

# The Electro-Magnetic Calorimeter R&D for spectrometer at HIAF

## HIAF谱仪中的电磁量能器预研



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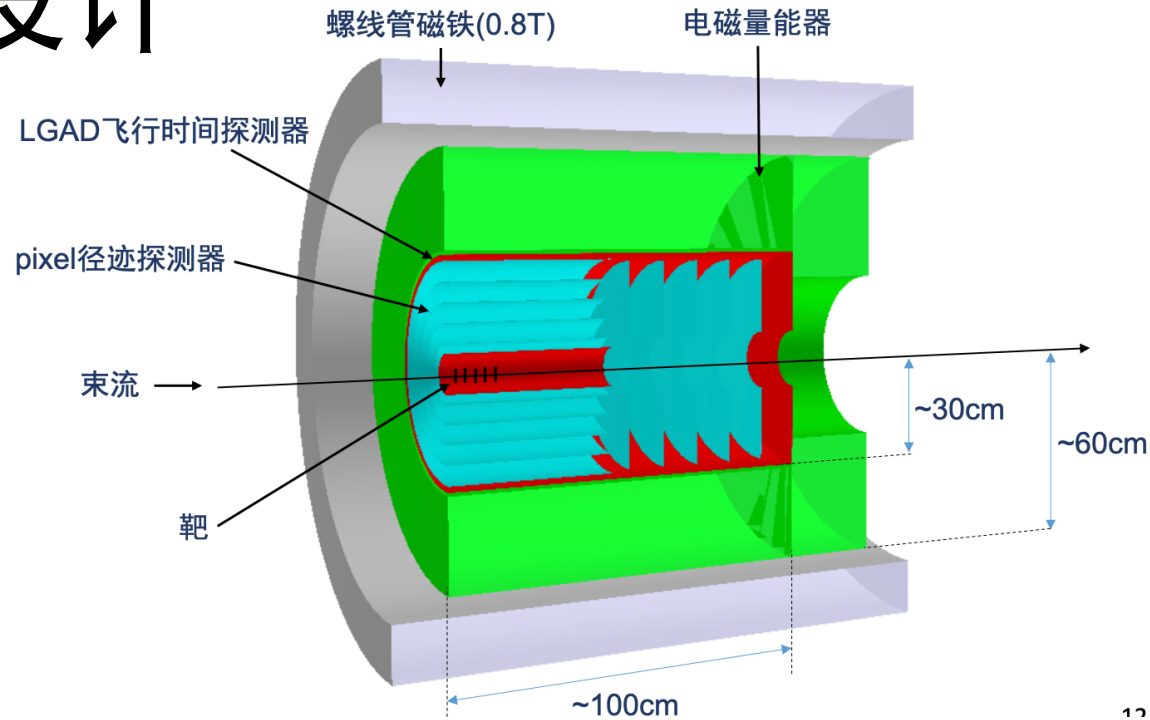
2024年HIAF 高能终端谱仪合作组会议

2024 - 11 - 16

# Outline

- 电磁量能器介绍、材料的选择和设计
- 铅玻璃Geant4 模拟和性能
  - 带电  $e/(\pi, \mu)$  PID
  - 中性  $\gamma / n$  鉴别
- ADRIANO2 量能器介绍和模拟结果

# 谱仪概念设计



## 电磁量能器的主要性能需求：

- 鉴别gamma，压低中子本底（无动量信息）
- 高的事例率（100M Hz），快时间响应
- 鉴别电子，压低 $\pi^+$ -本底（有径迹探测器提供动量信息）
- 光子、电子能量分辨率尽量好  $\rightarrow$   $\pi^0$ 、 $\eta$ 不变质量峰更窄、信噪比更高
- 尽量大的覆盖角度 $10^\circ - 95^\circ$ ，以及较低的价格

# 常用量能器材料比较

Calorimeter type	Pros	Cons	Total cost
Pure CsI	<ul style="list-style-type: none"> <li>• Good energy resolution <math>\sim 2.5\%/\sqrt{E}</math></li> <li>• Time resolution</li> </ul>	<ul style="list-style-type: none"> <li>• High price</li> <li>• Ultraviolet sensitive spectrum, readout by APD</li> </ul>	~ 4000万(上海硅酸盐所)
Lead glass	<ul style="list-style-type: none"> <li>• Low price</li> <li>• Pure Cherenkov light</li> <li>• Good time resolution</li> </ul>	<ul style="list-style-type: none"> <li>• <math>\sim 6\%/\sqrt{E}</math> energy resolution</li> <li>• Low light yield</li> <li>• Radiation resistance</li> <li>• Long length</li> <li>• No production in China</li> </ul>	~1000万 (参考俄罗斯报价, 实现国产会更低)
PbF <sub>2</sub>	<ul style="list-style-type: none"> <li>• Very good time resolution</li> <li>• Pure Cherenkov light</li> </ul>	<ul style="list-style-type: none"> <li>• High price</li> <li>• <math>\sim 5\%/\sqrt{E}</math> energy resolution</li> <li>• Radiation resistance</li> </ul>	>5000万(上海硅酸盐所)
Shashlik	<ul style="list-style-type: none"> <li>• Low price</li> </ul>	<ul style="list-style-type: none"> <li>• <math>\sim 5\%/\sqrt{E}</math> energy resolution</li> <li>• Long length, design difficult</li> </ul>	< 1000万 (NIKA MPD in batch)
ADRIANO2 (REDTOP)	<ul style="list-style-type: none"> <li>• Dual-readout for PID</li> <li>• Good time and energy resolution (<math>\sim 3\%/\sqrt{E}</math>)</li> </ul>	<ul style="list-style-type: none"> <li>• High price</li> <li>• Long length</li> </ul>	4000-5000万

# 铅玻璃以及量能器性能

- 其它实验用于量能器的铅玻璃主要来自**俄罗斯**，包括**TF1**和**F101**两个型号。
- **F101抗辐照性能更好**，但是光衰减也更强。**倾向于F101，并将采购对比测试。**
- **和国内铅玻璃厂家合作**，研发含铅量高、光产额高、抗辐照好的型号  
(ADRIANO2 目前测试用的是国内生产的铅玻璃)

## F101铅玻璃性质

性质	数值
折射率	~ 1.65
密度	3.86 g/cm <sup>3</sup>
辐照长度	2.5 – 2.8 cm
Moliere半径	3.6 cm
长度	<b>30cm (11X<sub>0</sub>)</b>
读出	大光阴极PMT (or SiPM)

## 国外铅玻璃量能器分辨率

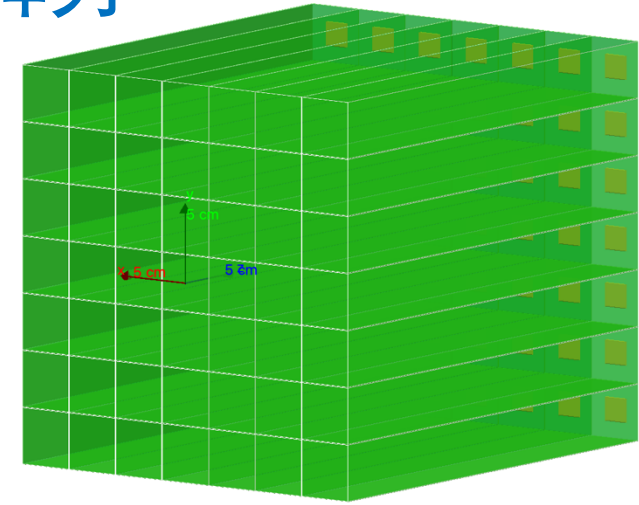
- >16X<sub>0</sub> + PMT (无磁场)
- 光产额约**1000**Np.e./GeV
- 能量分辨率 ~ **6%/√E**

探测器项目	能量分辨率 (%)
HADES	6.9@1GeV
SOS (TF1, Jlab Hall C)	6/√E ⊕ 1
HMS (TF1, Jlab Hall C)	3.75/√E ⊕ 1.64 ⊕ 1.96/E
SHMS (F101, Jlab Hall C)	6/√E
COMPASS	6.2/√E ⊕ 1.4

# 铅玻璃Geant4模拟

## 7x7 阵列

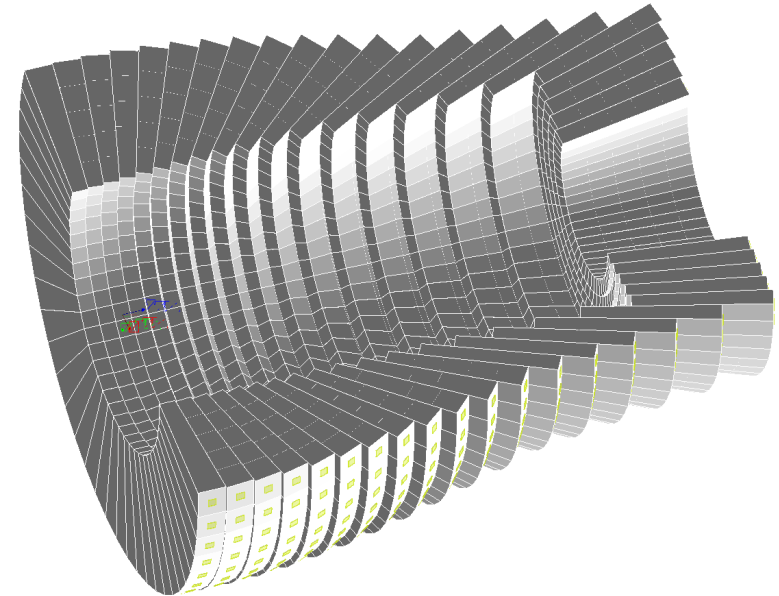
- 分别采用7x7阵列以及完整的实际桶状量能器
- 铅玻璃30cm长度，相当于11X<sub>0</sub>。
- 目前用1.8cm边长的正方形SiPM作为光收集，总面积3.24cm<sup>2</sup>，相当于9个6mm边长的SiPM



