ATLAS/CMS 探测器简介

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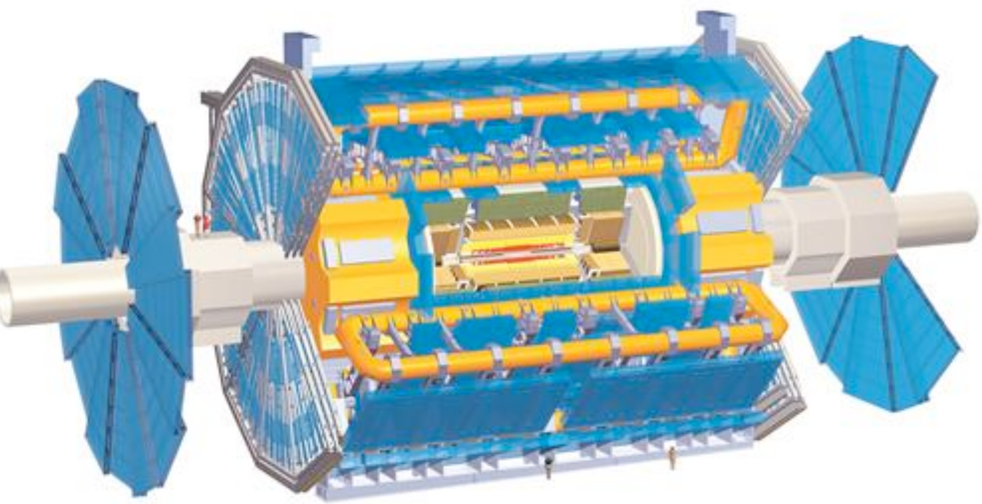
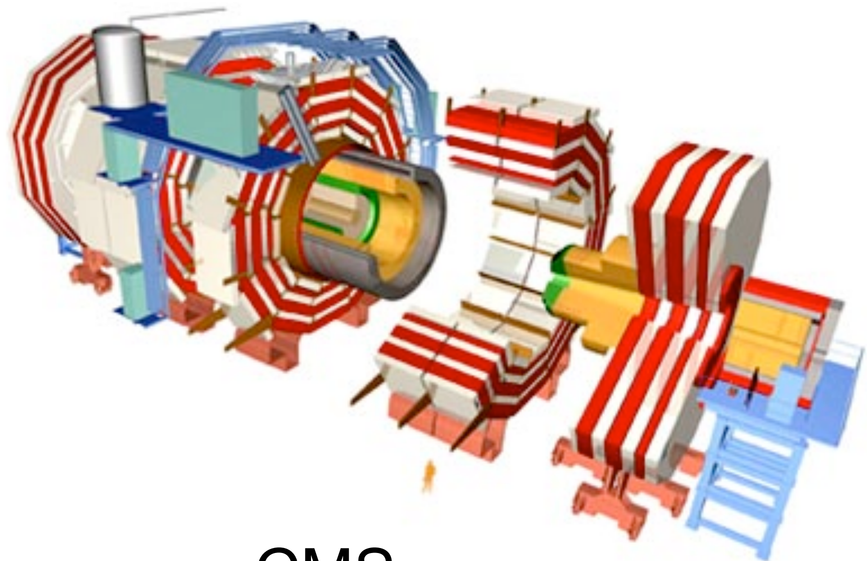
课程内容安排

- 探测器总体设计 （课程 I）
- 径迹探测系统（课程 II）
- 量能器系统（课程 III）
- 缪子探测器系统（课程 IV）

ATLAS/CMS 探测器



ATLAS

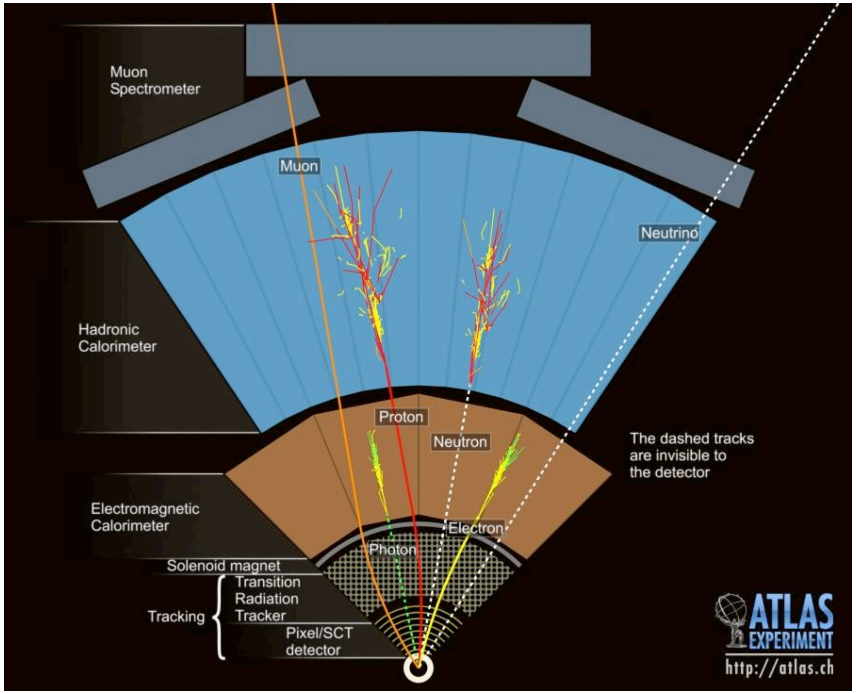


CMS

- 广泛的物理计划，探测器设计尽可能采用不同设计理念以及不同技术，从而降低LHC项目整体风险，并且可以相互验证实验结果（例如发现Higgs）。

探测器基本结构

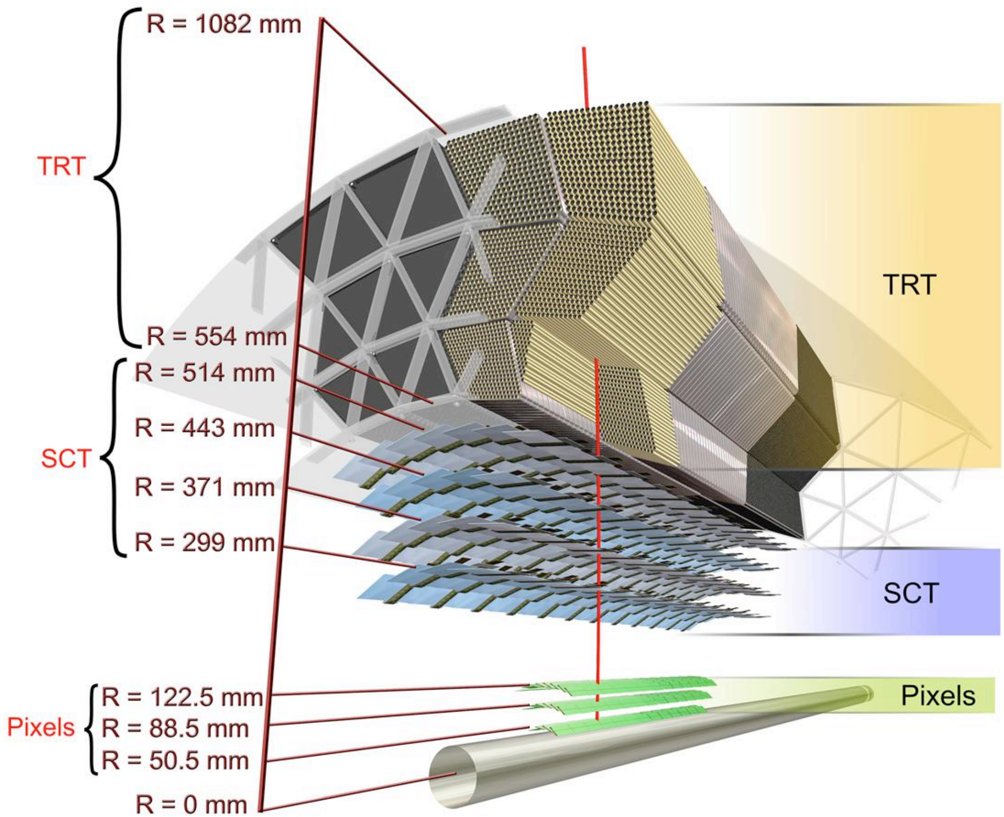
- 内层（靠近对撞点）：径迹探测器位于螺线管磁场内，精确测量从对撞点出发的各类带电粒子的动量；
- 中间层：电磁量能器和强子量能器吸收并测量电子、光子和强子的能量；
- 外层：缪子探测器以测量高能缪子（穿透量能器）的动量



