



基于加速器缪子源寻找新物理 ——正反缪子素转换实验研究进展



Jian Tang(唐健)

2022年4月17日

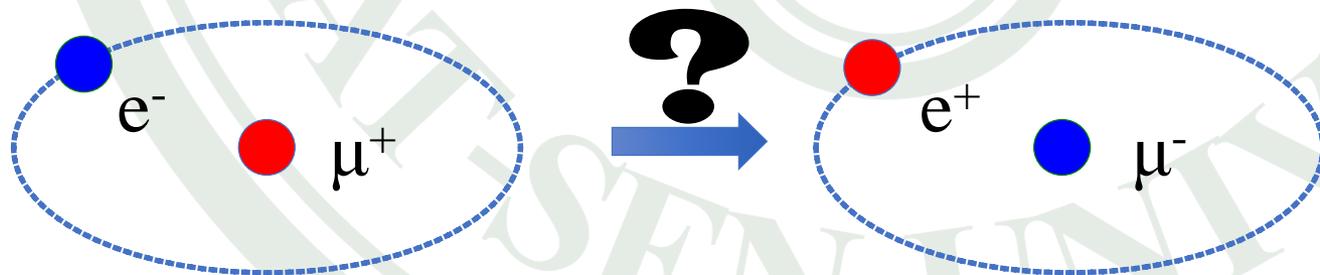
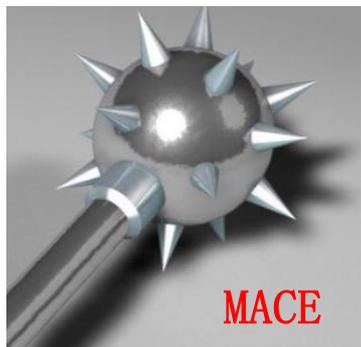
《缪子束加速和对撞技术及其应用》前沿论坛

合作者：中山大学SMOOTH实验室—陈羽、沈韩、黄臻成、徐宇

余涛、杨航、胡碧莹、钟嘉豪、孙铭辰、赵诗涵、蒋辉、宁云松、周逸行、白爱毓等

IHEP—唐靖宇、袁野、李海波、张瑶、赵光、nikos、妙晗、鲍煜等日本大阪大学—吴琛

致谢：中科院近物所—何源、贾欢、陈良文等，上海交通大学—许金祥



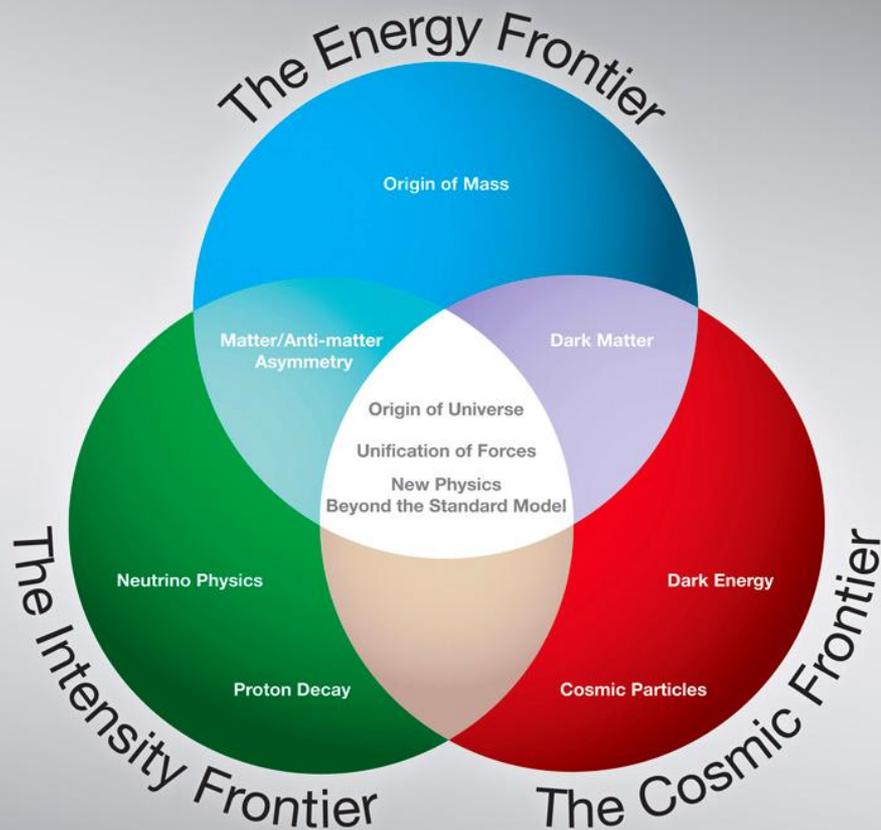
Muonium to Antimuonium Conversion Experiment(MACE)



内容概述

- 研究动机
- MACE关键技术路线
- 缪子素产生靶模拟与优化
- 磁谱仪基本设计与初步模拟
- MCP响应模拟
- 快速MC模拟结果
- 离线软件框架
- 总结

- 研究动机
- MACE基本设计方案与关键技术问题
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- 高能量前沿
- 高亮度前沿/高精度前沿
- 宇宙学前沿

寻找超越标准模型的新物理:

- 中微子质量起源问题
- 是否存在带电轻子味道破坏过程?
- 宇宙正反物质不对称性问题?
- 什么是暗物质?
-

• 中微子实验

- T2K, NOvA, T2HK, DUNE...
- JUNO...

• 带电轻子味道破坏实验cLFV:

- Mu2e(美国) $\mu^- + Al \rightarrow e^- + Al$
- **COMET(日本)** $\mu^+ \rightarrow e^+ \gamma$
- MEG(瑞士)
- Mu3e(瑞士) $\mu^+ \rightarrow e^+ e^- e^+$

• μ 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}

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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)

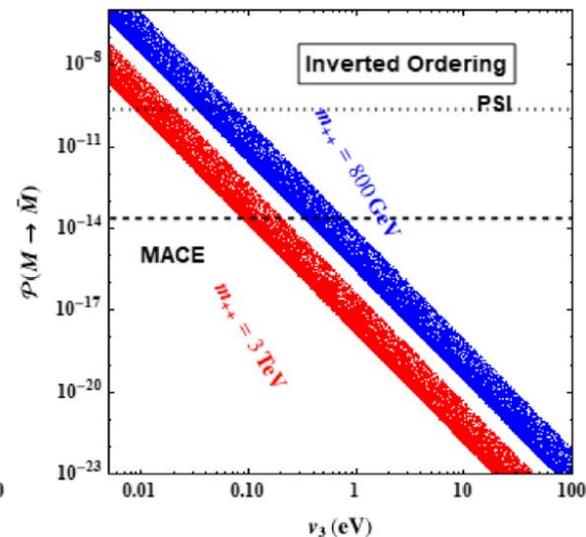
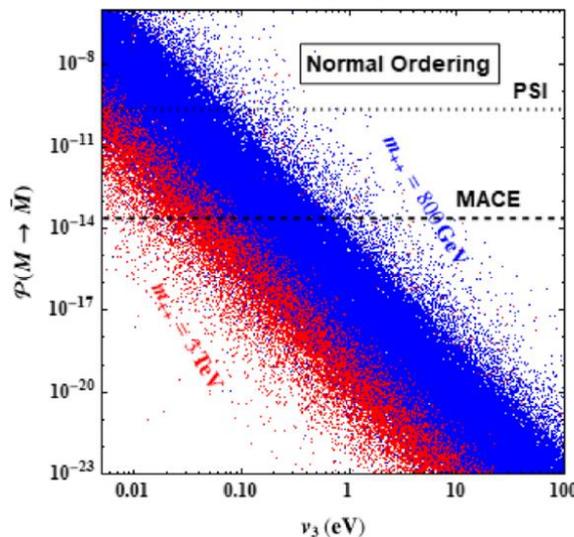
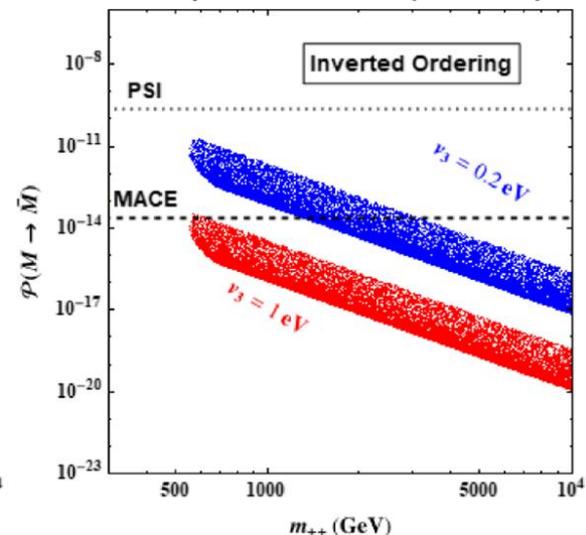
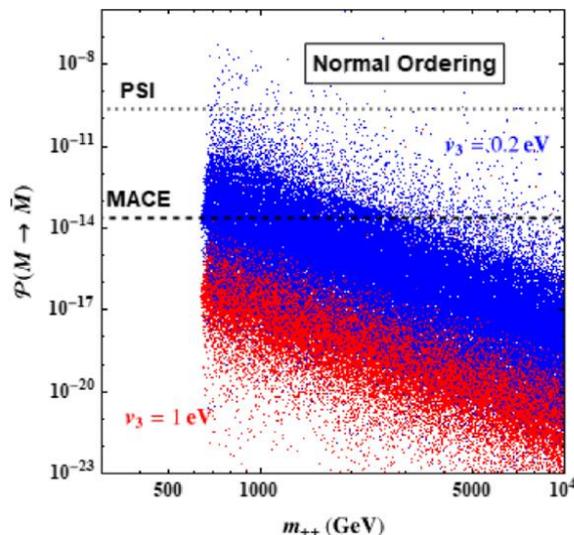
利用MACE鉴别中微子质量模型

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

$$B(\mu^+ \rightarrow e^+ e^- e^+) \leq 1.0 \times 10^{-12}$$

$$B(\mu \rightarrow e \gamma) < 4.2 \times 10^{-13}$$

- Type-II Seesaw模型
- Type-I+Type-II hybrid seesaw模型
- 已经考虑上述两个过程当前的限制
- MACE实验可以很好的限制TeV质量doubly charged Higgs粒子



Collaborators: 韩成成, 黄达, 张宇

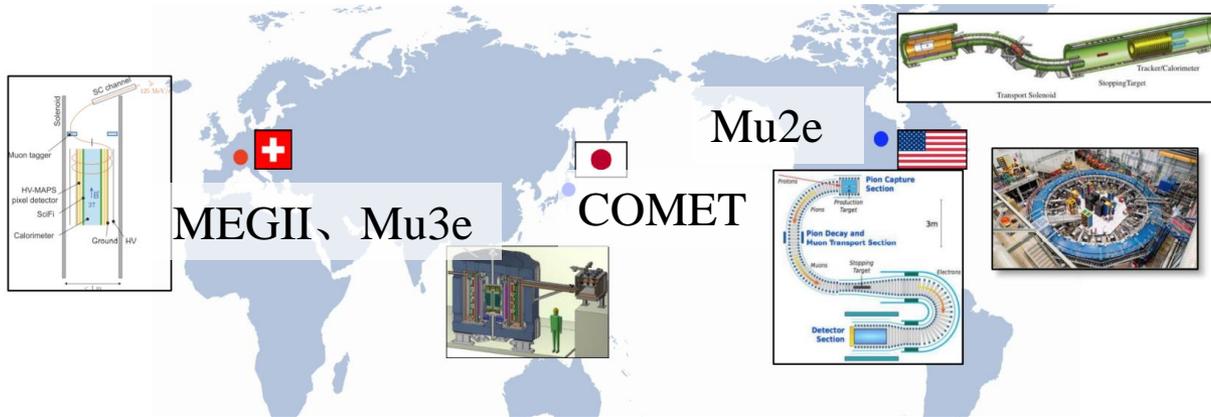
高亮度前沿/高精度前沿—cLFV实验



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)	$\mu^+ \rightarrow e^+ e^- e^+$	正在采集数据

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} 后的十几年, 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。



实验	机构	工作进展
MACS (1999年)	PSI (瑞士)	已完成采数
MACE	加速器缪源 (中国)	概念设计阶段
缪子素转换实验	J-PARC (日本)	概念设计阶段



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.

