Progress of MACE at EMuS

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2021.07.20

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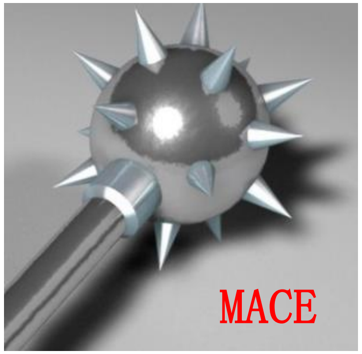

Muonium to Antimuonium Conversion Experiment(MACE)

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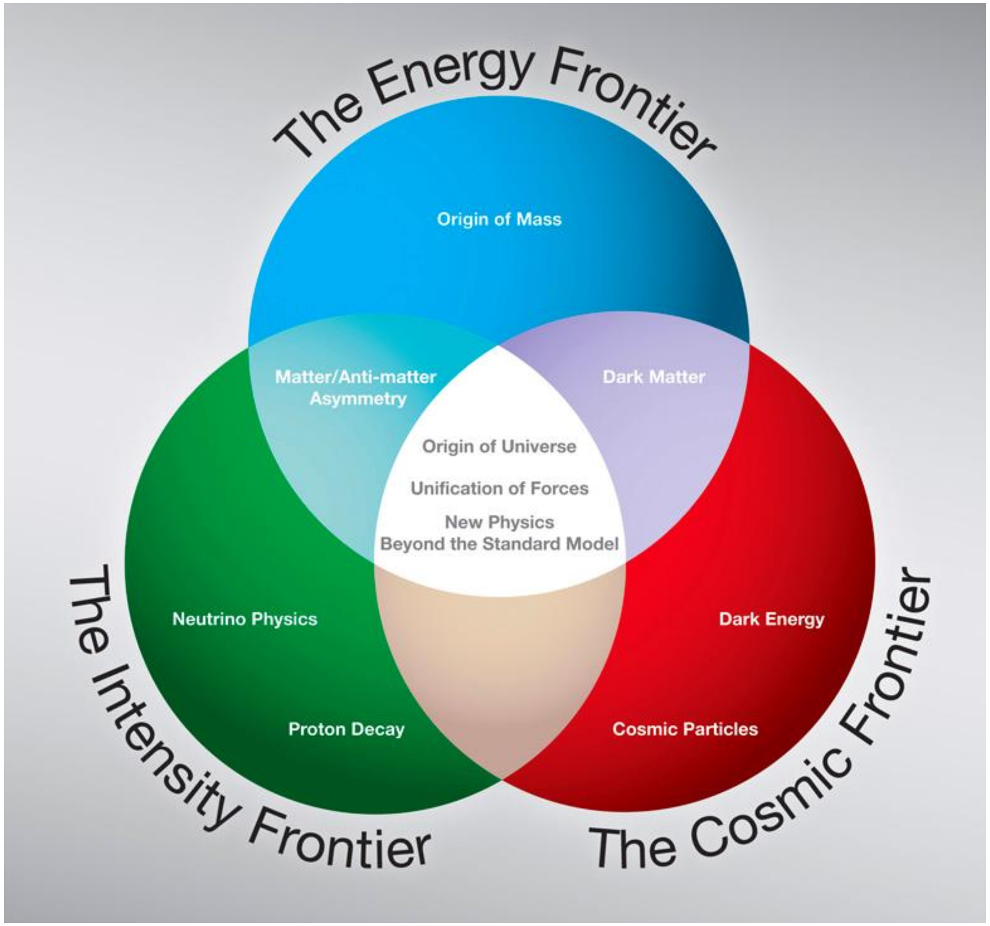
Three frontiers in Particle Physics

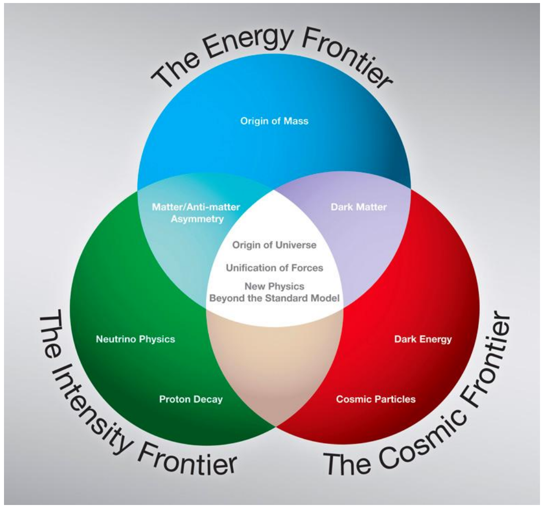


- High-energy frontier
- High-intensity frontier
- Cosmic Frontier

Search for new physics beyond SM:

- What's the origin of ν mass?
- Matter-antimatter asymmetry?
- What is DM?
- ……

High-intensity/high-precision frontier



- 中微子实验
  - T2K, NOvA, T2HK, DUNE…
  - JUNO, MOMENT…
- 带电轻子味道破坏实验cLFV：
  - Mu2e(美国)
  - **COMET(日本)**
  - MEG(瑞士)

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

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

- 轻子数破坏实验LNV：
  - 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。
  - J-PARC的MeuSEUM实验精确测量muonium超精细结构。

大湾区是强流加速器的聚集地

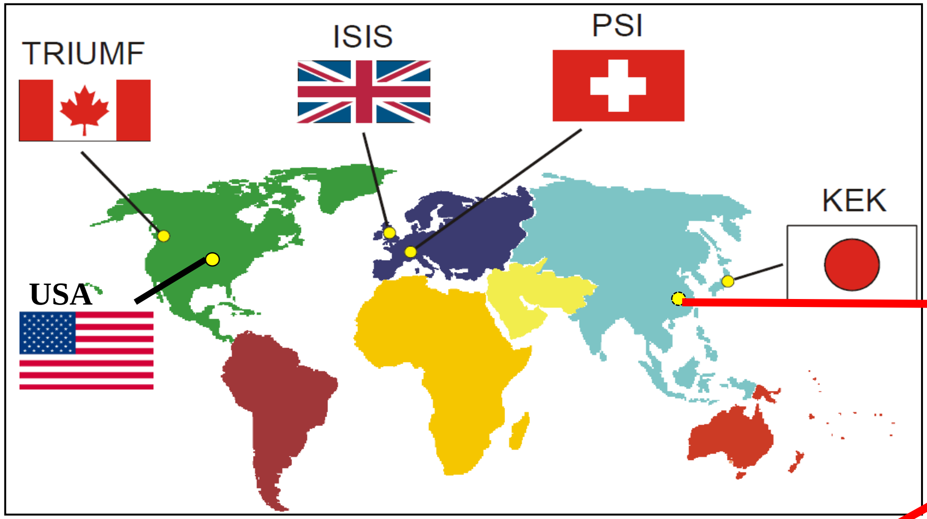
参考：中科院高能所，王生研究员报告

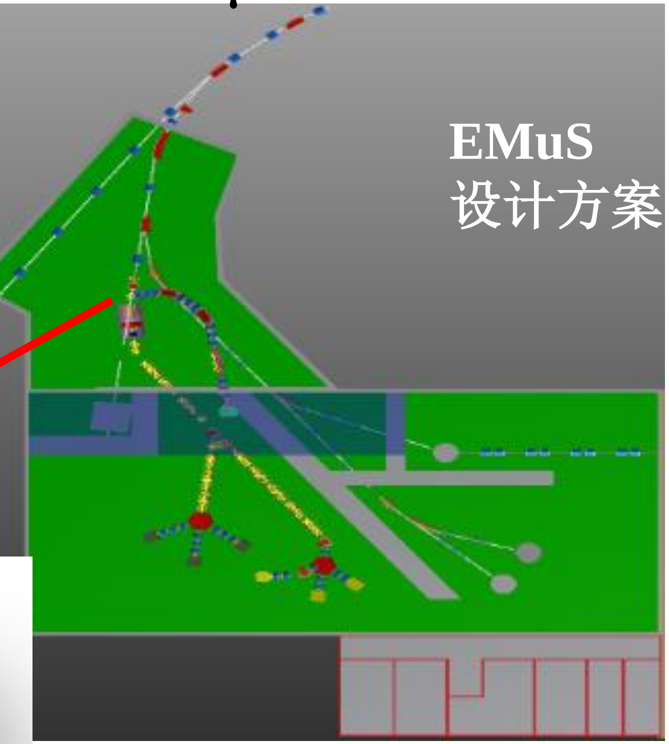
参考：中科院近物所，东江实验室詹文龙院士

我国强流质子/重离子加速器中心均希望建设“人有我无”加速器缪子源！

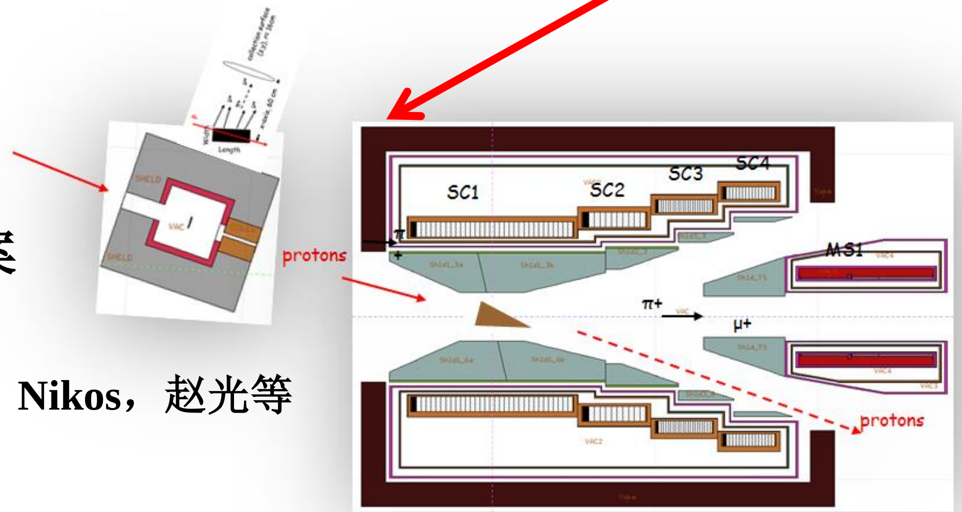
基于CSNS建造我国首个加速器缪子源EMuS计划

- 在中国散裂中子源建设我国第一个加速器μ源EMuS？





EMuS
设计方案

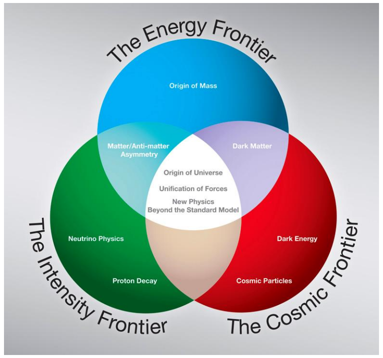


靶站方案

Courtesy:
IHEP袁野，Nikos，赵光等

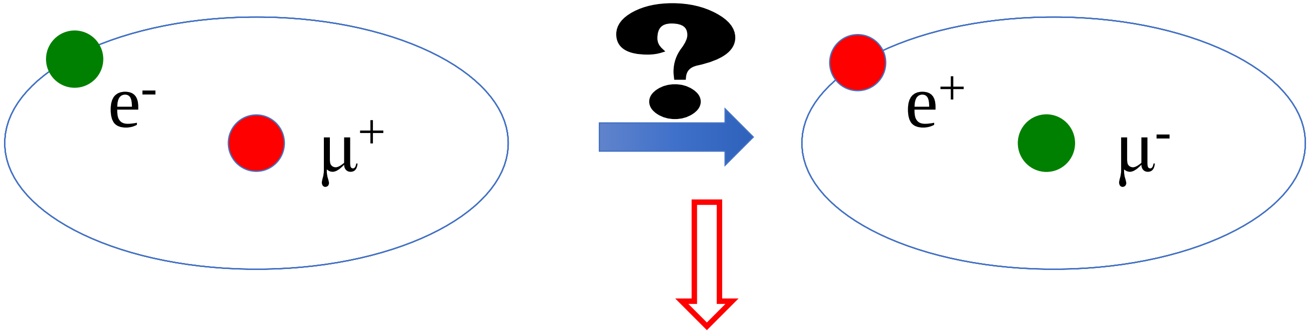
Courtesy: IHEP唐靖宇团队

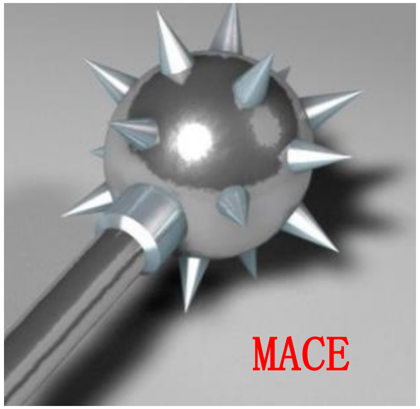
高精度前沿物理



- 带电轻子味道破坏实验cLFV：
  - Mu2e(美国)
  - COMET(日本)
  - MEG-II/Mu3e(瑞士)
  - Muonium to Antimuonium Conversion Experiment(中国CSNS)

