



中山大學

SUN YAT-SEN UNIVERSITY

物理學院

SCHOOL OF PHYSICS



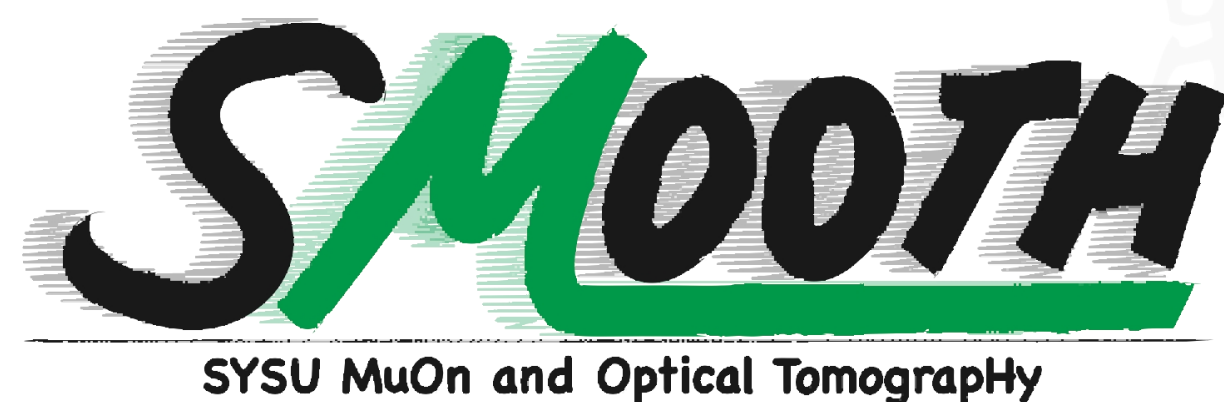
中山大學
SUN YAT-SEN UNIVERSITY

SMOOTH

宇生繆子自旋譜儀樣機研製與升級

孫銘辰，袁意，趙詩涵，祁頌然，白愛毓，余濤，寧雲松，張景頤

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NED 2026 登封

SMOOTH Lab, SCHOOL OF PHYSICS, SYSU

arXiv:2505.13877



- 缪子的自旋极化
- *Cosmic Ray Muon Spin Polarization Detector (CRmuSR)* 样机设计与标定结果
- 重建框架与测量结果
- 展望与总结



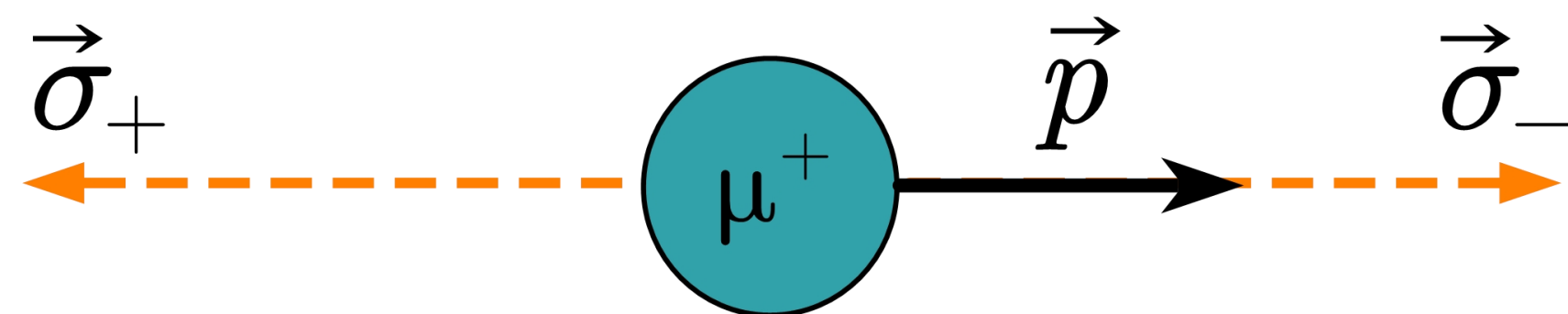
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1 缪子的自旋极化

缪子极化 $\mathbf{P}_\mu = \vec{\sigma} \cdot \frac{\vec{P}}{|\vec{P}|}$

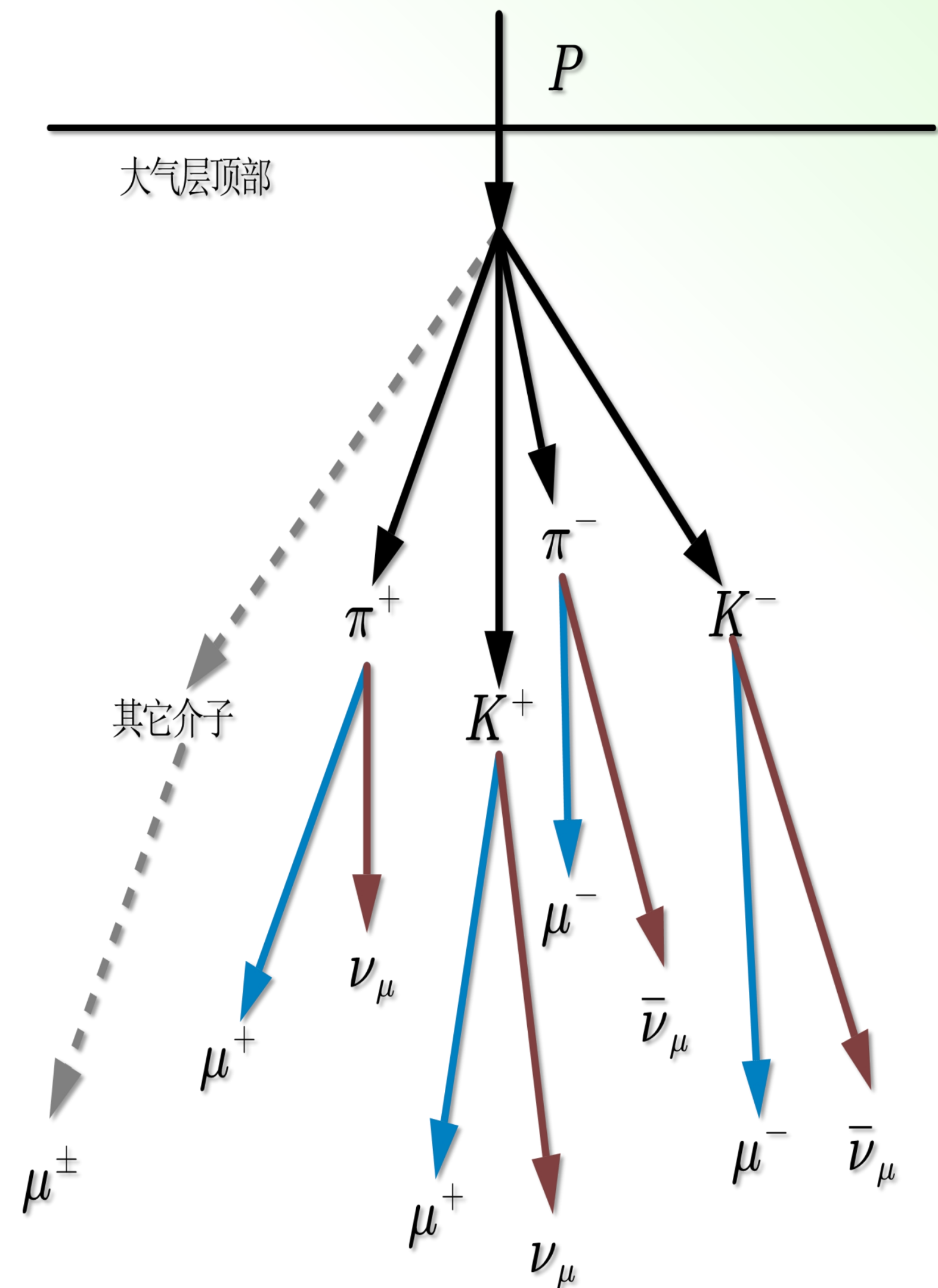
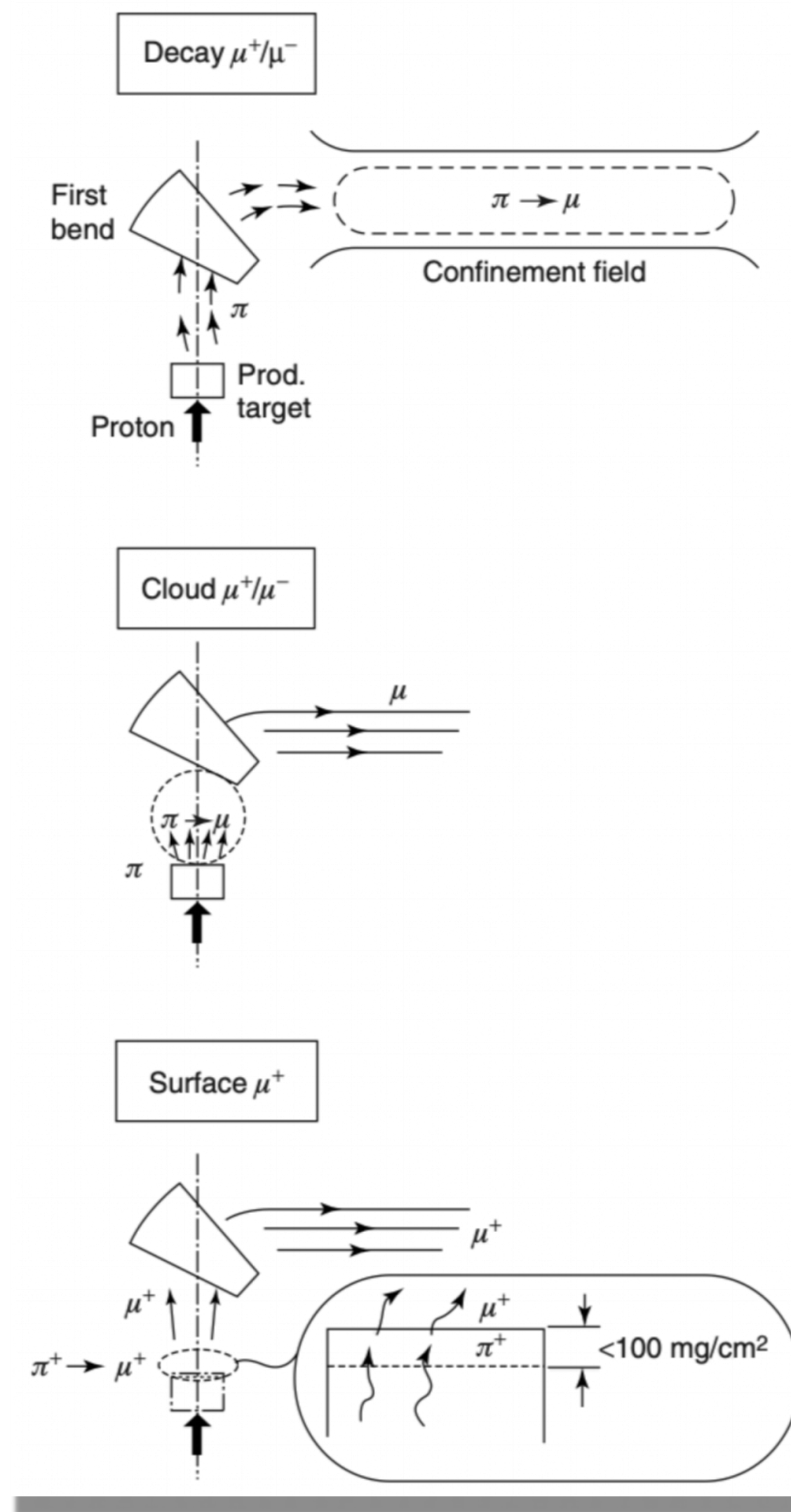
• 加速器缪子束流

$\pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$ 接近 100% 极化



• 宇生缪子

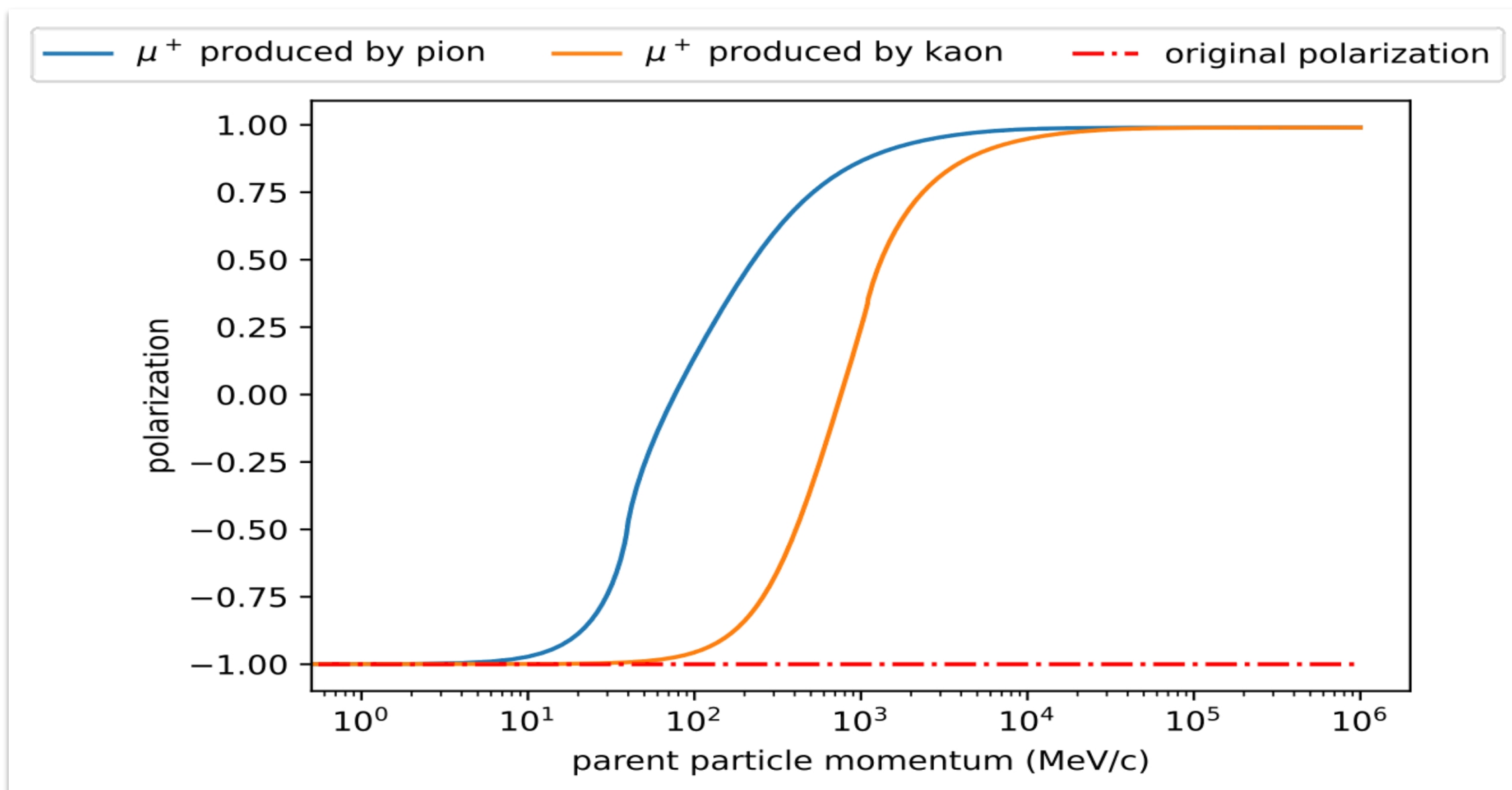
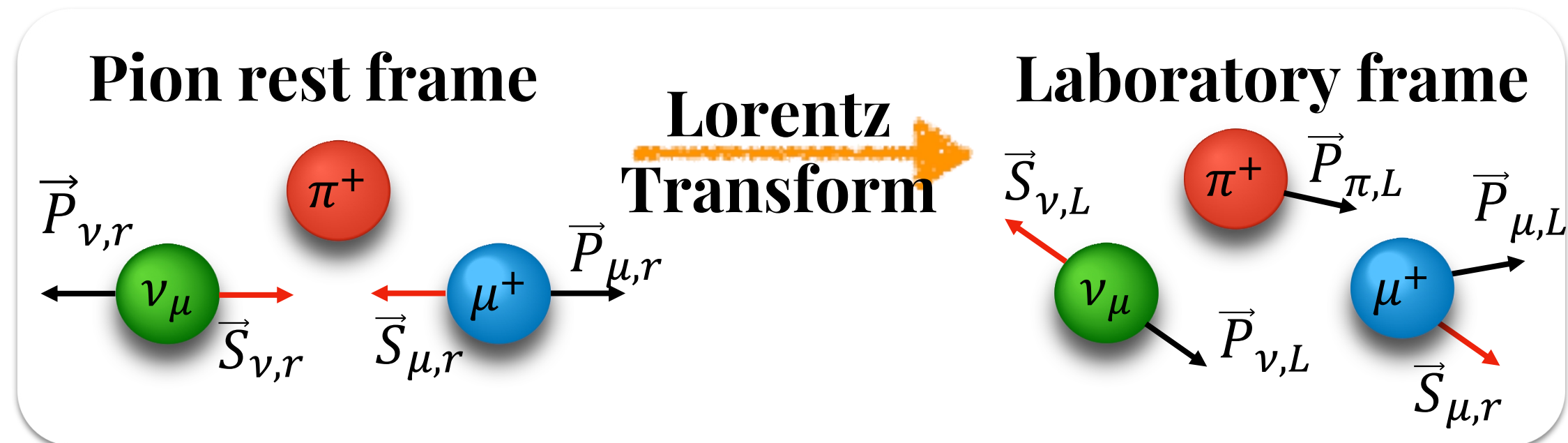
$\pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$
 $\{ \begin{array}{l} K^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu) \\ K_L^0 \rightarrow \pi^\pm + \mu^\mp + \bar{\nu}_\mu(\nu_\mu) \end{array} \right.$ 多种产生过程



宇生缪子应该具有更加复杂的自然极化属性

通过缪子极化测量 K/ π Ratio

由 π 和K衰变产生的缪子具有不同的极化分布
可以利用地面低能缪子反推出有效 **K/ π Ratio**



不同粒子产生的缪子的平均极化

物理目标:

通过测量宇生缪子极化, 测量大气级联中
 π 、K衰变对低能宇生缪子的相对贡献,
即**有效 K/ π Ratio**

K/ π Ratio:

- 大气级联的母粒子组成
- 强子产生模型的试验检验
- 约束大气中微子产生机制

从Michel电子角分布到 K/ π Ratio

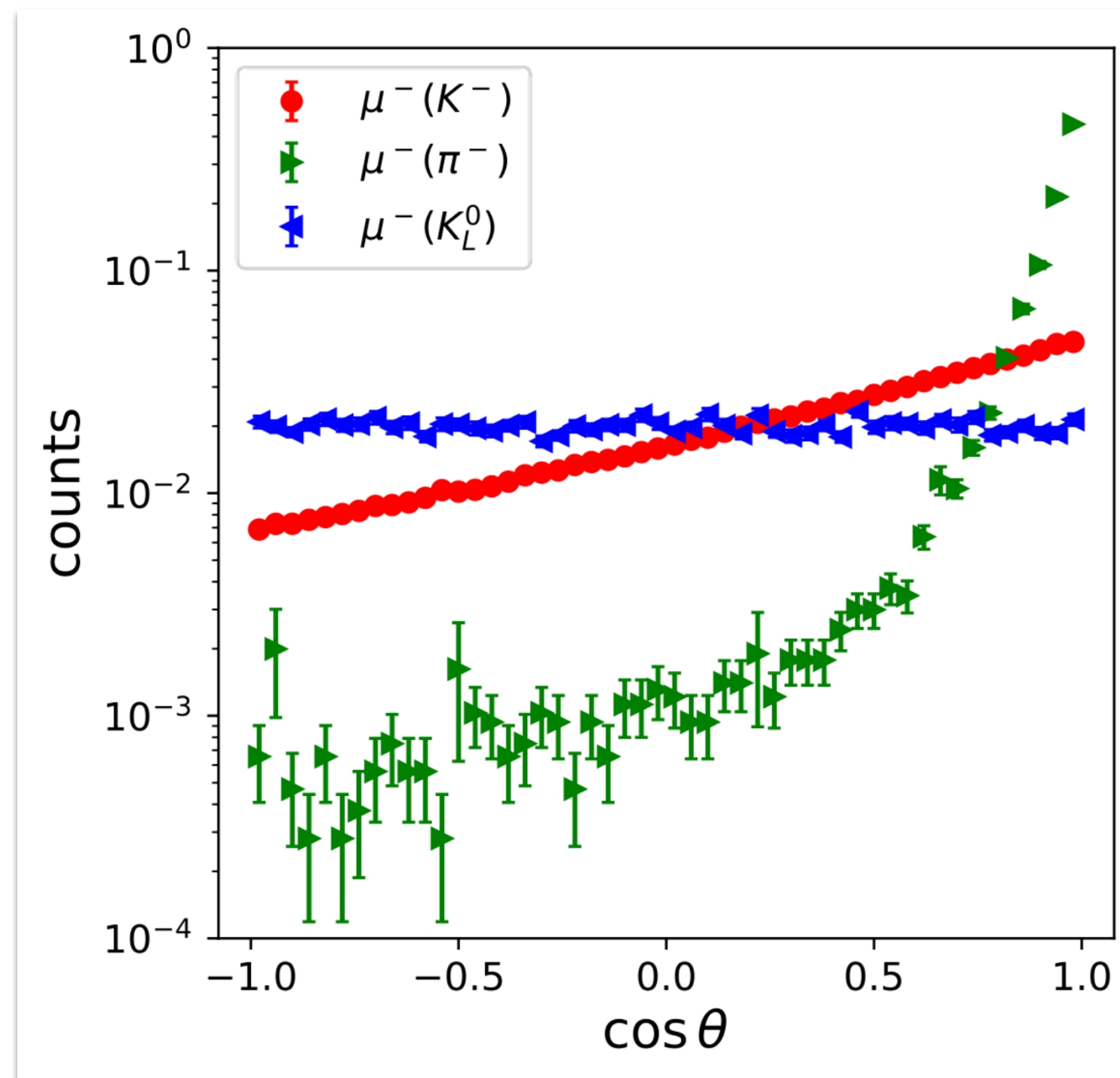
宇生缪子极化的测量方法: $\mu^\pm \rightarrow e^\pm + \bar{\nu}_\mu(\nu_\mu) + \nu_e(\bar{\nu}_e)$

$$N_{\text{Michel}} \propto 1 + A(E_e)P_\mu \cos\theta_e \quad \theta_e = \angle(\vec{p}_\mu, \vec{p}_e)$$

