

Conceptual design report of MACE

唐 健

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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、王晓冬、李晓华等



内容概述

- 前期科研进展的介绍
- 为什么研究缪子物理?
- MACE实验的预研进展
- 本地缪子实验室建设



这些年，这些事儿

拔尖人才培养

- 本科：以赛促学、以赛促研
- 研究生：培育卓越科学家
- 建设“一流”课程

教书
育人

物理
分析

大数据模拟和物理分析

- 拓展目标：JUNO、MACE实验
- 满足需求：快速部署、及时更新、百万核时级别的数据量
- 服务各类型前沿科学实验

轻子&
新物理

走出去和引进来

- 中德合作：JUNO实验
- 中日合作：COMET实验
- 欧盟合作：缪子对撞机预研

国际
合作

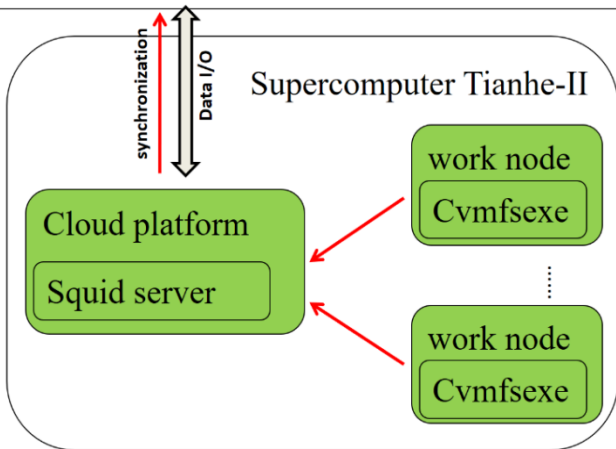
探测
技术

缪子径迹探测技术及其应用

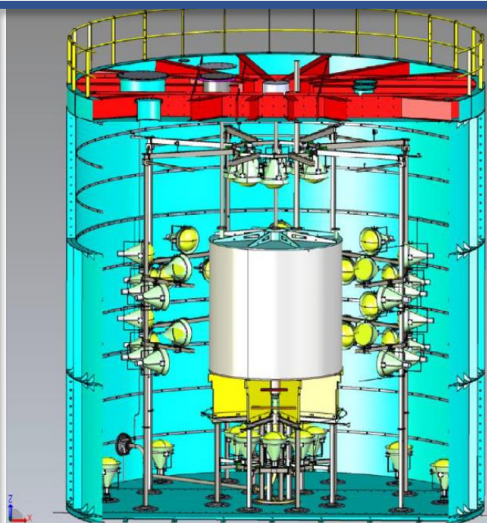
- 分辨率：时间—纳秒级、空间—毫米级
- 加速器缪子源：COMET、MACE实验
缪子对撞机计划
- 宇生缪子源：MuGrid及其多学科应用

以轻子为探针寻找超越标准模型新物理

Remote HEP Software repository: GLOBES, BOSS, ICEDUST, MACEsw...



依托超级计算机“天河二号”
建设粒子物理实验大数据平台



参与国际大科学实验JUNO
突破低本底探测器关键技术

软件框架

- General Detector Construction
- Geometry & Particle Generator
- Detector Simulation
- Reconstruction
- Event Display & Analysis

性能测试

实时取数

学生缪子探测器

- ① 低压直流、低功耗
- ② 固体探测器、易部署
- ③ 多通道远程实时监控
- ④ 具备径迹重建能力

径迹重建

自研电子学

径迹重建

Counts / 10⁵

Time Distance (cm)

建设缪子前沿科学与技术应用实验室
积累探测器核心技术面向多学科应用

鼓励探索，突出原创；聚焦前沿，独辟蹊径；需求牵引，突破瓶颈；共性导向，交叉融通。



工欲善其事必先利其器，软件平台和硬件研发同步推进



超算中心“天河二号”部署粒子物理实验大数据平台

Application of a supercomputer Tianhe-II in an electron-positron collider experiment BESIII*

Jing-Kun Chen,¹ Bi-Ying Hu,² Xiao-Bin Ji,³ Qiu-Mei Ma,^{3,†} Jian Tang,^{2,‡} Ye Yuan,^{3,4} Xiao-Mei Zhang,³ Yao Zhang,³ Wen-Wen Zhao,² and Wei Zheng³

¹School of Computer Science and Engineer, Sun Yat-sen University, Guangzhou, 510006, China

²School of Physics, Sun Yat-sen University, Guangzhou, 510275, China

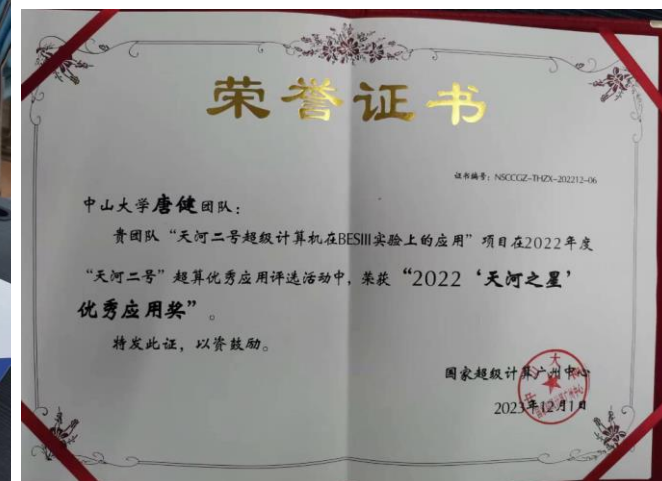
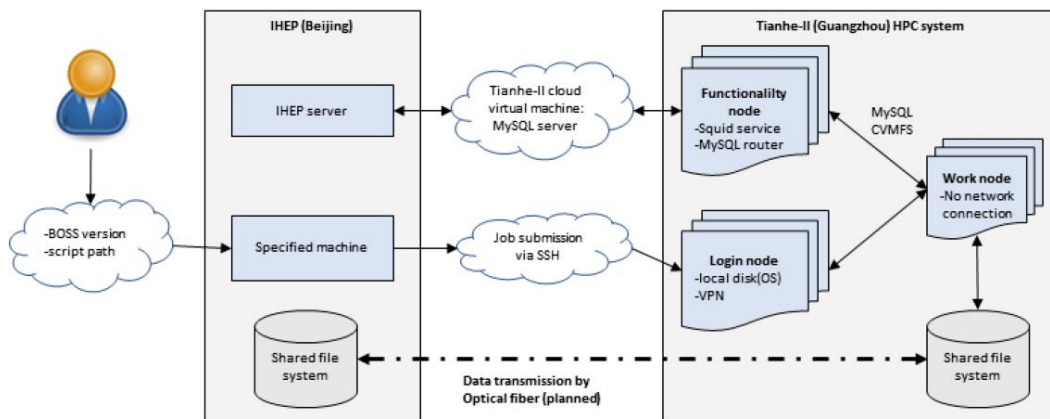
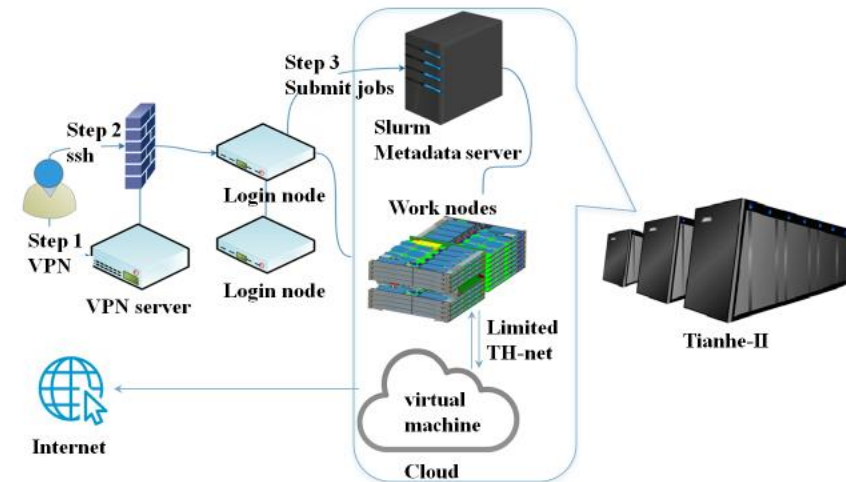
³Institute of High Energy Physics, Beijing, 100049, China

⁴University of Chinese Academy of Sciences, Beijing, 100049, China

Precision measurements and new physics searches require massive computation in high energy physics experiments. Supercomputer remains one of the most powerful computing resources in various areas. Taking the BESIII experiment as an illustration, we deploy the offline software BOSS into the top-tier supercomputer "Tianhe-II" with the help of Singularity. With very limited internet connection bandwidth and without root privilege, we synchronize and maintain the simulation software up to date through CVMFS successfully, and an acceleration rate in a comparison of HPC and HTC is realized for the same large-scale task. We solve two problems of the real-time internet connection and the conflict of loading locker by a deployment of a squid server and using fuse in memory in each computing node. We provide a MPI python interface for high throughput (HT) parallel computation in Tianhe-II. Meanwhile, the program to deal with data output is also specially aligned so that there is no queue issue in the input/output (I/O) task. The acceleration rate in simulation reaches 80%, as we have done the simulation tests up to 15K processes in parallel.

Keywords: High Performance Computer, Collider experiment, IO solutions

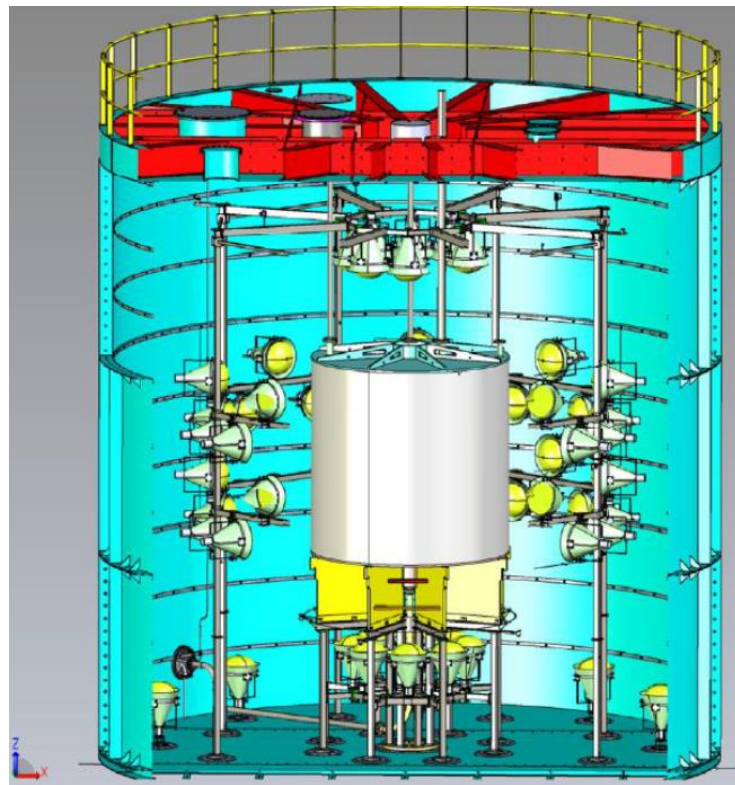
[JINST 18 \(2023\) 03, T03003](#)



突破中微子实验探测器关键技术

• 技术应用:

- (1) 世界上最大的有机玻璃球形探测器，直径35.4米，厚度12厘米，重约600吨
解决支撑节点强度不足的工艺问题，满足苛刻的物理需求。
- (2) **国际大科学工程**江门中微子实验采用中山大学开发的工艺技术
- (3) **成功研制并交付**同类型探测器，监测液闪痕量级同位素Rn-222



SMOOTH团队情况



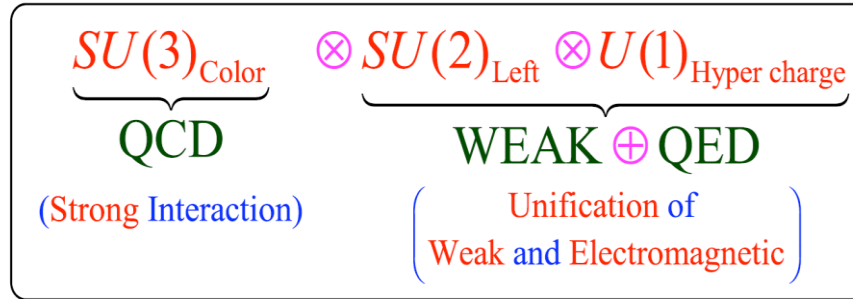
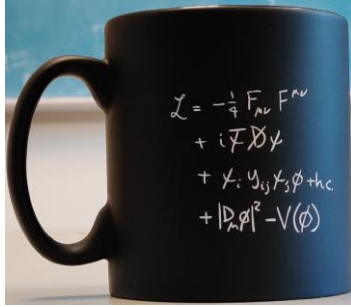
- 当前团队成员：博士后1名，博士生4名，在读硕士生6名，本科生科研项目学生10+名，电子学工程师1名，超算平台维护1名.....
- 校内合作伙伴：物理实验中心，测试中心，超算中心，材料科学与工程学院等
- 校外合作伙伴：中科大电子学实验室，中科院近代物理研究所，清华大学，中国散裂中子源等
- 国际合作伙伴：德国Mainz大学，日本Osaka大学和KEK，意大利INFN-Padova等



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Symmetries of SM



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

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

$$Q_L^i \sim (3, 2)_{1/6}, \quad U_R^i \sim (3, 1)_{2/3},$$

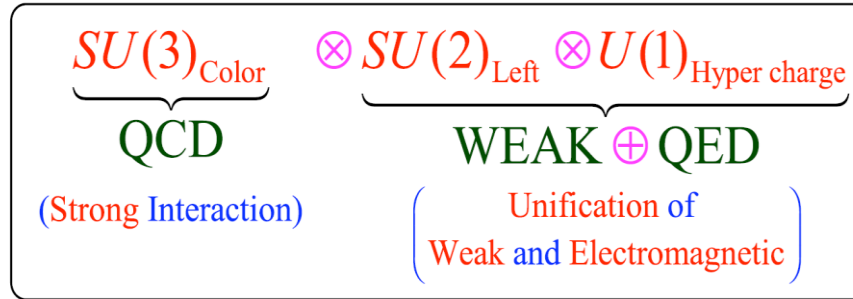
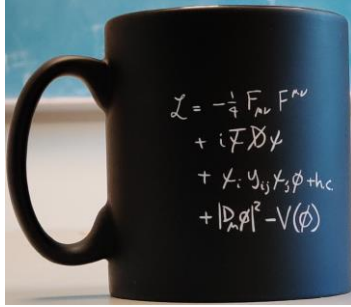
$$D_R^i \sim (3, 1)_{-1/3}, \quad L_L^i \sim (1, 2)_{-1/2},$$

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

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

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

Symmetries of SM



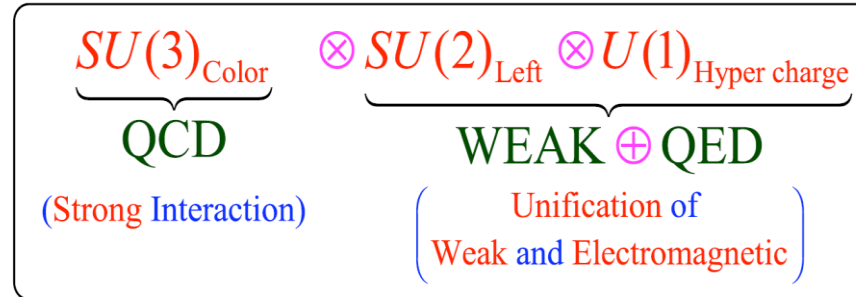
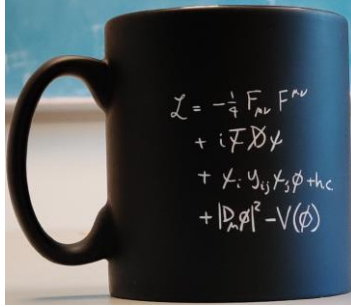
- Flavor physics
 - Within SM: weak and Yukawa interactions
- Flavor parameters in the quark sector
 - Within SM: 9 masses of charged fermions & 4 mixing parameters (3 angle + 1 CP phase)
- Flavor universal (flavor blind)
 - Within SM: QCD & QED
- Flavor diagonal
 - Within SM: Yukawa interactions

	Lepton number	Lepton family number (lepton flavor)		
		L_e	L_μ	L_τ
$e^- \ \& \ \nu_e$	1	1	0	0
$\mu^- \ \& \ \nu_\mu$	1	0	1	0
$\tau^- \ \& \ \nu_\tau$	1	0	0	1

Change the sign for all anti-leptons

轻子与夸克的flavor physics互补

Symmetries of SM



- 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

- Rephasing lepton and quark fields:

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

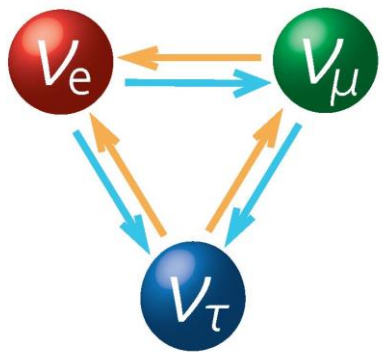
- Broken non-perturbatively, but unobservable. [t Hooft, PRL '76]
- True accidental global symmetry:

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

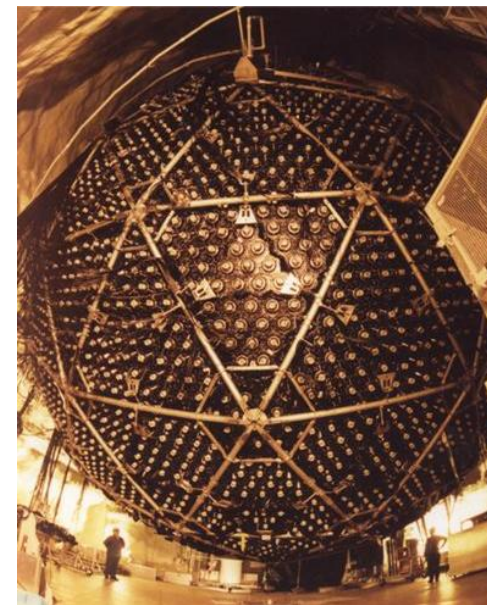
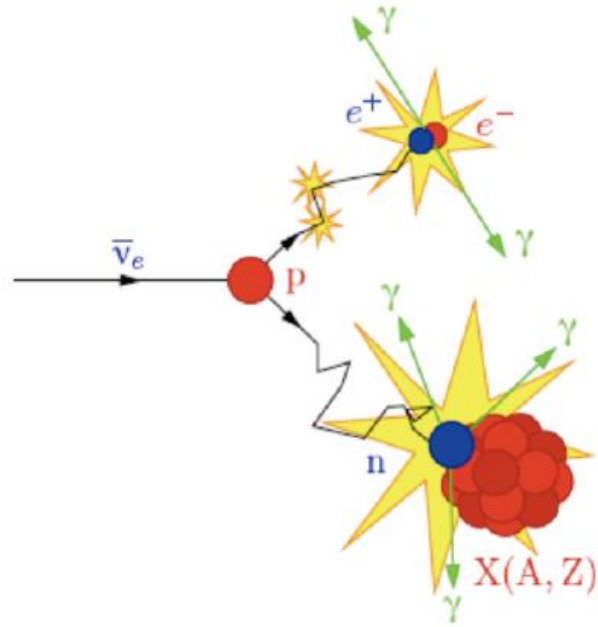
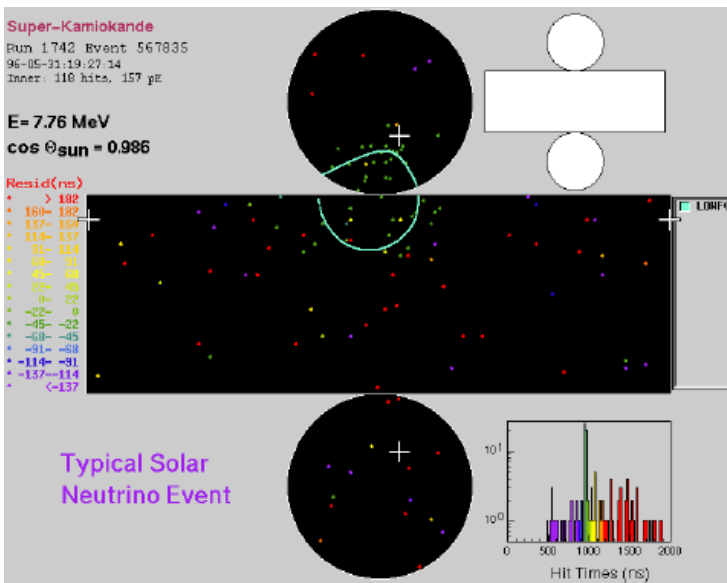
Lepton flavor conservation!
Prediction of Standard Model.

cLFV offers a chance of new physics discovery

中微子的PMNS混合



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



中微子振荡=轻子味道破坏?

