



中国科学技术大学

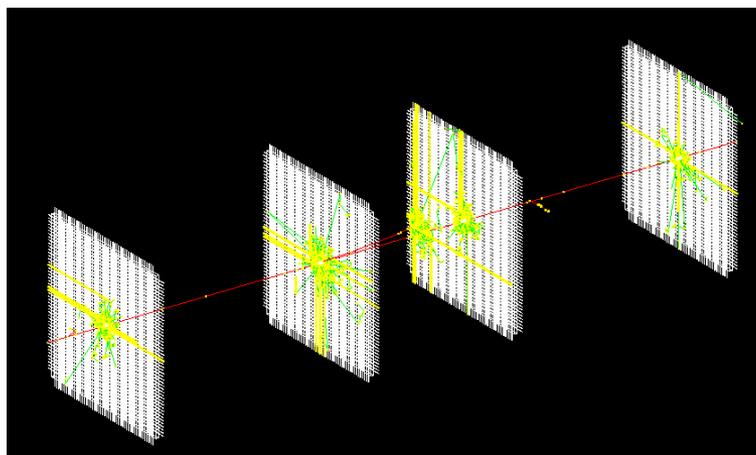
University of Science and Technology of China

# 缪子成像系统的模拟与原型机研制

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- 研究背景
- CRTTest程序
- 模拟结果
- 读出模块测试
- 下一步计划



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入射径迹追踪模块

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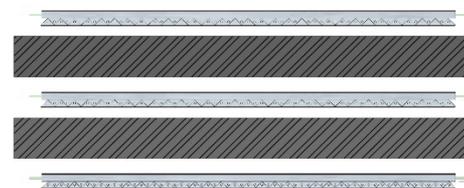
成像空间

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出射径迹追踪模块

量能  
模块



左图：模拟束流测试

上图：三角型塑闪宇宙线系统

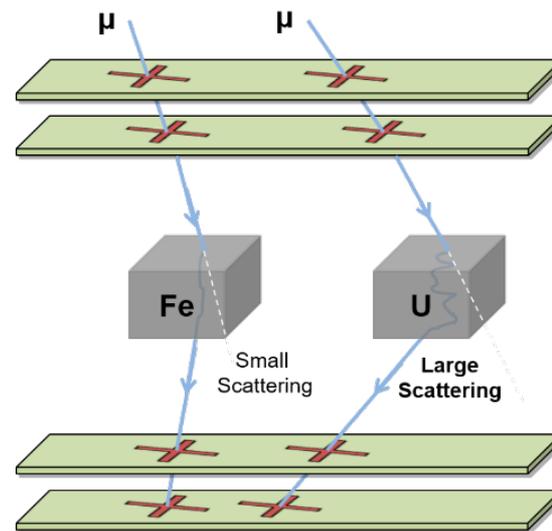
## • 宇宙线散射成像

- 天然的高能宇宙线 $\mu$ 子能够穿透常见的X射线屏蔽材料，是检测**高原子序数、高密度物质**的理想探针。

- 由美国LANL于2003年提出，为实现无源条件下的**放射性材料安全检查和长期监控**提供了解决方案。

## • 基本方法

- 记录 $\mu$ 子出入射径迹，重建其在成像空间内的散射信息，获取内部物质分布情况



图一宇宙线散射成像原理图



图一海关应用设计概念图

## • 探测器

- 波长迁移光纤读出的塑料闪烁体
- 闪烁光被吸收后二次发射在光纤中全反射

## • 实验方案

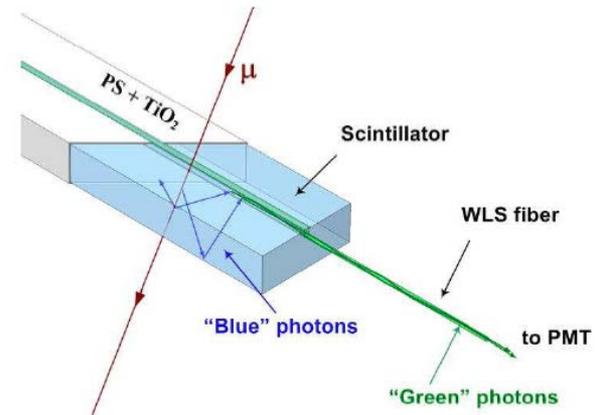
- 1) 长条模块，拼接组成探测单元
- 2) 整体平板，直接X-Y开槽读出

## • 优点

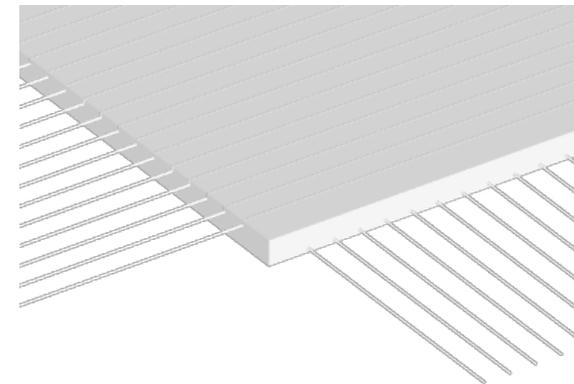
- 探测效率高，适用于低计数场景
- 性能稳定，可以长期运行
- 便于规模化制作并组成大面积探测系统