$$\mu^+ e^- \longrightarrow \mu^- e^+$$

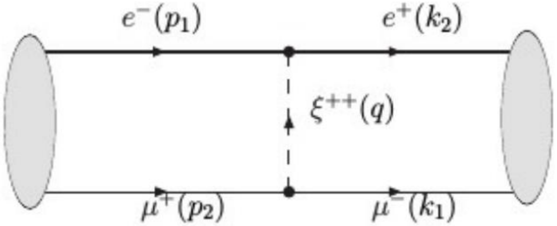


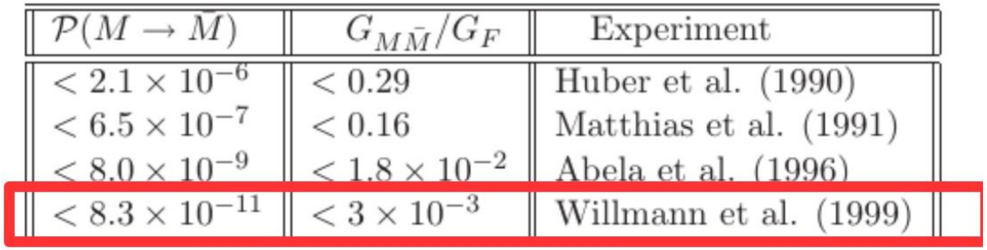


Proposed at the international Review of EMuS in November of 2019.

Muonium to antimuonium beyond SM

- Lepton flavour violation process beyond SM.
- For example, predicted by type-II seesaw model.





$\mathcal{P}(M \to \bar{M})$	$G_{M\bar{M}}/G_F$	Experiment
$< 2.1 \times 10^{-6}$	< 0.29	Huber et al. (1990)
$< 6.5 \times 10^{-7}$	< 0.16	Matthias et al. (1991)
$< 8.0 \times 10^{-9}$	$< 1.8 \times 10^{-2}$	Abela et al. (1996)
$< 8.3 \times 10^{-11}$	$< 3 \times 10^{-3}$	Willmann et al. (1999)

The best limit!

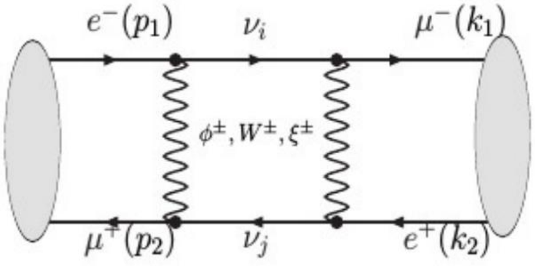


Figure 2.3: Dirac-Box (a)

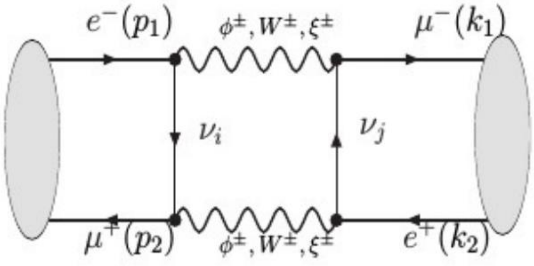


Figure 2.4: Dirac-Box (b)

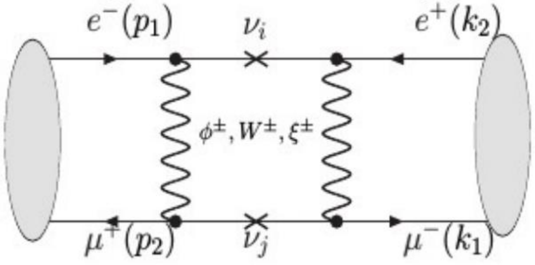


Figure 2.5: Majorana-Box (c)

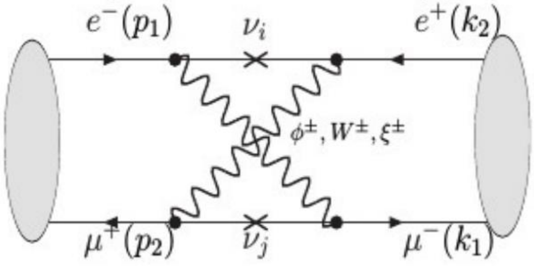
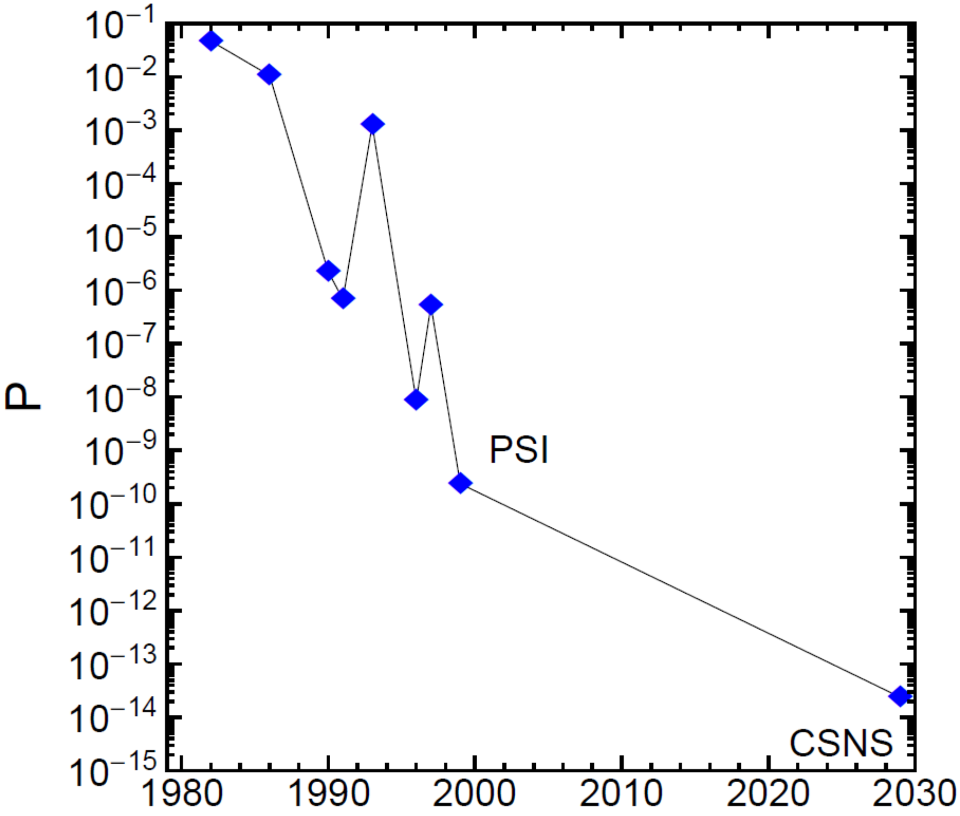


Figure 2.6: Majorana-Box (d)

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$10^8 \mu^+/s$？
- 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实验走到世界前列！

MACE实验: Muonium to Antimuonium Conversion Experiment.

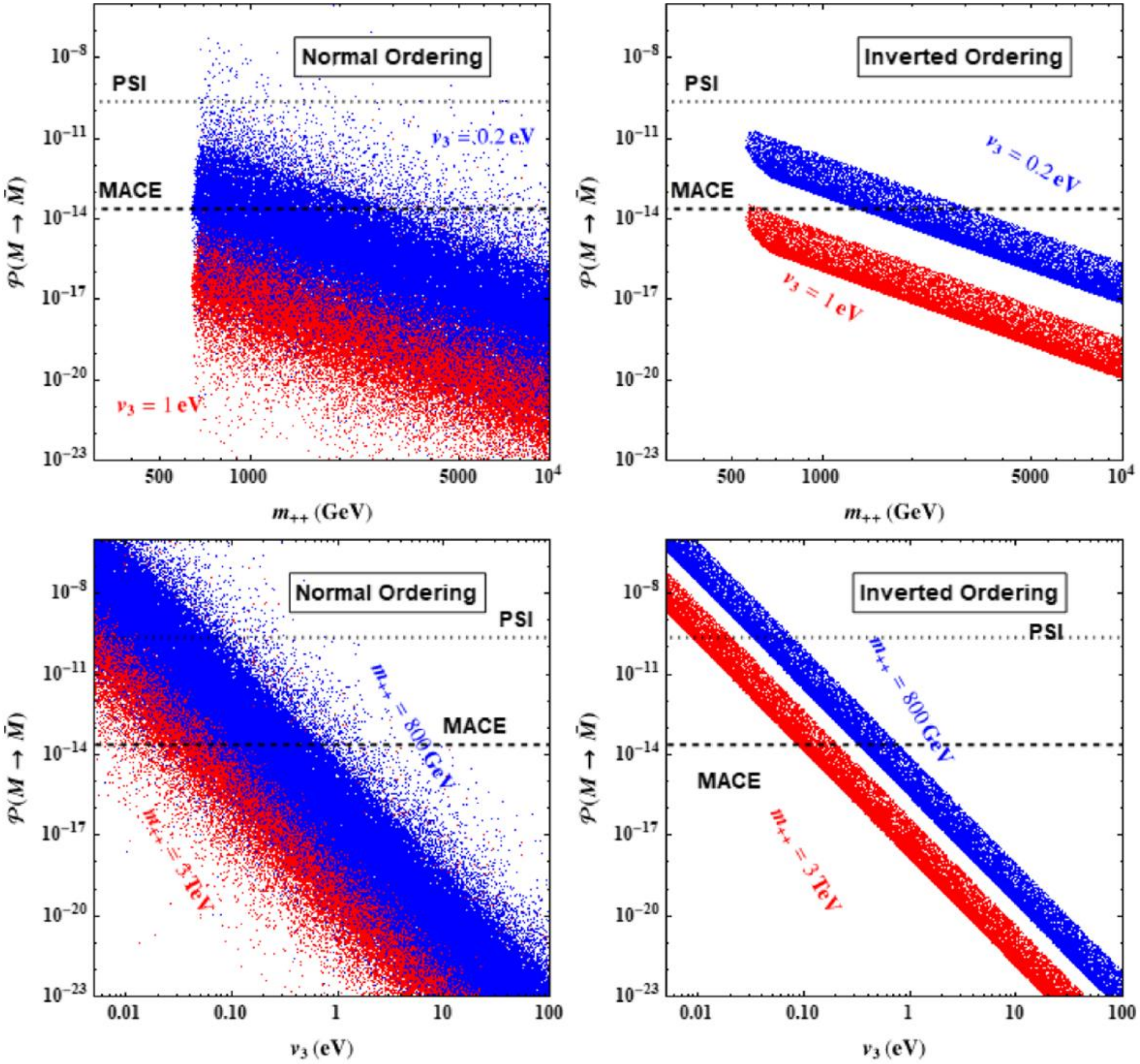
利用MACE鉴别中微子质量模型

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

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

- 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

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



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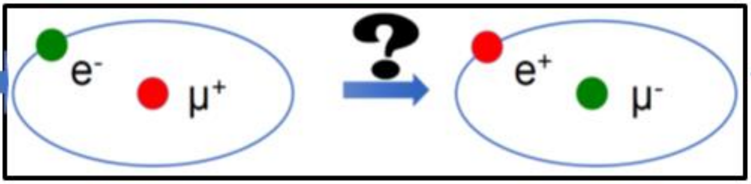
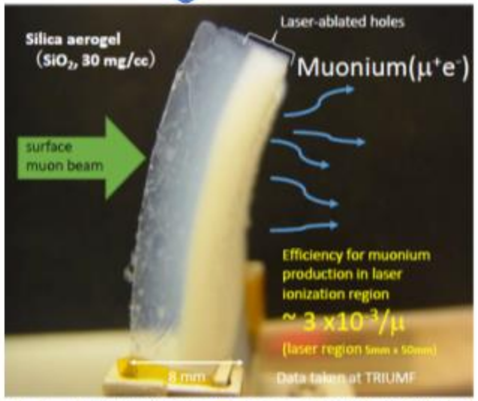
MC模拟软件开发和实验方案优化