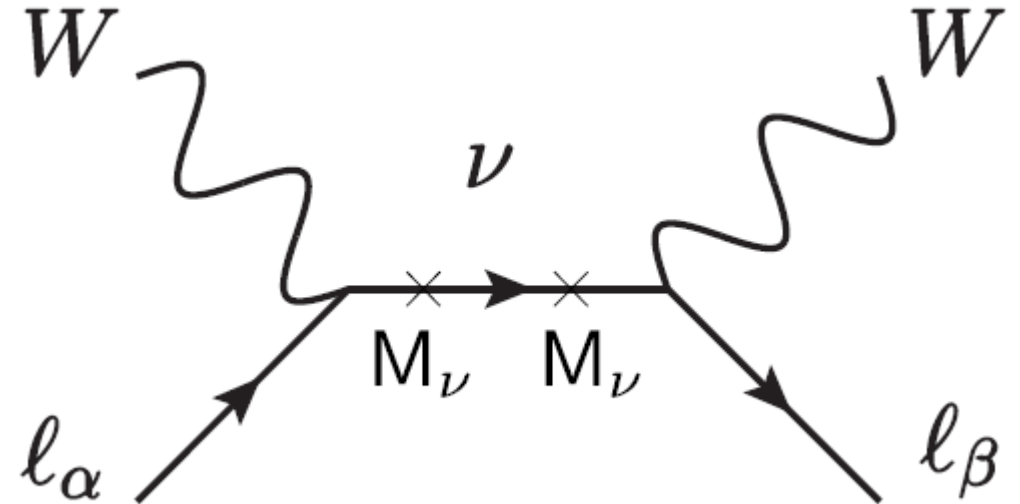
- 中微子振荡指向有质量中微子 $\rightarrow M_\nu \neq 0$
- 因此，我们需要轻子味道破坏 cLFV

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

- 但是， $\sim eV$ 量级中微子质量 \rightarrow 强烈压低 cLFV

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

- 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

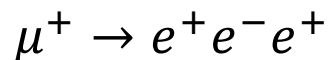
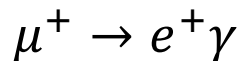
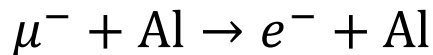
• 带电轻子味道破坏实验cLFV:

➢ Mu2e(美国)

➢ COMET(日本)

➢ MEG(瑞士)

➢ Mu3e(瑞士)



• 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。

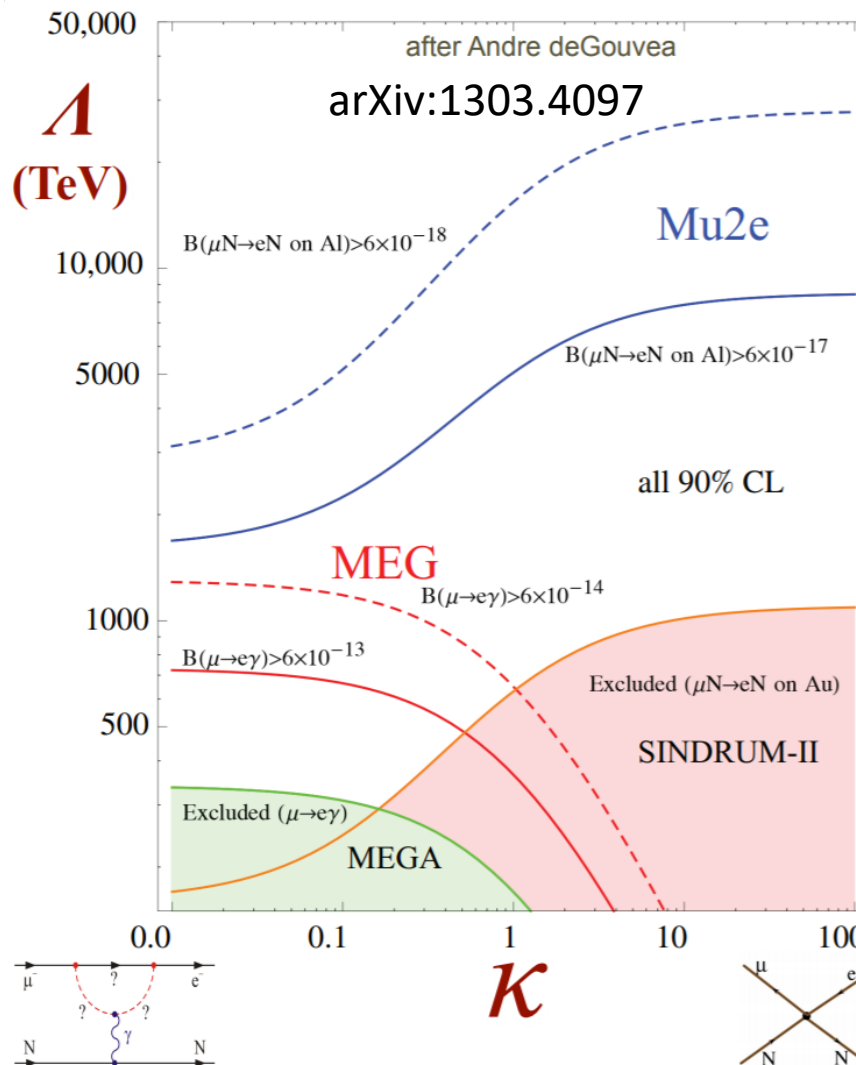
➢ 瑞士PSI实验室, MuCap实验测量 μ 子俘获的耦合常数。

➢ 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

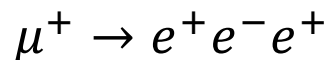
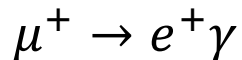
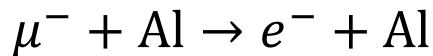
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➢ MEG(瑞士)

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• 缪子性质的精密测量:

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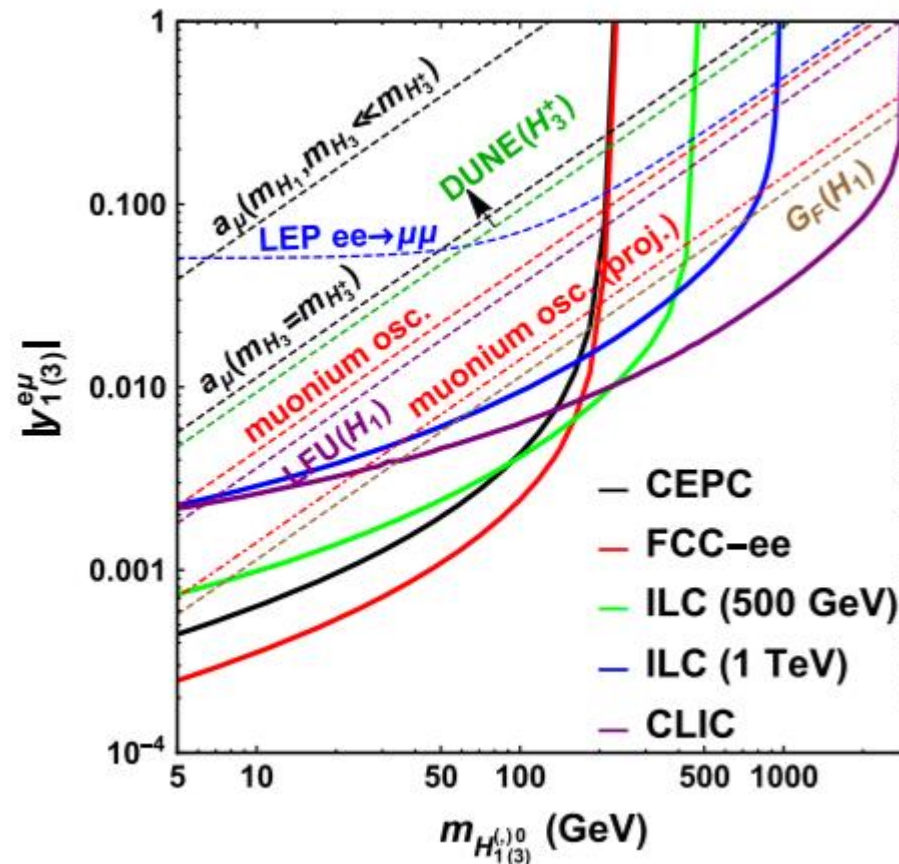
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REF: Tong Li, Michael A. Schmidt. *Phys.Rev.D* 100 (2019) 11, 115007

- 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

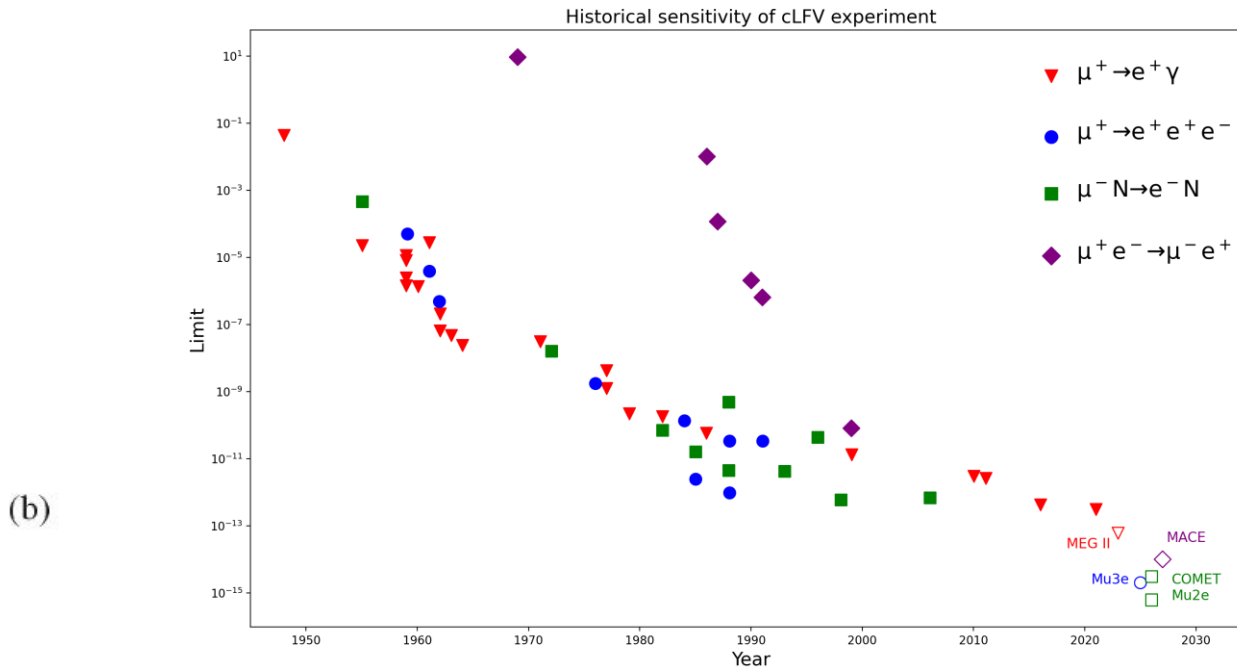
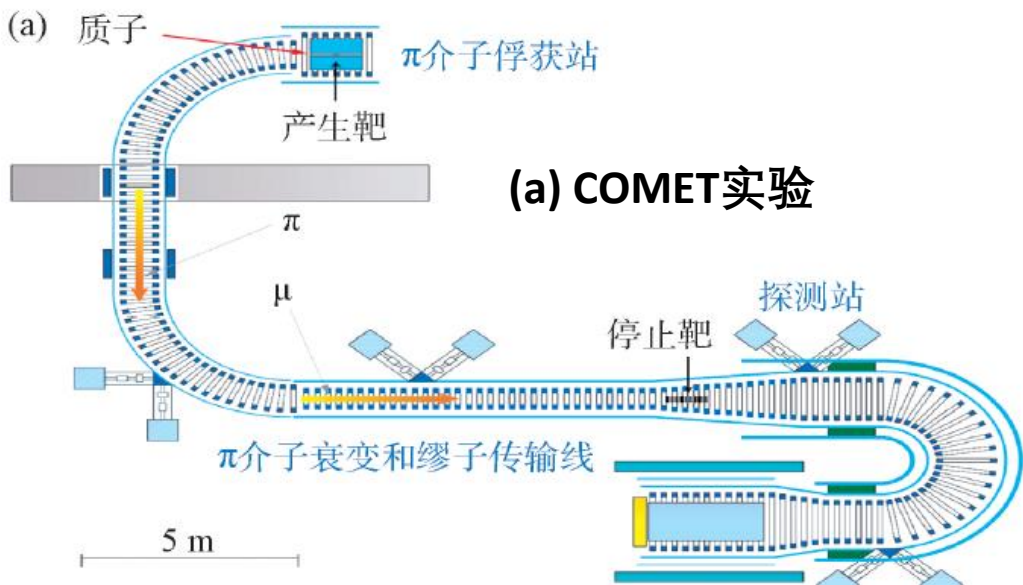
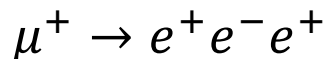
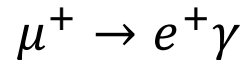
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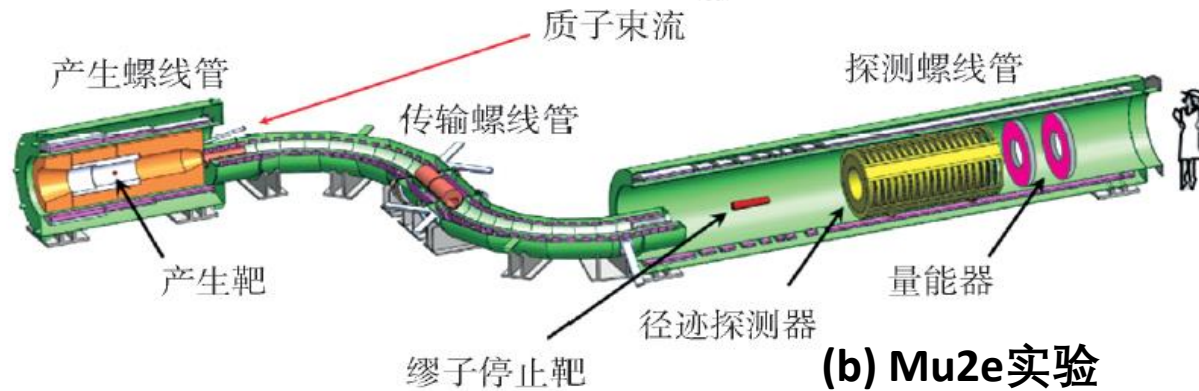
➤ COMET(日本)

➤ MEGII(瑞士)

➤ Mu3e(瑞士)



(b)



高亮度前沿/高精度前沿

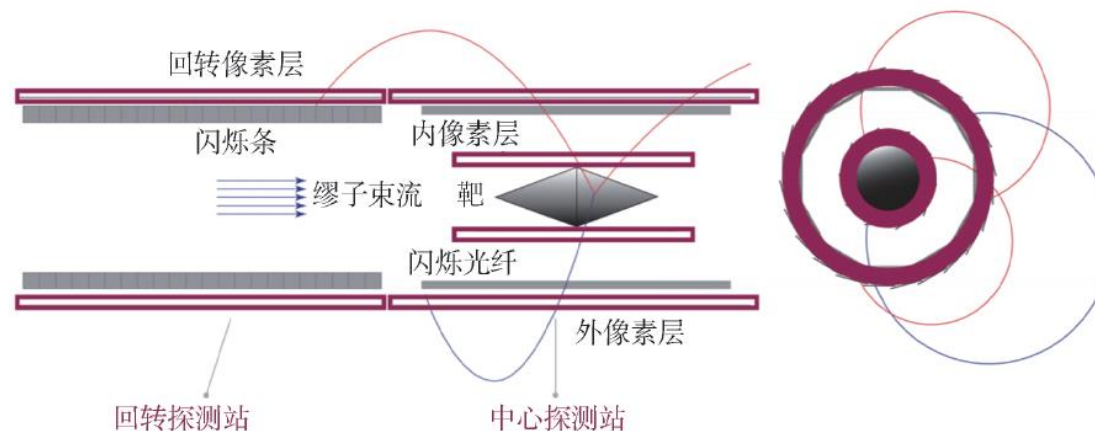
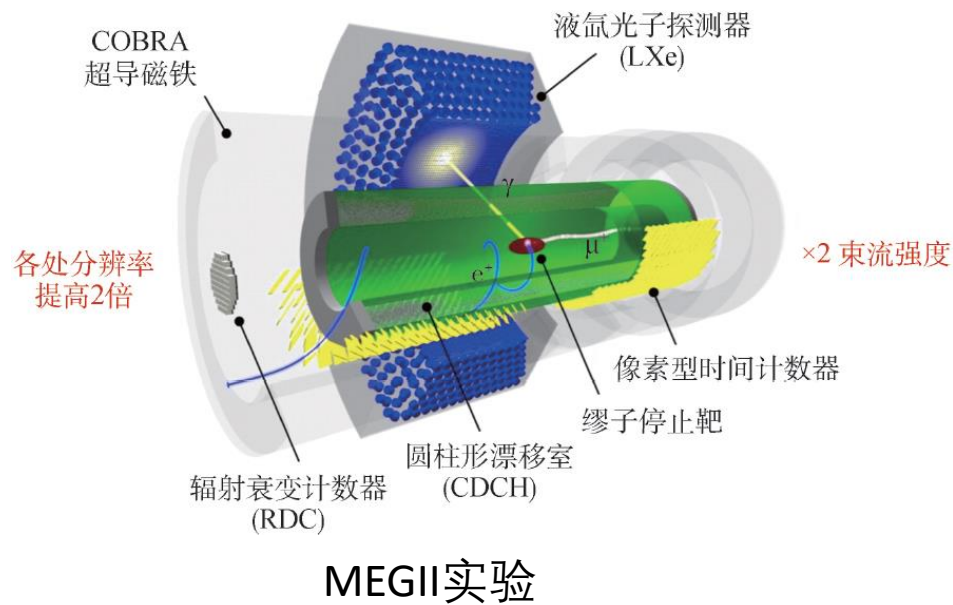
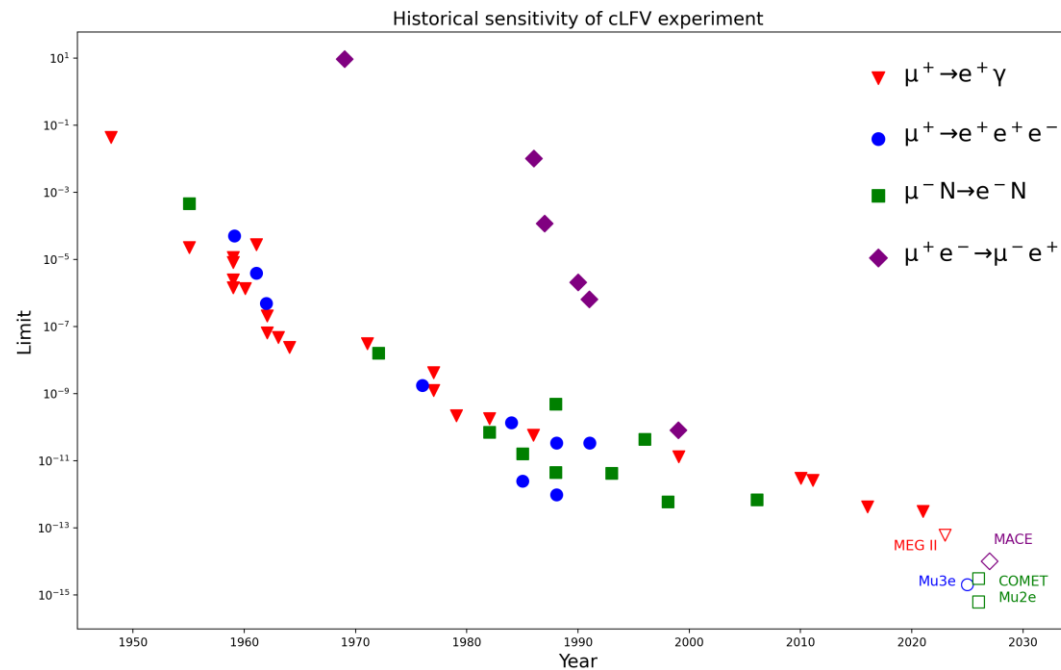
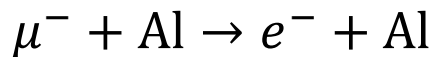
带电轻子味道破坏实验cLFV:

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➤ COMET(日本)

➤ MEGII(瑞士)

➤ Mu3e(瑞士)



粤港澳大湾区是强流加速器的聚集地



东莞已建成中国散裂中子源



惠州在建中国HIAF和CIADS

Ref: 中科院高能所, 王生研究员报告

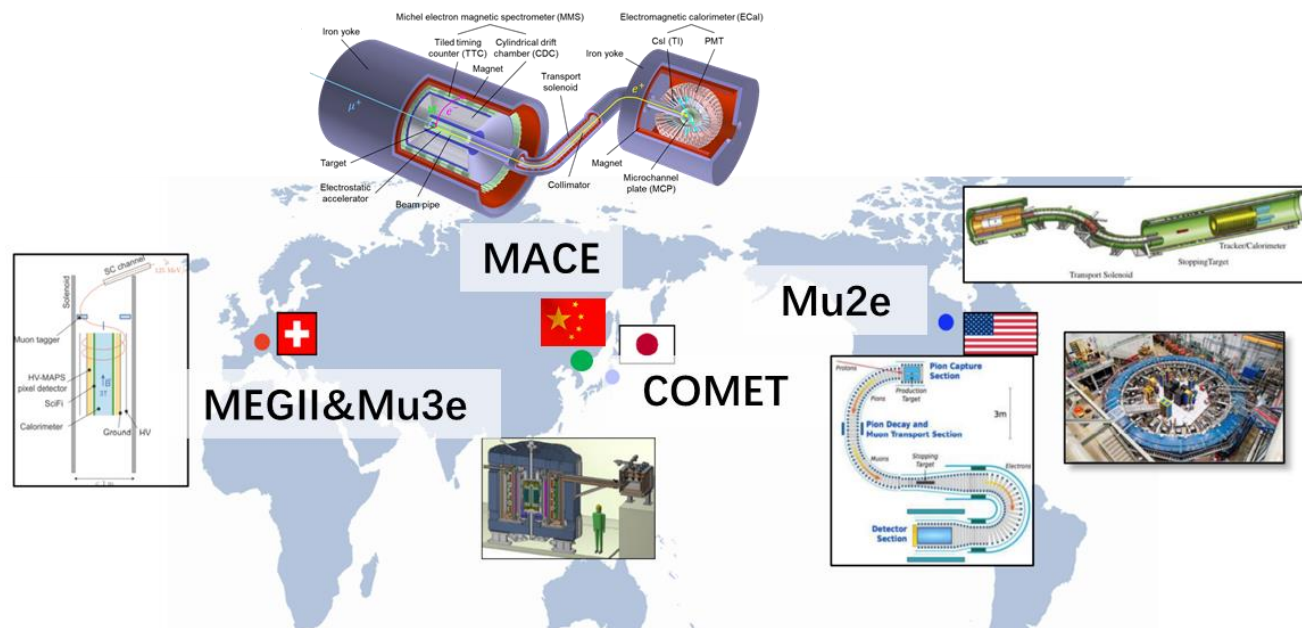
Ref: 中科院近物所, 东江实验室詹文龙院士报告

- (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?

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)	$\mu^+ \rightarrow e^+ \gamma$	正在采集数据
Mu2e	费米实验室 (美国)	$\mu^- N \rightarrow e^- N$	正在安装, 即将运行
COMET	J-PARC (日本)	$\mu^- Al \rightarrow e^- Al$	正在安装, 即将运行
Mu3e	PSI (瑞士)	$\mu^+ \rightarrow e^+ e^- e^+$	正在调试
MACS	PSI (瑞士)	$\mu^+ e^- \rightarrow \mu^- e^+$	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。





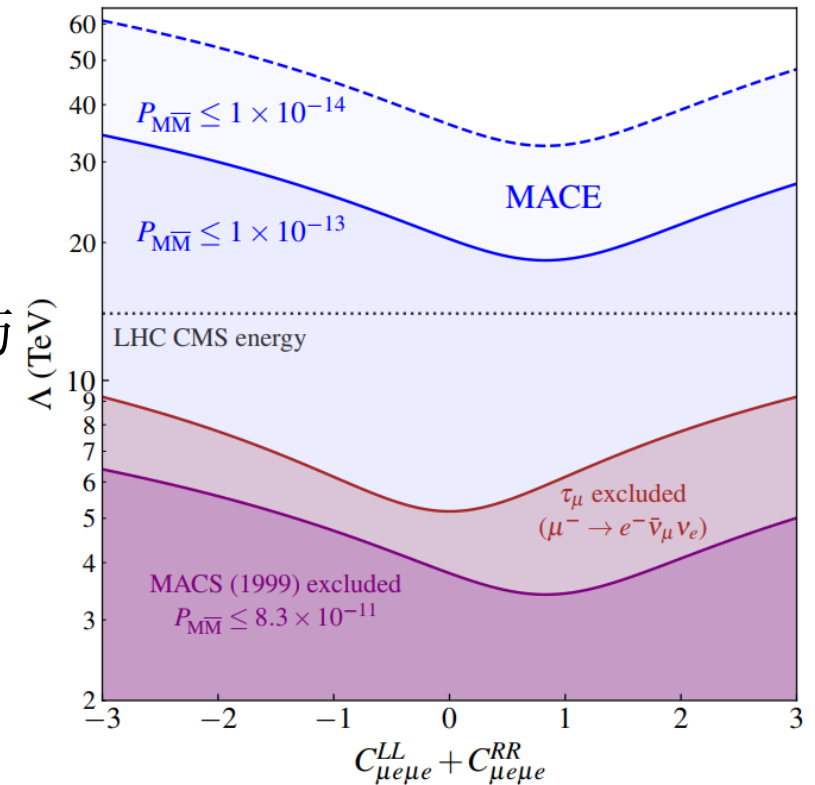
总结：MACE实验的研究动机

- 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



高亮度前沿/高精度前沿

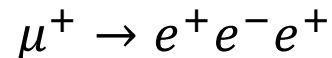
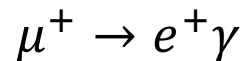
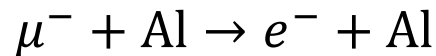
• 带电轻子味道破坏实验cLFV:

➤ Mu2e(美国)

➤ **COMET(日本)**

➤ MEG(瑞士)

➤ Mu3e(瑞士)



• 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。

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^{5,1,†} and Yu Zhang^{5,6}

¹School of Physics, Sun Yat-Sen University, Guangzhou 510275, China

²National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China

³School of Fundamental Physics and Mathematical Sciences, Hangzhou Institute for Advanced Study, University of Chinese Academy of Sciences, Hangzhou 310024, China

⁴International Center for Theoretical Physics Asia-Pacific, Beijing/Hangzhou 10010, China

⁵Institutes of Physical Science and Information Technology, Anhui University, Hefei 230601, China

⁶School 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 (Coordinator),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 Zhou²

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. Petrov¹

¹Department 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.