## • 应用

- LHAASO-KM2A ED
- OPERA Target Tracker
- MINOS Calorimeter



图一波长迁移光纤塑闪读出原理



图一塑料闪烁体平板二维开槽

## • 设计思路

- 基于Geant4实现通用宇宙线 $\mu$ 子探测及成像平台模拟
- 以闪烁体及波长迁移光纤过程为主要应用

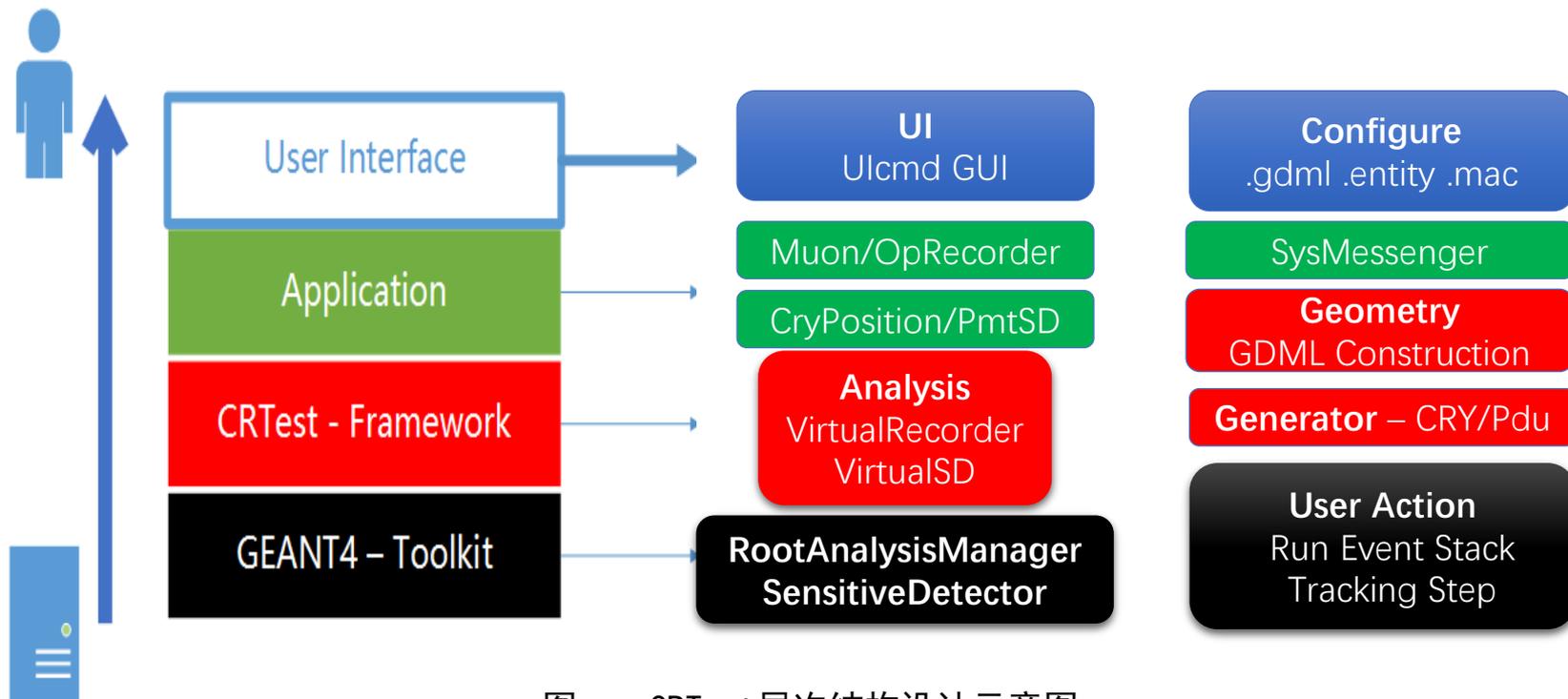


图 — CRTTest层次结构设计示意图

- 唯象模型
- S. Chatzidakis

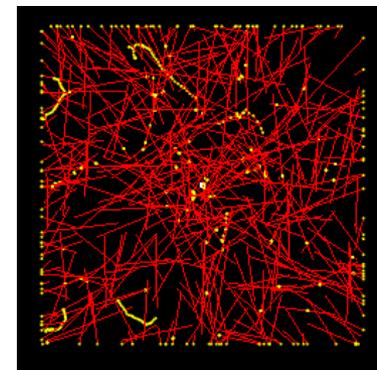
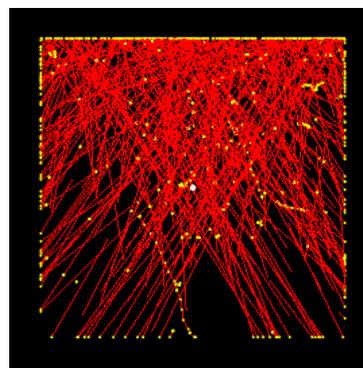
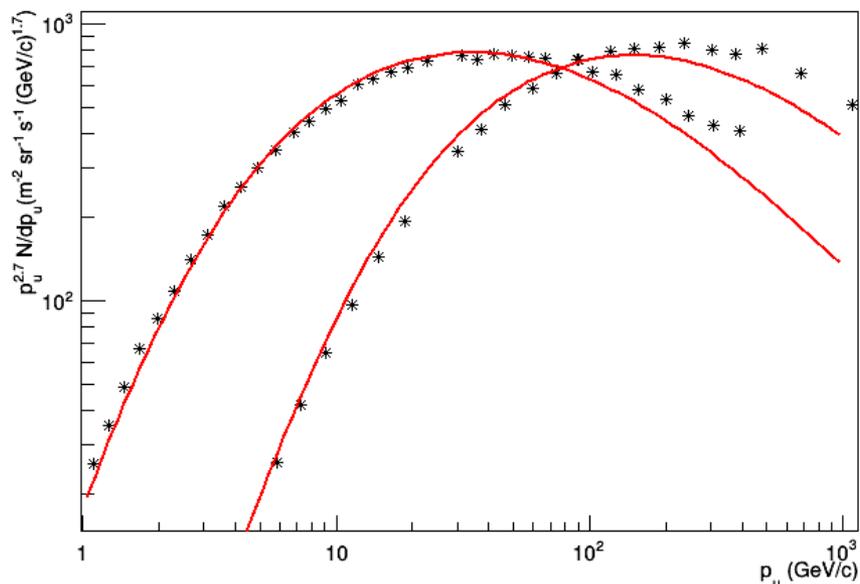
$$N_{\mu}(E_{\pi}, \theta) = \frac{AE_{\pi}^{-\gamma} P_{\mu} \lambda_{\pi} b j_{\pi}}{E_{\pi} \cos \theta + b j_{\pi}}$$

$$\frac{dN_{\pi}(E_{\pi}, y, \theta)}{dy} = \frac{AE_{\pi}^{-\gamma}}{\cos \theta} \exp\left(\frac{-y}{\lambda_p \cos \theta}\right) - \frac{N_{\pi}(E_{\pi}, y, \theta)}{\cos \theta} \left[\frac{1}{\lambda_{\pi}} + \frac{dt}{\tau}\right]$$

$$P_{\mu}(E_{\pi}, y, \theta) = \left[\frac{y E_{\mu}}{y_0 E_{\mu}^*}\right]^{(B_{\mu}/(E_{\mu}^* \cos \theta))} \quad B_{\mu} = \frac{b_{\mu} m_{\mu} y_0 c}{\tau_{\mu} \rho_0}$$

- Geant4模拟
- CRY by LLNL

Fit PDG Muon Data



## • 几何结构

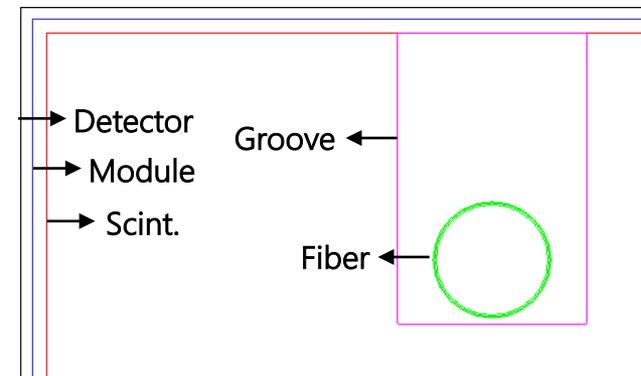
- Detector, Module, Scintillator
- Groove, Fiber – Cladding, Core, PMT/SiPM

## • 材料

- 塑料闪烁体 – EJ200, BC408
- 波长迁移光纤 – Y11, BCF92
- 耦合 – 空气 AIR, 光学胶EJ500

## • 信息获取与读出 – ROOT文件(Ntuple)

- 灵敏探测器：VirtualSD (CryPositionSD, PmtSD)
  - 基本信息：编号总能量沉积、平均时间、平均位置
  - 扩展模式：输出探测器内所有Hit
  - PmtSD：输出所有PMT计数
- 记录器：VirtualRecorder (MuonRecorder, OpRecorder)
  - 基本信息：记录对应粒子模拟过程中追踪信息G4Track
  - OpRecorder：记录发光过程和穿过各个表面光子计数

