



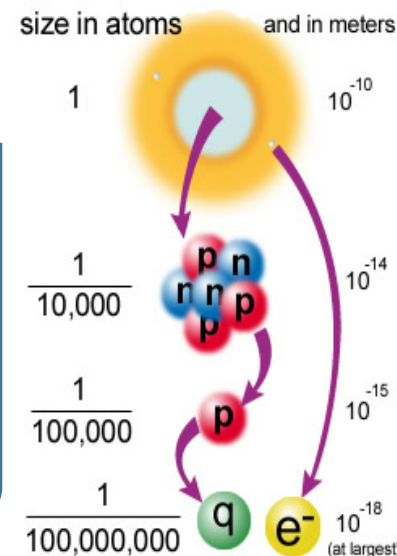
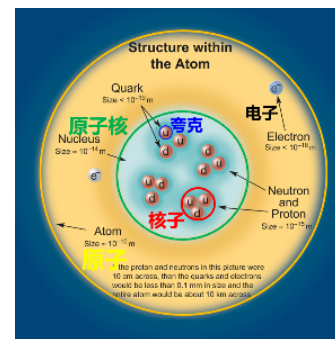
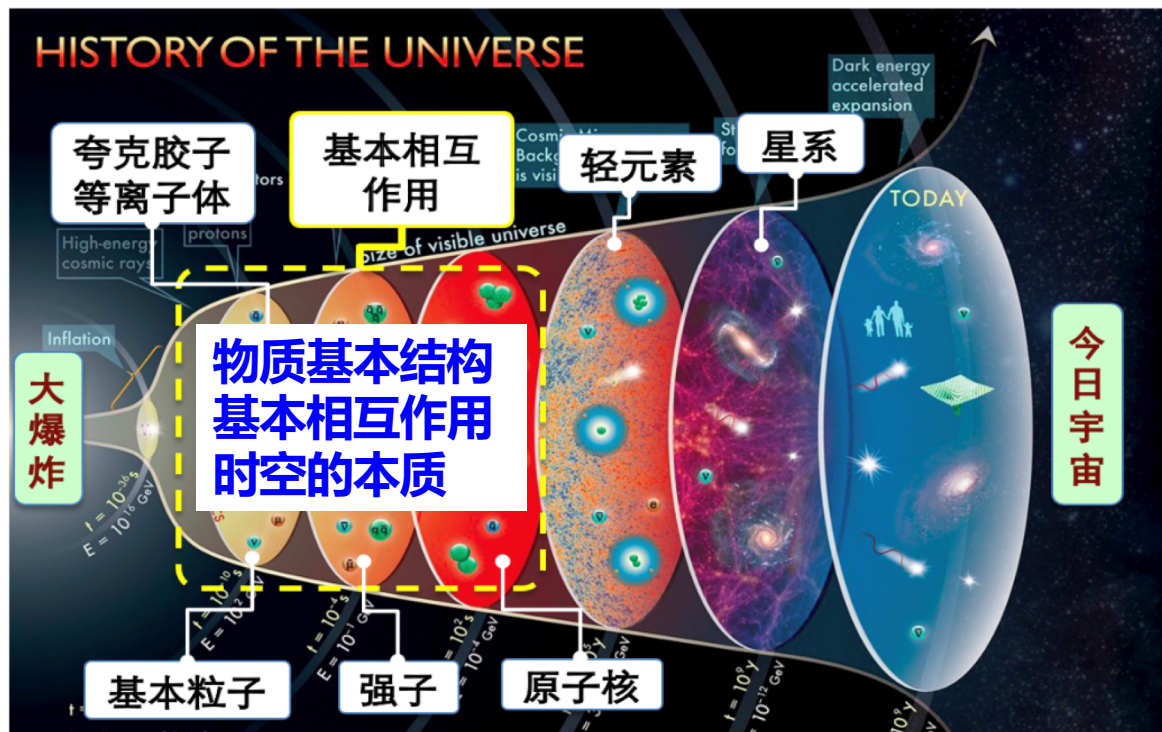
核与粒子物理实验中的粒子探测器

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中国科学技术大学**

全国辐射探测技术与应用研讨会
2022年8月7日

- **核与粒子物理**
- **加速器实验对粒子探测的要求与挑战**
- **粒子探测器技术的发展现状与趋势**
- **总结**



观测物质深层次结构需要**高能量**探针

E

$$\lambda = h/p$$

6 GeV → 12 GeV

Add beamline to new experimental area

Add 5 cryomodules

20 cryomodules

CHL-2

Add arc

Add 5 cryomodules

20 cryomodules

Upgrade magnets and power

Add new experimental area

PHENIX
0-90°
180-270°

STAR
90-180°
270-360°

RHIC

AGS

PS

SPS

LHC

1 MeV QX

100 GeV beam line

Design Parameters:
 Beam Energy = 100 GeV/nucleon
 No. Bunches = 57
 No. Ions/Bunch = 1×10^{11}
 1 turn = 10.9 nanoseconds
 $L_{max} = 1.5 \times 10^{11} \text{ cm}^{-2} \text{ sec}^{-1}$

[illegible]

Collision energy: 90-209 GeV
 Luminosity: $10^{31-32} \text{ cm}^{-2} \text{ s}^{-1}$

LEP
 SPS
 site
 Provison
 FRANCE
 SWITZERLAND

碰撞能量: 14 TeV
亮度: $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ LHC

An aerial photograph of the LHC tunnel, showing the landscape and the circular path of the tunnel. A yellow circle highlights a specific section of the tunnel.

对撞能量: 100 TeV
亮度: $10^{35} \text{ cm}^{-2} \text{ s}^{-1}$

FCC



CEPC/SPPC

Diagram illustrating the CEPC/SPPC circular collider system. The system consists of two concentric rings: the outer **CEPC Collider Ring** (green) and the inner **SPPC Collider Ring** (blue). The CEPC ring includes a **Booster** section and two interaction points, **IP1** and **IP2**. The SPPC ring includes a **Superfocusing Section (SS)** and a **Superfocusing Section (SSS)**. A central region contains a **Superfocusing Section (SS)** and a **Superfocusing Section (SSS)**. A central region contains a **Superfocusing Section (SS)** and a **Superfocusing Section (SSS)**. A central region contains a **Superfocusing Section (SS)** and a **Superfocusing Section (SSS)**.

加速器的能量和亮度不断提高

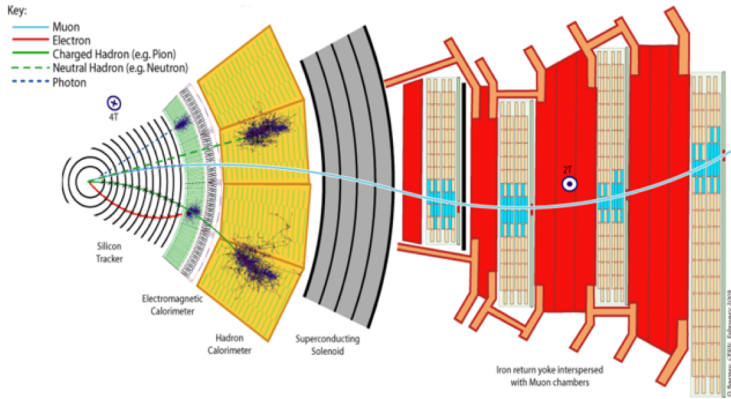
1. 3D-Modell des Roboters
2. 3D-Modell der Kamera
3. 3D-Modell des Roboterarms
4. 3D-Modell des Roboters
5. 3D-Modell der Kamera
6. 3D-Modell des Roboterarms

Diagram illustrating the SuperKEKB Main Ring structure. The ring is circular with a circumference of 3016 m. The HER (High Energy Ring) operates at 7 GeV, and the LER (Low Energy Ring) operates at 4 GeV. The diagram shows the locations of the Belle-II Detector, the SuperKEKB Main Ring, and various components including the RF Wiggler, Wiggler, Arc section, and Injection points. The diagram also shows the locations of the Belle-II Detector and the SuperKEKB Main Ring.

探测器 — 核与粒子物理实验中的眼睛

❖ 探测器用来探测粒子反应的末态产物，是进行核与粒子物理实验的核心工具。

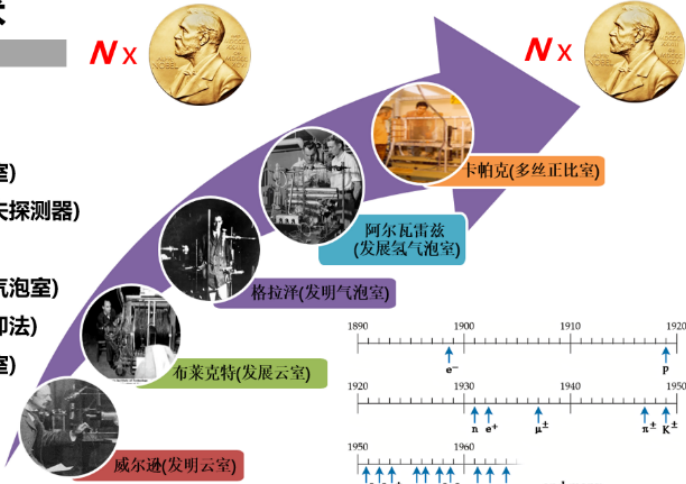
- ▶ 粒子测量：位置、时间、能量
- ▶ 粒子鉴别：分辨粒子种类



❖ 核与粒子物理的需求引导和驱动着探测技术的发展，而探测技术的进步又极大促进了核与粒子物理的发展。

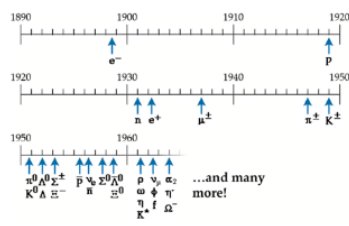
粒子探测技术

- 威尔逊(云室)
- 劳伦斯(加速器)
- 布莱克特(改进云室)
- 切伦科夫(切伦科夫探测器)
- 格拉泽(气泡室)
- 阿尔瓦雷兹(改进气泡室)
- 范德梅尔(随机冷却法)
- 卡帕克(多丝正比室)



重大物理发现

- 伦琴(X射线)
- 贝克勒尔+居里夫妇(放射性)
- 查德威克(中子)
- 赫斯(宇宙线)
- 安德森(正电子)
- 鲍威尔(π 介子+核乳胶照相法)
- 塞格雷+张伯伦(反质子)
- 里克特+丁肇中(重夸克)
- 鲁比亚(中间玻色子)
- 佩尔(τ 轻子)
- 莱因斯/莱德曼/施瓦茨 等(中微子)
- 恩格勒/希格斯(希格斯粒子)



加速器实验对粒子探测的要求和挑战



❖ 加速器的能量和亮度不断提高，对粒子探测性能提出了苛刻要求，对粒子探测技术提出了严峻挑战。

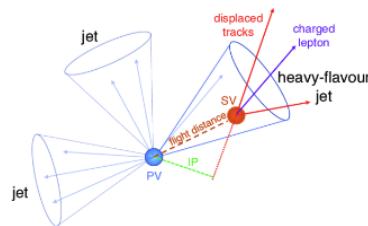


- **高亮度**：抗辐照，高计数，抗堆积
- **高能量**：高能动量测量，大动态范围
- **高精度**：高分辨，全覆盖，精密校准
- **大规模**：大面积，多通道，高性价比

