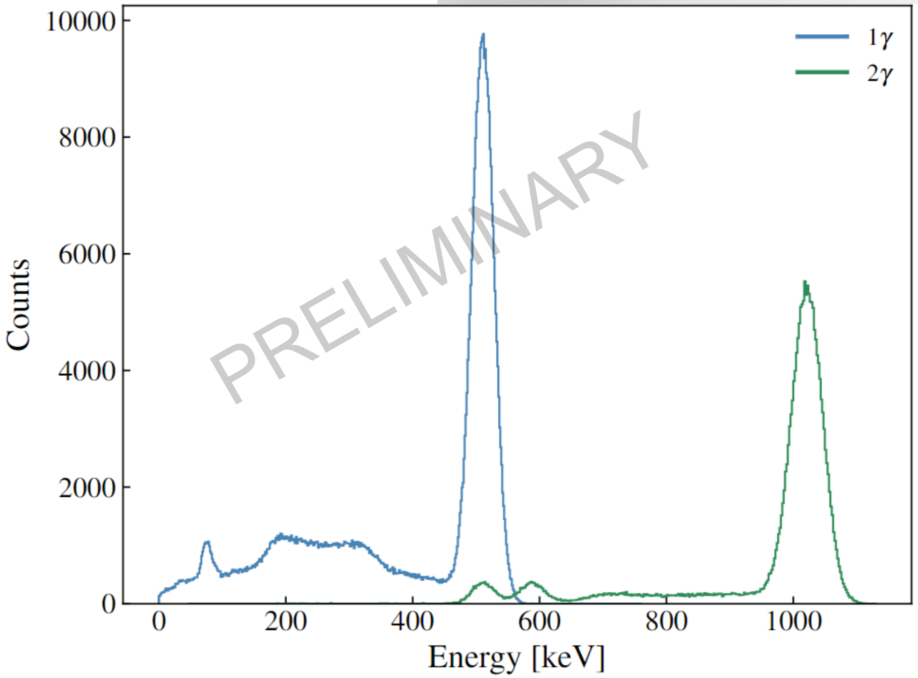
Design of calorimeter

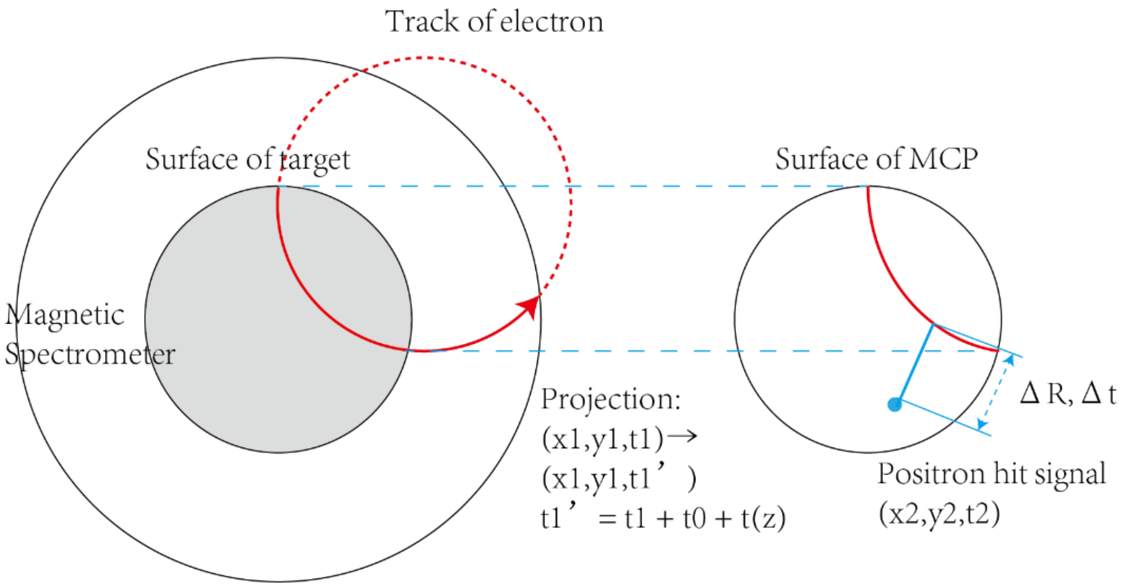
- Signal and Background https://arxiv.org/abs/2408.17114
  - Energy resolution: 8.4% at 0.511 MeV, 6% at 1.022 MeV
  - 68.1% signal efficiency (3σ region)

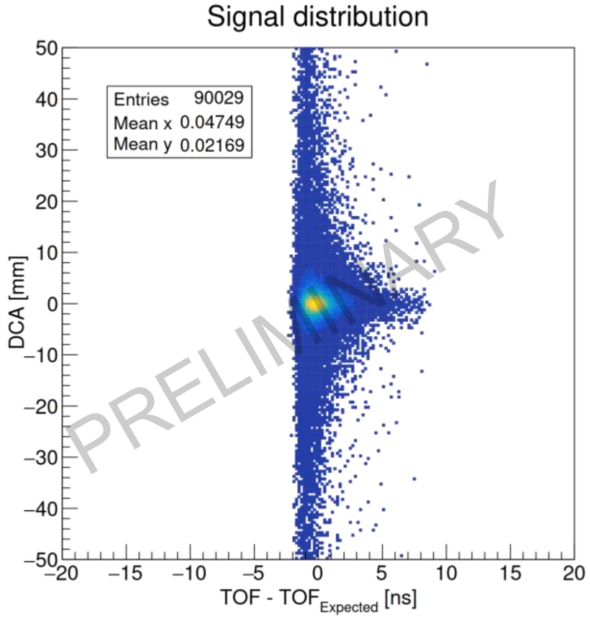






Simulation: muonium conversion signal

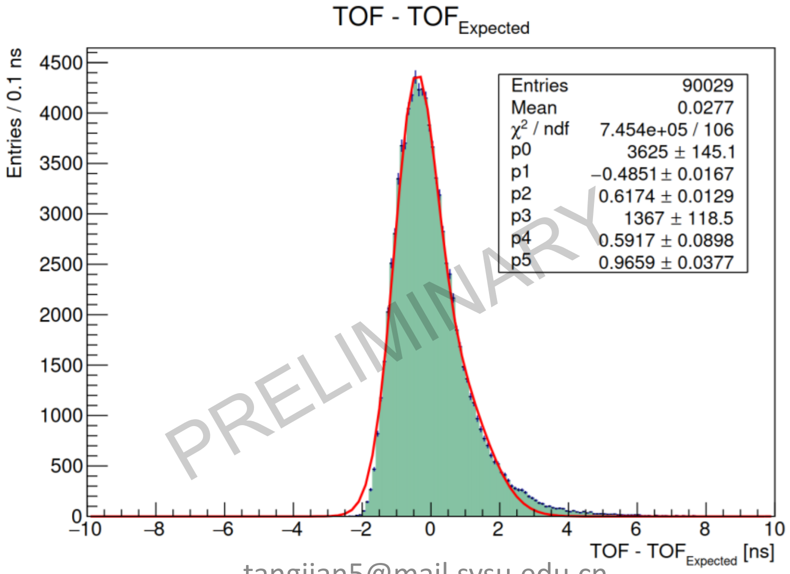


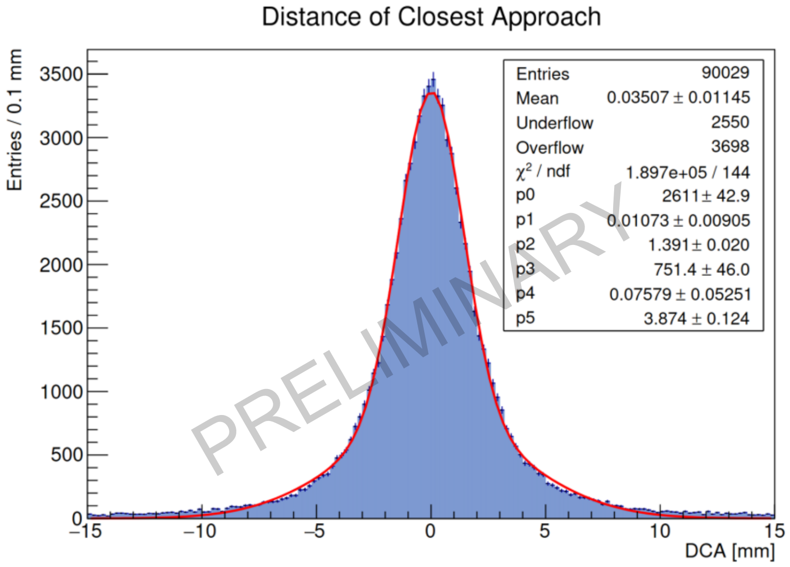


- Elliptical 3σ signal region:

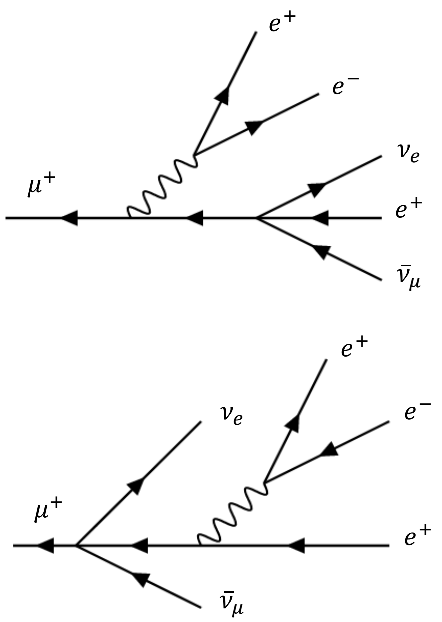
$$\left(\frac{\mathrm{TOF}-\mathrm{TOF_E}}{3\sigma_{\mathrm{TOF}}}\right)^2+\left(\frac{\mathrm{DCA}}{3\sigma_{\mathrm{DCA}}}\right)^2<1$$

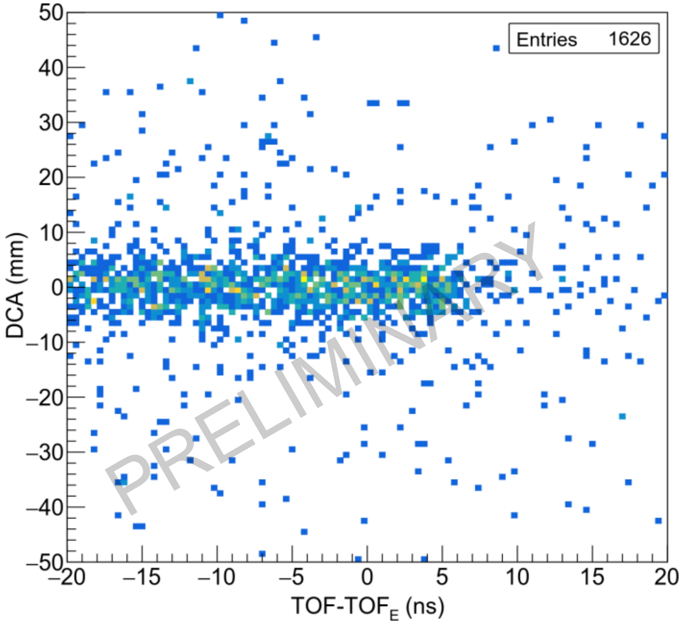
- $\varepsilon_{\text{signal region cut}} = 0.987$





Simulation: muon internal conversion decay

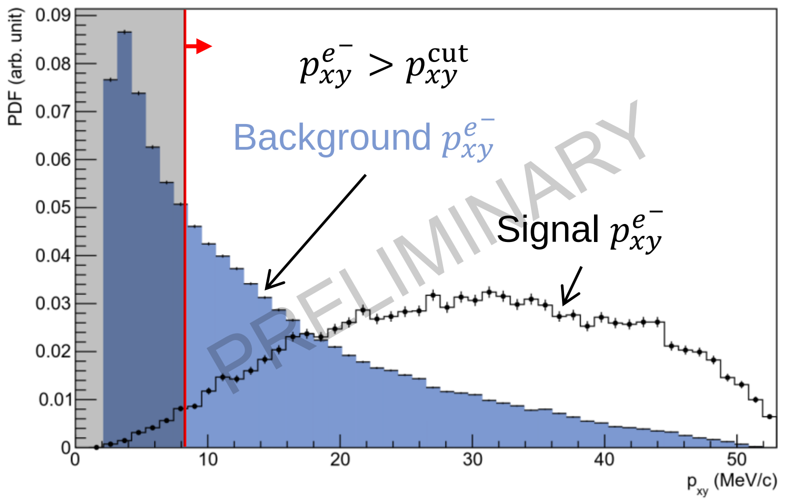




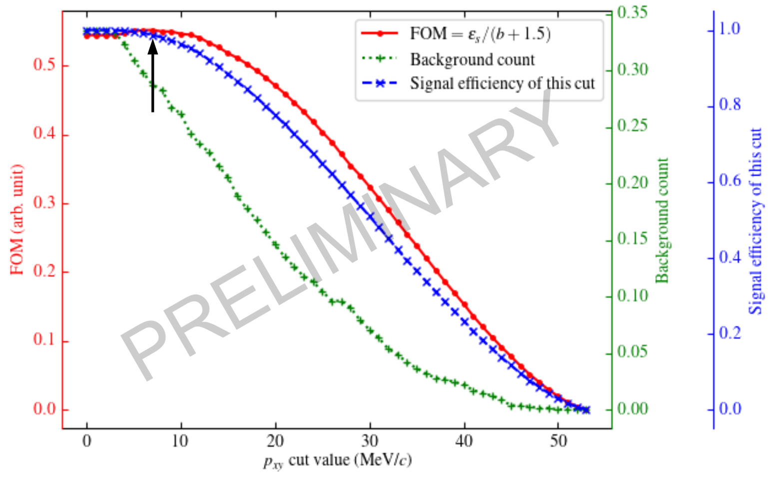
$\mu^+ \to e^+e^-e^+\bar{\nu}_\mu\nu_e$ simulation:

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

(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		count / (10^8 μ/s×365 d)
$\mu^+ \to e^+e^-e^+\bar{\nu}_\mu\nu_e$		0.287 ± 0.020
Accidental	Beam positron	< 0.07
	Cosmic ray (w/ veto)	< 0.1
Total		< 1

✓ O(10^{-14}) single event sensitivity is expected:

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

$$\mathrm{SES} = \frac{1}{\varepsilon_{\mathrm{Geom}}\varepsilon_{\mathrm{MMS}}\varepsilon_{\mathrm{MCP}}\varepsilon_{\mathrm{ECal}}\varepsilon_{\mathrm{cut}}y_{\mathrm{M}}N_{\mu^+}} = 1.3 \times 10^{-13}$$

- More background simulations and refined data analyses to be updated!