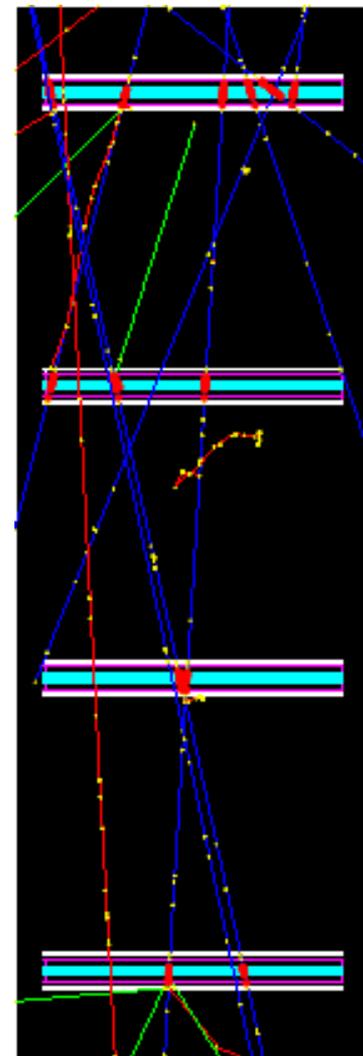
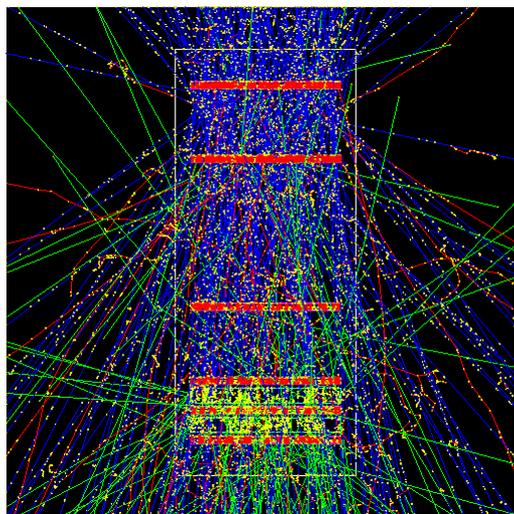
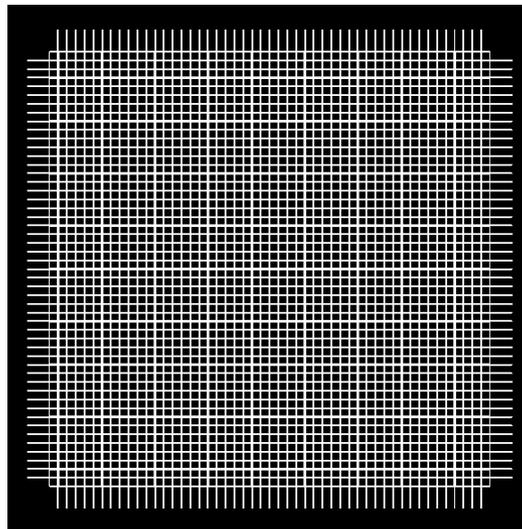
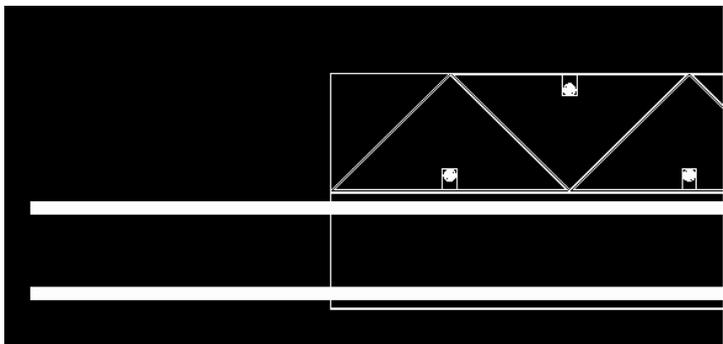
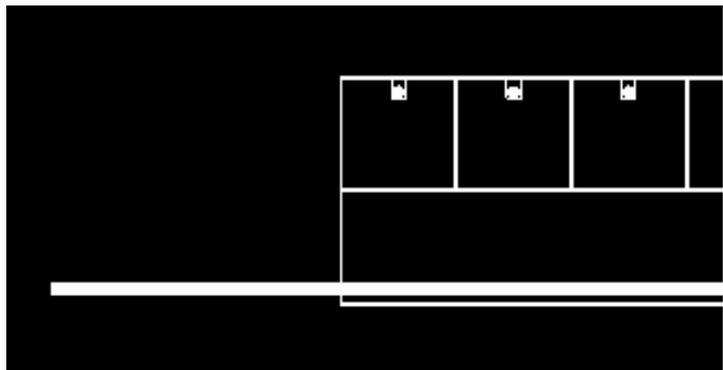
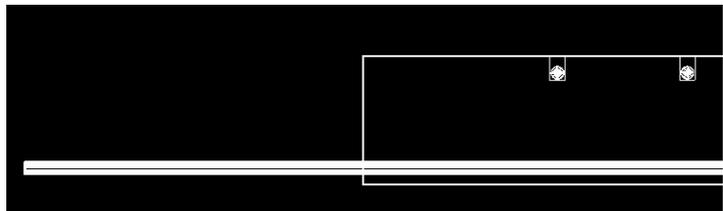


图一—探测模块基本几何结构示意图

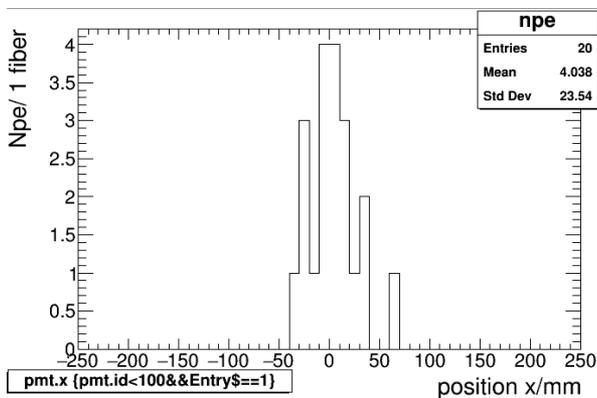
# 探测器设计



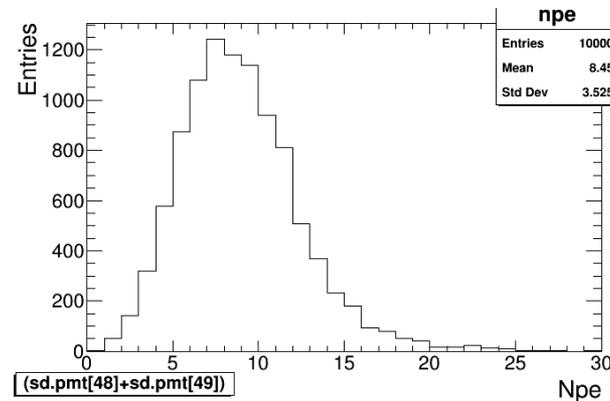
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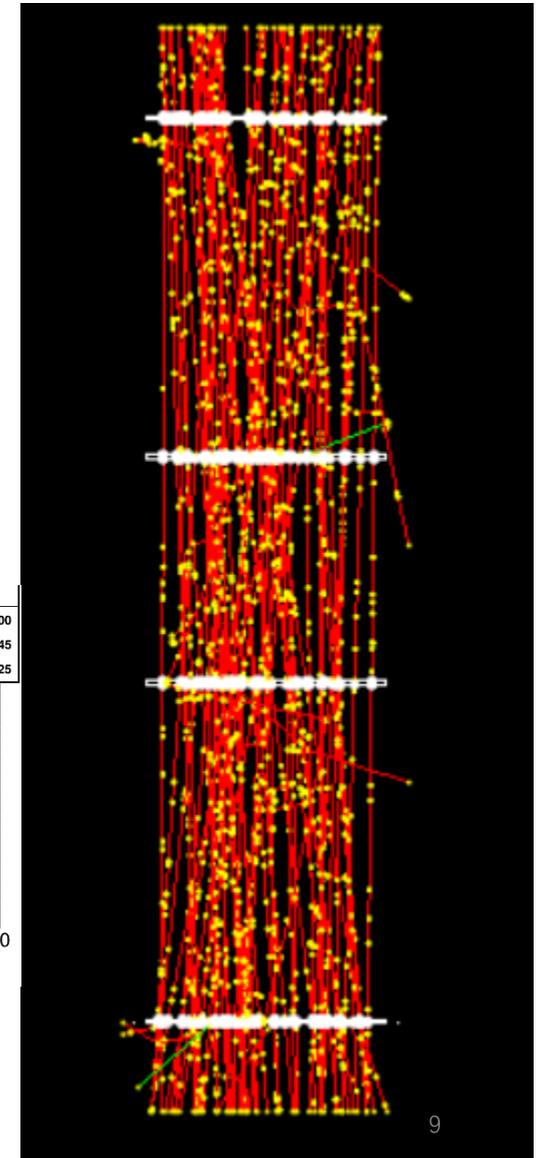
- 平板塑闪二维读出方案
  - $52 \times 52 \times 1 \text{ cm}^3$ , Kuraray Y11 (50x2), PMT H7546B
- 光产额 - 3 GeV  $\mu$ 子直入射中心位置
  - Npe:  $\sim 16$  (MPV-X),  $\sim 16$  (MPV-Y)
  - PMT计数分布: {1, 2, 2, 7, **HIT**, 7, 2, 2, 1}
- 位置分辨  $\sigma_{x/y} \sim 4 \text{ mm}$  - 宇宙线测试, Npe > 3



