Muon beams towards muonium physics and detection across the road

Jian Tang (唐健)

tangjian5@mail.sysu.edu.cn

May 8, 2025, Institute of High Energy Physics, Beijing

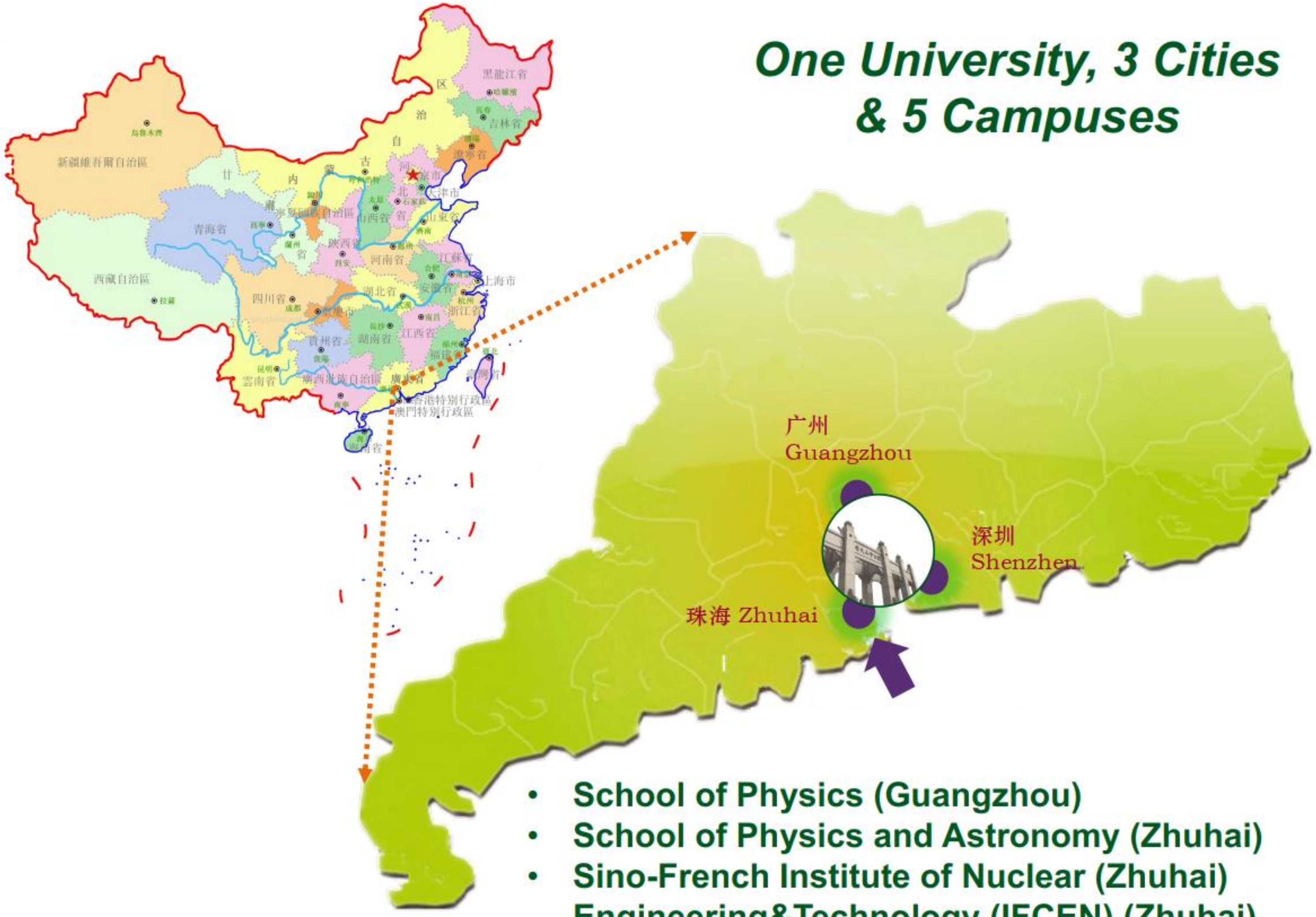
SMOOTH Lab @ SYSU & the MACE working group

SYSU MuOn and Optical TomograpHy

Muonium-to-Antimuonium Conversion Experiment

Reference: Conceptual Design of MACE, arXiv: 2410.18817

A strong team in SYSU

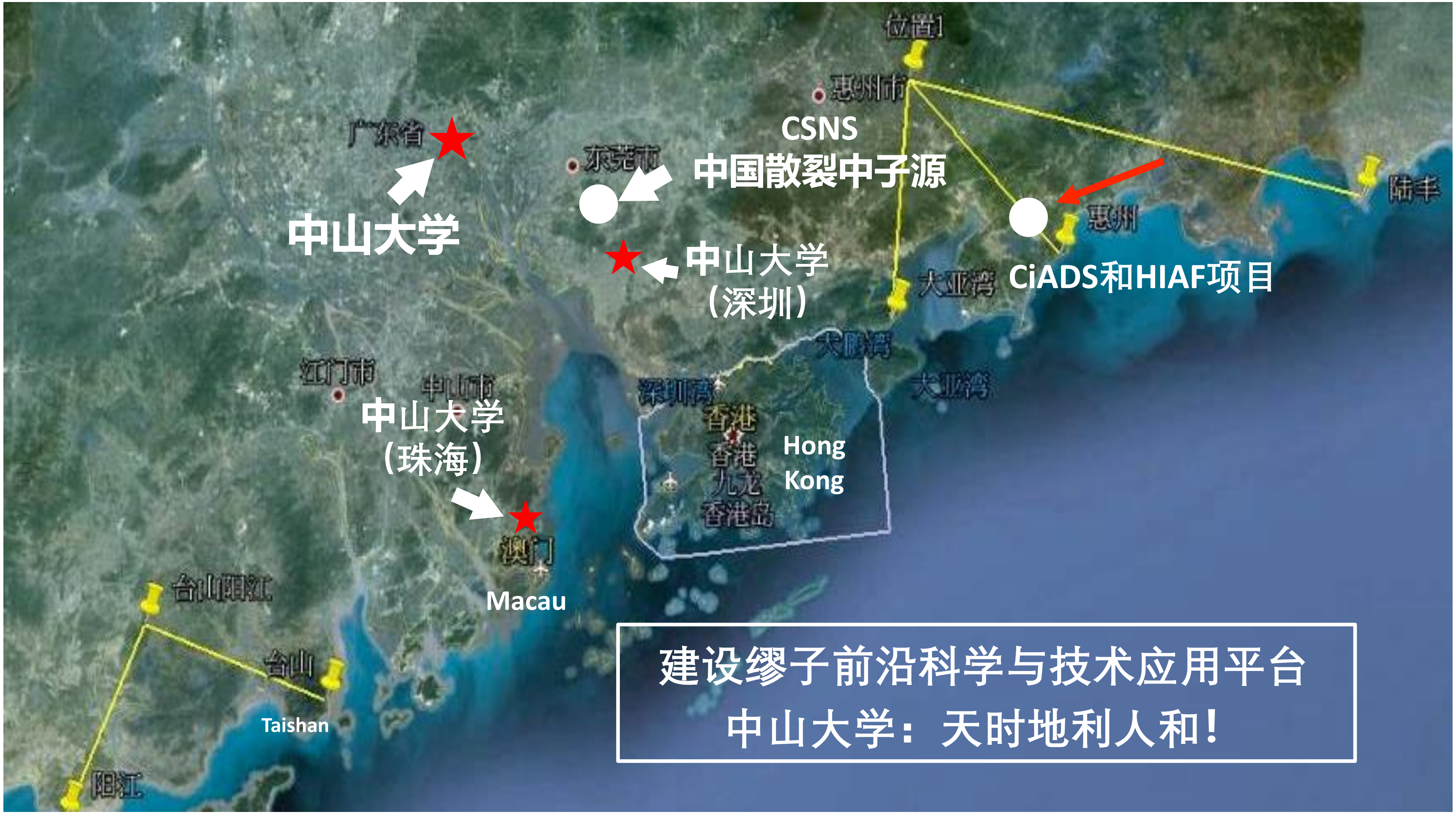


One University, 3 Cities & 5 Campuses

- School of Physics (Guangzhou)
- School of Physics and Astronomy (Zhuhai)
- Sino-French Institute of Nuclear (Zhuhai) Engineering&Technology (IFCEN) (Zhuhai)
- School of Science (Shenzhen)

- More than 30 faculty members working on HEP/NP-related areas: Th+Ph+Ex.
- Muon physics: COMET, Mu2e, MACE…
- Neutrino physics: Daya Bay, JUNO, DUNE, MOMENT, JNE, PandaX…
- Neutron physics: nuclear data…
- Collider physics: ATLAS, CMS, BESIII…
- Astroparticle physics: AMS, LHAASO, HERD, HUNT…
- Nuclear materials and radiation shield…

SYSU & National accelerator facilities



Platform for Muon Science and Technology

SMOOTH Laboratory

Table of contents

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

tangjian5@mail.sysu.edu.cn

Symmetries of SM

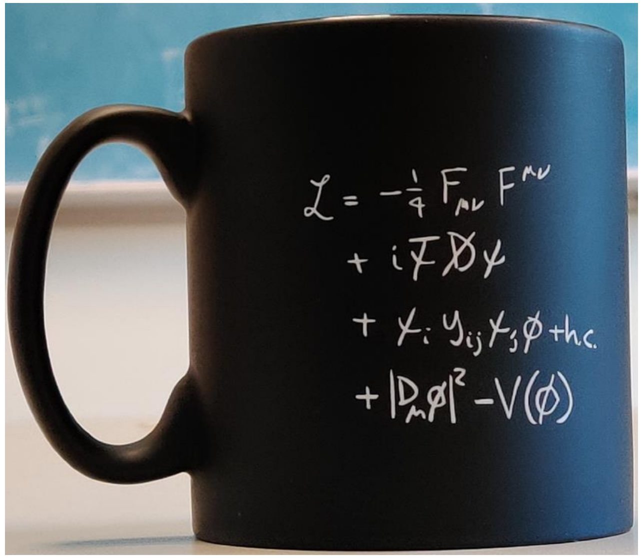
- The Standard Model (SM) gauge symmetry:

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

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

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

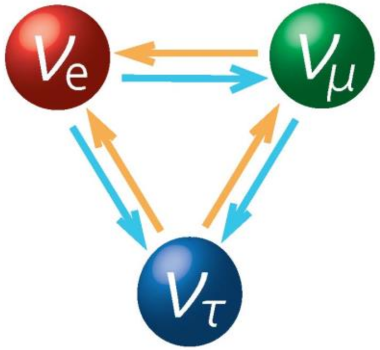
- Lepton flavor is always conserved **in the Standard Model,** however…



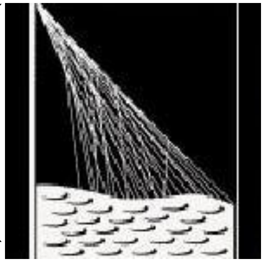
	Lepton number	Lepton family number (lepton flavor)		
		L_e	L_μ	L_τ
e^- & ν_e	1	1	0	0
μ^- & ν_μ	1	0	1	0
τ^- & ν_τ	1	0	0	1

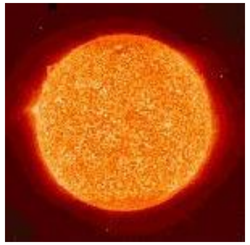
tangjian5@mail.sysu.edu.cn

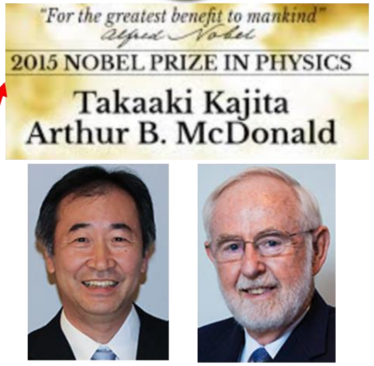
Neutral leptons oscillate!



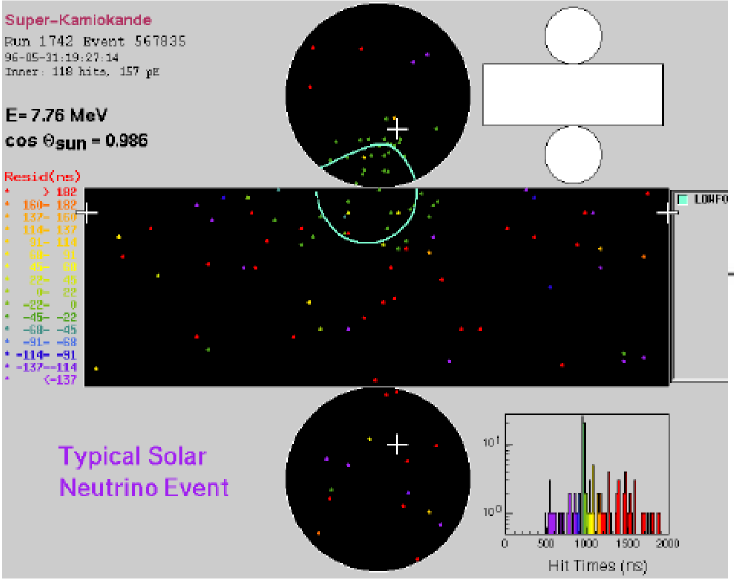
$$U_{\rm PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\, e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}\, e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

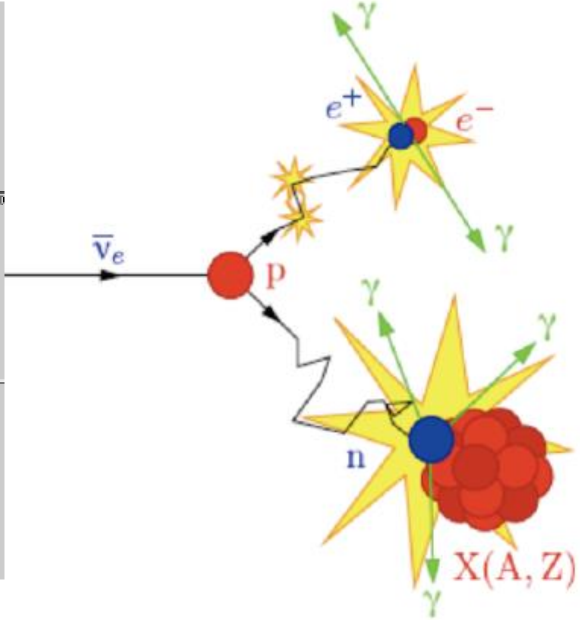
= () x (

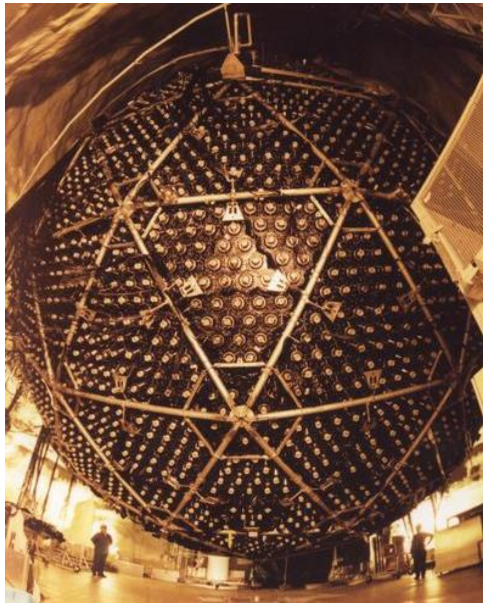
) x ()



"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.**

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

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

High-intensity/-precision frontier

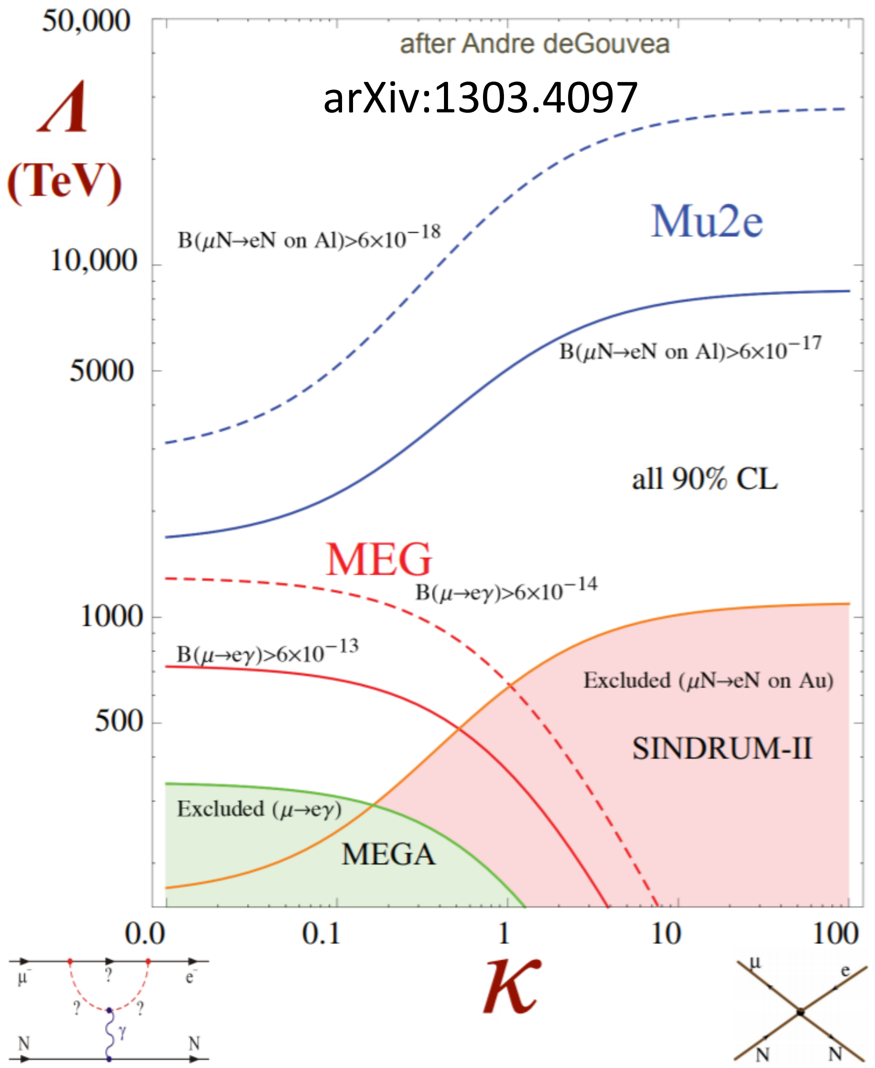
- **Experiments search for cLFV:**
  - Mu2e (Fermilab)
  - COMET (J-PARC)
  - MEG (PSI)
  - Mu3e (PSI)

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

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

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

- **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

High-intensity/-precision frontier

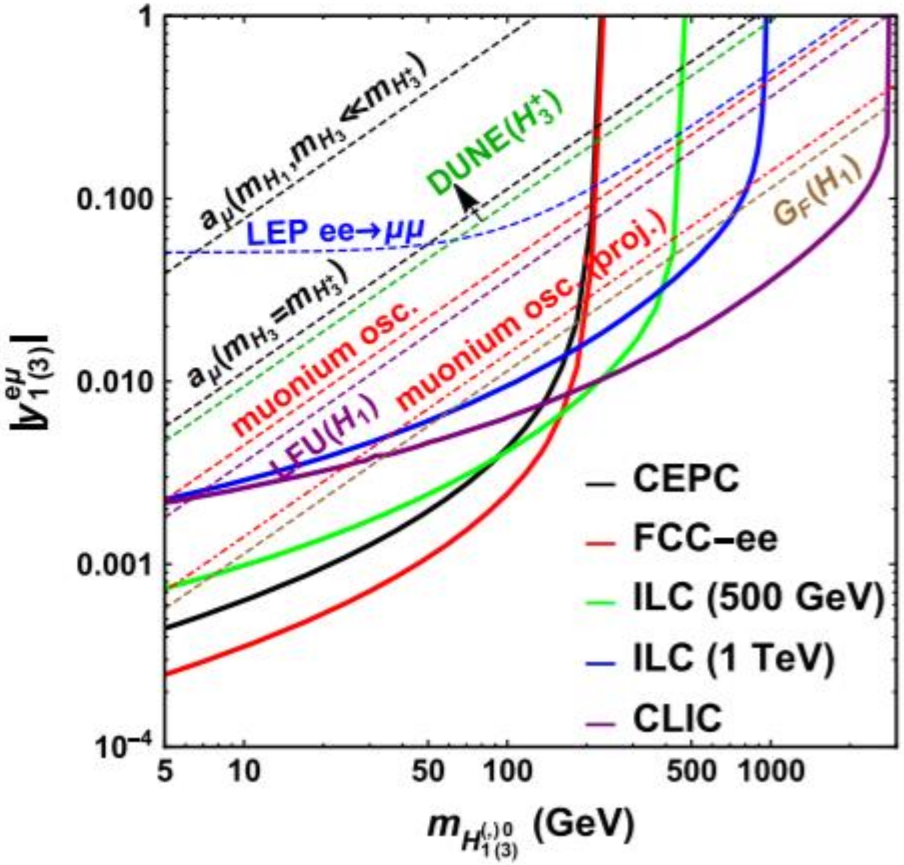
- **Experiments search for cLFV:**
  - Mu2e (Fermilab)
  - COMET (J-PARC)
  - MEG (PSI)
  - Mu3e (PSI)

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

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

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

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

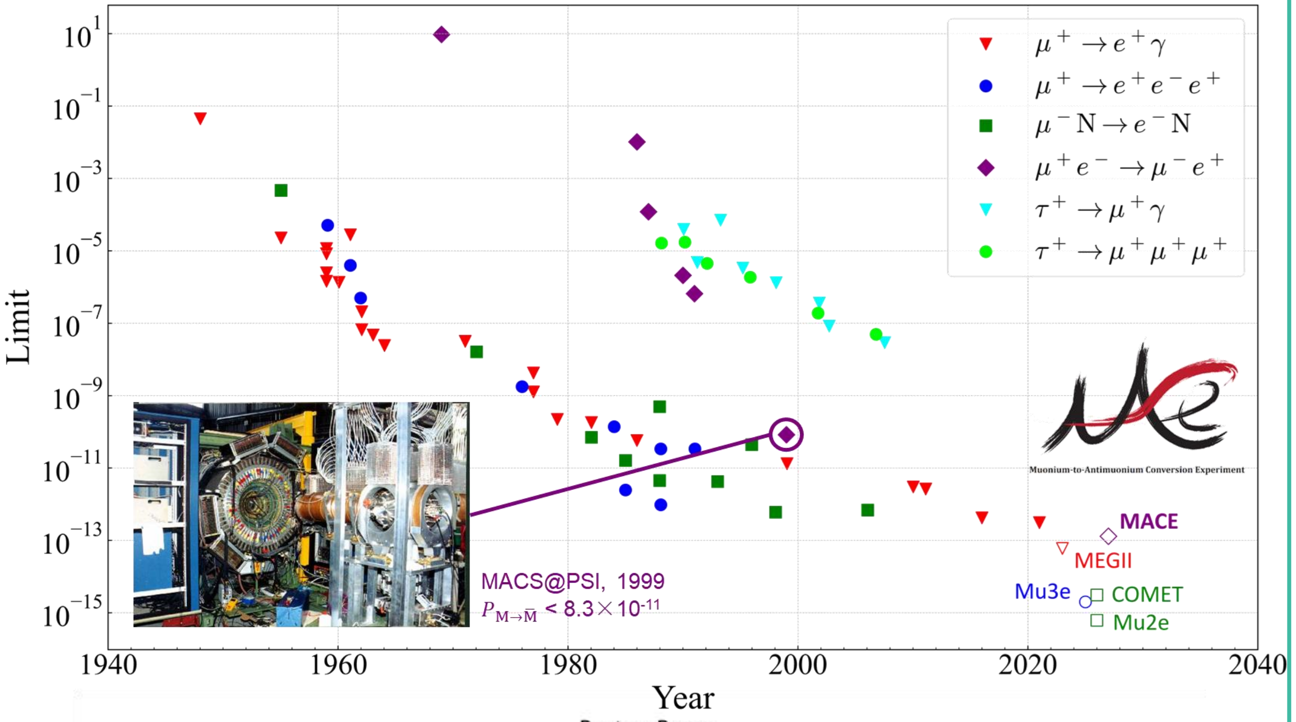


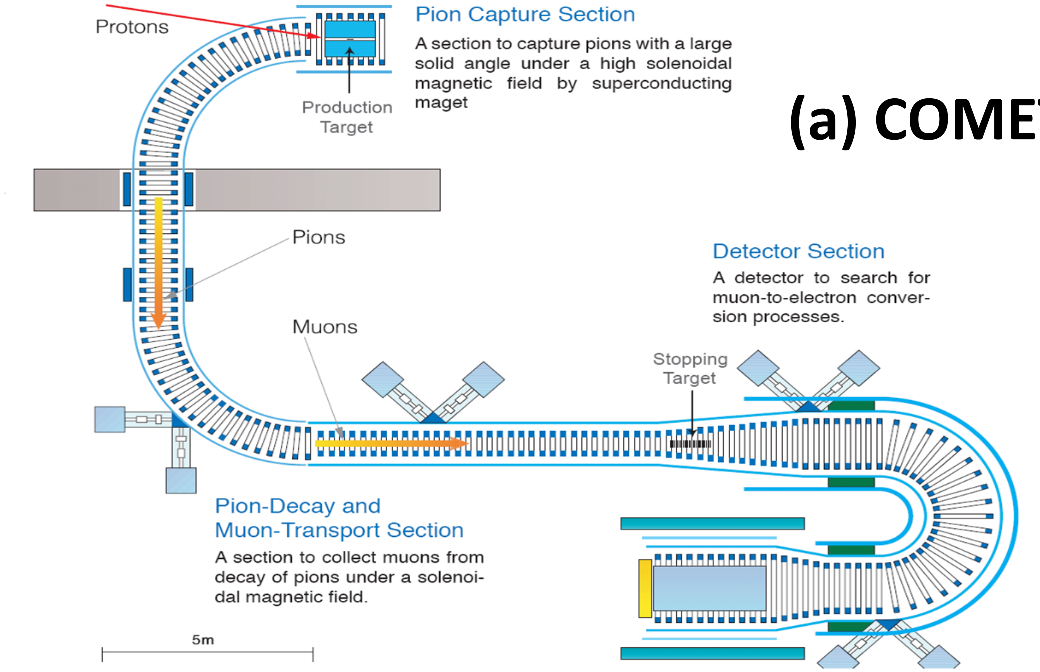
REF: Tong Li, Michael A. Schmidt. Phys.Rev.D 100 (2019) 11, 115007