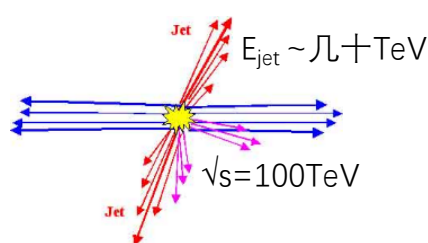
高亮度LHC上的堆积效应



顶点位置测量~几μm



高能双喷注事例



量能器通道~10⁸



粒子探测技术发展现状和趋势



- 高能量前沿

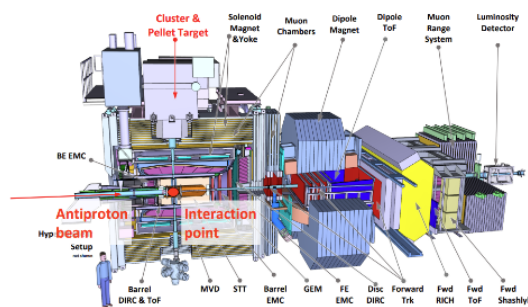
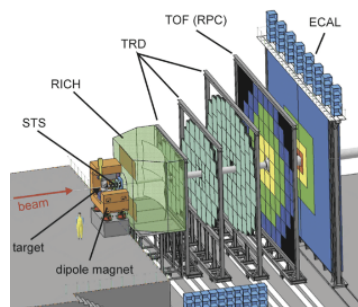
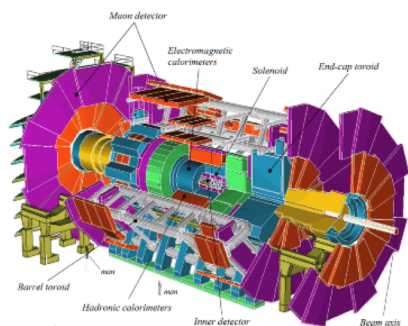
ATLAS, CMS, ILC-ILD/SiD, CLIC, FCC, CEPC ...

- 高精度前沿

BESIII, BELLE2, LHCb, Panda, SCTF, STCF ...

- 高能核物理前沿

STAR, ALICE, CBM, SPD, MPD, EIC-ECCE, EicC ...



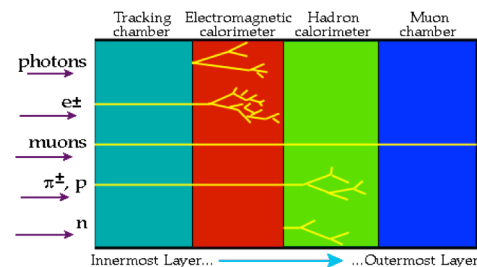
- ❖ 粒子测量

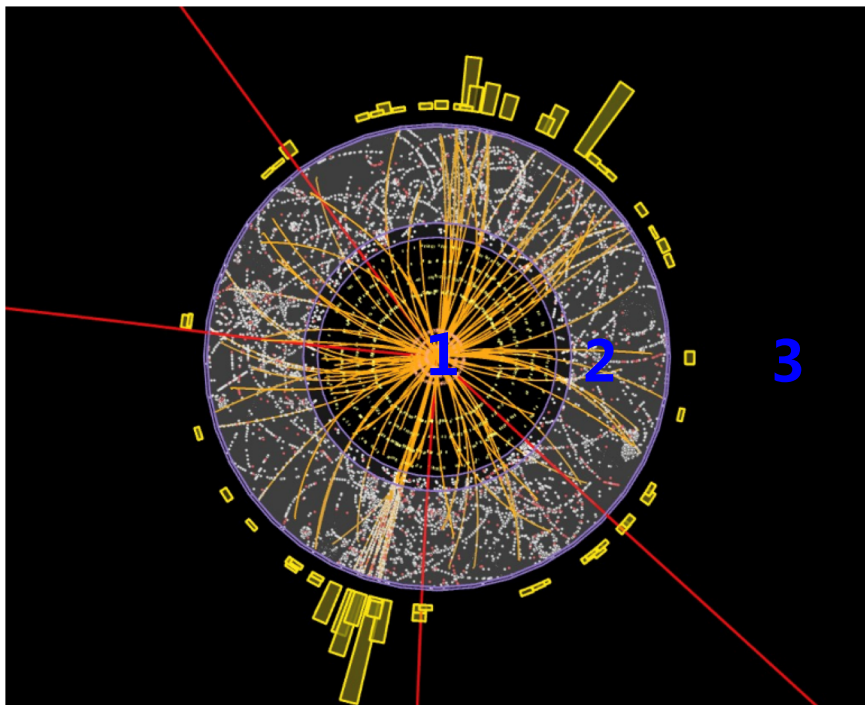
- ▶ 位置测量

- ▶ 时间测量

- ▶ 能量测量

- ❖ 粒子鉴别





1. 内部区域

高计数率，较小面积，顶点测量

2. 中心区域

中等计数率，大体积，动量测量

3. 外部区域

低计数率，极大面积，计数/径迹测量

径迹探测 — 内部区域

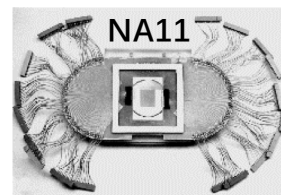
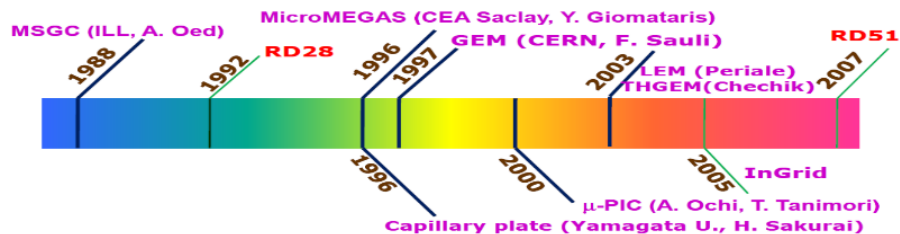


❖ 前沿：硅径迹探测器

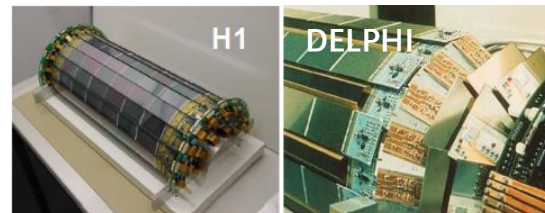
- ▶ 类型：硅像素、硅微条
- ▶ 特点：高位置分辨、高计数率能力、高造价

❖ 新颖：圆柱形微结构气体探测器

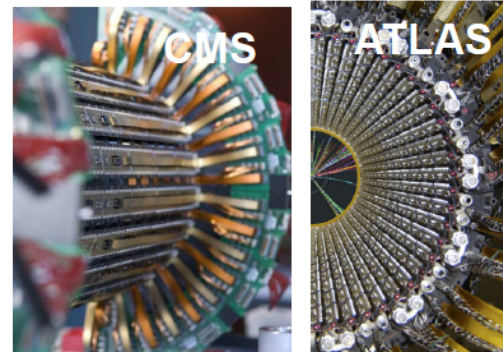
- ▶ 类型：GEM、Micromegas、uRWELL
- ▶ 特点：较好的位置分辨、高计数率能力、大面积、廉价



80年代
~0.002 m²



90年代
~2 m²



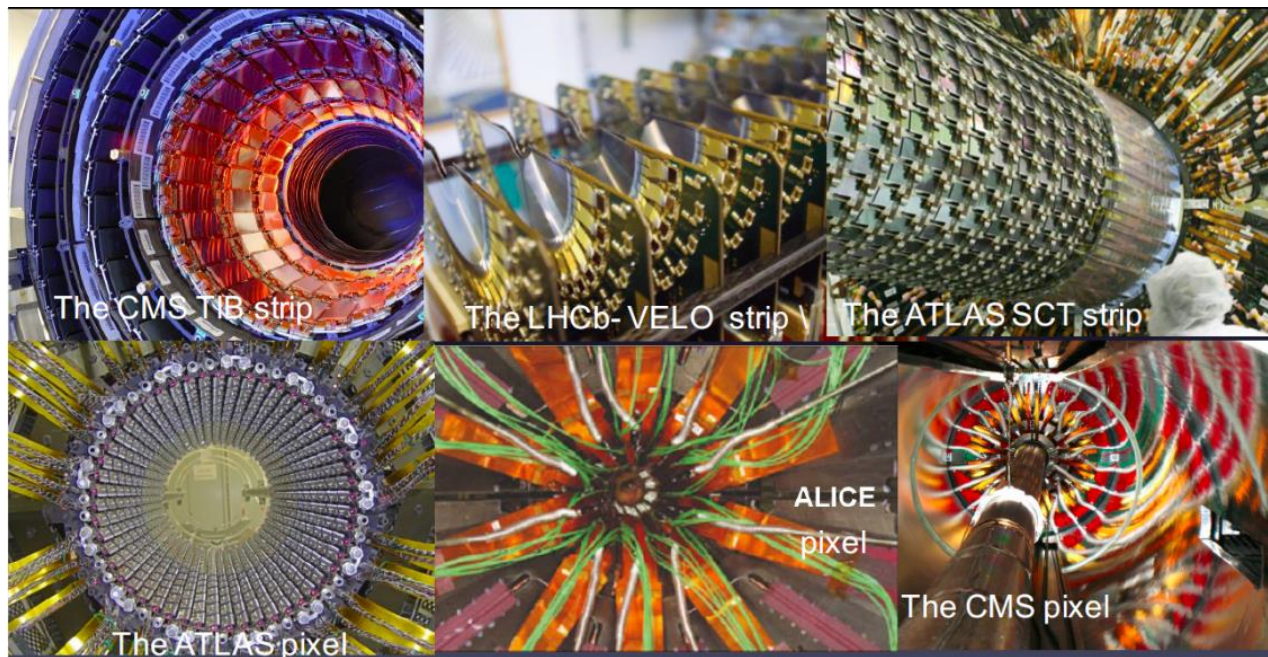
10年代
~200 m²

LHC实验上的硅径迹探测器



❖ LHC实验上有当前世界上最大规模的硅径迹探测器

- ▶ ATLAS：像素(8千万通道)+微条(0.6千万通道)， 62m^2
- ▶ CMS：像素(6.6千万通道)+微条(1.1千万通道)， 201m^2



硅微条探测器已经突破内部区域，扩展到了中心区域！

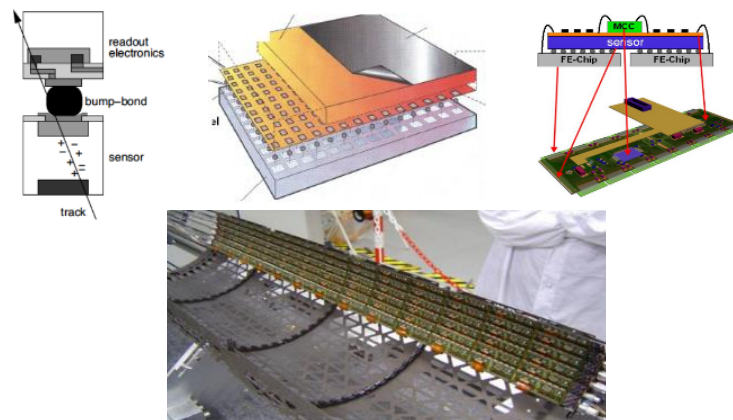
硅像素探测器紧靠反应点，承受着最高的辐照本底和计数率水平，是硅径迹探测器研发的重点和前沿。