重建K/ π Ratio 的关键:

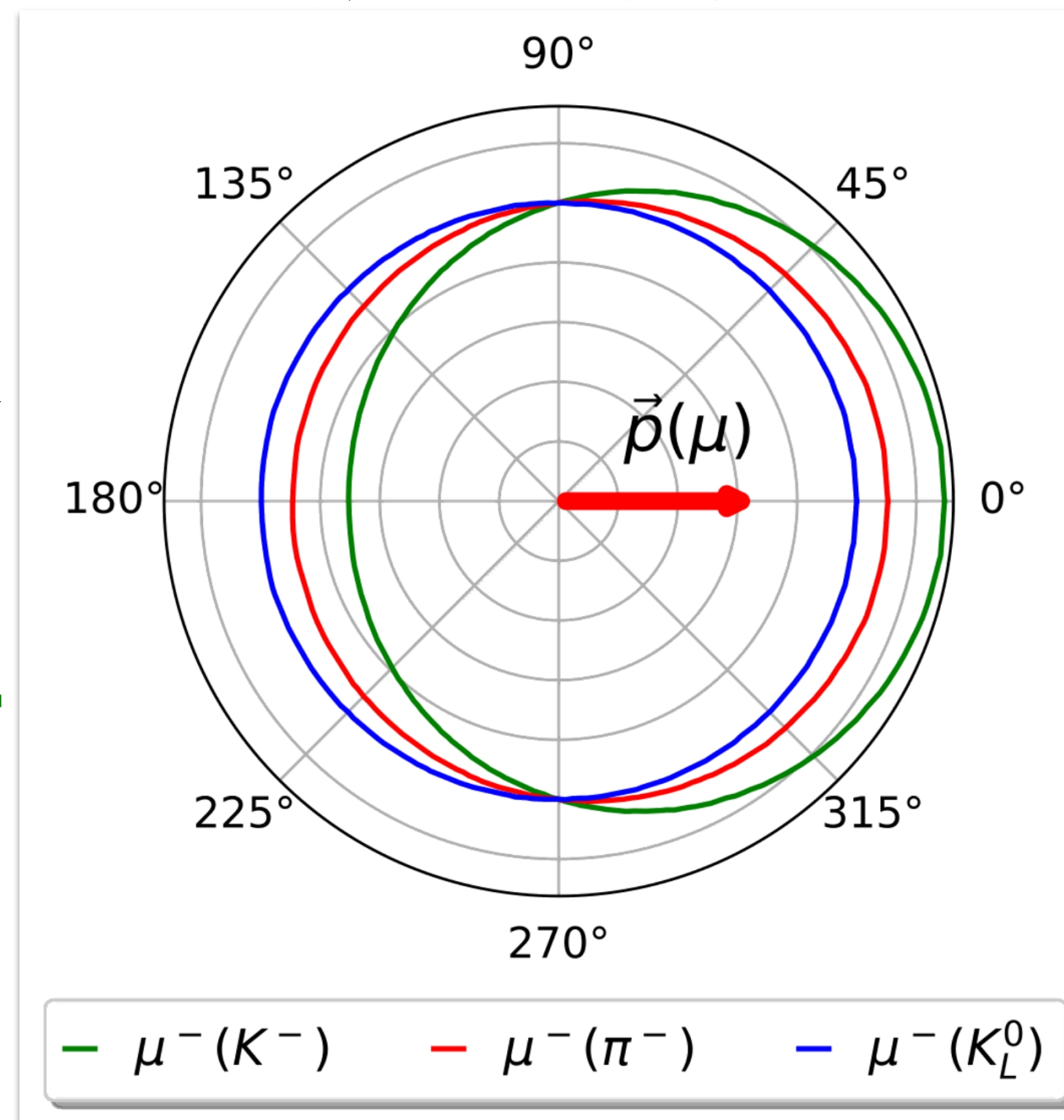
米歇尔电子相对于缪子动量方向的角分布

极化分布



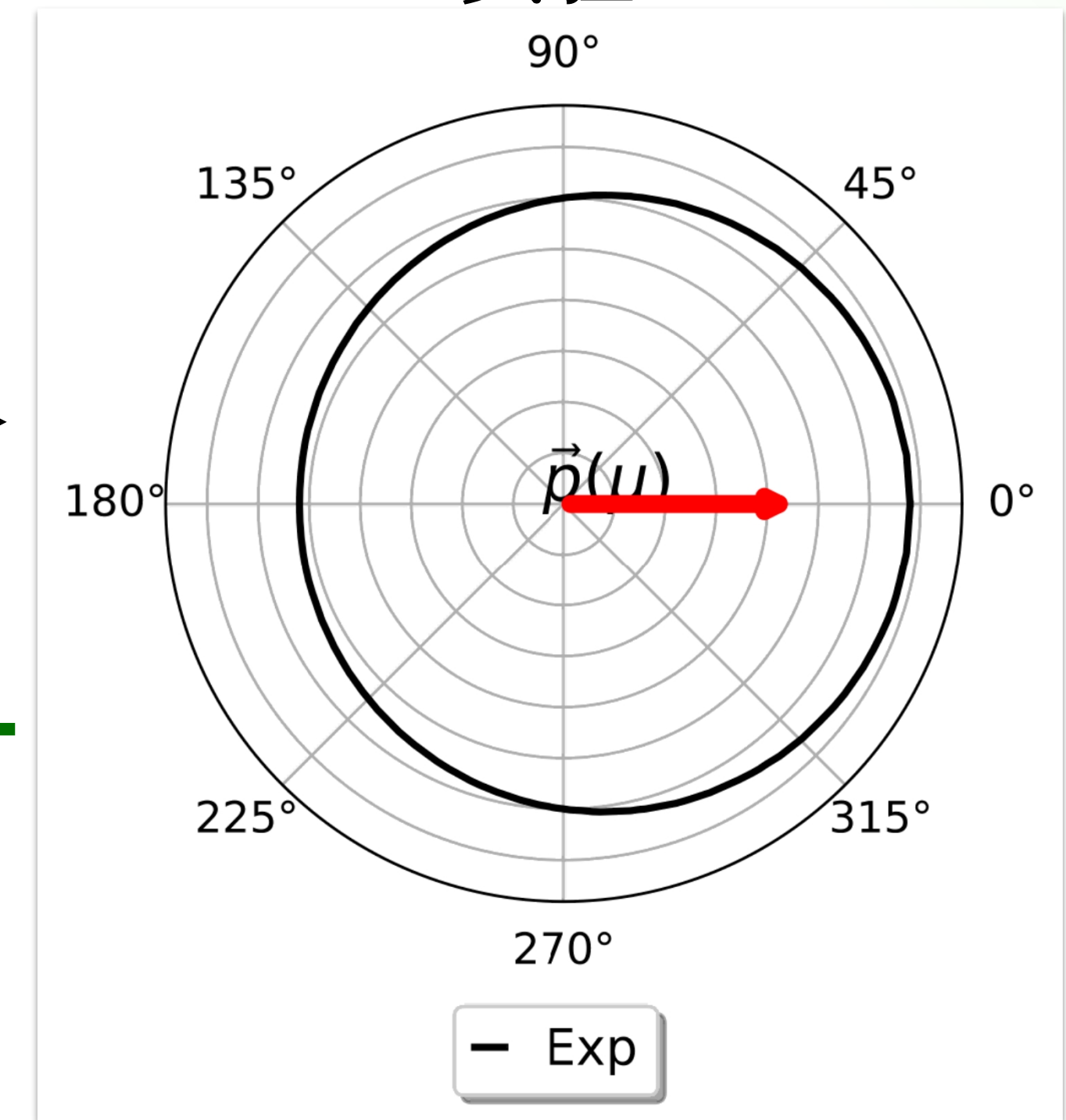
K/ π Ratio

米歇尔电子角分布



K/ π 分布谱拟合

实验



米歇尔电子角分布

历史上对宇生缪子极化的测量

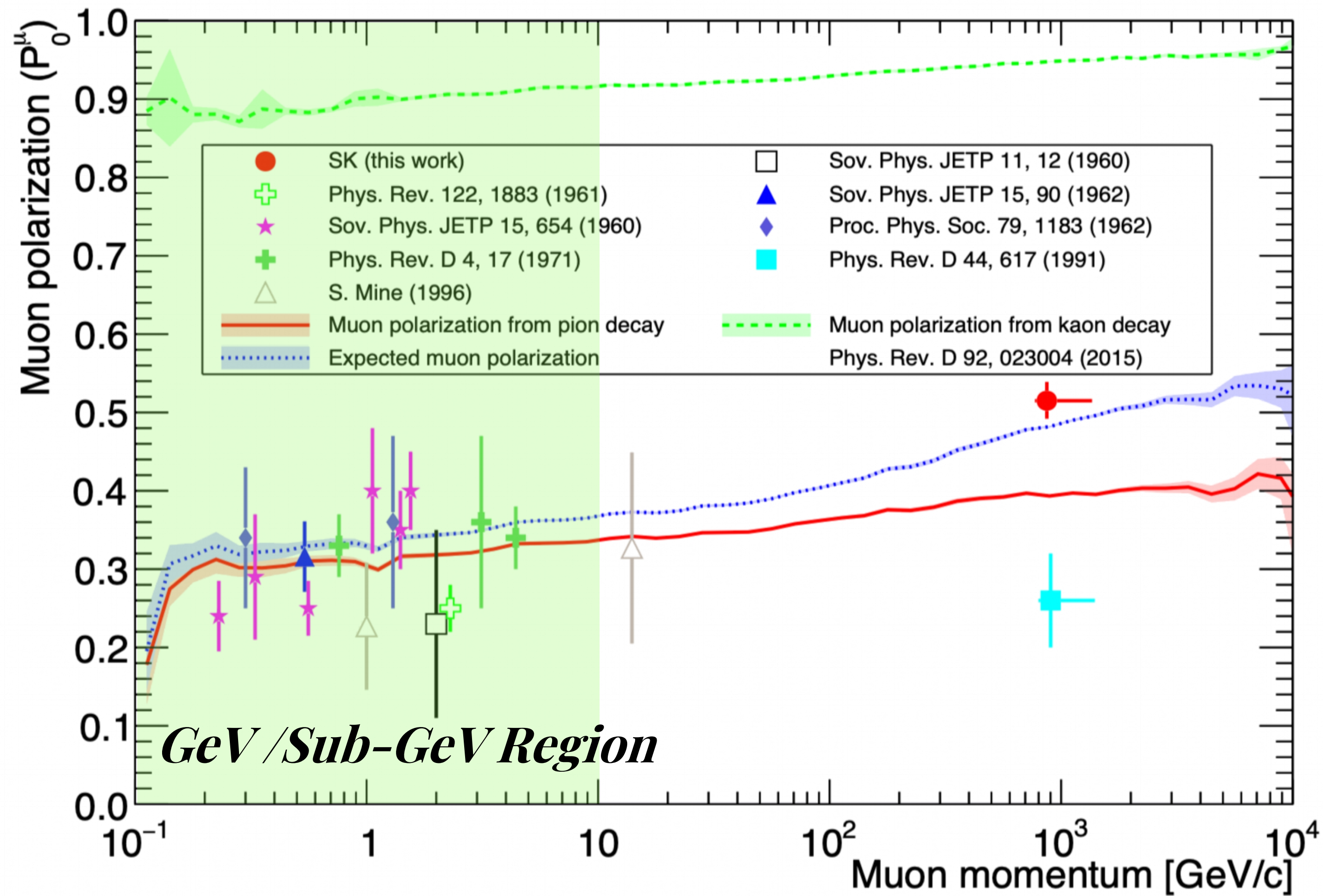


Figure1: 历史实验对宇生缪子自旋极化的测量结果

我们需要测量低能区的宇生缪子的自旋极化

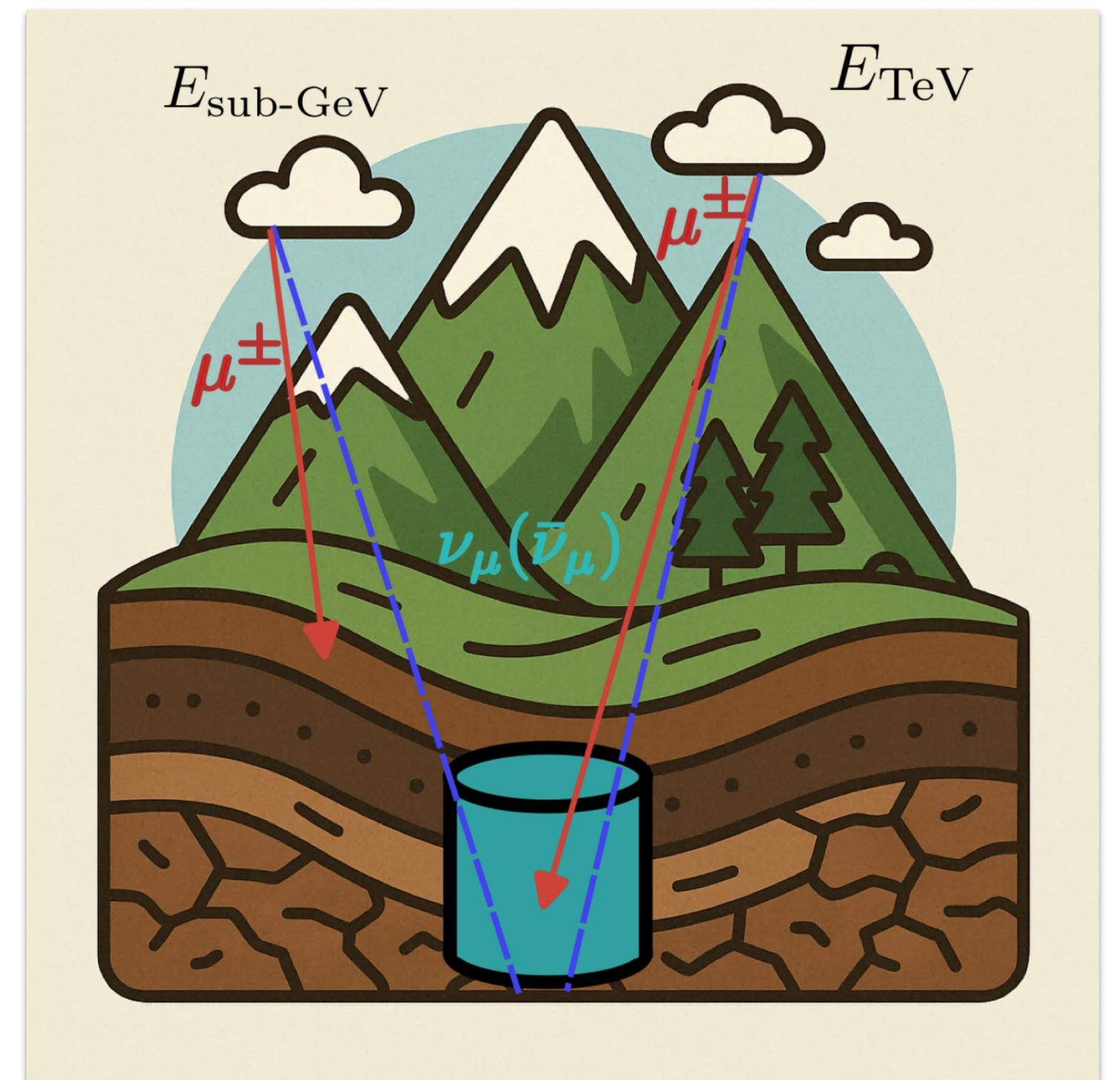
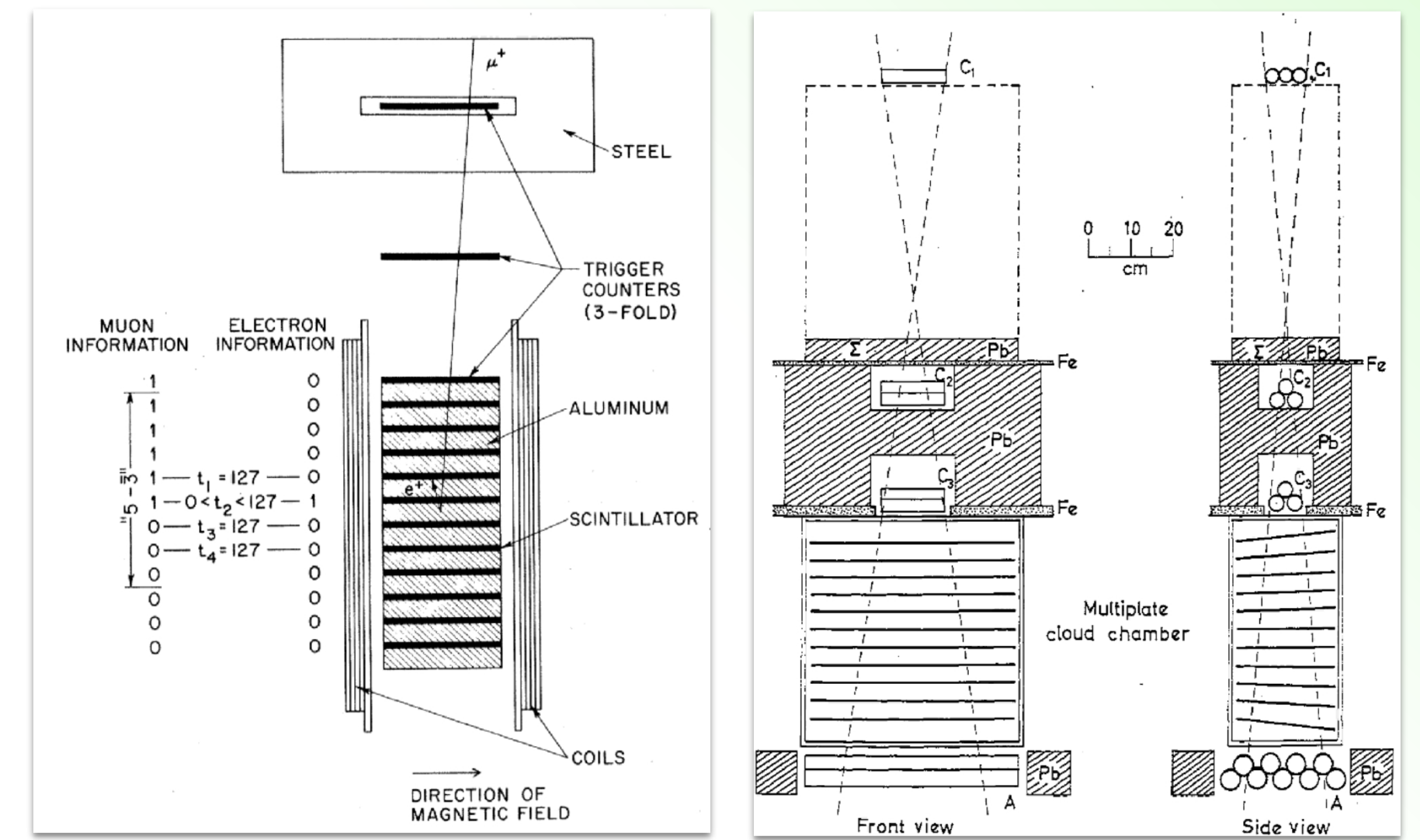


Figure2. 在深地实验中的宇生缪子自旋极化.