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

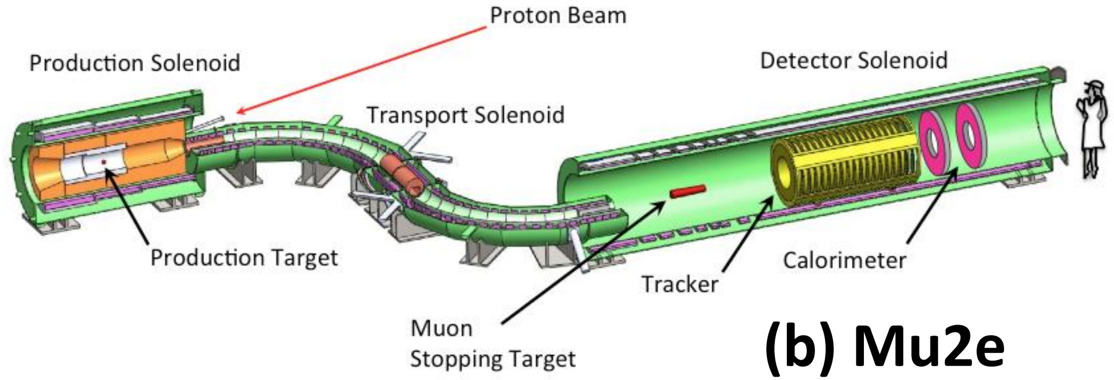
High-intensity/-precision frontier

- **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



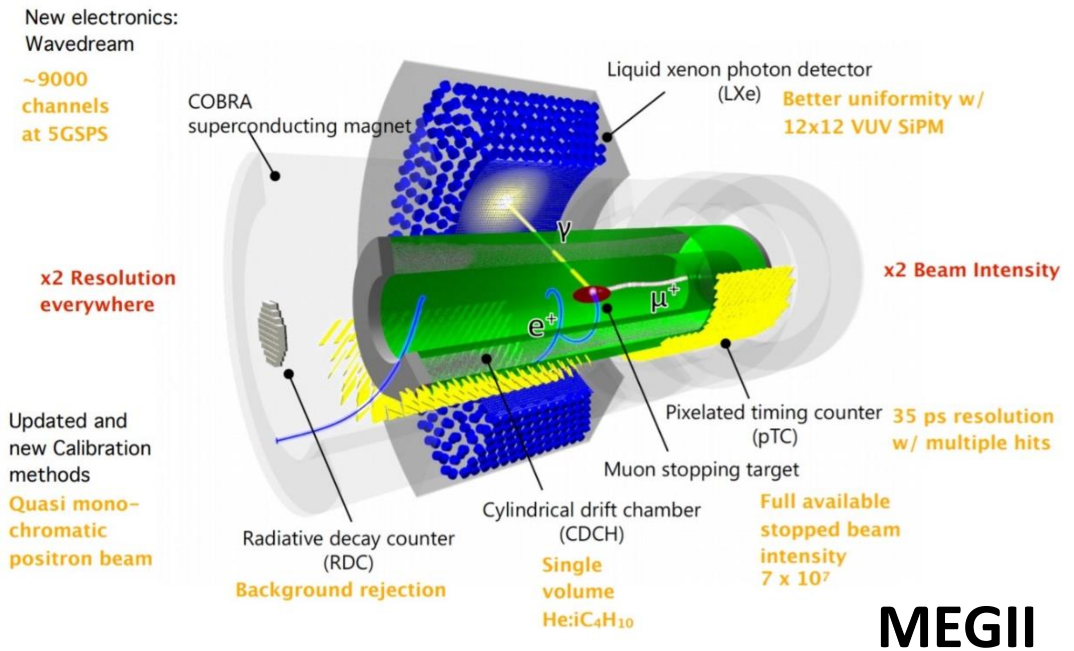
(b) Mu2e

High-intensity/-precision frontier

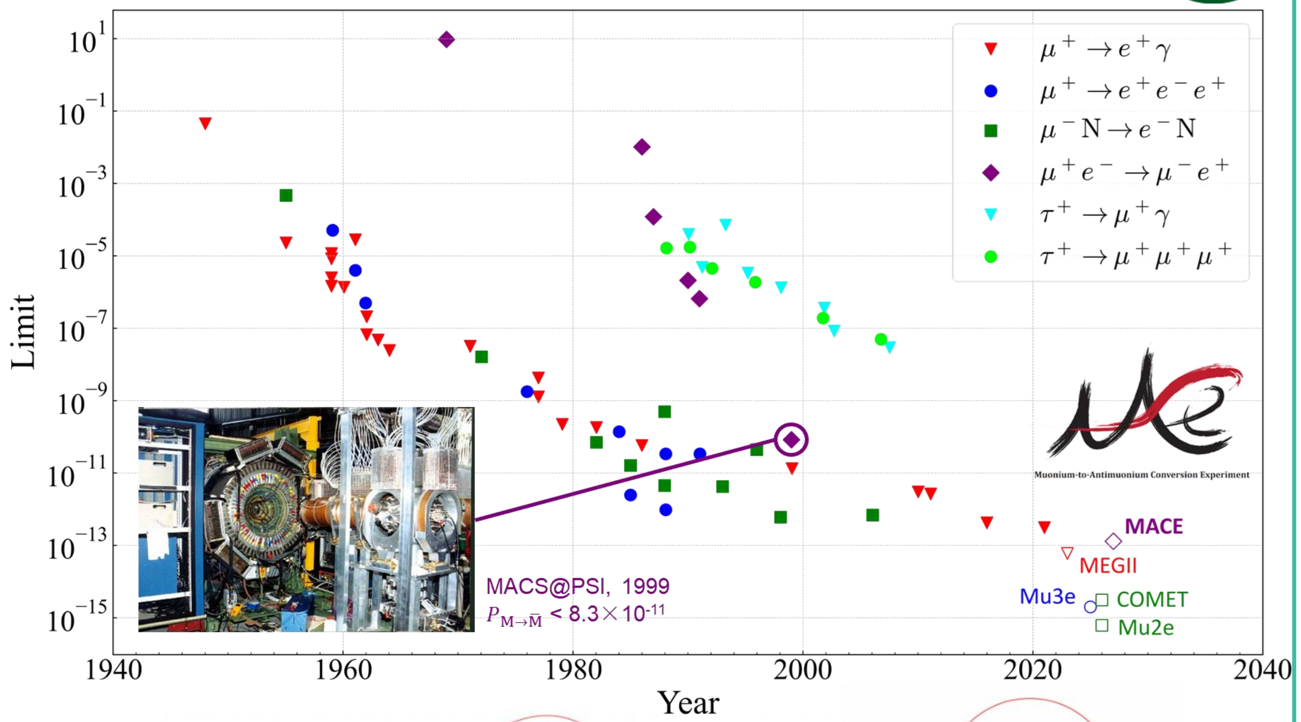
- **Experiments search for cLFV:**
  - Mu2e (Fermi lab)
  - COMET (J-PARC)

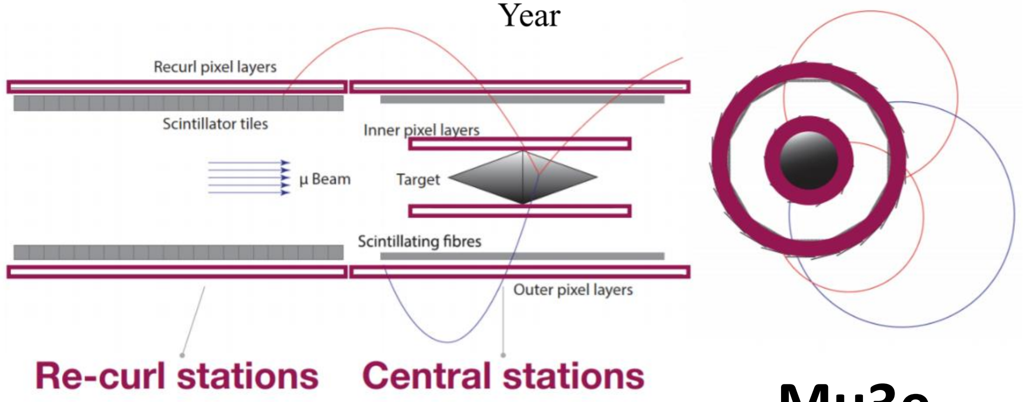
$$\mu^- + Al \rightarrow e^- + Al$$

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



MEGII

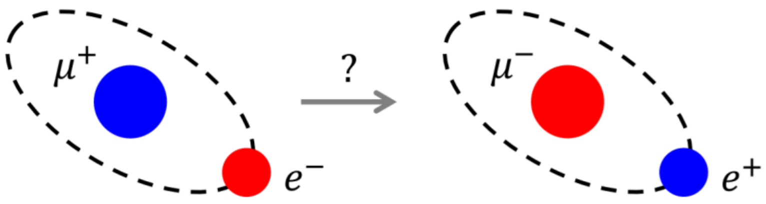




Mu3e

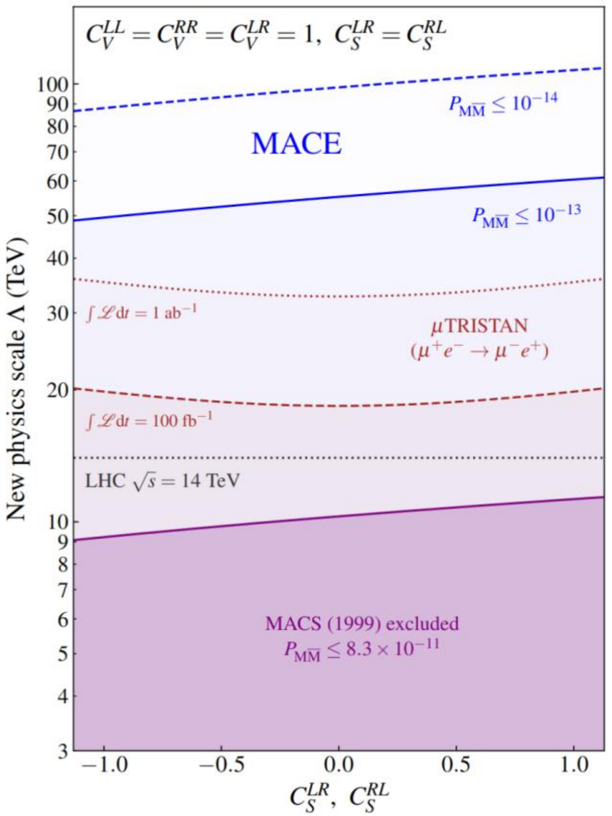
Muonium conversion: a cLFV process

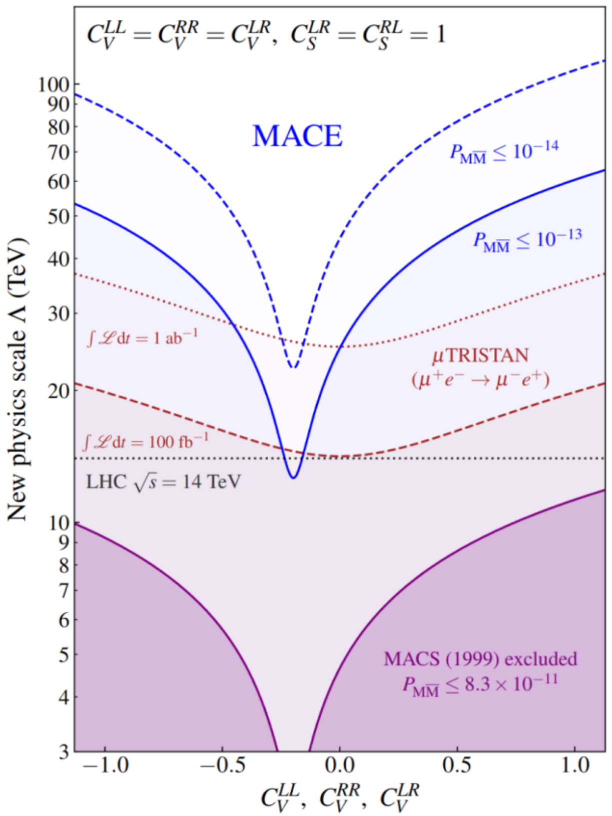
- Muonium ($\mathrm{M} = \mu^+ e^-$): a leptonic hydrogen isotope.
- **M-to-$\overline{\mathrm{M}}$ conversion**: $\mathrm{M} \to \overline{\mathrm{M}}$ $(\mu^+ e^- \to \mu^- e^+)$



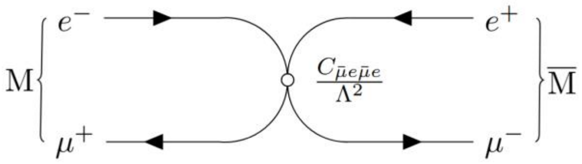
Current bound:
$P_{\mathrm{M}\to\overline{\mathrm{M}}} < 8.3\times10^{-11}$
(in 0.1T field, 90% C.L.)

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





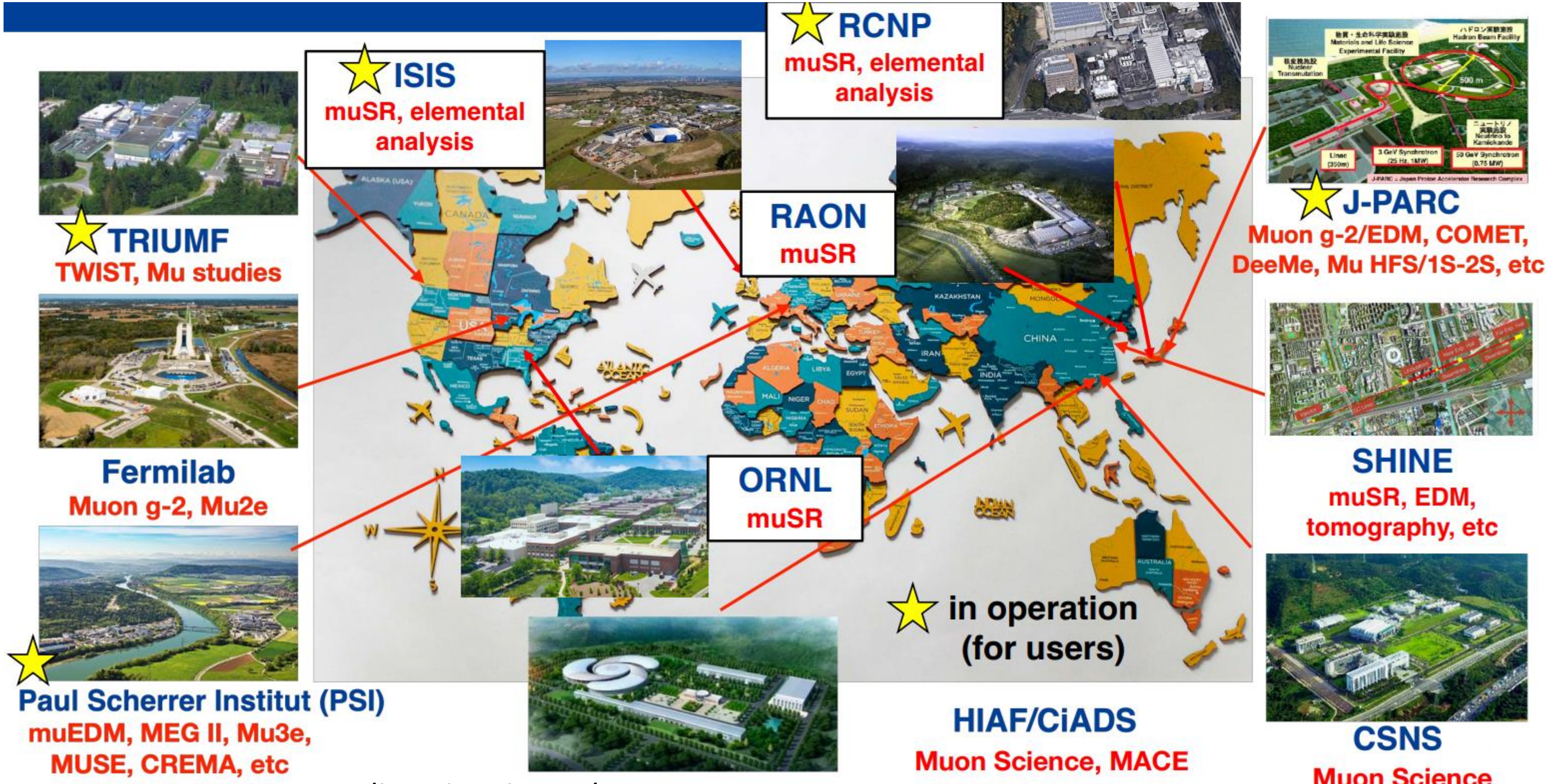
- $\mathrm{M} \to \overline{\mathrm{M}}$: an $\Delta L_\mu = -\Delta L_e = 2$ process.
  - ✓ Different EFT operators from $\Delta L_\mu = -\Delta L_e = 1$ proc. ($\mu \to e\gamma$, $\mu \to eee$, $\mu N \to eN$).
  - ✓ $\Delta L_\mu = -\Delta L_e = 2$ can be possible even if $\Delta L_\mu = -\Delta L_e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

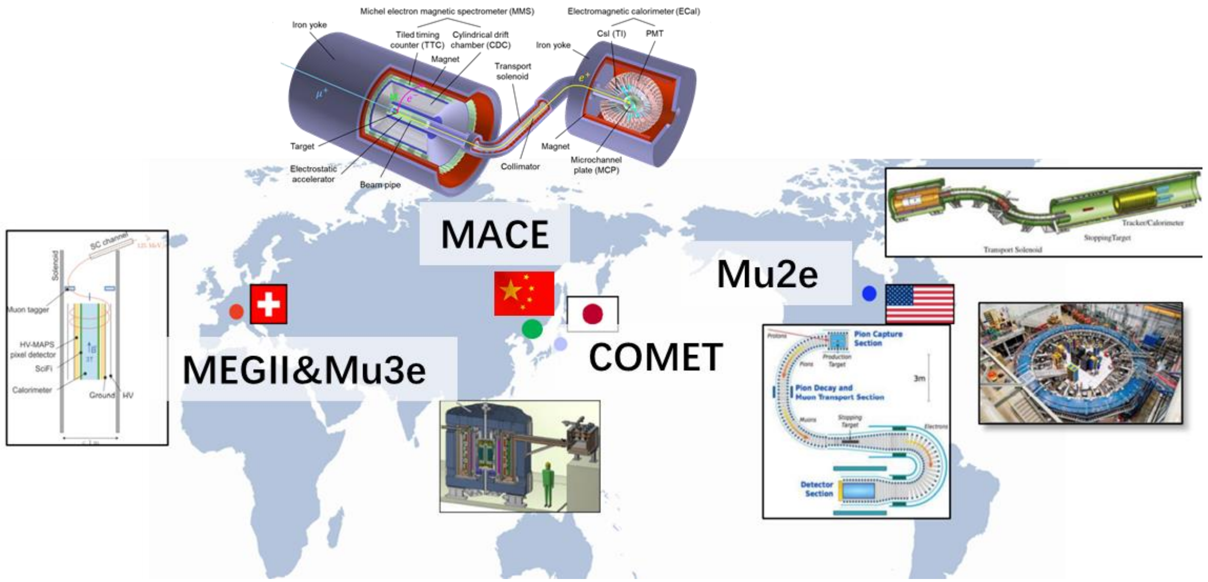


Credits: Kim-Siang Khaw

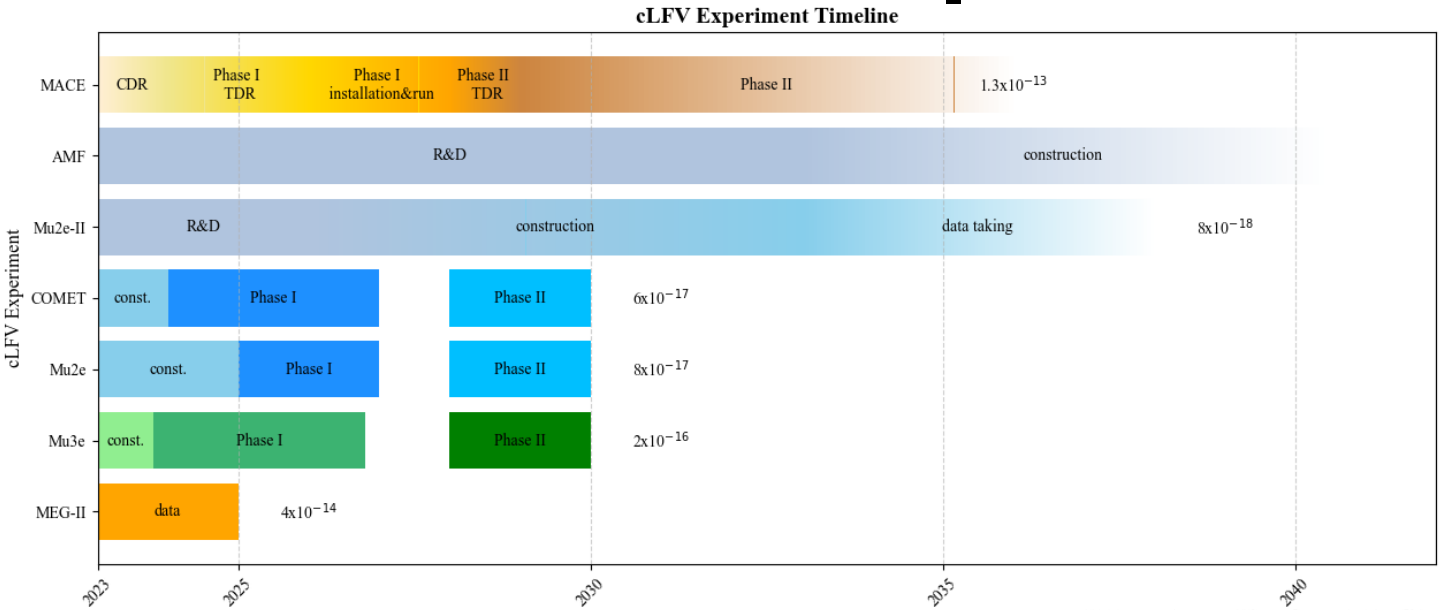
Worldwide cLFV experiments

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)

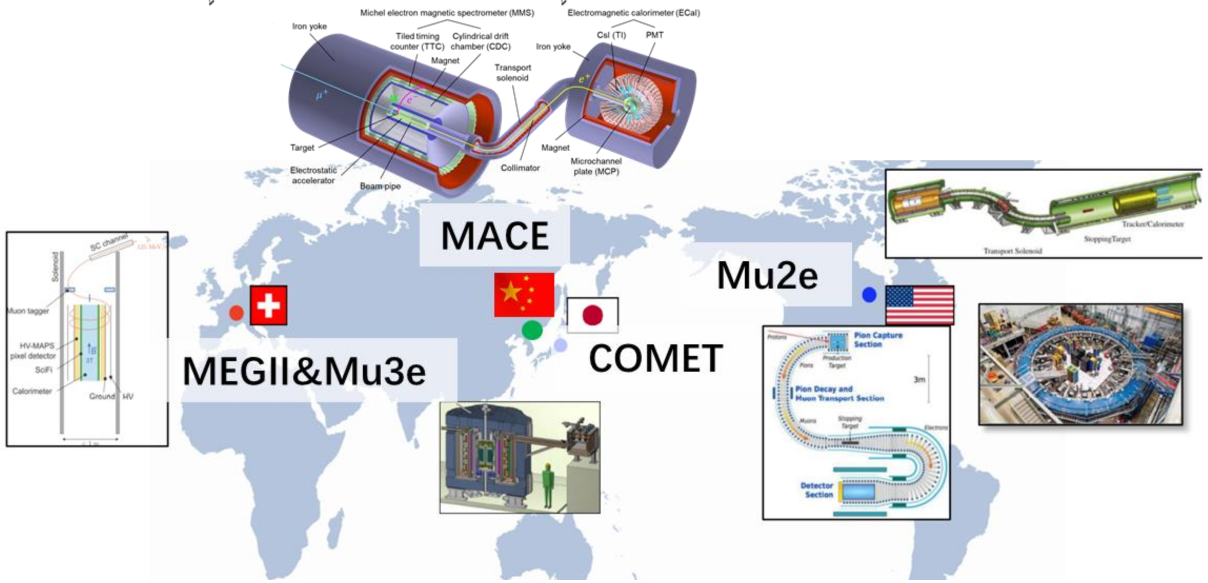
- Muonium conversion is a key cLFV process.
- After PSI set the bound $P < 8.3 \times 10^{-11}$ in 1999, no new experiments were proposed for >20 years.
- With enhanced beam intensity and advances in detector technology, breakthroughs in this field are anticipated.



Worldwide cLFV experiments



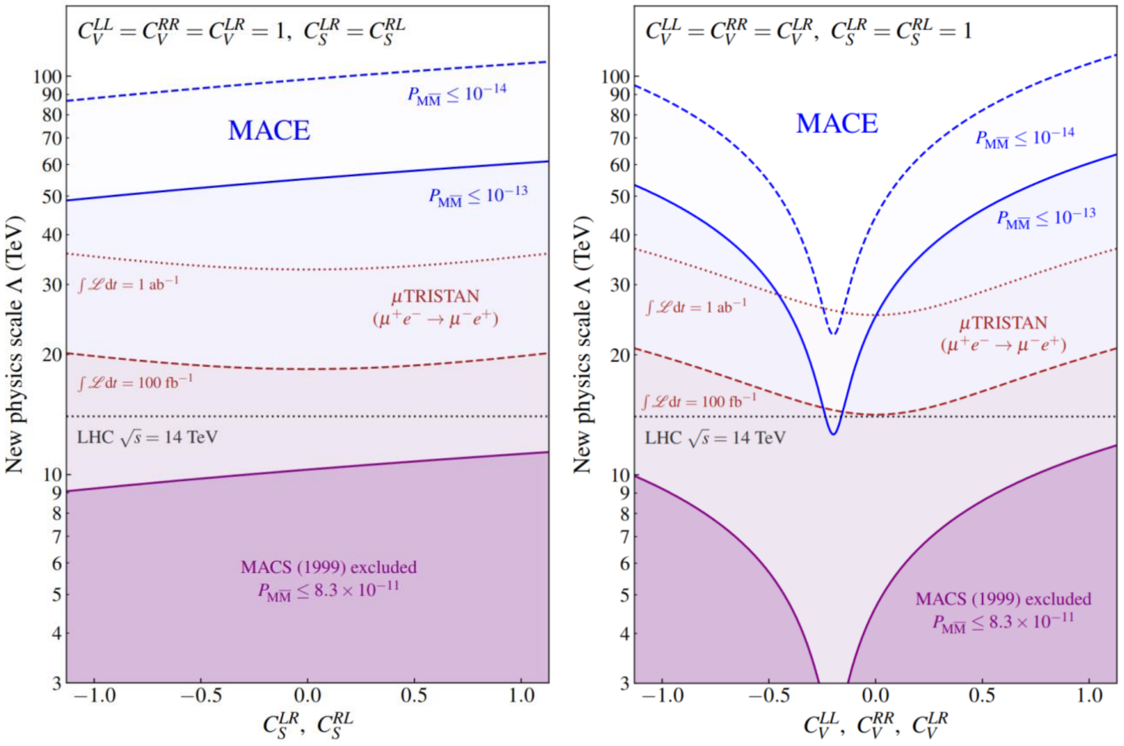
- Muonium conversion is a key cLFV process.
- After PSI set the bound P < 8.3×10^{-11} in 1999, no new experiments were proposed for 20 years.
- With enhanced beam intensity and advances in detector technology, breakthroughs in this field are anticipated.



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!



tangjian5@mail.sysu.edu.cn

Snowmass2021 - Letter of Interest

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

- **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.

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)]*

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.