图一3GeV直入射探测光子数分布



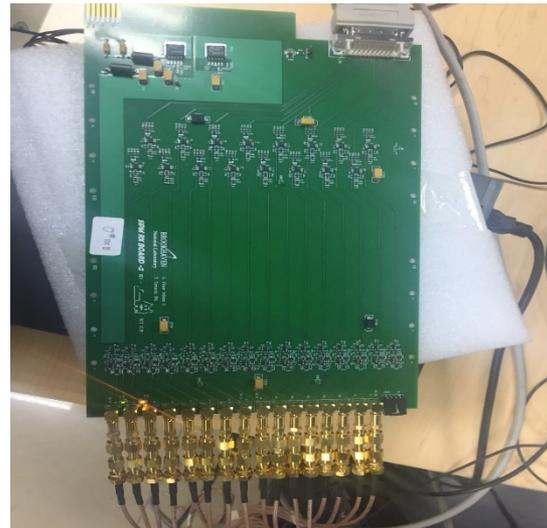
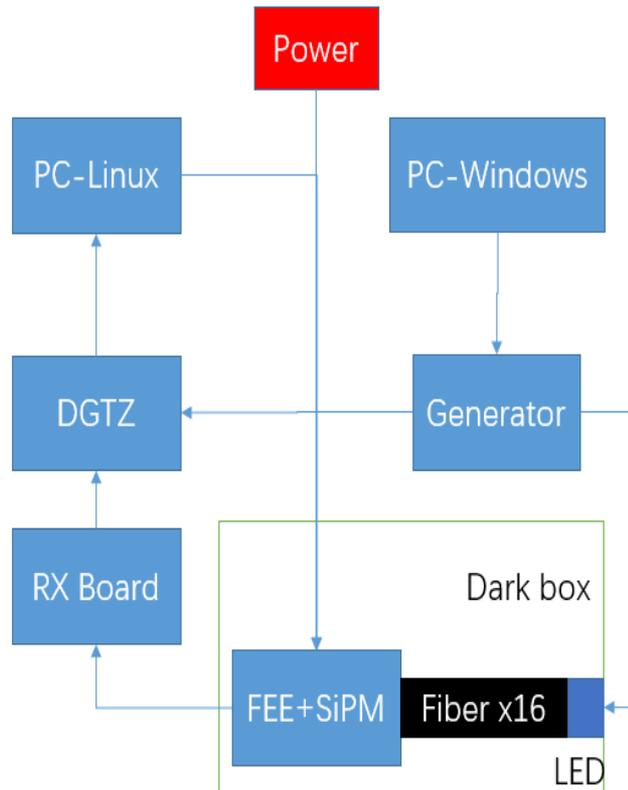
图一中心附近光纤探测光子数分布



# SiPM读出模块



- 系统设计与零部件展示
  - for STAR-EPD



- **Test Items**

- Surface(height)

- UI Curve

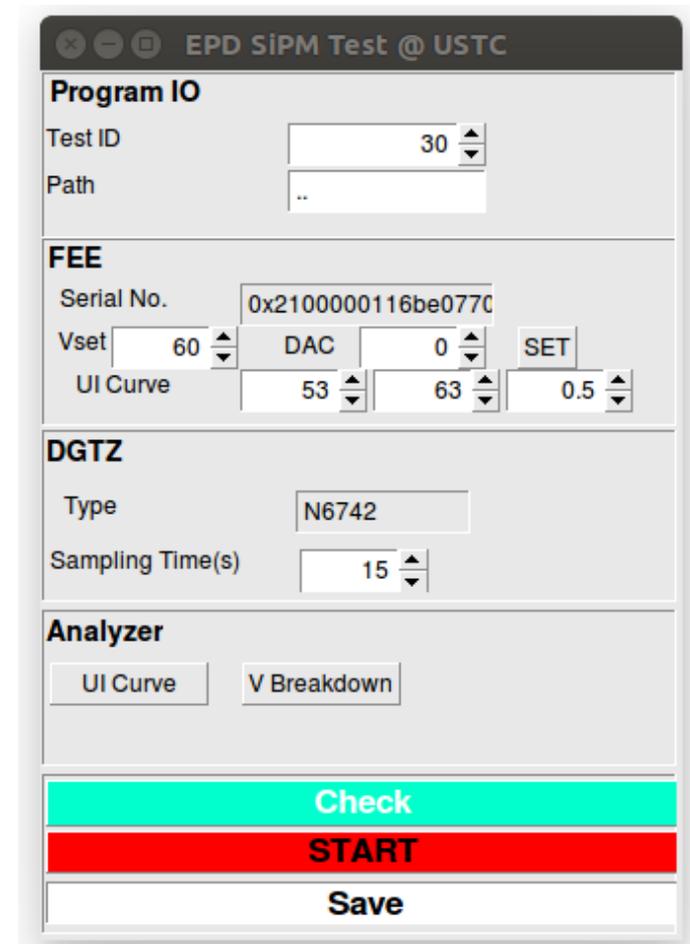
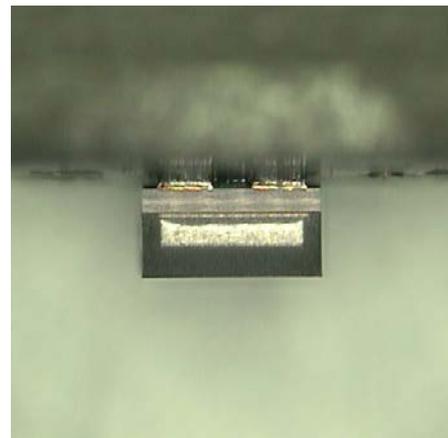
- [53:63:0.5]

- Pedestal/DAC

- [-127,0,127]

- Noise: FFT

- Signal



EPD SiPM Test @ USTC

**Program IO**

Test ID: 30  
Path: ..

**FEE**

Serial No.: 0x2100000116be0770  
Vset: 60 DAC: 0 SET  
UI Curve: 53 63 0.5

**DGTZ**

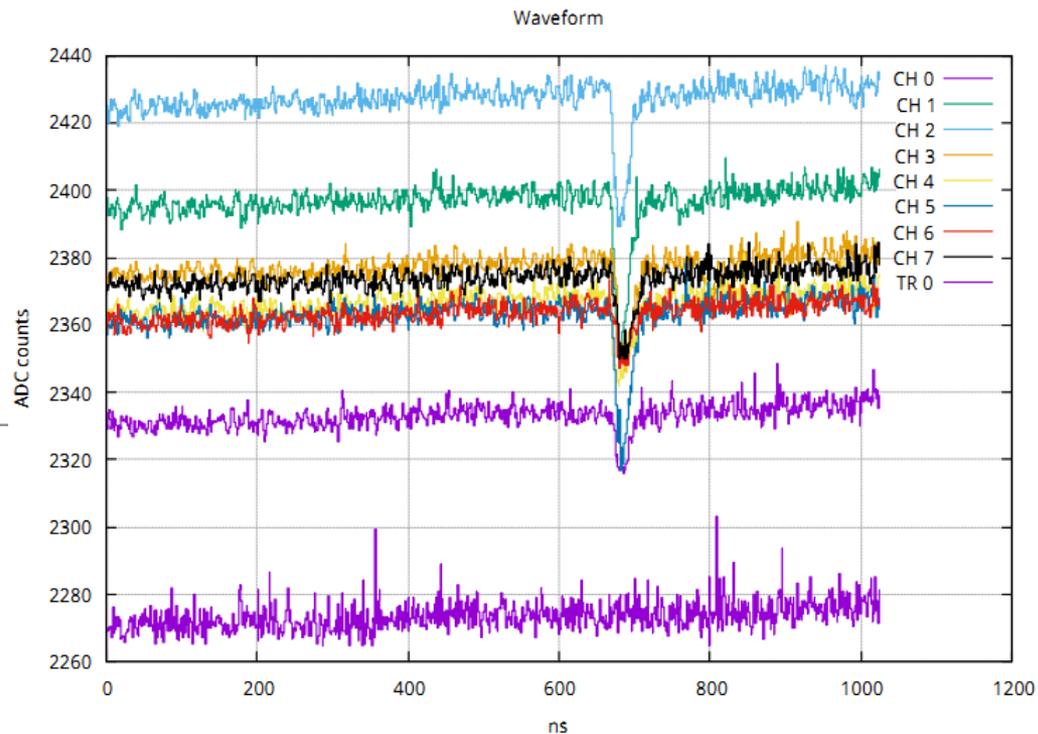
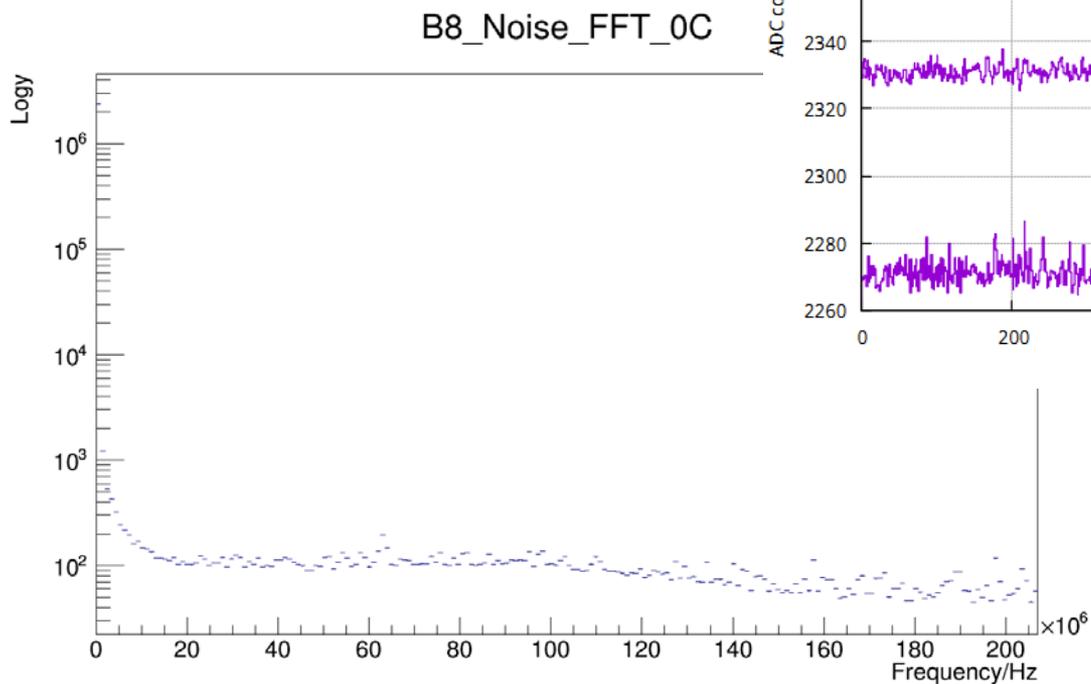
Type: N6742  
Sampling Time(s): 15