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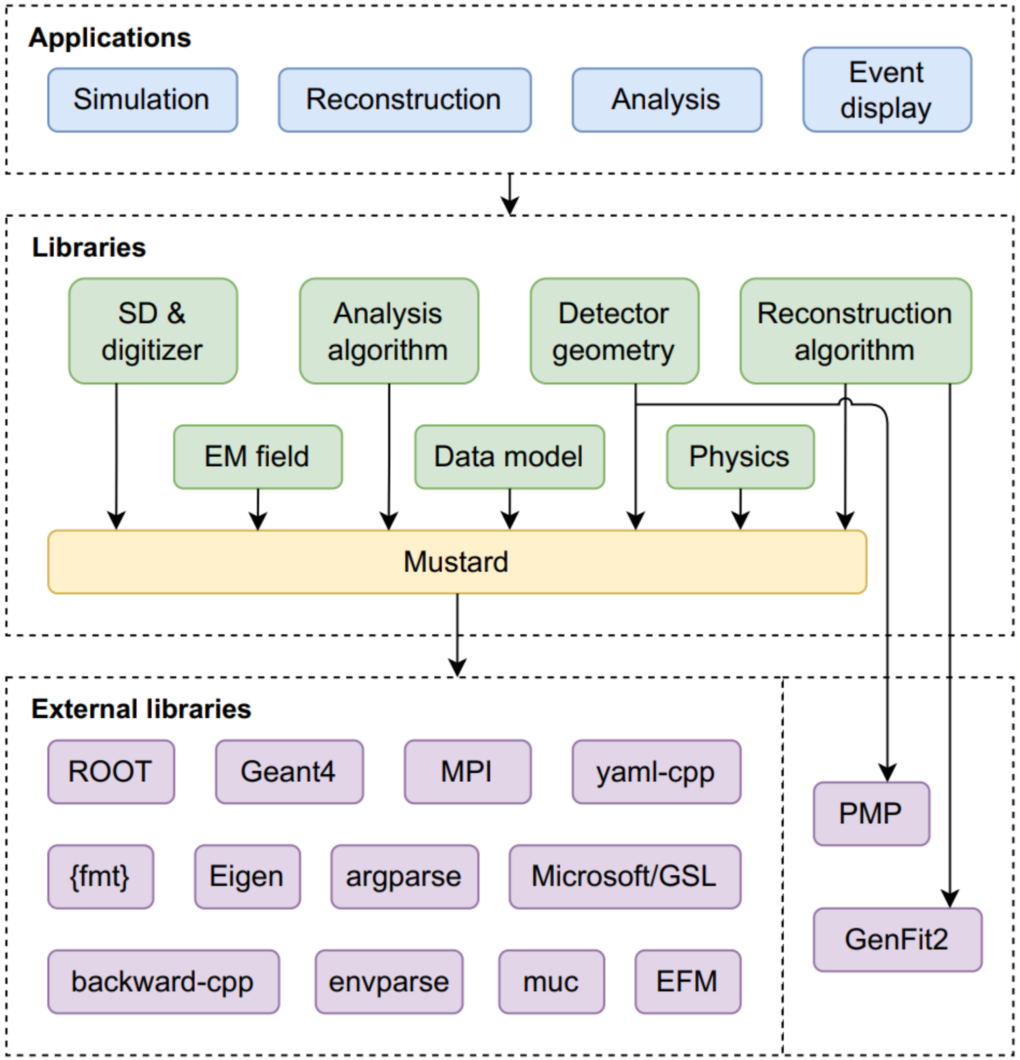
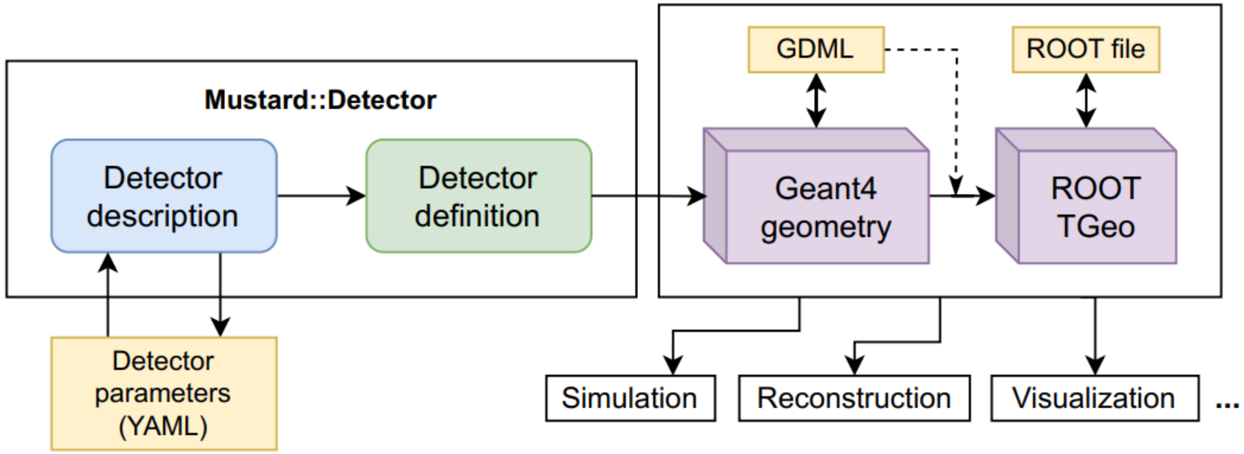
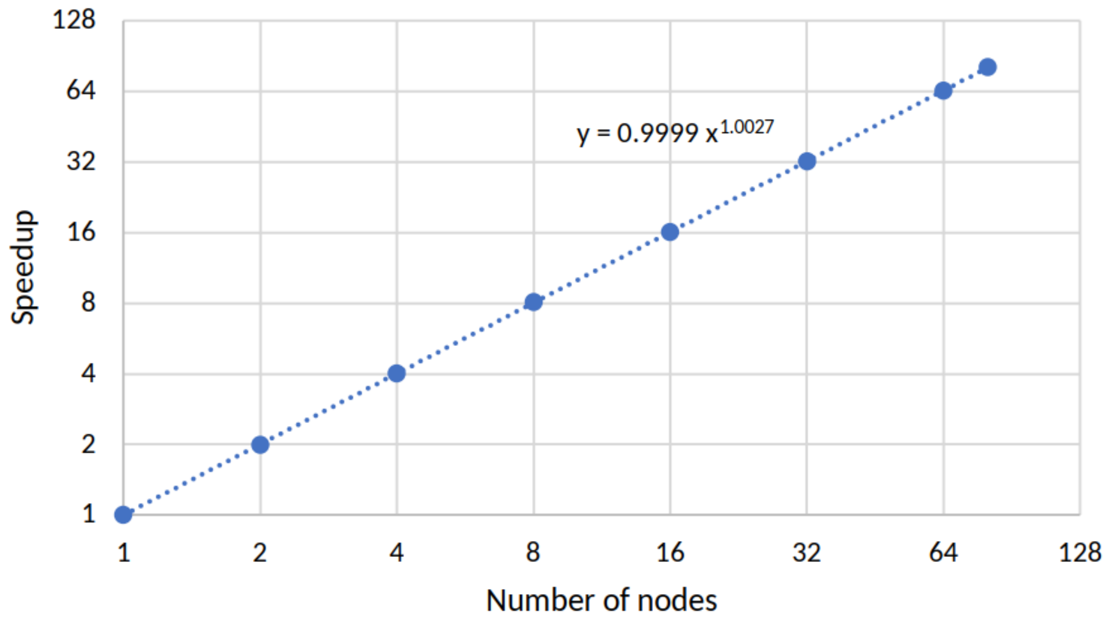
MACE offline software

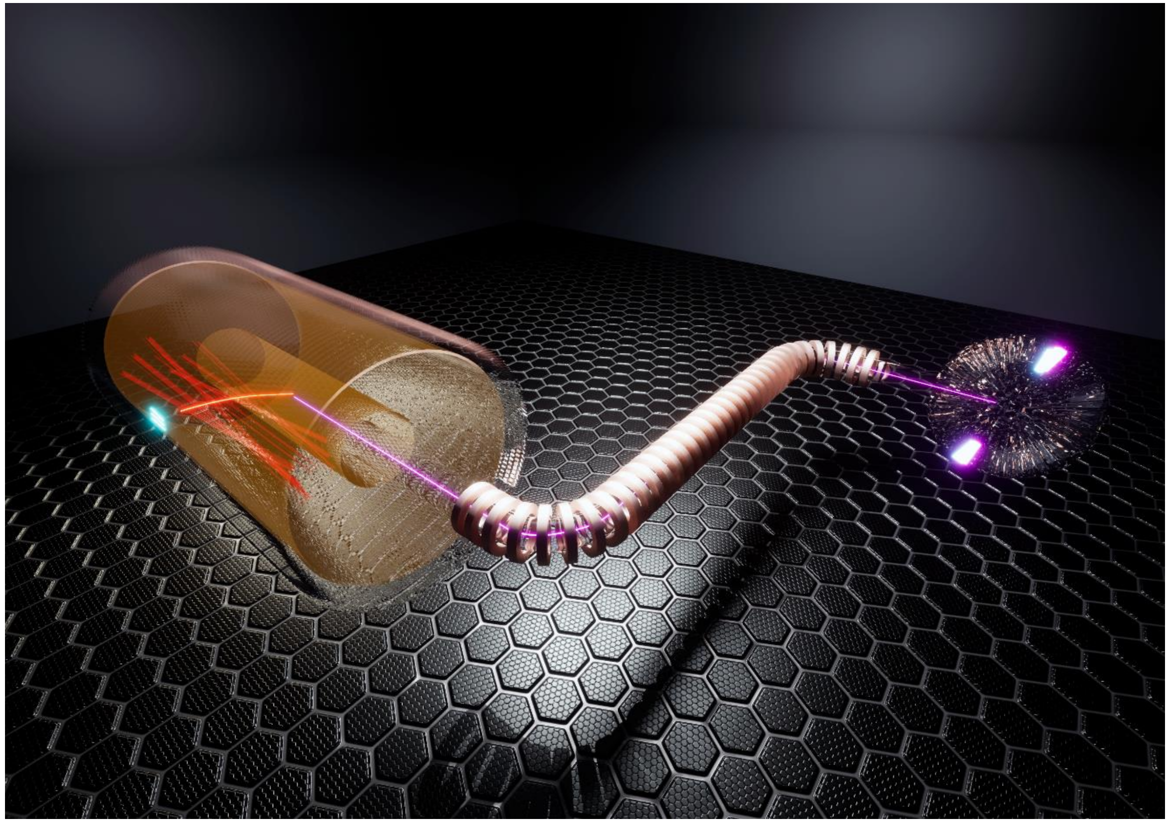






MACE event display

Credits: Weizhi Xiong



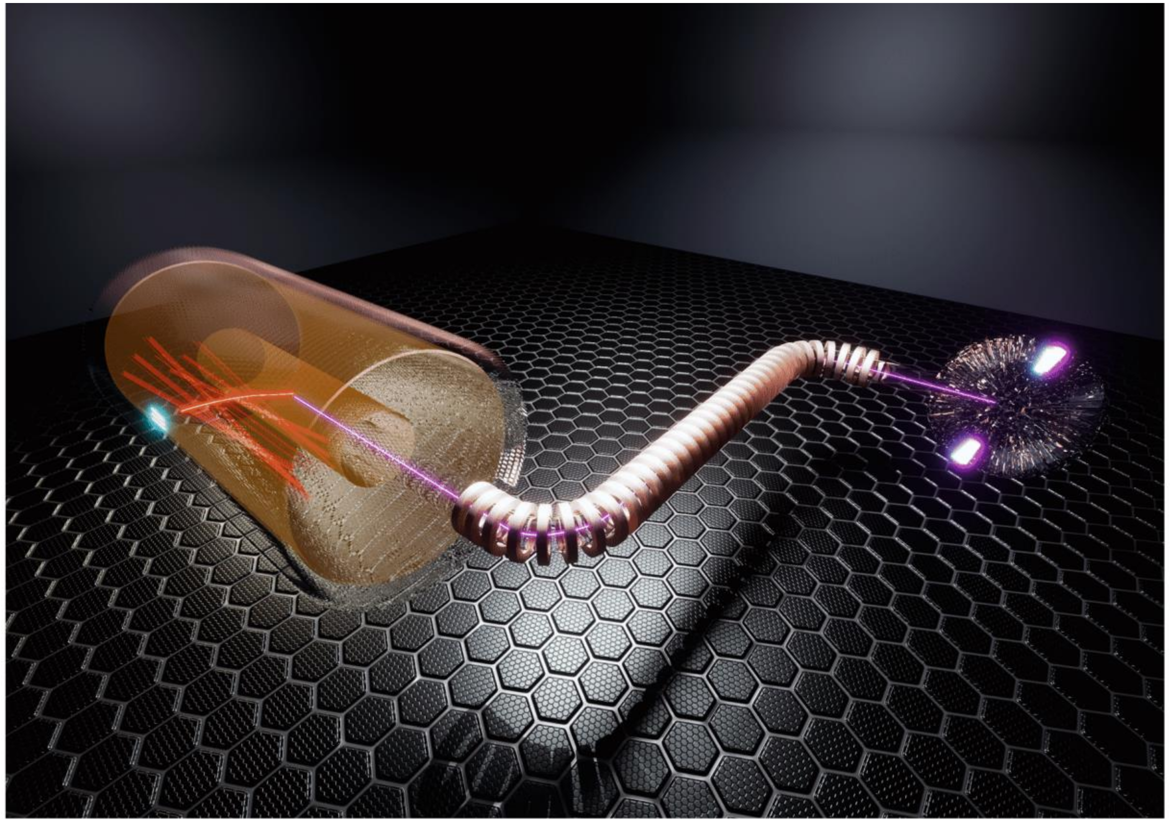


Table of contents

- Review of the past experience
- Motivations for muon physics
- Conceptual design of MACE
- Local laboratory: SMOOTH