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)
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- (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 $\mu^+ e^-$) to Antimuonium ($\mu^- e^+$) Conversion Experiment (MACE) will serve as a complementary experiment to search for charged lepton flavor violation processes, compared with other on-going experiments like MuBe ($\mu^+ \rightarrow e^+ e^- e^-$), MEG-II ($\mu^+ \rightarrow e^+ \gamma$) and Mu2e/COMET ($\mu^- \rightarrow e^- \gamma$). MACE aims at a sensitivity of $P(\mu^+ e^- \rightarrow \mu^- e^+) \sim O(10^{-11})$, 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.

- Experimental Letter of Intent

Snowmass LOI后的国际反响

Detectors and concepts for future CLFV experiments

Bertrand Echenard
Caltech

NuFact 2021
Cagliari - September 2021



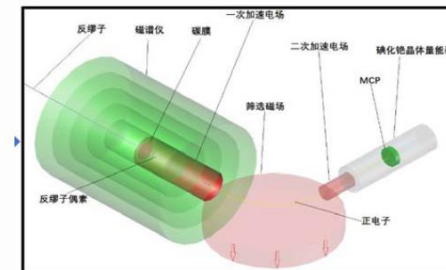
MACE at EMuS

EMuS – new muon facility in China



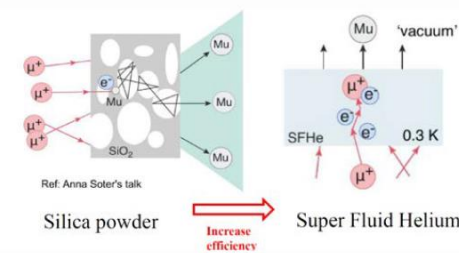
Jian Tang
(Snowmass 2021 RPP meeting)

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

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 Zhou²

¹School of physics, Sun Yat-sen University, China

²Institute of High Energy Physics, Chinese Academy of Science, China

³Research Center of Nuclear Physics, Osaka University, Japan

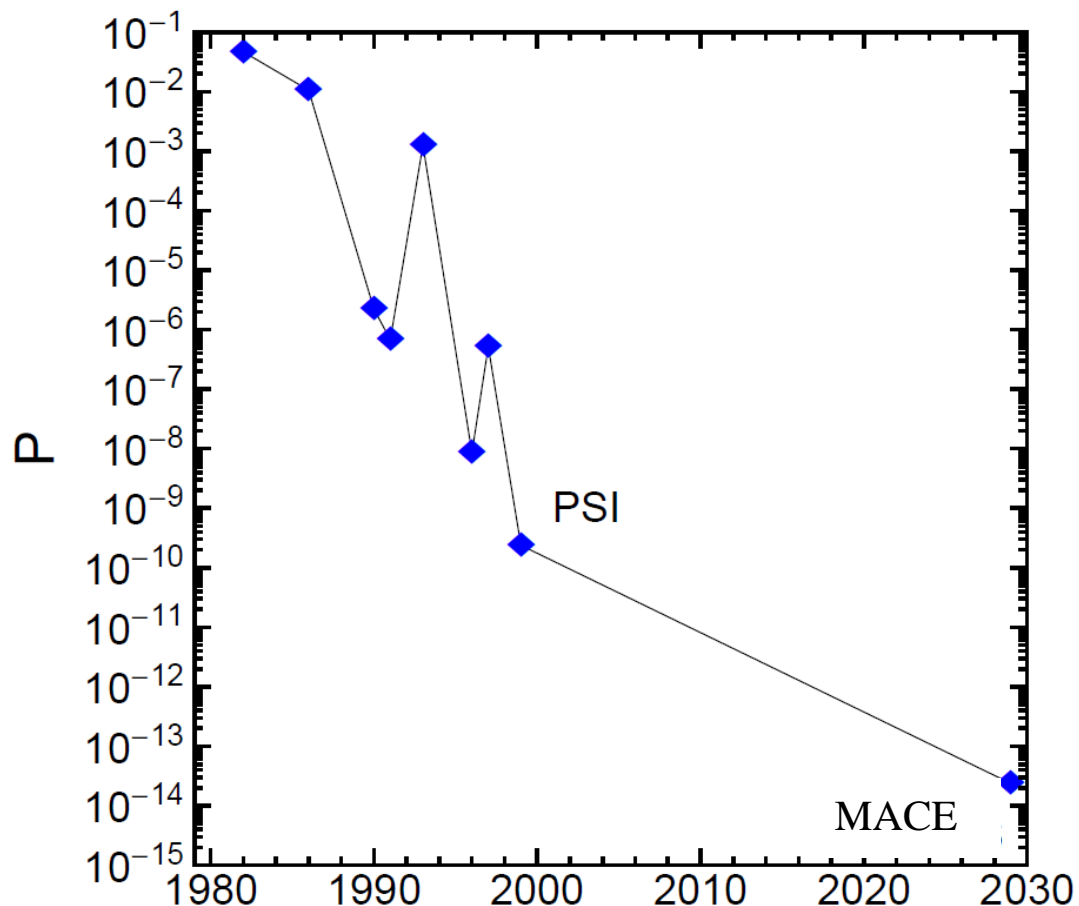
Reference: Snowmass2021 Whitepaper: Muonium to antimuonium conversion, arXiv:2203.11406

- 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，中微子散射研讨会vSTEP发起人



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 $E=29.8 \text{ MeV}$ ，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

8月26日完成CDR评审

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

Conceptual Design of the Muonium-to-Antimuonium Conversion

Experiment (MACE)

Ai-Yu Bai,¹ Hanjie Cai,² Siyuan Chen,¹ Xurong Chen,² Yu Chen,¹ Yukai Chen,³
Weibin Cheng,⁴ Rui-Rui Fan,³ Li Gong,⁴ Yinyuan Huang,⁴ Zhilong Hou,³ Huan Jia,²
Han-Tao Jing,³ Xiaoshen Kang,⁴ Hai-Bo Li,^{3,5} Jincheng Li,² Yang Li,³ Guihao Lu,¹
Han Miao,^{3,5} Yunsong Ning,¹ Jianwei Niu,² Huaxing Peng,^{3,5,6} Alexey A. Petrov,⁷
Yuanshuai Qin,² Ying-Peng Song,³ Mingchen Sun,¹ Jian Tang,^{1,*} Jing-Yu Tang,³ Ye Tian,²
Chen Wu,^{3,8} Rong Wang,² Weizhi Xiong,⁹ Tian-Yu Xing,^{3,5} Yu Xu,¹ Baojun Yan,^{3,6}
Ye Yuan,^{3,5} Yao Zhang,³ Zhilv Zhang,² Guang Zhao,³ Shihan Zhao,¹ and Luping Zhou³

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⁸*Research Center of Nuclear Physics (RCNP), Osaka University, Japan*

⁹*Institute of Frontier and Interdisciplinary Science,
Shandong University, Qingdao 266237, China*

(Dated: August 23, 2024)

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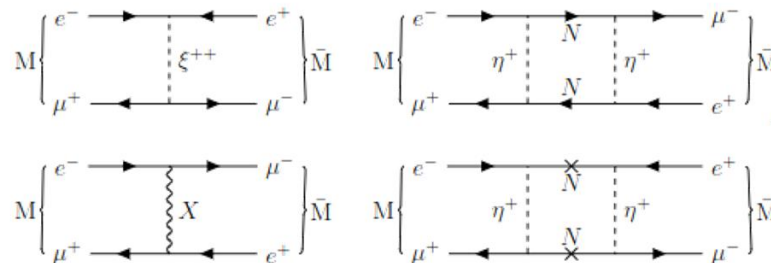
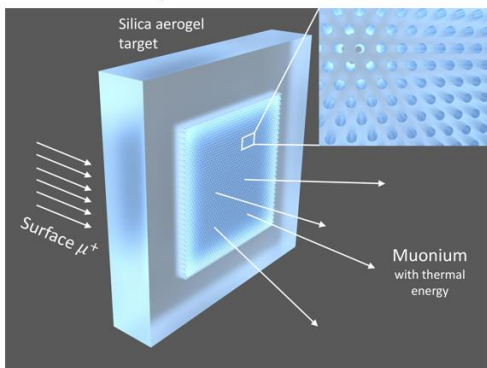
内容概述

- 前期科研进展的介绍
- 为什么研究缪子物理?
- **MACE实验的预研进展**
- 本地缪子实验室建设

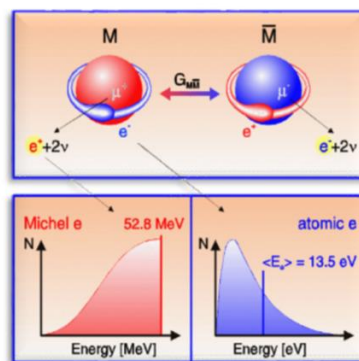
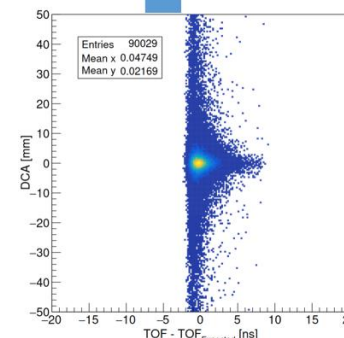
MACE实验关键技术路线

Muonium-to-Antimuonium Conversion Experiment

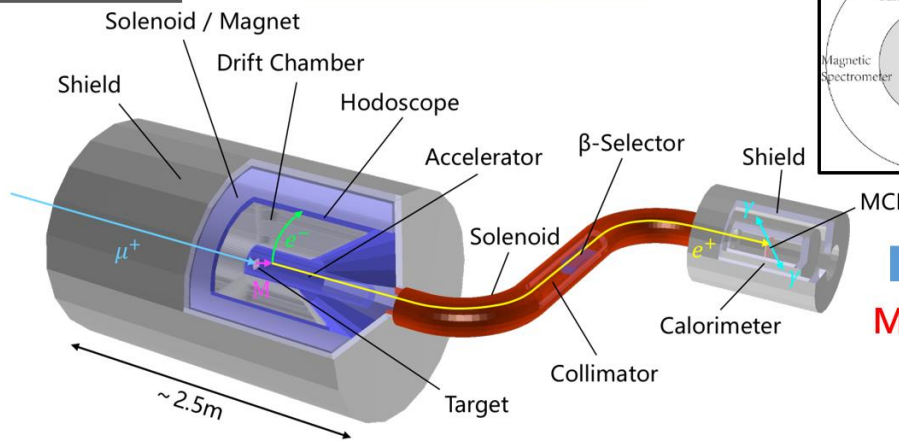
High-efficiency muonium production?



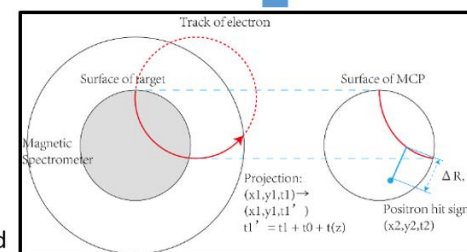
High signal/noise ratio



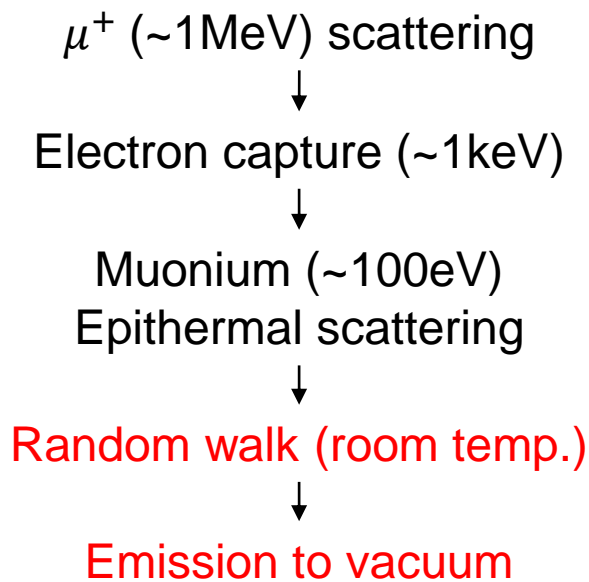
High-resolution spectrometer



Multiple coincidence?

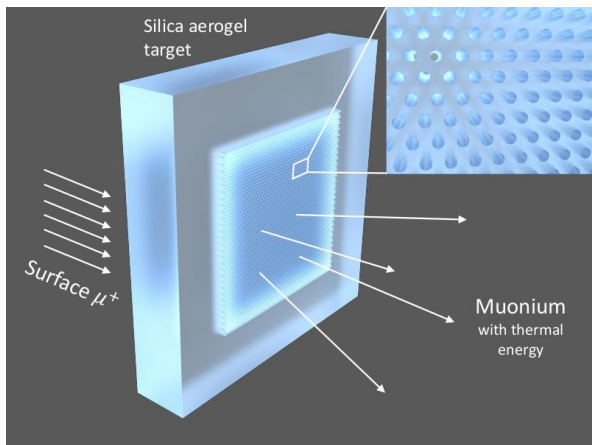
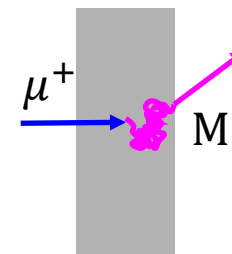


SiO₂气凝胶材料中缪子素的产生和运输

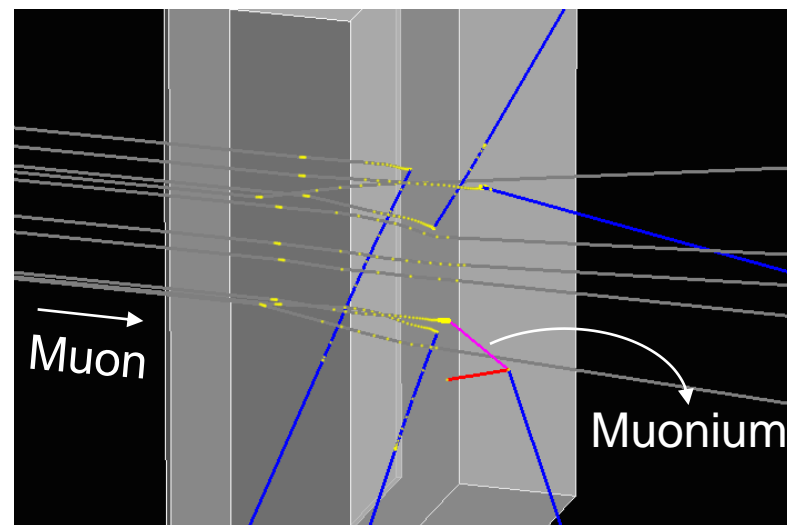


MC simulation for muonium transport has been developed under the MACE offline software framework.

- ① Geant4 low-energy EM process.
- ② Geant4 AtRest process, modeled phenomenologically.
- ③ Random walk approach to thermal muonium tracking.



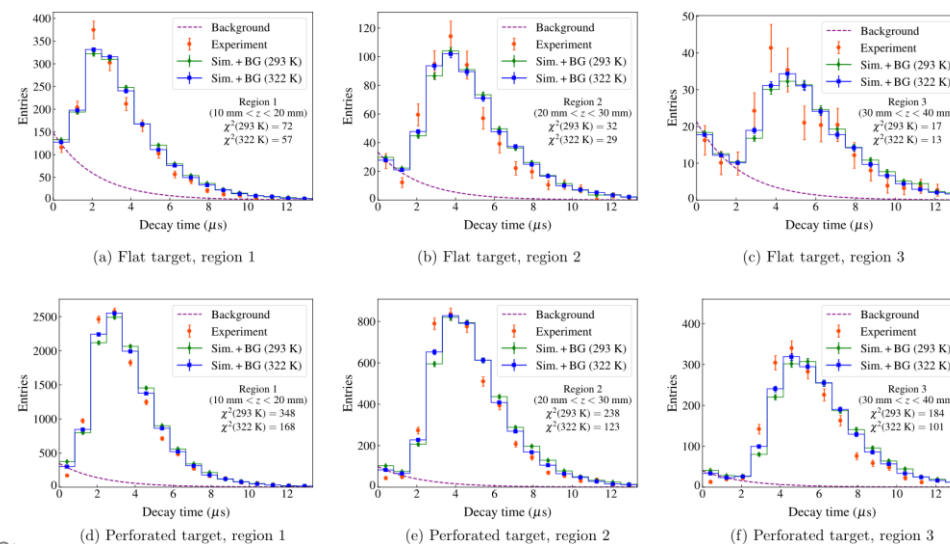
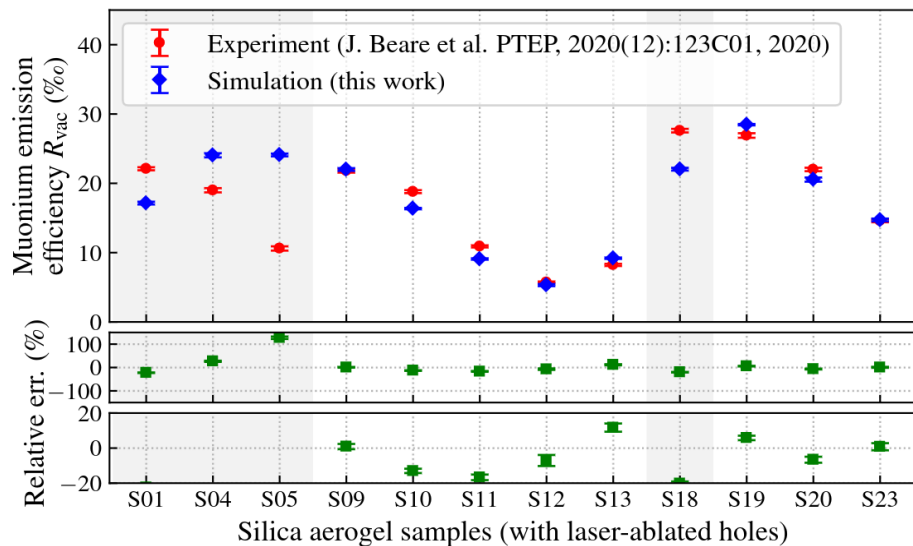
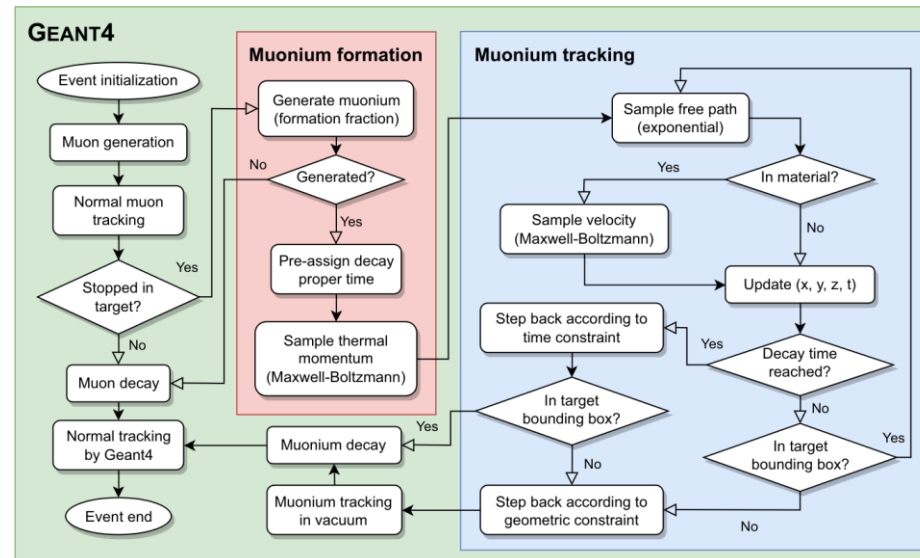
模拟的单个
缪子素产生
并逸出事例:



SiO₂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: $I_M^{vac} = I_{beam} Y_{\mu \rightarrow M}$
- $Y_{\mu \rightarrow M}$ 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.



SiO₂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

✓ $Y_{\mu \rightarrow M} = N_M^{\text{vac}} / N_{\mu}^{\text{total}} = 4.08\%$

✓ Nearly an order of magnitude improvement on $N_M^{\text{vac}} / N_{\mu}^{\text{total}}$.

➤ Still room for further optimization.

- Multi-layer target + intensive muon beam → intensive in-vacuum muonium source:

✓ $I_M^{\text{vac}} = I_{\text{beam}} Y_{\mu \rightarrow M} = 4 \times 10^6 / \text{s}$, assuming $I_{\text{beam}} = 10^8 / \text{s}$

➤ For comparison, MACS 1990s: $I_M^{\text{vac}} = 4 \times 10^4 / \text{s}$

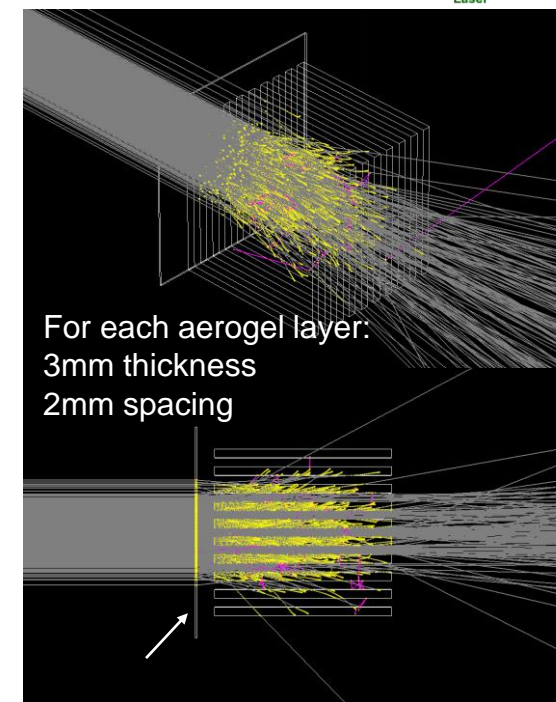
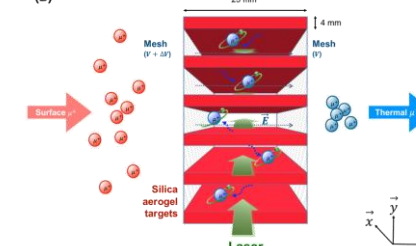
➤ **Expected two orders of magnitude improvements in in-vacuum muonium source intensity!**

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



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,h}, N. Saito ^e, K. Suzuki ^{h,i}, S. Uetake ^h, Y. Mao ^a

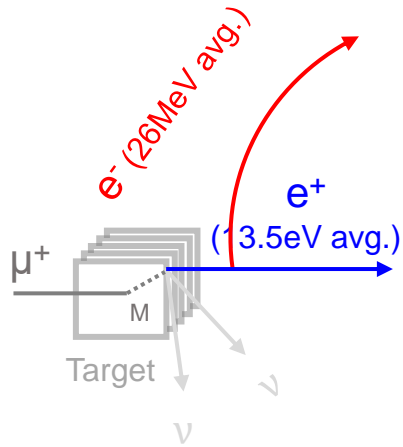


For each aerogel layer:
3mm thickness
2mm spacing

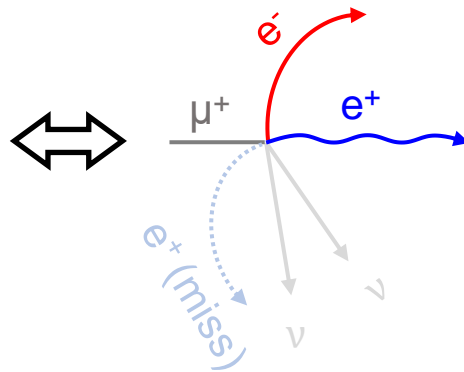
MACE实验信号和本底鉴别

Signal:

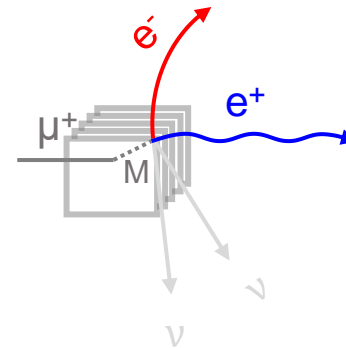
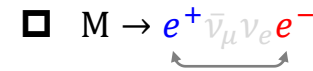
fast e^- + slow e^+