混合型 (Hybrid) 硅像素探测器



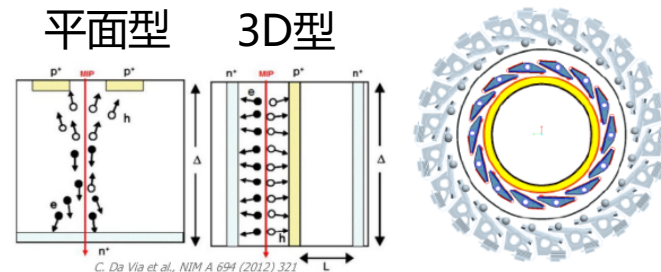
- ❖ 混合型硅像素探测器：传感器与信号处理分离，二者通过倒装焊技术连接。
- ❖ LHC上的硅像素探测器几乎都为平面混合型，代表了当前最成熟和先进的硅像素技术。

- ▶ ATLAS : $50\mu\text{m} \times 400\mu\text{m}$, $\sigma_{sp} \sim 10\text{-}20\mu\text{m}$
- ▶ CMS : $100\mu\text{m} \times 150\mu\text{m}$, $\sigma_{sp} \sim 10\text{-}20\mu\text{m}$
- ▶ n-in-n , $1 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$, 50MRad , $\sim 3\% \times X_0$
- ▶ 高效稳定运行 : 98%-99%



❖ 研发和小规模使用了3D混合型硅像素技术

- ▶ 更短的漂移距离，更小的俘获效应，较低的偏置电压和功耗
- ▶ 生产过程复杂，良品率低，成本高，电容较大，噪声较高
- ▶ 3D型是目前最抗辐照的硅像素技术
- ▶ ATLAS-IBL (2014年安装) 1/4采用了3D技术



HL-LHC硅径迹探测器升级



❖ ATLAS和CMS正在建造**全新和全硅**的径迹探测器

❖ 最大的挑战在内部区域 — **像素**

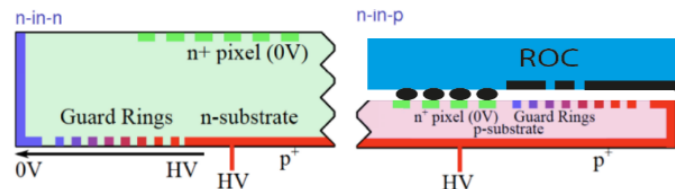
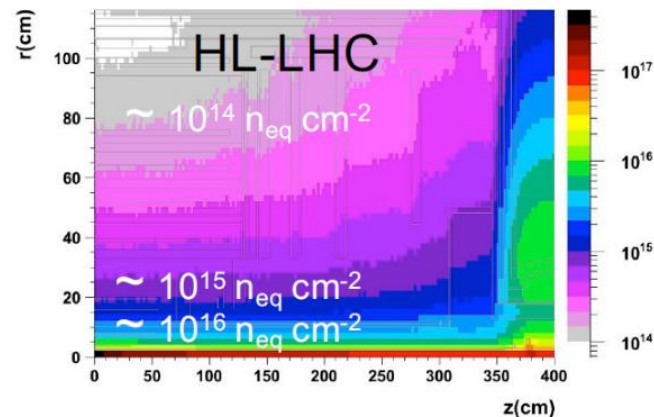
▶ $1\text{GHz}/\text{cm}^2, 10^{16}n_{\text{eq}}/\text{cm}^2$, $\text{TID} > 1\text{Grad}$

❖ **像素升级**

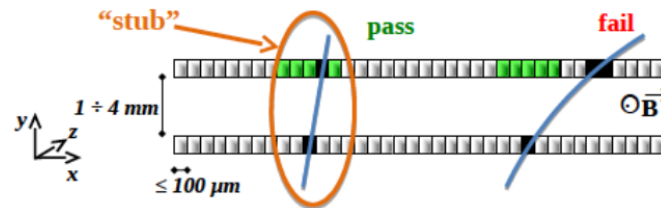
- ▶ 最内层：3D型， $50\mu\text{m} \times 50\mu\text{m}$
- ▶ 其他层：薄n-in-p平面型， $50\mu\text{m} \times 50\mu\text{m}$
- ▶ 65nm工艺读出芯片

❖ **微条升级**

- ▶ n-in-p平面型传感器
- ▶ Pt模块(CMS)：实现L1触发



FE-65
hit rate 2-3 GHz/cm ²
< 1 MHz trigger @ 12μs
3.5 mW/mm ²
rad hard: 2x10 ¹⁶ /cm ²
1 Grad
65 nm technology
pixel size 50 × 50 μm ²
~ 1000 M transistors



单片有源硅像素 (MAPS) 探测器



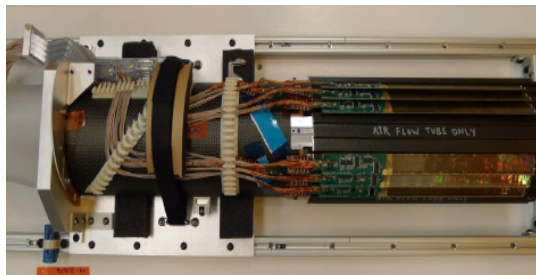
❖ 单片有源：把传感器与读出芯片合二为一

- ▶ 无需凸点焊接，高性价比
低质量，小像素，低功耗
- ▶ 读出速度和抗辐照性能有待提高

❖ 多种单片有源硅像素技术

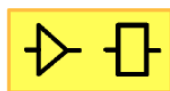
- ▶ CMOS-MAPS: STAR, ALICE
- ▶ DEPFET: BELLE2
- ▶ DMAPS (HR/HV-CMOS), SOI

HFT@STAR

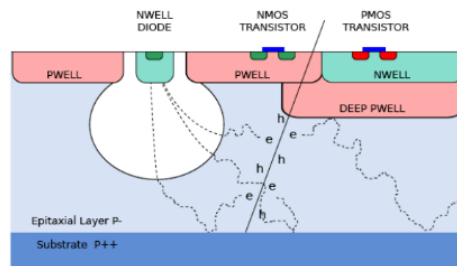


- 350 nm CMOS
- $< 30 \mu\text{m}$ pixels
- $0.37\% X_0$
- $50 \mu\text{m}$ thick
- frame time $< 200 \mu\text{s}$

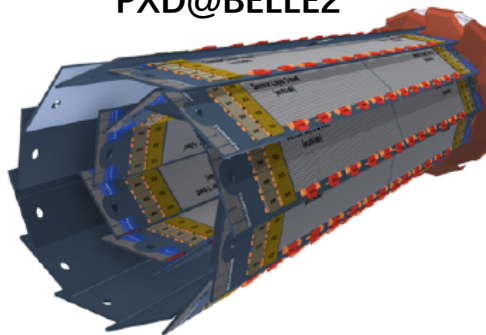
混合型



单一型



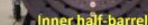
PXD@BELLE2



Number of pixels per module	250 x 1536
Pixel size (r-phi, z)	50 μm x (60-75) μm
Frame time	20 μs
Material budget per layer	0.15% X_0
Resolution (r-phi, z)	$< 10 \mu\text{m}$, $< 20 \mu\text{m}$
Occupancy at 1.8 cm radius	0.2 hits $\mu\text{m}^{-2}\text{s}^{-1}$
Radiation environment	$\sim 1 \text{ Mrad/year}$

- ▶ **10m², 1.25*10¹⁰通道**
- ▶ **顶点和径迹重建性能大幅提升**

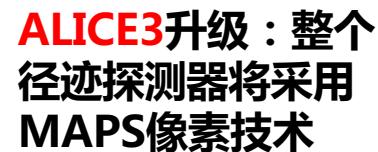
Inner Barrel assembly



On-surface commissioning lab

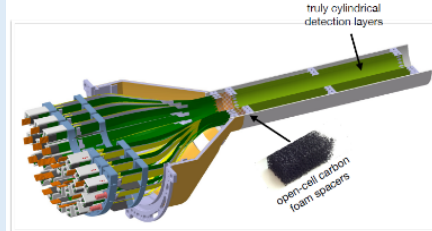


Detector fully assembled in Dec. 2019

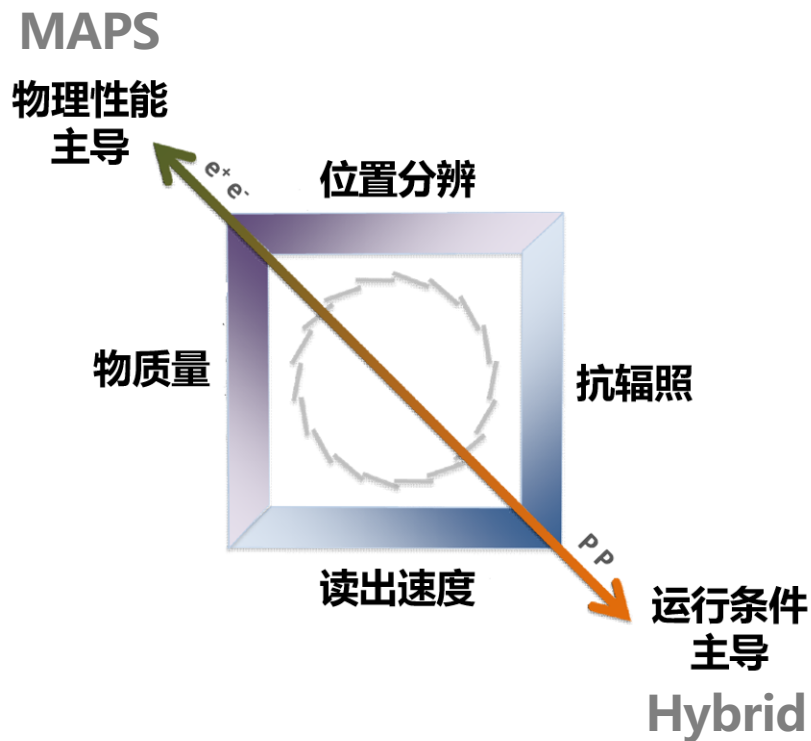


硅像素探测器也将突破内部区域，进入中心区域！

ITS3 (超低质量)



硅像素探测器的发展



	束团间隔	计数率	辐照强度	总电离剂量
	ns	kHz/mm ²	N _{eq} /cm ²	Mrad
LHC	25	1000	2*10 ¹⁵	80
HL-LHC	25	10000	2*10 ¹⁶	>1000
LHC-HI (ALICE)	20	10	>10 ¹³	0.7
RHIC	110	4	~10 ¹²	0.2
SKEKB	2	400	3*10 ¹²	10
ILC	350	250	10 ¹²	0.4