通用型探测器结构基本类似，具体布局和实现方法有差异，各部分子探测器会进一步介绍

ATLAS 径迹探测器

- 由内向外：PIXEL（硅像素）、SCT（硅微条）及TRT（跃迁辐射），测量精度从高到低（靠近对撞点粒子密度高，需要高空间分辨率区分，降低探测器占有率）

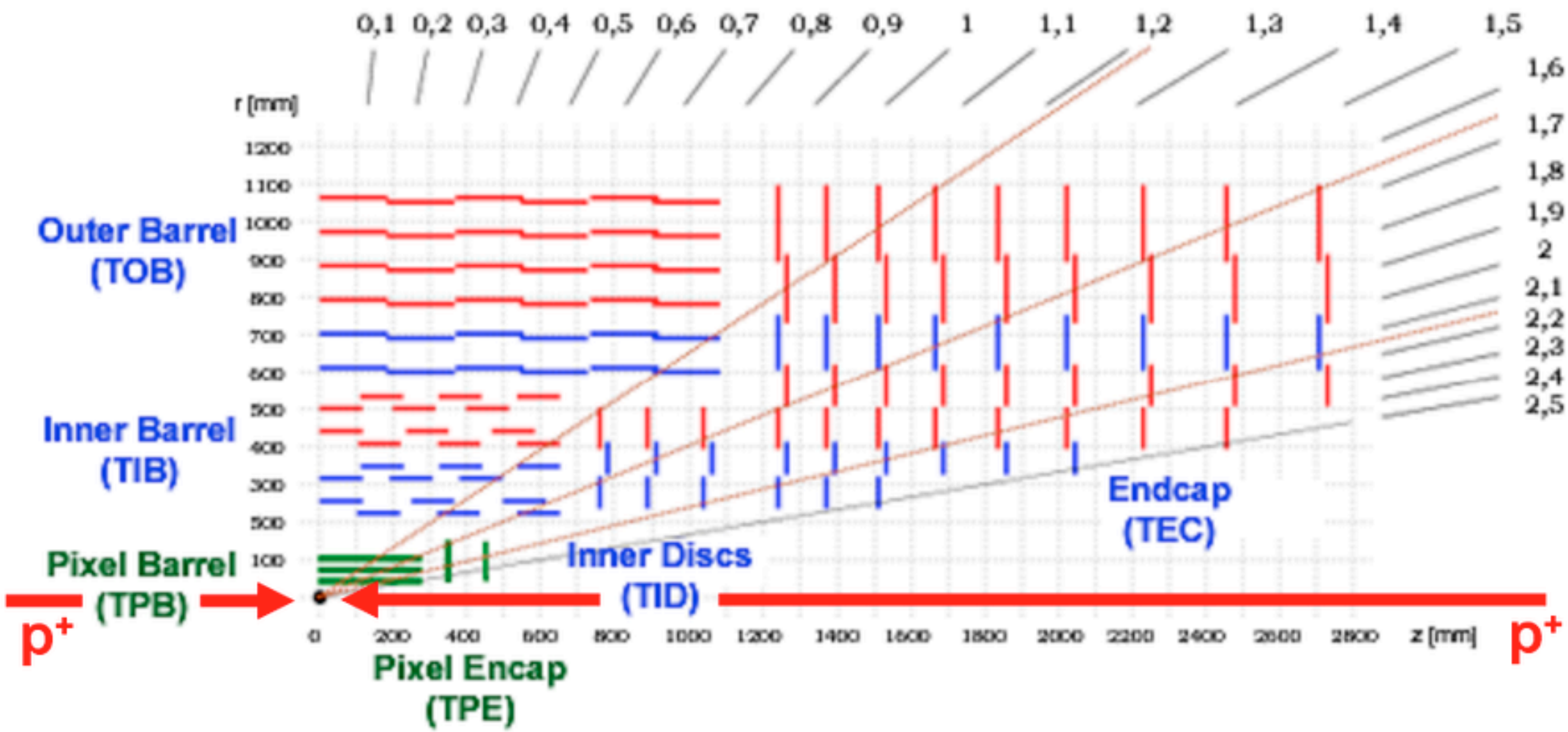


TRT：数十个测量点有利于寻迹（精度低于硅微条），电子甄别能力，造价低（相对于硅探测器）

PIXEL及**SCT**均为硅探测器，靠近对撞点，精度高、抗辐照

CMS 径迹探测器

- 仅有硅像素和硅微条探测器构成，最大的硅探测器



课程 III

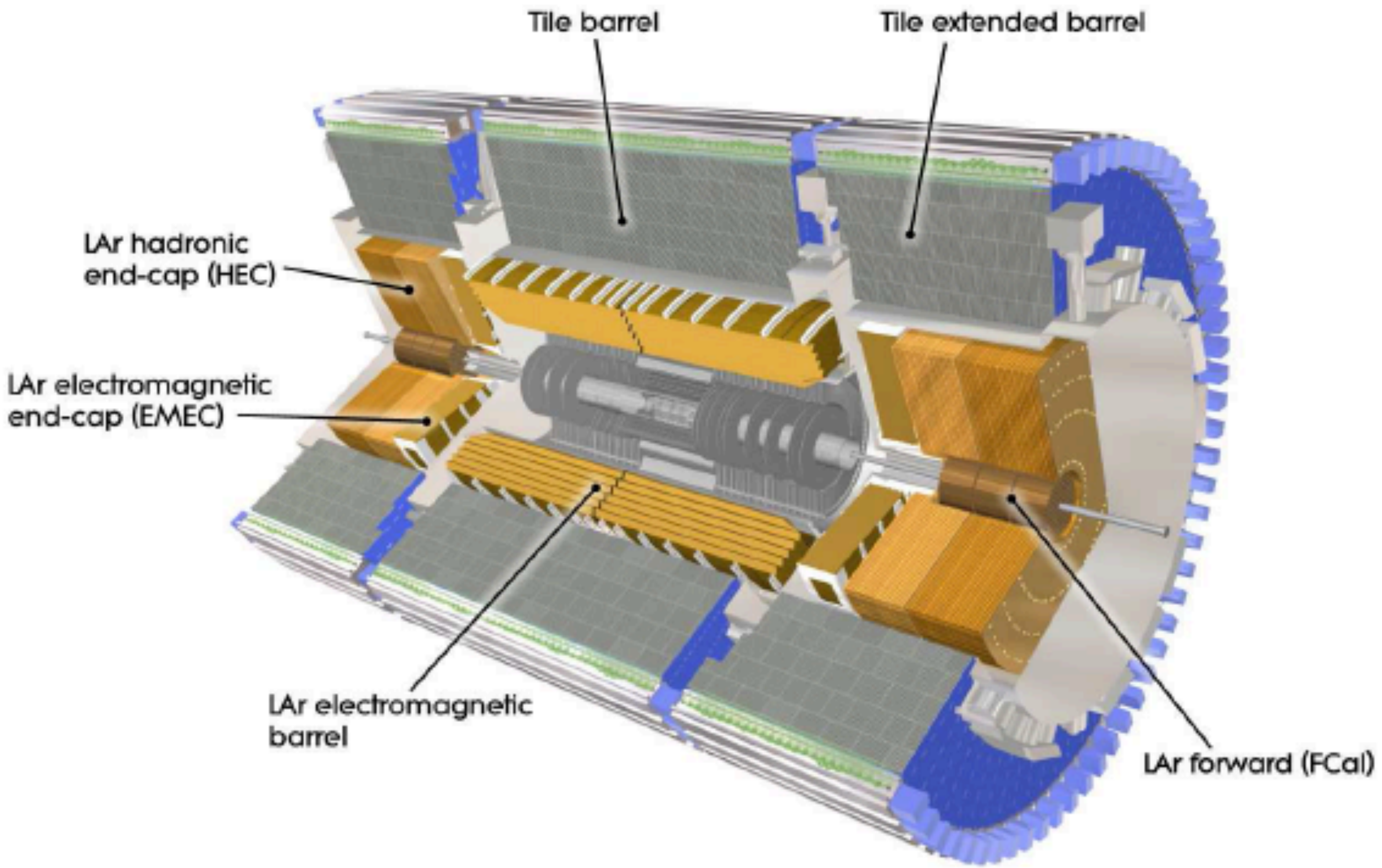
量能器系统

量能器系统考虑要点

- 由电磁量能器与强子量能器构成，物理需求驱动主要设计:
  - 要求探测器精确测量覆盖区域 $|\eta| \leq 2.5$ 内，对于电子、光子提供出色的粒子甄别，还要实现高精度的能量与位置分辨
  - 探测器完整容纳高能量喷注，具备出色的喷注能量分辨率，探测区域可以延伸至 $|\eta| \leq 5$（以便一定程度上区分丢失能量的来源，新物理前向）
  - 抗辐照要求，且需要稳定、可靠运行10年

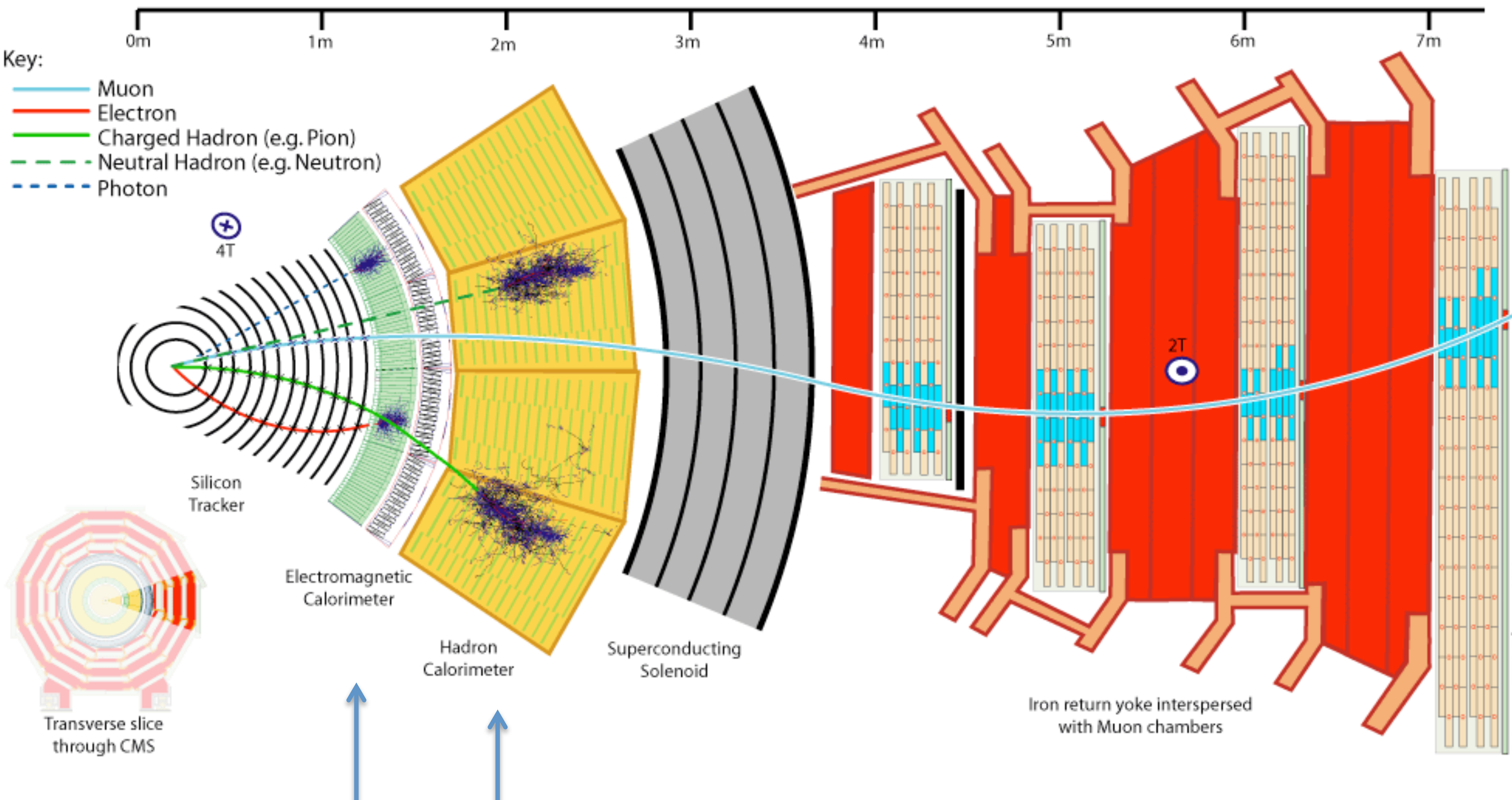
- ATLAS/CMS 在量能器技术方案方案上区别明显

ATLAS 量能器系统



Tile barrel
Tile extended barrel
LAr hadronic end-cap (HEC)
LAr electromagnetic end-cap (EMEC)
LAr electromagnetic barrel
LAr forward (FCal)

CMS 量能器系统

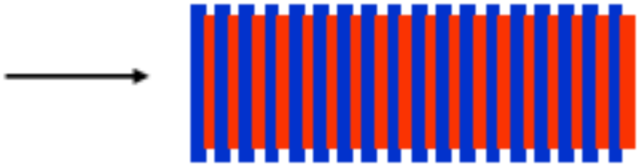


电磁量能器

强子量能器

能器测量

- **基本原理**：入射粒子与量能器介质通过电磁相互作用或强相互作用能量沉积在探测器中，所沉积能量通过介质中的灵敏部分转化为电离电荷、闪烁光等可测物理量。量能器按结构可分为：
  - **取样量能器**：吸收体与探测器灵敏材料交替，电磁/强子量能器均有使用。



ATLAS 电磁 + 强子量能器

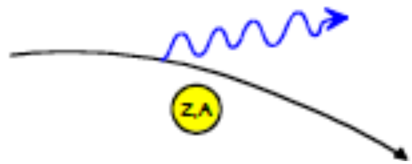
CMS 强子量能器

  - **全吸收/均匀量能器**：单一介质，同时作为吸收体和探测器灵敏材料。

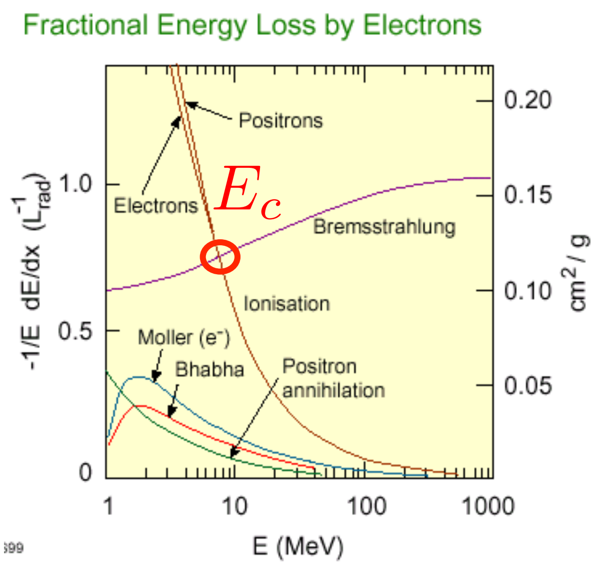
CMS 电磁量能器 （$PbWO_4$）

电磁量级联簇射

- 电磁级联簇射主要包含电子的韧致辐射和光子的电子对产生。



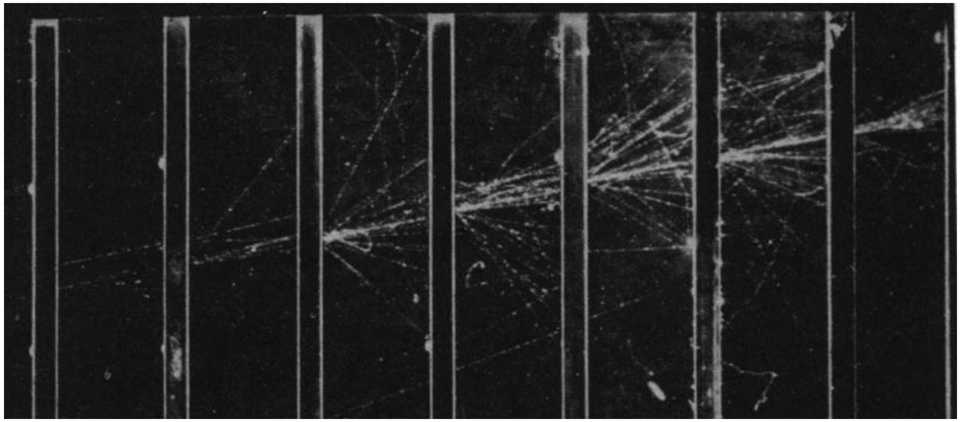
- 电子的韧致辐射能量损失可以用辐射长度（Radiation Length，***X₀***）表示，即经过***X₀***厚的吸收介质，电子平均丢失63.2%的能量：$E = E_0 e^{-x/X_0}$；电子对产生的自由作用距离：$\lambda_{\rm pair} = 9/7X_0$