1. Internal conv. (IC) decay

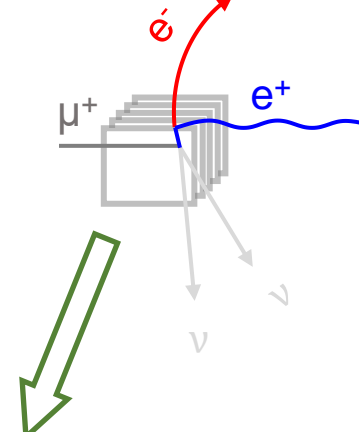


2. Final state scattering



3. Accidental bkg.

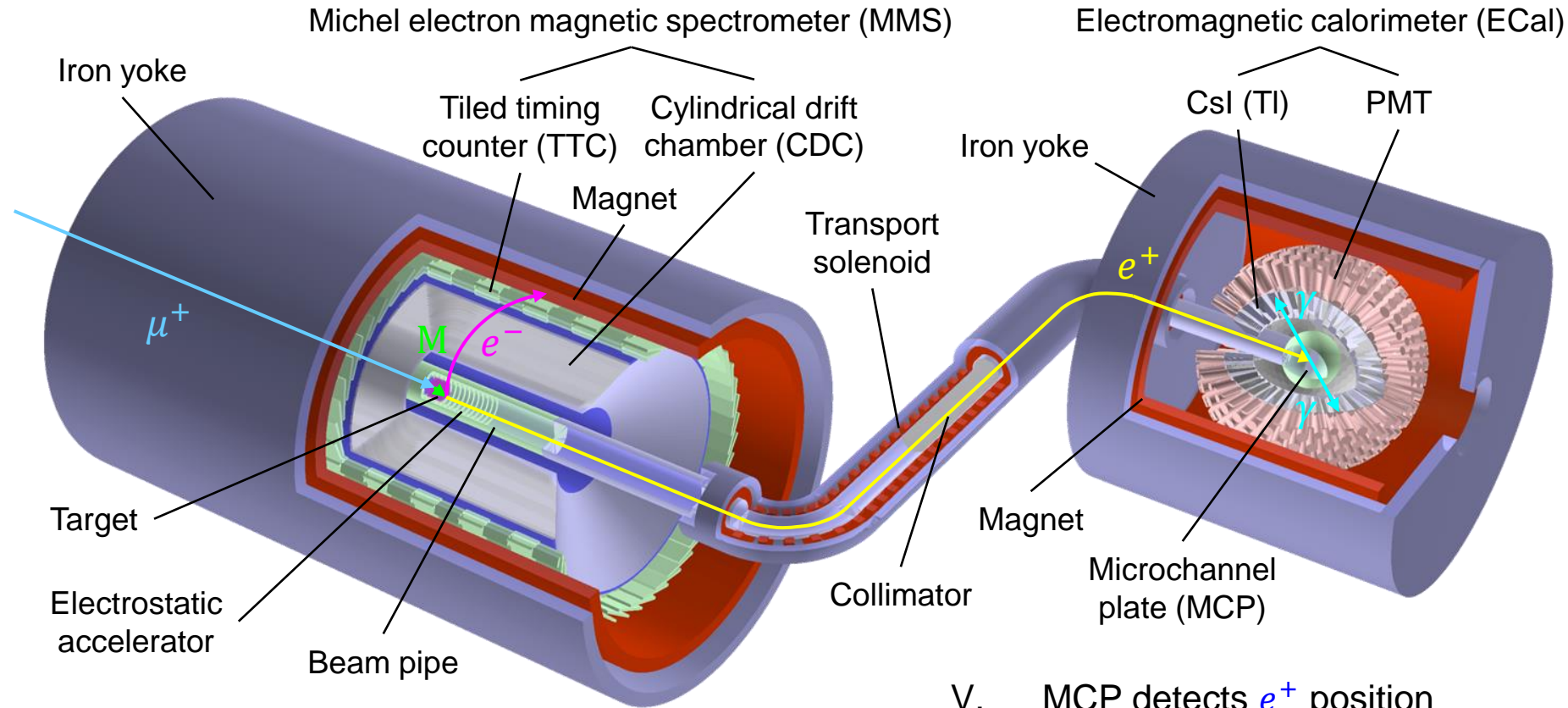
- Scattering/conv. e^-
- Misreconstruction
- Cosmic ray, etc.



- 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 \rightarrow muonium
- II. M diffuse into vacuum & convert to \bar{M}
- III. Decay in a vacuum: $\bar{M} \rightarrow e^+ e^- \nu_\mu \bar{\nu}_e$
- IV. CDC detects Michel e^- track
- V. Transport atomic e^+ to MCP (conserving transverse position)

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

Triple coincidence:

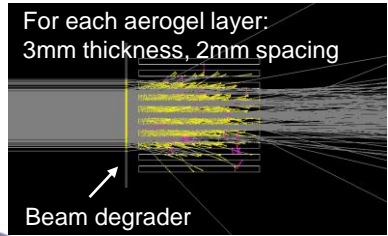
➤ **MMS + MCP + ECal**

↓
Michel e^- Atomic e^+

MACE实验基本设计方案v1

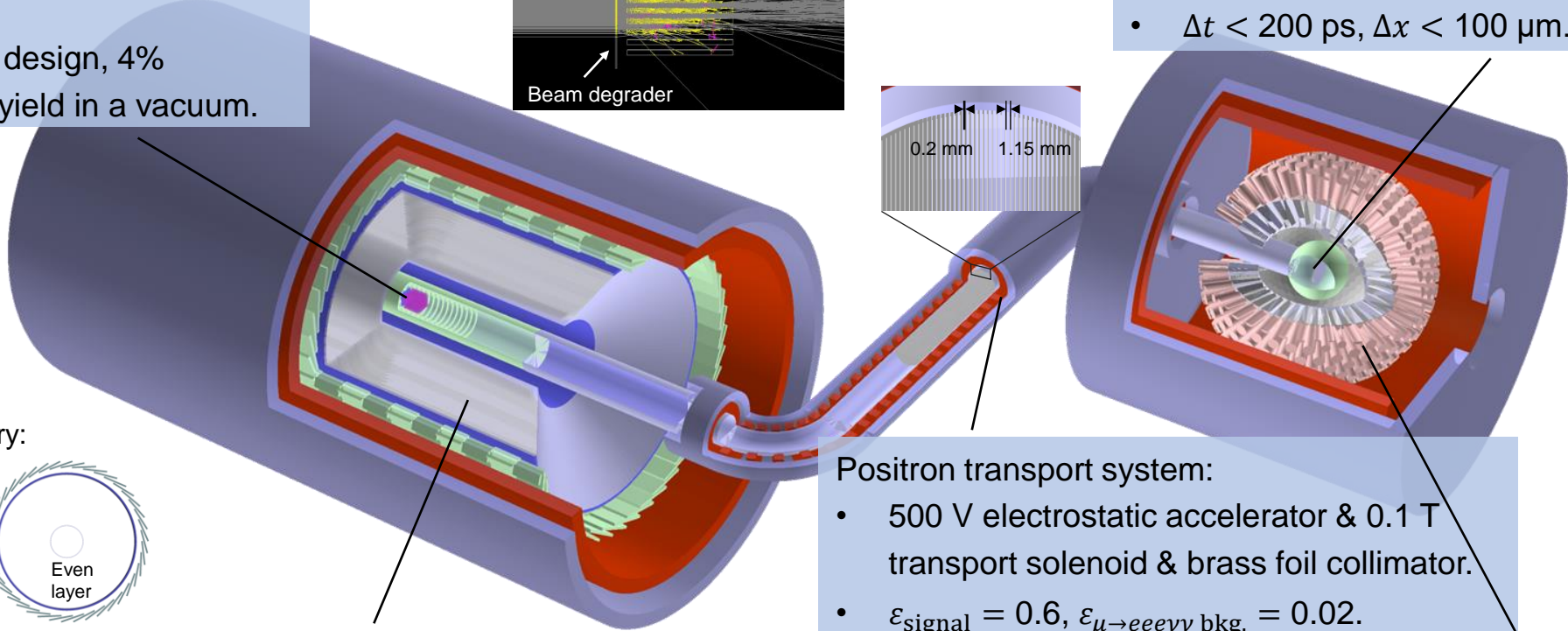
Muonium target:

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

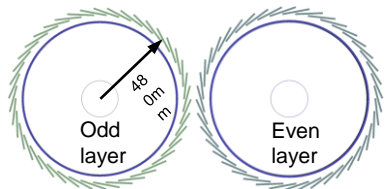


Microchannel plate (MCP) specifications:

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



TTC geometry:



Magnetic spectrometer:

- 0.1 T axial magnetic field.
- CDC: $\text{He}(\text{C}_4\text{H}_{10})$ 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.

Positron transport system:

- 500 V electrostatic accelerator & 0.1 T transport solenoid & brass foil collimator.
- $\epsilon_{\text{signal}} = 0.6$, $\epsilon_{\mu \rightarrow eee\nu}$ bkg. = 0.02.
- Signal e^+ position error 100 μm .

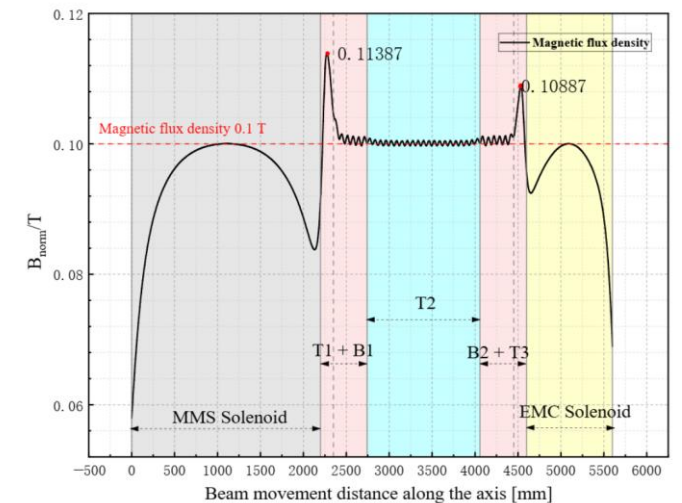
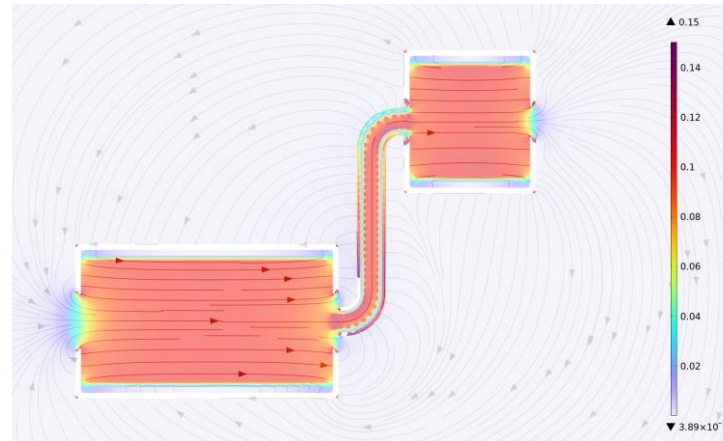
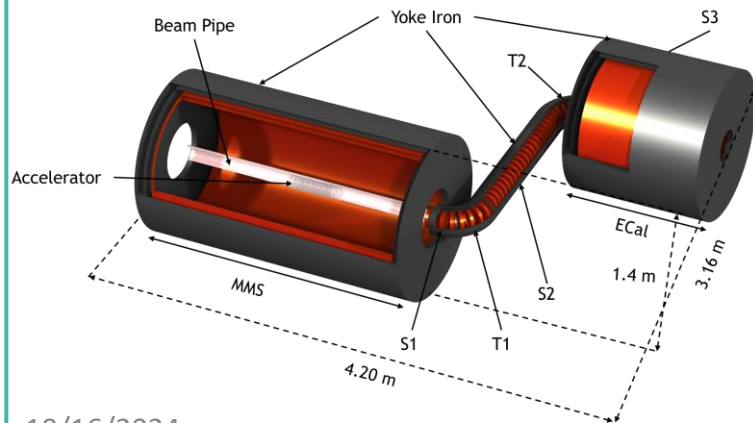
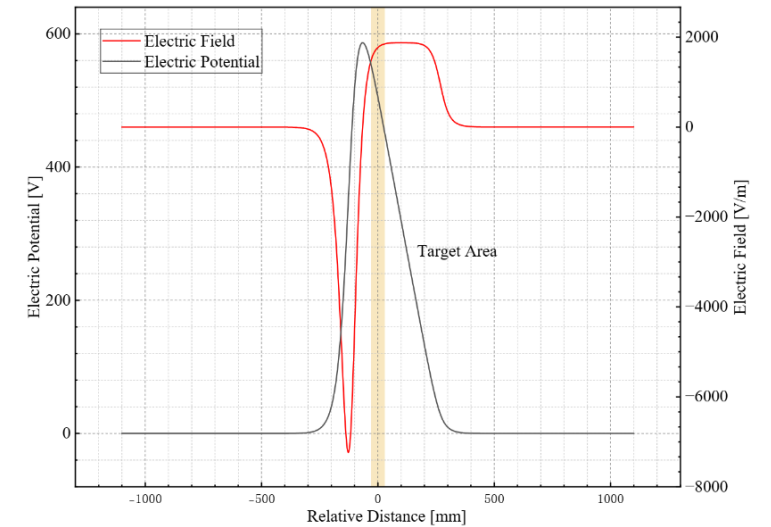
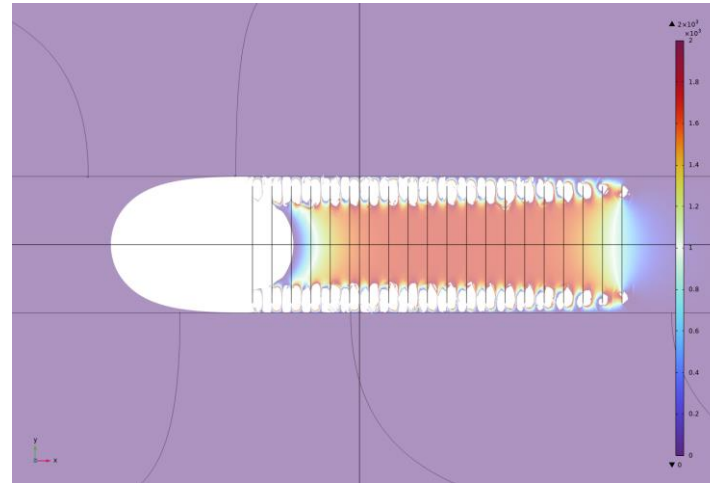
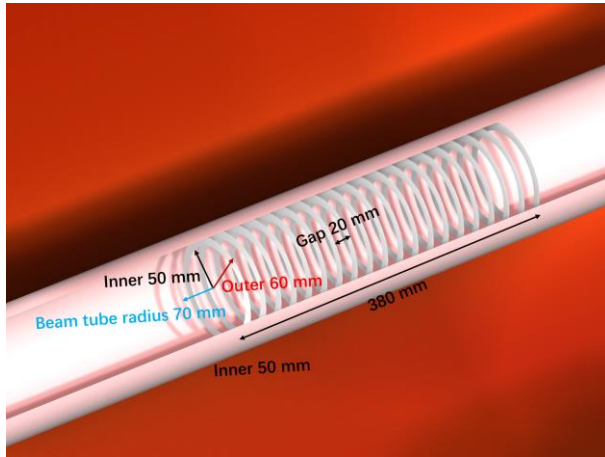
Electromagnetic calorimeter:

- Geometry: Class-I GP(4,0) Goldberg polyhedron.
- 622 CsI(Tl) crystals with 10 cm length, PMT readout.
- 97% geometry 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.

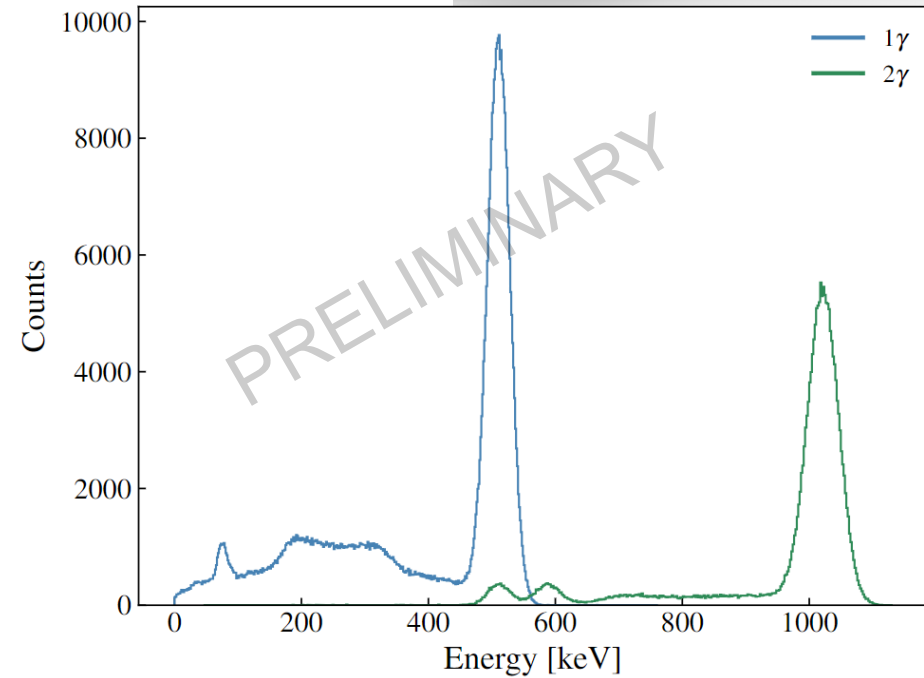
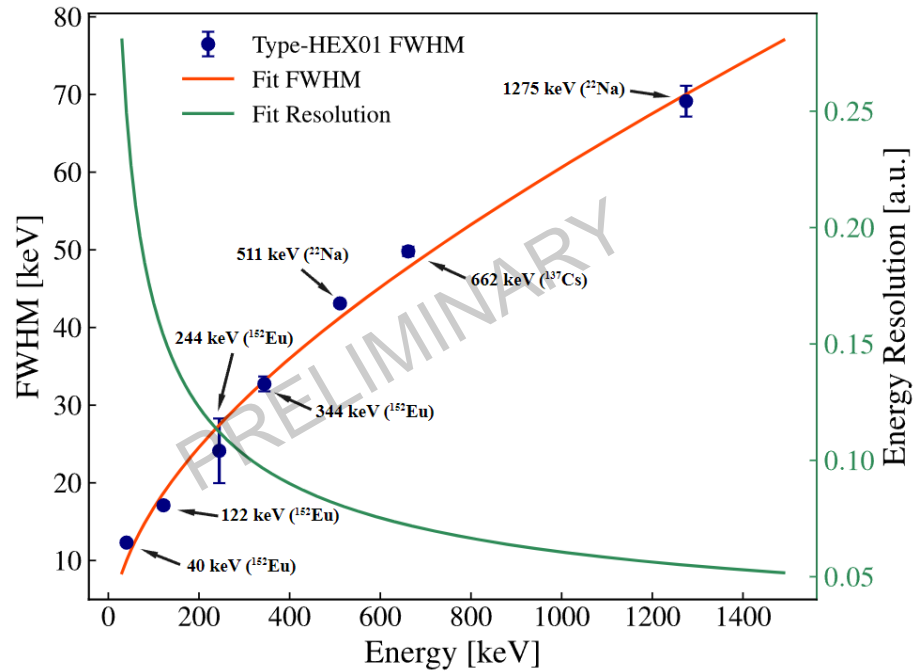
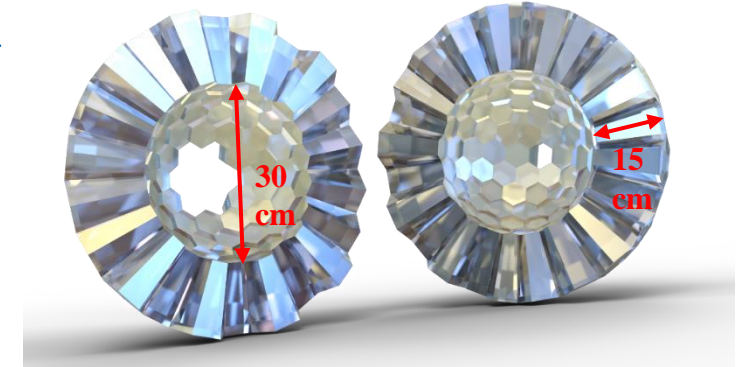


