STCF探测器研究进展

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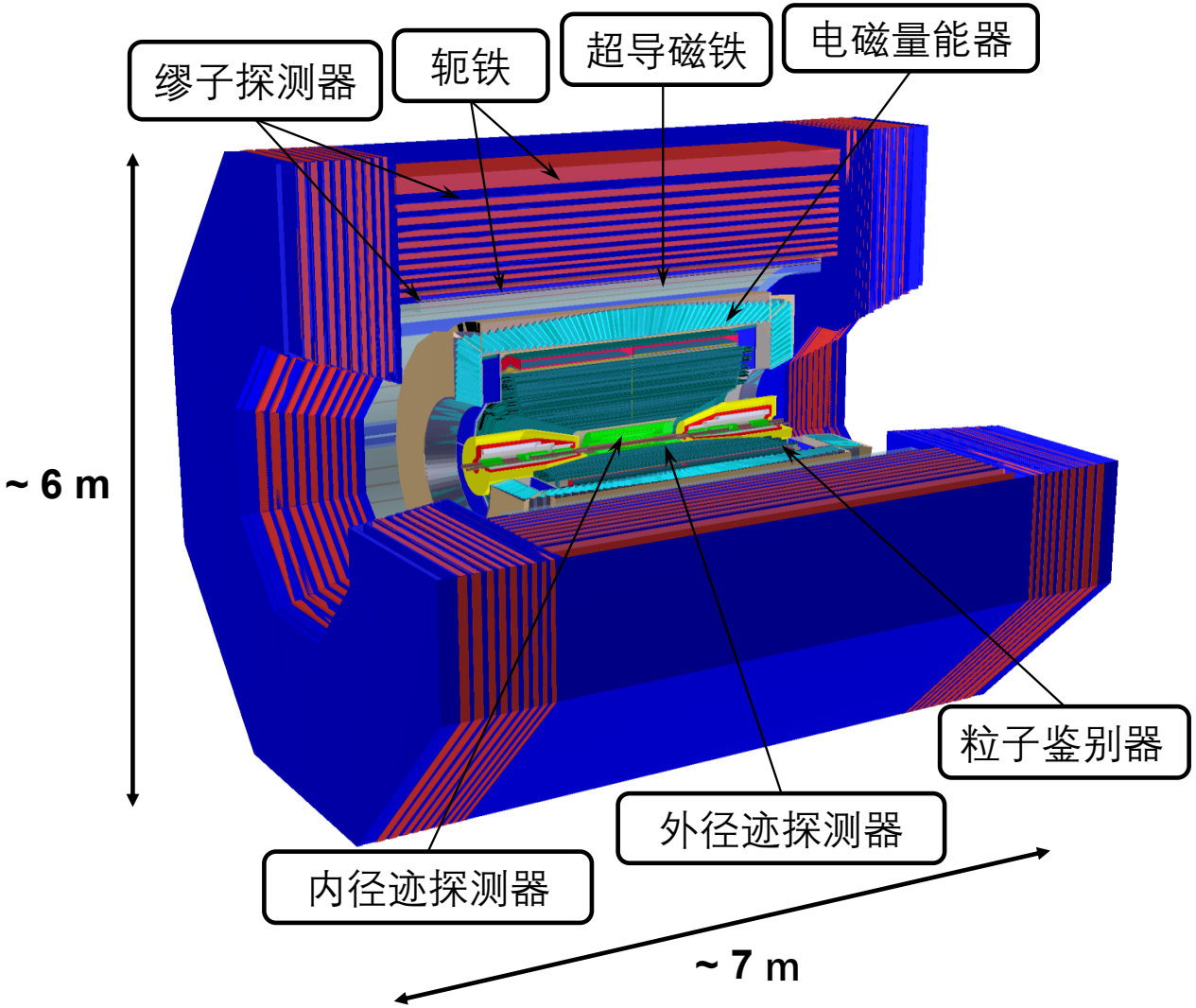
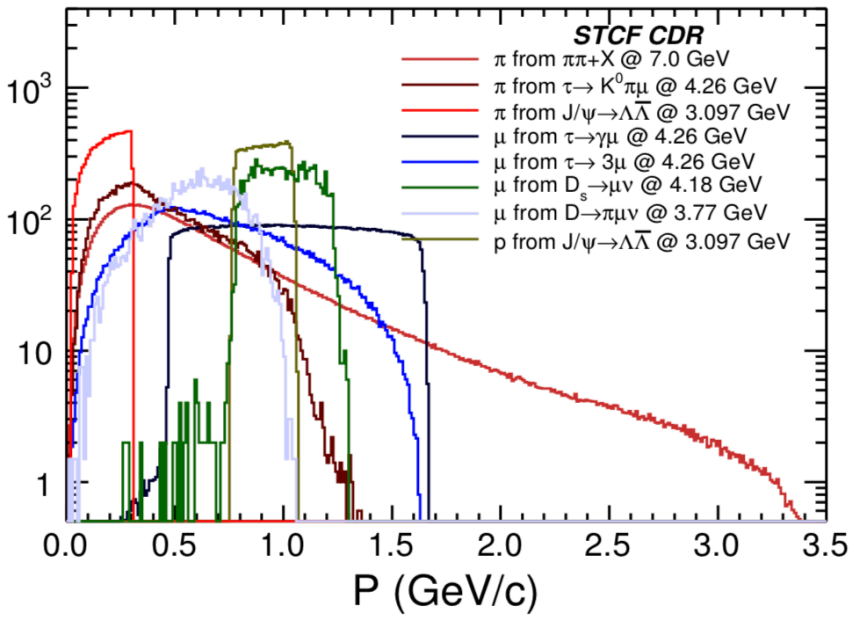
中国科学技术大学

STCF研究进展研讨会
2020年8月6日

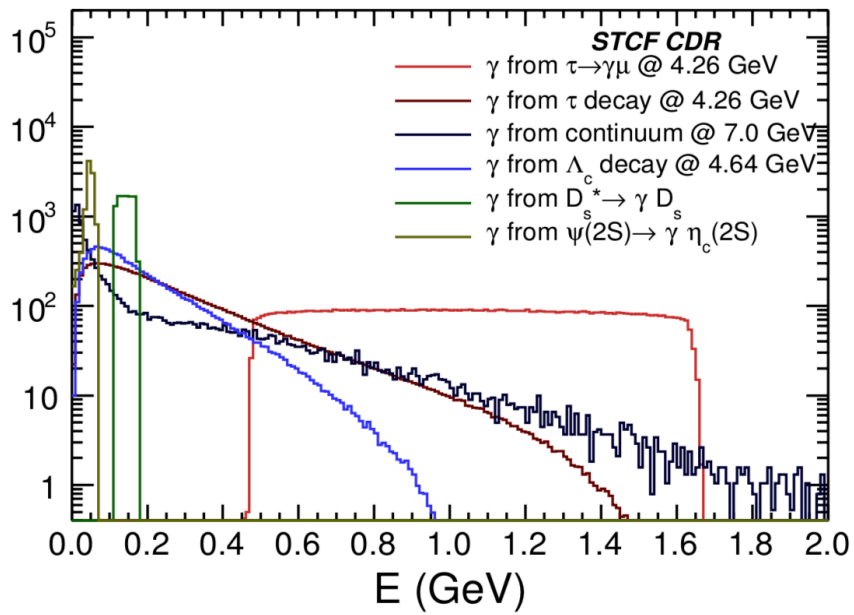
STCF探测器概念设计



物理要求



Charged particles



Photons

- 对低能/动量粒子(<1GeV) 有很好的探测性能:高效率、高分辨
- 宽动量范围的强子鉴别: 直到2GeV的pi/K分辨
- 很好的缪子鉴别能力：直到1.8GeV的mu/pi分辨
- …

定量化

- Tracking: Better tracking efficiency for low transverse momentum charged particles ($P_t < 150\,\mathrm{MeV}/c$) is requested, and it is proposed to have a 20% improvement of the tracking efficiency for low momentum charged tracks comparing with BESIII detector from the study of $\tau \to K_S \pi \nu_\tau$ process.

  The tracking efficiency for low-momentum charged particles as well as the efficiency of secondary vertex fit are getting lower when the particles is produced away from the interaction point by study $J/\psi \to \Lambda\bar{\Lambda}$ under BESIII software framework, which is due to the track fit involving the interaction point. We therefore propose to have an advanced track find algorithm to improve the efficiency deviation versue production point at STCF.

  A comparable momentum/position resolution as BESIII detetor is proposed at STCF though better resolution will of course improve the selection efficiency.

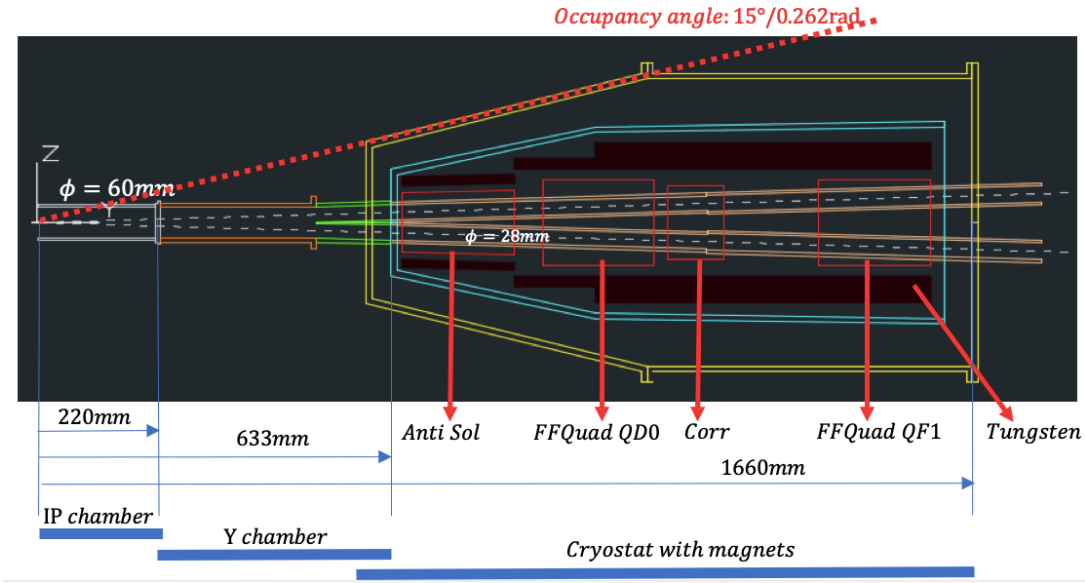
- Particle identification: Over 3σ K/π seperation power up to a momentum of 2 GeV/c is proposed from the study of $e^+e^- \to KK + X$. A π/μ separation power of 30 up to momentum of 2 GeV/c is proposed from the study of $\tau \to K_S \pi \nu_\tau$ and $\tau \to lll$ ($l = e, \mu$).

- Photon: The energy range for photon identification is from 25 MeV to 2 GeV with the energy resolution of 2.5% is proposed. Besides, the position resolution at STCF is proposed to be 70% of BESIII's position resolution, to be about 4 mm.

- Neutron: For a γ/n separation, a time resolution at ECAL better than 200 ps is required. For the reconstruction of momentum for neutron, a time resolution at ECAL better than 100 ps is required.

- K_L: To identify K_L, combining information at MUC and ECAL are required. Besides, the time resolution at ECAL can also help distinguish γ from K_L with a proposed 200 ps time resolution.

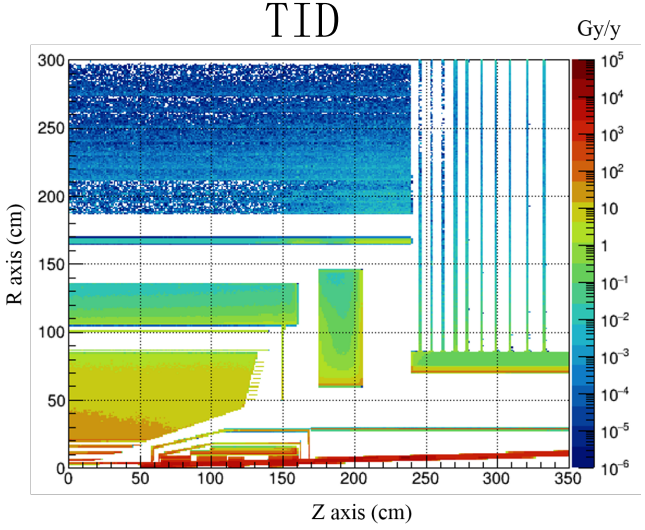
实验条件



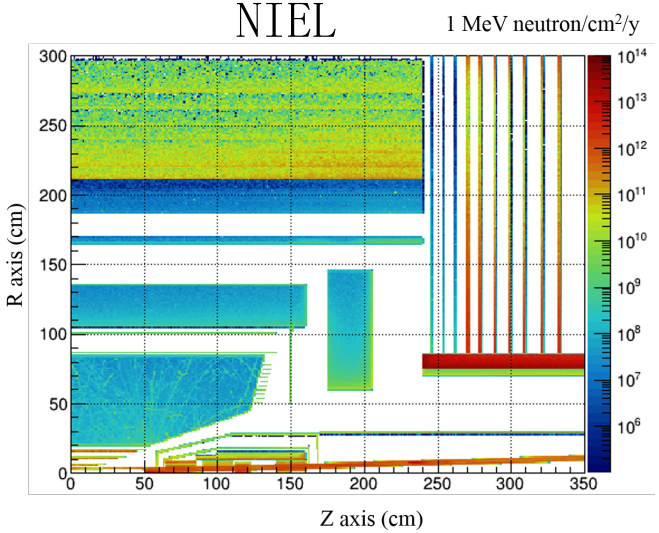
对撞区设计
中心束流管半径：60mm
对撞区张角：15度

束流和对撞本底

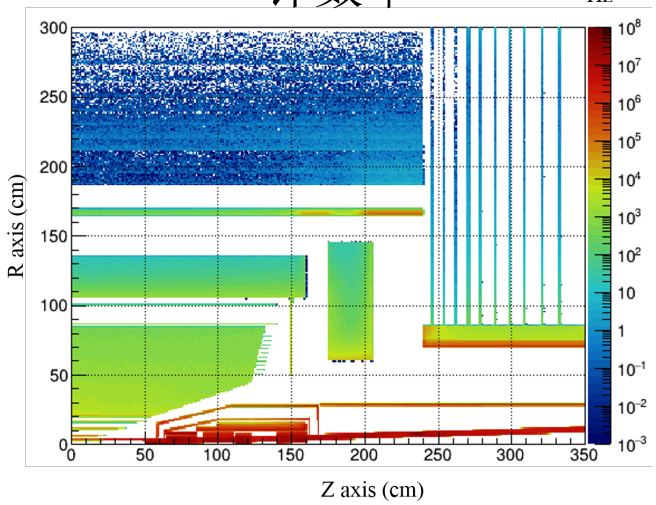
TID



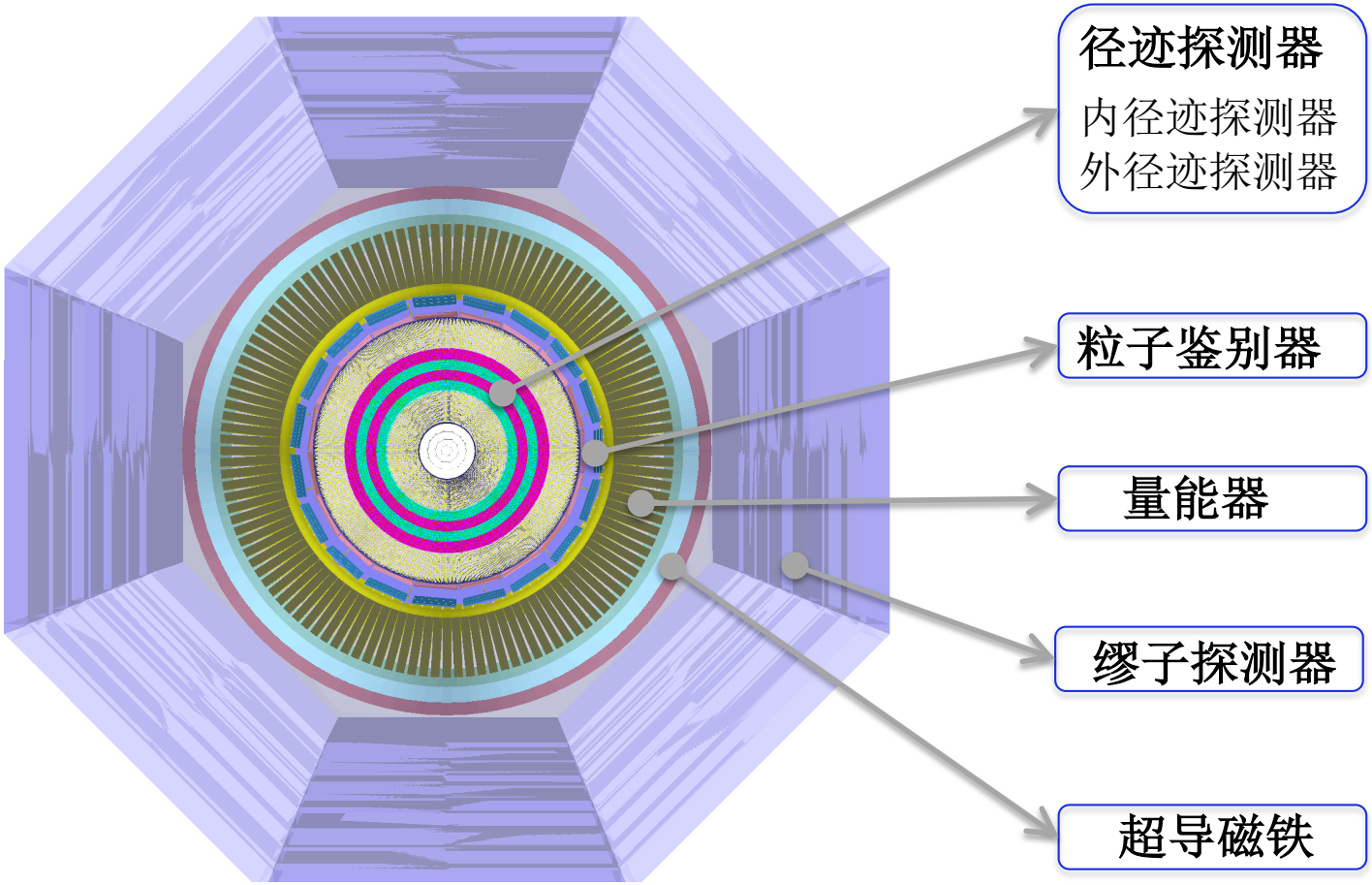
NIEL



计数率



各子系统的设计和技术研究



径迹探测系统

- 对低动量（～<1GeV）径迹有好的动量分辨，对极低动量（～<100MeV）径迹能仍保持很高的探测效率。
- 影响低动量径迹探测的主导因素：多次散射和能量损失
- 低质量（透明度）是关键
- 对撞区域本底水平很高，因此采用内外分开设计
  - 内部径迹探测器：抗辐照、高计数率能力
  - 外部径迹探测器：大体积
- 轴向磁场 1T

技术方案

- 内部径迹探测器： R<20 cm ， acceptance=20°
- 外部径迹探测器： 20 cm<R<85 cm， acceptance=20°

内部径迹探测器技术选项

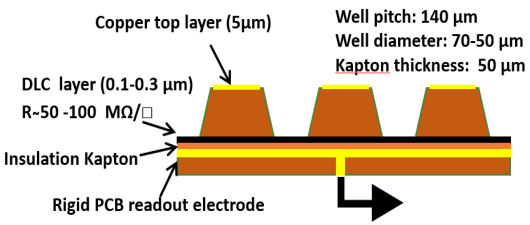
- 基准方案：微结构气体探测器 （cylindrical-μRWell探测器）
- 替代方案：硅探测器 （基于MAPS的硅像素探测器）