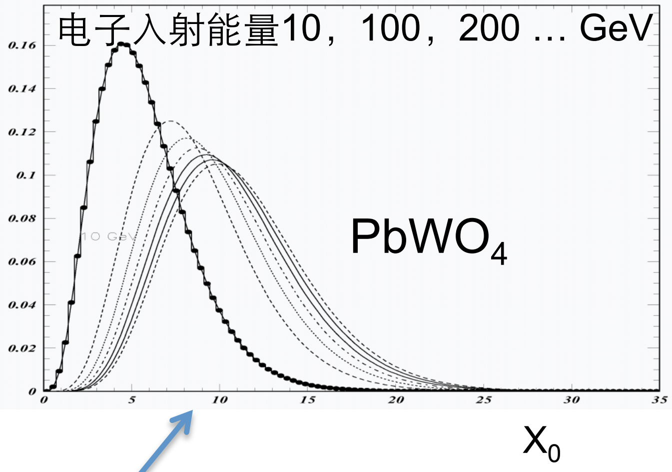
在临界能量***E***以下，电子的电离能损高于韧致辐射导致的能量损失。

相应地，光子还可以通过康普顿散射、光电效应等方式损失能量直至被吸收。

电磁量级联簇射包络

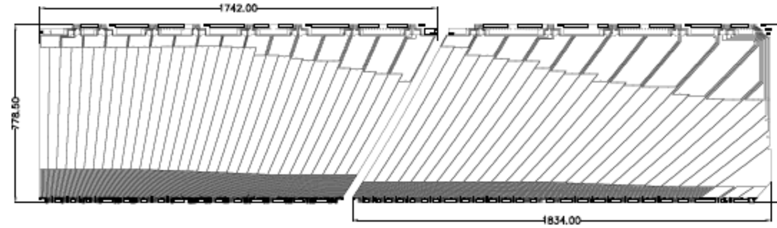


电子在云室（铅吸收体）中簇射

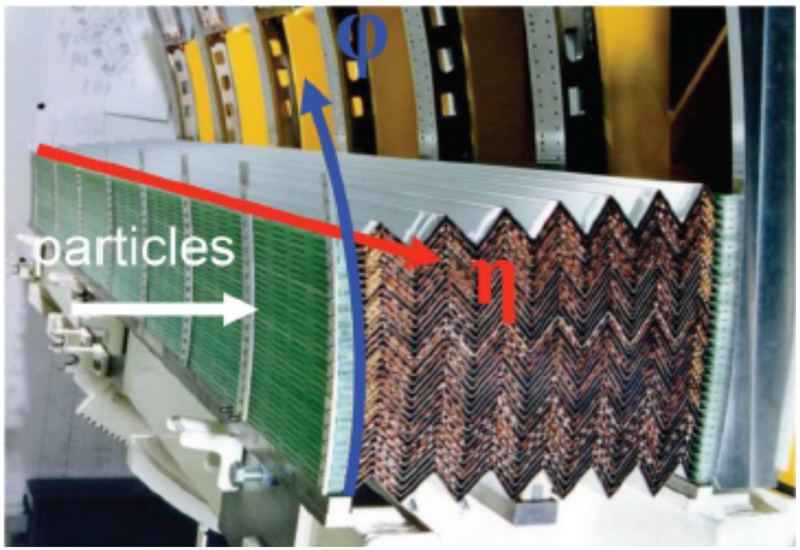


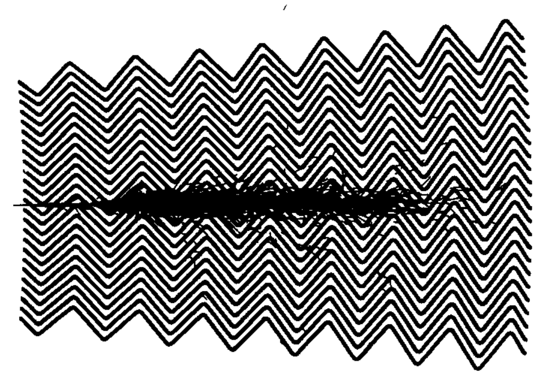
- 纵向簇射按照入射电子能量的指数方式增长，要求电磁量能器足够厚（辐射长度），尽可能容纳簇射从而避免泄漏。
- 横向簇射扩散主要由多次库伦散射导致，$2R_m$（Moliere Radius）内容纳95%的簇射，能量测量要求一定横向尺寸。
- 此外，簇射形状（Shower Shape）可以用于粒子甄别。

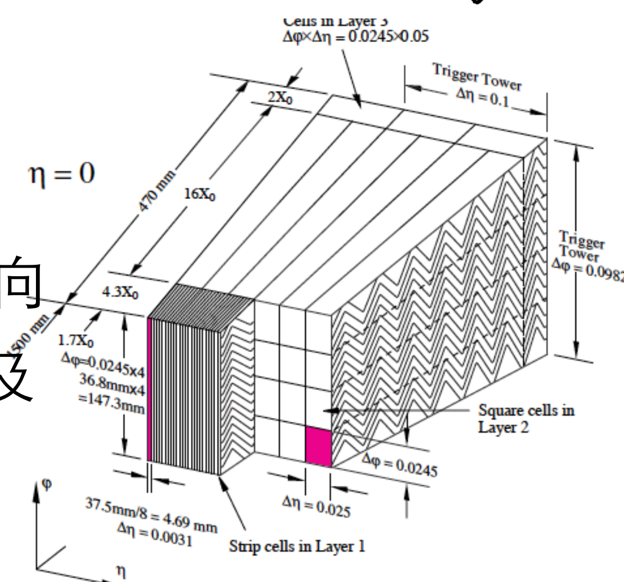
ATLAS 电磁量能器



- 取样量能器：液氩（探测灵敏材料）+铅（吸收体），采用手风琴结构减小探测器死区。



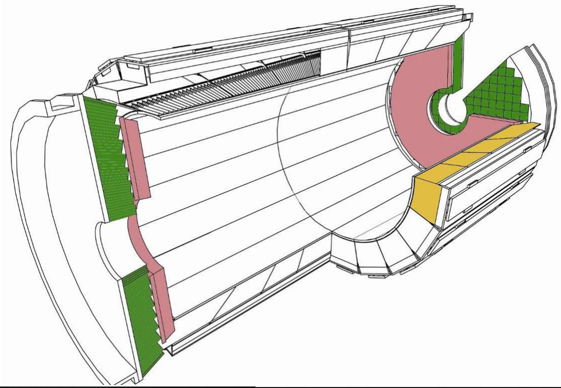


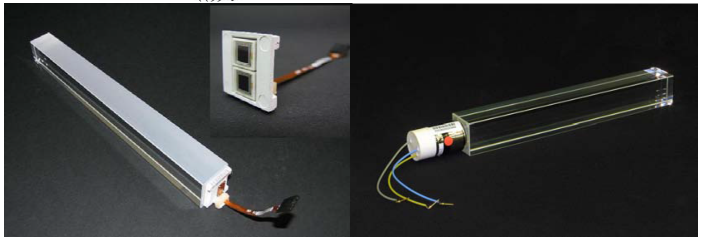


- 液氩内禀抗辐照性能；读出允许η、φ和纵向精细分割，有利于能量刻度（分辨率），及重建簇射形状（粒子甄别）。

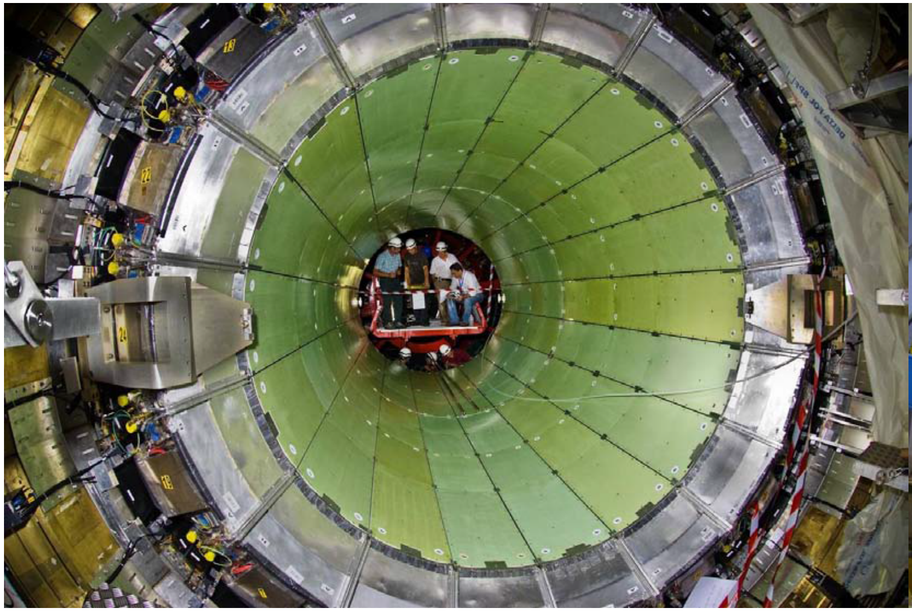
CMS 电磁量能器

- 全吸收/均匀量能器：$PbWO_4$闪烁晶体
  - 辐射长度 X0：0.89 cm
  - R_m：2.2 cm （cluster size 3×3或5×5）
  - 快速闪烁响应：80%（25 ns）