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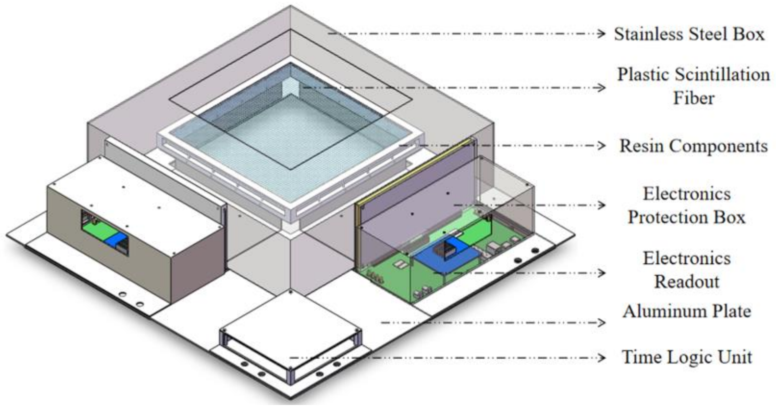
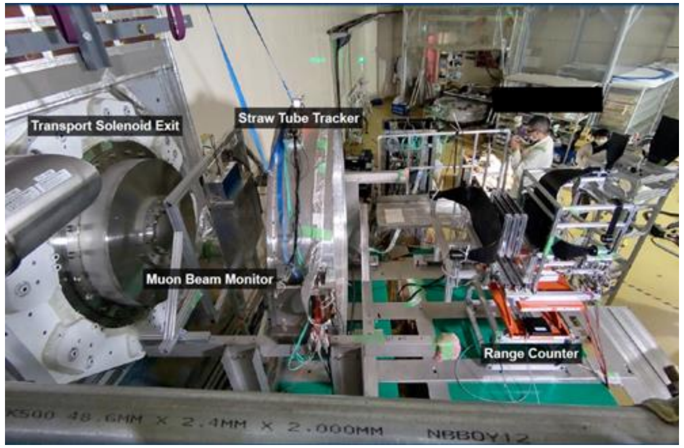
Gallery of the local lab

COMET muon beam monitor

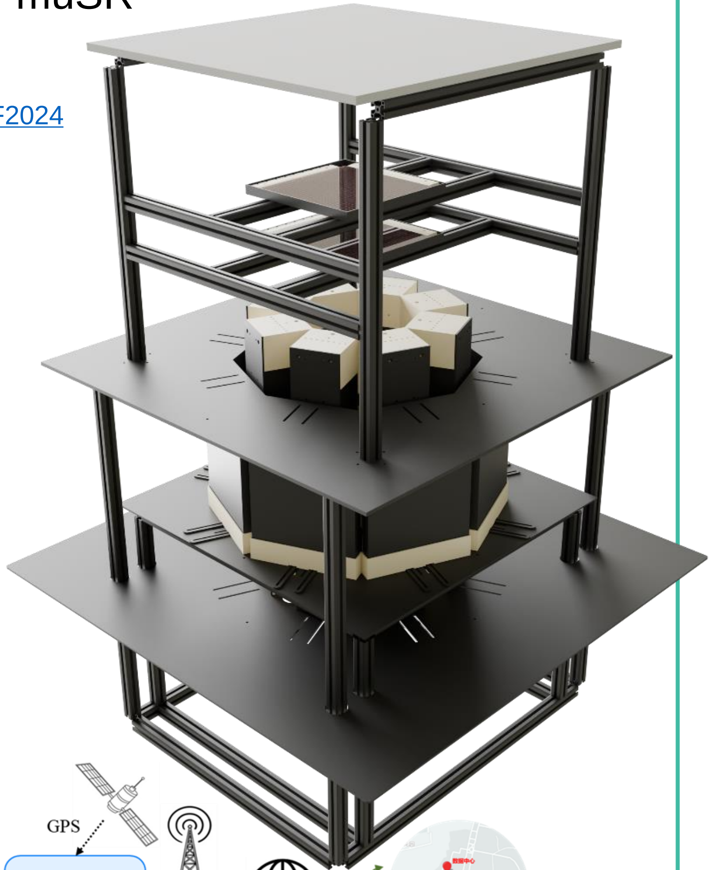
[Yu Xu et al, Nucl.Sci.Tech. 35 (2024) 4, 79]



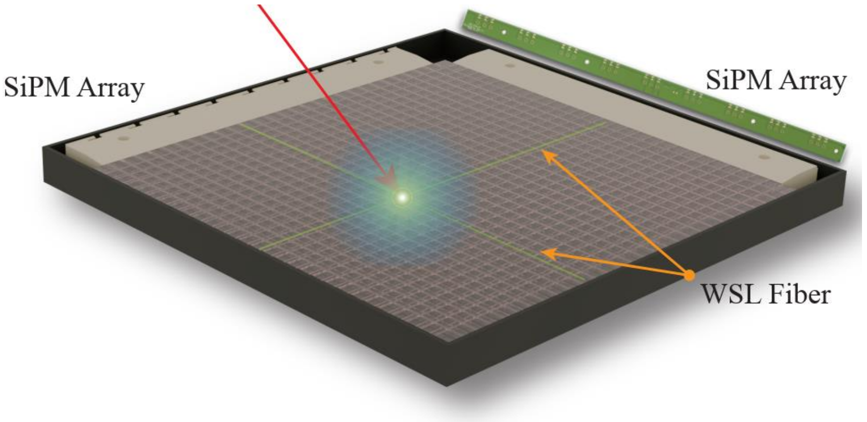


Cosmic-ray muSR (CRmuSR)

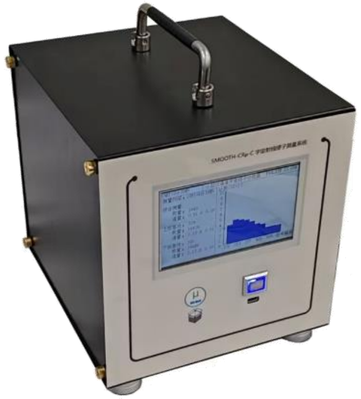
[M.-C. Sun, HHIF2024]

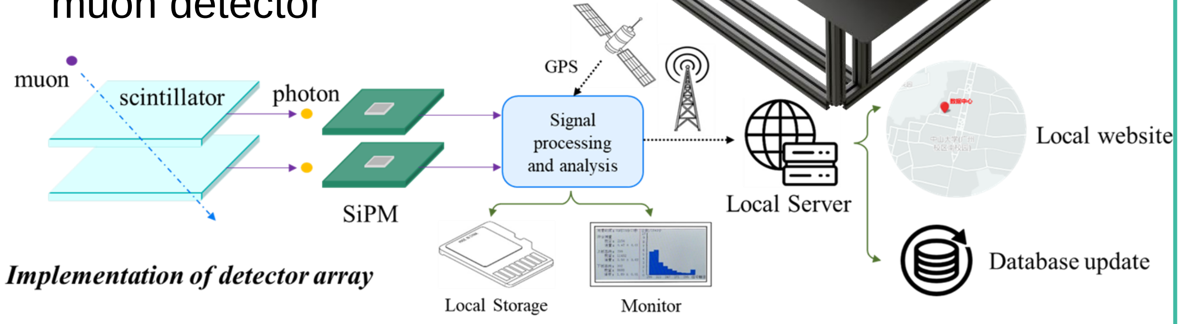


MuGrid v2 for muongraphy



Portable cosmic-ray muon detector

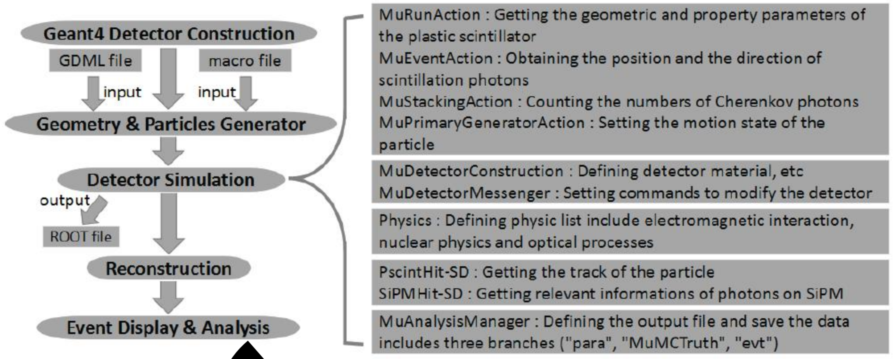


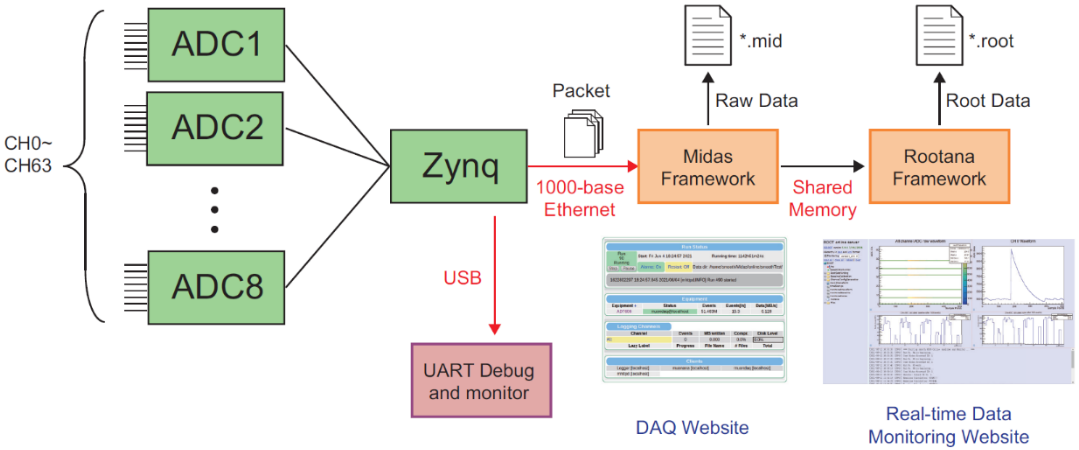


Implementation of detector array

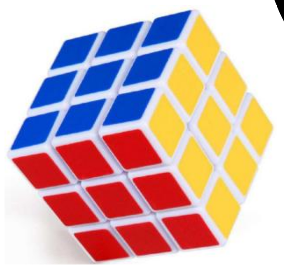
Detector R&D with cosmic muons: MuGrid

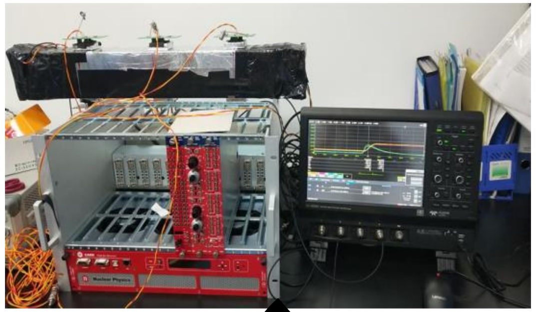
MC

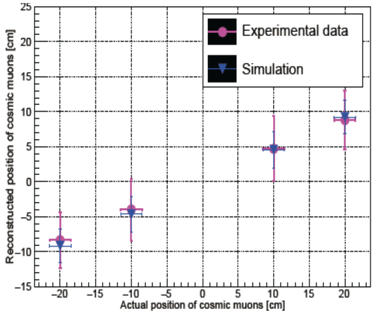




Module test





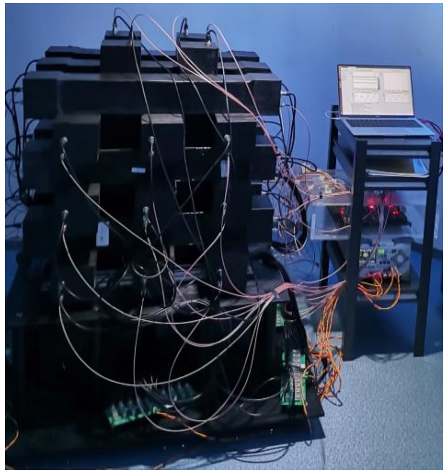


Customized electronics

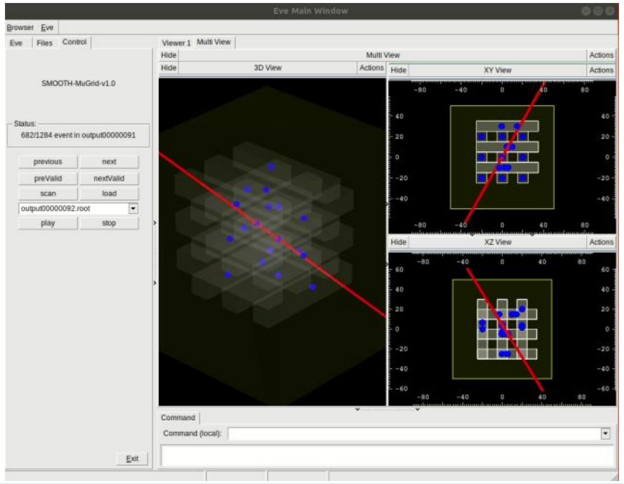
Track reconstruction

(a)