- 缪子的自旋极化
- ***Cosmic Ray Muon Spin Polarization Detector (CRmuSR)* 样机设计与标定结果**
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Momentum Direction Detector (MDD)

- 重建入射缪子的动量方向

Muon Stopping Target (Target)

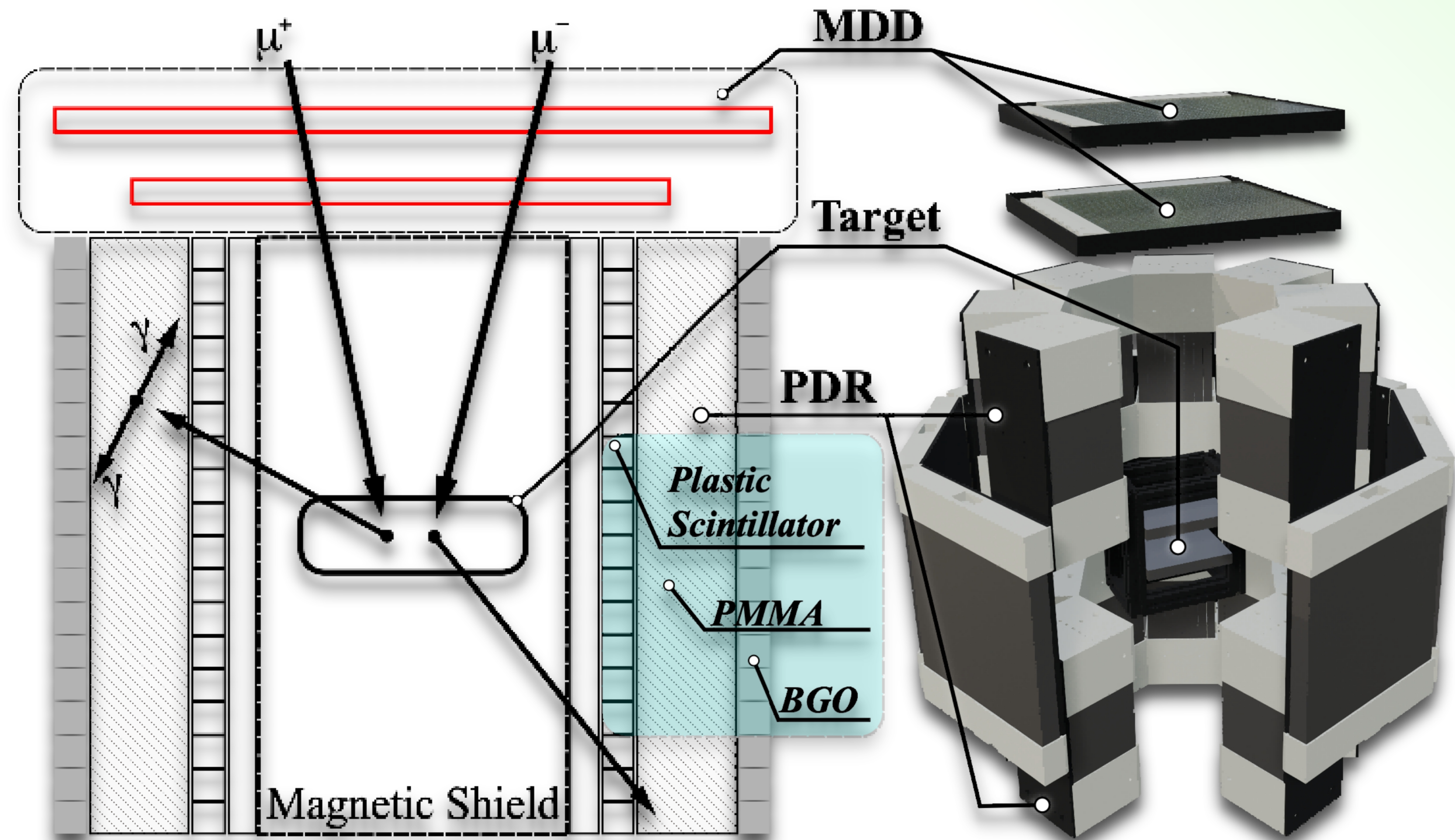
- 使低能缪子在靶中停止并衰变

Positron/electron Detector Ring (PDR)

- 重建Michel $e^\pm$ 的空间分布

Magnetic Shield

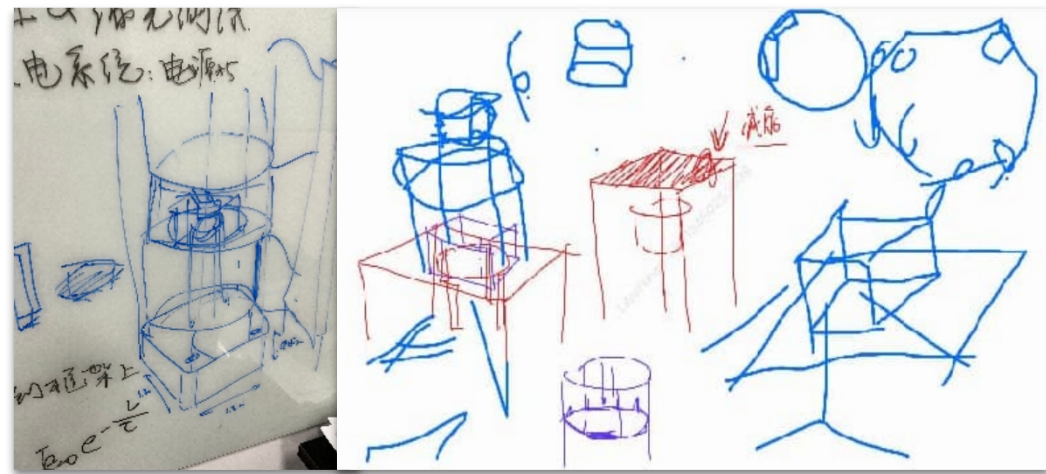
- 抑制地磁场引起的缪子自旋进动



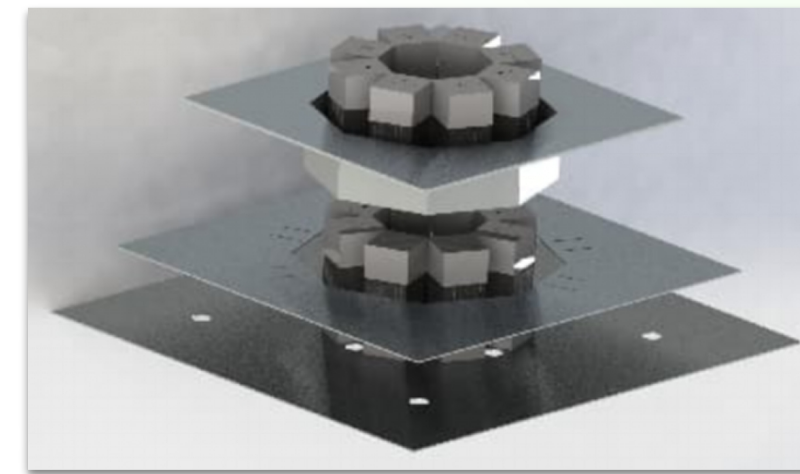
概念设计

CRmuSR样机

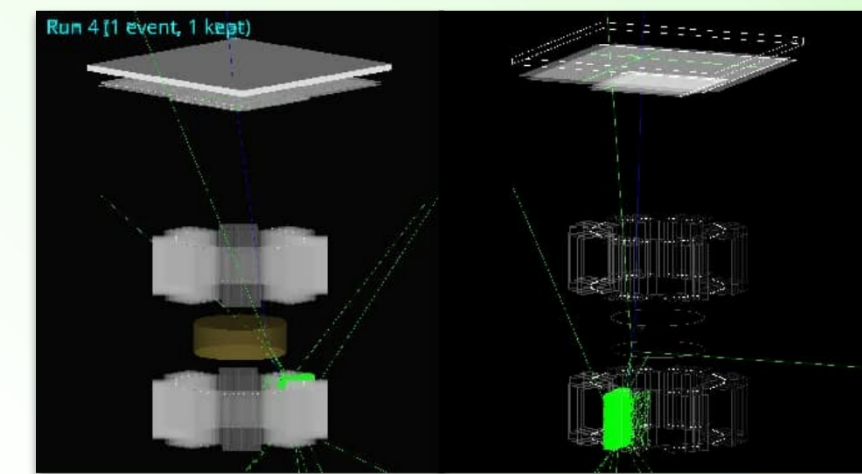
2 CRmuSR 样机



最开始的一些奇思妙想(Mainly by Mingchen Sun, Tao Yu, Yunsong Ning)



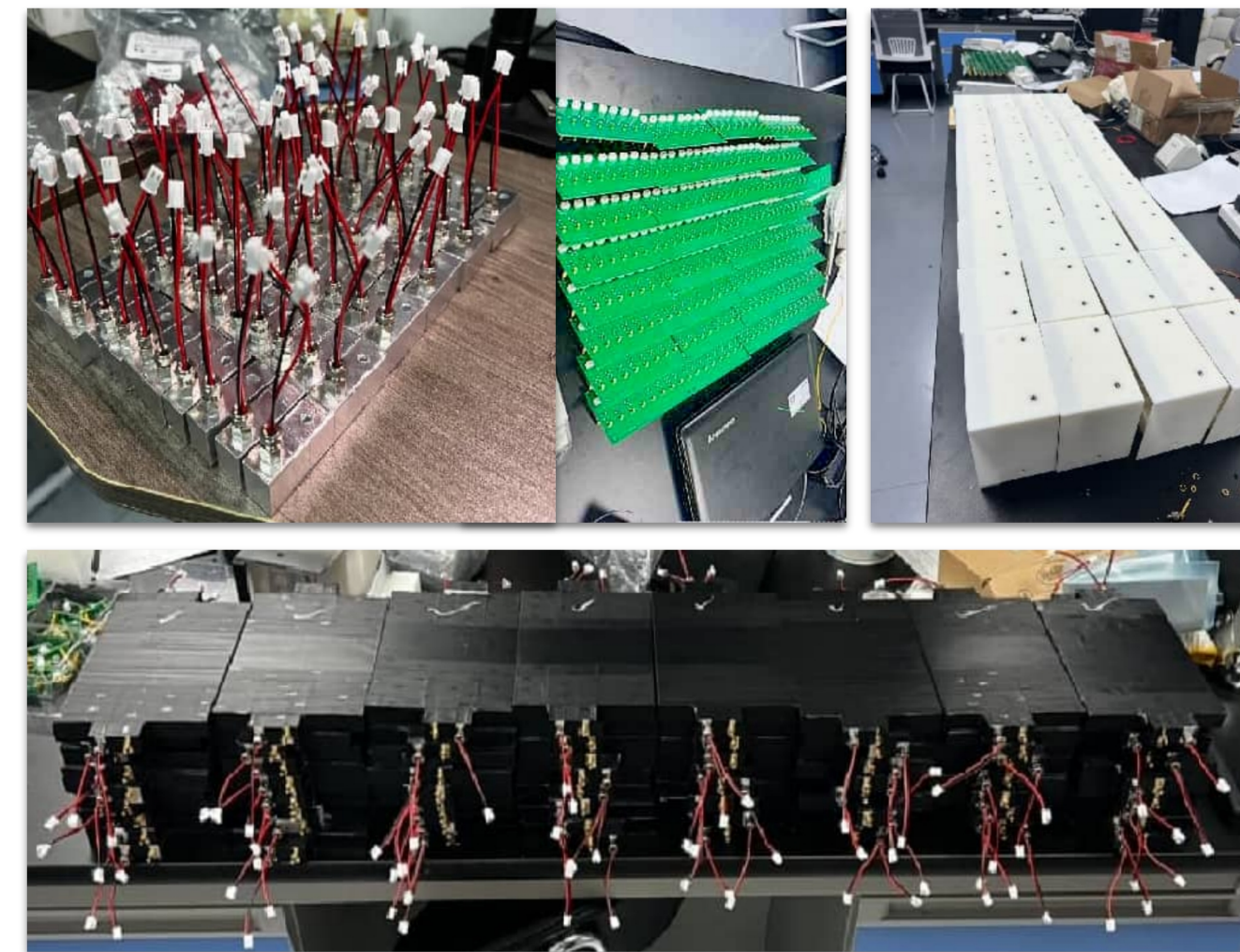
双层PDR初始设计



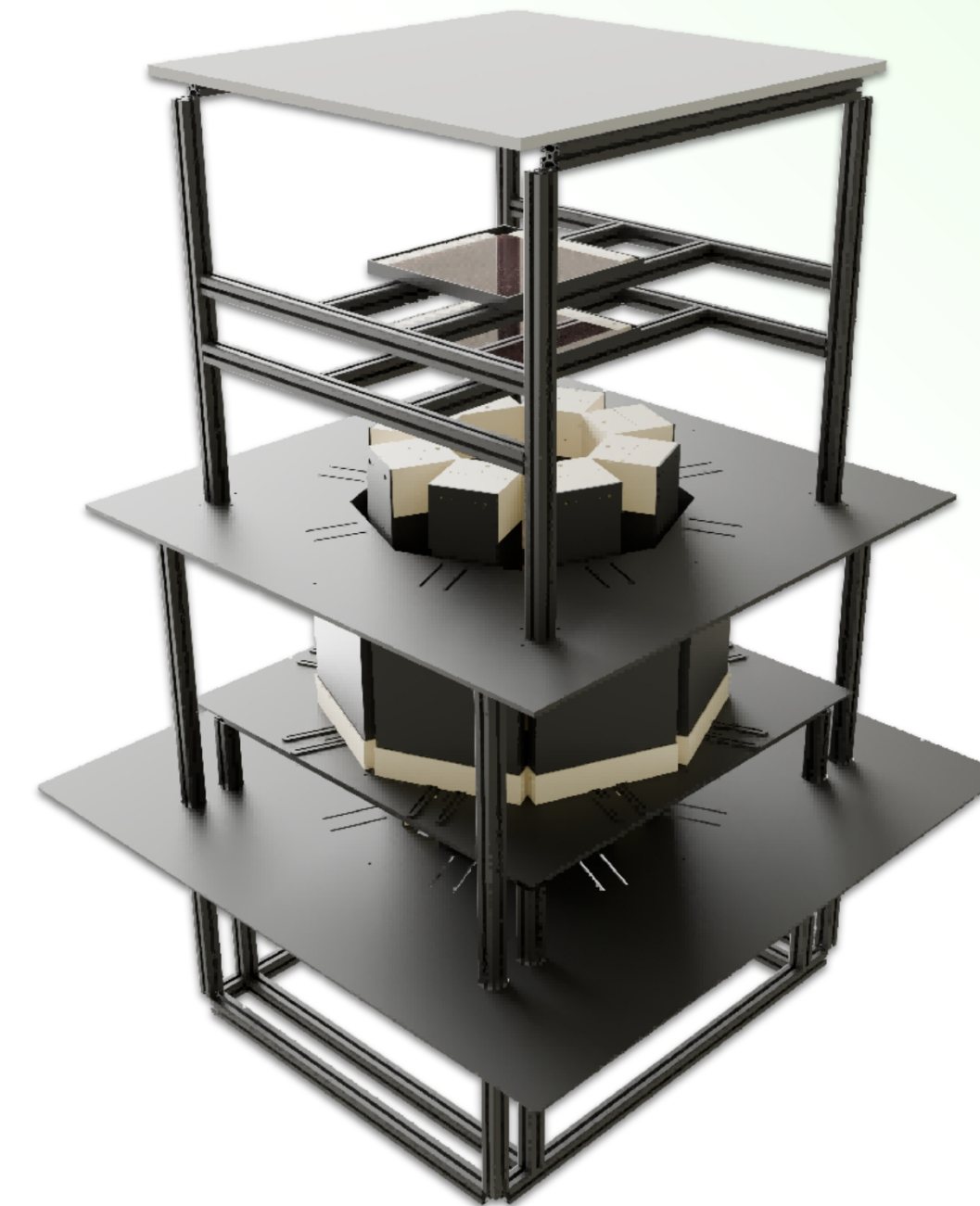
信号与背景模拟 (Mainly by Aiyu Bai)



CRmuSR正在采数



探测器模块的封装过程 (By SMOOTH lab)

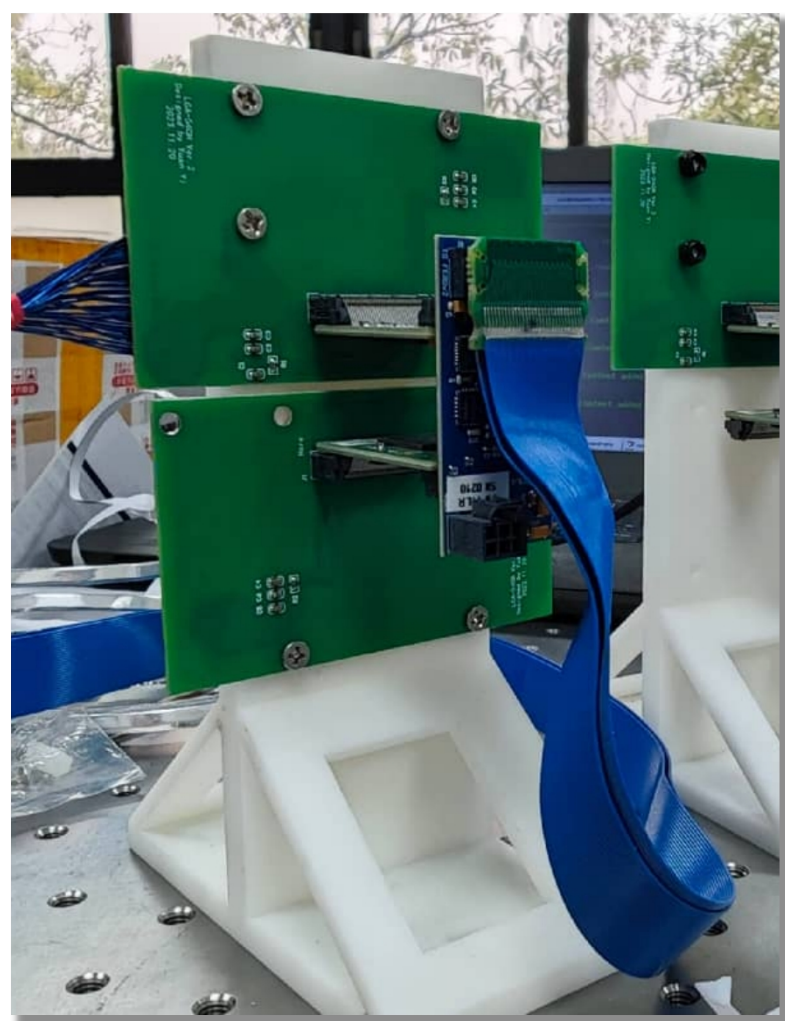


CRmuSR的最终设计

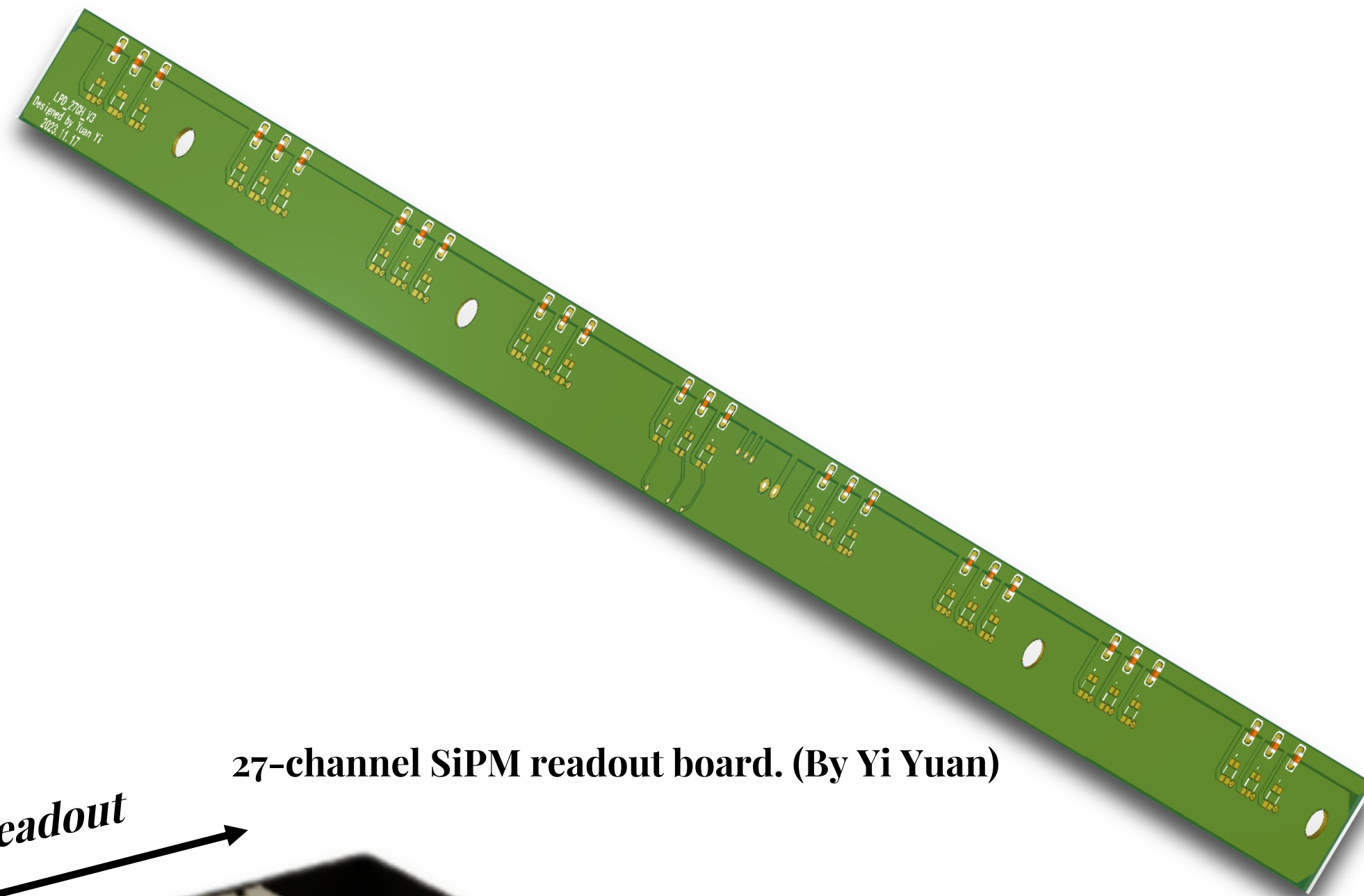


CRmuSR 的安装过程 (By SMOOTH lab)