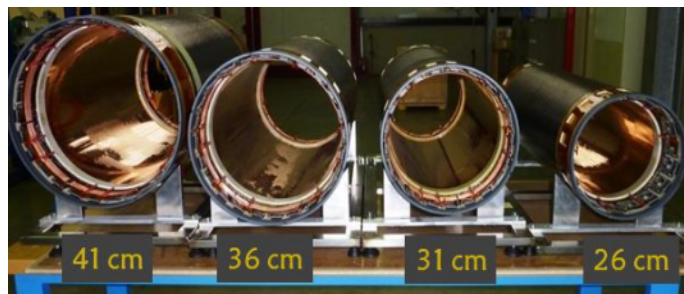
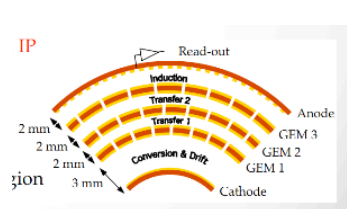
- LHC : 抗辐照、快读出 → 平面混合型
- HL-LHC : 更强的抗辐照和更快的读出 → 薄n-in-p平面混合型, 更小的像素, 更多的本地缓存, 新型传感器 (3D ...)
- 其他实验 : 低物质质量、更高分辨 → MAPS

- 混合型 : 探索新型的集成技术 → 更小的像素尺寸
- 单片型 : 很大的提升空间 → 超大芯片、自支撑 (拼接) , 提高速度和抗辐照性能 (耗尽型)

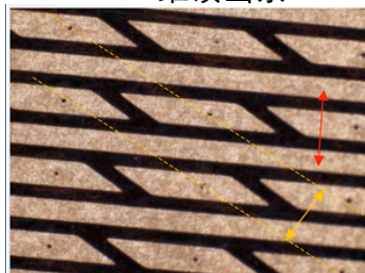
圆柱形微结构气体探测器



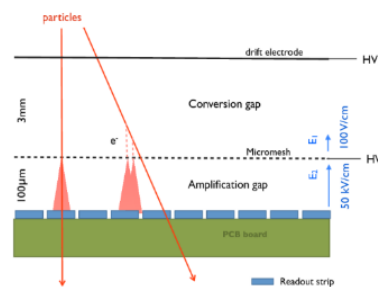
KLOE2 内部径迹探测器：圆柱形GEM径迹室



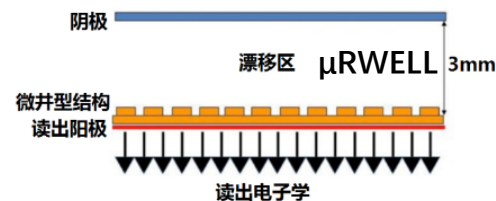
UV二维读出条



CLAS12 内部径迹探测器：圆柱形Micromegas径迹室

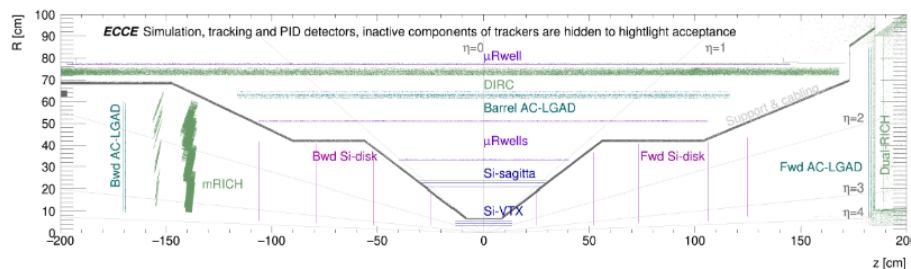


$$\sigma_x < \sim 100 \mu\text{m}$$

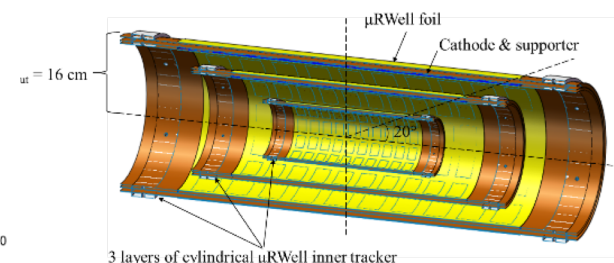


圆柱形μRWELL径迹室

EIC-ECCE



STCF



❖ 气体径迹室是中心区域径迹探测的传统技术选项：漂移室、时间投影室

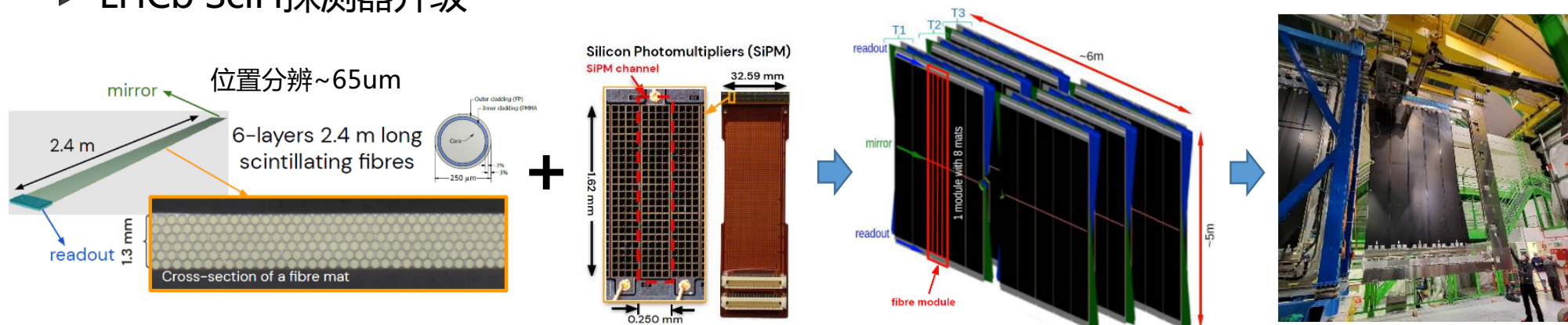
- ▶ 特点：低质量、大体积、廉价
- ▶ 应用：低能区（例如 BES、BELLE），不太高的计数率环境（例如 ILD、IDEA、CEPC）

❖ 随着硅径迹探测器技术的迅速发展，硅微条已进入中心区域，硅像素也将进入。

- ▶ ATLAS、CMS、ALICE

❖ 闪烁光纤径迹探测器也已发展起来，并开始大规模应用

- ▶ LHCb SciFi探测器升级



❖ 漂移室、时间投影室等气体径迹室在计数率较低の場合仍能发挥重要作用

- ▶ 低质量($<1\%X_0$)、大体积(几~几十 m^3)、较好的位置分辨($\sim 100\mu m$)、多次测量(几十~上百个位置测量点)

❖ 硅探测器 (内部区域) + 气体径迹室 (中心区域) 是径迹探测中的常用组合 : 优势互补

- ▶ BELLE2: PXD(硅像素)+SVD(硅微条)+CDC(中心漂移室)
- ▶ ALICE: ITS(内部硅径迹探测系统)+TPC
- ▶ ILD、IDEA、CEPC: VTX(硅像素)+SIT(硅微条)+TPC/DC

❖ 对于低能区实验 , 低质量的气体径迹室目前仍是唯一技术选项

- ▶ BES3、BELLE2 ...

❖ 极低物质量漂移室的设计和研发

- ▶ MEG-II、SCTF、STCF、IDEA

❖ BELLE2大型漂移室的成功建造和运行

❖ ALICE-TPC (目前世界最大TPC) 的读出探测器升级

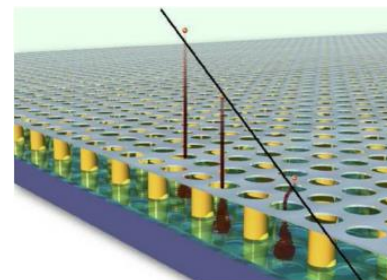
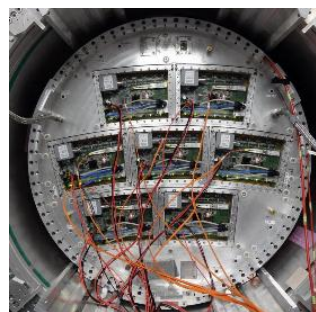
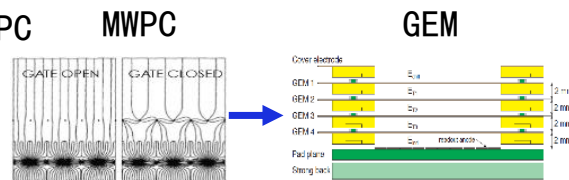
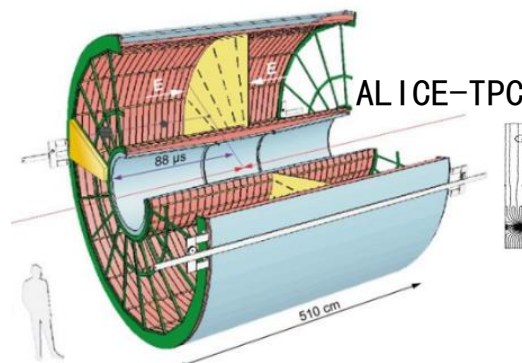
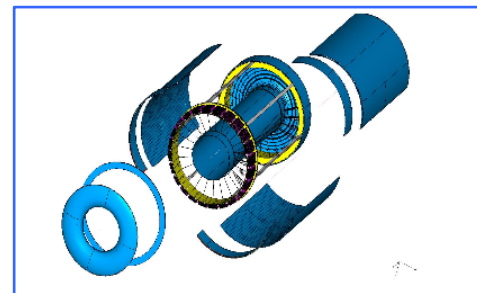
- ▶ MWPC→GEM, 无开关门, 连续读出

❖ 超大TPC (ILC-TPC、CEPC-TPC) 的设计和研发

- ▶ GEM , MM , MM+GEM , 像素读出



总物质量 $\sim 0.25\% \times X_0$

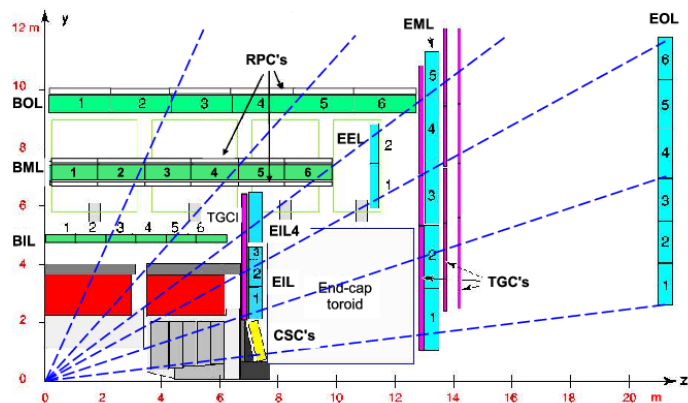


径迹探测 — 外部区域



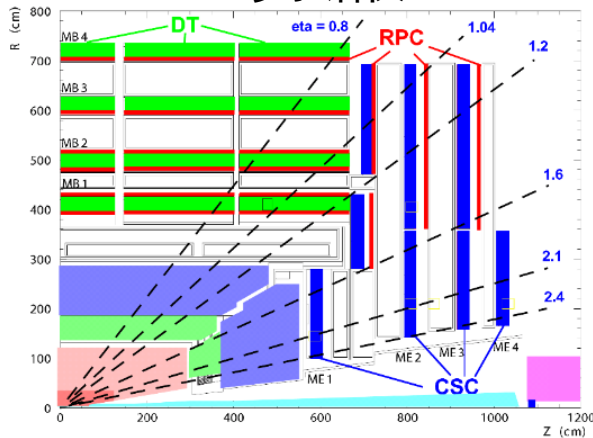
❖ 外部区域的探测对象主要是缪子 — 缪子探测器，其特点是探测面积极大，因此气体探测器仍然处于主导地位。