Muonium to Antimuonium Conversion Experiment(MACE)

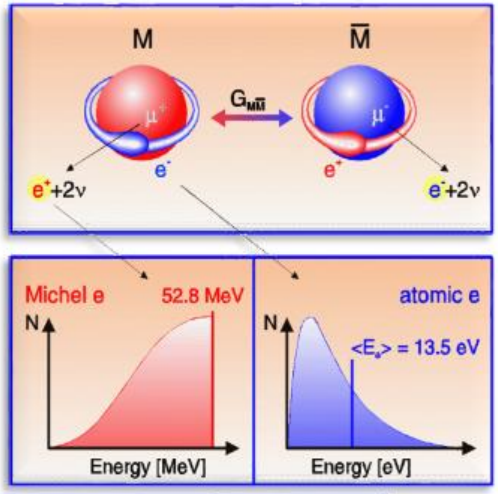
提高缪子素产生效率？

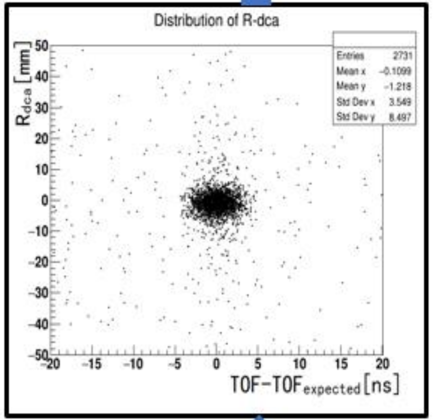


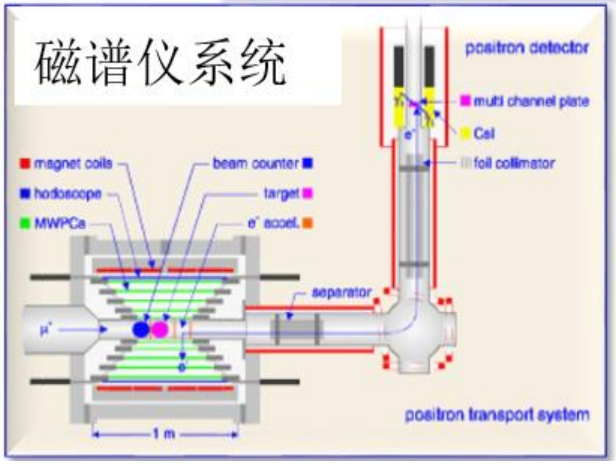
提高信噪比？

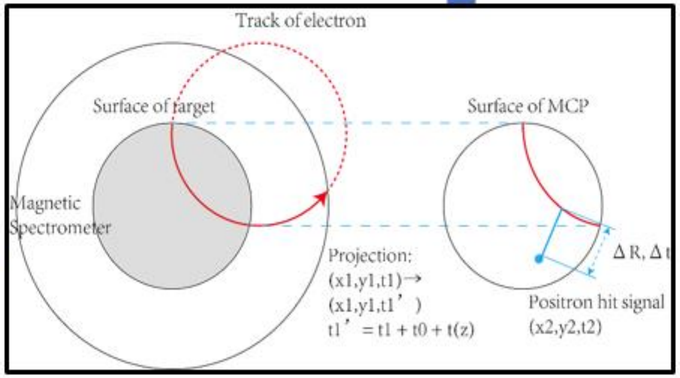


kule et al., PTEP 103C0 (2013), G. Beer et al., PTEP 091C01 (2014)







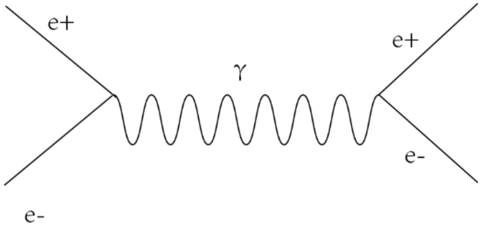


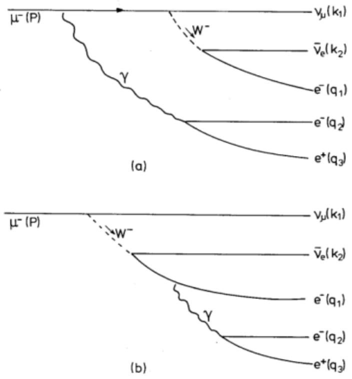
高分辨率磁谱仪？

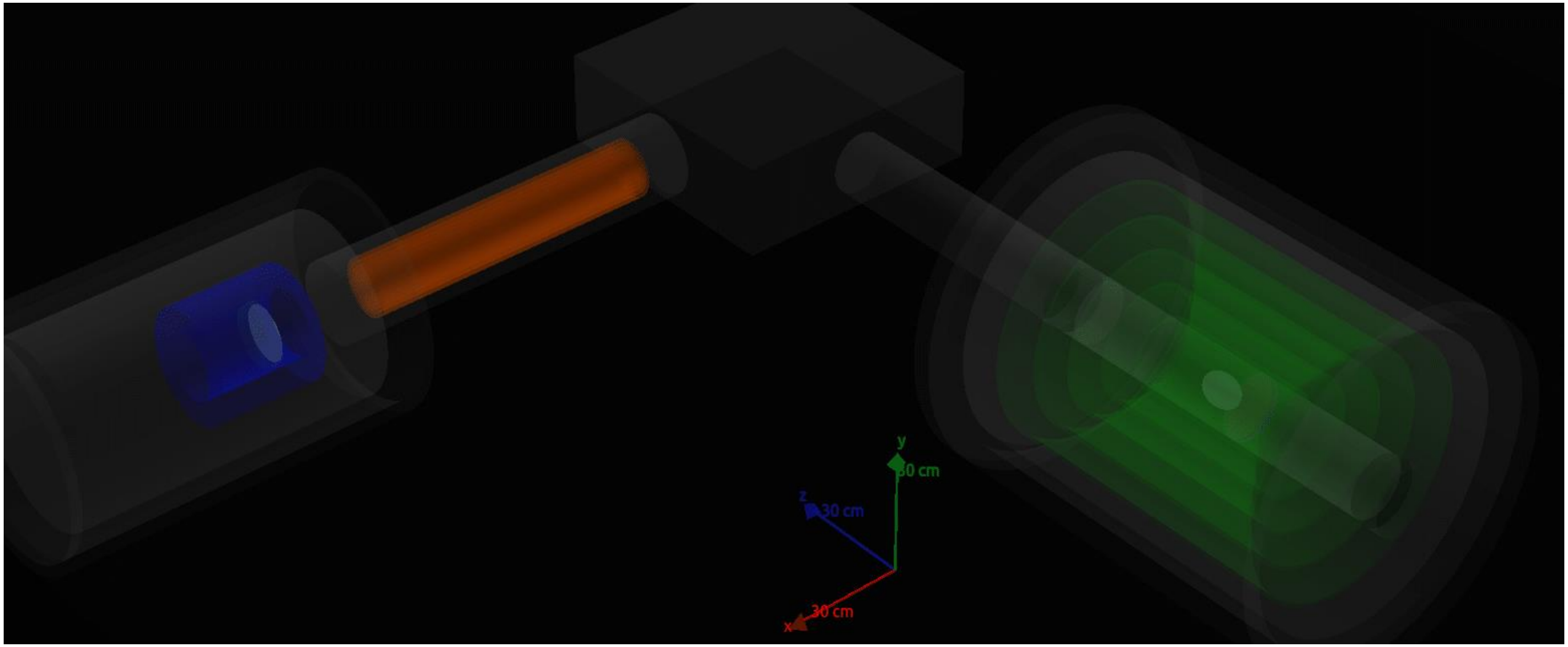
多重符合探测技术？

Toy MC simulation

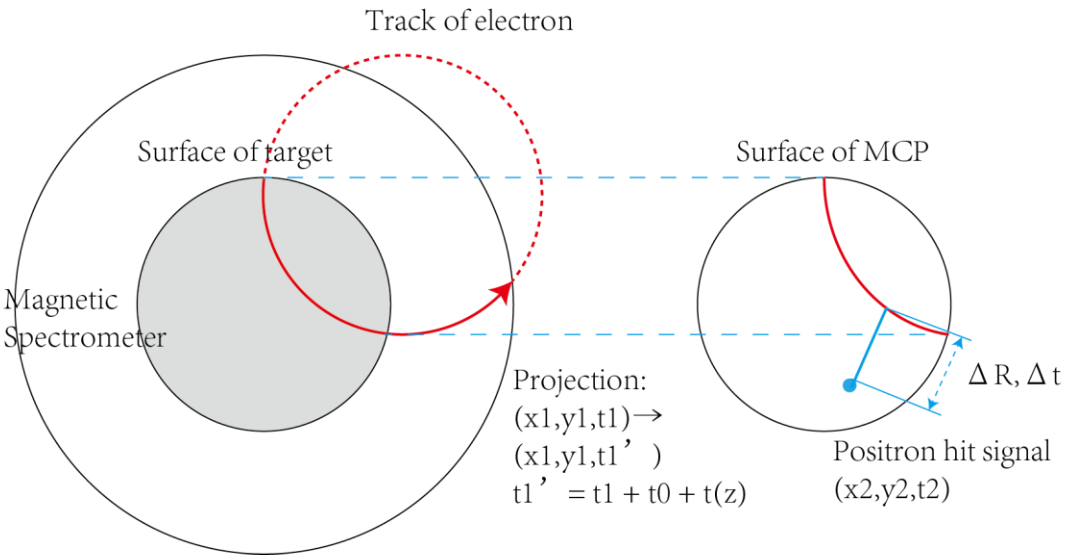
- Backgrounds:
  - μ^+ decays to e^+, Bhabha scattering to generate high-energy e^- in coincident with low-energy e^+
  - μ^+ decays: $\mu^+ \to e^+ \nu_e \overline{\nu_\mu} e^+ e^-$
- Anti-muonium decay signals by position-time coincidence

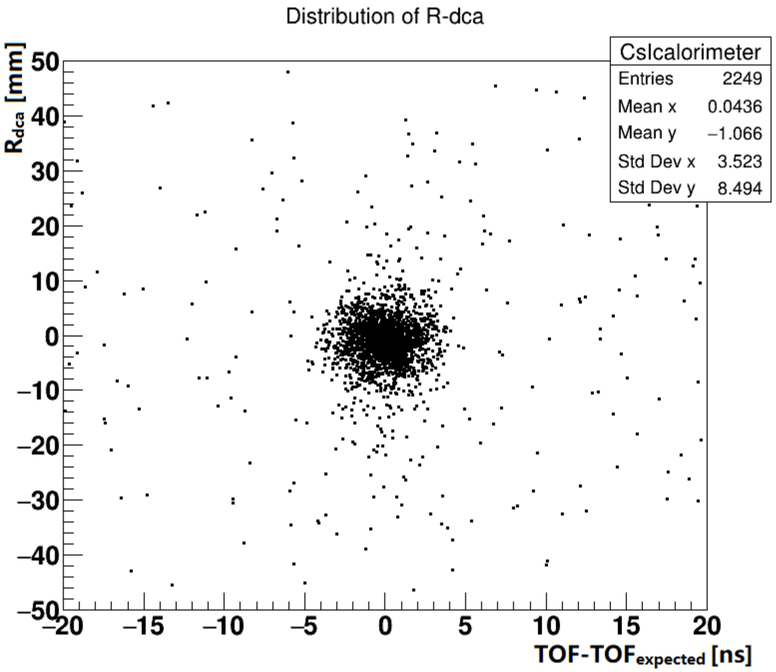






Muonium generators in Toy MC simulation





- Injected muons: 1.2×10^5 of μ^+
- In our simulation, 76% detection efficiency.
- Consistent with PSI muonium formation results.