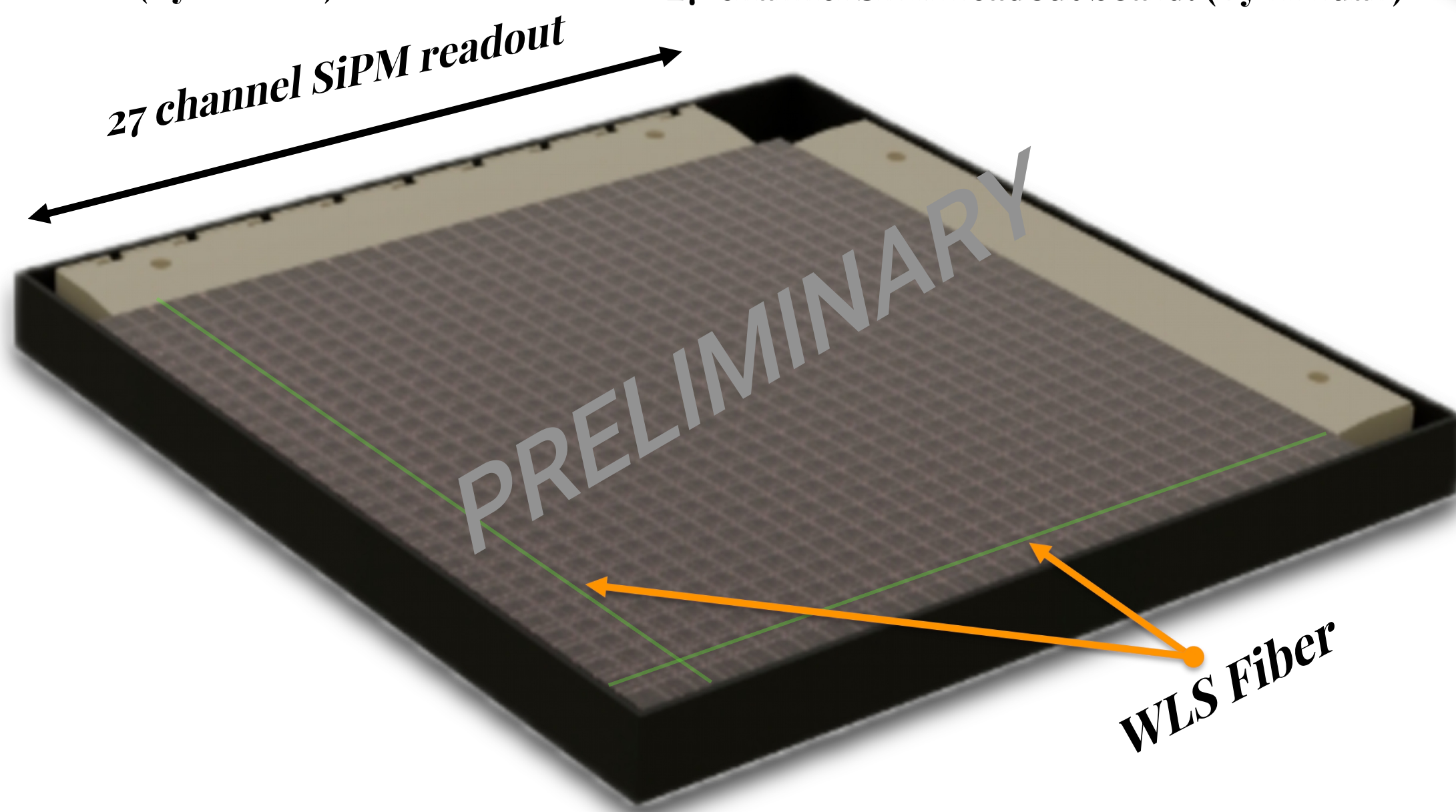
2 CRmuSR 样机的MDD模块



54-channel Signal board. (By Yi Yuan)

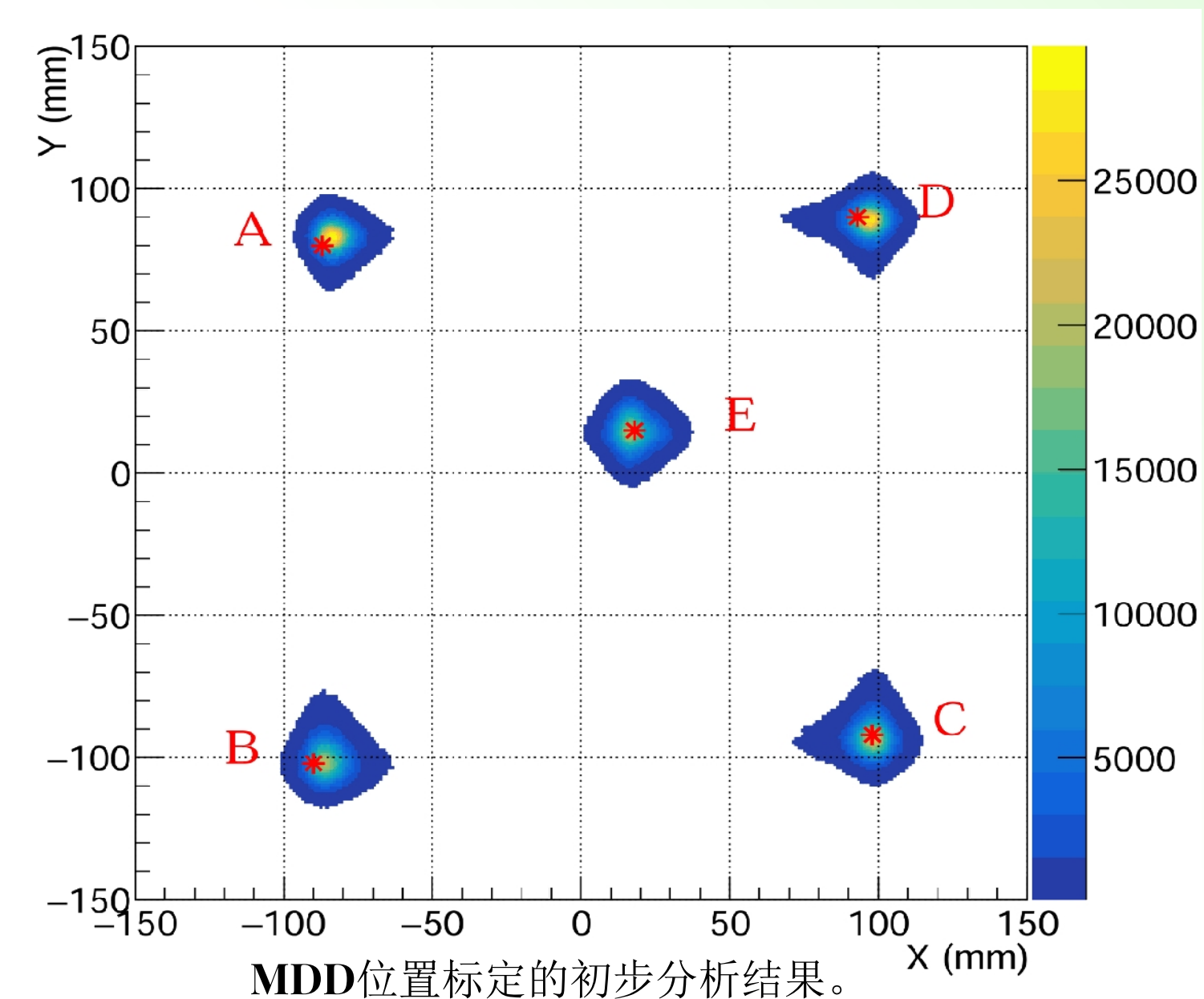


27-channel SiPM readout board. (By Yi Yuan)



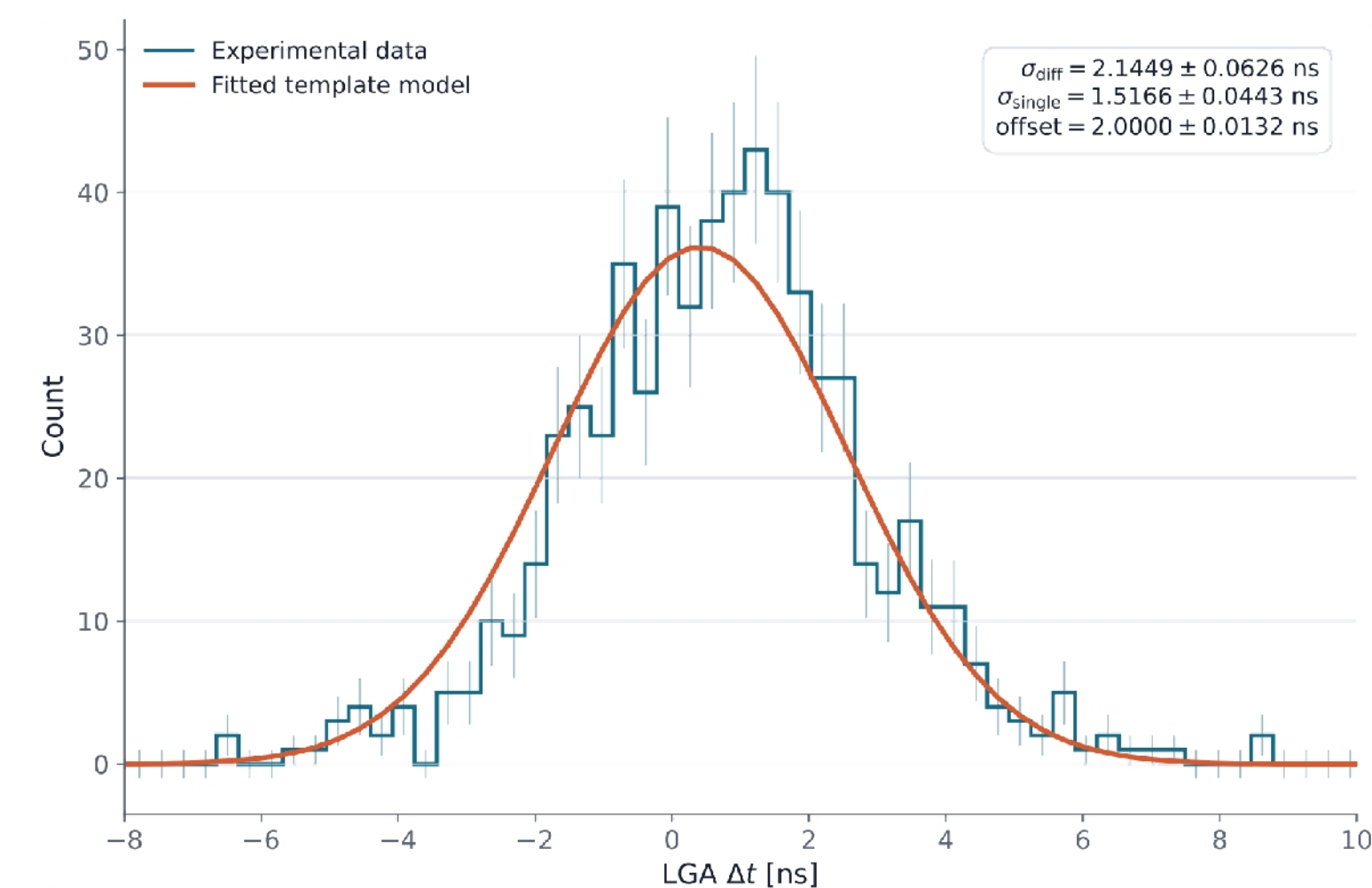
单层MDD探测单元设计 (27 通道版本).

位置分辨率 $\sigma \approx 4.3 \text{ mm}$



MDD位置标定的初步分析结果。

单个模块时间分辨率 $\sigma \approx 1.516 \text{ ns}$



MDD时间分辨的初步分析结果

2 CRmuSR 样机的PDR模块

PDR探测单元(16CH)

- 8根闪烁体探测条→PDR探测单元
- 采用双端读出，共16个读出通道。

PDR模块(128CH)

- 8个PDR探测单元→128通道
- 实现方位角方向近 2π 全覆盖。

CRmuSR样机(256CH)

- 共上下两层PDR模块
- 用于测量Michel $e^\pm$ 的空间分布。

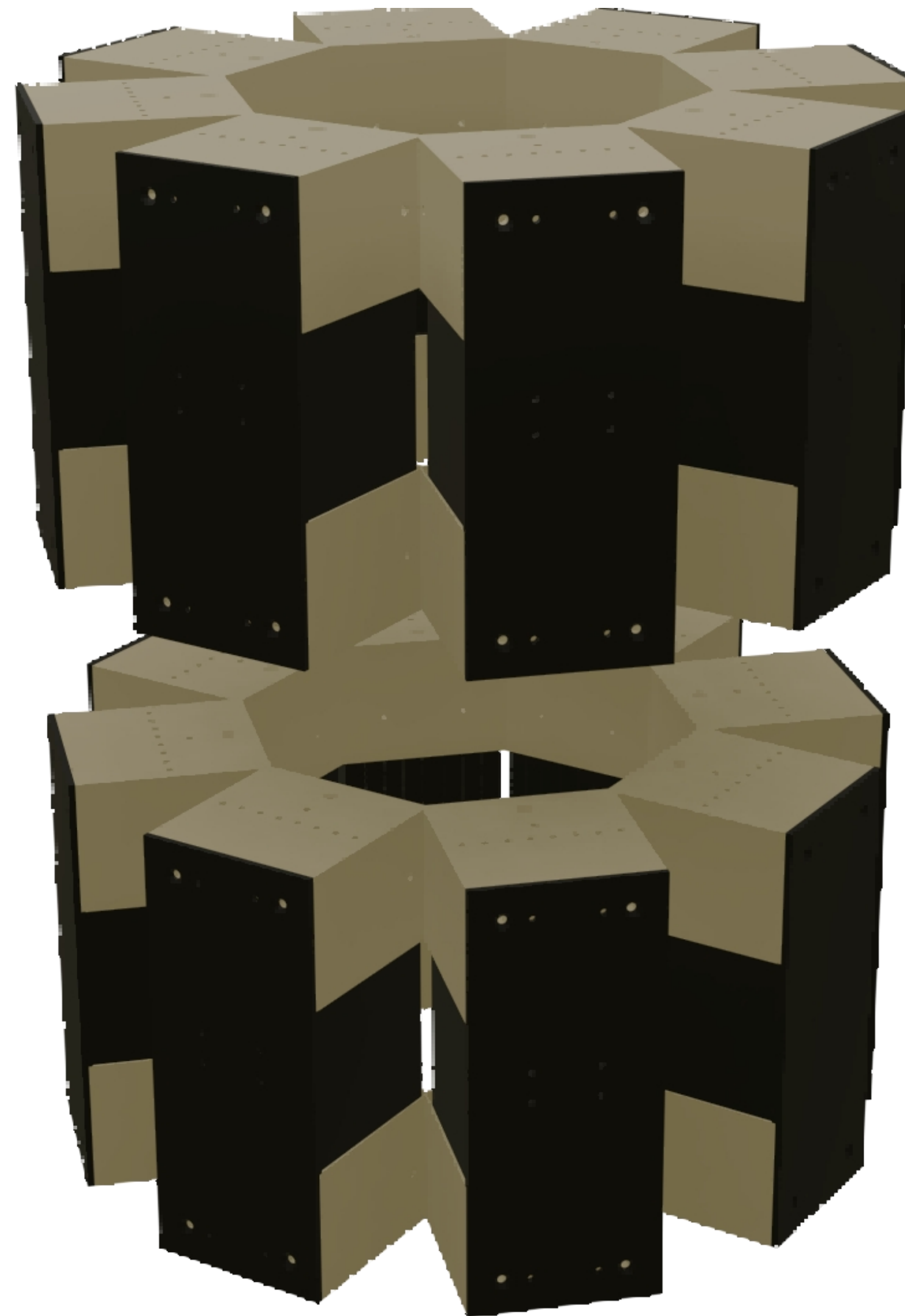
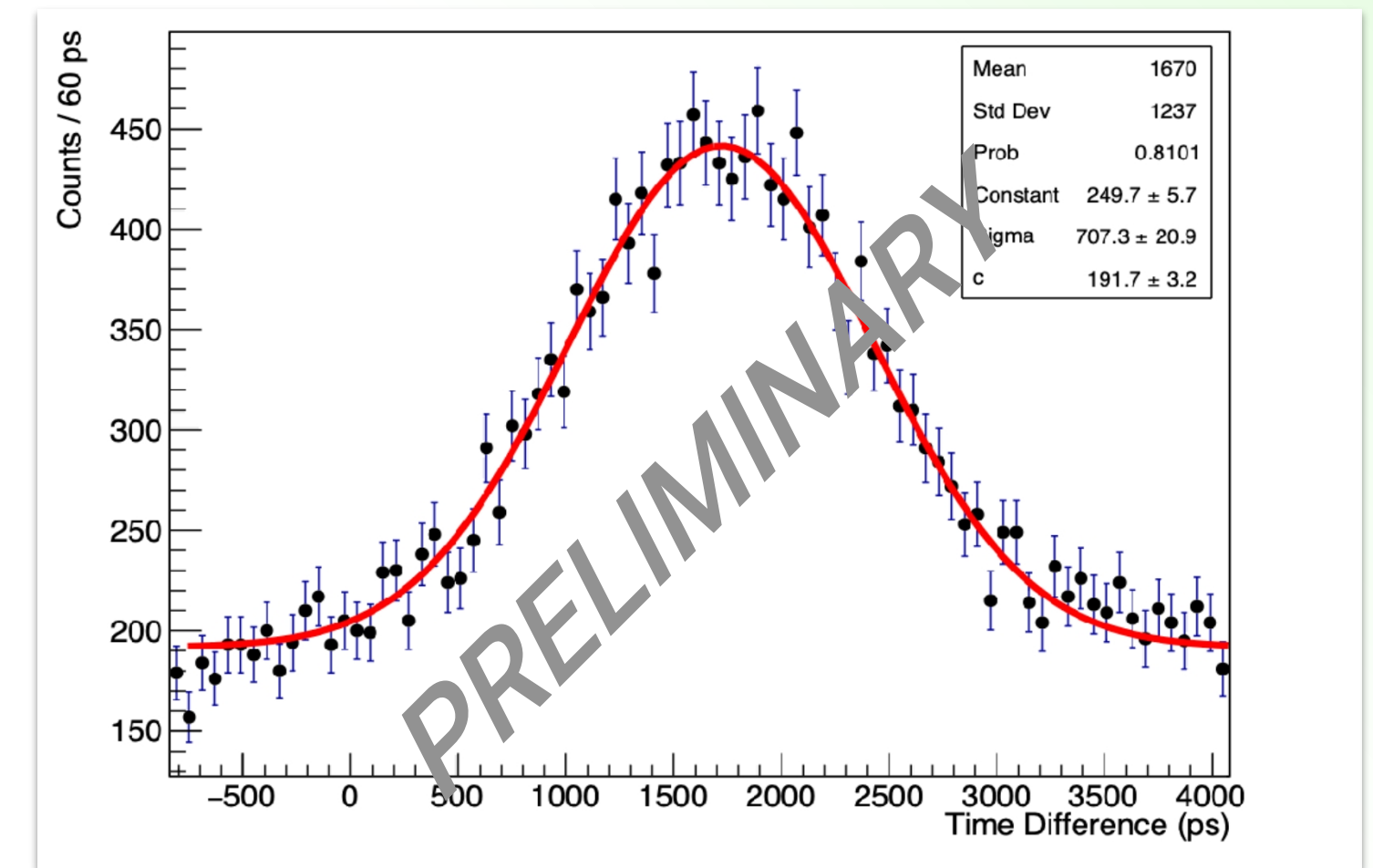


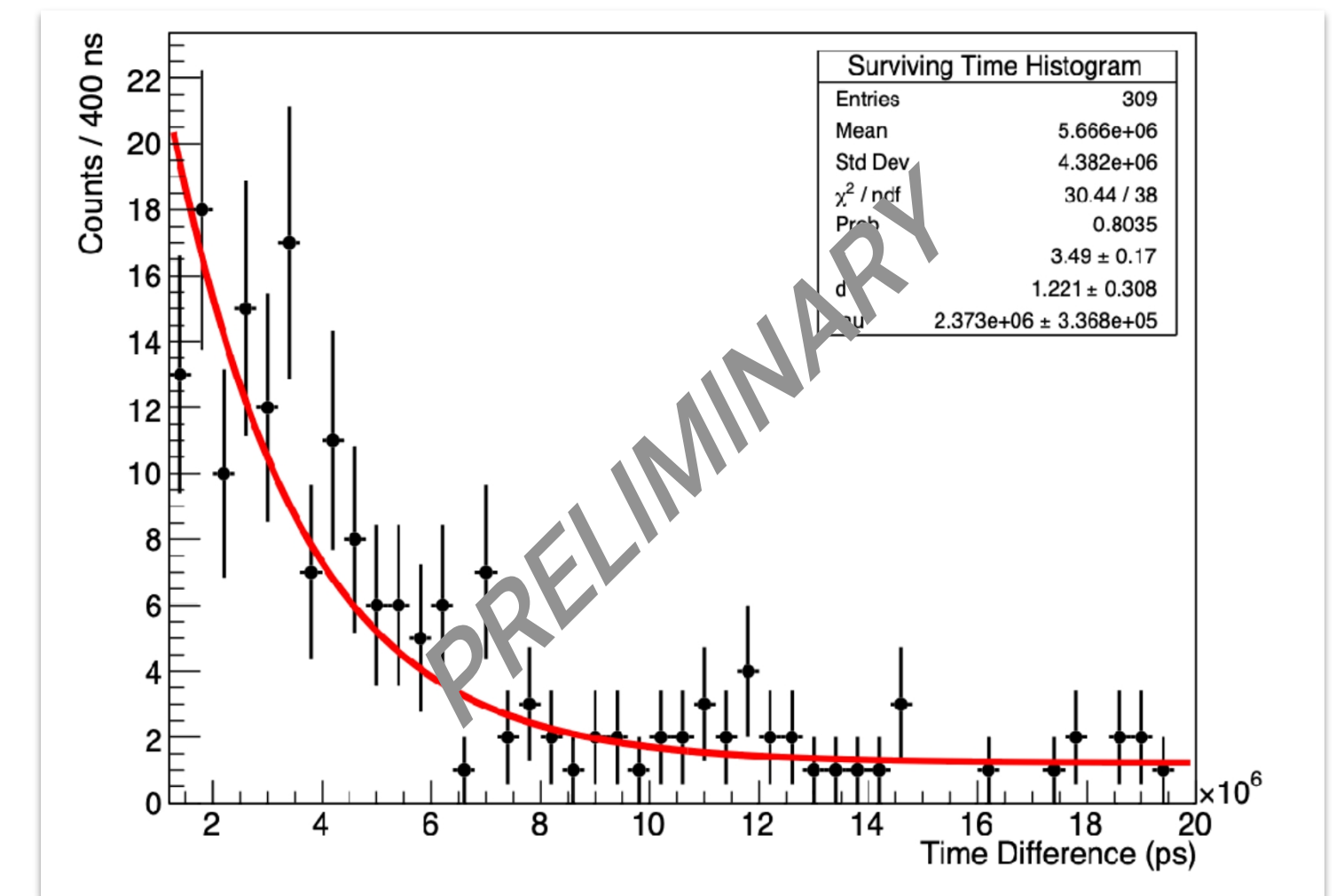
Figure: CRmuSR上下两个PDR模块的排列方式

时间分辨率约为1ns



PDR时间分辨率的初步分析结果。

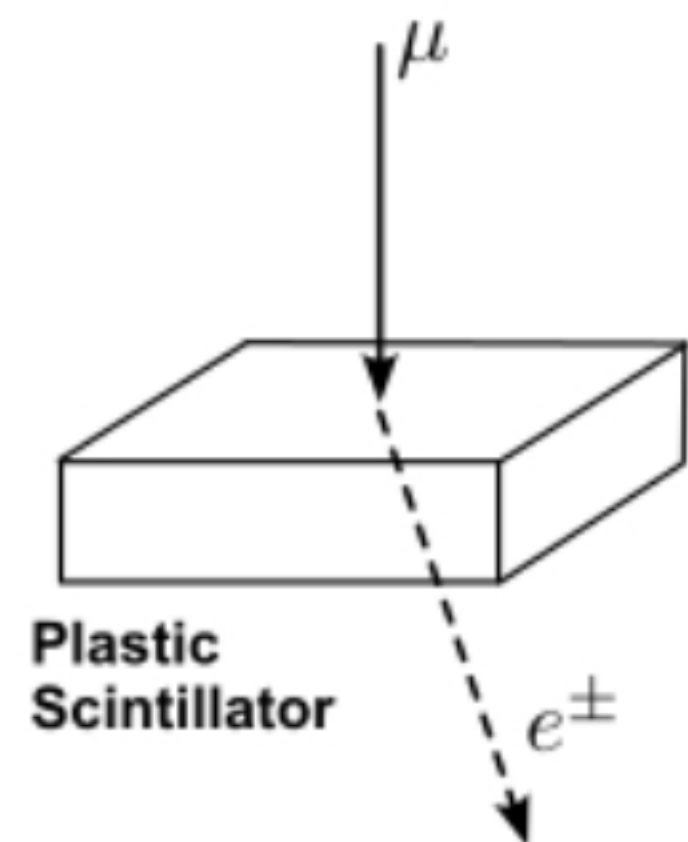
PDR初步测得 $\tau \approx 2.373 \pm 3.368 \mu s$