- 欢迎更多同行共同推进MACE实验
- 尤其欢迎有加速器缪子束线研发经验的同行加入



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

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)

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

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Snowmass process and contributed papers
 Frontier for Rare Processes and Precision Measurements

Alexey A. Petrov
 Wayne State University

- 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

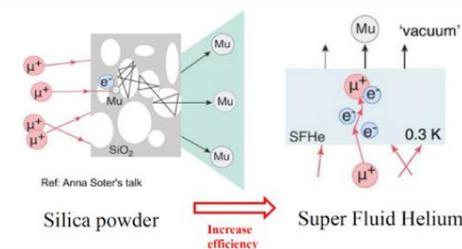
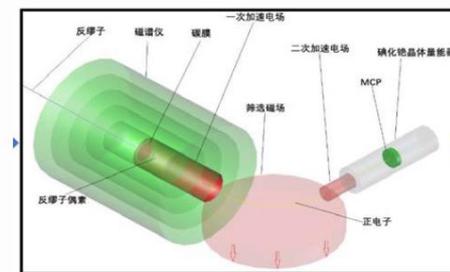


	Proton driver [MW]	Surface muons			Decay muons		
		Intensity [1E6/s]	Polarization [%]	Spread [%]	energy [MeV/c]	Intensity [1E6/s]	Spread [%]
PSI	1.3	420	90	10	85-125	240	3
ISIS	0.16	1.5	95	<15	20-120	0.4	10
RIKEN/RAL	0.16	0.8	95	<15	65-120	1	10
JPARC	1	100	95	15	33-250	10	15
TRIUMF	0.075	1.4	90	7	20-100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

Jian Tang
(Snowmass 2021 RPP meeting)

MACE concept



On-going physics studies and detector R&D

东莞已建成中国散裂中子源



惠州在建中国HIAF和CiADS

两装置总部区

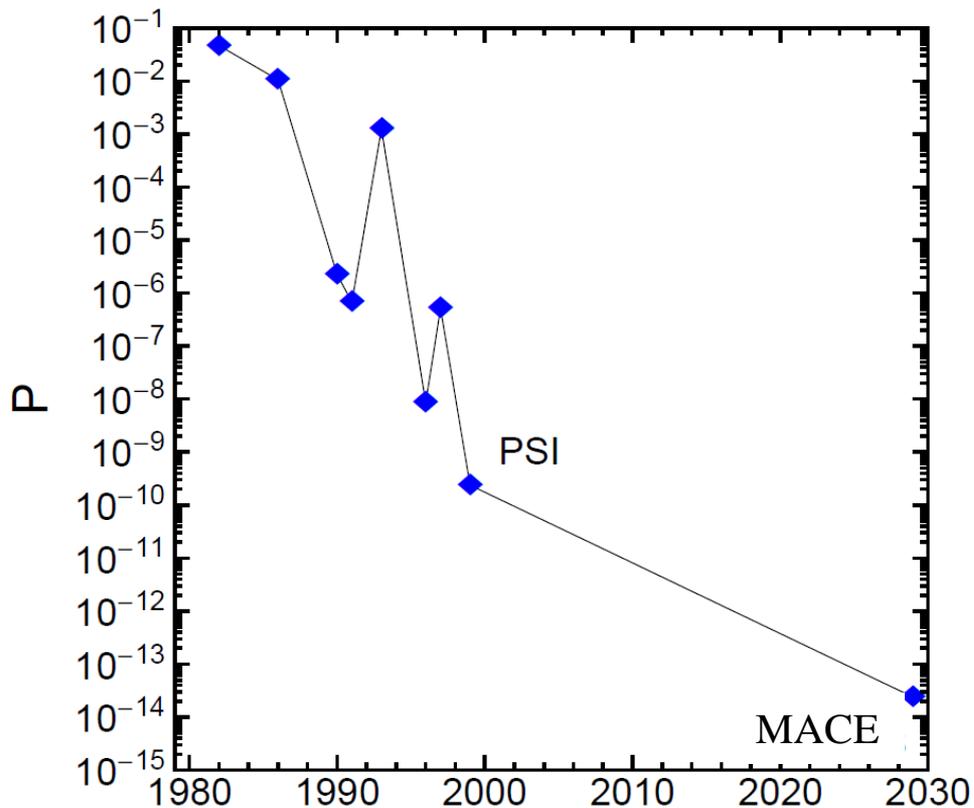


Ref: 中科院高能所, 王生研究员

Ref: 中科院近物所, 东江实验室詹文龙院士

- (1) 加速器缪子源, 国际上已有美国FNAL, 瑞士PSI, 日本J-PARC, 加拿大TRIUMF
- (2) 我们即将建设国内首个强流加速器缪子源?
- (3) 依托粤港澳大湾区的强流加速器 (CSNS, CiADS, HIAF), 基于加速器缪子源开展前沿研究?

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 $8 \times 10^6 \mu^+ / s$ 。
- 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.



内容概述

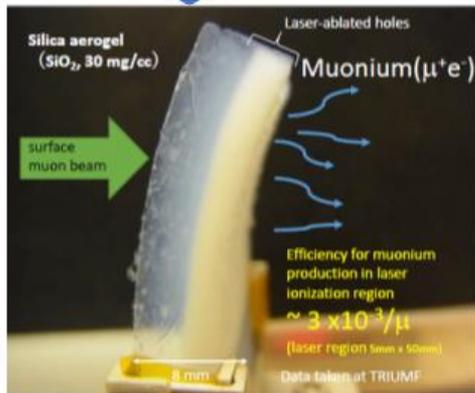
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MACE实验关键技术路线

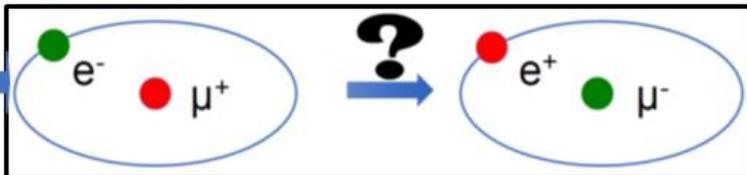


Muonium to Antimuonium Conversion Experiment(MACE)

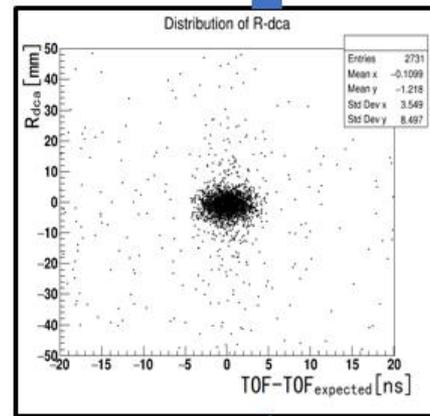
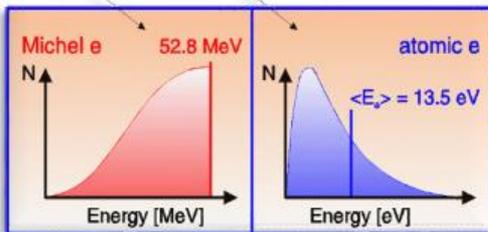
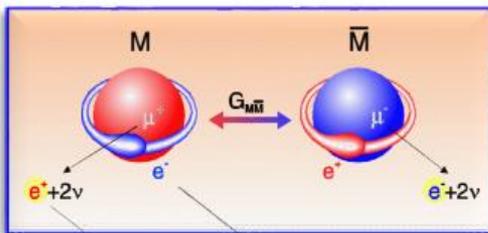
提高缪子素产生效率?



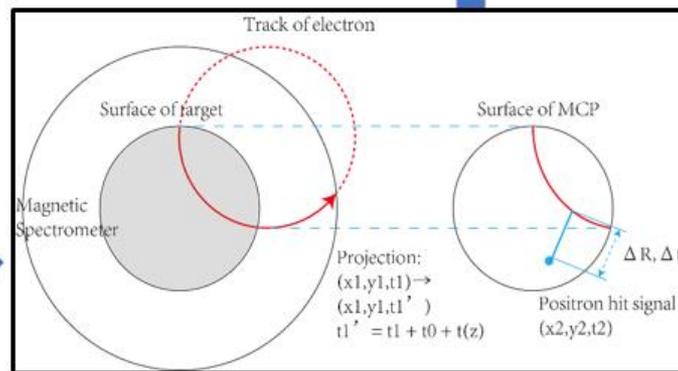
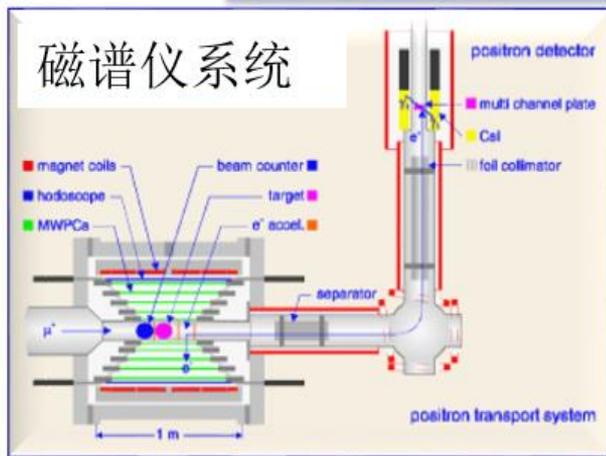
Ikule et al., PTEP 103C0 (2013), G. Beer et al., PTEP 091C01 (2014)



提高信噪比?



高分辨率磁谱仪?



多重符合探测技术?



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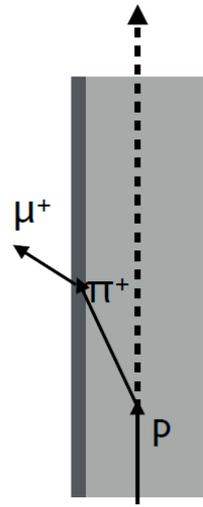
缪子的产生和缪子素的产生

relative μ^+ yield $\propto \pi^+$ stop density $\cdot \mu^+$ Range \cdot length

$$\propto n \cdot \sigma_{\pi^+} \cdot SP_{\pi^+} \cdot \frac{1}{SP_{\mu^+}} \cdot \frac{\rho_c(6/12)_c}{\rho_x(Z/A)_x}$$

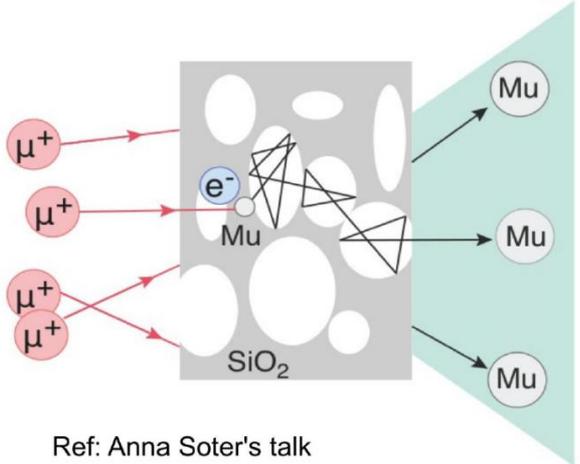
$$\propto Z^{1/3} \cdot Z \cdot \frac{1}{Z} \cdot \frac{1}{Z}$$

$$\propto \frac{1}{Z^{2/3}}$$



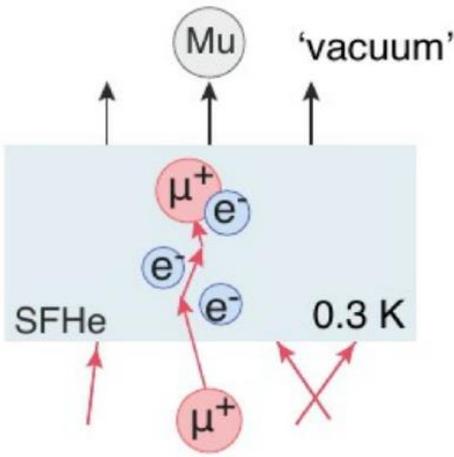
- Previous experience**
- Hot tungsten in 1986: 4% from 4 MeV μ^+
 - SiO₂ powder in 1990: 1%-2% from 4 MeV μ^+
 - SiO₂ film(cold) in 2012: 40% from 5 keV μ^+

Proposed target: aerogel, super fluid helium...