Design of calorimeter

- Signal and Background

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

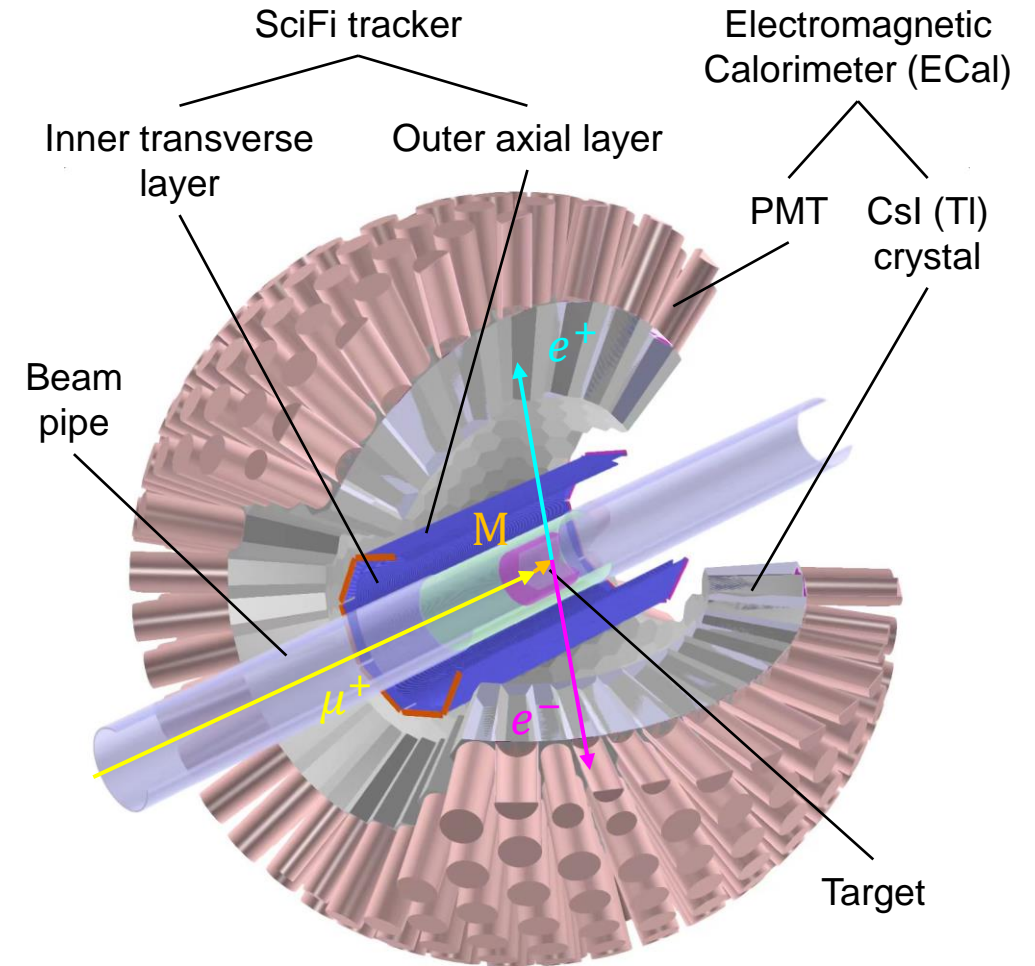


Design of MACE Phase-I

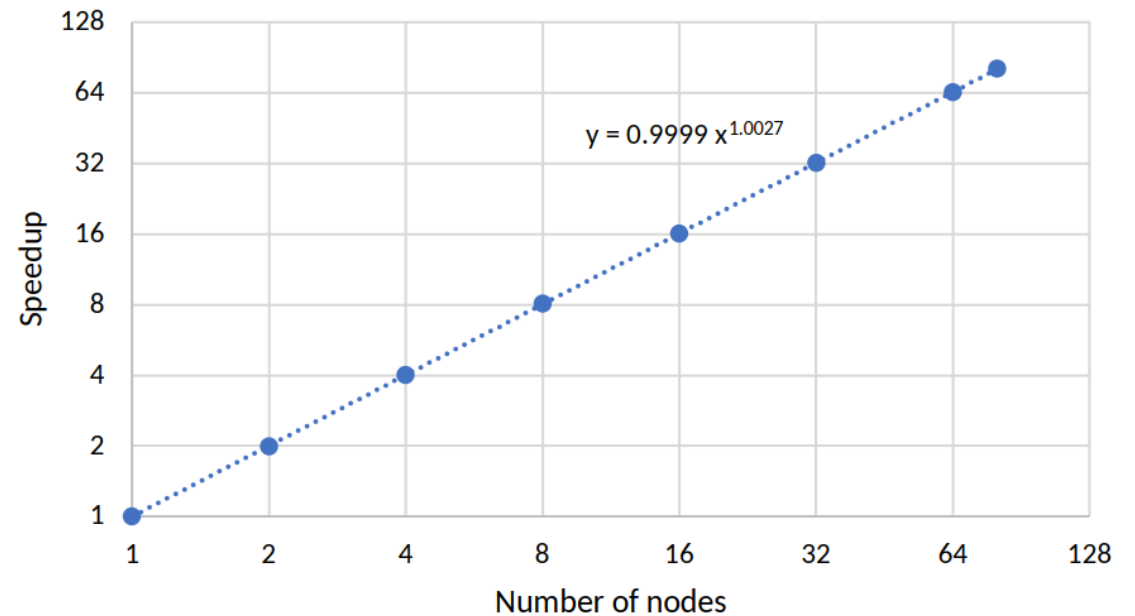
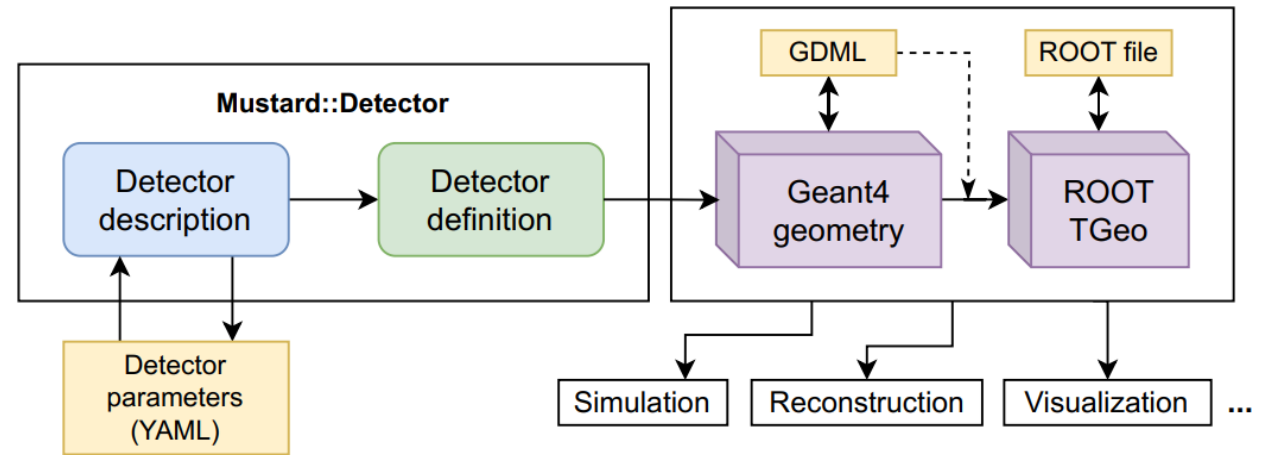
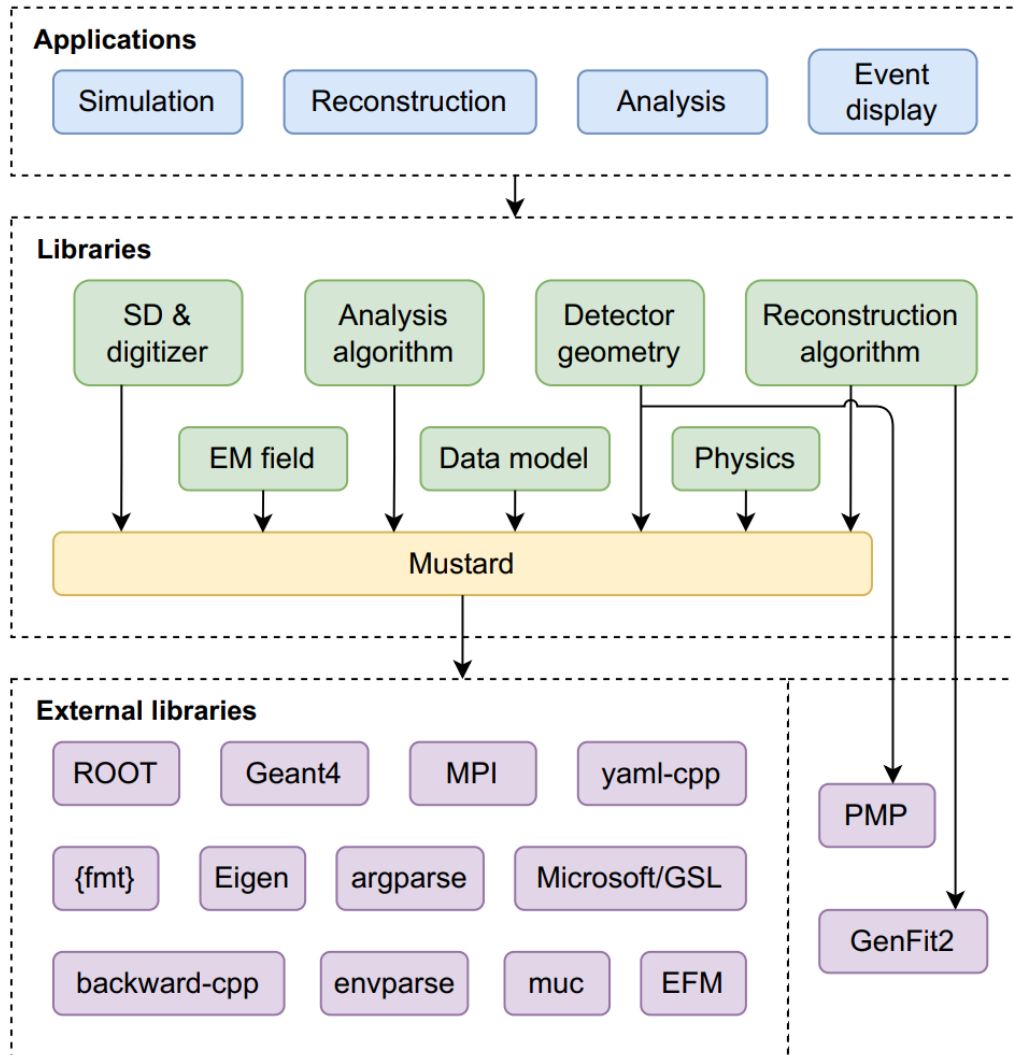
- We planned to construct the ECal first for the Phase-I experiment.
- Physics goal: search for rare muonium decay (e.g. $M \rightarrow ee$) with $O(10^{-11})$ sensitivity.
- Operates at $10^6 \sim 10^7 \mu^+$ /s surface muon beam.
- Challenges: (i) event pile up and (ii) efficiency loss due to different ECal energy range between Phase-I and Phase-II.

Detection scheme:

- I. Surface muon stop in target \rightarrow muonium
- II. Muonium rare decay: $M \rightarrow e^+e^-$
- III. SciFi Tracker detects back-to-back e^+e^- pair coincidence with ECal.



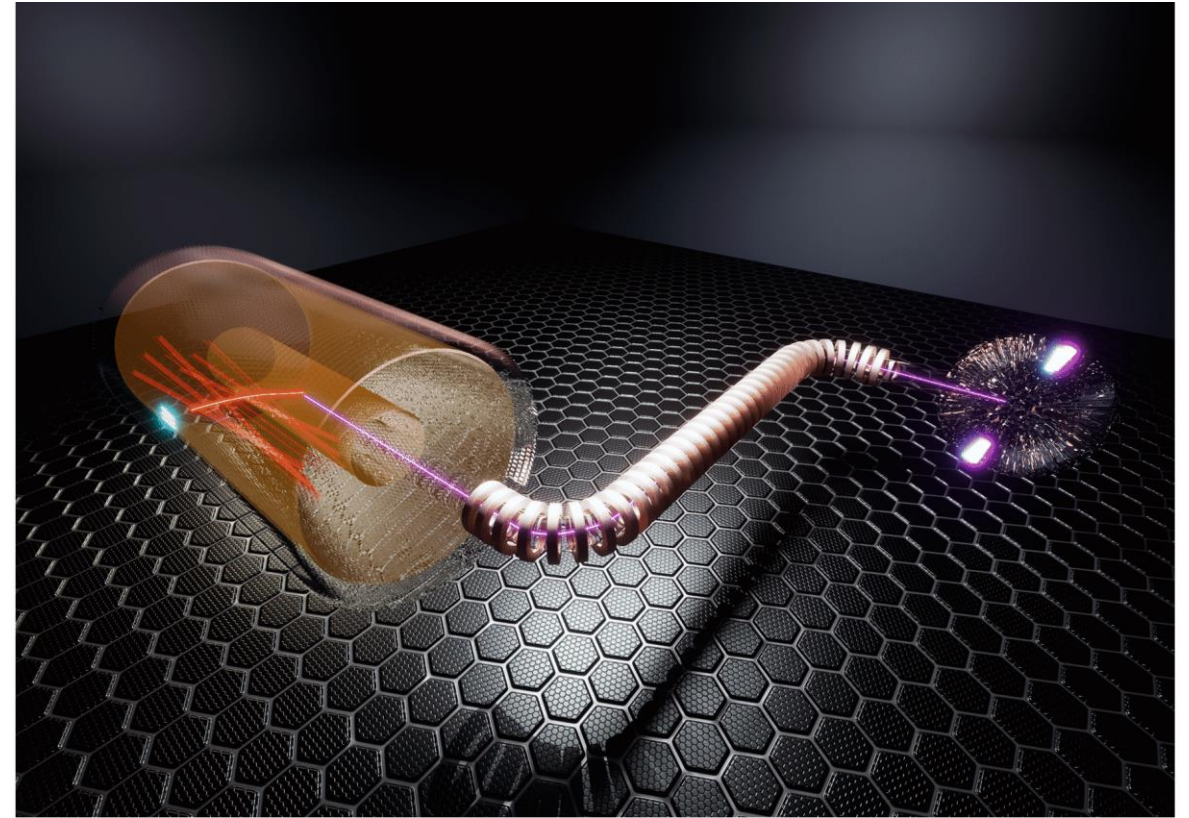
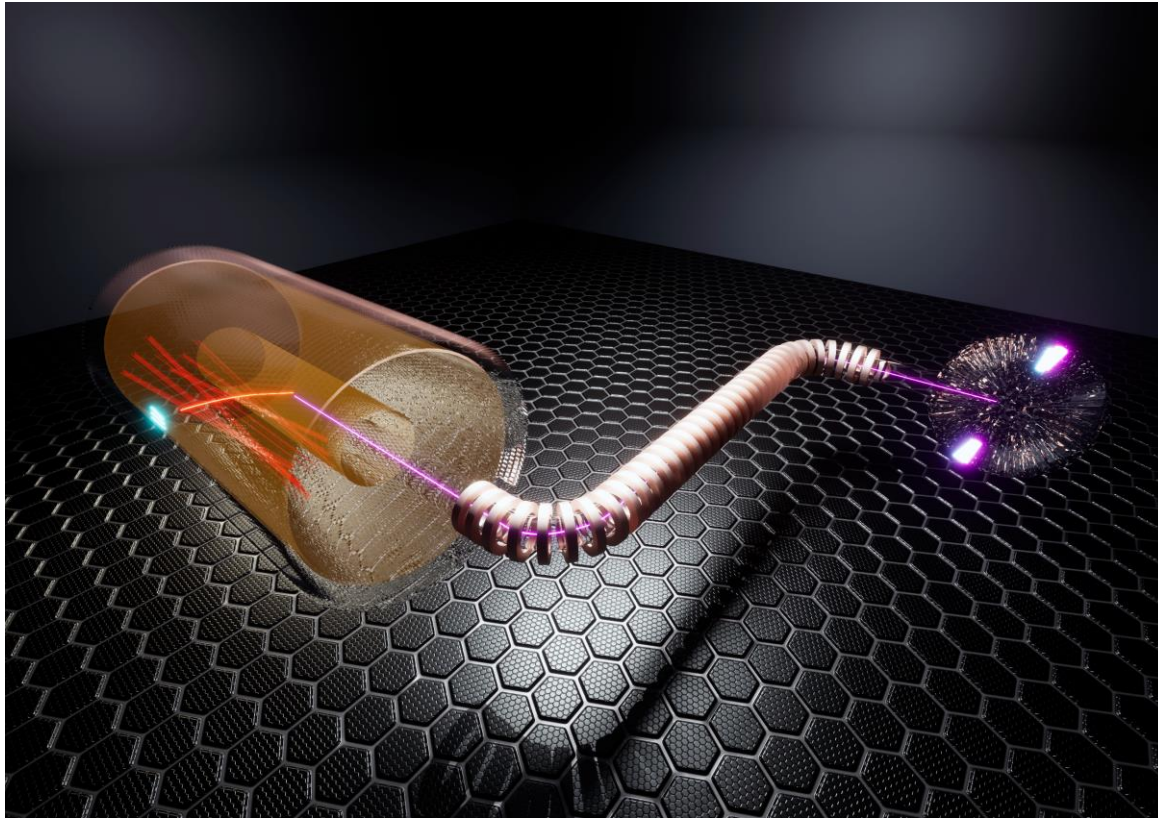
MACE离线软件框架和天河二号



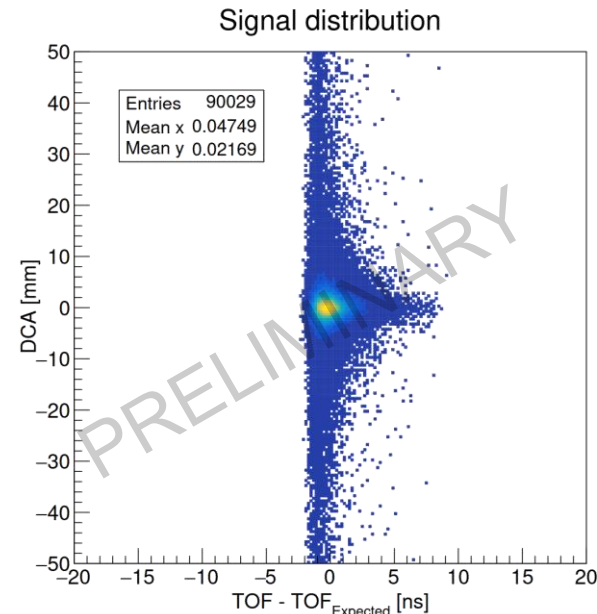
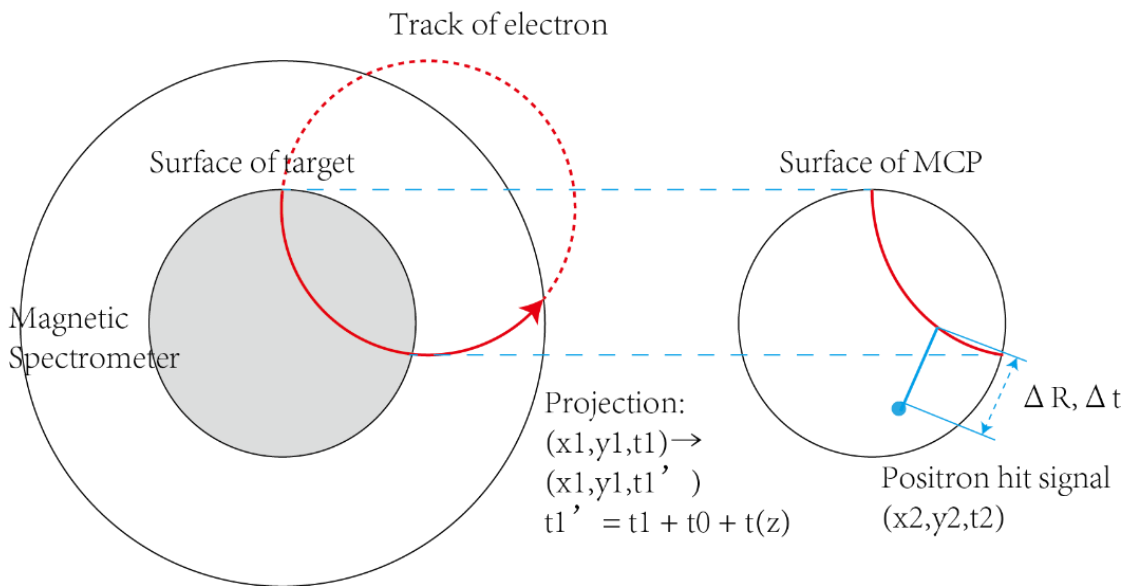
MACE事例显示器开发中



Credits: 熊伟志



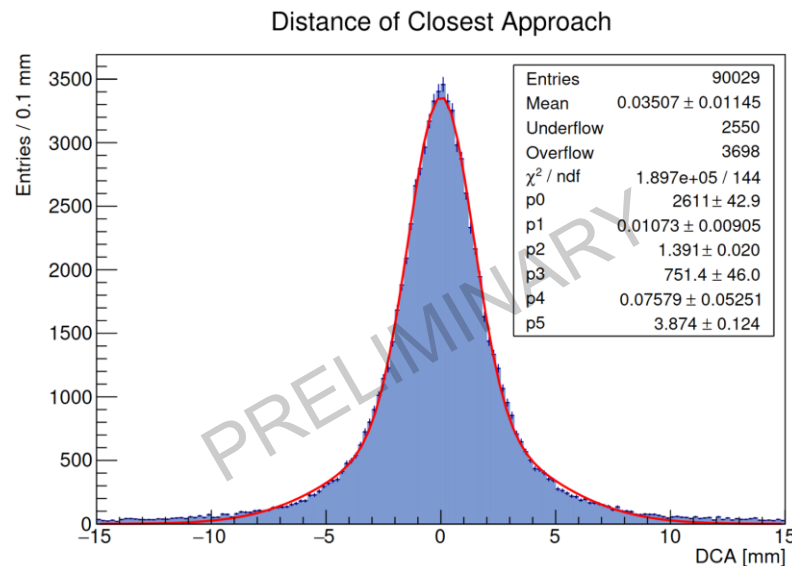
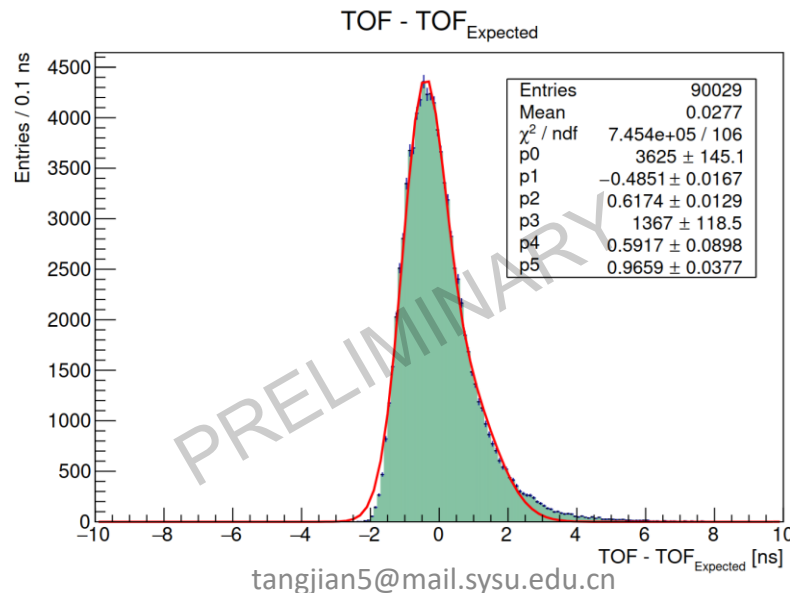
快速MC模拟: 缪子素探测



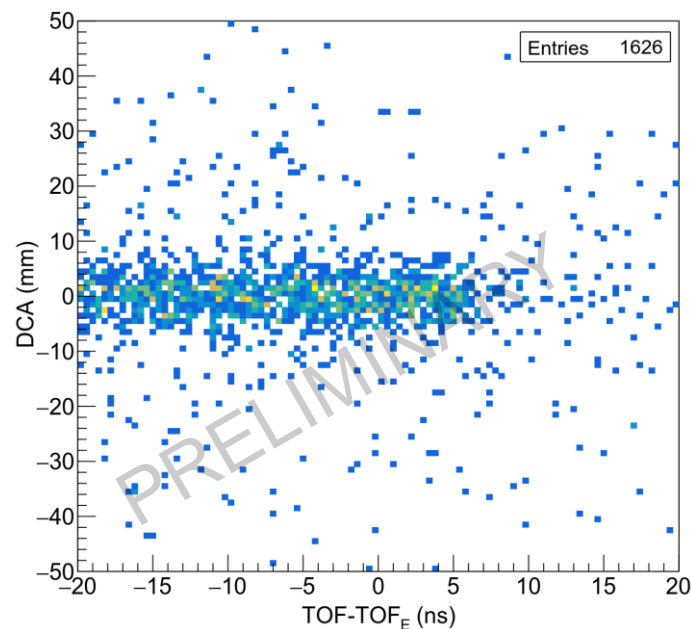
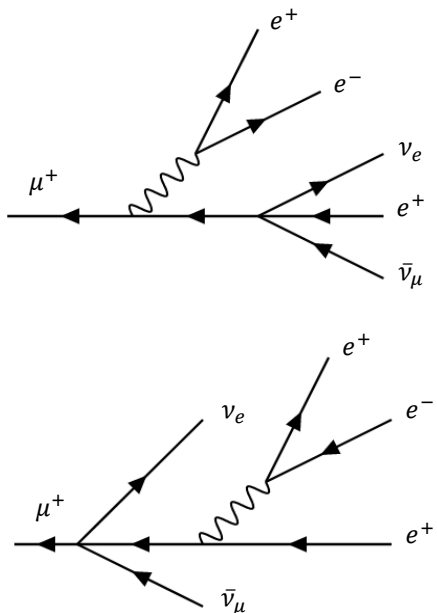
- Elliptical 3σ signal region:

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

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

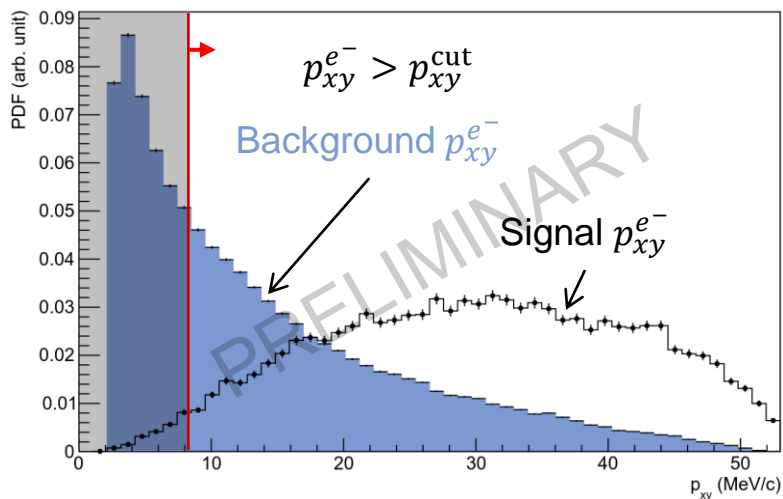


快速MC模拟: 五轻子末态

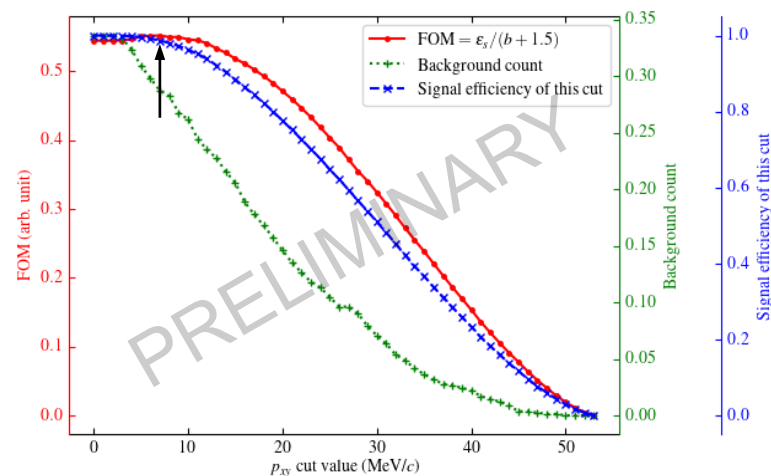


$\mu^+ \rightarrow e^+ e^- e^+ \bar{\nu}_\mu \nu_e$ simulation:

- Event selection:
 - 3σ signal region cut
 - $p_{xy} > 7 \text{ MeV}/c$
 - $\epsilon_{p_{xy} \text{ cut}} = 0.926$
 - $\epsilon_{\text{all cut}} = 0.914$
 - $N_{\text{bkg}} = 0.287 \pm 0.020$
- (in $10^8 \mu/s \times 365 \text{ d}$)



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



MACE实验灵敏度分析

- Summary of current full simulation results:

Background		count / ($10^8 \mu/s \times 365 \text{ d}$)
$\mu^+ \rightarrow e^+ e^- e^+ \bar{\nu}_\mu \nu_e$		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 acceptance ($\epsilon_{\text{MMS}}^{\text{geom}}$)	88.2%
	Reconstruction efficiency ($\epsilon_{\text{MMS}}^{\text{recon}}$)	$\sim 80\%$
Positron transport system (PTS)	Transmission efficiency (ϵ_{PTS})	65.8%
Microchannel plate (MCP)	Detection efficiency (ϵ_{MCP})	32.6%
Electromagnetic calorimeter (ECal)	Detection efficiency (ϵ_{ECal})	67.5%
Total detection efficiency		10.2%
Analysis	Signal efficiency (ϵ_{Cut})	$\sim 80\%$
Total signal efficiency		8.2%

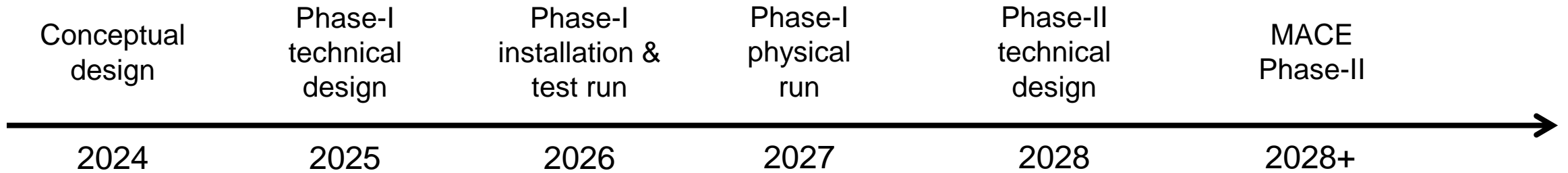
- ✓ $O(10^{-14})$ single event sensitivity is expected:

$$\text{SES} = \frac{1}{\epsilon_{\text{Geom}} \epsilon_{\text{MMS}} \epsilon_{\text{MCP}} \epsilon_{\text{ECal}} \epsilon_{\text{cut}} \mathcal{Y}_{\text{M}} N_{\mu^+}} = 9.5 \times 10^{-14}$$

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



Timeline



➤ Phase-I: $O(10^{-11})$ sensitivity for rare muonium decay (e.g. $M \rightarrow ee$)

- Data taking duration: 1 year

- Beam specifications:

- ❑ Surface muon, $10^6 \sim 10^7 \mu^+/s$
- ❑ 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, $10^8 \mu^+/s$
- ❑ Pulsed beam, repetition rate $20 \sim 50 \text{ kHz}$
- ❑ Momentum spreading: $\Delta p/p < 3\%$

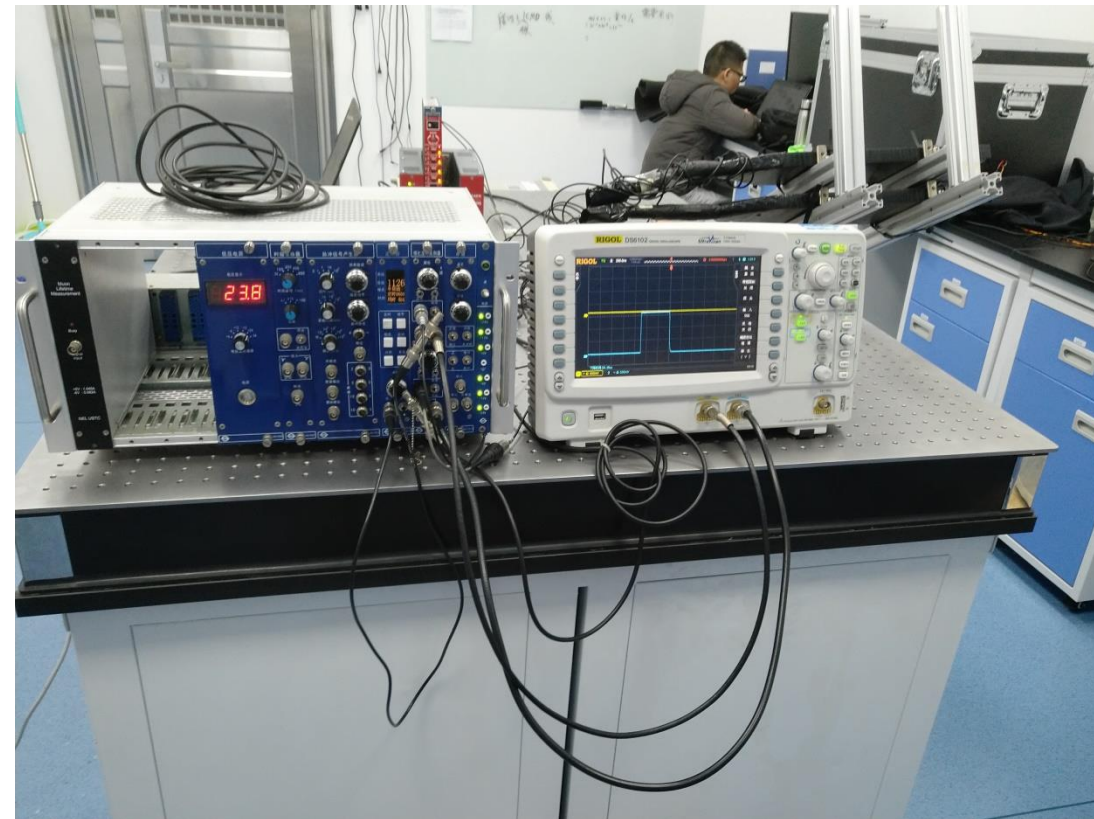
- Domestic muon beams in the near future: [Melody](#), [CiADS](#), [HIAF](#), [SHINE](#)



内容概述

- 前期科研进展的介绍
- 为什么研究缪子物理?
- MACE实验的预研进展
- 本地缪子实验室建设

建设本地缪子物理实验室



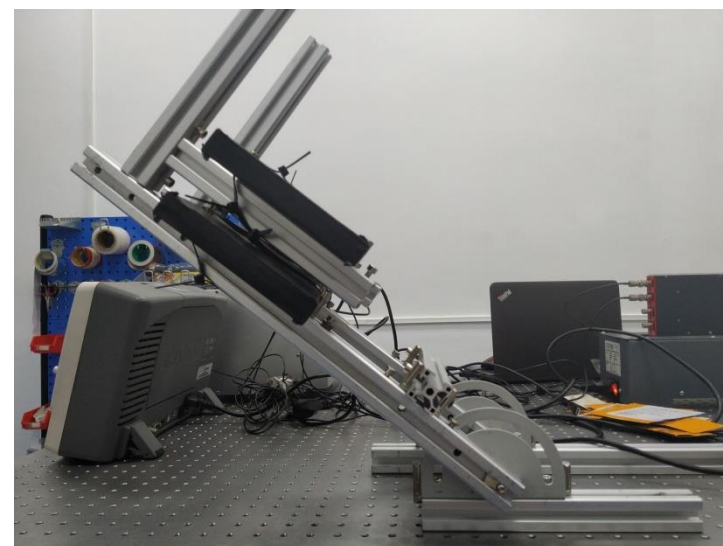
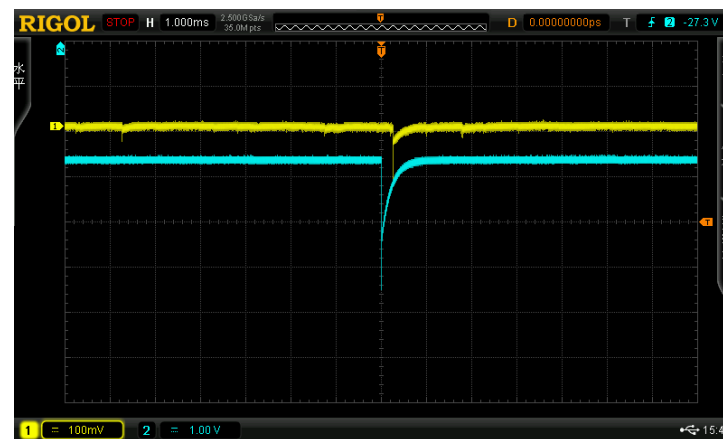
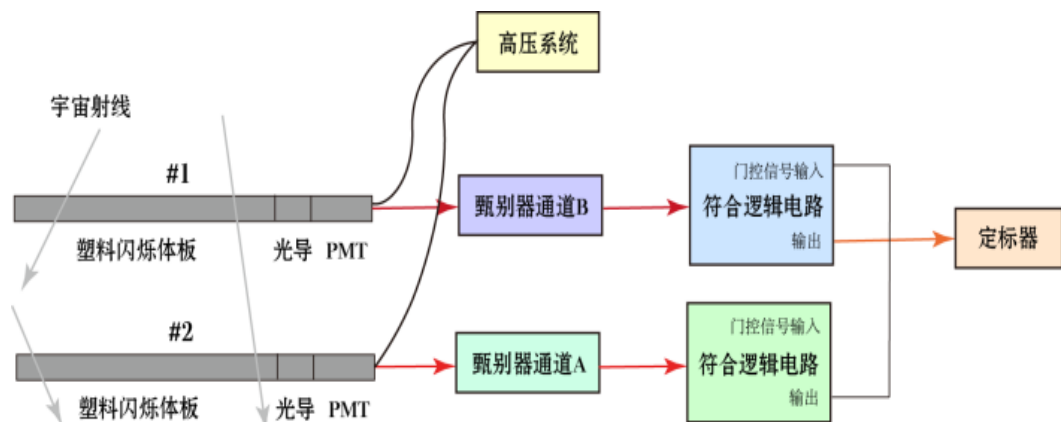
缪子前沿科学与技术应用实验室SMOOTH

感谢学院的支持，教学和科研融合的实验室，新实验楼装修中！

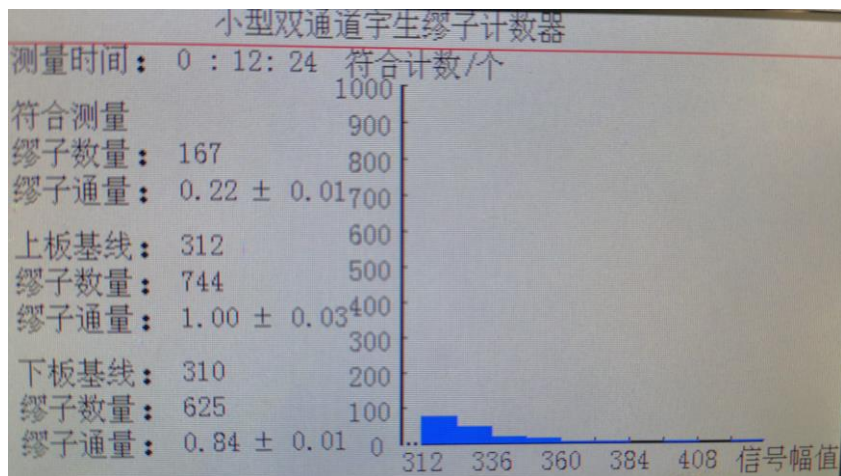
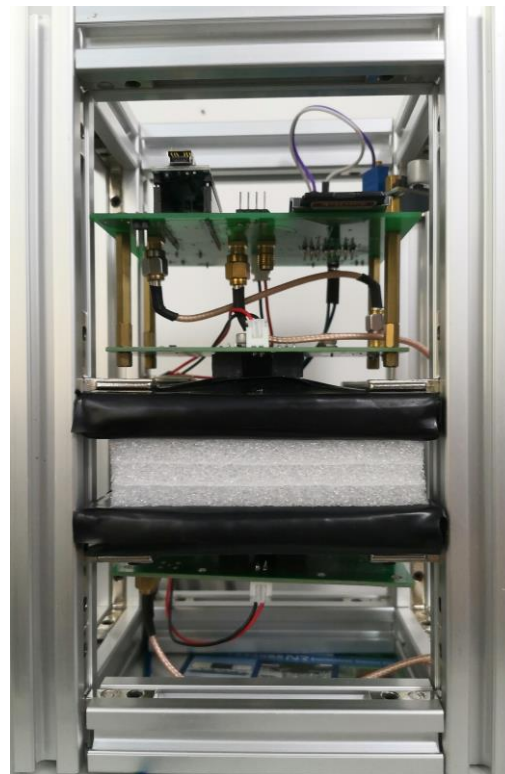
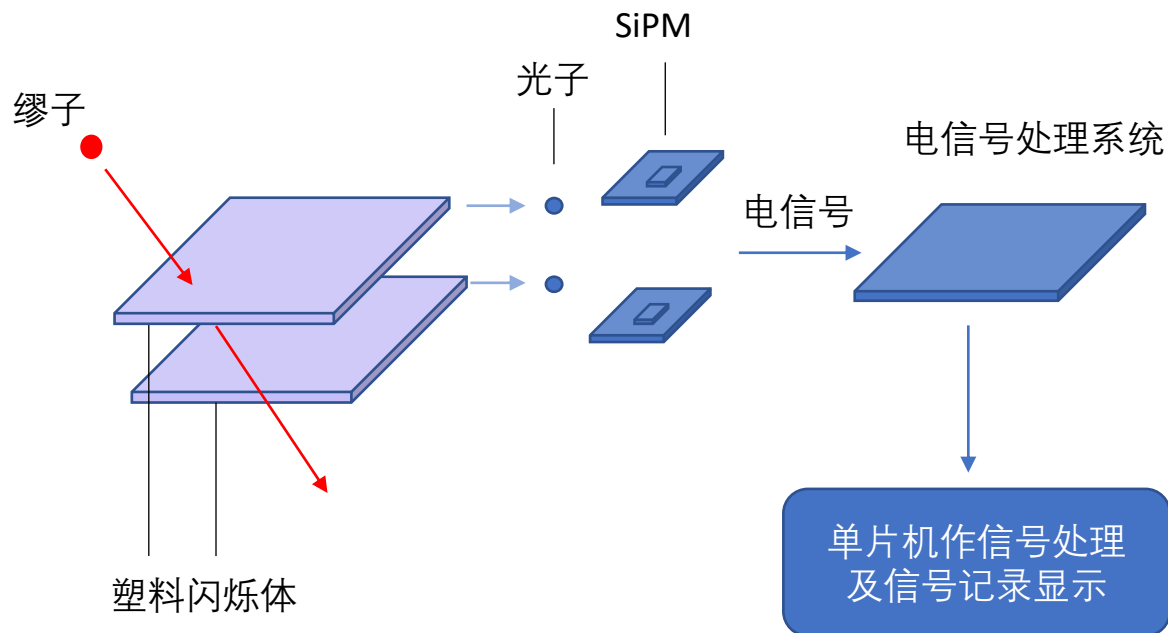
教学型宇生缪子探测器v1：符合探测

- Coincident method → oscilloscope to monitor PMT waveforms
→ NIM electronics to count rates and angular distributions

林海星, 宁云松等, 《物理实验》第41卷, 第2期, 2021年2月



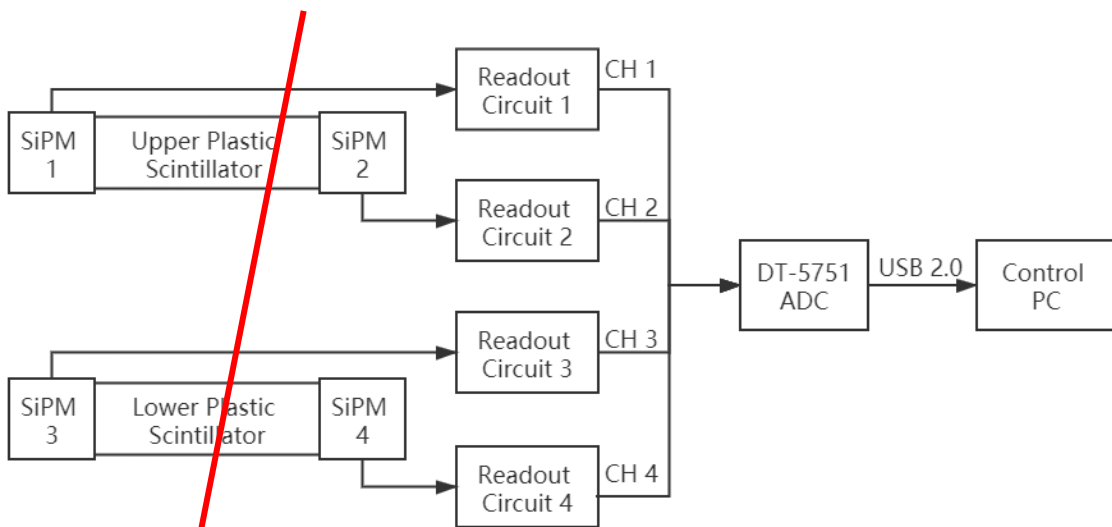
教学型宇生缪子探测器v2：小型化



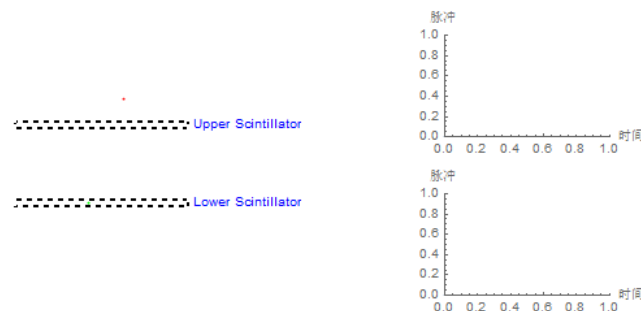
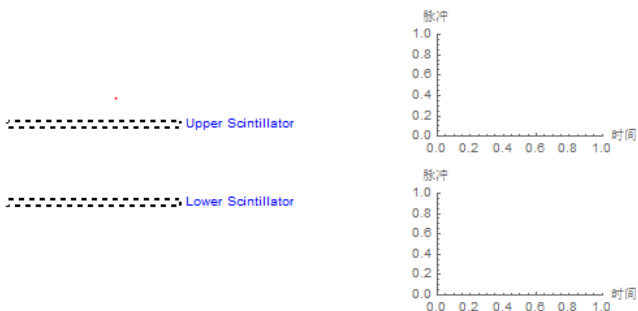
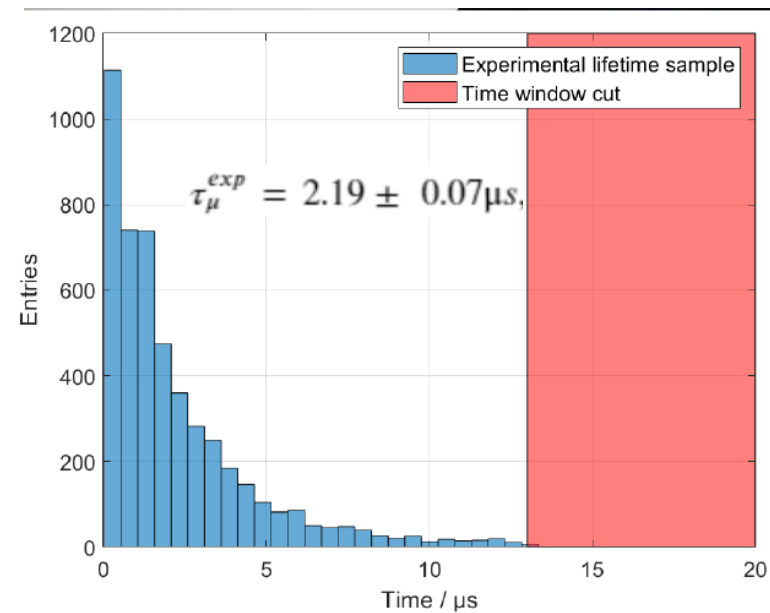
- 特点：便携式，北斗定位和授时，无线传输云平台，微信小程序，阵列集群...
- 已用于中山大学《专业物理实验》教学
- 开展科学普及、产学研推广等

Credit: 蒋辉, 宁云松, 林海星等

教学型宇生缪子探测器v3：寿命测量



μ^\pm

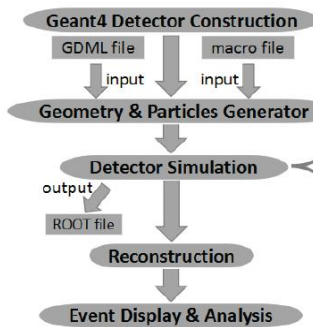


μ^\pm
 e^\pm

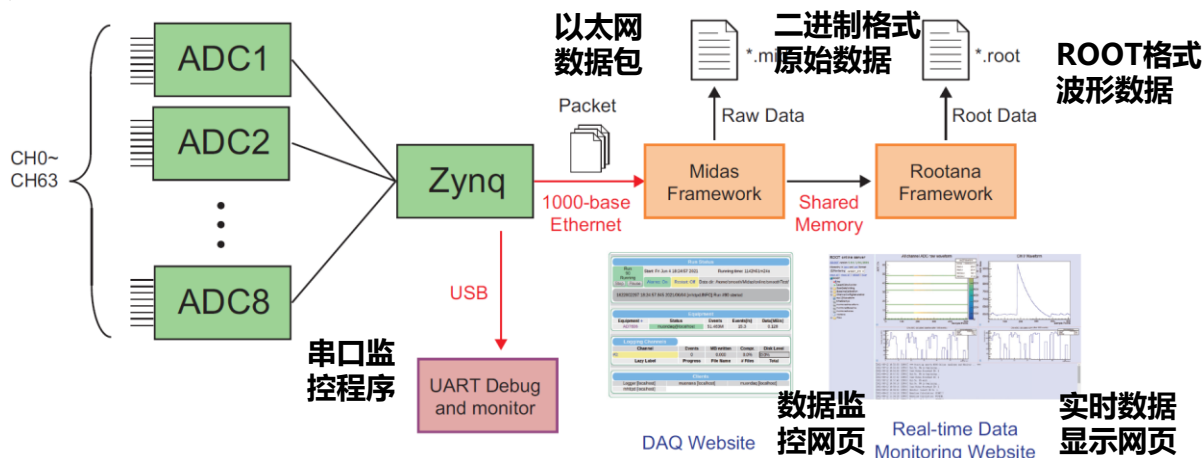
Credit: 廖健等, Nucl.Phys.Rev. 39 (2022) 1, 73-80

