缪子和新物理

唐 健

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2024年8月24日，中山大学广州南校园

第二届惠州大科学装置高精度物理研讨会

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、陈良文等，***IHEP*—**唐靖宇、袁野、李海波、吴琛、妙晗、张瑶、赵光、鲍煜等，***山东大学*—**熊伟志等，***辽宁大学*—**康晓坤、龚丽、程炜镔等

致谢：*上海交通大学*—许金祥，***北京大学*—**李强、张策等，*南开大学*—Lorenzo Calibbi，*湖南大学*—戴凌云、俞洁晟、张书磊等

内容概述

- 这些年，这些事儿
- 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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人才培养—以赛促学

第二与第一课堂融合

- 指导本科生参加物理学科类竞赛
- 多次指导本科生参加全国大学生物理实验竞赛，荣获**一等奖、二等奖**等
- 2019-2021年，大学生物理学术竞赛（CUPT）连续3年获得中南赛**一等奖**，指导教师
- 2022和2024，CUPT**一等奖**，指导教师

人才培养—以赛促学

- 兴趣与深度
- 知识背景
- 交叉程度

数理建模

实践空间

- 可操作性
- 实现成本
- 拓展空间

- 语言训练
- 思想交流
- 图文组织

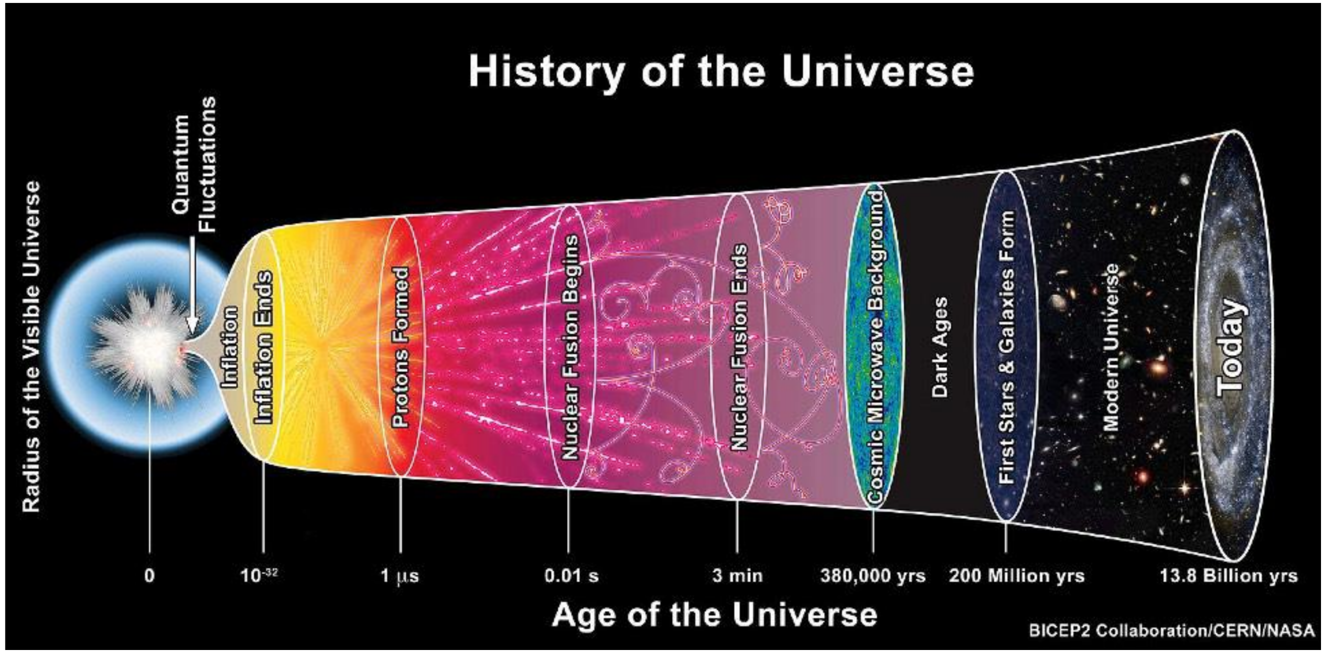
展示交流

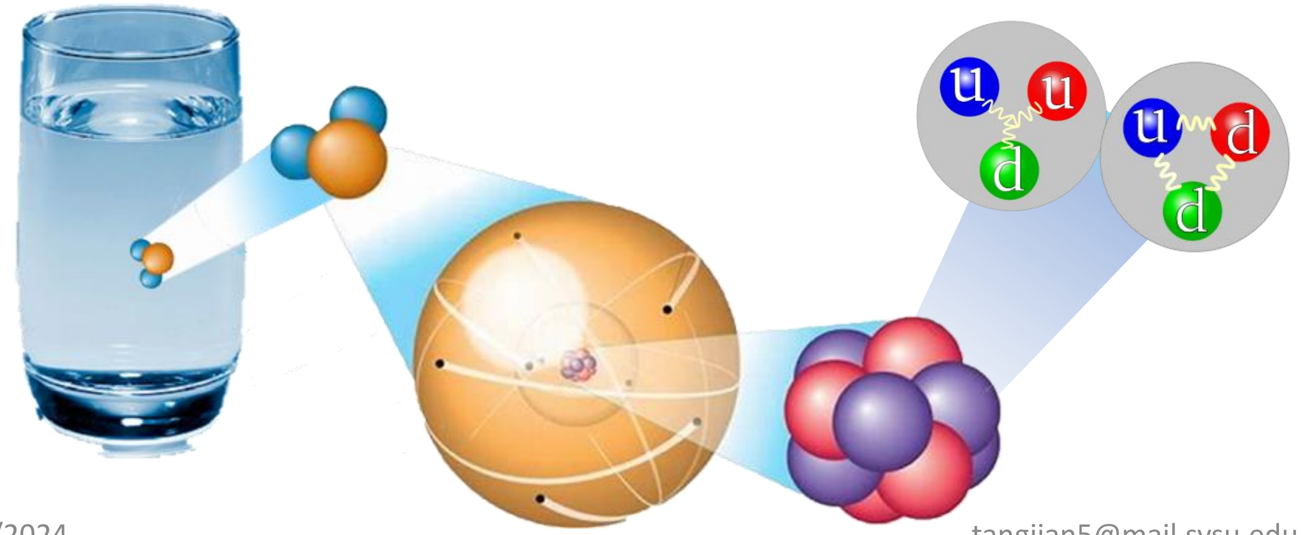
科研素养

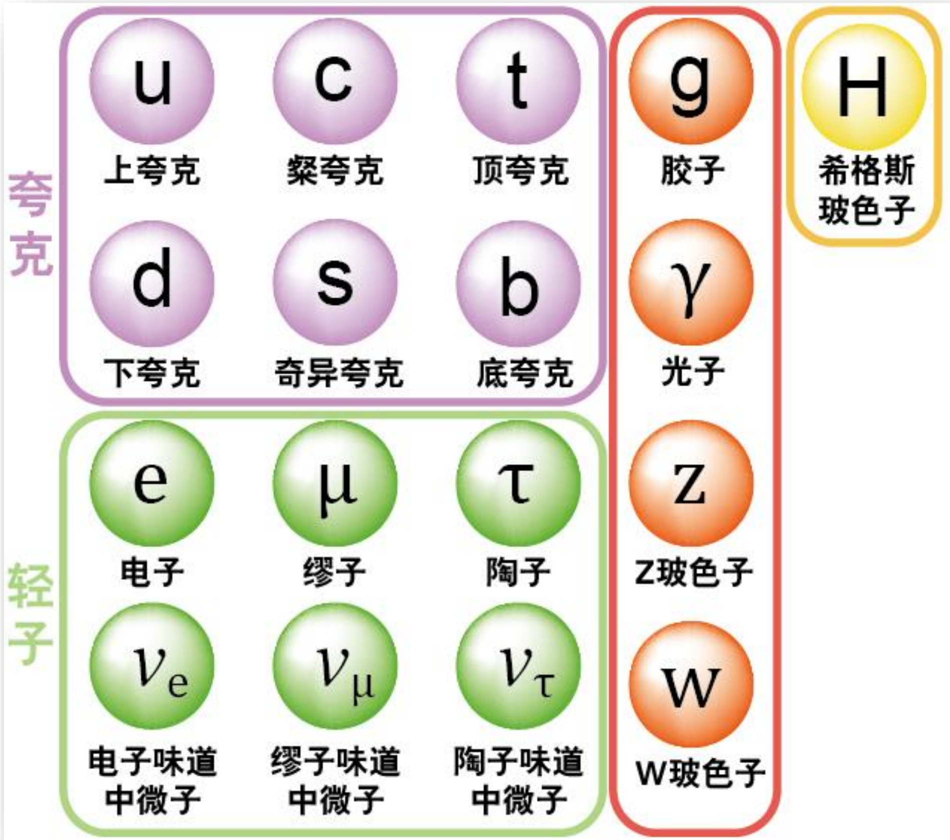
- 自我管理
- 团队协作
- 刻苦攻坚

以赛促学、以赛促练、以赛促研

粒子物理







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

QCD (Strong Interaction)

WEAK ⊕ QED (Unification of Weak and Electromagnetic)

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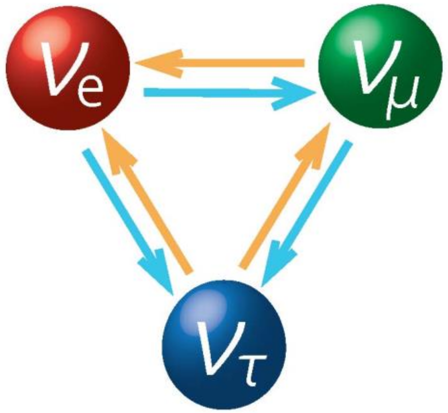
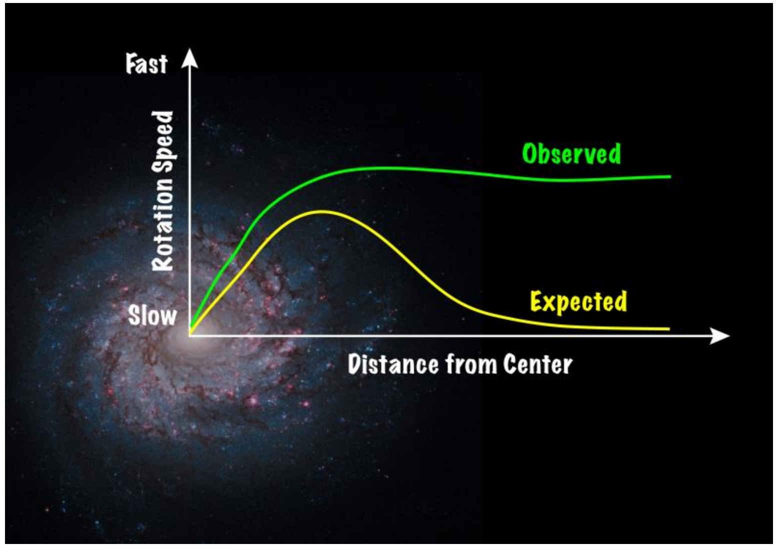
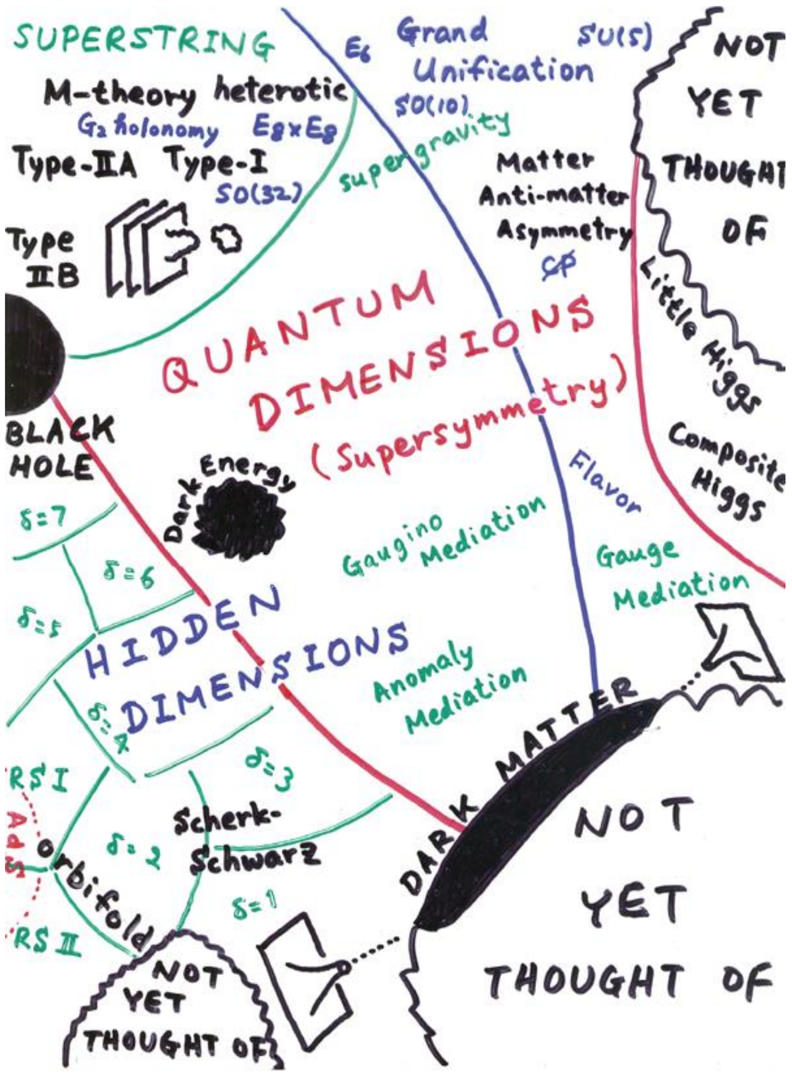
粒子物理重大科学问题

超越标准模型的重大科学问题：

- **中微子质量起源?** 是否有新相互作用?
- 轻子是否CP破坏?
- **中性轻子发生振荡，那么带电轻子呢?**
- 什么是暗物质?
- 宇宙正反物质不对称的起源? …







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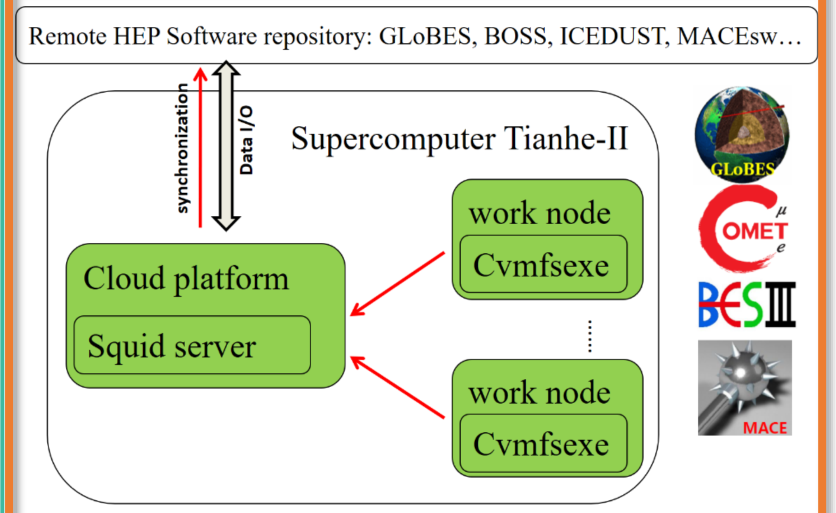
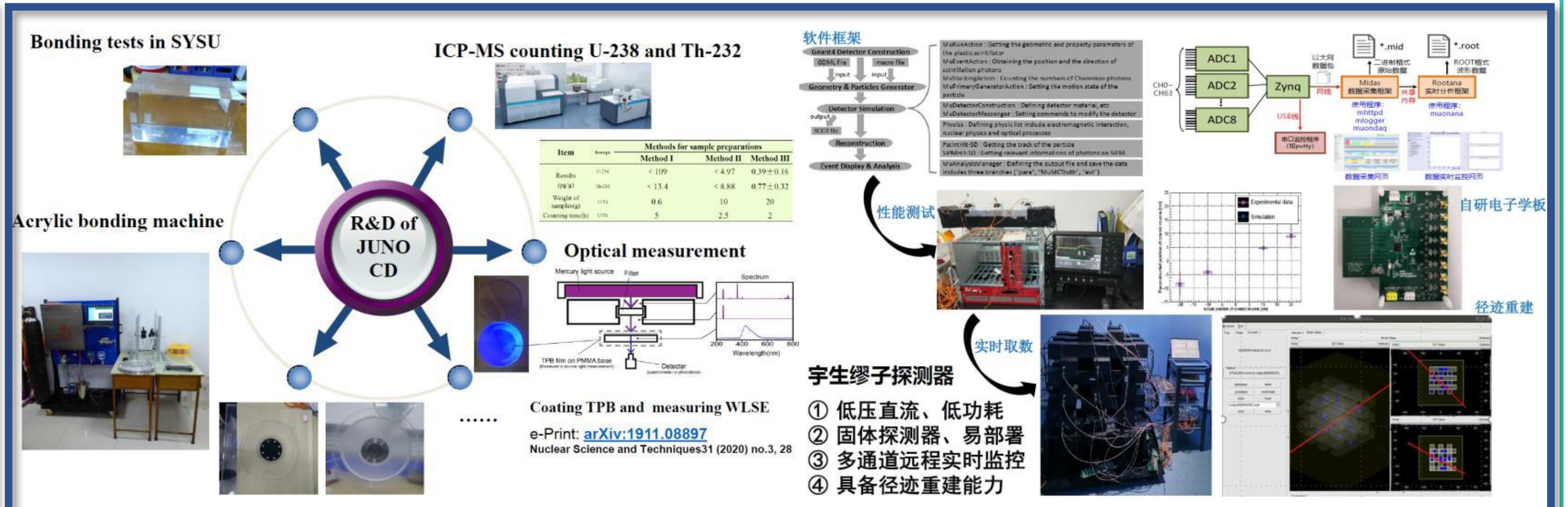
以轻子为探针寻找超越标准模型新物理



依托超级计算机"天河二号"

建设粒子物理实验大数据平台



参与国际大科学合作实验

突破低本底探测器关键技术

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

工欲善其事必先利其器，软件平台和硬件研发同步推进

→ 指方向，搭平台，组团队，续经费，育人才，出成果！

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*

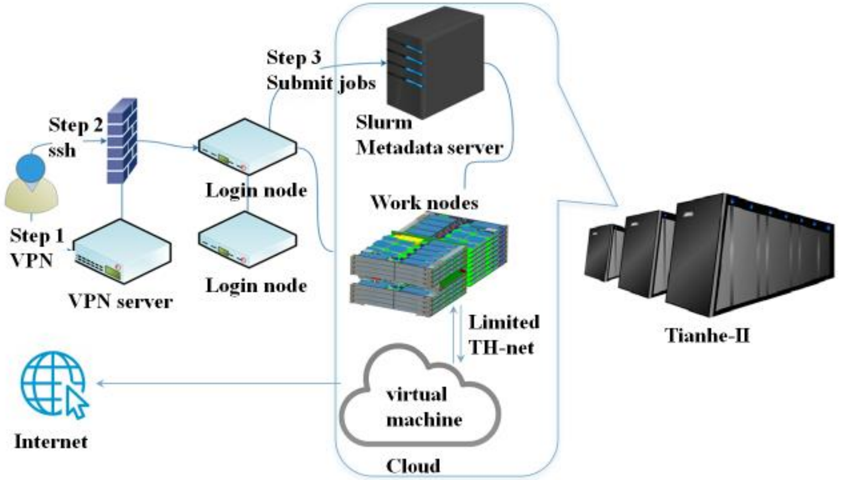
Jing-Kun Chen,[1] Bi-Ying Hu,[2] Xiao-Bin Ji,[3] Qiu-Mei Ma,[3,†] Jian Tang,[2,‡] Ye Yuan,[3,4] Xiao-Mei Zhang,[3] Yao Zhang,[3] Wen-Wen Zhao,[2] and Wei Zheng[3]

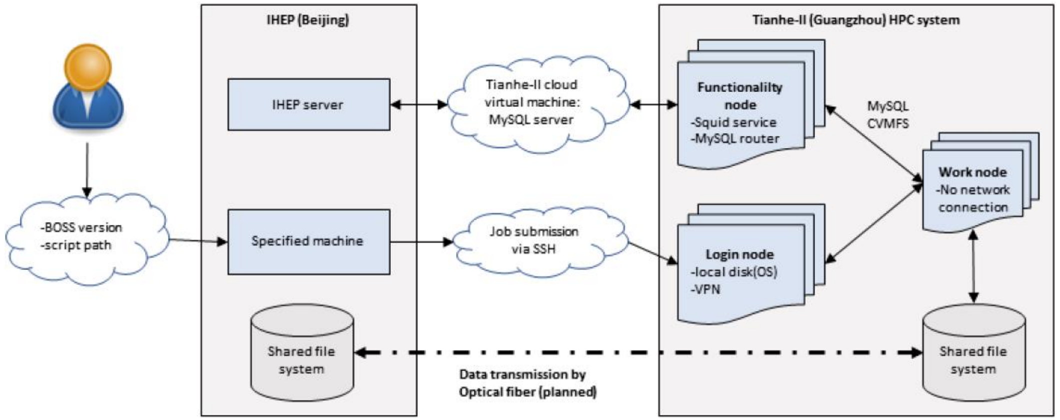
[1]*School of Computer Science and Engineer, Sun Yat-sen University, Guangzhou, 510006, China*
[2]*School of Physics, Sun Yat-sen University, Guangzhou, 510275, China*
[3]*Institute of High Energy Physics, Beijing, 100049, China*
[4]*University of Chinese Academy of Sciences, Beijing, 100049, China*

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





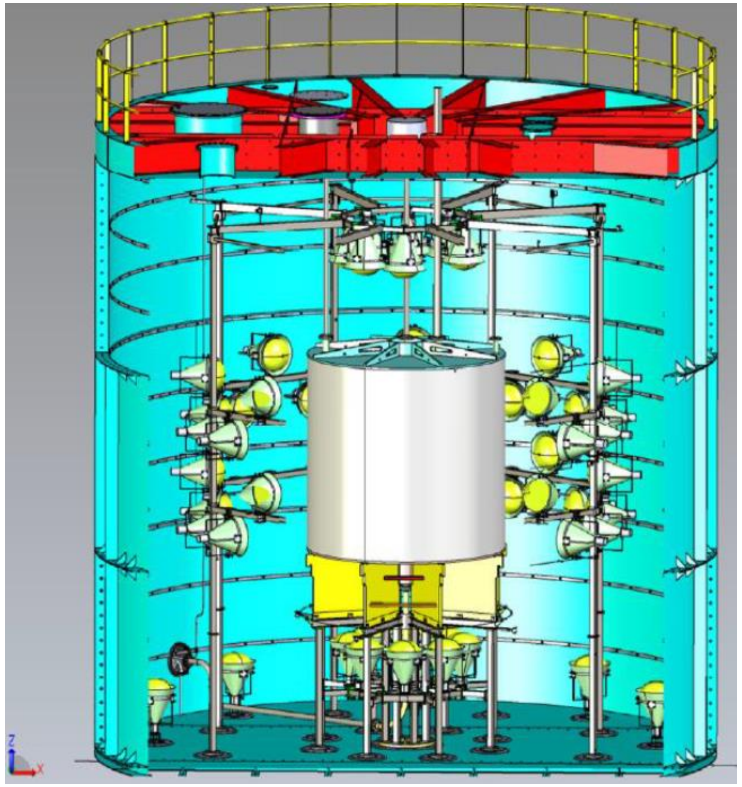
突破中微子实验探测器关键技术

- 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



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SMOOTH团队情况

- 当前团队成员：博士后1名，博士生3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

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

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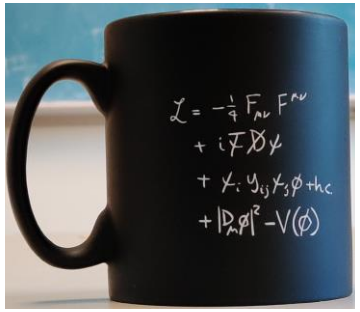
Symmetries of SM



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

QCD (Strong Interaction)

WEAK $\oplus$ QED (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) → $\mathcal{L}^{\text{SM}}_{\text{kinetic}}$
- EWSB, 2 params → $\mathcal{L}^{\text{SM}}_{\text{EWSB}}$
- SM flavour dynamics, flavour parameters → $\mathcal{L}^{\text{SM}}_{\text{Yukawa}}$

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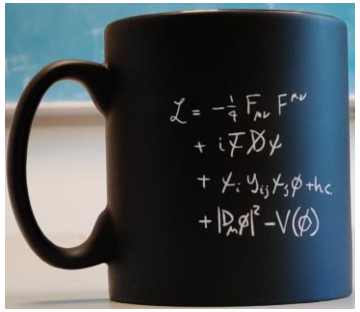
Symmetries of SM



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QCD (Strong Interaction)

WEAK ⊕ QED (Unification of Weak and Electromagnetic)

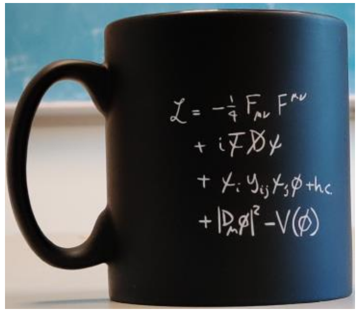
- Flavor physics
  - ➢ Within SM: weak and Yukawa interactions
- Flavor parameters in the quark sector
  - ➢ Within SM: 9 masses of charged fermions & 4 mixing parameters (3 angle + 1 CP phase)
- Flavor universal (flavor blind)
  - ➢ Within SM: QCD & QED
- Flavor diagonal
  - ➢ Within SM: Yukawa interactions

	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



$SU(3)_{Color} \otimes SU(2)_{Left} \otimes U(1)_{Hyper\ charge}$

QCD (Strong Interaction)

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- 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:

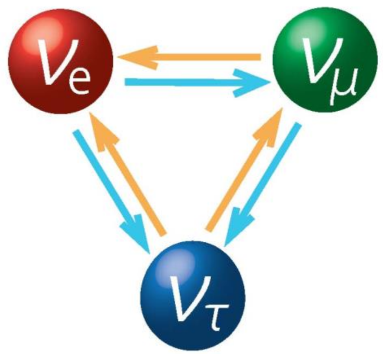
$$U(1)_{B-L} \times U(1)_{L_\mu - L_\tau} \times U(1)_{L_\mu + L_\tau - 2L_e}\,.$$

Lepton flavor conservation!

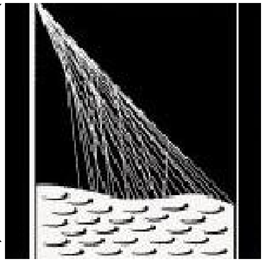
Prediction of Standard Model.