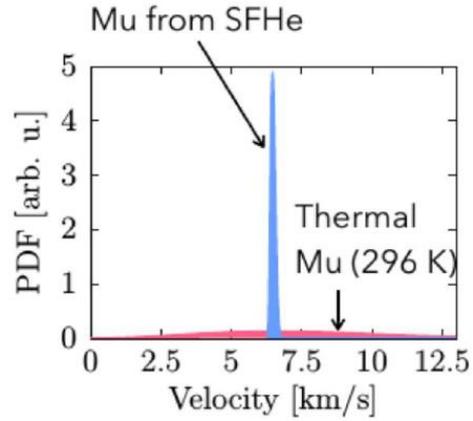


Ref: Anna Soter's talk

Silica powder



Super Fluid Helium



SiO₂气凝胶材料中缪子素的产生和输运



μ^+ 入射 ($\sim 1\text{MeV}$)，散射、减速

电子捕获 ($\sim 1\text{keV}$)

M过热散射 ($\sim 100\text{eV}$)

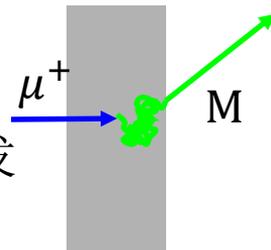
降至室温

随机游走 (室温)

发射到真空



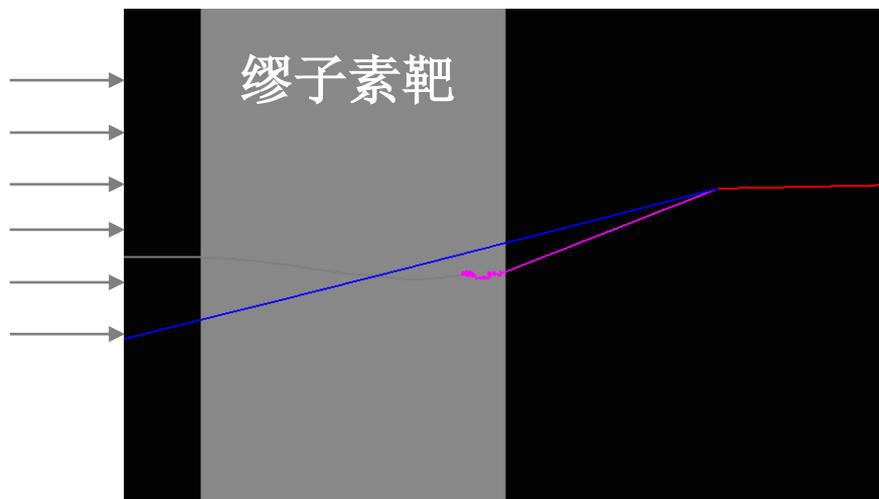
目前已在MACE离线软件框架下开发
缪子素产生靶模拟子程序SimTarget:



- ① 采用Geant4低能电磁过程;
- ② Geant4不提供电子捕获, 自定AtRest过程, 按概率抽样;
- ③ 缪子素与靶达到热平衡, 通过随机游走模型模拟缪子素在气凝胶中的输运。

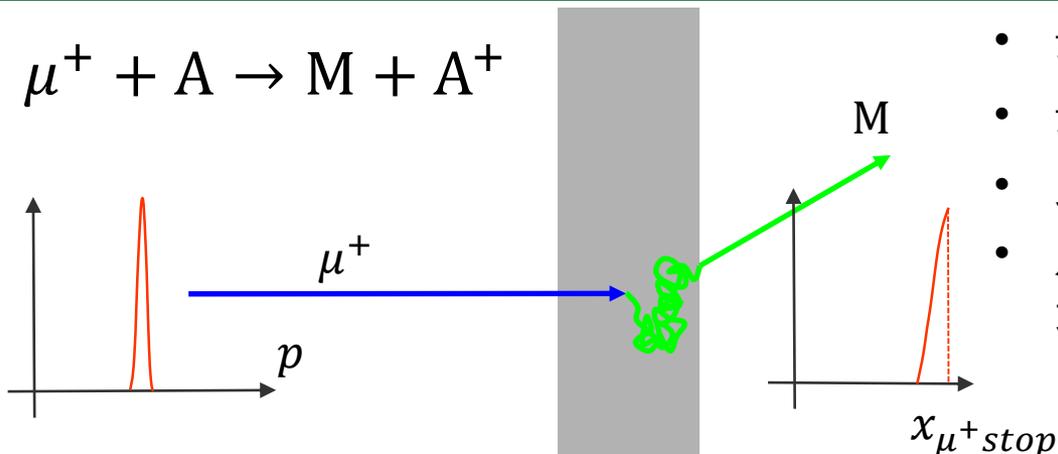


模拟的单个
缪子素产生
并逸出事例:



SiO₂气凝胶样品已经制备, 待束流实验

SiO₂气凝胶靶材缪子素产额优化 - 窄分布



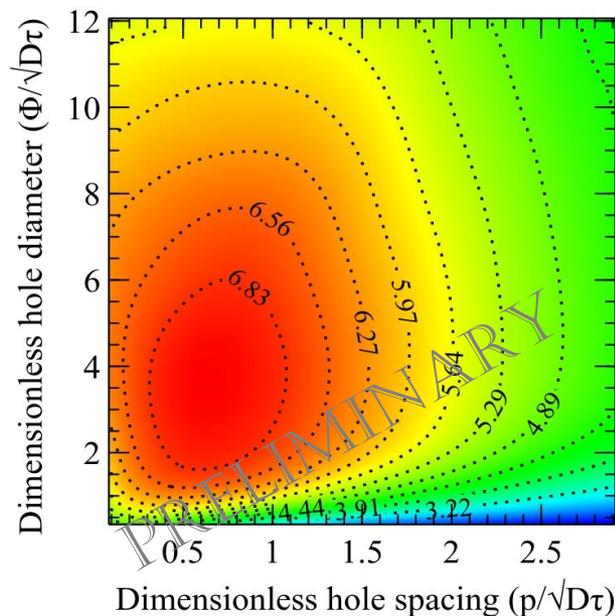
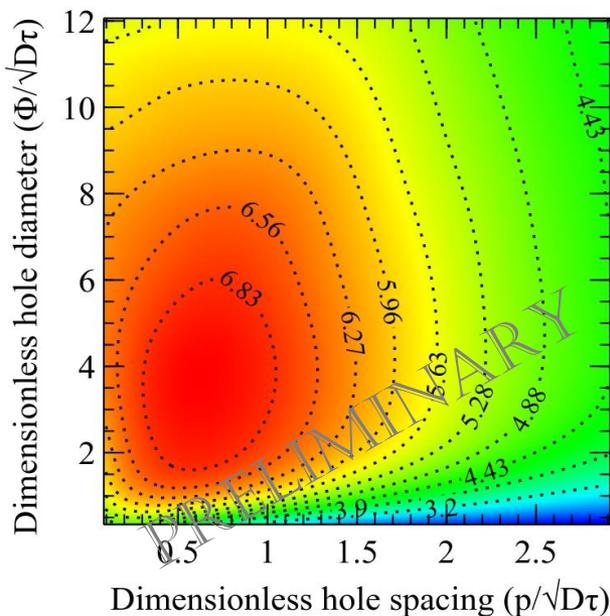
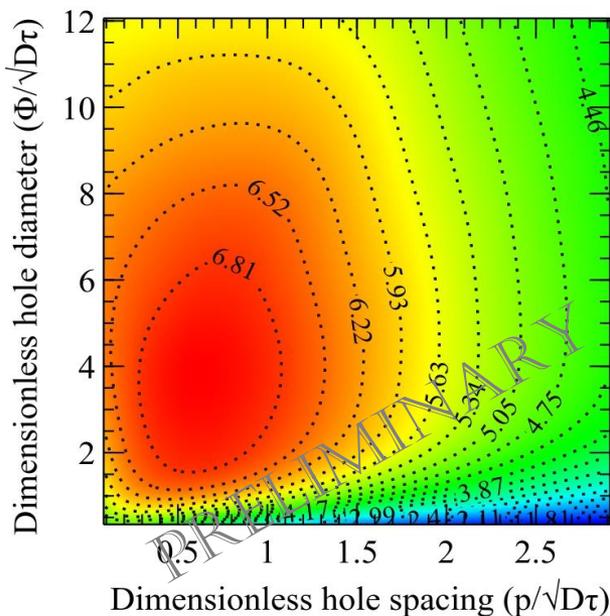
- 最优孔径: $\Phi = 3.68\sqrt{D\tau}$ (= 86.0um)
- 最优间距: $p = 0.64\sqrt{D\tau}$ (= 15.0um)
- 此时产额比无孔靶高7.1倍。
- 产生的Muonium中有23.3%可离开靶, 无孔靶为3.28%。

Ref: 赵诗涵

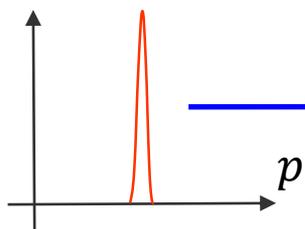
d=2.5mm

d=5.0mm

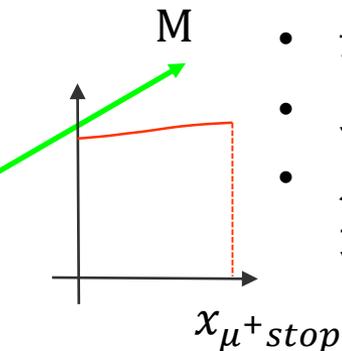
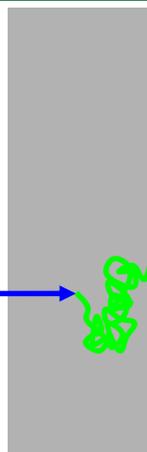
d=7.5mm



SiO₂气凝胶靶材缪子素产额优化 - 宽分布



d=2.5mm

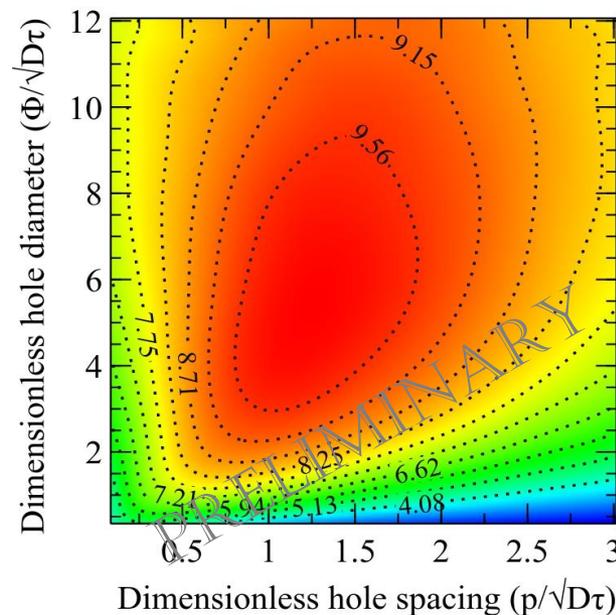
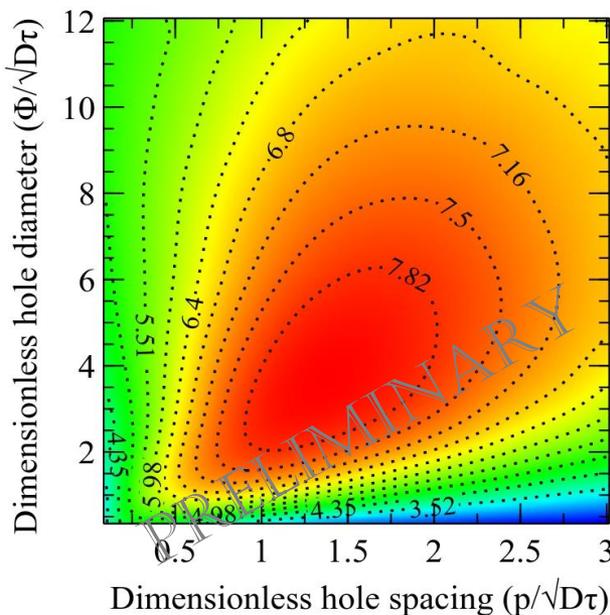
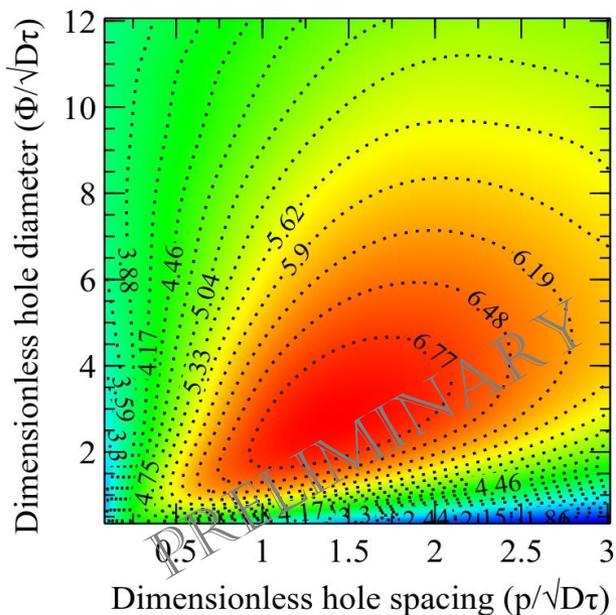


d=5.0mm

- 最优孔径: $\Phi = 5.35\sqrt{D\tau}$ (= 125.1 μ m)
- 最优间距: $p = 1.25\sqrt{D\tau}$ (= 29.2 μ m)
- 此时产额比无孔靶高9.9倍。
- 产生的Muonium中有2.04%可离开靶, 无孔靶为0.205%