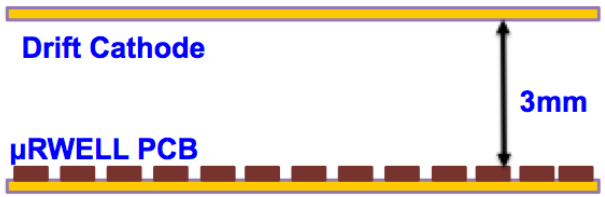
外部径迹探测器技术方案

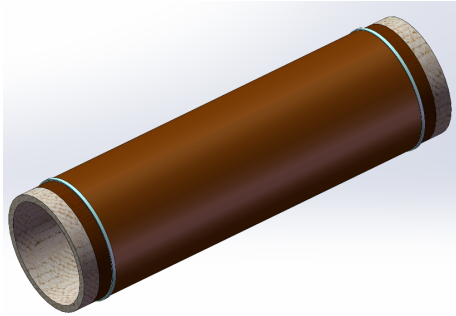
- 多丝漂移室

uRWELL:一种新型的微结构气体探测器

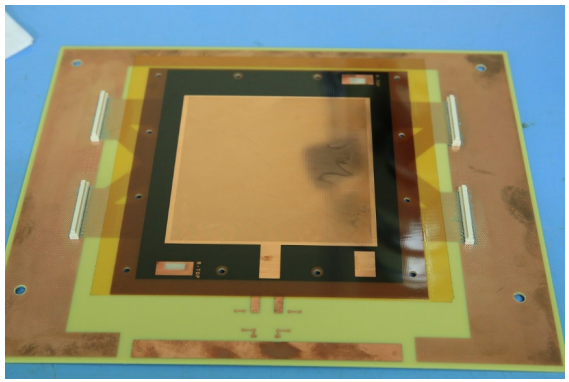
- Very compact, spark protected, simple to assemble, flexible in shapes (rather easy to make a cylindrical detector)

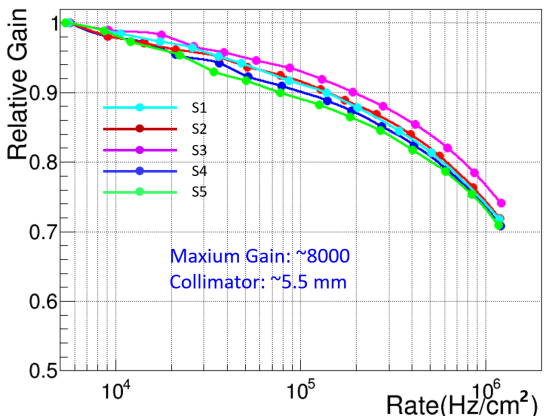


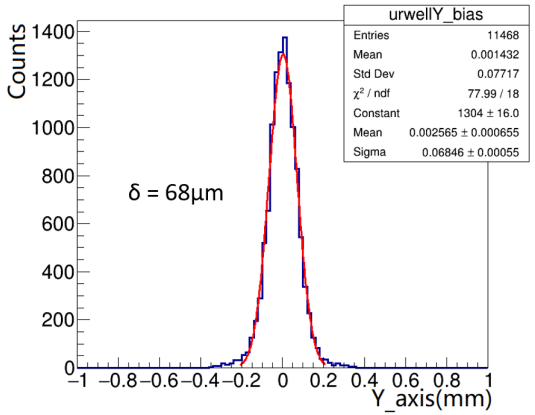




- Intensive R&D underway



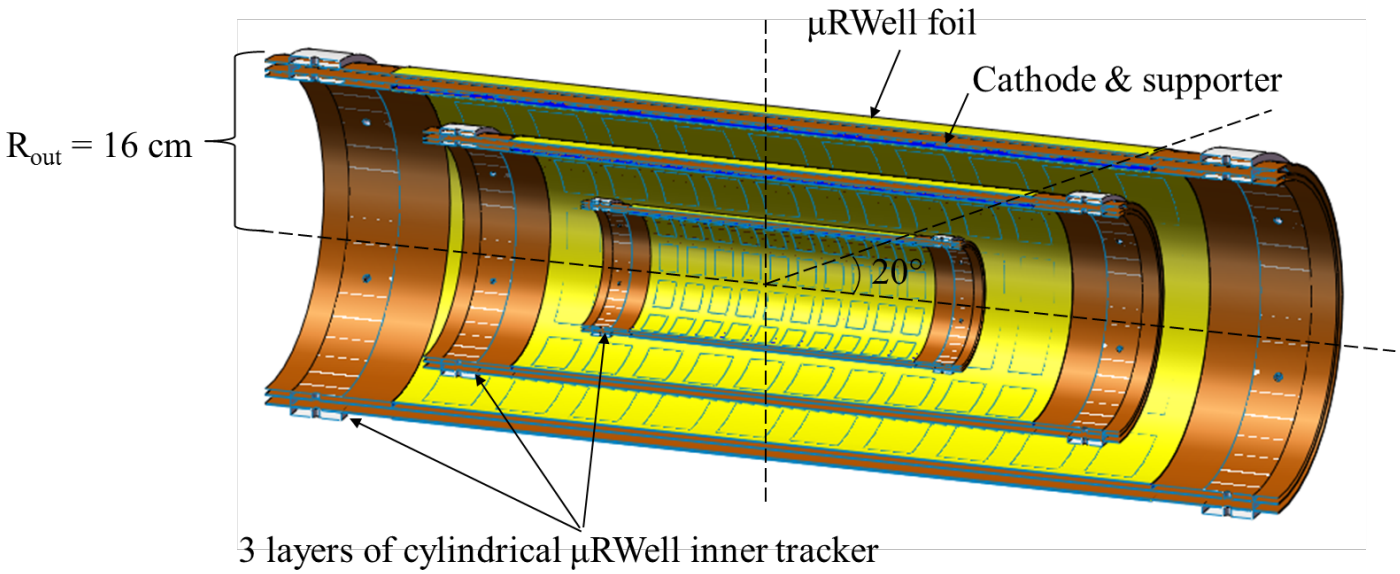




内径迹探测器基准设计

三层独立的c-μRWell探测器：

- 半径分别为6 cm, 11 cm, 16 cm;
- 单层探测器物质量0.2~0.25% X/X_0;
- XV二维读出，最高本底情况下计数率112 kHz/cm^2。



C-μRWell 技术研究

Honeycomb-based Inner tracker：

- 以2 mm厚honeycomb为基础完成全尺寸探测器结构模型制作；
- 气密空间接缝均以硅胶、树脂密封；
- 能承压0.05 bar不变形、不漏气。

Rohacell-based Inner tracker：

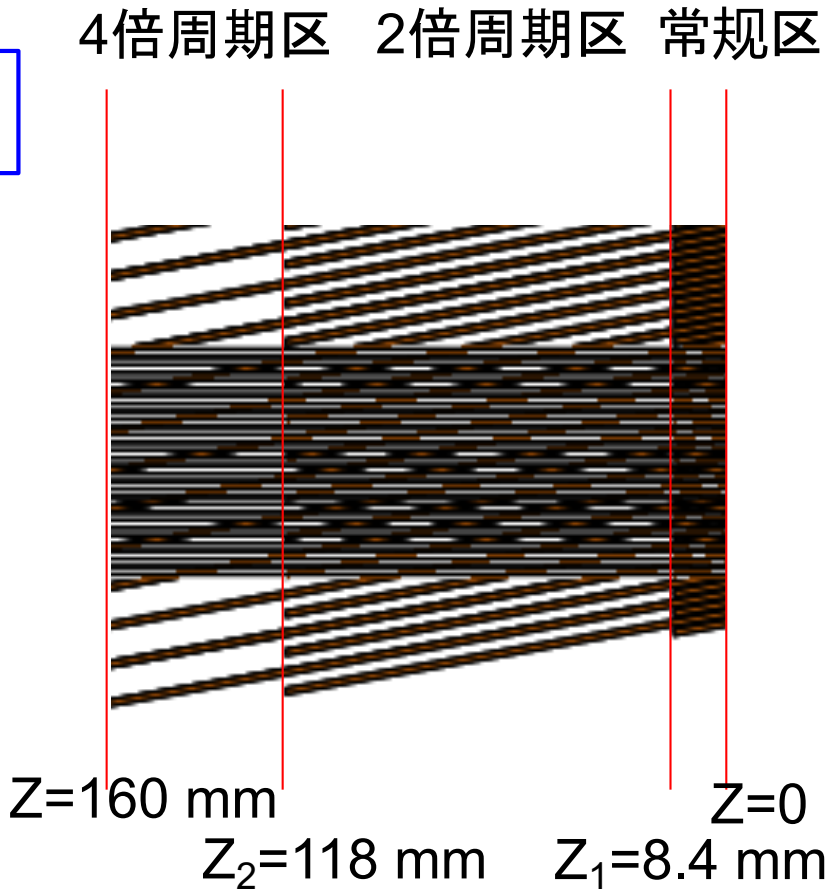
- 以1 mm厚Rohacell泡沫为基础试制探测器内芯；
- 基本掌握并改进了液态树脂粘接法，实现均匀、少量的树脂层涂布。

	内PI膜	内粘结层	承压层	外粘结层	外PI膜	总物质量
Honeycomb-based	0.028%	0.009%	0.033%	0.009%	0.030%	0.105%
Rohacell-based	0.028%	0.009%	0.010%	0.008%	0.029%	0.084%

C-μRWell读出方案

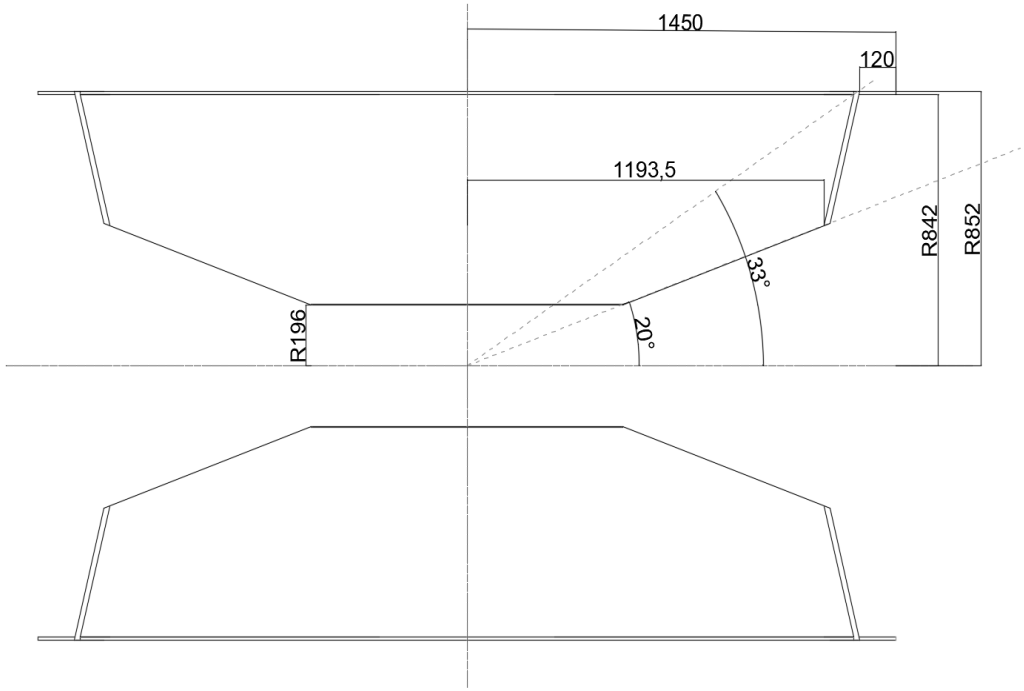
将V向读出条周期分段倍增以减少占有率

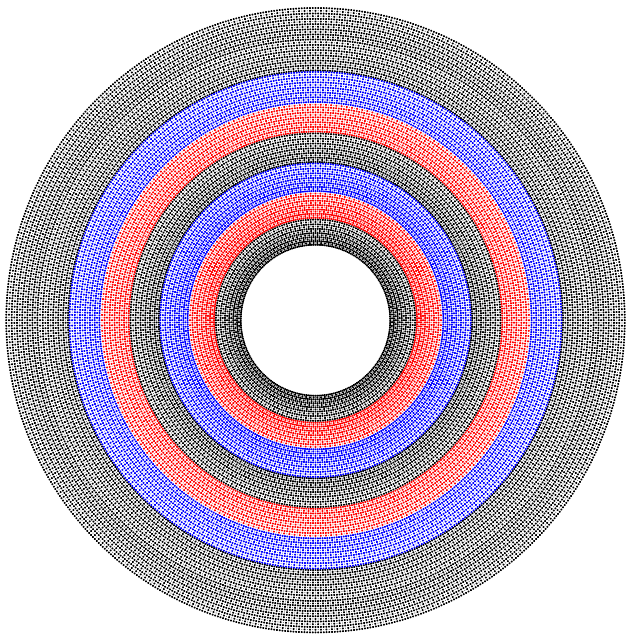
- **常规区**：V-strip保持400 μm周期，信号电子云投影最多V-strip 4条
- **2倍周期区**：V-strip周期800 μm，信号电子云投影最多V-strip 4条
- **4倍周期区**：V-strip周期1600 μm，信号电子云投影最多V-strip 3条



Detector	Inner-μRWell1	Inner-μRWell2	Inner-μRWell3
Channels	≈2100	≈3800	≈5550
Occupancy	**3.7%**	**1.5%**	**0.71%**

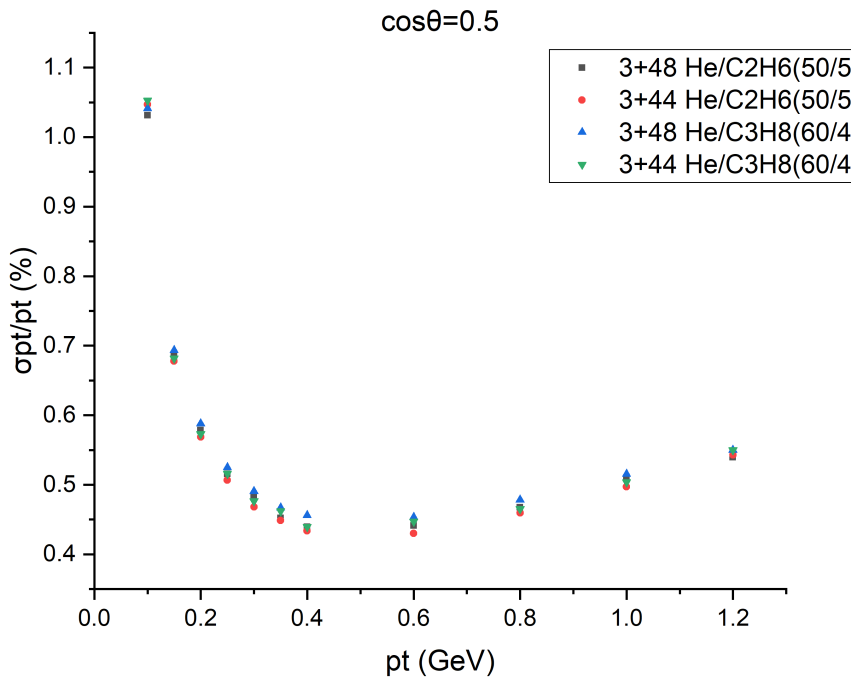
外部径迹探测器：圆柱漂移室

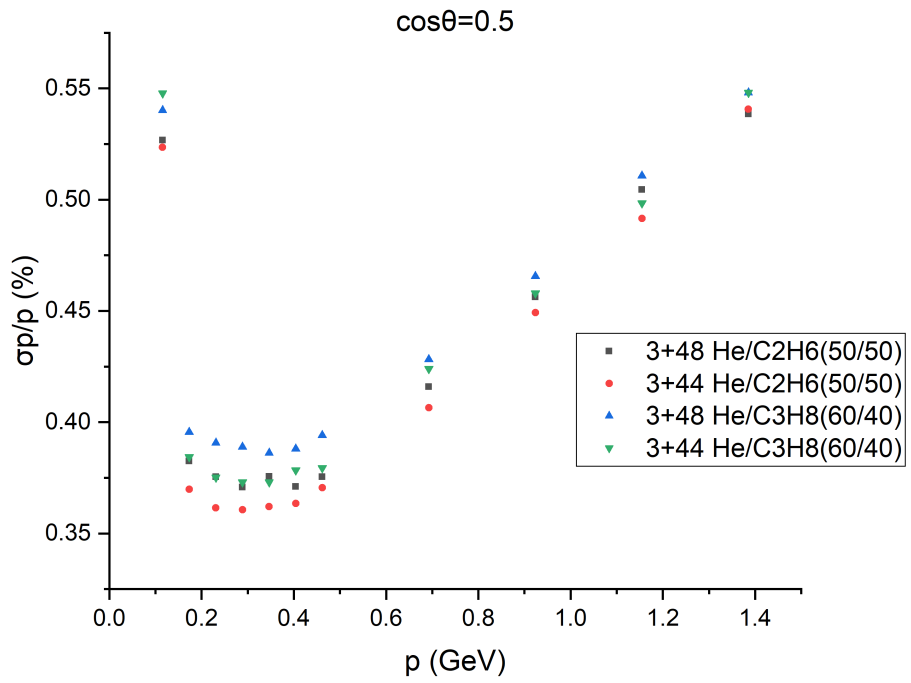




- Helium-based gas: He/C_3H_8 (60/40)
- Small square cells, 48 layers
- Sense wire: 20 um W, Field wire: 100 um Al
- Carbon fiber for both inner and outer walls