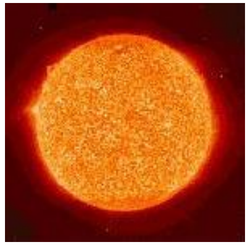
cLFV offers a chance of new physics discovery

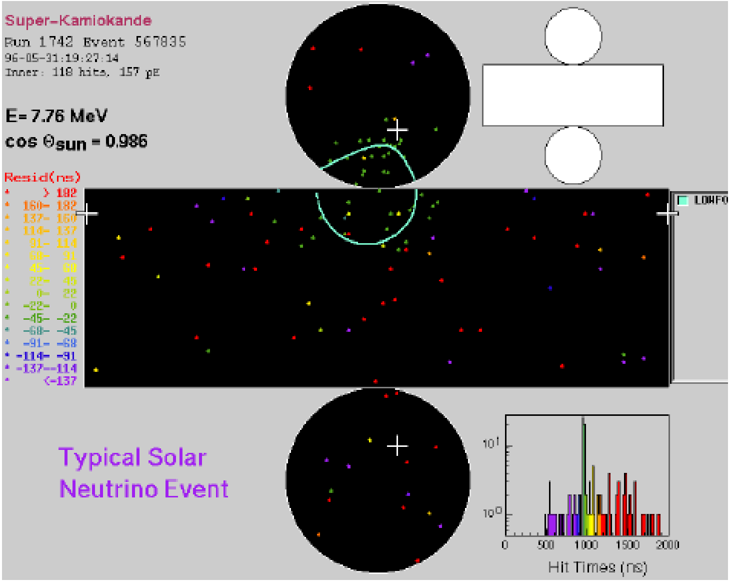
中微子的PMNS混合

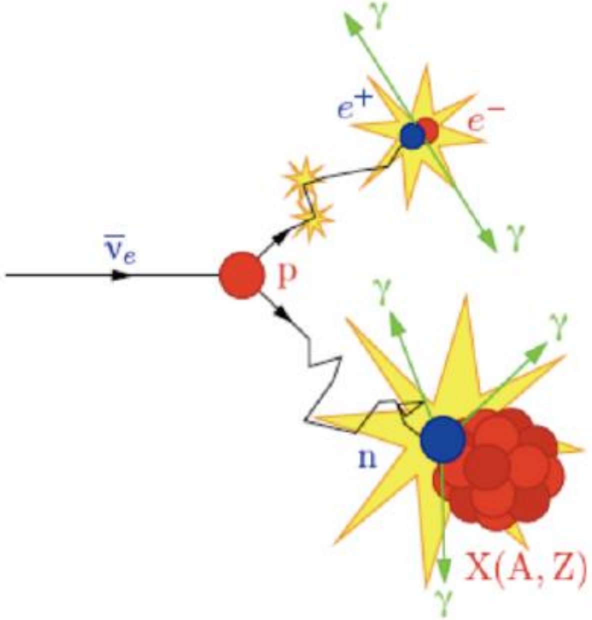


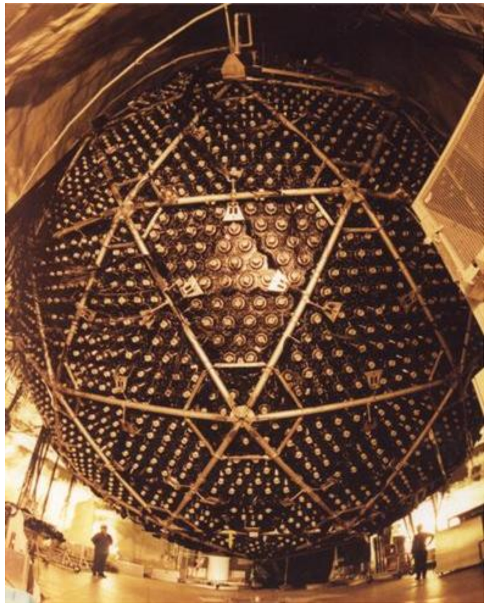
$$U_{\rm PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\,e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}\,e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

= () x (

) x ()







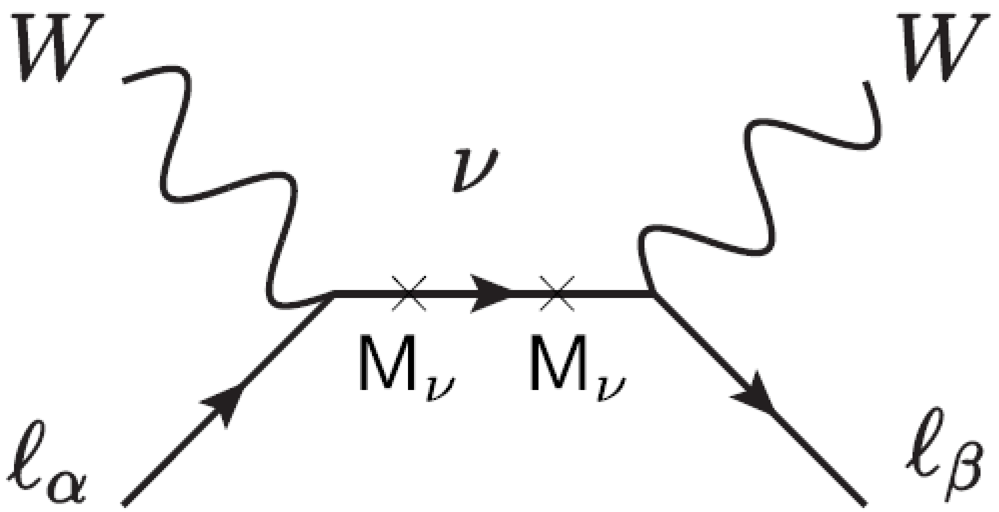
中微子振荡=轻子味道破坏?

- 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

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

- 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

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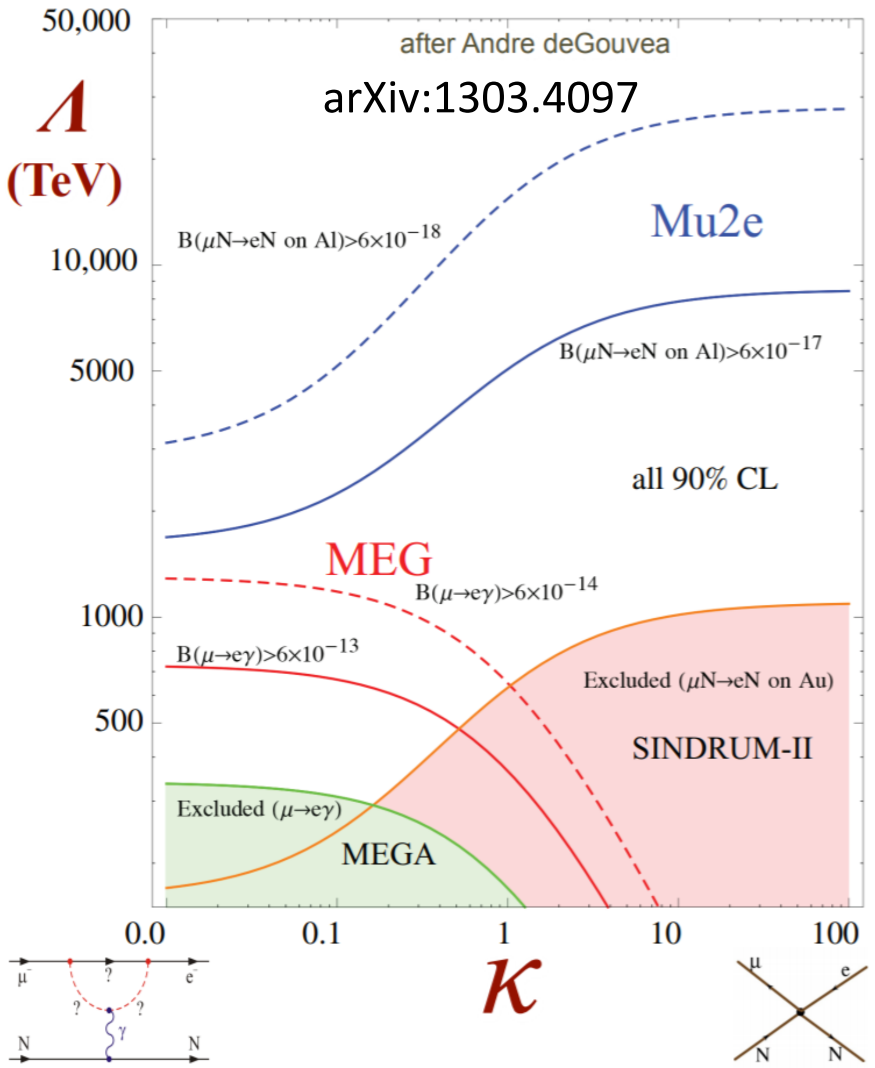
高亮度前沿/高精度前沿

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

- **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

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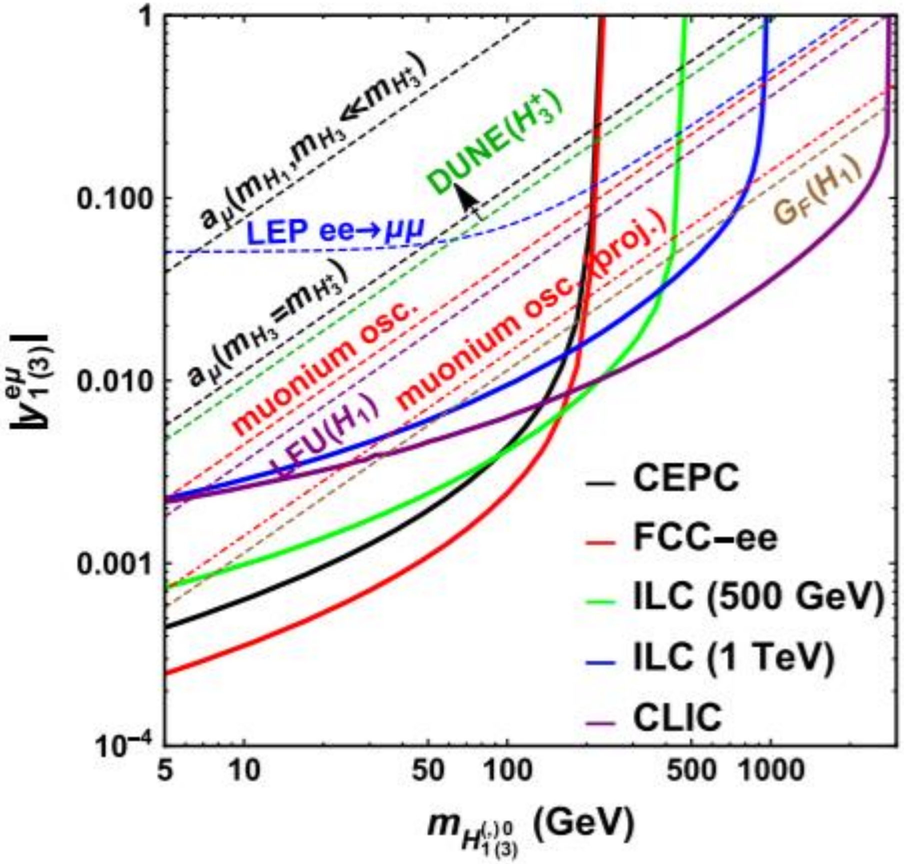


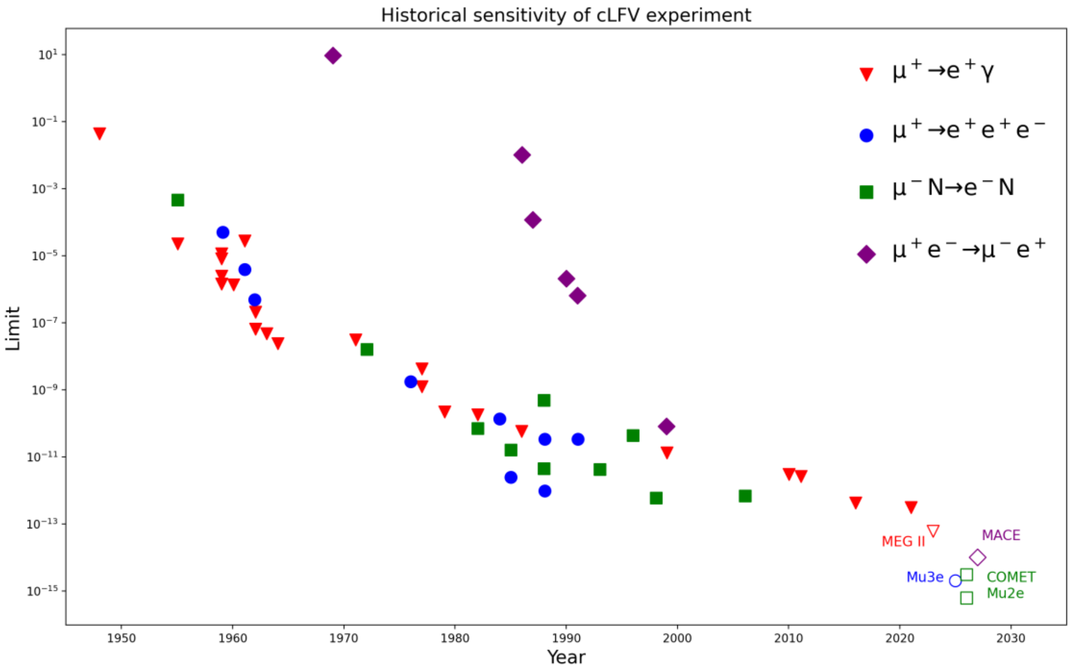
REF: Tong Li, Michael A. Schmidt. Phys.Rev.D 100 (2019) 11, 115007

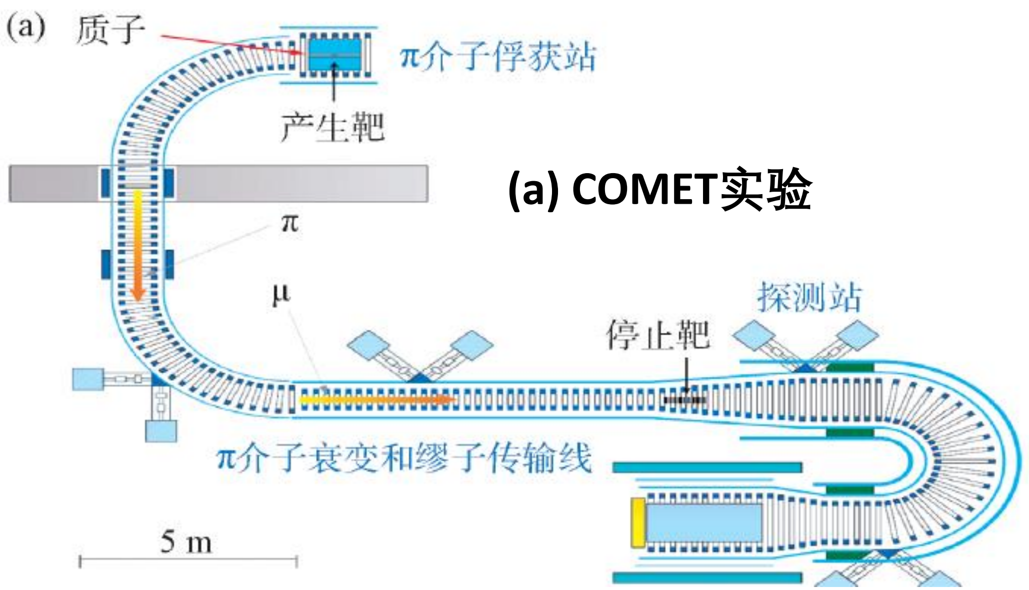
- **低能cLFV实验结果，与high energy frontier互补**
- **cLFV与neutrino physics互补**

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)

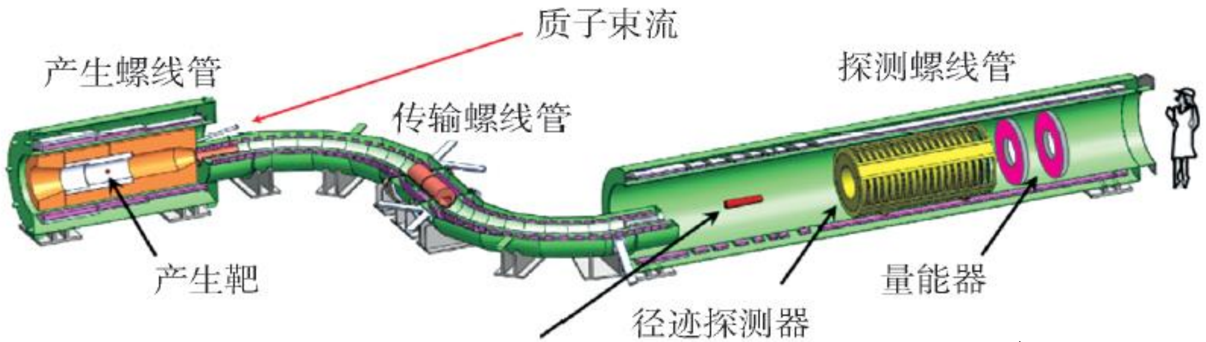
    $\mu^- + Al \rightarrow e^- + \mathrm{Al}$
  - ➢ MEGII(瑞士)　$\mu^+ \rightarrow e^+\gamma$
  - ➢ Mu3e(瑞士)　$\mu^+ \rightarrow e^+e^-e^+$





(a) COMET实验

(b)



(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)

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

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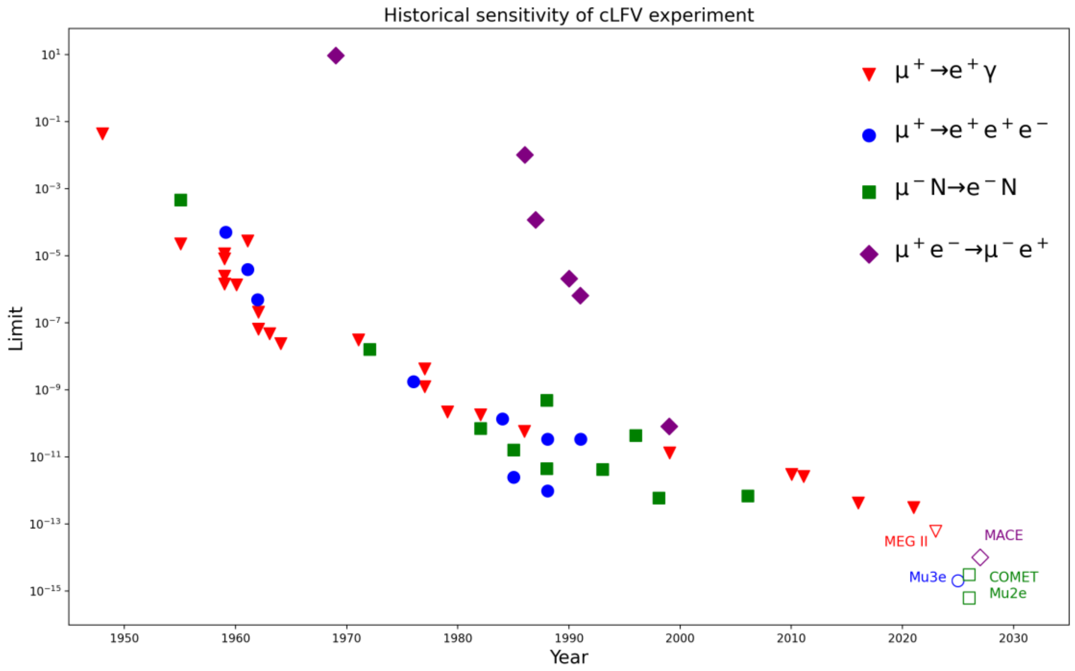
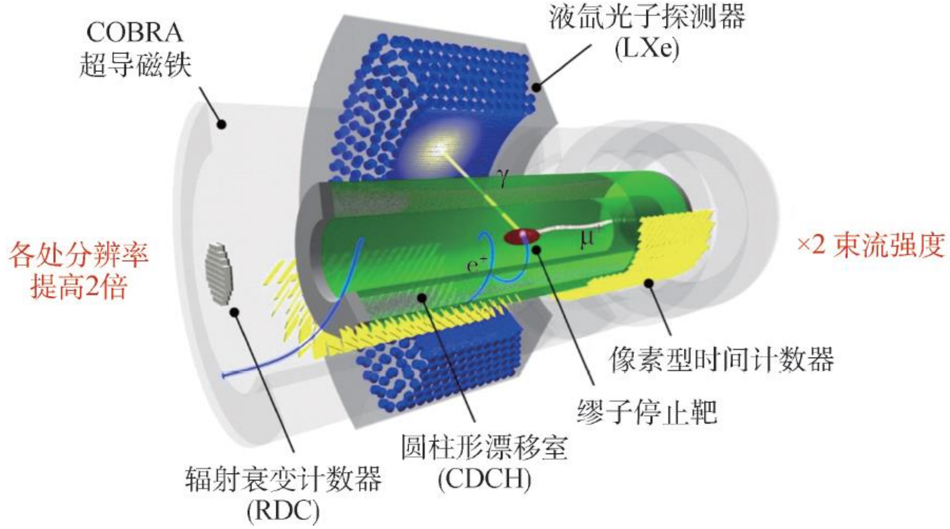
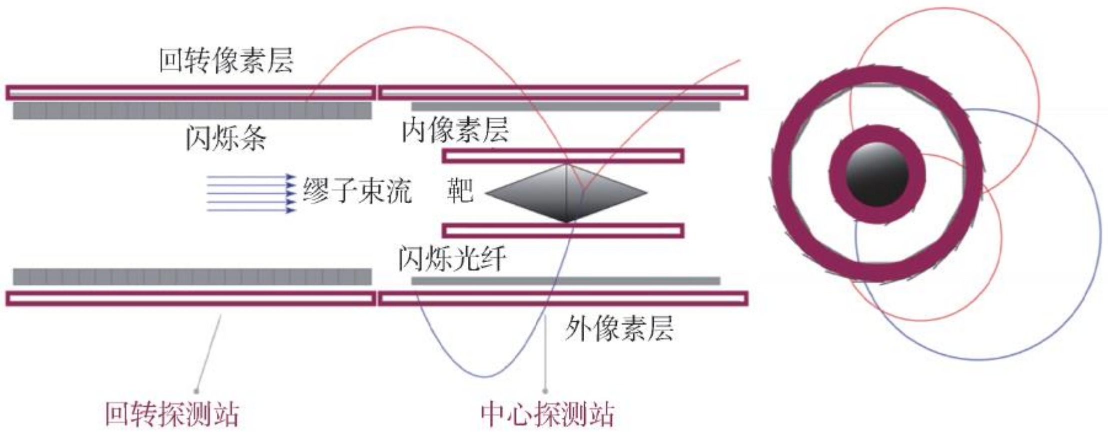


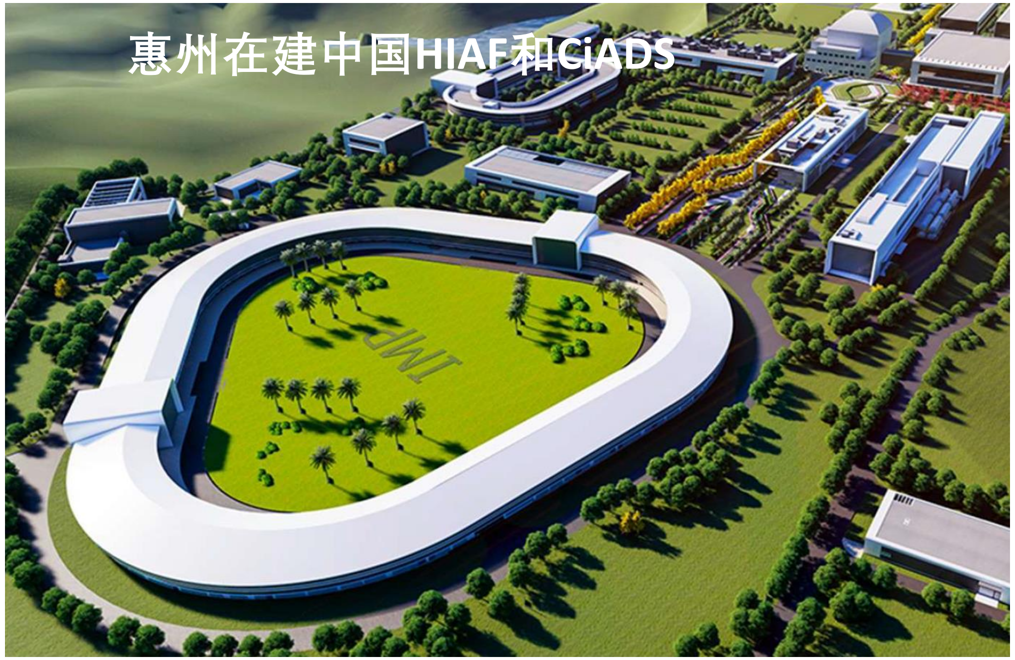


MEGII实验



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？

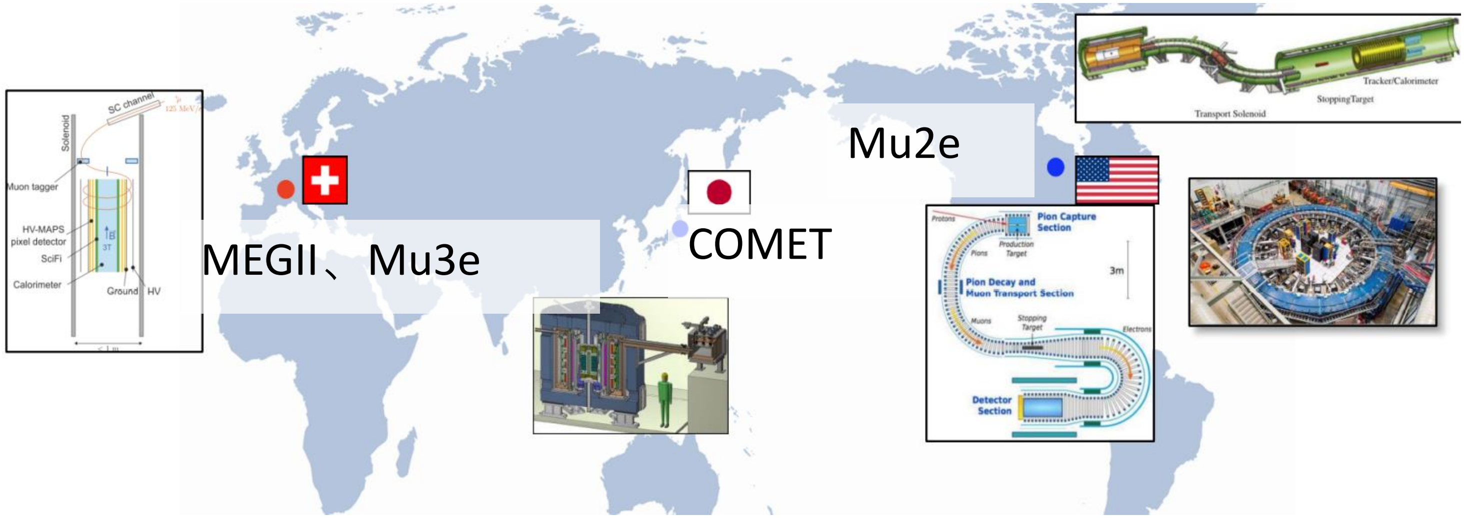
(3）基于加速器缪子源开展前沿研究?

tangjian5@mail.sysu.edu.cn

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

- 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)** $\mu^- + \mathrm{Al} \rightarrow e^- + \mathrm{Al}$
  - MEG(瑞士) $\mu^+ \rightarrow e^+\gamma$
  - Mu3e(瑞士) $\mu^+ \rightarrow e^+e^-e^+$

- **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。

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

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

Snowmass2021 whitepaper

March 23, 2022

arXiv: 2203.11406

Muonium to antimuonium conversion: Contributed paper for Snowmass 21

Ai-Yu Bai,[1] Yu Chen,[1] Yukai Chen,[2] Rui-Rui Fan,[2] Zhilong Hou,[2] Han-Tao Jing,[2] Hai-Bo Li,[2] Yang Li,[2] Han Miao,[2,3] Huaxing Peng,[2,3] Alexey A. Petrov (Coordindator),[4] Ying-Peng Song,[2] Jian Tang (Coordinator),[1] Jing-Yu Tang,[2] Nikolaos Vassilopoulos,[2] Sampsa Vihonen,[1] Chen Wu,[5] Tian-Yu Xing,[2] Yu Xu,[1] Ye Yuan,[2] Yao Zhang,[2] Guang Zhao,[2] Shi-Han Zhao,[1] and Luping Zhou[2]

