正反缪子素转化实验MACE研发进展

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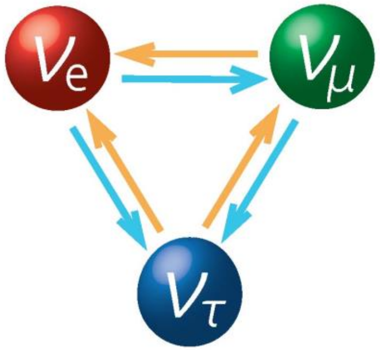
2024年10月28日，第二十一届全国重味物理和CP破坏研讨会，南华大学，湖南衡阳

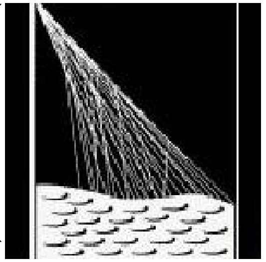
合作者：*SMOOTH实验室* *——陈羽、张炳隆、孙铭辰、陈思远、余涛、宁云松、赵诗涵、白爱毓、高睿萱、陈宏昆、袁意、刘和生、鲁桂昊、黄胤元、李禹烨、王志超、冼亮、姚赞杰等，**中科院近物所**—何源、贾欢、蔡汉杰、陈良文、陈旭荣、王荣等，**IHEP**—唐靖宇、袁野、李海波、吴琛、妙晗、张瑶、赵光等，**山东大学**—熊伟志等，**辽宁大学**—康晓坤、龚丽、程炜镔等，**湖南大学**—戴凌云、俞洁晟、张书磊、姚德良，**东南大学**—张永超，**南华大学**—王晓冬等*

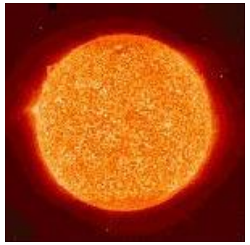
致谢： *__上海交通大学__—许金祥，__北京大学__—李强、张策等，__南开大学__—李佟、Lorenzo Calibbi，__南华大学__—郑波、李小华等*

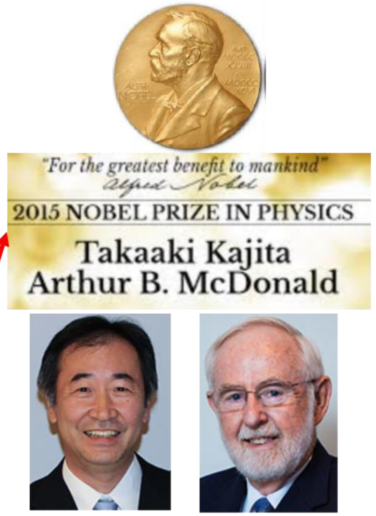
中微子已经振荡了，带电轻子们还远吗?



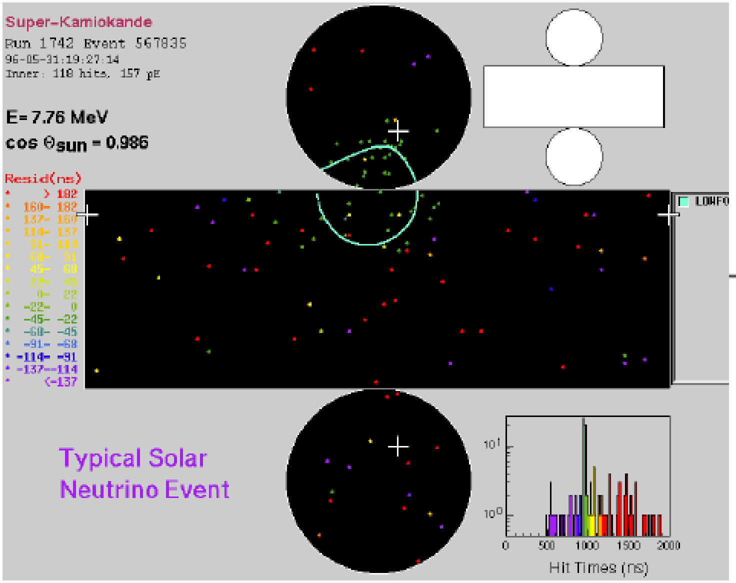
$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\, e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}\, e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}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

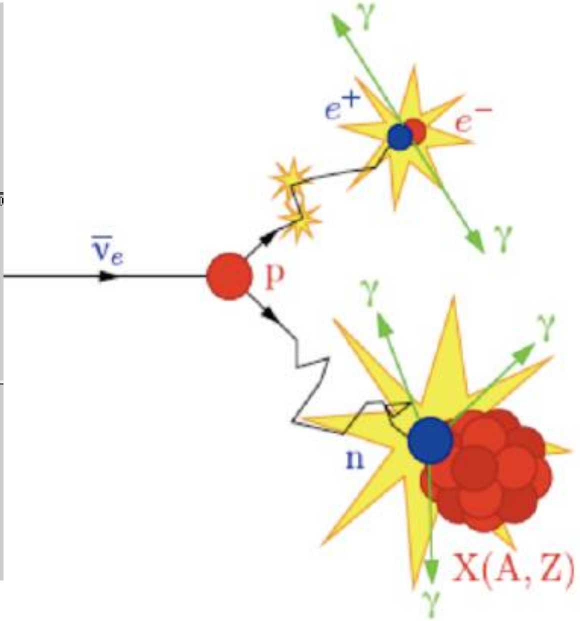
= () x (

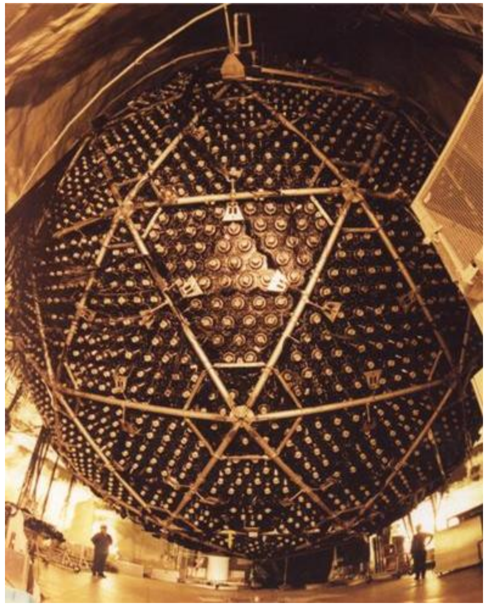
) x ()



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







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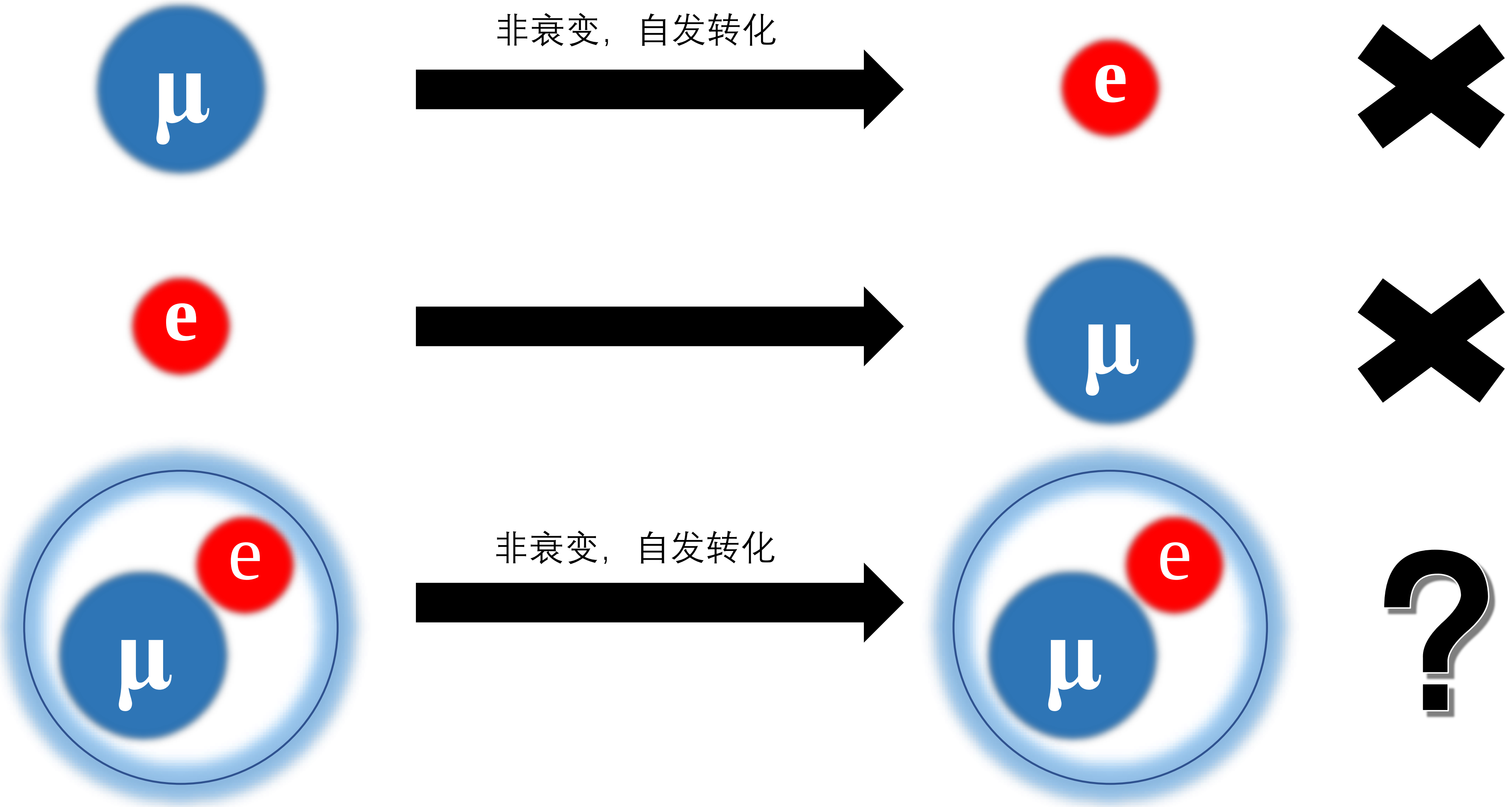

内容概述

- 为什么研究缪子物理?
- MACE实验的预研进展
- 本地缪子实验室建设

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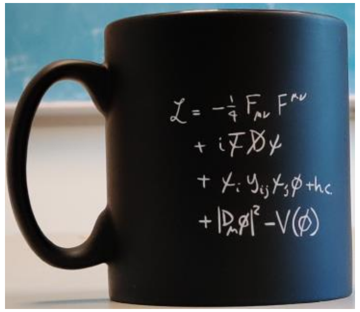
Symmetries of SM



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

(Strong Interaction)

(Unification of Weak and Electromagnetic)

$$\mathcal{G}^{\text{SM}}_{\text{local}} = SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$\mathcal{G}^{\text{SM}}_{\text{local}} \to SU(3)_c \times U(1)_{\text{EM}}$$

$$Q^i_L \sim (3,2)_{1/6}\,,\;\; U^i_R \sim (3,1)_{2/3}\,,$$

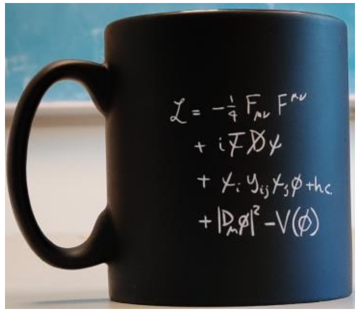
$$D^i_R \sim (3,1)_{-1/3}\,,\;\; L^i_L \sim (1,2)_{-1/2}\,,$$

$$\phi \sim (1,2)_{1/2}\,,\;\; \langle \phi^0 \rangle \equiv \frac{v}{\sqrt{2}} \simeq 174\text{GeV}$$

$$\mathcal{L}_{\text{SM}} = \mathcal{L}^{\text{SM}}_{\text{kinetic}} + \mathcal{L}^{\text{SM}}_{\text{EWSB}} + \mathcal{L}^{\text{SM}}_{\text{Yukawa}}$$

- simple and symmetric (g, g', g_s)
- EWSB, 2 params
- SM flavour dynamics, flavour parameters

Symmetries of SM



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(Strong Interaction)

Unification of Weak and Electromagnetic

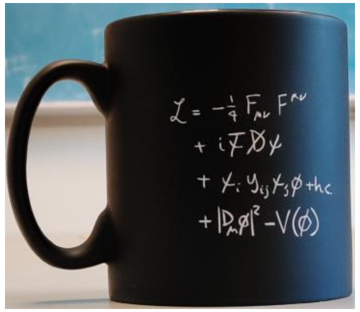
- Flavor physics
  - ➢ Within SM: weak and Yukawa interactions
- Flavor parameters in the quark sector
  - ➢ Within SM: 9 masses of charged fermions & 4 mixing parameters (3 angle + 1 CP phase)
- Flavor universal (flavor blind)
  - ➢ Within SM: QCD & QED
- Flavor diagonal
  - ➢ Within SM: Yukawa interactions

	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

Change the sign for all anti-leptons

轻子与夸克的flavor physics互补

Symmetries of SM



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  - ➢ Within SM: QCD & QED
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  - ➢ Within SM: Yukawa interactions

- Rephasing lepton and quark fields:

$$U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$$
$$=$$
$$\cancel{U(1)_{B+L}} \times U(1)_{B-L} \times U(1)_{L_\mu - L_\tau} \times U(1)_{L_\mu + L_\tau - 2L_e}\,.$$

- Broken non-perturbatively, but unobservable. ['t Hooft, PRL '76]
- True accidental global symmetry:

$$\boxed{U(1)_{B-L} \times U(1)_{L_\mu - L_\tau} \times U(1)_{L_\mu + L_\tau - 2L_e}\,.}$$

Lepton flavor conservation!

Prediction of Standard Model.

cLFV offers a chance of new physics discovery

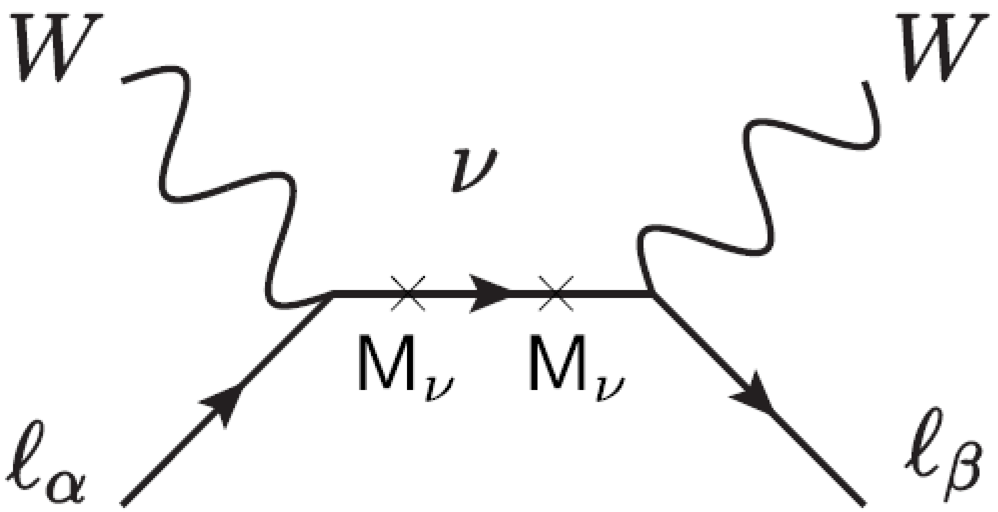
中微子振荡=轻子味道破坏?