气体选择



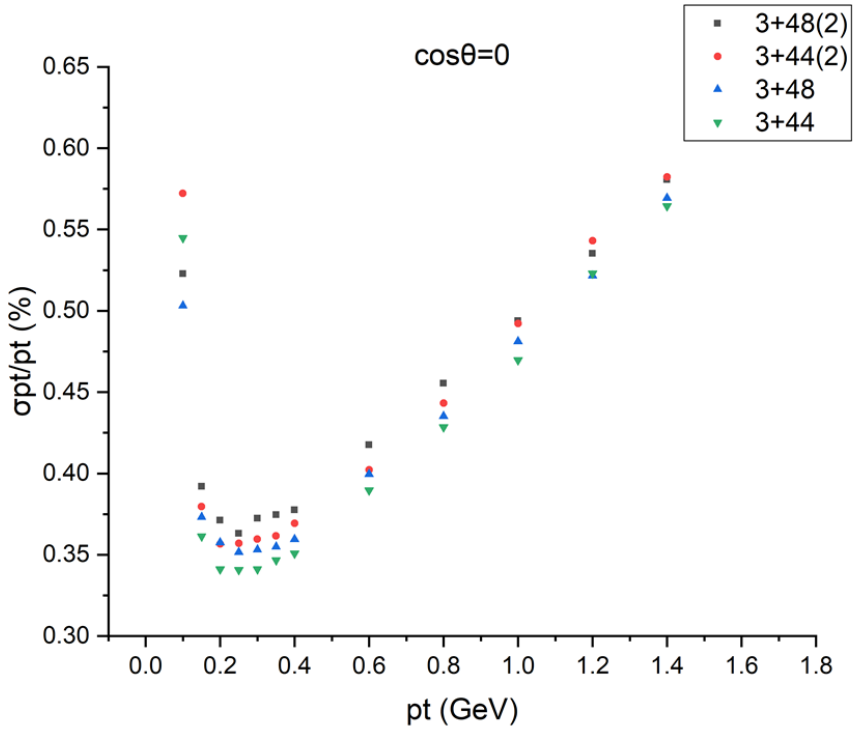


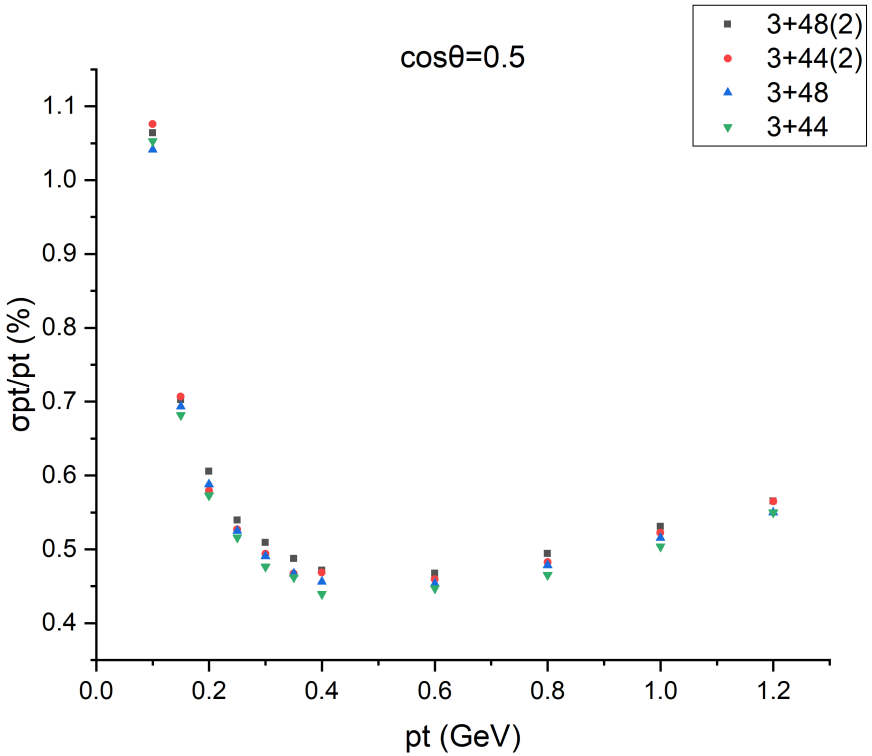
Tracker系统的横动量、动量分辨模拟结果

- 同样位置分辨下He/C2H6(50/50)气体动量分辨略好
- 但He/C2H6(50/50)气体位置分辨和dE/dx分辨略差

丝径及材料选择

- 信号丝选为Al，场丝选为W，外表面均镀上Au或Ag
- 信号丝直径为20，场丝直径为100μm



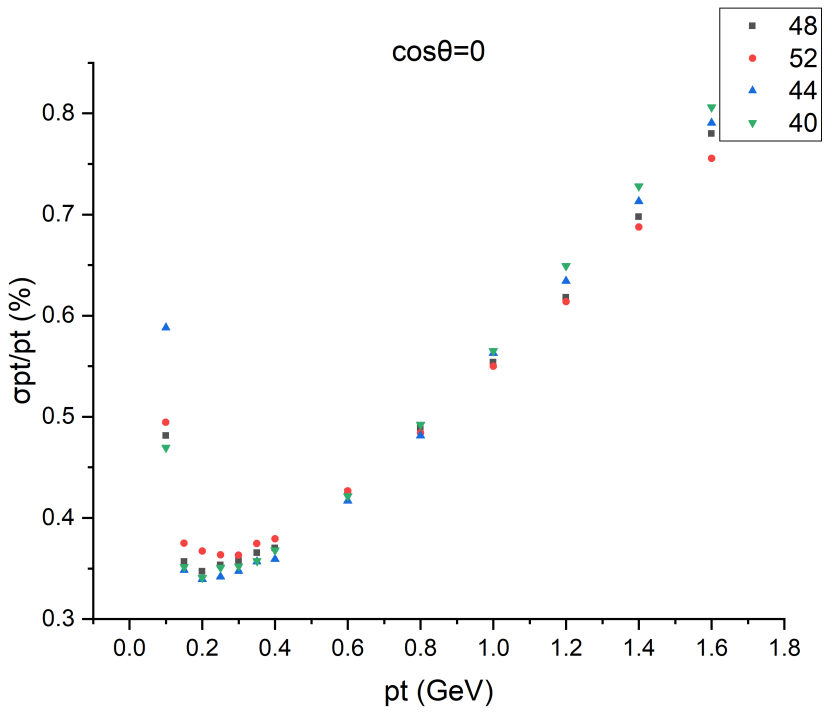


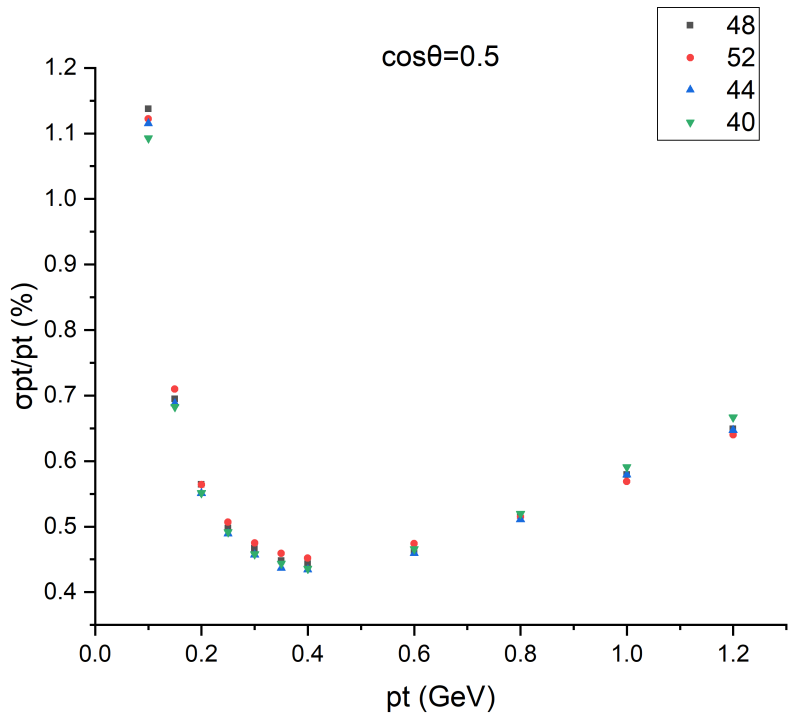
Tracker系统的横动量分辨模拟结果

不带(2)的为细丝(20+100)，带2的为粗丝(25+110)

丝层设置

- 每个超层单元半宽随超层半径递增，斜丝倾角约为40-60mrad
- 为了方便事例重建，漂移室按照A、U、V丝层间隔排列，模拟了不同层数漂移室的动量分辨





小单元可提升计数率，同时增加dE/dx测量点数，减小漂移时间

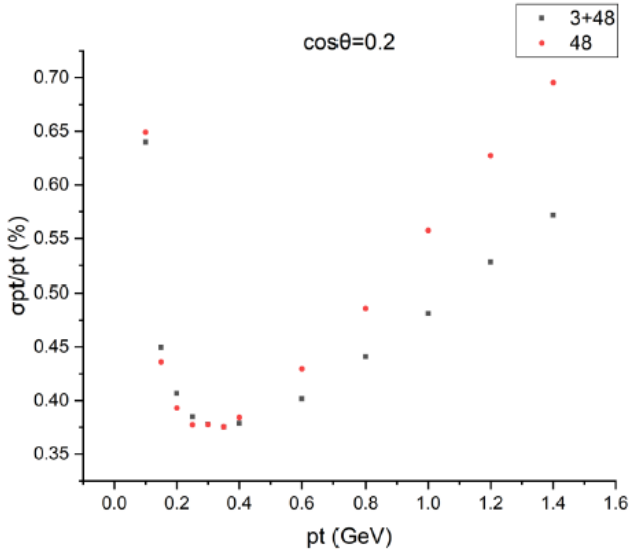
漂移室整体物理设计

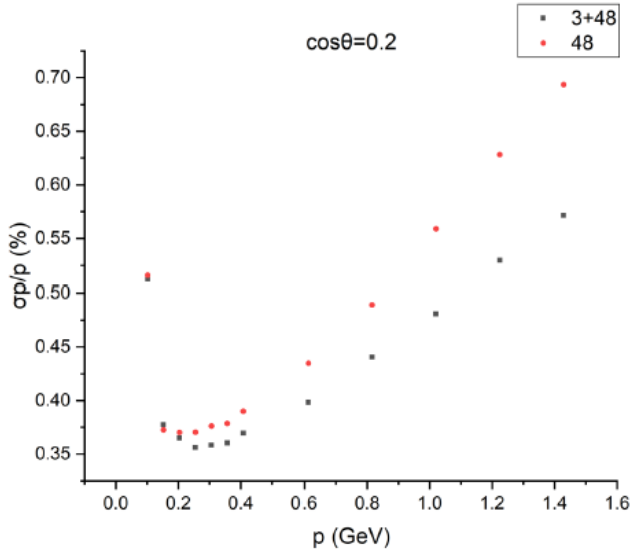
设定漂移室：

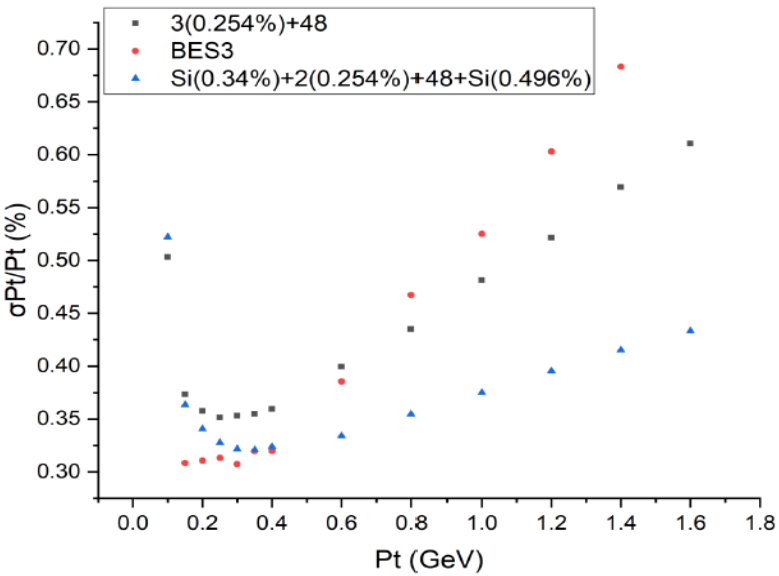
- 48层，共8个超层，每个超层6层
- 气体为He/C_3H_8(60/40)
- 信号丝为20μmAl+0.5μmAu，场丝为100μmW+0.5μmAg

超层	位置(R,mm)	每超层层数	倾斜角(mrad)	每层单元数	单元大小(mm)
A	200.0	6	0	128	9.8~12.5
U	271.6	6	39.3~47.6	160	10.7~12.9
V	342.2	6	-41.2~-48.4	192	11.2~13.2
A	419.2	6	0	224	11.7~13.5
U	499.8	6	50.0~56.4	256	12.3~13.8
V	578.1	6	-51.3~-57.2	288	12.6~14.0
A	662.0	6	0	320	13.0~14.3
A	744.0	6	0	352	13.3~14.5
总计	200~827.3	48		11520	

径迹探测器总体动量分辨

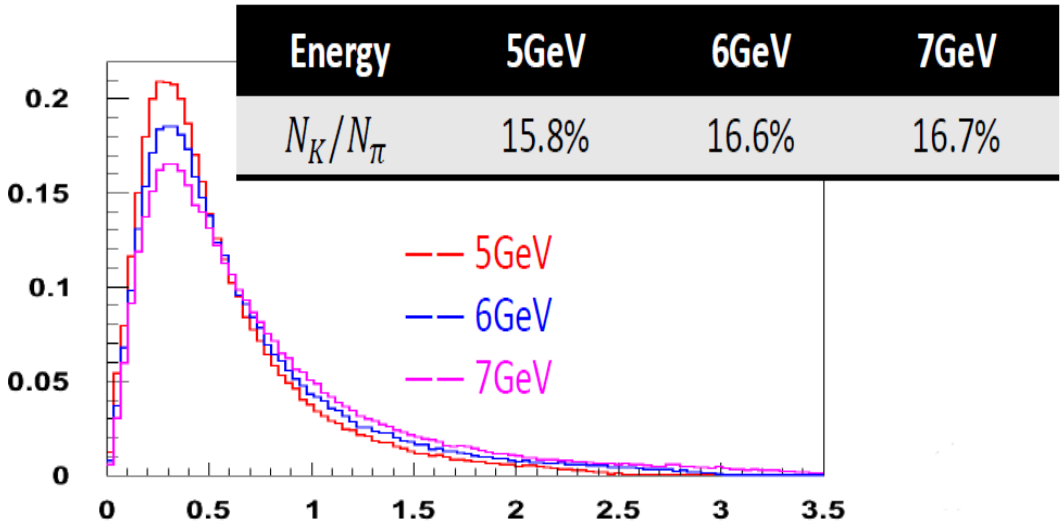






粒子鉴别探测器

- π/K separation up to 2 GeV.
  - Cherenkov-based technology is favorable.
  - Very low p region (<~0.6GeV) is covered by trackers through dE/dx measurement
- Compact (<20cm) and low mass (<0.5X_0)



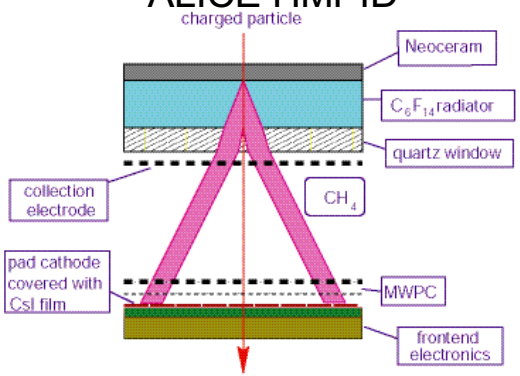
Energy	5GeV	6GeV	7GeV
N_K/N_π	15.8%	16.6%	16.7%

Collins效应测量要求高动量π/K分辨

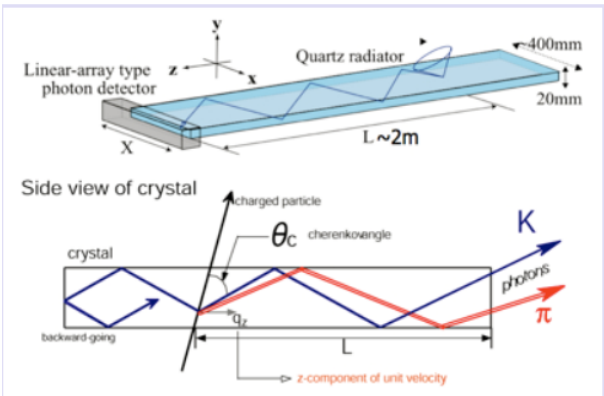
探测器选项

- RICH
  - Very powerful over a wide range of momentum
  - Reconstruction straightforward
  - Additional space for Cherenkov cone expansion: less compact
  - A large number of readout channels : cost, cooling …
- DIRC-like: iTOP, FTOF, DIRC …
  - Very compact, operation convenient
  - Reconstruction complicated
  - Quartz manufacturing and processing very challenging

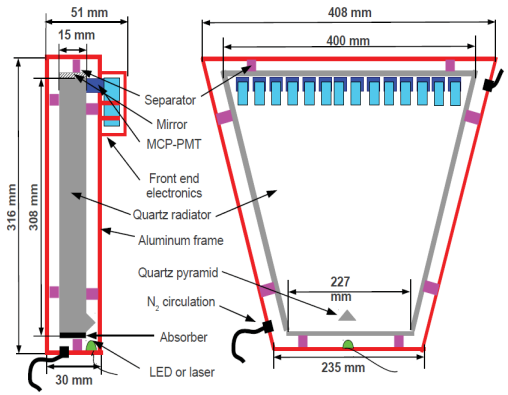
ALICE HMPID



iTOP for BELLE2



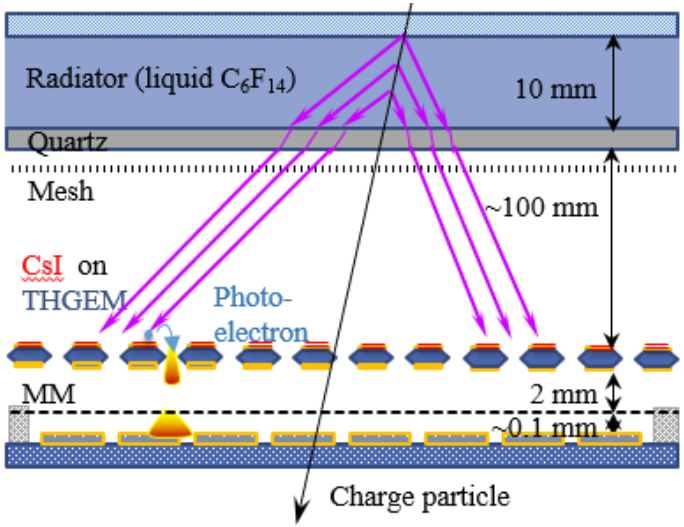
FTOF for superB



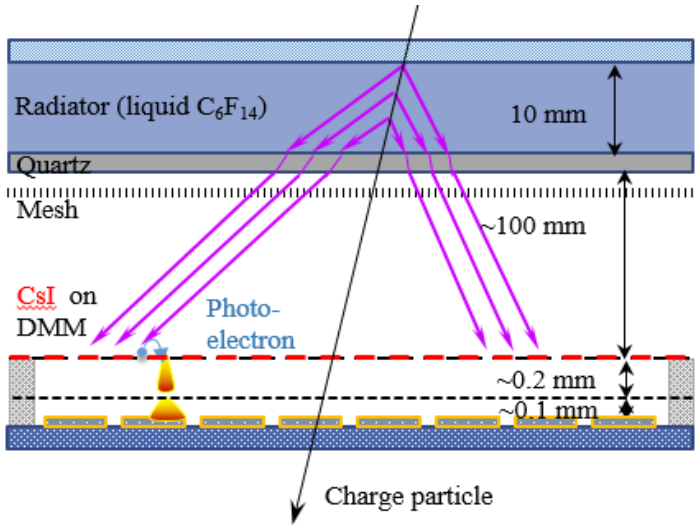
RICH方案

- Proximity focusing RICH with CsI-coated MPGD readout
  - avoid photon feedback
  - less ion backflow to CsI
  - Fast response, high rate capacity
  - Radiation hard
- Proximity gap ~10cm
- Radiator: liquid C_6F_{14}, n~1.3