Online monitor

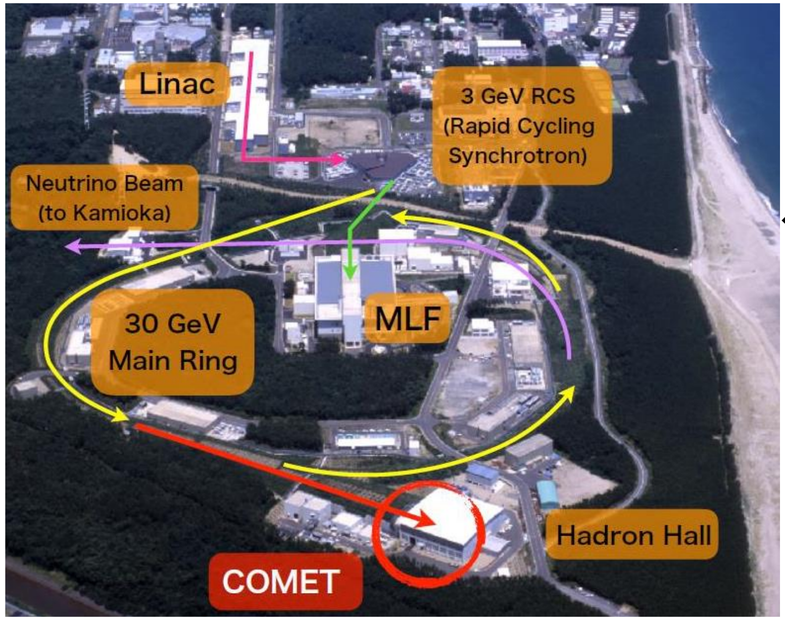


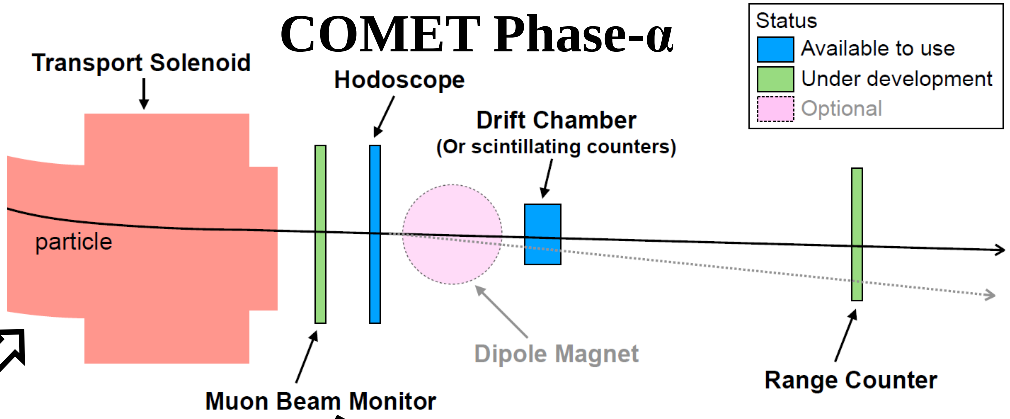
(b)

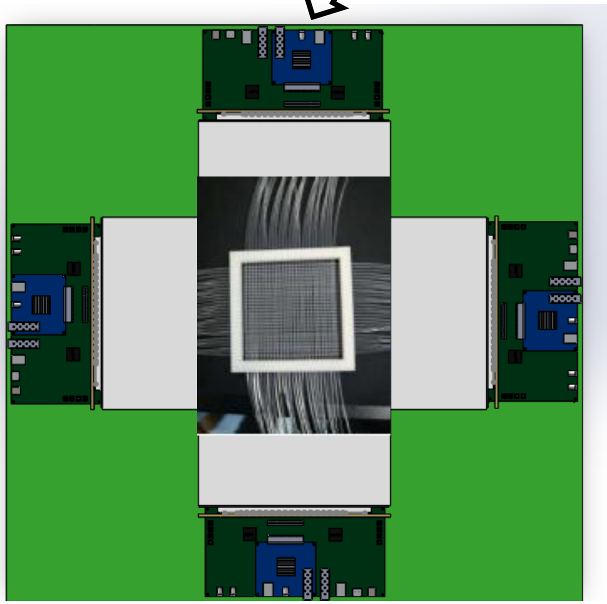


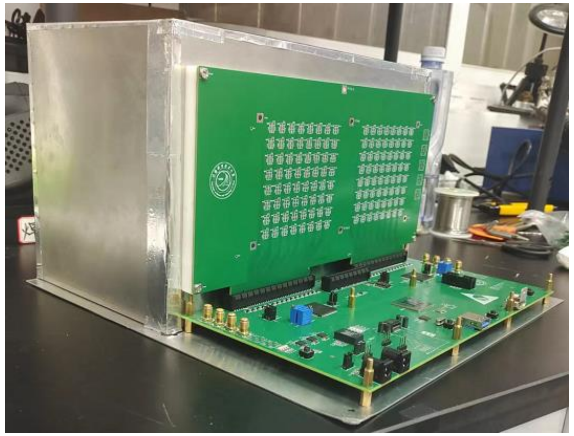
Nuclear Inst. and Methods in Physics Research, A1042 (2022) 167402

Muon beam monitor for COMET









SciFi → SiPM → FEB → DAQ → PC

e-Print: [2308.15253](https://arxiv.org/abs/2308.15253) [physics.ins-det]

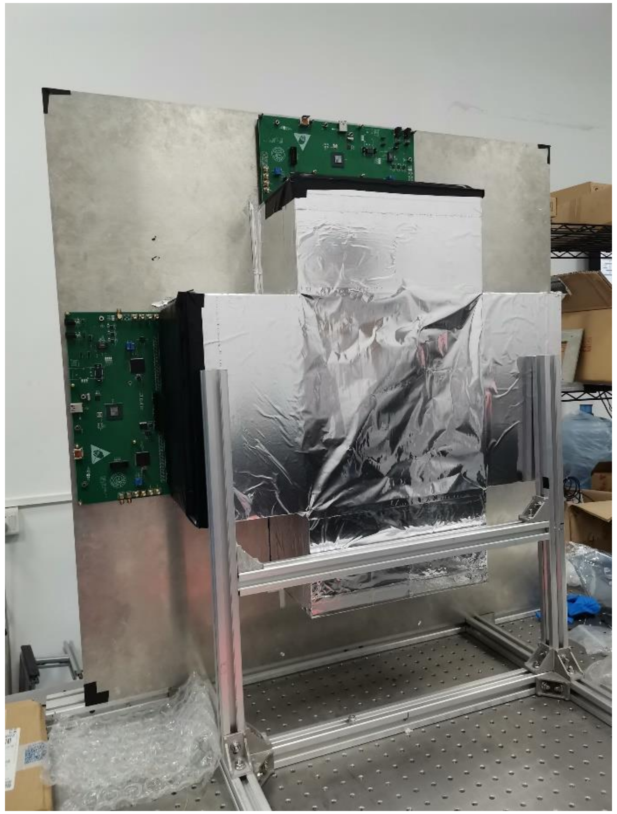
Nuclear Science and Techniques 35 (2024) 4, 79

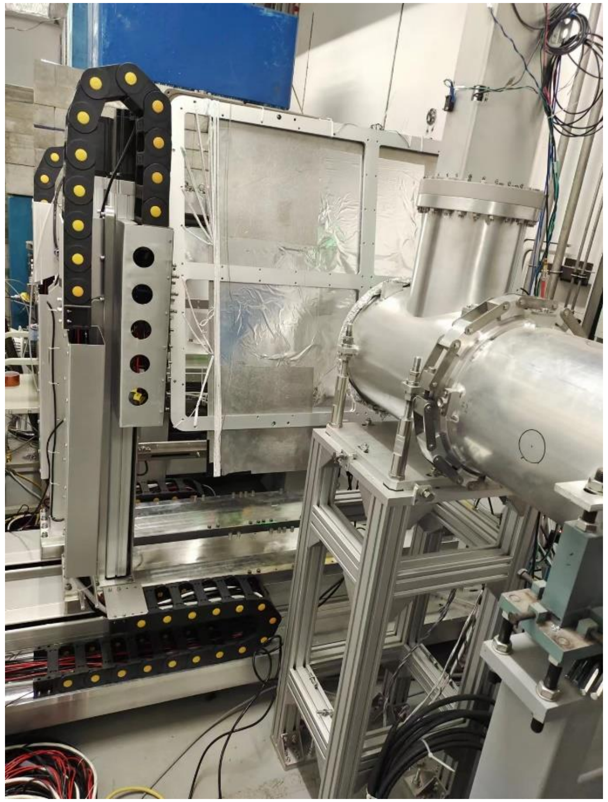
Credits：SMOOTH lab
USTC electronics group led by Chang-Qin Feng

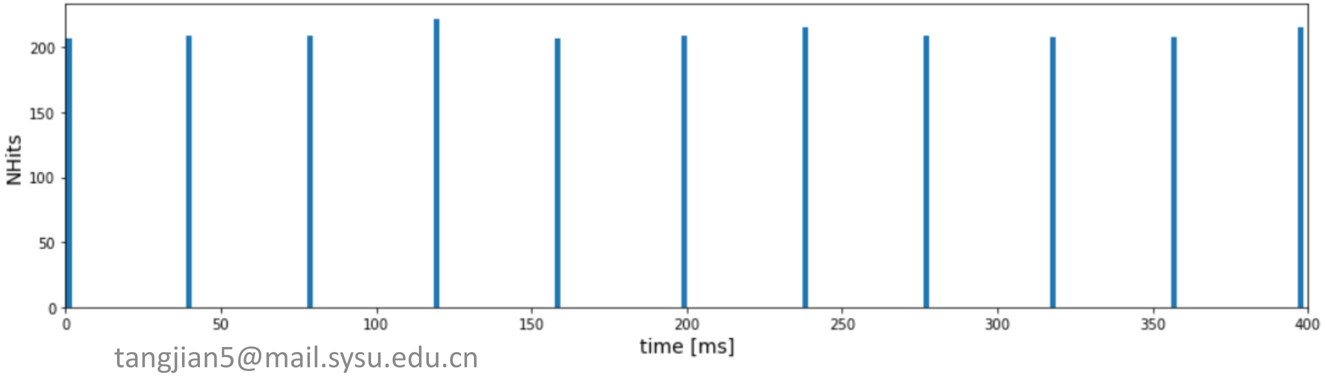
Muon beam monitor for COMET

- CSNS proton beam time: 2022/7/20
- Beam window:
  - 1cm×1cm
  - Energy: 30 MeV, 35 MeV, 40 MeV, 45 MeV, 50 MeV, 55 MeV, 60 MeV
  - Time: 90s per point
  - Beam rate: 1.7×10^{7} protons/s/cm^{2}