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

Chengcheng Han,[1] Da Huang,[2,3,4,*] Jian Tang,[1,†] and Yu Zhang[5,6]
[1]School of Physics, Sun Yat-Sen University, Guangzhou 510275, China
[2]National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China
[3]School of Fundamental Physics and Mathematical Sciences, Hangzhou Institute for Advanced Study, University of Chinese Academy of Sciences, Hangzhou 310024, China
[4]International Center for Theoretical Physics Asia-Pacific, Beijing/Hangzhou 10010, China
[5]Institutes of Physical Science and Information Technology, Anhui University, Hefei 230601, China
[6]School of Physics and Materials Science, Anhui University, Hefei 230601, China

PHYSICAL REVIEW D **103,** 055023 (2021)

Snowmass2021 whitepaper

March 23, 2022

arXiv: 2203.11406

Muonium to antimuonium conversion: Contributed paper for Snowmass 21

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,[2,3] Huaxing Peng,[2,3] Alexey A. Petrov (Coordindator),[4] Ying-Peng Song,[2] Jian Tang (Coordinator),[1] Jing-Yu Tang,[2] Nikolaos Vassilopoulos,[2] Sampsa Vihonen,[1] Chen Wu,[5] Tian-Yu Xing,[2] Yu Xu,[1] Ye Yuan,[2] Yao Zhang,[2] Guang Zhao,[2] Shi-Han Zhao,[1] and Luping Zhou[2]

[1] *School of Physics, Sun Yat-sen University, Guangzhou 510275, China*
[2] *Institute of High Energy Physics, Beijing 100049, China*
[3] *University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China*
[4] *Department of Physics and Astronomy Wayne State University, Detroit, Michigan 48201, USA*
[5] *Research Center of Nuclear Physics (RCNP), Osaka University, Japan*

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 summarized.

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)
- $\Delta L=2$ 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

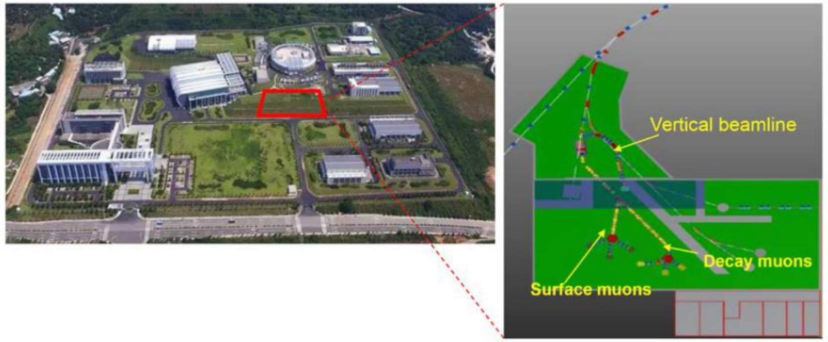
Bertrand Echenard
Caltech

NuFact 2021
Cagliari - September 2021

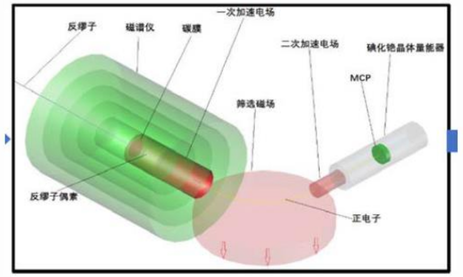
MACE at EMuS

Jian Tang
(Snowmass 2021 RPP meeting)

EMuS – new muon facility in China

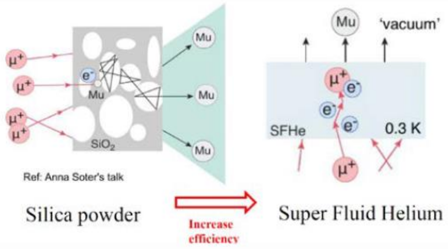


MACE concept



	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

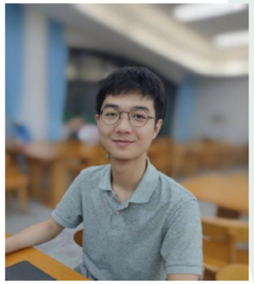


On-going physics studies and detector R&D

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]

[1] *School of physics, Sun Yat-sen University, China*

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

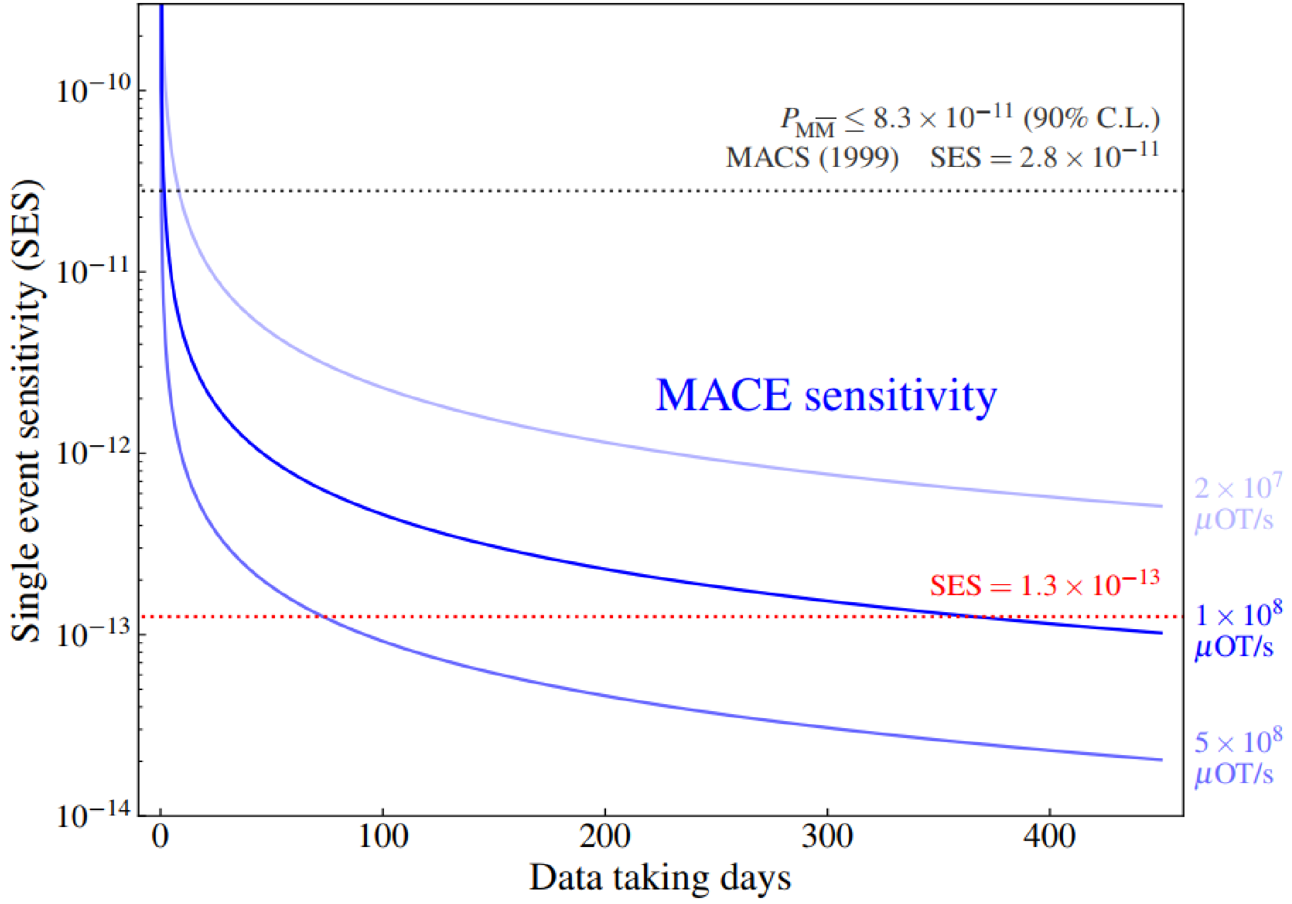
[3] *Research Center of Nuclear Physics, Osaka University, Japan*

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 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.

MACE conceptual design report

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

CDR review - 8/26

<https://arxiv.org/abs/2410.18817>

arXiv:2410.18817v1 [hep-ex] 24 Oct 2024

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

Ai-Yu Bai,[1] Hanjie Cai,[2,3] Chang-Lin Chen,[4] Siyuan Chen,[1] Xurong Chen,[2,3,5] Yu Chen,[1] Weibin Cheng,[6] Ling-Yun Dai,[4,7] Rui-Rui Fan,[8,9,10] Li Gong,[6] Zihao Guo,[11] Yuan He,[2,3] Zhilong Hou,[8] Yinyuan Huang,[1] Huan Jia,[2,3] Hao Jiang,[1] Han-Tao Jing,[8] Xiaoshen Kang,[6] Hai-Bo Li,[8,3] Jincheng Li,[2,3] Yang Li,[8] Shulin Liu,[8,3,12] Guihao Lu,[1] Han Miao,[8,3] Yunsong Ning,[1] Jianwei Niu,[2,13] Huaxing Peng,[8,3,12] Alexey A. Petrov,[14] Yuanshuai Qin,[2] Mingchen Sun,[1] Jian Tang,[1,*] Jing-Yu Tang,[15] Ye Tian,[2] Rong Wang,[2,3] Xiaodong Wang,[16,17] Zhichao Wang,[1] Chen Wu,[8,9] Tian-Yu Xing,[18,19] Weizhi Xiong,[20] Yu Xu,[21] Baojun Yan,[8,12] De-Liang Yao,[4,7] Tao Yu,[1] Ye Yuan,[8,3] Yi Yuan,[1] Yao Zhang,[8] Yongchao Zhang,[11] Zhilv Zhang,[2] Guang Zhao,[8] and Shihan Zhao[1]

[1]*School of Physics, Sun Yat-sen University, Guangzhou 510275, China*
[2]*Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*
[3]*University of Chinese Academy of Sciences, Beijing 100049, China*
[4]*School of Physics and Electronics, Hunan University, Changsha 410082, China*
[5]*Southern Center for Nuclear Science Theory (SCNT), Institute of Modern Physics, Chinese Academy of Sciences, Huizhou 516000, Guangdong Province, China*
[6]*School of Physics, Liaoning University, Shenyang 110036, China*
[7]*Hunan Provincial Key Laboratory of High-Energy Scale Physics and Applications, Hunan University, Changsha 410082, China*
[8]*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China*
[9]*China Spallation Neutron Source, Dongguan 523803, China*
[10]*State Key Laboratory of Particle Detection and Electronics, Beijing, 100049, China*
[11]*School of Physics, Southeast University, Nanjing 211189, China*
[12]*State Key Laboratory of Particle Detection and Electronics, Beijing 100049, China*
University of South Carolina, Columbia, South Carolina 29208, USA
[15]*School of Nuclear Science and Technology, University of Science and Technology of China, Hefei 230026, China*
[16]*School of Nuclear Science and Technology, University of South China, Hengyang 421001, China*
[17]*Key Laboratory of Advanced Nuclear Energy Design and Safety (MOE), University of South China, Hengyang 421001, China*
[18]*INFN Sezione di Milano, Milano 20133, Italy*
[19]*Universita degli Studi di Milano, Milano 20122, Italy*
[20]*Key Laboratory of Particle Physics and Particle Irradiation (MOE), Institute of Frontier and Interdisciplinary Science, Shandong University, Qingdao 266237, China*
[21]*Advanced energy science and technology Guangdong laboratory, Huizhou 516007, China*

(Dated: October 25, 2024)

CONTENTS

I. Introduction 6

II. Overview of theoretical framework 7
A. Phenomenology of muonium conversion 8
B. Muonium conversion and new physics beyond the Standard Model 10
C. Muonium rare decays 18

III. M-to-$\overline{\text{M}}$ conversion signals and backgrounds 22
A. Signal event signature 23
B. Backgrounds 24

IV. Beamline 30
A. Accelerator and proton beam 30
B. Muon production and transport 32
1. Muon production target 32
2. Muon beamline conceptual design 33

V. Muonium production target 36
A. Introduction 36
B. Design and optimization of the single-layer target 38
C. A multi-layer target design 42

VI. Overview of detector system 45

VII. Michel electron magnetic spectrometer 47
A. Magnetic field and magnet 48
B. Cylindrical drift chamber 49
1. Objectives 49
2. Wire configurations 50
C. Tiled timing counter 54
1. Objectives 55
2. Conceptual design 58
D. Performance 59

VIII. Positron transport system 62
A. Magnet and transport solenoid 63
B. Electrostatic accelerator 66
C. Performance 68

IX. Positron detection system 72
A. Microchannel plate 72
B. Electromagnetic calorimeter 77
1. Overview 77
2. Conceptual design 78
3. Simulation 80
C. Performance 82

X. Offline software 83
A. Introduction 83
B. Framework 84
C. Parallel computing 85
D. Event data model 87
E. Detector geometry and field 88
F. Continuous integration 89
G. Event display 89

XI. Background estimation 93
A. Physical backgrounds 93
B. Accidental backgrounds 93

XII. Sensitivity 94

XIII. Phase-I Experimental Concept 95
A. Overview 95
B. Muon beam 97
C. Detector system design 98
1. Electromagnetic calorimeter 98
2. Tracker 98
D. Sensitivity estimation 101

XIV. Summary 102

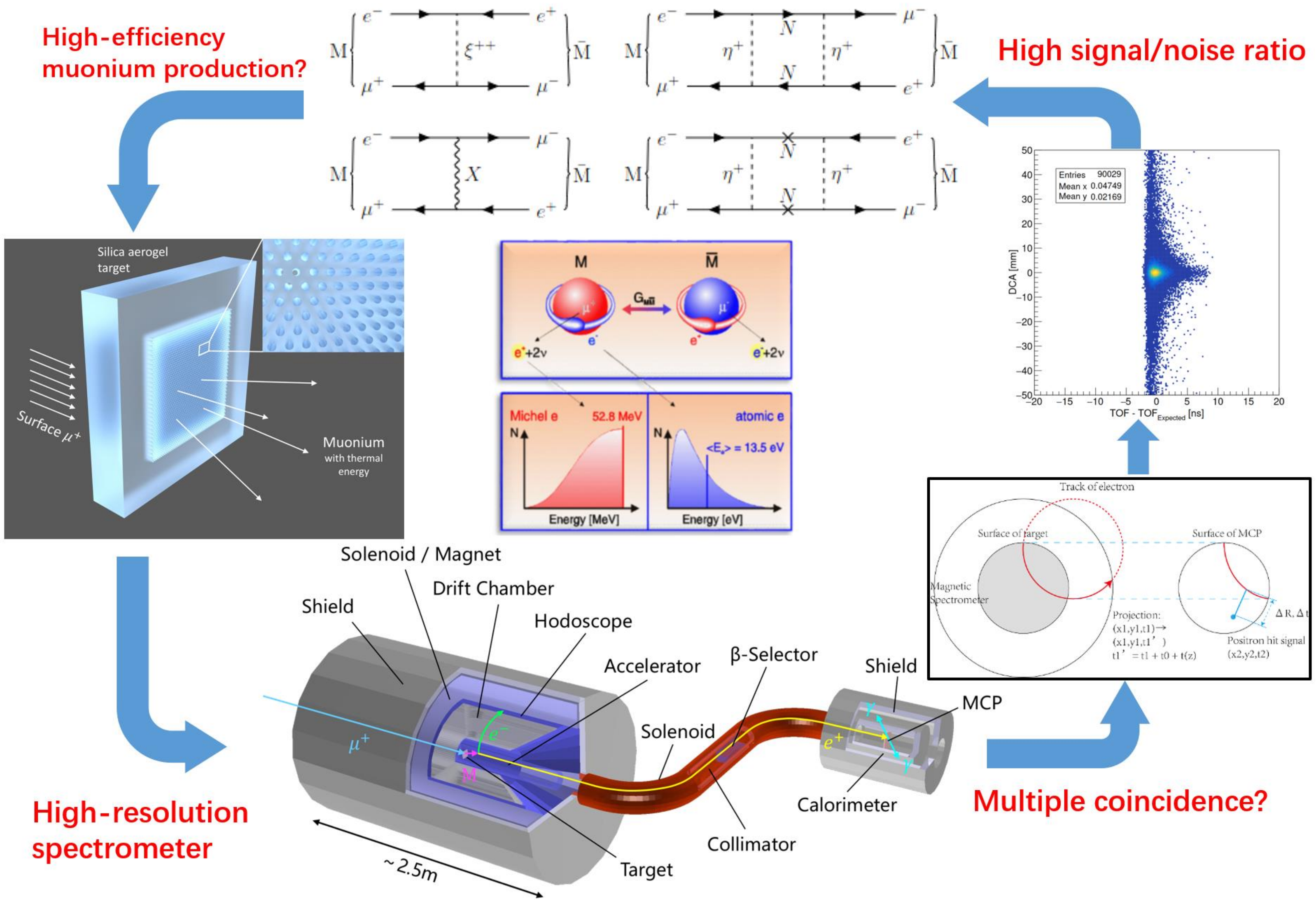
Table of contents

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

tangjian5@mail.sysu.edu.cn

Challenges and solutions for MACE

Muonium-to-Antimuonium Conversion Experiment



Muonium production in silica aerogel

μ^+ (~1MeV) scattering

↓

Electron capture (~1keV)

↓

Muonium (~100eV)
Epithermal scattering

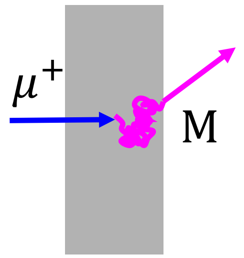
↓

Random walk (room temp.)

↓

Emission to vacuum

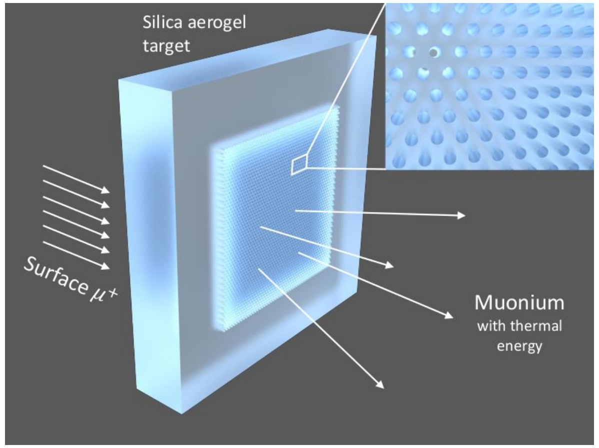
MC simulation for muonium transport has been developed under the MACE offline software framework.

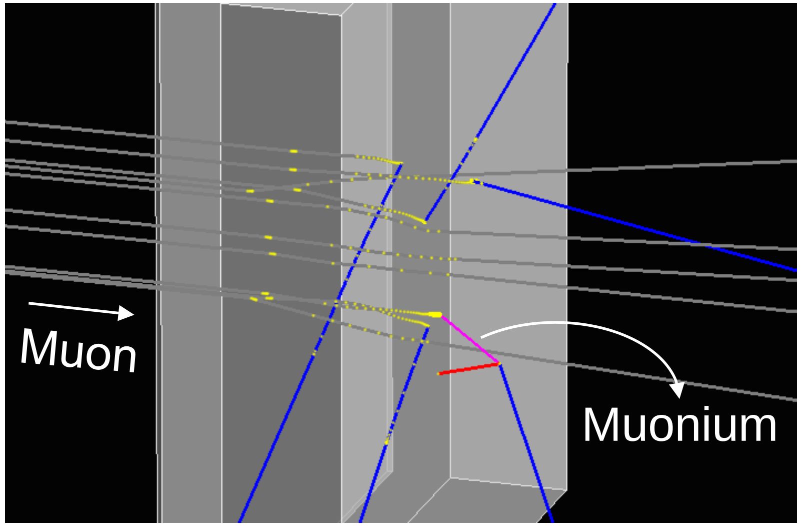


① Geant4 low-energy EM process.

② Geant4 AtRest process, modeled phenomenologically.

③ Random walk approach to thermal muonium tracking.



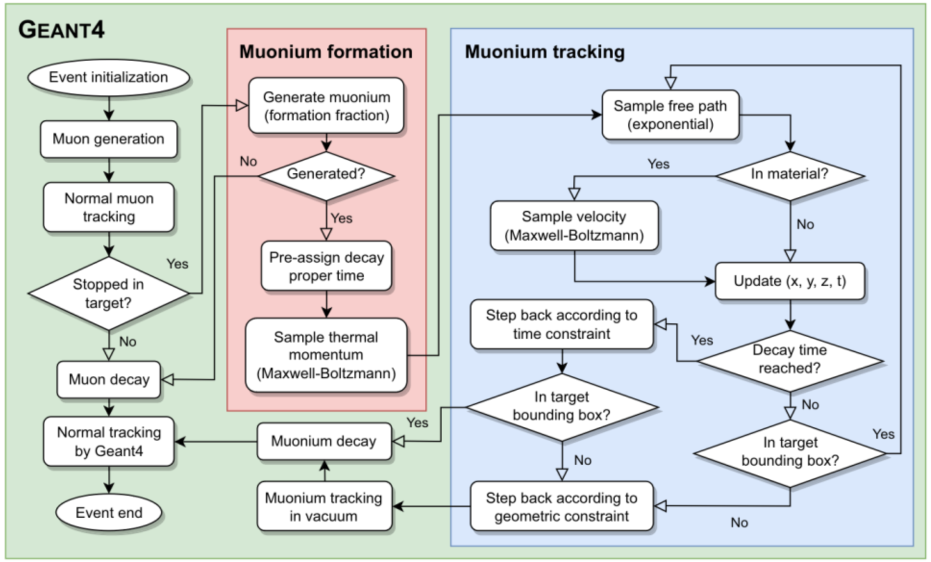


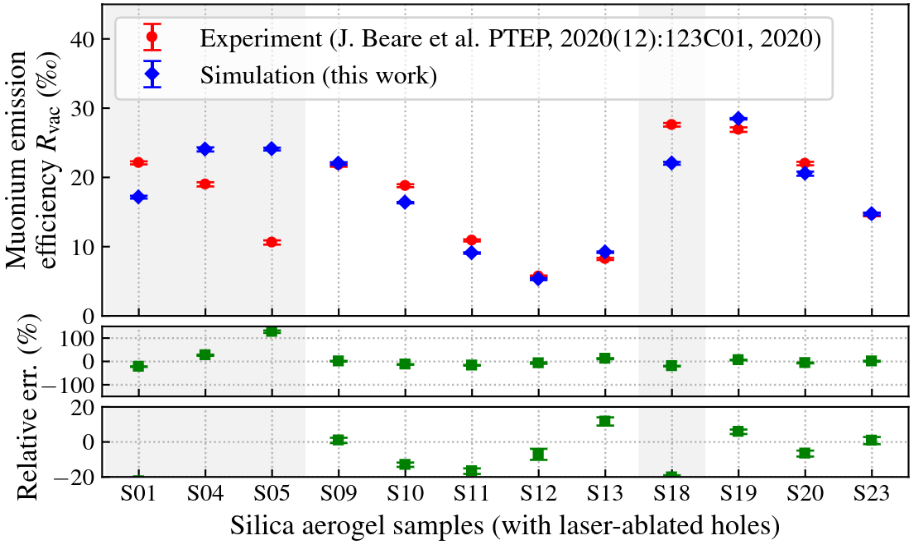
tangjian5@mail.sysu.edu.cn

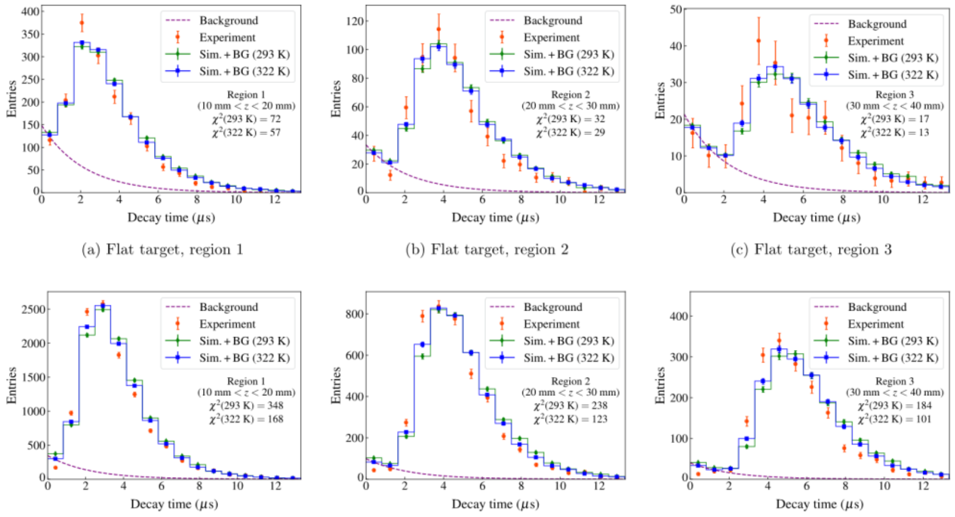
Optimization of muonium yield in perforated silica aerogel

- 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

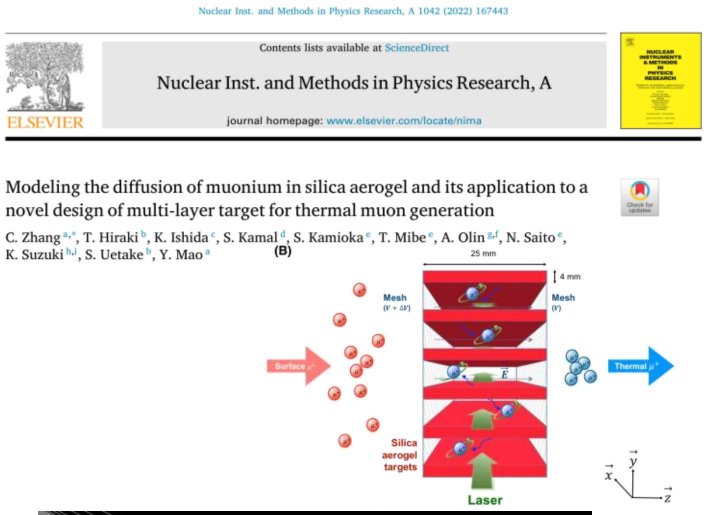
(d) Perforated target, region 1 (e) Perforated target, region 2 (f) Perforated target, region 3

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

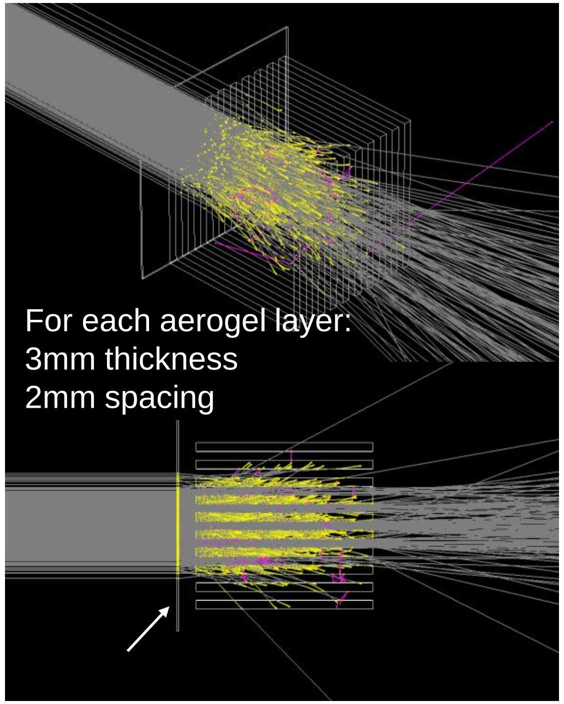
Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

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

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

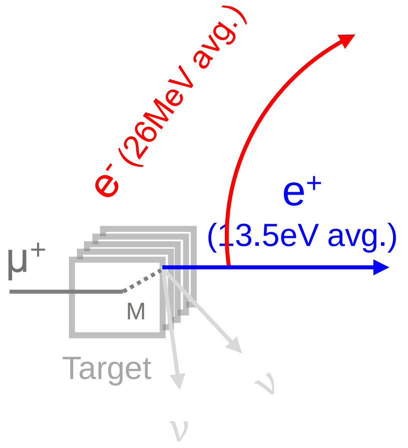
C. Zhang[a,*], T. Hiraki[b], K. Ishida[c], S. Kamal[d], S. Kamioka[e], T. Mibe[e], A. Olin[g,f], N. Saito[e], K. Suzuki[h,i], S. Uetake[b], Y. Mao[a]