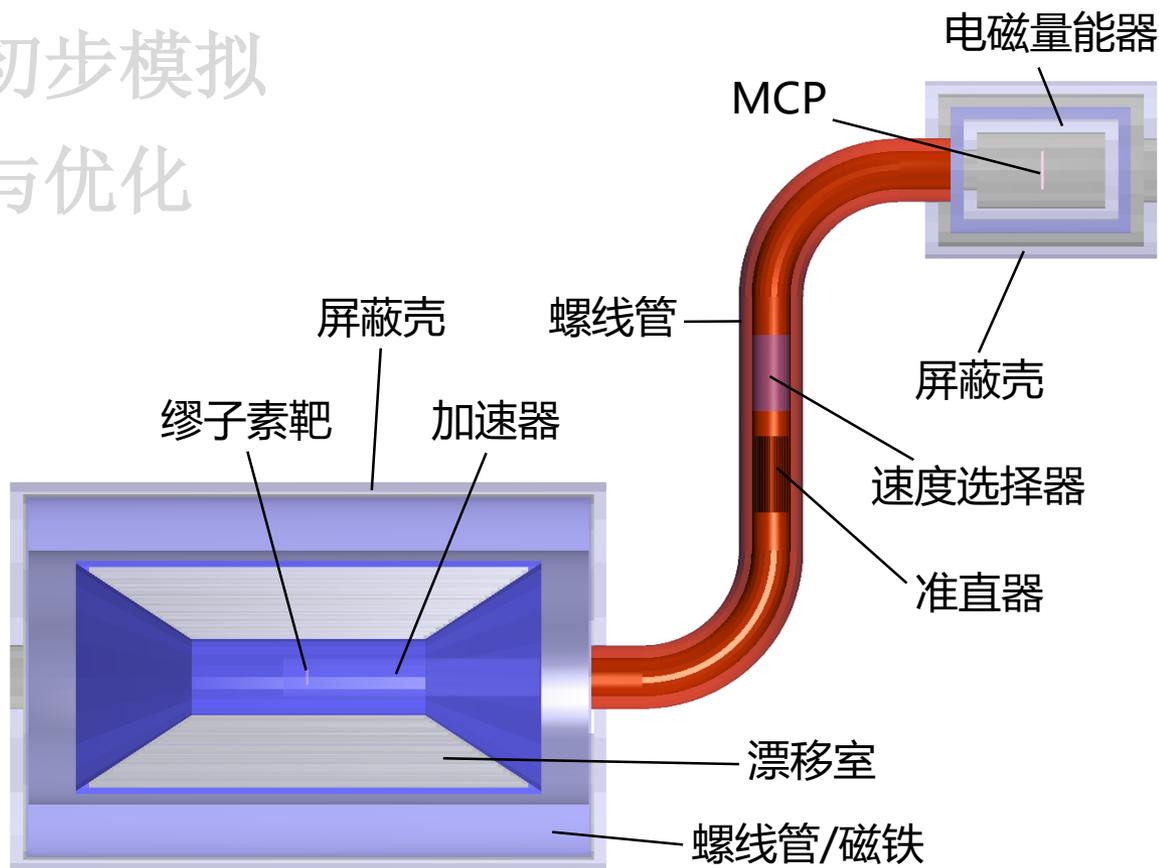
Ref: 赵诗涵

d=7.5mm



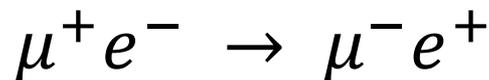
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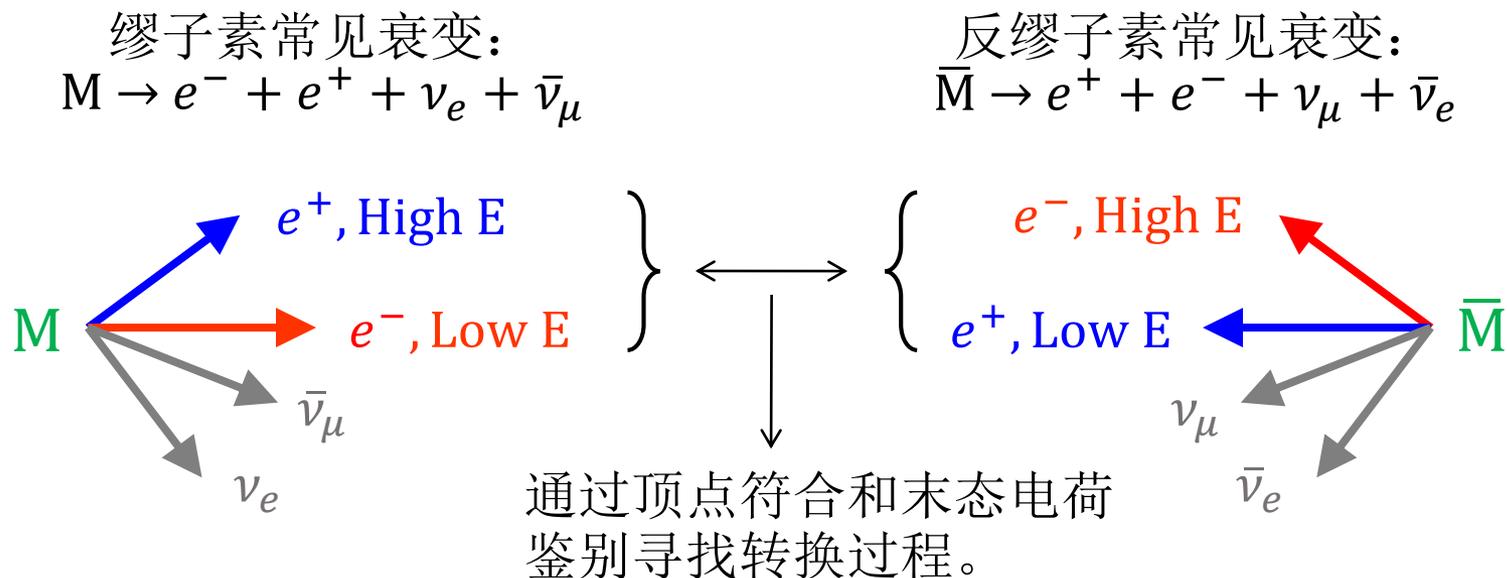


MACE实验基本设计方案

- 正反缪子素转换如何探测？



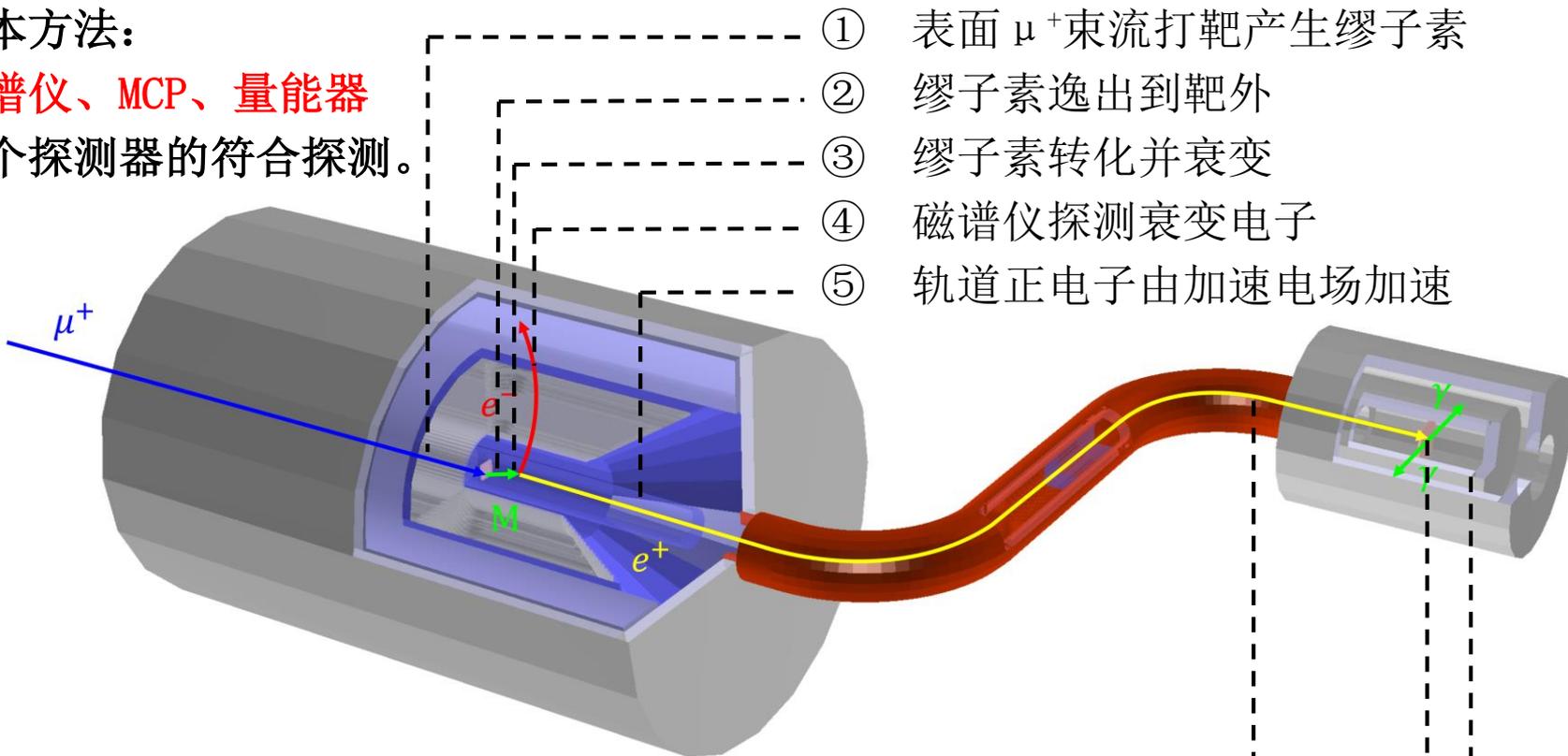
- 通过鉴别衰变末态寻找转换过程：



MACE实验基本设计方案

基本方法:

磁谱仪、MCP、量能器
三个探测器的符合探测。

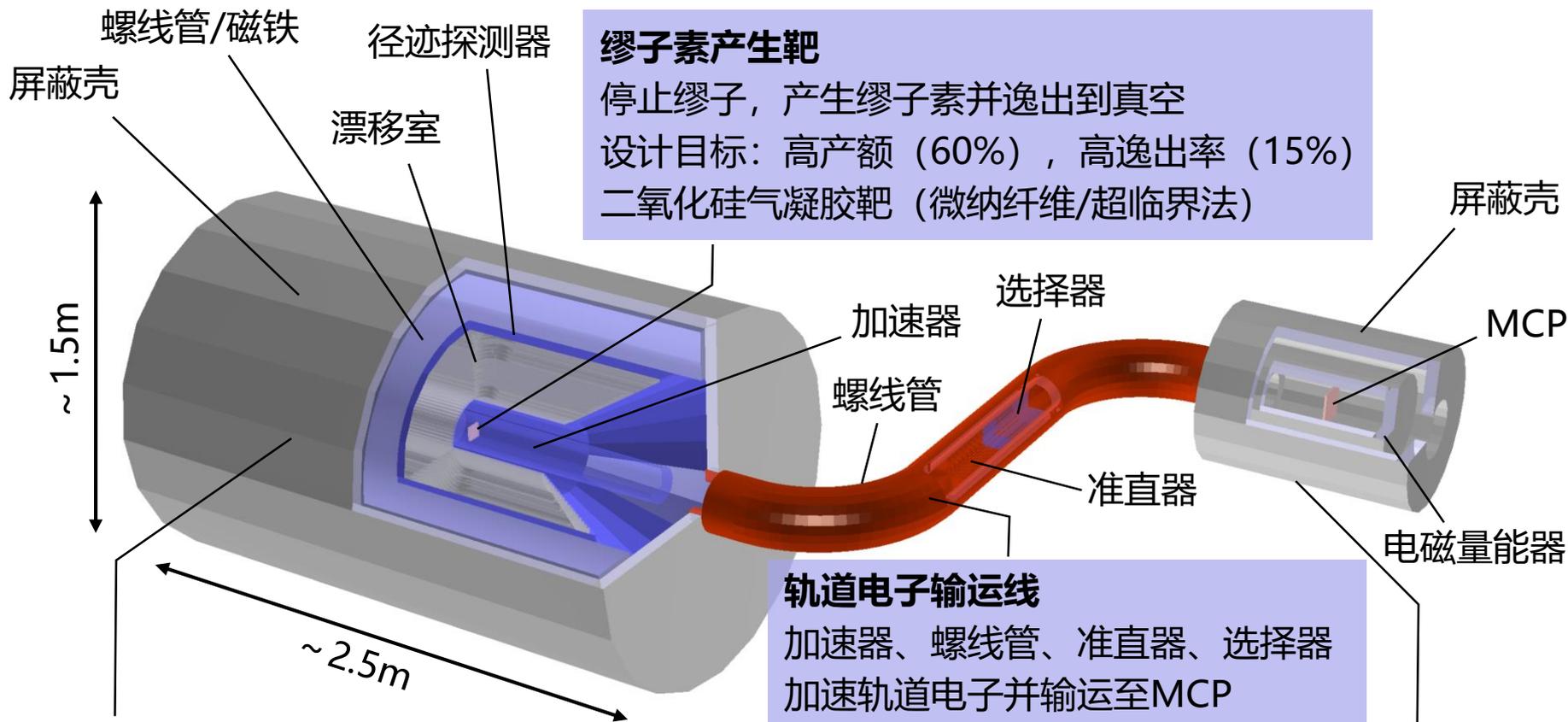


- ① 表面 μ^+ 束流打靶产生缪子素
- ② 缪子素逸出到靶外
- ③ 缪子素转化并衰变
- ④ 磁谱仪探测衰变电子
- ⑤ 轨道正电子由加速电场加速

- 通过磁谱仪实现米歇尔电子判别;
- 通过谱仪径迹和MCP探测的投影位置实现衰变顶点符合;
- 通过量能器实现正电子鉴别。

- ⑥ 正电子输送到远端
- ⑦ MCP探测正电子位置
- ⑧ 量能器探测正电子湮灭光

MACE实验基本设计方案



缪子素产生靶
 停止缪子，产生缪子素并逸出到真空
 设计目标：高产额（60%），高逸出率（15%）
 二氧化硅气凝胶靶（微纳纤维/超临界法）

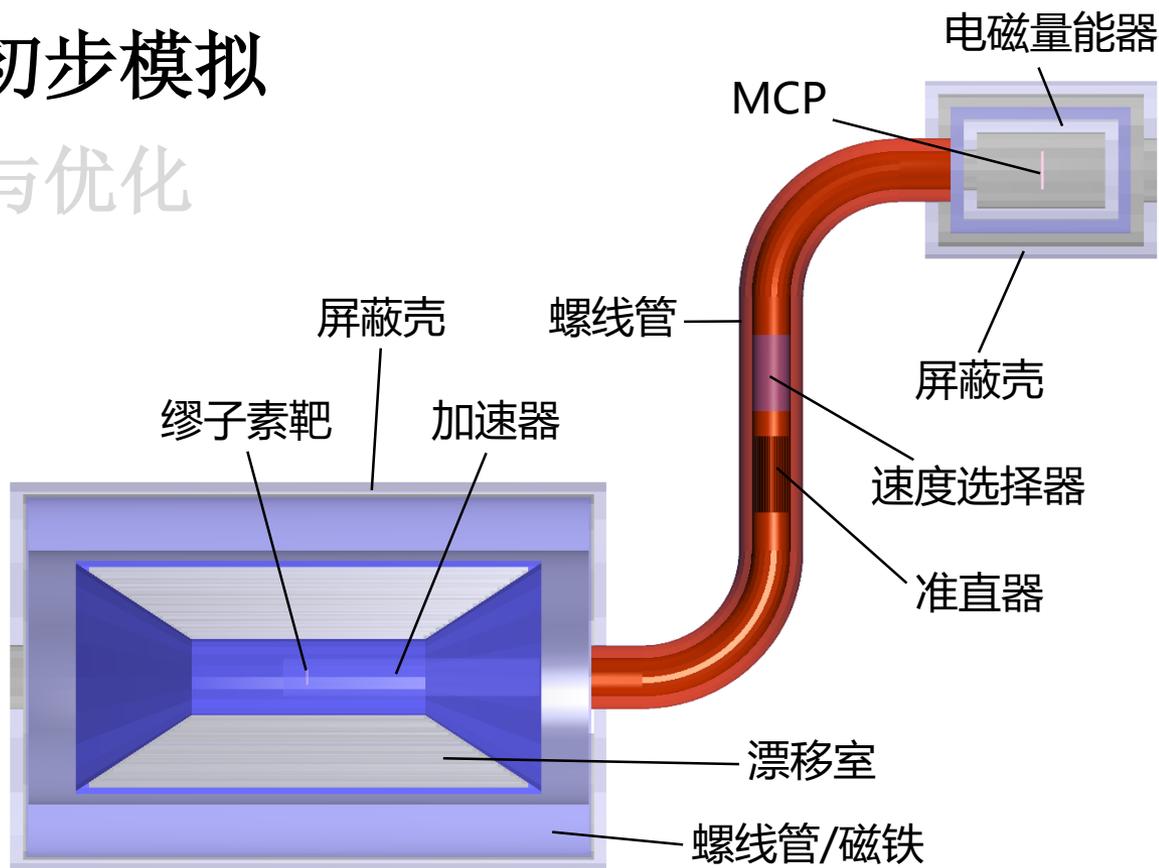
轨道电子输运线
 加速器、螺线管、准直器、选择器
 加速轨道电子并输运至MCP

磁谱仪系统
 探测米歇尔正负电子（平均37MeV，最大52.8MeV）
 设计目标：高电荷分辨（错误率 $<10^{-5}$ ）、高位置分辨（ $<3\text{mm}$ ）、高动量分辨（ $<500\text{keV}/c$ ）
 探测器：中心漂移室（ $\cos\theta=0.9$ ）设计工作磁场：0.1T

轨道电子位置符合探测系统
 MCP探测衰变顶点投影位置；
 量能器探测511keV光子检测正电子产生；
 与谱仪径迹探测做符合测量

内容概述

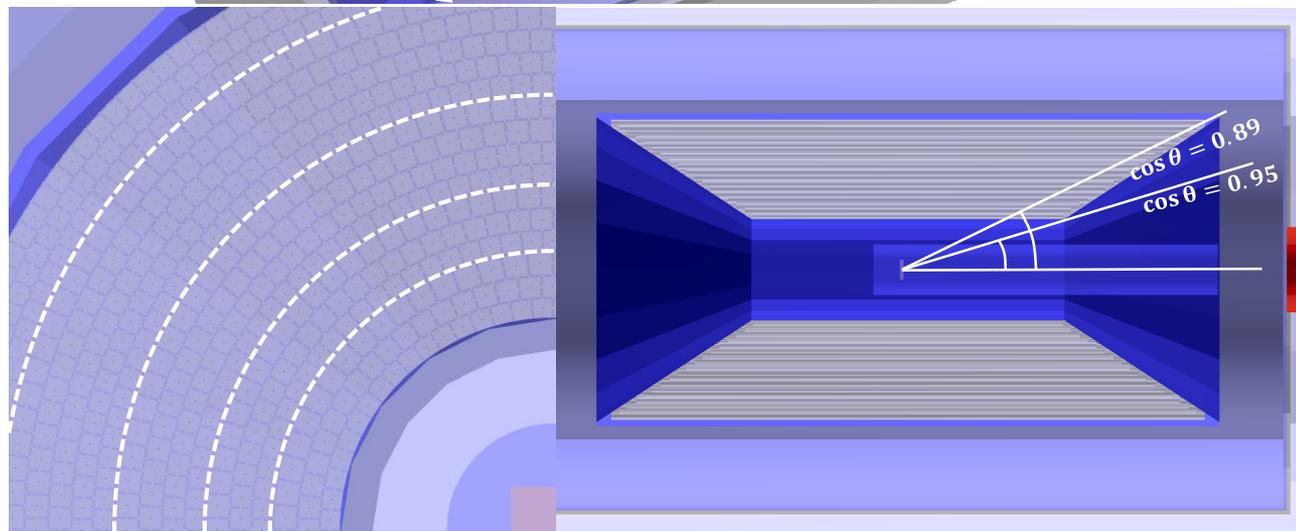
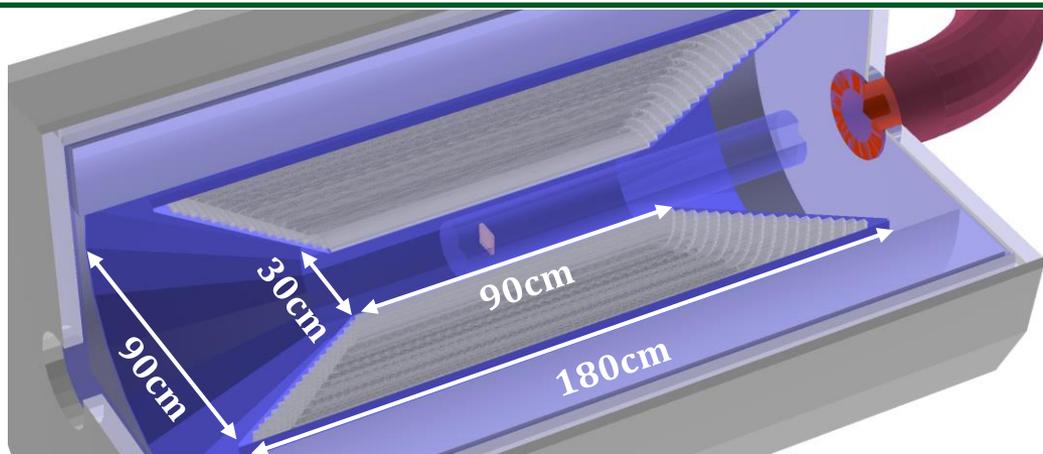
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磁谱仪基本设计

模拟选用的基准设计:

- 漂移室内径: 30cm
- 漂移室外径: 90cm
- 漂移室内筒长: 90cm
- 漂移室外筒长: 180cm
- 覆盖立体角: 89.4%
- 单元宽度: 16.2mm
- 场丝: 铝, 110um
- 信号丝: 钨, 25um
- 读出层数: 18
- 单元数: 2112
- 工作气体: He基气体
- 工作磁场: 0.1T



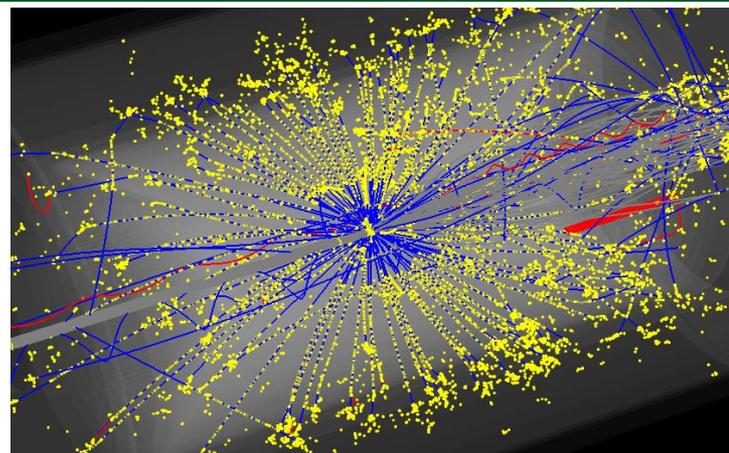
丝层排布: 18个读出层分为5个超层, 每个超层由内向外含3、3、4、5、3个读出层, 每个超层内读出层单元错开半个单元宽度。

漂移室初步模拟

- 使用MACE实验集成模拟程序SimMACE，对15个漂移室几何设计各产生160万入射缪子事例，初步实施了漂移室的快速模拟：

- 模拟中直接记录漂移距离；
- 暂未实现斜丝层，记录z击中坐标；
- 漂移距离加入 $\sigma_d = 0.2\text{mm}$ 噪声；
- z击中坐标加入 $\sigma_z = 3\text{mm}$ 噪声。

世界现有漂移室常规性能指标。



- 使用直接最小二乘法拟合径迹：

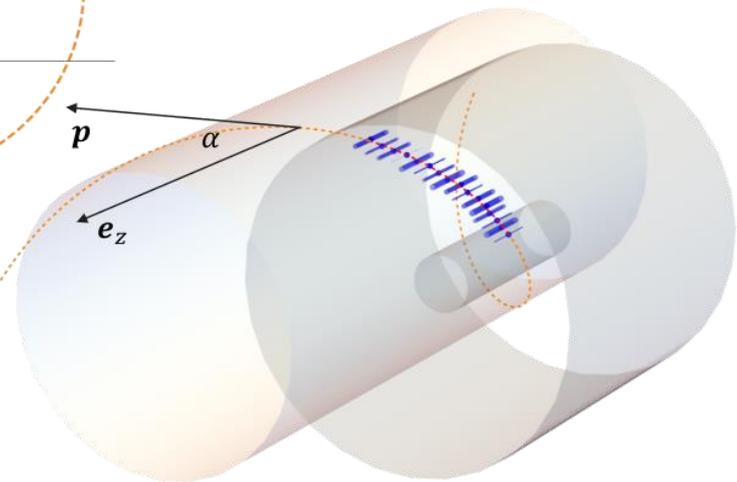
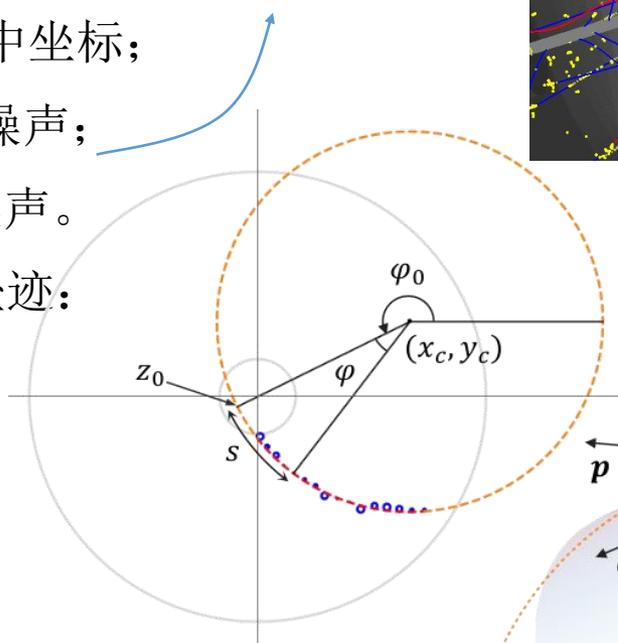
径迹模型采用五参数螺旋线，

$$\begin{cases} x = x_c + R \cos(\varphi + \varphi_0) \\ y = y_c + R \sin(\varphi + \varphi_0) \\ z = z_0 + s \cot \alpha \end{cases}$$