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

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

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 $\mu^- N \to e^+ N$
- 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
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□ (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

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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

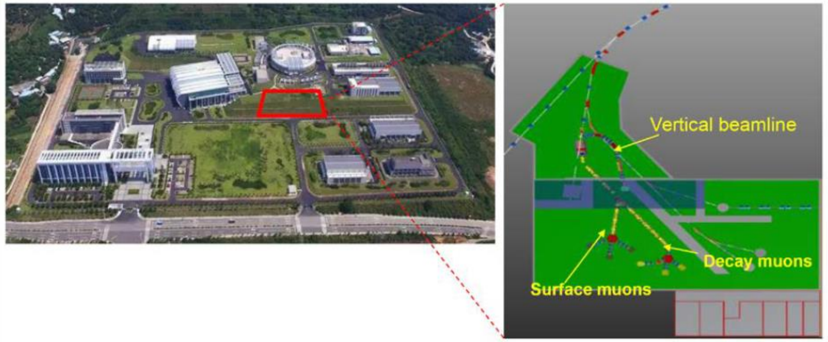
Bertrand Echenard
Caltech

NuFact 2021
Cagliari - September 2021

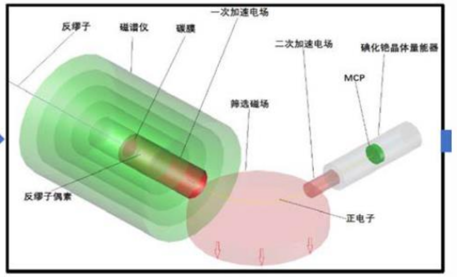
MACE at EMuS

Jian Tang
(Snowmass 2021 RPP meeting)

EMuS – new muon facility in China

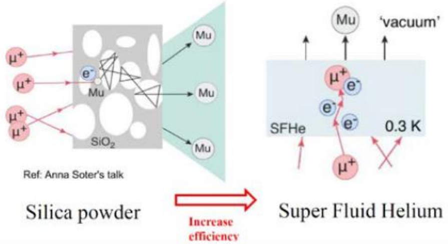


MACE concept



	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

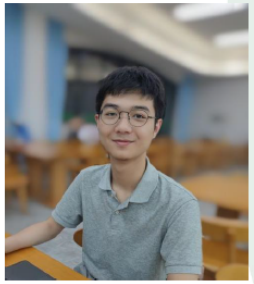


On-going physics studies and detector R&D

Snowmass2021后的反响

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*

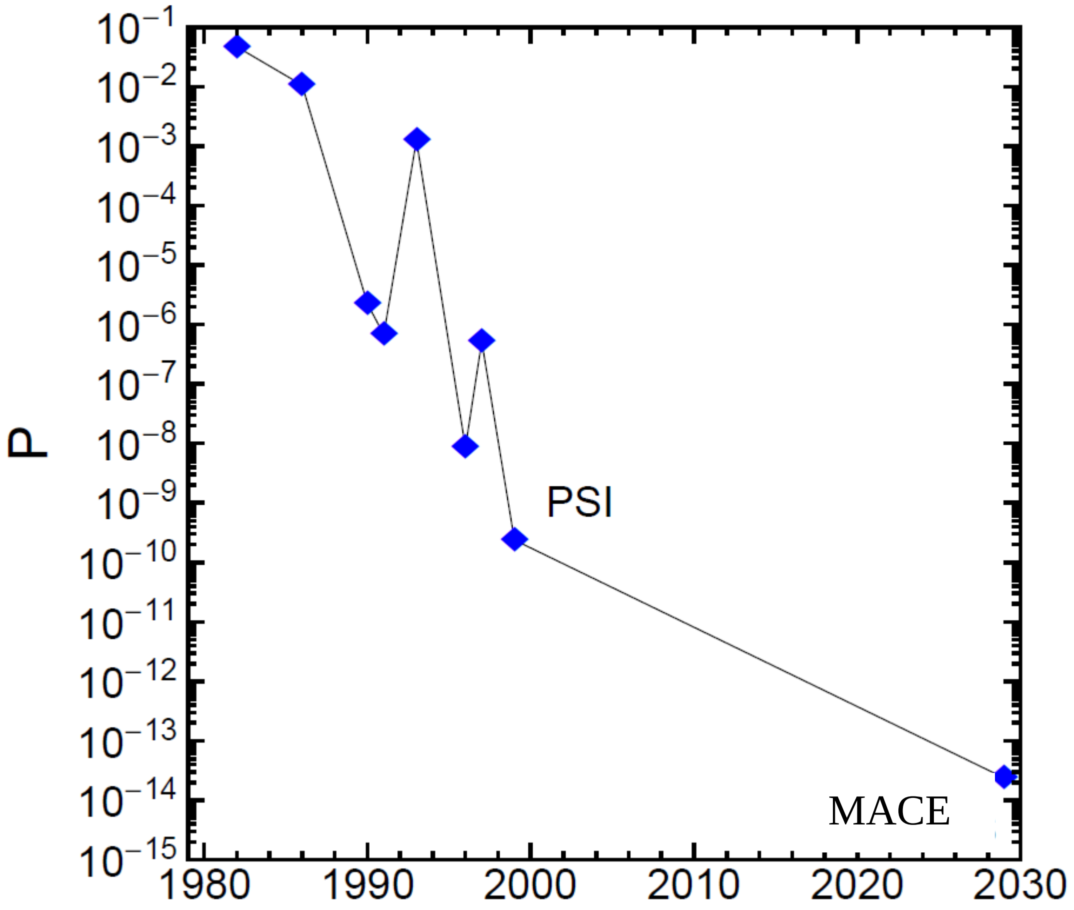
Reference: Snowmass2021 Whitepaper: Muonium to antimuonium conversion, arXiv:2203.11406

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

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 $8\times10^6\mu^+/s$。
- 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

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 Zhou[3]

[1]*School of Physics, Sun Yat-sen University, Guangzhou 510275, China*

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[5]*University of Chinese Academy of Sciences, Beijing 100049, China*

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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)

CONTENTS

内容概述

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

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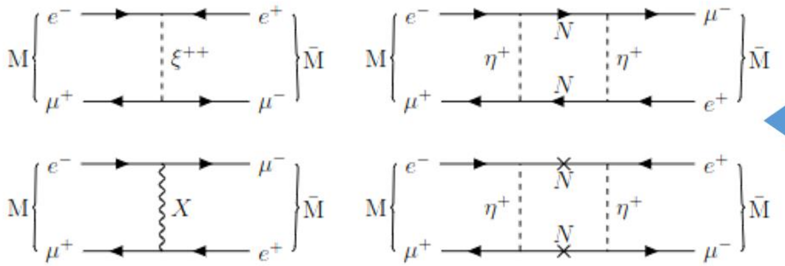
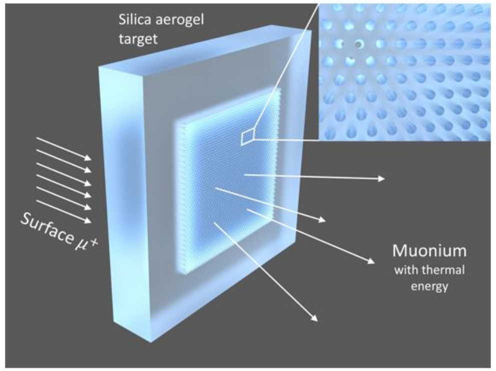
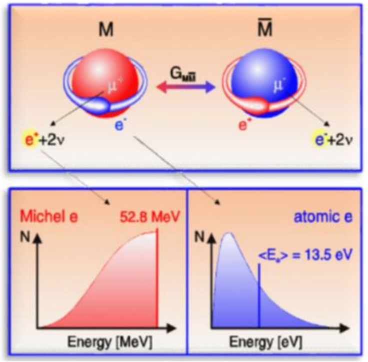
MACE实验关键技术路线

Muonium-to-Antimuonium Conversion Experiment

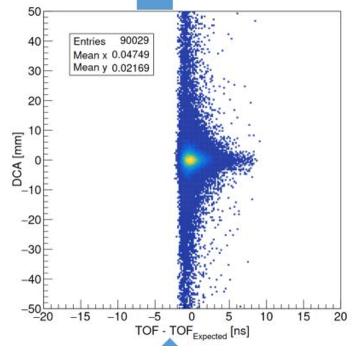
High-efficiency muonium production?

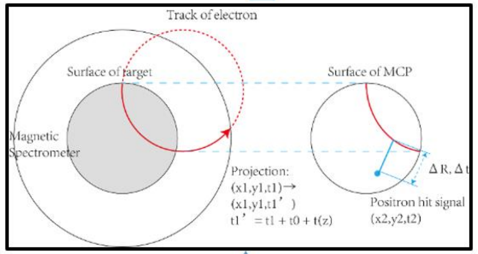


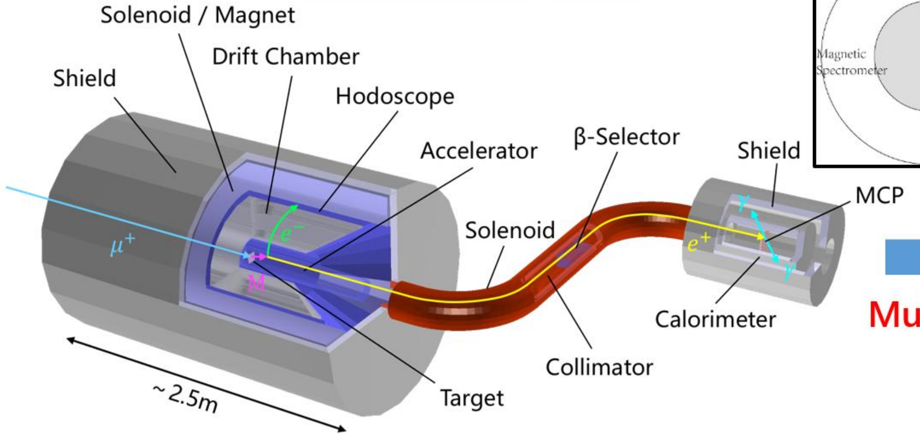




High signal/noise ratio







High-resolution spectrometer

Multiple coincidence?

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

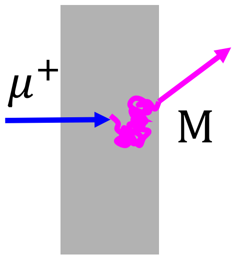
↓

Random walk (room temp.)

↓

Emission to vacuum

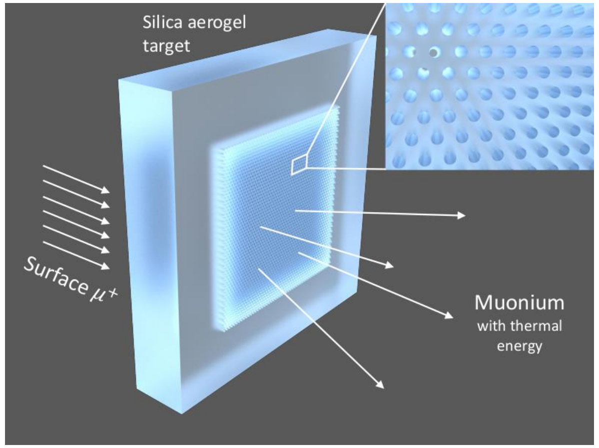
MC simulation for muonium transport has been developed under the MACE offline software framework.



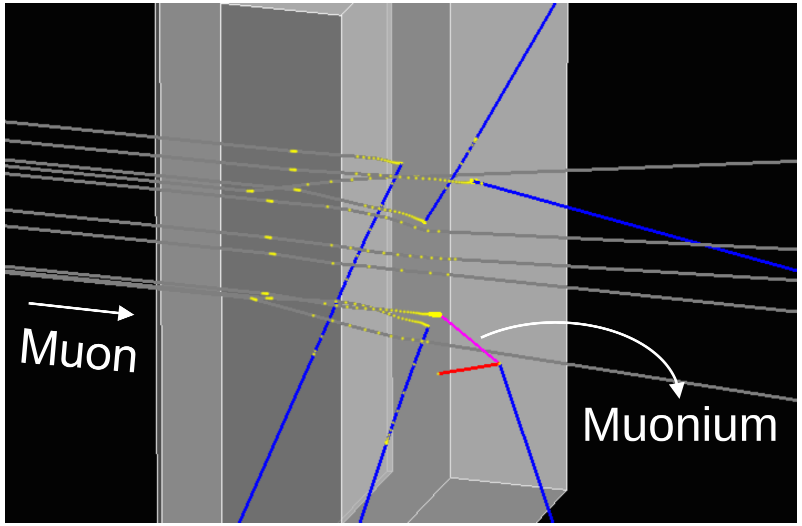
① Geant4 low-energy EM process.

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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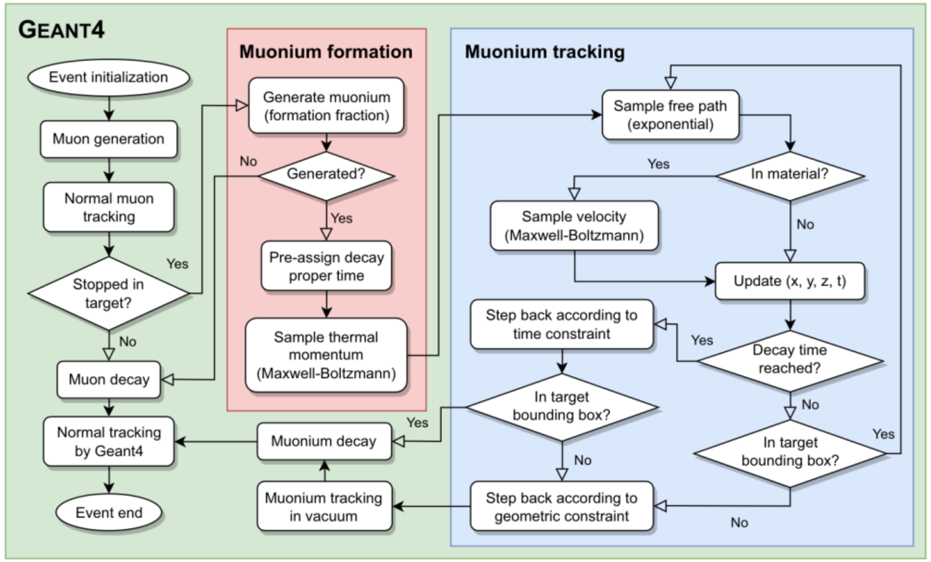
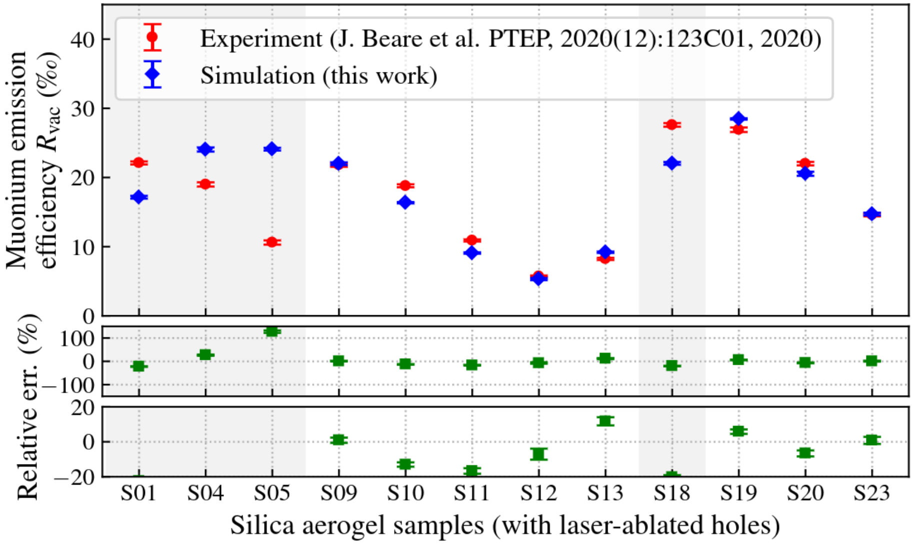
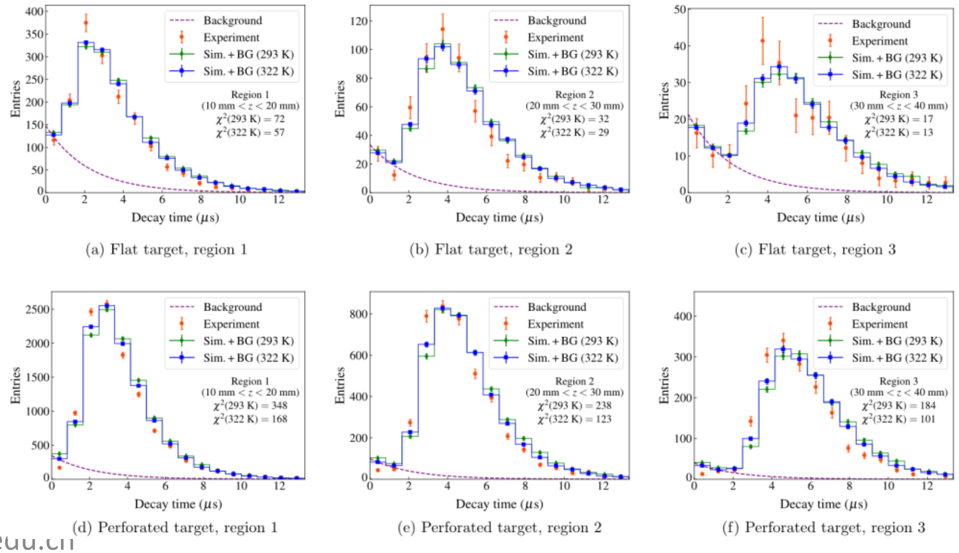
SiO_2气凝胶靶材缪子素产额优化

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.

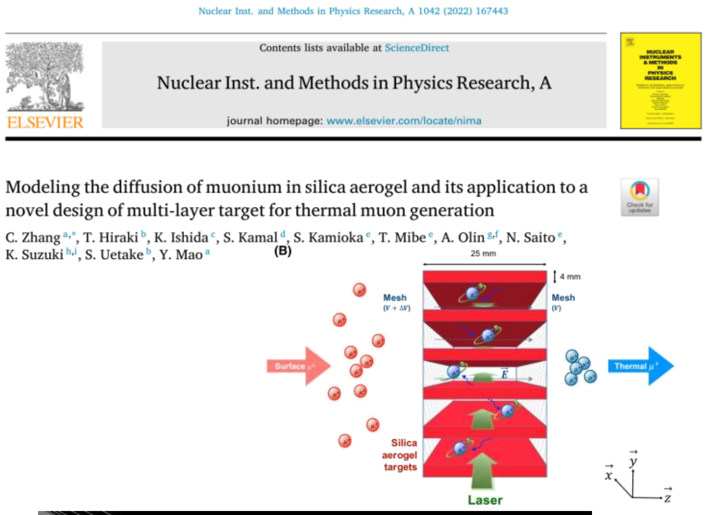






SiO_2气凝胶靶材缪子素产额优化

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


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

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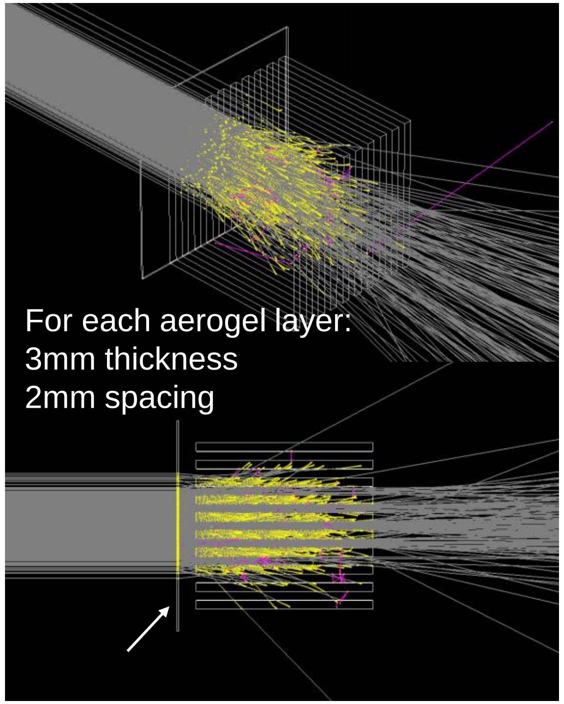
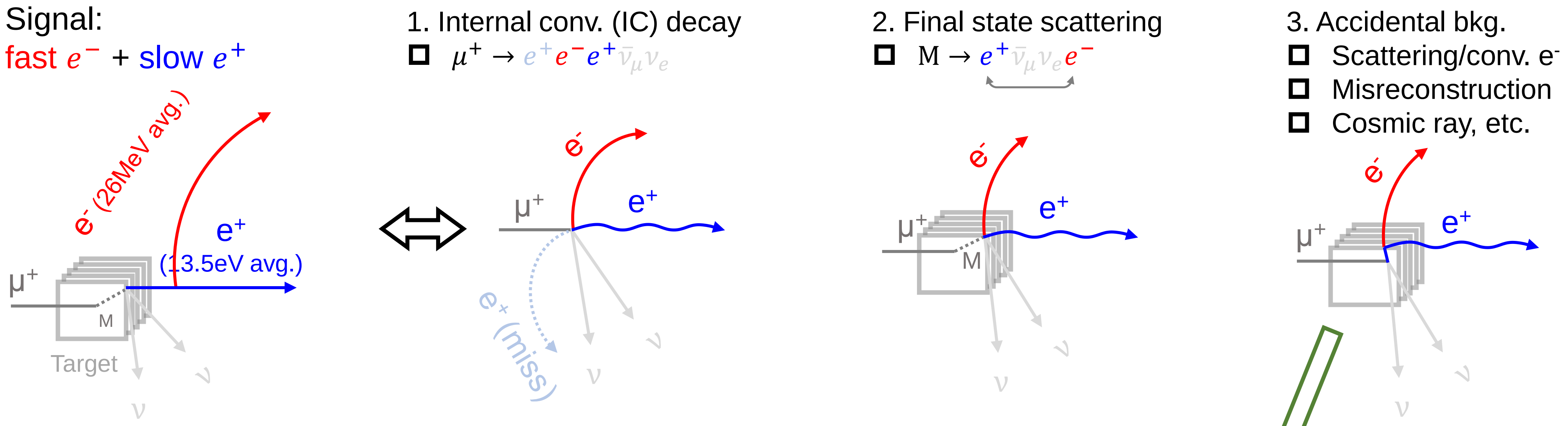
Modeling the diffusion of muonium in silica aerogel and its application to a novel design of multi-layer target for thermal muon generation

C. Zhang[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



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

➢ A "clean" data taking duration
- Pulsed muon beam

➢ Excellent vertex resolution
- e^+/e^- spatial resolution
- Precise e^+ transport in EM field

➢ Excellent time resolution
- e^+/e^- time resolution

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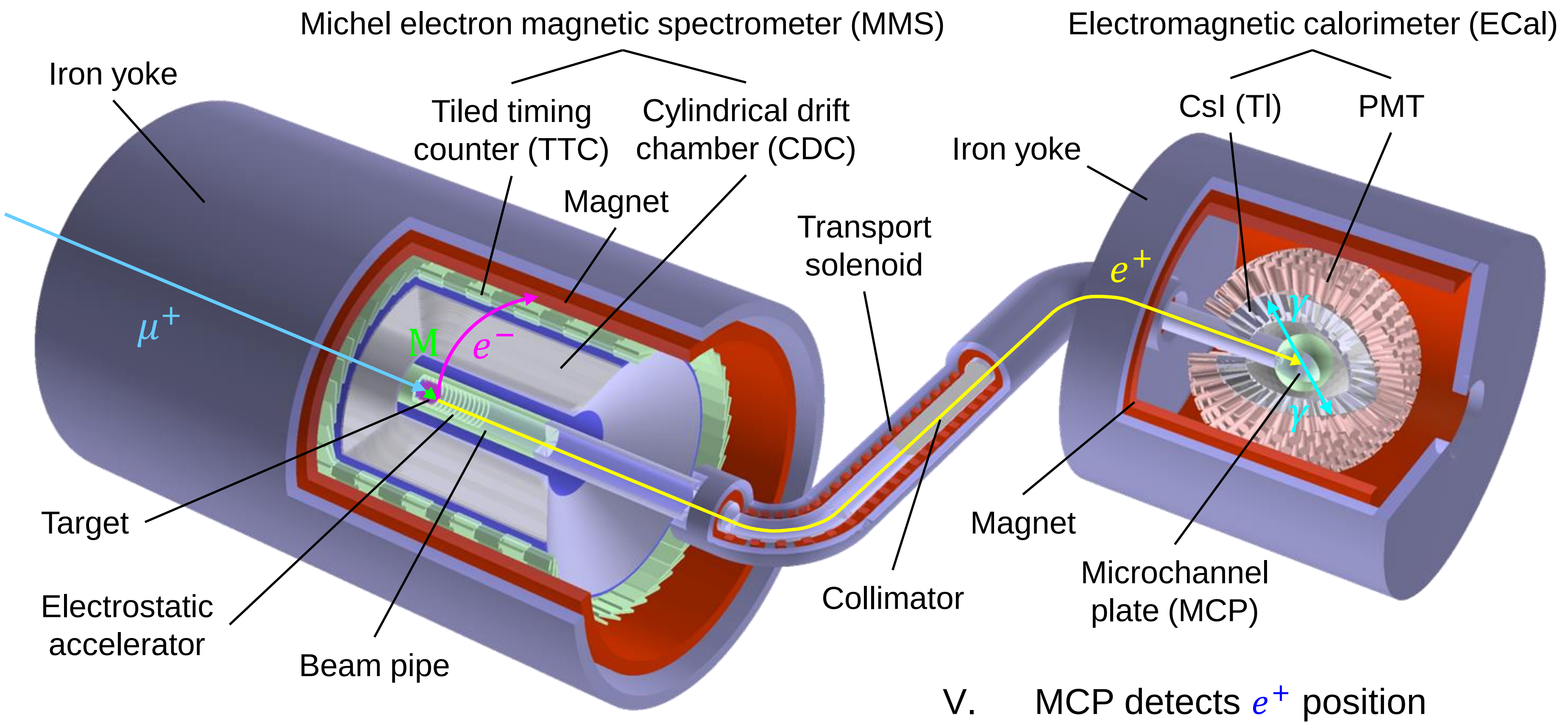
MACE实验基本设计方案v1



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 + MCP + ECal**

MMS ↓ Michel e^-; MCP + ECal → Atomic e^+

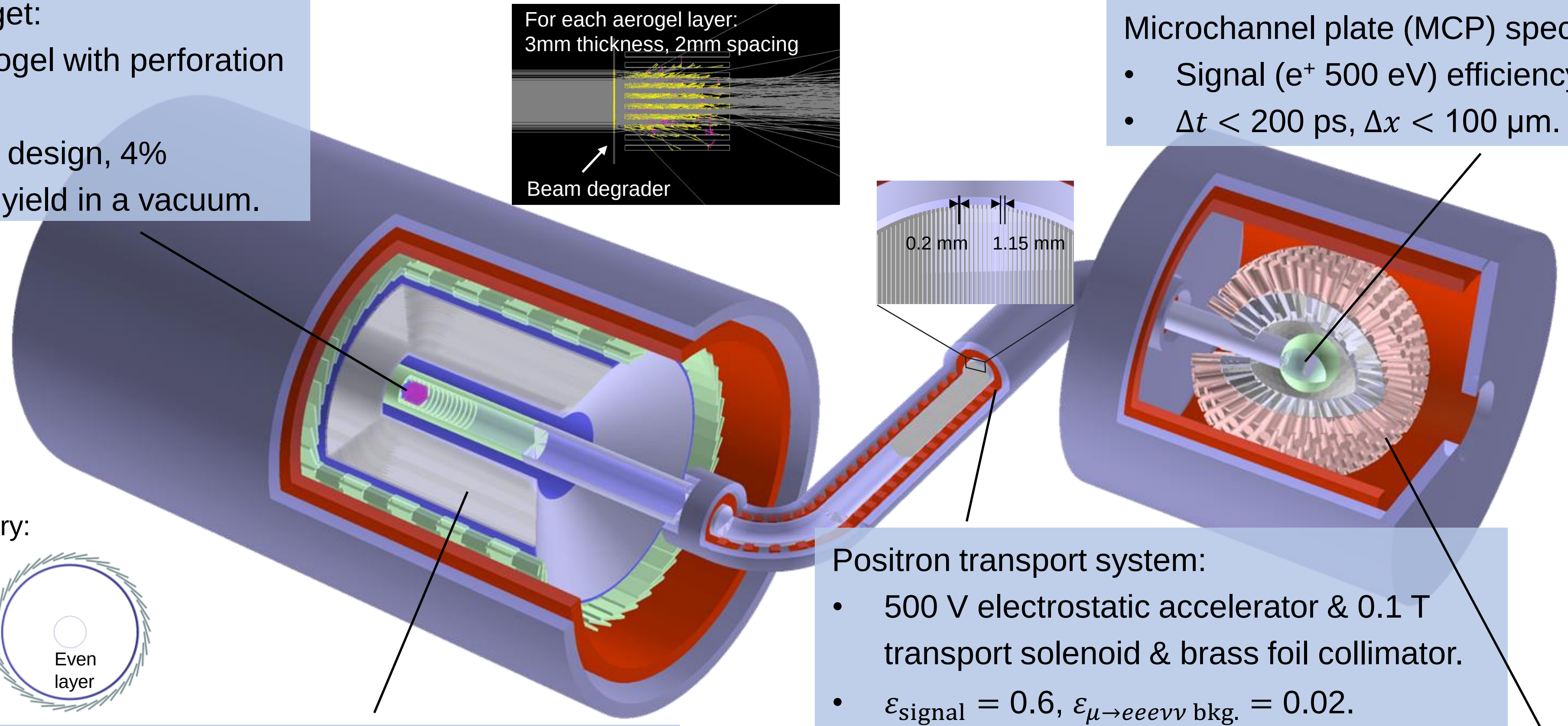
MACE实验基本设计方案v1

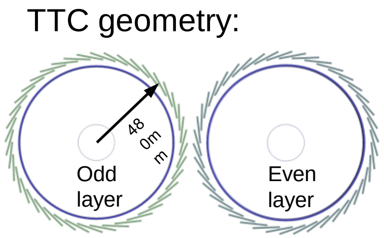
Muonium target:

- 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.