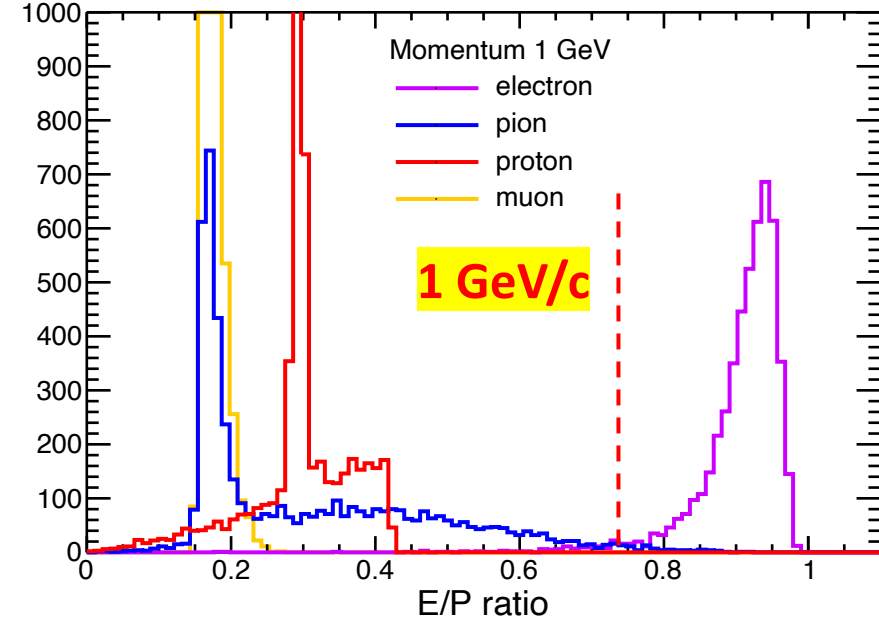
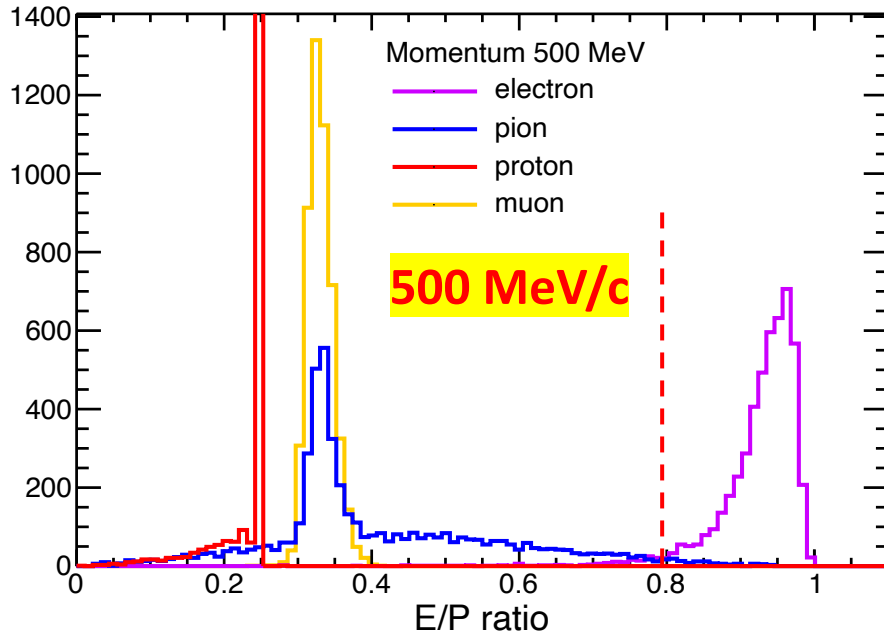
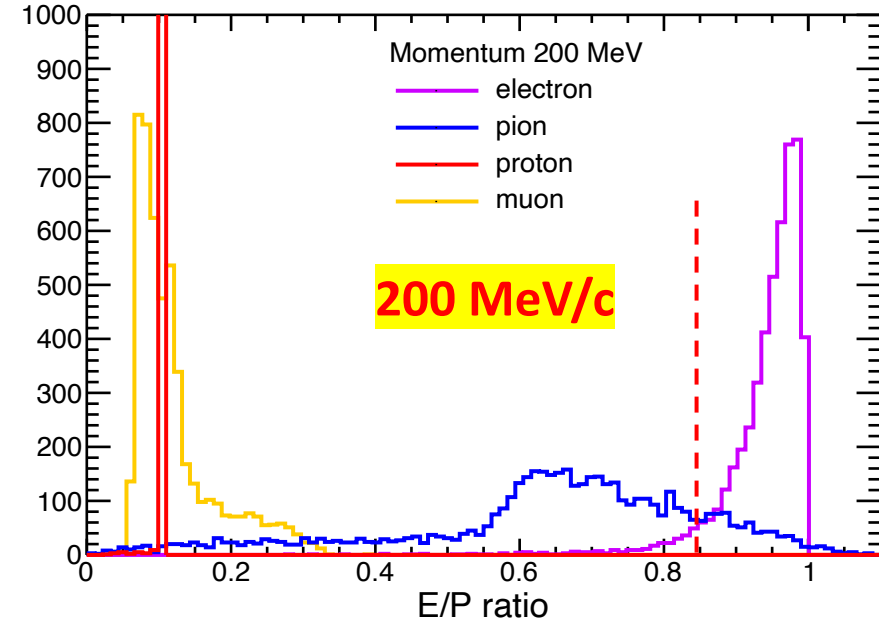
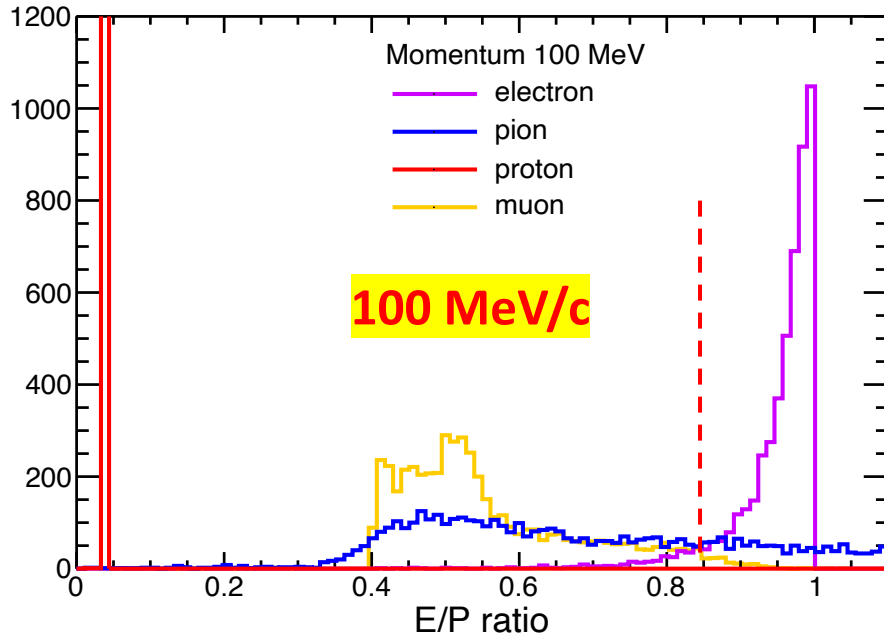
## 关于切伦科夫光：

- 单个带电粒子产生的光谱  $\frac{dN}{d\lambda} = \frac{2\pi\alpha z^2 L}{\lambda^2} \left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)$
- 影响最终收集到的光子数的因素包括 1.光传输过程中的衰减（材料衰减长度+包裹材料反射） 2. 光收集器件（尺寸、光谱、量子效率） 3. 材料的成分。
- 原初切伦科夫光约50000 NPE/GeV

## 实际桶状量能器模拟

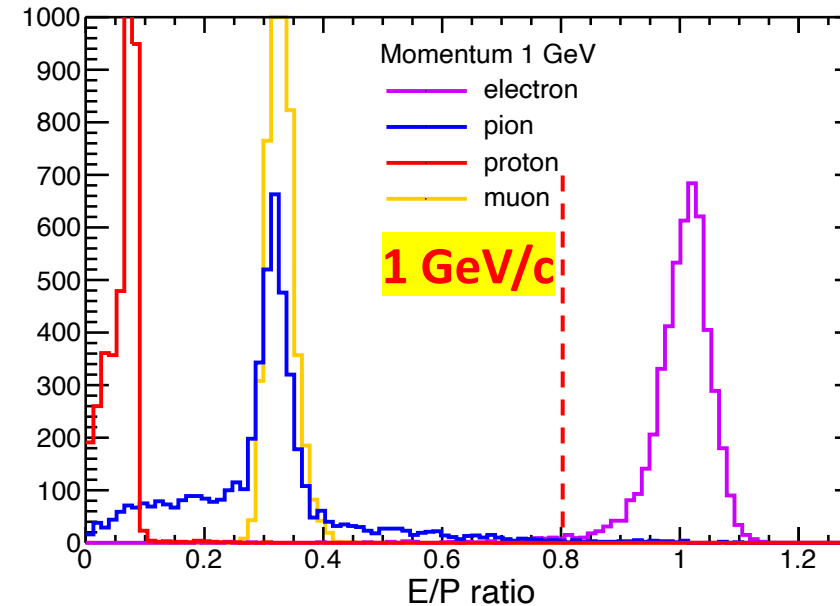
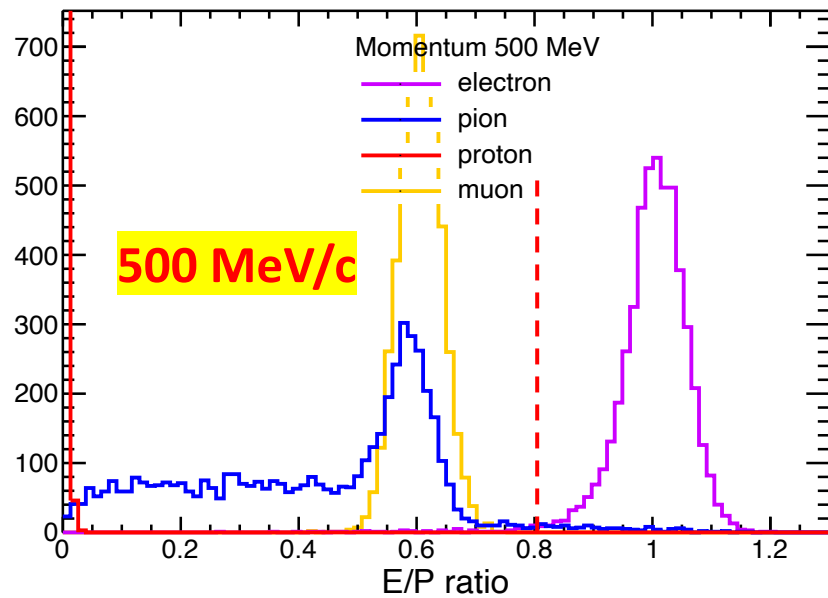
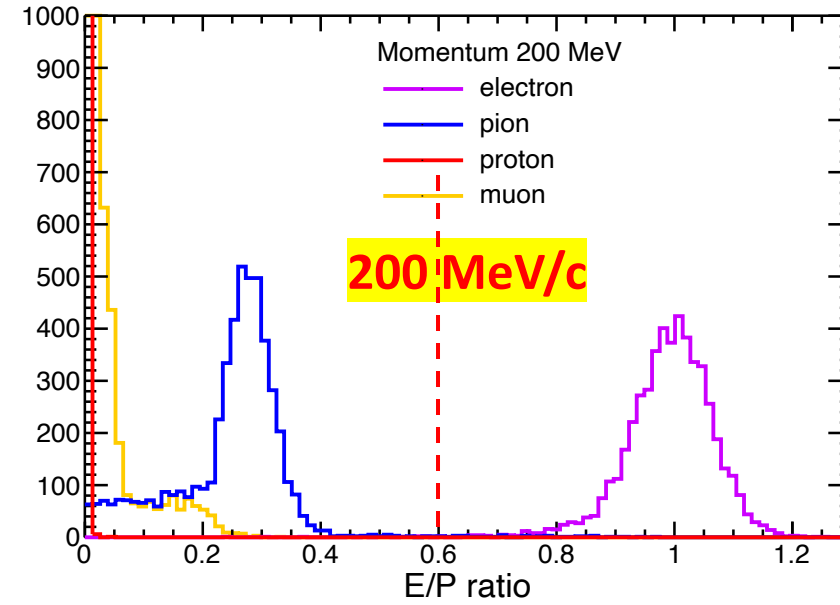
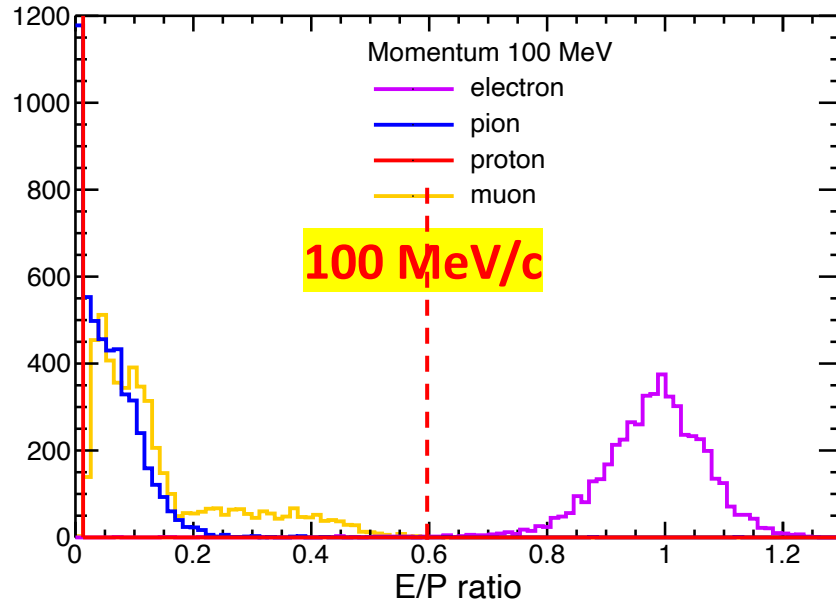