- 中微子振荡指向有质量中微子→$M_\nu \neq 0$
- 因此，我们需要轻子味道破坏cLFV

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

- 但是， ~eV量级中微子质量→强烈压低cLFV

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



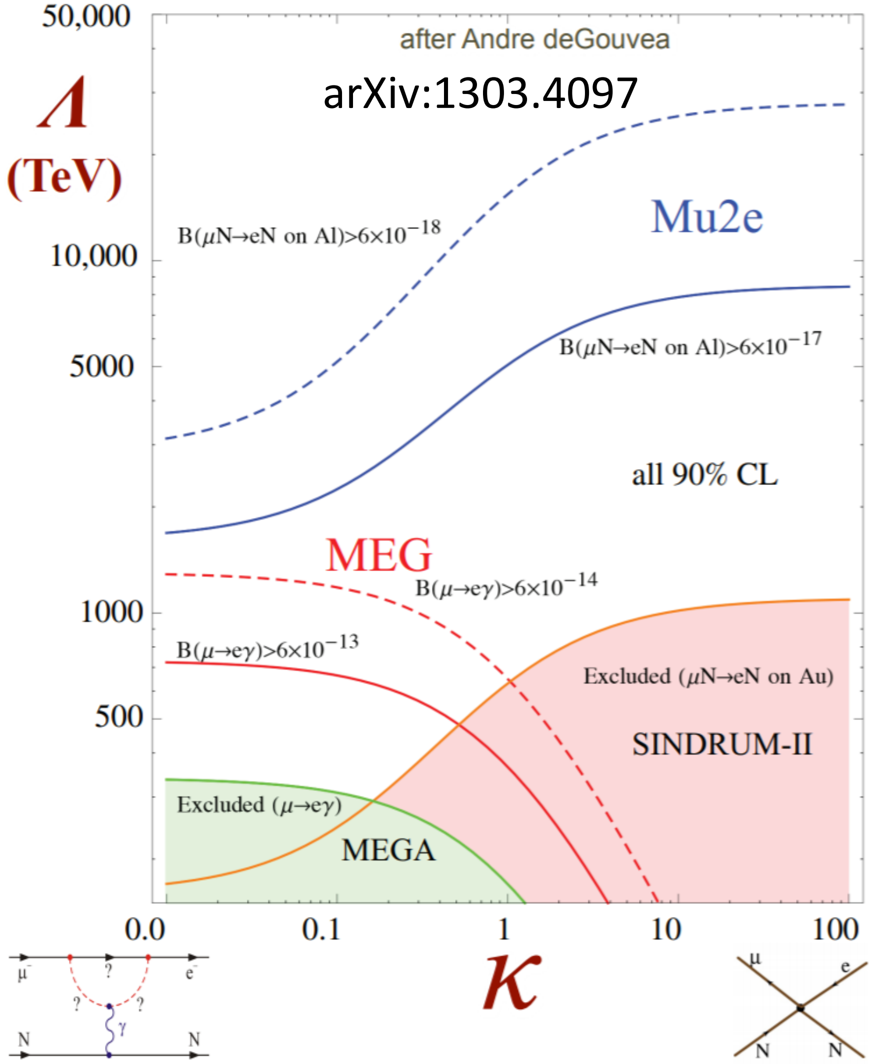
- 许多中微子质量模型，如seesaw模型等，预言可观测的cLFV!

cLFV判选中微子质量起源seesaw机制

高亮度前沿/高精度前沿

- **带电轻子味道破坏实验cLFV：**
  - Mu2e(美国) $\mu^- + \mathrm{Al} \to e^- + \mathrm{Al}$
  - COMET(日本)
  - MEG(瑞士) $\mu^+ \to e^+\gamma$
  - Mu3e(瑞士) $\mu^+ \to e^+e^-e^+$

- **缪子性质的精密测量：**
  - 瑞士PSI实验室， MuLan和FAST实验精确测量μ子寿命。
  - 瑞士PSI实验室， MuCap实验测量μ子俘获的耦合常数。
  - MuSun实验精确测量μ子电弱相互作用，同时开展μ子极化测量。
  - 加拿大TRIUMF的TWIST实验精确测量μ子弱衰变的关键参数。
  - 美国费米国家实验室的g-2实验精确测量μ子磁矩和J-PARC g-2实验。
  - J-PARC的MeuSEUM实验精确测量muonium超精细结构。



低能cLFV实验结果，与high energy frontier互补

高亮度前沿/高精度前沿

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  - Mu2e(美国)
  - COMET(日本)　　$\mu^- + \mathrm{Al} \to e^- + \mathrm{Al}$
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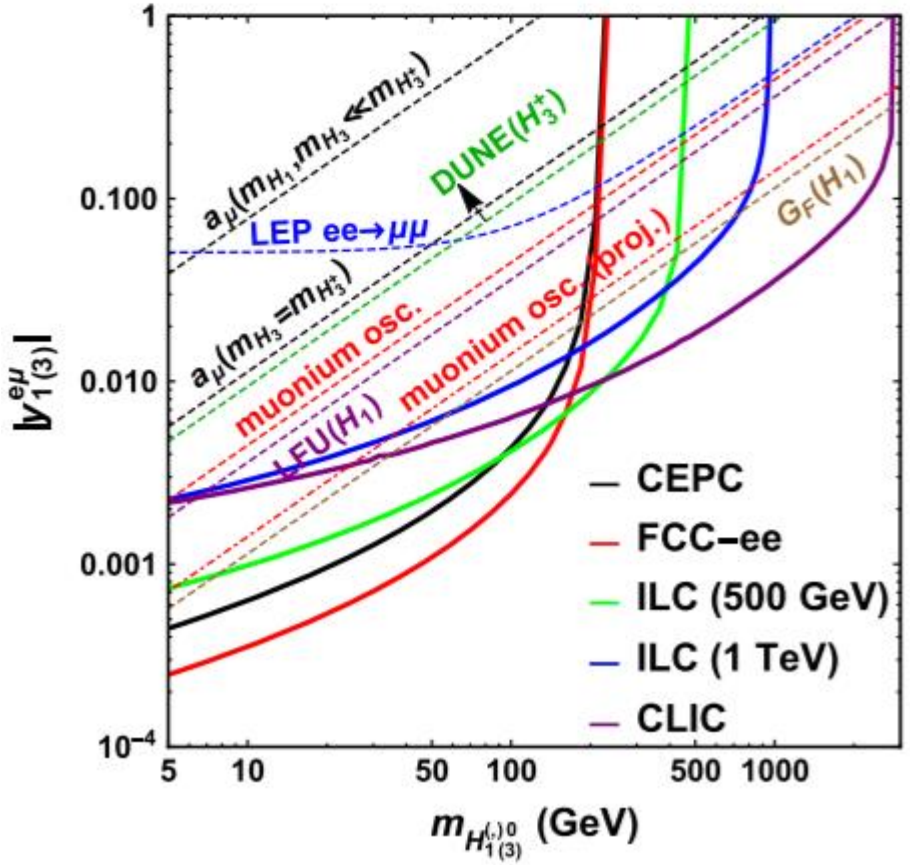


REF: *Tong Li, Michael A. Schmidt. Phys.Rev.D* 100 (2019) 11, 115007

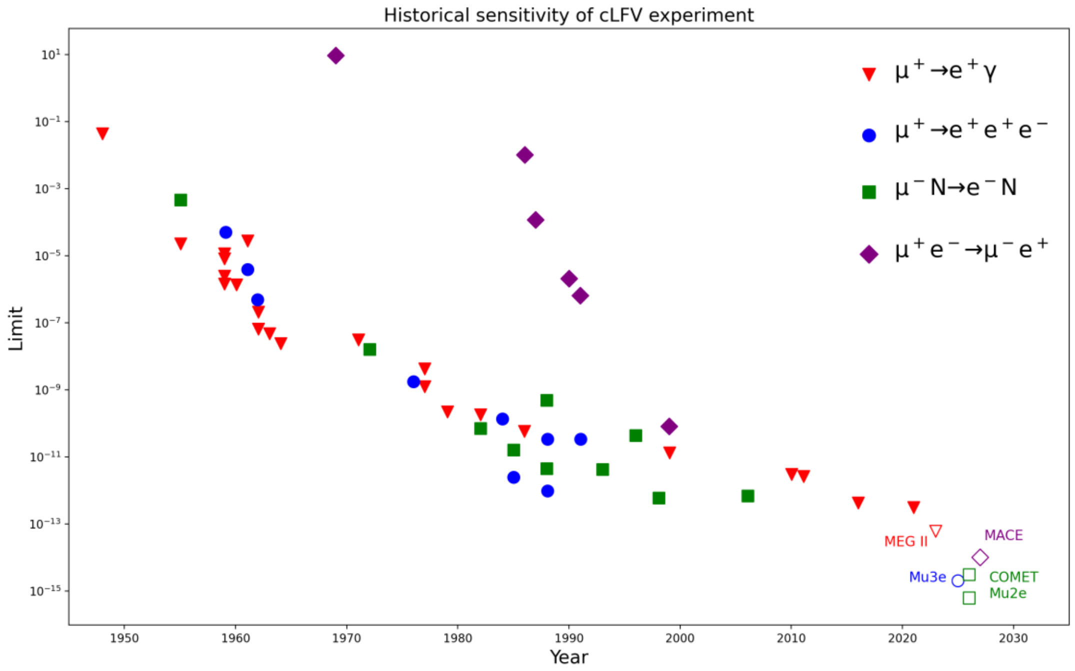
- **低能cLFV实验结果，与high energy frontier互补**
- **cLFV与neutrino physics互补**

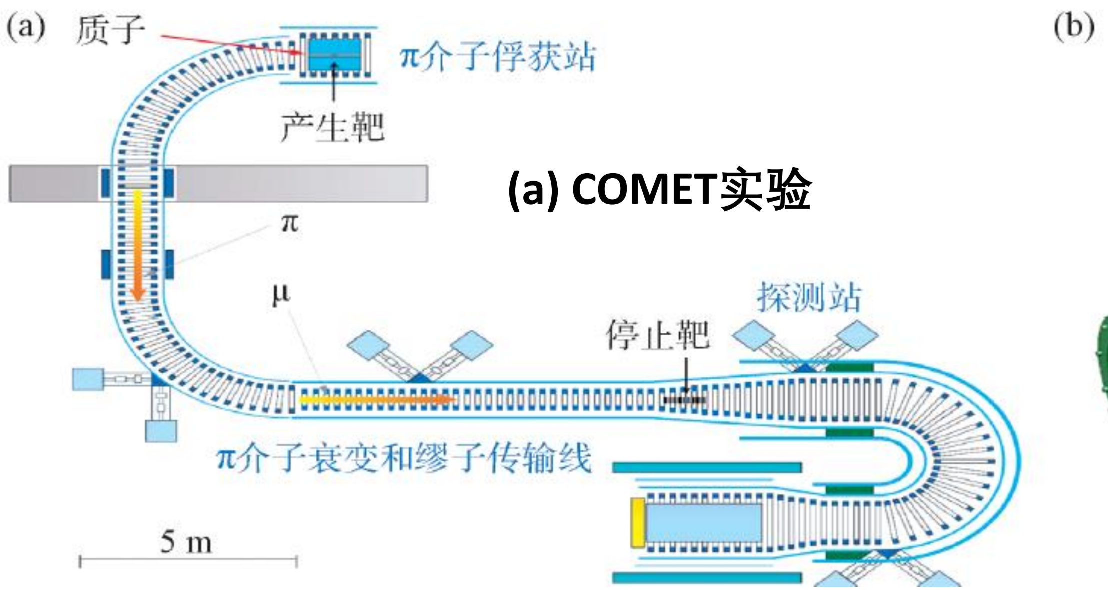
高亮度前沿/高精度前沿

- 带电轻子味道破坏实验cLFV：
  - ➢ Mu2e(美国)
  - ➢ COMET(日本)

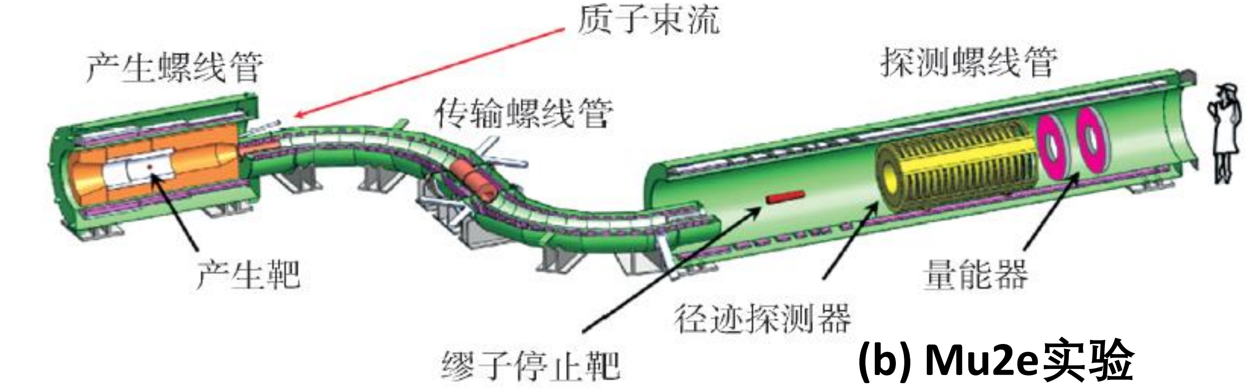
  $$\mu^- + Al \rightarrow e^- + Al$$

  - ➢ MEGII(瑞士) $\mu^+ \rightarrow e^+\gamma$
  - ➢ Mu3e(瑞士) $\mu^+ \rightarrow e^+e^-e^+$





(a) COMET实验



(b) Mu2e实验

高亮度前沿/高精度前沿

- **带电轻子味道破坏实验cLFV：**
  - Mu2e(美国)
  - COMET(日本)

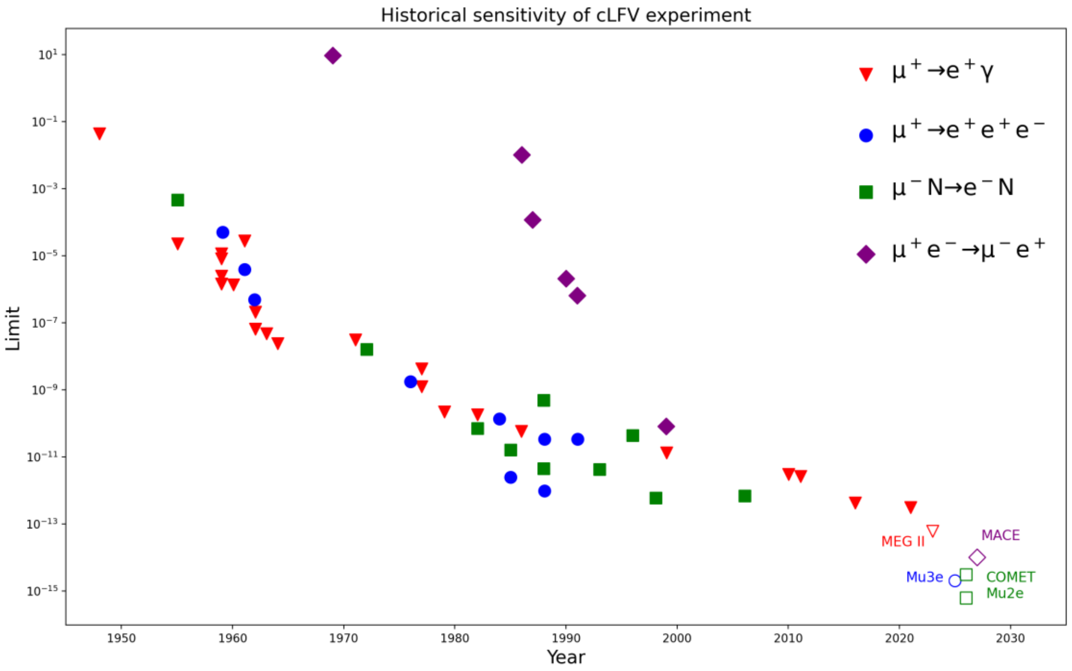
    $$\mu^- + \mathrm{Al} \to e^- + \mathrm{Al}$$