- Happen at the same vertex:

  $|\Delta R| \sim R_{dca} < 12.0$ mm

- Happen at the same time:

  $|\Delta t| \sim TOF\text{-}TOF_{expected} < 4.5$ ns:
  $TOF = t0 + t(z)$

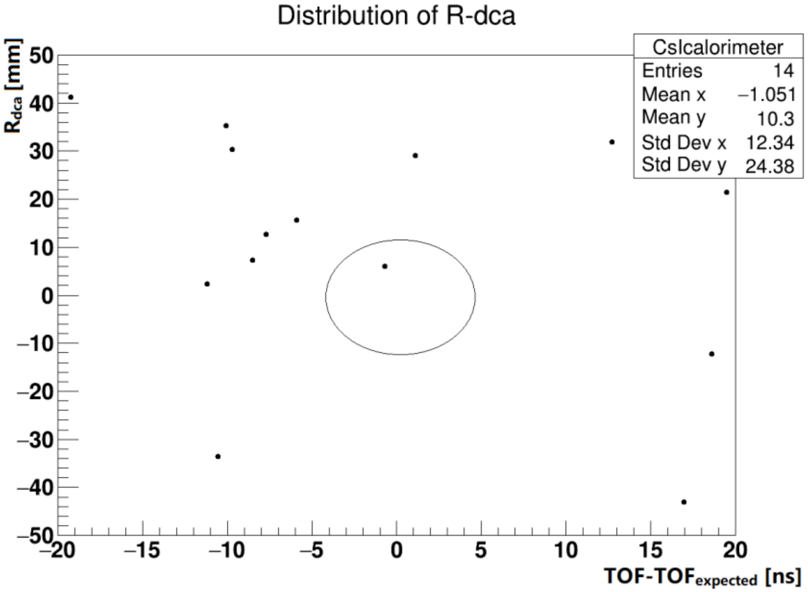
Courtesy: Yu-Zhe Mao

Rare decays in Toy MC simulation

1. Preliminary results in simulation

- 1.056×10^{8} of μ^{+}
- BR of $\mu^+ \rightarrow e^+e^-e^+\nu_e\overline{\nu_\mu}$

is set to 100%.



2. Compared with PSI estimates

- 9.459×10^{7} of μ^{+} Rare decay
- 1.7 background events expected.

- Happen at the same vertex:

  $|\Delta R| \sim R_{dca} < 12.0$ mm

- Happen at the same time:

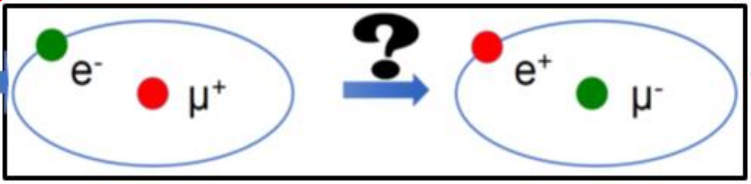
  $|\Delta t| \sim \text{TOF-TOF}_{expected} < 4.5$ ns:
  TOF = t0 + t(z)

Courtesy: Yu-Zhe Mao ⇨ Cross check and improvement on the way.

MC模拟软件开发和实验方案优化

Muonium to Antimuonium Conversion Experiment(MACE)

提高缪子素产生效率？



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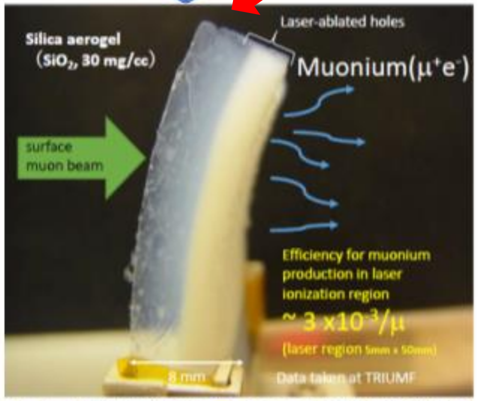

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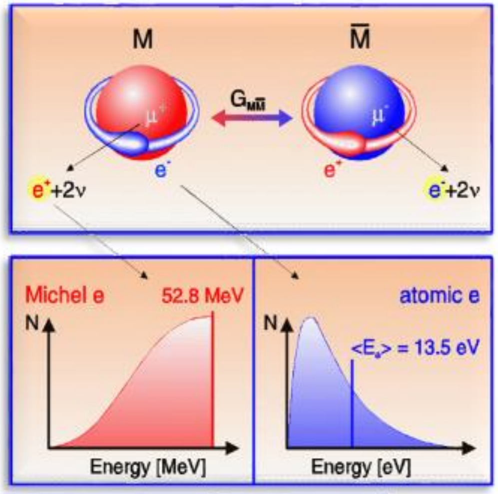
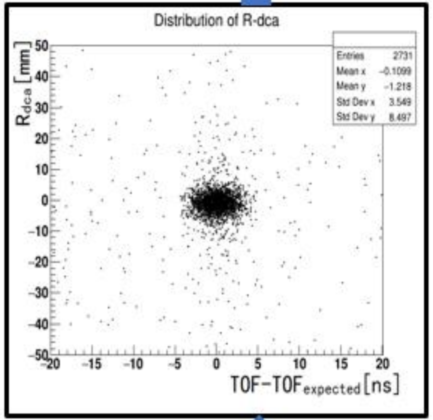
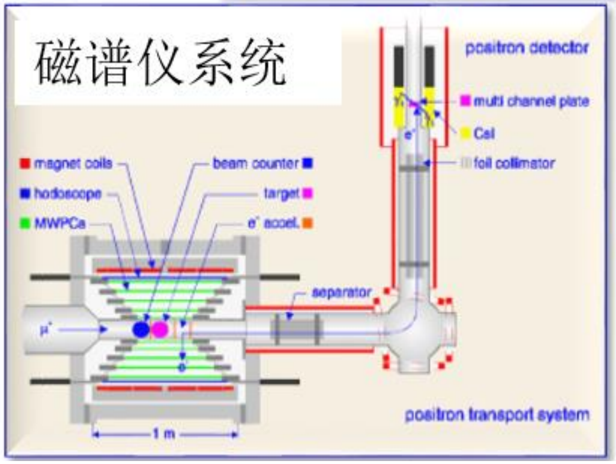
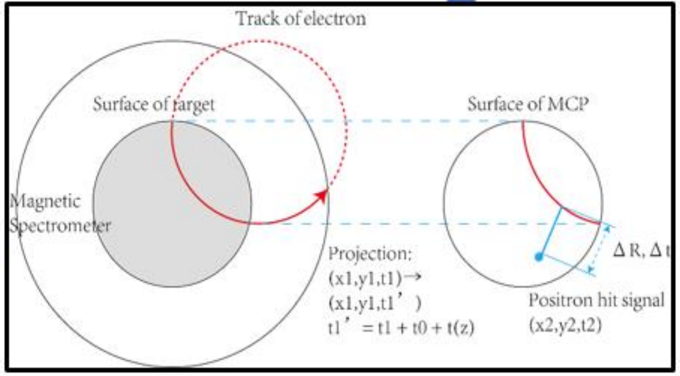






高分辨率磁谱仪？



多重符合探测技术？

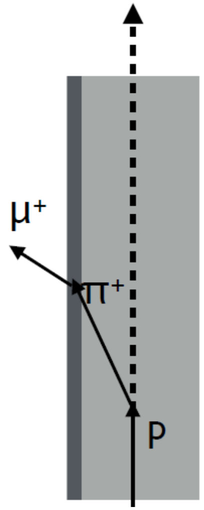
缪子的产生和缪子素的产生

$$\text{relative } \mu^{+} \text{ yield } \propto \pi^{+} \text{stop density} \cdot \mu^{+} \text{Range} \cdot \text{length}$$

$$\propto n \cdot \sigma_{\pi^{+}} \cdot SP_{\pi^{+}} \cdot \frac{1}{SP_{\mu^{+}}} \cdot \frac{\rho_{C}(6/12)_{C}}{\rho_{x}(Z/A)_{x}}$$

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

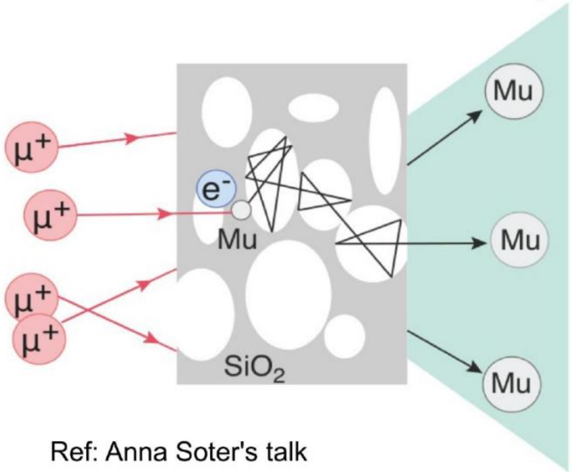
$$\propto \frac{1}{Z^{2/3}}$$



Previous experience

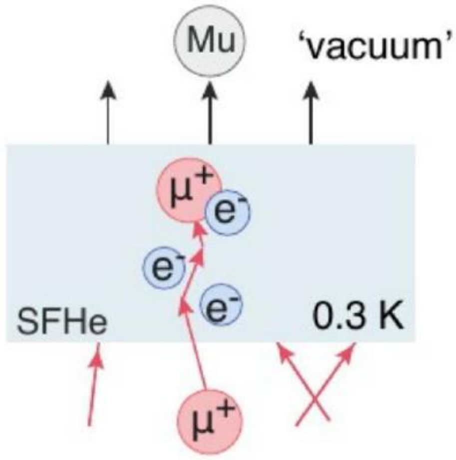
- Hot tungsten in 1986: 4% from 4 MeV μ^{+}
- SiO_2 powder in 1990: 1%-2% from 4 MeV μ^{+}
- SiO_2 film(cold) in 2012: 40% from 5 keV μ^{+}

Proposed target: aerogel, super fluid helium…

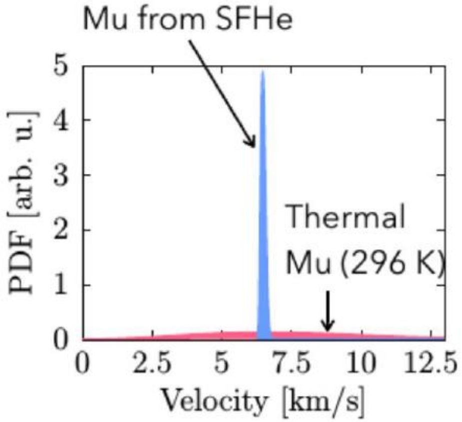


Ref: Anna Soter's talk

Silica powder



Super Fluid Helium



Thermal diffusion of Muonium in SiO_2

- 实验中muonium产额自然越高越好。muonium产额主要受两个方面影响：

缪子停在靶中的数量 ↓ muonium的绝对产率

有多少muonium飘出材料进入真空 ↓ 有用的muonium的产量

研究muonium在靶中的输运

- 使用带吸收项的输运方程研究muonium的输运：

输运项

$$\boxed{\frac{\partial\rho}{\partial t} - D\nabla^2\rho} + \boxed{\gamma\rho} = 0$$

sink term（吸收项）：muonium衰变

ρ：输运中位置的概率分布

D：等效扩散系数 → 唯象参数

γ：衰变常数的倒数

Ph.D Thesis
Alex Grossmann, Myonium produktion beim Experiment zur Suche nach Myonium Antimyonium Oszillationen (1995)

Thermal diffusion of Muonium in SiO$_2$ gel

- <u>稳态粒子数密度分布</u>

$$\frac{\partial\psi}{\partial t} - D\nabla^2\psi + \frac{\psi}{\tau} = 0$$

对单粒子：位置分布
对粒子群：数密度分布

持续的束流打靶：源项

$$\frac{\partial\psi}{\partial t} - D\nabla^2\psi + \frac{\psi}{\tau} = f$$

弛豫时间量级：1 μs

靶内muonium从产生到跑出靶外/衰变的时间量级：1 μs

$$\left(\nabla^2 - \frac{1}{D\tau}\right)\psi = f \xrightarrow[\Omega\text{：靶区域}]{\text{靶外形优化}}$$

$$\left(\nabla^2\psi - \frac{1}{D\tau}\right)\psi = f$$

$$\psi_{\partial\Omega} = 0$$

$$\text{Find :}\quad \Omega \to \max \oint_{\partial\Omega} \frac{\partial\psi}{\partial n}$$

Alex Grossmann, Myoniumproduktion beim Experiment zur Suche nach Myonium Antimyonium Oszillationen (1995)