# Energy deposit / P ratio for different particles



# Reconstructed energy / P ratio for different particle

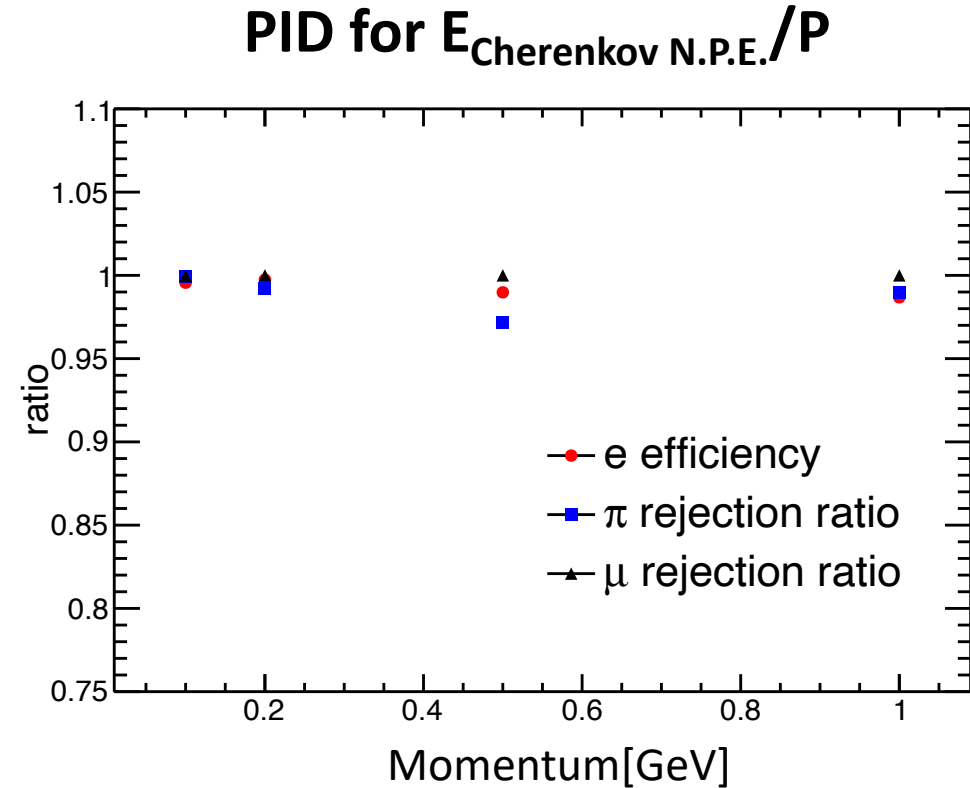
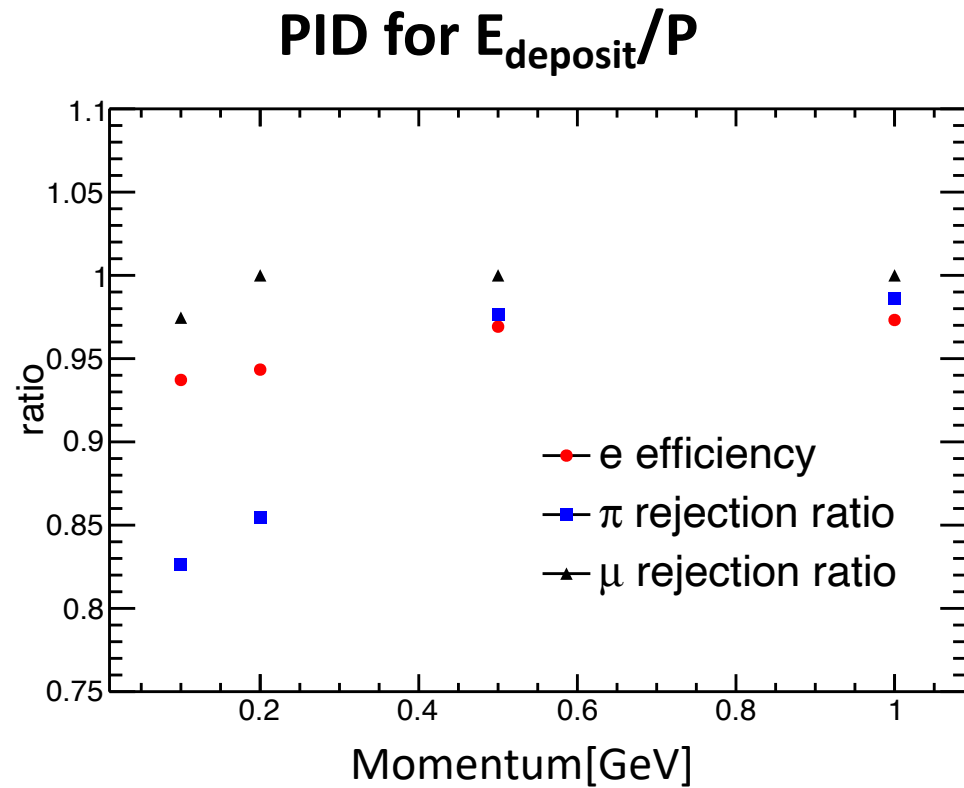
Energy reconstructed by the number of collected **Cherenkov photons**



e/pi鉴别有明显提升!  
Proton信号明显压低。



# $e/(\pi,\mu)$ PID for energy deposit and Cherenkov N.P.E.



The pure Cherenkv calorimeter **improve low momentum  $e/(\pi,\mu)$  PID significantly!**

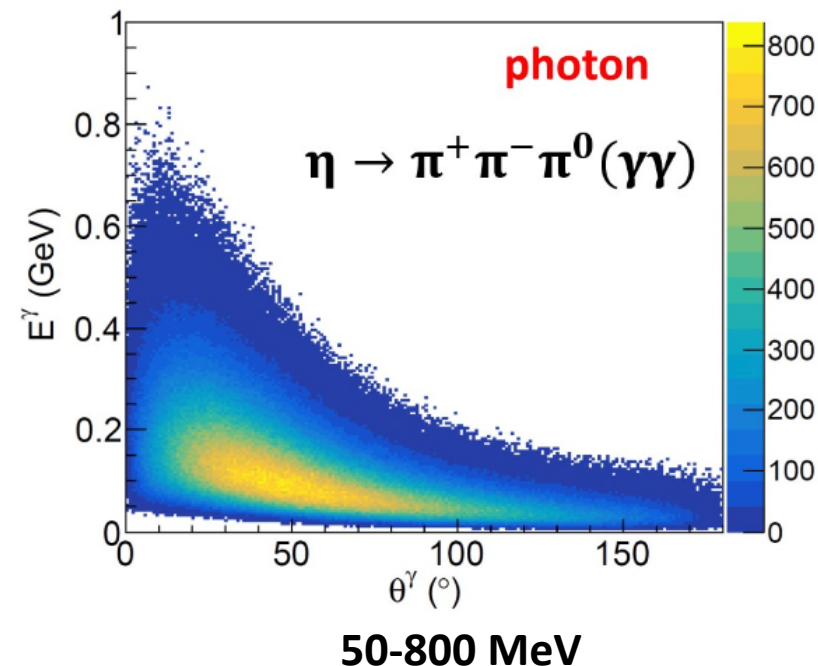
# $\gamma/n$ PID based on generator events

产生子 (GiBUU, 王荣)

- 1.8 GeV 动能 p 轰击 Li 靶
- $\eta$  衰变产生的  $\pi^0$  和产生的 neutron 本底比约 1:20 ( $\gamma/n$  比 1:10)
- 能量 cut 设定为 50 MeV