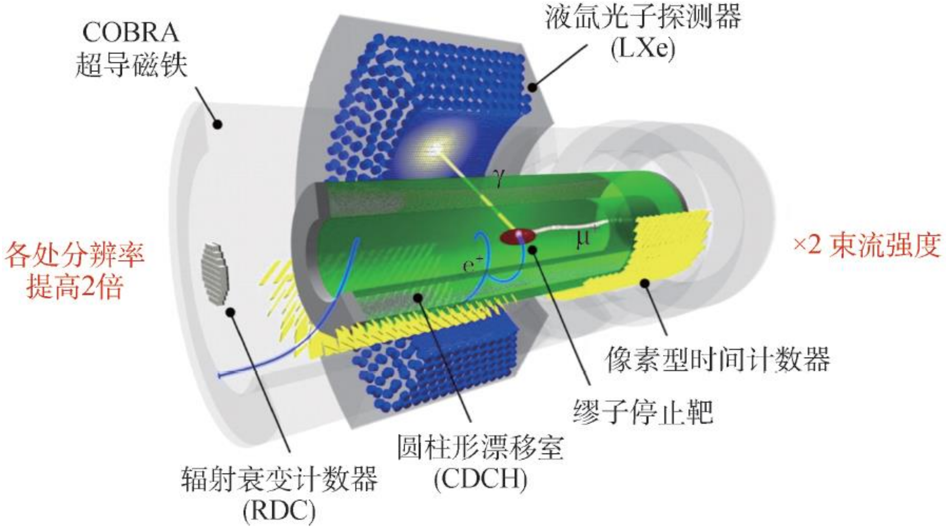
  - **MEGII(瑞士)**

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

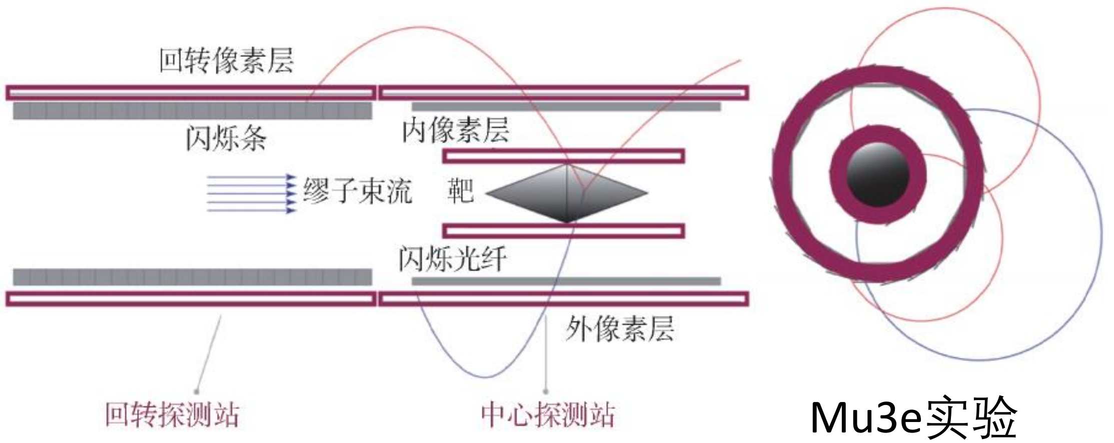
  - **Mu3e(瑞士)**

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



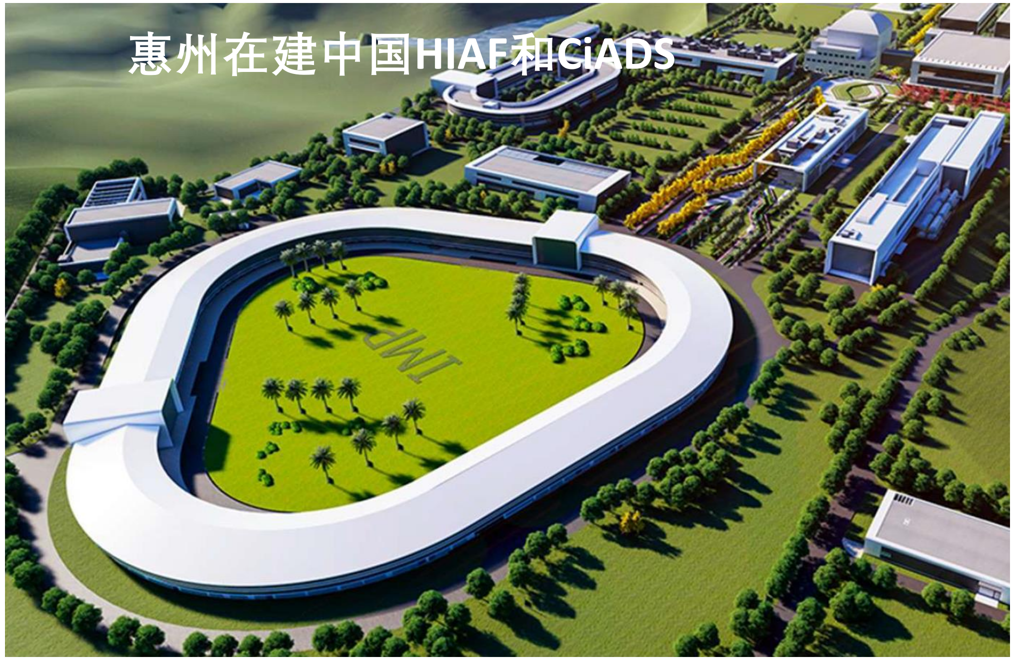


MEGII实验



Mu3e实验

粤港澳大湾区是强流加速器的聚集地



Ref：中科院高能所，王生研究员报告

Ref：中科院近物所，东江实验室詹文龙院士报告

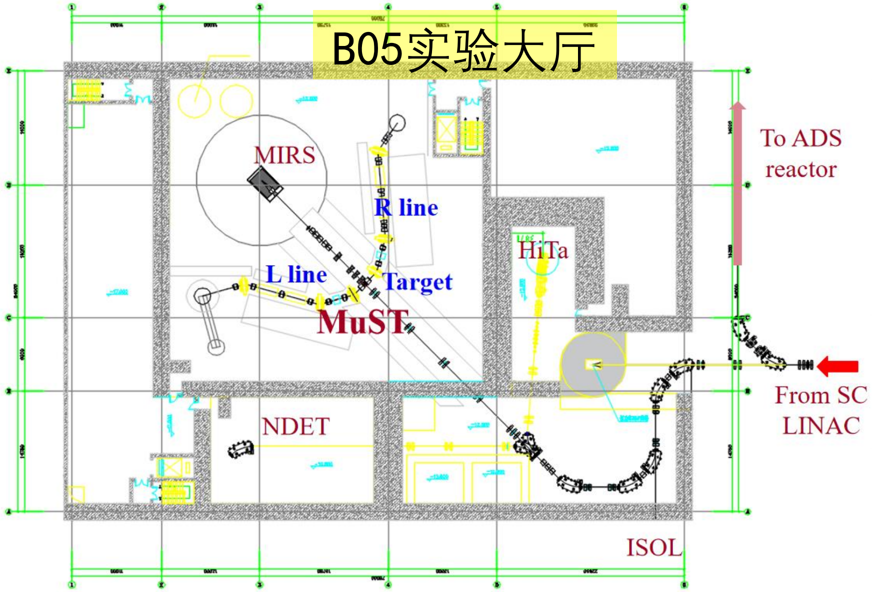
(1）国际上加速器缪子源，已有美国FNAL，瑞士PSI，日本J-PARC，英国ISIS

(2）依托粤港澳大湾区的强流加速器（ CSNS, CiADS, HIAF），即将建设国内首个强流加速器缪子源？

(3）基于加速器缪子源开展前沿研究?

基于CiADS的缪子源

- 加速器驱动核燃料嬗变装置CiADS，反应堆年运行3个月，建设MuST平台



H.-J Cai et al, **Phys.Rev.AB** 27, 023703, 2024

束流功率 (kW)	靶方案	束线聚焦方案	缪子强度 (μ^+/s)
300	石墨转靶	螺线管+四极铁	>1E8
		全螺线管	>5E8
3000	液态锂靶	螺线管+四极铁	>2E9
		全螺线管	>1E10

2025～2026年

25 kW:
500MeV & 50μA

- 加速器建设
- 束流调试

2026～2027年

250 kW:
500MeV & 500μA

- 加速器束流稳定性试验
- 缪子束流打靶试验
- 1个靶站、两条缪子束线

2027~2030年

2.5 MW:
500MeV & 5mA

- 2.5 MW 高功率调试
- 长期运行2.5 MW束流
- 2个靶站、2调缪子束线
- 缪子束流及其多学科应用

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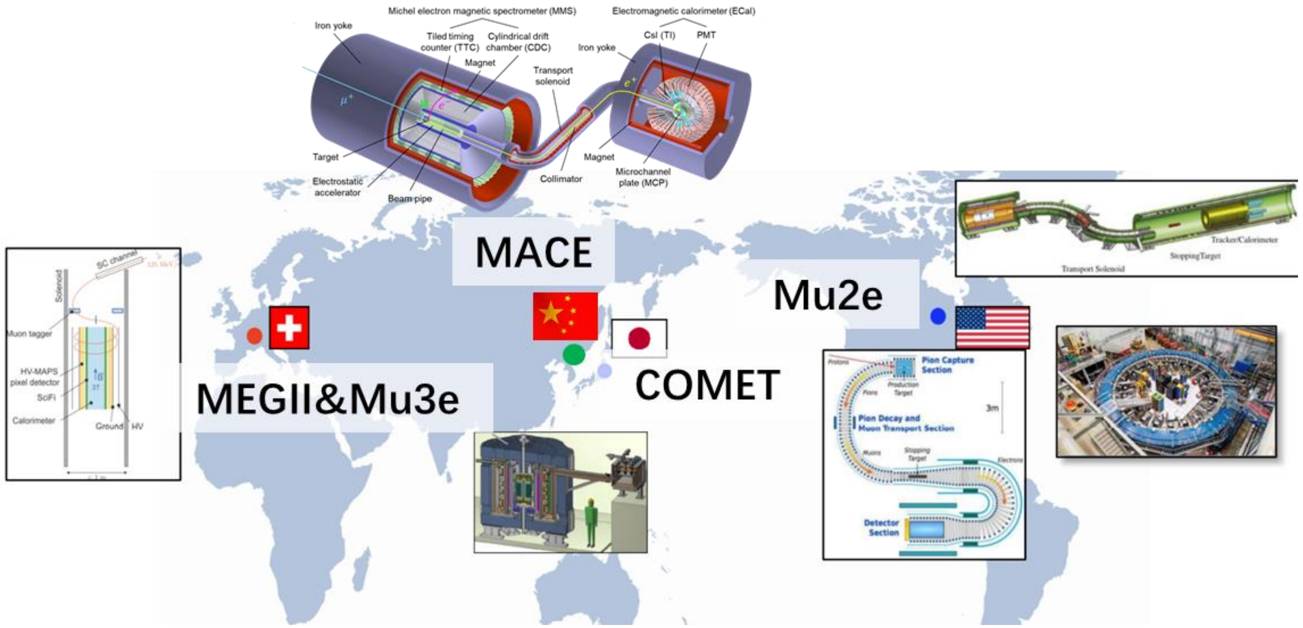
国际上各种类型cLFV实验

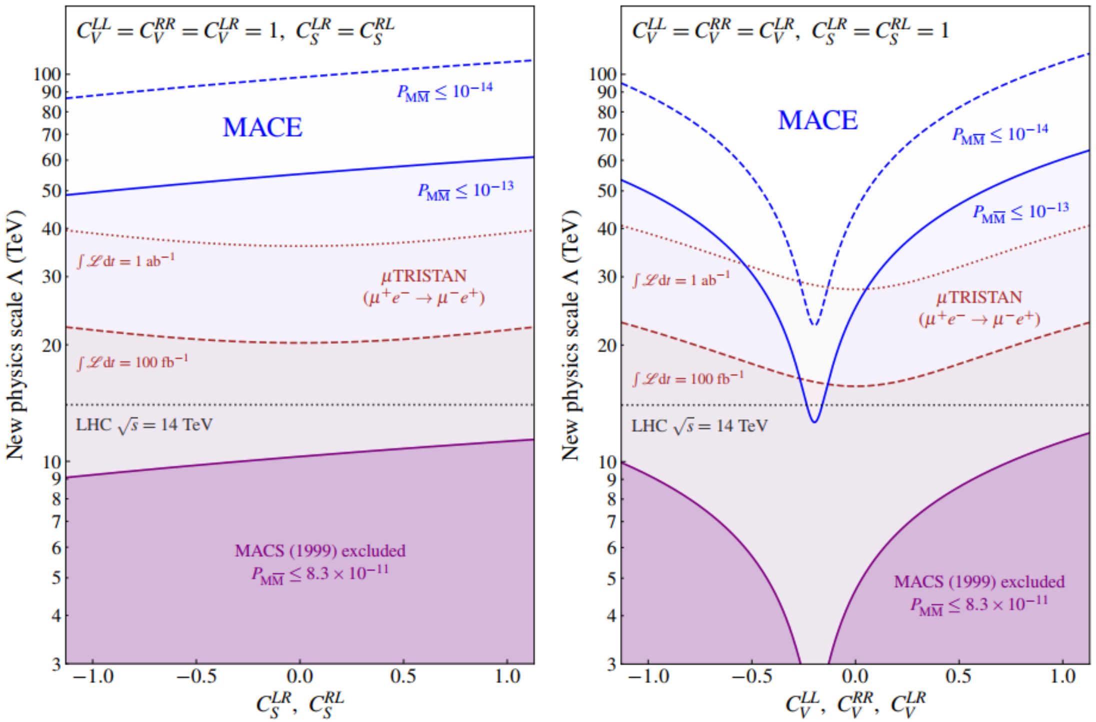
实验	机构	物理过程	工作进展
MEGII	PSI（瑞士）	$\mu^+ \to e^+\gamma$	正在采集数据
Mu2e	费米实验室（美国）	$\mu^-\mathrm{N} \to e^-\mathrm{N}$	正在安装，即将运行
COMET	J-PARC（日本）	$\mu^-\mathrm{Al} \to e^-\mathrm{Al}$	正在安装，即将运行
Mu3e	PSI（瑞士）	$\mu^+ \to e^+e^-e^+$	正在调试
MACS	PSI（瑞士）	$\mu^+e^- \to \mu^-e^+$	1999年完成，当今最佳结果

- 正反缪子素转换是重要的cLFV过程，1999年PSI将转换概率限制在8.3×10^{-11}后的20年，无新实验提出；
- 随着束流亮度提升和探测器技术进步，20年后在这一领域有望取得突破。



总结：MACE实验的研究动机

- 中微子已经振荡，带电轻子们振荡不远了？



- 科技前沿研究的需要：
  1) cLFV判选中微子质量起源seesaw机制；
  2) 带电轻子和中微子共享Yukawa couplings，cLFV与neutrino physics互补；
  3) 轻子cLFV与夸克的flavor physics互补；
  4) 低能cLFV实验，与high energy frontier互补；
  5) 正反缪子素转化实验，已多年停滞不前，机遇和挑战；

- 国家重大科研设施的契机：
  - ➢ 我国即将建设强流加速器缪子源，什么样的物理值得做？另辟蹊径做MACE实验！

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  - ➢ 美国费米国家实验室的g-2实验精确测量μ子磁矩和J-PARC g-2实验。
  - ➢ J-PARC的MeuSEUM实验精确测量muonium超精细结构。

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 ($\mu^+ \rightarrow e^+e^-e^-$), MEG-II ($\mu^+ \rightarrow e^+\gamma$) and Mu2e/COMET ($\mu^-N \rightarrow e^-N$). MACE aims at a sensitivity of P($\mu^+e^- \rightarrow \mu^-e^+$) $\sim \mathcal{O}(10^{-13})$, 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]
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[2]*National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, 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

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.

Snowmass LOI后的国际反响

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 $\mu^- N \rightarrow e^+ N$
- Muonium – antimuonium (MACE)
- General Low Energy Muon Facility (FNAL)
- Light new physics in muon decays (MEG-Fwd)

Bertrand将MACE实验列为下一代轻子味道破坏重要实验方案

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 ($\mu^+ \rightarrow e^+e^-e^-$), MEG-II ($\mu^+ \rightarrow e^+\gamma$) and Mu2e/COMET ($\mu^- N \rightarrow e^- N$). MACE aims at a sensitivity of $P(\mu^+e^- \rightarrow \mu^-e^+) \sim \mathcal{O}(10^{-13})$, 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

Snowmass LOI后的国际反响

Detectors and concepts for future CLFV experiments

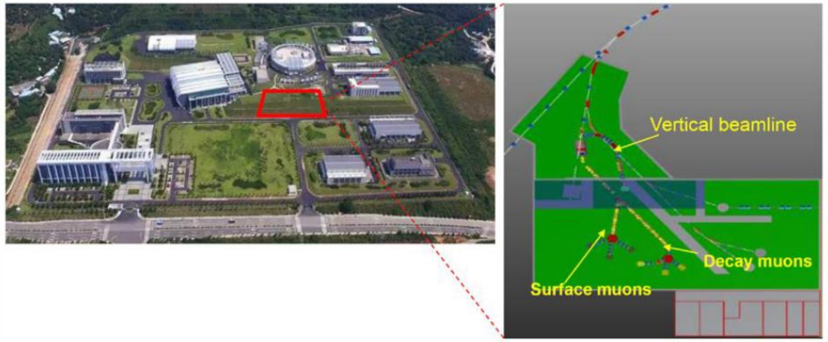
Bertrand Echenard
Caltech

NuFact 2021
Cagliari - September 2021

MACE at EMuS

Jian Tang
(Snowmass 2021 RPP meeting)

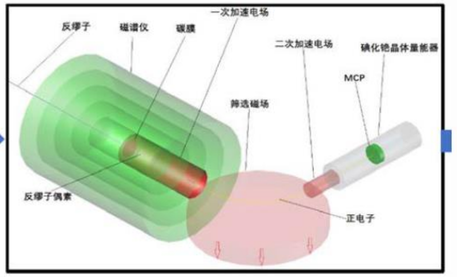
EMuS – new muon facility in China

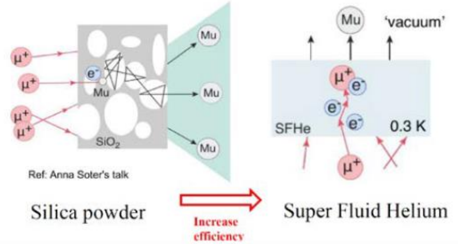


	Proton driver [MW]	Surface muons			Decay muons		
		Intensity [1E6/s]	Polarization [%]	Spread [%]	energy [MeV/c]	Intensity [1E6/s]	Spread [%]
PSI	1.3	420	90	10	85-125	240	3
ISIS	0.16	1.5	95	<15	20-120	0.4	10
RIKEN/RAL	0.16	0.8	95	<15	65-120	1	10
JPARC	1	100	95	15	33-250	10	15
TRIUMF	0.075	1.4	90	7	20-100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