- CsI光阴极：紫外光收集和探测（很多问题的根源）

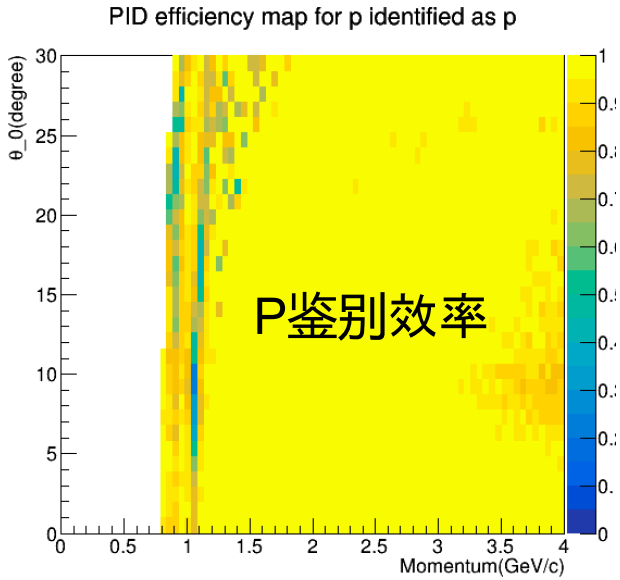


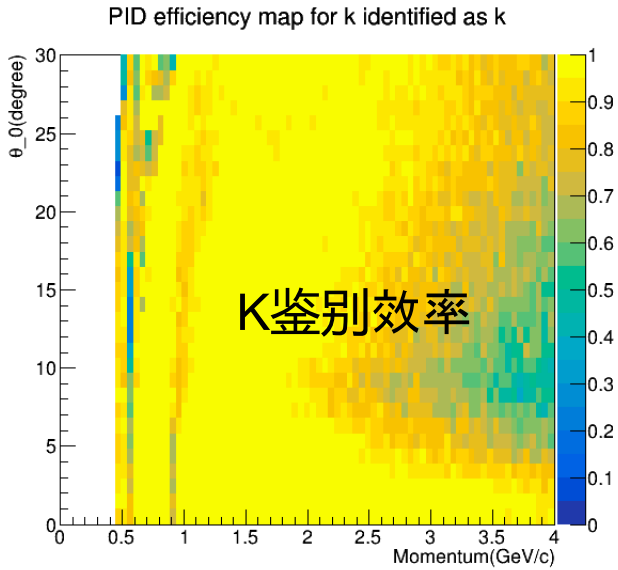
THGEM + MM

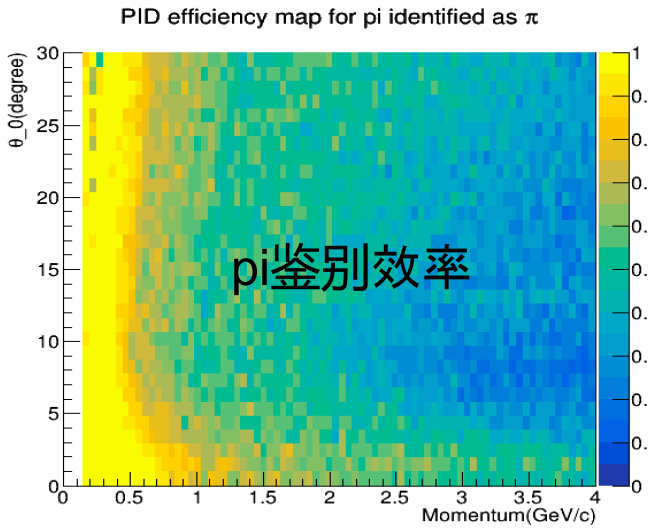


DMM

预期性能

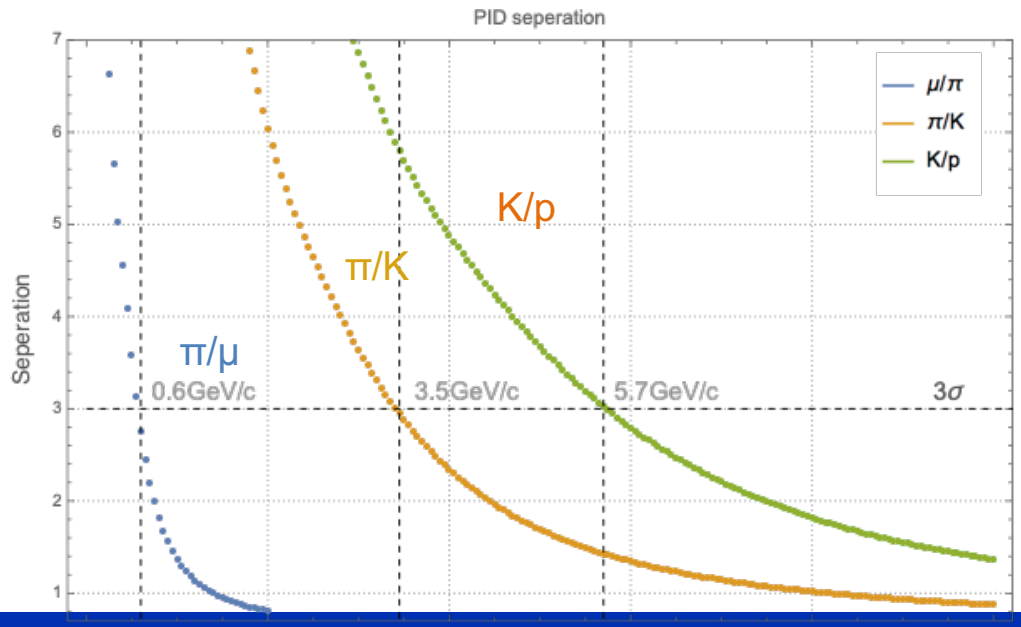






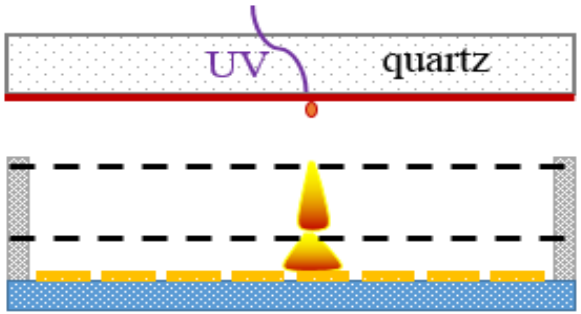
高动量的pi/mu无法有效鉴别

- The K/p ability can reach to 5.7 GeV/c with 3σ separation.
- π/K goes up to 3.5 GeV/c. Fulfill the requirements of STCF.
- The low momentum π/μ separation is also possible.

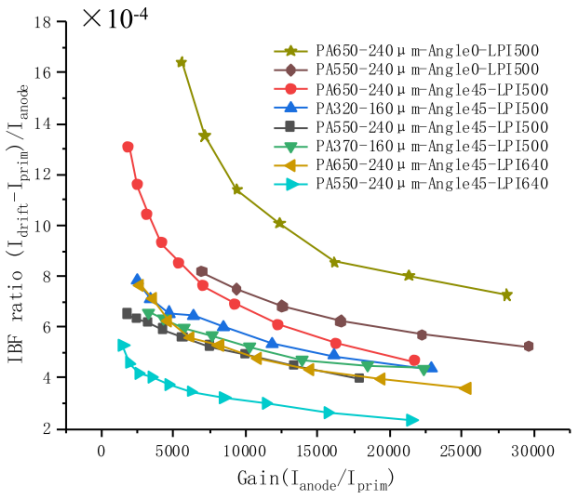


离子反馈抑制：双丝网Micromegas

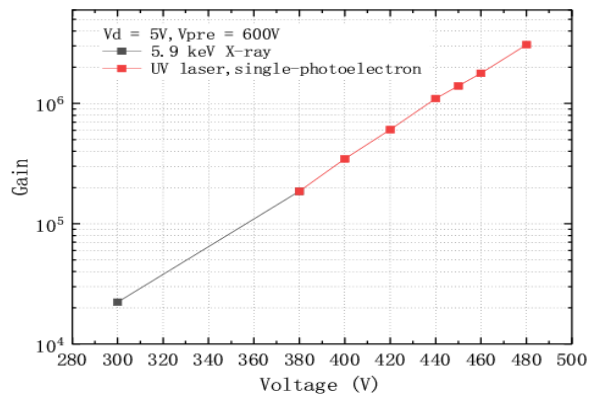
- DMM: Double-mesh Mircromegas detector, which is being developed at USTC
  - High gain and very low ion backflow
  - Very suitable for single photon detection (with a proper photon-electron converter)
  - An promising photon detector option for STCF-RICH



IBF ~ 0.03%

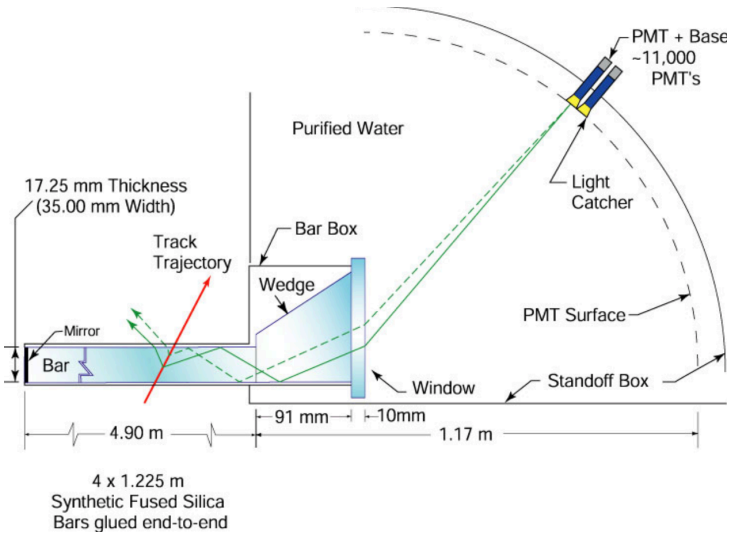


Gain ~ 3×10^6

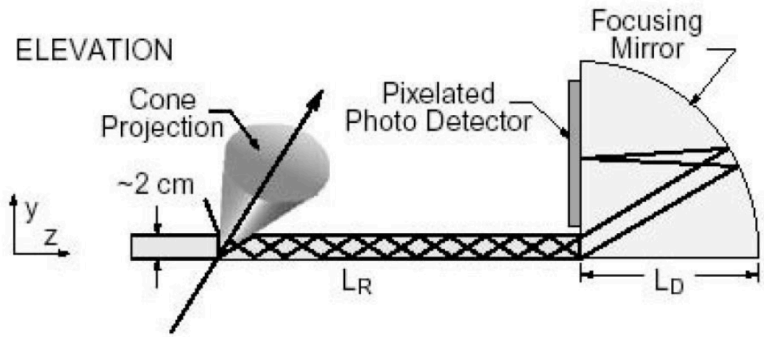


DIRC方案

First DIRC at a HEP experiment (Babar)

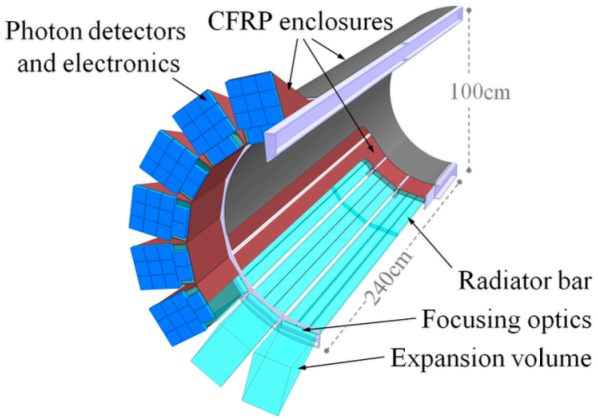


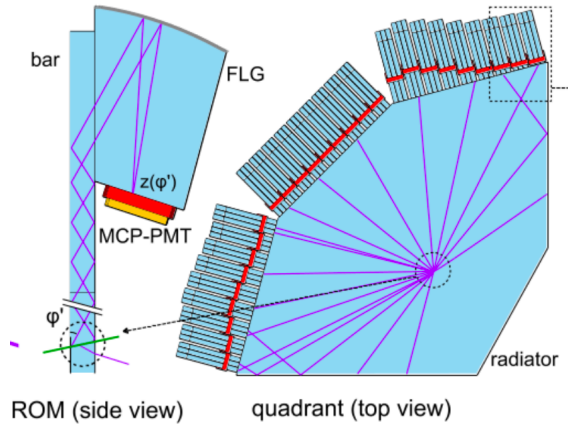
Advent of high performance silicon photon sensors (magnetic field resistant, high-gain, fine granularity, compact, high time resolution) makes a compact DIRC possible



A focused DIRC concept

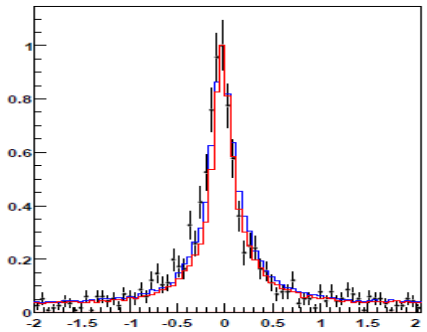
Panda DIRCs (barrel and endcaps)





DIRC飞行时间探测器：FTOF

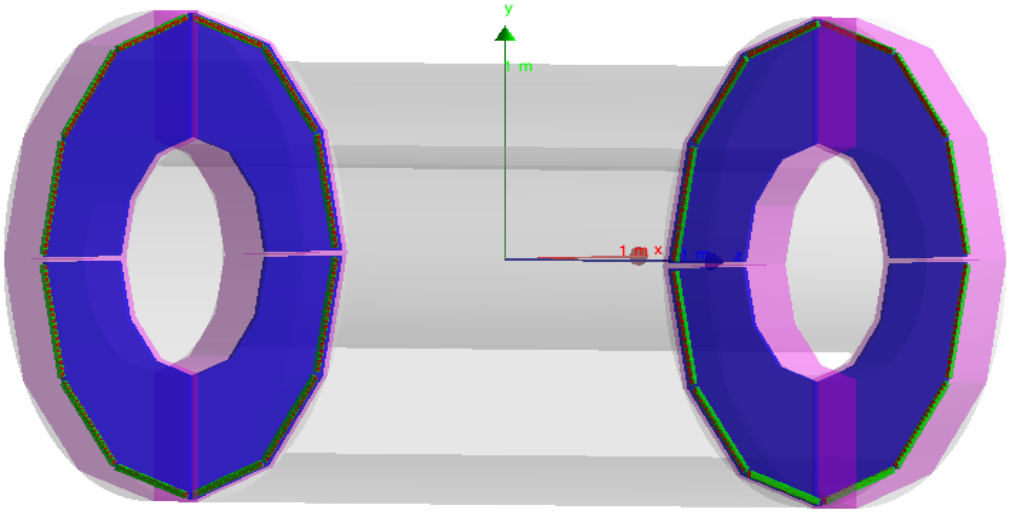
- DIRC-like forward TOF detector (FTOF: quartz + MCP-PMT) was developed at LAL for the SuperB factory project.
  - No Cherenkov angle reconstruction, simple and no need for space for optical expansion → very compact!
- Flight length to STCF endcaps ~ 1.4 m, making FTOF a feasible PID detector option for STCF endcaps.
  - A time resolution of ~40 ps is required for pi/K separation to reach 2GeV.

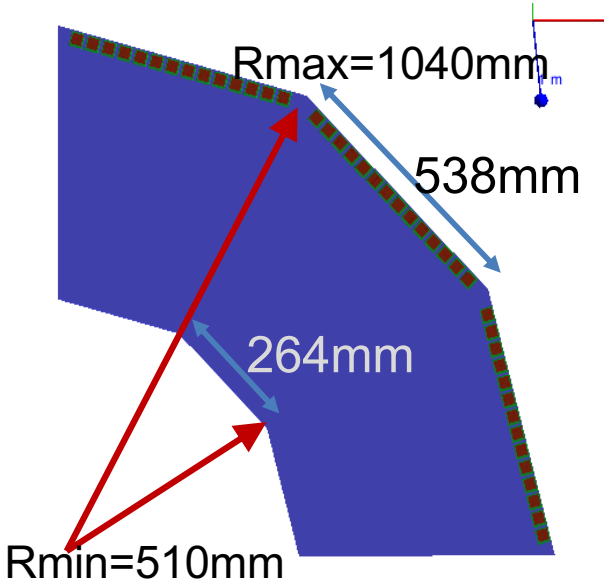


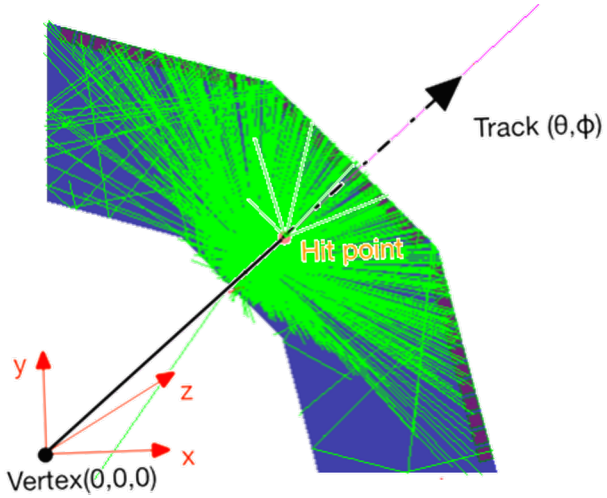
From SuperB R&D

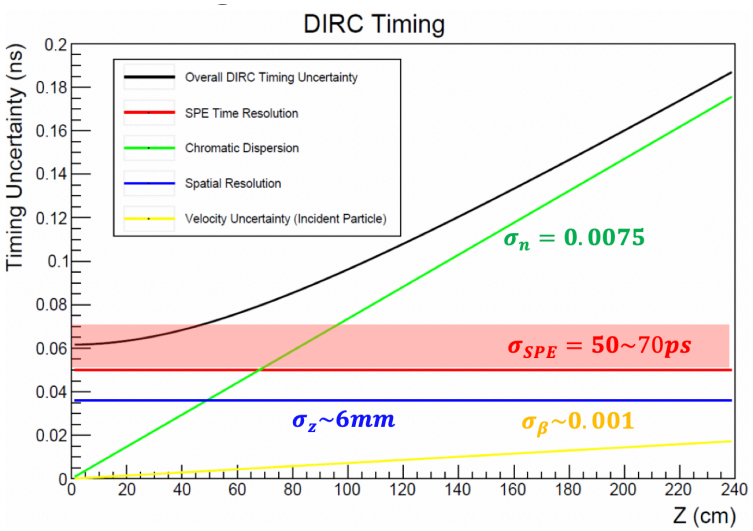
~ 80ps per PE

FTOF概念设计

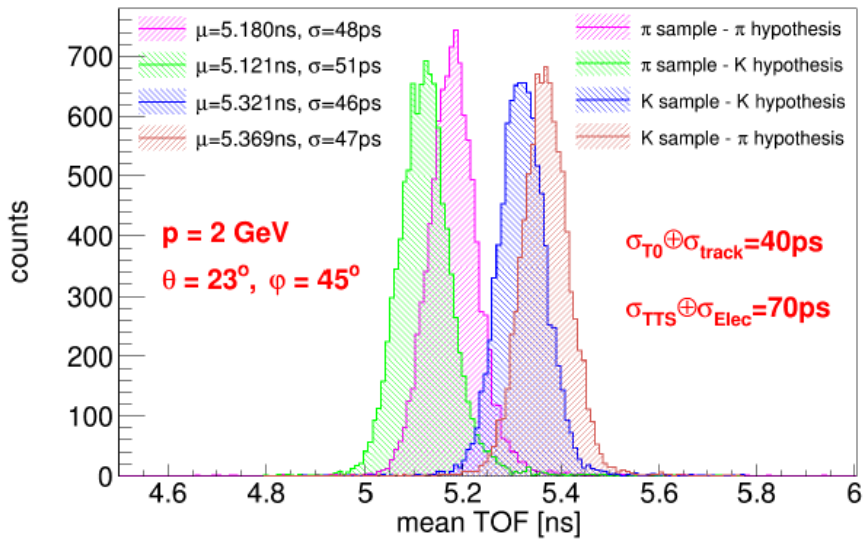


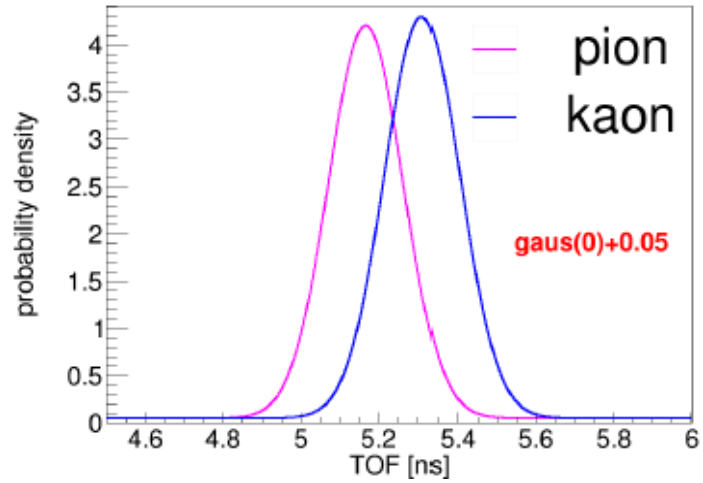

Rmax=1040mm
538mm
264mm
Rmin=510mm

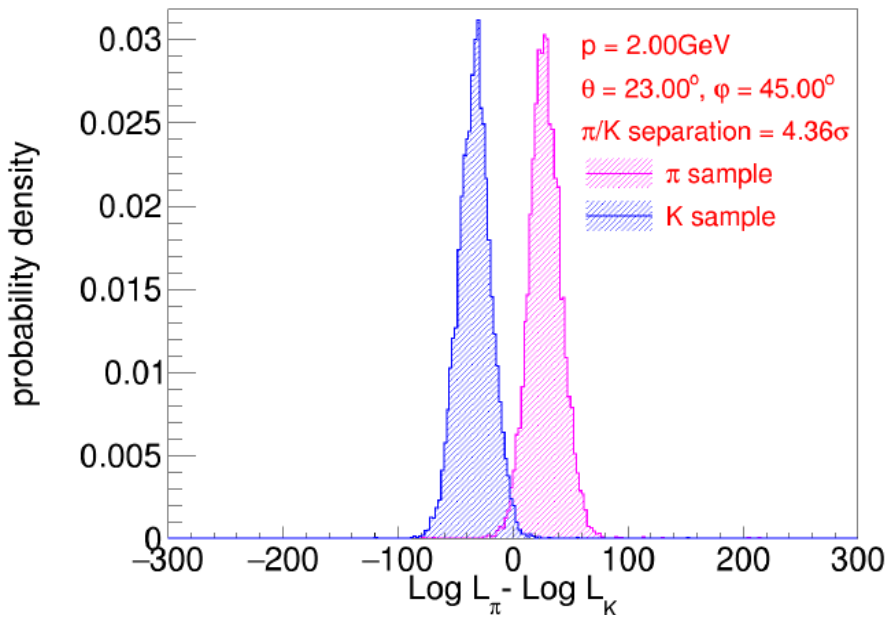

Track (θ,ϕ)
Hit point
y
z
x
Vertex(0,0,0)