**Analyzer**

UI Curve V Breakdown

Check  
START  
Save

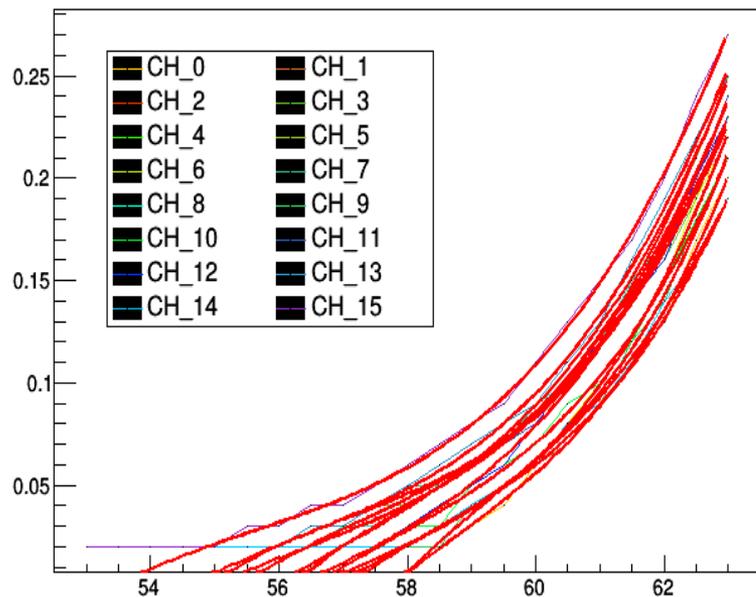
- 噪声为FFT



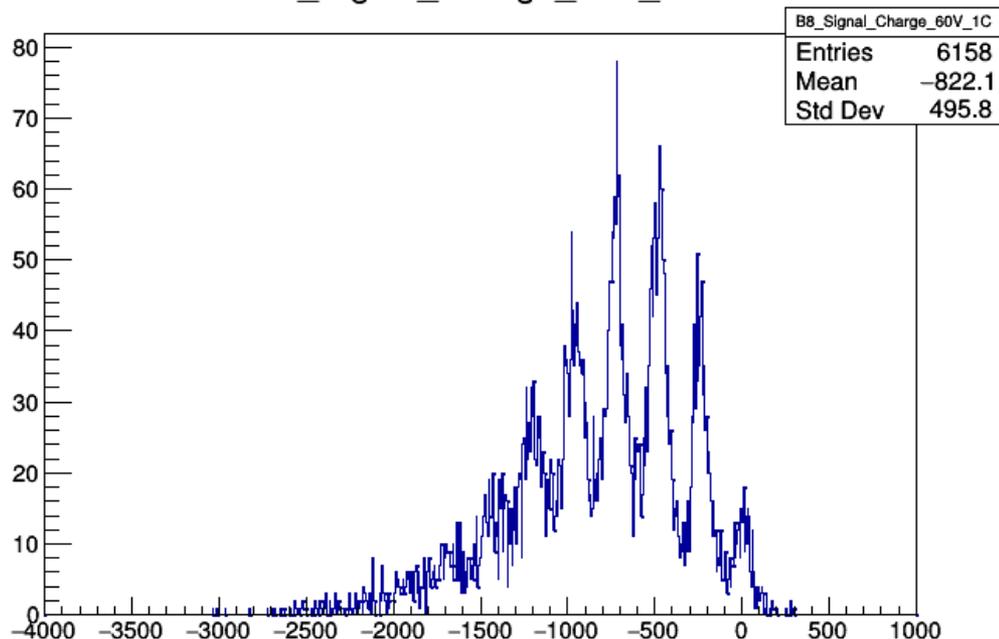
# UI曲线、信号积分谱



UI Curve of SiPM



B8\_Signal\_Charge\_60V\_1C



MRPC

STAR-EPD

FEE Board

RX Board

SiPM

Detail View

Toolbar

Search

UID	Serial No.	Connection	Noise	Signal	Result	Comment
1	0x4d00000116e33c70	PASS	PASS	PASS	SHOW	-
2	0xbe00000116cb2e70	PASS	PASS	PASS	SHOW	-
3	0x1d00000116d98e70	PASS	PASS	PASS	SHOW	-
4	0x7e00000116e77f70	PASS	PASS	PASS	SHOW	-
5	0x5f00000116dae470	PASS	PASS	PASS	SHOW	-
6	0x6800000116dcb370	PASS	PASS	FAIL	SHOW	CH-00 No Signal
7	0x0000000116e21a70	PASS	PASS	PASS	SHOW	-
8	0x9700000116d7eb70	PASS	PASS	PASS	SHOW	-
9	0xe800000116c31970	PASS	PASS	PASS	SHOW	-
10	0x5700000116e90170	PASS	PASS	PASS	SHOW	-
11	0xd500000116e51a70	PASS	PASS	PASS	SHOW	-
12	0x8200000116db7c70	PASS	PASS	PASS	SHOW	-
13	0x2800000116e80770	PASS	PASS	PASS	SHOW	-
14	0x8900000116c78370	PASS	PASS	PASS	SHOW	-
15	0x9e00000116ce7a70	PASS	PASS	PASS	SHOW	-
16	0x5700000116e81870	PASS	PASS	PASS	SHOW	-

Content

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- ✓初步实现了可灵活扩展的宇宙线探测成像系统模拟框架
- ✓完成SiPM读出模块的基本测试
  
- 设计并开展塑闪光纤读出的小型实验
- 修正模拟程序参数设置

# 谢谢！



- Code Repo. : [https://github.com/yatowoo/CRTest\\_DetectorDB](https://github.com/yatowoo/CRTTest_DetectorDB)
- LANL : Schultz, Larry Joe. *Cosmic ray muon radiography*. Diss. PSU, 2003.
- Geant4 : <http://geant4.cern.ch>
- PDG : Patrignani, C., and Particle Data Group. Chinese physics C 40.10 (2016): 100001.
- CRY : Hagmann, et al. "Cosmic-ray shower library (CRY)." LLNL, UCRL-TM-229453, March (2012).
- MuonGenerator : Chatzidakis, S. et al. NIM A 804 (2015): 33-42.
- OpenGATE : Strulab D, et al. Nuclear Physics B-Proceedings Supplements, 2003, 125: 75-79.
- LHAASO KM2A ED : Jing Z, et al. Chinese physics C, 2014, 38(3): 036002.
- OPERA : T. Adam et al. / Nuclear Instruments and Methods in Physics Research A 577 (2007) 523-539
- ITEP : T. Adam et al. / Nuclear Instruments and Methods in Physics Research A 577 (2007) 523-539
- OpticalProcess : J. Nilsson et al./Applied Radiation and Isotopes 103 (2015) 15-24



- 宇宙线成像
- 光学过程细节
- 光学表面具体参数
- 更多模拟结果

## • 相关参数

- 折射率、吸收长度
- 反射率、镜面反射常数 (ss、sl)
- 透射率、背散射常数、探测效率

## • 表面设计

- Detector – 黑胶布 Black
- Module – 镀膜 Al/TiO<sub>2</sub>, 包装Tyvek/Al-foil
- Scintillator – 光面EJ200-polished, 毛面EJ200-ground
- Groove – 抛光groove\_surf
- Fiber – 外包层抛光fiber\_surf, 端面光滑
- PMT – 光阴极全吸收, 效率 (Const., R5610A, H7546)

- 注：实际光学表面非常复杂，通常需要具体实验结果参考调节

材料	折射率
闪烁体 PS	1.58
光纤内芯 PS	1.60
内包层 PMMA	1.49
外包层 FluorPMMA	1.42
光学胶 EJ500	1.58

## • LHAASO KM2A-ED

- 参考文献 : Jing Z, et al. Chinese physics C, 2014, 38(3): 036002.