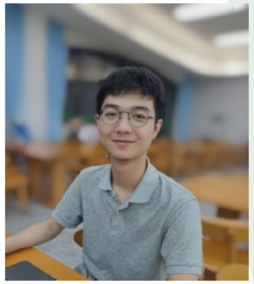


On-going physics studies and detector R&D

国际研讨会的邀请报告

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*

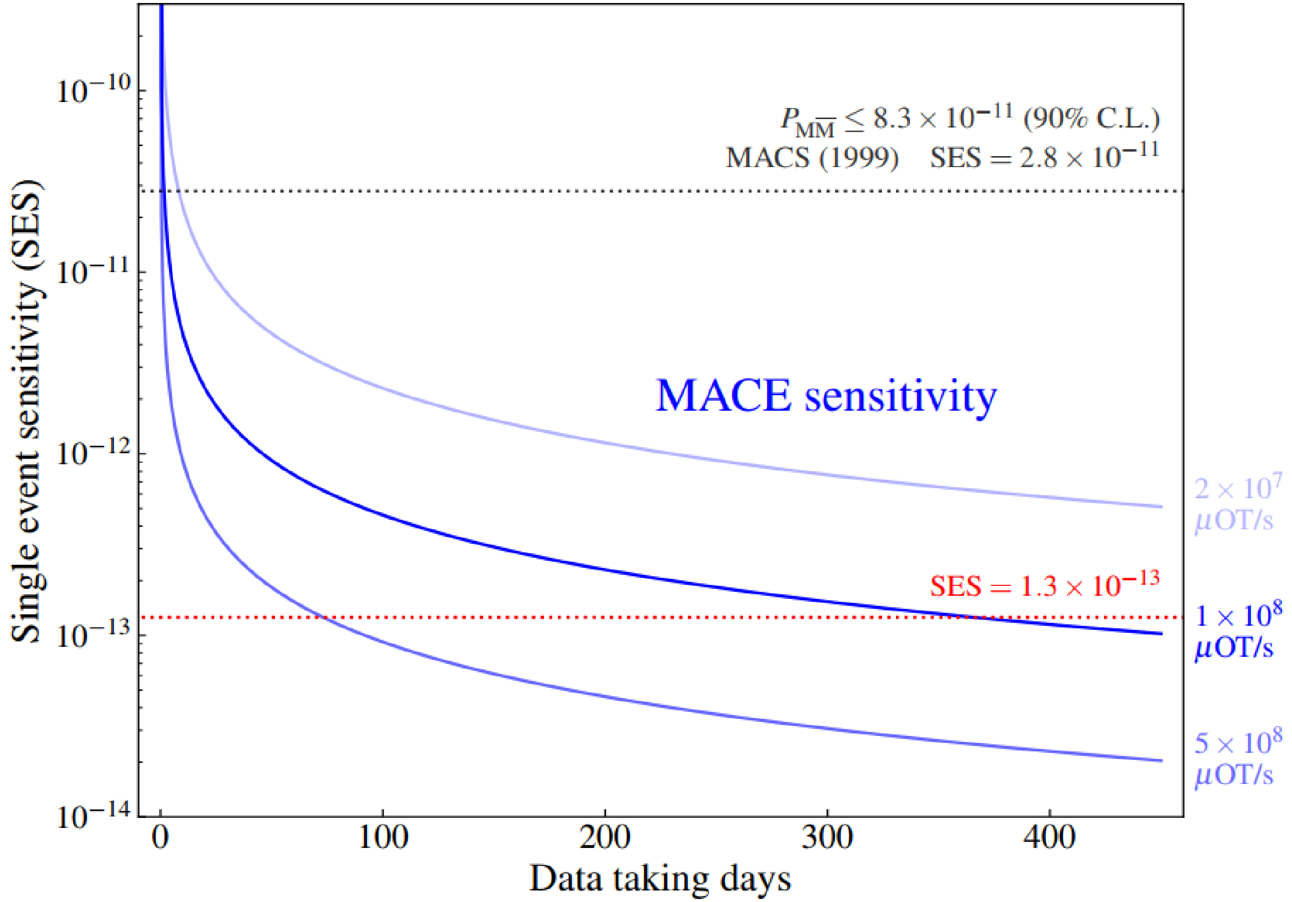
[3]*Research Center of Nuclear Physics, Osaka University, Japan*

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

- ICHEP分会场报告，受邀参加美国费米实验室未来缪子源研讨会，线上报告，会议文集https://arxiv.org/abs/2309.05933
- NuFact国际顾问委员会成员

受邀参加德国海德堡大学CLFV2023，大会报告

基础前沿研究从“0”到“1”的突破口



- 最新的实验结果是1999年PSI完成，缪子通量 $8 \times 10^6 \mu^+/s$。
- 需求：我国加速器缪子源提供 $10^8 \mu^+/s$，表面缪子E=29.8 MeV，动量展宽<10%?
- 20+年，探测器技术长足进步；
- 我国加速器技术和粒子探测突飞猛进；
- 目前国际上没有正在进行的相关实验；
- 新一代实验探测灵敏度相比1999年PSI实验结果，预期提高**两个数量级以上**!
- MACE实验有望走到世界前列!

MACE实验: Muonium to Antimuonium Conversion Experiment.

MACE实验概念设计报告

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

8月26日完成CDR评审

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]

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[11] *School of Physics, Southeast University, Nanjing 211189, China*
[12] *State Key Laboratory of Particle Detection and Electronics, Beijing 100049, China*
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(Dated: October 25, 2024)

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

CONTENTS

内容概述

- 前期科研进展的介绍
- 为什么研究缪子物理?
- MACE实验的研究进展

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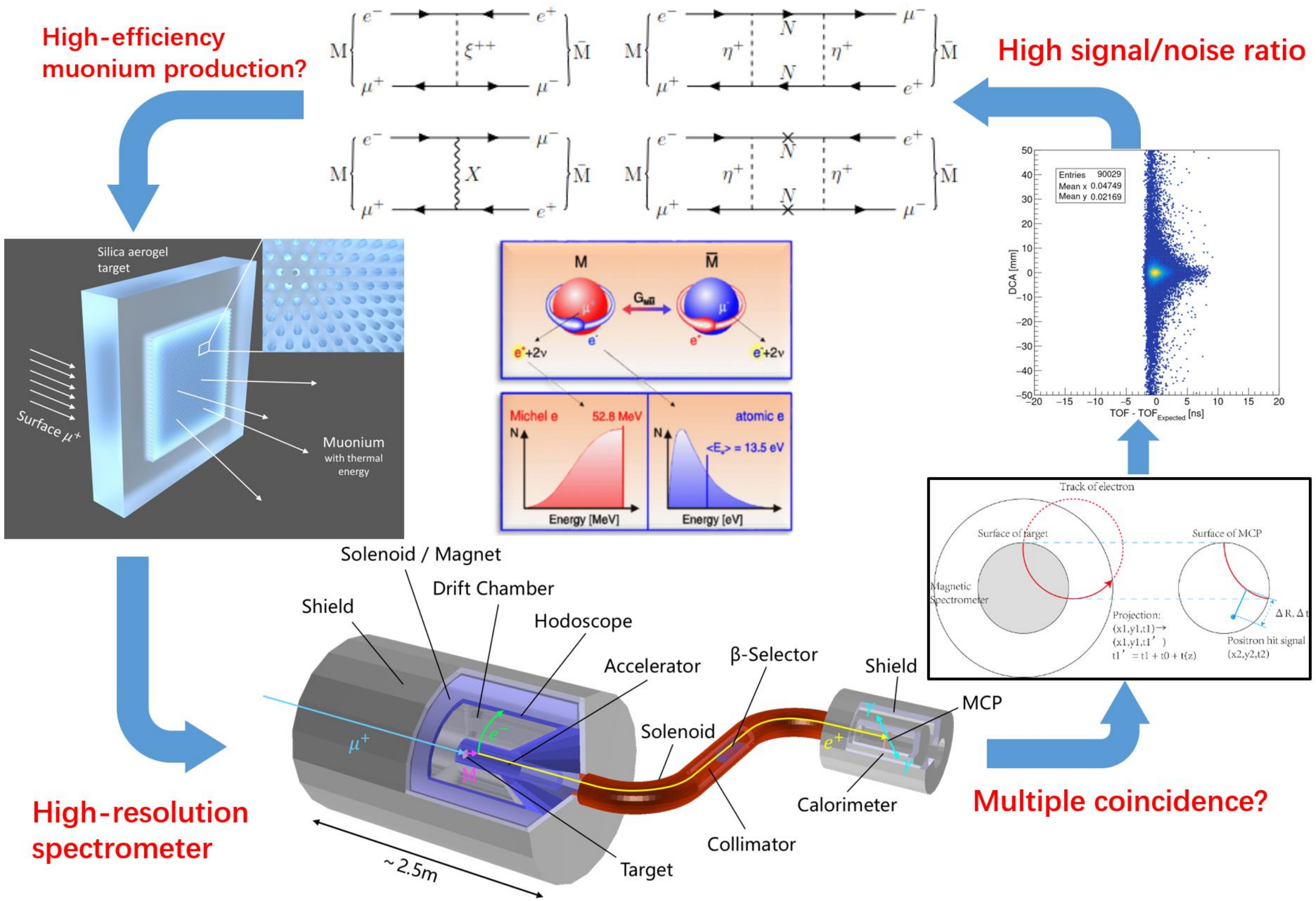
MACE实验关键技术路线

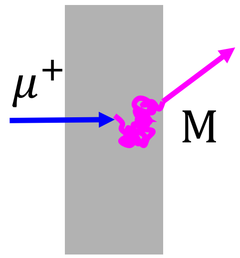
Muonium-to-Antimuonium Conversion Experiment



SiO_2气凝胶材料中缪子素的产生和输运

μ^+ (~1MeV) scattering
↓
Electron capture (~1keV)
↓
Muonium (~100eV)
Epithermal scattering
↓
Random walk (room temp.)
↓
Emission to vacuum

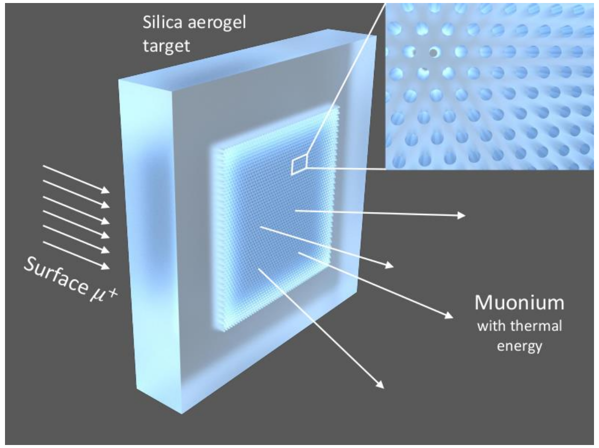
MC simulation for muonium transport has been developed under the MACE offline software framework.



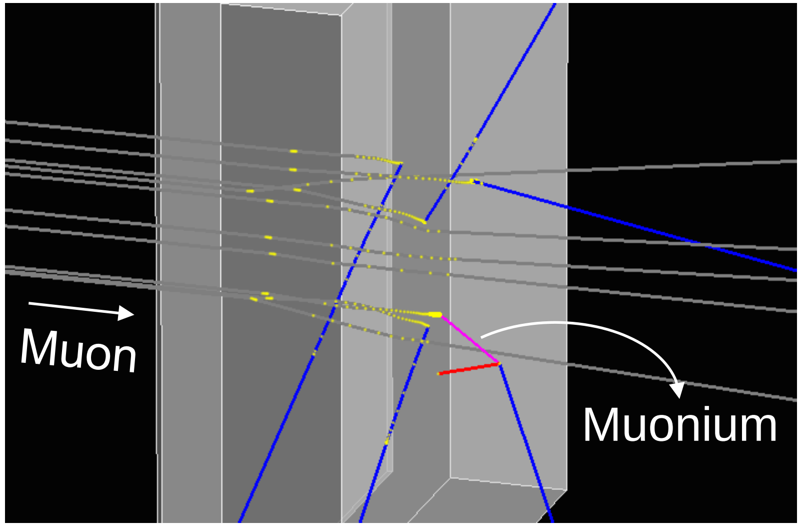
① Geant4 low-energy EM process.

② Geant4 AtRest process, modeled phenomenologically.

③ Random walk approach to thermal muonium tracking.



模拟的单个
缪子素产生
并逸出事例:



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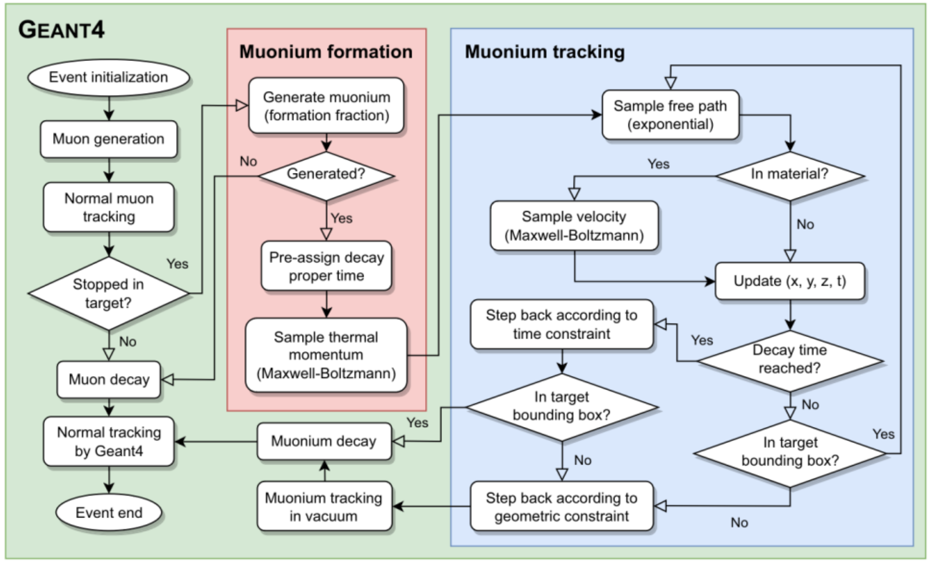
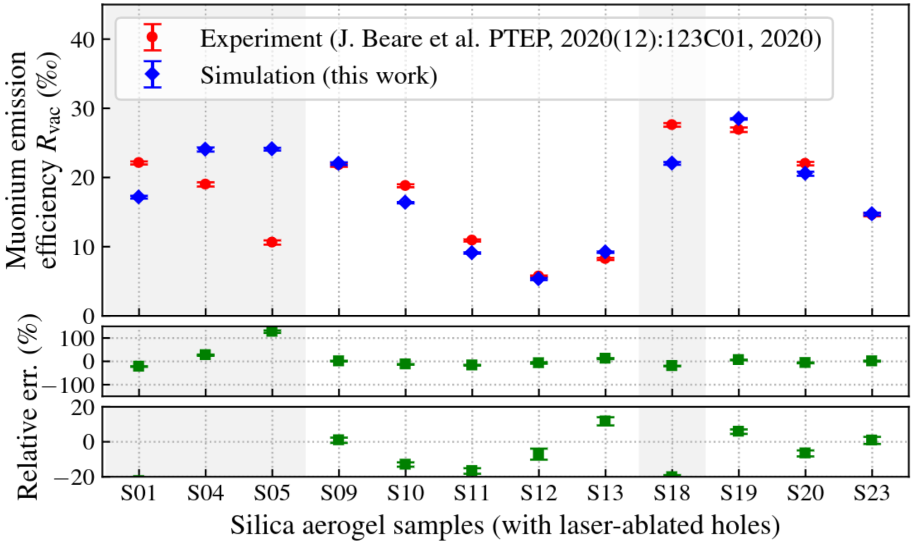
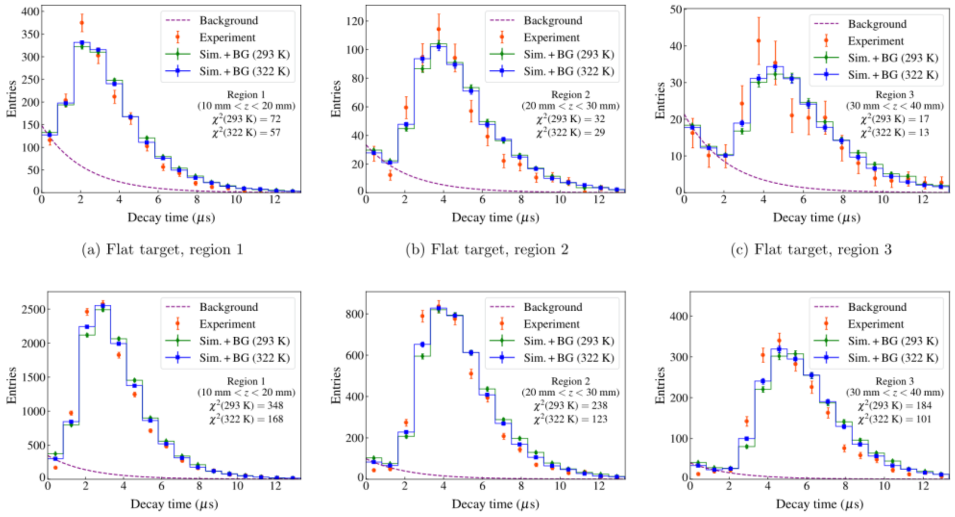
SiO_2气凝胶靶材缪子素产额优化

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

- Intensity of in-vacuum muonium source: $I_{\mathrm{M}}^{\mathrm{vac}} = I_{\mathrm{beam}} Y_{\mu\to\mathrm{M}}$
- $Y_{\mu\to\mathrm{M}}$ can be improved by utilizing porous materials, ideally perforated silica aerogel.
- 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.