Thermal diffusion of Muonium in SiO_2 gel

- <u>无界空间点源解的验证</u>

利用点源解验证

$$\left(\nabla^2 - \frac{1}{D\tau}\right)\psi = f$$

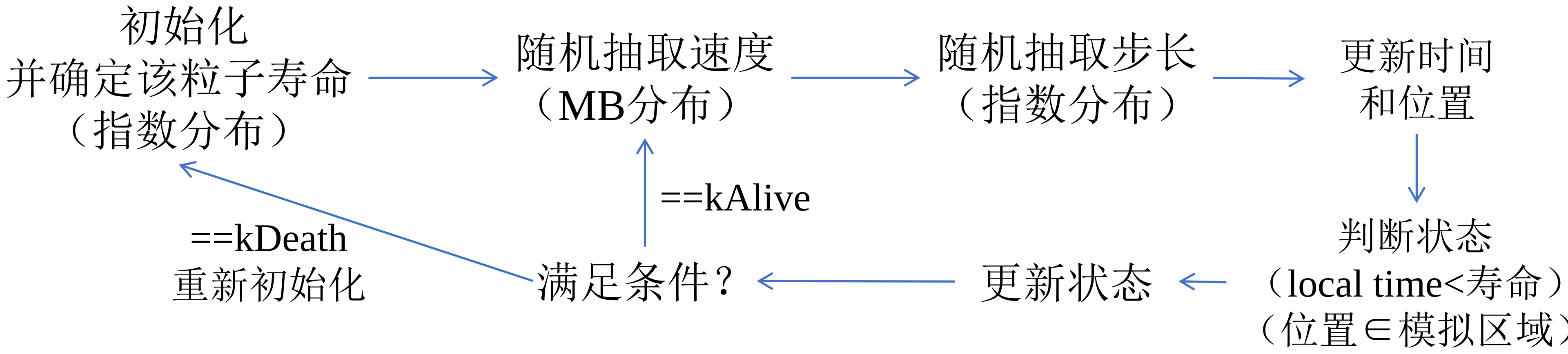
处理random flight问题的有效性：
（给定平均自由程和温度）

$$D = \frac{1}{3}\langle\lambda\rangle\sqrt{\frac{8kT}{\pi m}}$$

点源解：

$$\left(\nabla^2\psi - \frac{1}{D\tau}\right)\psi = 4\pi\delta(\vec{r}) \longrightarrow \psi(\vec{r}) = \frac{e^{-\frac{r}{\sqrt{D\tau}}}}{r}$$

Monte Carlo模拟random flight：（CLHEP + ROOT + OpenMPI）



初始化
并确定该粒子寿命
（指数分布）

随机抽取速度
（MB分布）

随机抽取步长
（指数分布）

更新时间
和位置

判断状态
（local time<寿命）
（位置∈模拟区域

更新状态

满足条件？

==kAlive

==kDeath
重新初始化

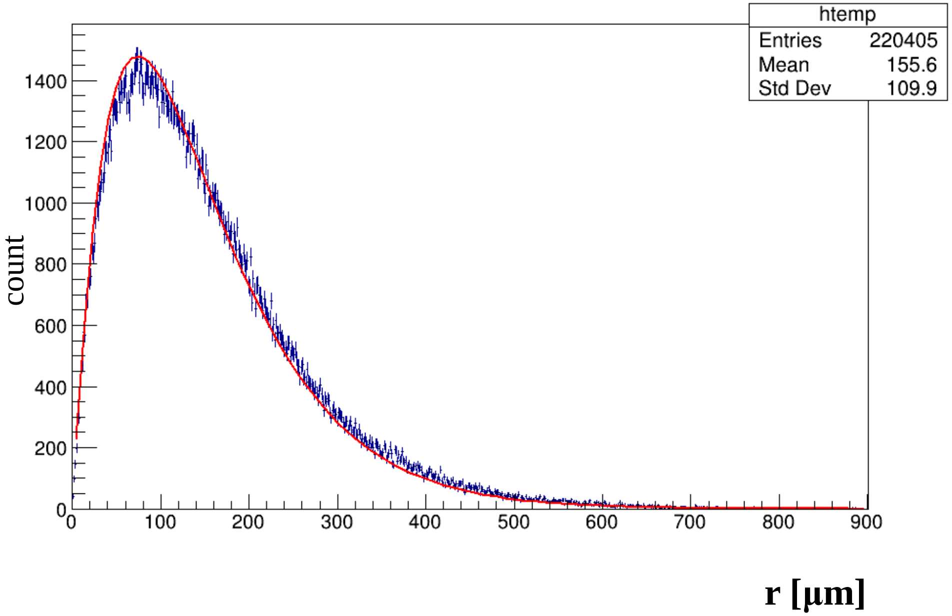
Thermal diffusion of Muonium in SiO$_2$ gel

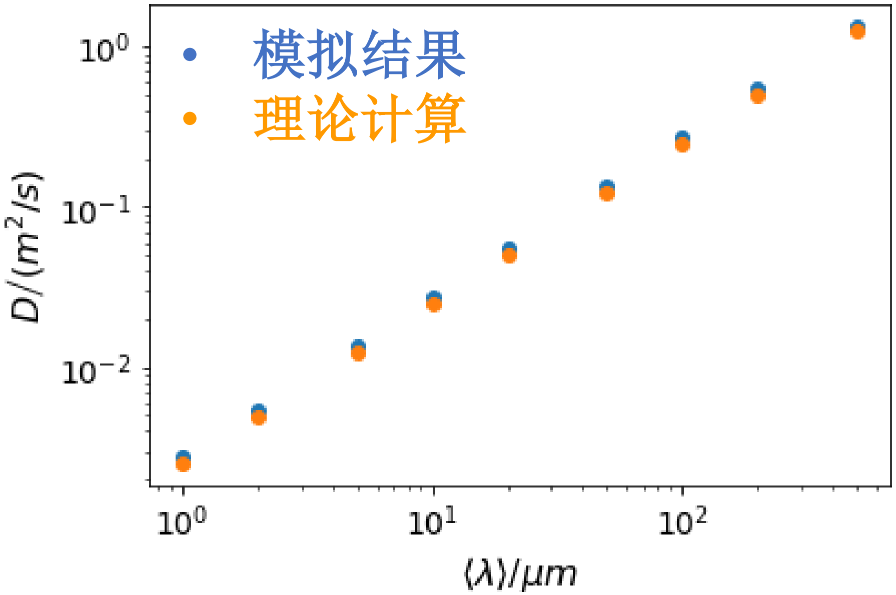
- 无界空间点源解的验证

点源解是球对称的，只用关心径向分布 $4\pi r^2\psi(r) = 4\pi A \times r e^{-\frac{1}{\sqrt{D\tau}}r}$

下图：300K，平均自由程1μm的MC结果。
红线代表理论解

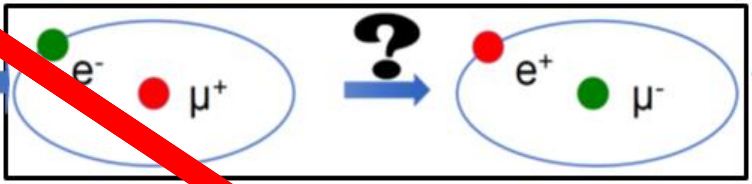
300K，不同平均自由程下模拟和理论给出的扩散系数：$D = \frac{1}{3}\langle\lambda\rangle\sqrt{\frac{8kT}{\pi m}}$
理论值比模拟值偏小8～9%，可以接受。





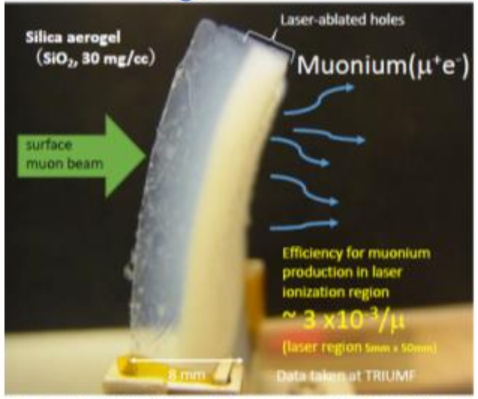
径迹重建算法的实现

Muonium to Antimuonium Conversion Experiment(MACE)

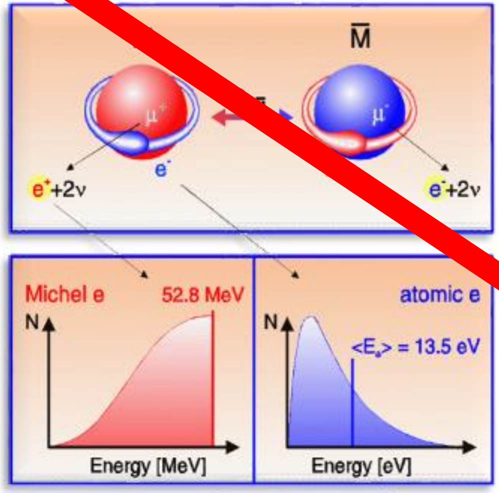


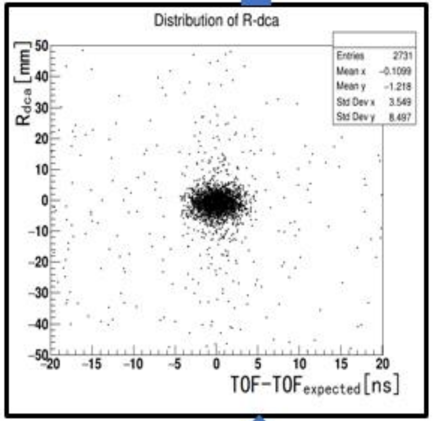
提高缪子素产生效率？

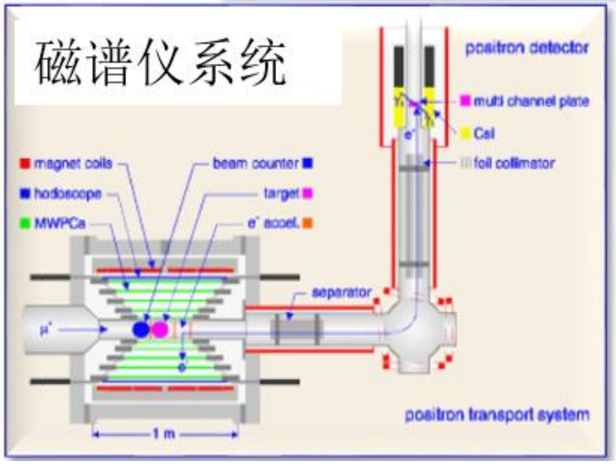
提高信噪比？

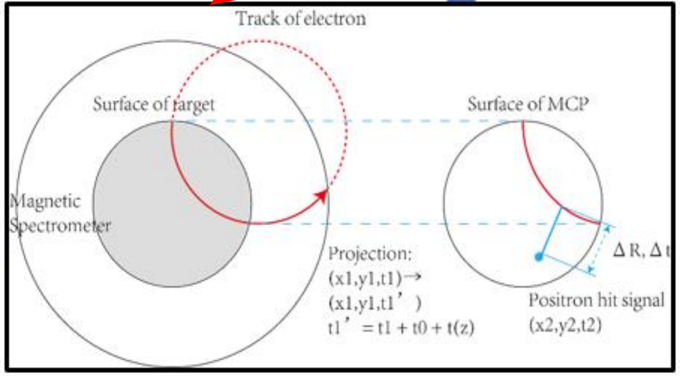


ıkule et al., PTEP 103C0 (2013), G. Beer et al., PTEP 091C01 (2014)









高分辨率磁谱仪？

多重符合探测技术？

MACE实验末态粒子重建需求

- 事例准确重建的关键在于重建磁谱仪中的带电粒子轨迹(螺旋线)。

- 磁谱仪由多层探测器（MWPC/TPC）组成，每个带电粒子飞过其中时会在多层记录下它的位置信息，这是轨迹重建的起点。

- 处理两方面的内容：
  1. 哪些点属于同一条轨迹；
  2. 一条轨迹对应的是什么参数（位置、动量...）

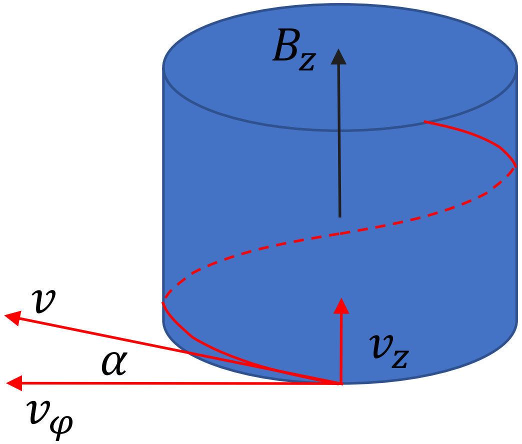
- 由于模拟的数据很干净，可以直接处理后者，即确定径迹的参数。前者是模式识别的任务，但相对复杂，引入噪声和更高本底之后再做考虑。先讨论参数的确定。