ATLAS缪子谱仪



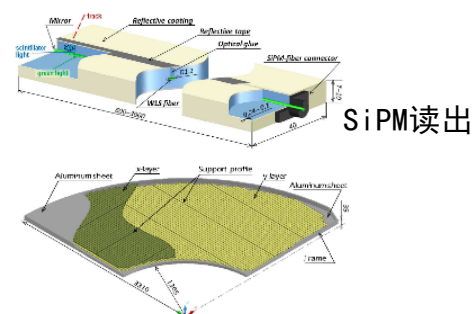
MDT：监控漂移管
CSC：阴极条室
TGC：窄间隙室
RPC：阻性板室

CMS缪子谱仪

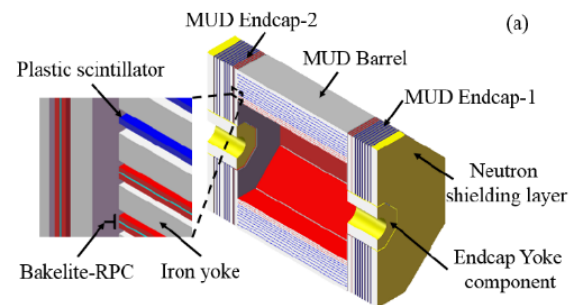


DT：漂移管
CSC：阴极条室
RPC：阻性板室

BELLE2 KLM探测器：塑闪条



STCF缪子探测器：RPC+塑闪条



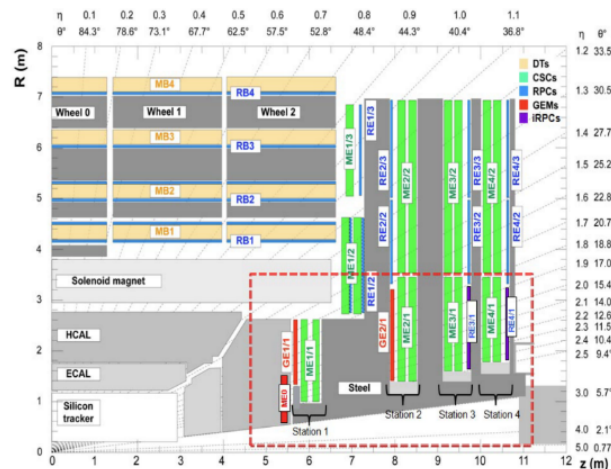
全部是气体探测器，并且除RPC外，全部都是丝室！

ATLAS/CMS缪子探测器升级



❖ Phase1

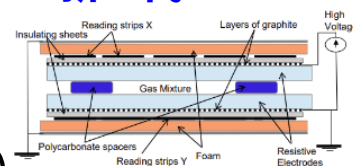
- ▶ ATLAS : 更换MDT/TGC/CSC → **MicroMegas**/sTGC
 - 增强端盖Muon触发能力
- ▶ CMS : 安装**GEM**(GE1/1)
 - 增强端盖Muon触发能力



❖ Phase2

- ▶ ATLAS : 安装**窄气隙RPC**+sMDT(BI)
 - 增强桶部Muon触发能力
- ▶ CMS : 安装**GEM**(GE2/1, ME0), RPC(RE3/1, RE4/1)
 - 增强Muon触发冗余性和Muon探测器接受度

新一代RPC



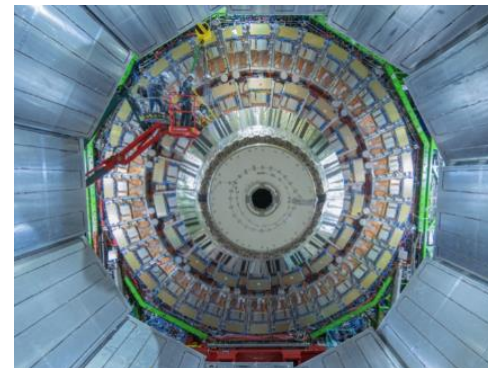
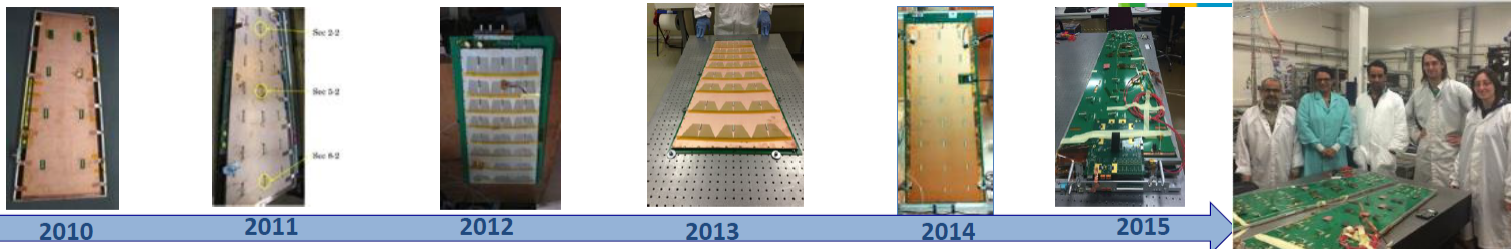
	Atlas Standard RPC	B1S78 RPC
Detector		
Gas Gap width	2 mm	1 mm
Electrode Thickness	1.8 mm	1.2 mm
Gas Mixture	95% TFE, 4.7% i-C4H10, 0.3% SF6	95% TFE, 4.7% i-C4H10, 0.3% SF6
Time Resolution	1 ns	~0.4 ns
Space Resolution	6 mm	1 mm
Gaps per chamber	2	3
Readout electronics	2D orthogonal	2D orthogonal

随着对撞机亮度升级，计数率和本底水平不断升高，**微结构气体探测器**开始进入了端盖和前向的缪子探测中。

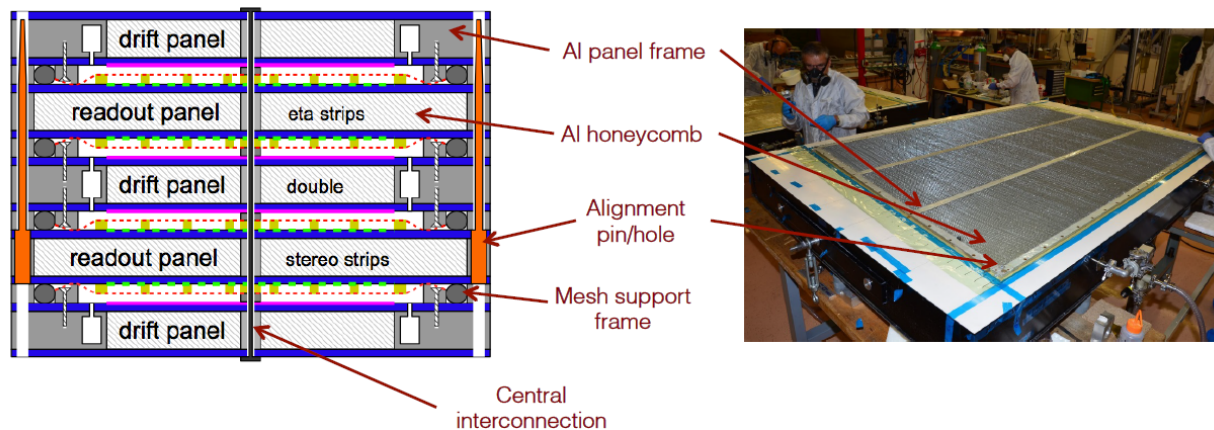
大面积微结构气体探测器



CMS GE1/1 GEM



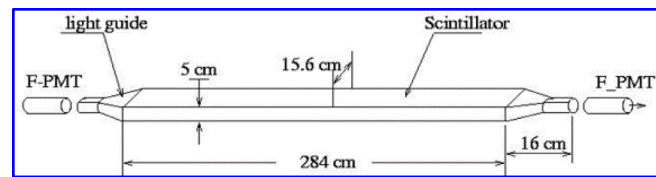
ATLAS NSW MicroMegas



❖ 传统技术：塑闪+PMT、多气隙阻性板室 (MRPC)

► BELLE、BES、ALICE、STAR、CBM

BESIII-塑闪：100 ps(单) , 80 ps(双)



❖ 技术前沿与挑战：高计数率、高颗粒度、高时间分辨

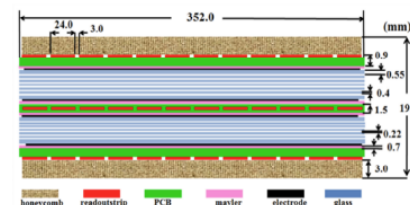
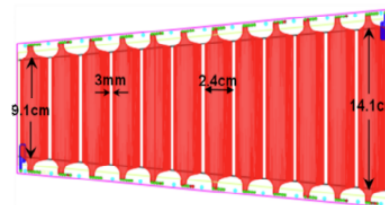
► CBM：低阻玻璃MRPC

► PANDA：塑闪+SiPM

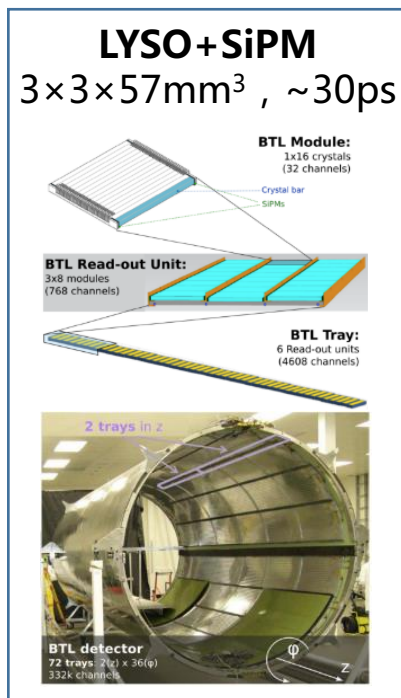
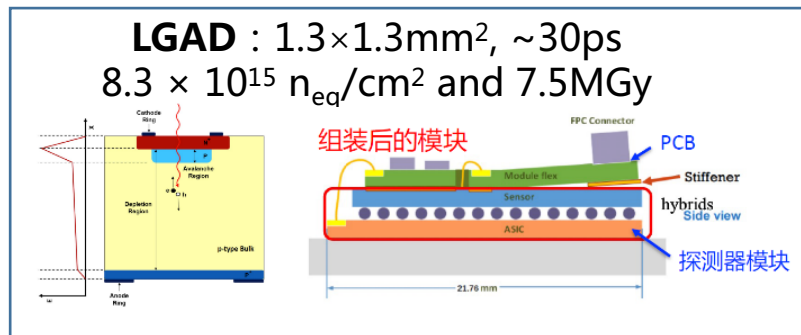
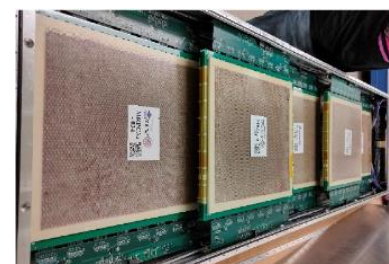
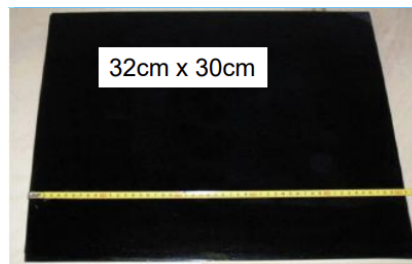
► CMS：LYSO+SiPM