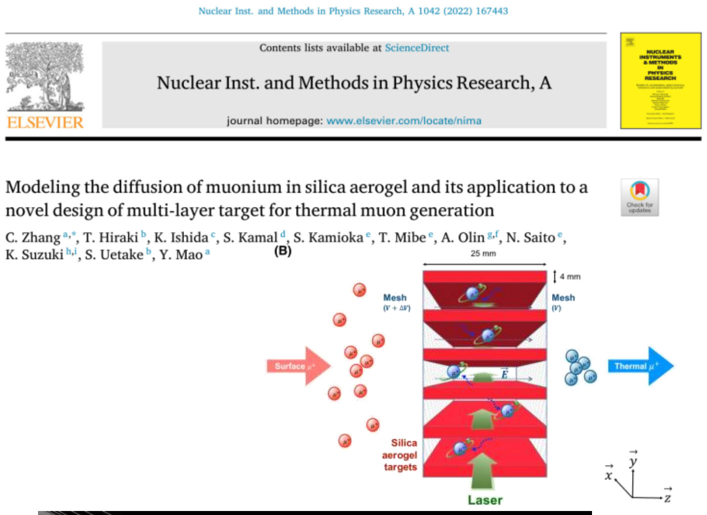


(a) Flat target, region 1 (b) Flat target, region 2 (c) Flat target, region 3

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

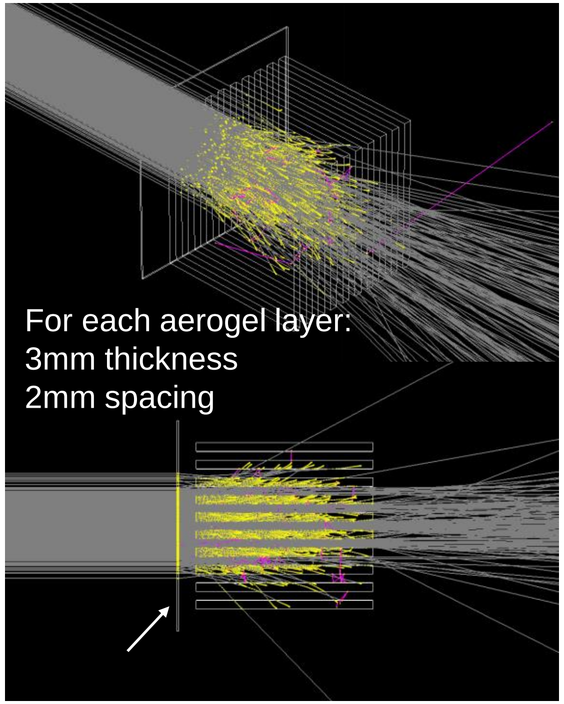
SiO_2气凝胶靶材缪子素产额优化

- A novel multi-layer design is expected considerably increase muonium yields in a vacuum (Ce Zhang et al.).
- The simulation result achieves
  - ✓ $Y_{\mu\rightarrow\mathrm{M}} = N_{\mathrm{M}}^{\mathrm{vac}} / N_{\mu}^{\mathrm{total}} = 4.08\%$
  - ✓ 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:
  - ✓ $I_{\mathrm{M}}^{\mathrm{vac}} = I_{\mathrm{beam}} Y_{\mu\rightarrow\mathrm{M}} = 4 \times 10^6/\mathrm{s}$, 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

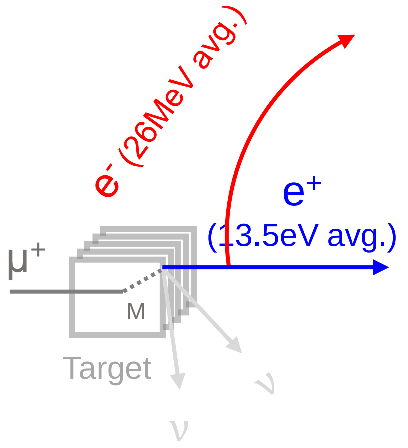
C. Zhang[a,*], T. Hiraki[b], K. Ishida[c], S. Kamal[d], S. Kamioka[e], T. Mibe[e], A. Olin[g,f], N. Saito[e], K. Suzuki[h,i], S. Uetake[b], Y. Mao[a]



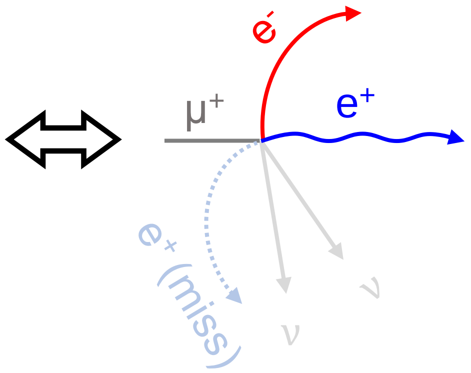
Shihan Zhao and Jian Tang, Optimization of muonium yield in perforated silica aerogel, **Phys. Rev. D** 109, 072012

MACE实验信号和本底鉴别

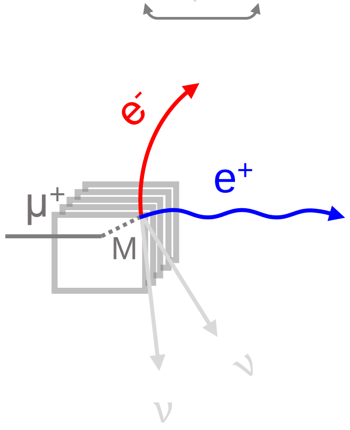
Signal:
fast e^- + slow e^+



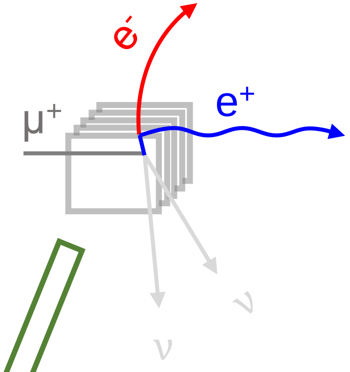
1. Internal conv. (IC) decay
- ☐ $\mu^+ \to e^+e^-e^+\bar{\nu}_\mu\nu_e$



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



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



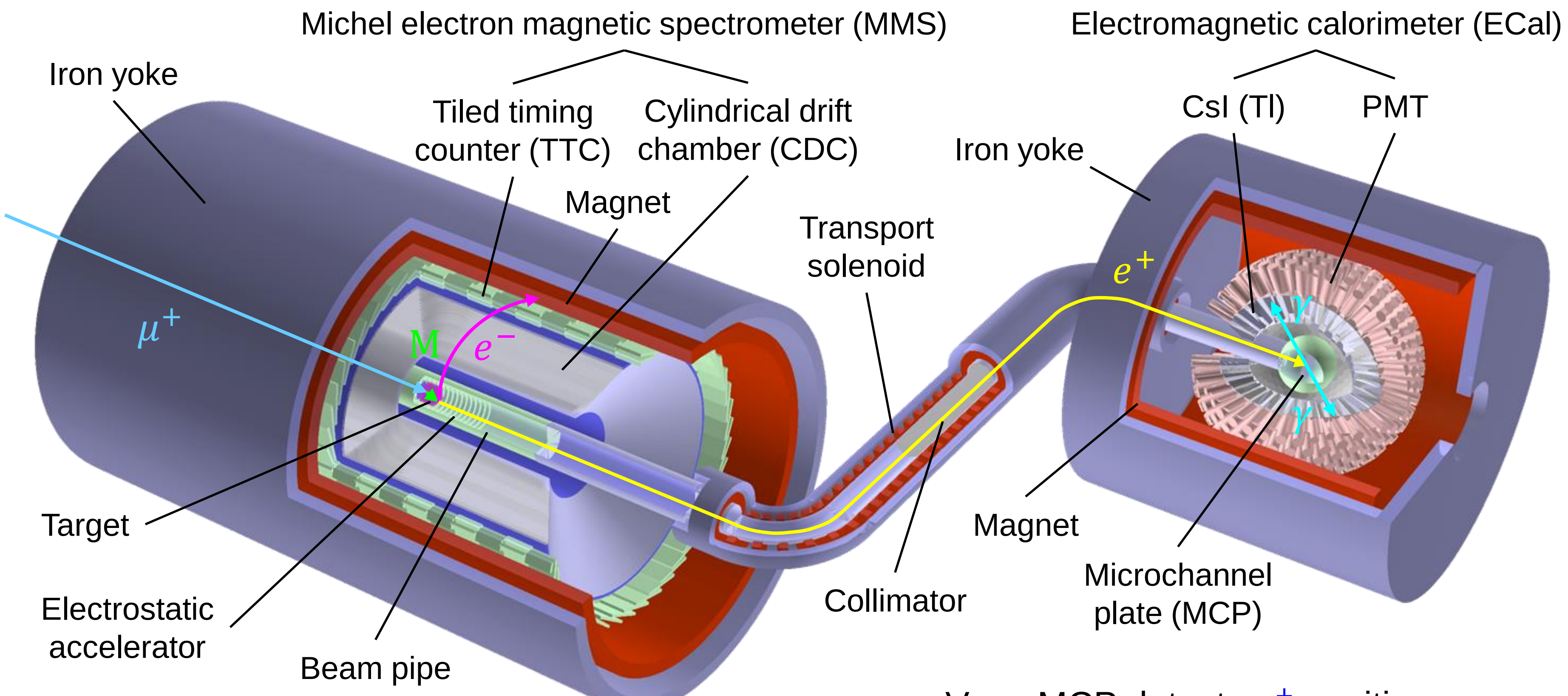
- **Coincidence of a fast e^- and a slow e^+**
- **Common vertex (by selecting e+/e- track DCA)**
  - ✓ Select p_{xy} of e+
  - ✓ Reject accidental e-
- **Time coincidence (by selecting e+ TOF)**
  - ✓ Select p_z of e+
  - ✓ Reject e+ from IC decay or Bhabha scattering
- **Charge identification (by e-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

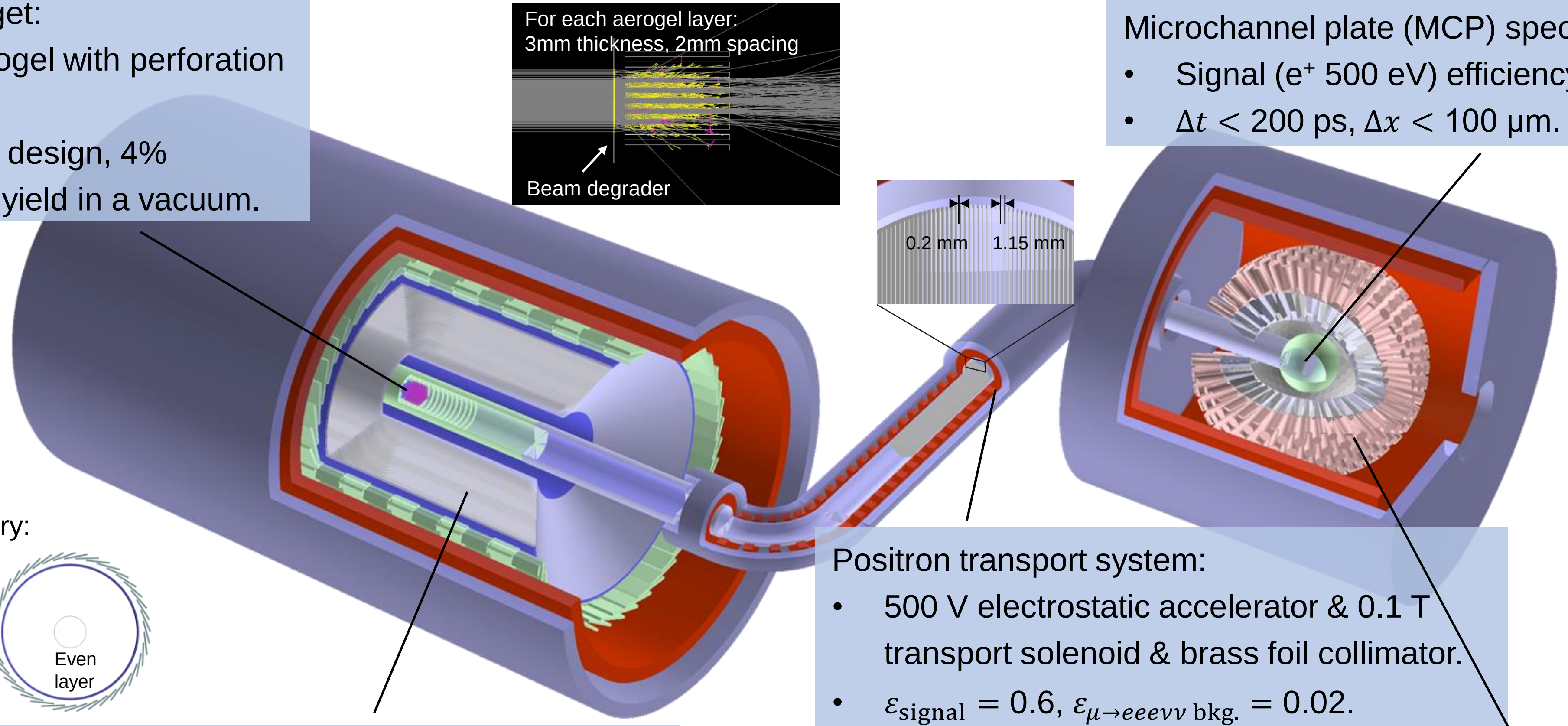
Triple coincidence:

- **MMS + $\underbrace{\text{MCP + ECal}}_{\text{Atomic } e^+}$**

MMS ↓ Michel e^-

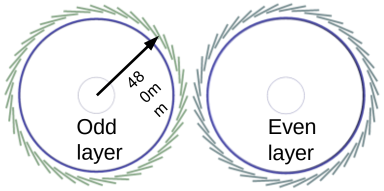
MACE实验基本设计方案v1

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.

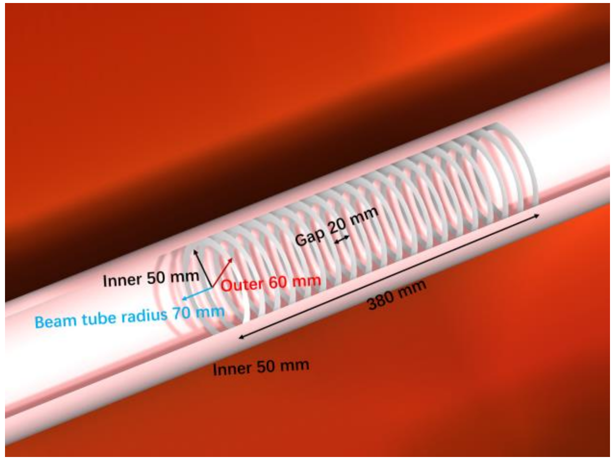
Magnetic spectrometer:
- 0.1 T axial magnetic field.
- CDC: $He(C_4H_{10})$ gas, 21 layers, 3540 cells. 89% geometry acceptance, $\Delta p \approx 500$ keV.
- TTC: 756 fast scintillators with SiPM readout, slant ± 15 deg, $\Delta t < 100$ ps.