MACE实验末态粒子重建初步结果

- 轴向和切向是不耦合的，可以分开处理。

$$\vec{F} = e\vec{v} \times \vec{B}$$
$$\vec{v} = v(\vec{e}_\varphi \cos\alpha + \vec{e}_z \sin\alpha) \Rightarrow \begin{cases} x = x_c + R\sin(\omega t + \varphi_0) \\ y = y_c + R\cos(\omega t + \varphi_0) \\ z = z_0 + vt\sin\alpha \end{cases}$$
$$\vec{B} = B_z\vec{e}_z$$

$$R = \frac{mv}{eB_z}\cos\alpha \qquad \omega = \frac{eB_z}{m}$$



- 为方便最小二乘法，用标准方程避开时间t：

$$(x - x_c)^2 + (y - y_c)^2 = R^2$$
$$z = z_0 + R\varphi\tan\alpha$$

- 对于切向（圆），最小化的目标是

$$\xi = x - \bar{x} \quad \eta = y - \bar{y}$$

$$L(\xi_c, \eta_c, R) = \sum_{i=0}^{n} R^2 - (\xi_i - \xi_c)^2 - (\eta_i - \eta_c)^2$$

MACE实验末态粒子重建初步结果

- 目标函数可以直接最小化，得到圆心和半径三个参数。

$$\nabla_{(\xi_c,\eta_c,R)}L=0 \quad \Rightarrow \quad \begin{cases} \xi_c = \dfrac{1}{2}\dfrac{\sum\eta_i^2\sum\xi_i(\xi_i^2+\eta_i^2)-\sum\xi_i\eta_i\sum\eta_i(\xi_i^2+\eta_i^2)}{\sum\xi_i^2\sum\eta_i^2-\sum\xi_i\eta_i\sum\xi_i\eta_i} \\ \eta_c = \dfrac{1}{2}\dfrac{\sum\xi_i^2\sum\eta_i(\xi_i^2+\eta_i^2)-\sum\xi_i\eta_i\sum\xi_i(\xi_i^2+\eta_i^2)}{\sum\xi_i^2\sum\eta_i^2-\sum\xi_i\eta_i\sum\xi_i\eta_i} \\ R = \sqrt{\dfrac{1}{n}\sum_i(\xi_i-\xi_c)^2-(\eta_i-\eta_c)^2} \end{cases}$$

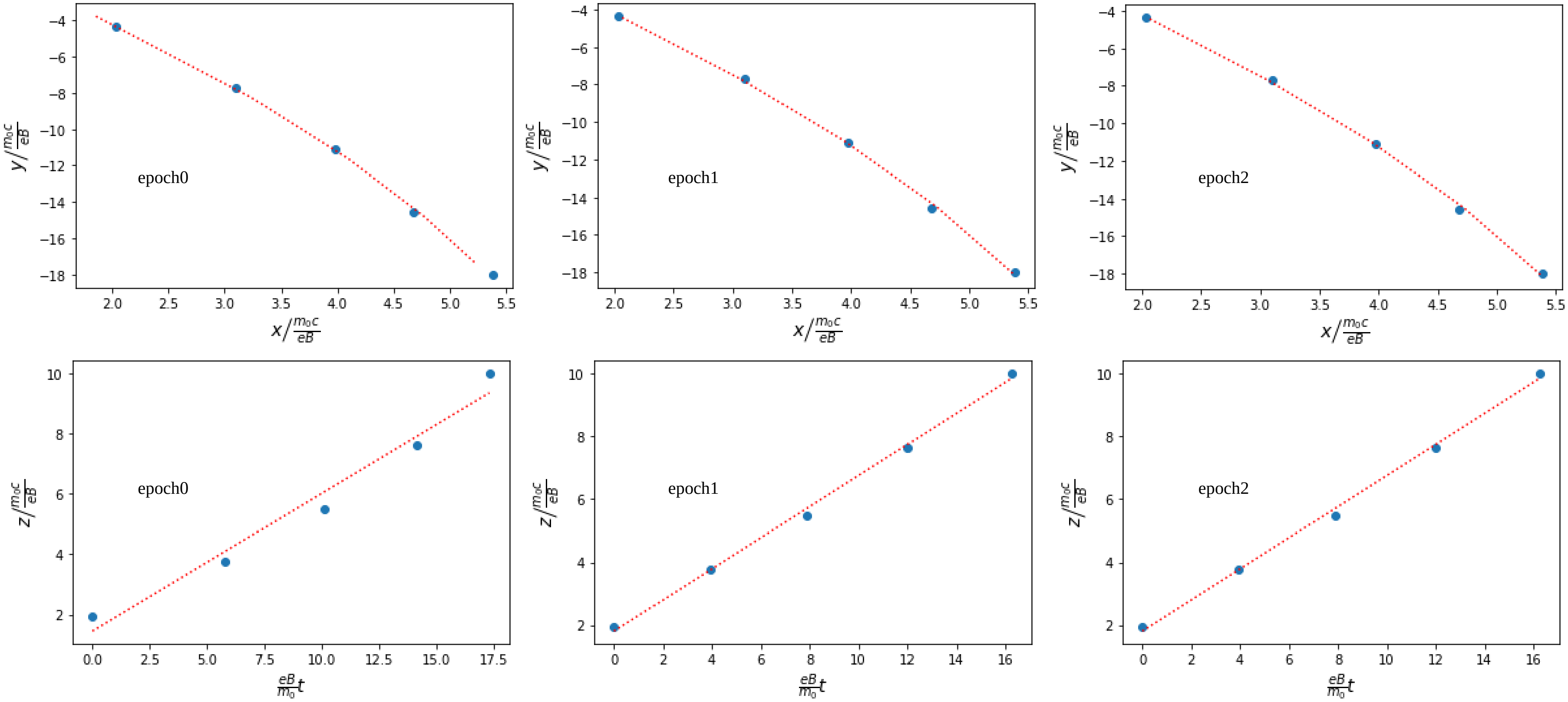
- 对z方向，从坐标重建角度φ后，拟合z和φ得到剩下两个参数。

$$(x_i,y_i)\to\varphi_i \quad \longrightarrow \quad z=z_0+R\varphi\tan\alpha \quad \longrightarrow \quad \begin{aligned} \tan\alpha &= \frac{\overline{R\varphi z}-\overline{R\varphi}\,\overline{z}}{\overline{(R\varphi)^2}-\overline{R\varphi}^2} \\ z_0 &= \overline{z}-\overline{R\varphi}\tan\alpha \end{aligned}$$

MACE实验末态粒子重建初步结果

- 某个事件两次迭代拟合(已经无量纲化处理)

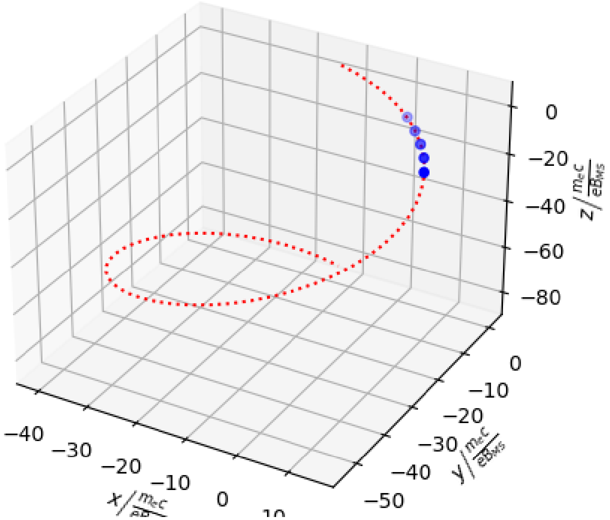
$$r^* = r \Big/ \frac{m_0 c}{eB} \qquad t^* = \frac{eB}{m_0} t \qquad v^* = \frac{v}{c}$$



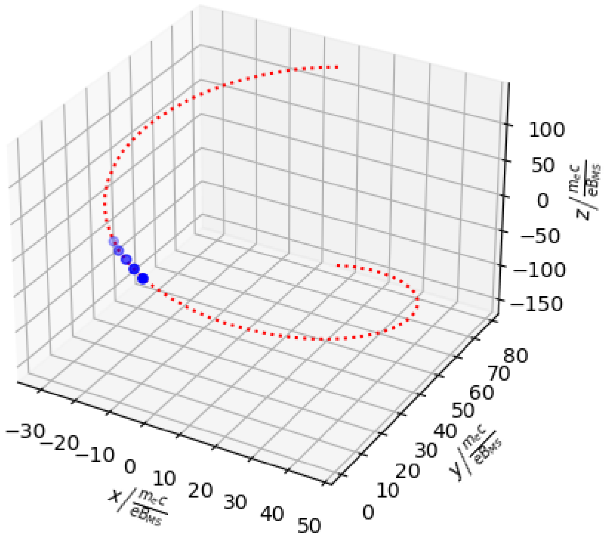
- 从Toy MC走向更真实探测器的可观测量!

MACE实验末态粒子重建初步结果

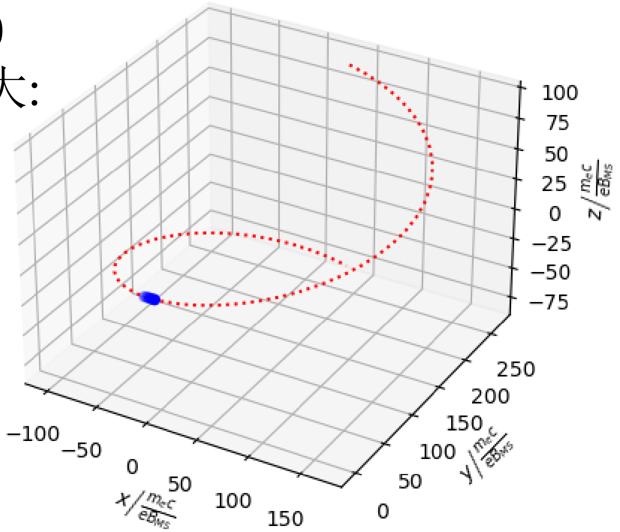
$v_z < 0$:



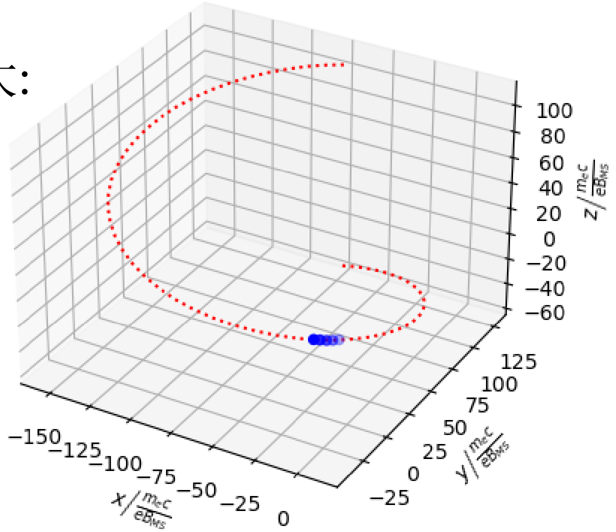
$v_z > 0$:



$v_z < 0$
动量更大:



$v_z > 0$
动量更大:

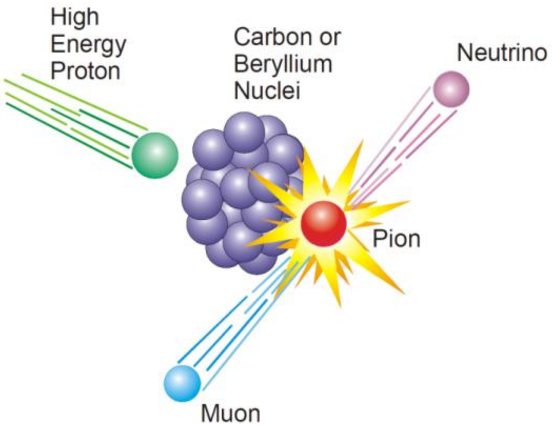


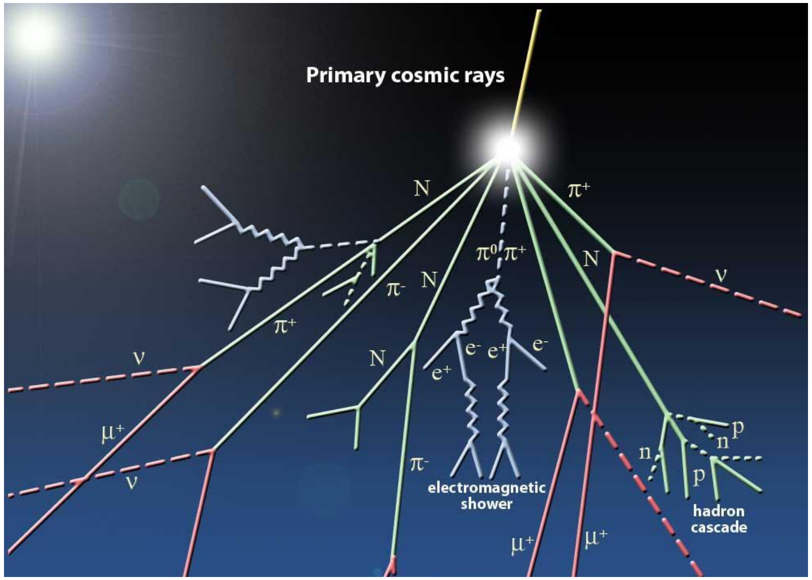
- 从Toy MC走向更真实探测器的可观测量!