## • 基本设置

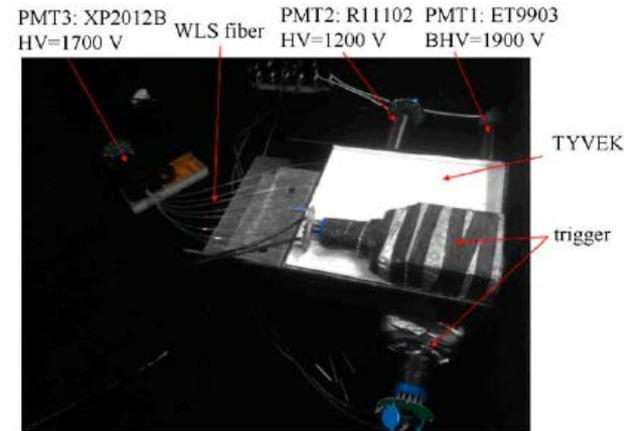
- 25\*25\*1.5 cm<sup>3</sup>, BCF92 x8, 光纤间隔 3 cm

## • 表面过程 - 与参考文献给出的模拟数据基本一致

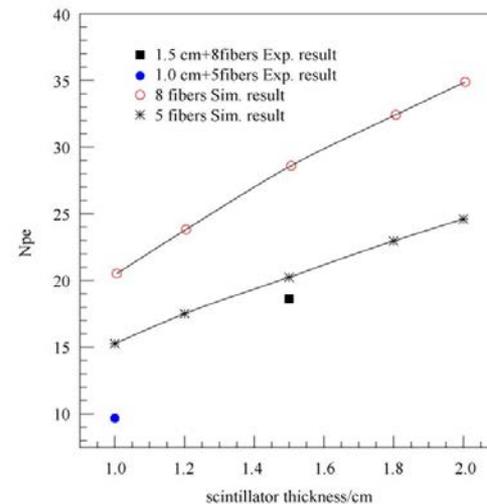
- Scintillator-Groove : ~33%
- OpWLS : ~50% (~16%) [M] ; ~40% (~13%) [S]
- Fiber-PMT : ~9.3% (~1.5%) [M] ; ~7.8% (~1.0%) [S]

## • 光产额对比 - Q.E.=10% , 3 GeV $\mu$ 子 直入射

Thickness/ mm	10	12	15	18	20
CRTTest	13	16	21	26	30
Paper Simu.	20	24	29	32	35
Paper Exp.			18		25



图一-KM2A ED测试装置



图一参考文献中不同厚度塑闪光产额

- 多重散射公式 [8]

- $$\Delta\theta_{rms} = \frac{15 \text{ MeV}}{p v} \sqrt{\frac{L}{L_0}}$$

- 散射参数： $Y \stackrel{\text{def}}{=} \frac{15}{p v} \text{ (mrad)}$

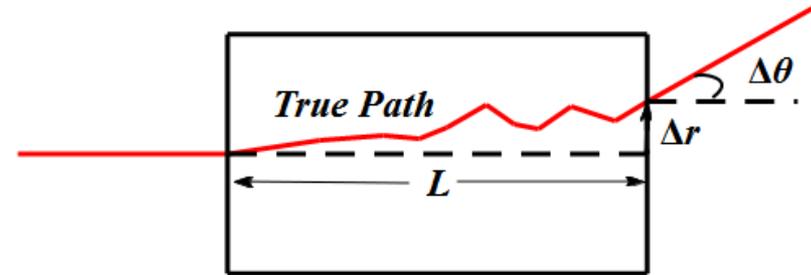
- 散射密度—— $\lambda \stackrel{\text{def}}{=} \frac{Y_0^2}{L_0} \text{ (mrad}^2 \cdot \text{cm}^{-1}\text{)}$

- $$f(\Delta\theta) = \frac{1}{\sqrt{2\pi}\Delta\theta} e^{-\Delta\theta^2/2\Delta\theta_0^2}$$

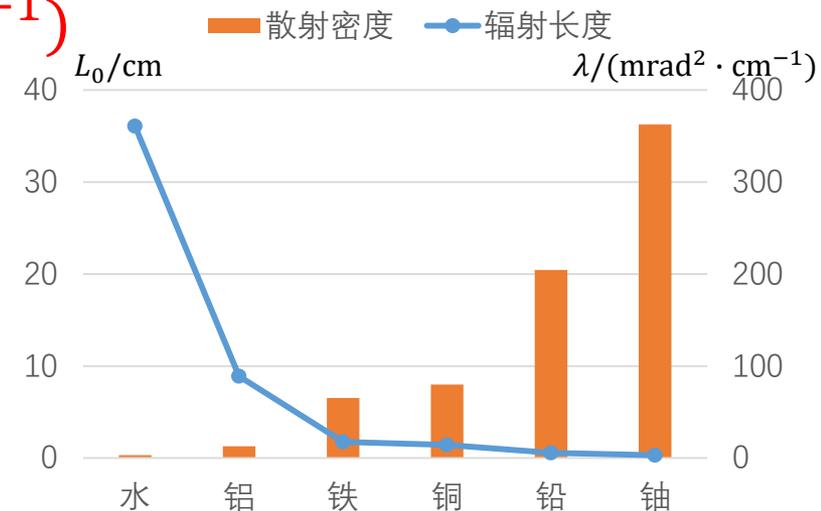
- $$\Delta\theta_0^2 = \lambda Y_r^2 L, \quad Y_r = Y/Y_0$$

- $$\hat{\lambda} = \text{Var}\left(\frac{\Delta\theta}{Y_r\sqrt{L}}\right) = \overline{s^2}$$