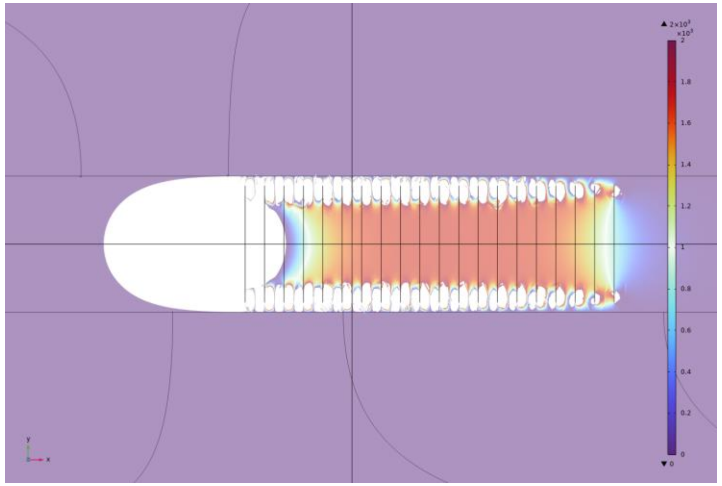
Electromagnetic calorimeter:
- Geometry: Class-I GP(4,0) Goldberg polyhedron.
- 622 CsI(Tl) crystals with 10 cm length, PMT readout.
- 97% geoemtry acceptance, $\Delta E/E = 7.5\%$ (signal 2γ event), 67.5% signal efficiency.

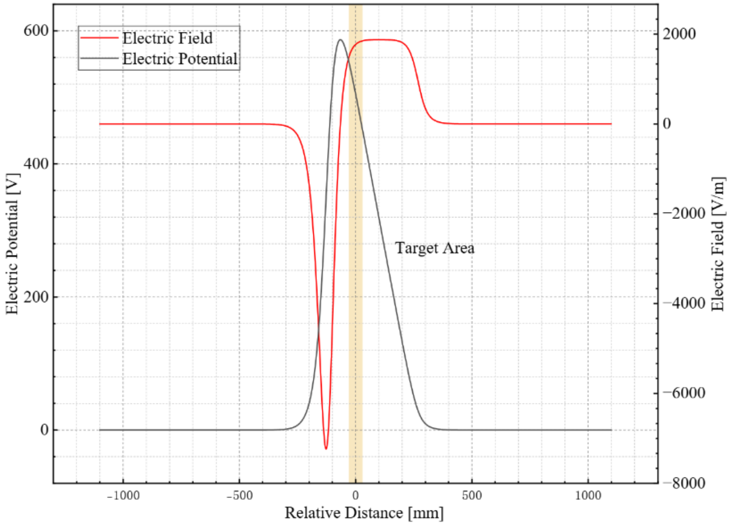
Positron transport system

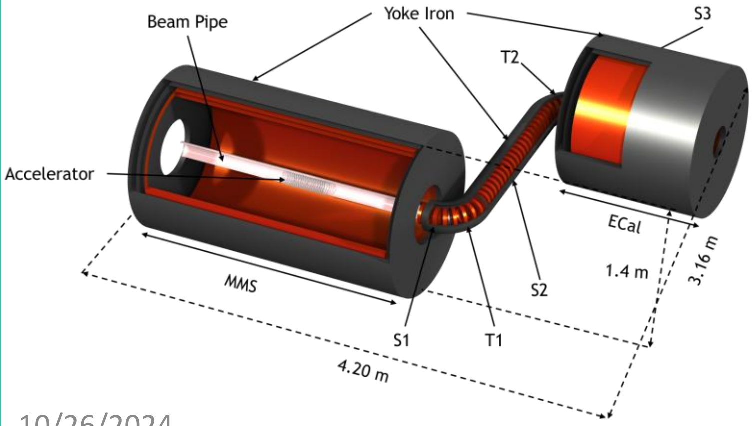
See Guihao Lu (鲁桂昊)'s poster (MIP2024)

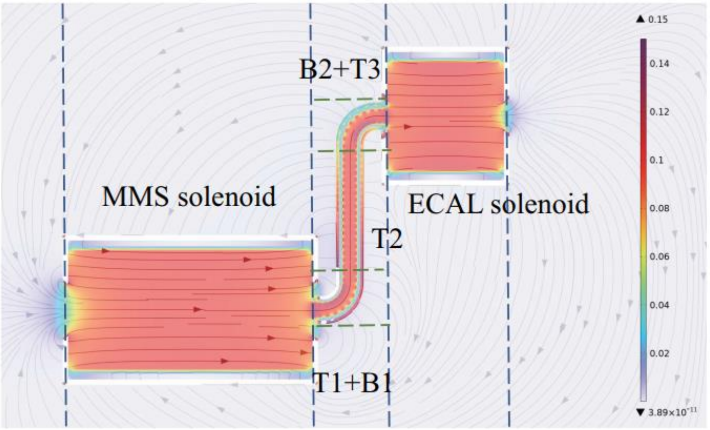
- Near-stationary signal positron should be accelerated and transport to MCP with transverse position preserved.
- Components: electrostatic accelerator & solenoid.

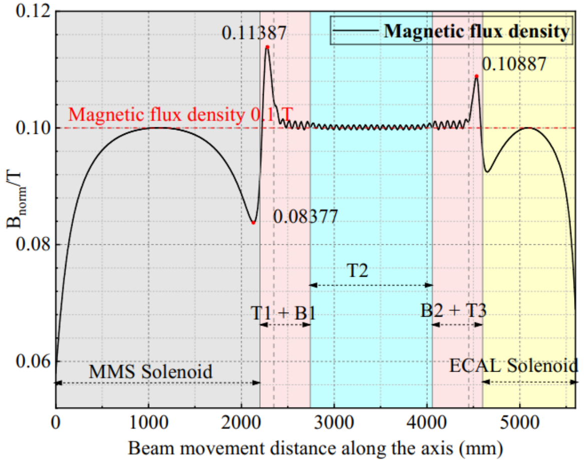












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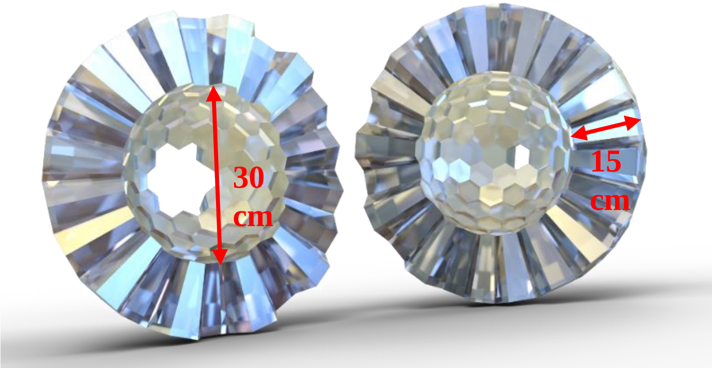
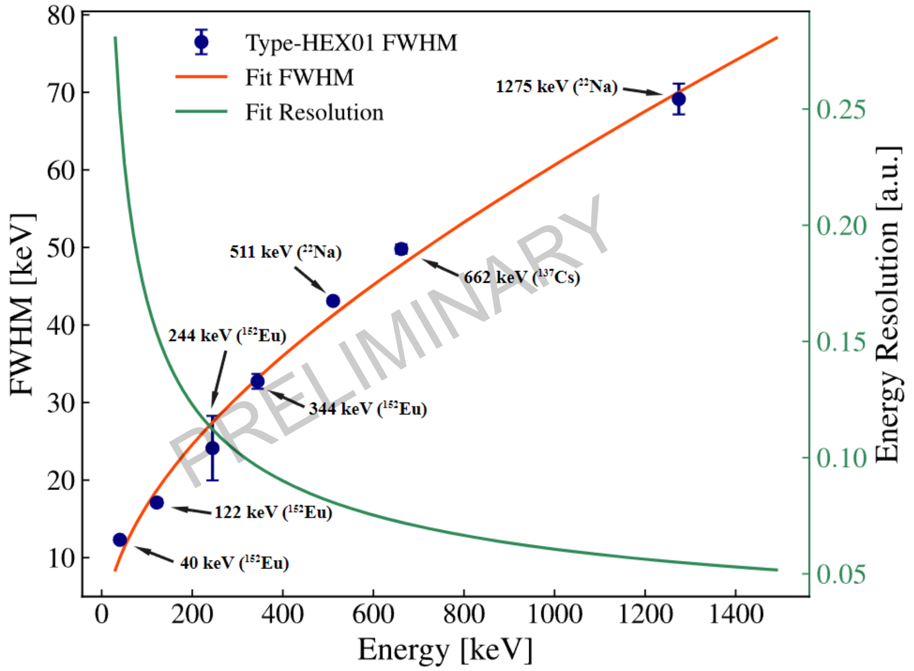
Design of calorimeter

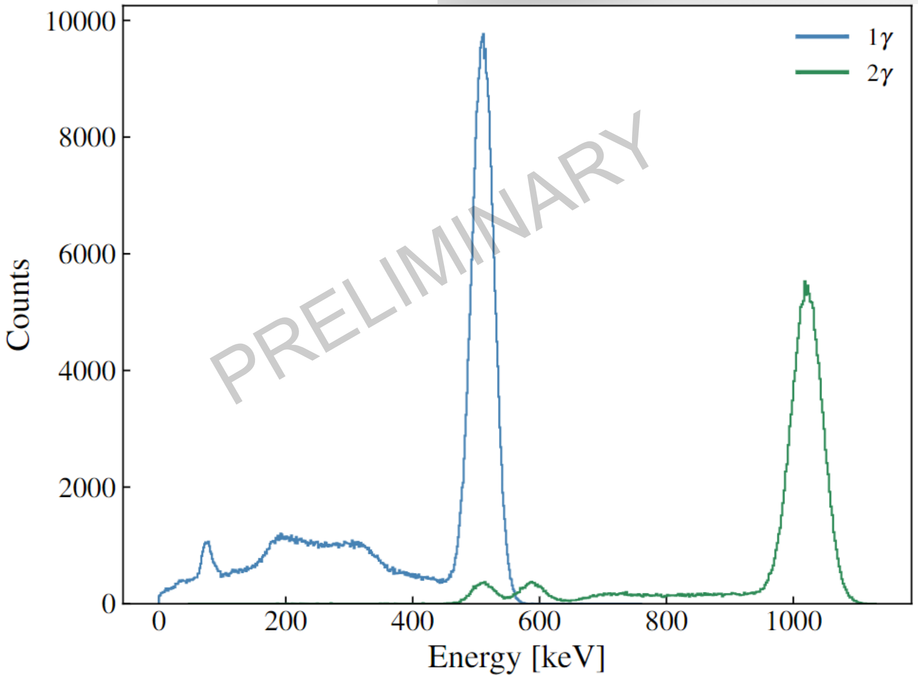
- Signal and Background

See [Siyuan Chen (陈思远)'s poster (MIP2024)]
[https://arxiv.org/abs/2408.17114]

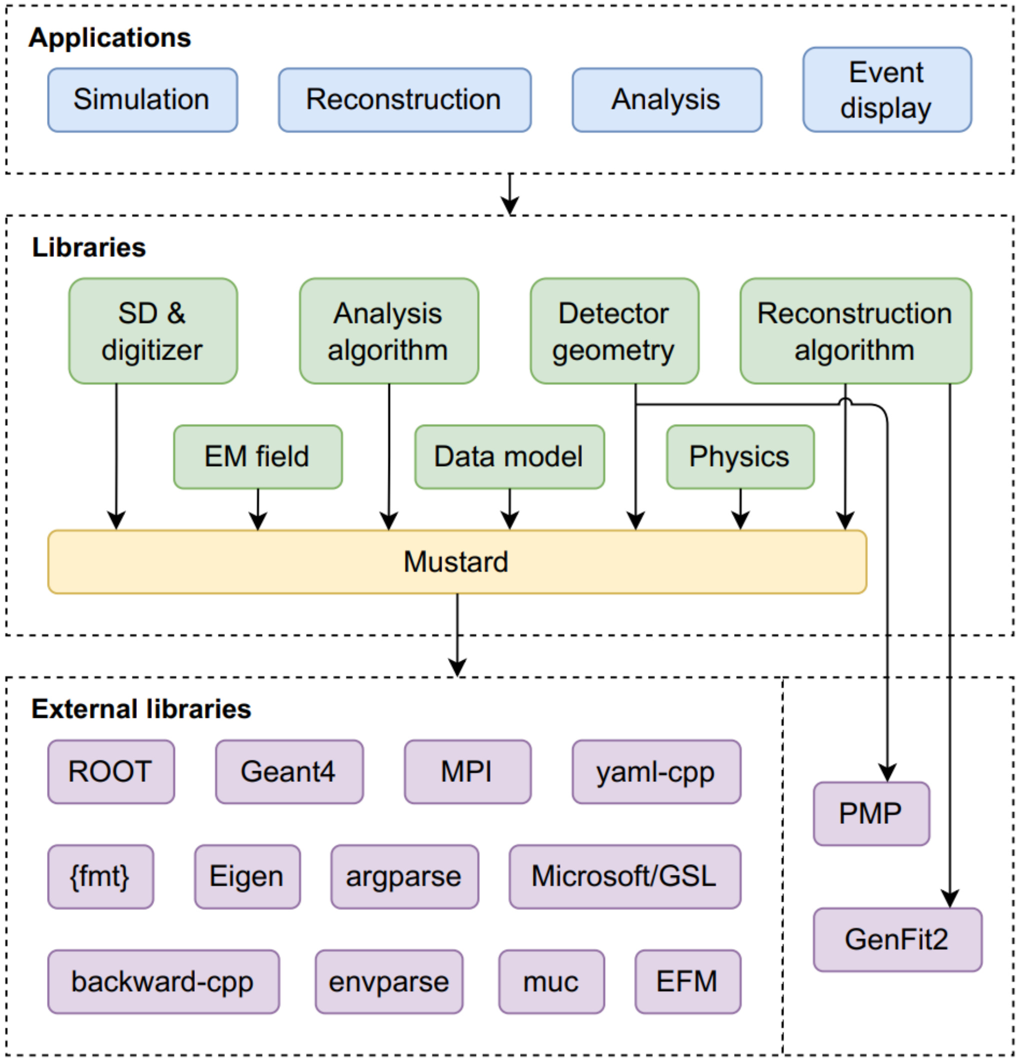
  - Energy resolution: 8.4% at 0.511 MeV, 6% at 1.022 MeV
  - 68.1% signal efficiency (3σ region)