DIRC Timing
Timing Uncertainty (ns)
Z (cm)
Overall DIRC Timing Uncertainty
SPE Time Resolution
Chromatic Dispersion
Spatial Resolution
Velocity Uncertainty (Incident Particle)
$\sigma_n = 0.0075$
$\sigma_{SPE} = 50\sim70ps$
$\sigma_z\sim6mm$
$\sigma_\beta\sim0.001$

FTOF预期性能

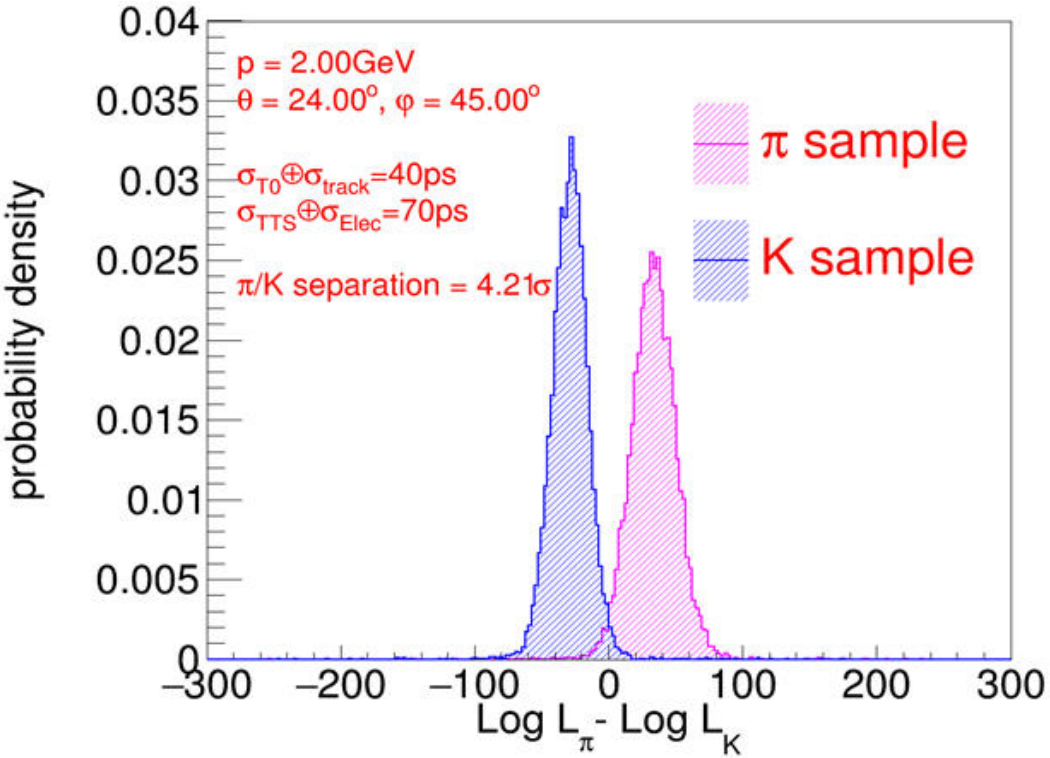


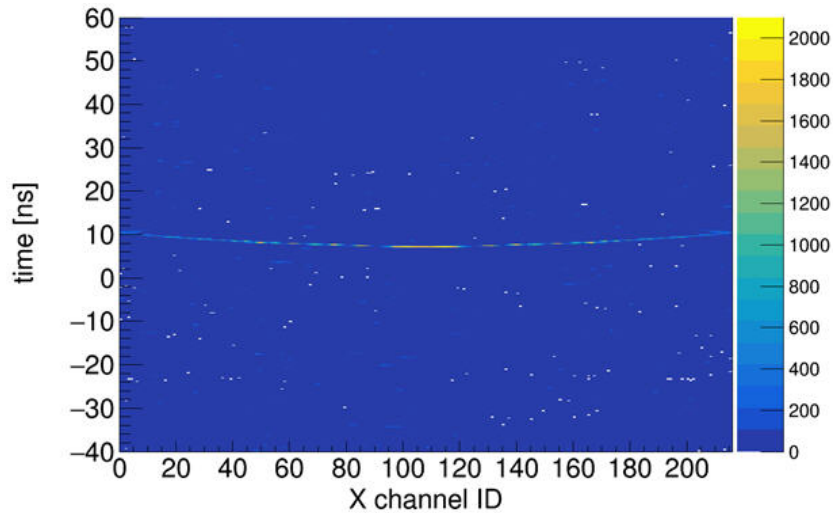


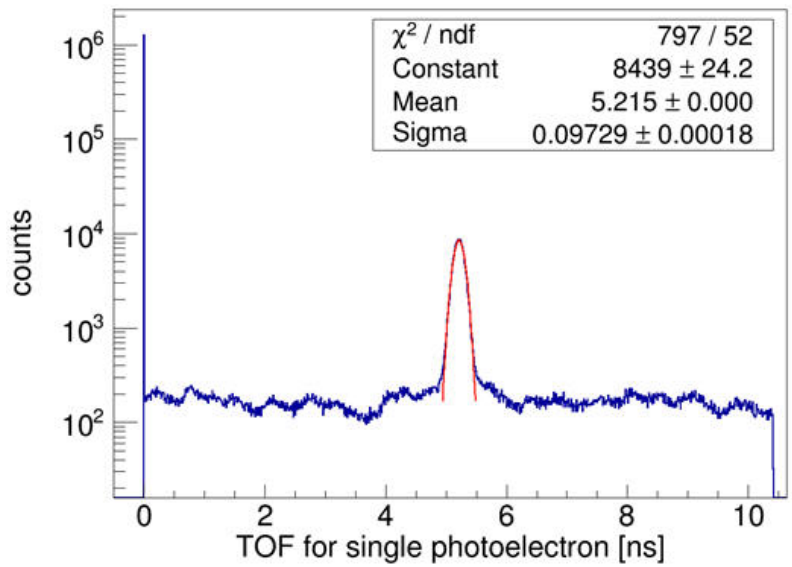


$$\mathcal{L}_h = \prod_{i=1}^{n} f_h\left(TOF_i^h\right) \qquad \ell = Log\,\mathcal{L}_\pi - Log\mathcal{L}_K$$

本底影响



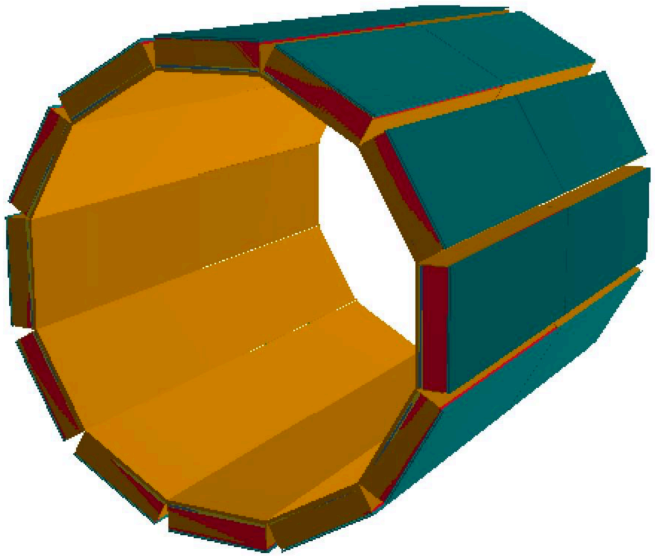


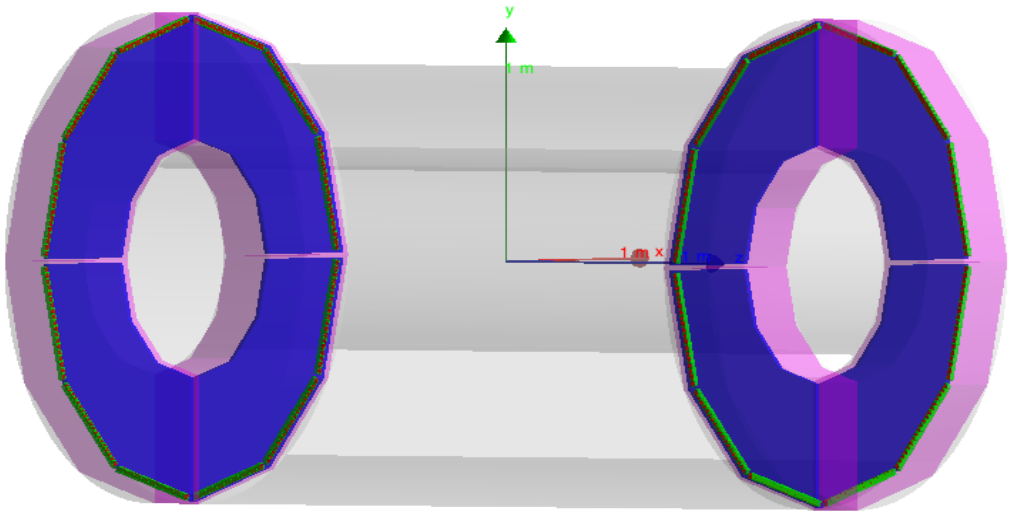


本底对FTOF-PID能力仅有微小影响。但对MCP-PMT寿命影响显著：本底导致MCP-PMT阳极累积电荷达10~100C/cm²（STCF十年运行）

粒子鉴别器概念设计

- RICH in Barrel + FTOF in Endcaps



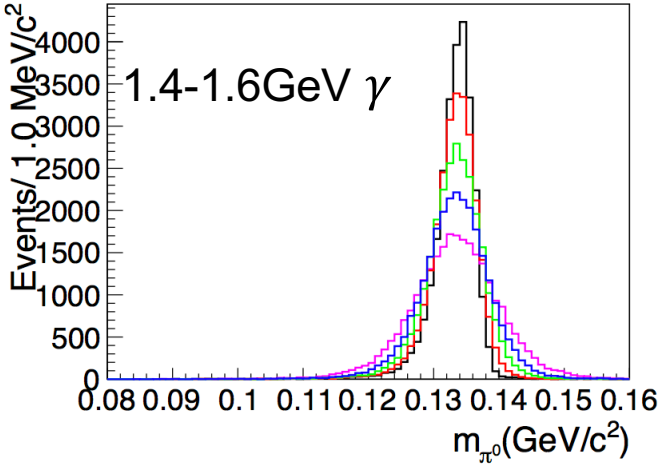


Issues to be clarified:

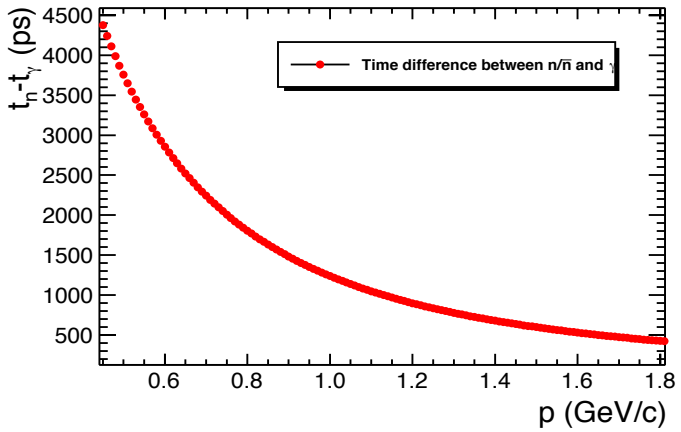
- Size of dead area between detector sectors (particularly in the case of RICH)
- RICH performance degradation at large incident angles
- Timing uncertainty due to longitudinal beam size

电磁量能器

- 核心是能在高本底计数下精确测量能量 (20 MeV - 2 GeV)
  - 探测器方案：快发光晶体 + 半导体光电器件
- 此外，位置测量和时间测量也很重要。量能器设计应同时充分考虑这两方面的要求。



Invariant mass of high energy π^0 vs. γ position resolution



Difference in TOF of n and **γ**

Precise ECAL timing is very useful in suppressing **γ** background and measuring TOF of neutrons to infer their momenta.

定时量能器

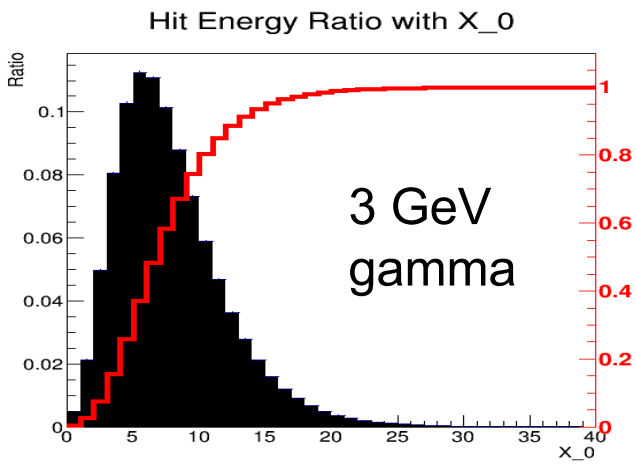
候选晶体

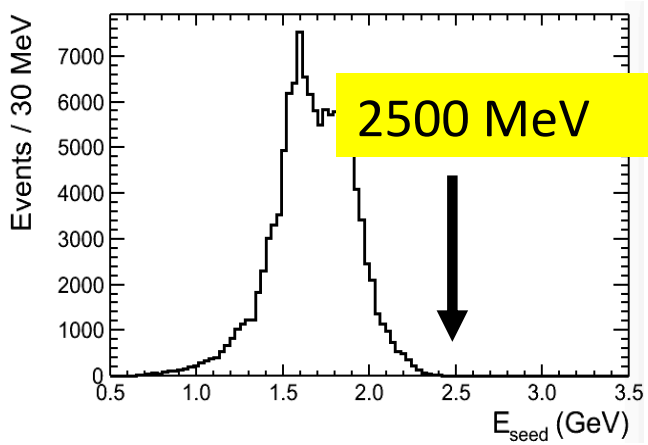
Crystal	Pure CsI	LYSO	GSO	YAP	PWO	BGO	CsI (Tl)
Density (g/cm^3)	4.51	7.40	6.71	5.37	8.30	7.13	4.51
Melting Point (°C)	621	2050	1950	1872	1123	1050	621
Radiation Length (cm)	1.86	1.14	1.38	2.7	0.89	1.12	1.86
Moliere Radius (cm)	3.57	2.07	2.23	4.50	2.00	2.23	3.57
Refractive index	1.95	1.82	1.85	1.95	2.20	1.82	1.95
Hygroscopicity	Slight	No	No	No	No	No	Slight
Luminescence (nm)	310	402	430	370	425 420	480	550
Decay time (ns)	30 6	40	60	30	30 10	300	1220
Light yield (%)	3.6 1.1	85	20	65	0.3 0.1	20	165
Dose rate dependent	No	No	TBA	TBA	Yes	Yes	No
d(LY)/dT (%/°C)	-1.4	-0.2	-0.4	TBA	-2.5	-1.0	0.4
Experiment	KTeV Mu2e				CMS ALICE PANDA	L3	BESIII BELLE(II) BaBar

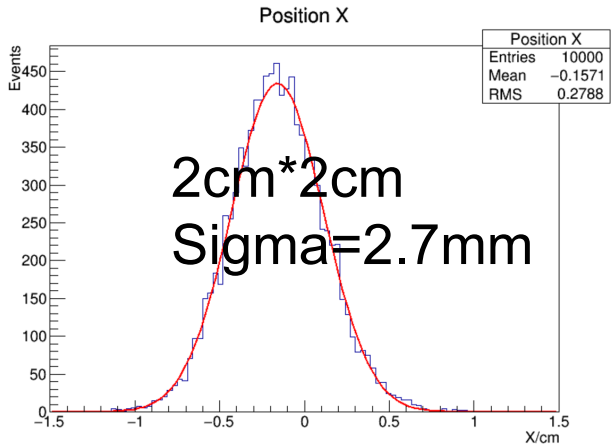
STCF-EMC选用纯CsI(pCsI)晶体

单元设计

- 长度：15 X_0
- 横截面： 5cm*5cm
- 动态范围：1 MeV ~2000 MeV
  - APD是比较合适的光探测器
- 时间分辨： 几百ps

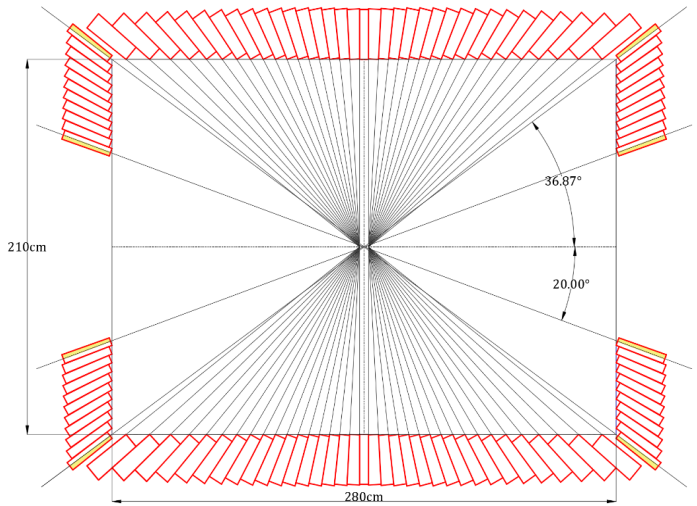


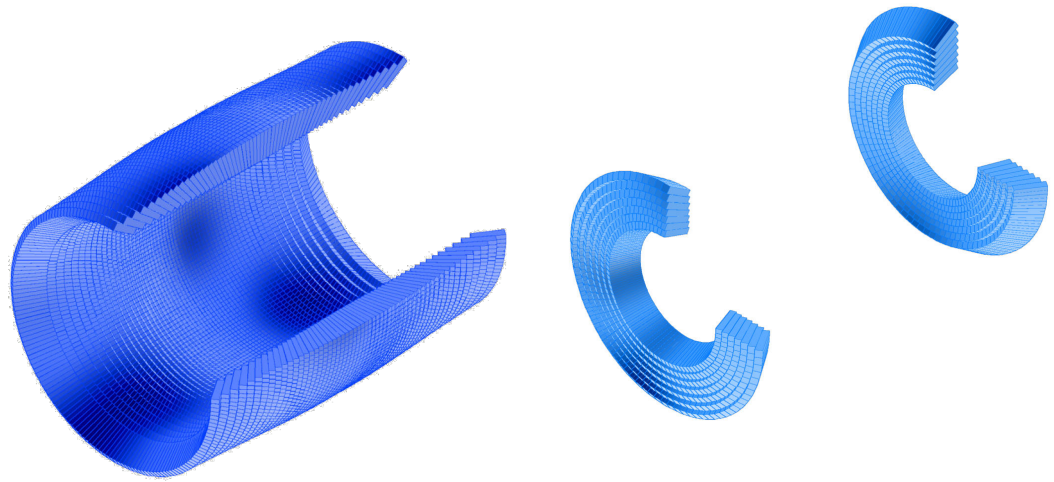




晶体排布

- Barrel includes 4200 pCsI crystals arranged in 35 rings (along Z) of 120 crystals each.
- Endcap is composed of 1256 pCsI crystals.
- ～15 X_0