CMS 电磁量能器桶部及端盖$PbWO_4$晶体



CMS 电磁量能器桶部

CMS 电磁量能器端盖

电磁量能器分辨率

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

随机项 *a*

信号过程的随机涨落，即光电子数目的涨落

常数项 *b*

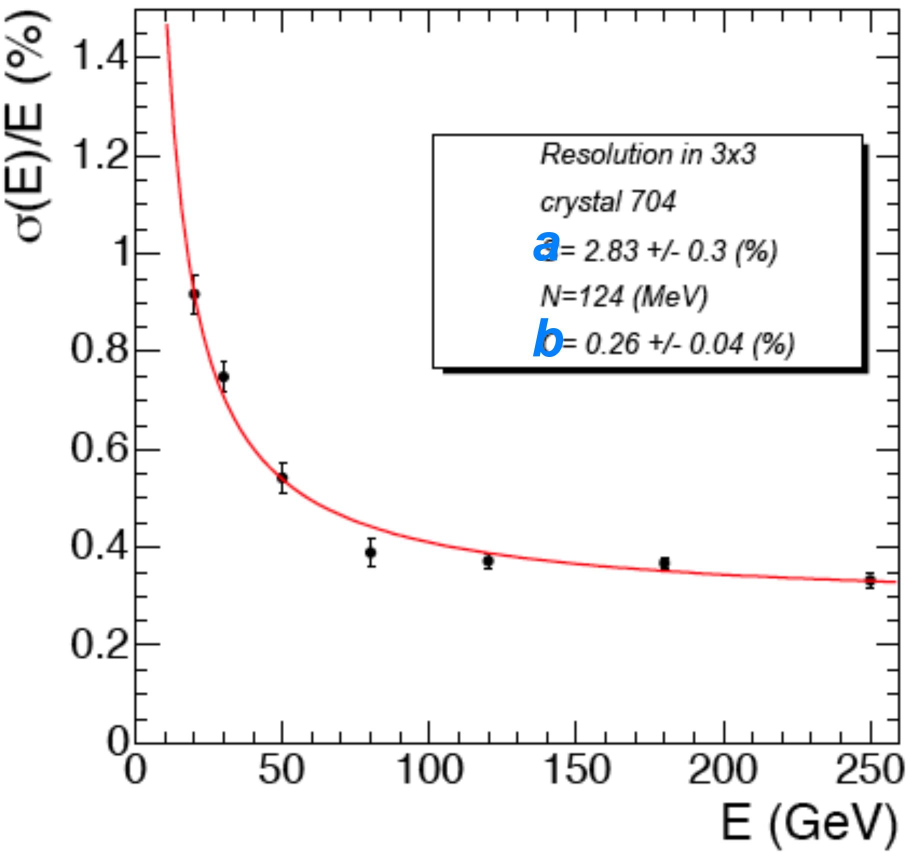
量能器不均匀响应，刻度误差，能量丢失在探测器死区等

噪声项 *c*

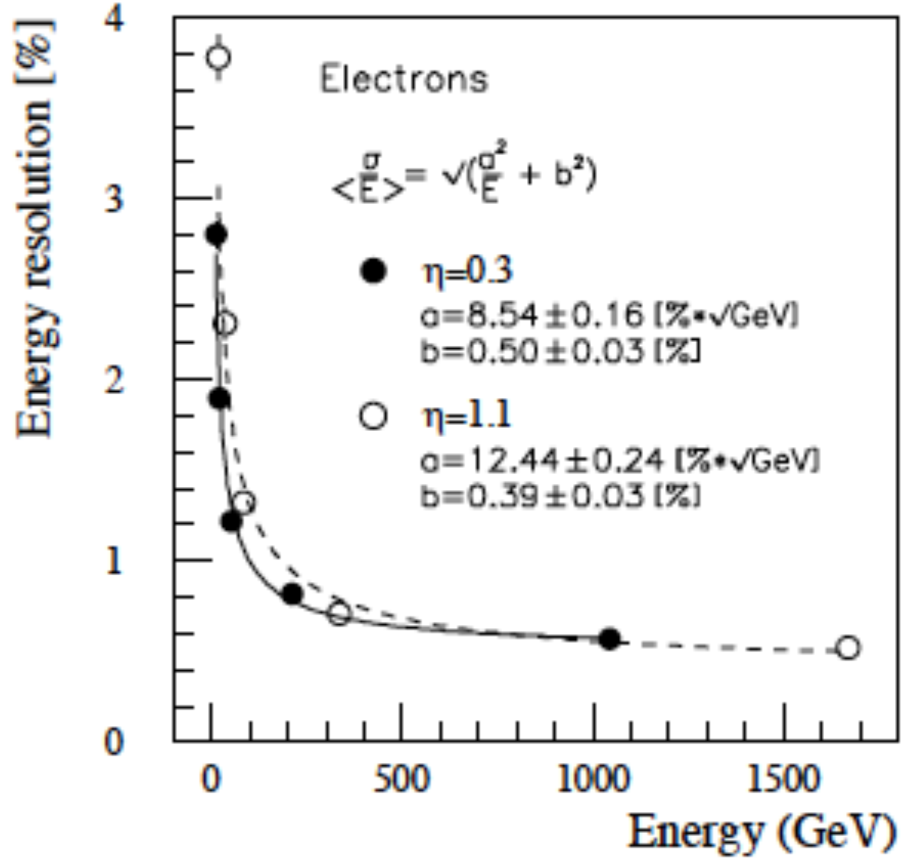
读出电子学噪声，堆积事例贡献等

ATLAS/CMS 能量分辨率

CMS ECAL



ATLAS ECAL



ATLAS/CMS 电磁量能器设计

As evident from Table 8, the ATLAS ECAL has been designed with both excellent lateral and longitudinal granularity, with samplings in depths optimized for energy loss corrections (presampler) and for shower-pointing accuracy together with γ/π^0 and electron/jet separation (strips). In contrast, the CMS EM crystal calorimeter has no longitudinal segmentation but a fine lateral granularity over most of the η-coverage, and much better intrinsic resolution (see Section 4.2 for more

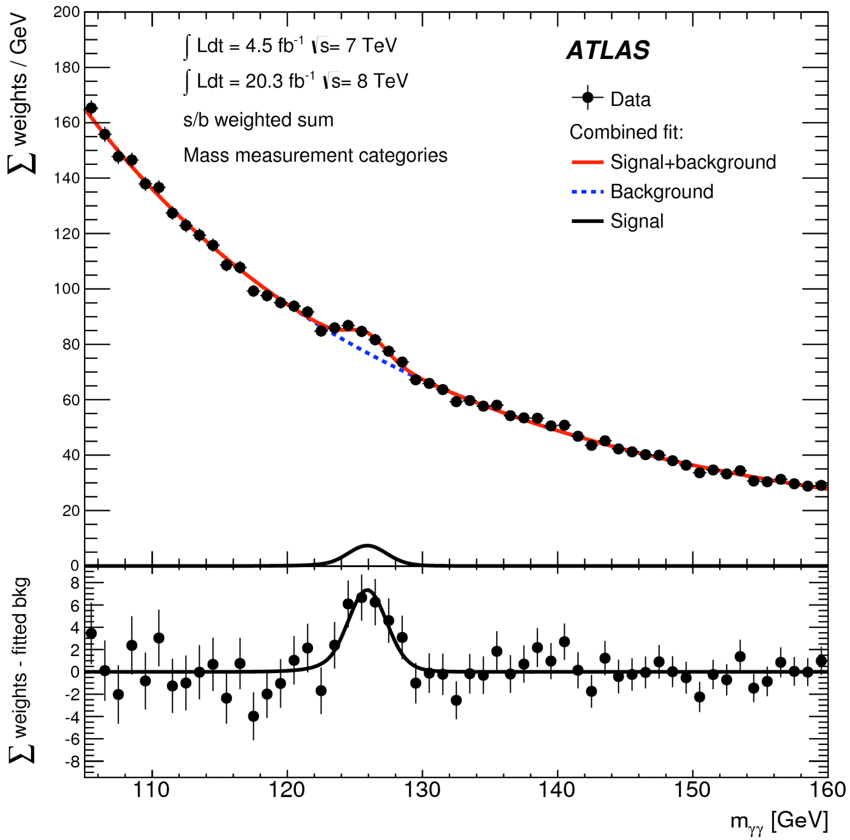
ATLAS/CMS 电磁量能器比较

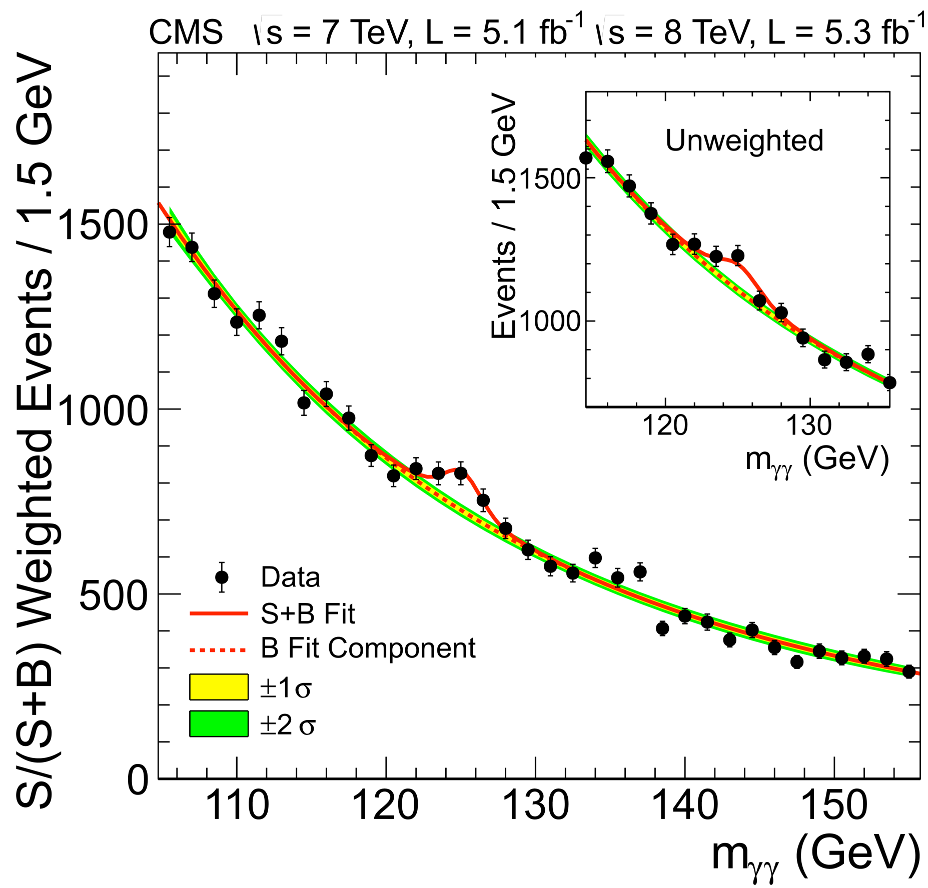
TABLE 8 Main parameters of the ATLAS and CMS electromagnetic calorimeters

	ATLAS		CMS	
Technology	Lead/LAr accordion		$PbWO_4$ scintillating crystals	
Channels	Barrel	End caps	Barrel	End caps
	110,208	63,744	61,200	14,648
Granularity	$\Delta\eta \times \Delta\phi$		$\Delta\eta \times \Delta\phi$	
Presampler	0.025×0.1	0.025×0.1		
Strips/ Si-preshower	0.003×0.1	0.003×0.1 to 0.006×0.1		32×32 Si-strips per 4 crystals
Main sampling	0.025×0.025	0.025×0.025	0.017×0.017	0.018×0.003 to 0.088×0.015
Back	0.05×0.025	0.05×0.025		
Depth	Barrel	End caps	Barrel	End caps
Presampler (LAr)	10 mm	2×2 mm		
Strips/ Si-preshower	$\approx 4.3\ X_0$	$\approx 4.0\ X_0$		$3\ X_0$
Main sampling	$\approx 16\ X_0$	$\approx 20\ X_0$	$26\ X_0$	$25\ X_0$
Back	$\approx 2\ X_0$	$\approx 2\ X_0$		
Noise per cluster	250 MeV	250 MeV	200 MeV	600 MeV
Intrinsic resolution	Barrel	End caps	Barrel	End caps
Stochastic term *a*	10%	10 to 12%	3%	5.5%
Local constant term *b*	0.2%	0.35%	0.5%	0.5%

电磁量能器性能

$\text{Higgs} \rightarrow \gamma\gamma$





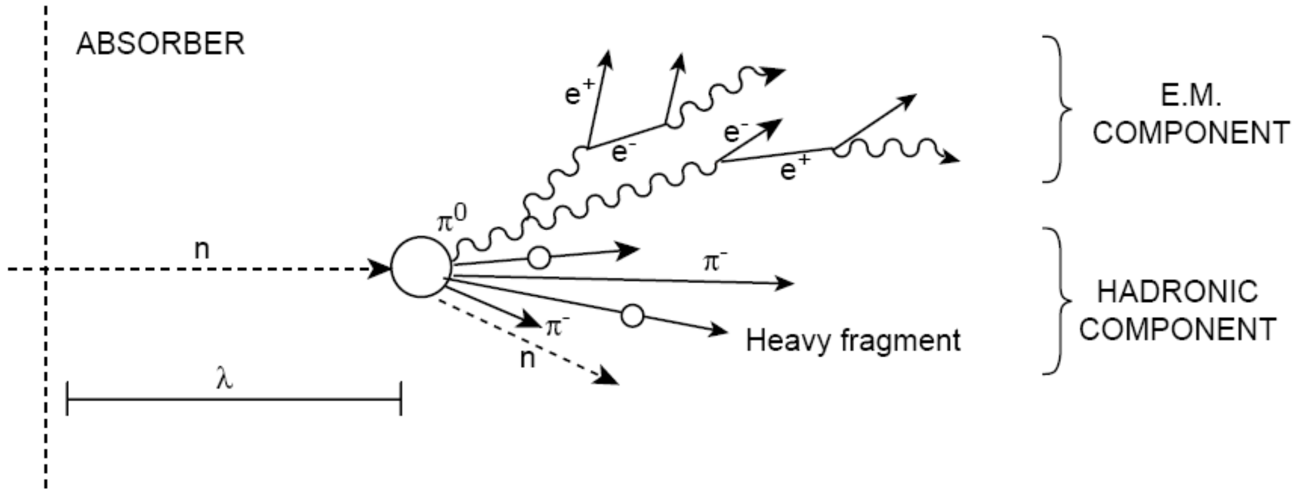
电磁量能器升级

- ATLAS电磁量能器液氩具有内禀抗辐照性能，可以承受高亮度升级后的强辐照，主体部分不需要升级，但是电子学需要升级。前向量能器考虑升级，可能的技术方案包括金刚石等。