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.

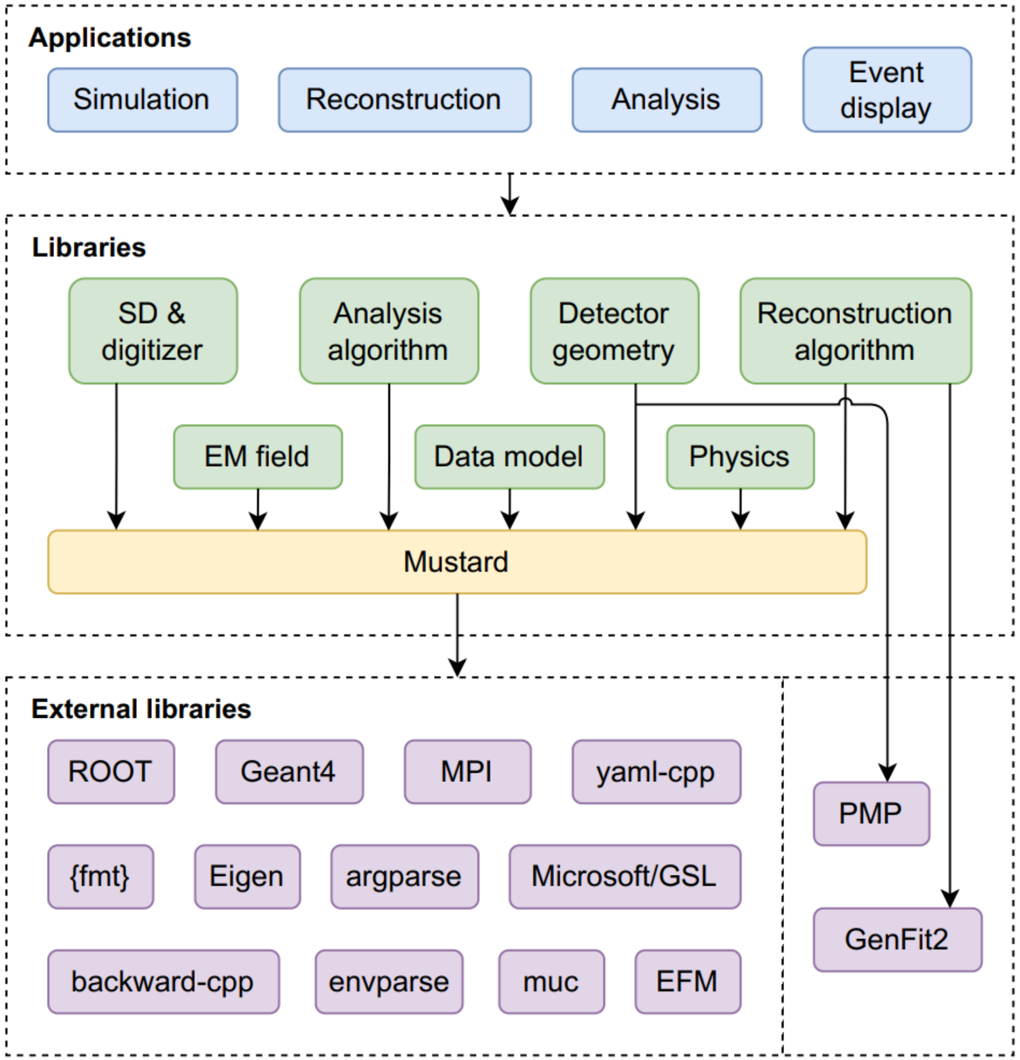
Magnetic spectrometer:

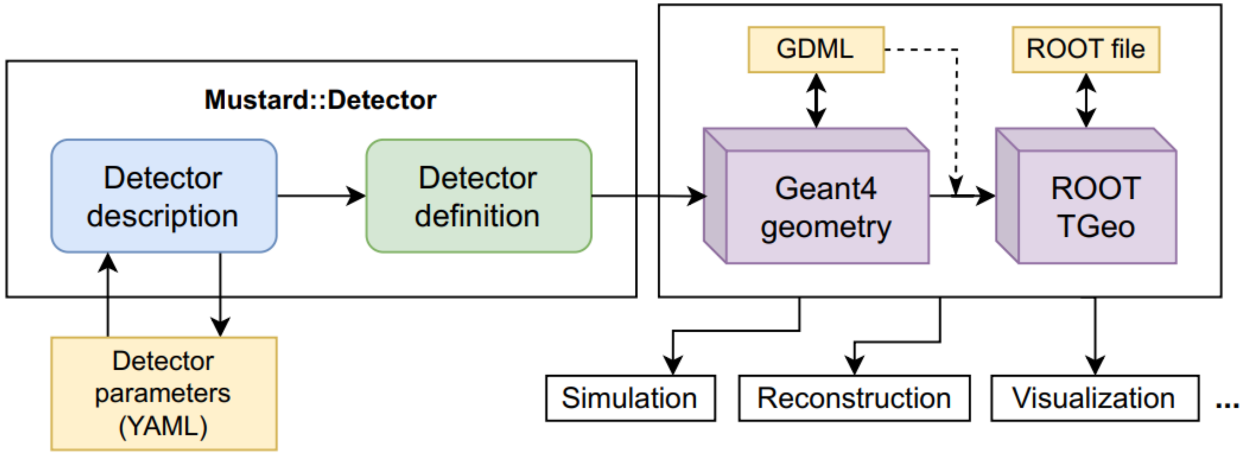
- 0.1 T axial magnetic field.
- CDC: $He(C_4H_{10})$ gas, 21 layers, 3540 cells. 89% geometry acceptance, $\Delta p \approx 500$ keV.
- TTC: 756 fast scintillators with SiPM readout, slant ± 15 deg, $\Delta t < 100$ ps.

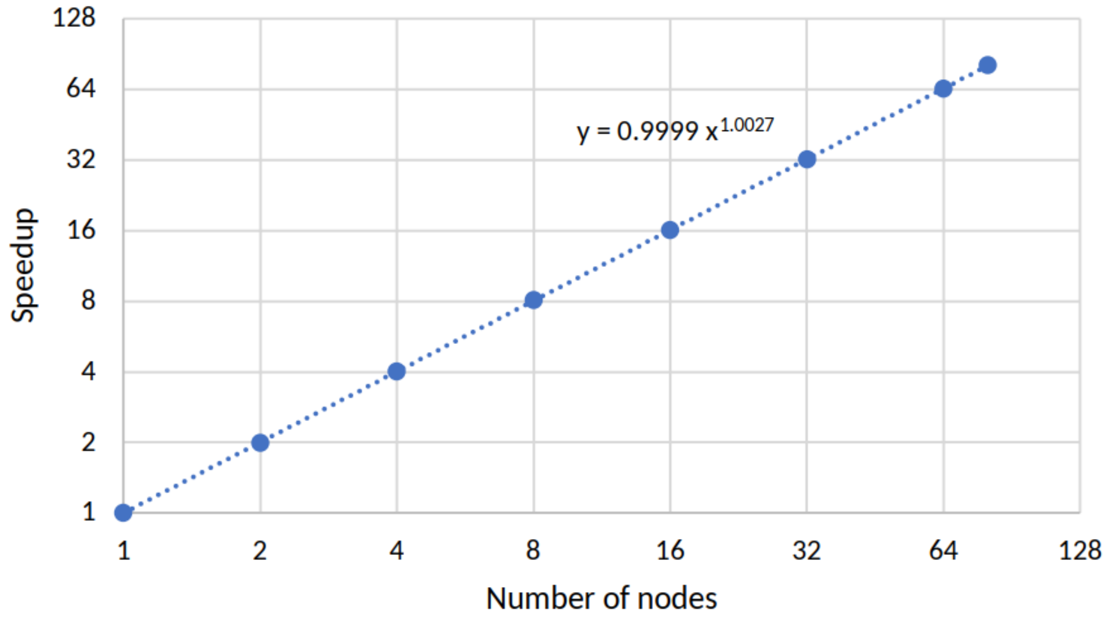
Electromagnetic calorimeter:

- 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.

MACE离线软件框架和天河二号

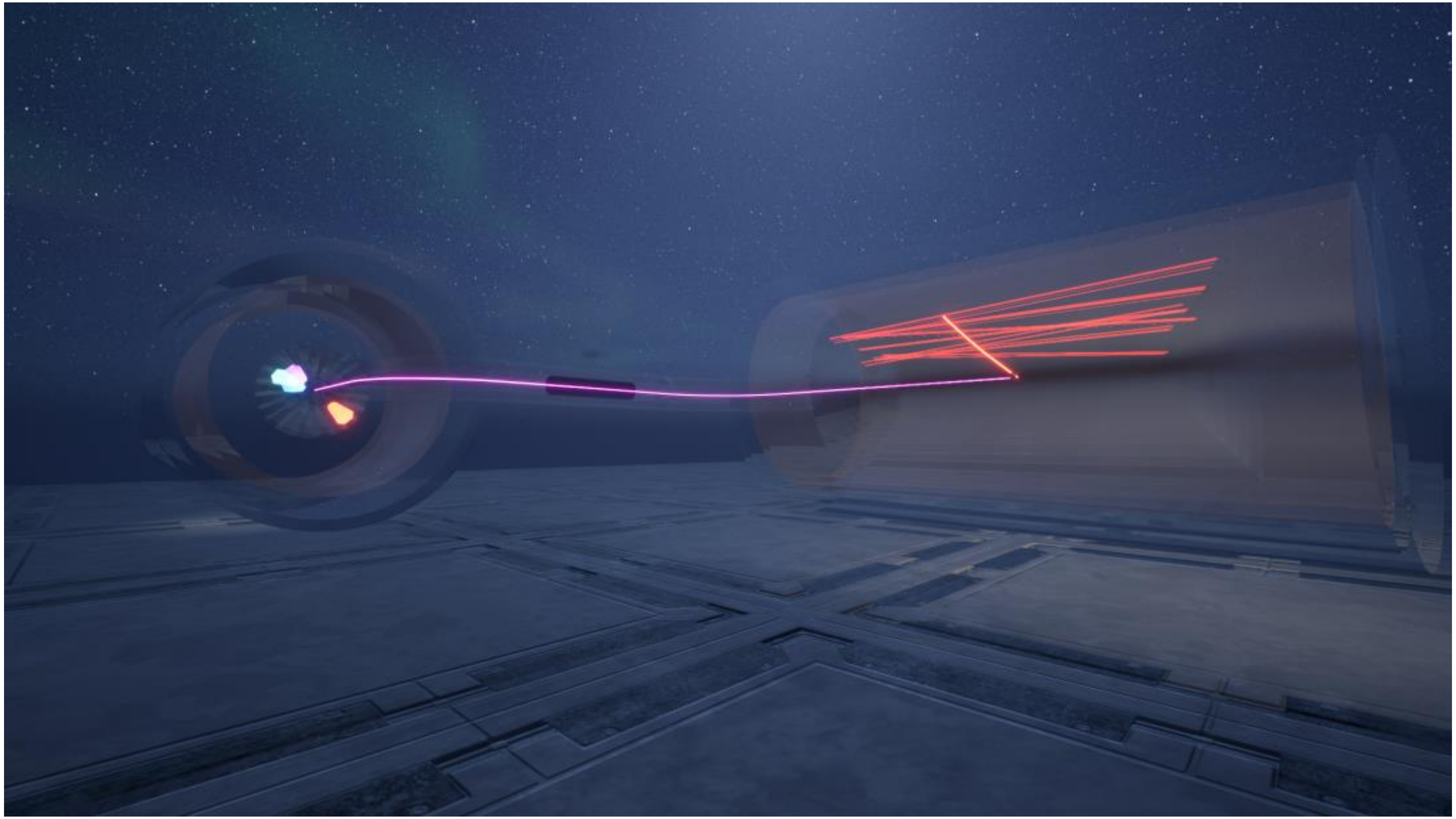




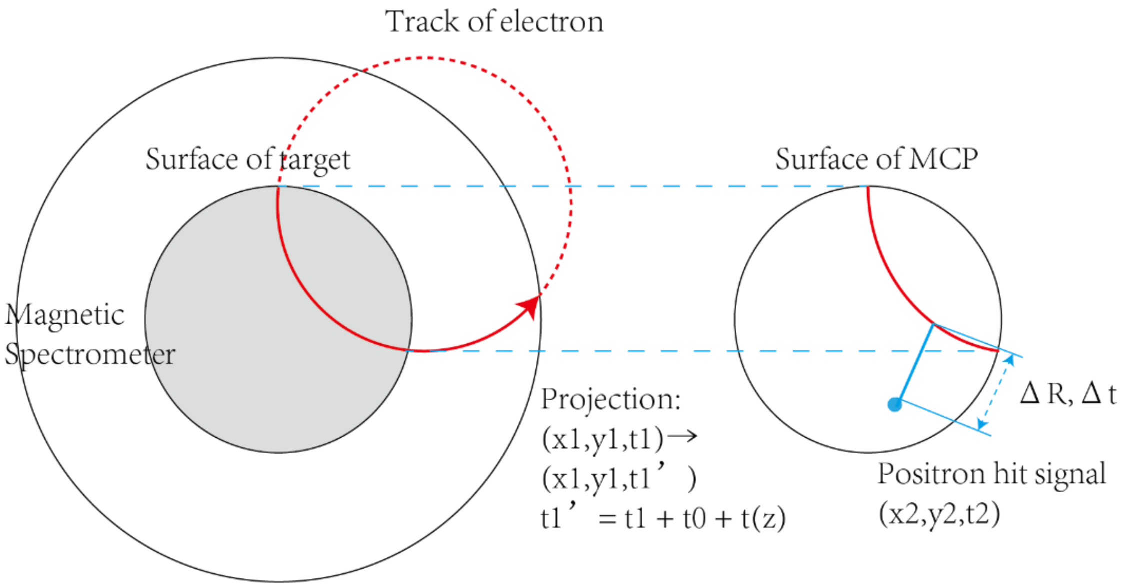


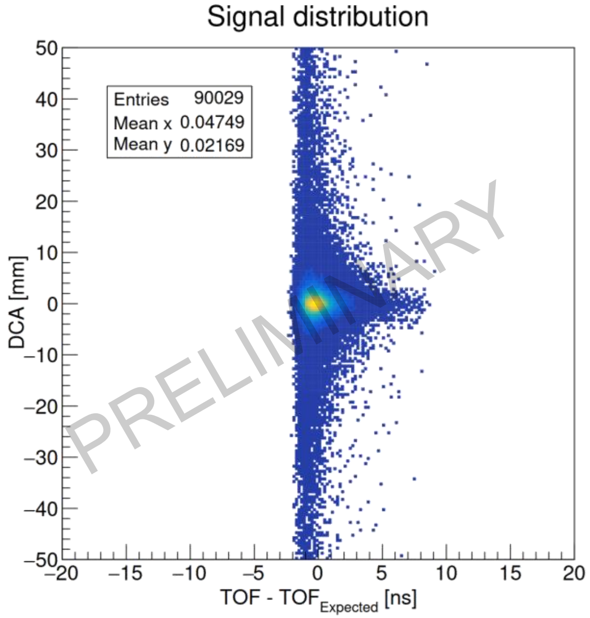
MACE事例显示器开发中

Credits：熊伟志



快速MC模拟: 缪子素探测

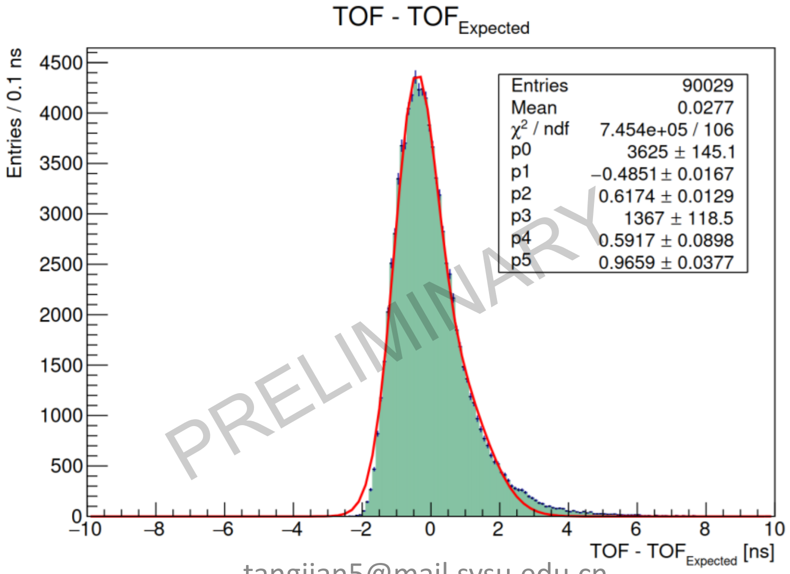


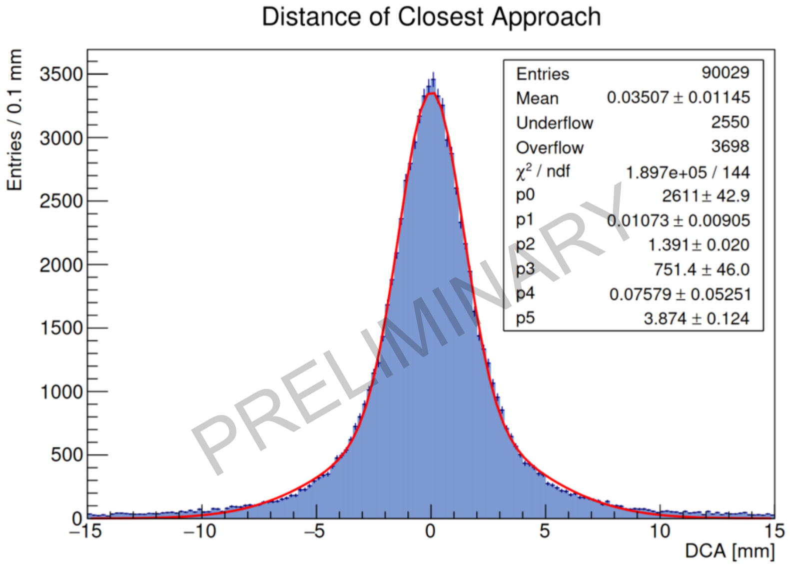


- Elliptical 3σ signal region:

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

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





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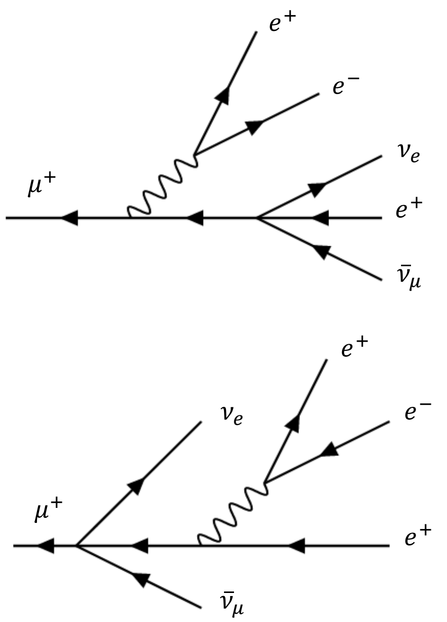
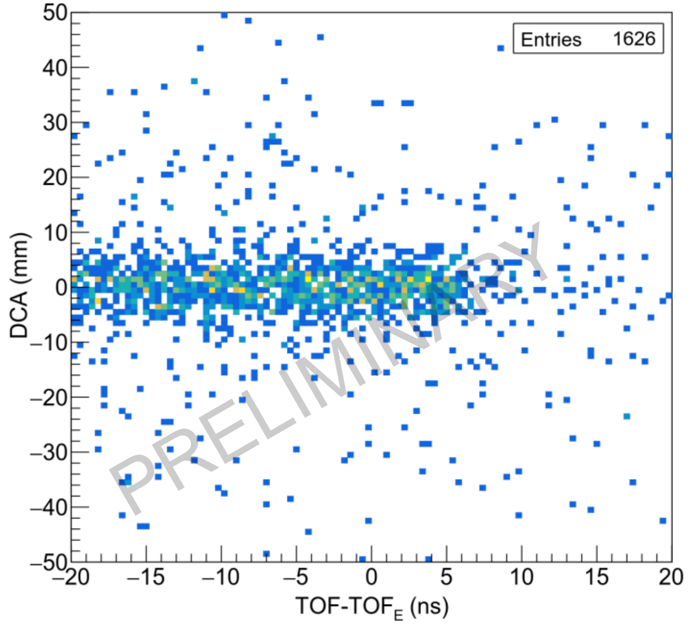
快速MC模拟: 五轻子末态

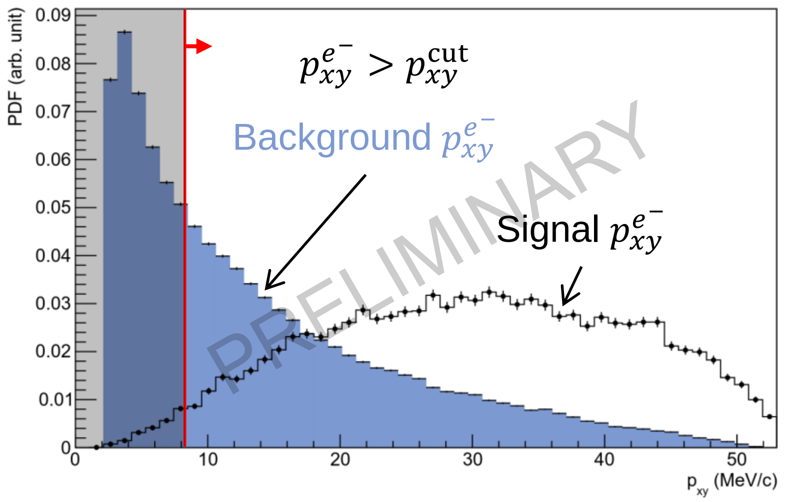




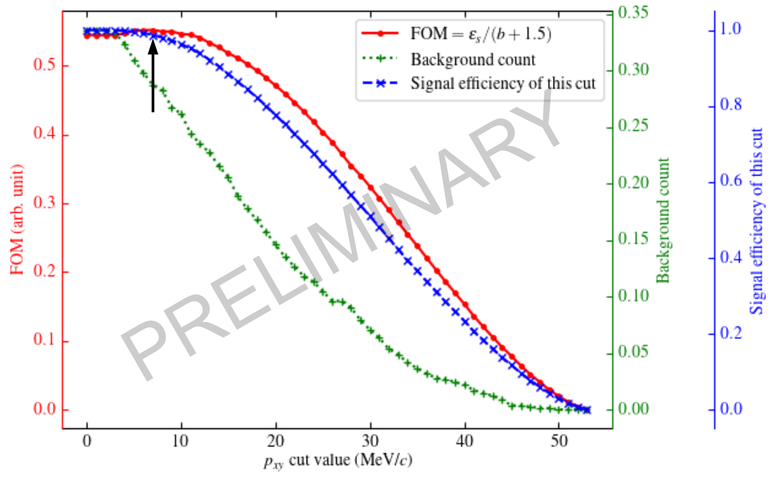
$\mu^+ \to e^+e^-e^+\bar{\nu}_\mu\nu_e$ simulation:

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

(in 10^8 μ/s × 365 d)



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



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MACE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 acceptance ($\varepsilon_{\text{MMS}}^{\text{geom}}$)	88.2%
	Reconstruction efficiency ($\varepsilon_{\text{MMS}}^{\text{recon}}$)	~ 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 ($\varepsilon_{\text{ECal}}$)	67.5%
Total detection efficiency		10.2%
Analysis	Signal efficiency (ε_{Cut})	~ 80%
Total signal efficiency		8.2%