Acknowledgment: CSNS proton beamline







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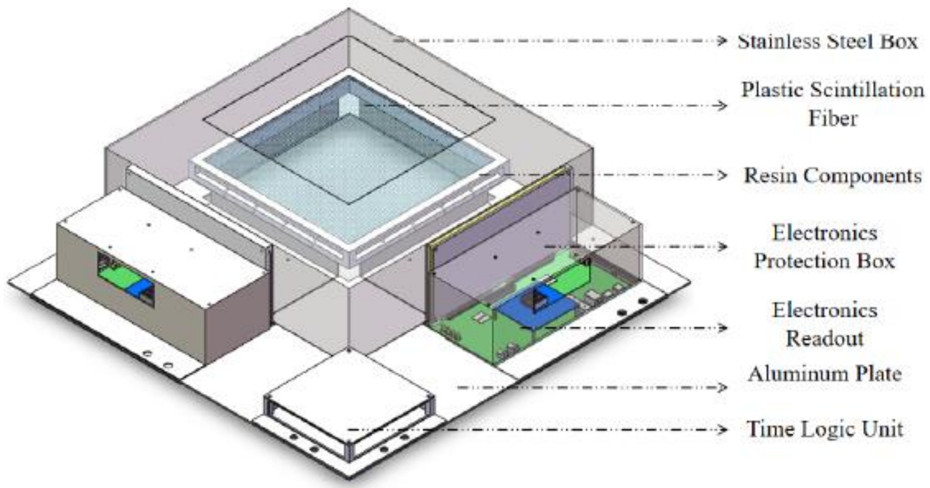
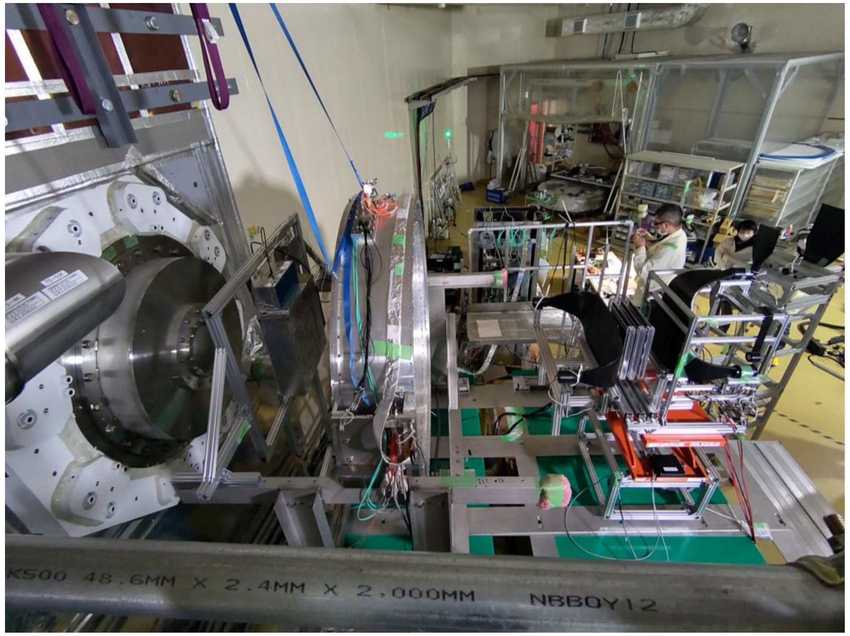
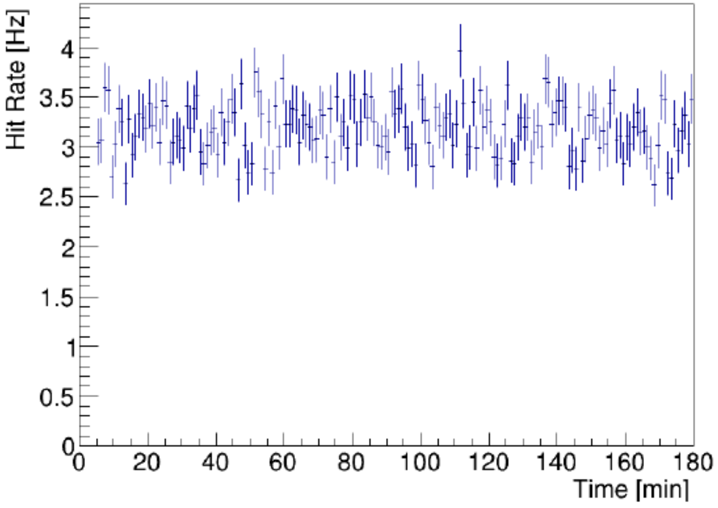
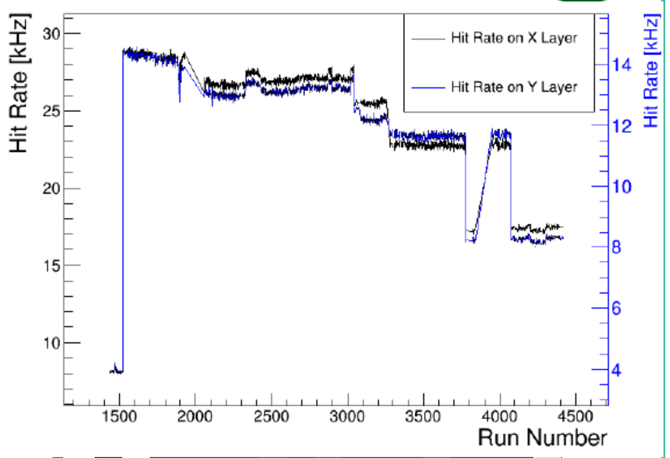
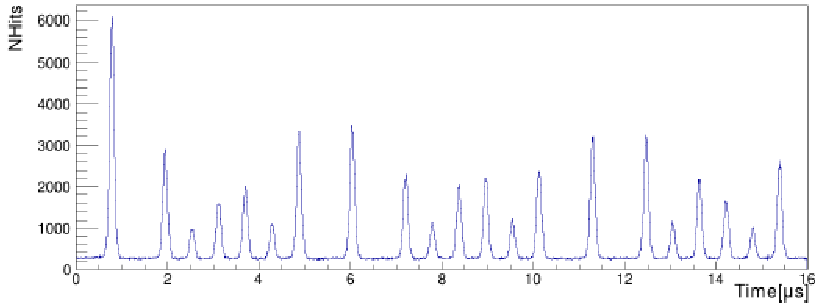
Muon beam monitor for COMET

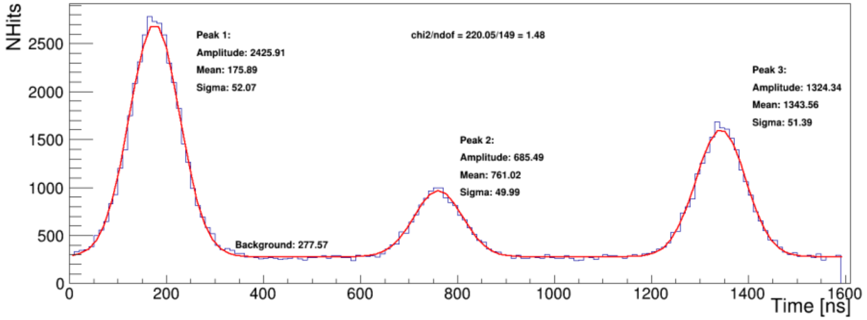


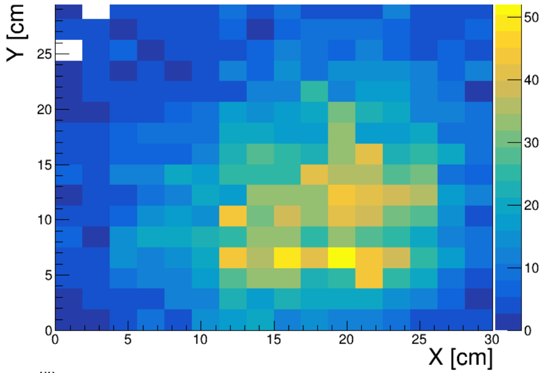


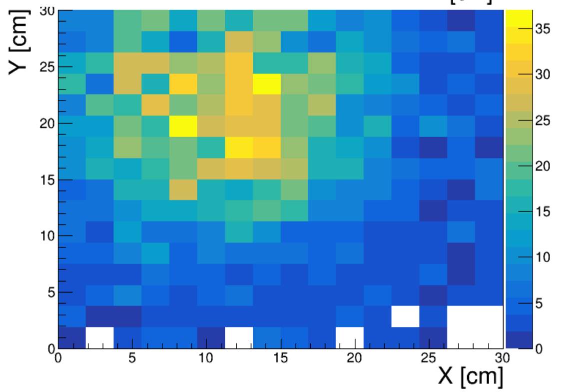












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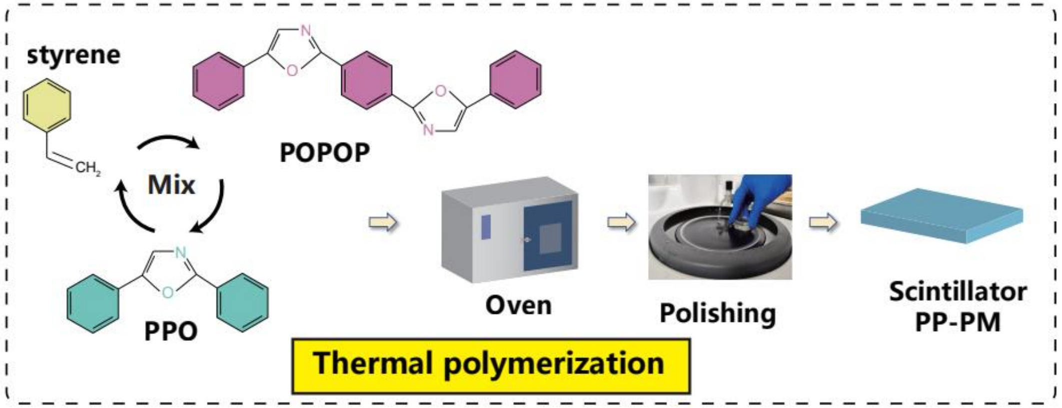
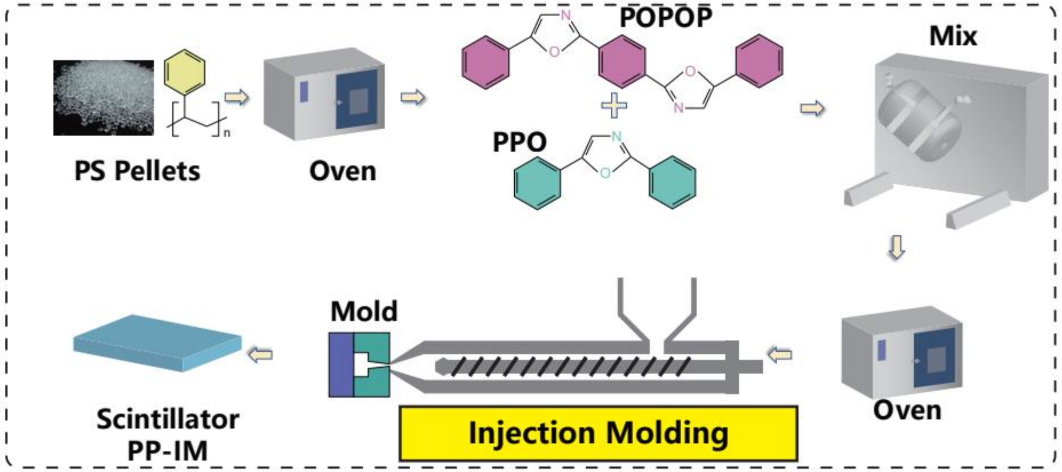
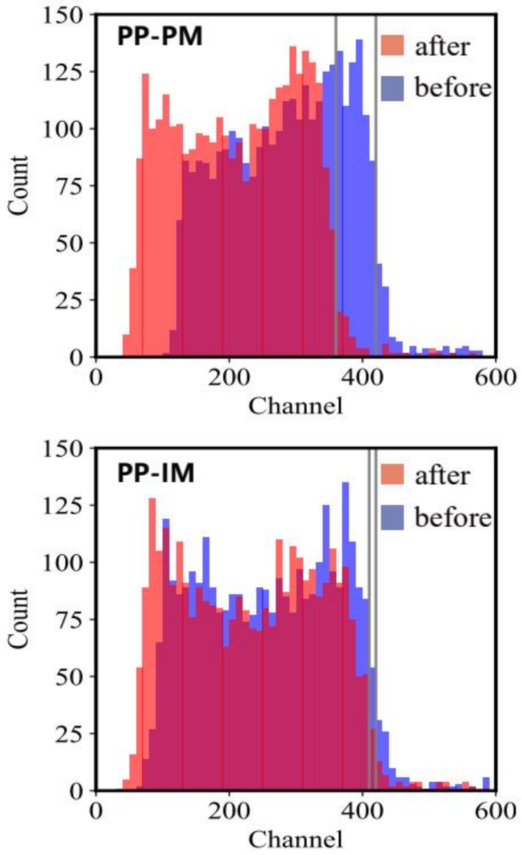
R&D of new plastic scintillators for muon detections

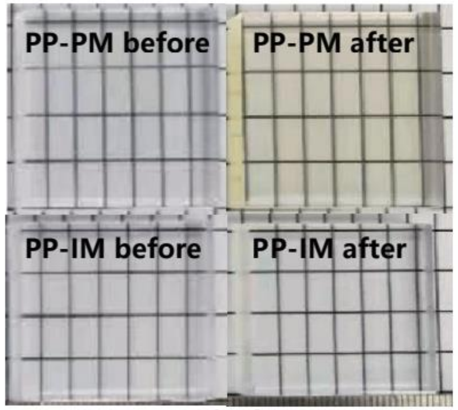




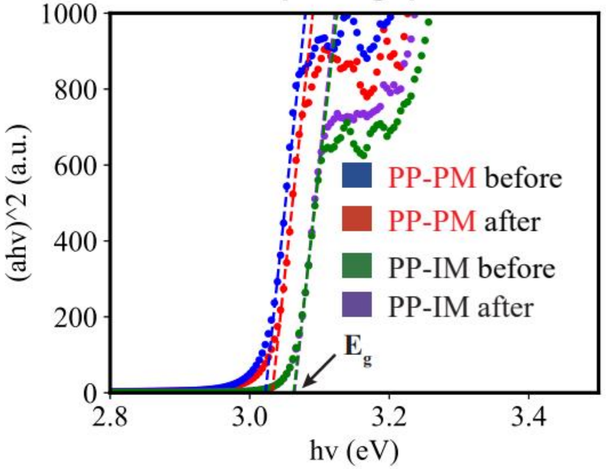
Light Yield



Appearance



Optical gap



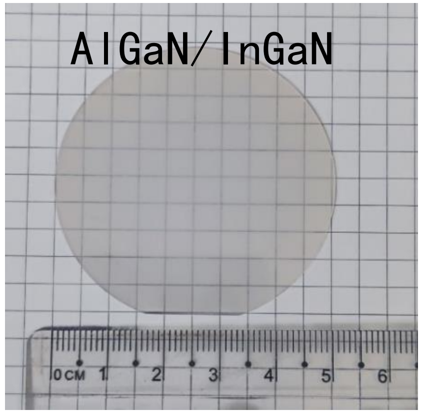
Enhancing plastic scintillator performance through advanced injection molding techniques