- CMS电磁量能器的$PbWO_4$晶体光子辐照损伤可恢复，强子辐照则产生永久性损伤。端盖量能器必须替换，计划采用新型高颗粒度量能器（HGCAL），钨（吸收体）+硅（探测灵敏）读出。

强子簇射

- 强子簇射远比电磁簇射复杂，强子作用长度（Hadronic Interaction Length, λ_I）表示能量衰减到1/e处的相互作用长度。



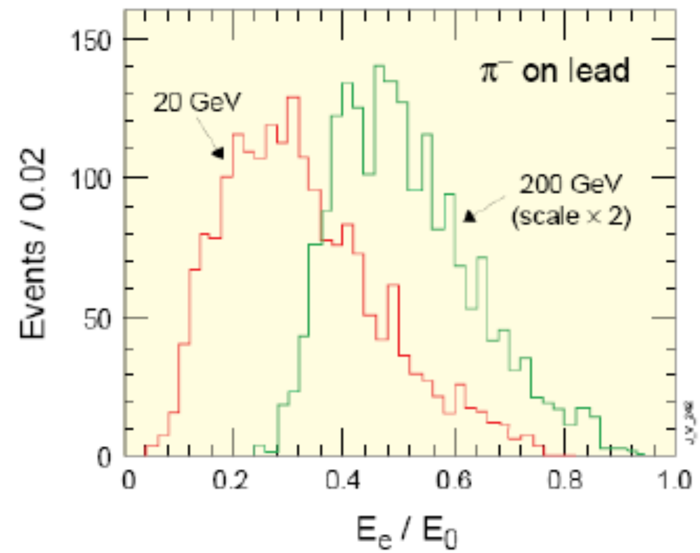
- 强子簇射纵向入射深度及横向宽度均显著大于电磁簇射，导致强子量能器体积明显大于电磁量能器。

能量测量

- 强子量能器分辨率很大程度上取决于“不可见”的损失能量，包括核激发伴随的延迟光子（通常不可探测），低能中子，核结合能等。“不可见”损失能量存在涨落，影响内禀分辨率。

Hadron energy dissipation in Pb

Nuclear break-up (invisible)	42%
Charged particle ionisation	43%
Neutrons with $T_N \sim 1$ MeV	12%
Photons with $E_\gamma \sim 1$ MeV	3%

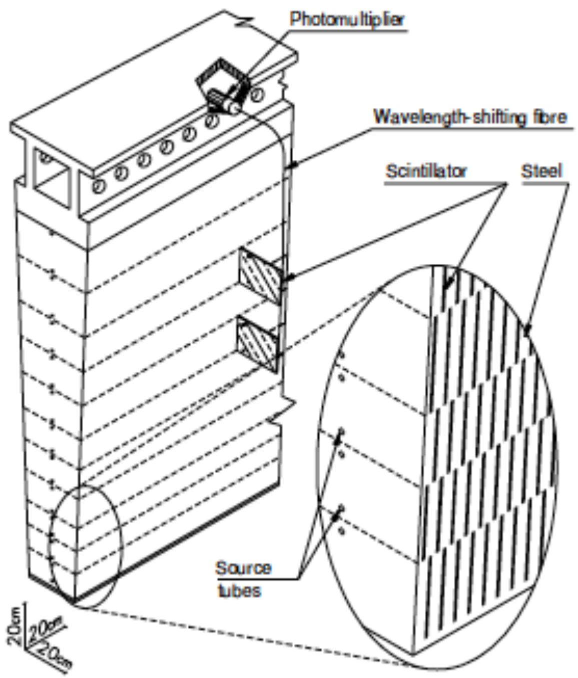


- 其它影响：量能器对于簇射中电磁分量的响应因能量而异。
- 总体而言，簇射中强子分量产生的信号弱于电磁分量，*e/h > 1*。

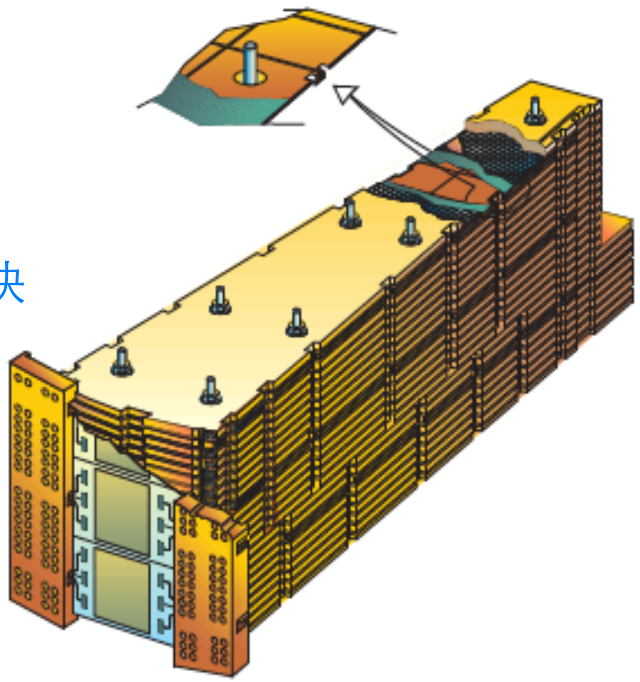
ATLAS 强子量能器

- 桶部量能器（$|\eta| < 1.0$以及$0.8 < |\eta| < 1.7$），钢（吸收体）+闪烁体（探测灵敏材料）；液氩端盖量能器（$1.5 < |\eta| < 3.2$），铜（吸收体）+液氩（探测灵敏测量）；前向量能器，铜/钨（吸收体）+液氩（探测灵敏测量）。

桶部模块

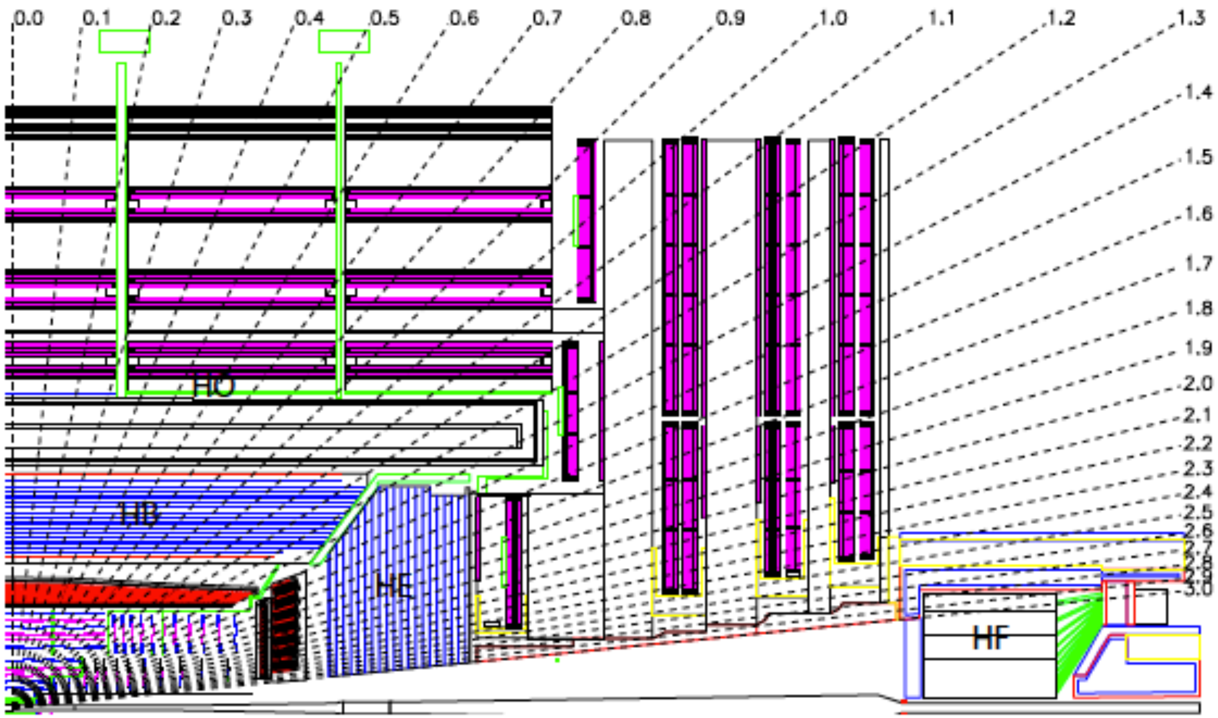


端盖模块



CMS 强子量能器

- 桶部（HB）/外层桶部（HO）/端盖（HE），主要吸收体为黄铜（70%铜+30%锌）；前向（HF）吸收体为钢，探测灵敏材料均为闪烁体



强子量能器分辨率

随机项 ***a***

常数项 ***b***

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} + b \cdot \left| \frac{\varepsilon_e}{\varepsilon_h} - 1 \right|$$

e/h > 1

补偿：增大ε_h、减小ε_e或是离线补偿（根据簇射精确数据单个事例修正）

ATLAS/CMS 强子量能器比较

TABLE 9 Main parameters of the ATLAS and CMS hadronic calorimeters

	ATLAS	CMS
Technology		
Barrel/Ext. barrel	14 mm iron/3 mm scint.	50 mm brass/3.7 mm scint.
End caps	25–50 mm copper/8.5 mm LAr	78 mm brass/3.7 mm scint.
Forward	Copper (front) - Tungsten (back)/0.25–0.50 mm LAr	Steel/0.6 mm quartz
Channels		
Barrel/Ext. barrel	9852	2592
End caps	5632	2592
Forward	3524	1728
Granularity ($\Delta\eta \times \Delta\phi$)		
Barrel/Ext. barrel	0.1×0.1 to 0.2×0.1	0.087×0.087
End caps	0.1×0.1 to 0.2×0.2	0.087×0.087 to 0.18×0.175
Forward	0.2×0.2	0.175×0.175
Samplings ($\Delta\eta \times \Delta\phi$)		
Barrel/Ext. barrel	3	1
End caps	4	2
Forward	3	2
Abs. lengths (min.-max.)		
Barrel/Ext. barrel	9.7–13.0	7.2–11.0 10–14 (with coil/HO)
End caps	9.7–12.5	9.0–10.0
Forward	9.5–10.5	9.8