- 采用牛顿法和共轭梯度法→

最小化目标函数：

$$f(x_c, y_c, R) = \sum_i \min \left(\sqrt{(x_i - x_c)^2 + (y_i - y_c)^2} - (R \pm d_i) \right)$$



漂移室初步模拟

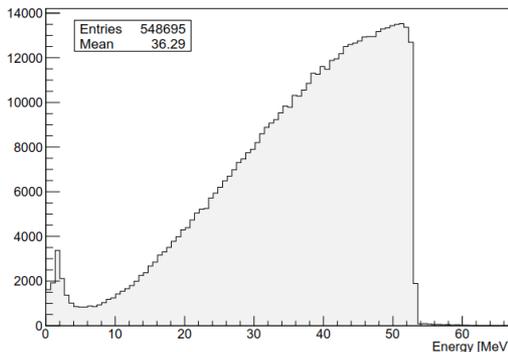
实施了15个漂移室几何设计的模拟：

- 内径 20~60cm;
- 外筒长 1.2~2m;
- 读出层数 12~24 层;
- 覆盖立体角相同。

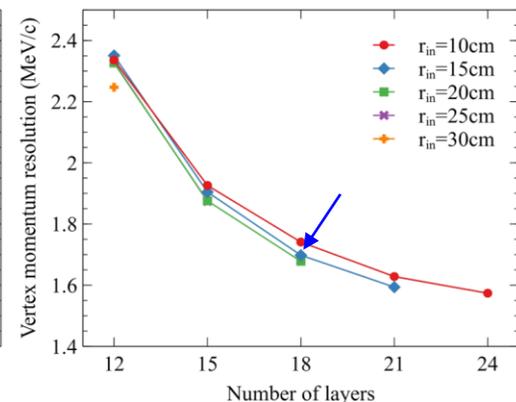
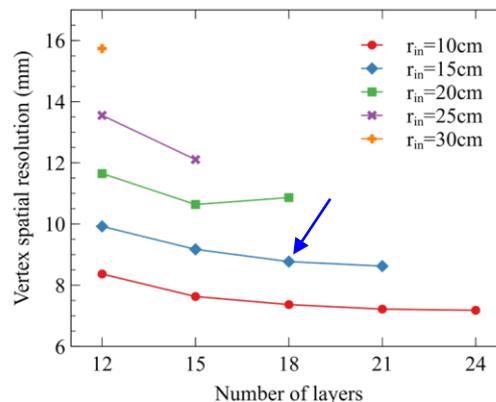
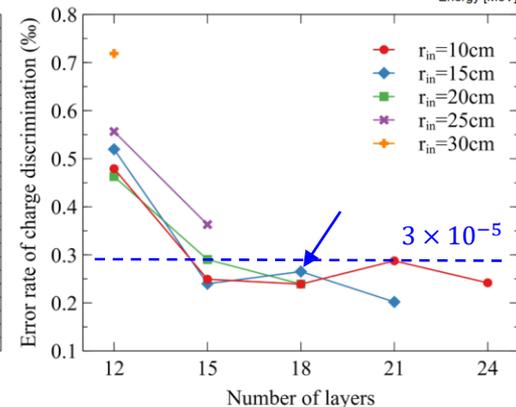
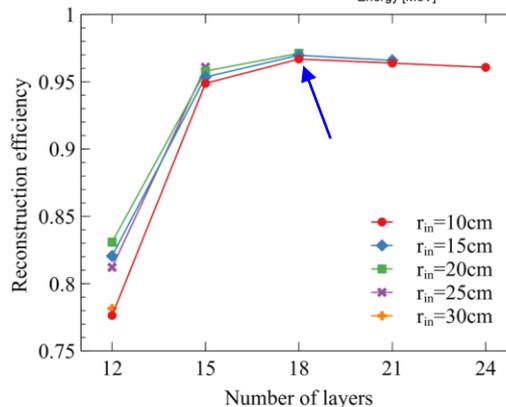
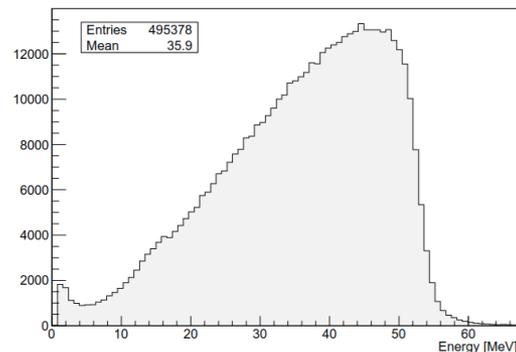
初步结论：

- 对于读出层>15，重建效率和电荷分辨能力接近；
- 考虑最优分辨和可实现性，选择基准设计为：内/外筒半径 15/45cm、内/外筒长 90/180cm，18读出层。
- 径迹重建算法未考虑物质效应，分辨本领受此限制。改进后有望实现电荷错误率 $<10^{-5}$ 、动量分辨 $<500\text{keV}/c$ 。
- 单独的漂移室模拟程序SimCDC正在开发，实现进一步细化设计；正在开发基于Kalman filter的径迹重建算法。

Generated energy spectrum

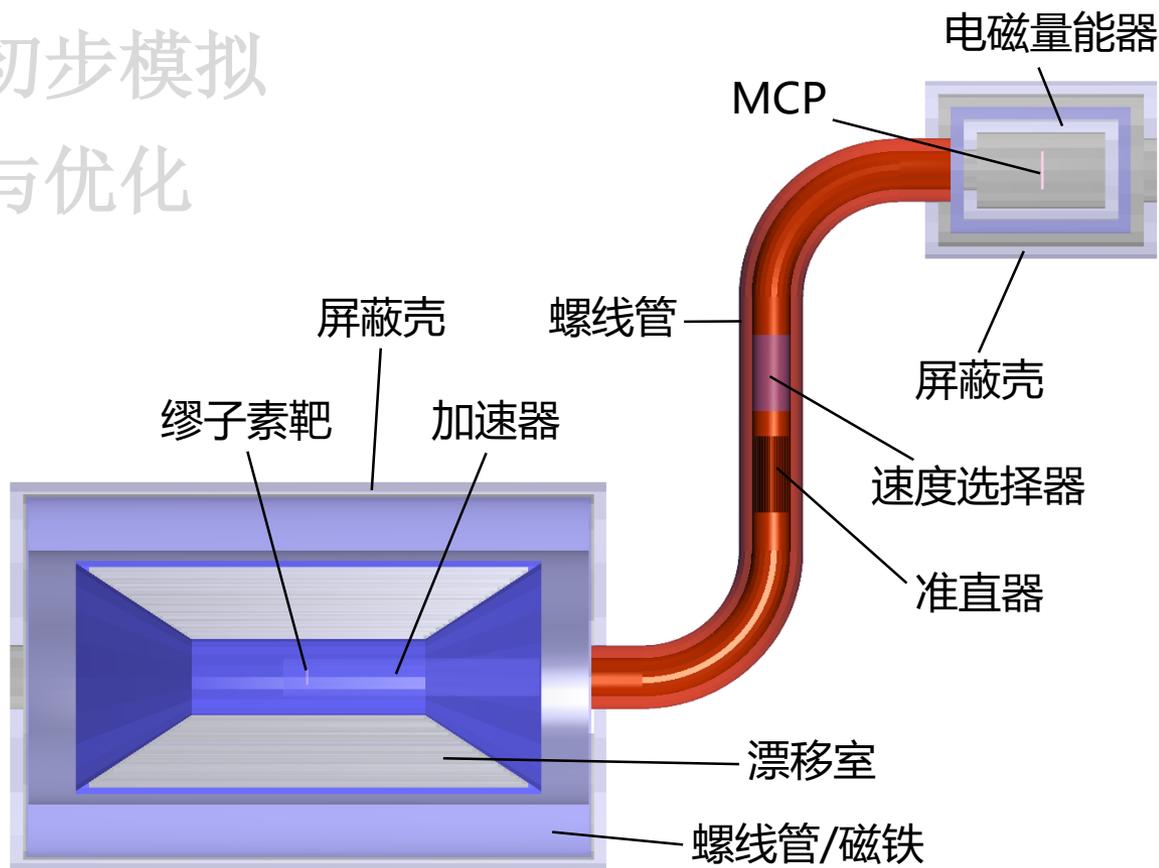


Reconstructed energy spectrum



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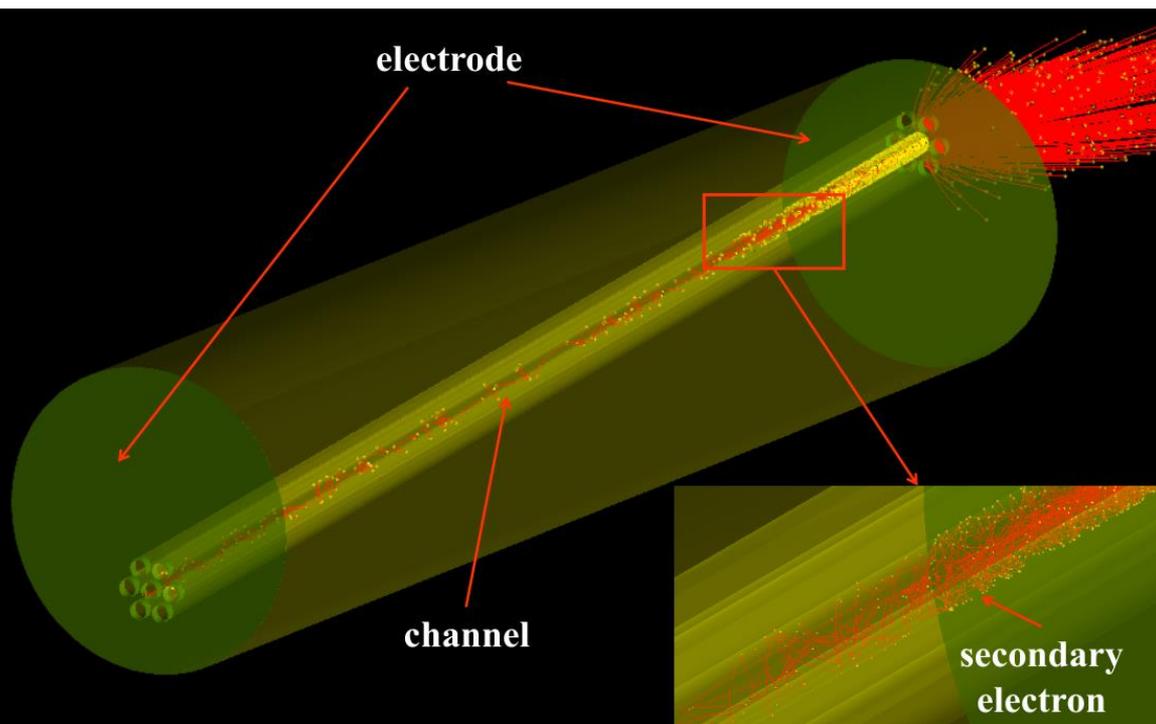