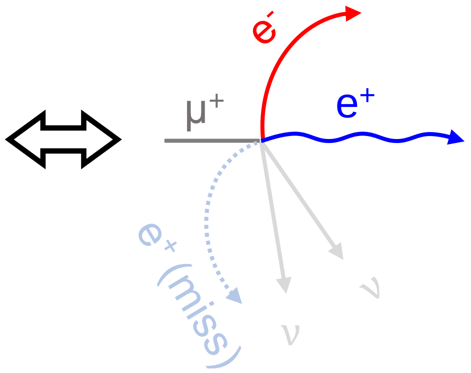
Shihan Zhao and Jian Tang, Optimization of muonium yield in perforated silica aerogel, **Phys. Rev. D** 109, 072012

MACE signal and background

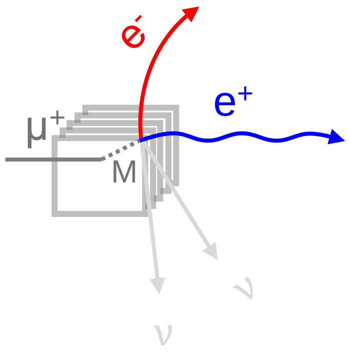
Signal:
fast e^- + slow e^+



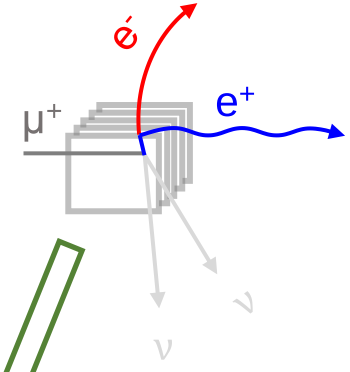
1. Internal conv. (IC) decay
- ☐ $\mu^+ \to e^+ e^- e^+ \bar{\nu}_\mu \nu_e$



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



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



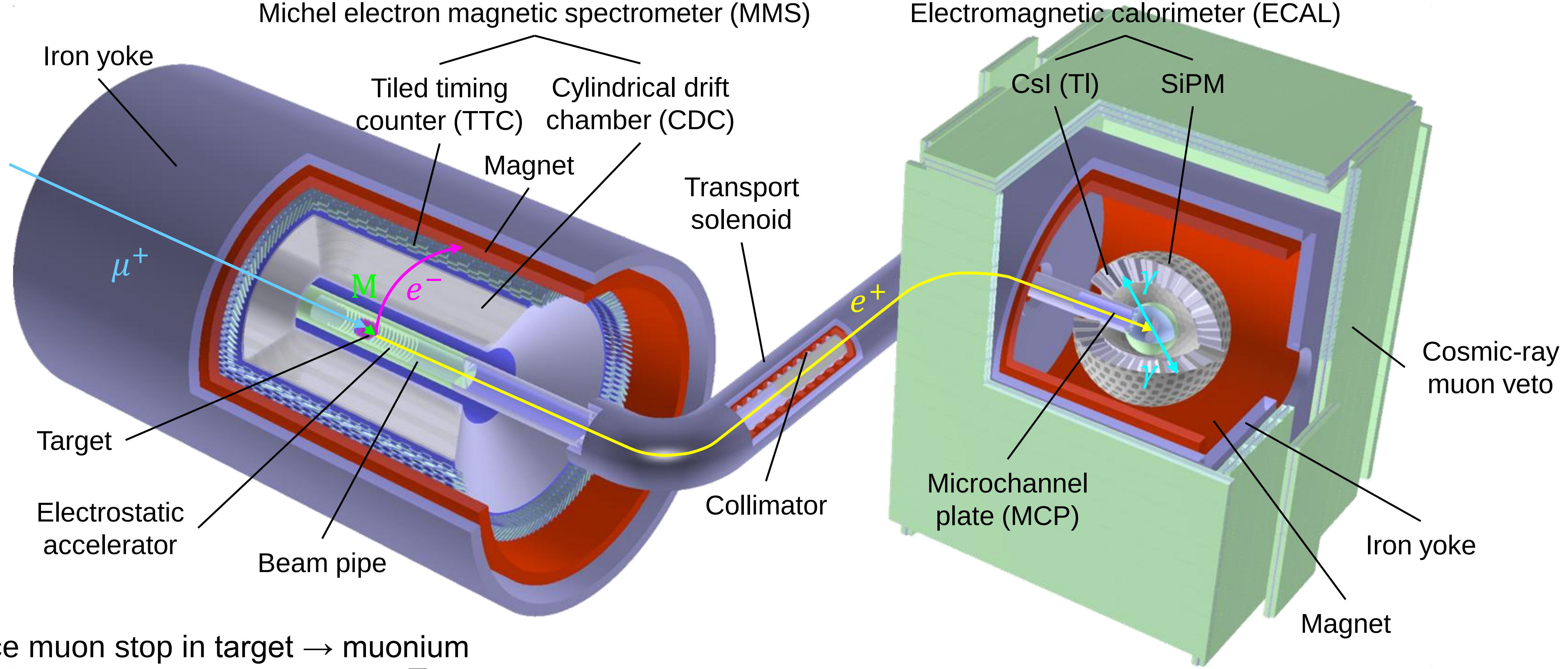
- **Coincidence of a fast e^- and a slow e^+**
- **Common vertex (by selecting e+/e- track DCA)**
  - ✓ Select p_{xy} of e+
  - ✓ Reject accidental e-
- **Time coincidence (by selecting e+ TOF)**
  - ✓ Select p_z of e+
  - ✓ Reject e+ from IC decay or Bhabha scattering
- **Charge identification (by e-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

MACE baseline design v1



I. Surface muon stop in target → muonium

II. M diffuse into vacuum & convert to $\bar{\mathrm{M}}$

III. Decay in a vacuum: $\bar{\mathrm{M}} \to e^+ e^- \nu_\mu \bar{\nu}_e$

IV. CDC detects Michel e^- track

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

VI. MCP detects e^+ position

VII. e^+ annihilates on MCP

VIII. ECAL detects 2 back-to-back annihilation γ

Triple coincidence:

- **MMS + MCP + ECal**

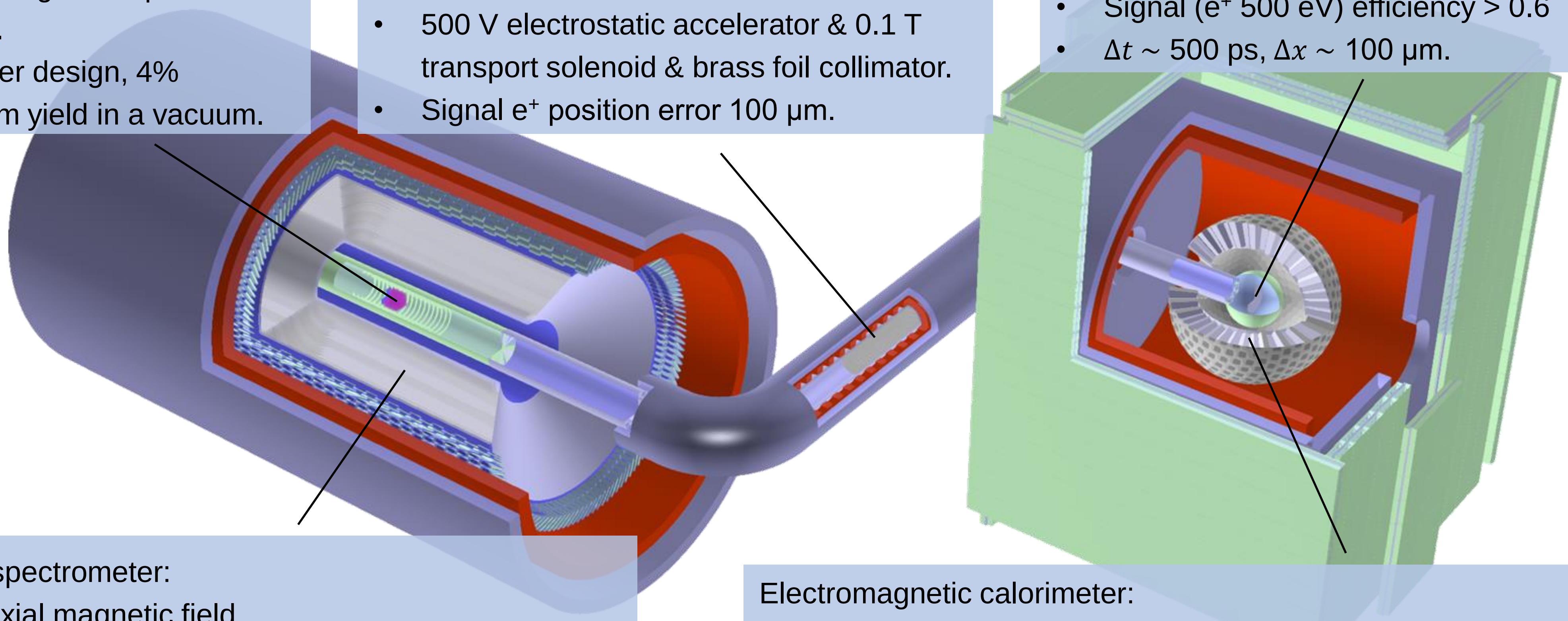
Michel e^- (MMS) Atomic e^+ (MCP + ECal)

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.

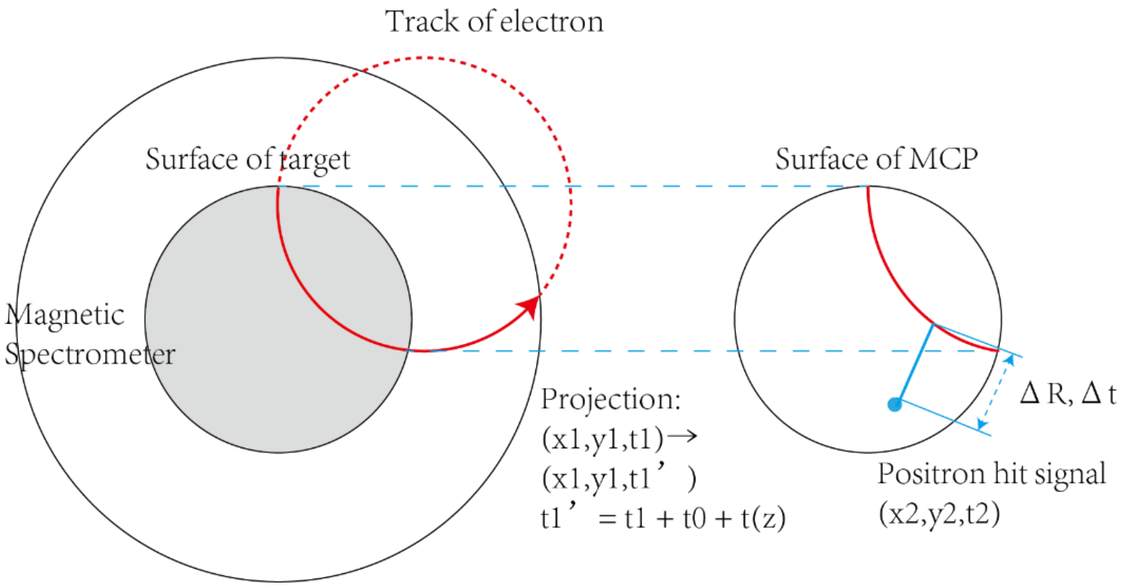
Microchannel plate (MCP) specifications:
- Signal (e^+ 500 eV) efficiency > 0.6
- $\Delta t \sim$ 500 ps, $\Delta x \sim$ 100 μm.

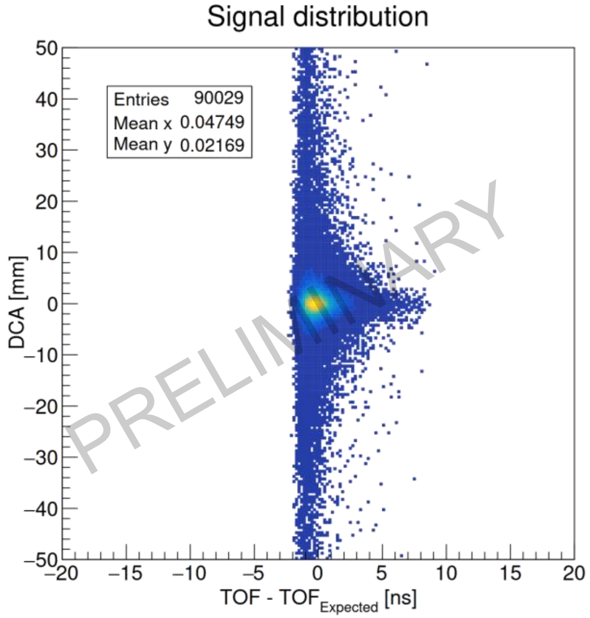


Magnetic spectrometer:
- 0.1 T axial magnetic field.
- CDC: He(C_4H_{10}) gas, 21 layers, 3540 cells. 89% geometry acceptance, $\Delta p \approx$ 500 keV.
- TTC: 5124 fast scintillators with SiPM readout, slant 46 deg, $\Delta t \sim$ 100 ps.

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

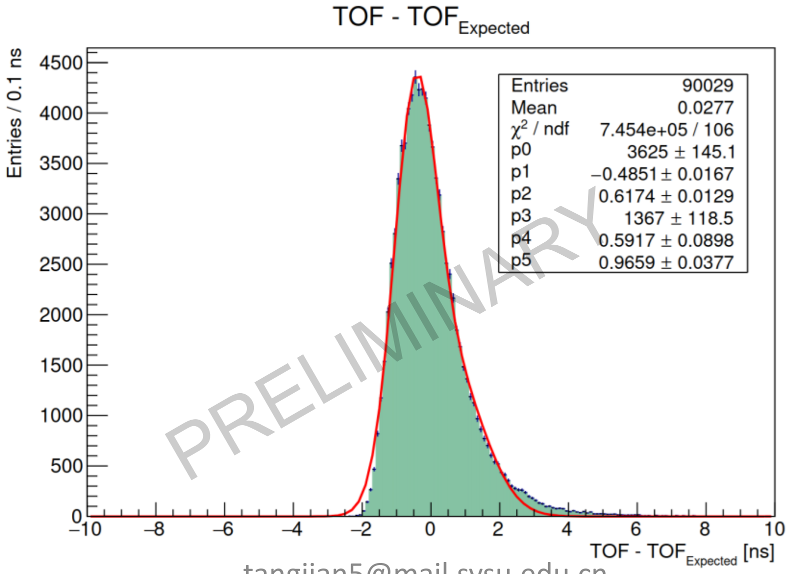


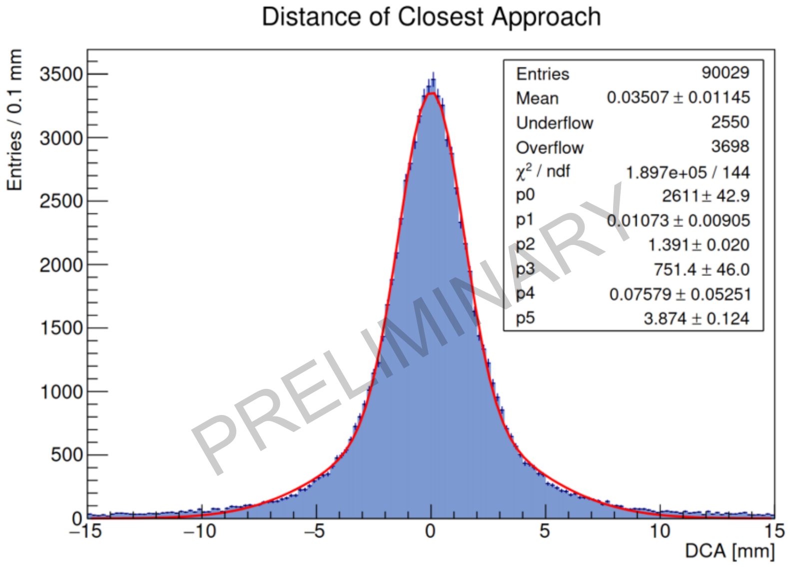


- Elliptical 3σ signal region:

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

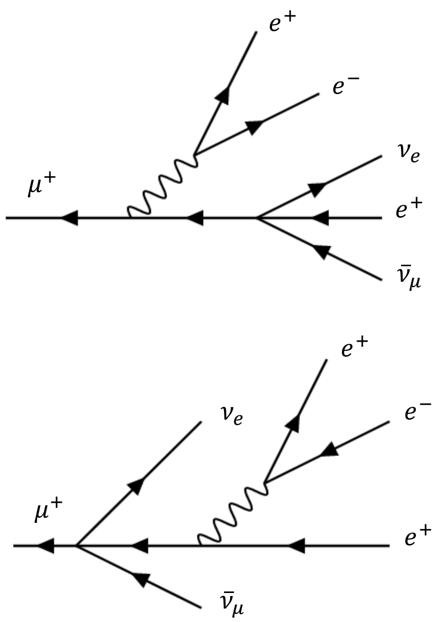
- $\varepsilon_{\text{signal region cut}} = 0.987$

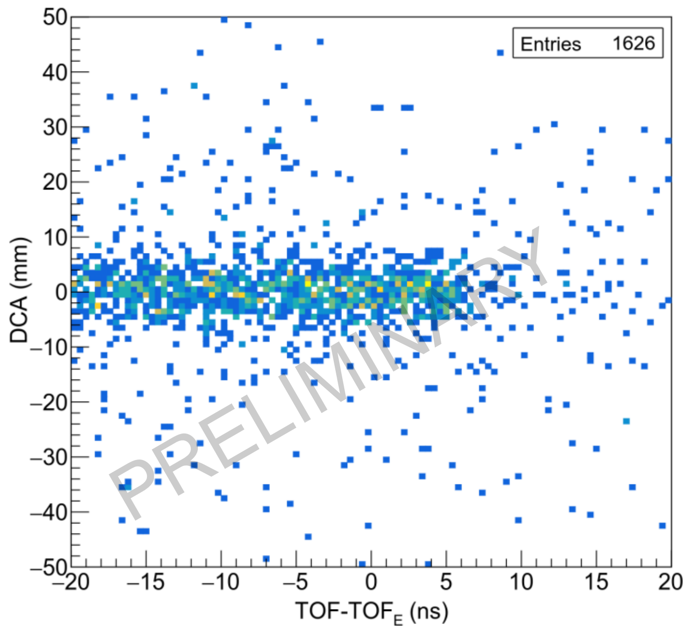




tangjian5@mail.sysu.edu.cn

Simulation: muon internal conversion decay

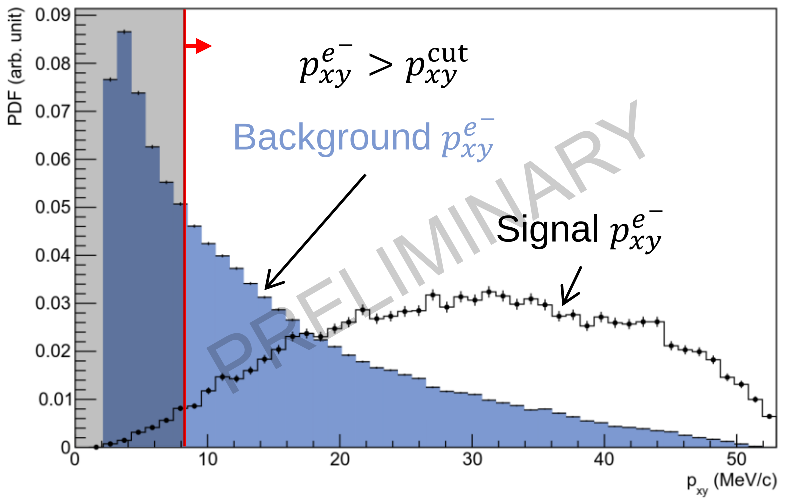




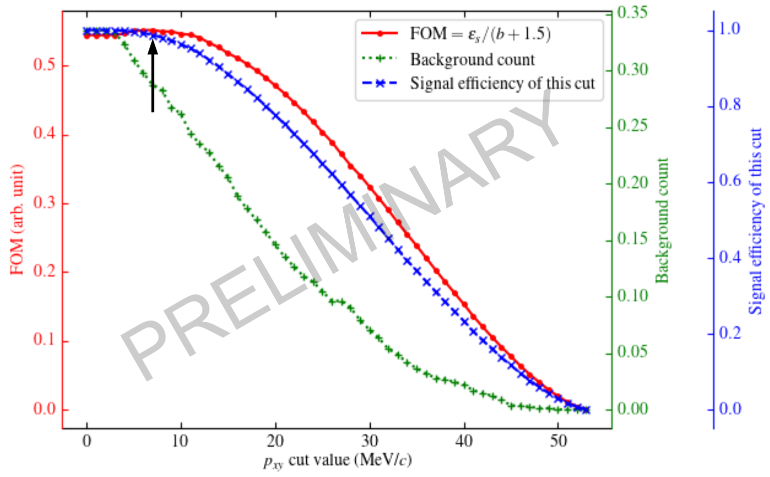
$\mu^+ \to e^+ e^- e^+ \bar{\nu}_\mu \nu_e$ simulation:

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

(in 10^8 μ/s × 365 d)



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

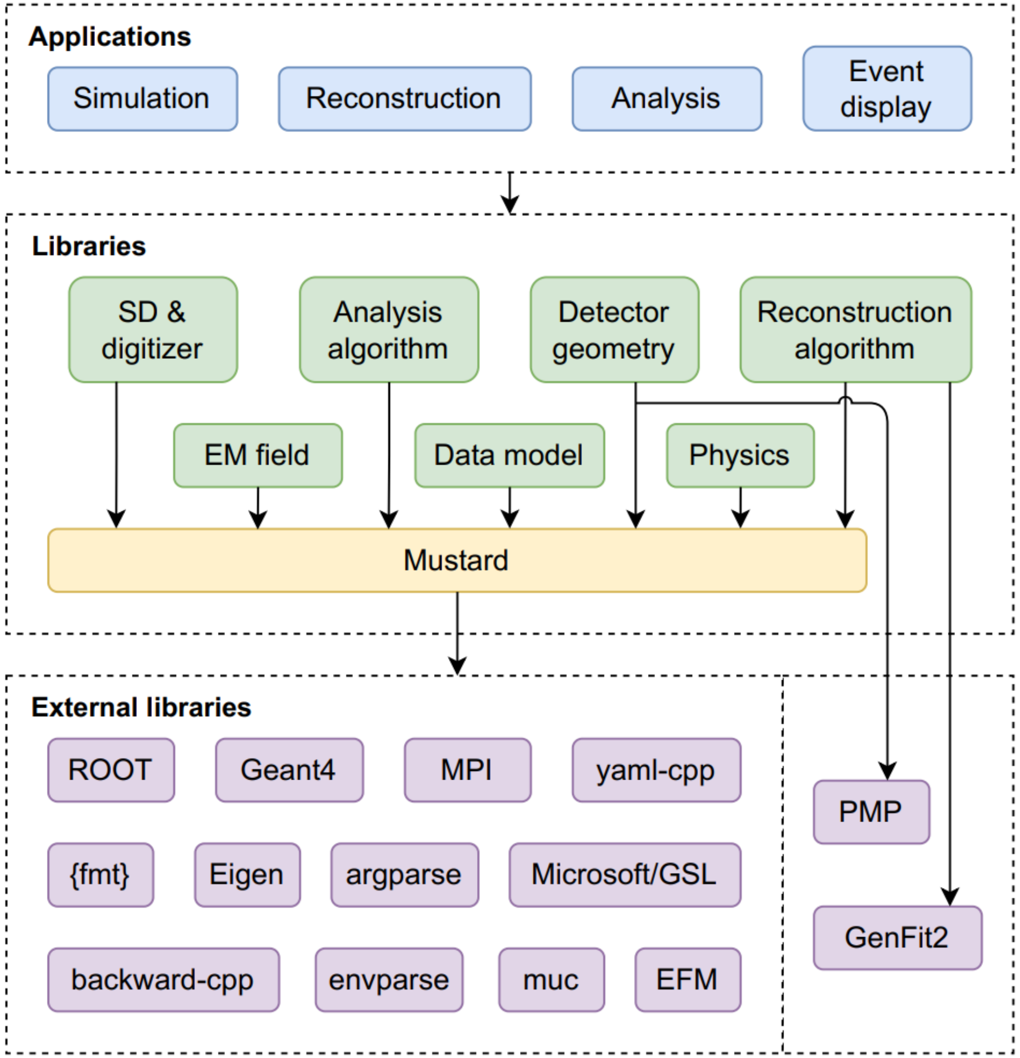


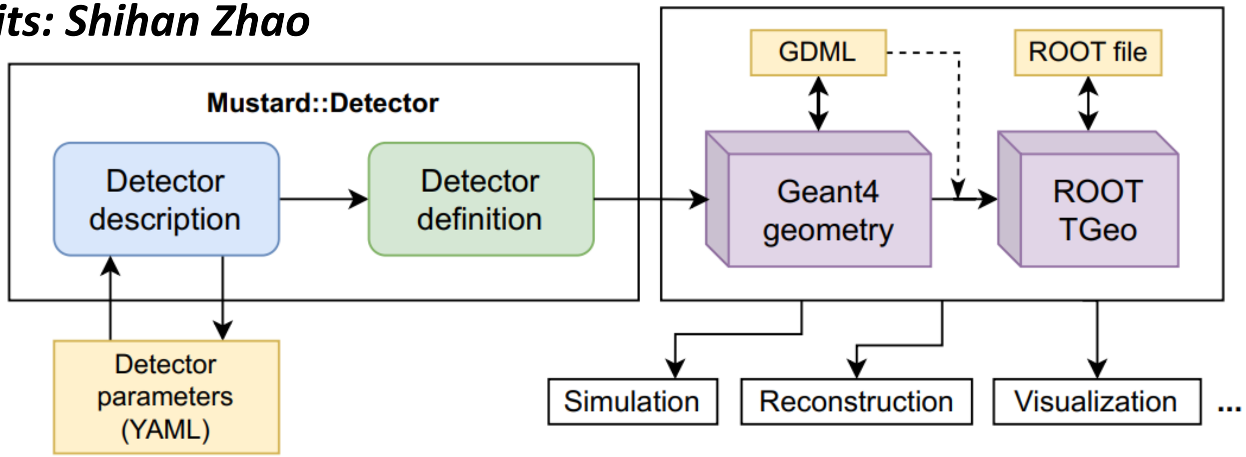
tangjian5@mail.sysu.edu.cn

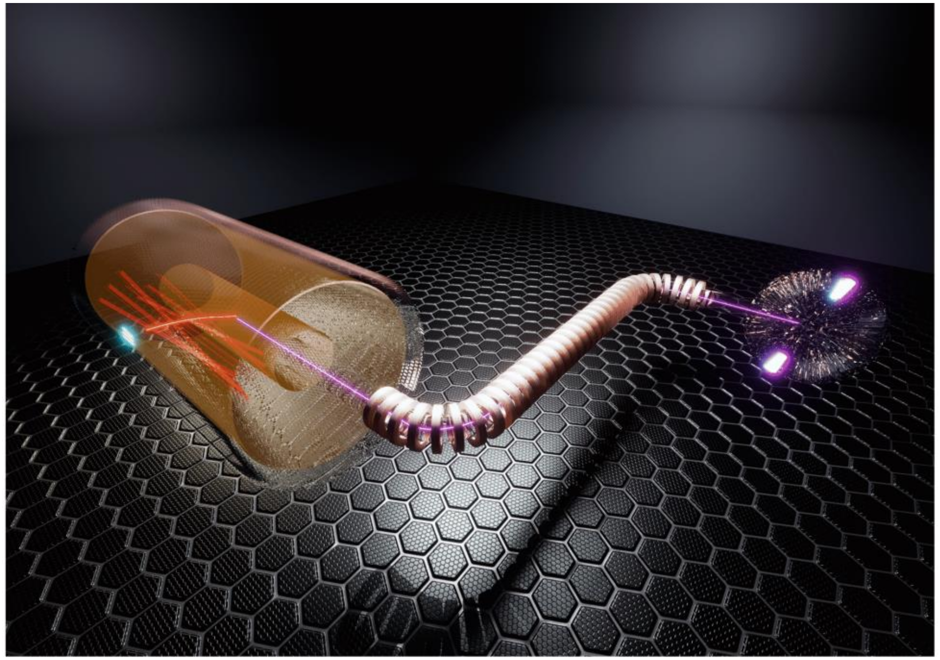
MACE offline software

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

Credits: Shihan Zhao







Credits: Weizhi Xiong

tangjian5@mail.sysu.edu.cn

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

Detector, component or analysis	Efficiency type	Efficiency value
Magnetic spectrometer (MMS)	Geometric efficiency ($\varepsilon_{\mathrm{MMS}}^{\mathrm{geom}}$)	84.6%
	Reconstruction efficiency ($\varepsilon_{\mathrm{MMS}}^{\mathrm{recon}}$)	~ 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 ($\varepsilon_{\mathrm{Cut}}$)	~ 80%
Total signal efficiency		6.6%