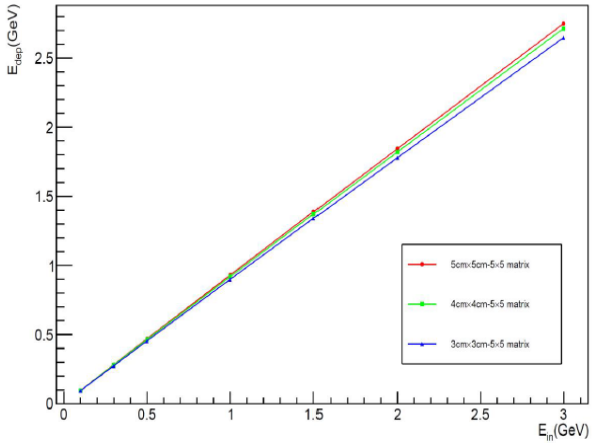
能量分辨研究

1. 本征分辨（只考虑能量沉积）
2. 引入光电子涨落
3. 引入晶体荧光收集非均匀性
4. 引入APD对次级带电粒子的响应
5. …

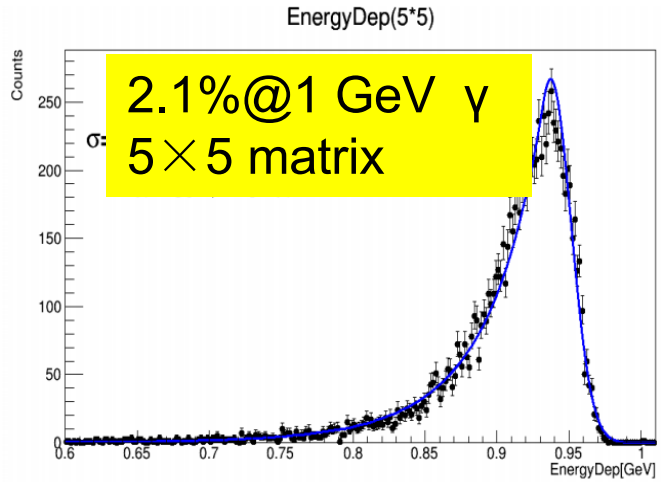
	无包装	有包装	光电子涨落			不均匀性（100 pe/MeV)		
			20	50	100	0%	5%	10%
桶部	0.85%	0.96%	1.58%	1.30%	1.14%	1.07%	1.02%	1.12%
端盖	1.05%	1.25%	1.62%	1.37%	1.22%	1.21%	1.37%	1.48%

1 GeV 光子

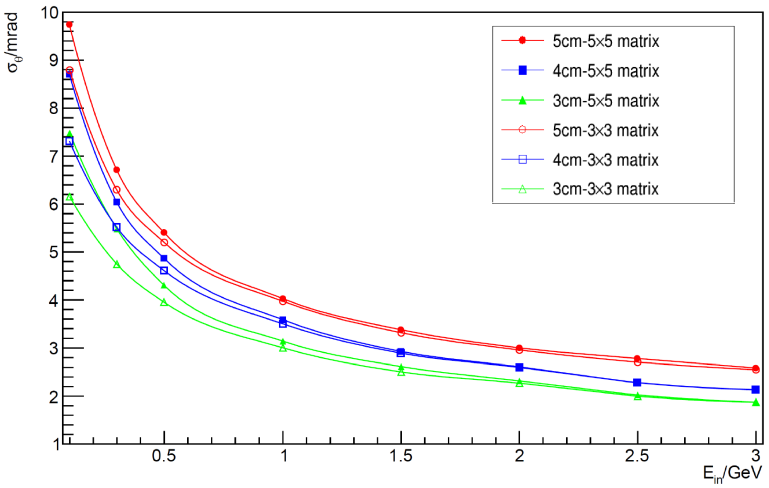
EMC预期性能



能量线性



能量分辨率



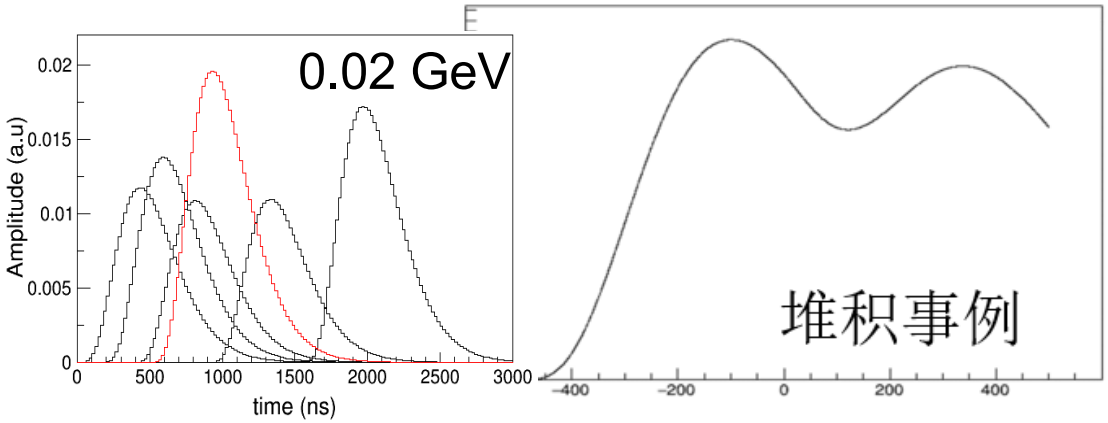
位置分辨率

本底的影响

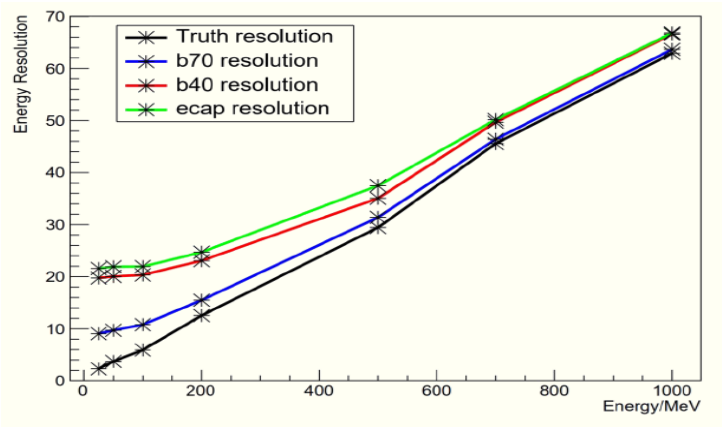
signal

BKG

$$v_0(t) = L^{-1}[V_o(s)] = \frac{Q}{C_f} \cdot \frac{1}{m!}\left(\frac{t}{\tau}\right)^m e^{-t/\tau} \cdot u(t)$$



- 采用本底计数估计作为输入
- 考虑完整电子学响应
- 模拟堆积效应



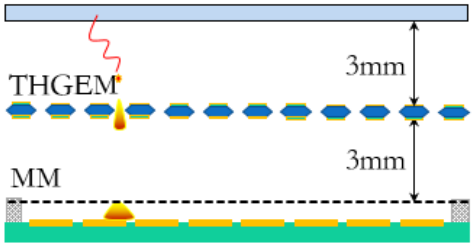
对低能光子能量分辨影响很大，需要进一步研究。

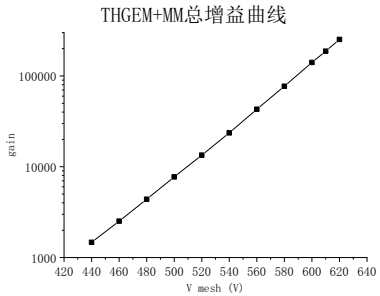
Highlights of PID&ECAL R&D

探测器原理样机束流测试@DESY

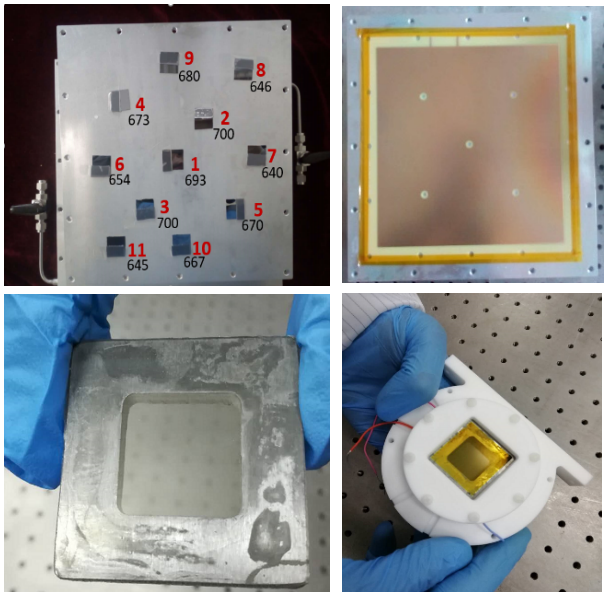
RICH样机研制

- CsI光电阴极
- MPGD光电探测器
  - 基于THGEM+MM基准方案

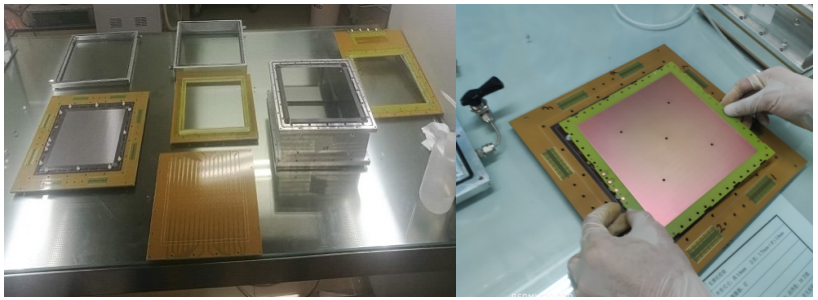




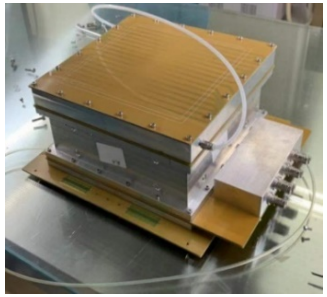
光电探测器性能测试

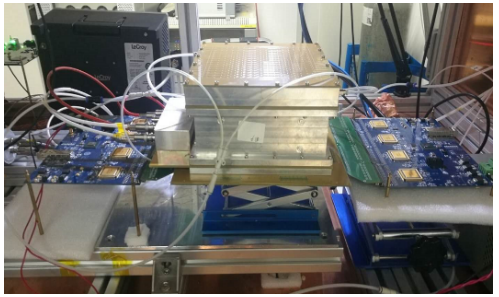


CsI 光电阴极的制备



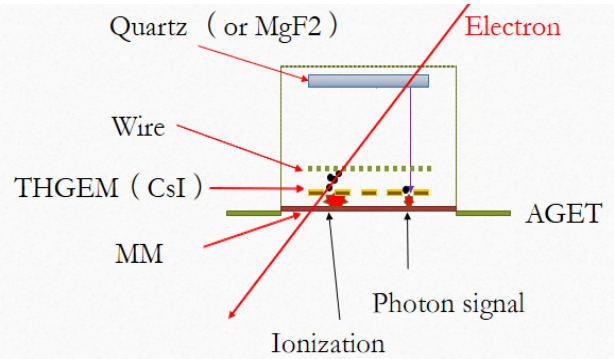
RICH样机组建



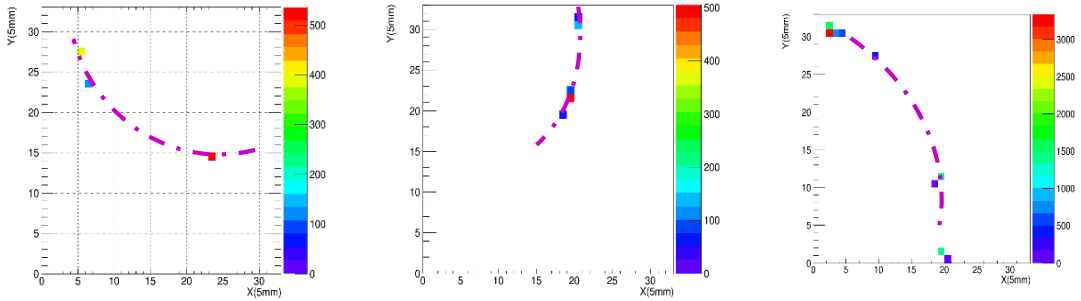


连接电子学读出联调

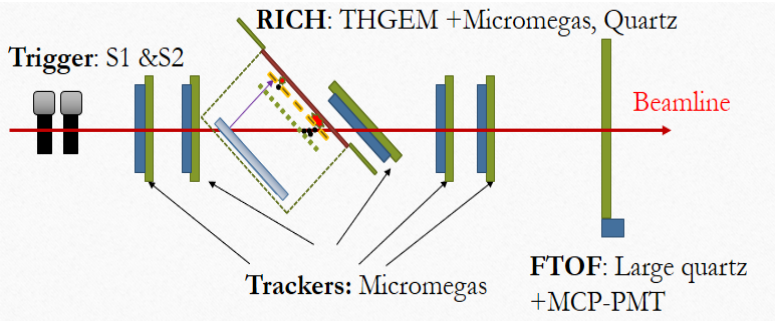
RICH样机宇宙线及束流测试



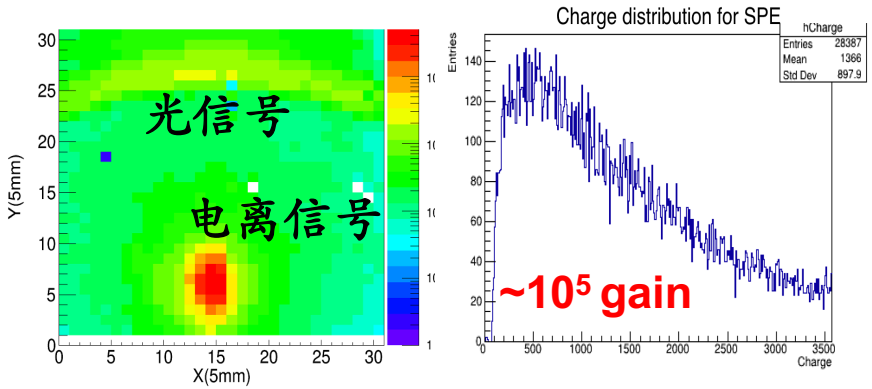
宇宙线μ子及高能电子束流测试示意图



宇宙线μ子产生的切伦科夫光信号候选事例



高能电子束流测试实验设置

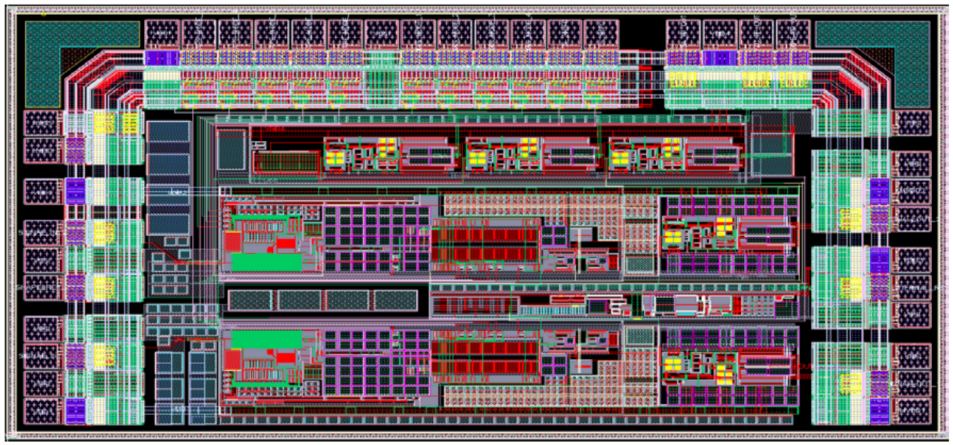


束流测试切伦科夫光信号

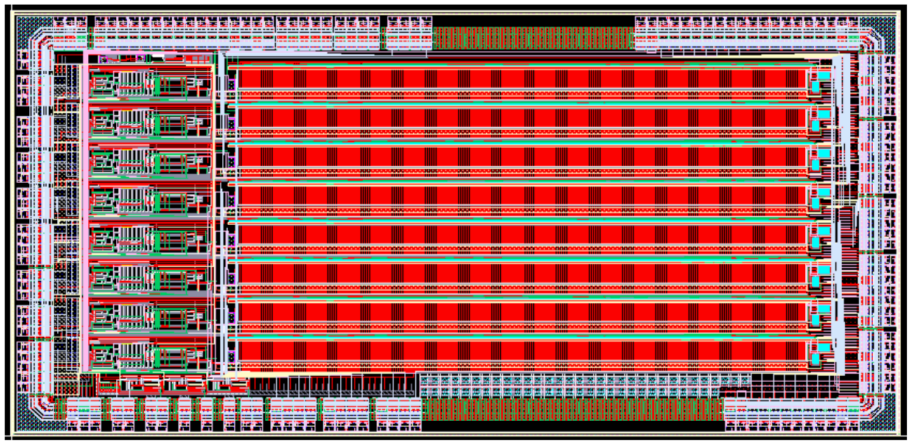
RICH Readout ASIC

STCF RICH 前端读出ASIC设计

- 近期，STCF RICH的ASIC设计完成，并已进行了投片，目前芯片正在制作中。此次投片的原理验证ASIC共包含两种：
  - 纯模拟前端双通道芯片：仅包含电荷灵敏前置放大器、极零相消及成形电路，用于评估模拟部分的电路性能；
  - 模数混合8通道芯片： 包含模拟前端电路、开关电容采样阵列及片内ADC，降低后端电路复杂性。