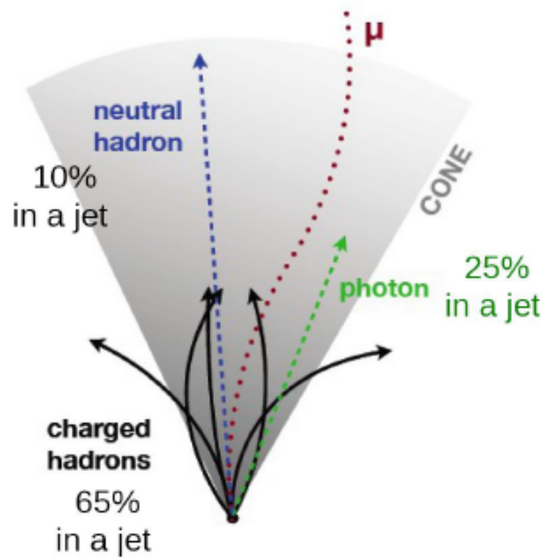
ATLAS/CMS 量能器能量分辨率

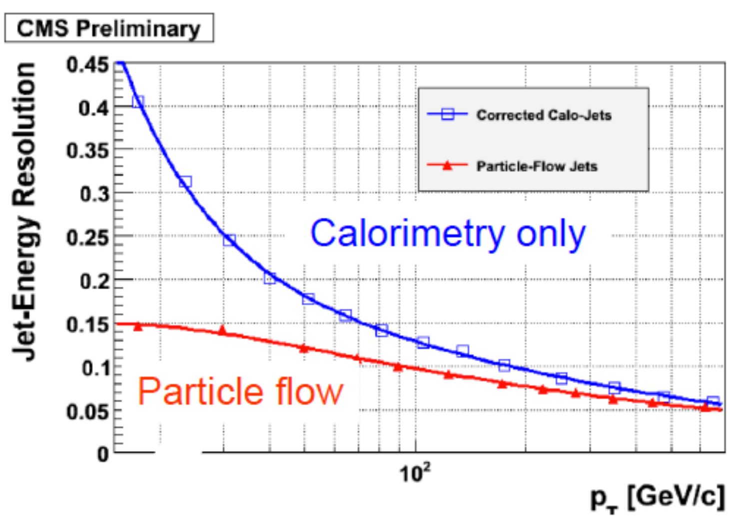
TABLE 10 Main performance parameters of the different hadronic calorimeter components of the ATLAS and CMS detectors, as measured in test beams using charged pions in both stand-alone and combined mode with the ECAL

	ATLAS				CMS	
	Barrel LAr/Tile		End-cap LAr			
	Tile	Combined	HEC	Combined	Had. barrel	Combined
Electron/hadron ratio	1.36	1.37	1.49			
Stochastic term	$45\%/\sqrt{E}$	$55\%/\sqrt{E}$	$75\%/\sqrt{E}$	$85\%/\sqrt{E}$	$100\%/\sqrt{E}$	$70\%/\sqrt{E}$
Constant term	1.3%	2.3%	5.8%	$< 1\%$		8.0%
Noise	Small	3.2 GeV		1.2 GeV	Small	1 GeV

The measured electron/hadron ratios are given separately for the hadronic stand-alone and combined calorimeters when available, and the contributions (added quadratically except for the stand-alone ATLAS tile calorimeter) to the pion energy resolution from the stochastic term, the local constant term, and the noise are also shown, when available from published data.

粒子流算法（PFA）





Make combined use of

- Tracker information
- fine grained information from the ECAL and HCAL detectors

Particle Flow Calorimetry

- Charged particles measured with tracker when better
- Photons measured in ECAL
- Leaves only neutral hadrons in HCAL (+ECAL)

Only 10% of the jet energy (the neutral hadrons) left to be measured in the poorer resolution HCAL

Dramatic improvements for overall jet energy resolution

课程 IV

缪子探测器系统

缪子探测器主要考虑

1. Resolution: The "golden" decay of the Standard Model Higgs boson into four muons, $H \rightarrow ZZ \rightarrow 4\mu$, requires the ability to reconstruct the momentum and thus the mass of a narrow two-muon state with a precision of 1%. At the upper end of the spectrum, both experiments aim at a 10% momentum resolution for 1 TeV muons.

   动量分辨率

2. Wide rapidity coverage: Almost two-thirds of the decays of an intermediate-mass Higgs boson to four muons have at least one muon in the region $|\eta| > 1.4$. A hermetic system, which measures muons to $|\eta| \sim 2.5$, is the best compromise.

   探测器覆盖范围

3. Identification inside dense environments, e.g., hadronic jets or regions with high backgrounds.

   粒子甄别

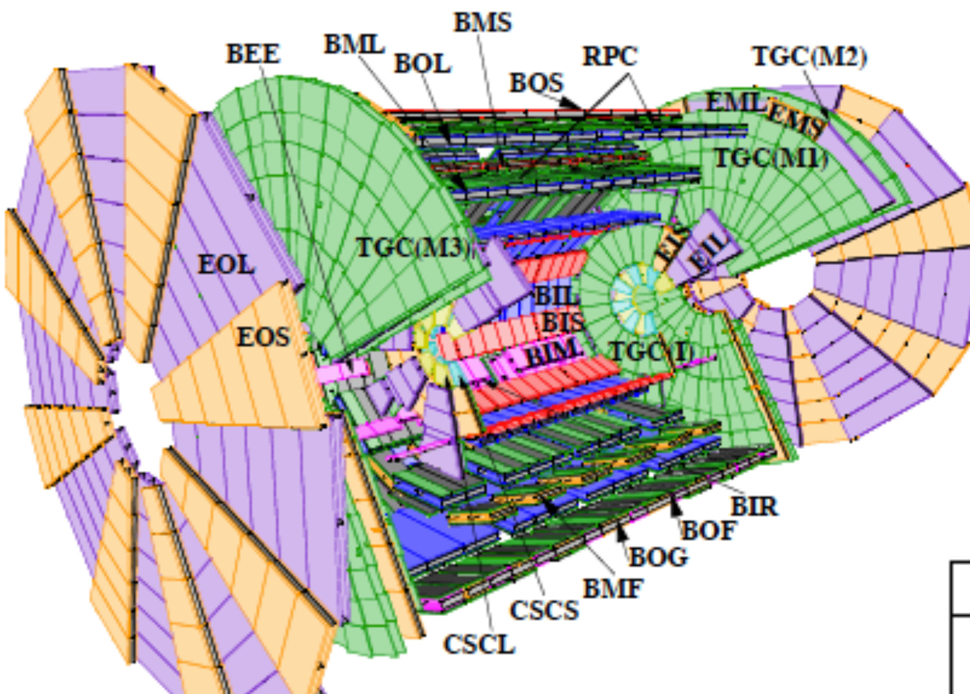
4. Trigger: The ability to measure the momenta of muons online on a stand-alone basis, i.e., without reference to any other detector subsystem, and to select events with muons above 5–10 GeV momentum is of paramount importance.

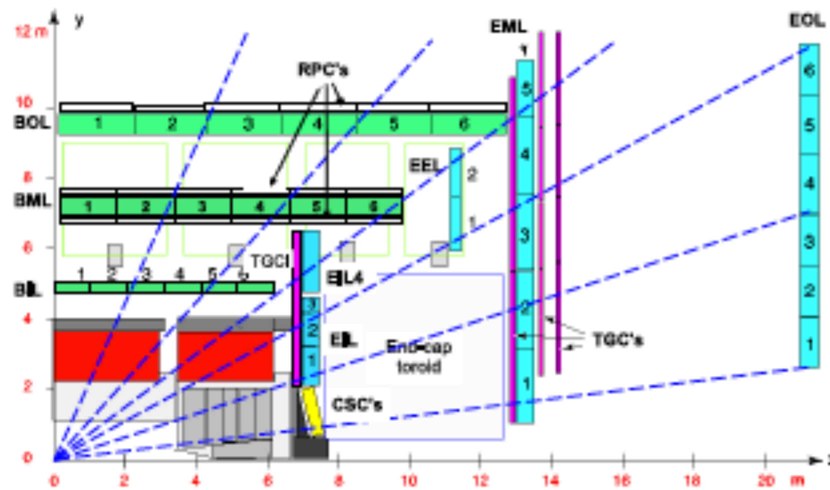
   触发

ATLAS 缪子探测器

- ATLAS 缪子探测器按照区域、功能采用多种探测器技术：

  Monitored Drift Tube chamber (**MDT**), Cathode-Strip Chambers (**CSC**), Resistive Plate Chambers (**RPC**), Thin Gap Chambers (**TGC**)



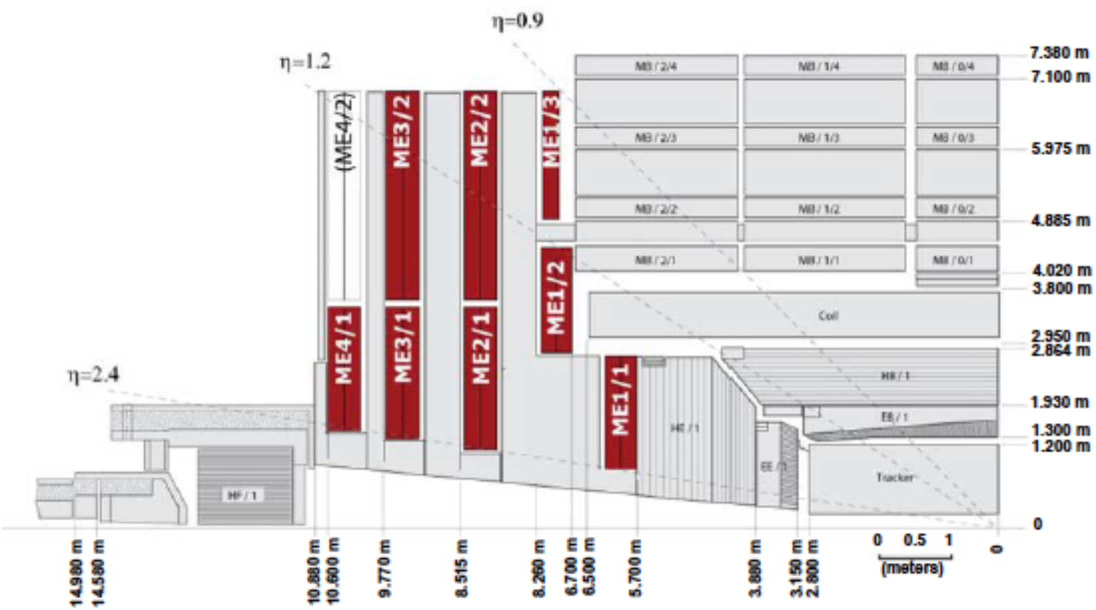


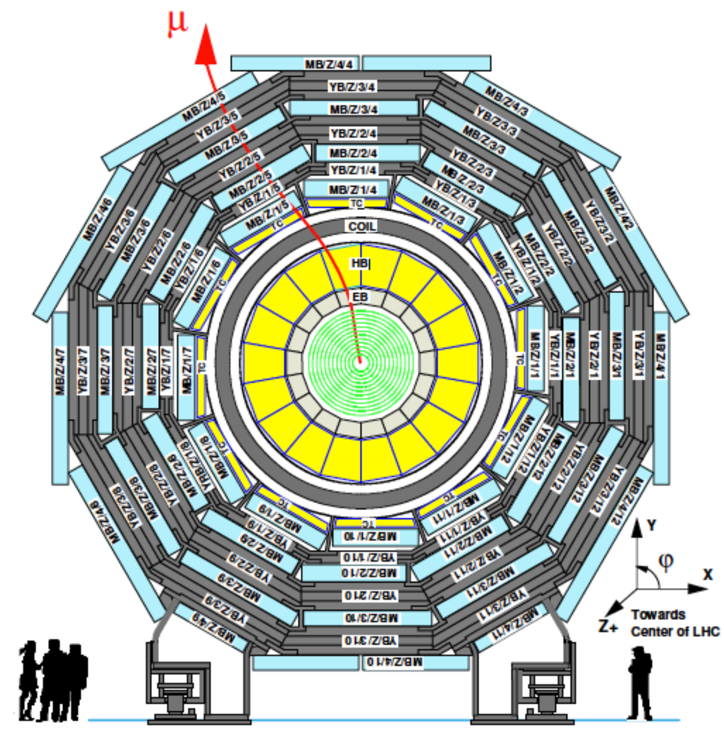
Type	Function	Chamber resolution (RMS) in z/R	φ	time
MDT	tracking	35 μm (z)	—	—
CSC	tracking	40 μm (R)	5 mm	7 ns
RPC	trigger	10 mm (z)	10 mm	1.5 ns
TGC	trigger	2–6 mm (R)	3–7 mm	4 ns

CMS 缪子探测器

- CMS 缪子探测器探同样采用多种测器技术:

  Drift Tube (**DT**), Cathode-Strip Chambers (**CSC**), Resistive Plate Chambers (**RPC**)

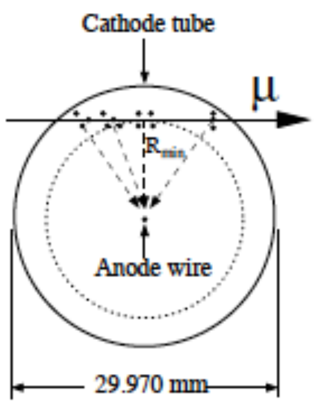




MDT

桶部内层 $|\eta| < 2.0$ 外层$|\eta| < 2.7$, 寻迹

- 漂移管内充加压混合气体（氩/二氧化碳, 93/7），钨-铼阳极丝（直径50微米，加高压3080V）收集电离产生的电子。



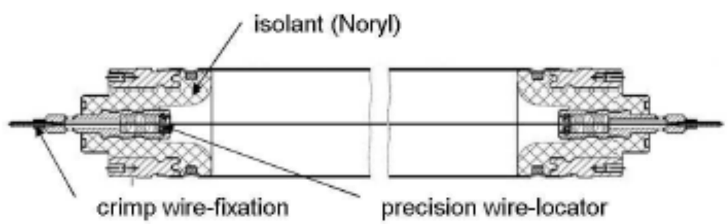


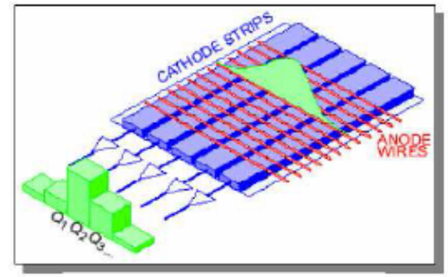
Table 6.2: Main MDT chamber parameters.