- $$g(s) = \frac{1}{\sqrt{2\pi\lambda}} e^{-s^2/2\lambda}$$

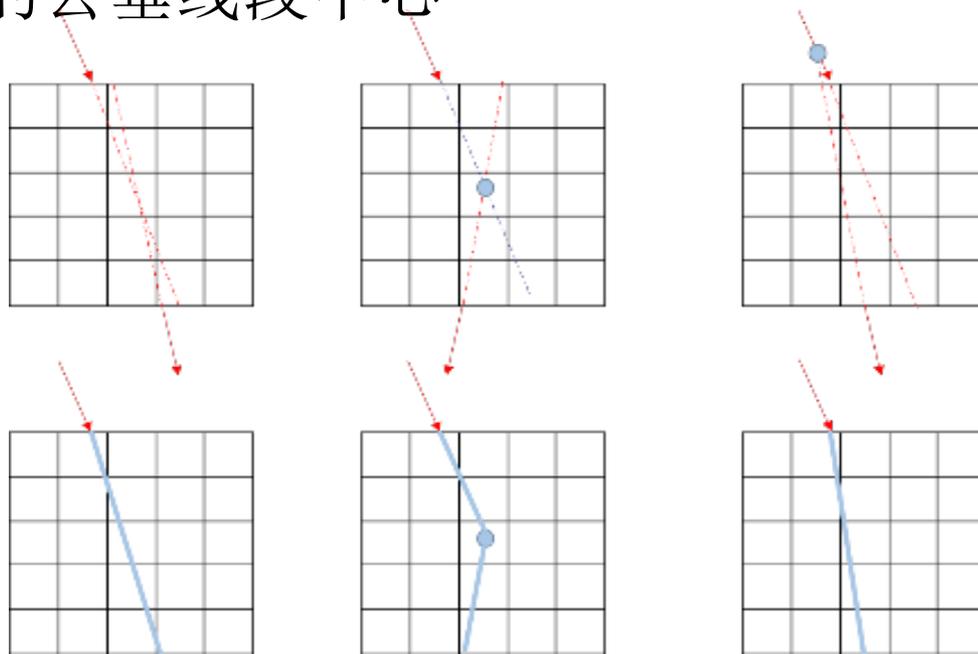
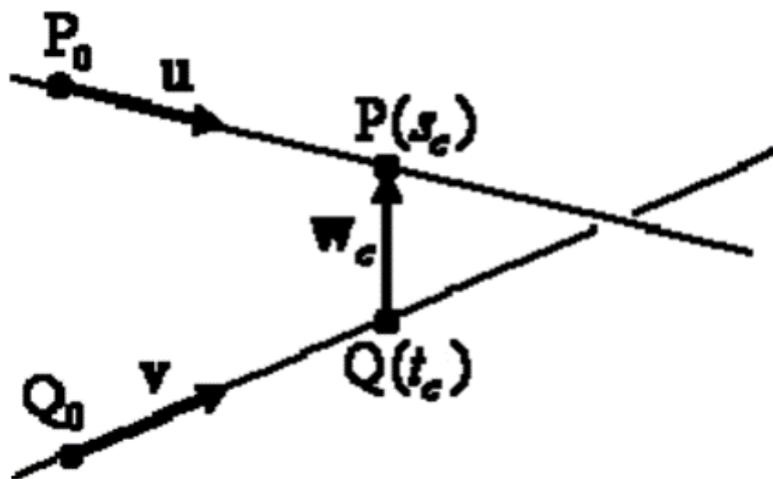


图一 多重散射过程示意图



图一 典型材料辐射长度与散射密度

- 逼近点算法 (PoCA, Point of Approaching Closest)
  - 取出入射径迹所在直线的公垂线段中心



$D = (\Delta\theta, \Delta r)^T$  符合联合高斯分布  
 $\Delta r^{rms} = \Delta\theta^{rms} L/\sqrt{3}$ ,  $\rho(\Delta\theta, \Delta r) = \sqrt{3}/2$

$$P_{ij}(D_{ij}|\vec{\lambda}) = \frac{1}{2\pi\sqrt{|\Sigma_{ij}|}} \exp\left(-\frac{1}{2}D_{ij}^T\Sigma_{ij}^{-1}D_{ij}\right)$$

$$\ln[L(D|\vec{\lambda})] = -\frac{1}{2}\left(\sum_{i:Event} \sum_{j:Voxel} \ln|\Sigma_{ij}| + D_{ij}^T\Sigma_{ij}^{-1}D_{ij}\right)$$

$$\begin{aligned} \lambda_j^{(n+1)} &= \frac{1}{2M_j} \sum_{i:Event} S_{ij}^{(n)} \\ &= \lambda_j^{(n)} \left(1 + \frac{\sum_i K_{ij}}{2M_j} \lambda_j^{(n)}\right) \end{aligned}$$

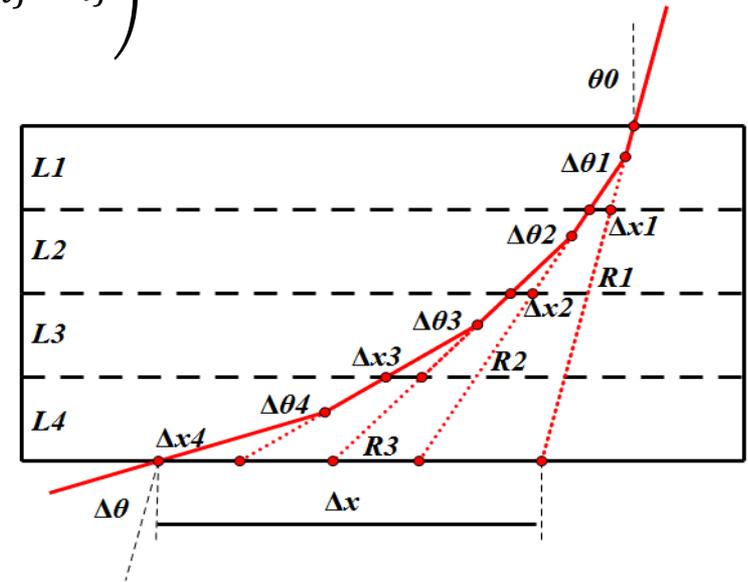
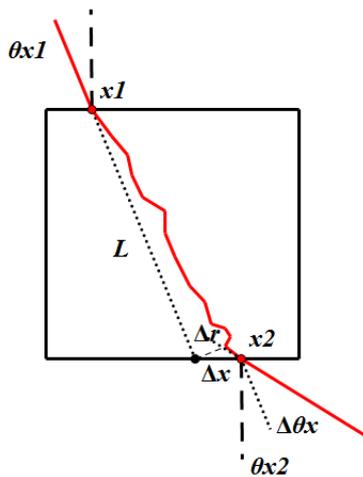
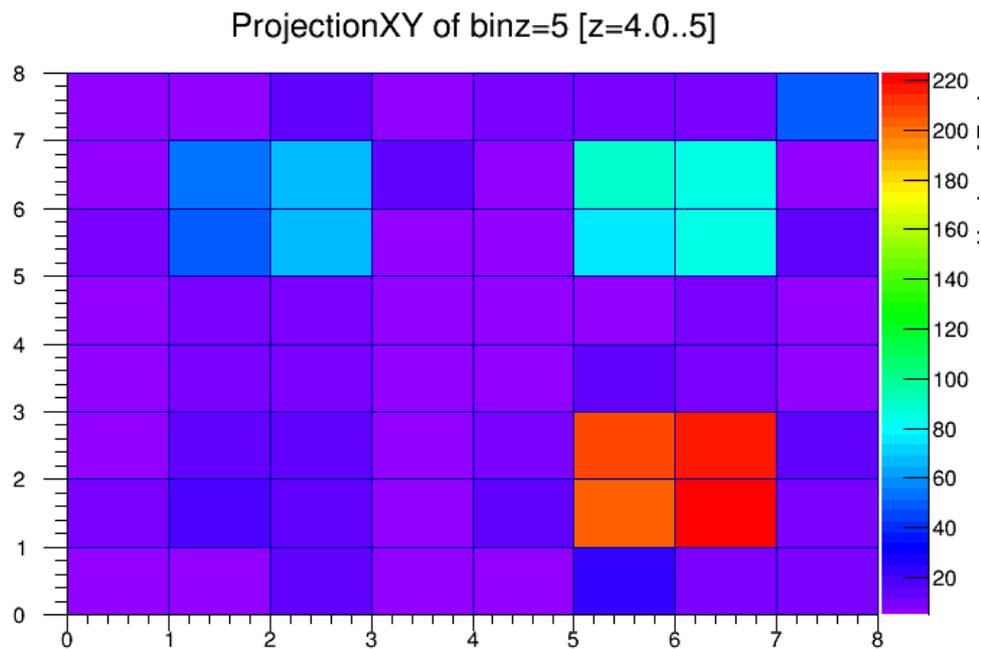