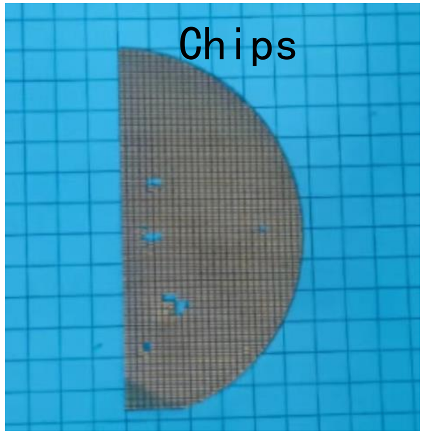
Credits: Jiahao Zhong, Nouman, Jian Zhou

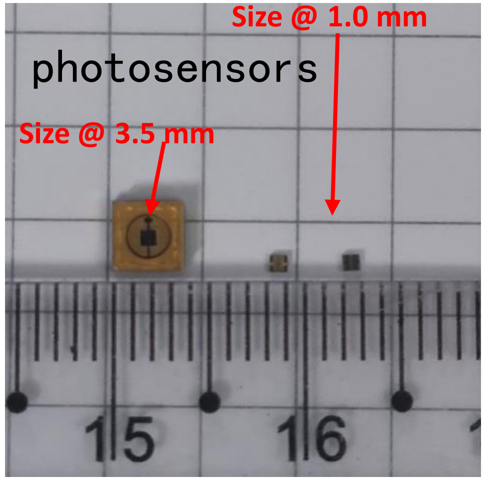
Radiation Physics and Chemistry *226 (2025) 112193*

R&D of new photosensors for muon detections

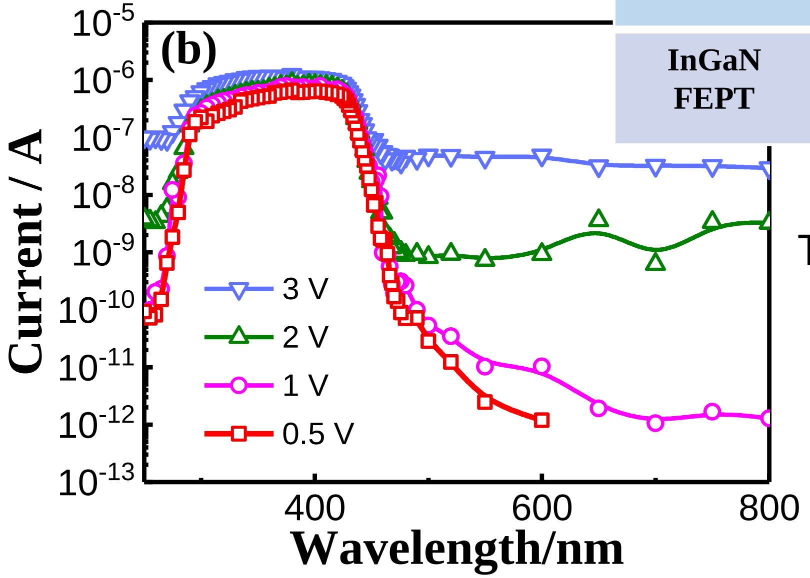
- Wavelength: 280~450 nm
- Low cost, low power consumption
- To replace SiPM/MPPC?



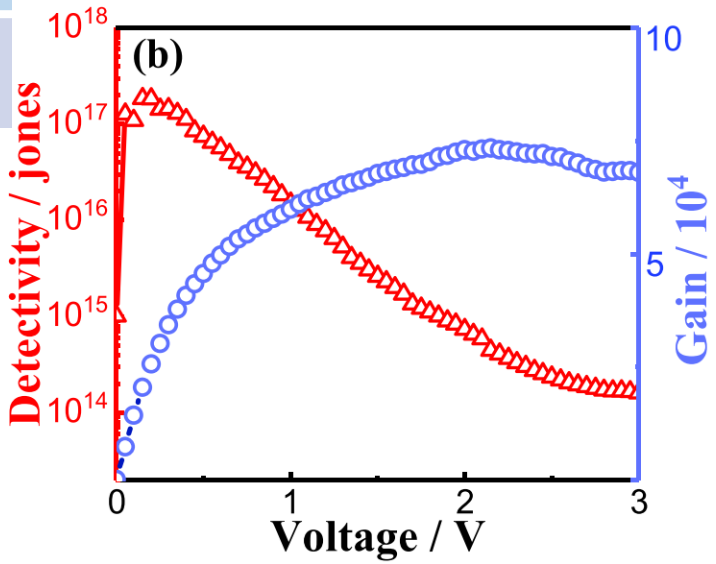




Structure	Working voltage	Dark counts	Sensitivity	Gain	Risetime/ fall time
InGaN FEPT	1.0 V	0.2 pA @ 1 V	2×10^4 A/W @6.8μW/cm^2	6.2×10^4	15 / 160 ns

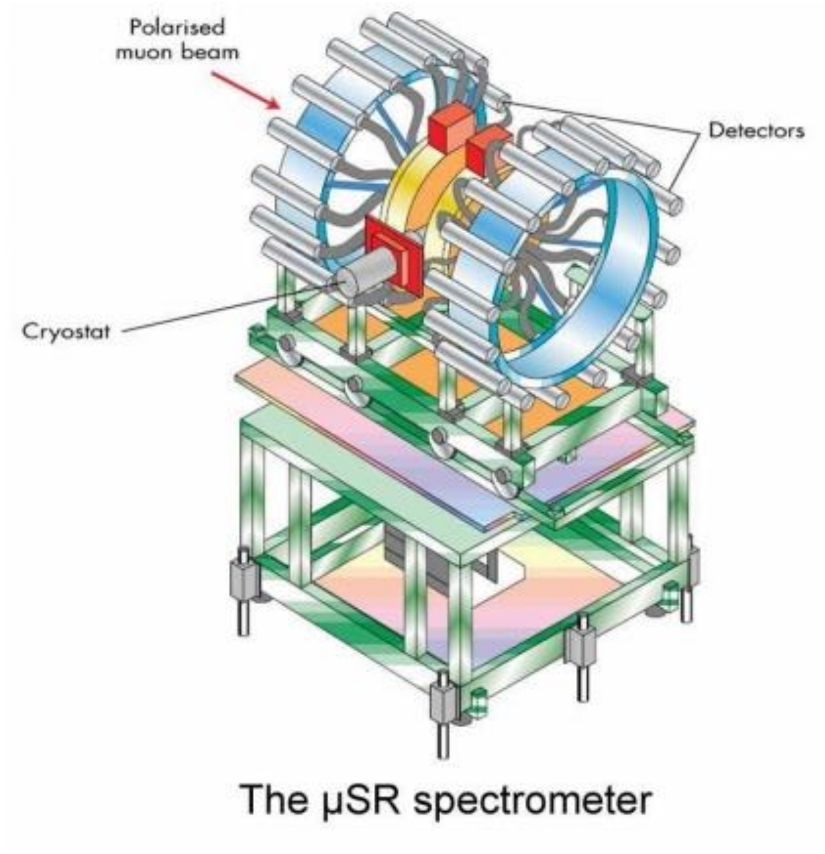


To collaborate with my previous students!

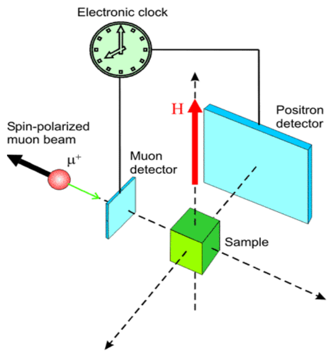


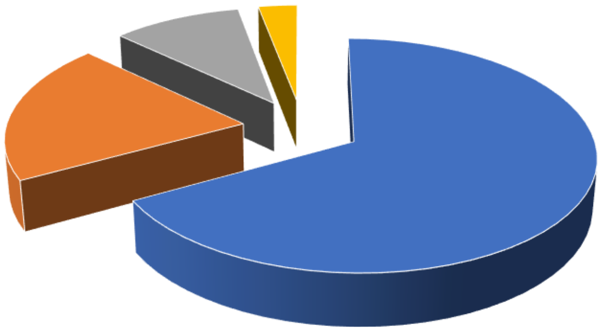
Appl. Phys. Lett. 125, 191104 (2024); *Appl. Phys. Lett.* 123, 051103 (2023)

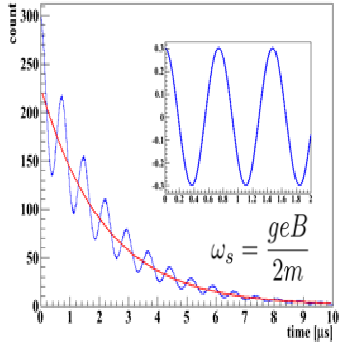
Muon Spin Relaxation, Rotation and Resonance (μSR)



Nature Materials 16, 467–473 (2017)







Physics → *Magnetism*, *Superconductivity*, *Surface physics*, *Fundamental physics*

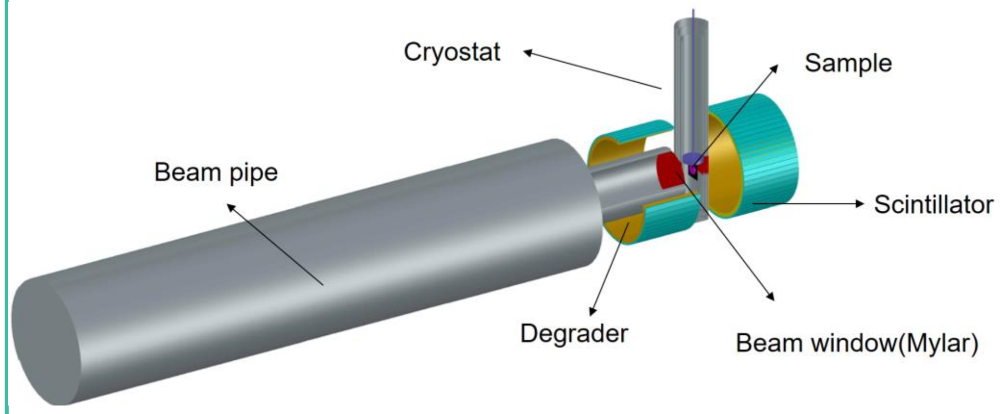
Chemistry → *Molecular dynamics*, *Oxides*, *Muonium in materials*

Materials → *Polymers*, *Semiconductors*, *Hydrogen storage material*

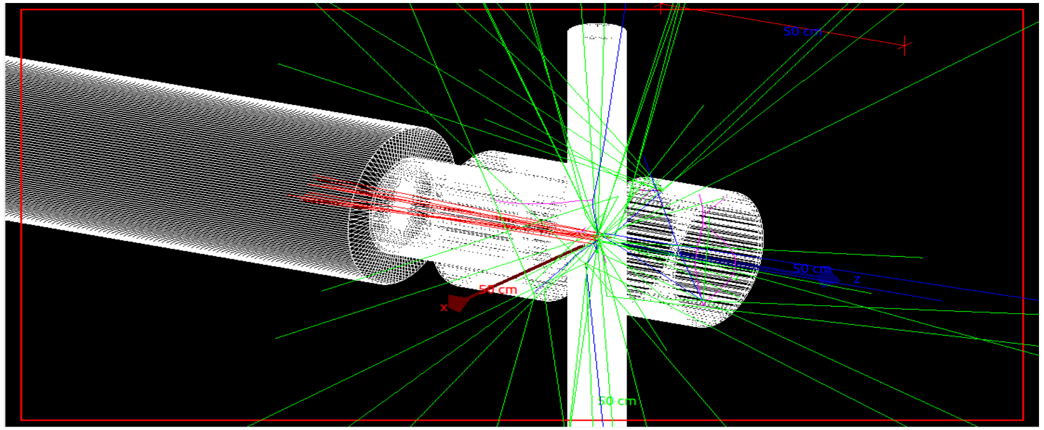
Biology → *proteins*, *DNA*

Design and simulation of μSR

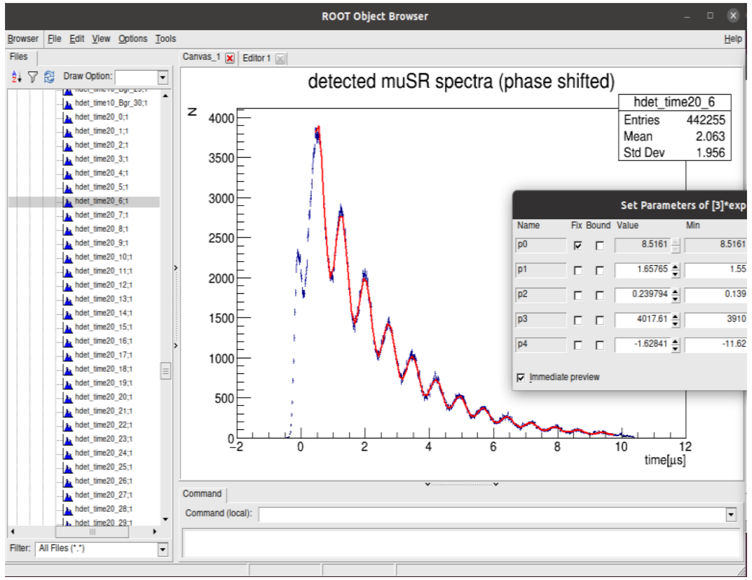
- Two detector rings, degraders, a cryostat, and a beam pipe.