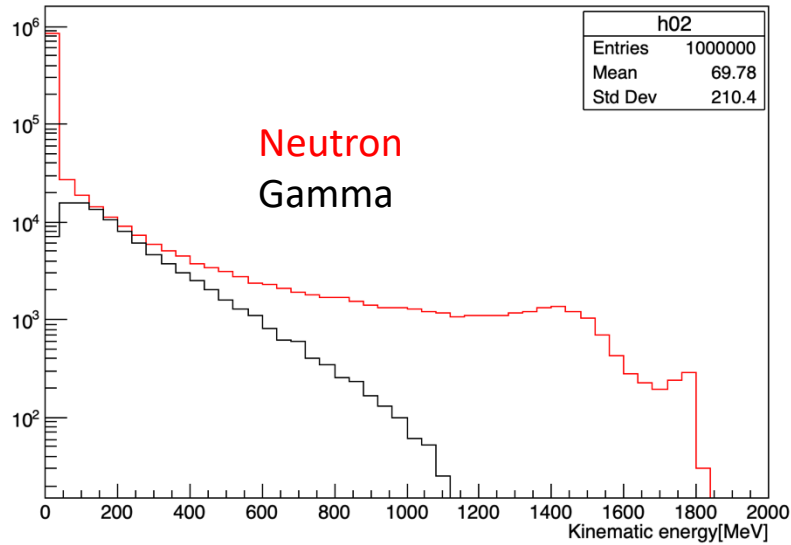
$\gamma/n$  PID 当前主要方法

- 能量沉积 以及 切伦科夫光收集
  1. 同样动能的中子比  $\gamma$  沉积能量更少, 从而一部分中子沉积能量低于阈值
  2. 沉积同样的能量, 中子产生的切伦科夫光光子数小于  $\gamma$ , 大幅度排除中子
- 时间信息
  - 飞行时间 (小角度 1m 的飞行距离)
- 簇射形状

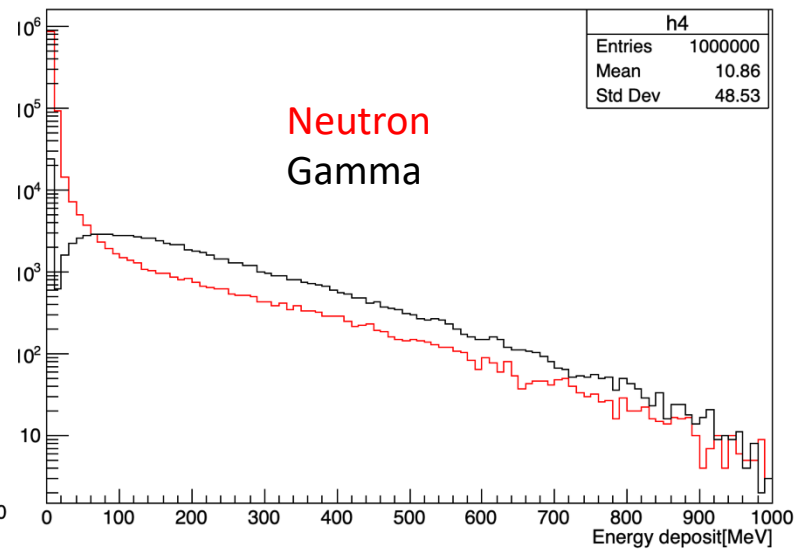


# Simulation result

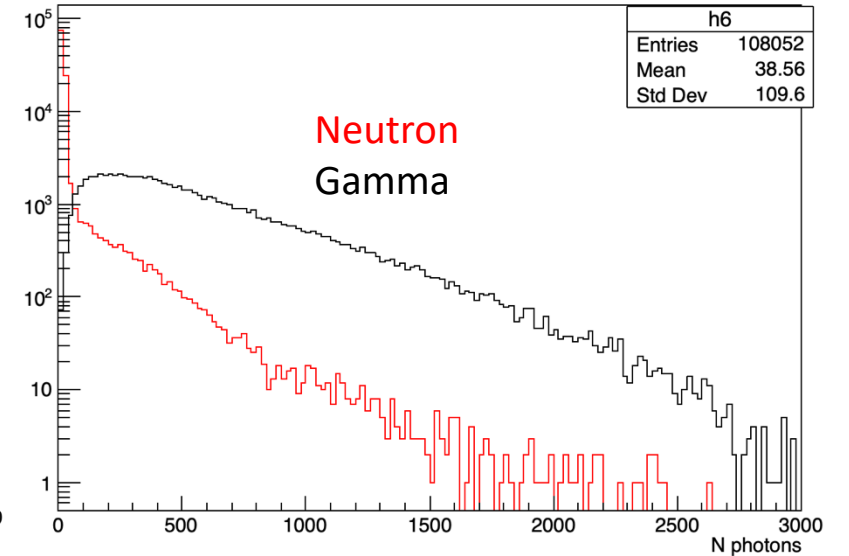
Initial kinetic energy



Energy deposit in Lead Glass



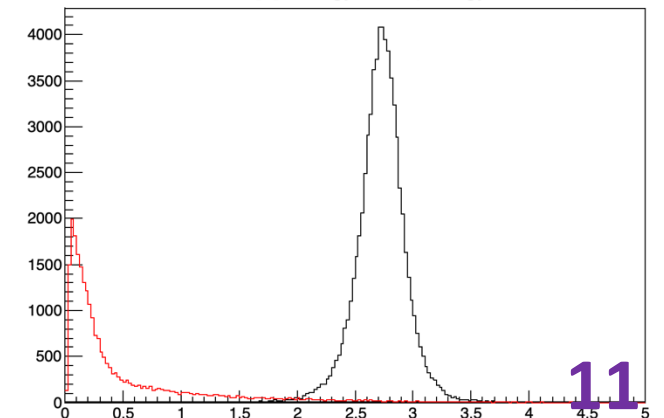
N photons collected by SiPM



Cut	Initial from generator	50 MeV deposit energy	130 N.P.E (50 MeV) cut, only primary cluster
N Gammas passed	100k	69k	69k
N neutrons passed	1M	37k	6.7k
$\gamma/n$ ratio	<b>1:10</b>	<b>1.86:1</b>	<b>10.5:1</b>

**Nphotons/MeV**

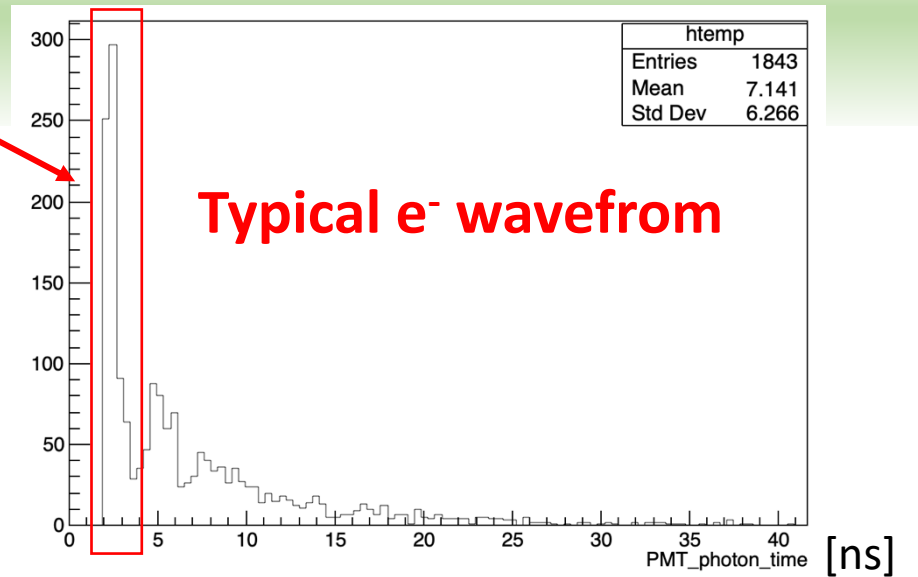
`NPhotons_re[0]/Energy_scin {Energy_scin>50}`



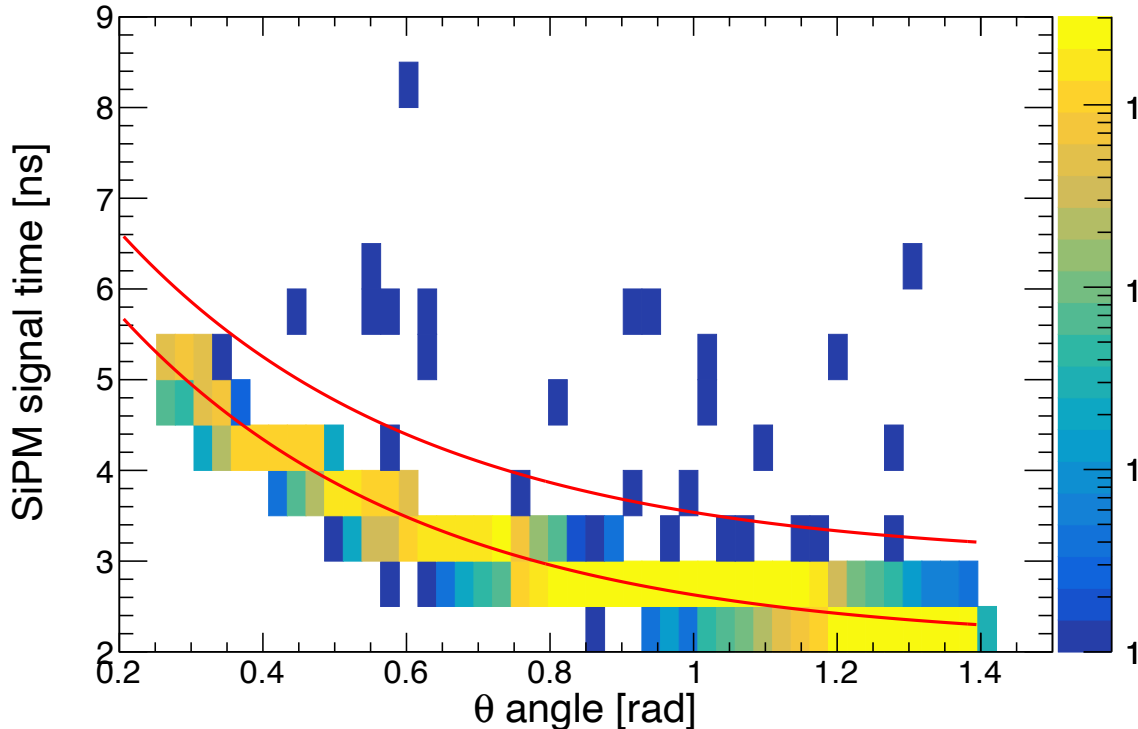
# Time flight cut

- Neutrons have low speed and more flight time.
- Applying time cut for  $\gamma/n$  separation.