Credits: Shihan Zhao

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

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

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

Plan and timeline

2024	2025	2026	2027	2028	2029	2030
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

- Phase-I: $O(10^{-11})$ sensitivity for muon(ium) rare decay (e.g. $\mu\to e\gamma\gamma$ & $M\to\gamma\gamma$)
- Data taking duration: 1 year
- Beam specifications:
  - Surface muon, $10^6 \sim 10^7$ μ^+ OT /s
  - Pulsed or CW beam
  - 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
  - Pulsed beam, repetition rate 20 ~ 50 kHz
  - Momentum spreading: $\Delta p/p \sim 10\%$
  - Beam spot size ~ 50 mm

- Matched with domestic muon beams in the near future: Melody, CiADS, HIAF, SHINE

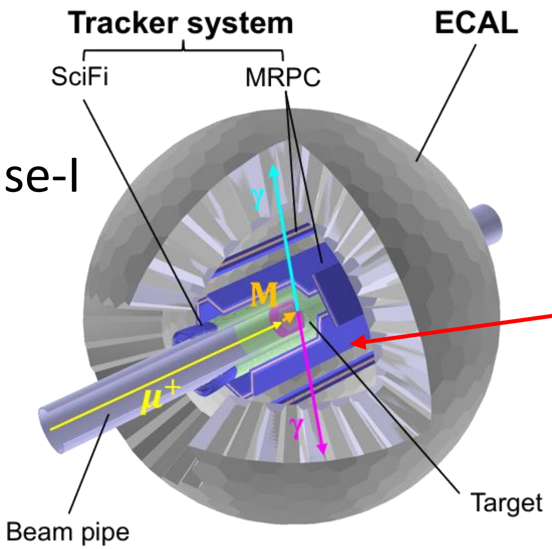
tangjian5@mail.sysu.edu.cn

MACE Phase-I：SciFi tracker

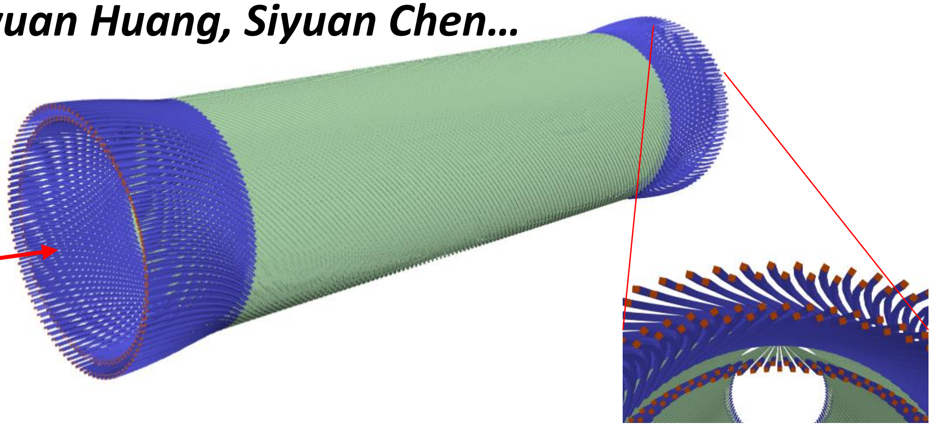
Goals:

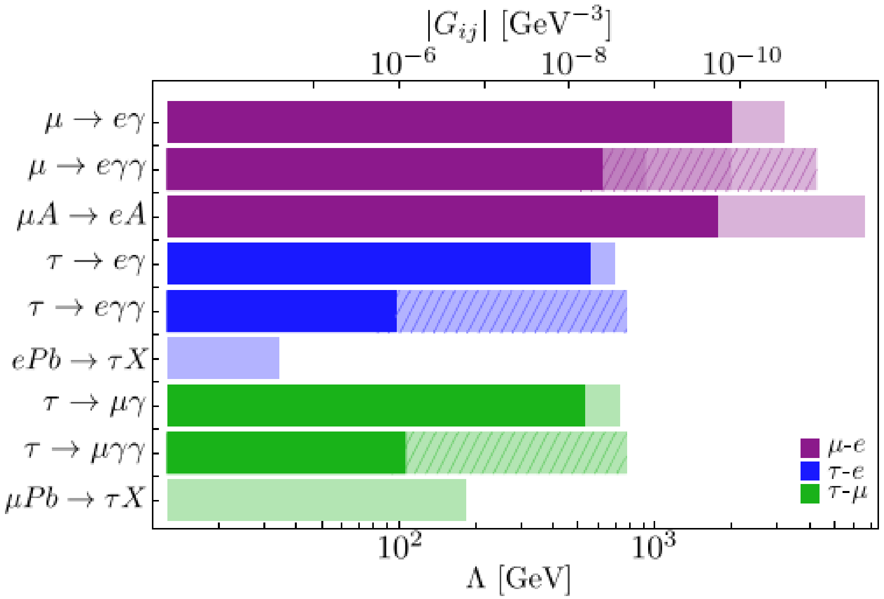
- $\mu^{+}e^{-}\rightarrow\gamma\gamma$
- $\mu^{+}\rightarrow e^{+}\gamma\gamma$

Phase-I



Credits: Yinyuan Huang, Siyuan Chen…



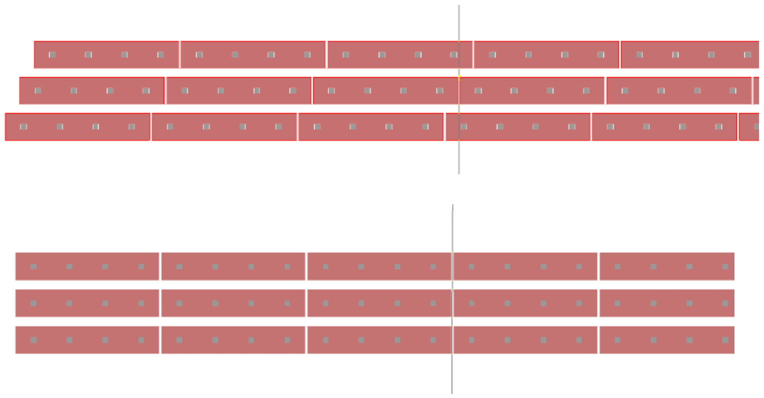


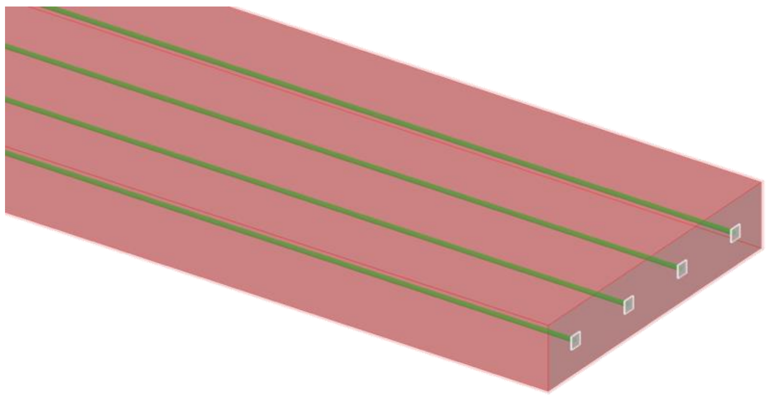
- SciFi tracker:
  - Plastic Scintillation Fiber (Green)
  - Light guide (Blue)
  - SiPM (Red)
- Design:
  - 3 layers with twisting
- Simulation results:
  - Signal efficiency: 94%
  - Spatial resolution 1 mm
  - Time resolution 0.85 ns

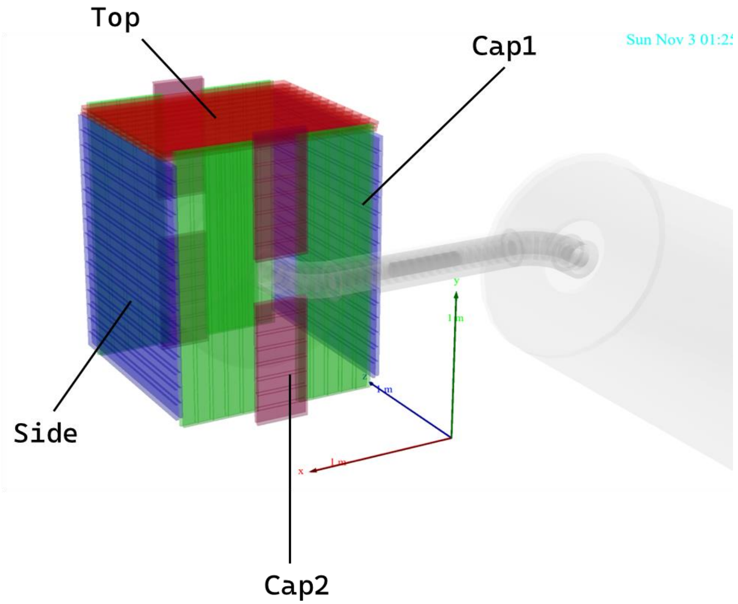
Cosmic ray veto (CRV)

- Purpose
  - Veto cosmic-ray-induced accidental background
- Goals
  - Efficiency ≥ 99.5%
  - Time resolution < 5 ns
- Design
  - Wavelength-shifting (WLS) fiber-embedded plastic strip scintillator
  - Stepped staggered stacking of 2--3 layers of strips

Credits: Zhichao Wang

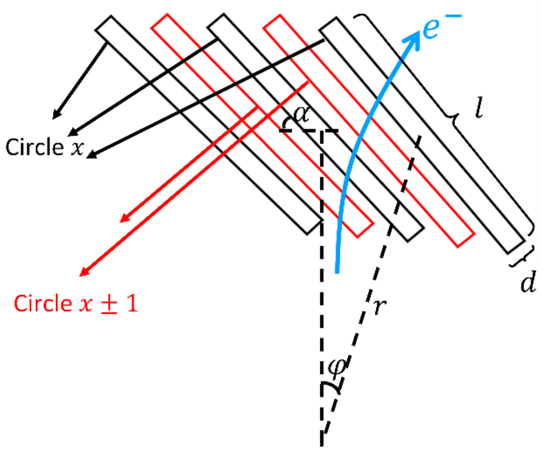


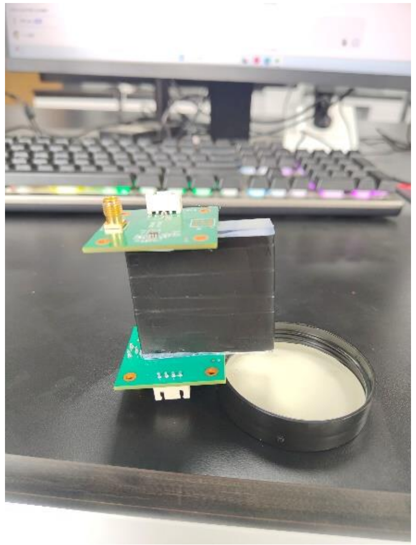


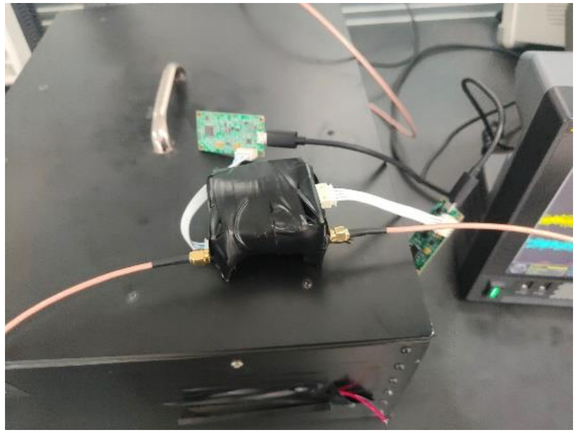


Tiled timing counter (TTC)

- TTC objective:
  - Event rate: ~10^4 / tile / s
  - Time resolution ~ 100 ps
  - 50 mm spatial resolution
- TTC design
  - Plastic scintillator array
  - 122 (φ) × 42 (z) = 5124 tiles
  - Center radius: 480 mm
  - $\varphi = 2.95^{\circ}, \alpha = 46^{\circ}$
- Features:
  - ✓ Two tile coincidence
  - ✓ 88.2% acceptance
  - ✓ Scintillator width 3--5 mm



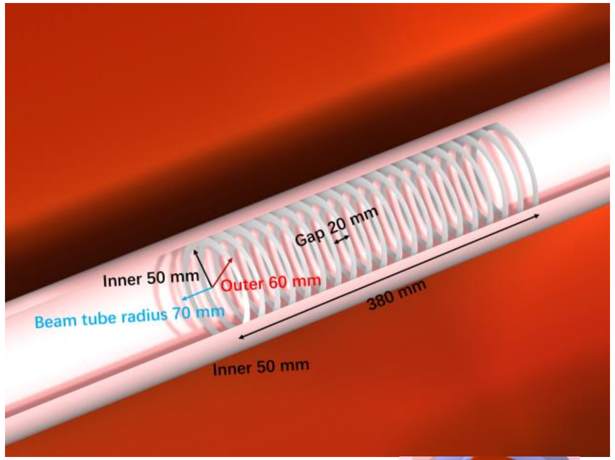


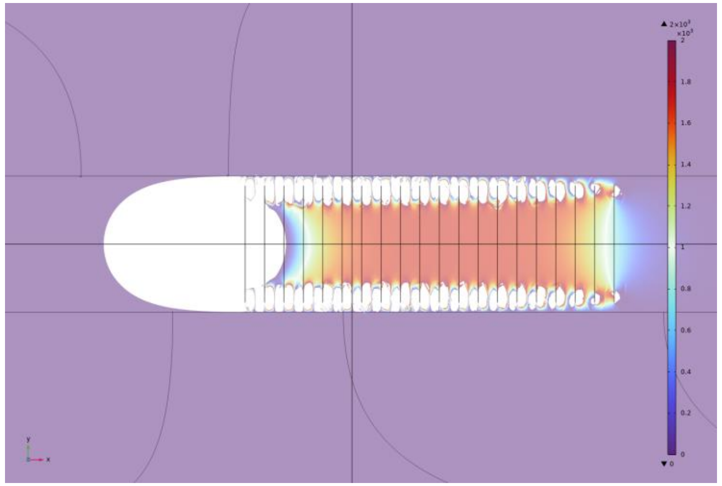


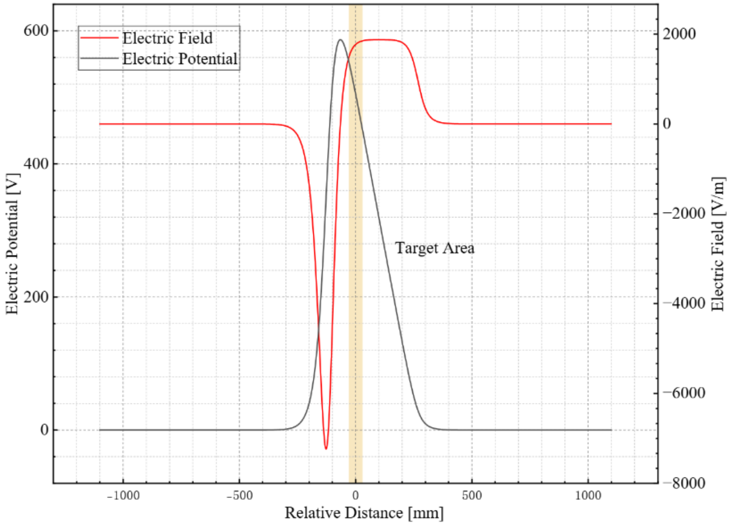
Positron transport system

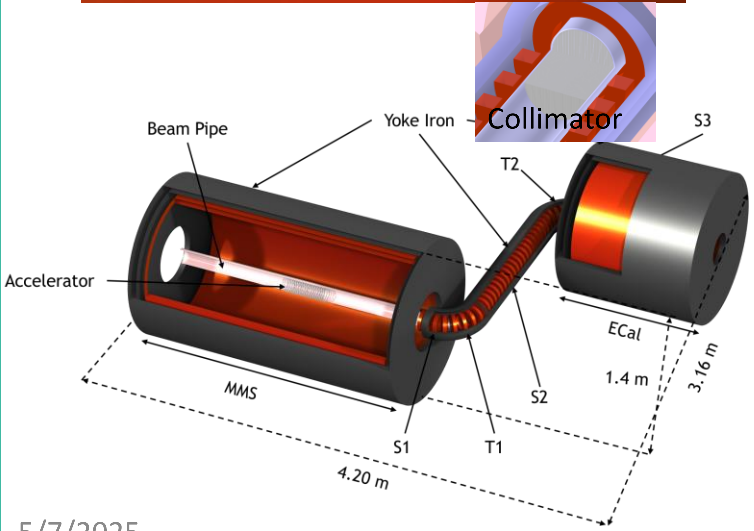
See Guihao Lu's poster (MIP2024)

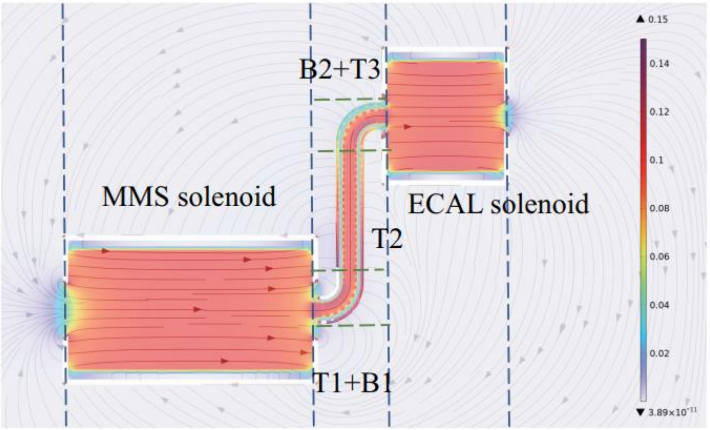
- Near-stationary signal positron should be accelerated and transport to MCP with transverse position preserved.
- Components: electrostatic accelerator & solenoid.

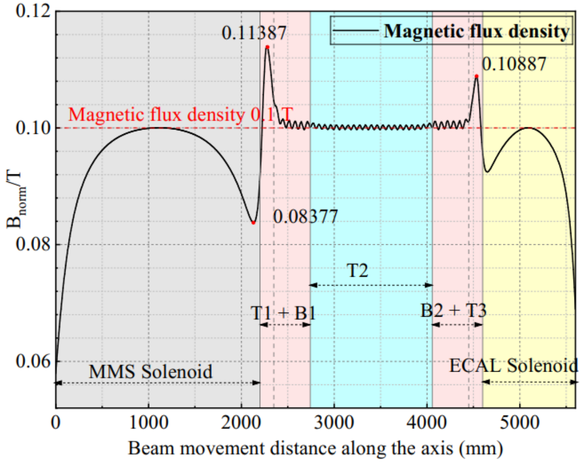












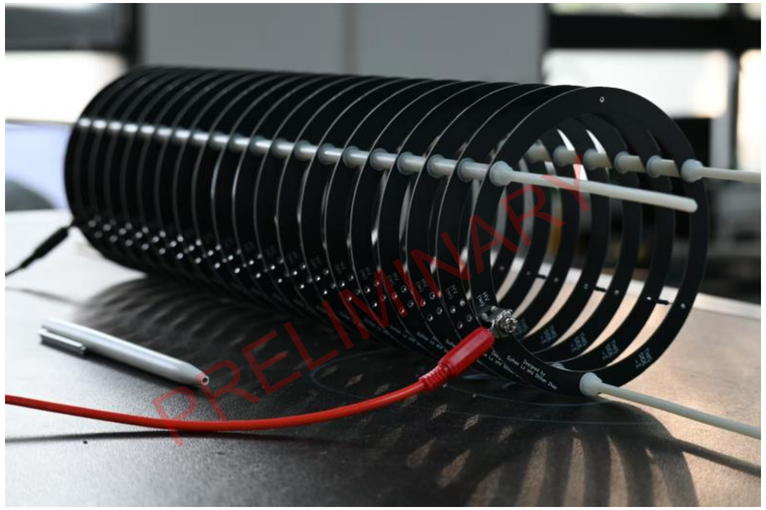
tangjian5@mail.sysu.edu.cn

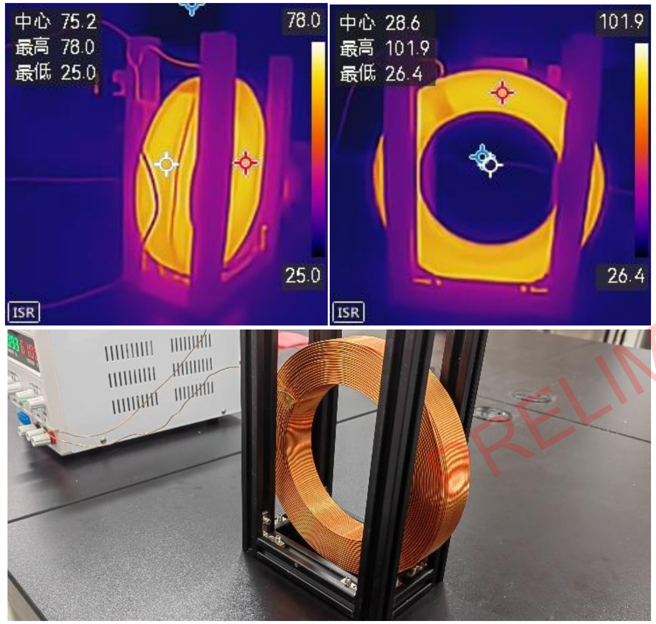
Positron transport system: prototype

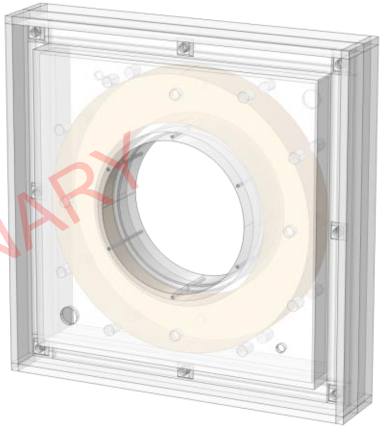
- Accelerator module prototype
  - Multi-layer PCB
  - High voltage > 2 kV

Credits: Guihao Lu

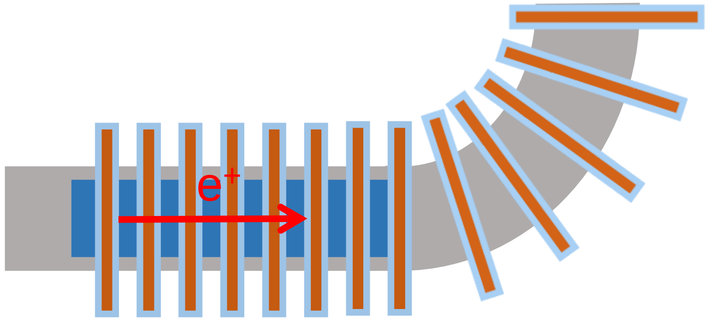
- TS solenoid coil
  - Validate its field distribution and feasibility.