使用PDR对宇生缪子寿命的初步分析

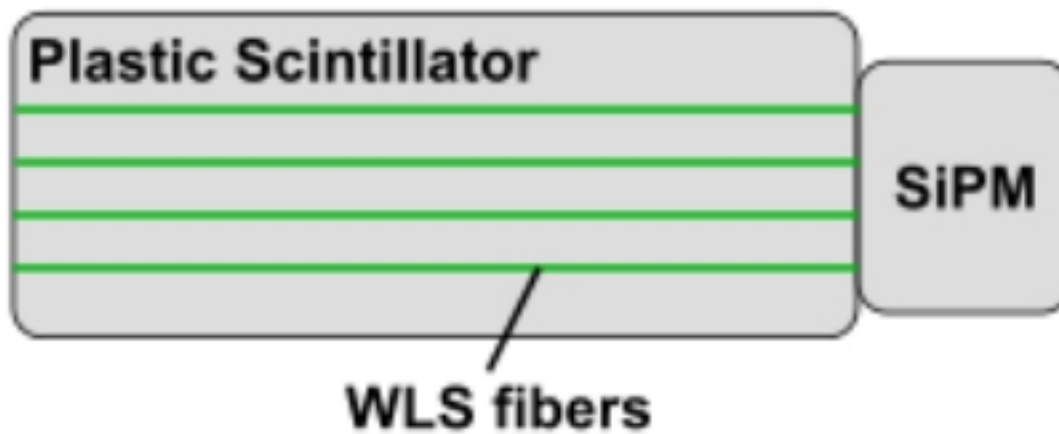
2 CRmuSR 样机的电子学读出系统

Cosmic-ray muon /
Michel positron



Light collection and coupling

MDD: WLS fiber coupling
Hamamatsu S13360-3075



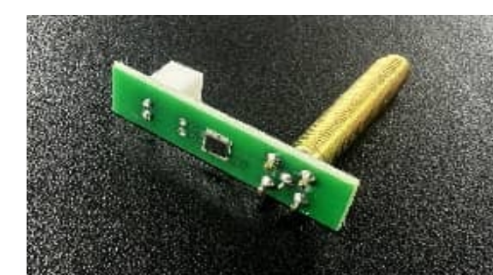
PDR: Direct optical coupling
SensL MicroFC-30035



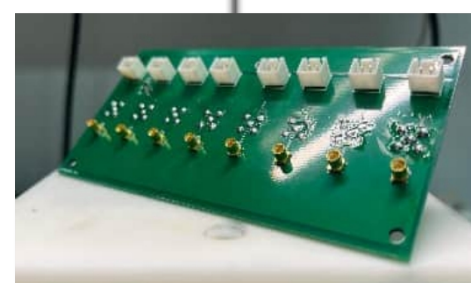
SM (monitor): Direct optical coupling
SensL MicroFC-30035



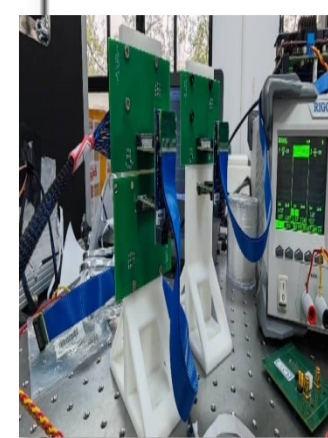
Front-End Readout Electronics



SiPM
carrier boards

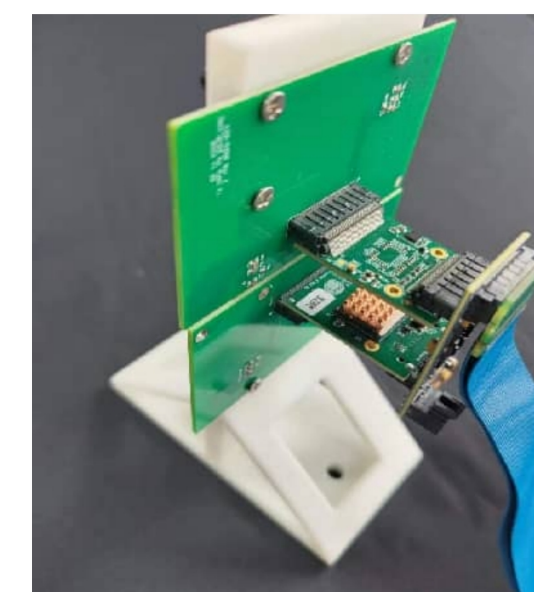


Support boards
(filtering,
channel aggregation...)



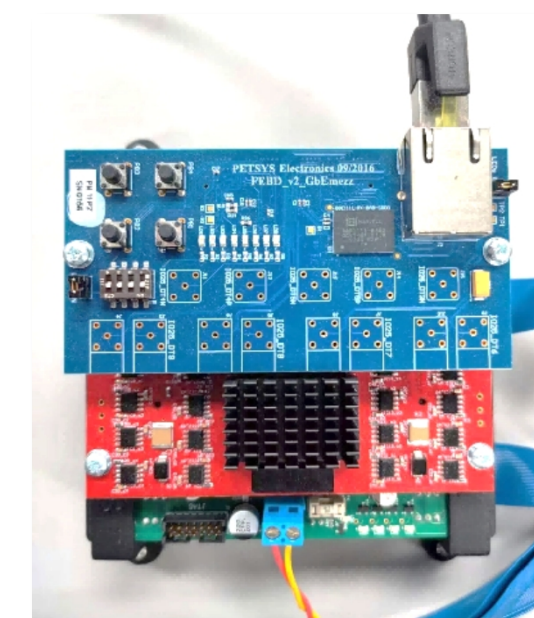
Adapter boards
(Samtec connectors)

Data acquisition system



PETsys TOFPET2 ASIC
+
MotherBoard

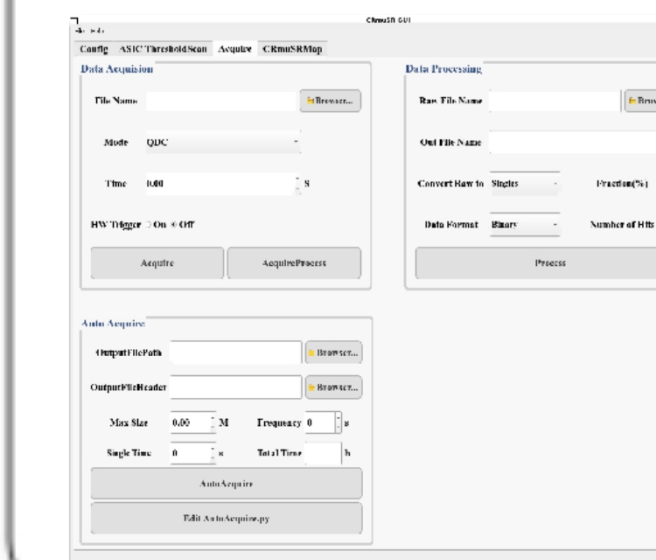
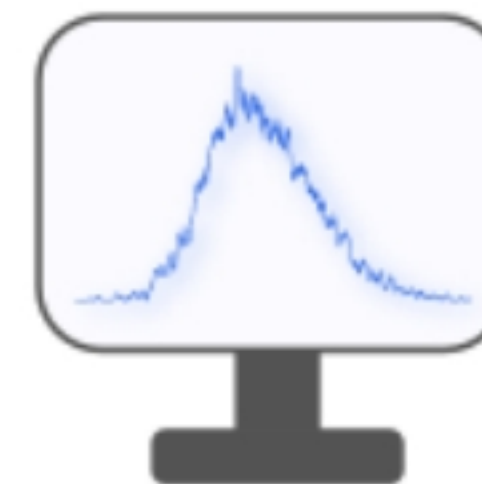
64 channel/chip
TDC 30ps
up to 1024 channel



Output



PC / DAQ
Software



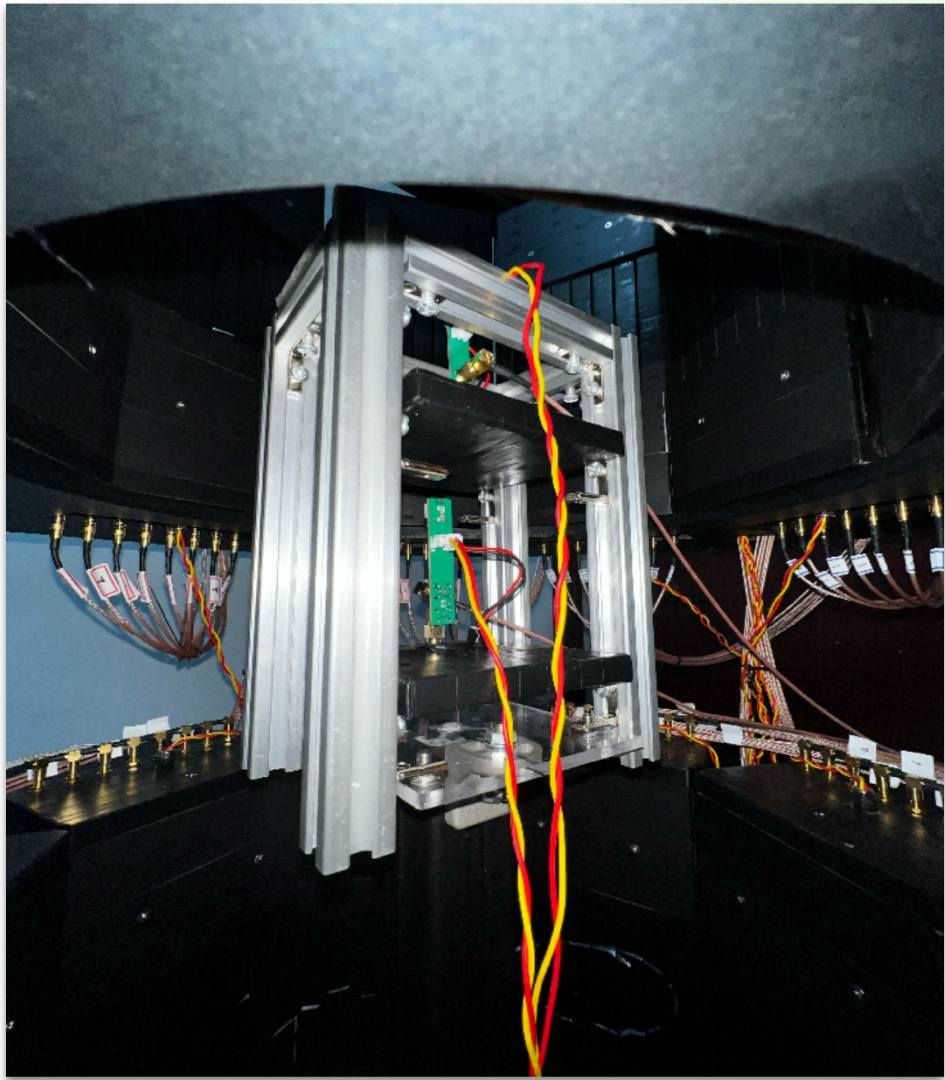


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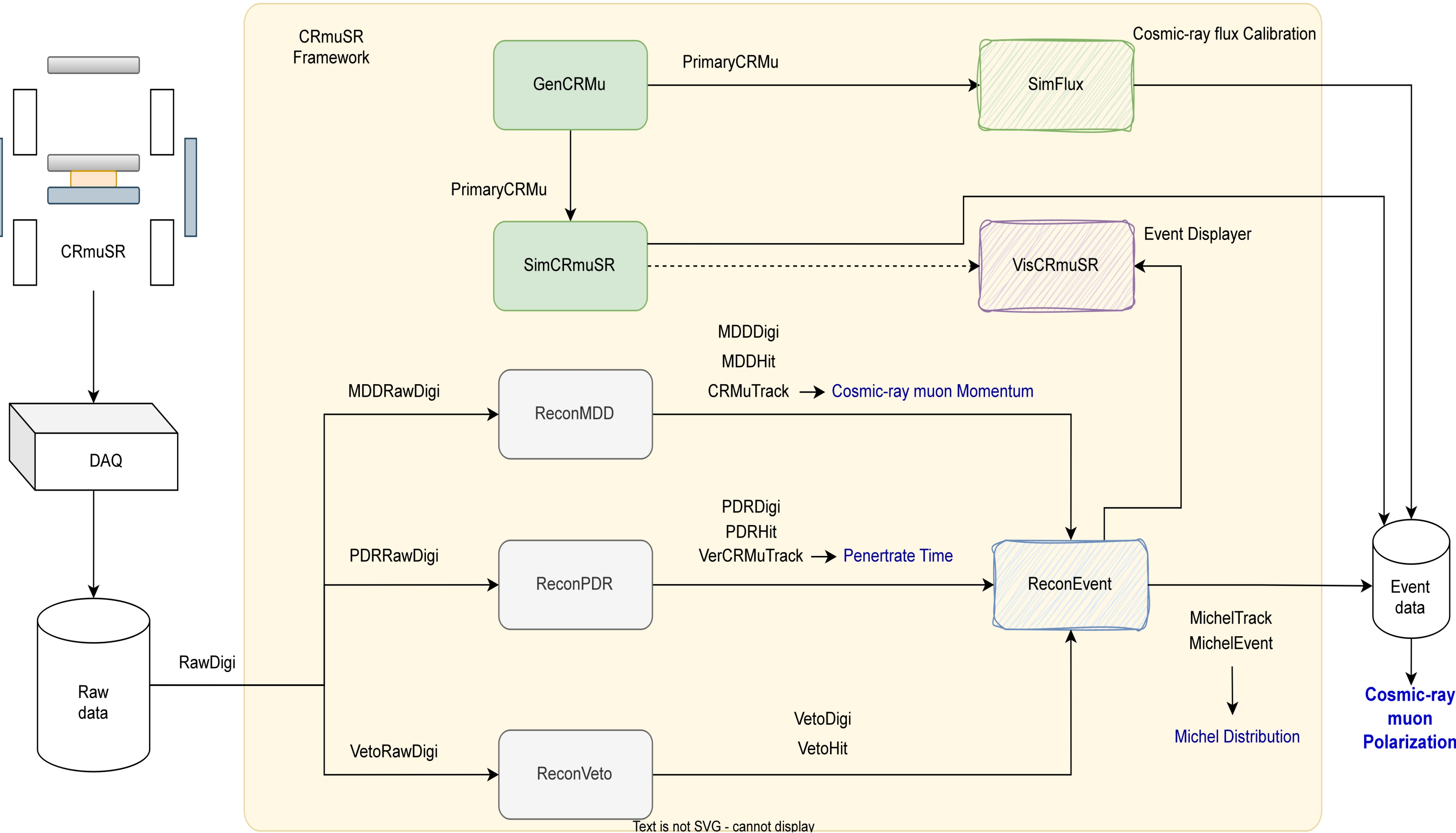
3 重建框架与初步测量结果

上下衰变不对称性

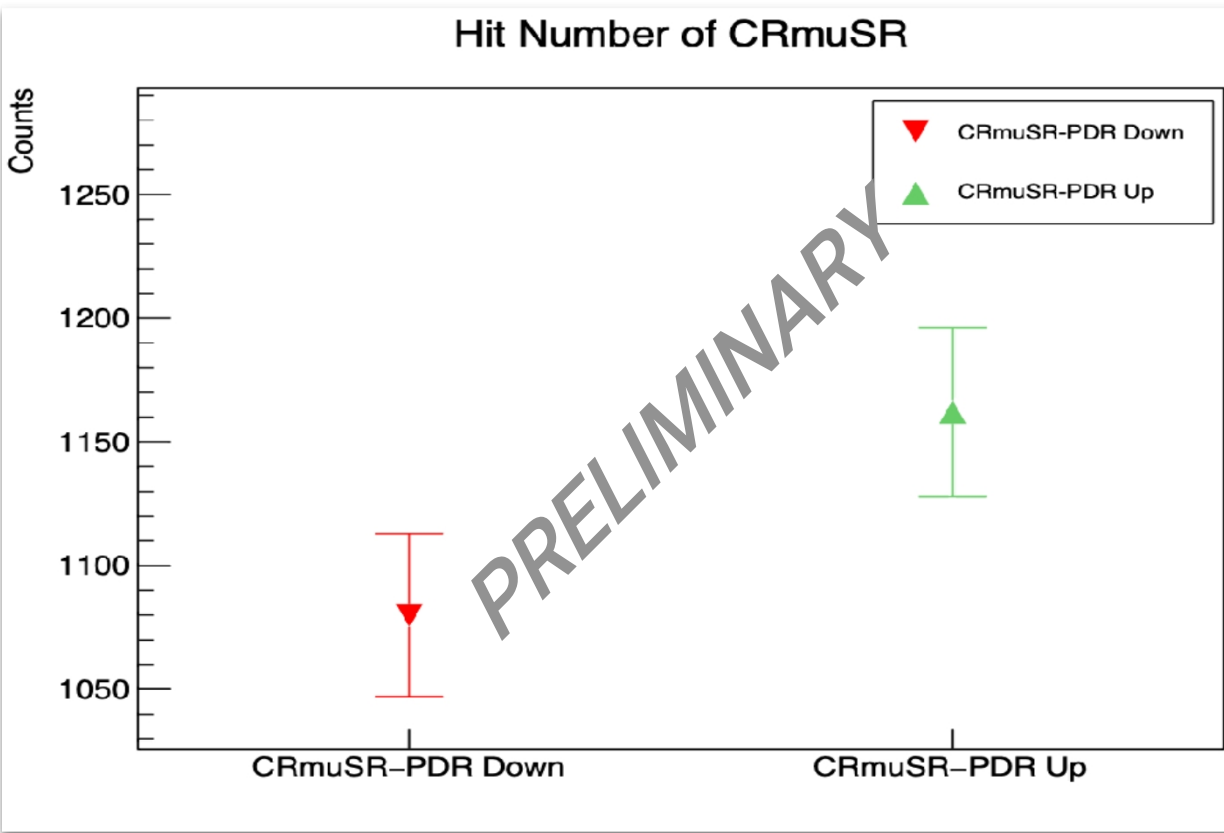
$$\alpha_e = \frac{N_u - N_d}{N_u + N_d} = 0.036 \pm 0.021$$