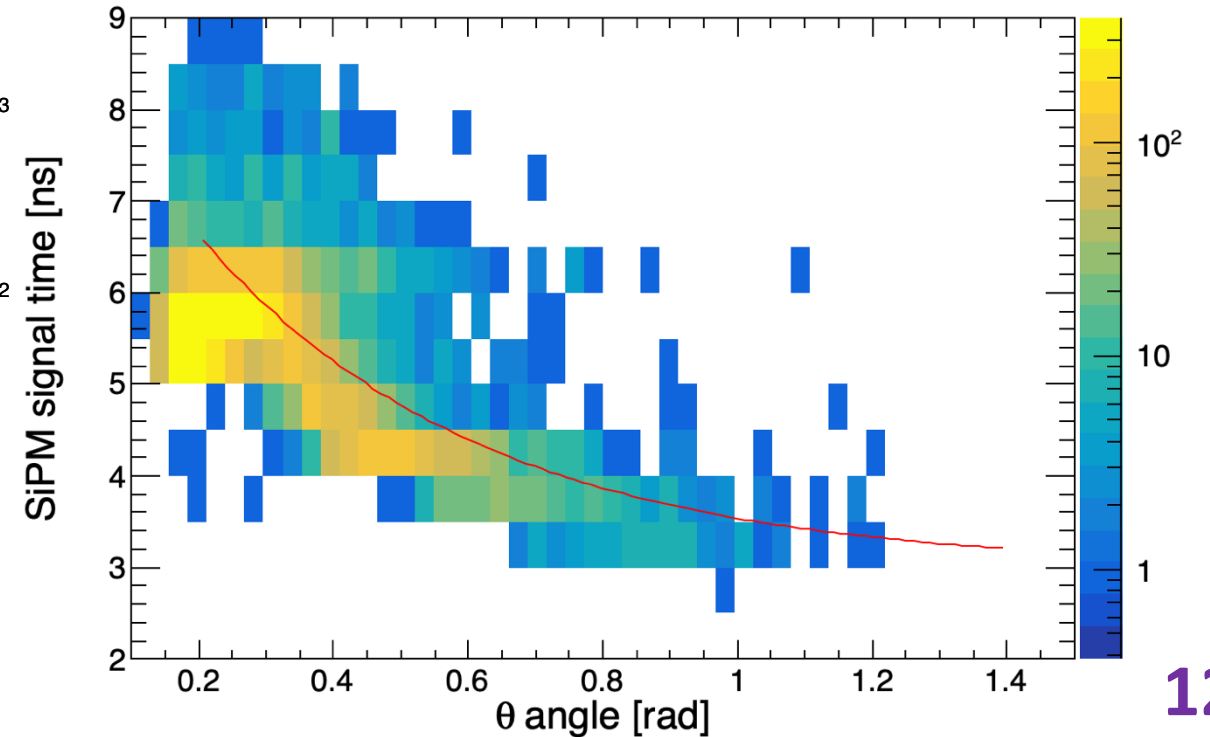
Determine time



## Electron time distribution

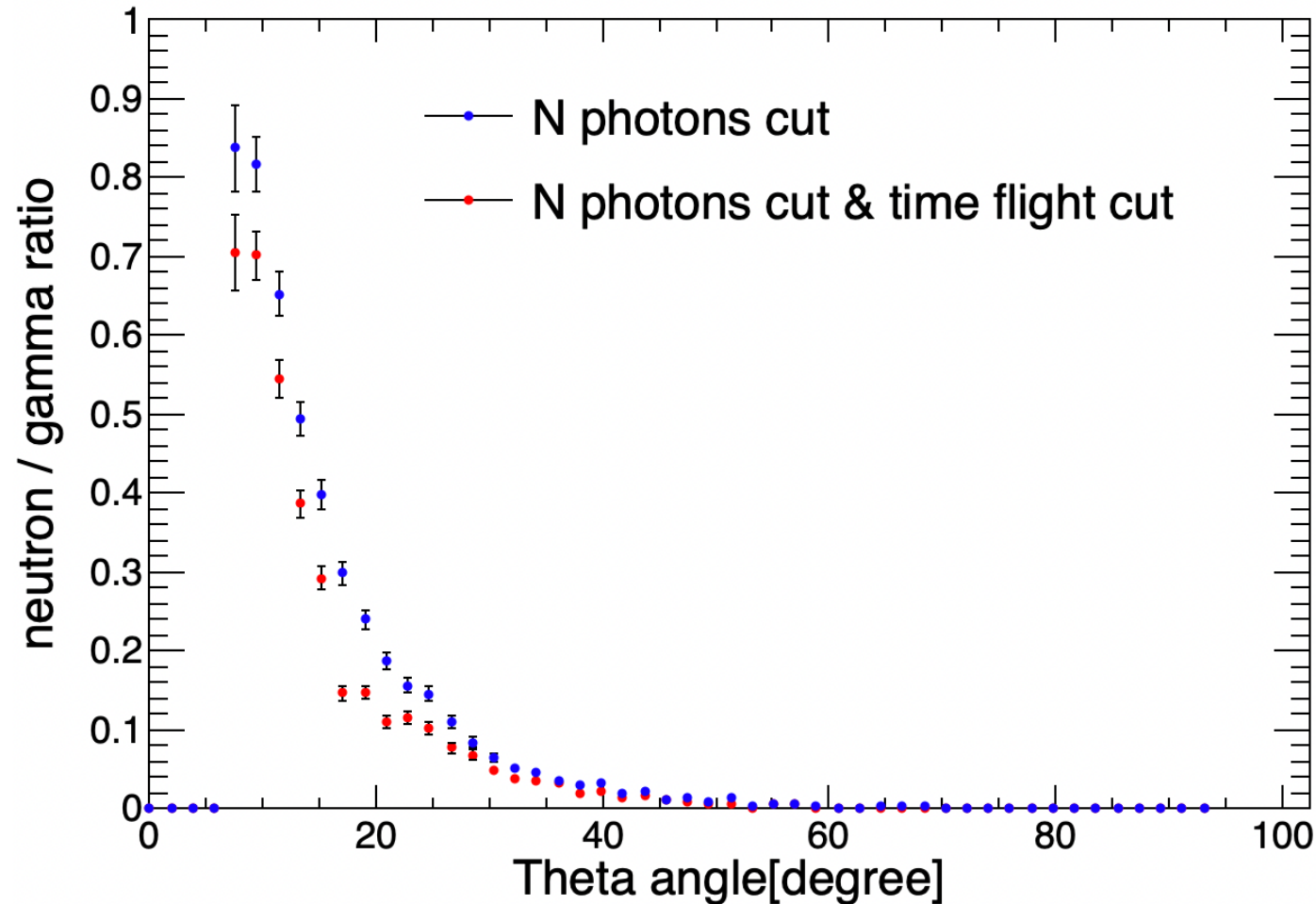


## Neutron time distribution



# n/ $\gamma$ ratio with time flight cut

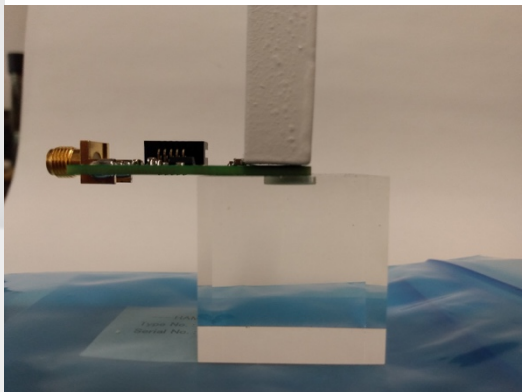
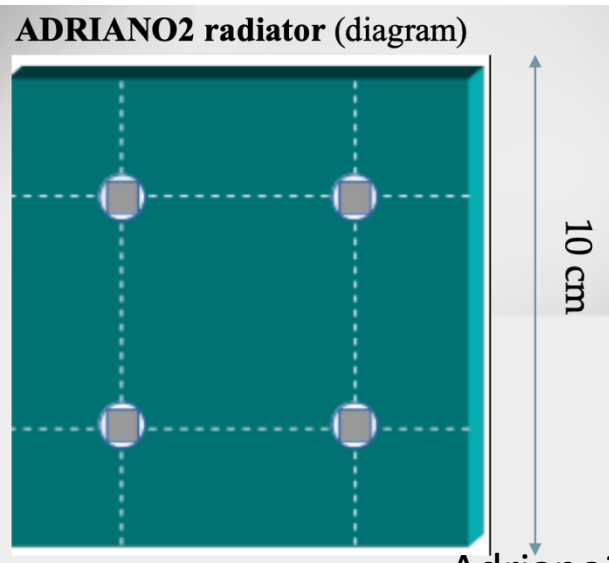
About 1/4 additional neutron events are discarded after time cut.