► CMS、ATLAS：LGAD

BESIII-玻璃MRPC：60 ps



CBM-低阻玻璃MRPC：80 ps @50kHz/cm²



能量测量 — 量能器



❖ 量能器是最“多才多艺”的探测器

- ▶ 带电粒子，中性粒子
- ▶ 能量、位置、角度、时间

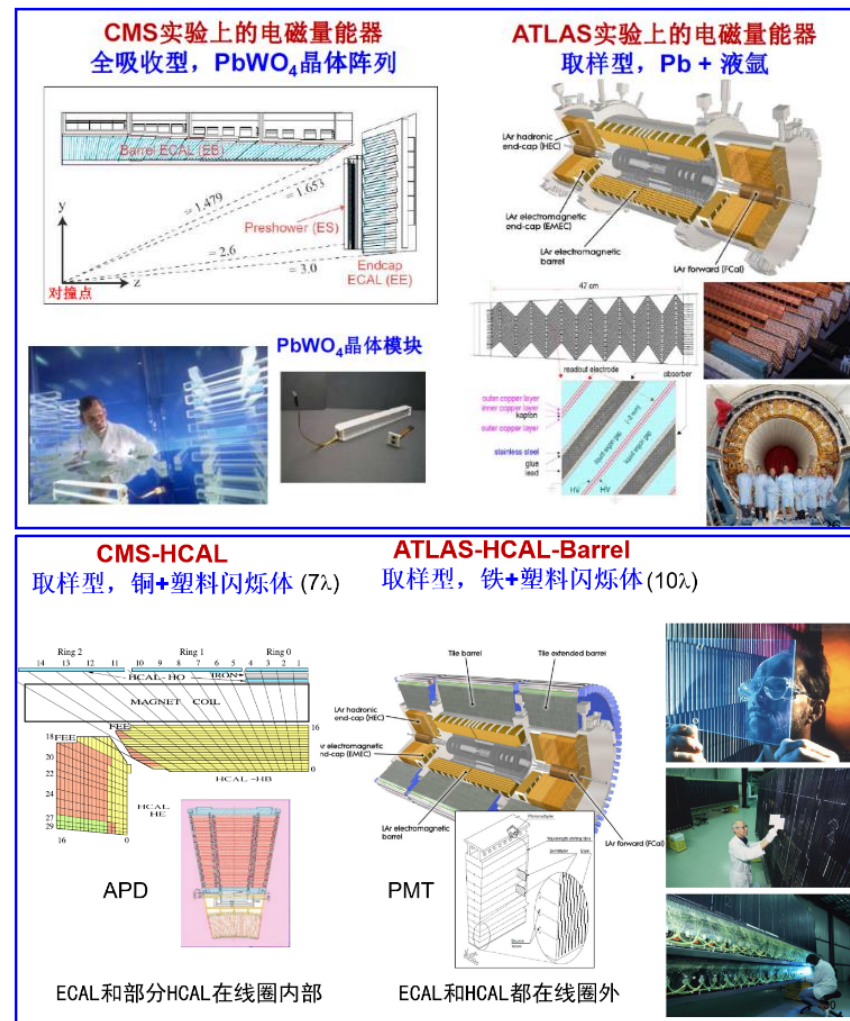
❖ LHC实验上具有丰富类型的量能器

- ▶ ATLAS：铅+液氩，铁+塑闪+PMT
- ▶ CMS：PbWO₄晶体+APD，铜+塑闪+PMT
- ▶ LHCb：吸收体+塑闪，Shashlik
- ▶ ALICE：吸收体+塑闪，Shashlik

❖ 高精度晶体量能器 $\sigma_E/E \sim 2\%/\sqrt{E(\text{GeV})}$

- ▶ BELLE、BESIII：CsI晶体+PD
- ▶ SCTF、STCF：pCsI晶体+APD

晶体量能器是很多高精度实验的技术选项，晶体是其关键部件：光产额、发光时间、抗辐照 ...



❖ 在强子衰变末态中分辨W与Z玻色子 → 强子喷注能量分辨率提高1倍

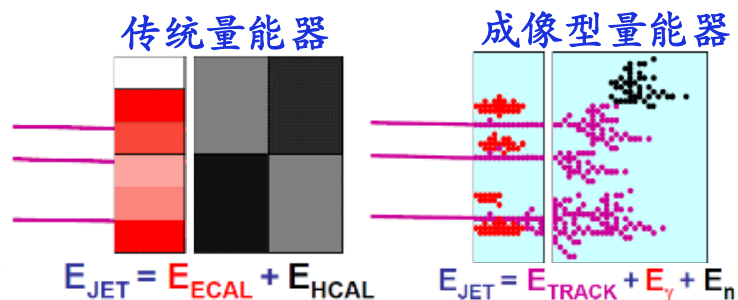
❖ 关键：如何克服强子簇射巨大涨落的影响？

$$\sigma_E/E \sim 60\%/\sqrt{E(\text{GeV})} \rightarrow 30\%/\sqrt{E(\text{GeV})}$$

❖ 两种途径

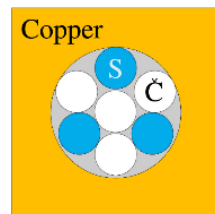
▶ 粒子流算法 → 成像型量能器 (极高颗粒度)

▶ 改善单个强子能量分辨 → 双读出量能器 (契伦科夫光+闪烁光)



重建并分辨出单粒子簇射，与径迹进行匹配，量能器中带电强子的能量沉积用径迹探测器的测量结果取代。

双读出量能器



$$\left. \begin{aligned} C &= E \left[f_{\text{em}} + \frac{1}{(e/h)_C} \times (1 - f_{\text{em}}) \right] \\ S &= E \left[f_{\text{em}} + \frac{1}{(e/h)_S} \times (1 - f_{\text{em}}) \right] \end{aligned} \right\} \text{ where } \chi = \frac{1 - 1/(e/h)_S}{1 - 1/(e/h)_C}$$
$$E = \frac{S - \chi C}{1 - \chi}$$

在每个簇射事例中测量电磁贡献所占比例

成像型量能器



- 针对各种技术方案，建造了多个物理样机，通过束流测试完成了原理验证。
- 由物理样机转向技术样机，解决工程建造问题。

ECAL



Si-W ECAL: 30 layers, $1 \times 1 \text{ cm}^2$ cells

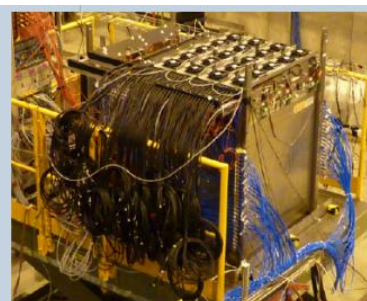


Sc-W ECAL: 30 layers, $1 \times 4.5 \text{ cm}^2$ cells

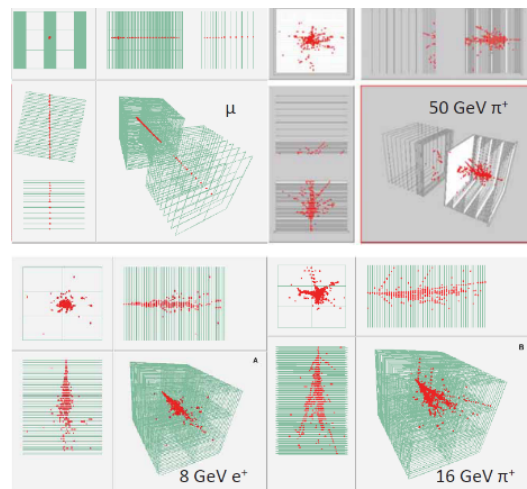
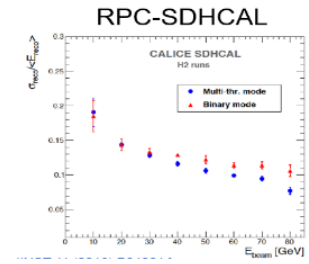
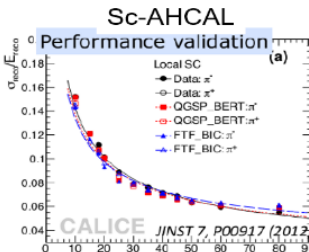
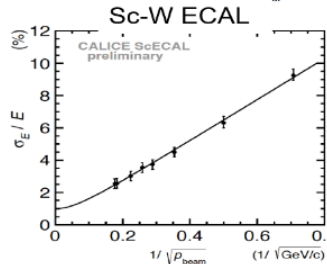
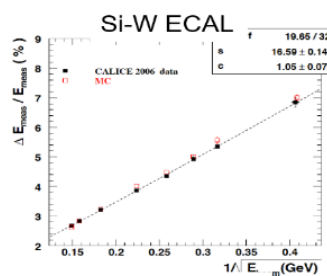
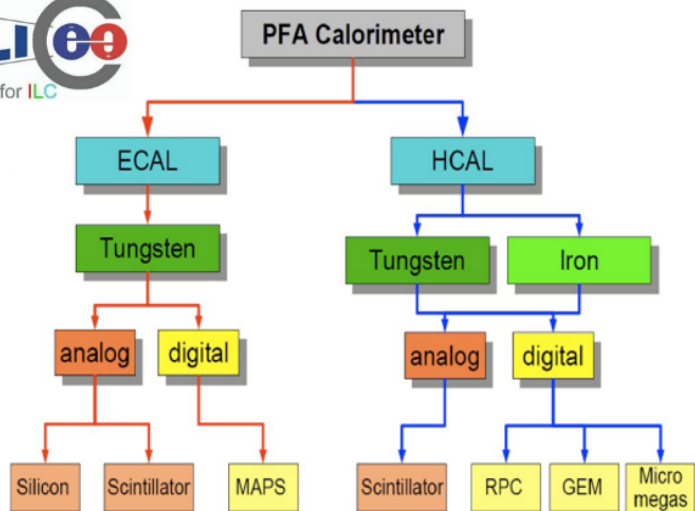
HCAL



Sc-AHCAL, Fe&W: 38 layers, $3 \times 3 \text{ cm}^2$ cells



GRPC-SDHCAL, Fe: 48 layers, $1 \times 1 \text{ cm}^2$ cells



成像型量能器的应用 — CMS端盖量能器升级

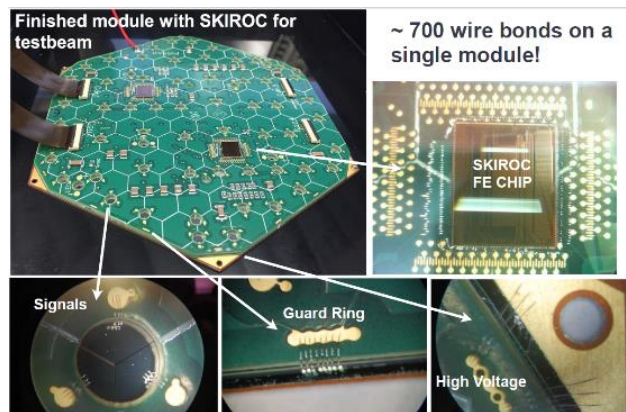
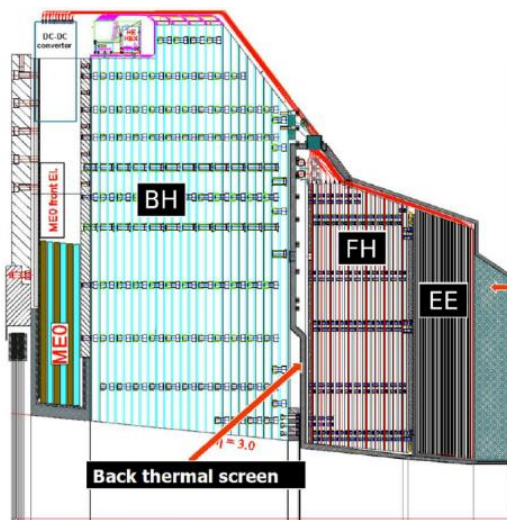