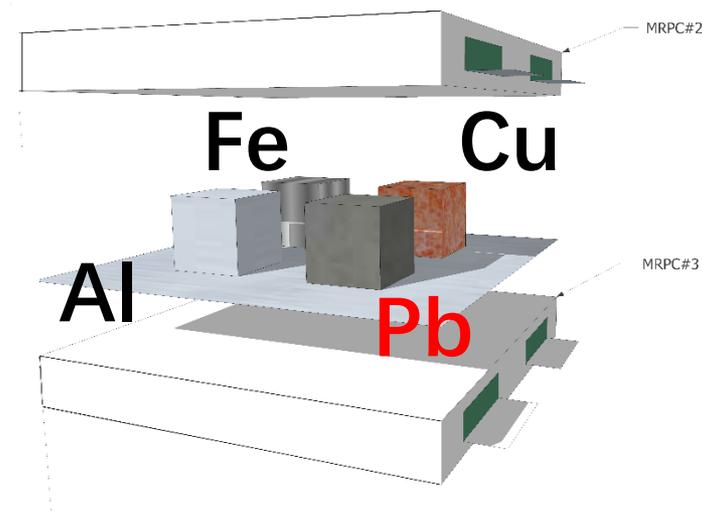
图 — 带电粒子粒子介质内多重散射过程

- 物品定位与材料鉴别

- MuVoxel尺寸: 5 cm x 5 cm x 5 cm



图一 宇宙线成像典型示例

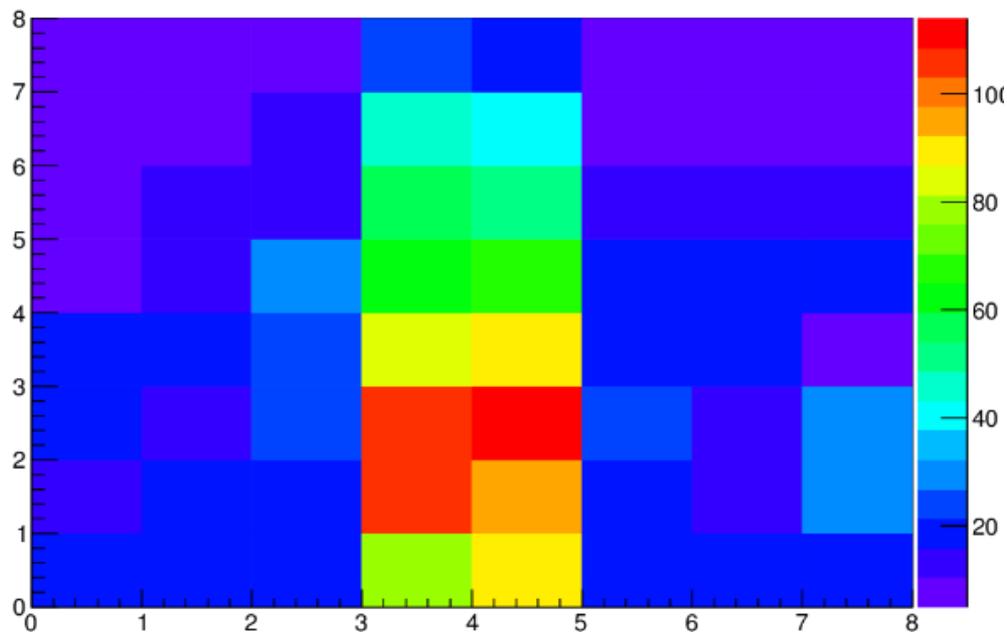


图一 模拟样品设置

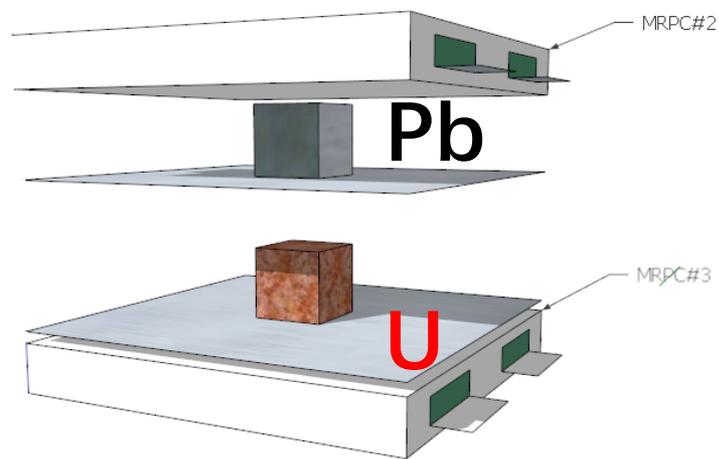
## • 铅屏蔽下铀块成像

- MuVoxel尺寸: 5 cm x 5 cm x 5 cm

Muon Imaging - ProjXZ



图一 铅屏蔽下铀块成像 (ML-EM)



图一 模拟样品设置

$$\hat{\lambda} = \text{Var} \left( \frac{\Delta\theta}{Y_r \sqrt{L}} \right) = s^2$$

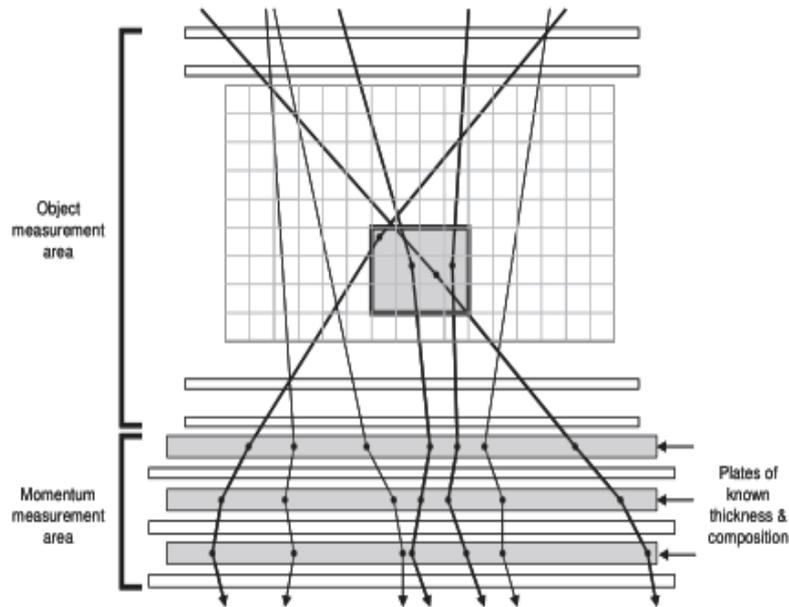


图 — 动量估计方案——MCS (LANL)

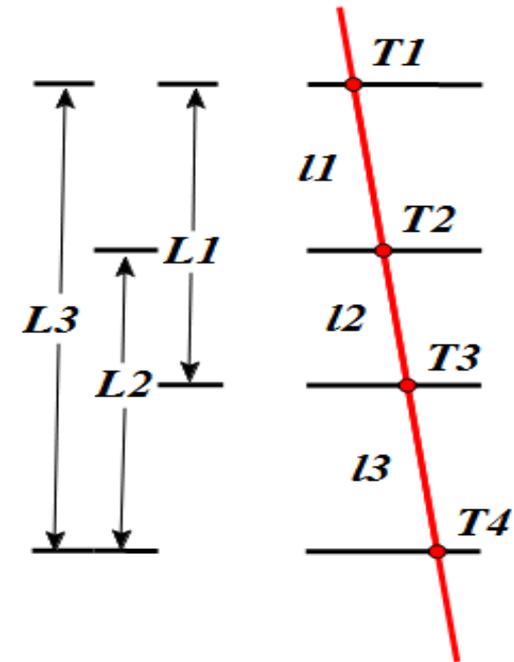
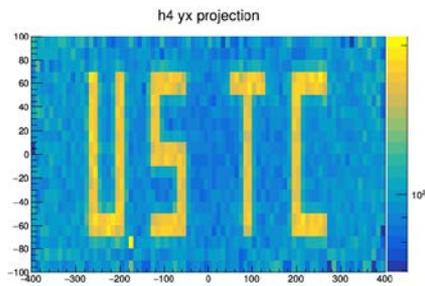
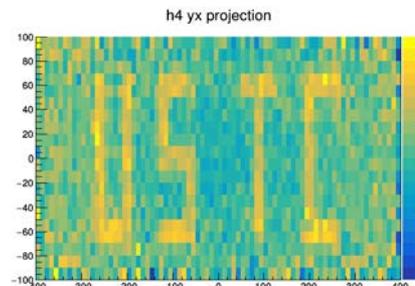


图 — 动量估计方案——TOF

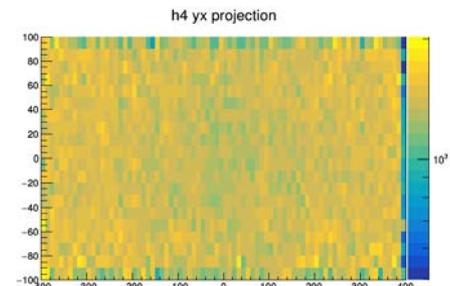
# 位置分辨对成像效果的影响



1mm



2mm



4mm

字样的总面积约为 $9 \times 9 \text{ cm}^2$ ，厚度为2 cm