CAD design

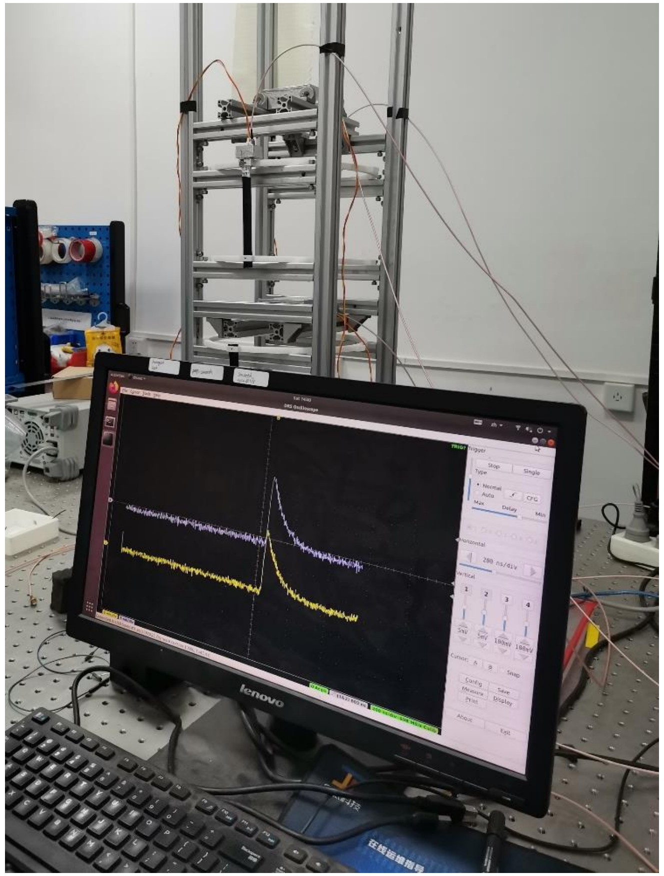


MC simulations



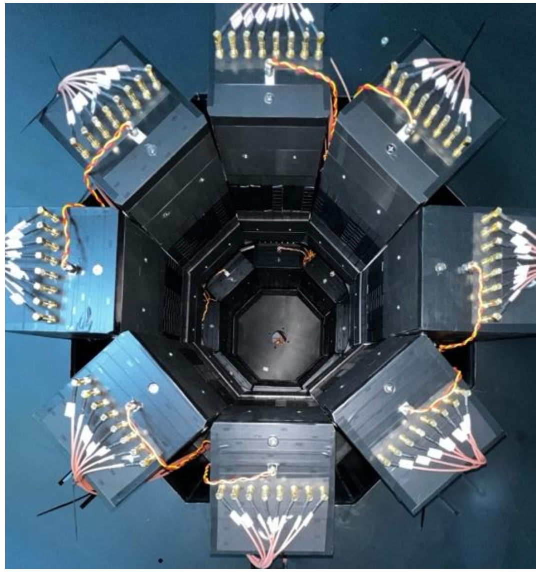
Mock data analysis and fit

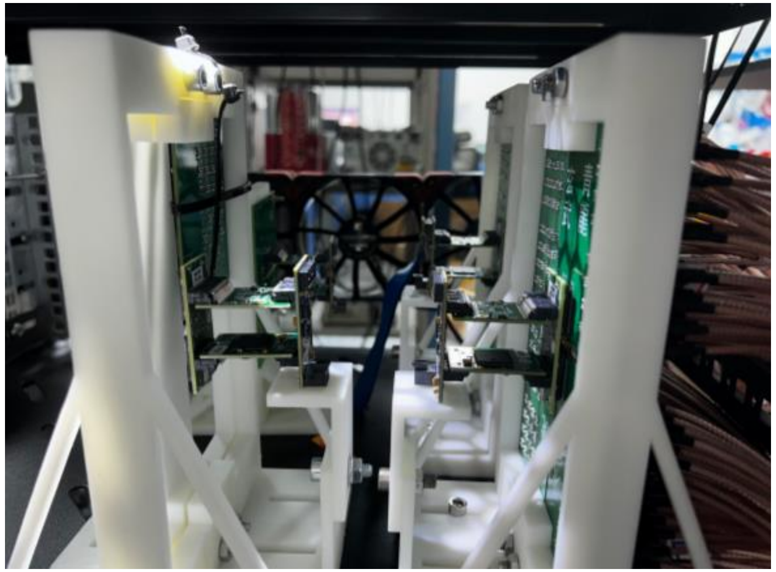
Credits： Yi-Xing Zhou

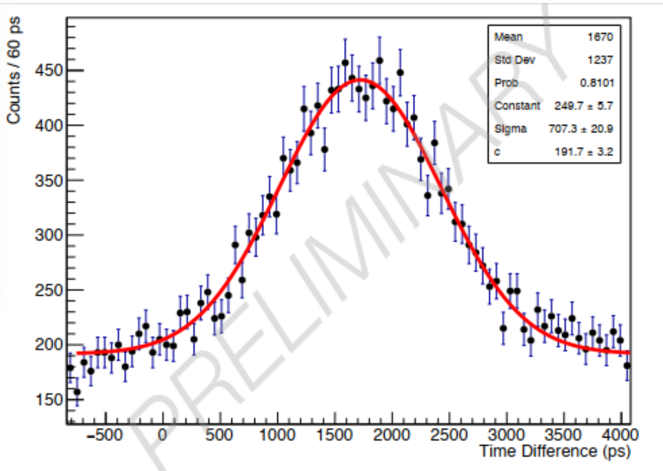


Prototype tests by CRμ

R&D of μSR







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Summary

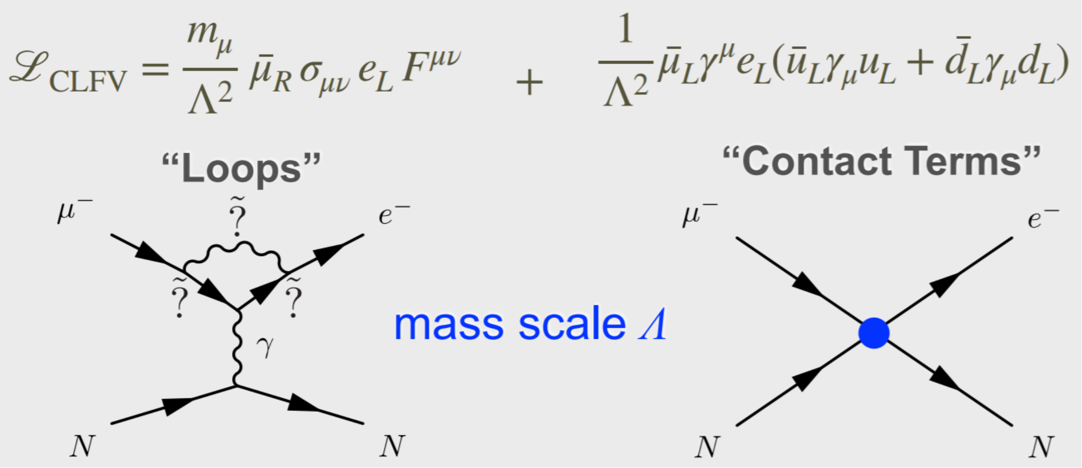
- Muon physics is a hot topic, enabling precise tests of QED theory and probe of new physics beyond SM.
- MACE experiment will make a breakthrough in muon physics.
- Significant progress has been made in experiment design, muonium target design, and offline software development.
- Ongoing development 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!

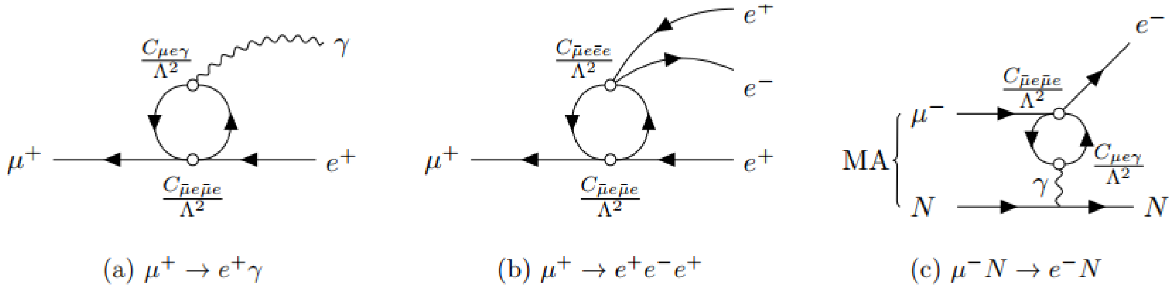
Thanks!

- *Thanks for the invitation from Dr. Paolo Beltrame and Dr. Ce Zhang.*
- *In collaboration with Prof. Changqin Feng (USTC) at electronics readout in detector R&D.*
- *Appreciate fabrication of Silica aerogel at school of material science and engineer by Prof. Jian Zhou.*
- *Supported by NSFC no. 12075326, Guangdong province and Guangzhou natural science foundation.*
- *Special thanks to SYSU and excellent bachelor students!*

SMEFT

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_{d>4} \sum_{n} \frac{c_n^{(d)}}{\Lambda^{d-4}} \mathcal{O}_n^{(d)}$$





REF: *By A. DeGouvea and P. Vogel, arXiv:1303.4097. EFT treatment by S. Davidson and B. Echenard. arXiv: 2010.00317*

SMEFT

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM}^{(4)} + \frac{1}{\Lambda}\sum_i C_i^{(5)} Q_i^{(5)} + \frac{1}{\Lambda^2}\sum_i C_i^{(6)} Q_i^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right).$$

- The first-order effective operator beyond the Standard Model has a dimension of 5, corresponding to Λ^{-1}; this order generates the Majorana mass term for neutrinos.
- Subsequent effective Lagrangian corresponds to Λ^{-2}, where operators of this order can produce cLFV at tree-level.
- Different processes typically exhibit sensitivity to certain classes of operators while being insensitive to others.
  - For example, muonium conversion is sensitive to the $\bar{\mu}e\bar{\mu}e$ coupling but not to $\bar{\mu}e\bar{e}e$ or $\bar{\mu}e\gamma$; so conversly do $\mu \to eee$ and $\mu \to e\gamma$.
- Muon conversion is directly generated by the $\bar{\mu}e\bar{\mu}e$ coupling, with $M^2 \propto \frac{1}{\Lambda^4}$;
- In contrast, $\mu \to e\gamma$ at the EFT tree-level does not involve the $\mu\bar{e}\bar{\mu}e$ coupling; if one insists to involve $\mu\bar{e}\bar{\mu}e$, it would require two EFT vertices, resulting in $M^2 \propto \frac{1}{\Lambda^8}$ suppression.

SMEFT

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

- $\mu^+ e^- \to \mu^- e^+$ SMEFT Lagrangian with vector $\bar{\mu} e \bar{\mu} e$ couplings only:

$$\mathcal{L}_{\text{SMEFT}}^{\Delta L_\mu = 2} \supset \frac{1}{\Lambda^2}\Big(C^{LL}_{\mu e \mu e} (\bar{\mu}_L \gamma^\alpha e_L)(\bar{\mu}_L \gamma_\alpha e_L) + C^{LR}_{\mu e \mu e} (\bar{\mu}_L \gamma^\alpha e_L)(\bar{\mu}_R \gamma_\alpha e_R) + C^{RR}_{\mu e \mu e} (\bar{\mu}_R \gamma^\alpha e_R)(\bar{\mu}_R \gamma_\alpha e_R) \Big) + \text{h.c.}$$

- 3 Wilson coefficients, time-independent conversion probability writes

$$P \approx \frac{1}{\Lambda^4}\left(\frac{7.58 \times 10^{-7}}{G_F^2} \left| C^{LL}_{\mu e \mu e} + C^{RR}_{\mu e \mu e} - 1.68 C^{LR}_{\mu e \mu e} \right|^2 + \frac{4.27 \times 10^{-7}}{G_F^2} \left| C^{LL}_{\mu e \mu e} + C^{RR}_{\mu e \mu e} + 0.68 C^{LR}_{\mu e \mu e} \right|^2 \right) .$$

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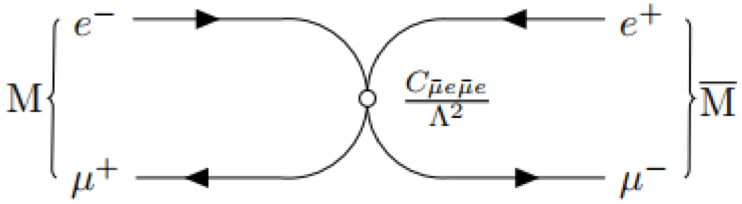
SMEFT