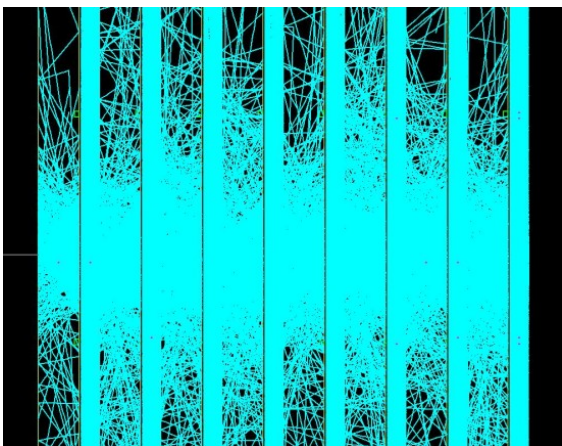
# ADRIANO2 设计介绍

既可以作为电磁量能器，也可以作为强子量能器（加额外的吸收层）

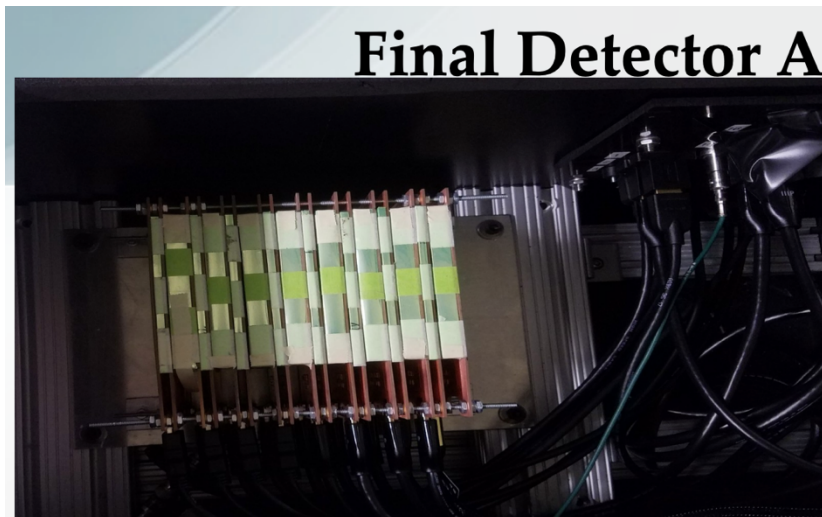
## 横向



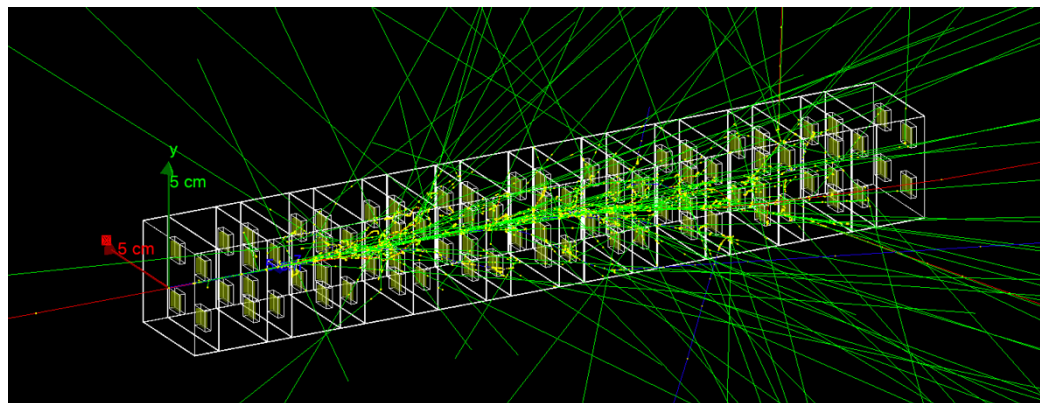
Adriano2 10层光子示例



## 纵向



- 8 glass + 8 plastic tiles
- Total 64 channel
- FEB readout (mu2e)



# ADRIANO2

It has two main roles:

- 1) measuring the energy of neutral particles with sufficient precision
- 2) the PID systems to separate EM particles from proton and neutrons.

The main requirements for REDTOP Calorimeter are summarized below:

- Energy resolution  $\sigma(E)/E=3\%/\sqrt{E}$
- Particle Identification (PID) between electromagnetic and hadronic showers with an efficiency better than 99%;
- Time resolutions <80psec;
- Detector response within ~100nsec

In summary, ADRIANO2 merges the benefits of a dual-readout and of a CALICE-type calorimeter, creating the base for a new generation of high-performance detectors, target detector design: REDTOP and EIC.

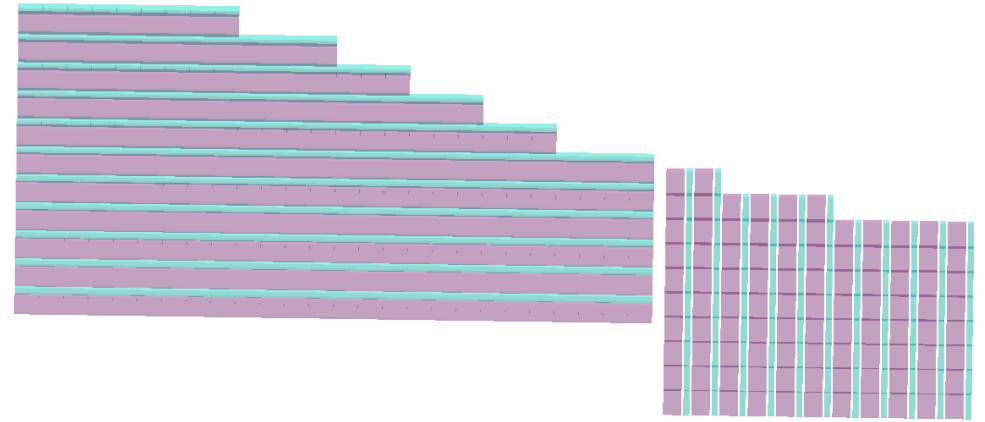
## Rationale for ADRIANO2

- Advantages:
  - 1) Prompt Cerenkov signal for timing resolution and L0-trigger
  - 2) Small Pb-glass tile unaffected by aging
  - 3) Good energy resolution
  - 4) High-granularity
- Disadvantaged
  - 1) Cost
  - 2) Large number of readout channels

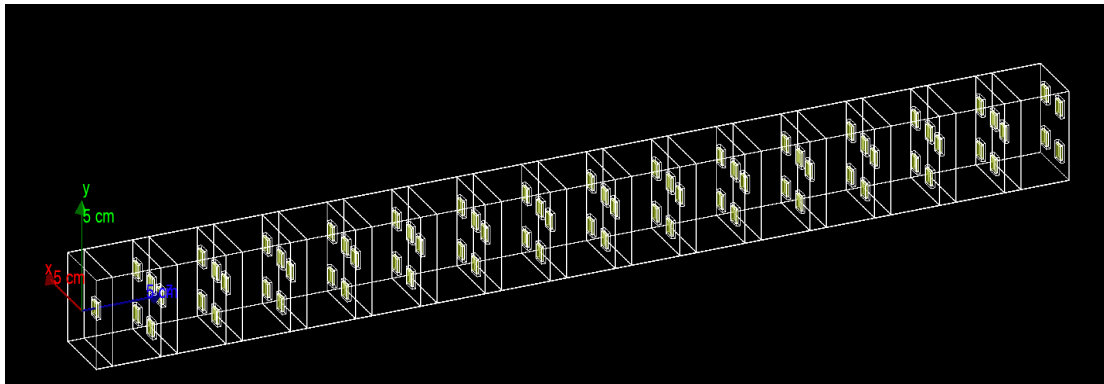
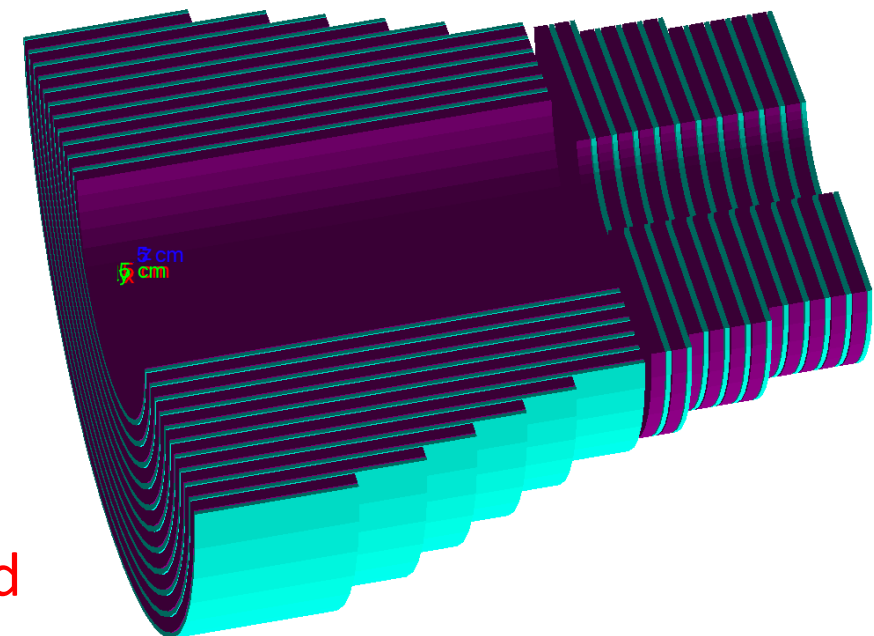
# Optimized ADRIANO2 design for HIAF

Design introduction:

- Radiation length: 11-12  $X_0$
- Inner lateral size 4 x 4 cm<sup>2</sup>, 5 SiPMs each layer
- 11 layers x (3 cm lead glass + 1 cm plastic scintillator + 2 x 0.35 cm PCB) = 52 cm
- 1600 modules, 15000 layers
- Each module is readout by 2-3 groups