MCP响应模拟

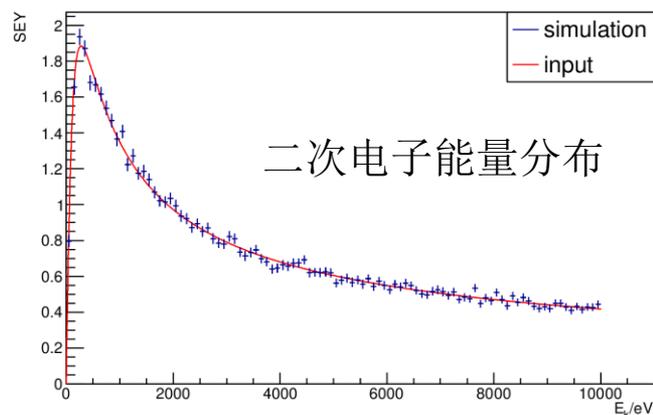
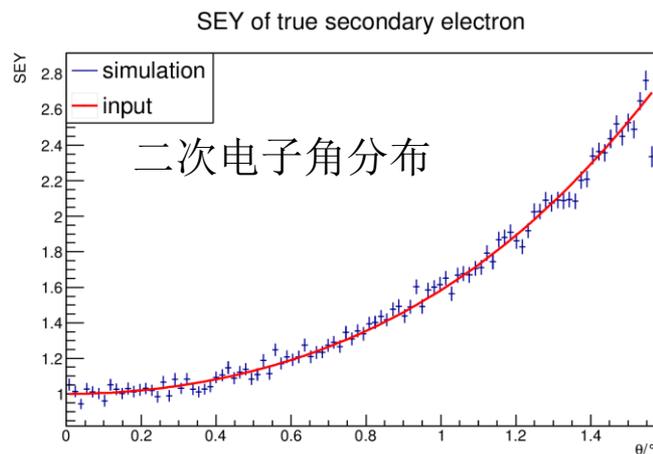
现已开发MCP的模拟程序，可实现MCP中少数通道电子倍增过程的模拟。

- 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



MCP响应模拟

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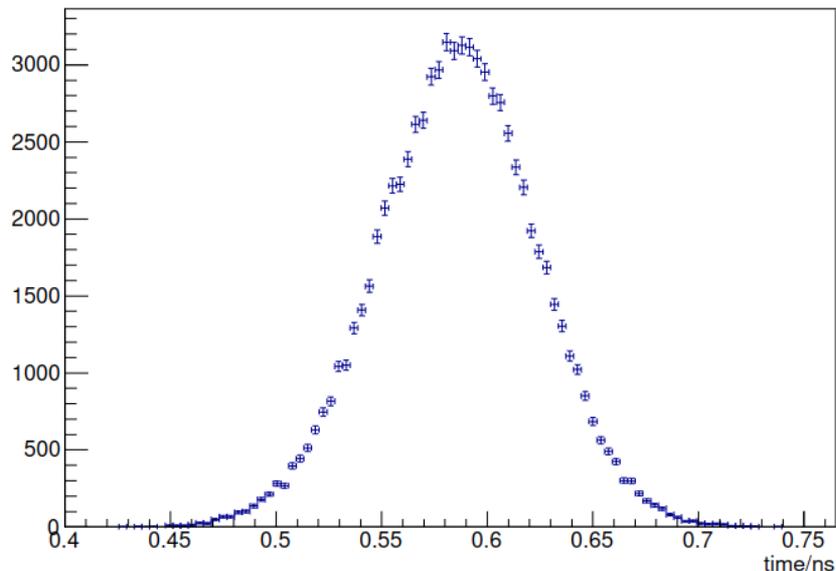
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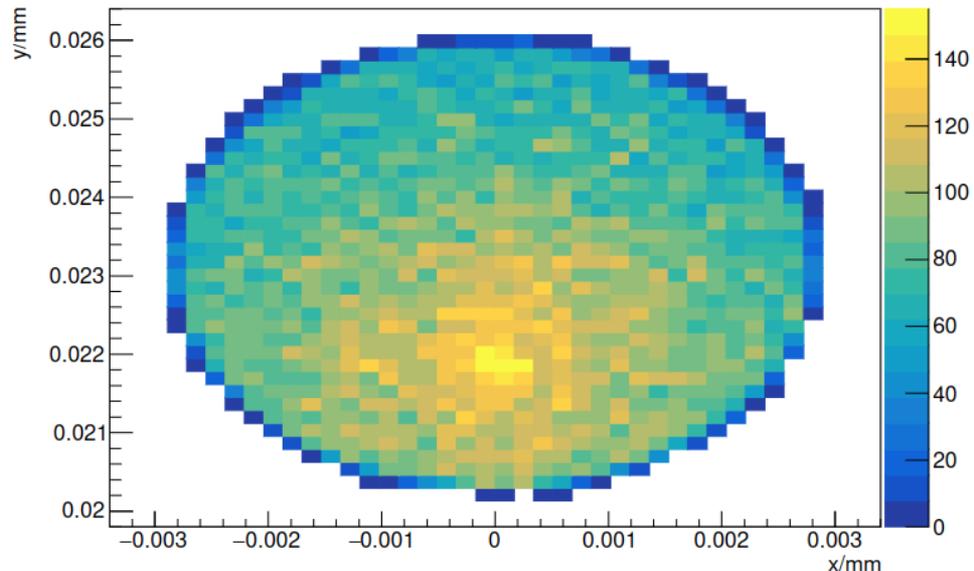
模拟的MCP响应波形：

Time when secondary electrons arriving electronics



二次电子到达位置分布模拟：

Position when secondary electrons arriving electronics





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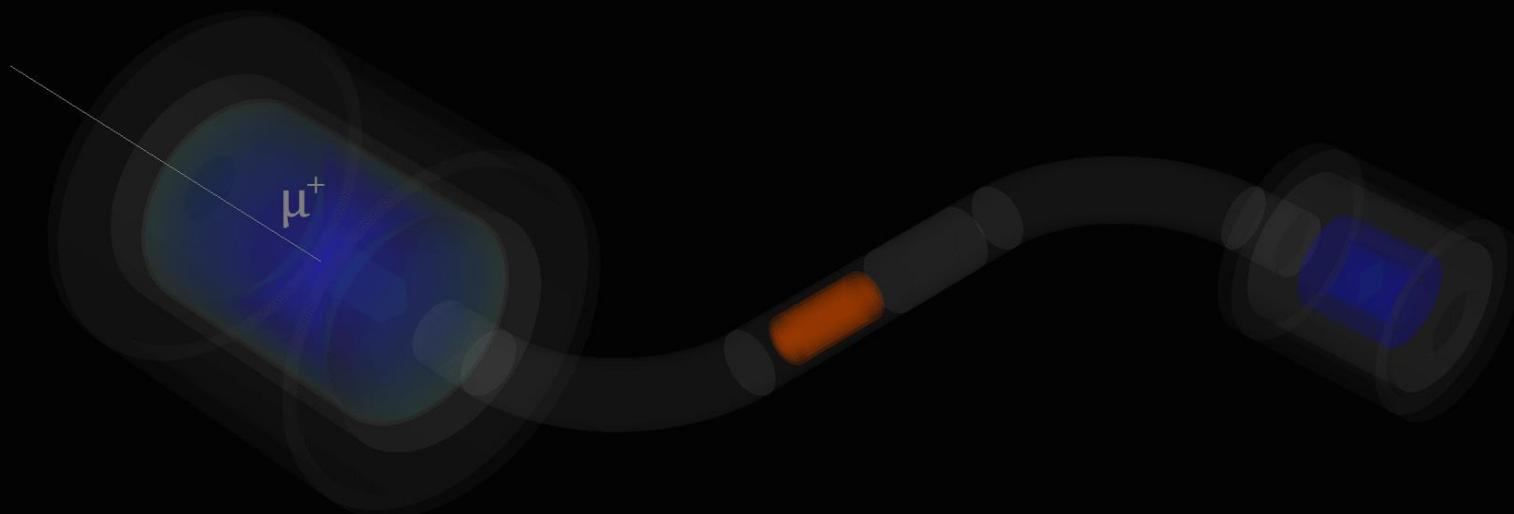
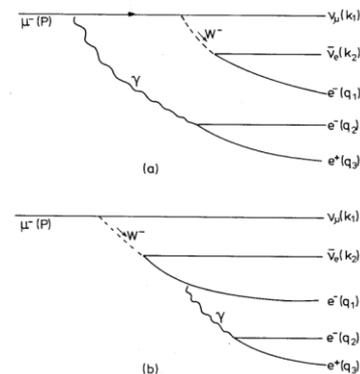
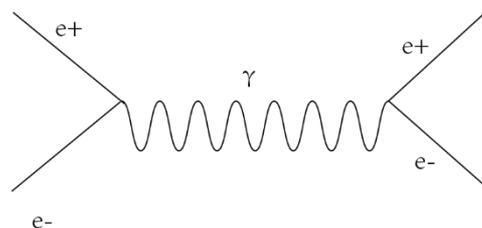
快速MC模拟

- Backgrounds:

- μ^+ decays to e^+ , Bhabha scattering to generate high-energy e^- in coincident with low-energy e^+

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

- Anti-muonium decay signals by position-time coincidence

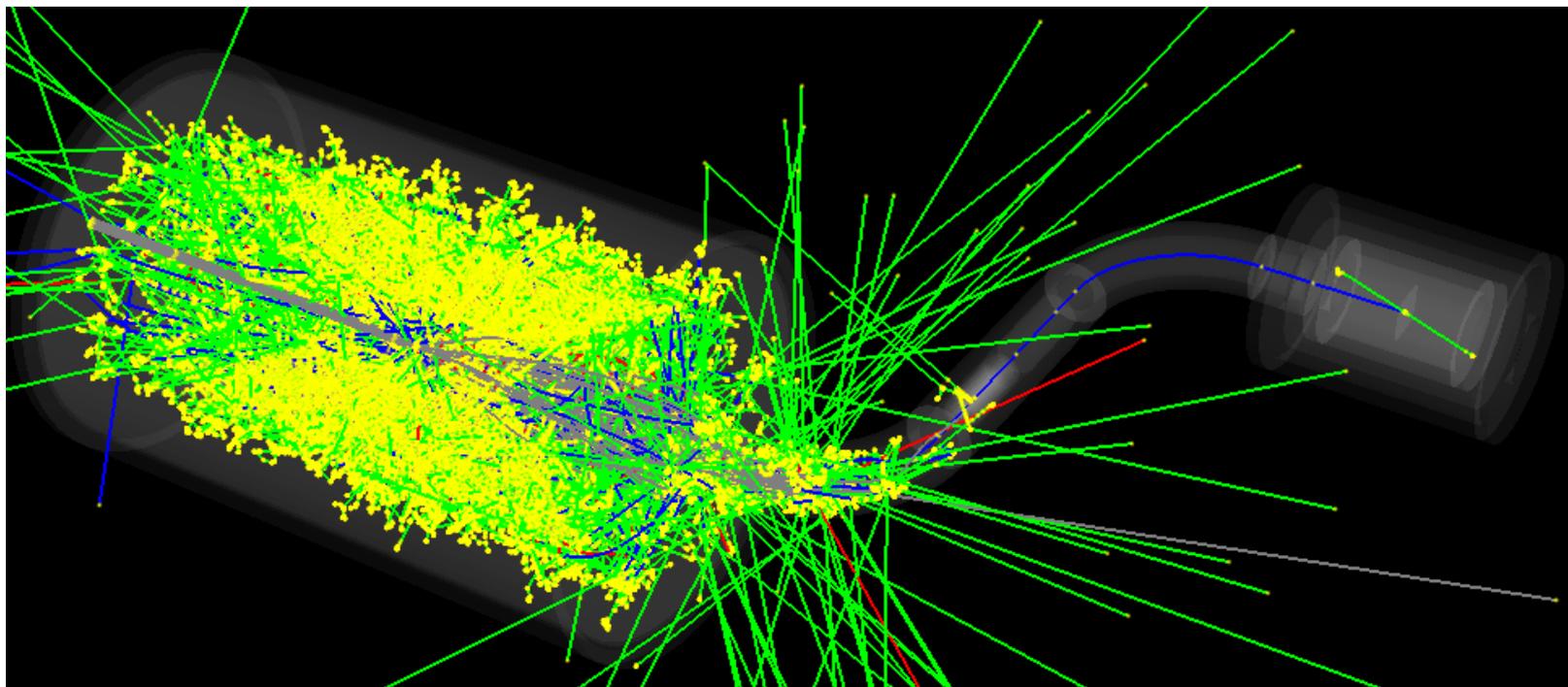
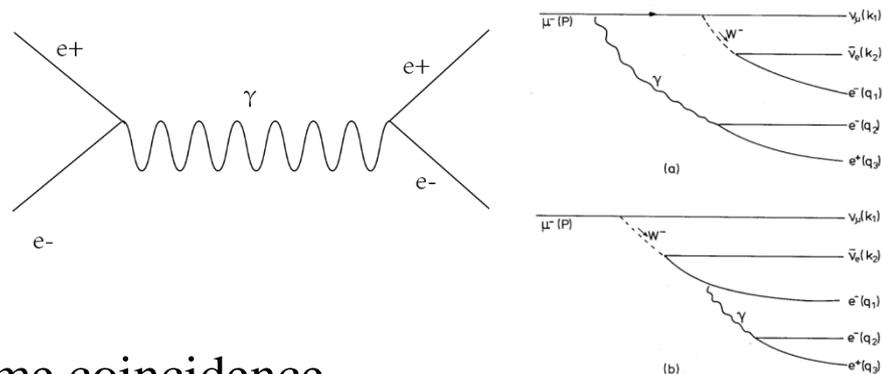