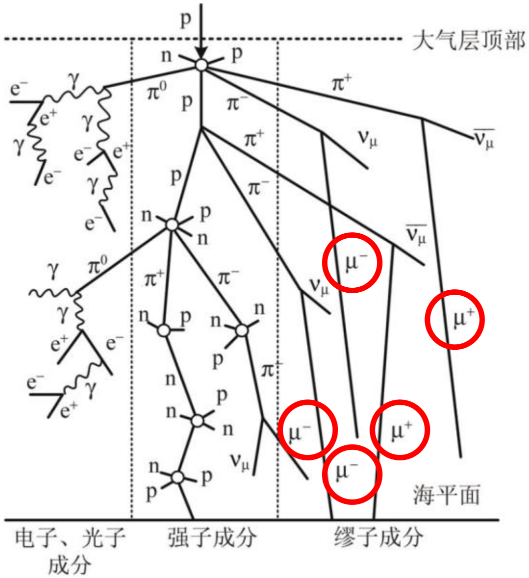
Table of contents

加速器缪子 v.s 宇生缪子

- 缪子μ: 带电轻子，参与电磁和弱相互作用
- 缪子质量：105 MeV，寿命：2.2 微秒(μs)
- 缪子源: 宇生缪子源，加速器缪子源



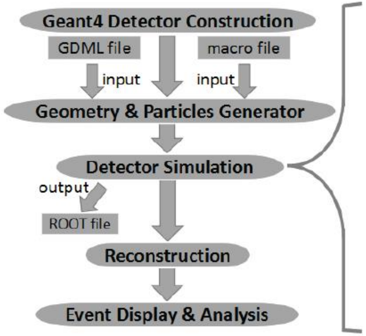




中山大学SMOOTH实验室建设

- 我国暂时无法提供具有方向性、高通量、单能可调的加速器缪子源
- 如何搭建本地的缪子前沿科学与技术应用实验室呢？
- To be or not to be?
- 宇宙射线撞击大气层产生的宇生缪子：纯天然、无公害
- 教学型探测器→研究型探测器，本科生→研究生

SMOOTH-MuGrid径迹探测器的研制



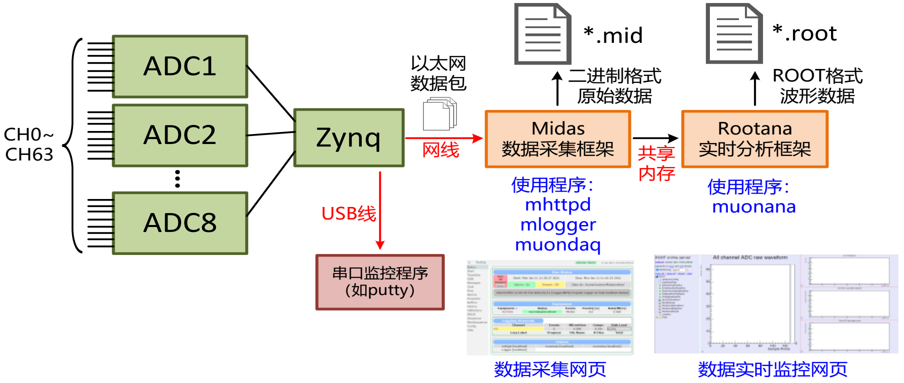
MuRunAction : Getting the geometric and property parameters of the plastic scintillator
MuEventAction : Obtaining the position and the direction of scintillation photons
MuStackingAction : Counting the numbers of Cherenkov photons
MuPrimaryGeneratorAction : Setting the motion state of the particle

MuDetectorConstruction : Defining detector material, etc
MuDetectorMessenger : Setting commands to modify the detector

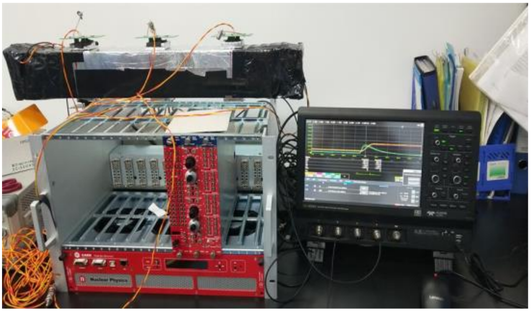
Physics : Defining physic list include electromagnetic interaction, nuclear physics and optical processes

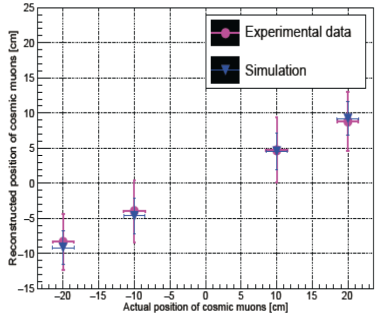
PscintHit-SD : Getting the track of the particle
SiPMHit-SD : Getting relevant informations of photons on SiPM

MuAnalysisManager : Defining the output file and save the data includes three branches ("para", "MuMCTruth", "evt")