Parameter	Design value
Tube material	Al
Outer tube diameter	29.970 mm
Tube wall thickness	0.4 mm
Wire material	gold-plated W/Re (97/3)
Wire diameter	50 μm
Gas mixture	$Ar/CO_2/H_2O$ (93/7/$\leq$ 1000 ppm)
Gas pressure	3 bar (absolute)
Gas gain	2 x 10^4
Wire potential	3080 V
Maximum drift time	$\sim$ 700 ns
Average resolution per tube	$\sim$ 80 μm

- 位置精度可至35微米，用作径迹测量。但是高光子本底环境下精度会下降。计数率低于150 Hz/cm^2。

CSC

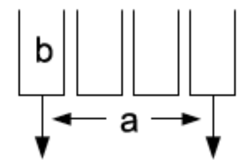
端盖 $2.0 < |\eta| < 2.7$，寻迹

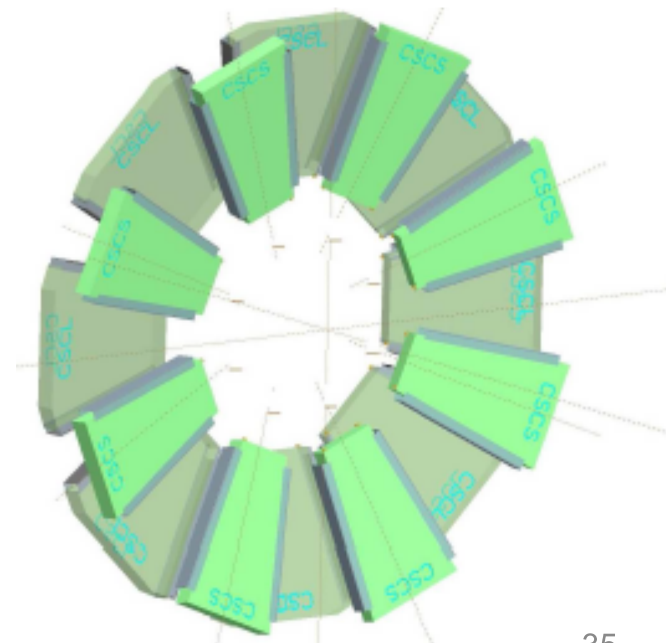


- 多丝正比室中的丝按径向排列

Table 6.6: Operating parameters of the CSC's.

Parameter	Value
Operating voltage	1900 V
Anode wire diameter	30 μm
Gas gain	6×10^4
Gas mixture	Ar/CO_2 (80/20)
Total ionisation (normal track)	90 ion pairs





- 主要优点:
  - 双径迹分辨，位置分辨 40 微米
  - 电子漂移时间小于40ns，时间分辨7ns
  - 体积小，不含氢，对中子本底不敏感
  - 计数率可至 1000 Hz/cm^2

RPC

桶部 $|\eta| < 1.05$，触发

- 平行电极板之间充工作气体，径迹穿越时电离并形成雪崩放大，电荷再被电极收集，时间分辨1.5ns。

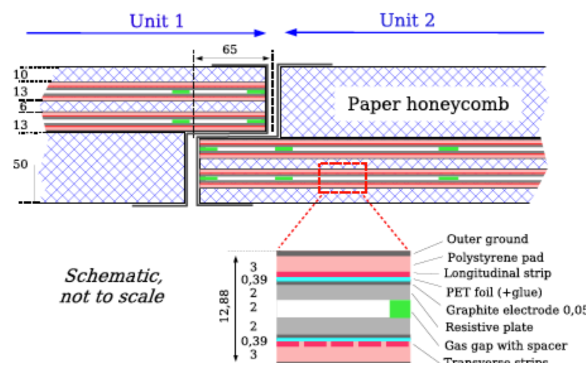
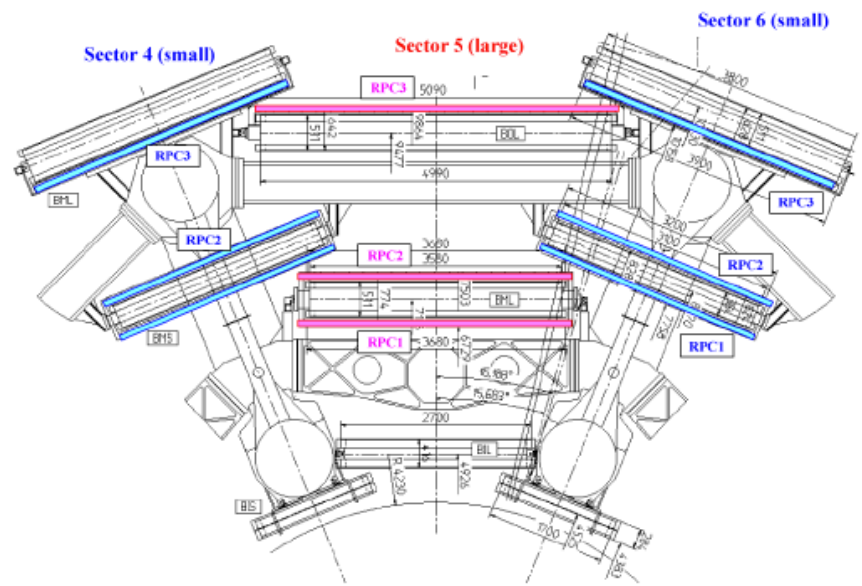


Table 6.10: RPC parameters and performance.

Parameter	Design value
E-field in gap	4.9 kV/mm
Gas gap	2 mm
Gas mixture	$C_2H_2F_4/Iso\text{-}C_4H_{10}/SF_6$ (94.7/5/0.3)
Readout pitch of η and ϕ-strips	23–35 mm
Detection efficiency per layer	$\geq$98.5%
Efficiency including spacers and frames	$\geq$97%
Intrinsic time jitter	$\leq$1.5 ns
Jitter including strip propagation time	$\leq$10 ns
Local rate capability	$\sim$1 kHz/cm^2
Streamer probability	$\leq$1%



TGC

端盖$1.05 < |\eta| < 2.4$，触发

- 多丝正比室，丝-阴极间距（1.4 毫米）小于丝间距（1.8毫米），内充工作气体，高增益（3×10^5）。
- 时间分辨率~4 ns。

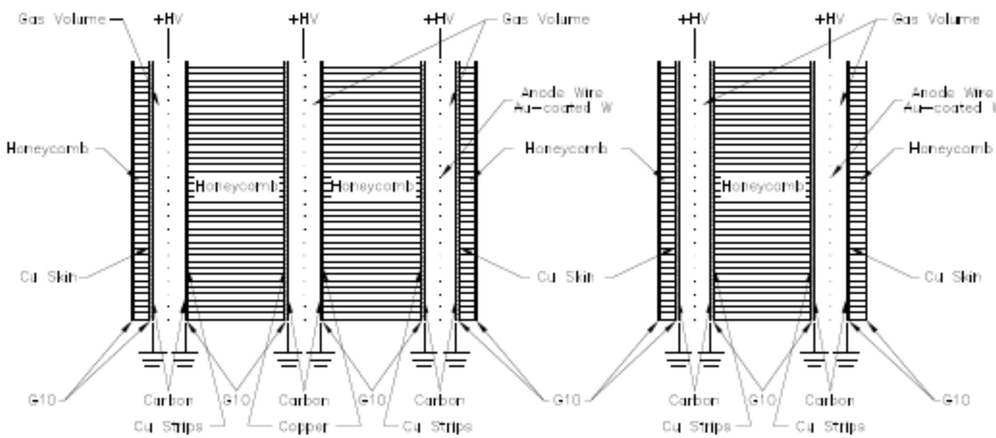


Figure 6.32: Cross-section of a TGC triplet and doublet module. The triplet has three wire layers but only two strip layers. The dimensions of the gas gaps are enlarged with respect to the other elements.

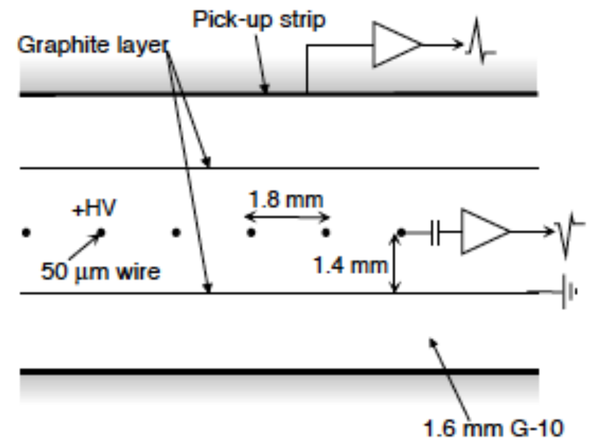


Table 6.12: Main TGC operational parameters.