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

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

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

Timeline

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

- 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: $\Delta p/p < 3\%$

- 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

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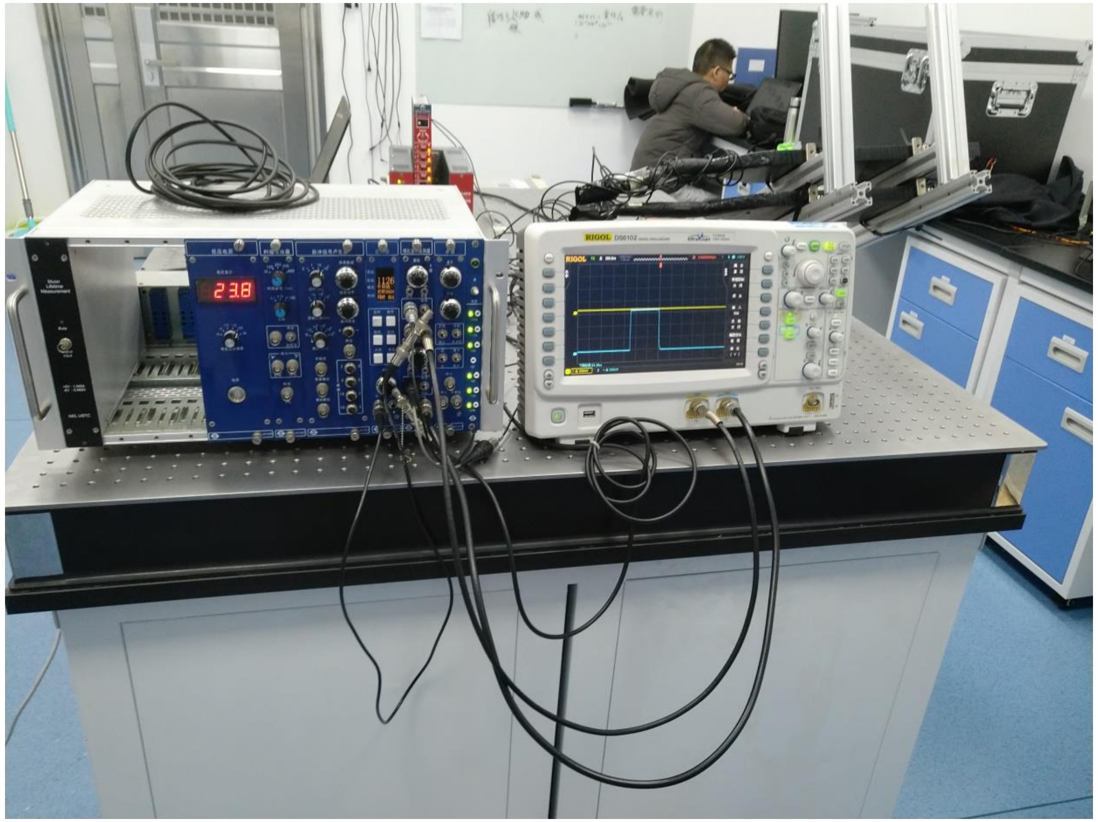
建设本地缪子物理实验室



缪子前沿科学与技术应用实验室SMOOTH

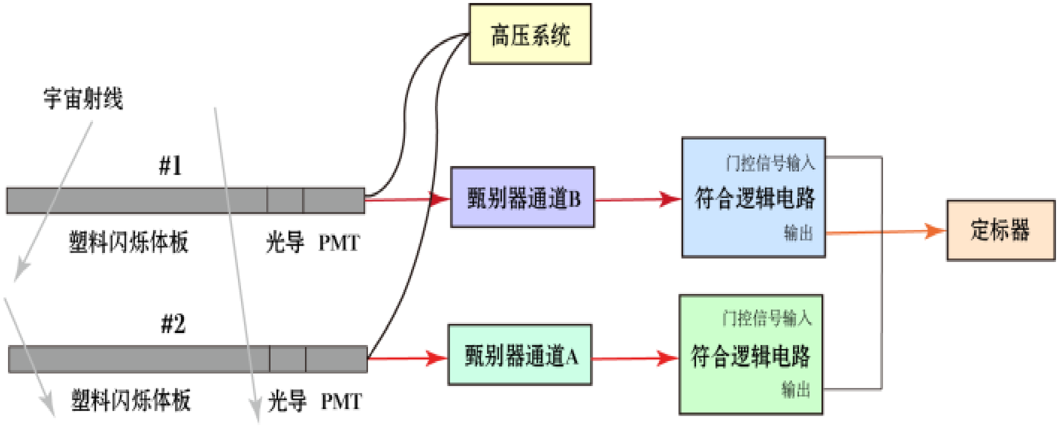
感谢学院的支持，教学和科研融合的实验室，新实验楼装修中！

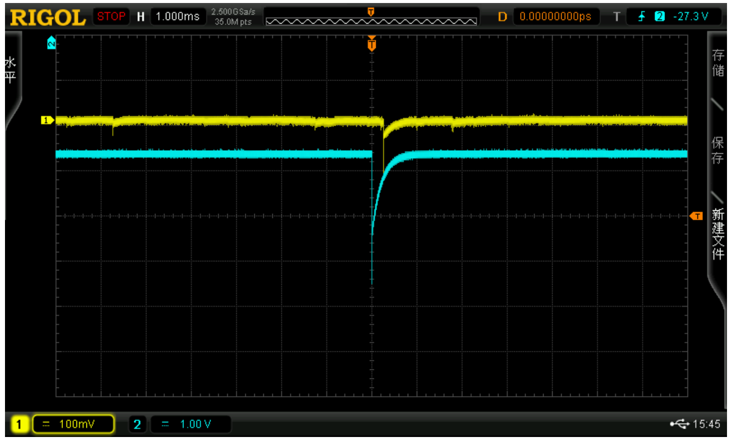
教学型宇生缪子探测器v1：符合探测

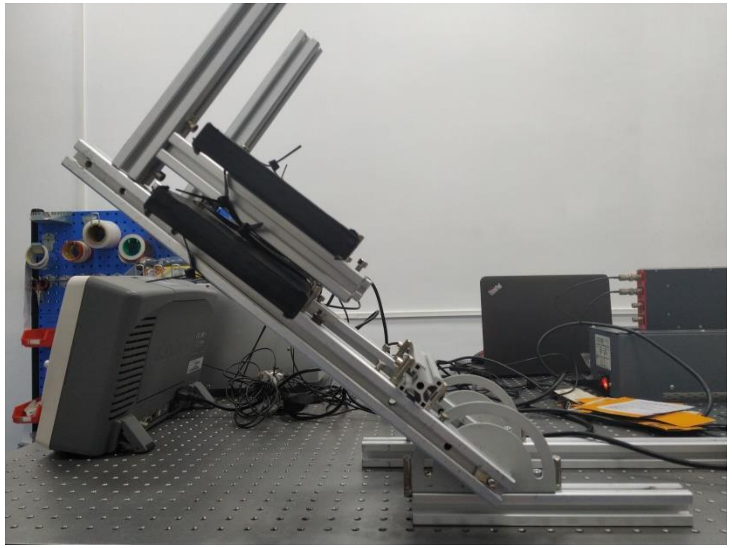
- Coincident method→ oscilloscope to monitor PMT waveforms

→ NIM electronics to count rates and angular distributions

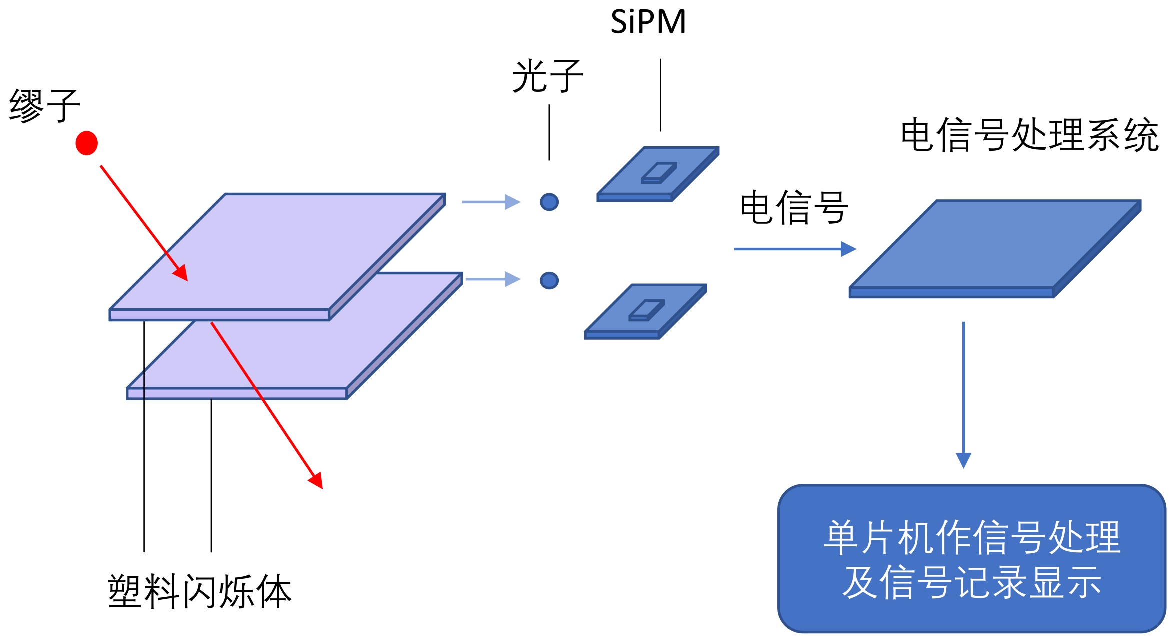
林海星，宁云松等，《物理实验》第41卷，第2期，2021年2月

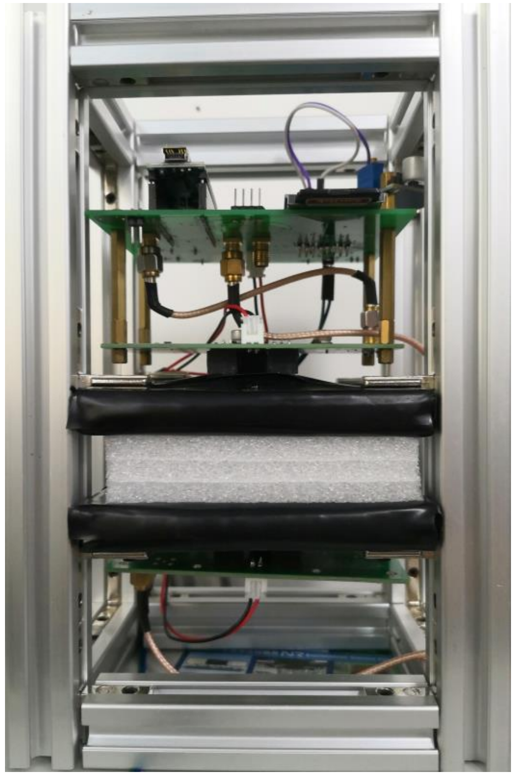


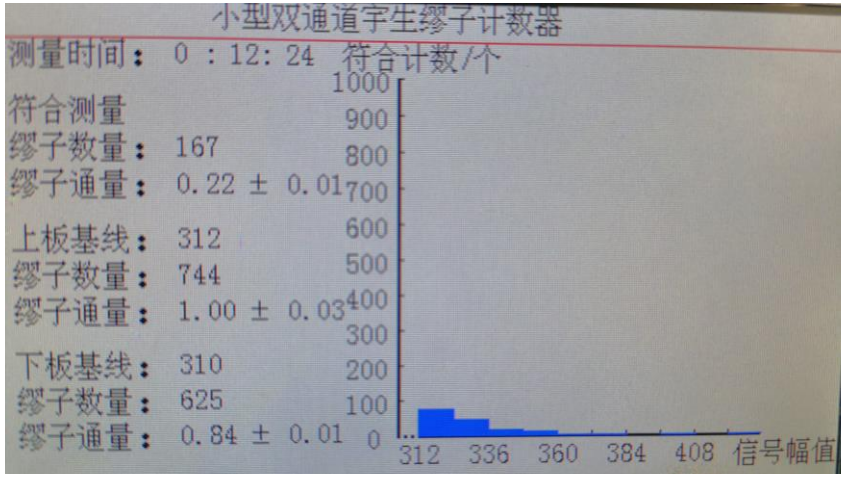




教学型宇生缪子探测器v2：小型化



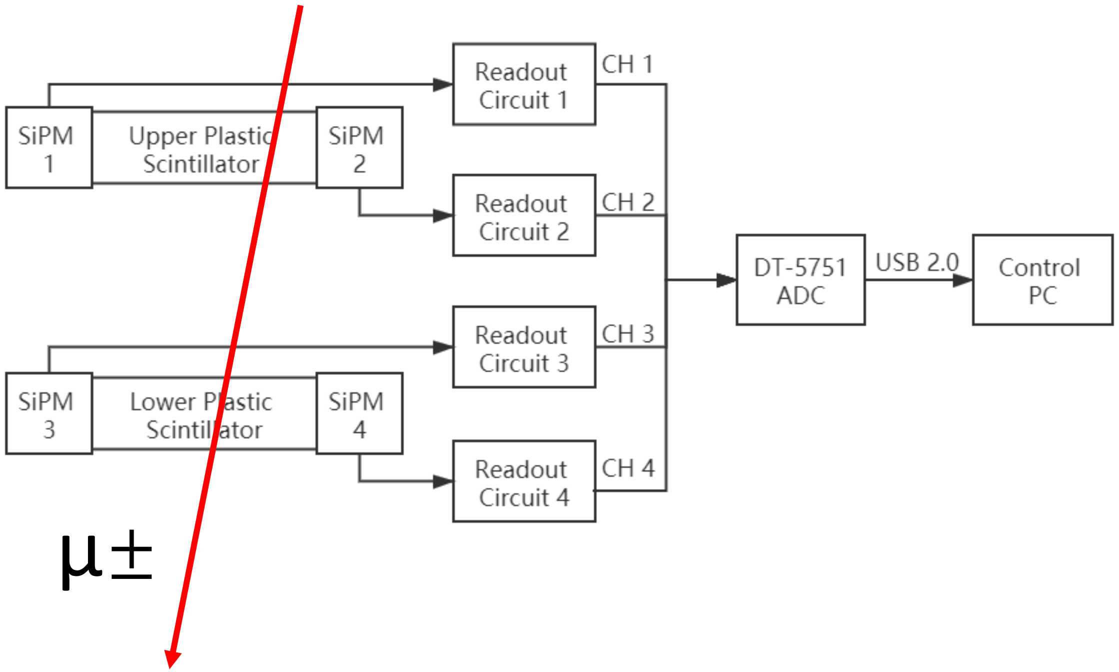


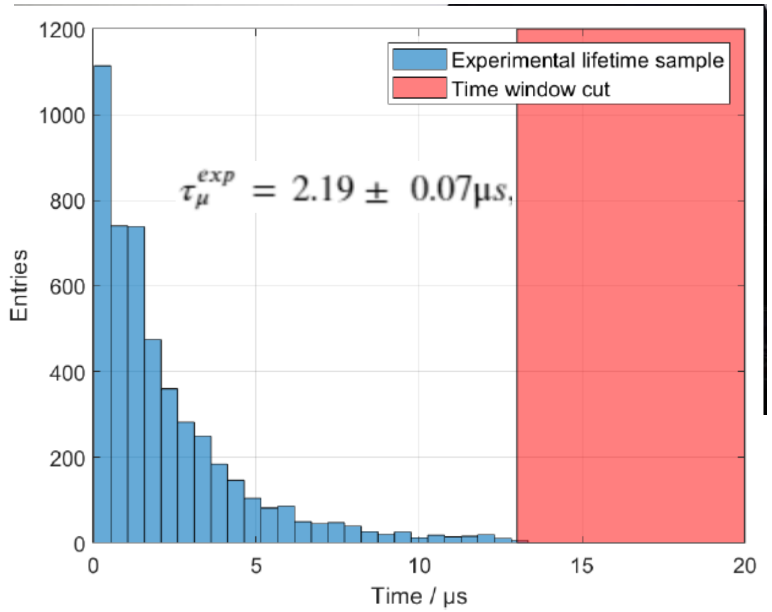


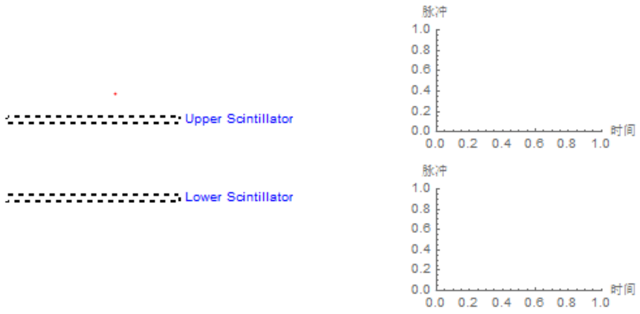
- 特点：便携式，北斗定位和授时，无线传输云平台，微信小程序，阵列集群...
- 已用于中山大学《专业物理实验》教学
- 开展科学普及、产学研推广等

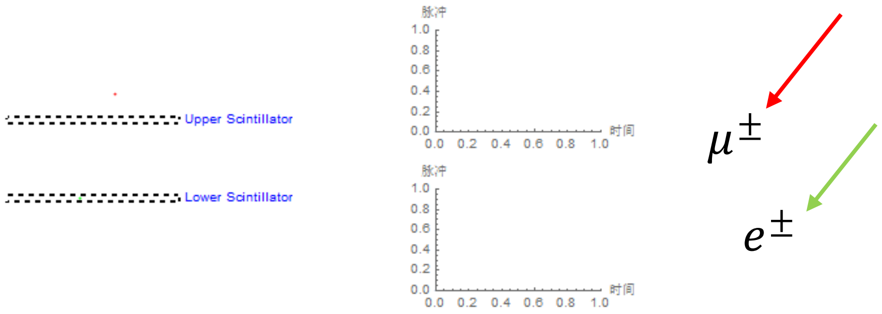
Credit: 蒋辉，宁云松，林海星等

教学型宇生缪子探测器v3：寿命测量





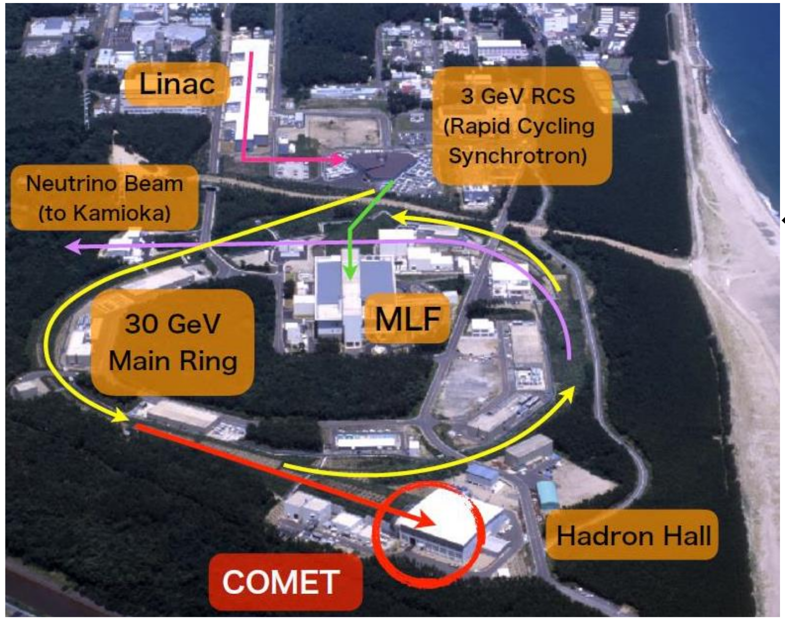


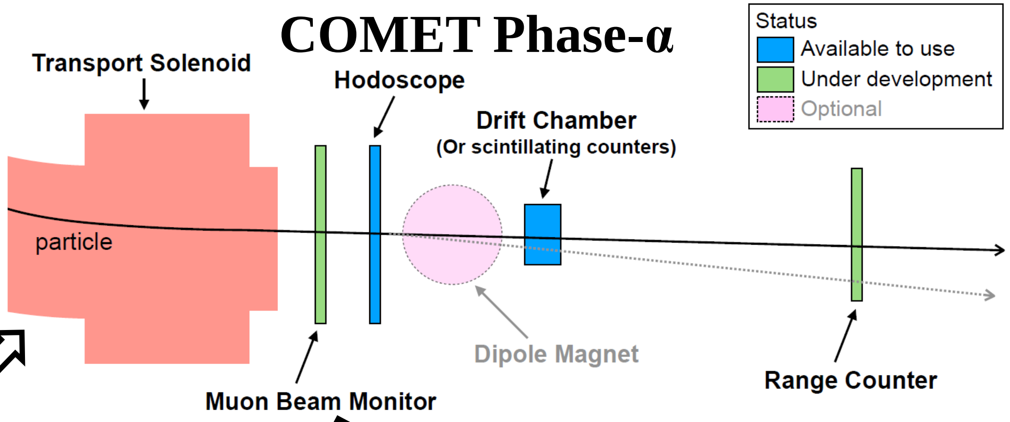


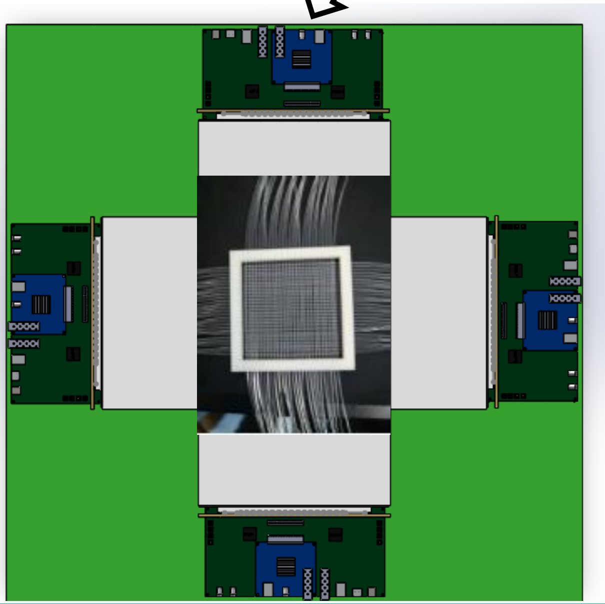
Credit: 廖健等，Nucl.Phys.Rev. 39 (2022) 1, 73-80

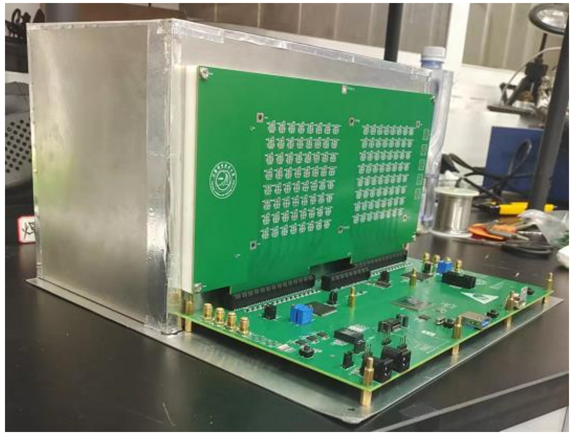
COMET实验缪子束流监测探测器研制

- 积极参与国际合作COMET实验，进一步提升探测器研发水平。









SciFi → SiPM → FEB → DAQ → PC

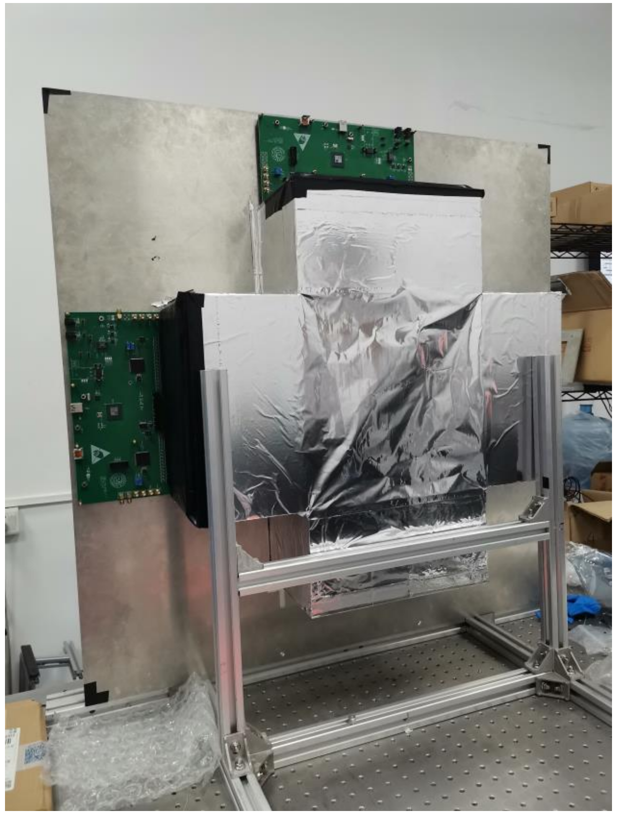
e-Print: 2308.15253 [physics.ins-det]

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/cm^{2}



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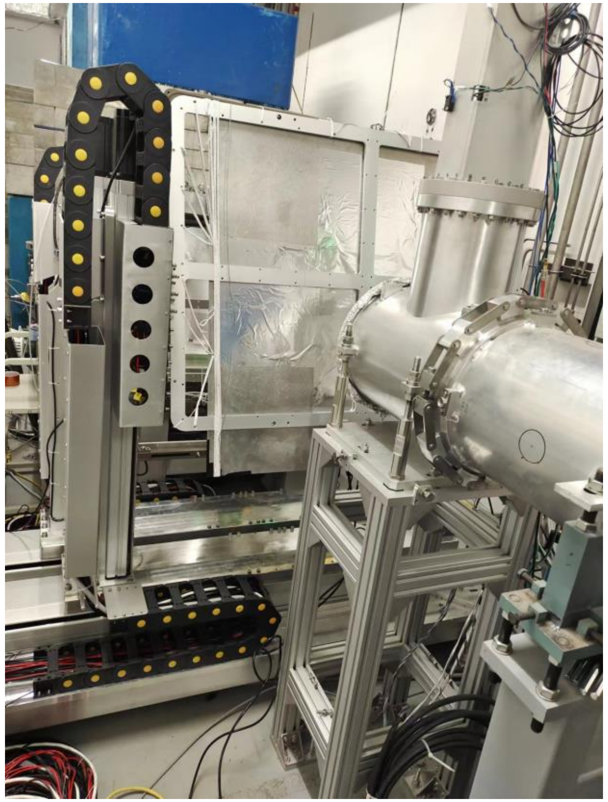
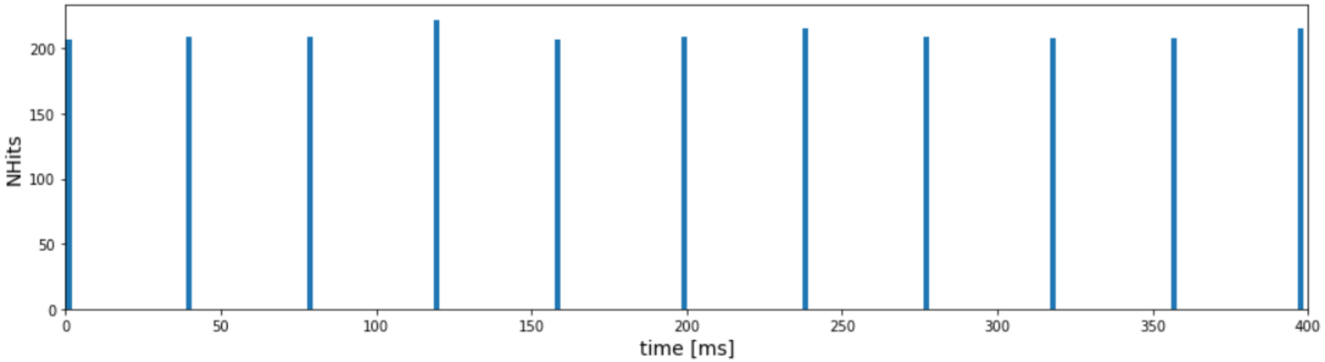
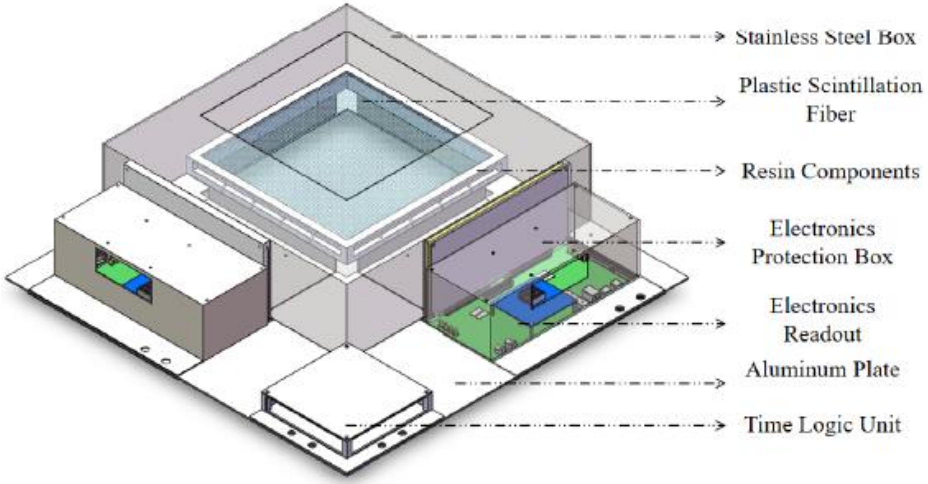
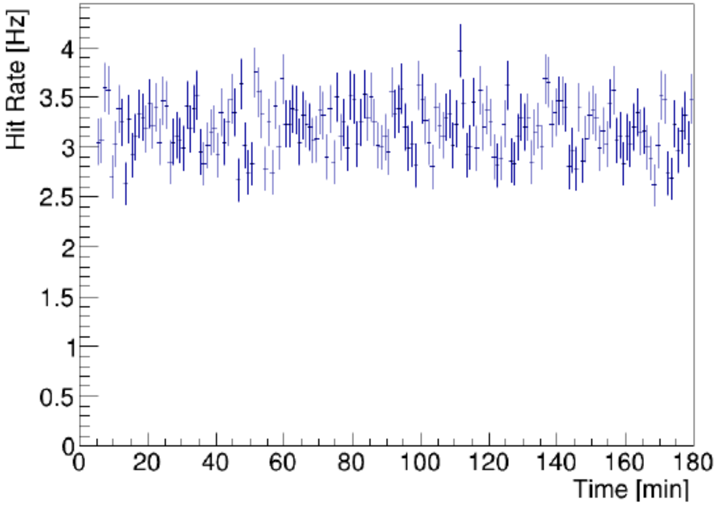