- PTS validation
  - Testing with TS solenoids and accelerator module



tangjian5@mail.sysu.edu.cn

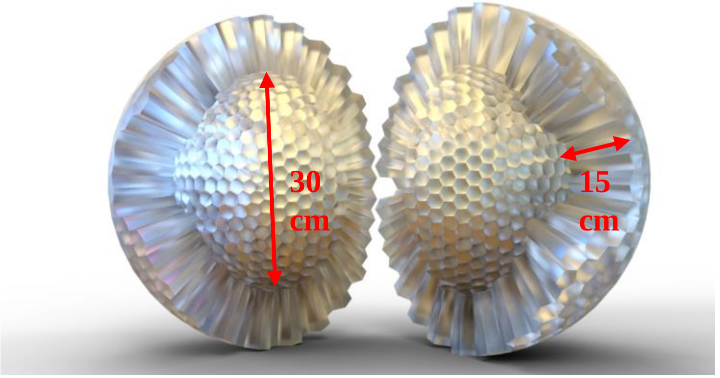
Design of calorimeter

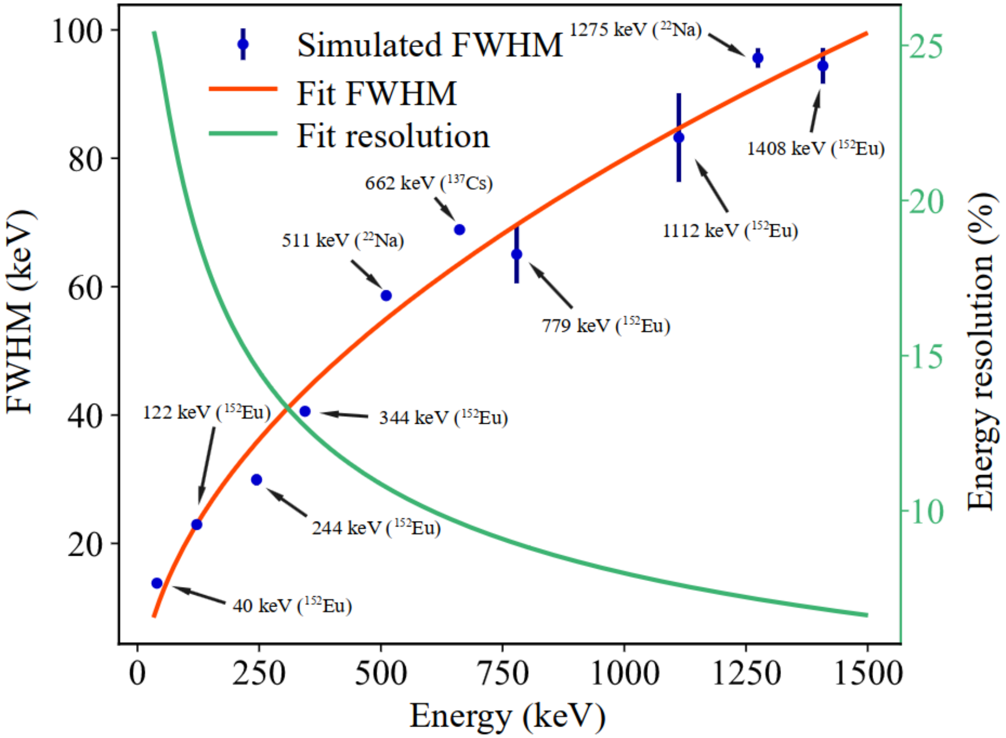
- Signal and Background

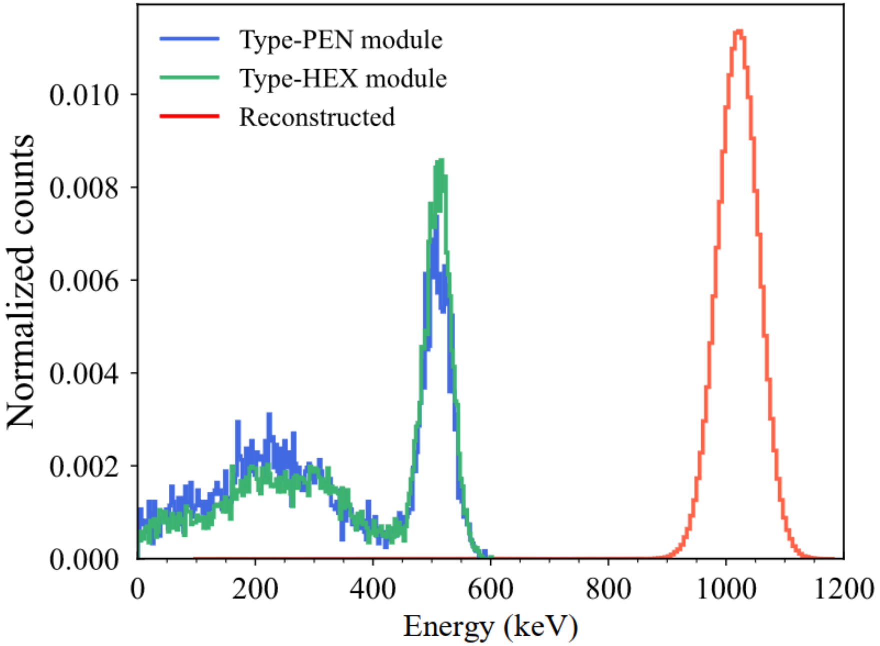
https://arxiv.org/abs/2408.17114 ***Frontier of Physics*** *20 (2025), 035202.*

Credits: Siyuan Chen

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





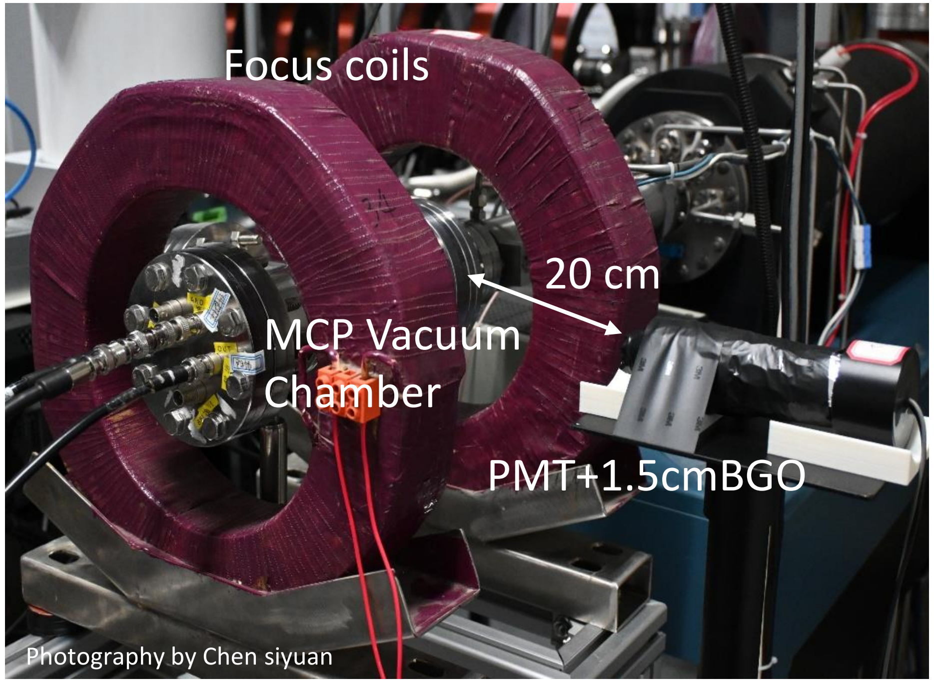


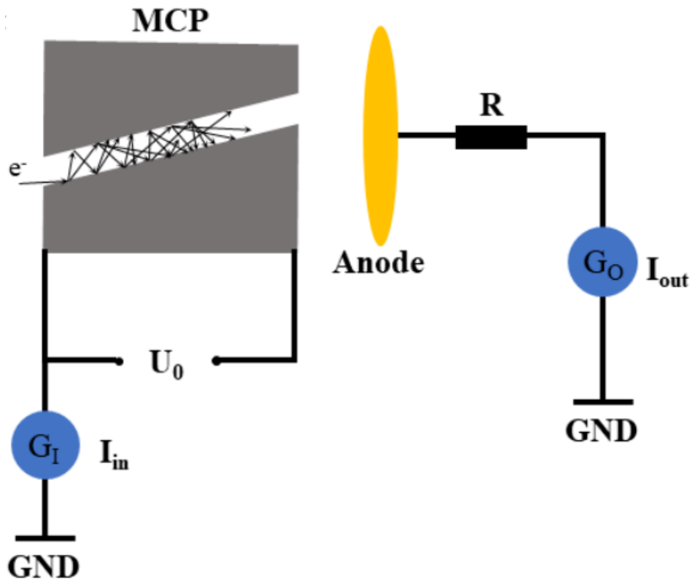
tangjian5@mail.sysu.edu.cn

MCP+ECal: prototype tests with a positron beam

- Beam source:
  - IHEP slow e⁺ beam
  - Positron in CW/Pulse
  - $3 \times 10^4\ e^+/s$
- Currently MCP efficiency 25 ~ 30%
  - Can reach 50% efficiency through MgO/C thin layer

Credits: Siyuan Chen





- Data analysis in progress...

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

Table of contents

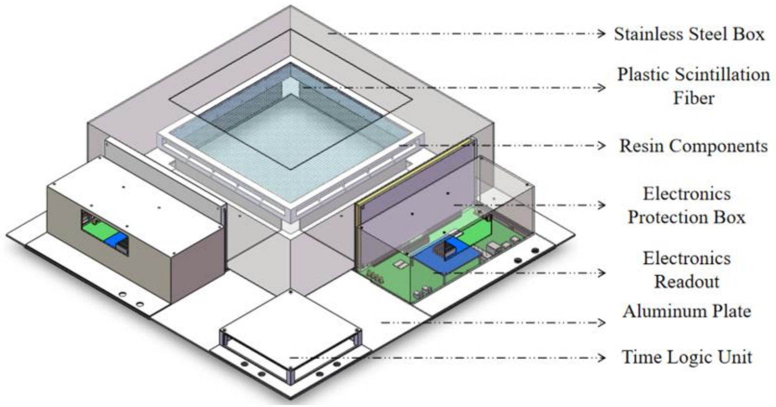
- Review of the past experience
- Motivations for muon physics
- Conceptual design of MACE
- Local laboratory: SMOOTH

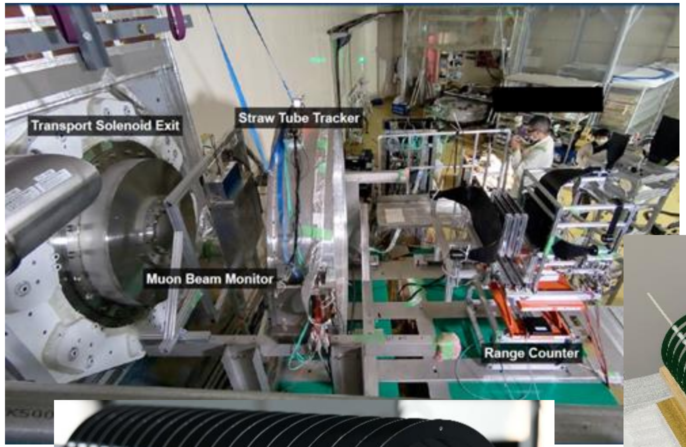
tangjian5@mail.sysu.edu.cn

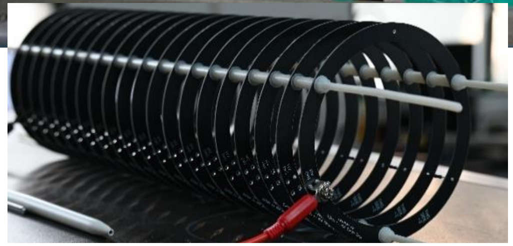
Gallery of the local lab

COMET muon beam monitor

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

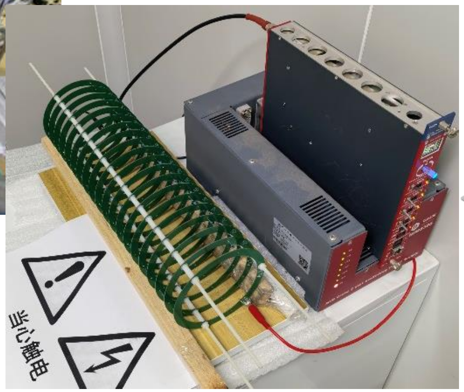




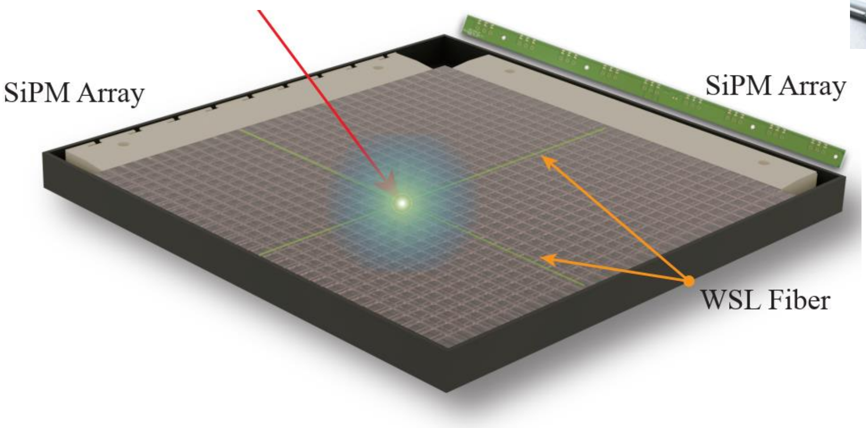


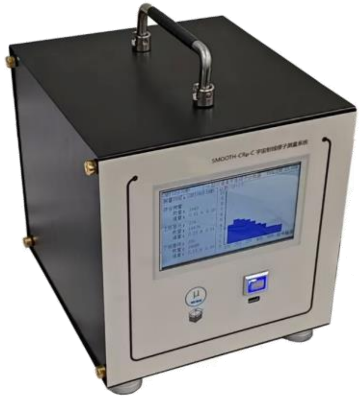
Cosmic-ray muSR (CRmuSR)

[M.-C. Sun, HHIF2024]

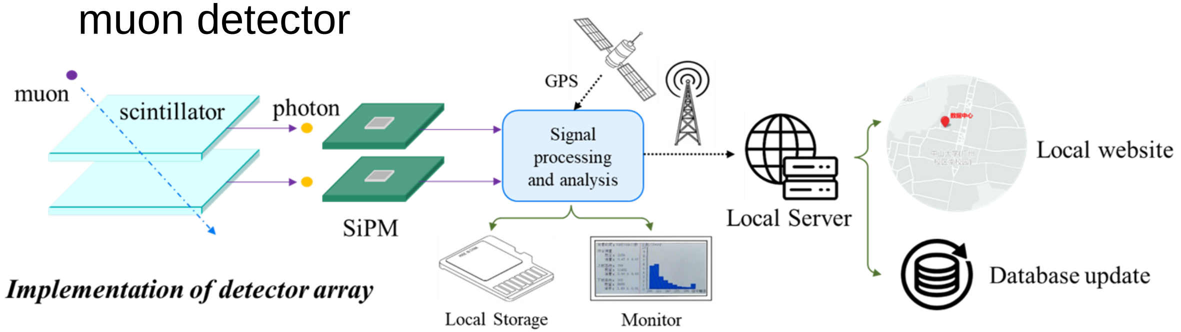


MuGrid-v2 for muography

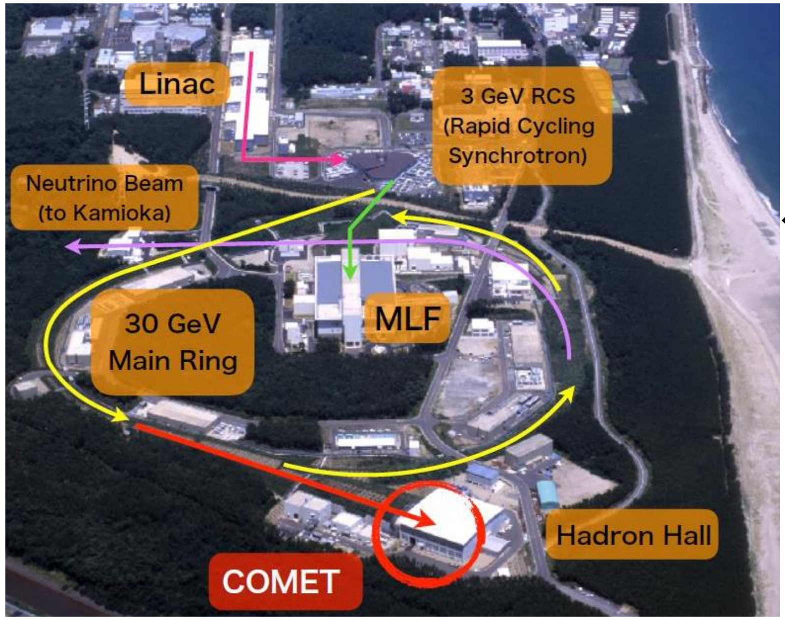


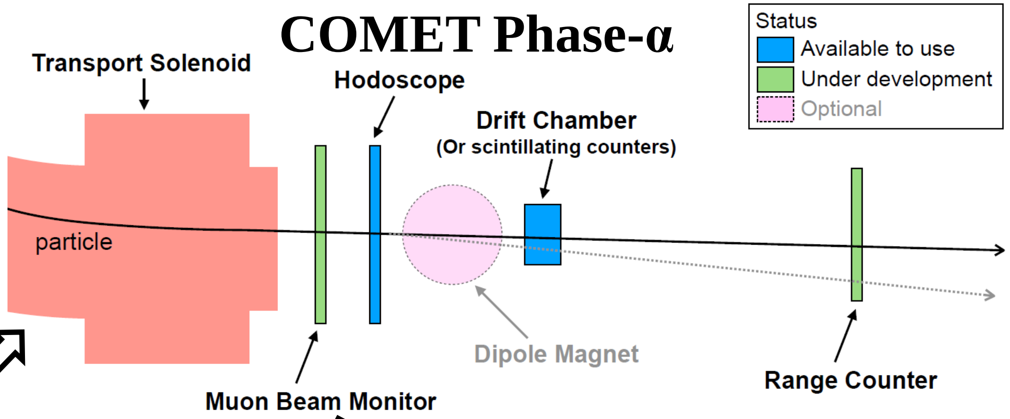


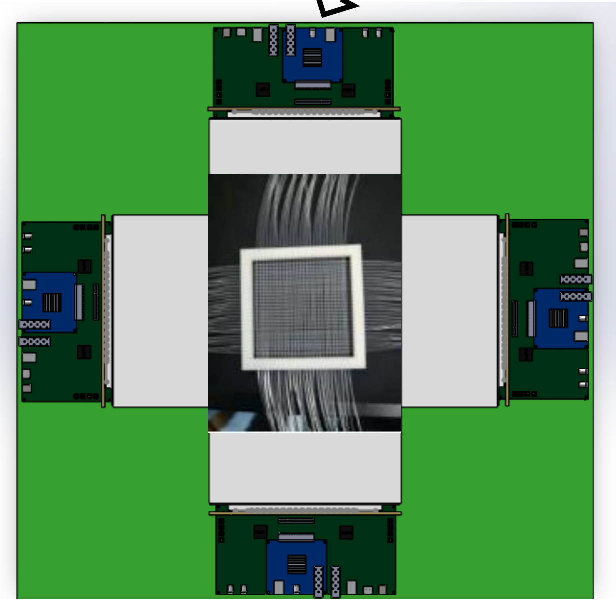
Portable cosmic-ray muon detector

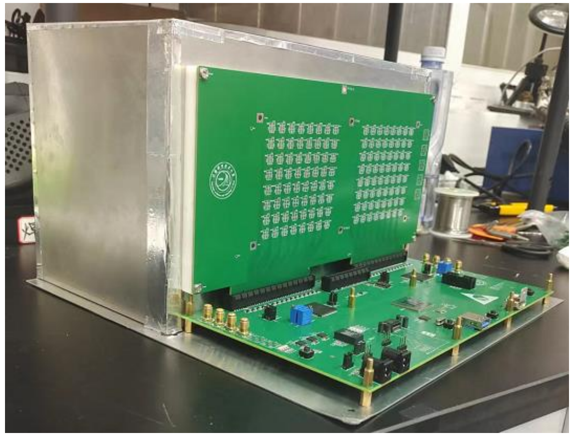


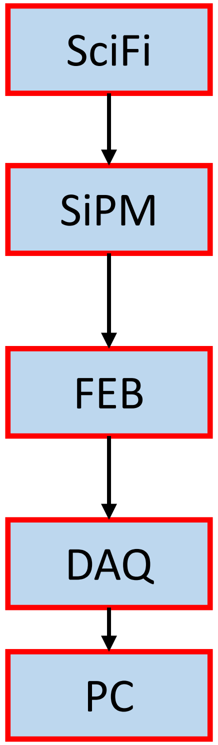
Muon beam monitor for COMET











e-Print: 2308.15253 [physics.ins-det]

Nuclear Science and Techniques 35 (2024) 4, 79

Credits： SMOOTH lab

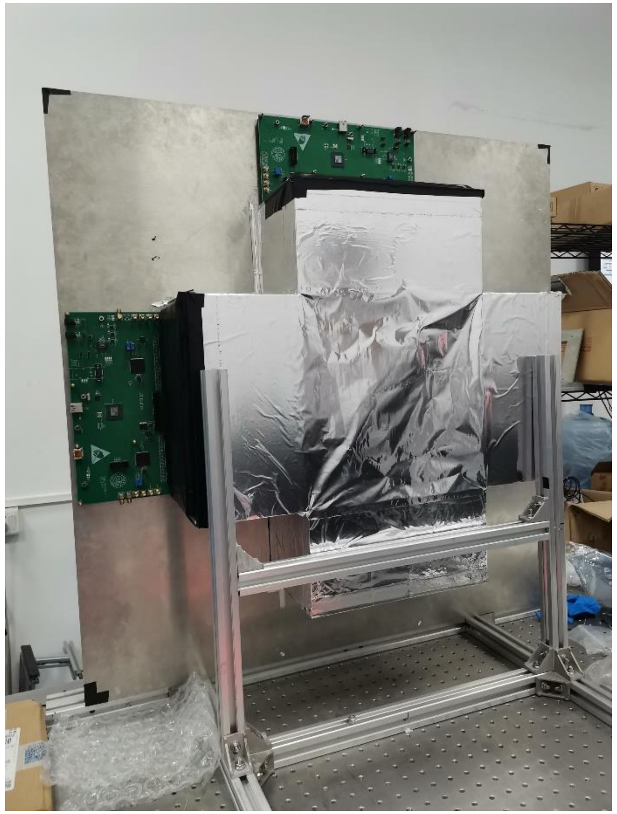
USTC electronics group led by Chang-Qin Feng