当前使用的 CRmuSR 测试靶



CRmuSR重建宇生缪子极化的软件框架



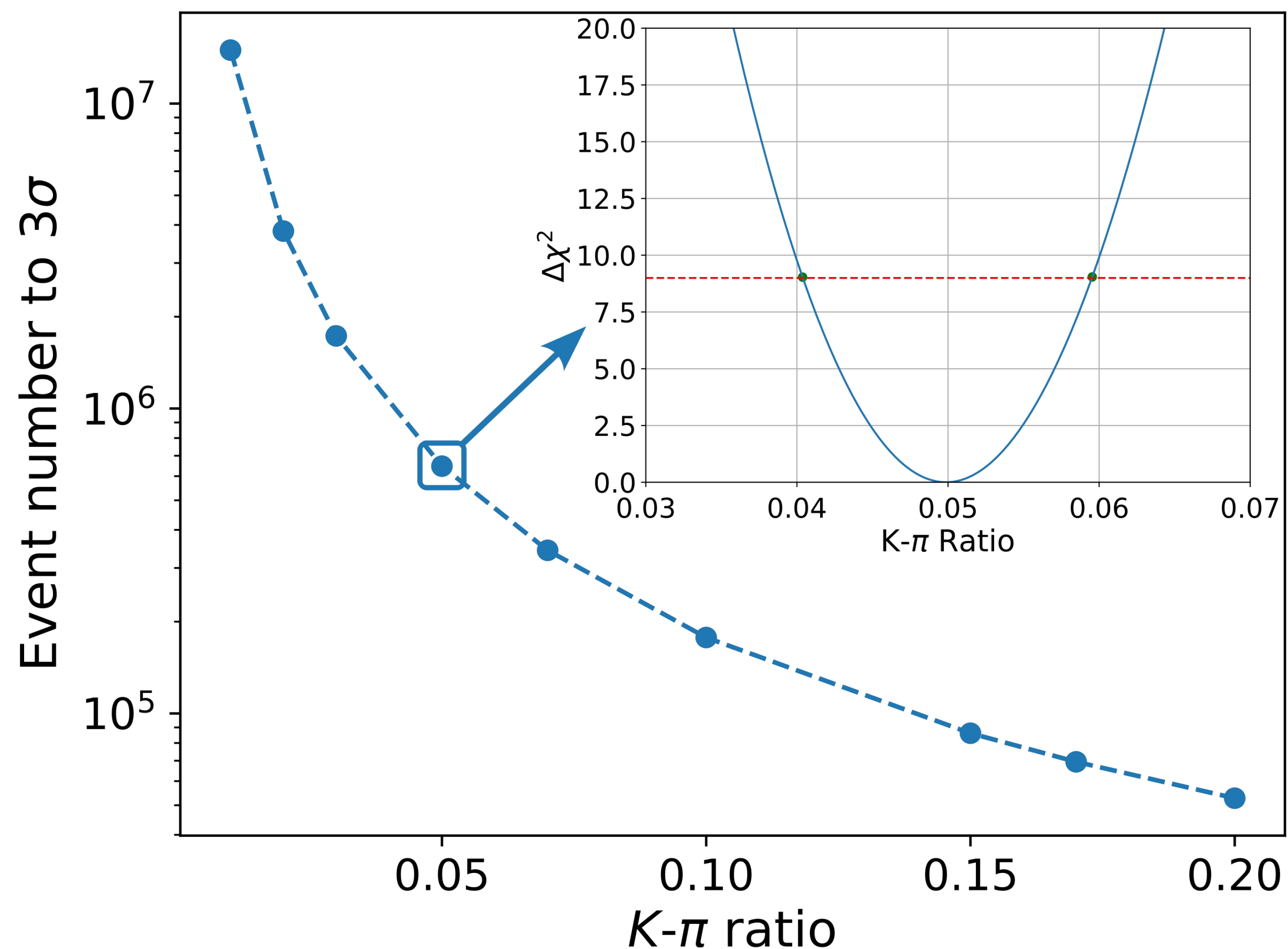
CRmuSR对Michel $e^\pm$ 上下不对称性的粗略分析。



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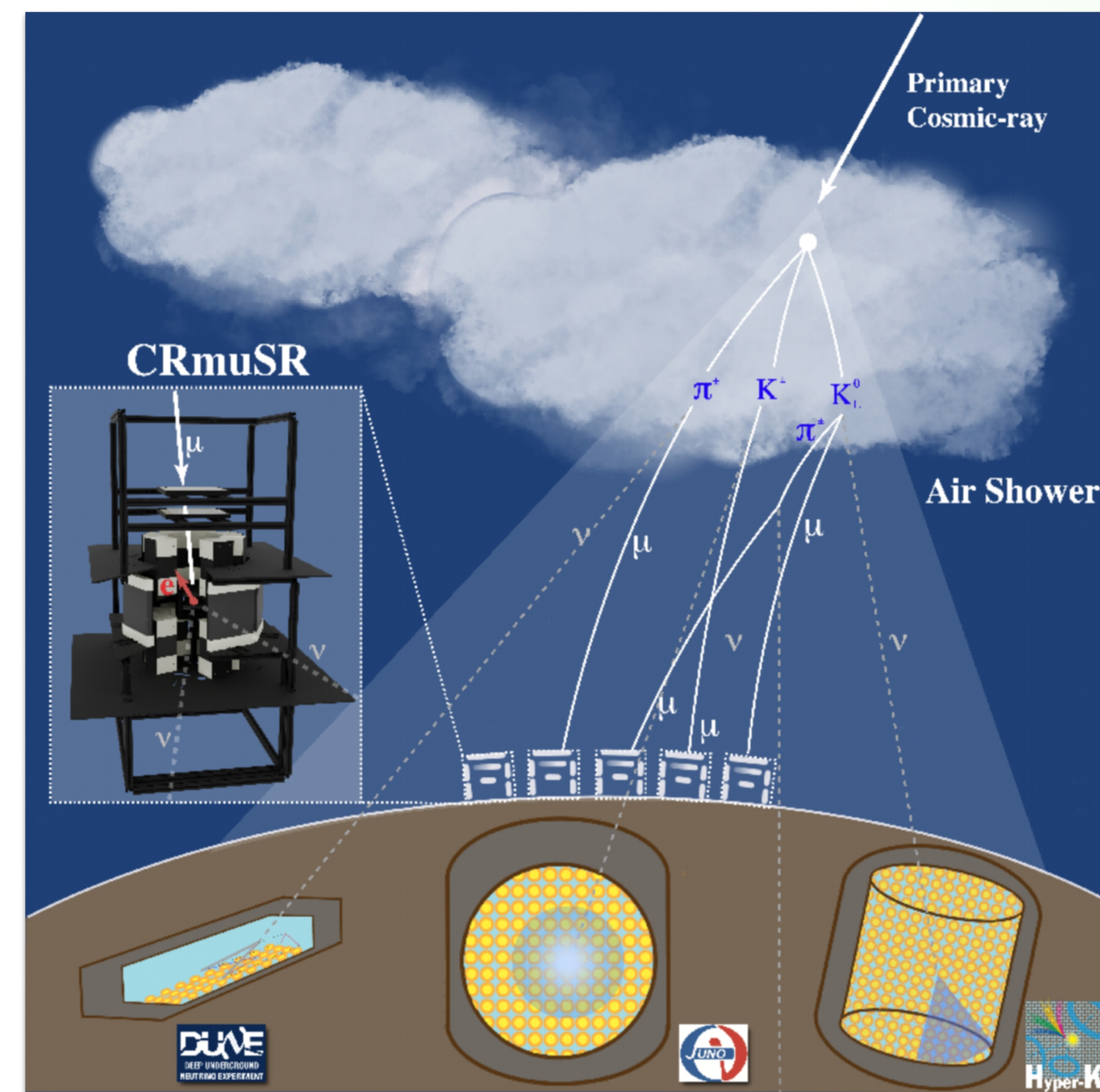
4 CRmuSR需要大统计量——阵列化

- 低能区 K - π ratio 较低, 需要大量有效事例数
- Michel $e^\pm$ 事例率为 $100 \text{ events}/\text{m}^2 \cdot \text{day}$
- K - π **Ratio** = $0.05 \sim 10^6 \text{ events} \sim \mathcal{O}(100)\text{m}^2$



× 做一台 100m^2 有效探测面积的探测器 ×

√ 做100台 1m^2 有效探测面积的探测器 √



- 并行积累有效事例
- 灵活扩展有效面积
- 模块交叉标定

多模块 → 定制化触发、联调系统

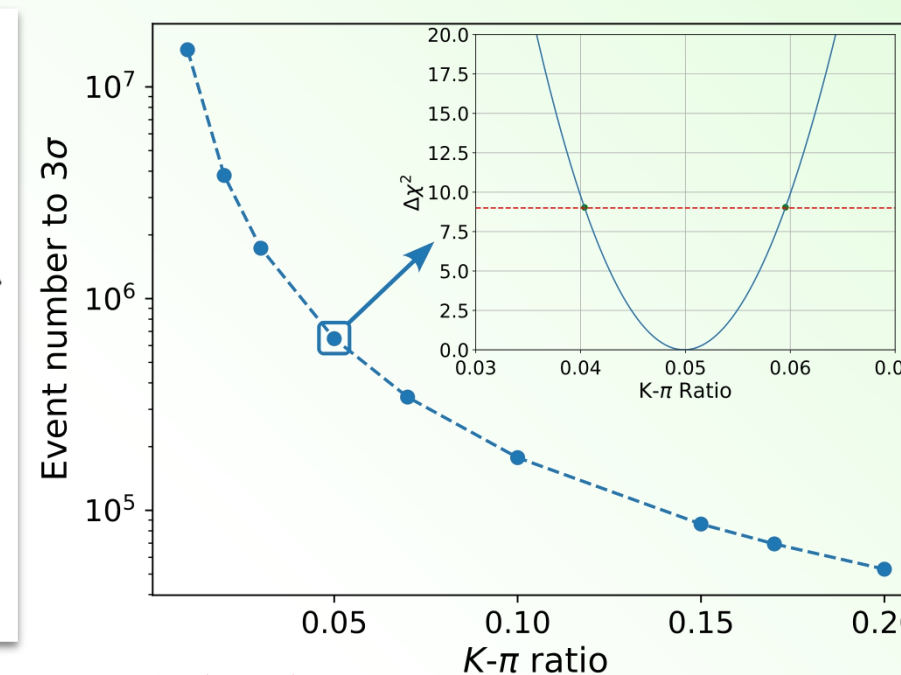
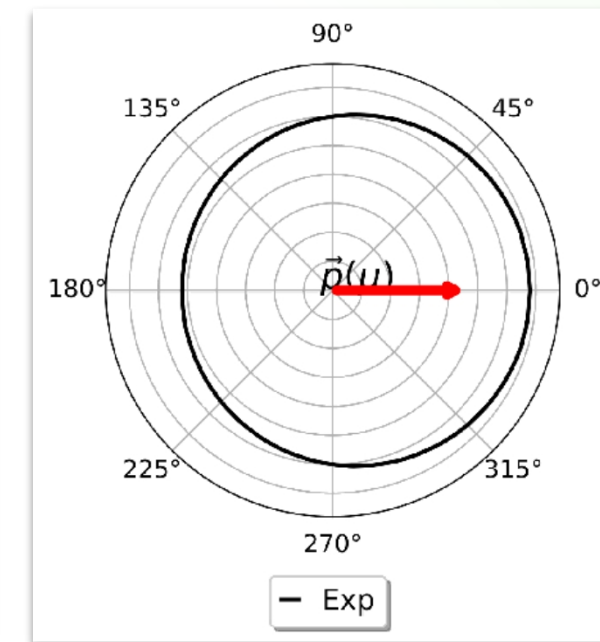
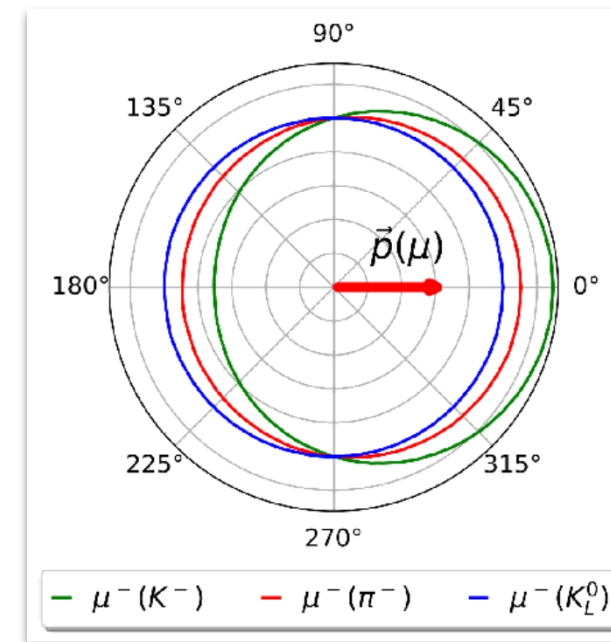
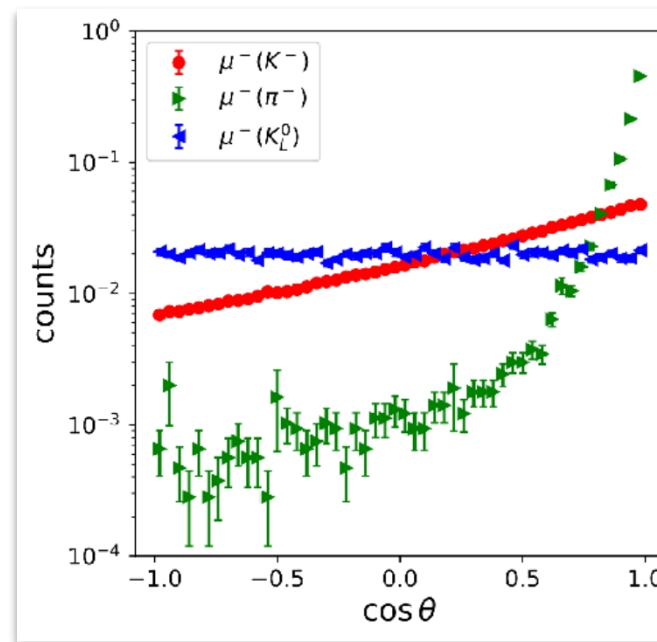
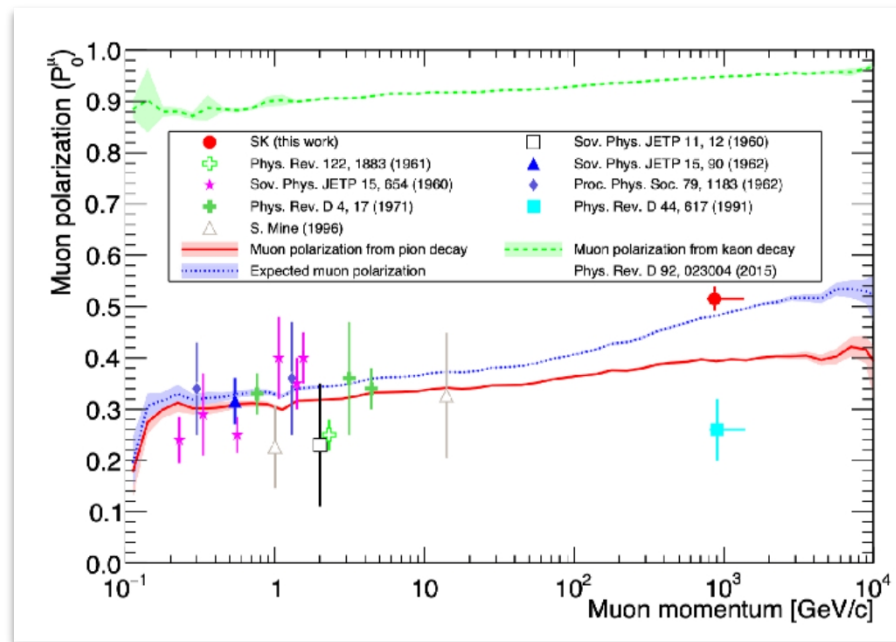
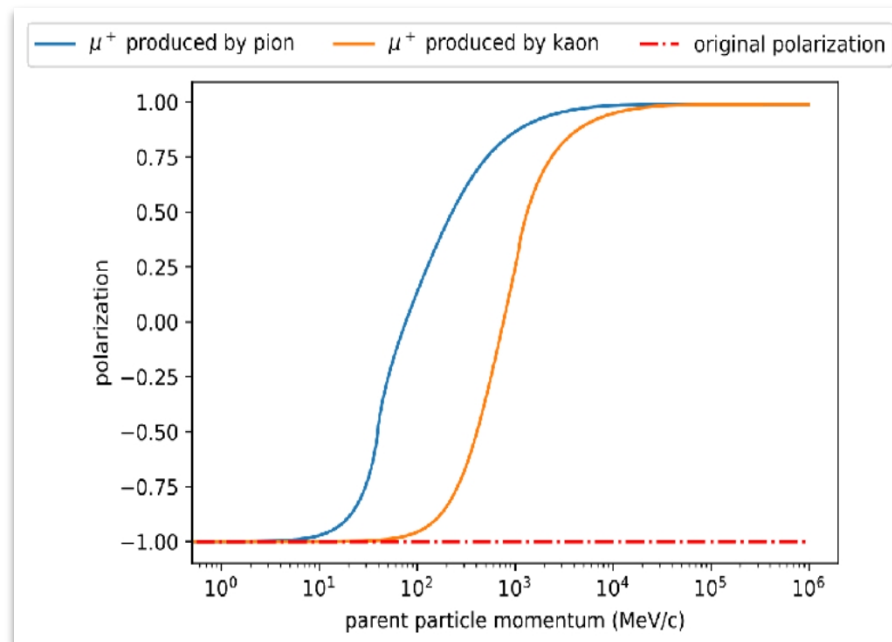
阵列化 → 适配的数据传输方式

高精度 → 高时间分辨率、能量分辨率

重建框架 → 适配的数据格式便于分析

→ 一套高适配、可扩展的电子学平台





约束 $K - \pi$ Ratio

物理目标

更新低能宇生缪子极化数据

通过 *CRmuSR* 谱仪

宇生缪子极化测量

缪子极化的重建框架

检验目标与通量要求

探测器进展

探测器样机

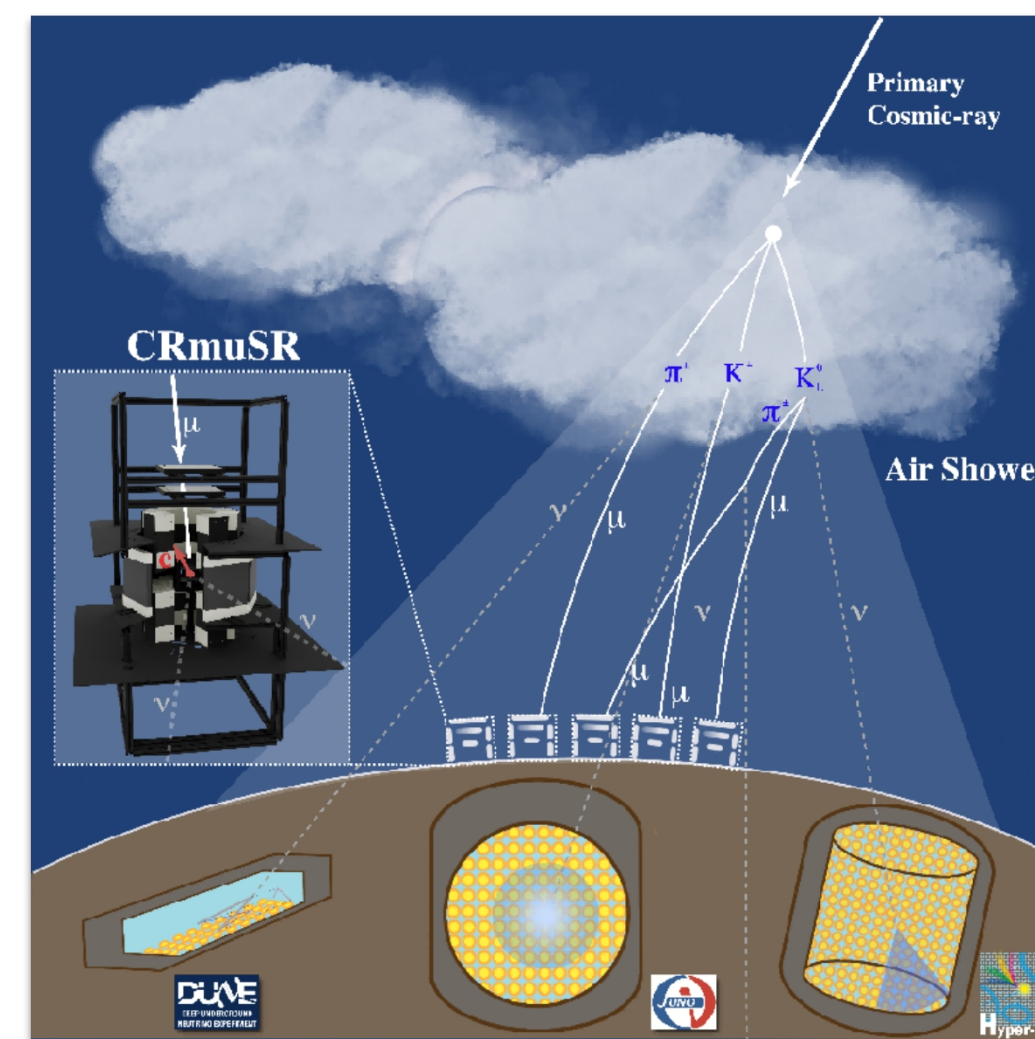
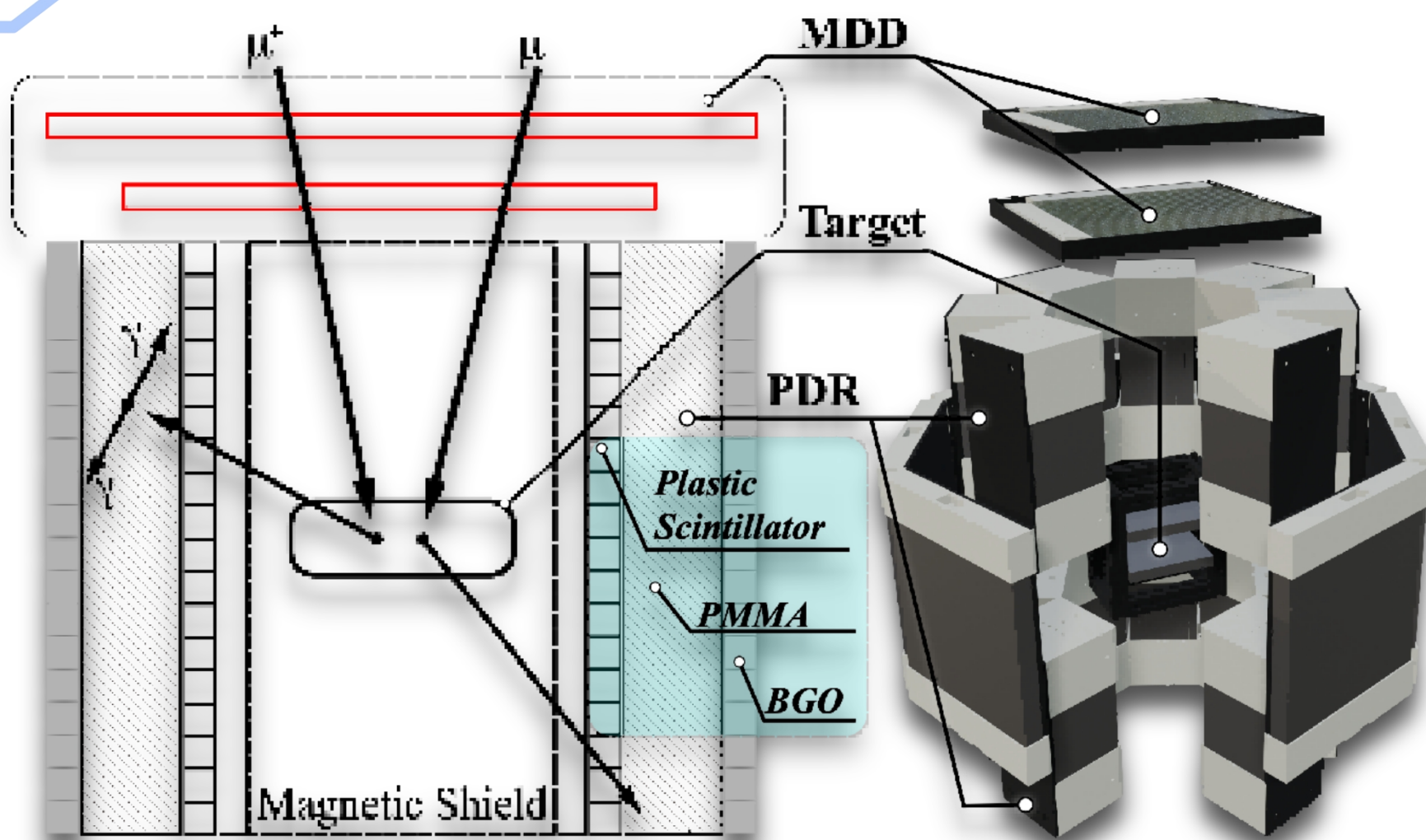
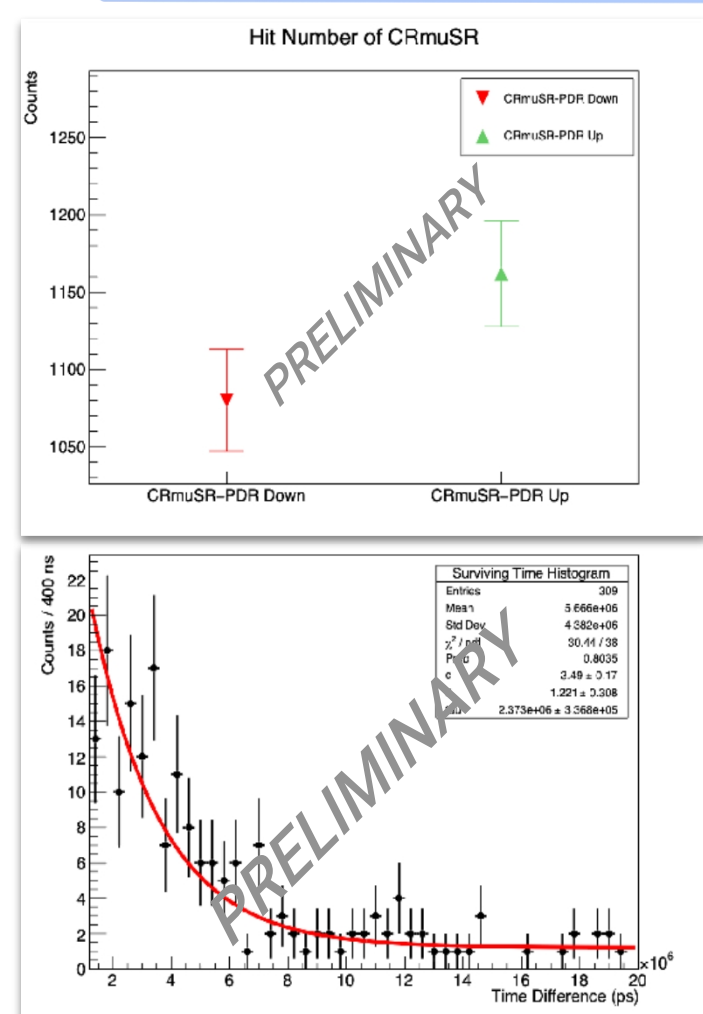
测量宇生缪子极化信息