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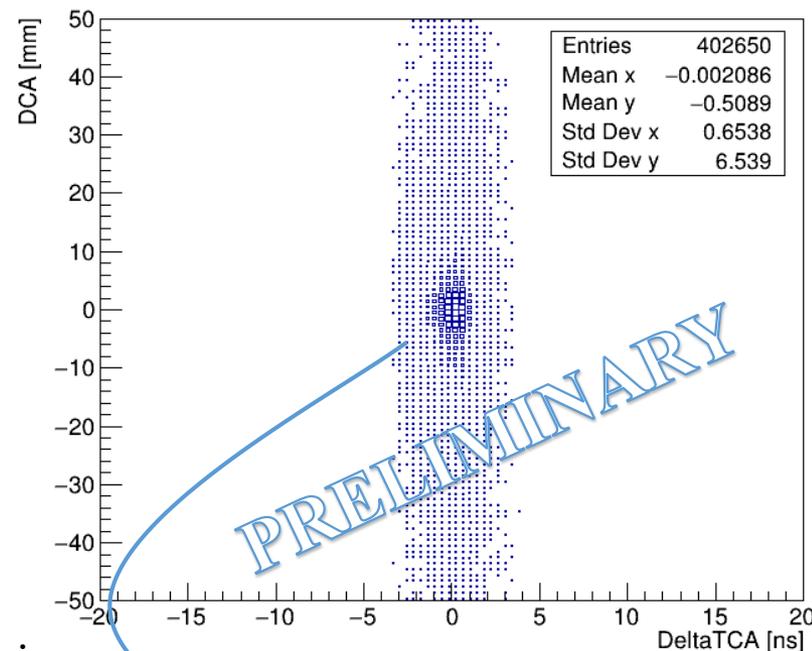
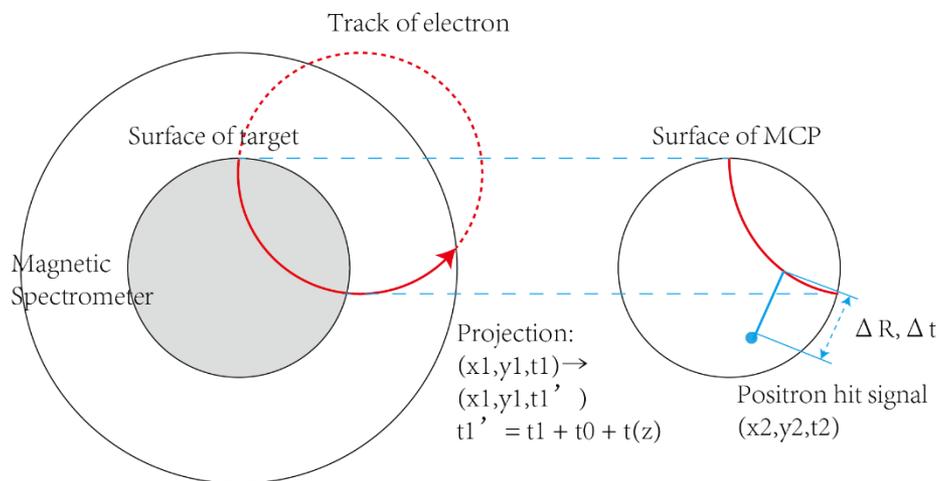
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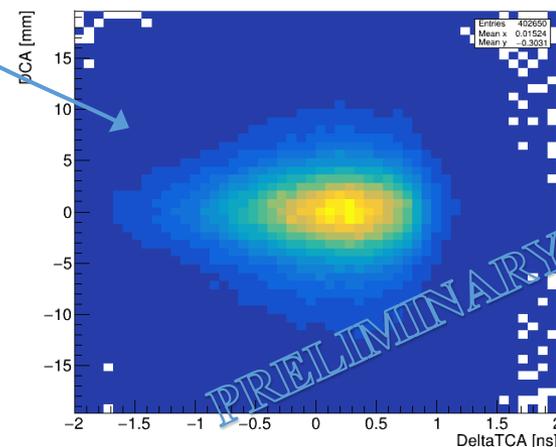
快速MC模拟: 缪子素探测



3σ Region:

- Injected muons:
 2×10^8 of μ^+
- Resolution better than PSI muonium formation results.

- Happen at the same vertex:
 $|\Delta R| \sim DCA < 12.0$ mm
- Happen at the same time:
 $|\Delta t| \sim \text{TOF} - \text{TOF}_{\text{expected}} \sim \text{TCA} < 4.5$ ns:
 $\text{TOF} = t_0 + t(z)$



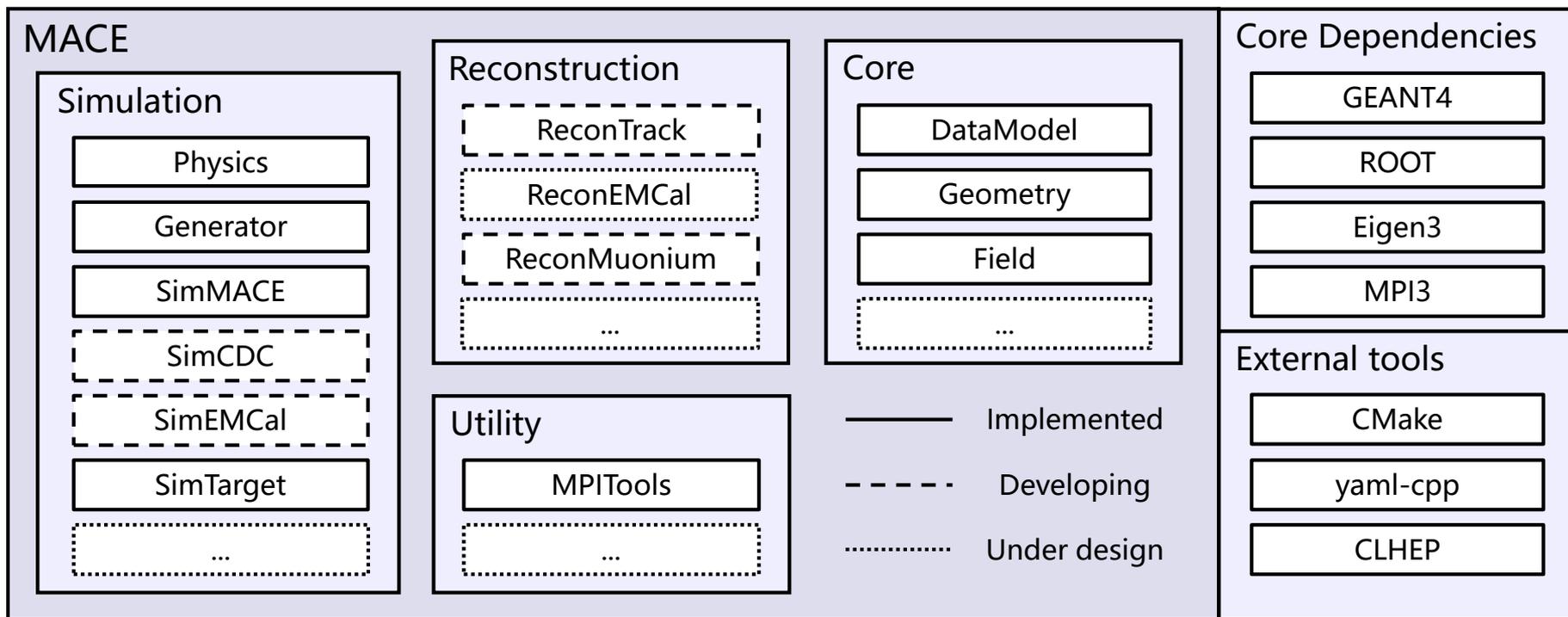


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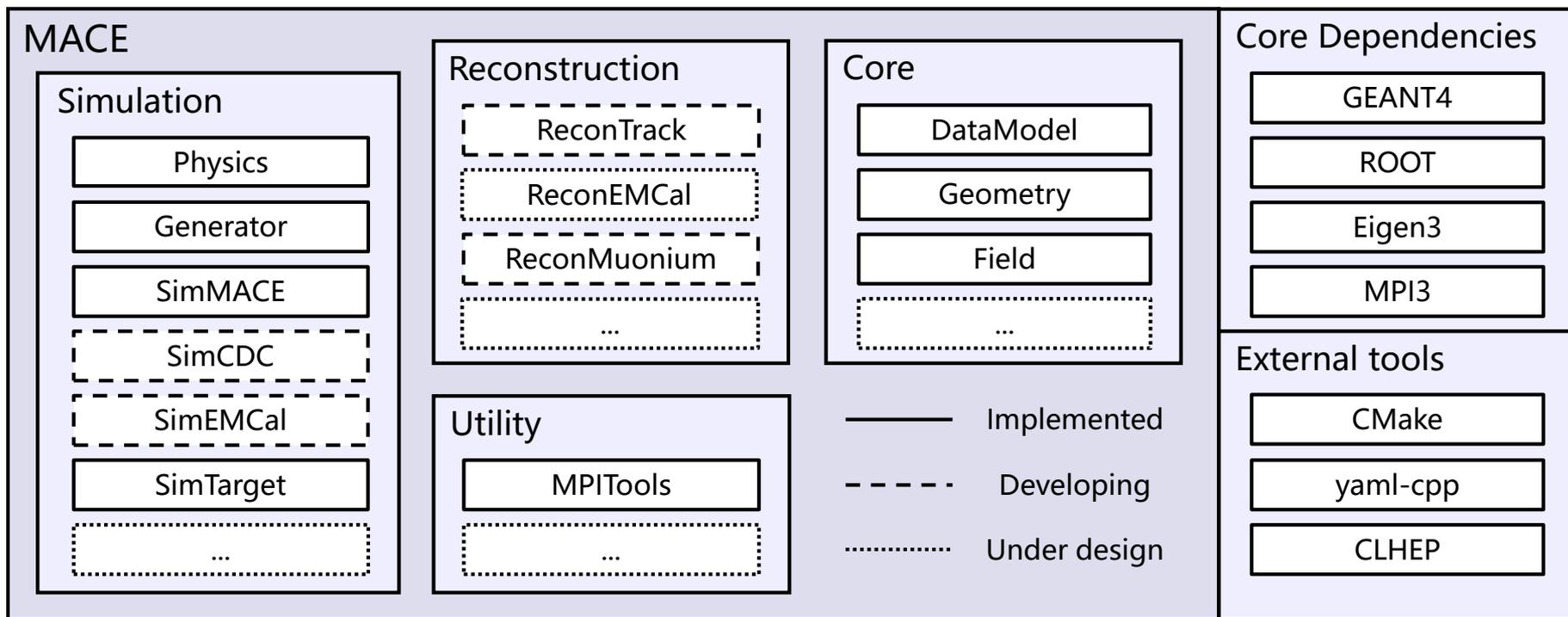
MACE离线软件框架

- MACE离线软件系统负责实验的前期设计、模拟、和离线数据分析工作；
- 统一的功能性界面和接口；
- 采用C++最佳实践和设计模式编写与设计；
- 引入C++20标准，受益于最新语言特性：概念、约束，范围库，新语言特性——代码风格清晰，增强可读性和可维护性；
- 后续计划引入更多成熟软件工程实践：持续集成、自动测试与部署.....



MACE离线软件框架

- **Core:** 提供统一的事例数据模型、数据I/O及相应接口；提供探测器几何、电磁场的统一管理、配置与I/O；
- **Simulation:** 负责各个子探测器模块和整个实验的模拟工作。其中Physics和Generator子模块提供公用的物理过程和产生子；
- **Utility:** 提供公用的实用工具。
- **Reconstruction:** 负责模拟、实验数据的重建任务。各个子模块内部自成体系；
- **外部库:** 模拟基于GEANT4框架；数据库服务、数据分析工具基于ROOT；Eigen3提供高性能线性代数库；通过MPI实现并行计算。
- 方便部署到超算中心“天河二号”高能物理实验模拟平台



- 带电 μ 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。
- 本土缪子实验项目将在缪子束流、缪子素产生及探测器设计等重要环节上取得“0到1”的重要原始创新，有望将现有实验精度提高**两个量级**以上。
- 我们已重现了PSI实验20年前的结果，在实验总体设计、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。
- 2022年，即将发布MACE实验的CDR。
 - 感谢IHEP唐靖宇、袁野、鲍煜等共同推动加速器缪子源(EMuS)。
 - 感谢中大陈羽博士和王自鑫老师积极参加预研。
 - 感谢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、广东省自然科学基金和中科院先导计划等项目给与经费支持。
 - 感谢基础物理实验中心提供有效支持!

The background features a large, light green watermark of the Tsinghua University logo. The logo is circular and contains the university's name in Chinese characters '清華大學' at the top and 'TSINGHUA UNIVERSITY' at the bottom. In the center of the logo is a detailed illustration of a building with a central tower and the year '1924' at the base. Two dark green rectangular shapes are positioned on the left and right sides of the slide, partially overlapping the watermark.

THANK YOU