宇生缪子径迹探测器SMOOTH-MuGrid

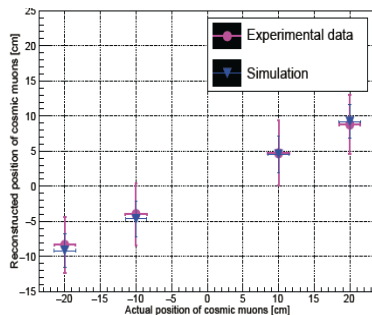
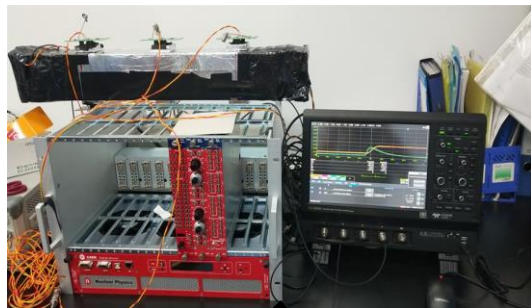
MC模拟



- MuRunAction : Getting the geometric and property parameters of the plastic scintillator
- MuEventAction : Obtaining the position and the direction of scintillation photons
- MuStackingAction : Counting the numbers of Cherenkov photons
- MuPrimaryGeneratorAction : Setting the motion state of the particle
- MuDetectorConstruction : Defining detector material, etc
- MuDetectorMessenger : Setting commands to modify the detector
- Physics : Defining physic list include electromagnetic interaction, nuclear physics and optical processes
- PscintHit-SD : Getting the track of the particle
- SiPMHit-SD : Getting relevant informations of photons on SiPM
- MuAnalysisManager : Defining the output file and save the data includes three branches ("para", "MuMCTruth", "evt")



性能测试



自研电子学板

径迹重建

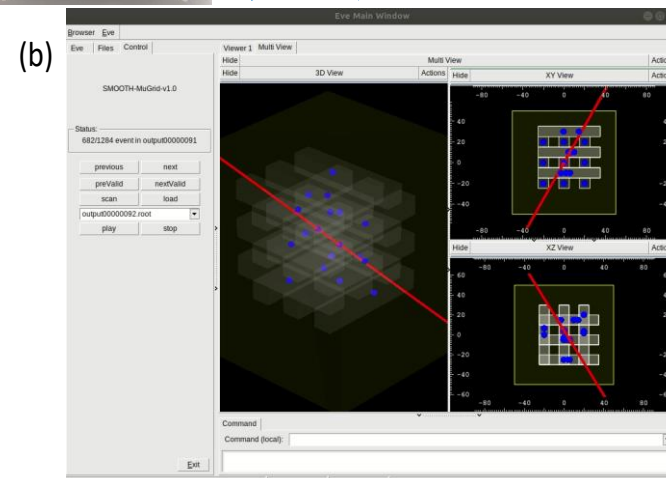
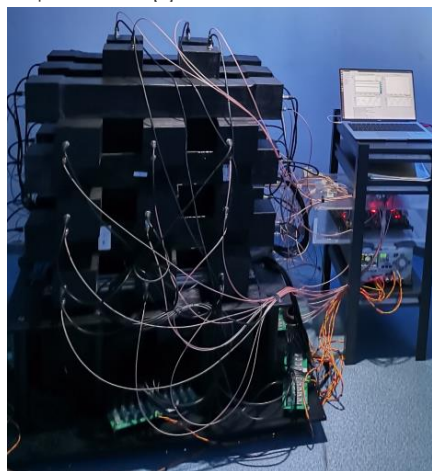
多通道宇生缪子探测器



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

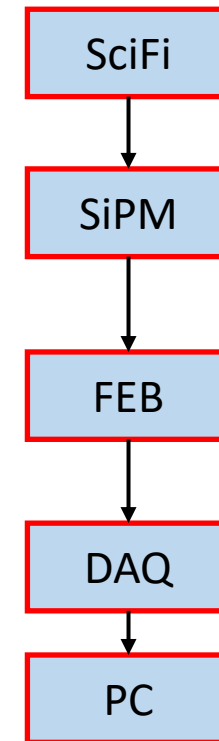
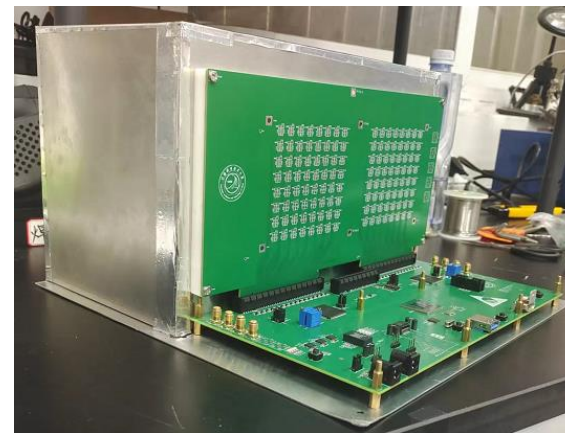
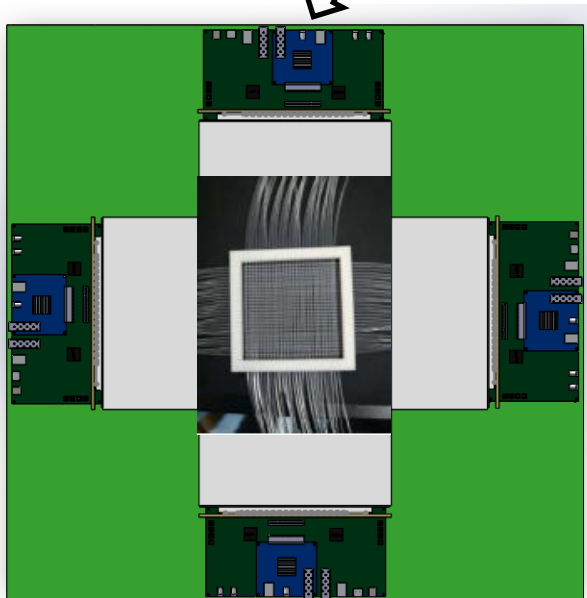
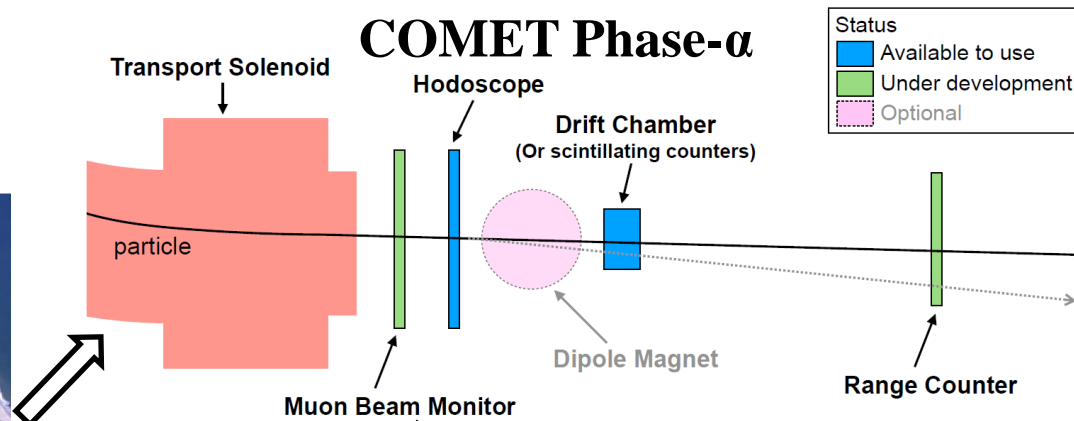
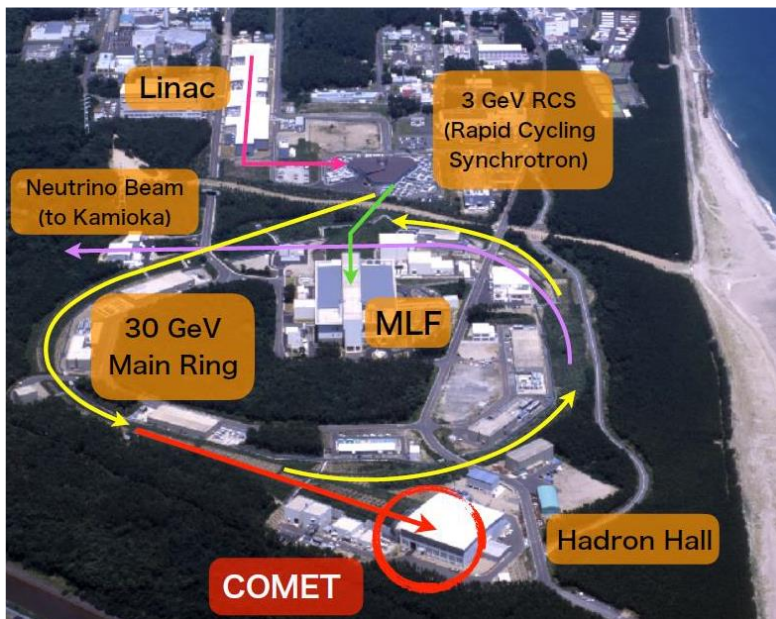
10/16/2024

实时取数



COMET实验缪子束流监测探测器研制

- 积极参与国际合作COMET实验，进一步提升探测器研发水平。



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

Nuclear Science and Techniques 35 (2024) 4, 79

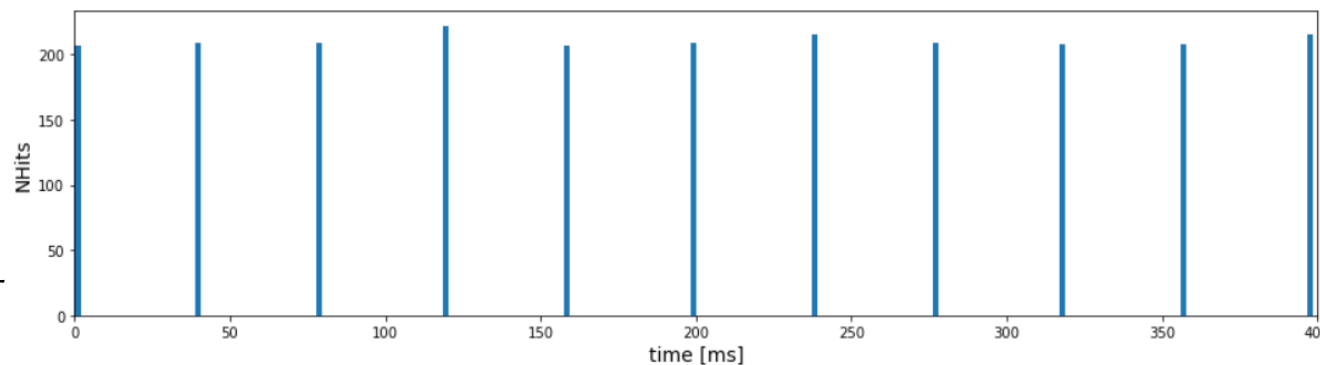
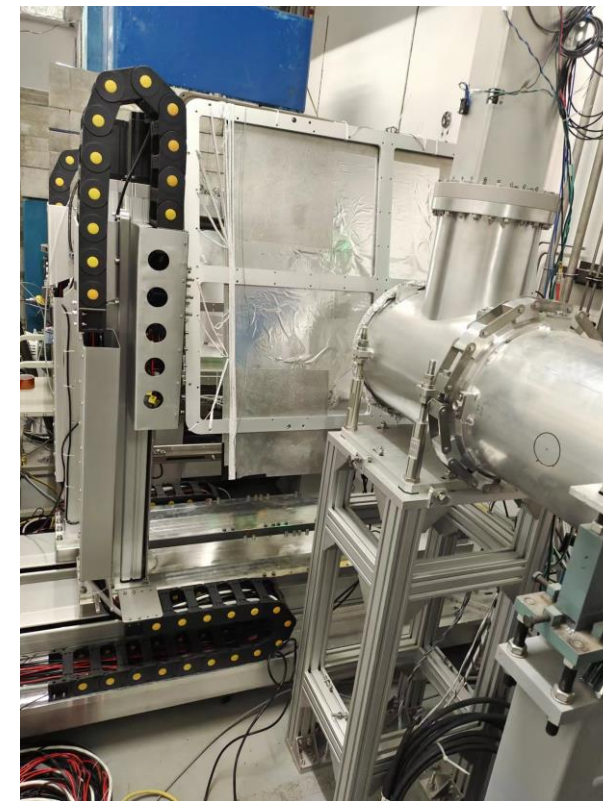
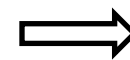
Credits: SYSU 徐宇、宁云松、孙铭辰、余涛等
USTC 封常青、腾尧、秦治臻等
感谢郑州大学刘义的帮忙!

COMET实验缪子束流监测探测器研制

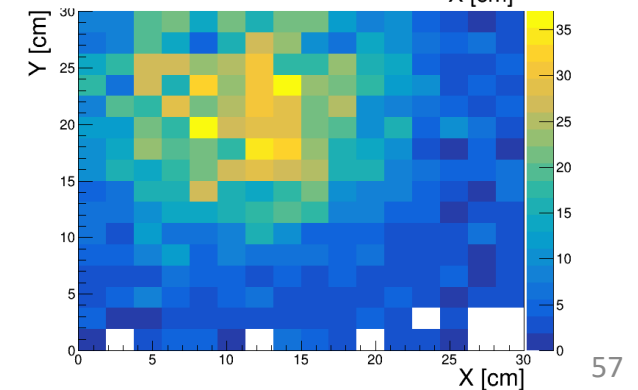
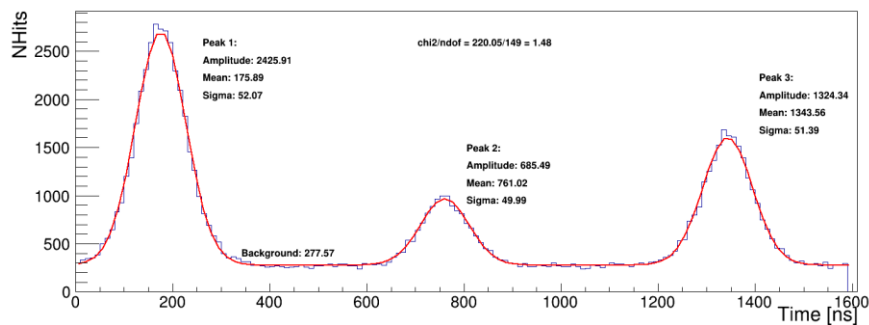
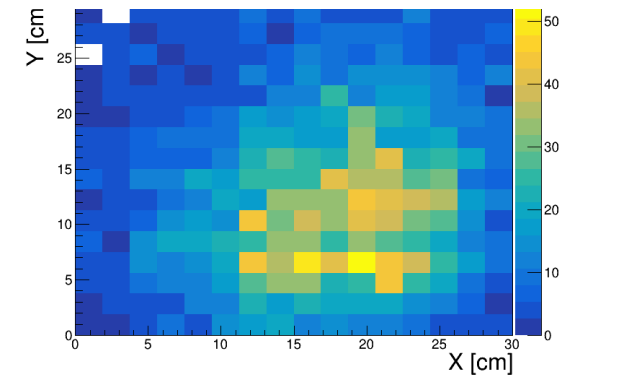
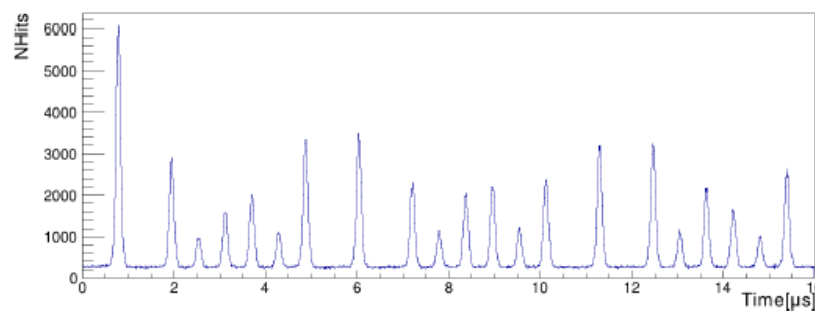
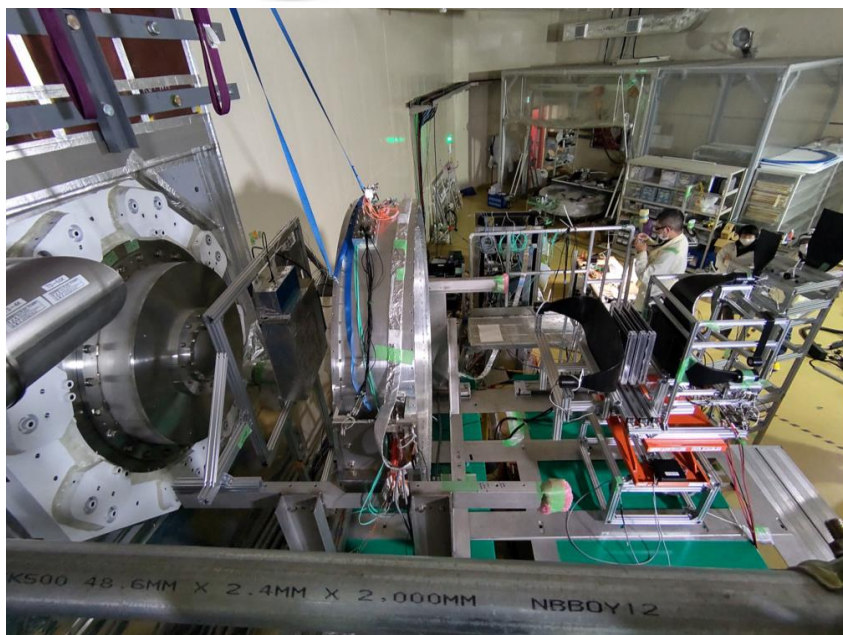
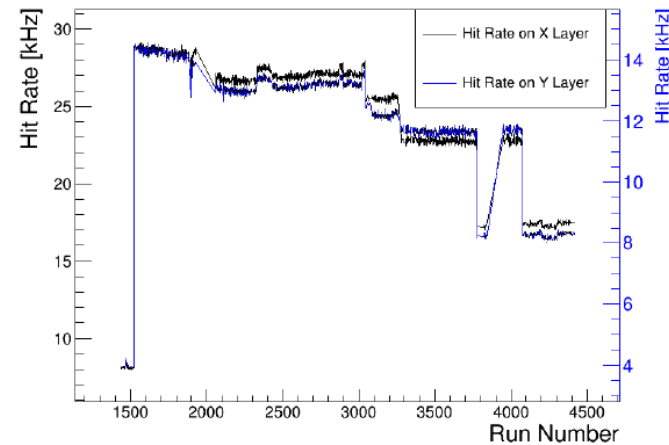
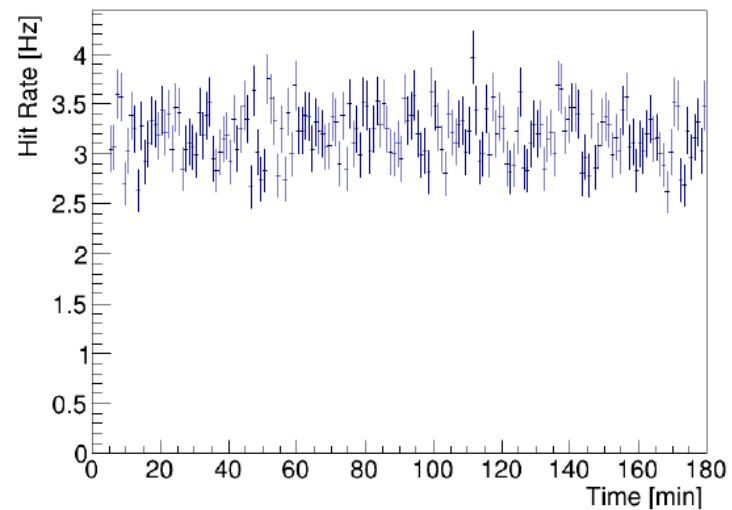
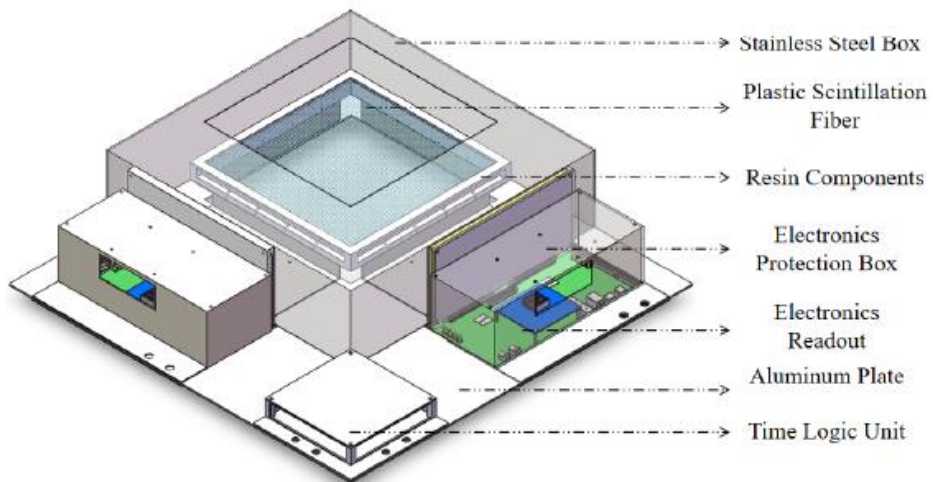
- CSNS proton beam time: 2022/7/20
- Beam window:
 - 1cm×1cm
 - Energy: 30 MeV, 35 MeV, 40 MeV, 45 MeV, 50 MeV, 55 MeV, 60 MeV
 - Time: 90s per point
 - Beam rate: 1.7×10^7 protons/s/cm²



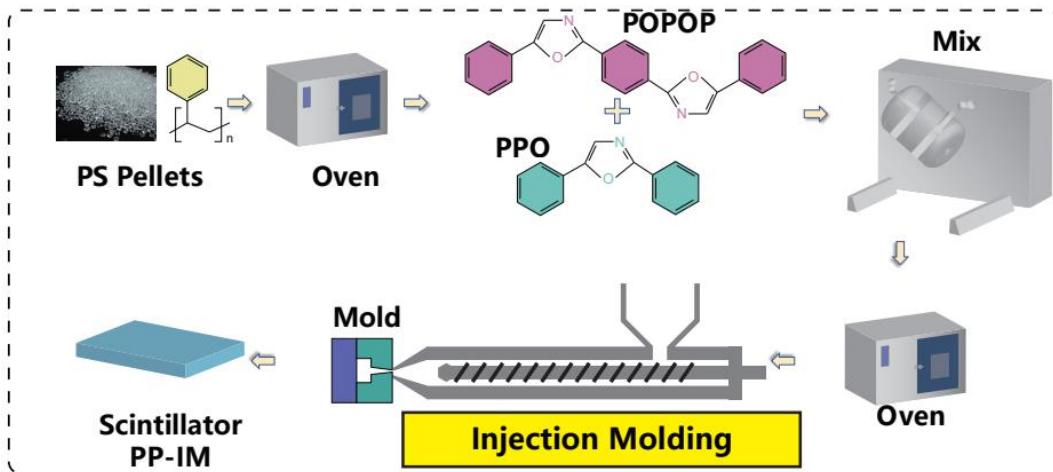
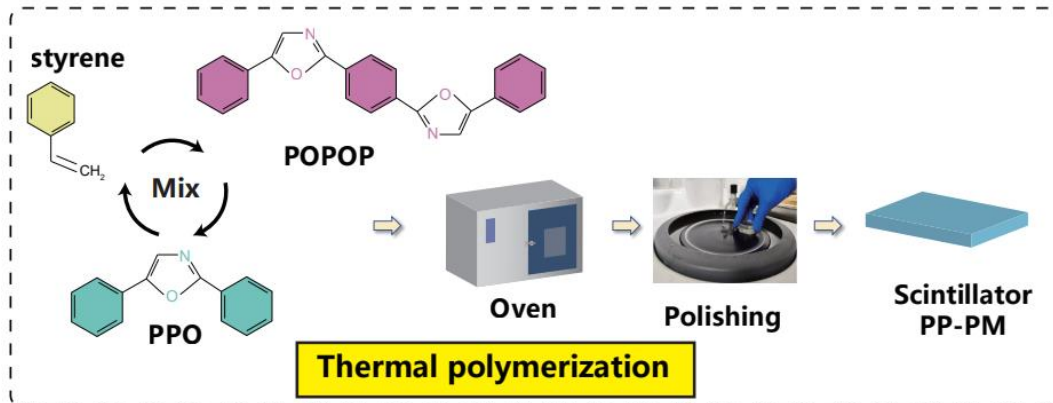
致谢：CSNS质子束流平台敬汉涛、谭志新等