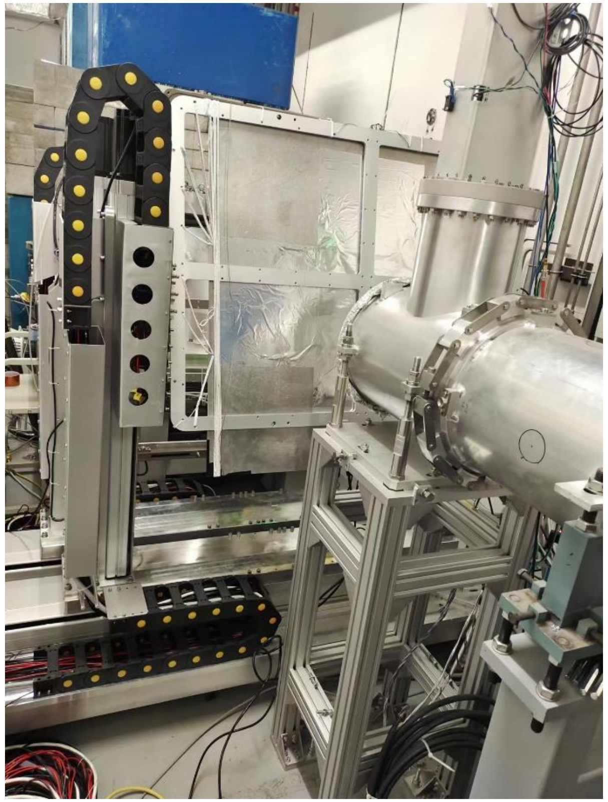
JINST 19 (2024) 10, P10022

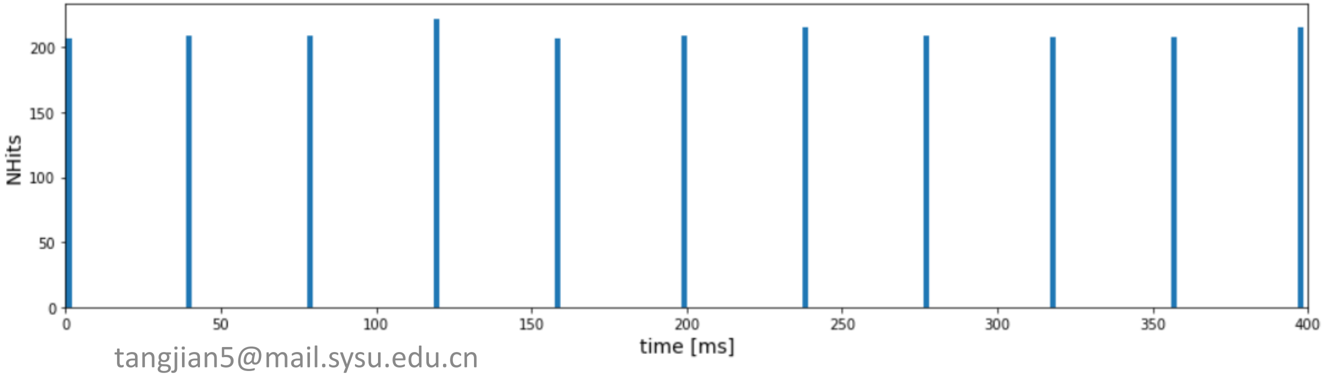
Muon beam monitor for COMET

- 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

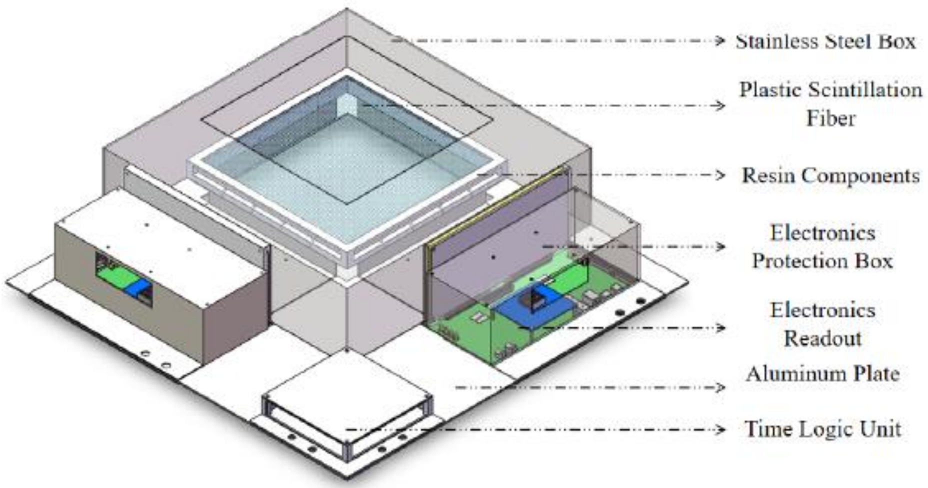


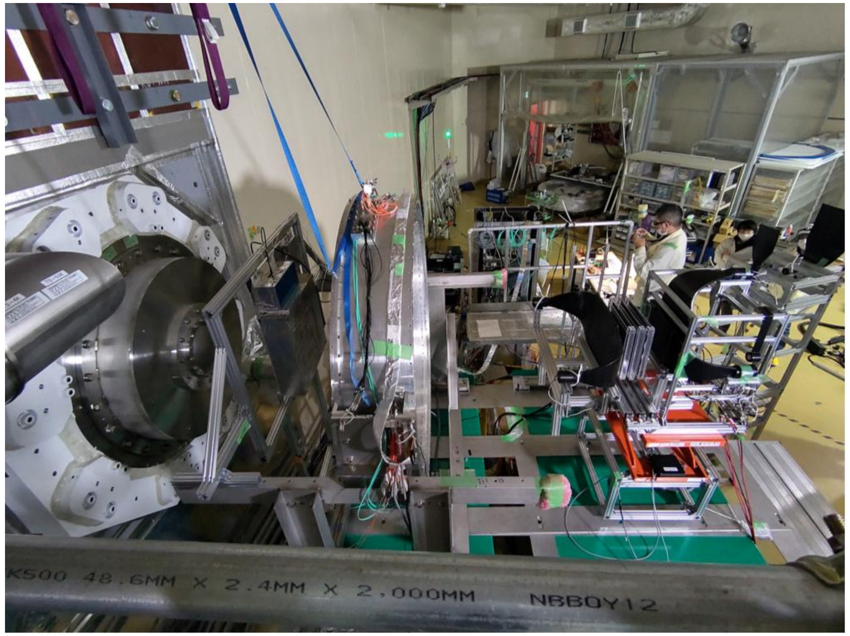


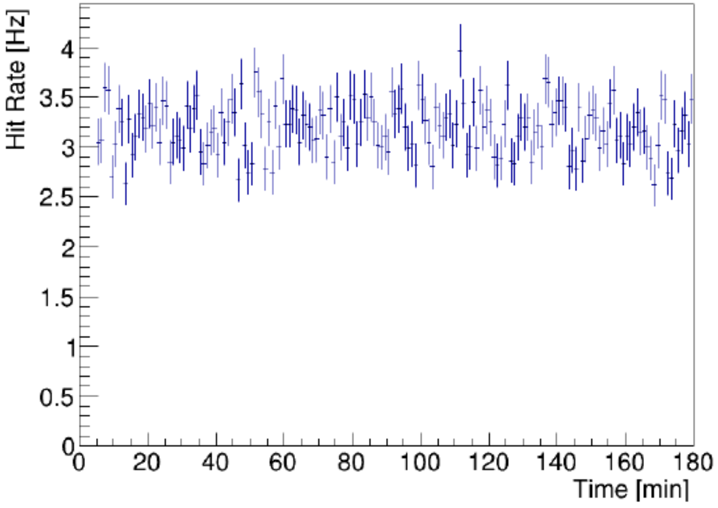


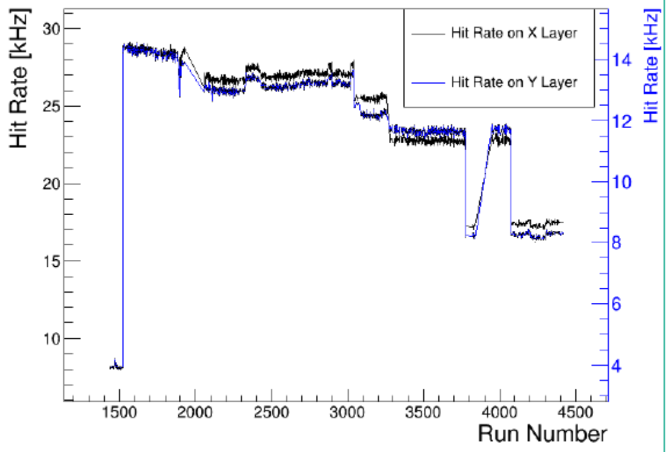
tangjian5@mail.sysu.edu.cn

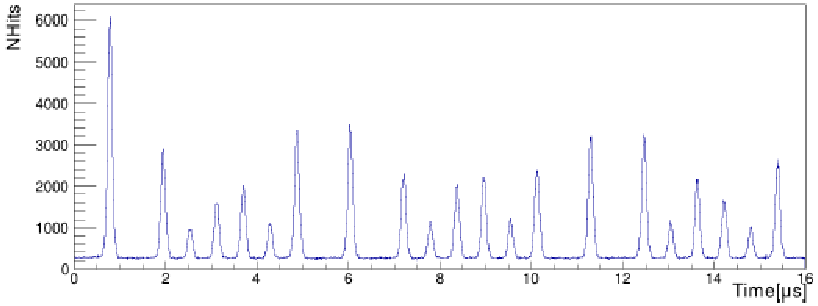
Muon beam monitor for COMET

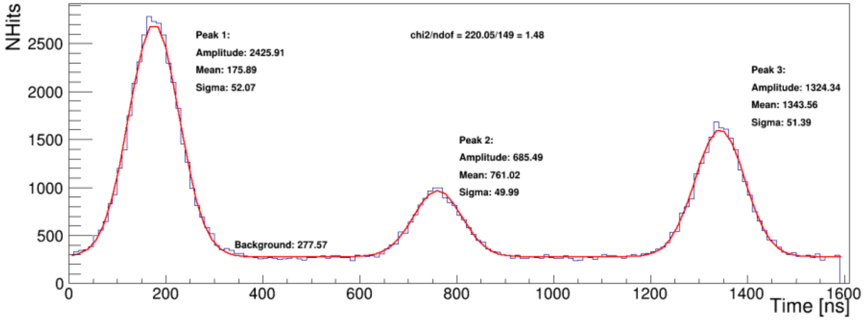


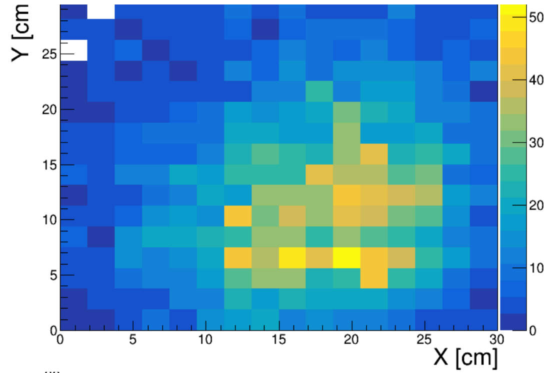


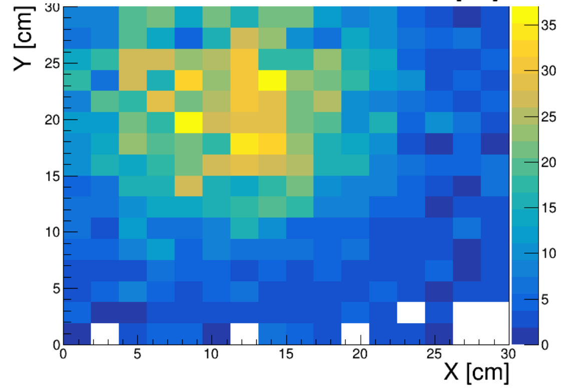








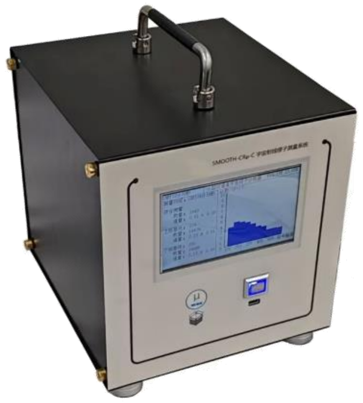


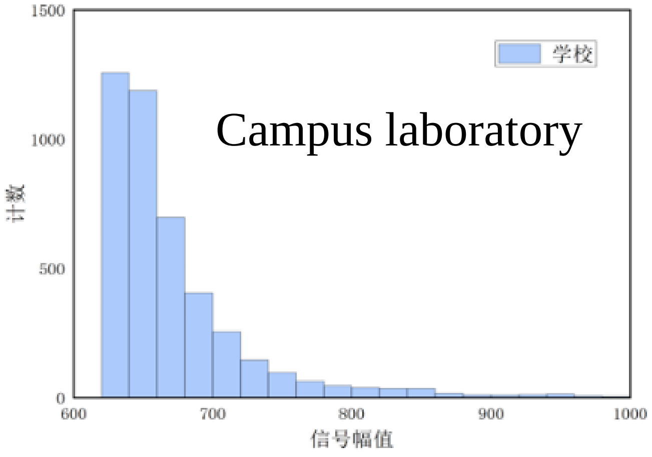


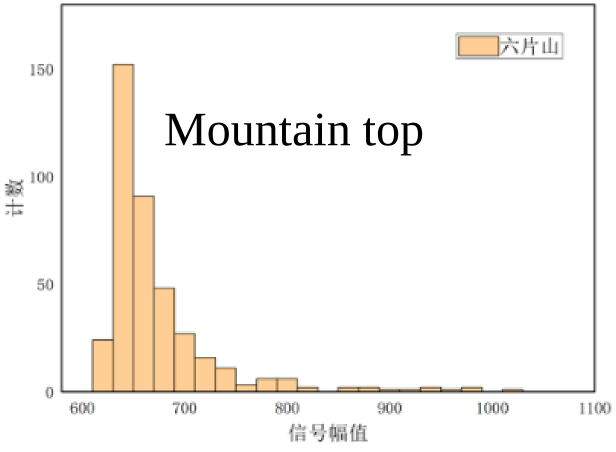
tangjian5@mail.sysu.edu.cn

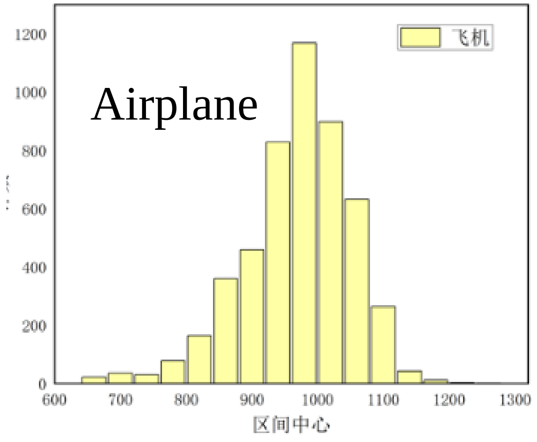
CRμ: educational kit and its application

https://arxiv.org/abs/2503.18800



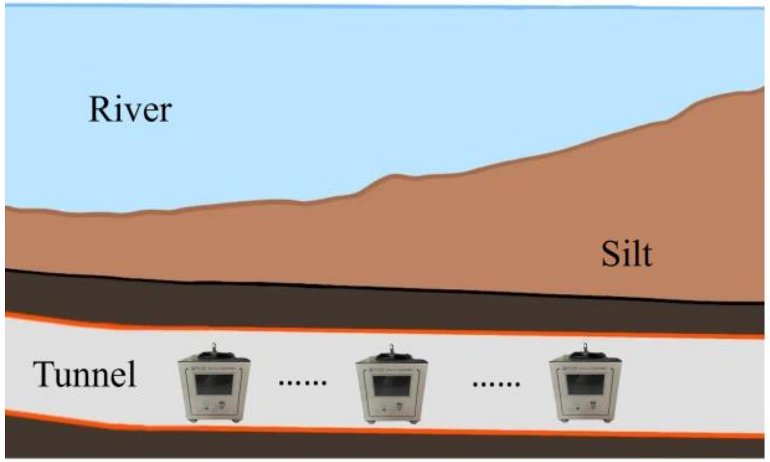


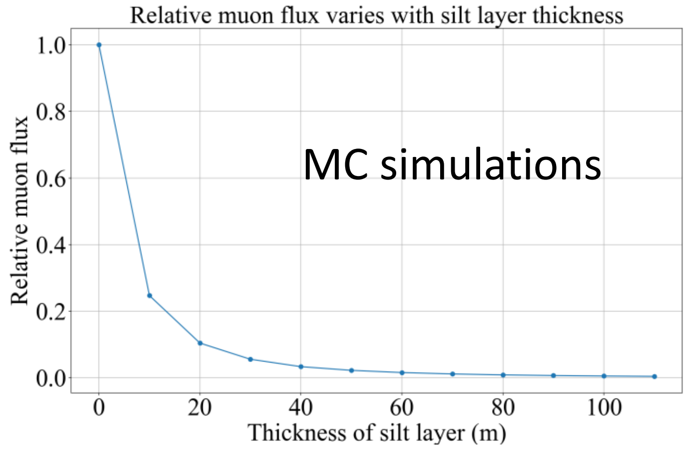


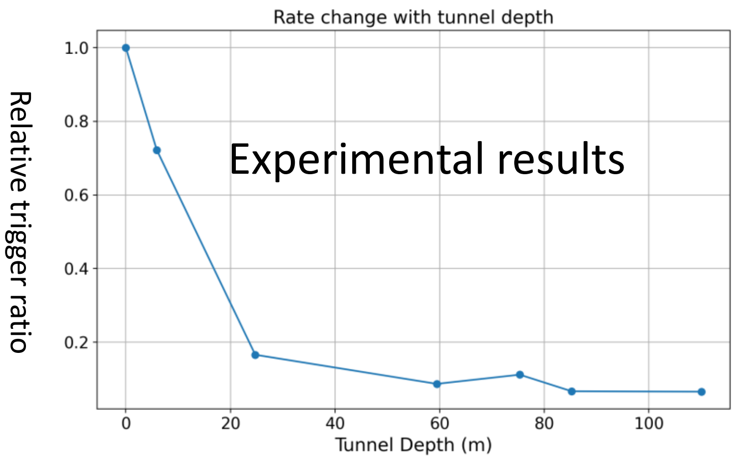


23年-24年 | 22年秋 | 23年6月

Height: 0 m | 250 m | 8000 m



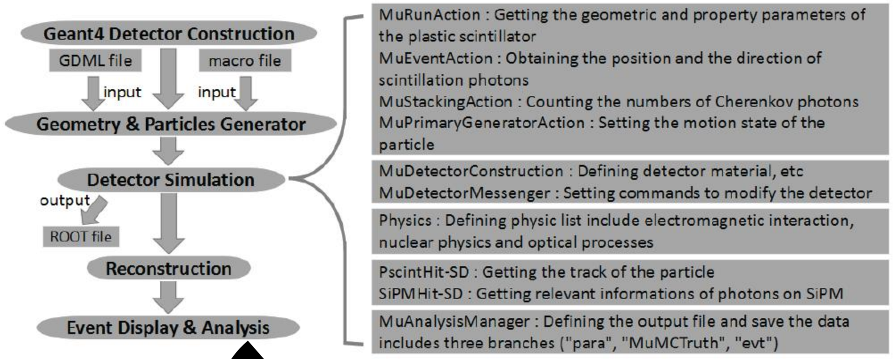


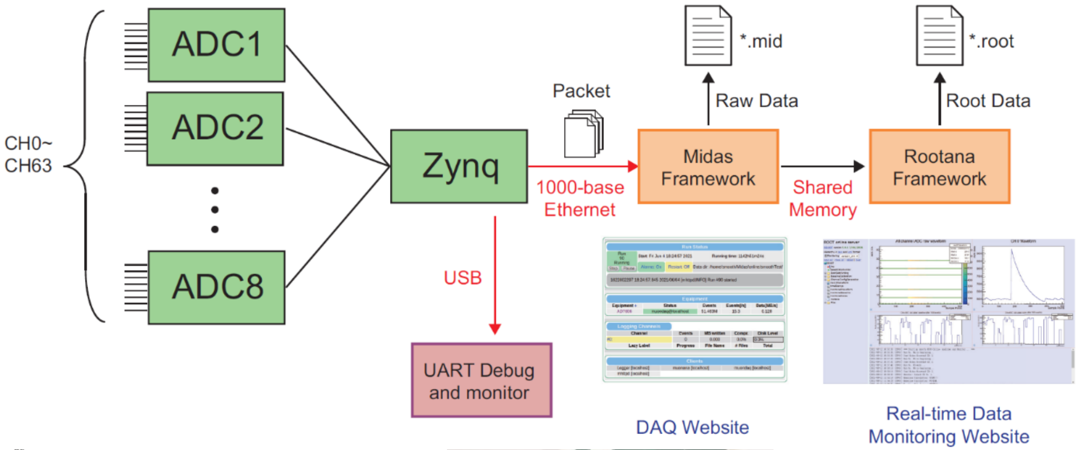


tangjian5@mail.sysu.edu.cn

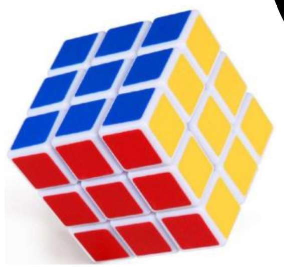
Detector R&D with cosmic muons: MuGrid-v1

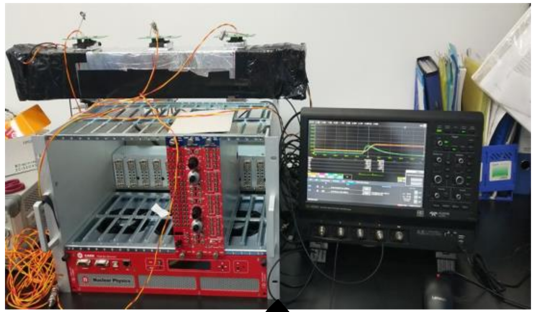
MC

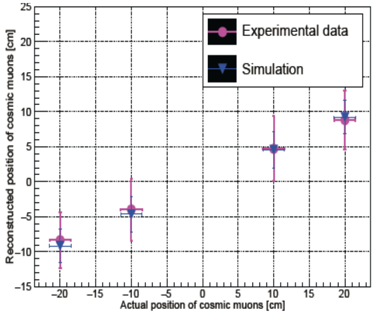




Module test







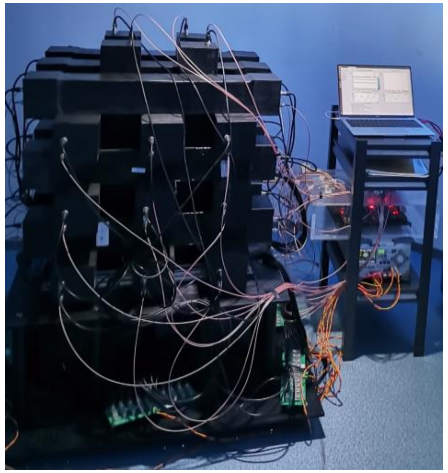
Customized electronics

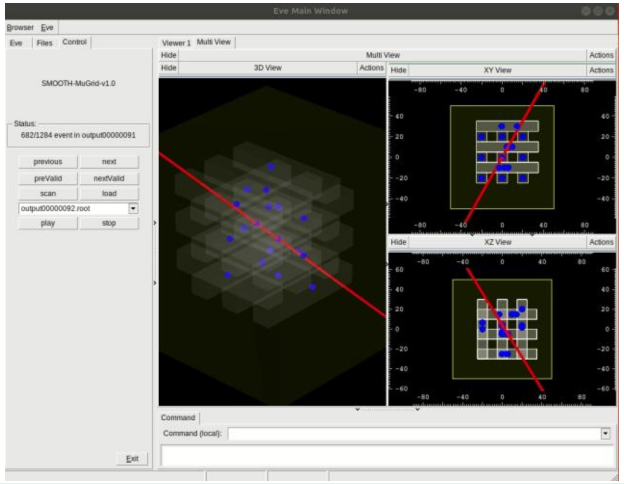
Track reconstruction

(a)

(b)

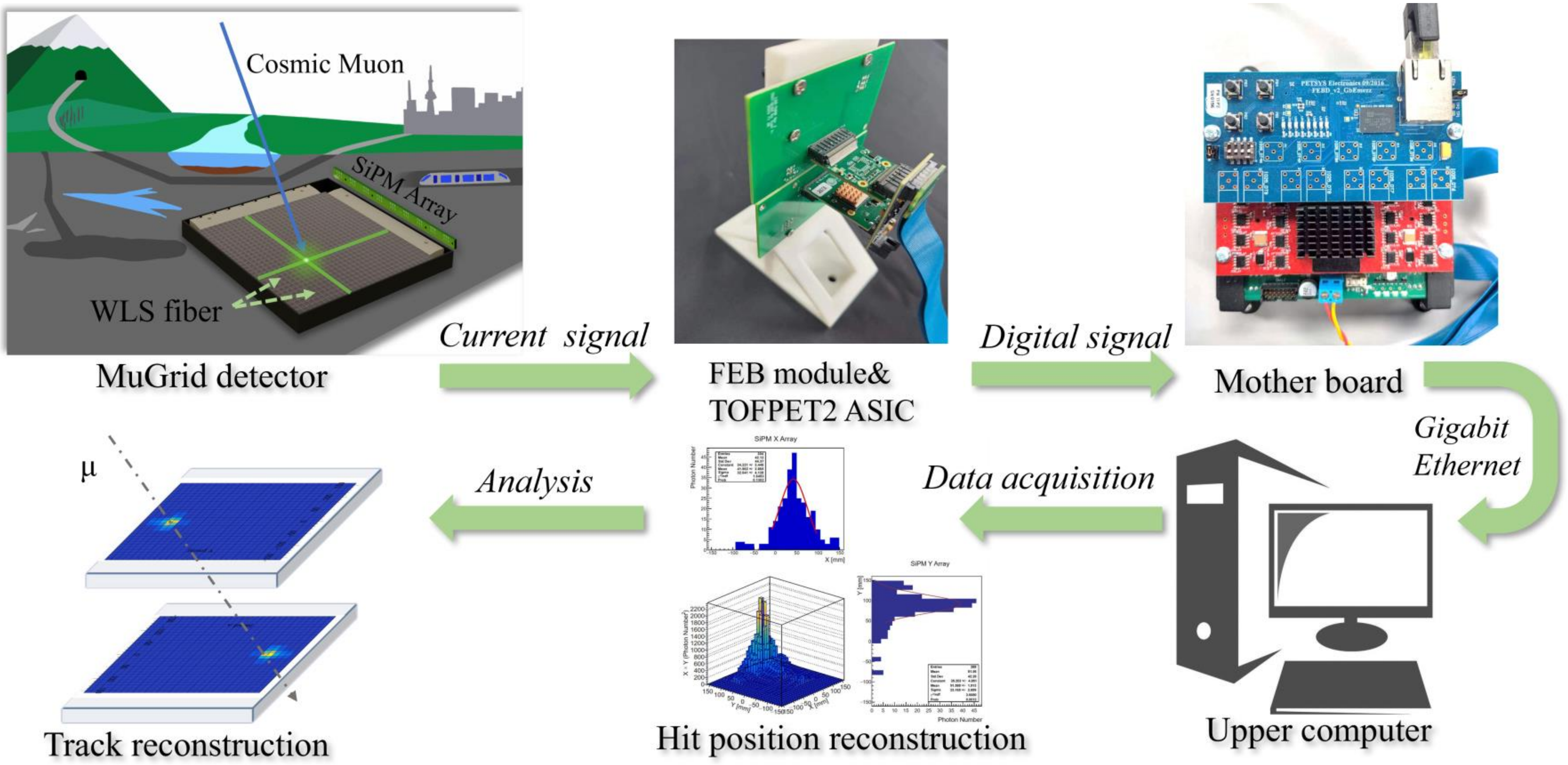
Online monitor





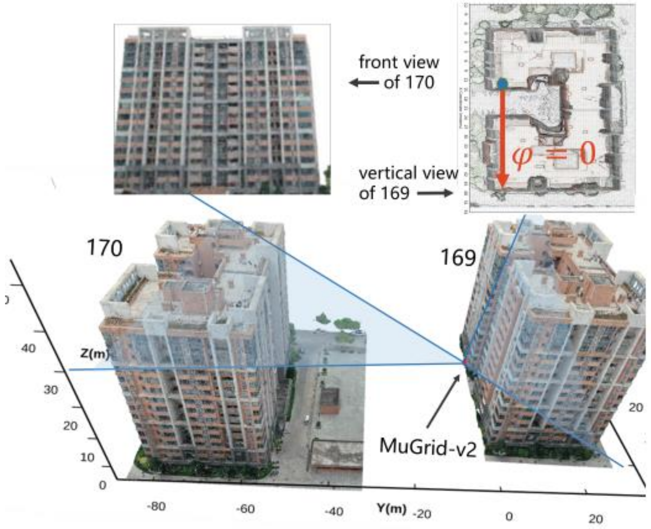
Nuclear Inst. and Methods in Physics Research, A1042 (2022) 167402

Upgrade: MuGrid-v2

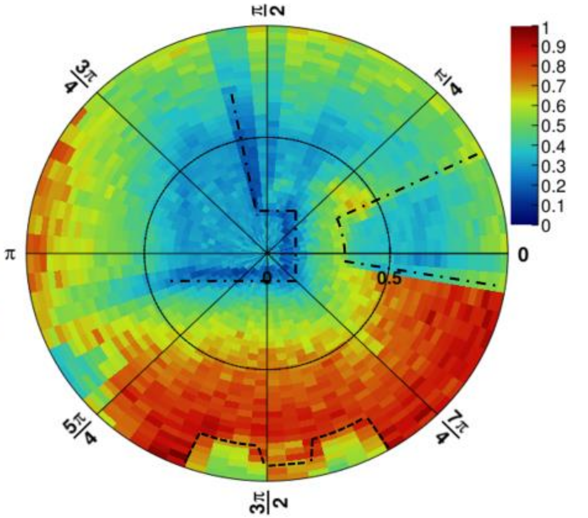


Upgrade: MuGrid-v2

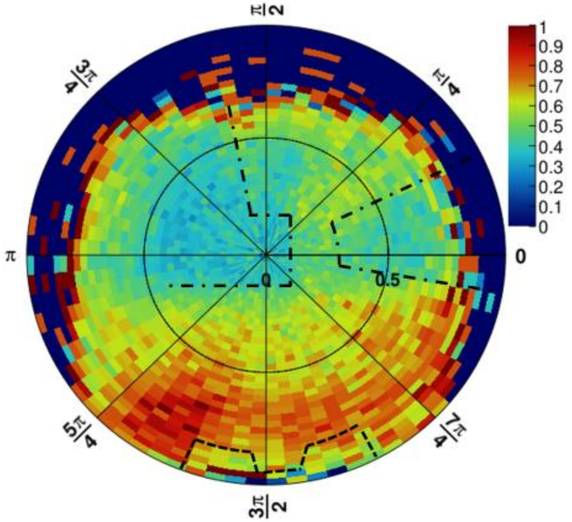
Credits: Tao Yu, Songran Qi, Shihan Zhao…



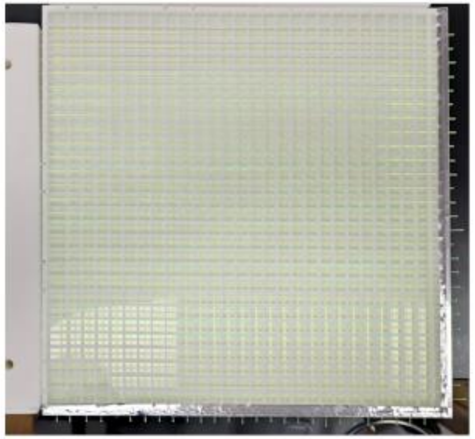
(a) An illustration of experimental setup.

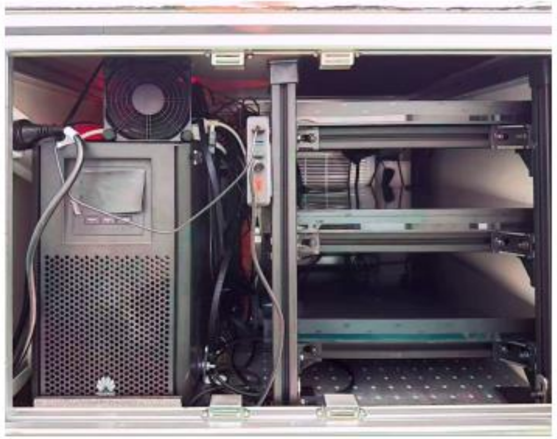


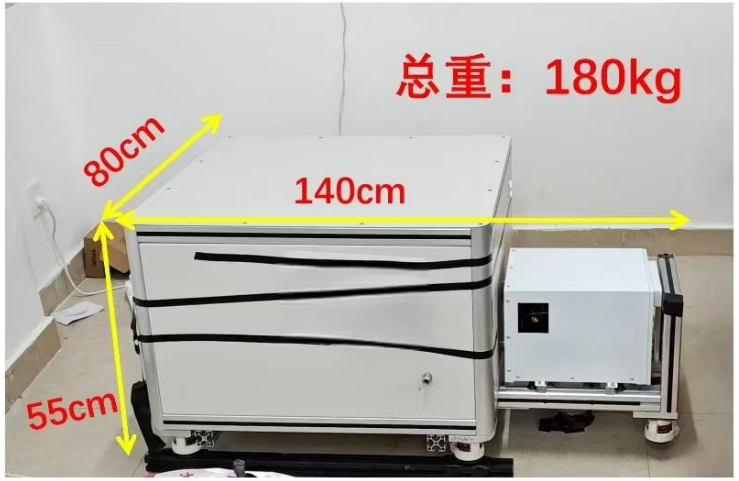
(b) Muon survival ratio in simulation.



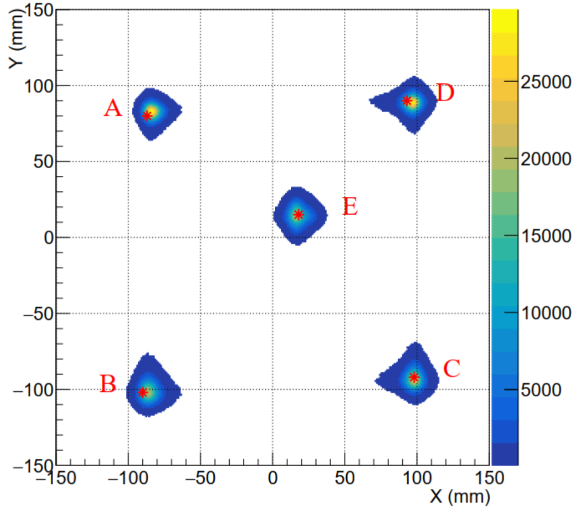
(c) Muon survival ratio in experiment.