❖ CMS端盖量能器升级-HGCAL

- ▶ FE : Si+W, 28层 , $25X0+1.3\lambda$
- ▶ FH : Si+Fe, 12层 , 3.5λ
- ▶ BH : Sc+Fe, 11层 , 5.5λ

❖ 关键参数

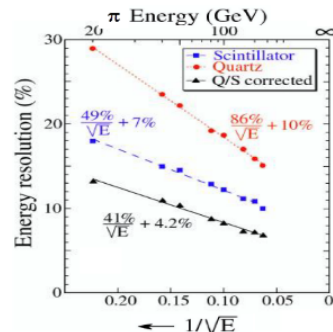
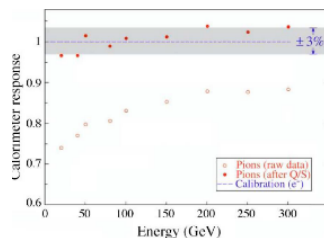
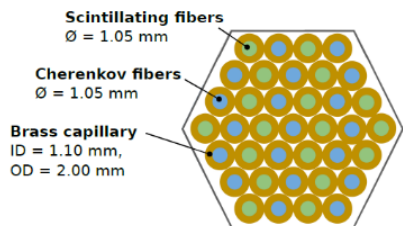
- ▶ 593m^2 Si , 单元颗粒度 $0.5\text{-}1\text{cm}^2$, $\sigma_t \sim 50\text{ps}$
- ▶ 6百万通道 , 21660个模块 , 92000个FE-ASIC
- ▶ 功耗115kW
- 成像型量能器不仅能显著提高喷注能量分辨 , 也能有效去除堆积效应。
- CMS-HGCAL将是第一个应用于实验中的大型成像型量能器。



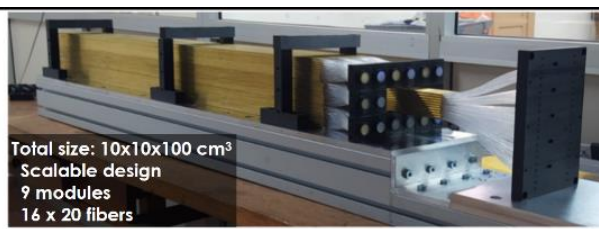
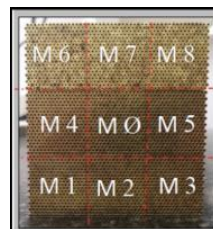
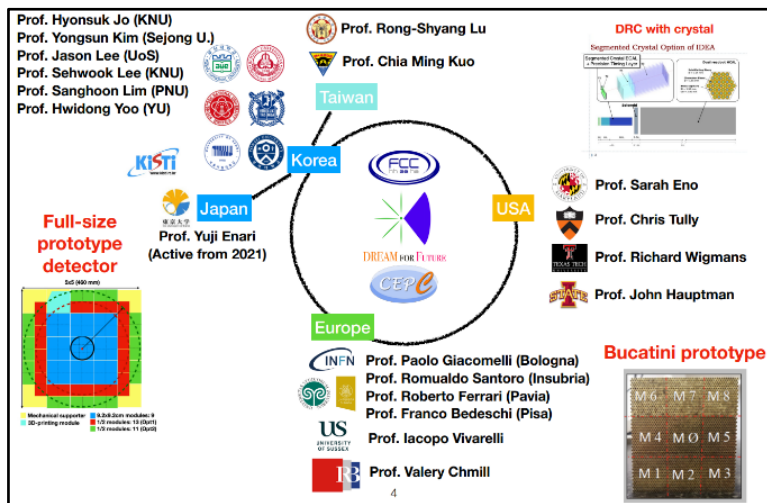
❖ DREAM: Dual READout Method–CERN RD52项目

► 同时测量闪烁光（非相对论电磁成分+强子成分）和契伦科夫光（相对论电磁成分）

DREAM原型



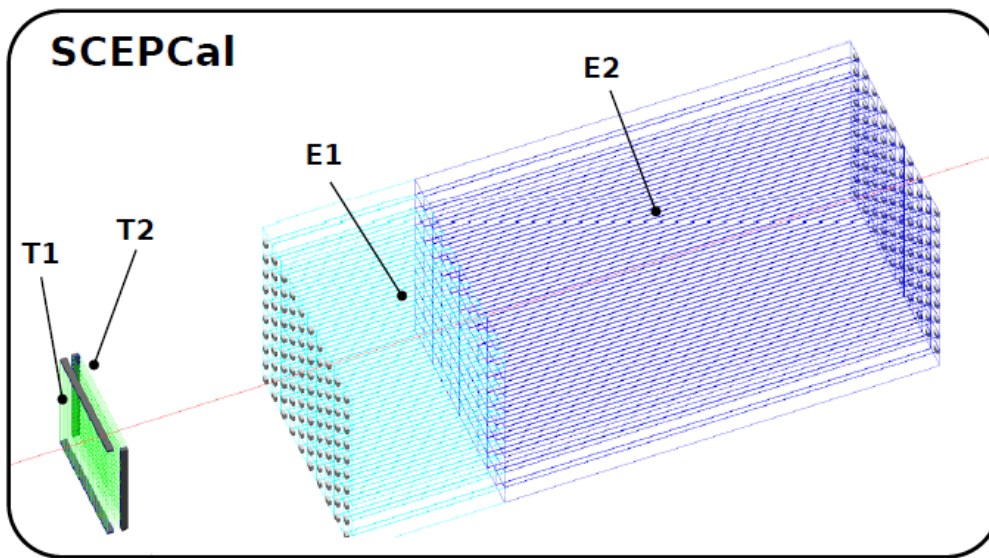
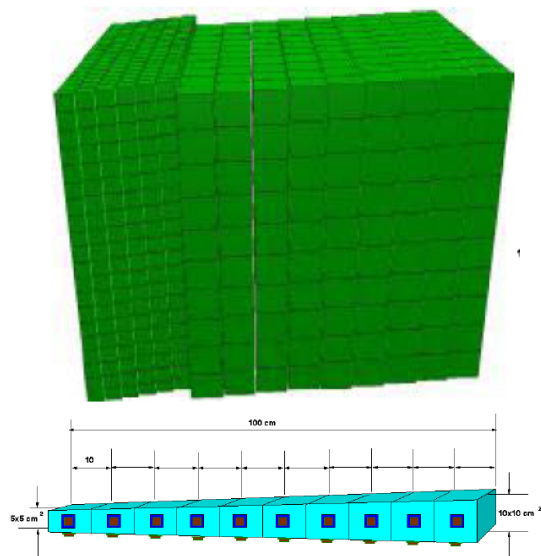
FCC、CEPC



全吸收双读出？



- ❖ 全吸收强子量能器，采用双读出改善强子能量分辨。
- ❖ 通过方向、波长或信号时间特征区分闪烁光和契伦科夫光。
- ❖ 找到合适的晶体和读出方法是关键！



重要发展趋势：集多种测量功能于一体

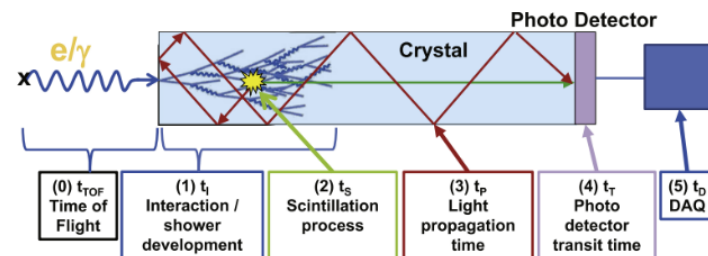
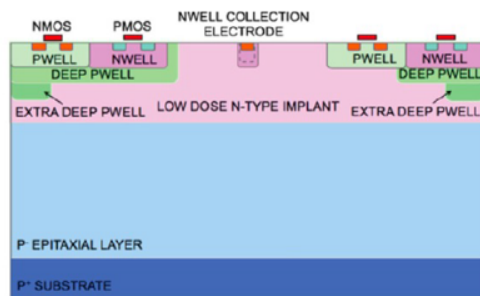
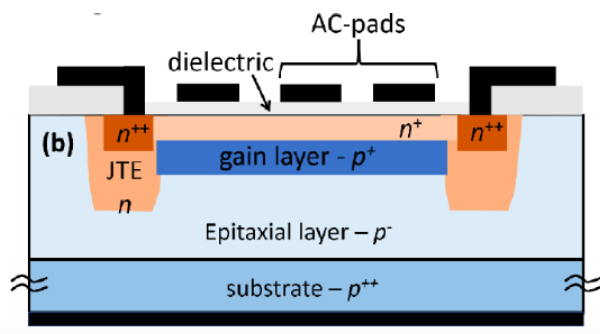


❖ 位置+时间：四维径迹探测器（4D tracker： $\sigma_x \sim < 10\mu\text{m}$ + $\sigma_t \sim < 100\text{ps}$ ）

► AC-LGAD, 3D hybrid, DMAPS ...