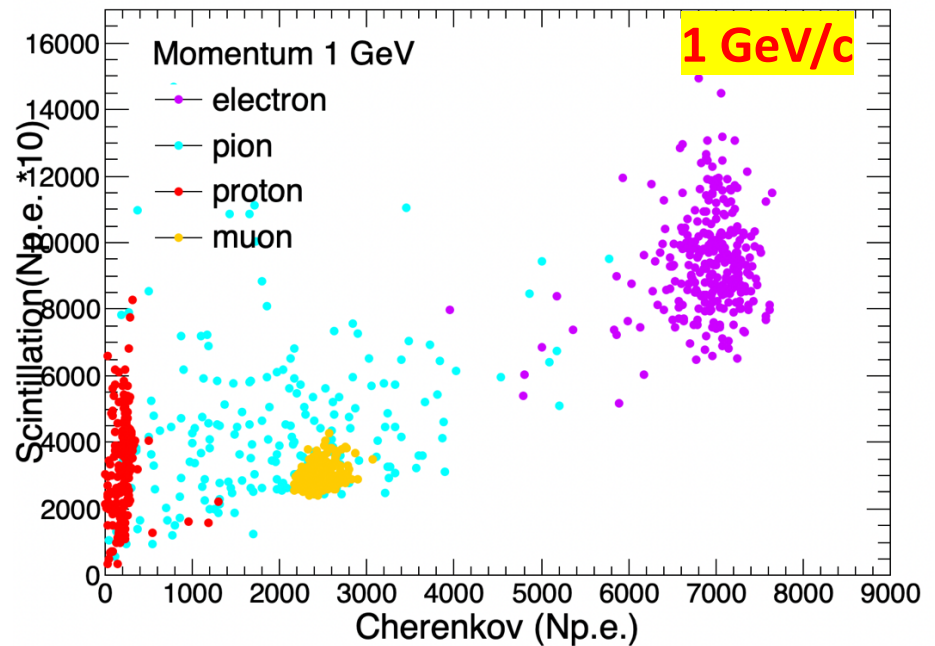
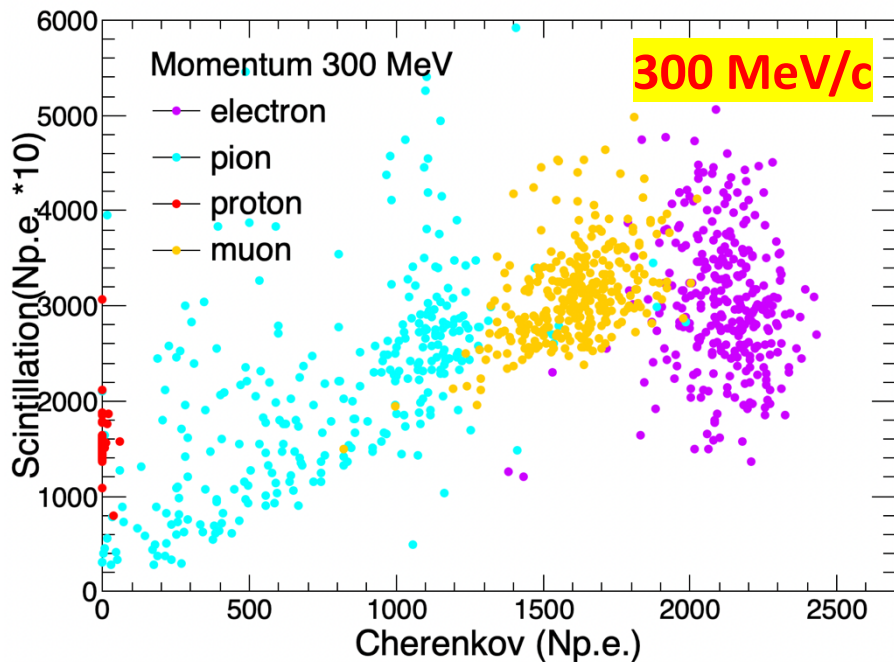
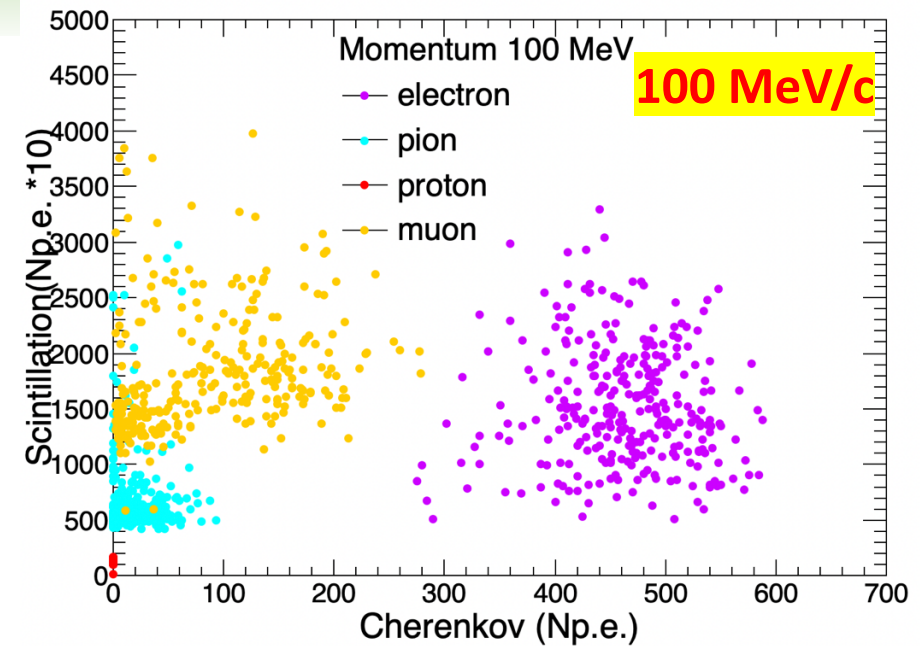
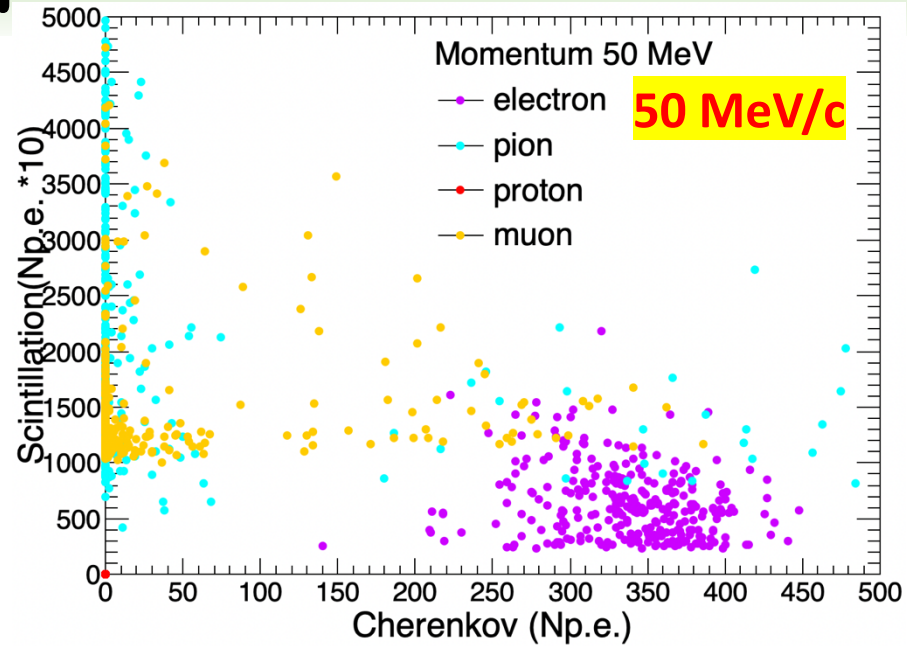
3 cm  
1 cm



**Challenge:** Radiation hardness, design, assembly and electronics!



# PID performance for different momentum



# 能量分辨率模拟

- 闪烁体和铅玻璃的能量沉积比例大约**1:12**，**铅玻璃主导能量分辨率**
- 铅玻璃平均光产额7142 p.e./GeV，闪烁体100k. p.e./GeV
- 能量分辨率主要受层数影响：层数越多，铅玻璃的厚度越小，收集的切伦科夫光越多，其主导的能量分辨率越高

Fitting data	Electron energy resolution (%)	
	1 GeV	100 MeV
Lead glass	3.2	10.9
Scintillator	13.2	43
Both	<b>2.7</b>	<b>9.1</b>

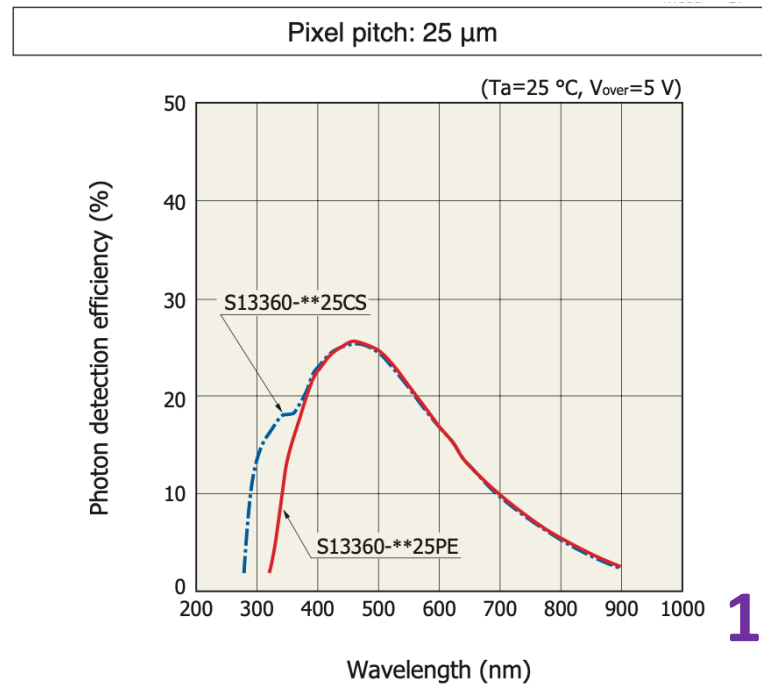
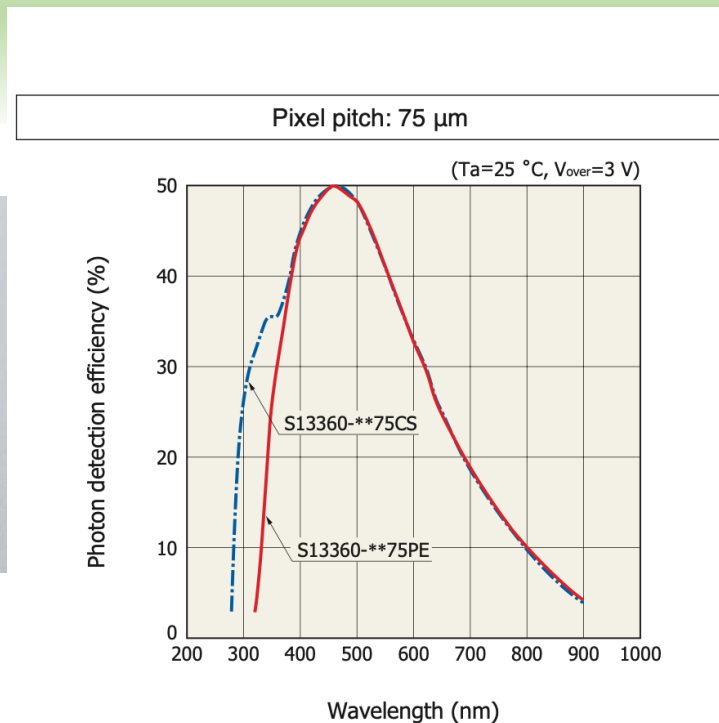
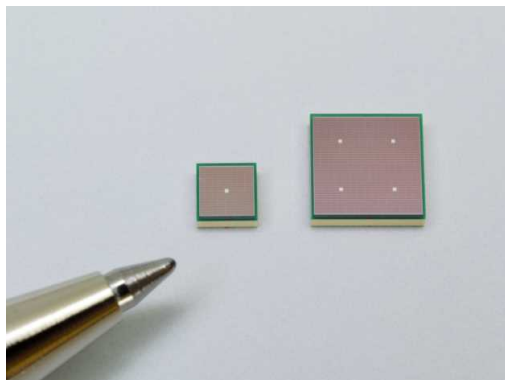
**相关系数 : -0.0127**