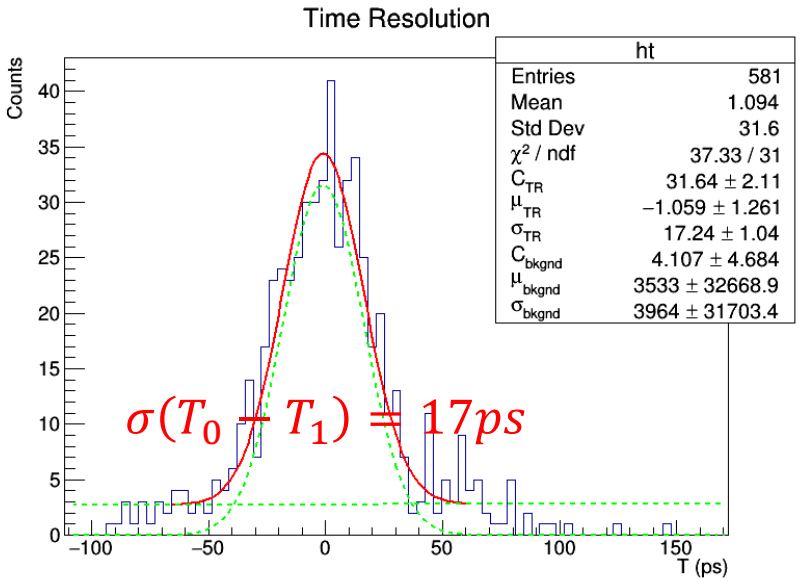


纯模拟前端双通道电路版图



模数混合8通道芯片版图

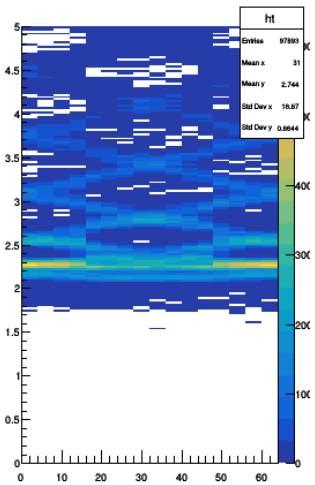
FTOF原型制作和测试

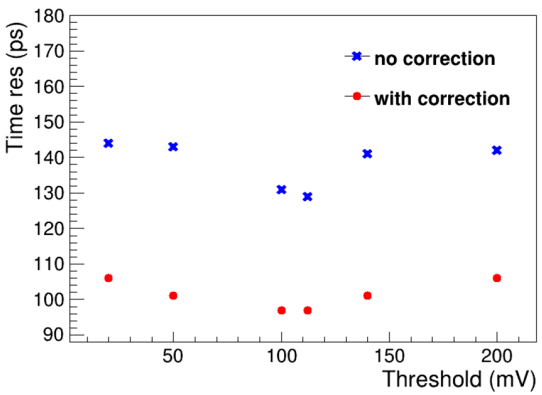


参考时间T_0的时间分辨

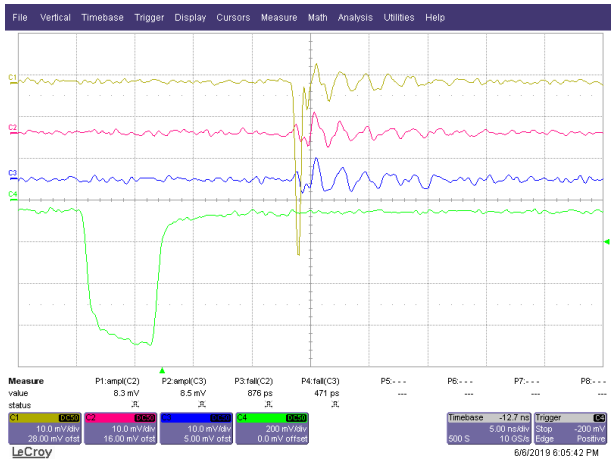
FTOF原理样机及束流测试

50cm x 12cm x 1.5cm 熔融石英晶体（全光谱透过率~ 90%@波长>190nm），表面及侧面抛光质量分别达到100Å RMS。



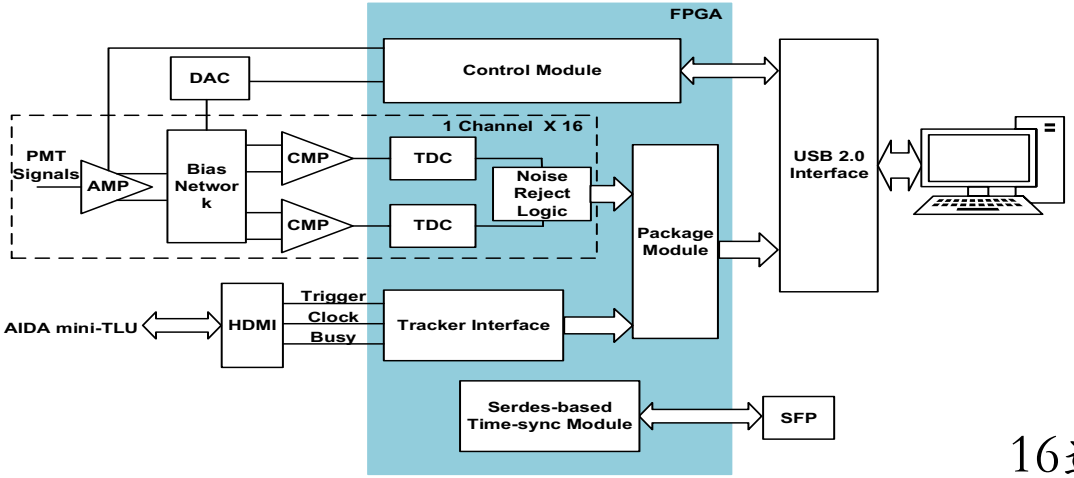


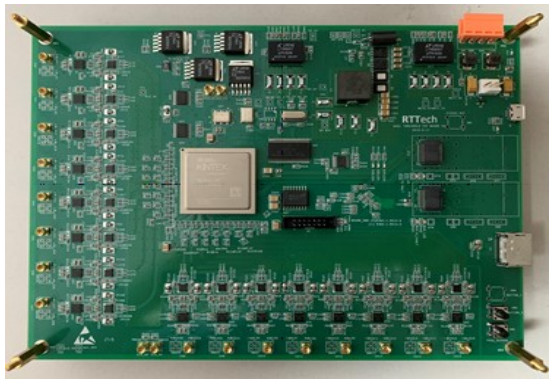
初步分析单光电子时间分辨~**100ps**



FTOF读出电子学研究

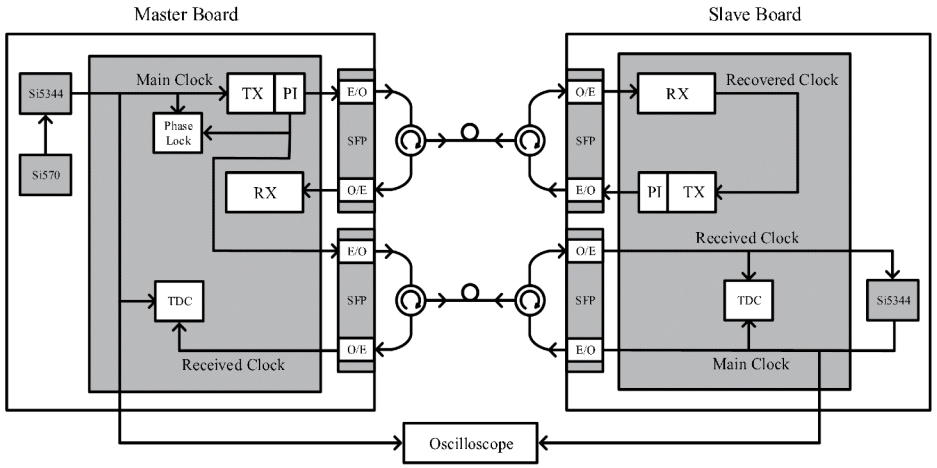
FTOF双阈值定时电路

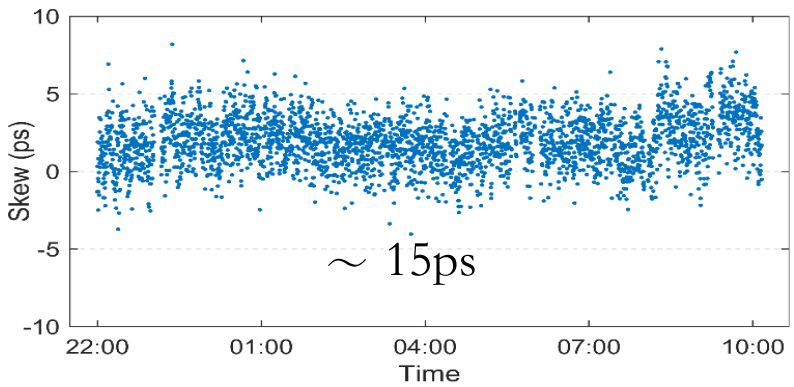




16通道，TOT修正，定时精度~8ps

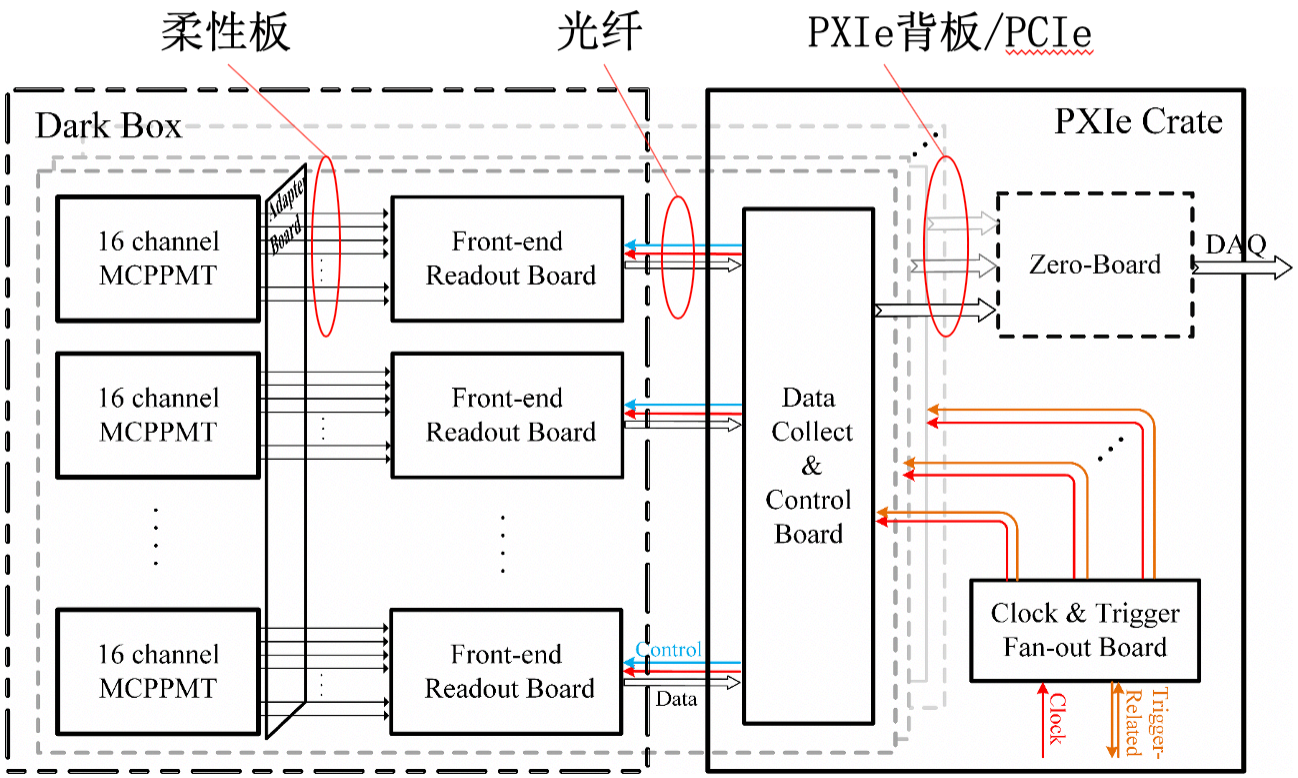
高精度时钟分发电路





FTOF读出电子学设计

FTOF系统整体设计结构

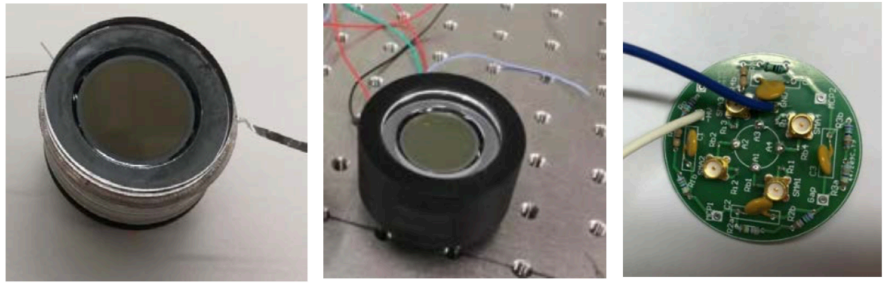


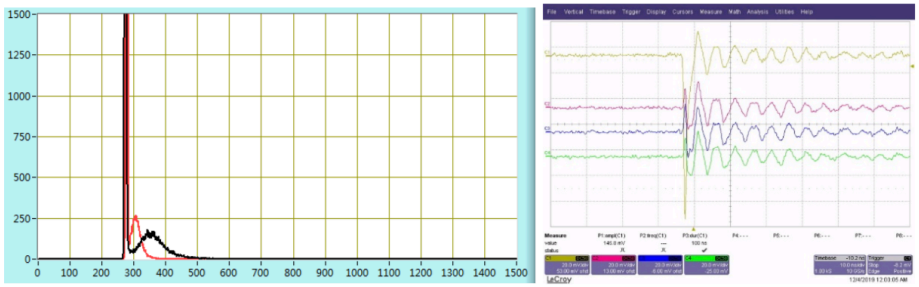
- 640通道/6192通道
- 前端板尽量贴近探测器，两者之间用插座或柔性板连接
- 数据控制板在PXIe机箱
- 数据控制板和前端板之间的数据、时钟、控制信号（含触发）通过光纤(serdes)传输
- 数据控制板的数据通过PXIe机箱的背板传输到机箱的0槽控制板进行汇总。
- 时钟和触发扇出板用来给各个数据控制板做第一级的时钟、触发的分发

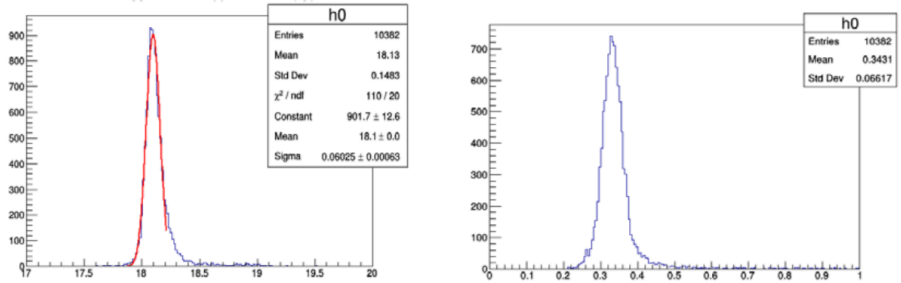
MCP-PMT Development

中科大-西光所MCP-PMT联合研制

- 西光所-中科大研究人员组成了联合研究组，在STCF项目的支持下先后完成了单阳极和多阳极MCP-PMT的研发和测试，主要性能接近或达到国际同型号产品的先进水平。



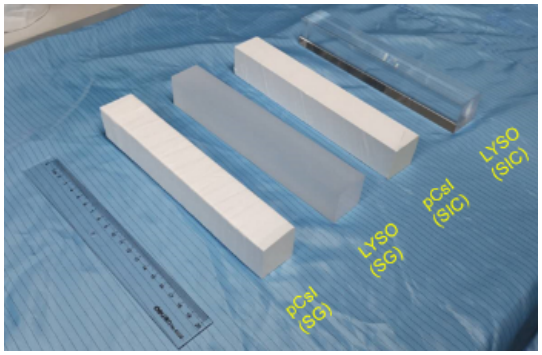


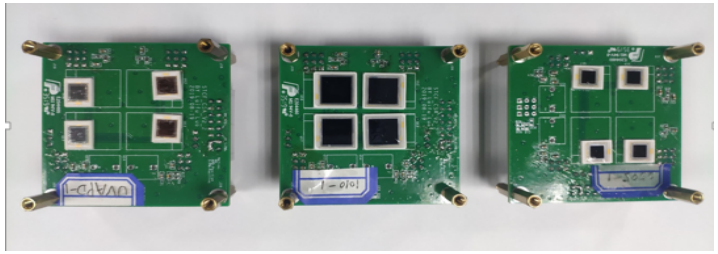


PMT编号	量子效率	增益	峰谷比	时间分辨(ps)	上升时间 (ps)	串扰信号幅度比
1#	22%@400nm	1.5×10^7@2100V	3.4	~70 (σ)	340	~13%
2#	24%@400nm	1.3×10^7@1900V	4.0	~55 (σ)	350	~16%
Photonis M16	22%@~400nm	$>10^6$	>2	35-50 (σ)	500	~10-20%
Hamamatsu M16	24%@~400nm	$>10^6$	>2	70-100 (FWHM)	180	~10-20%

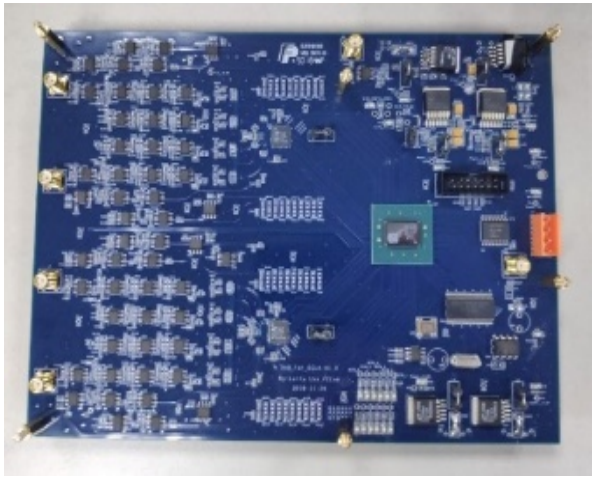
ECAL关键技术研究

ECAL探测单元（晶体+APD）

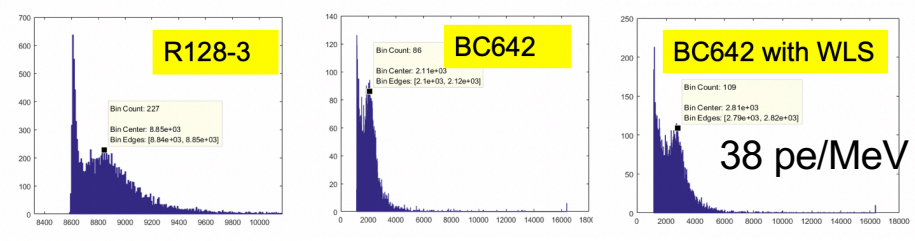




ECAL读出电子学
电荷灵敏前放+成形放大

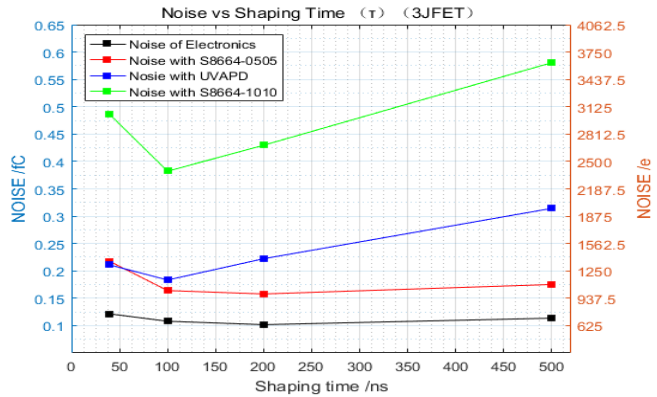


ECAL探测单元光产额



目前研究重点：提高pCsI荧光产额

噪声水平



谬子探测器

- 探测器技术选项：RPC、塑闪+SiPM
- 采用RPC-塑闪混合式设计可以有较好的中性强子识别能力。

采用RPC-塑闪复合探测器设计：

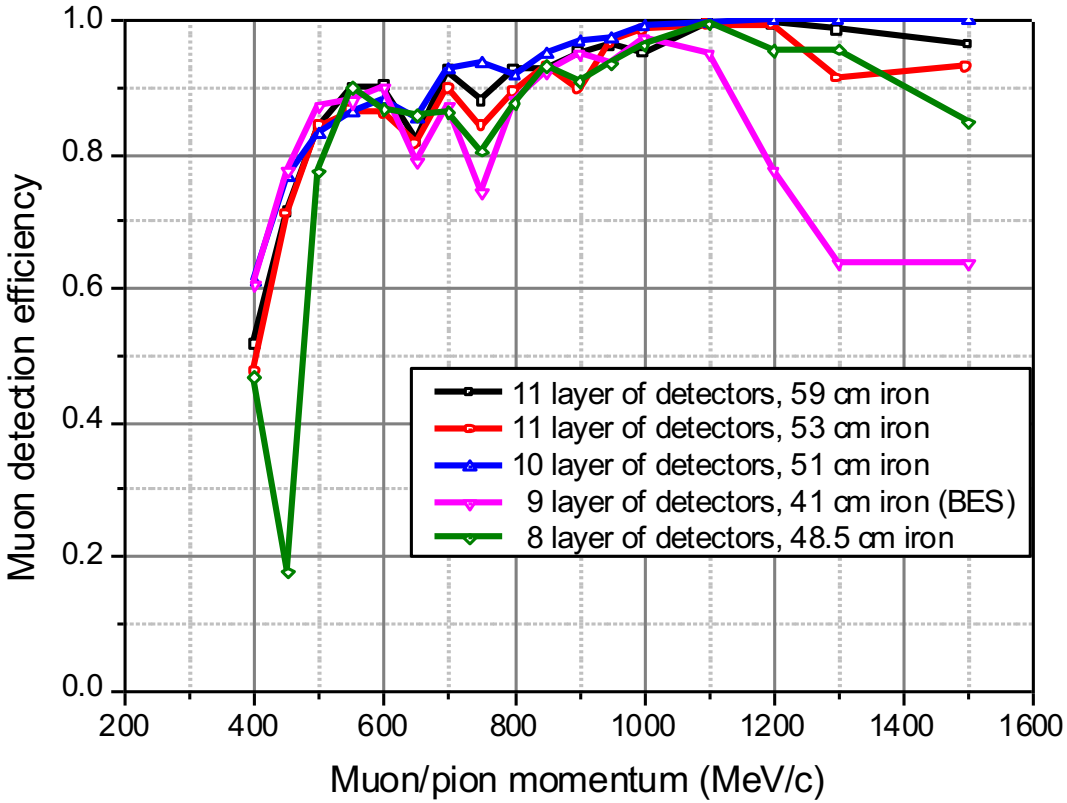
- 内3层为Bakelite-RPC，过滤高本底区域的大部分干扰计数
- 外7层为塑闪，保证信本比的同时提高中性强子探测效率