CRmuSR 后续升级

探测器阵列化

适配的电子学读出系统

初步分析探测器性能

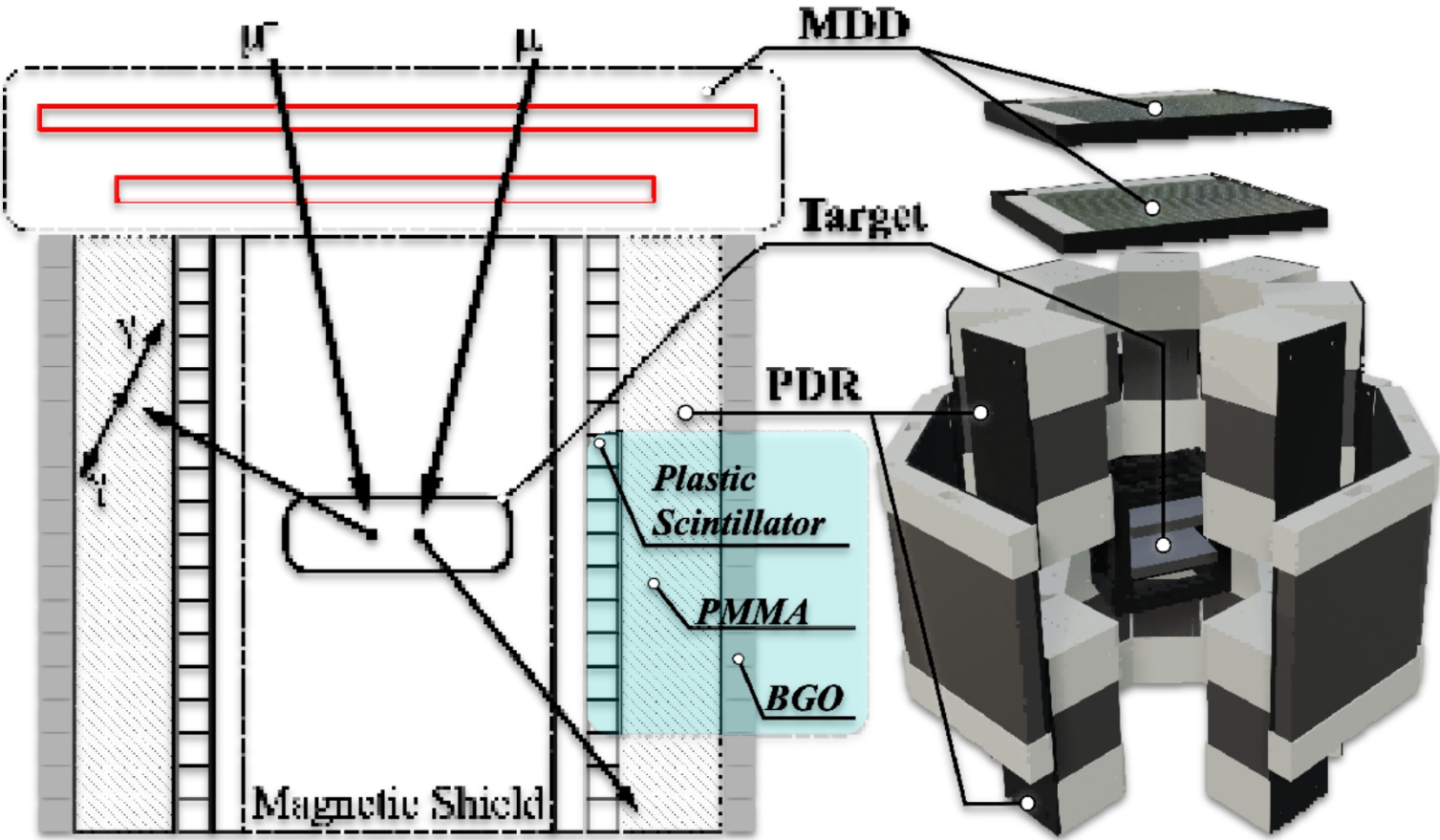




Cosmic Ray Muon Experiment



arXiv:2505.13877

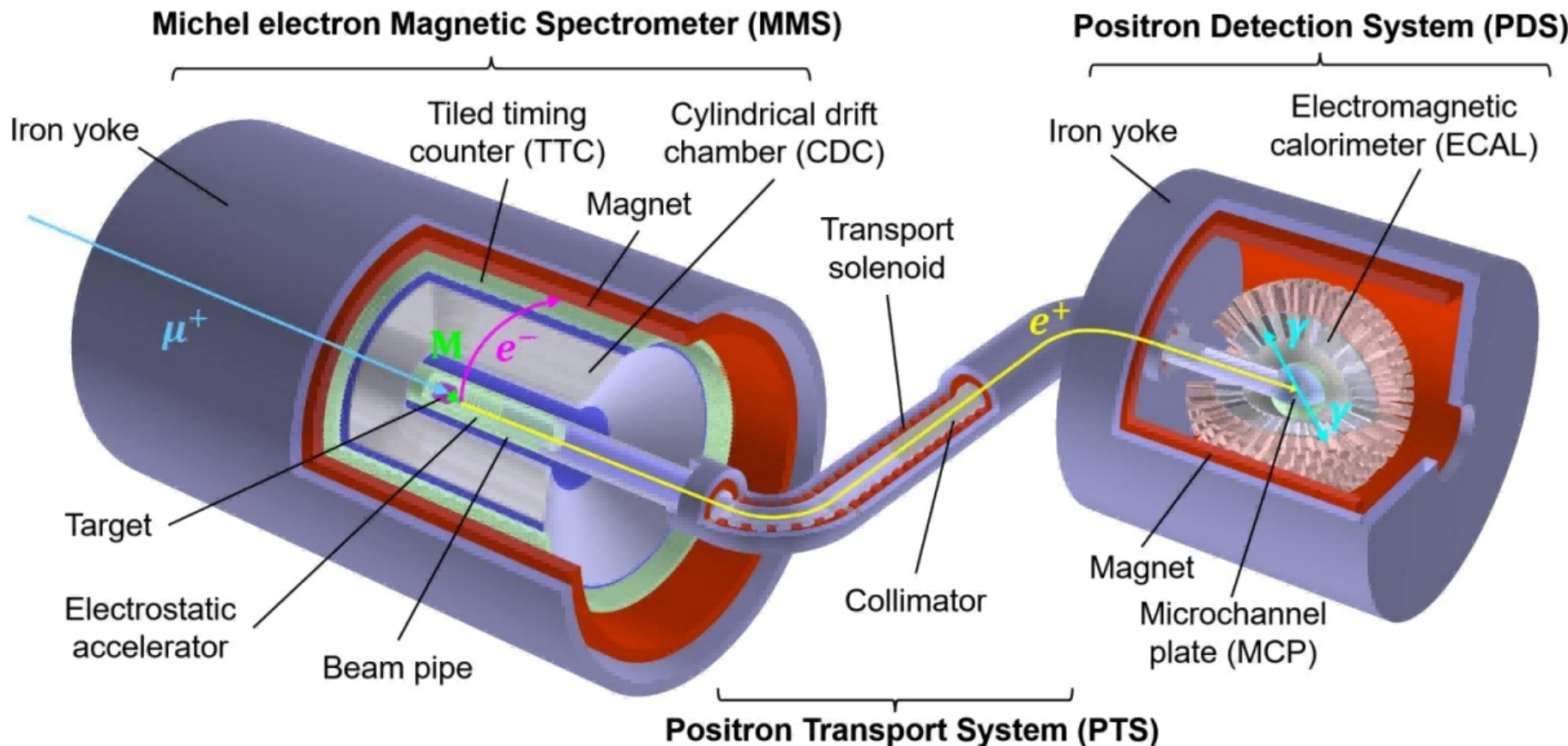


New Physics Experiment

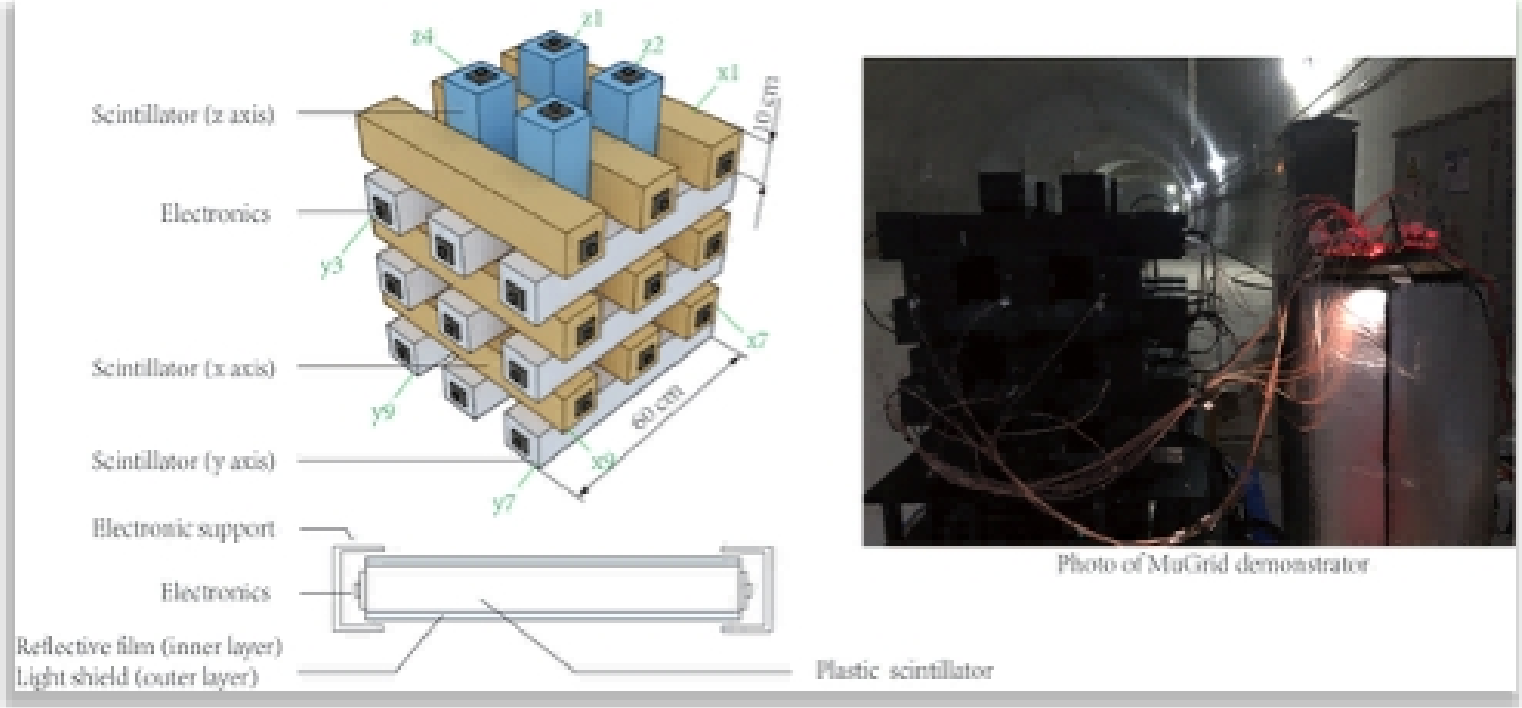


Muonium-to-Antimuonium Conversion Experiment

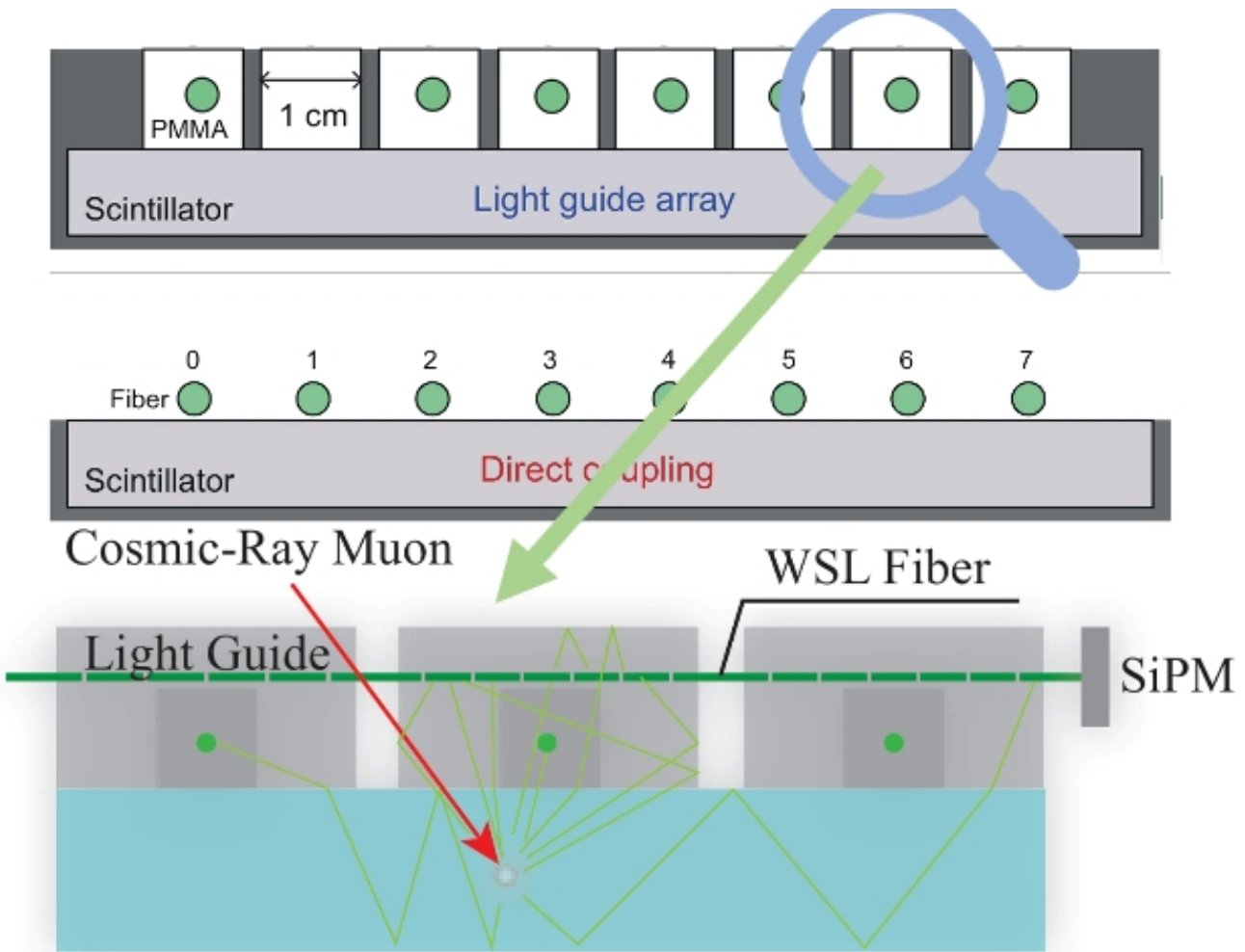
arXiv:2410.18817



Muon Related Application



arXiv:2505.19777



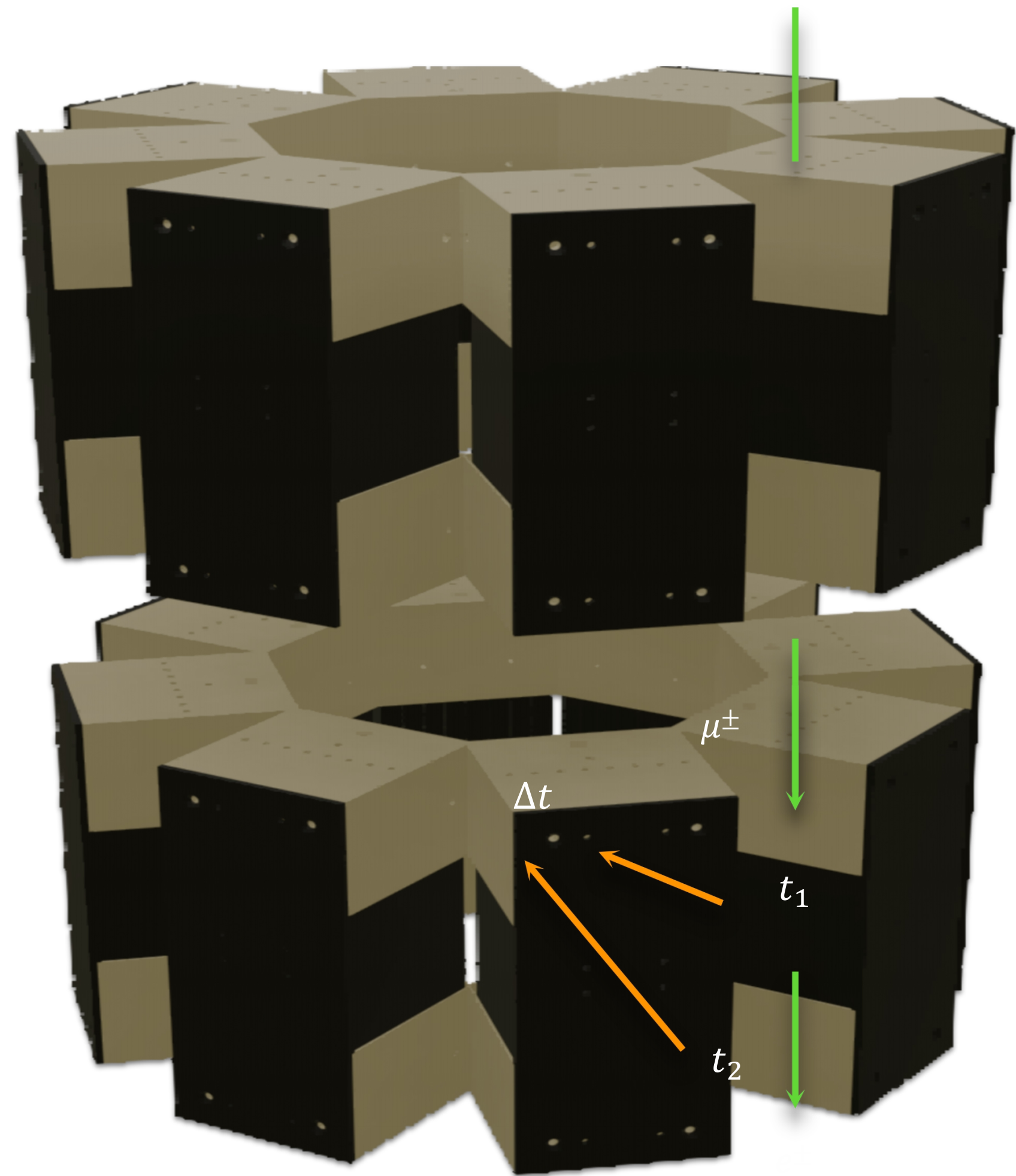
Thanks

5 CRmuSR 测量宇生缪子寿命

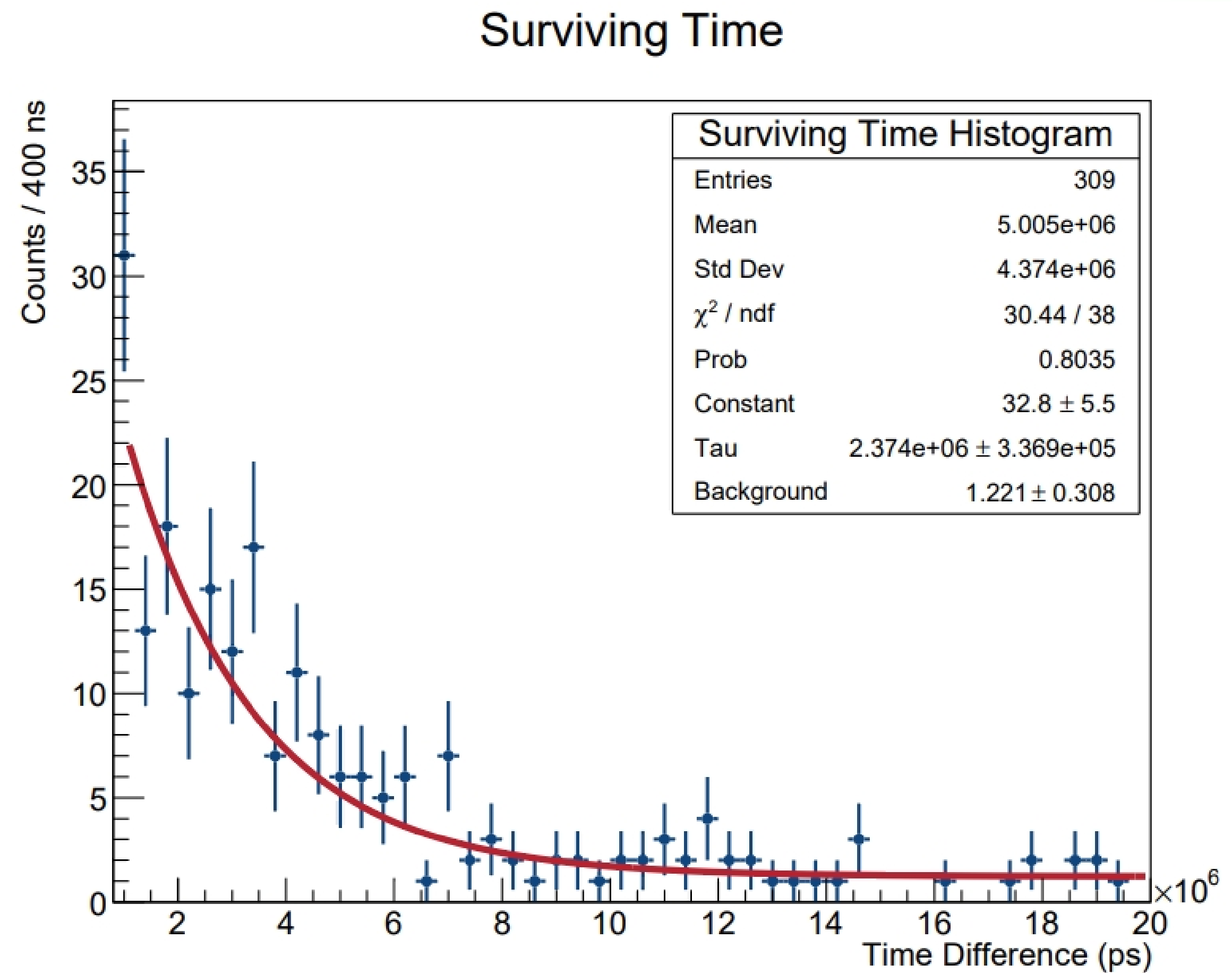
拟合函数: $N = N_0 e^{-\frac{t}{\tau}} + \text{BackGround}$

全部数据: 缪子寿命 $\tau \approx (2.251 \pm 0.25)\mu\text{s}$

剔除本底: $\tau \approx (2.374 \pm 0.36)\mu\text{s}$



Lifetime of cosmic-ray muon decay in PDR.

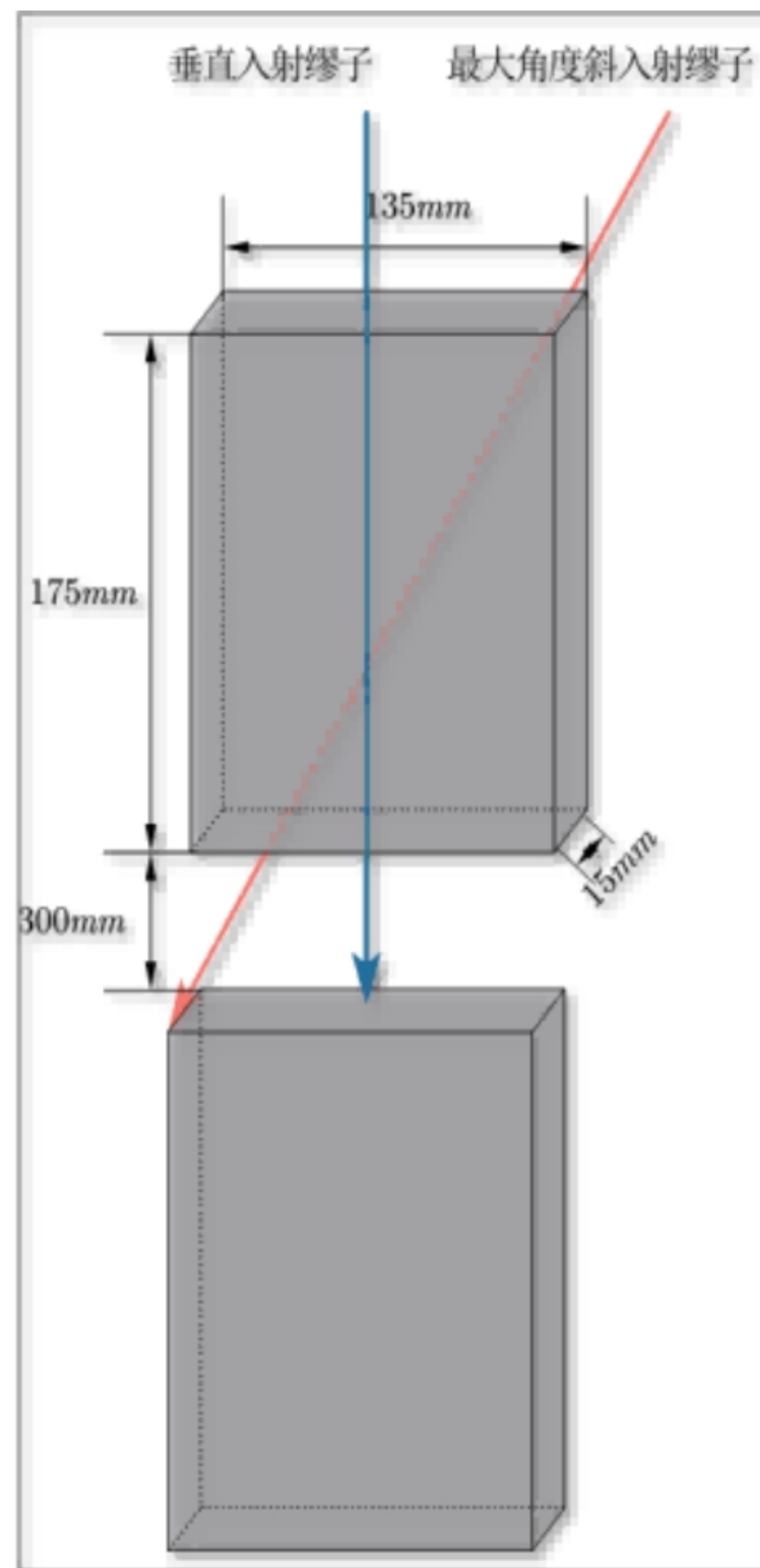
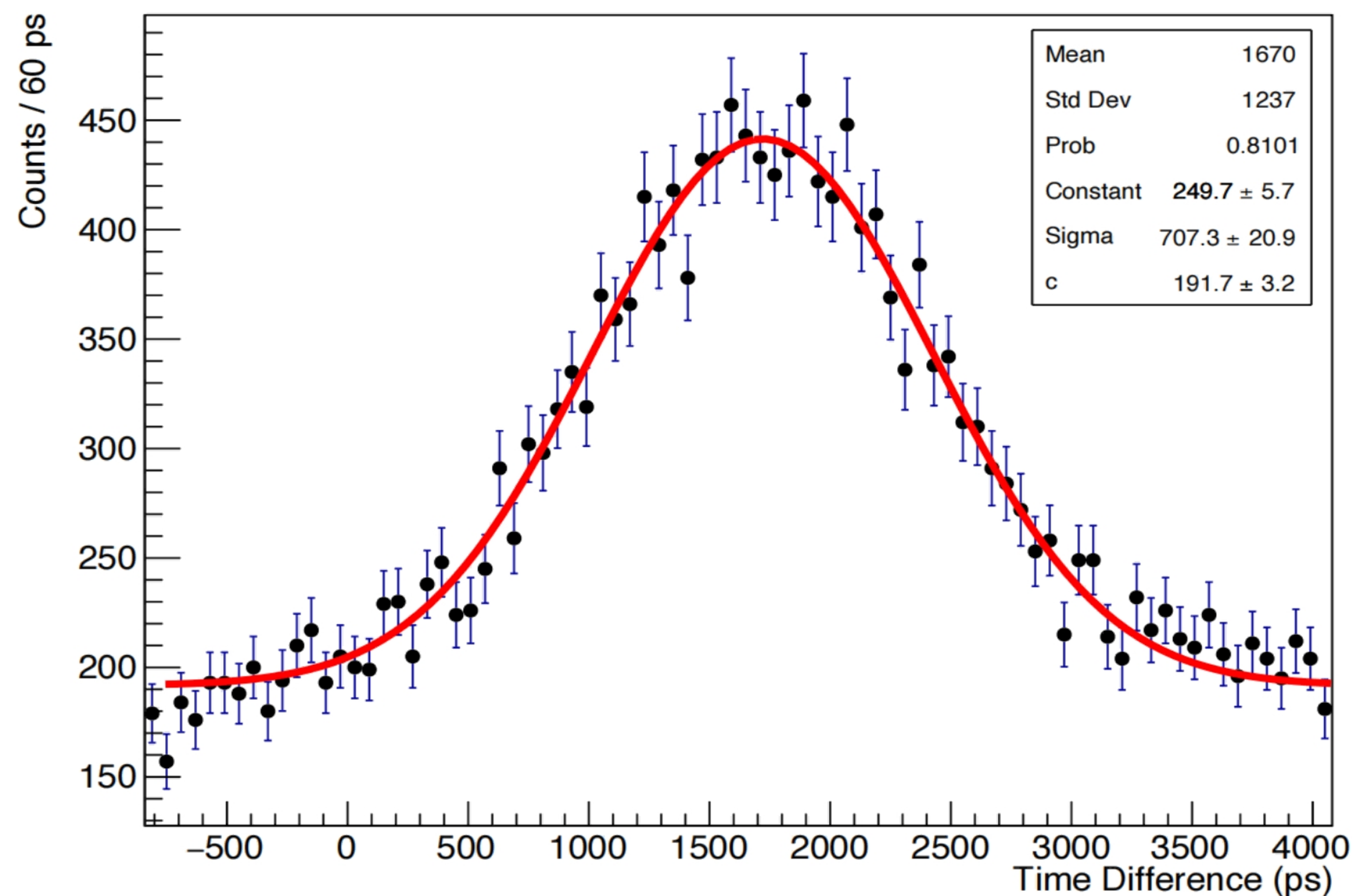


5 CRmuSR 时间分辨率测量

使用高斯函数拟合:

时间分辨率定义为测量同一事件的时间抖动, 即高斯分布中的标准差 σ 。

时间分辨率: $\sigma \approx (707.3 \pm 20.9)ps$



➤ 正入射的缪子触发两层闪烁体的时间差为:

$$\Delta t = \frac{300\text{mm} + 175\text{mm}}{3 \times 10^8 \text{ m/s}} = 1.58\text{ns}$$

➤ 最大角度入射的缪子触发两层闪烁体的时间差为:

$$\Delta t = \frac{\sqrt{l_z^2 + l_z^2 + l_y^2}}{c} = 1.65\text{ns}$$

➤ 实际测得时间:

$$\Delta t = \text{Mean} = 1.67\text{ns}$$

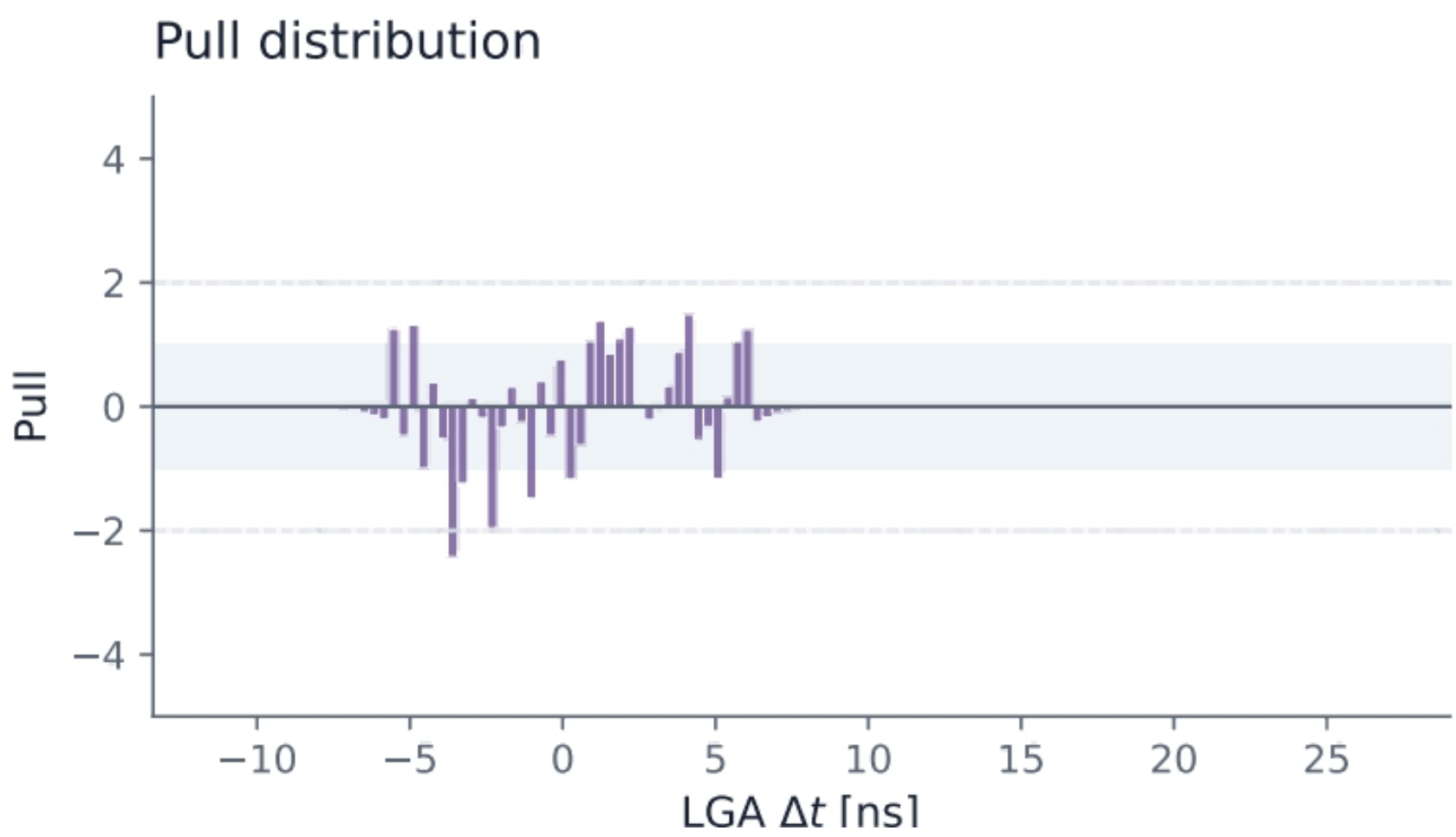
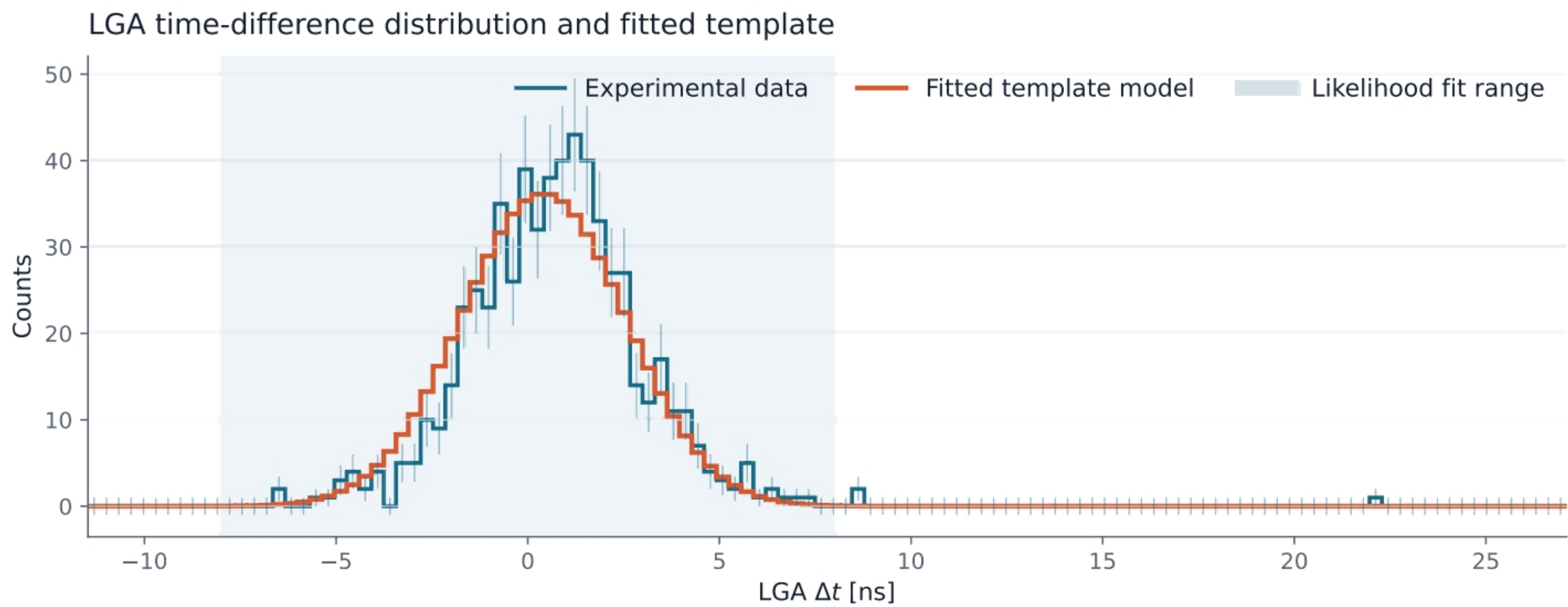