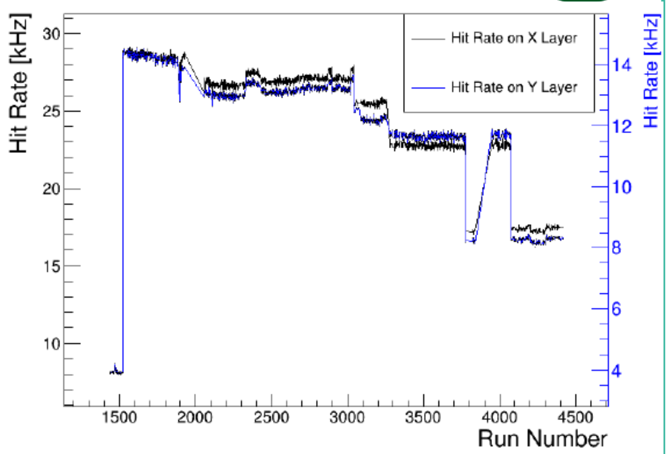


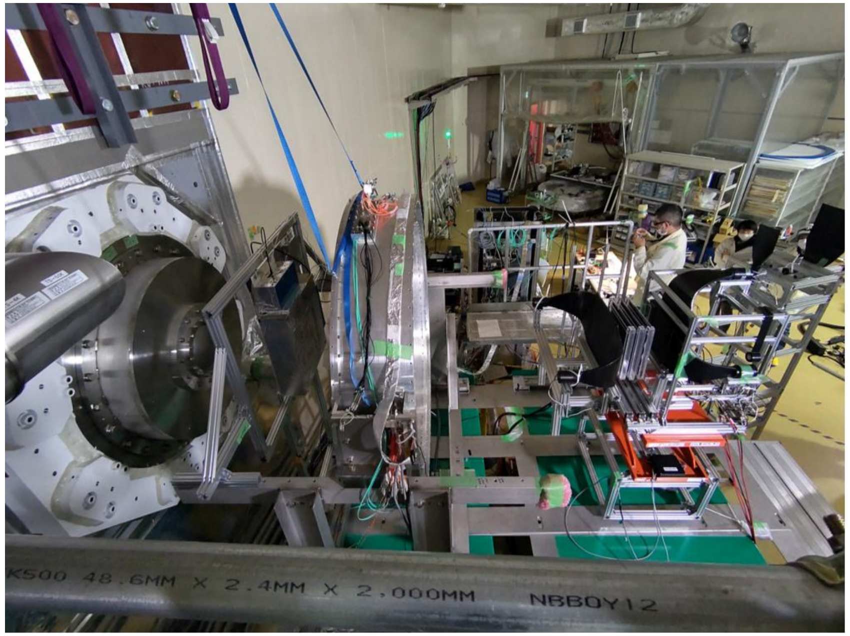
致谢：CSNS质子束流平台敬汉涛、谭志新等

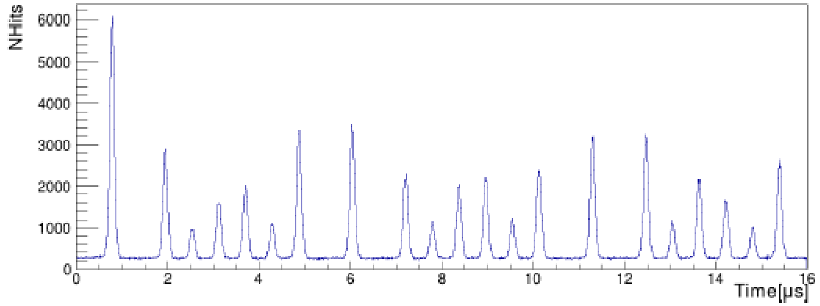
COMET实验缪子束流监测探测器研制

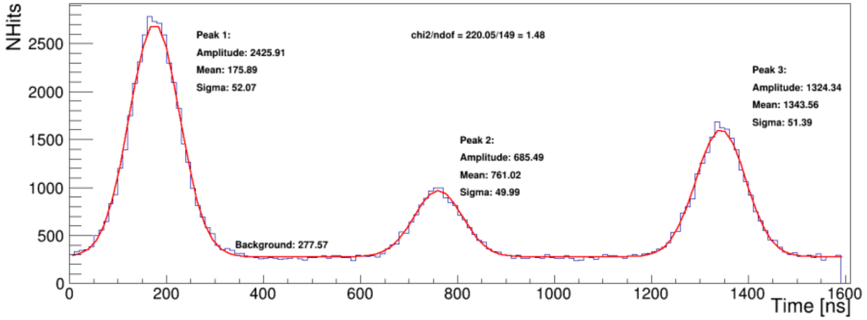


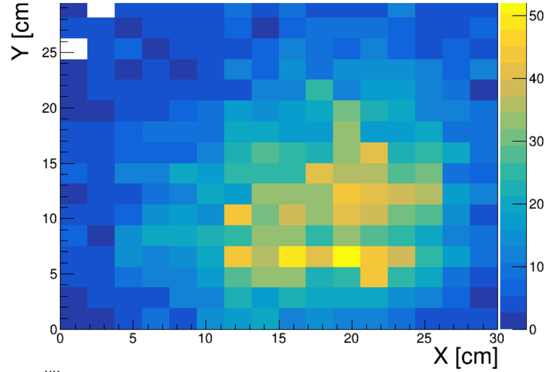


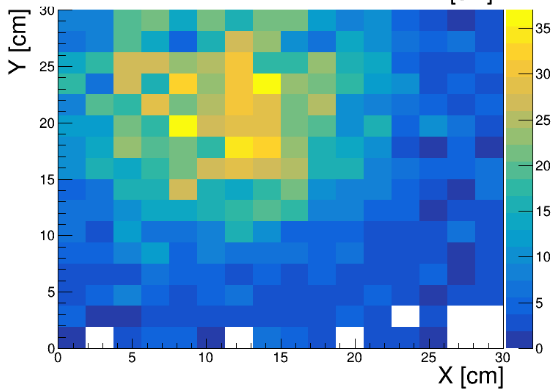




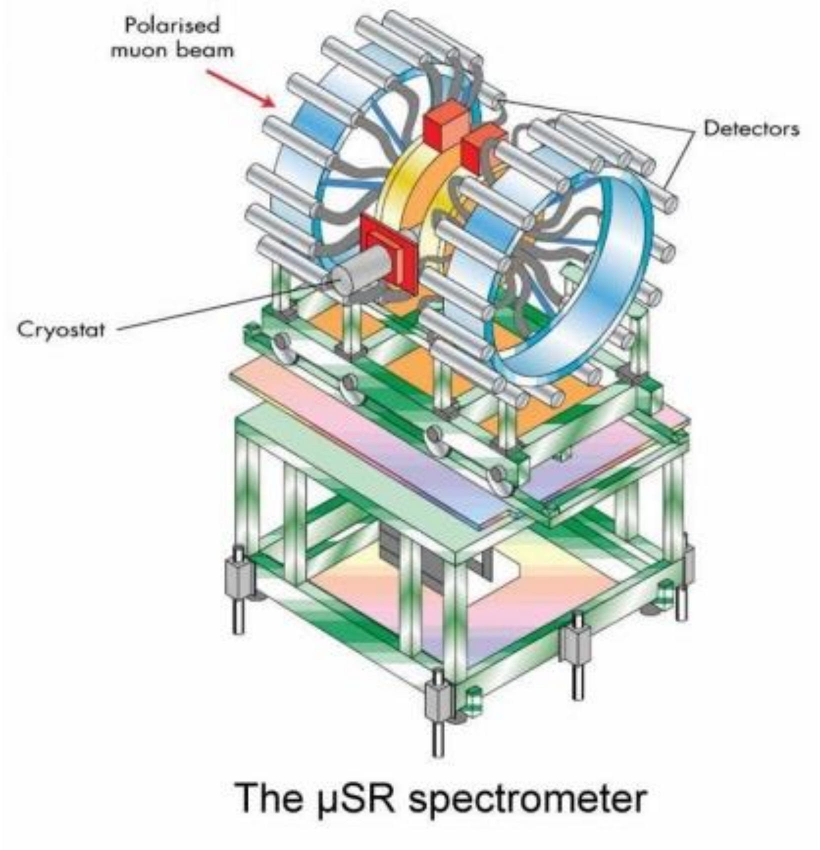




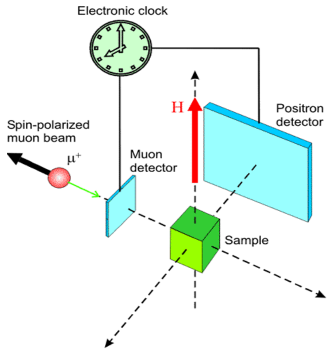


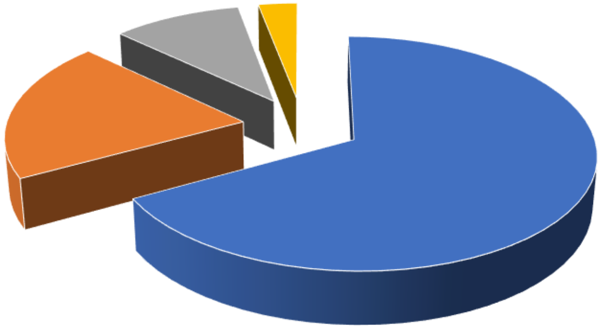


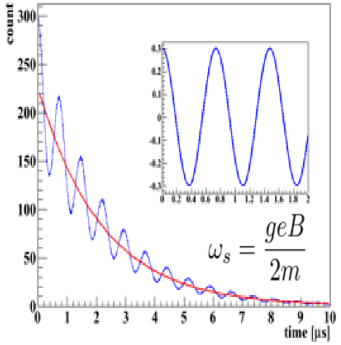
Muon Spin Relaxation, Rotation and Resonance (μSR谱仪)



Nature Materials 16, 467–473 (2017)





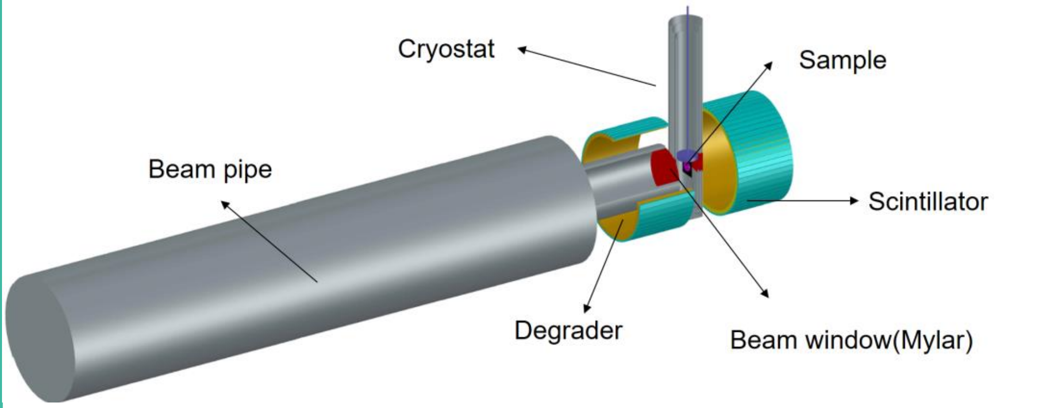


- 物理：*磁性*、*超导性*、*表面物理*、*基础物理*
- 化学：*分子动力学*、*氧化物*、*μ偶素*
- 材料：*多聚物*、*半导体*、*储氢材料*
- 生物：*蛋白质*、*DNA*

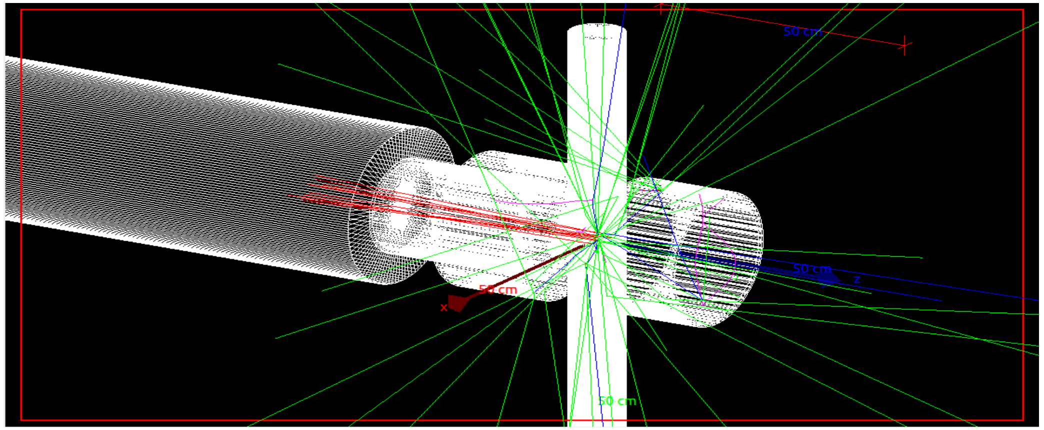
主要谱仪类型：不加磁场(ZF-μSR)、加横向磁场(TF-μSR)、加纵向磁场(LF-μSR)、自旋回波 (μSE)、自旋共振(RF- μSR)、Level Crossing共振(μACLR)

μSR谱仪的设计和模拟

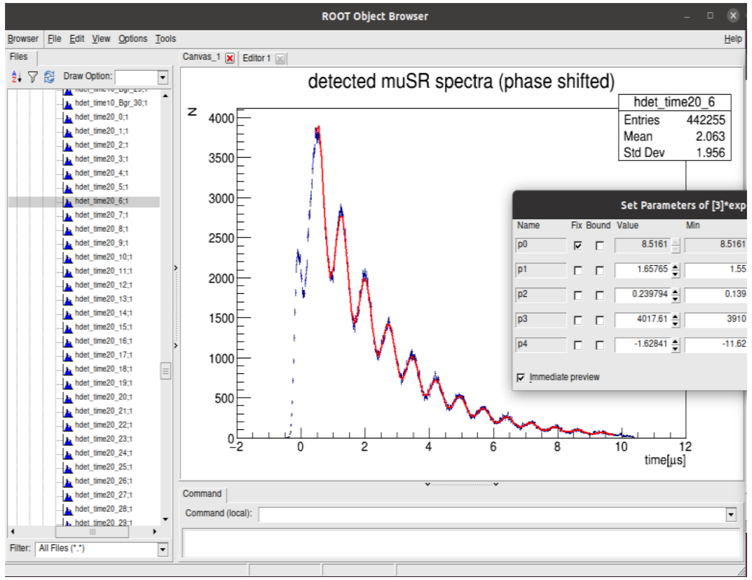
- Two detector rings, degraders, a cryostat, and a beam pipe.



谱仪的CAD设计

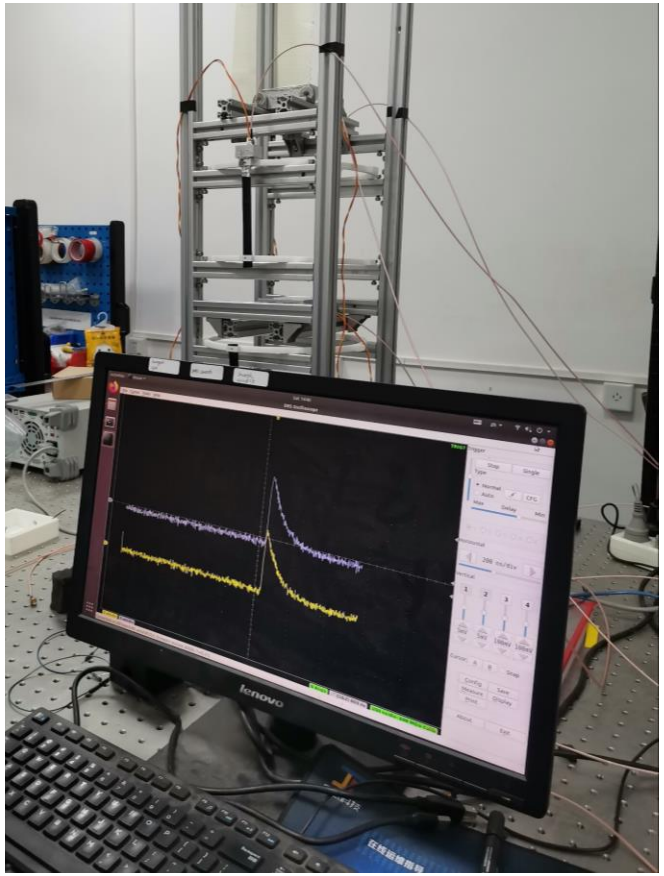


谱仪MC模拟和仿真



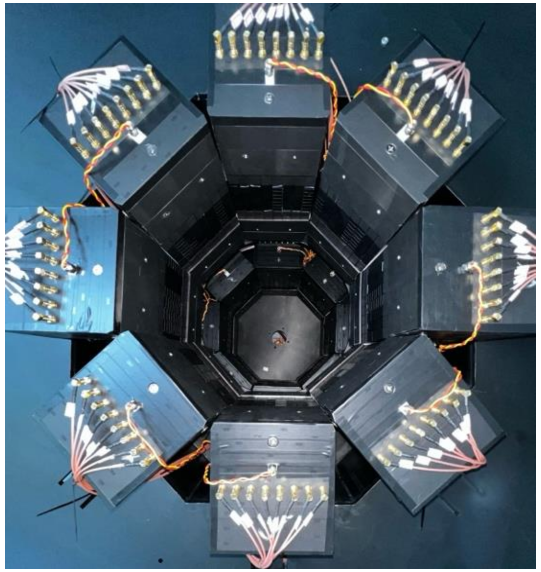
模拟数据分析和拟合

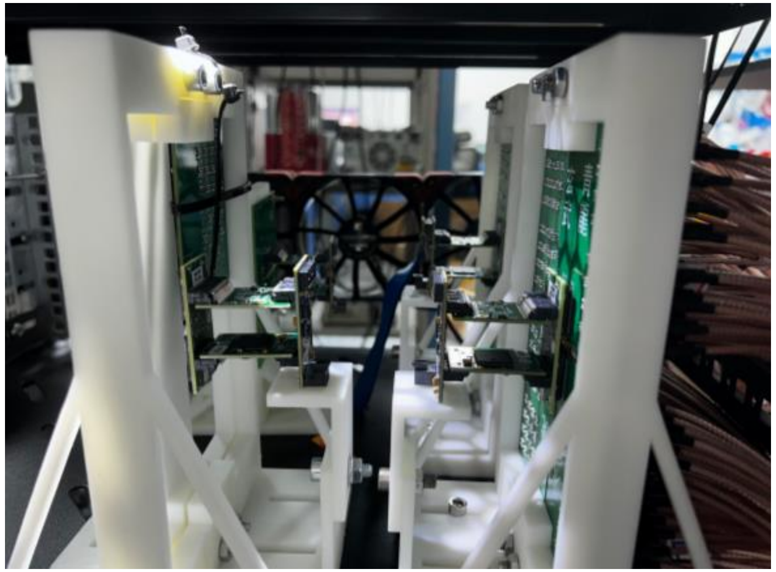
Credits： 周逸行

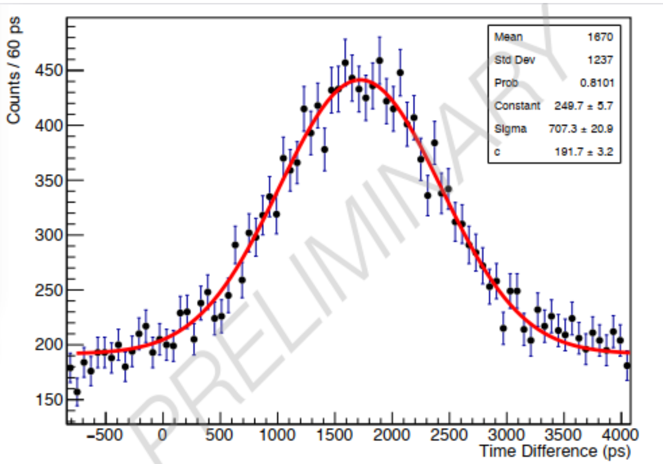


谱仪prototype的测试

μSR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！

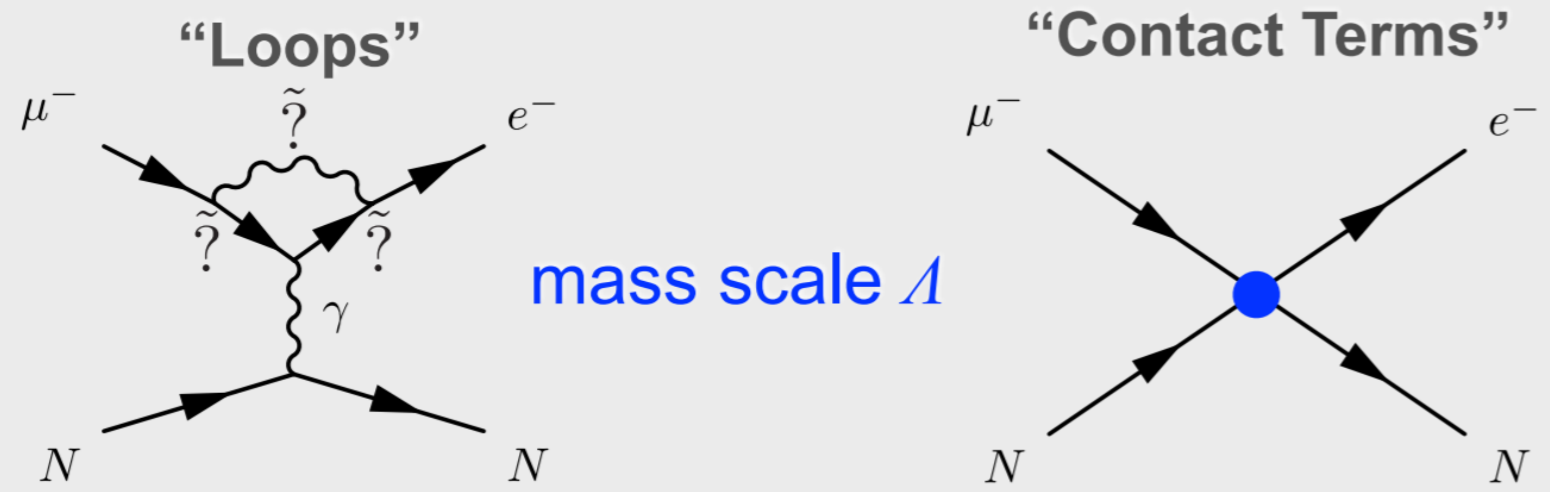
谢谢！

- *感谢USTC封常青老师课题组助力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为我们制备气凝胶二氧化硅样品。*
- *感谢国家自然科学基金12075326 、广东省自然科学基金等项目给与经费支持。*
- *感谢中大物理学院提供有效支持，感谢给力的本科生们！*

Toy Lagrangian

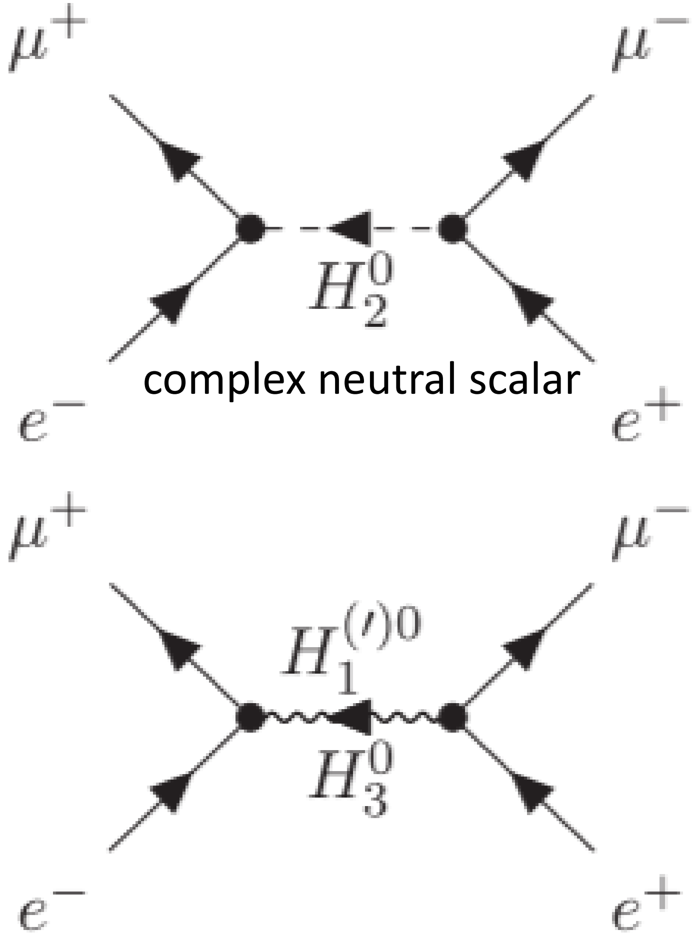
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_{d>4} \sum_{n} \frac{c_n^{(d)}}{\Lambda^{d-4}} \mathcal{O}_n^{(d)}$$