## 不同层数的能量分辨率

不同层数	能量分辨率 (%) [1 GeV]
3	4.3
4	3.5
7	2.9
15	2.7

# 光电器件SiPM选择

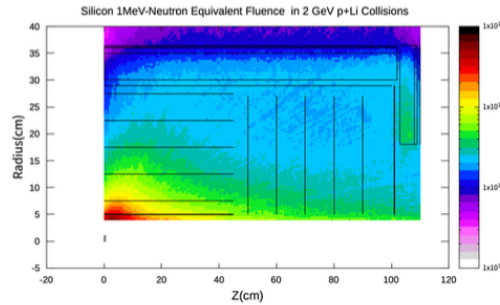
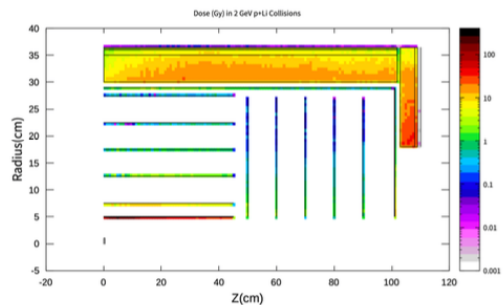
- SiPM整体尺寸越大越好 ( $6 \times 6 \text{ mm}^2$ ) , 光探测面积大
- 铅玻璃光产额低, 选用量子效率高、动态范围小的大像素SiPM, 例如滨松的75um像素SiPM
- 闪烁体光产额高, 选用动态范围大的小像素SiPM, 例如25um或者15um的像素
- 国产的价格更便宜, 像素尺寸最大25um



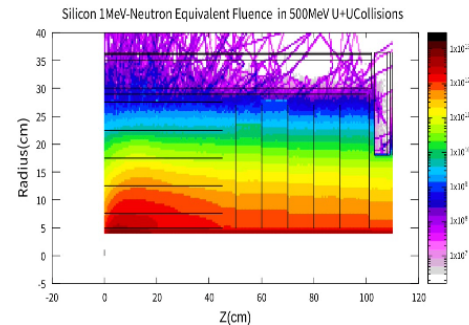
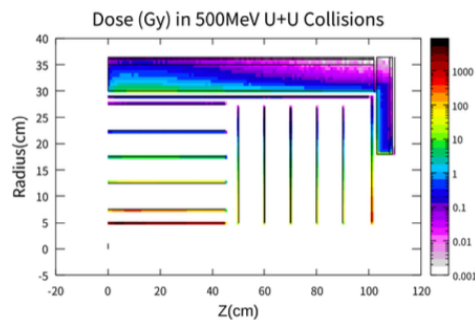
SiPM	Pixel [ $\mu\text{m}$ ]	Max sensitive area [ $\text{mm}^2$ ]	Max Np.e.	Max Quantum Efficiency (QE)	Dark noise rate [ $\text{kHz}/\text{mm}^2$ ]
北师大	20	6.24	90k	46%	150
滨松 S13360	75	6	6.4k	50%	50
	25	6	58k	25%	44

# 辐照剂量估计

2 GeV p+Li, 100MHz, 1个月



500 MeV U+U, 1MHz, 1个月



	FLUKA模拟结果		参考抗辐照性能		
	辐射剂量 (Gy)	Si1MeV等效中子通量( $n_{eq}/cm^2$ )	探测器/材料	辐射剂量 (Gy)	Si1MeV等效中子通量 ( $n_{eq}/cm^2$ )
最内层硅	3000	$3 \times 10^{12}$	pixel	$2 \times 10^4$	$1.7 \times 10^{13}$
			LGAD		$1 \times 10^{15}$
最内层EMC	50	$3 \times 10^{11}$	铅玻璃	20	
			SiPM		$1 \times 10^{14}$

- 大部分探测器部件、材料可以满足抗辐照要求
- 铅玻璃收到的辐射剂量接近其极限 (TF101: 接收20Gy辐照后光传输率降低1%)
  - 研发抗辐照更好的铅玻璃 /  $PbF_2$ 晶体替代 / 紫外光或高温恢复

# 造价估计

设计辐照长度11-12  $X_0$ （用塑料闪烁体长度会增加），横向尺寸**4 x 4 cm<sup>2</sup>**，总共约1500块，每层5个SiPMs

- Design 1: **11 layers** x ( **3 cm lead glass** + **1 cm plastic scintillator** + 0.7 cm PCB) = **52 cm**
- Design 2: **11 layers** x ( **2 cm lead glass** + **0.5 cm pCsl** + 0.5 cm PCB) = **33 cm**
- Design 3: **15 layers** x ( **2 cm lead glass** + **1 cm plastic scintillator** + 0.7 cm PCB) = **55.5 cm**

单个module价格计算：

- Design1 : 11层x (SiPM 750元 + 加工200元 + 塑闪100) x1.7 = 2万
- Design2 : 11层x (SiPM 750元 + 加工200元 + 纯碘化铯500) x1.5 = 2.4万
- Design3 : 15层x (SiPM 750元 + 加工200元 + 塑闪100) x1.8 = 2.8万

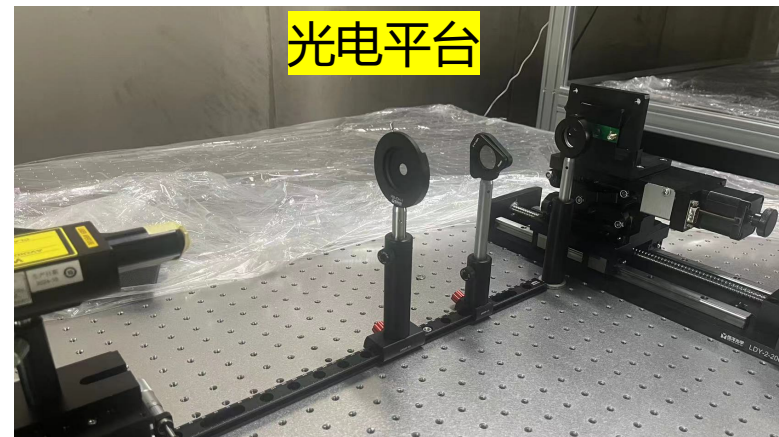
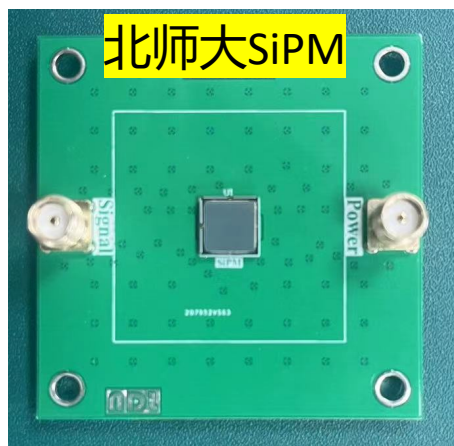
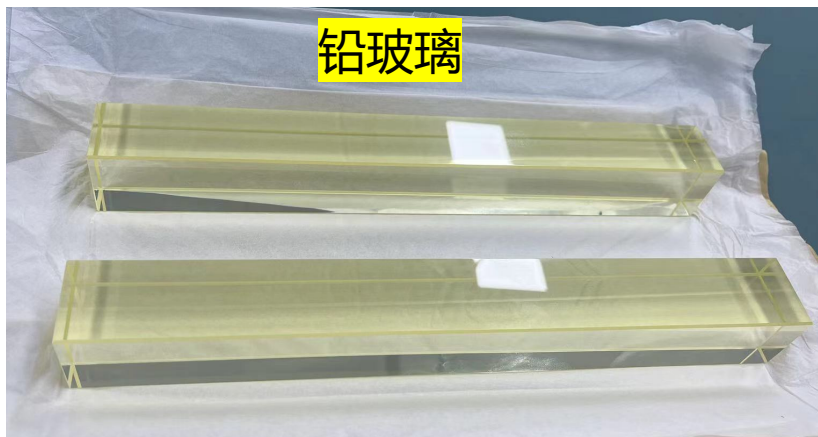
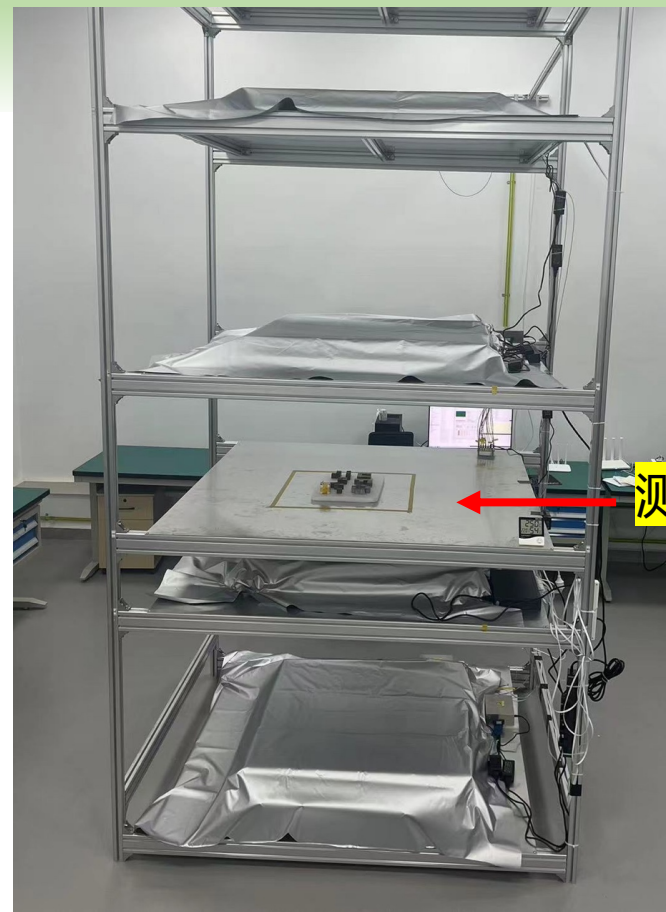
总价格计算：

- 按1500块计算，**探测器本身总造价3000 ~ 4000万元**。
- 每个module分3段分别读出切伦科夫光和闪烁光，总共电子学道数约1500\*2\*3=**9000道**。  
1000元/ch，**DAQ 900万**。
- 总共3900万到4900万，**预估4500万左右**

费用中SiPM（150元/个）占比约一半，降低该费用能明显减少造价！

# 未来硬件测试工作

- ✓ 宇宙线测试平台
- ✓ 光电测试暗室
- 铅玻璃和塑料闪烁体的测试
- SiPM的测试
- 原型的组装和测试
- 电子学的选择和测试



# 总结和展望

- ✓ ADRIANO2 量能器有好的PID、能量分辨率等，具有广阔的前景，研究应用到HIAF谱仪量能器
- ✓ 预期能量分辨率能达到  $\sim 3\%/\sqrt{E}$
- ✓ 相比于闪烁光型量能器，带有切伦科夫双读出的双读出量能器有更好的 $e/\pi$  和  $\gamma/n$ 鉴别能力( $\gamma/n$  实现从 1:10 到 13.5:1)
- 进一步根据物理目标对ADRIANO2设计做模拟和优化，减少造价
- 对铅玻璃和SiPM进行全面测试，特别是抗辐照性能
- 研究电子学读出

谢谢！