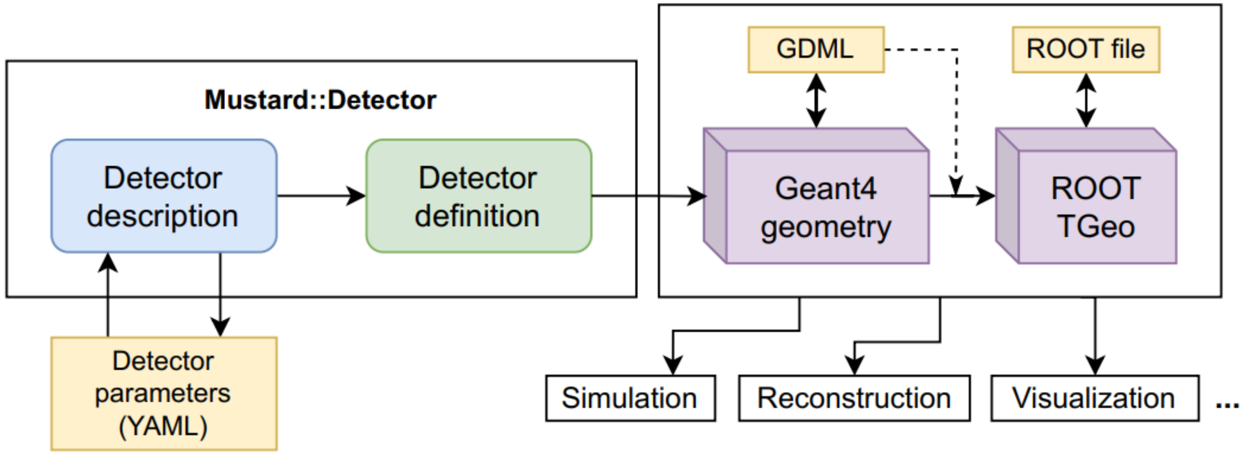


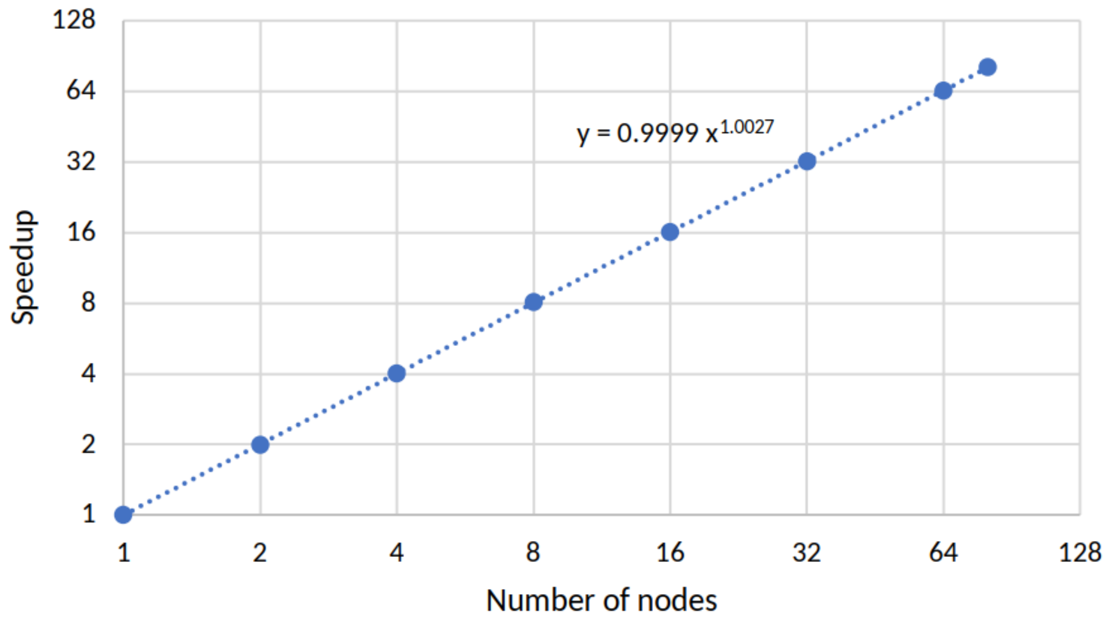




MACE离线软件框架和天河二号

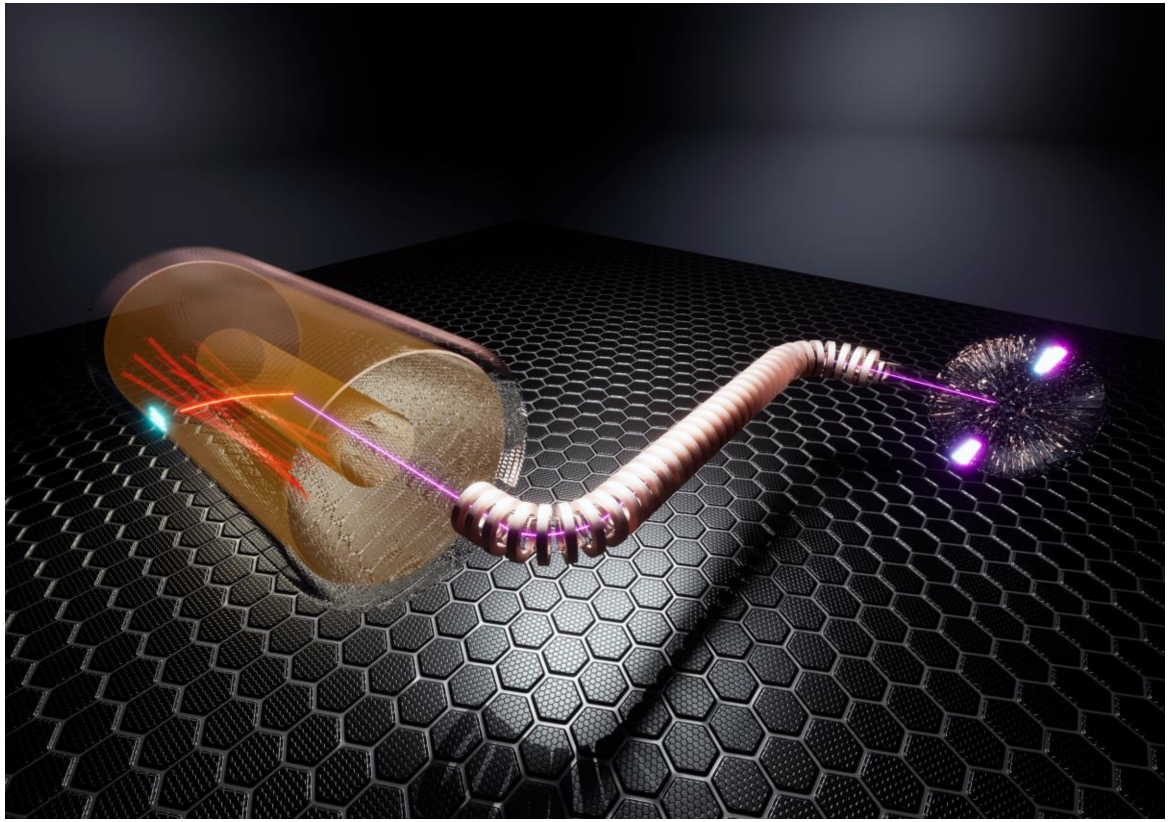


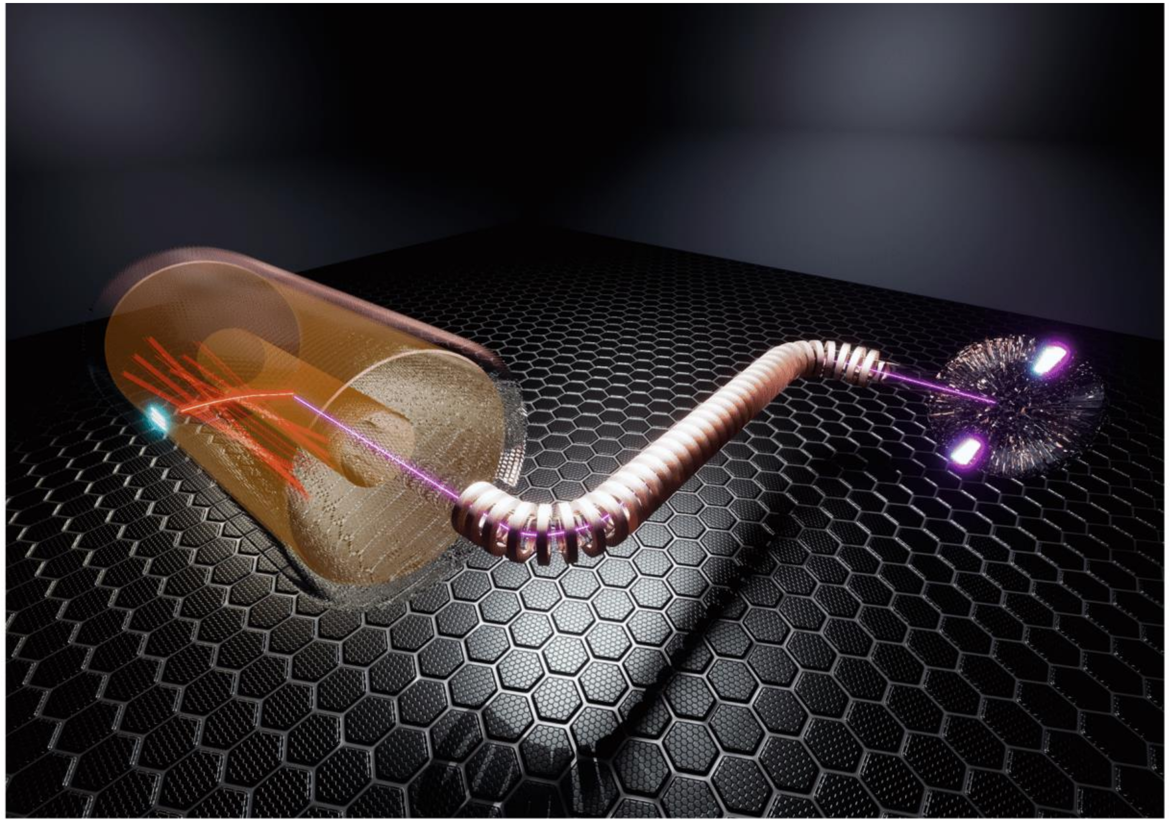




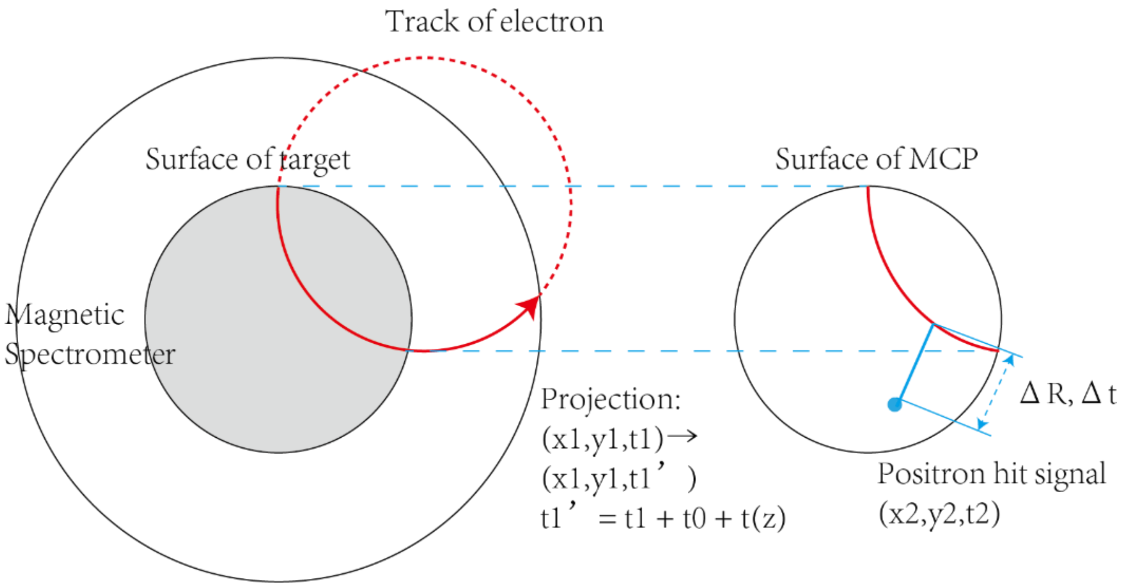
MACE事例显示器开发中

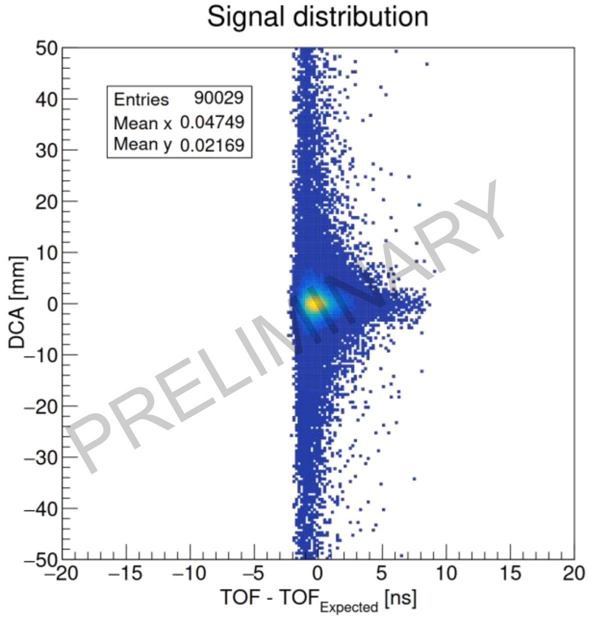
Credits：熊伟志





快速MC模拟: 缪子素探测

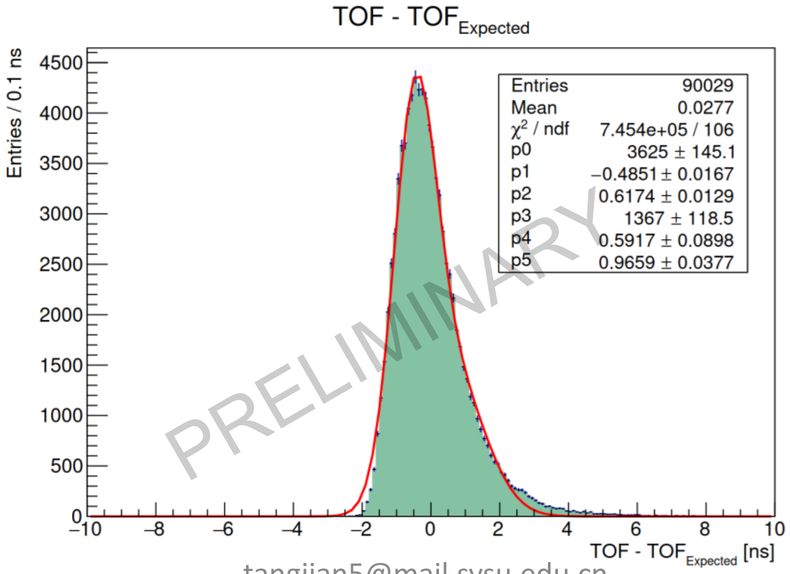


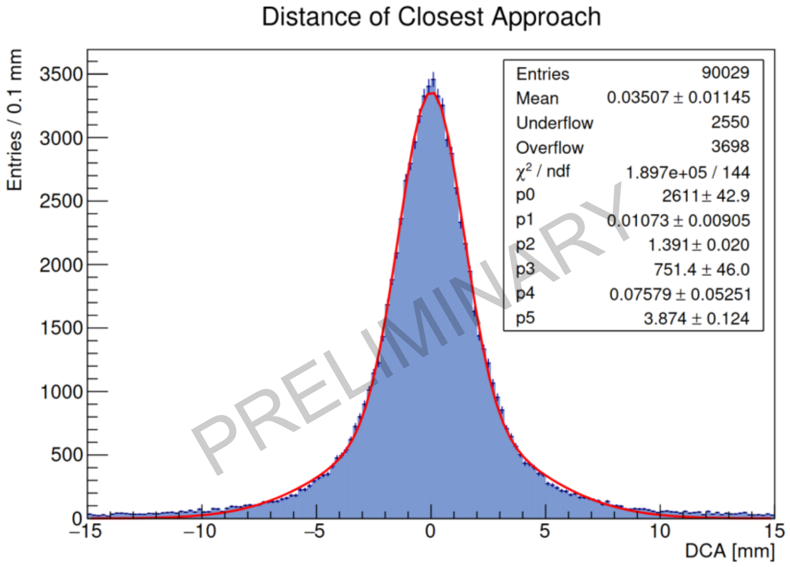


- Elliptical 3σ signal region:

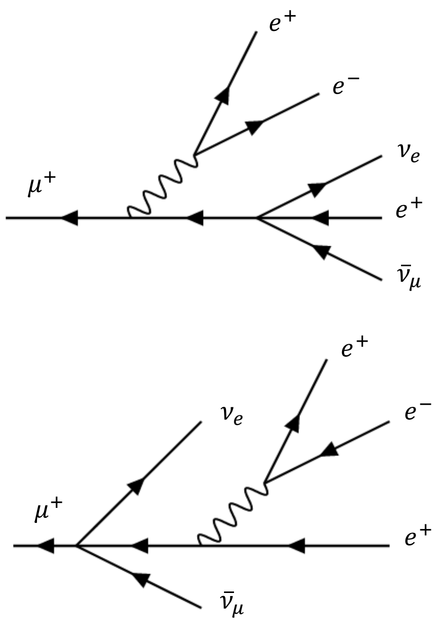
$$\left(\frac{\mathrm{TOF}-\mathrm{TOF_E}}{3\sigma_{\mathrm{TOF}}}\right)^2+\left(\frac{\mathrm{DCA}}{3\sigma_{\mathrm{DCA}}}\right)^2<1$$

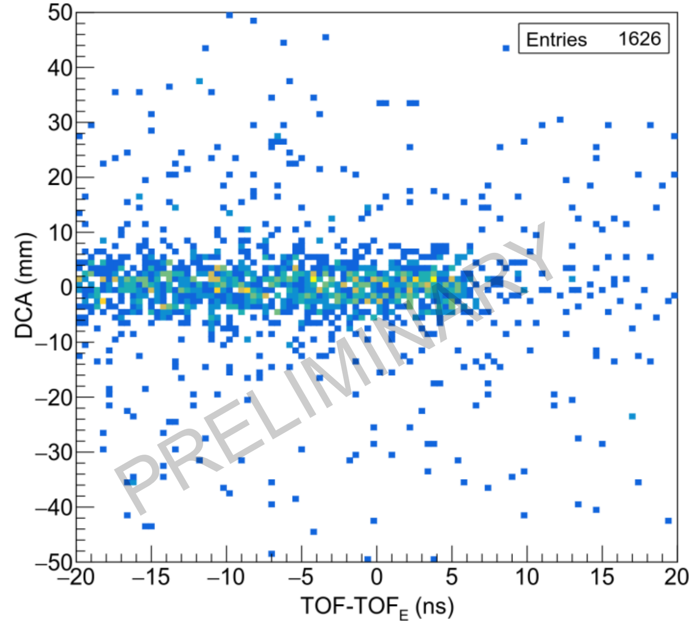
- $\varepsilon_{\text{signal region cut}} = 0.987$