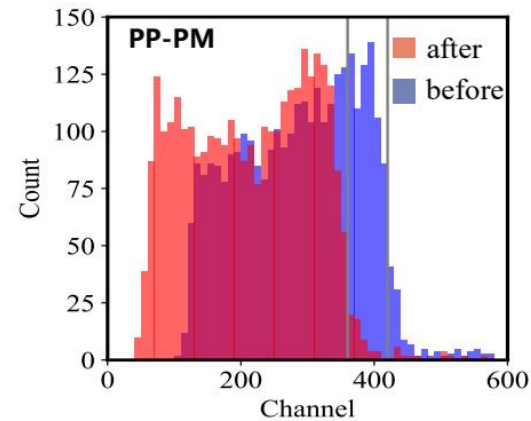
COMET实验缪子束流监测探测器研制



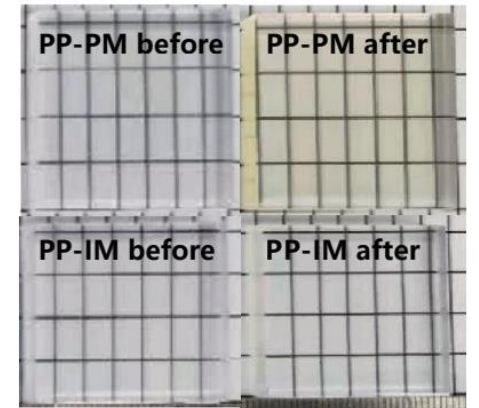
新型塑料闪烁体的研制——交叉学科



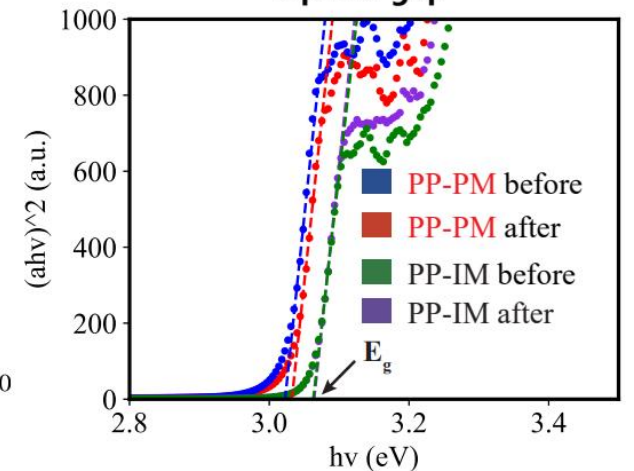
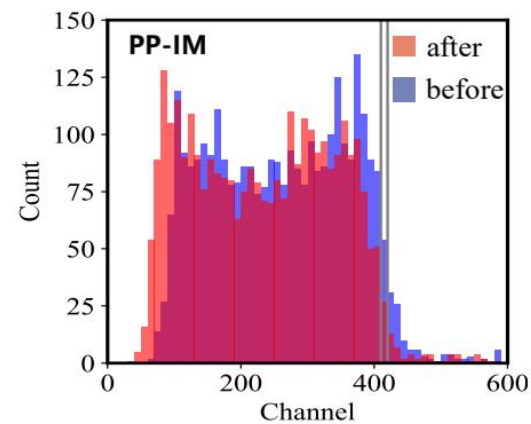
Light Yield



Appearance



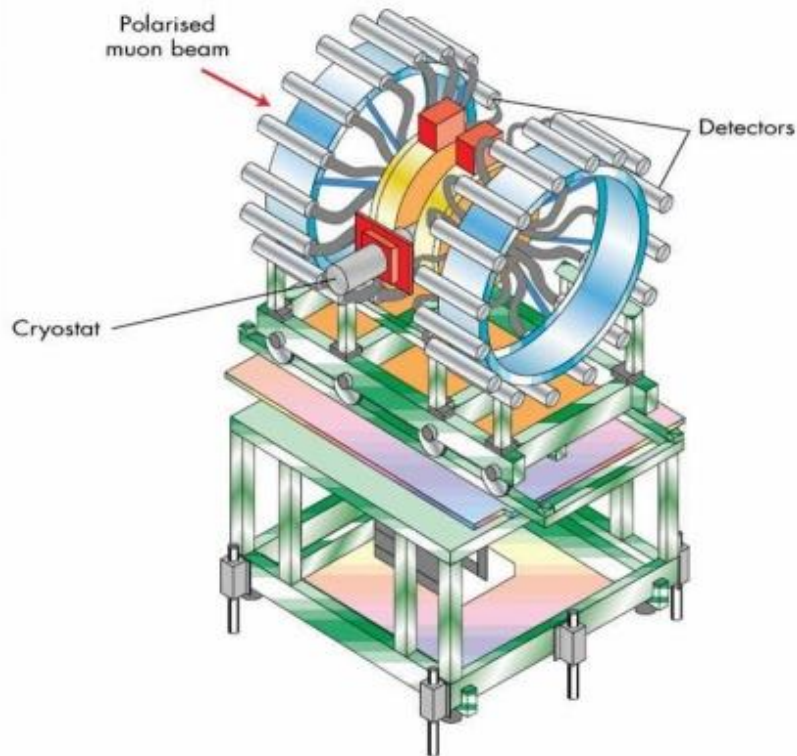
Optical gap



Enhancing plastic scintillator performance through advanced injection molding techniques

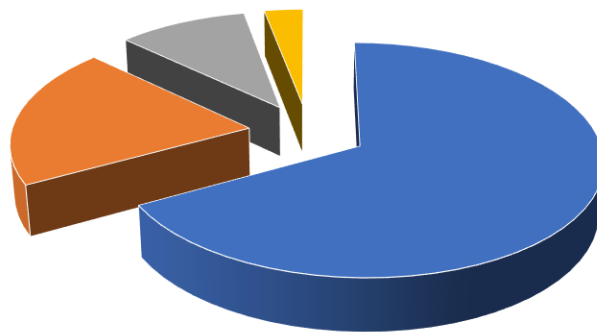
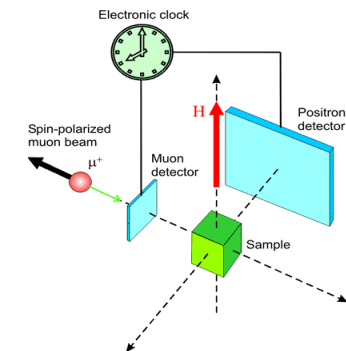
Credits: 钟嘉豪、阮天龙、Nouman、周剑等
Radiation Physics and Chemistry 226 (2025) 112193

Muon Spin Relaxation, Rotation and Resonance (μ SR谱仪)

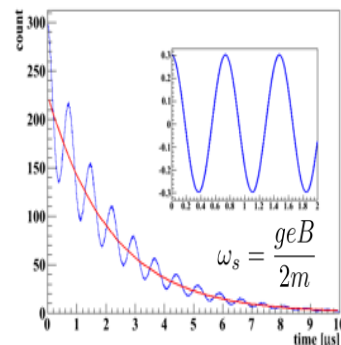


The μ SR spectrometer

Nature Materials 16, 467–473 (2017)



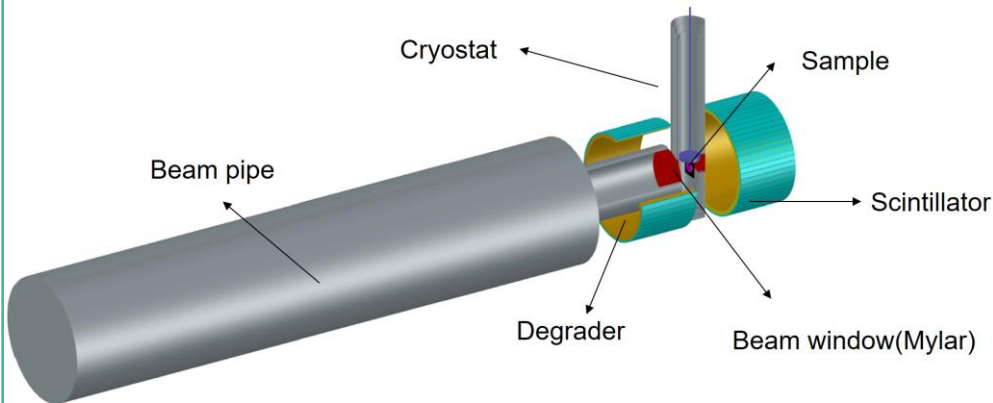
- 物理
 - 磁性
 - 超导性
 - 表面物理
 - 基础物理
- 化学
 - 分子动力学
 - 氧化物
 - μ 偶素
- 材料
 - 多聚物
 - 半导体
 - 储氢材料
- 生物
 - 蛋白质
 - DNA



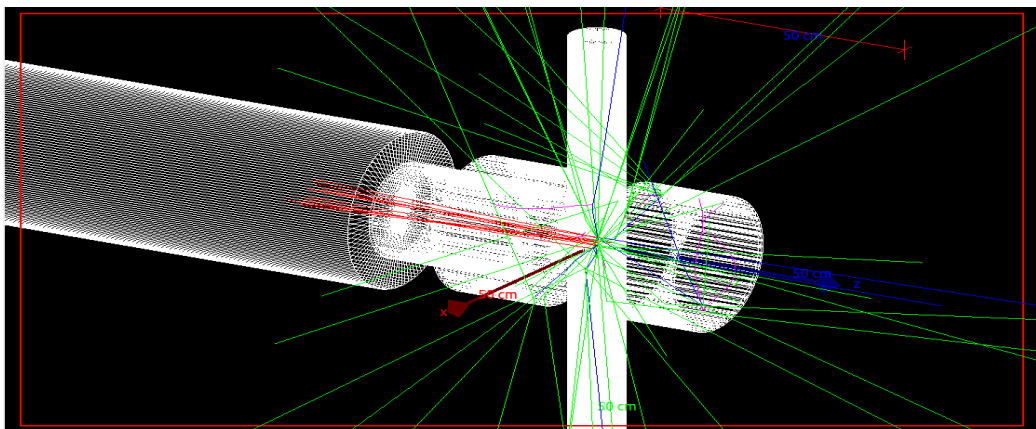
主要谱仪类型：不加磁场(ZF- μ SR)、加横向磁场(TF- μ SR)、加纵向磁场(LF- μ SR)、自旋回波(μ SE)、自旋共振(RF- μ SR)、Level Crossing共振(μ ACLR)

μ SR谱仪的设计和模拟

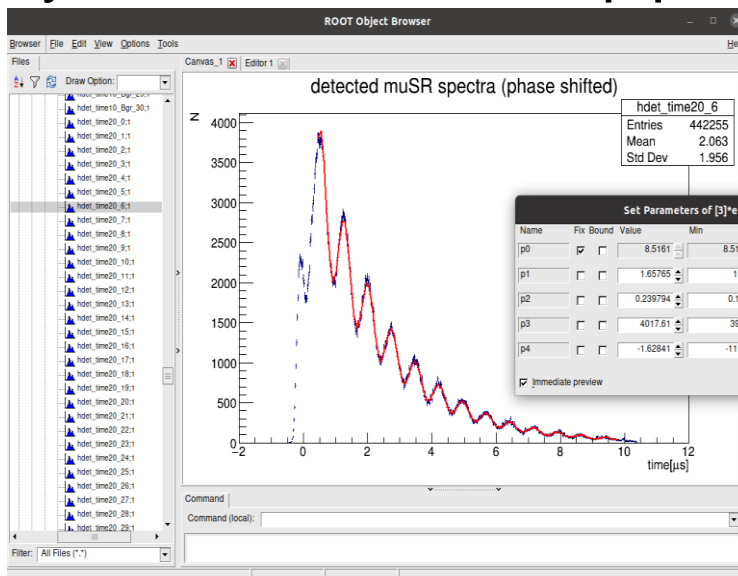
- Two detector rings, degraders, a cryostat, and a beam pipe.



谱仪的CAD设计

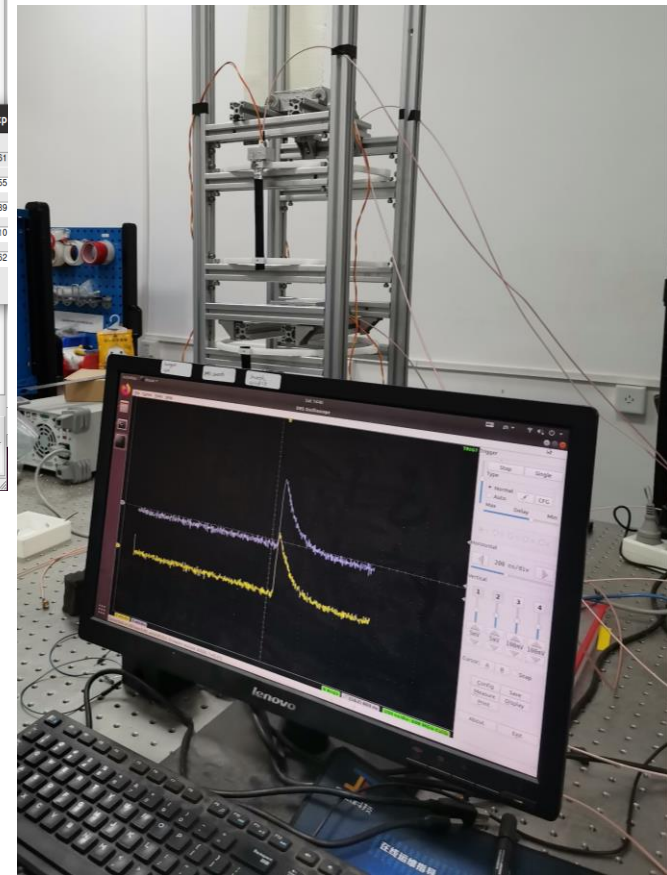


谱仪MC模拟和仿真



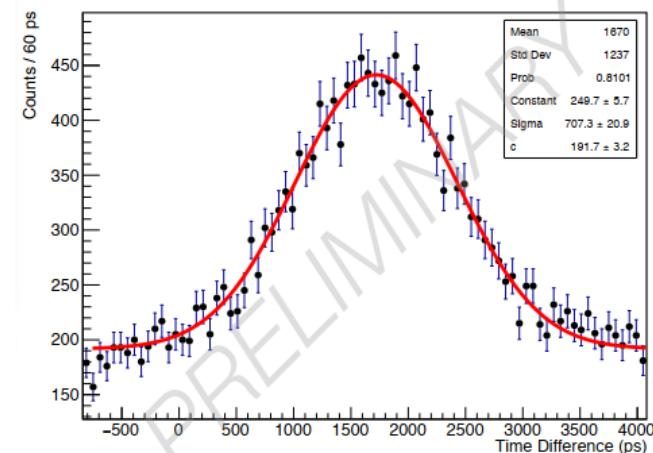
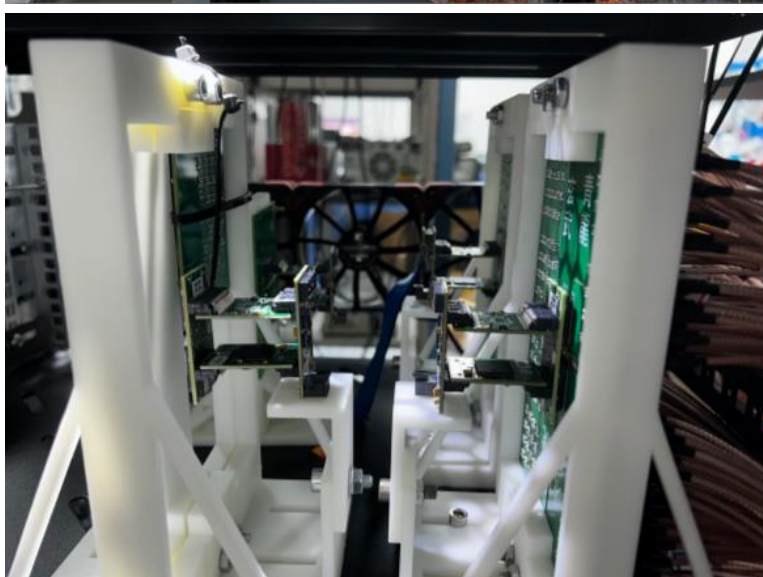
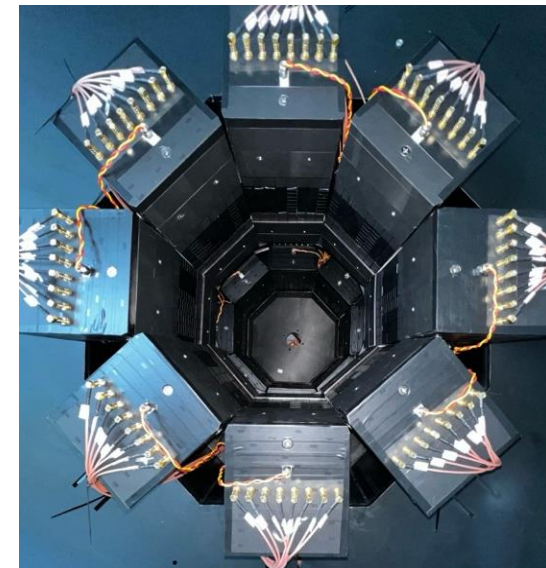
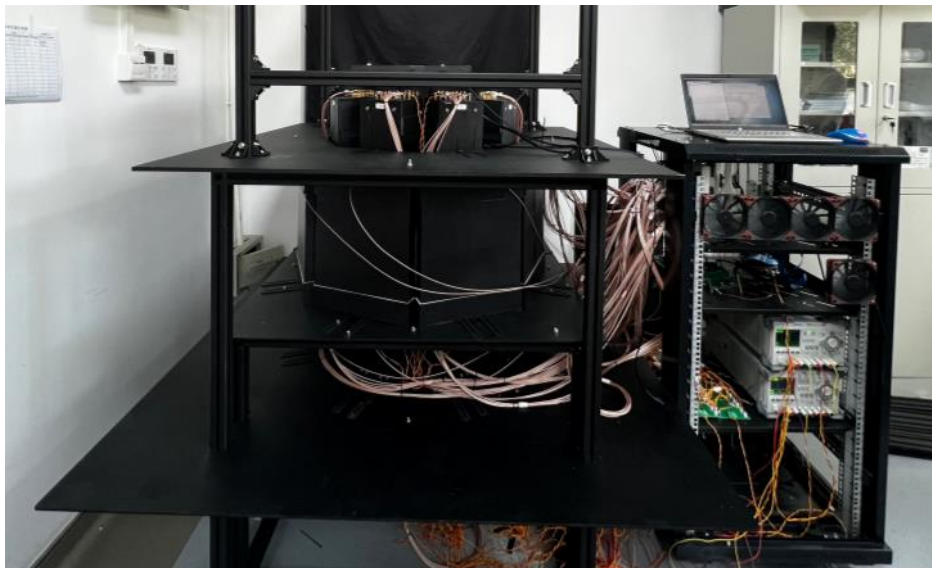
模拟数据分析和拟合

Credits: 周逸行



谱仪prototype的测试

μ SR谱仪样机的研制



Credit: 孙铭辰、余涛、宁云松、白爱毓等
“优秀的工程师会给自己留够余量”

By 宁云松

不走寻常路，期待有惊喜!



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 μ SR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- μ SR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!

- 感谢杭州高等研究院**周也铃**博士的邀请。
- 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！

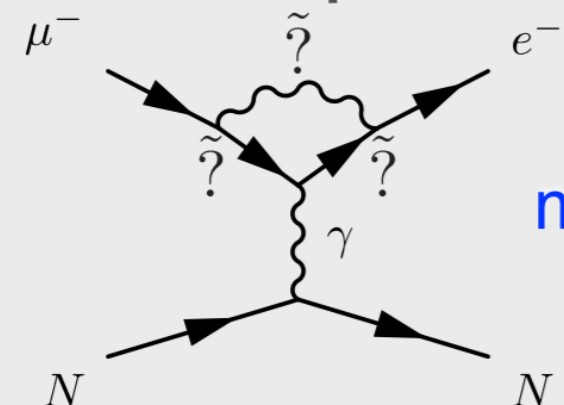


标准模型有效场论SMEFT

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

$$\mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{1}{\Lambda^2} \bar{\mu}_L \gamma^\mu e_L (\bar{u}_L \gamma_\mu u_L + \bar{d}_L \gamma_\mu d_L)$$

“Loops”

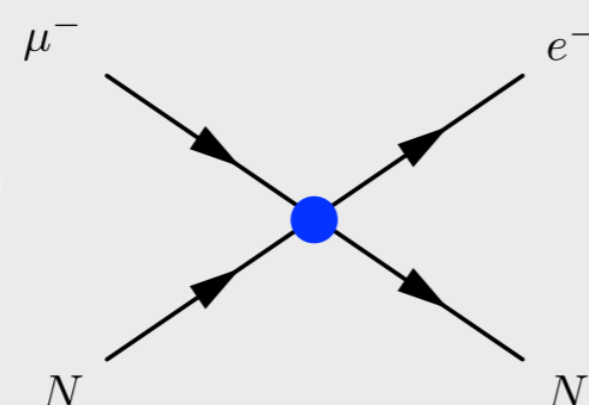


μ^- e^-

N N

γ

“Contact Terms”



μ^- e^-

N N

mass scale Λ

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



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； $\mu \rightarrow eee$ 和 $\mu \rightarrow e\gamma$ 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 $\mu \rightarrow e\gamma$ 在 EFT 树图阶不涉及 $\bar{\mu}e\bar{\mu}e$ 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）。



标准模型有效场论SMEFT

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

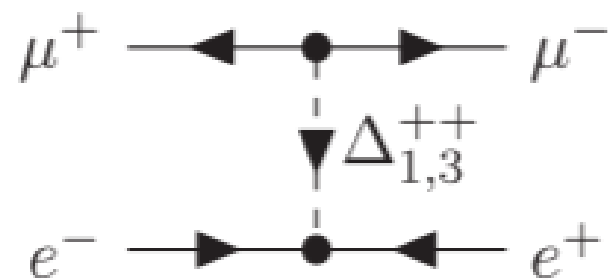
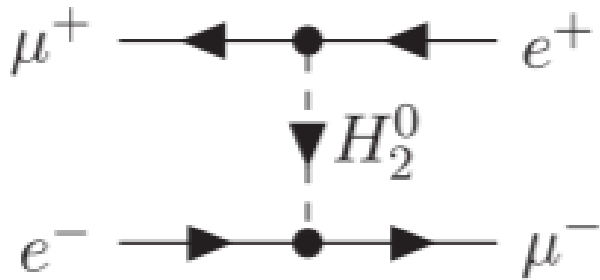
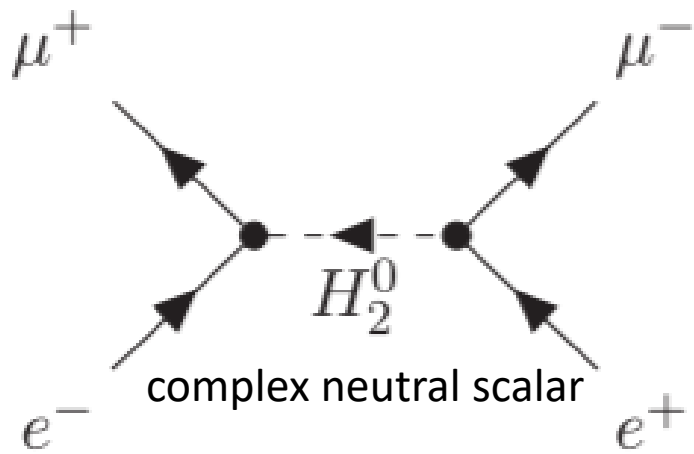
- 一般的 $\mu^+ e^- \rightarrow \mu^- e^+$ 的 SMEFT 拉氏量包括所有的 $\bar{\mu} e \bar{\mu} e$ 耦合:

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

- 其中有三个 Wilson 系数, 积掉时间的缪子素转化概率为

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

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