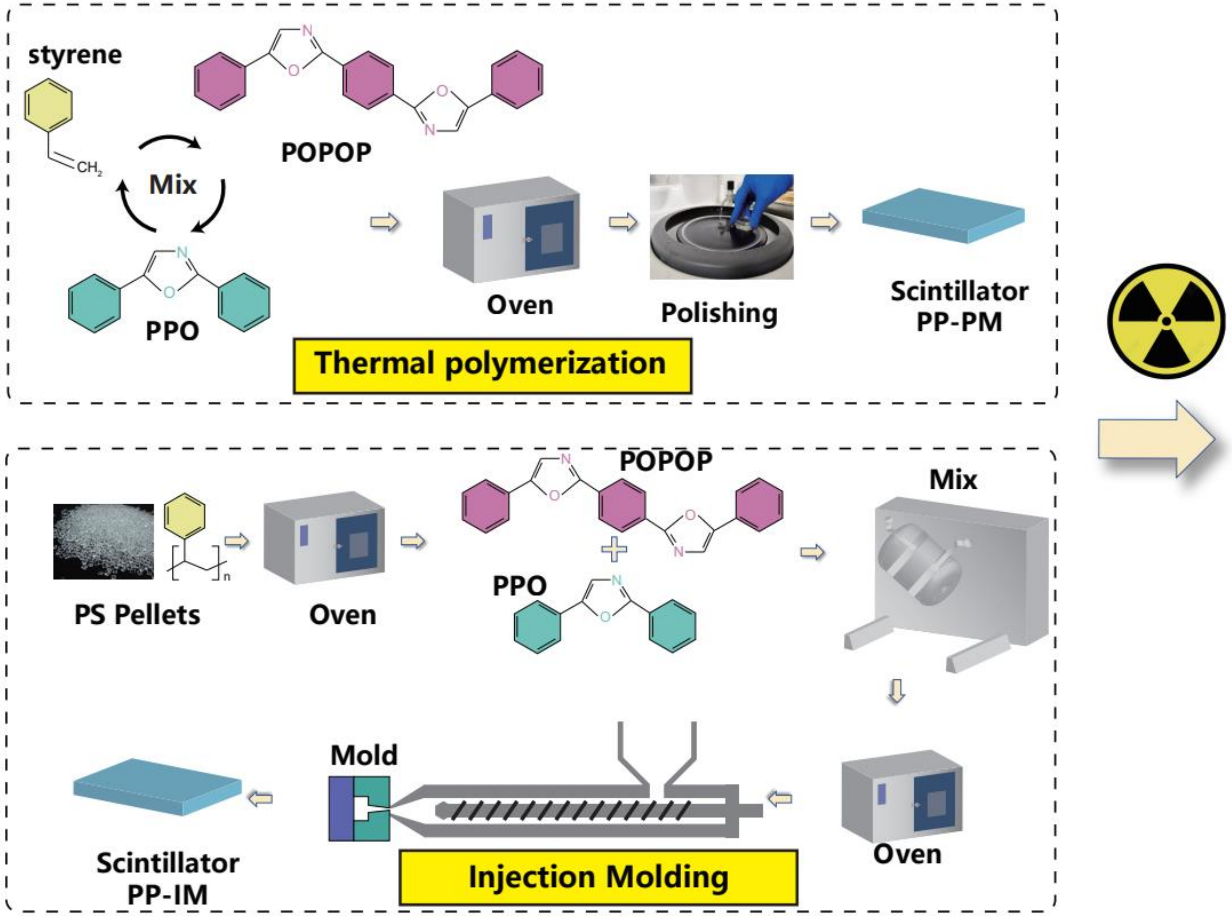


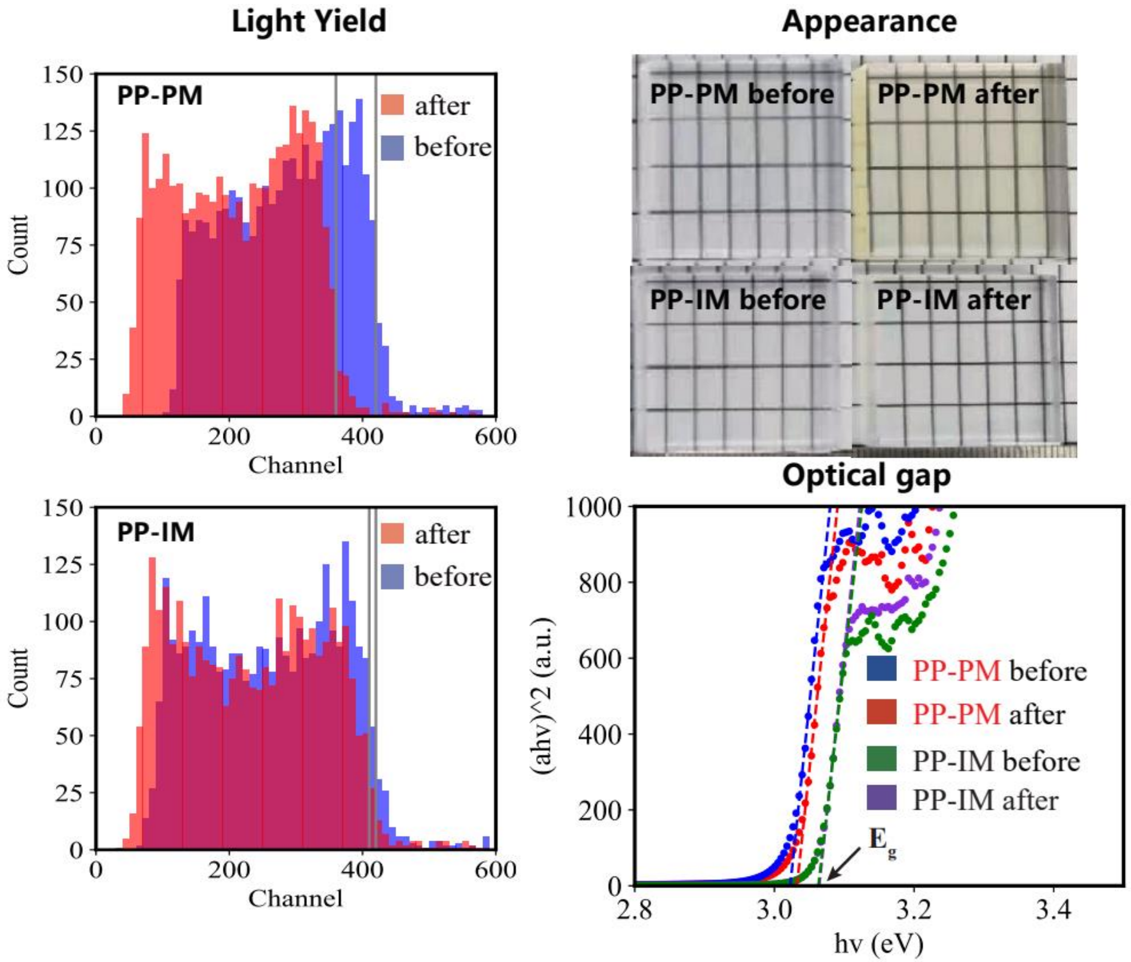
The detector MuGrid-v2 after assembly.



Calibrations with the energy and timestamp information.

R&D of new plastic scintillators for muon detections



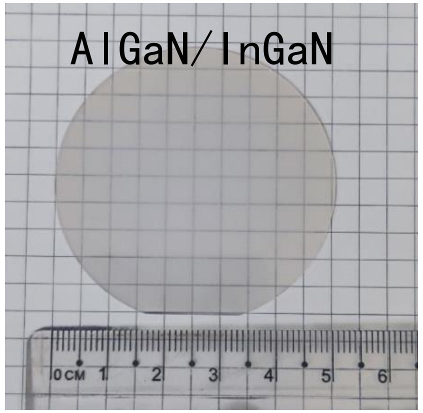


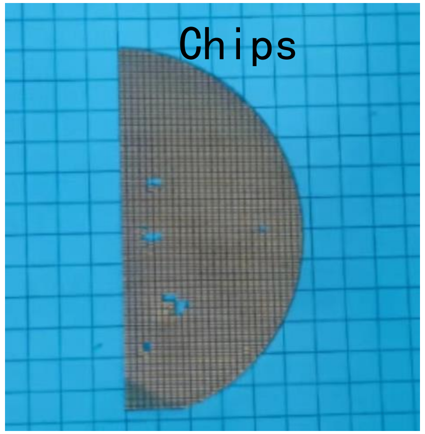
Enhancing plastic scintillator performance through advanced injection molding techniques

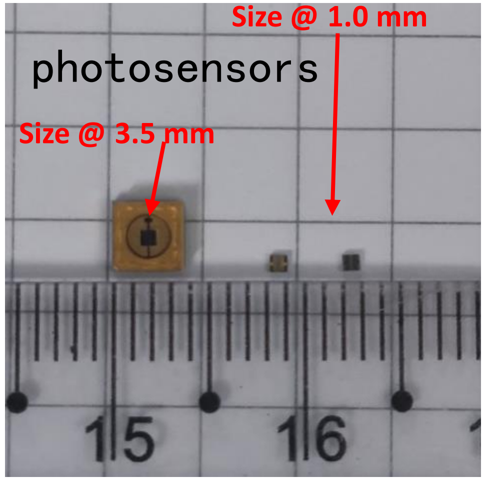
Credits: Jiahao Zhong, Nouman, Jian Zhou, ***Jian Tang***
Radiation Physics and Chemistry *226 (2025) 112193*

R&D of new photosensors for muon detections

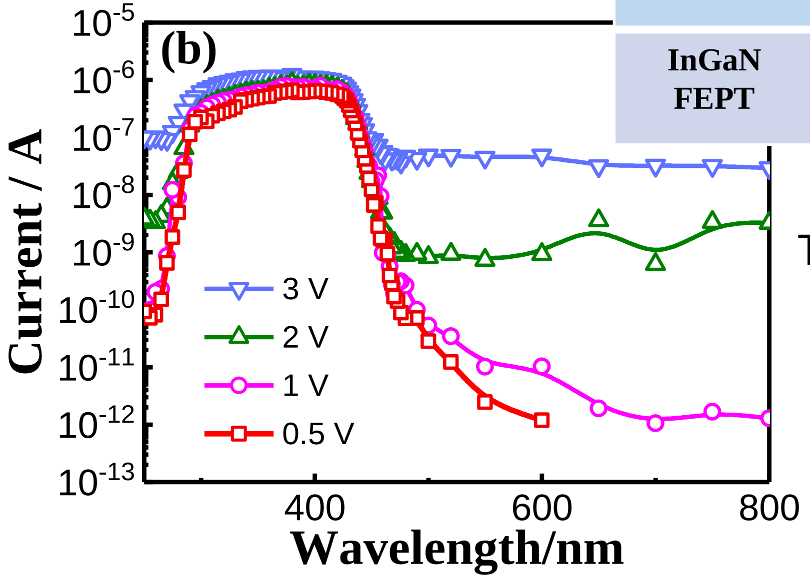
- Wavelength: 280~450 nm
- Low cost, low power consumption
- To replace SiPM/MPPC?





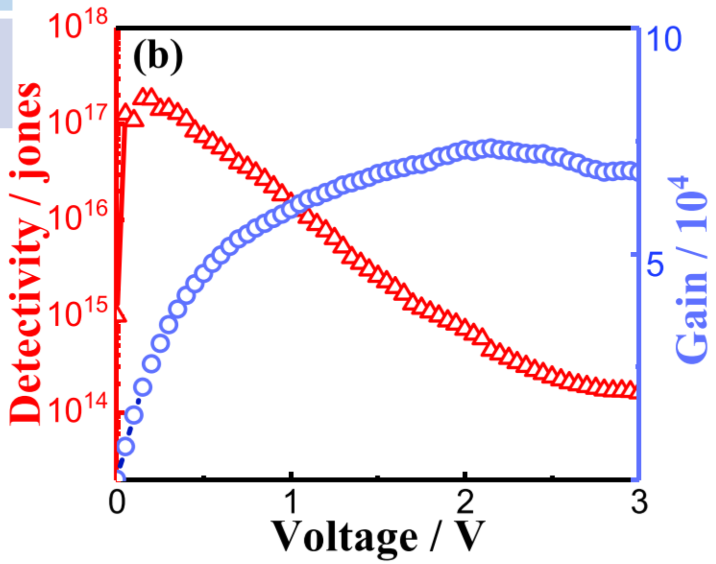


Structure	Working voltage	Dark counts	Sensitivity	Gain	Risetime/ fall time
InGaN FEPT	1.0 V	0.2 pA @ 1 V	2×10^4 A/W @6.8μW/cm^2	6.2×10^4	15 / 160 ns



To collaborate with my previous students!

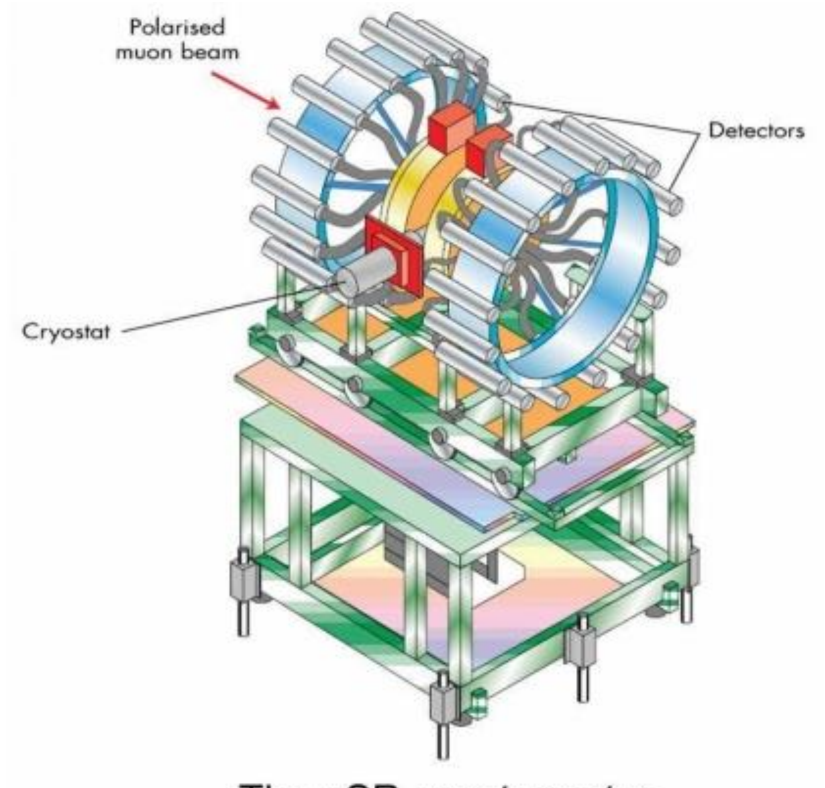
Credits: Zhesheng Lv



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

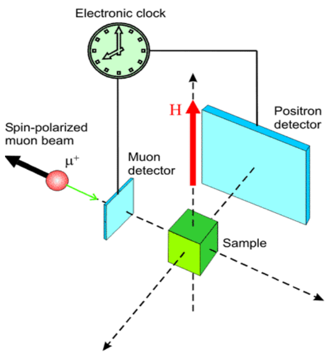
tangjian5@mail.sysu.edu.cn

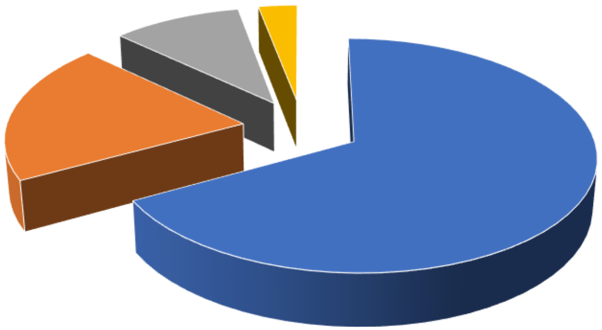
Muon Spin Relaxation, Rotation and Resonance (μSR)

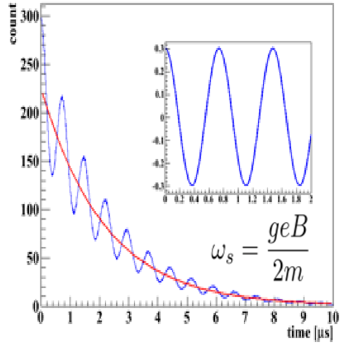


The μSR spectrometer

Nature Materials 16, 467–473 (2017)

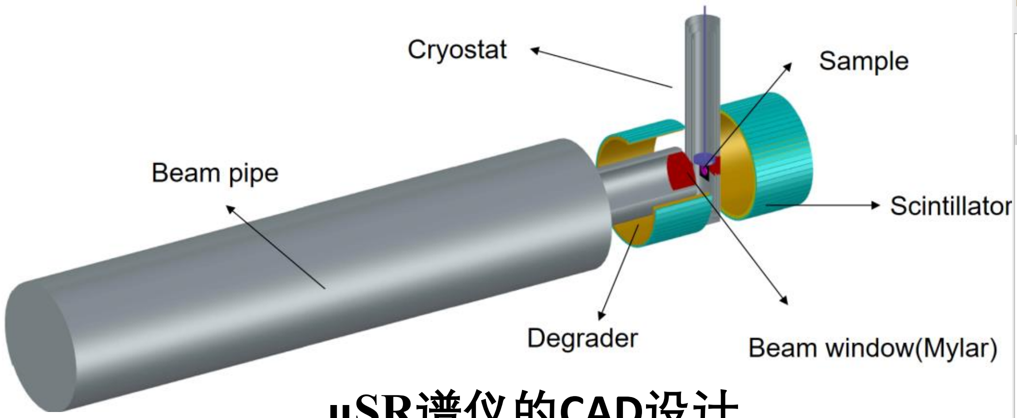




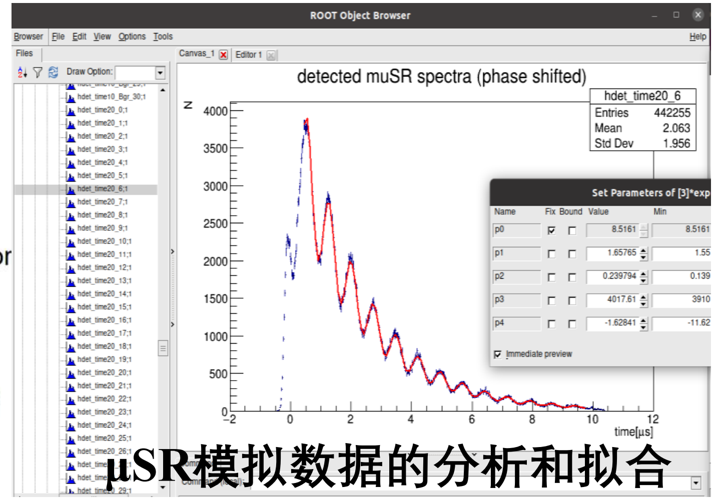


- Physics
  - *Magnetism*
  - *Superconductivity*
  - *Surface physics*
  - *Fundamental physics*
- Chemistry
  - *Molecular dynamics*
  - *Oxides*
  - *Muonium in materials*
- Materials
  - *Polymers*
  - *Semiconductors*
  - *Hydrogen storage material*
- Biology
  - *proteins*
  - *DNA*

R&D of μSR prototype: CRμSR

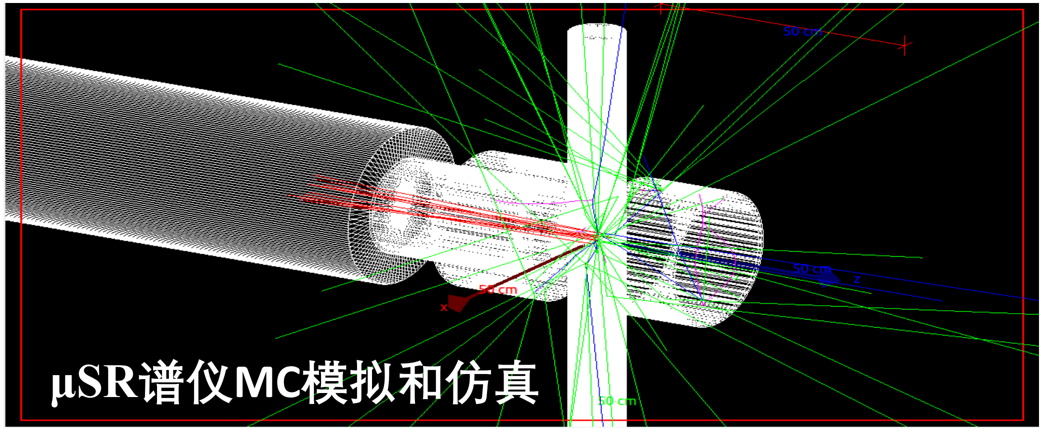


μSR谱仪的CAD设计



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

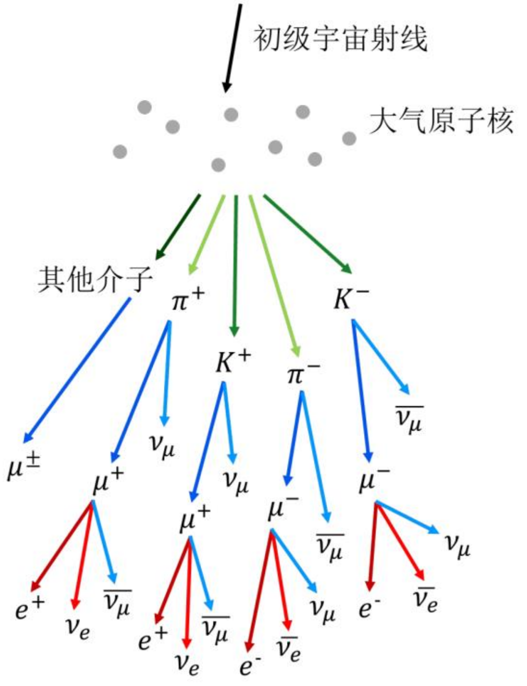
Credits: Mingchen Sun, Tao Yu, Yunsong Ning, Shihan Zhao…

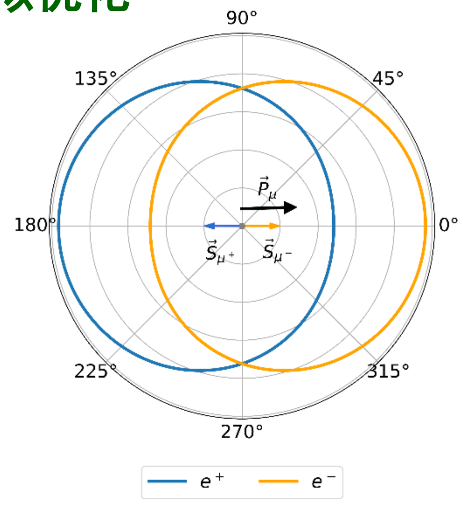
CRμSR to facilitate atmospheric neutrino physics

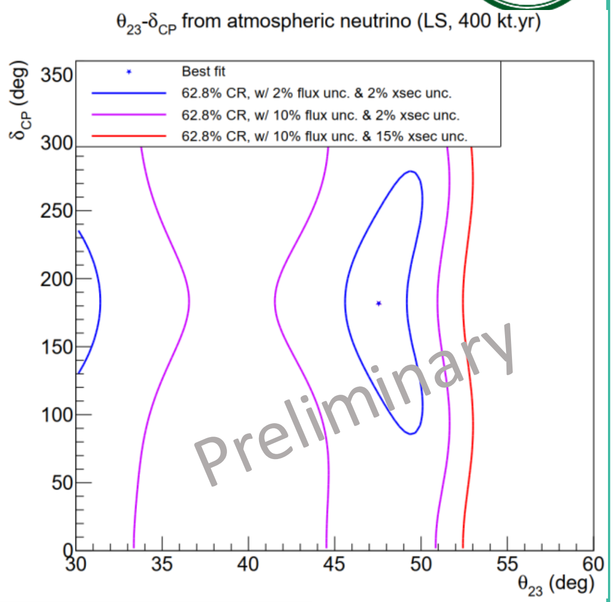
- **宇生缪子物理信息可用于大气中微子模拟优化**
  - 通量、能量、角分布、**极化**

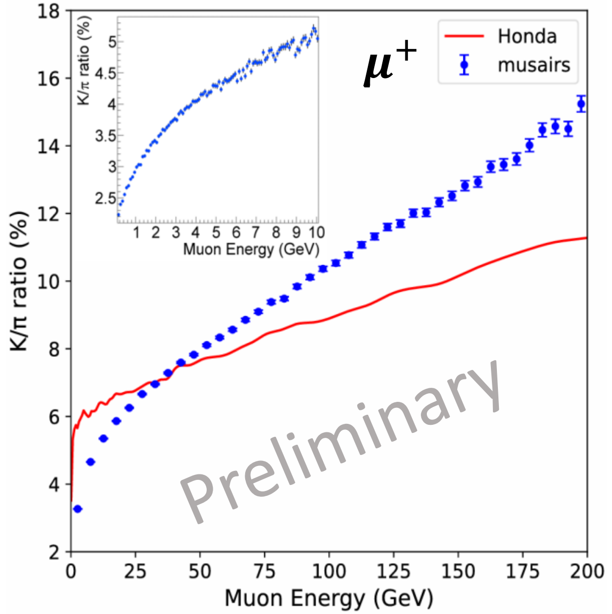
μ自旋极化 $\rightarrow \pi\ K \ \rightarrow \ \nu$

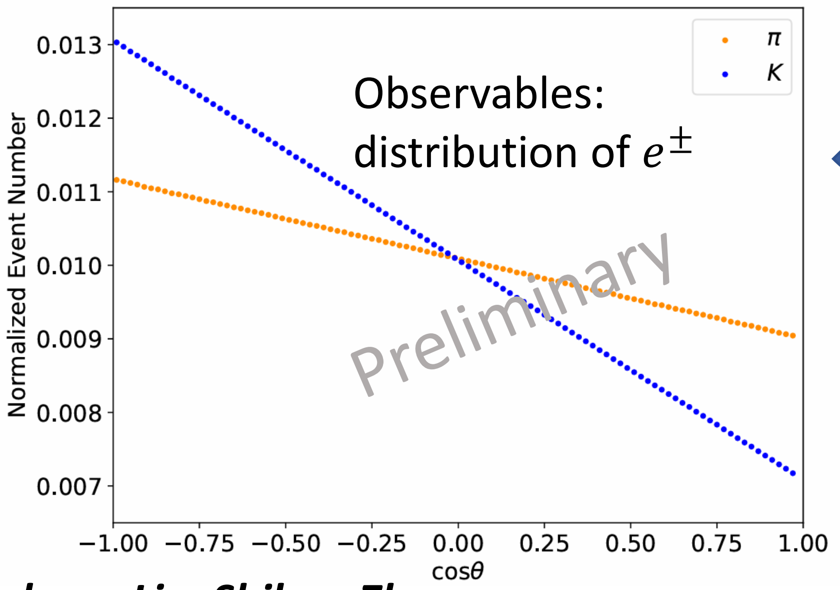
$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$
$$K^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$
$$\mu^{\pm} \rightarrow e^{\pm} + \nu_{e}(\bar{\nu}_{e}) + \bar{\nu}_{\mu}(\nu_{\mu})$$











$$e \leftrightarrow \mu \leftrightarrow \pi K \leftrightarrow \nu$$

Credits: Mingchen Sun, Ruixuan Gao, Hesheng Liu, Shihan Zhao…

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, 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)