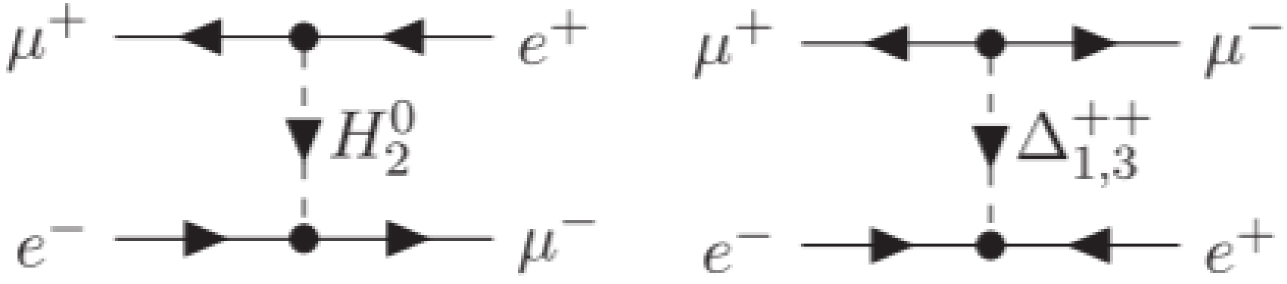
$$\mathscr{L}_{\mathrm{CLFV}} = \frac{m_\mu}{\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} \quad + \quad \frac{1}{\Lambda^2} \bar{\mu}_L \gamma^\mu e_L (\bar{u}_L \gamma_\mu u_L + \bar{d}_L \gamma_\mu d_L)$$



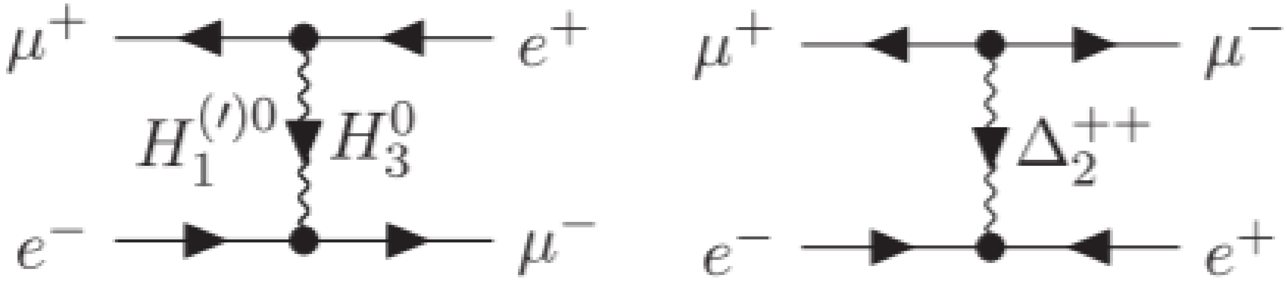
REF: By A. DeGouvea and P. Vogel, arXiv:1303.4097. EFT treatment by S. Davidson and B. Echenard. arXiv: 2010.00317

Muonium to antimuonium conversion





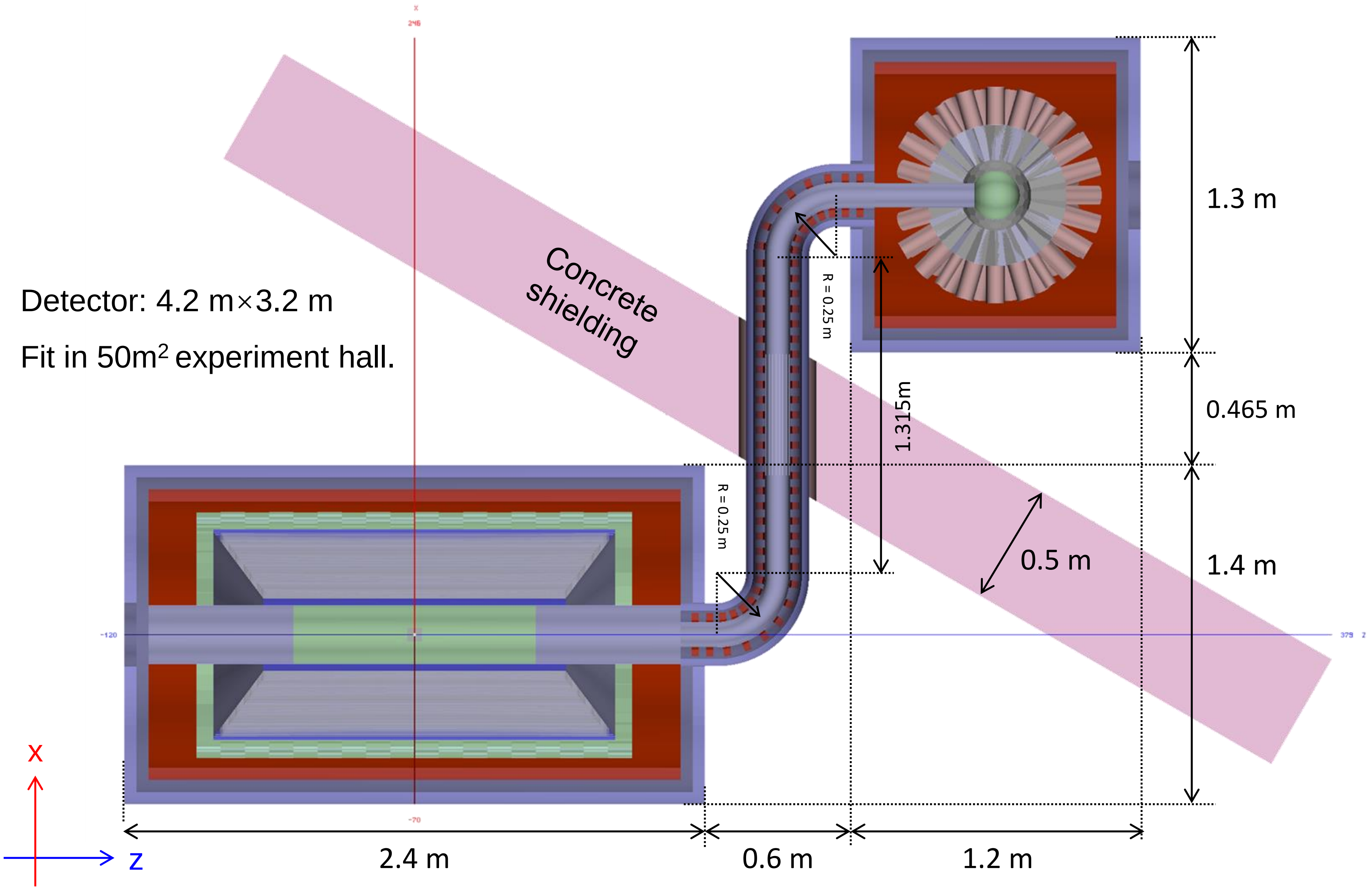
REF: Tong Li, Michael A. Schmidt. Phys.Rev.D 100 (2019) 11, 115007



tangjian5@mail.sysu.edu.cn

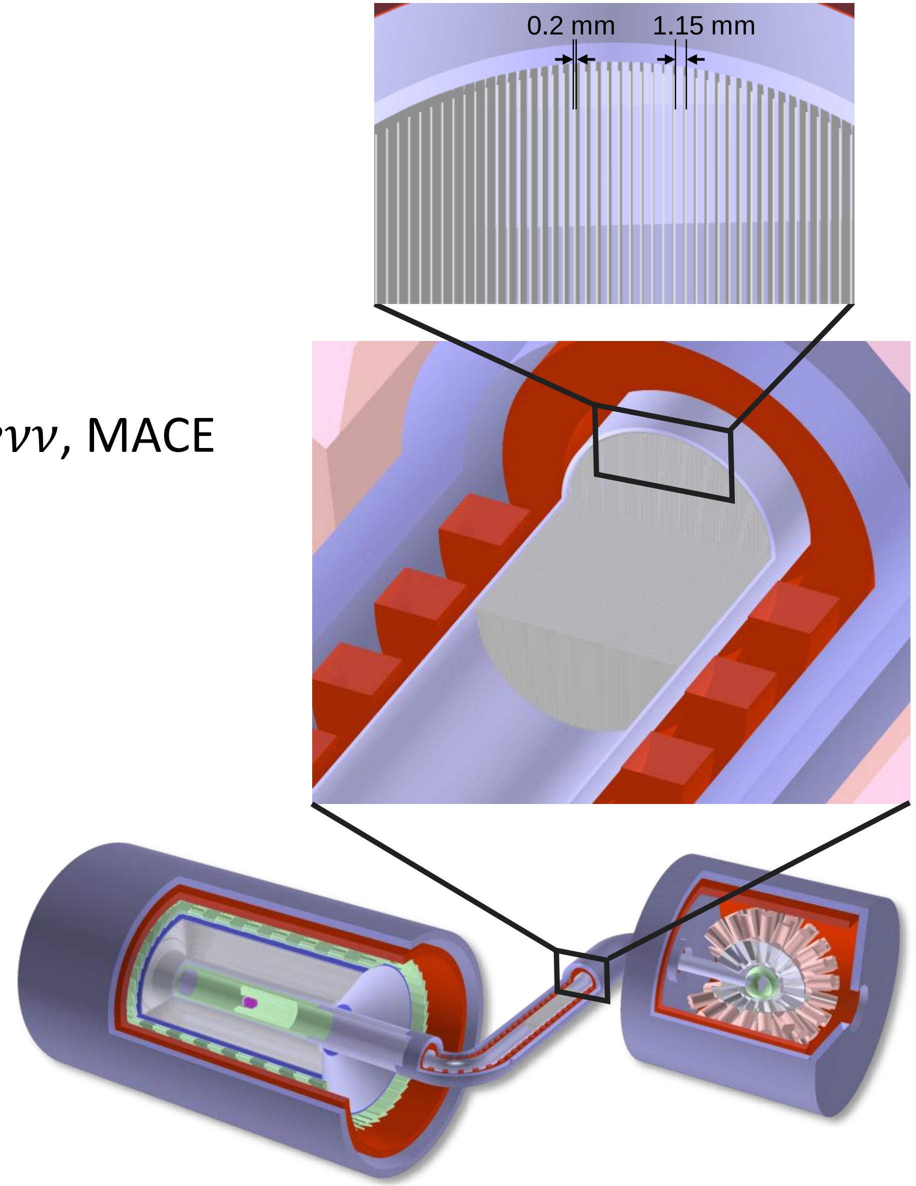
MACE dimensions

- Detector: 4.2 m×3.2 m
- Fit in 50m² experiment hall.



Collimator design

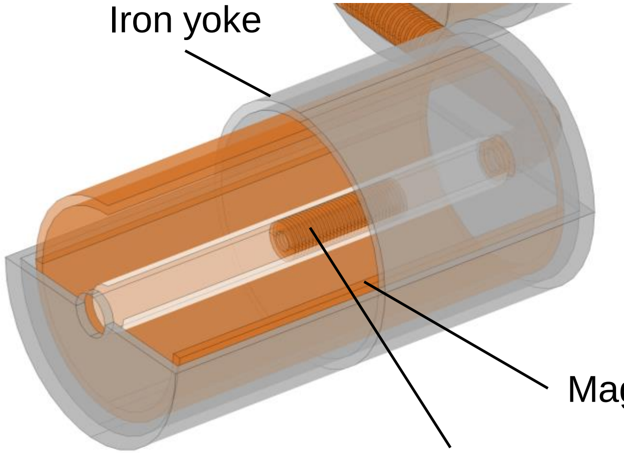
- Collimator selects p_{xy} of transported particles.
  - ➢ Narrowly spaced copper sheets, parallel to z-axis.
  - ➢ Sheet thickness: 0.2 mm, optimize pitch accordingly.
- Background level is simulated by McMule LO $\mu \to eee\nu\nu$, MACE detector & simple signal region cut applied.
- Optimize pitch by maximize $\varepsilon_s/(b+1.5)$.
- Optimization result:
  - ✓ Optimal pitch: 1.15 mm $\rightarrow$ $p_{\mathrm{xy}}^{\max} = 14\ \mathrm{keV}/c$
  - ✓ Signal e^+ efficiency: 68%
  - ✓ Reject 98% of $\mu \to eee\nu\nu$ background



Electromagnetic field design

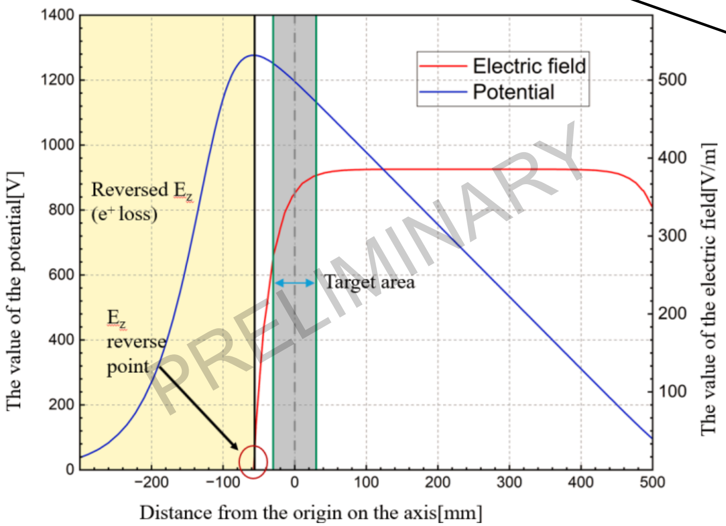
See Guihao Lu (鲁桂昊)'s poster (MIP2024)

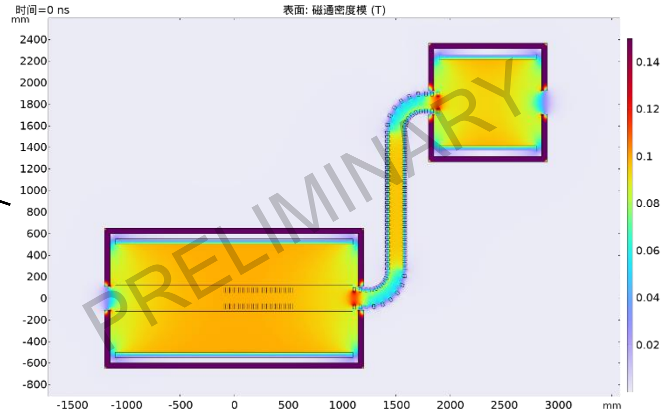
Iron yoke



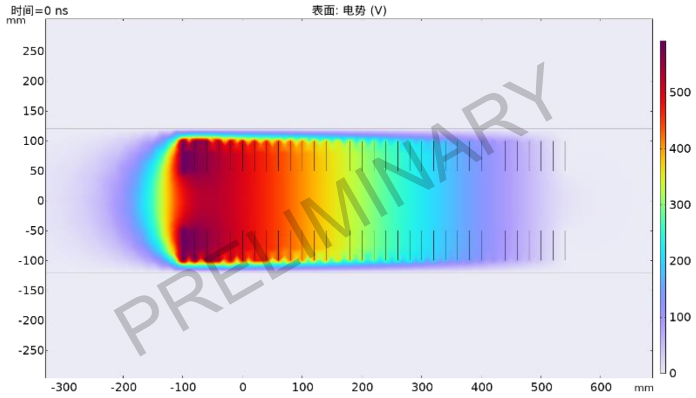
Magnet

Electrostatic accelerator





B=0.1T



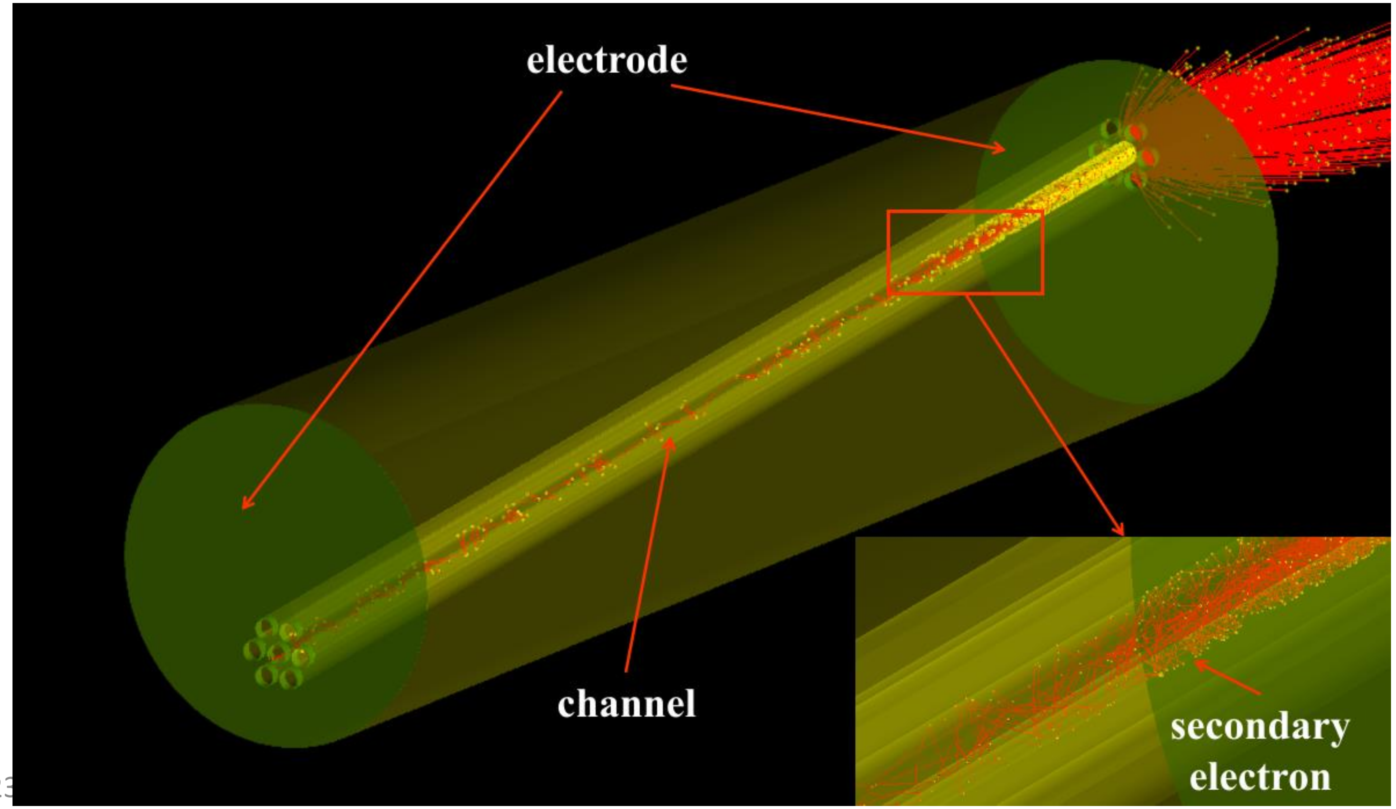
U=500V

MCP响应模拟

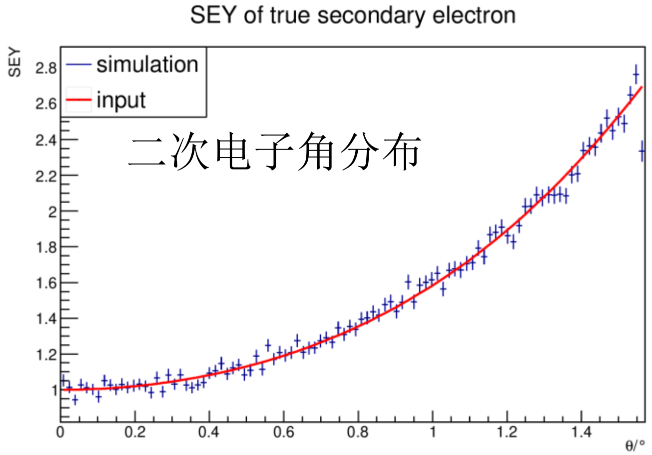
现已开发MCP的模拟程序，可实现MCP中少数通道电子倍增过程的模拟。

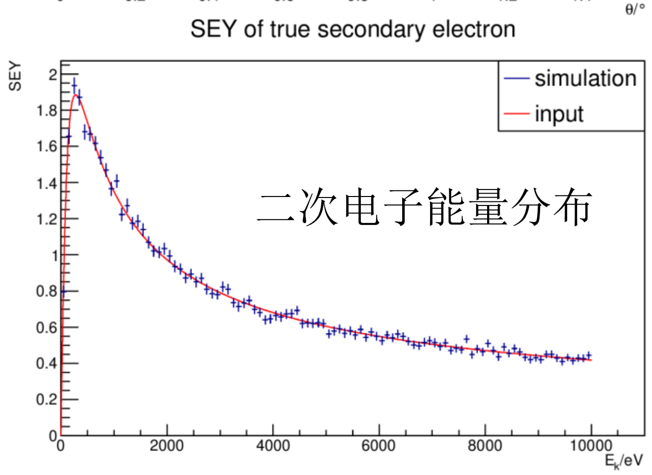
- 二次电子发射模型：Furman模型（二次电子产额与角分布）；
- 模拟MCP的7个通道，得到单电子响应未来将用于MCP的快速模拟；

Credit: IHEP妙晗.



Parameter	Value
Thickness	0.48 mm
Radius of channel	3.0 μm
Angle of inclination	5.5°
Distance between channels	8.0 μm
Thickness of electrode	0.2 μm
Length of electrode in channels	3.0 μm
High voltage	800 V

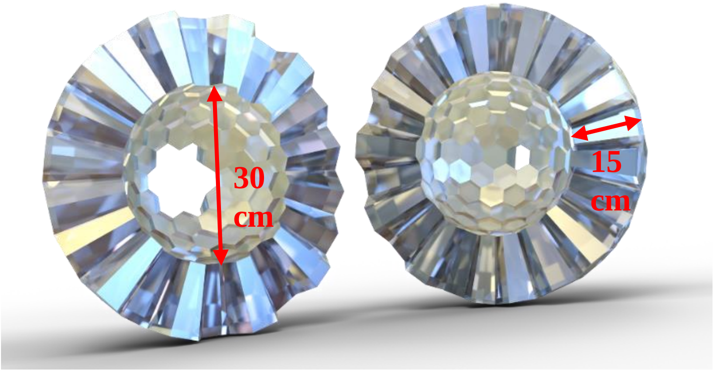


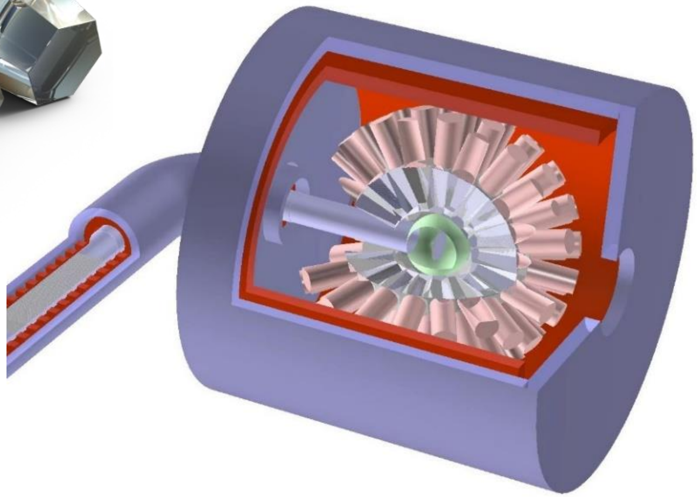


Design of calorimeter

- Specification:
  - Excellent energy resolution for background discrimination
  - High signal efficiency
- Geometry:
  - Class I *GP*(4,0) Goldberg polyhedron
  - 154 inorganic scintillators with PMTs (preliminarily CsI:Tl)
  - 97.5% solid angle coverage
  - Inner diameter: 30 cm
  - Crystal length: 15 cm
- Advantages:
  - Large solid angle coverage
  - Symmetry for precise reconstruction
  - Self-supporting structure

See Siyuan Chen (陈思远)'s poster (MIP2024)



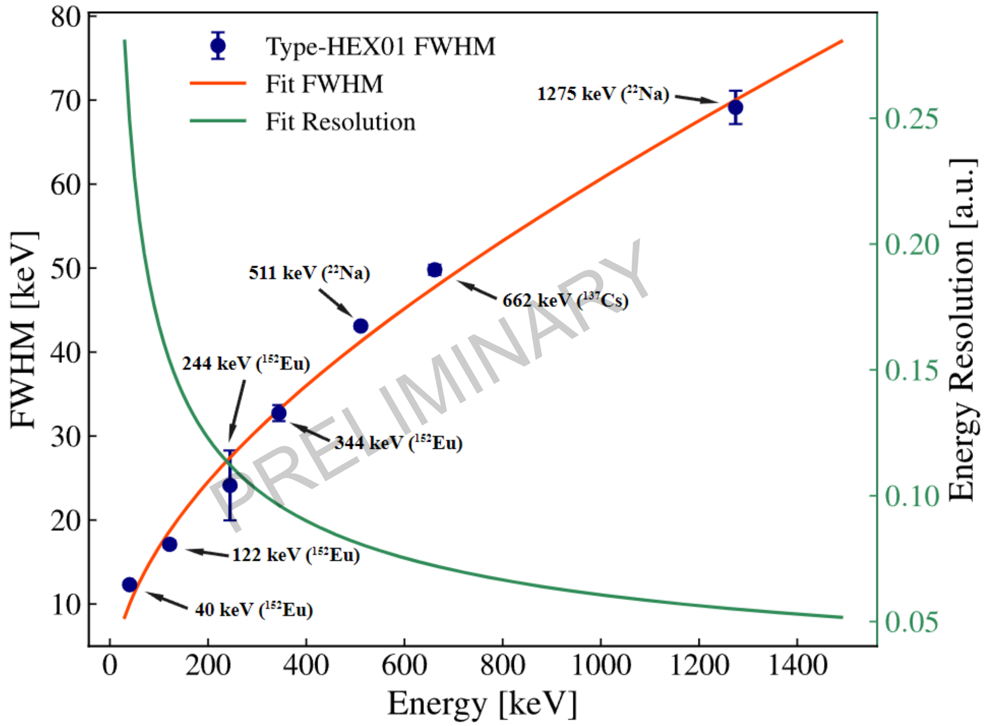


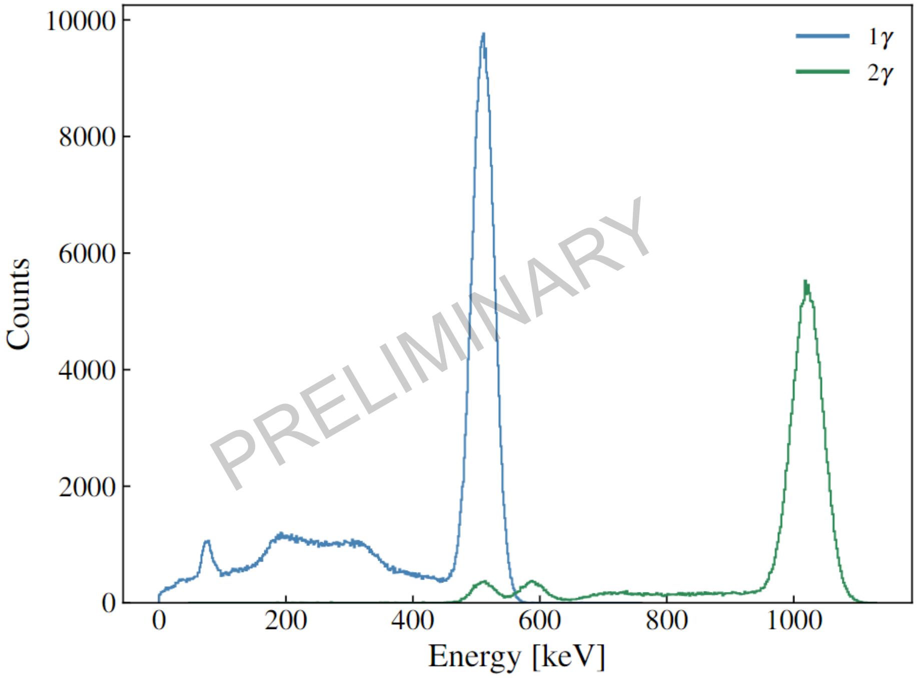
Design of calorimeter

- Signal and Background

See Siyuan Chen (陈思远)'s poster (MIP2024)