Parameter	Design value
Gas gap	2.8 ± 0.10 mm
Wire pitch	1.8 ± 0.05 mm
Wire diameter	50 μm
Wire potential	2900 ± 100 V
Operating plateau	200 V
Gas mixture	CO_2/n-pentane (55/45)
Gas amplification	3×10^5

ATLAS /CMS 缪子探测器参数比较

TABLE 11 Main parameters of the ATLAS and CMS muon chambers

	ATLAS	CMS
Drift Tubes	MDTs	DTs
-Coverage	$\|\eta\| < 2.0$	$\eta\| < 1.2$
-Number of chambers	1170	250
-Number of channels	354,000	172,000
-Function	Precision measurement	Precision measurement, triggering
Cathode Strip Chambers		
-Coverage	$2.0 < \|\eta\| < 2.7$	$1.2 < \|\eta\| < 2.4$
-Number of chambers	32	468
-Number of channels	31,000	500,000
-Function	Precision measurement	Precision measurement, triggering
Resistive Plate Chambers		
-Coverage	$\|\eta\| < 1.05$	$\|\eta\| < 2.1$
-Number of chambers	1112	912
-Number of channels	374,000	160,000
-Function	Triggering, second coordinate	Triggering
Thin Gap Chambers		
-Coverage	$1.05 < \|\eta\| < 2.4$	—
-Number of chambers	1578	—
-Number of channels	322,000	—
-Function	Triggering, second coordinate	—

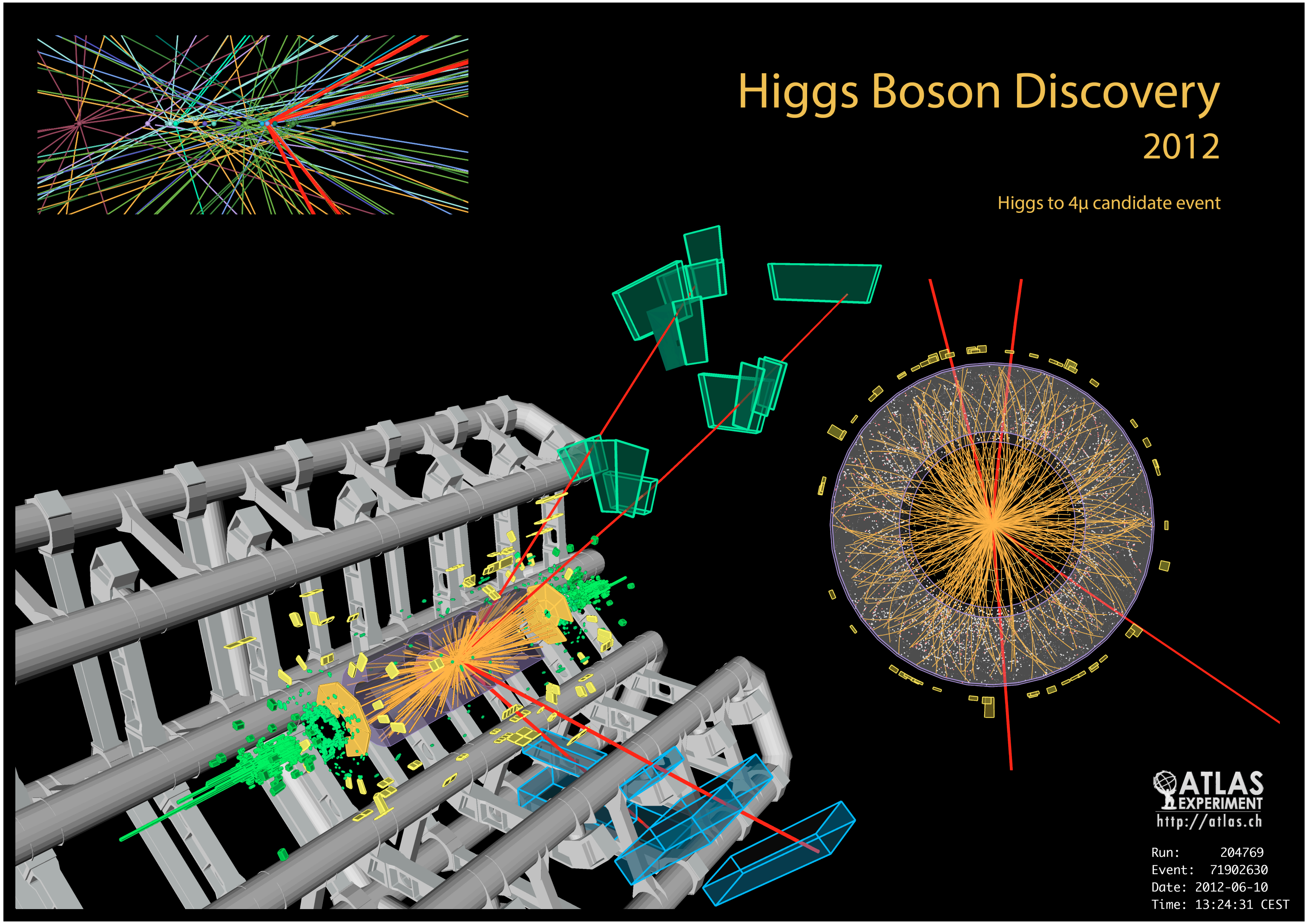
ATLAS /CMS 缪子探测性能比较

TABLE 12 Main parameters of the ATLAS and CMS muon measurement systems as well as a summary of the expected combined and stand-alone performance at two typical pseudorapidity values (averaged over azimuth)

Parameter	ATLAS	CMS
Pseudorapidity coverage		
-Muon measurement	$\|\eta\| < 2.7$	$\|\eta\| < 2.4$
-Triggering	$\|\eta\| < 2.4$	$\|\eta\| < 2.1$
Dimensions (m)		
-Innermost (outermost) radius	5.0 (10.0)	3.9 (7.0)
-Innermost (outermost) disk (z-point)	7.0 (21–23)	6.0–7.0 (9–10)
Segments/superpoints per track for barrel (end caps)	3 (4)	4 (3–4)
Magnetic field B (T)	0.5	2
-Bending power (BL, in T· m) at $\|\eta\| \approx 0$	3	16
-Bending power (BL, in T· m) at $\|\eta\| \approx 2.5$	8	6
Combined (stand-alone) momentum resolution at		
-p = 10 GeV and $\eta \approx 0$	1.4% (3.9%)	0.8% (8%)
-p = 10 GeV and $\eta \approx 2$	2.4% (6.4%)	2.0% (11%)
-p = 100 GeV and $\eta \approx 0$	2.6% (3.1%)	1.2% (9%)
-p = 100 GeV and $\eta \approx 2$	2.1% (3.1%)	1.7% (18%)
-p = 1000 GeV and $\eta \approx 0$	10.4% (10.5%)	4.5% (13%)
-p = 1000 GeV and $\eta \approx 2$	4.4% (4.6%)	7.0% (35%)

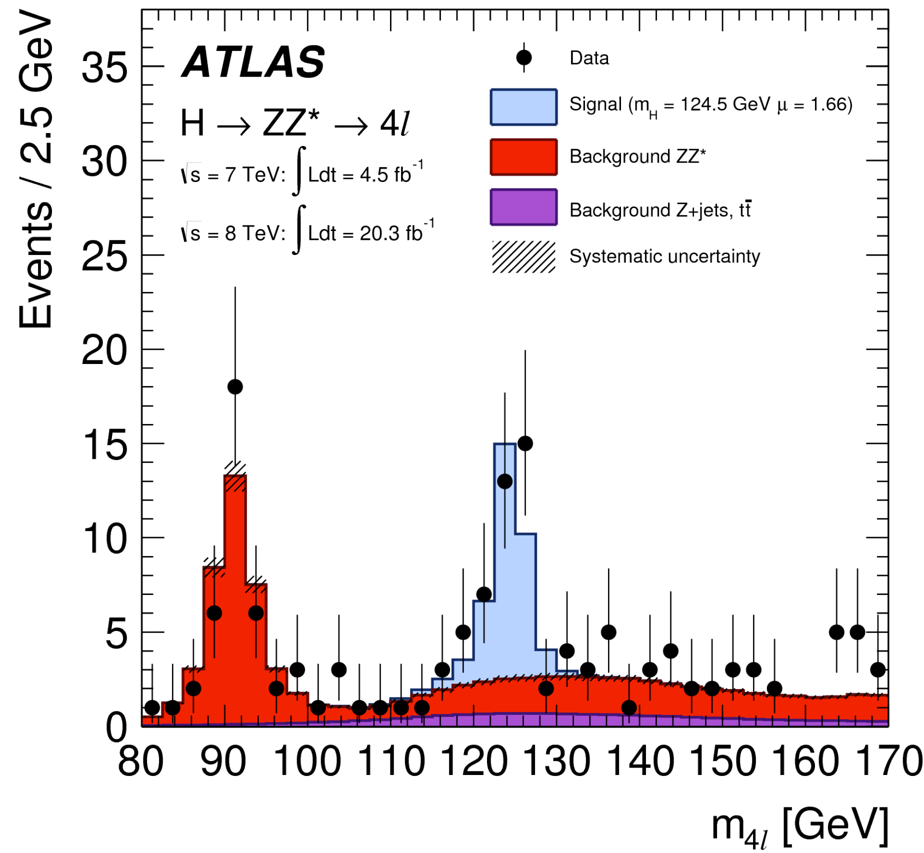
Higgs事例

$$H \to ZZ^* \to 4\mu$$



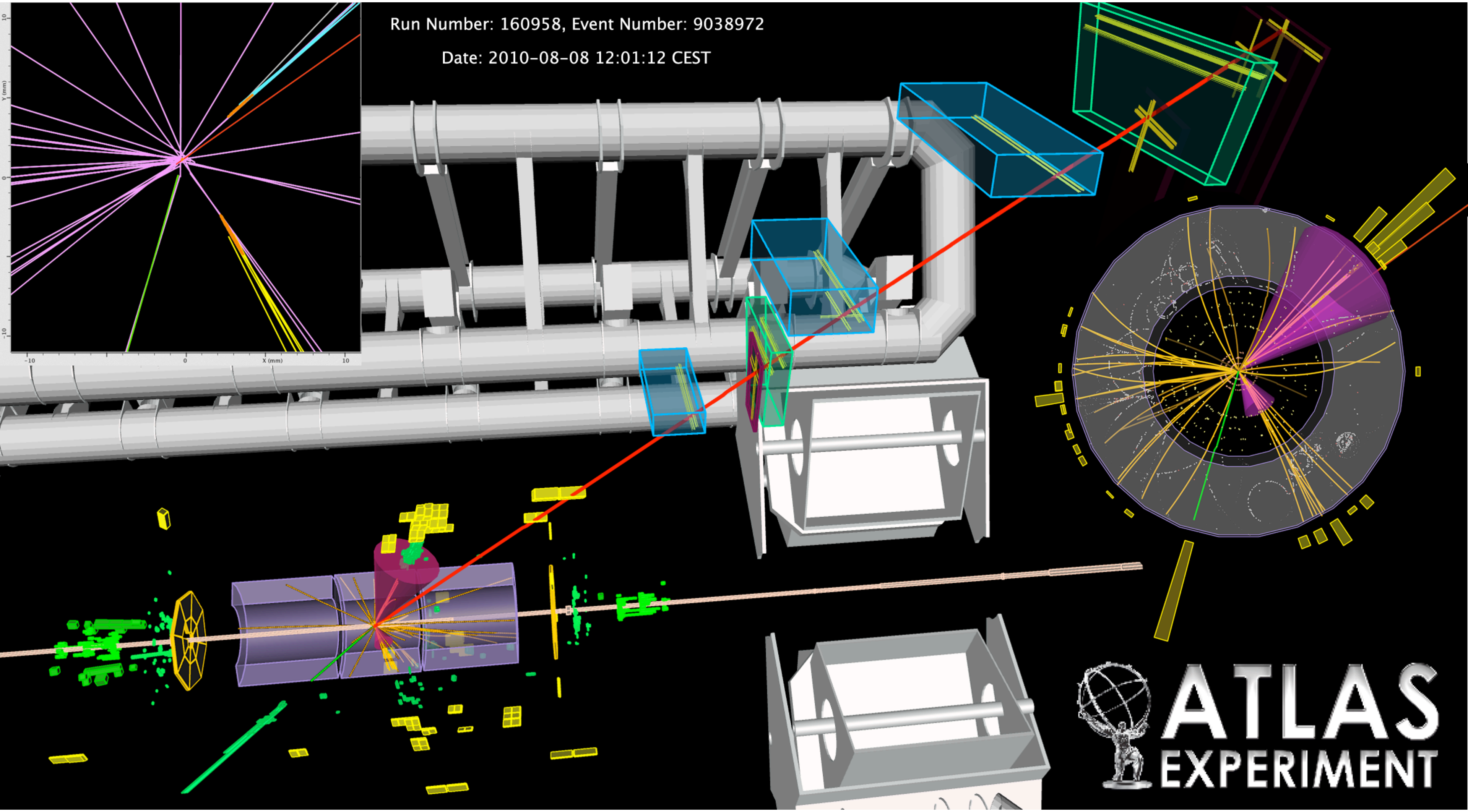
Higgs质量

- 4轻子不变质量谱，Higgs信号与本底分离，依赖于缪子、电子的准确甄别（+事例拓扑），动量/能量的精确测量。



顶夸克对事例

末态：电子、缪子、（*b*-）喷注，完整事例重建依赖于几乎所有子探测器



总结

- 简单介绍 ATLAS/CMS 探测器基本结构（通用探测器），主要探测器技术及相关概念，具体原理略过。

- 在开展物理分析的同时，掌握探测器概念，具备一定的探测器/电子学制作和操作经验非常重要。