误差来自:

- 入射缪子的天顶角分布。
- 缪子信号到被测量之间的复杂过程。
- 缪子时间戳的测量。

5 MDD模块时间分辨率测量

LGA detector time-resolution result

Signed experimental LGADeltaT fitted with the reflected simulation template



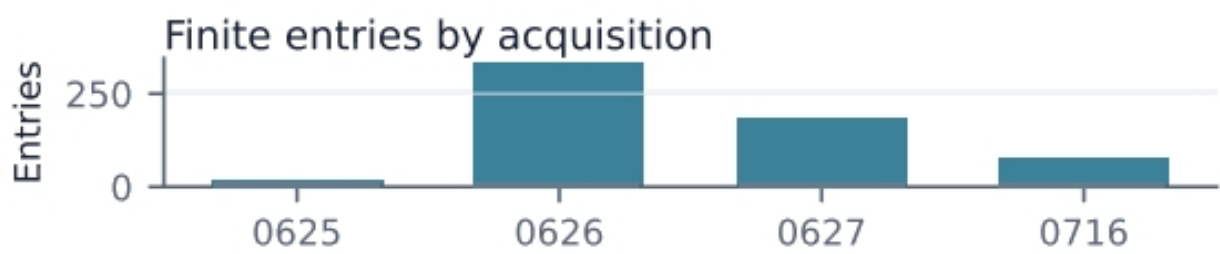
Fit result

$$\sigma_{\text{single}} = 1.5166 \pm 0.0443 \text{ ns}$$

$$\sigma_{\text{diff}} = 2.1449 \pm 0.0626 \text{ ns}$$

$$\text{offset} = 2.0000 \pm 0.0132 \text{ ns}$$

Fit status = 0 CovQual = 3 chi2/ndf = 0.675
Entries: 603 fitted / 606 finite



两个模块的总时间分辨率为:

$$\sigma \approx (2.145 \pm 0.062) \text{ ns}$$

单层时间分辨率为:

$$\sigma \approx (1.516 \pm 0.044) \text{ ns}$$

Average Polarization Calculation

$$\mathcal{P}_\mu = \frac{\cos \alpha \sqrt{1 + R_p^2} + R_p + g(\alpha, R_p, R_m)}{\sqrt{2R_p \cos \alpha \sqrt{1 + R_p^2} + (1 + \cos^2 \alpha)R_p + 2 \cdot \sqrt{1 + g^2(\alpha, R_p, R_m)}}},$$

$$g(\alpha, R_p, R_m) = \frac{\cos \alpha \sqrt{1 + R_p^2} + R_p + R_m}{\sqrt{1 + R_m^2} \sqrt{2R_p \cos \alpha \sqrt{1 + R_p^2} + (1 + \cos^2 \alpha)R_p + 2}}.$$

$R_m = m_\mu/m_M$ *is the mass ratio between muon and its parent particle*

$R_p = p_M/E_M$ *is the momentum-to-energy ratio of muon parent particles*

α *is the angle between muon momentum direction and Michel electron momentum direction*