- 优化轭铁厚度排布，避免muon探测效率曲线出现大的波动
- 桶部单层塑闪，简化读出排布，端盖双层塑闪，利用符合降低本底
- 端盖额外添加本底中子屏蔽层与轭铁组件

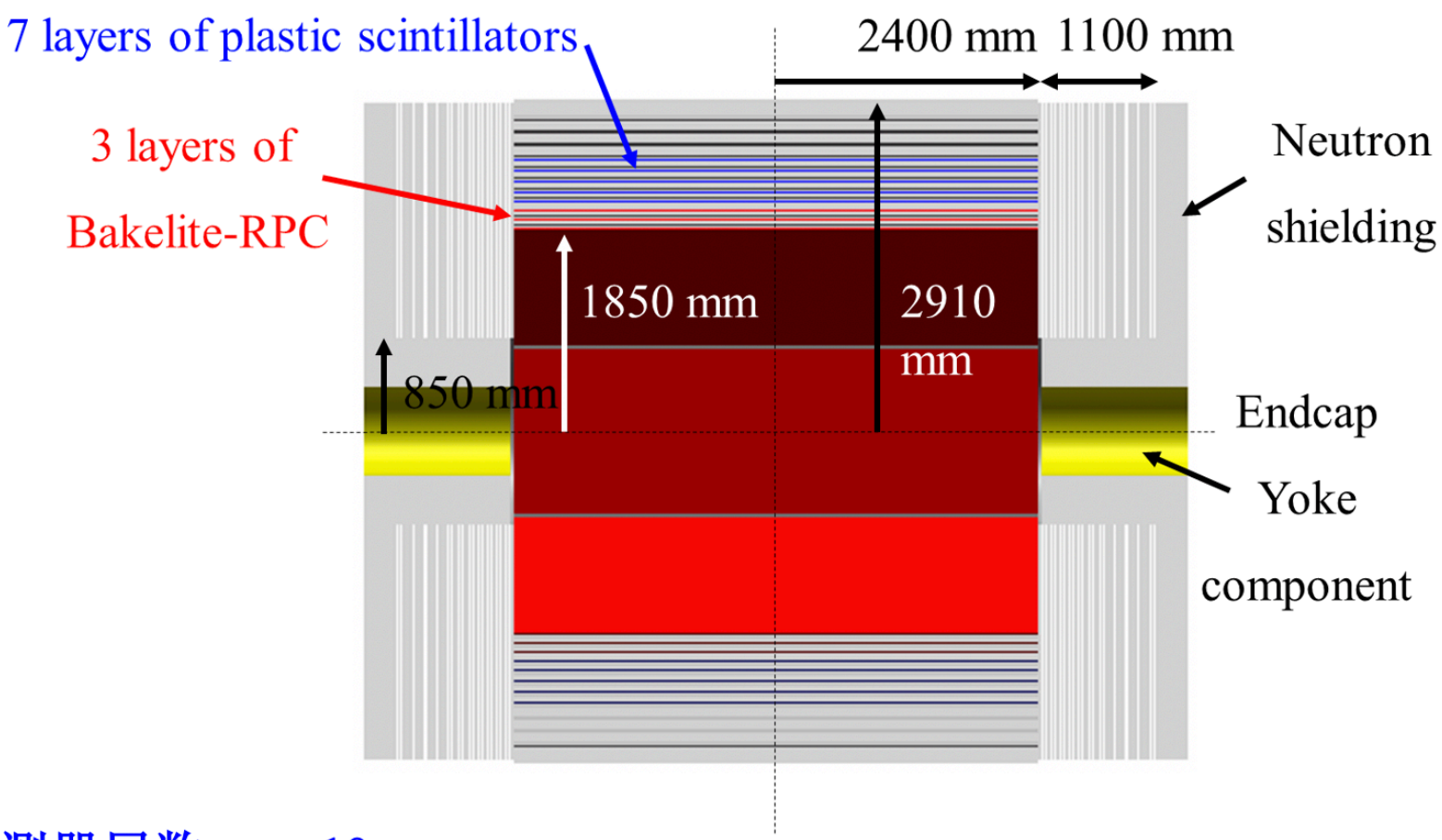
设计优化

天顶角方向Muon探测效率曲线@3% fake rate

- 10层探测器搭配较好的BDT算法，可实现近似11层探测器的探测效率；
- 单层轭铁厚度从4 cm逐渐升到8 cm，同时满足低、高动量muon 径迹测量需求。



缪子探测器概念设计

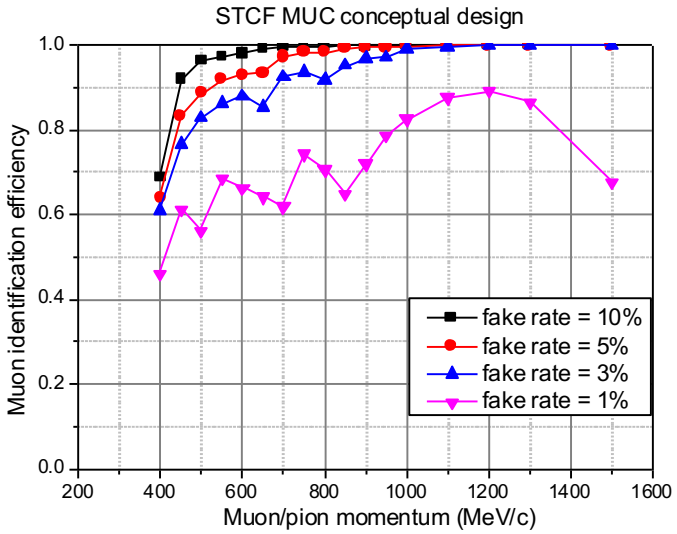


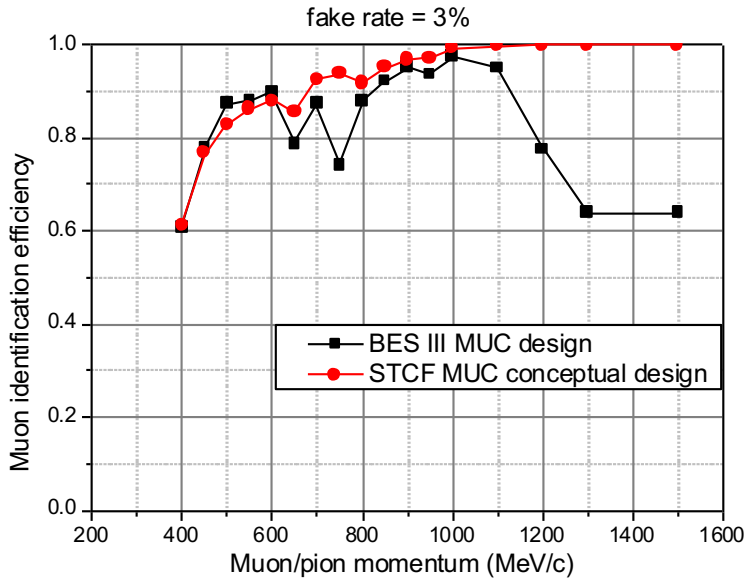
探测器层数	**10**
轭铁厚度 [cm]	**4/4/4.5/4.5/6/6/6/8/8**
(λ=16.77 cm)	Total: 51 cm, 3.04 λ

接受度	94% ×4π in total
总面积 [m^2]	~1237 in total

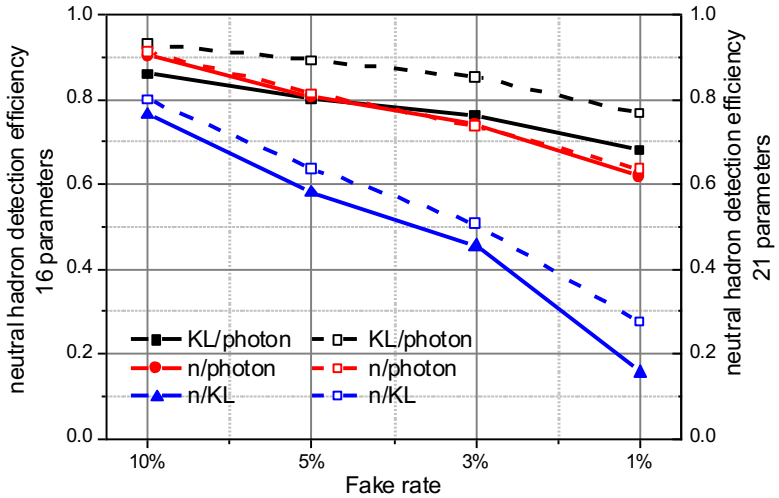
预期性能

Muon/pi分辨





中性强子识别

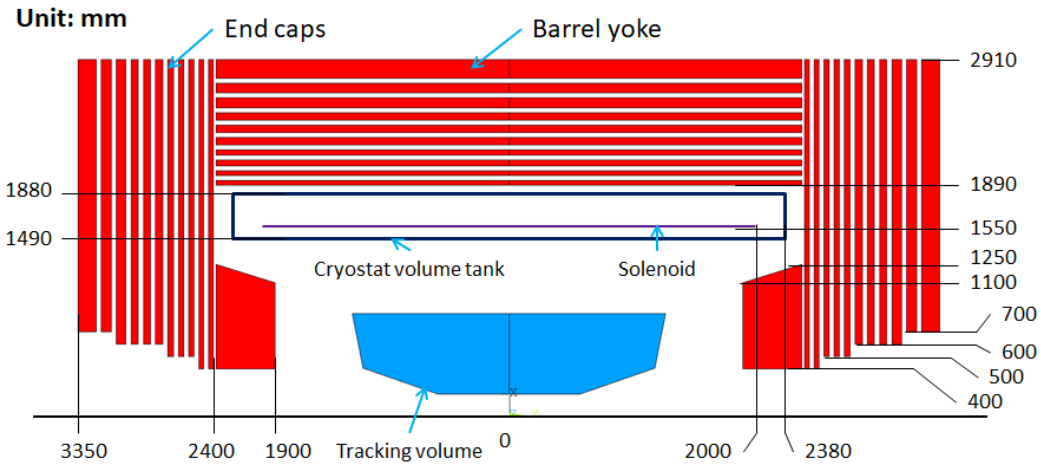


加入ECAL shower形状参数前后的鉴别效果

实线：加入前

虚线：加入后

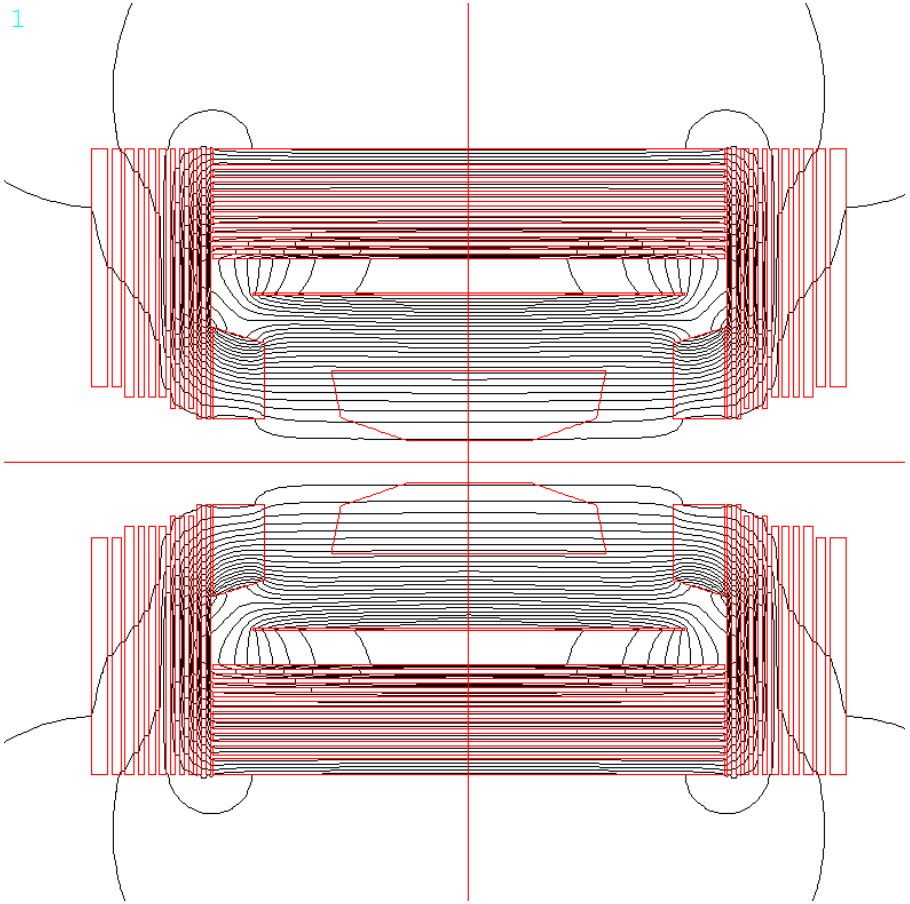
超导磁铁设计

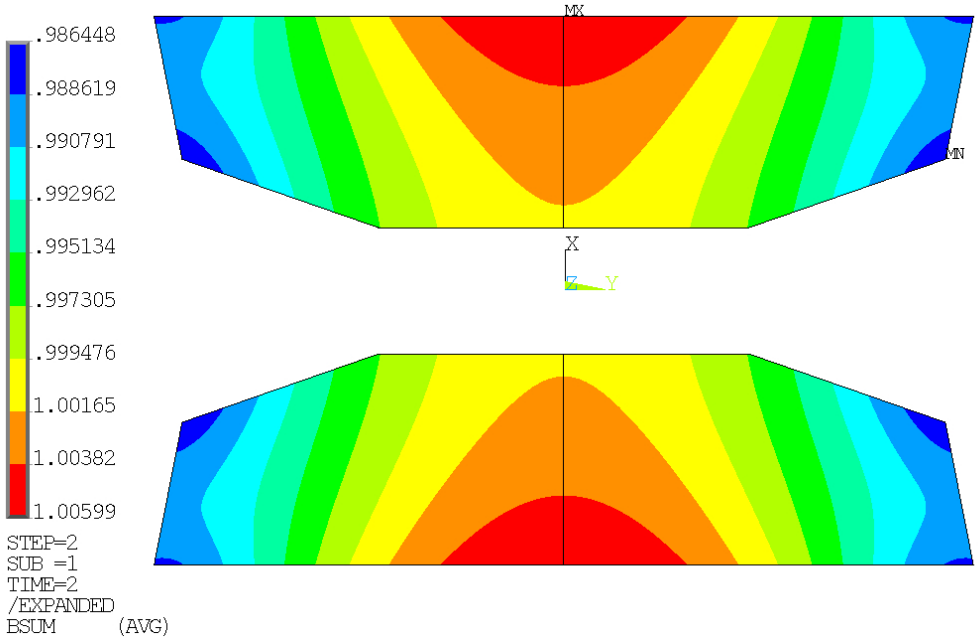


端部轭铁厚度（从内向外）：480、40、40、40、45、45、60、60、60、80、80、150；
筒部轭铁厚度（从内向外）：40、40、45、45、60、60、60、80、80、150；
轭铁之间空气间隙：40mm。

Cryostat	
Inner radius	1.490 m
Outer radius	1.880 m
Length	4.760 m
Coil	
Mean radius	1.565 m
Length	4.000 m
Conductor dimension	4.67*15.0 mm^2
Electrical parameters	
Central field	1.0 T
Nominal current	3820 A
Inductance	1.6854 H
Stored energy	12.3 MJ
Cold mass	3.6 ton
Radiation thickness	1.9 X_0
Cool down time from room temperature	≤7 days
Quench recovery time	≤7 hours

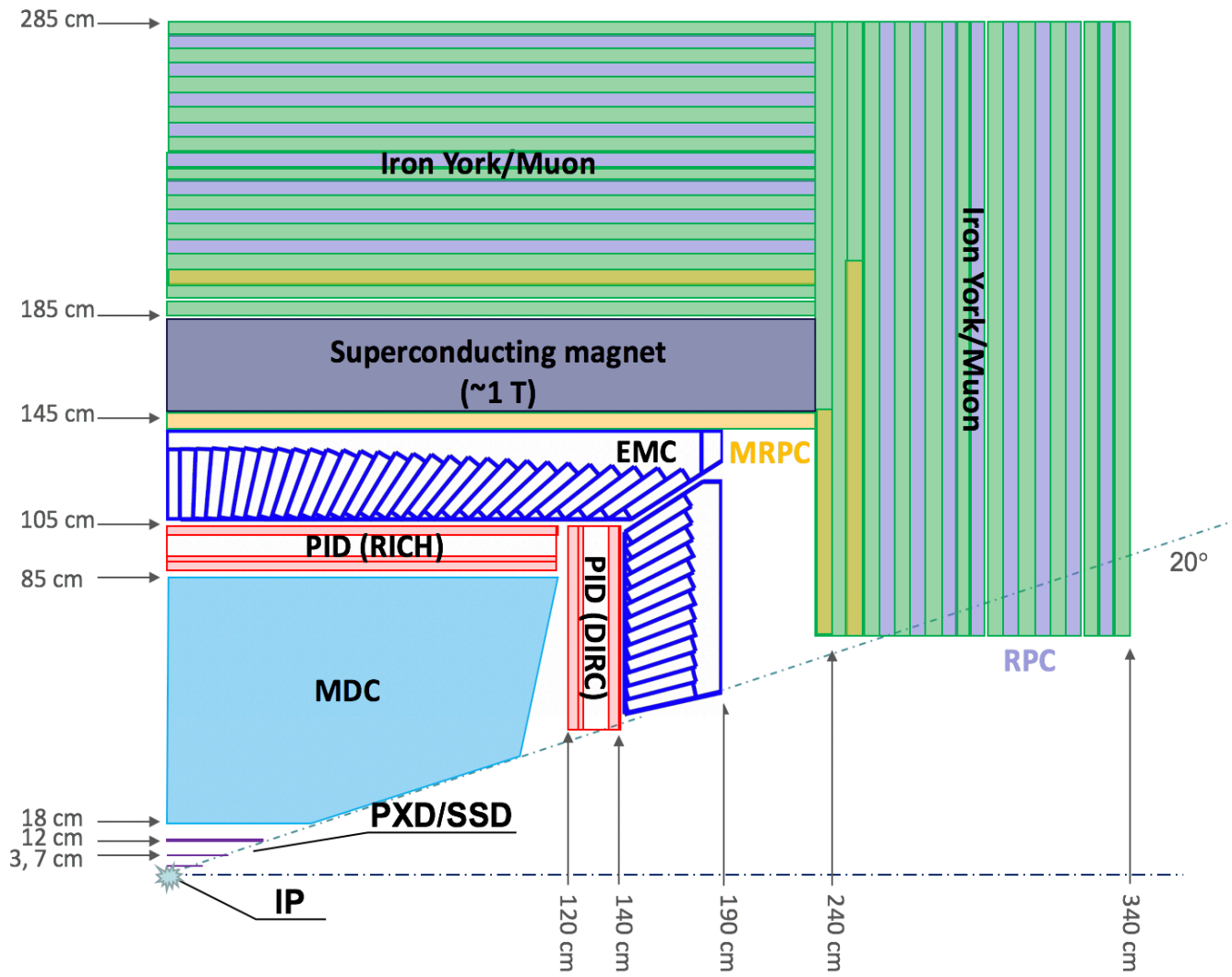
预期磁场均匀性





均匀性好于2%

结束



PXD

- ~<0.25%X_0 / layer
- σ_{xy}< 130 μm

MDC

- σ_{xy}< 130 μm
- σ_p/p ~ 0.5% @ 1 GeV
- dE/dx~6%

PID

- π/K (and K/p) 3-4σ separation up to 2GeV/c

EMC

E range: 0.025-2GeV

σ_E (%) @ 1 GeV

Barrel: 2 .5

Endcap: 4

Pos. Res. : ~ 4 mm

MUD

- 0.4 - 1.8 GeV
- π suppression >30