Complete $\mu^+e^- \to \mu^-e^+$ SMEFT Lagrangian, with vector and scalar couplings:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{n>4} \frac{1}{\Lambda^{n-4}} \sum_i C_i^{(n)} Q_i^{(n)} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\sum_i C_i^{(5)} Q_i^{(5)} + \frac{1}{\Lambda^2}\sum_i C_i^{(6)} Q_i^{(6)} + \cdots$$

$$Q_V^{LL} = (\bar\mu_L \gamma_\alpha e_L)(\bar\mu_L \gamma^\alpha e_L), \quad Q_V^{RR} = (\bar\mu_R \gamma_\alpha e_R)(\bar\mu_R \gamma^\alpha e_R),$$

$$Q_V^{LR} = (\bar\mu_L \gamma_\alpha e_L)(\bar\mu_R \gamma^\alpha e_R),$$

$$Q_S^{LR} = (\bar\mu_L e_R)(\bar\mu_L e_R), \qquad Q_S^{RL} = (\bar\mu_R e_L)(\bar\mu_R e_L).$$

$$\mathcal{L}_{\text{eff}} = \frac{1}{\Lambda^2}\left(C_V^{LL}Q_V^{LL} + C_V^{RR}Q_V^{RR} + C_V^{LR}Q_V^{LR} + C_S^{LR}Q_S^{LR} + C_S^{RL}Q_S^{RL} + C_V^{L\nu}Q_V^{L\nu} + C_V^{R\nu}Q_V^{R\nu}\right)$$

Follows the same steps as that for the $B\bar{B}$ or $K\bar{K}$ mixing

$$P(\text{M}\to\overline{\text{M}}) = S_B(B_0, f_P)\left(f_P P(\text{M}_P \to \overline{\text{M}}_P) + (1-f_P) P(\text{M}_V \to \overline{\text{M}}_V)\right)$$

$$P(\text{M}\to\overline{\text{M}}) = \left(\frac{f_P}{2}\left(x_P^2 + y_P^2\right) + \frac{1-f_P}{2}\left(x_V^2 + y_V^2\right)\right) S_B(B_0, f_P)$$

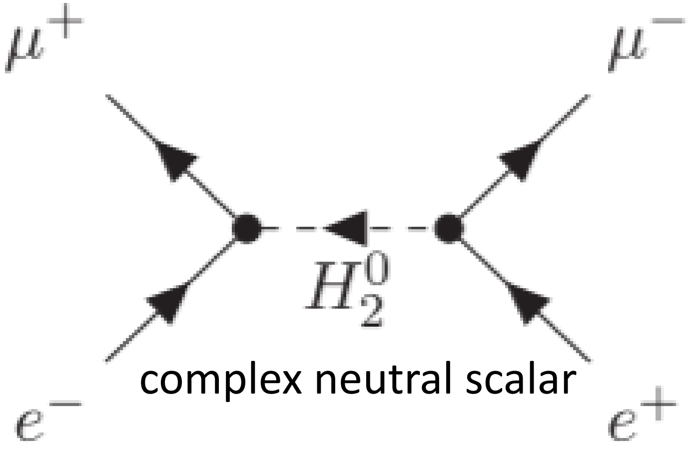
$$x_P = \frac{4(\alpha\mu)^3}{\pi\Gamma\Lambda^2}\left(C_V^{LL} + C_V^{RR} - \frac{3}{2}C_V^{LR} - \frac{1}{4}\left(C_S^{LR} + C_S^{RL}\right)\right), \qquad x_V = -\frac{12(\alpha\mu)^3}{\pi\Gamma\Lambda^2}\left(C_V^{LL} + C_V^{RR} + \frac{1}{2}C_V^{LR} + \frac{1}{4}\left(C_S^{LR} + C_S^{RL}\right)\right),$$

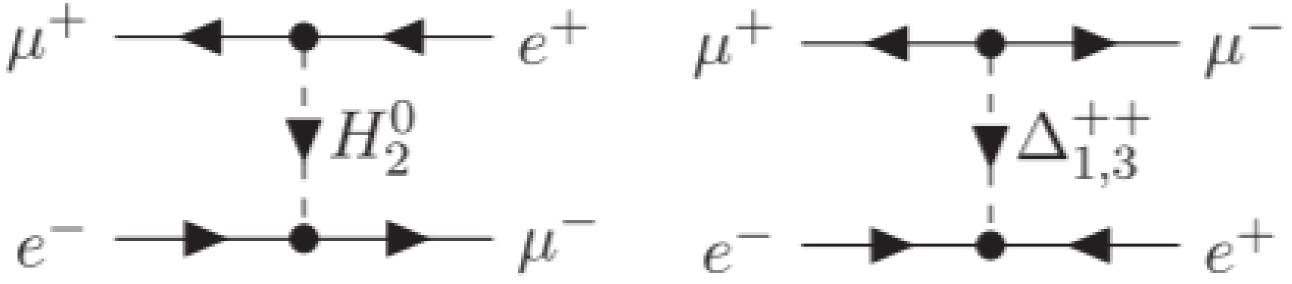
$$y_P = \frac{G_F}{\sqrt{2}\Lambda^2}\frac{m^2(\alpha\mu)^3}{\pi^2\Gamma}\left(C_V^{L\nu} - C_V^{R\nu}\right). \qquad y_V = -\frac{G_F}{\sqrt{2}\Lambda^2}\frac{m^2(\alpha\mu)^3}{\pi^2\Gamma}\left(5C_V^{L\nu} + C_V^{R\nu}\right).$$

$$P(\text{M}\to\overline{\text{M}}) = \frac{8(\alpha\mu)^6}{\pi^2\Gamma^2\Lambda^4}\left(f_P\left(C_V^{LL} + C_V^{RR} - \frac{3}{2}C_V^{LR} - \frac{1}{4}\left(C_S^{LR} + C_S^{RL}\right)\right)^2 + 9(1-f_P)\left(C_V^{LL} + C_V^{RR} + \frac{1}{2}C_V^{LR} + \frac{1}{4}\left(C_S^{LR} + C_S^{RL}\right)\right)^2\right) S_B(B_0, f_P)$$

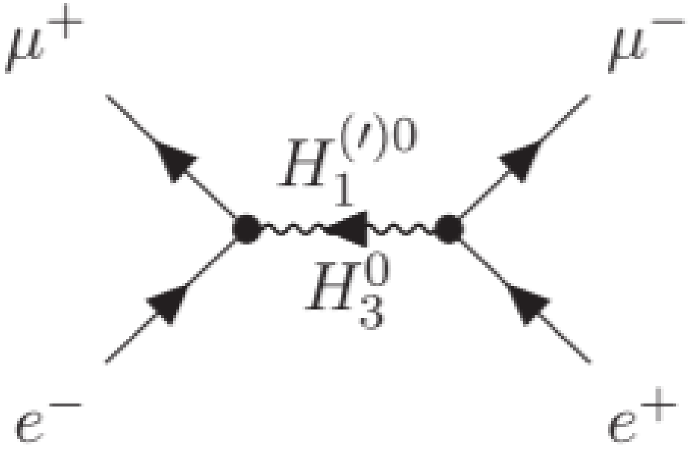
Process	Type	Experiment	Current bound
$\text{M} \to \overline{\text{M}}$	$\text{M} - \overline{\text{M}}$ mixing	MACS [10], MACE	$P < 8.3 \times 10^{-11}/S_B(0.1\ \text{T})$ [10]
$\mu^+e^- \to \mu^-e^+$	Scattering	μTRISTAN [39]	None
$\mu^+\mu^+ \to e^+e^+$			
$\mu^+\mu^+ \to \tau^+\tau^+$			
$\mu^+ \to e^+\bar\nu_e\nu_\mu$	Decay	τ_μ measurement	$\Delta\tau_\mu/\tau_\mu = 1 \times 10^{-6}$ [23]
$Z \to \ell'^\pm\ell'^\pm\ell^\mp\ell^\mp$		CEPC [40], FCC-ee [41]	None

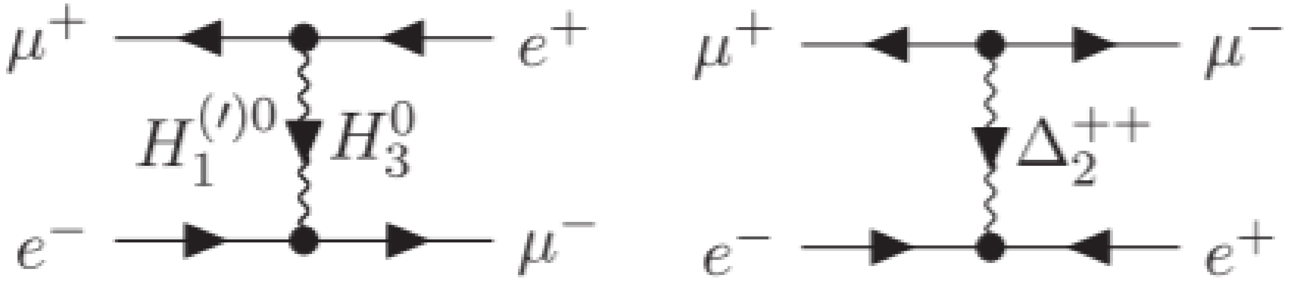
Model dependent muonium conversion





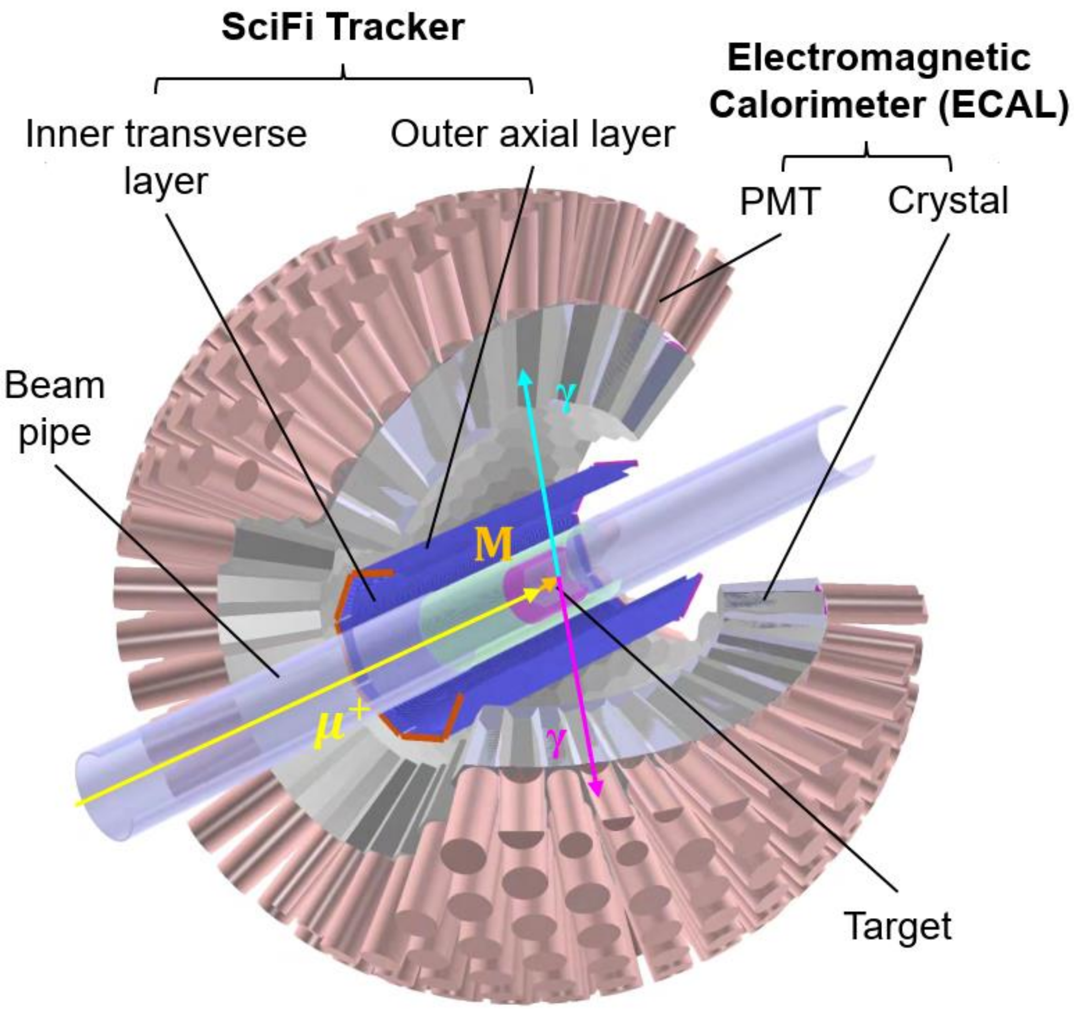
REF: Tong Li, Michael A. Schmidt. Phys.Rev.D 100 (2019) 11, 115007





MACE Phase-I concept

- Searching for the neutrinoless double radiative decay of muon(ium), i.e.
  - $\mathrm{M} \to \gamma\gamma$ (unsearched)
  - $\mu^+ \to e^+\gamma\gamma$ (no experimental progress since the 1986)*
- Beamline: $1 \times 10^7\ \mu^+/\mathrm{s}$, CW
- Detector:
  - BGO calorimeter
  - Scintillating fiber tracker
- A sensitivity of $\mathcal{O}(10^{-12})$ expected!



*$\mathcal{BR} < 7.2 \times 10^{-11}$ at 90% C. L. *Phys.Rev.D* 38 (1988) 2077