快速MC模拟: 五轻子末态

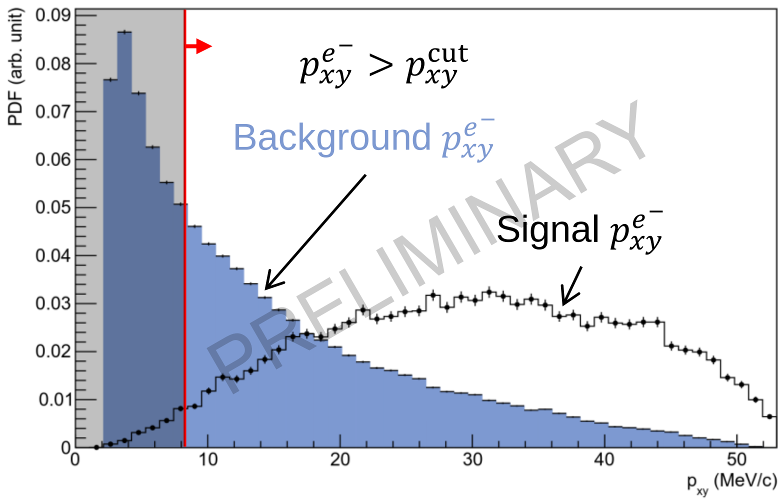




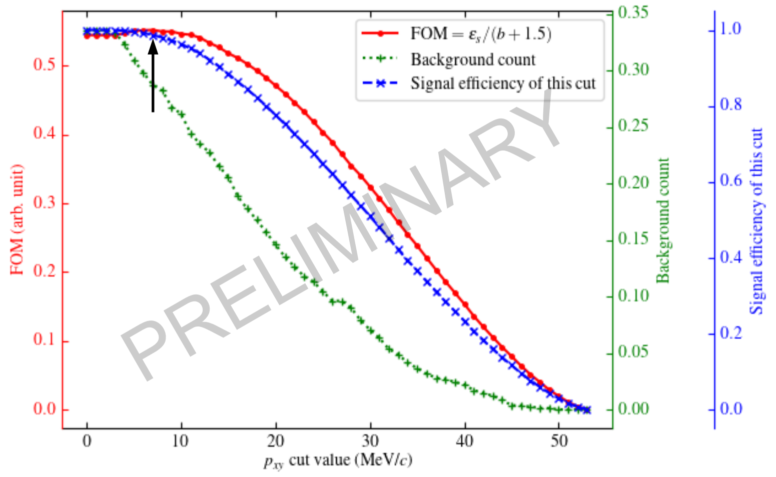
$\mu^+ \to e^+e^-e^+\bar{\nu}_\mu\nu_e$ simulation:

- 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)



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



MACE实验灵敏度分析

- 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 ($\varepsilon_{\mathrm{MMS}}^{\mathrm{recon}}$)	$\sim$ 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%

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

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

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

Timeline

Conceptual design	Phase-I technical design	Phase-I installation & test run	Phase-I physical run	Phase-II technical design	MACE Phase-II
2024	2025	2026	2027	2028	2028+

- Phase-I: $O(10^{-11})$ sensitivity for rare muonium decay (e.g. M→ee)
- Data taking duration: 1 year
- Beam specifications:
  - Surface muon, $10^6 \sim 10^7$ μ^+/s
  - Pulsed or CW beam
  - Momentum spreading: $\Delta p/p < 5\%$

- Phase-II: $O(10^{-14})$ sensitivity for muonium conversion
- Data taking duration: 1 year
- Beam specifications:
  - Surface muon, 10^8 μ^+/s
  - Pulsed beam, repetition rate 20 ~ 50 kHz
  - Momentum spreading: $\Delta p/p < 3\%$

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

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总 结

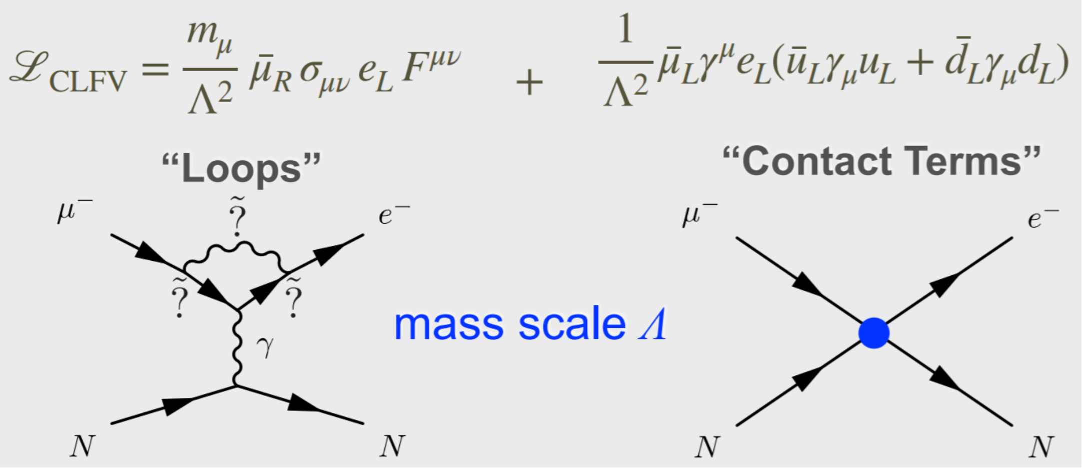
- 带电缪子的前沿科学研究方兴未艾，精确检验QED理论，稀有物理过程是研究超越SM新物理的极佳工具。
- 我们推进MACE实验，将为我国在缪子物理实验领域实现零的突破，做出**世界最好**的物理结果。
- 我们在MACE实验的总体设计、缪子素产生、离线软件研发上已经获得关键性进展；已获得气凝胶靶样品，正在开展新型探测器系统的优化和设计，持续推进各子探测器的研发(MBM、EMCal等)和重建算法的实现。
- 本地缪子实验室SMOOTH，已开发了多种探测器：宇生缪子探测器、缪子束流监测探测器和μSR样机等。
- MACE实验CDR初稿已完成，前沿科学必将带动技术应用，SMOOTH-μSR样机研制成功，期待开展多学科应用。
- 缪子物理大有可为，星星之火可以燎原，合作共赢！

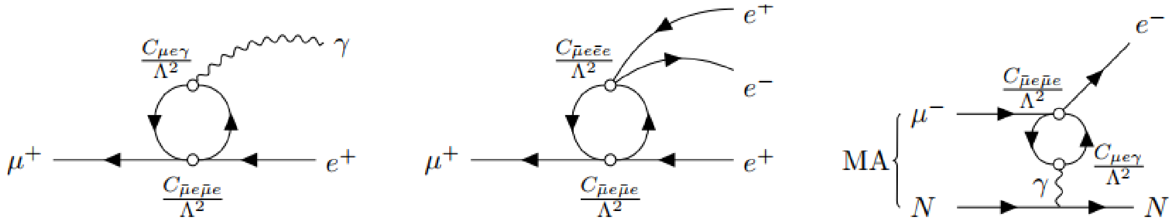
谢谢！

- *感谢南华大学会议组委会的邀请。*
- *感谢USTC封常青老师课题组协助电子学读出系统的研制。*
- *感谢中大陈羽等同事共同参加预研。*
- *感谢中大材工学院周剑老师合作研发塑闪，制备气凝胶二氧化硅样品。*
- *感谢国家自然科学基金12075326 、广东省和广州市自然科学基金等项目经费支持。*
- *感谢中大物理学院提供有效支持，感谢给力的本科生们！*

标准模型有效场论SMEFT

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





(a) $\mu^+ \to e^+ \gamma$ (b) $\mu^+ \to e^+ e^- e^+$ (c) $\mu^- N \to e^- N$

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

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标准模型有效场论SMEFT

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

- 标准模型后的首阶有效算符量纲为5，对应 Λ^{-1} 阶；该阶只产生中微子的 Majorana 质量项。
- 此后为对应 Λ^{-2} 阶的有效拉氏量，该阶算符可在树图阶直接产生 cLFV。
- 不同的过程通常只对某类算符灵敏，而对另一类算符不灵敏。
- 例如：缪子素转化对 $\bar{\mu}e\bar{\mu}e$ 耦合灵敏，但对 $\bar{\mu}e\bar{e}e$ 和 $\bar{\mu}e\gamma$ 不灵敏； $\mu \to eee$ 和 $\mu \to e\gamma$ 反之。
- 缪子素转化由 $\bar{\mu}e\bar{\mu}e$ 耦合直接产生，$M^2 \propto \frac{1}{\Lambda^4}$。而 $\mu \to e\gamma$ 在 EFT 树图阶不涉及 $\mu\bar{e}\bar{\mu}e$ 耦合；如要强行涉及则需要两个 EFT 顶点，$M^2 \propto \frac{1}{\Lambda^8}$（这种图似乎还具有来自于更高阶有效拉氏量的抵消项）。

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标准模型有效场论SMEFT

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

- 一般的 $\mu^+e^- \to \mu^-e^+$ 的 SMEFT 拉氏量包括所有的 $\bar{\mu}e\bar{\mu}e$ 耦合：

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

- 其中有三个 Wilson 系数，积掉时间的缪子素转化概率为

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

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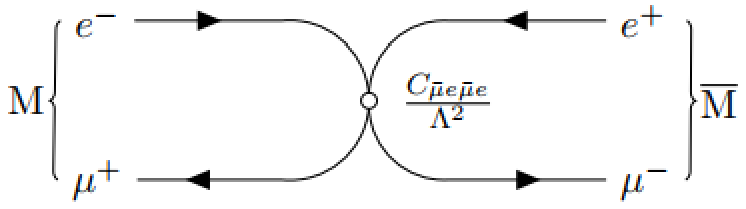
标准模型有效场论SMEFT



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

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

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

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

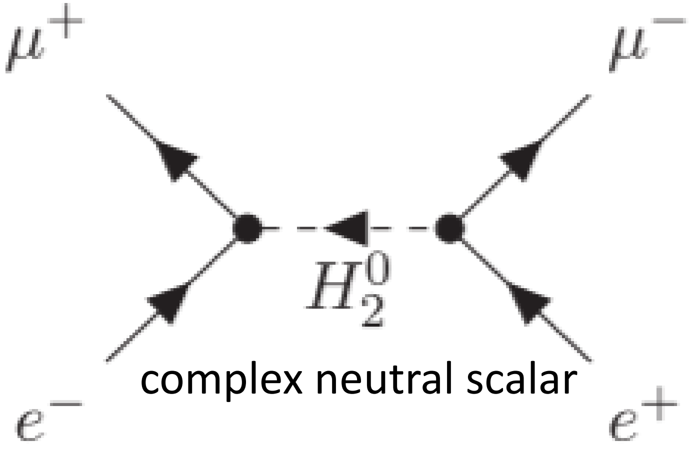
$$P(\mathrm{M} \to \overline{\mathrm{M}}) = S_B(B_0, f_P)\left(f_P P(\mathrm{M}_P \to \overline{\mathrm{M}}_P) + (1 - f_P) P(\mathrm{M}_V \to \overline{\mathrm{M}}_V)\right)$$
$$P(\mathrm{M} \to \overline{\mathrm{M}}) = \left(\frac{f_P}{2}(x_P^2 + y_P^2) + \frac{1 - f_P}{2}(x_V^2 + y_V^2)\right) S_B(B_0,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

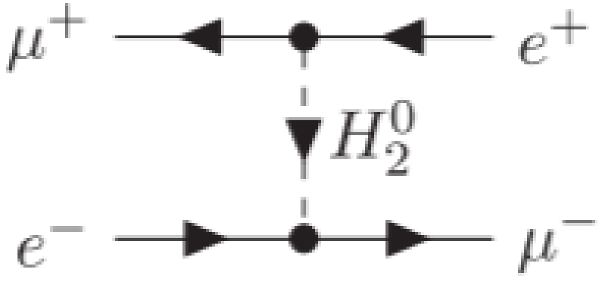
$$x_P = \frac{4(\alpha\mu)^3}{\pi\Gamma\Lambda^2}\left(C_V^{LL} + C_V^{RR} - \frac{3}{2} C_V^{LR} - \frac{1}{4}(C_S^{LR} + C_S^{RL})\right), \qquad x_V = -\frac{12(\alpha\mu)^3}{\pi\Gamma\Lambda^2}\left(C_V^{LL} + C_V^{RR} + \frac{1}{2} C_V^{LR} + \frac{1}{4}(C_S^{LR} + C_S^{RL})\right),$$
$$y_P = \frac{G_F}{\sqrt{2}\Lambda^2}\frac{m^2(\alpha\mu)^3}{\pi^2\Gamma}(C_V^{L\nu} - C_V^{R\nu}). \qquad y_V = -\frac{G_F}{\sqrt{2}\Lambda^2}\frac{m^2(\alpha\mu)^3}{\pi^2\Gamma}(5C_V^{L\nu} + C_V^{R\nu}).$$

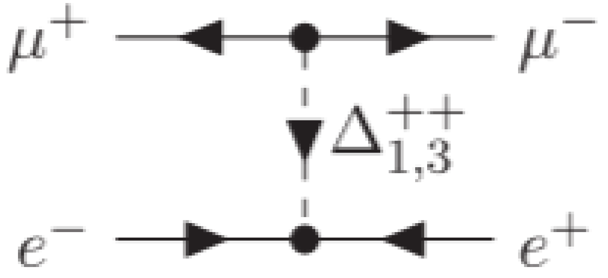
$$P(\mathrm{M} \to \overline{\mathrm{M}}) = \frac{8(\alpha\mu)^6}{\pi^2\Gamma^2\Lambda^4}\left(f_P\left(C_V^{LL} + C_V^{RR} - \frac{3}{2} C_V^{LR} - \frac{1}{4}(C_S^{LR} + C_S^{RL})\right)^2 + 9(1 - f_P)\left(C_V^{LL} + C_V^{RR} + \frac{1}{2} C_V^{LR} + \frac{1}{4}(C_S^{LR} + C_S^{RL})\right)^2\right)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

Process	Type	Experiment	Current bound
$\mathrm{M} \to \overline{\mathrm{M}}$	$\mathrm{M} - \overline{\mathrm{M}}$ mixing	MACS [10], MACE	$P < 8.3 \times 10^{-11}/S_B(0.1\ \mathrm{T})$ [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

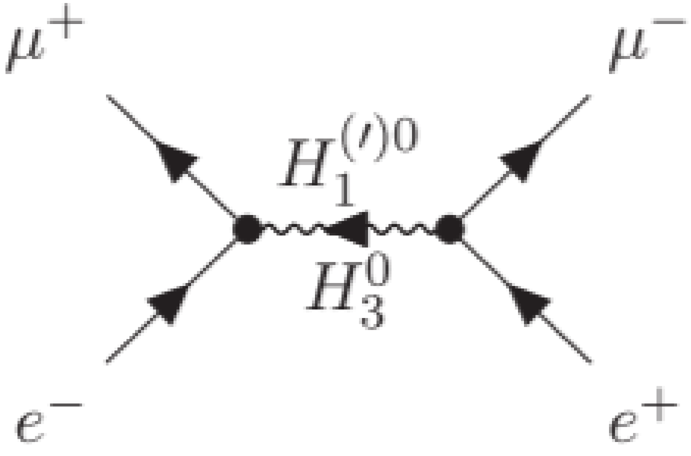
特定模型的正反缪子素转化过程

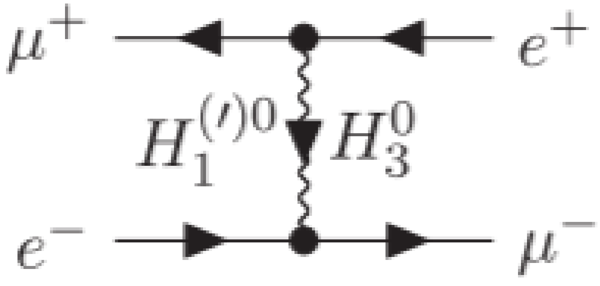


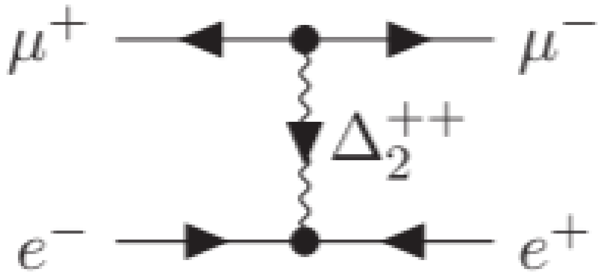




REF: Tong Li, Michael A. Schmidt. Phys.Rev.D 100 (2019) 11, 115007







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