❖ 能量+时间：定时量能器

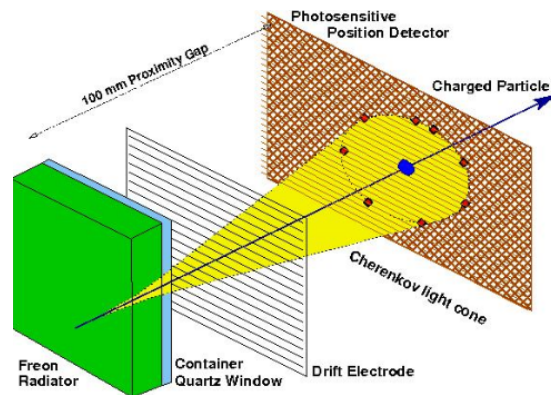
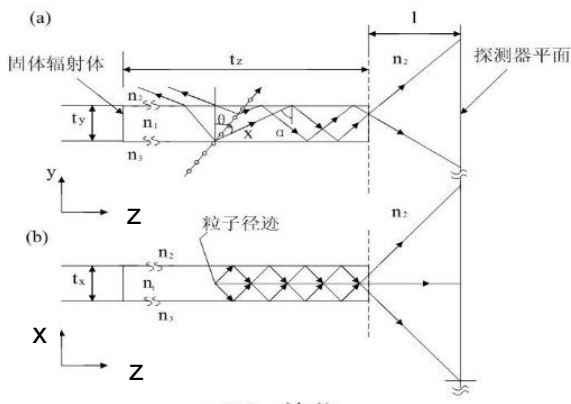
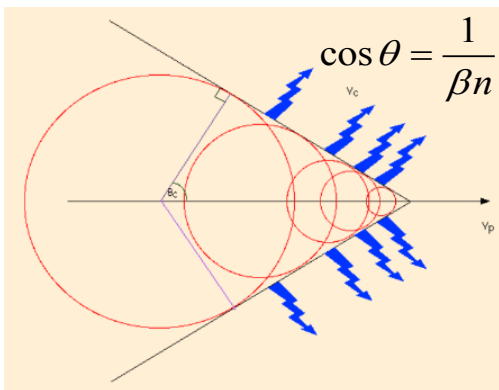
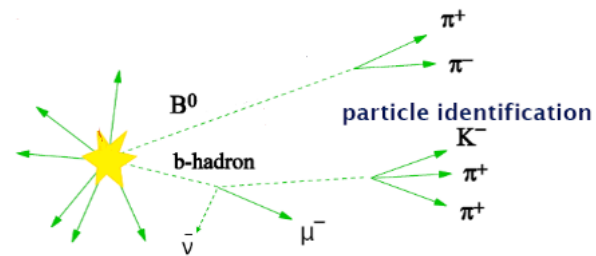
❖ 位置+能量+时间：五维量能器（定时PFA量能器）



❖ 粒子（强子）鉴别在很多物理实验中发挥着关键作用

❖ 主要技术路线

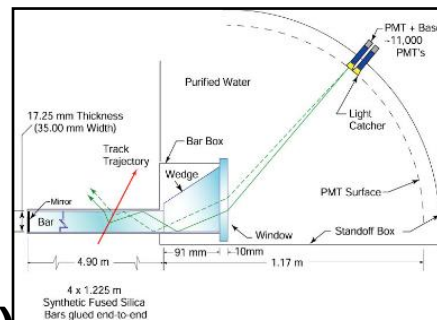
- ▶ 飞行时间法：时间测量已涵盖
- ▶ 内反射契伦科夫探测器：DIRC (detection of internally reflected Cherenkov light)
- ▶ 环形成像契伦科夫探测器：RICH (Ring imaging Cherenkov)



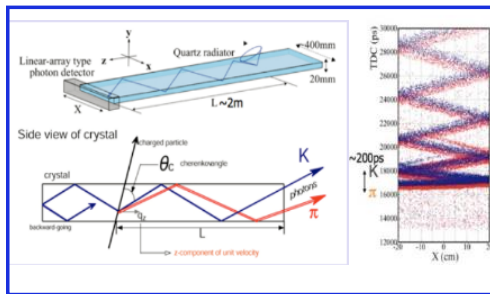
DIRC探测器



- ❖ BaBar-DIRC : 首个DIRC探测器, 主要测量位置/角度, 时间精度要求不高。
- ❖ 结合位置+精确时间测量, DIRC类探测器在粒子鉴别中有很大的应用潜力。
- ❖ 光探测通常采用多阳极MCP-PMT: 单光子灵敏、高时间分辨、抗磁性好、可以有很好的位置分辨。
- ❖ 石英是目前唯一可行的辐射体: 适用于动量不是很高的情况 (例如几个GeV/c)

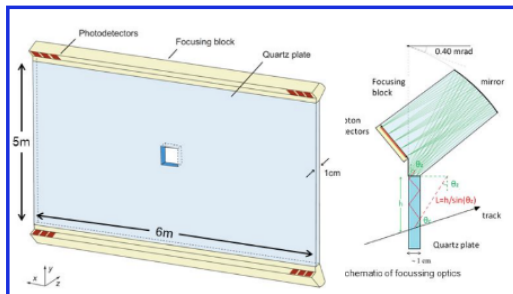


Belle2-TOP (完成建造)



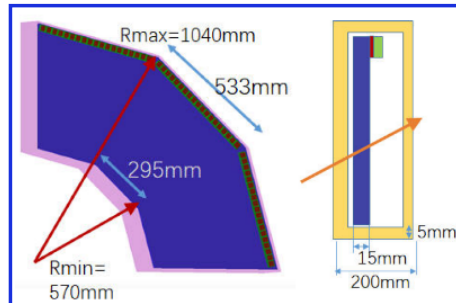
- 位置+时间(传播时间为主)
- 多阳极MCP-PMT
- 波形采样ASIC
- 单光子<100ps

LHCb-TORCH (研发中)



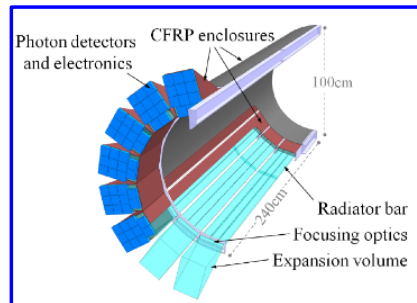
- 位置+时间(飞行时间为主)
 - 多阳极MCP-PMT
 - NINO+HPTDC
 - $\sigma_{TOF}=10-15\text{ps}/\text{track}$
 - PMT读出颗粒度~0.4mm
- 本质上是一个飞行时间探测器

STCF-DTOF (研发中)



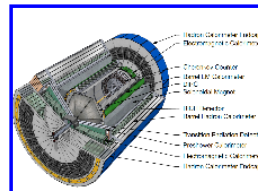
- 位置+时间
- 多阳极MCP-PMT
- 前放+TDC
- $\sigma_{TOF}=30\text{ps}/\text{track}$

PANDA-DIRC (研发中)



- 位置+时间
- 具有较大的光学扩展区
- 多阳极MCP-PMT
- 成像为主

EIC实验



Finally, detection of internally reflected Cerenkov light (DIRC) is under consideration for a high performance DIRC (hpDIRC), and would outperform the DIRC at BaBar and PANDA

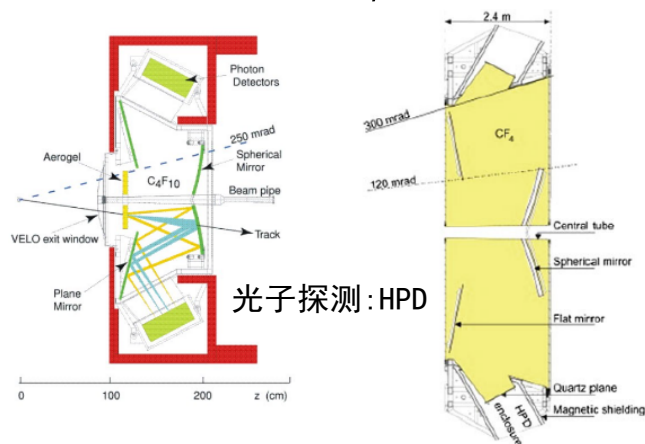
RICH探测器



❖ 最早应用在大型实验中的RICH：CRID@SLD, RICH@DELPHI

❖ 大动量范围/高动量粒子鉴别的重要技术选项可以高达（100GeV/c）。

LHCb-RICH1, RICH2



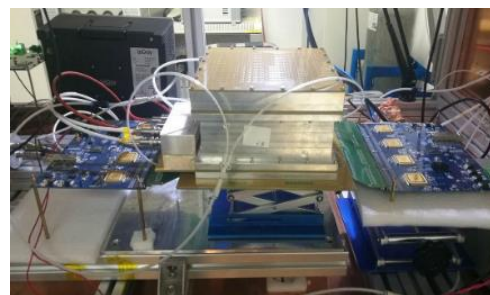
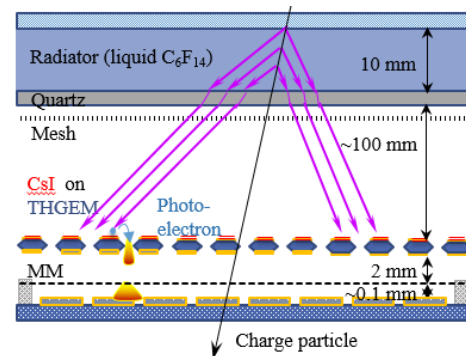
RICH1: Aerogel $L=5\text{cm}$ $p: 2 \rightarrow 10\text{ GeV}/c$
 $n=1.03$ (nominal at 540 nm)
 C_4F_{10} $L=85\text{ cm}$ $p: < 70\text{ GeV}/c$
 $n=1.0014$ (nominal at 400 nm)
 Upstream of LHCb Magnet
 Acceptance: 25 $\rightarrow$ 250 mrad (vertical)
 300 mrad (horizontal)
 Gas vessel: $2 \times 3 \times 1\text{ m}^3$

RICH1: 10-65GeV

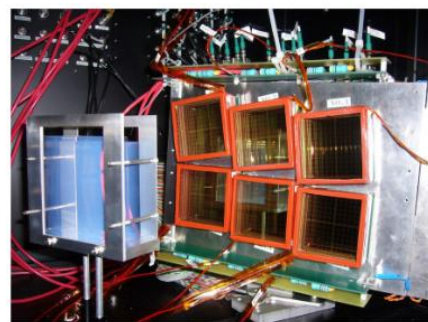
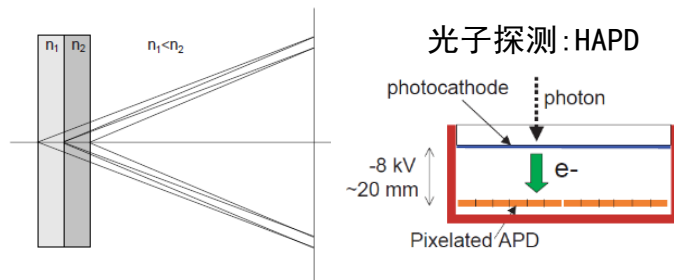
RICH2: CF_4 $L=196\text{ cm}$ $p: < 100\text{ GeV}/c$
 $n=1.0005$ (nominal at 400 nm)
 Downstream of LHCb Magnet
 Acceptance: 15 $\rightarrow$ 100 mrad (vertical)
 120 mrad (horizontal)
 Gas vessel: 100 m^3

RICH2: 15-100GeV

STCF-RICH



BeI le2-ARICH



- double aerogel, $n_0=1.050, 1.065$
- $d=19.8, 19.9\text{mm}$
- $\theta_c=336\text{mrad}$
- $\sigma_\theta=15.8\text{mrad}$
- $N_{\text{det}}=11.4$
- $>5\sigma\pi/K$ 分辨 $\sim 4\text{GeV}$

❖ 硅像素技术（包括读出以及二者的集成）

- ▶ 混合型、单片型、高精度定时

❖ 大面积微结构气体探测器（MPGD）技术

❖ 新型量能器技术

- ▶ 快速高分辨晶体量能器、强子能量精确测量、高精度定时

❖ 高计数率高精度快速定时技术(<30ps)

- ▶ 半导体、闪烁体、气体

❖ 快响位敏单光子探测技术

- ▶ 真空（MCP）、固体（SiPM）、气体（MPGD）

❖ 位置测量

- ▶ 硅像素是重点，单片有源型开启了一个新时代，即将进入中心区域。

❖ 时间测量

- ▶ 高计数率高颗粒度下的快速定时是前沿

❖ 能量测量

- ▶ 晶体十分重要，高颗粒度和双读出是前沿。

❖ 粒子鉴别

- ▶ 契伦科夫是核心，高时间分辨的DIRC技术是个热点。

❖ 缪子探测

- ▶ 传统气体探测器依然主导，微结构气体探测器开始进入。

探测器源于物理实验，其发展从根本上由实验需求指引。