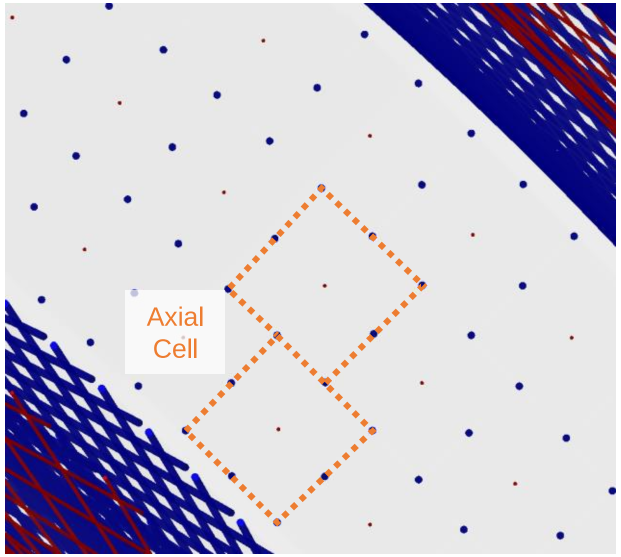
  - Energy resolution: 8.4% at 0.511 MeV, 6% at 1.022 MeV
  - 68.1% signal efficiency (3σ region)

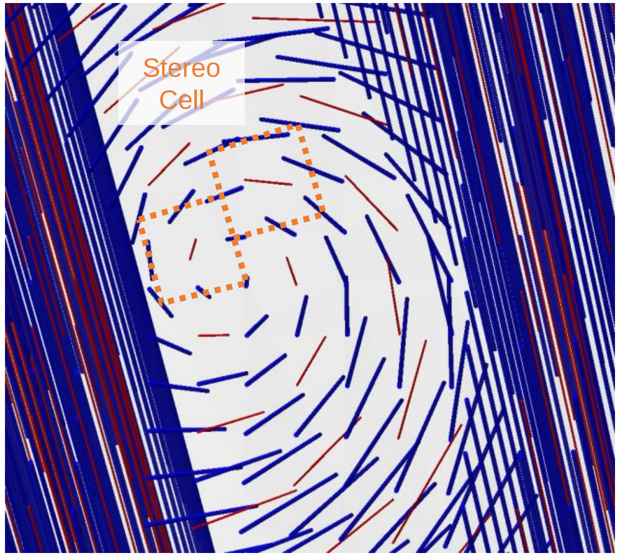




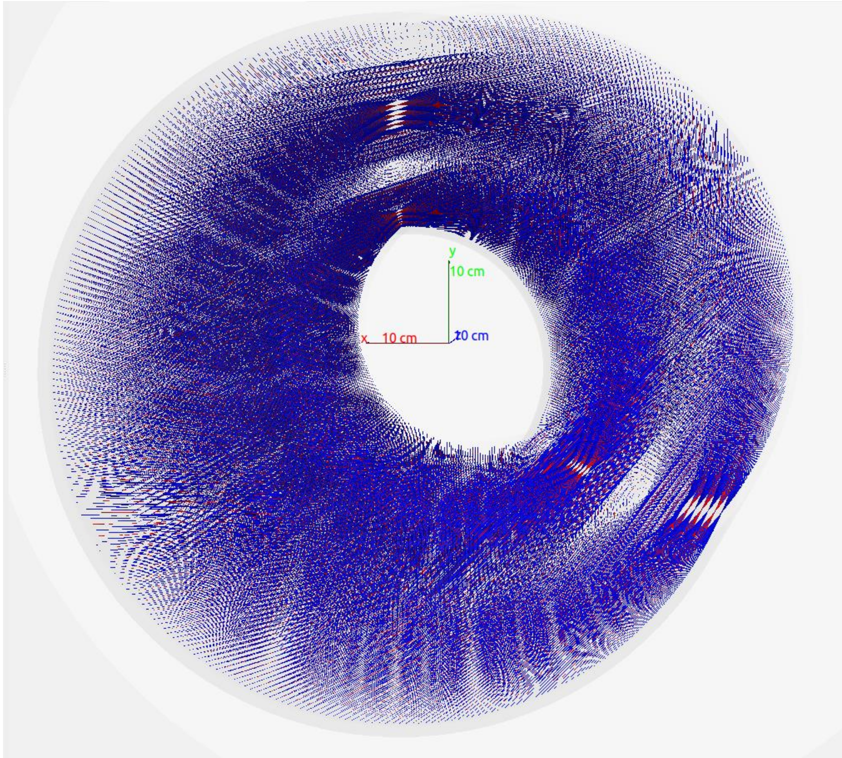
Design of cylindrical drift chamber

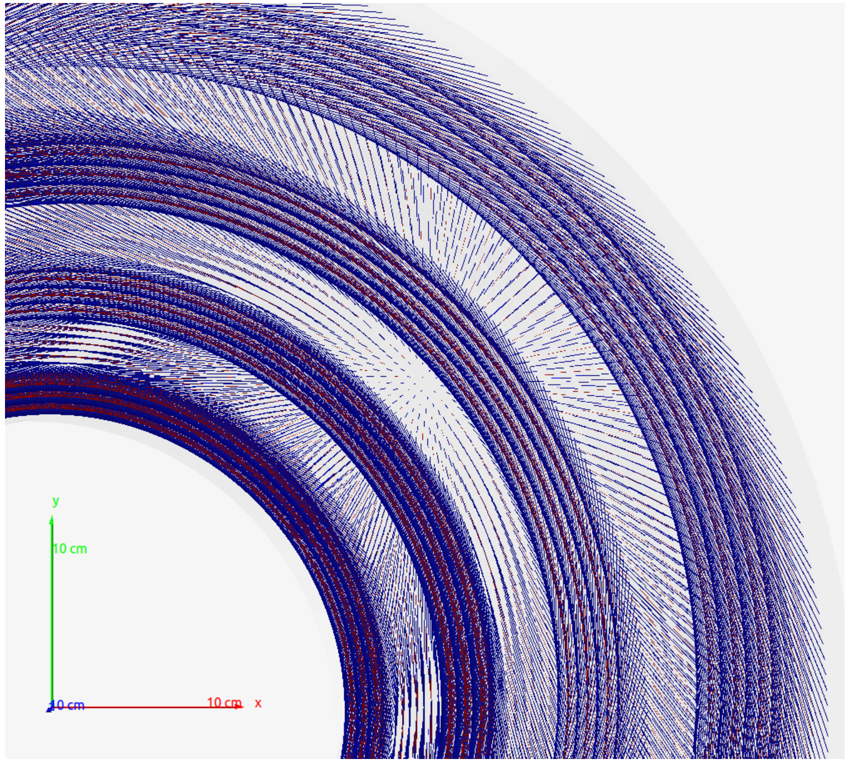
- Design goal:
  - ✓ Large acceptance
  - ✓ High rate capability
  - ✓ Excellent vertex resolution (O(1) mm)
  - ✓ Good momentum resolution (O(1) MeV in 0.1 T field)
- Specifications:
  - ✓ Near-square drift cell, minimum deformation
  - ✓ Alternated axial / stereo layer
- Preliminary design:
  - ➢ 7 (super) × 3 (sense) = 21 layers
  - ➢ 12 stereo layers, 9 axial layers
  - ➢ Cell width: 8 mm ~ 12 mm
  - ➢ Length: 1.2 m (inner) / 1.6 m (outer)
  - ➢ Radius: 150 mm (inner) / 417 mm (outer)
  - ➢ Acceptance: 89% ~ 97%
  - ➢ Stereo layer angle: 6 deg at minimum
  - ➢ Gas: He:C_4H_{10} = 85:15





Design of cylindrical drift chamber

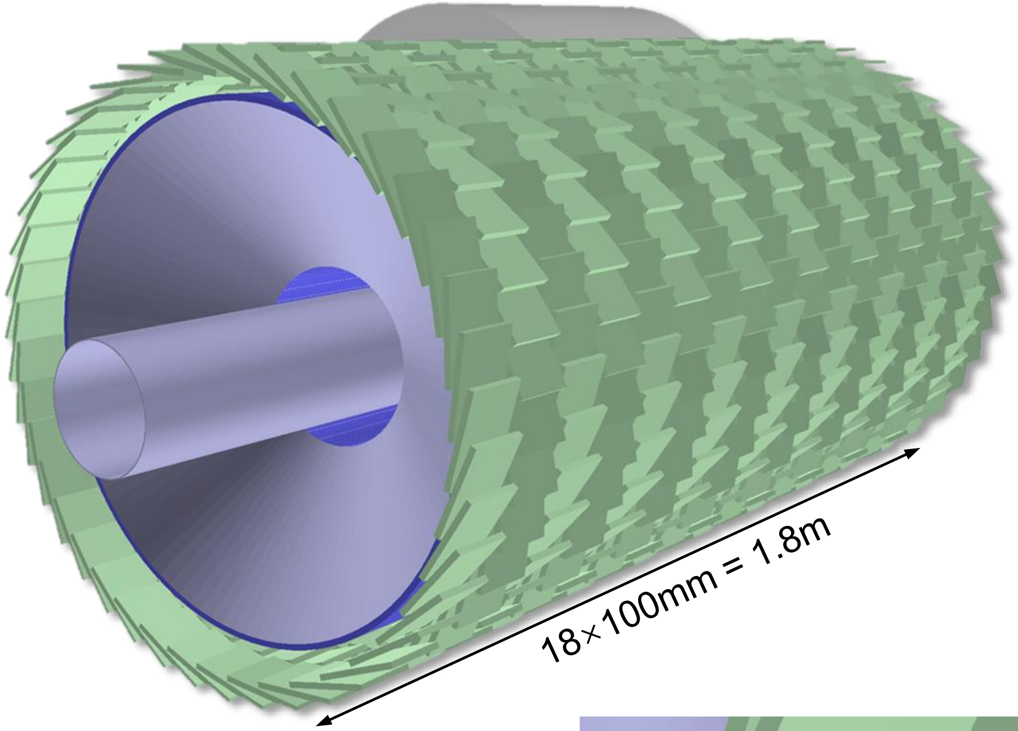


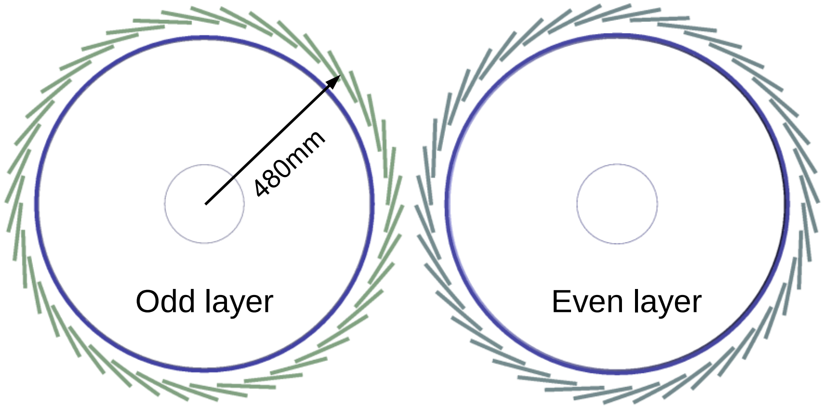


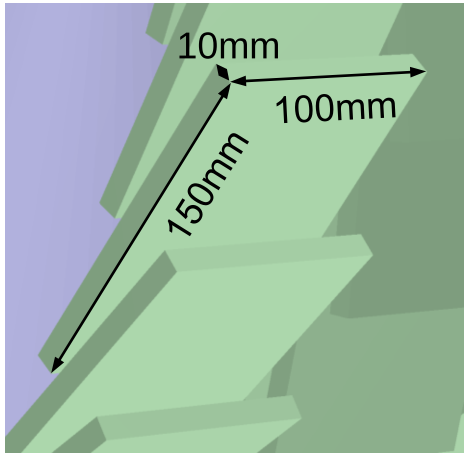
- We have developed an parameterized drift chamber geometry, allowing us to continue to optimize the geometry design of drift chamber.
- Figure: generated drift chamber preliminary design. Wires are scaled to be clearly visible (blue: field wire, red: sense wire).

Timing counter design

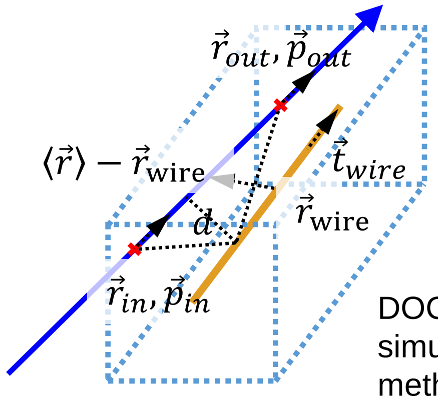
- Design goal:
  - ✓High rate capability
  - ✓Excellent time resolution (<100 ps)
  - ✓Good spatial resolution (10 cm)
- Specifications:
  - ✓Two tile coincidence
  - ✓Overall efficiency same for e^+ / e^-
- Preliminary design:
  - ➢Plastic scintillator array
  - ➢18 (φ) × 42 (z) = 756 tiles
  - ➢Center radius: 480 mm
  - ➢Slant angle: ±15 deg



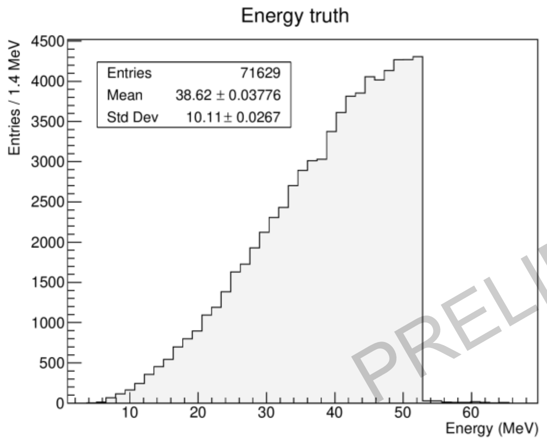


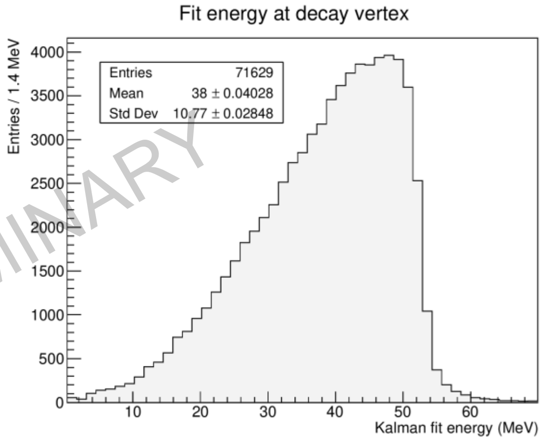


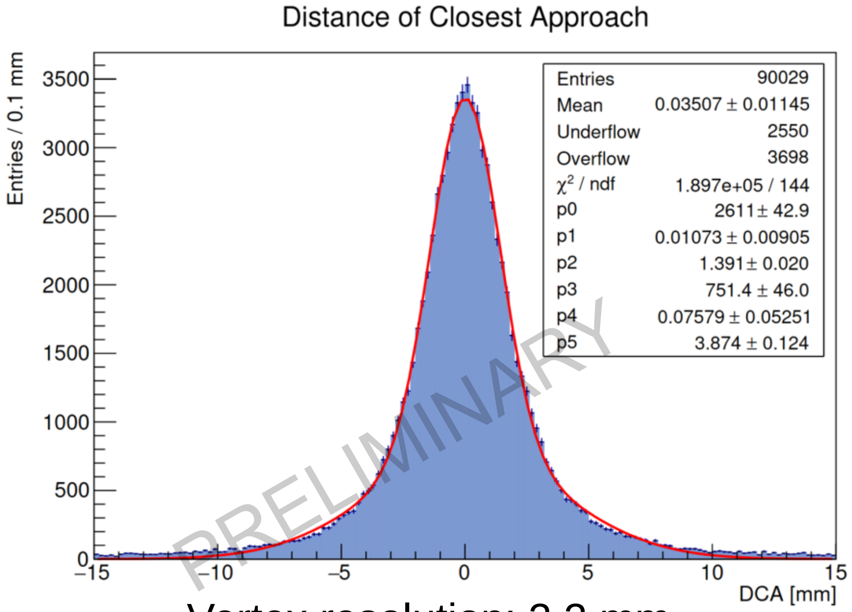
Simulation of magnetic spectrometer



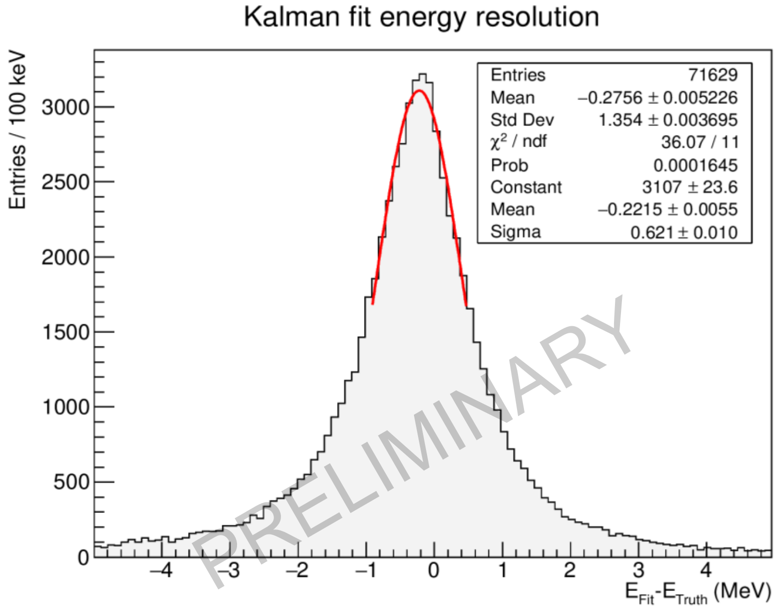
DOCA simulation method







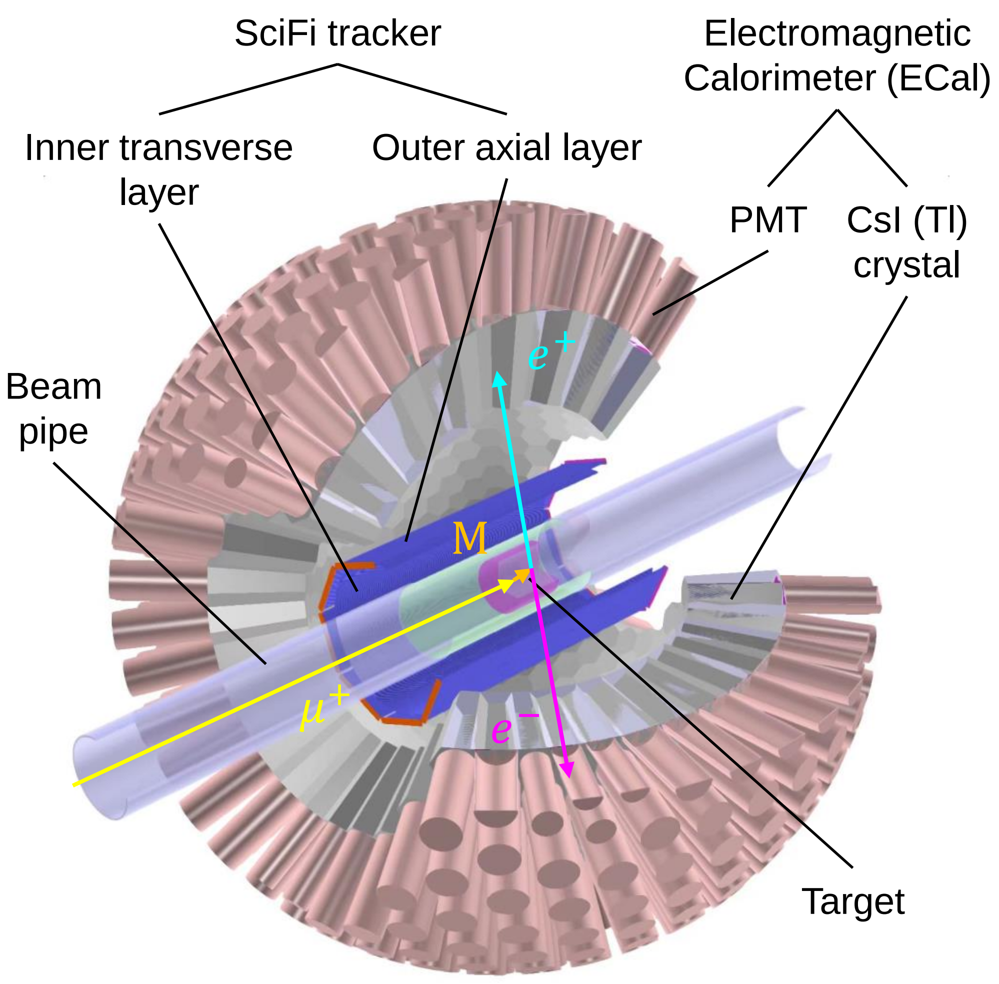
Vertex resolution: 2.2 mm
(double gaussian fit std. dev.)



Momentum (energy) resolution: ~1.5 MeV (FWHM)

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→ee) with $O(10^{-11})$ sensitivity.
- Operates at $10^6 \sim 10^7$ μ^+/s surface muon beam.
- Challeges: (i) event pile up and (ii) efficiency loss due to different ECal energy range between Phase-I and Phase-II.



Detection scheme:

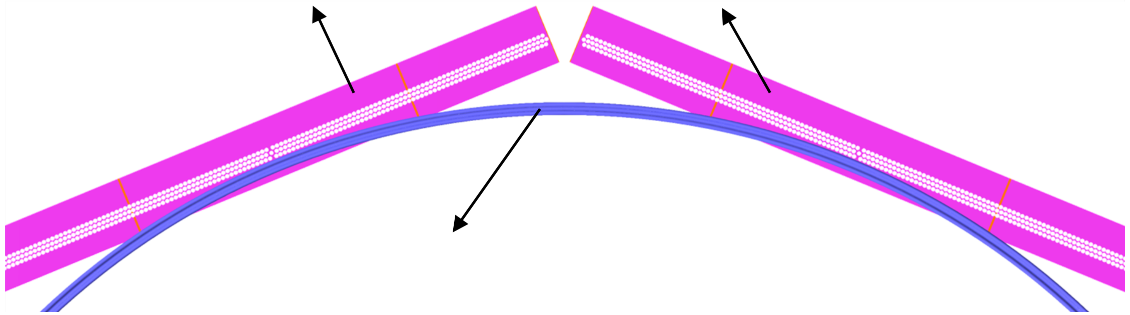
I. Surface muon stop in target → muonium

II. Muonium rare decay: $\mathrm{M} \to e^+e^-$

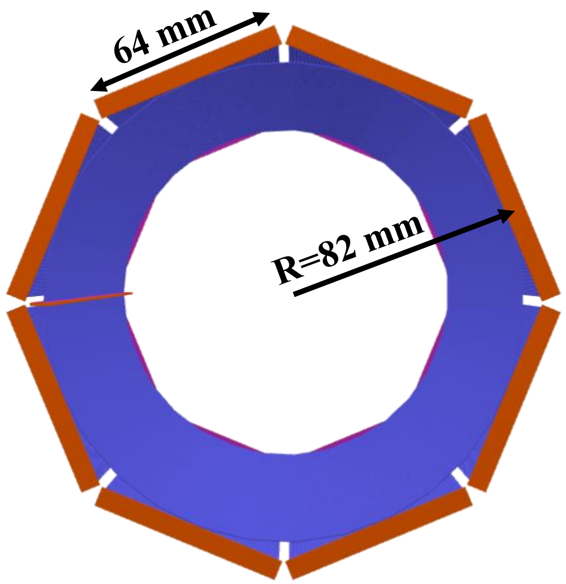
III. SciFi Tracker detects back-to-back e^+e^- pair coincidence with ECal.

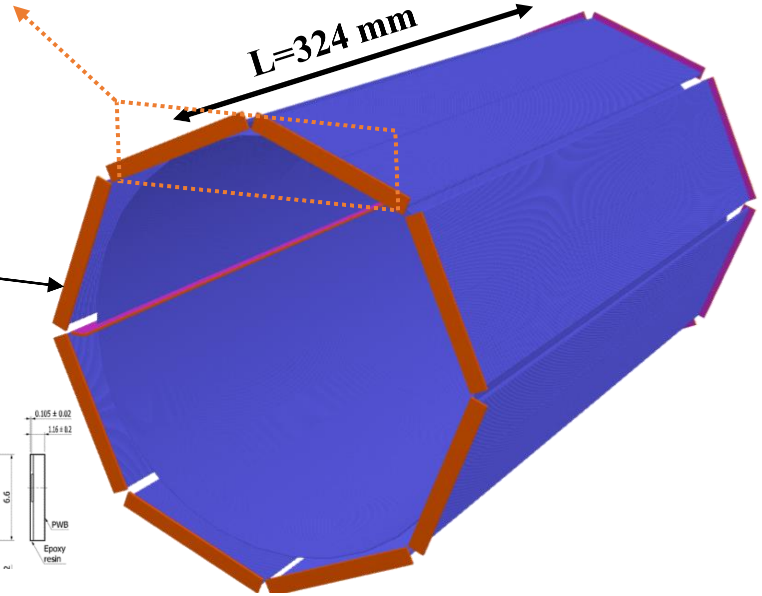
Phase-I SciFi Tracker

- Conceptual design:
  - Dual layer geometry:
    - Axial layer: 1536 axial fibres arrange in 8 modules with 3 sublayers each.

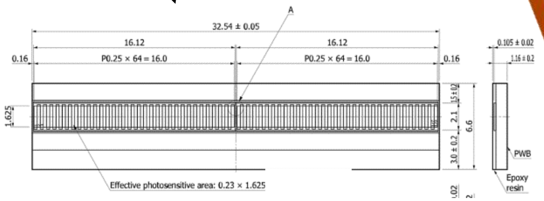


    - Transverse layer: 320 fibres arrange in 3 cylindrical sublayers, layer radius 82 mm.
    - 1856 fibres in total.
  - Kuraray multi-cladding fibre, Φ 500 um.
  - Readout: Hamamatsu S13552 MPPC.





- Specifications:
  - Spatial resolution ~250um.
  - Detection efficiency >99%



国家级大学生创新项目

大学生创新训练项目总结报告

正反缪子素转换实验方案的优化

Optimizing Scheme of the Muonium-to-antimuonium Conversion Experiment

专　　业:　物理学
本 科 生:　赵诗涵、王士摄、凌嘉骋、蒋辉
指导教师:　唐健 教授

中山大学物理学院
2022 年 12 月 10 日

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中山大学优秀本科毕业论文

本科生毕业论文（设计）

题目： MACE 实验模拟软件开发和粒子重建研究

姓　名　赵诗涵
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专　业　物理学
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2023 年 5 月 10 日

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