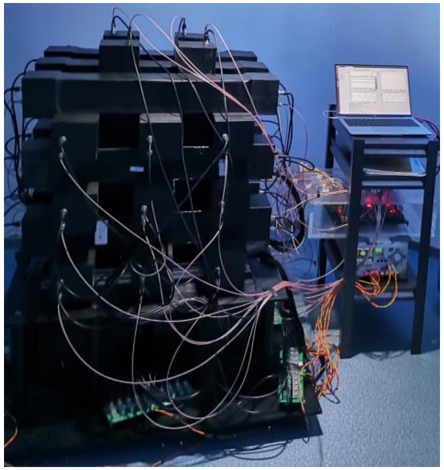
性能测试



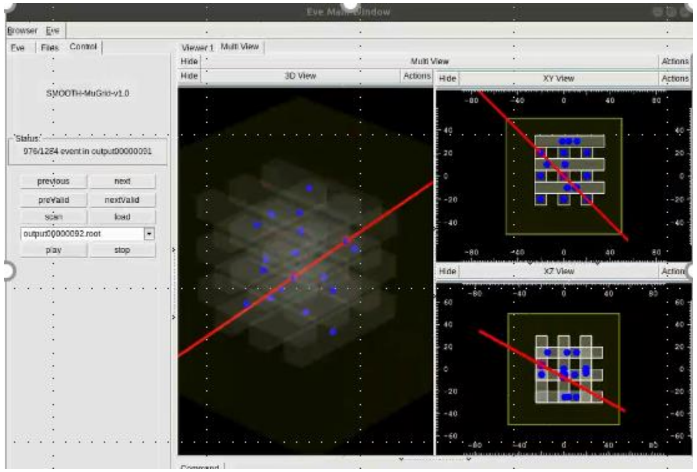


自研电子学板

实时取数



径迹重建



SMOOTH-MuGrid-v1.0

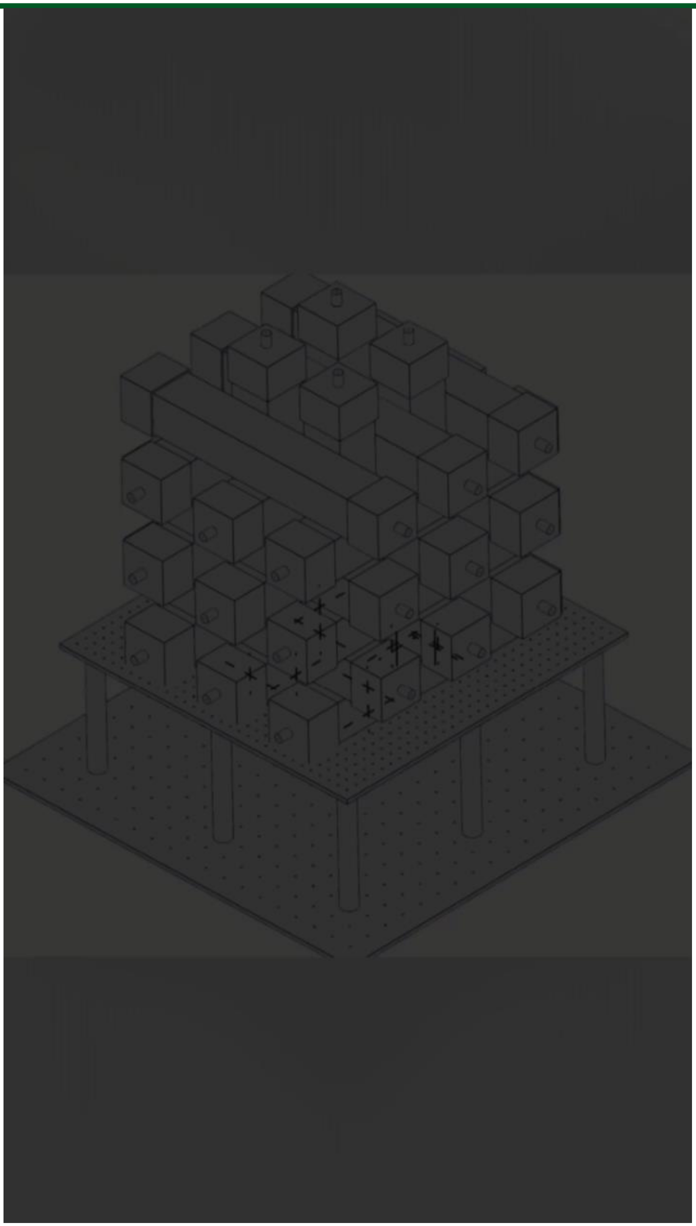
Status:
976/1284 event in output0000001

output0000092.root

宇生缪子探测器

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

SMOOTH-MuGrid研发历程

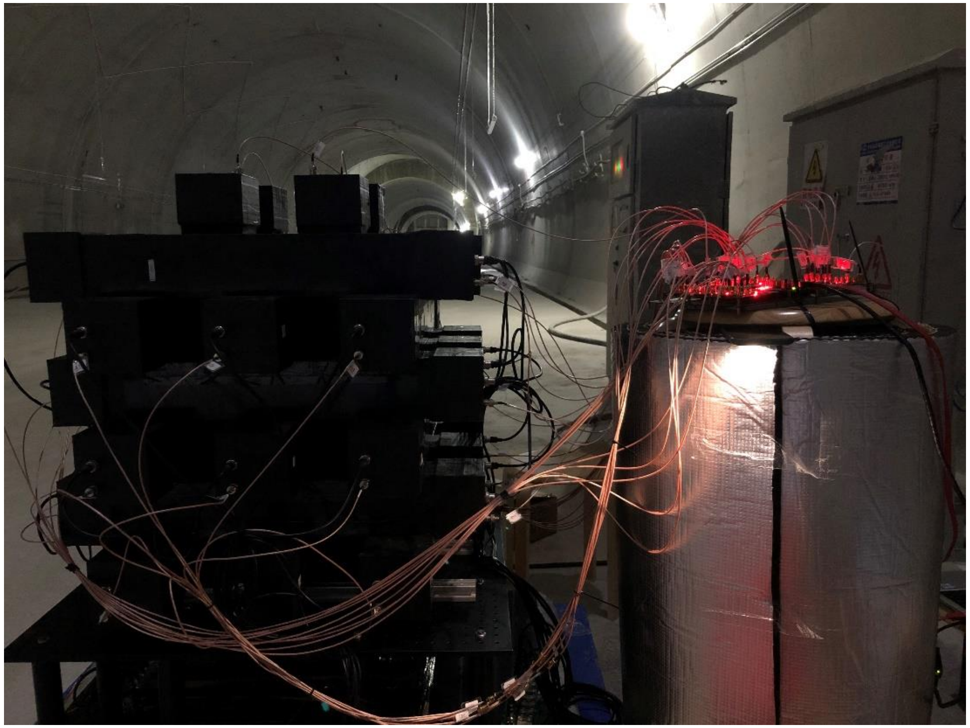


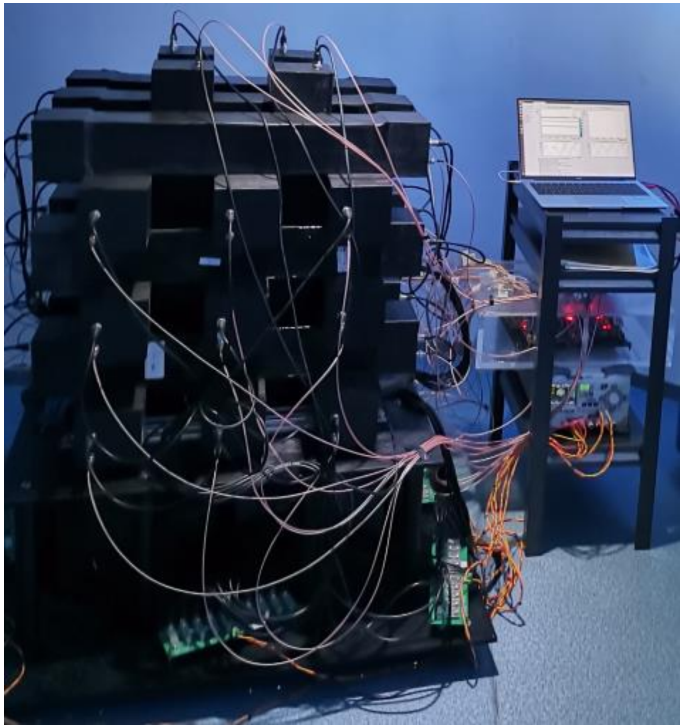
项目分工：

- DAQ电子学：**陈羽**
- 机械设计与结构：**沈韩、黄臻成**
- 探测器模拟仿真：**杨航、赵诗涵**
- 探测器封装：**余涛、黄俊尧**
- 实验室耗材：**胡碧莹**
- 教学型探测器：**林海星、宁云松…**
- 新型探测器研制：**徐宇、周逸行…**

SMOOTH-MuGrid山洞采集数据

- 感谢中山大学物理与天文学院，尤其感谢杨莉莉老师的鼎力支持
- 感谢天琴中心的建设者们

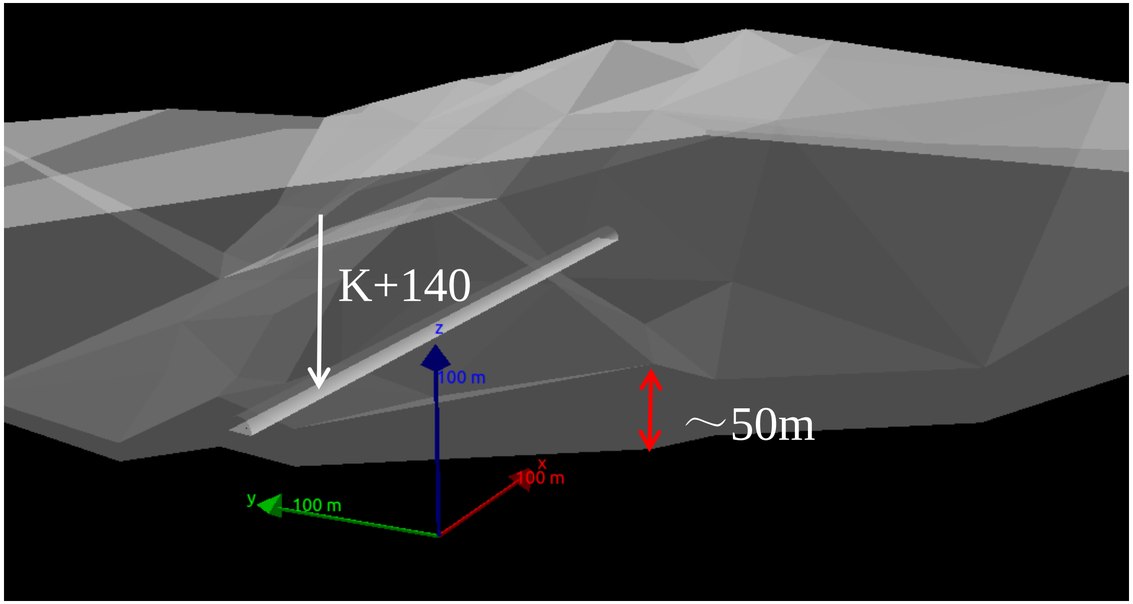


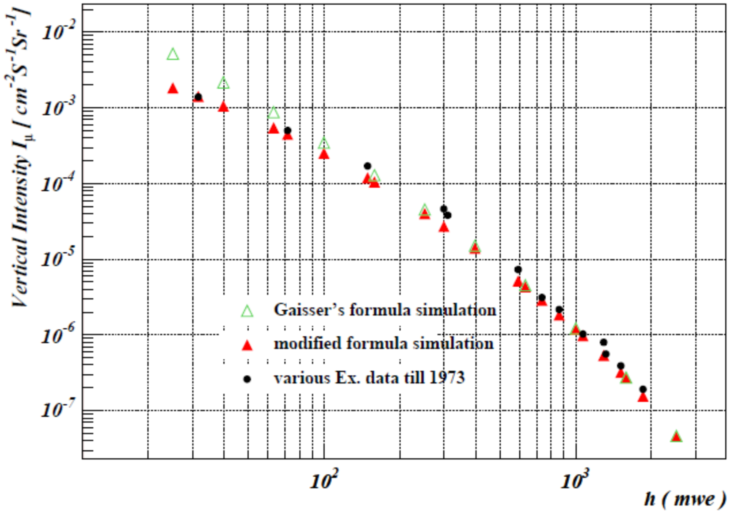


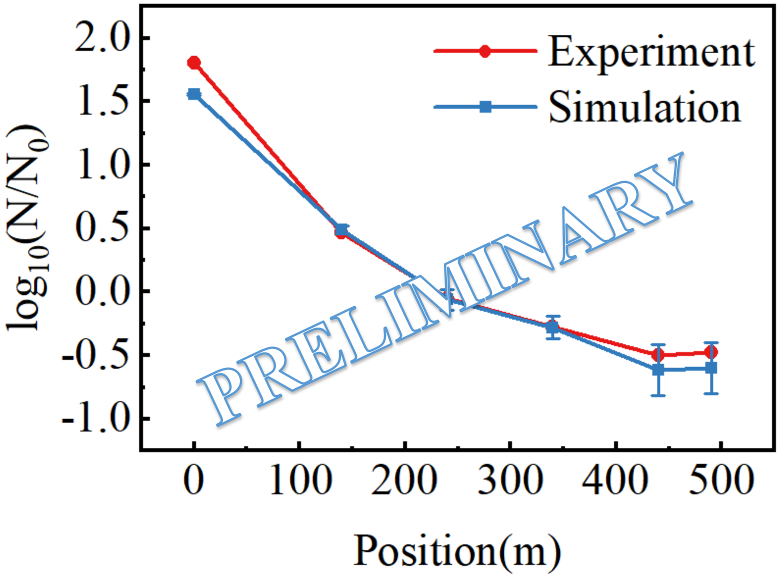
天琴山洞实验：定点、等间距测量

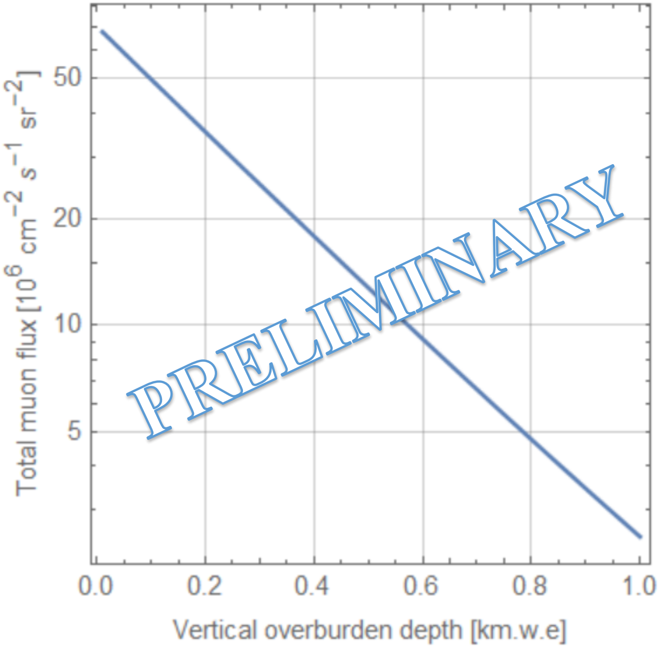
地面采集数据

山洞数据的分析


K+140
z
100 m
～50m
x
100 m
y
100 m

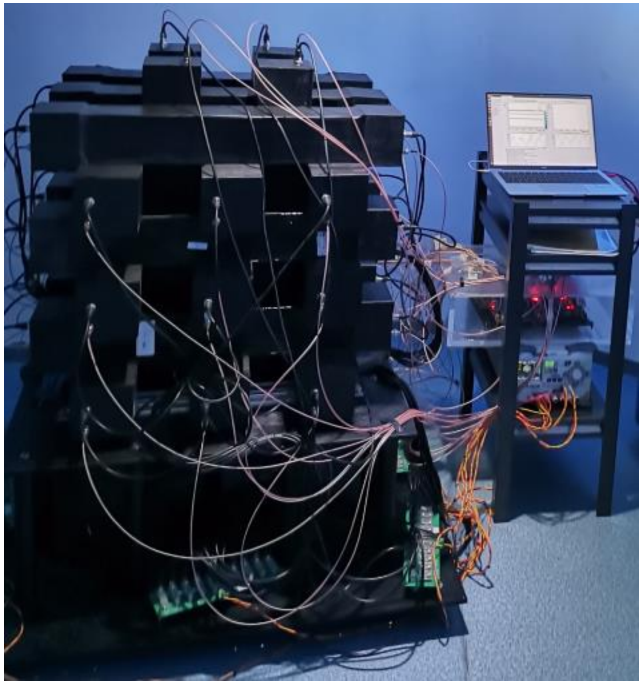

Vertical Intensity I_μ / $cm^{-2}S^{-1}Sr^{-1}$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{2}
10^{3}
h (mwe)
△ Gaisser's formula simulation
▲ modified formula simulation
● various Ex. data till 1973


$\log_{10}(N/N_0)$
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
0
100
200
300
400
500
Position(m)
Experiment
Simulation
PRELIMINARY

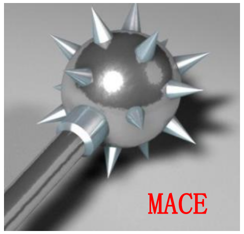

Total muon flux [10^6 cm^{-2} s^{-1} sr^{-2}]
50
20
10
5
0.0
0.2
0.4
0.6
0.8
1.0
Vertical overburden depth [km.w.e]
PRELIMINARY

SMOOTH-MuGrid演示实验

- 演示对象：高年级本科生
- 地点：中山大学南校园陆祐堂二楼
- 校园网内，利用MIDAS系统可实现远程实时监控



Summary



- 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。
- 我们利用Toy MC重现了PSI实验20年前的结果，缪子素产生和重建算法已经获得关键性进展，正在开展新型探测器系统的优化和设计
- 中山大学缪子科学与技术实验室SMOOTH已经初具规模
  - ➢ 缪子径迹探测器迭代升级中，可用于MACE实验的宇生缪子veto。
  - ➢ 加速器缪子束流监测探测器研制中，将在COMET实验进行束流测试。

- ○ *感谢IHEP唐靖宇、袁野、鲍煜等共同推动加速器缪子源(EMuS)及其应用。*
- ○ *感谢中大陈羽博士和王自鑫老师积极参加预研。*
- ○ *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！*
- ○ *感谢中大优秀本科生和实验室开放基金对本地缪子物理实验室的支持！*

THANK YOU