CMS 探测器

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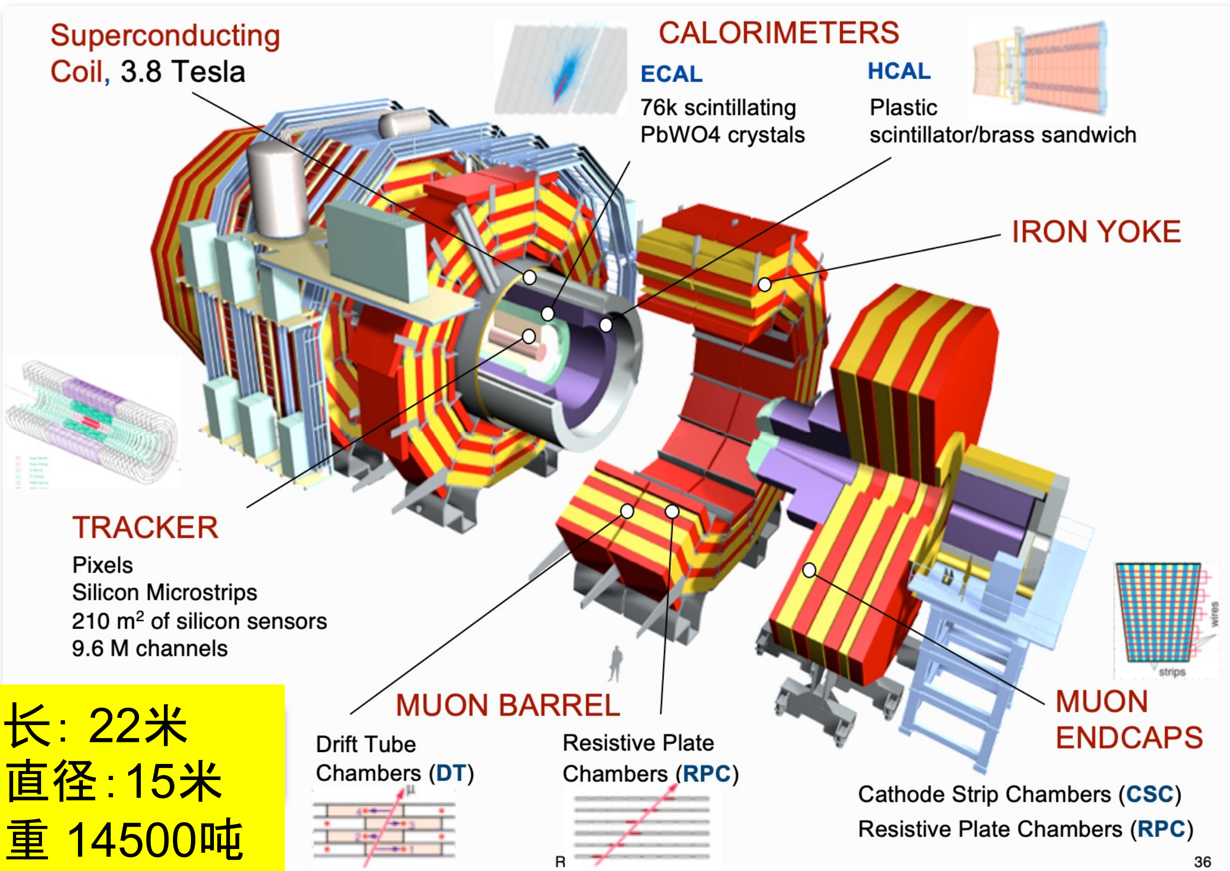
Ref. CMS induction course

CMS 探测器介绍

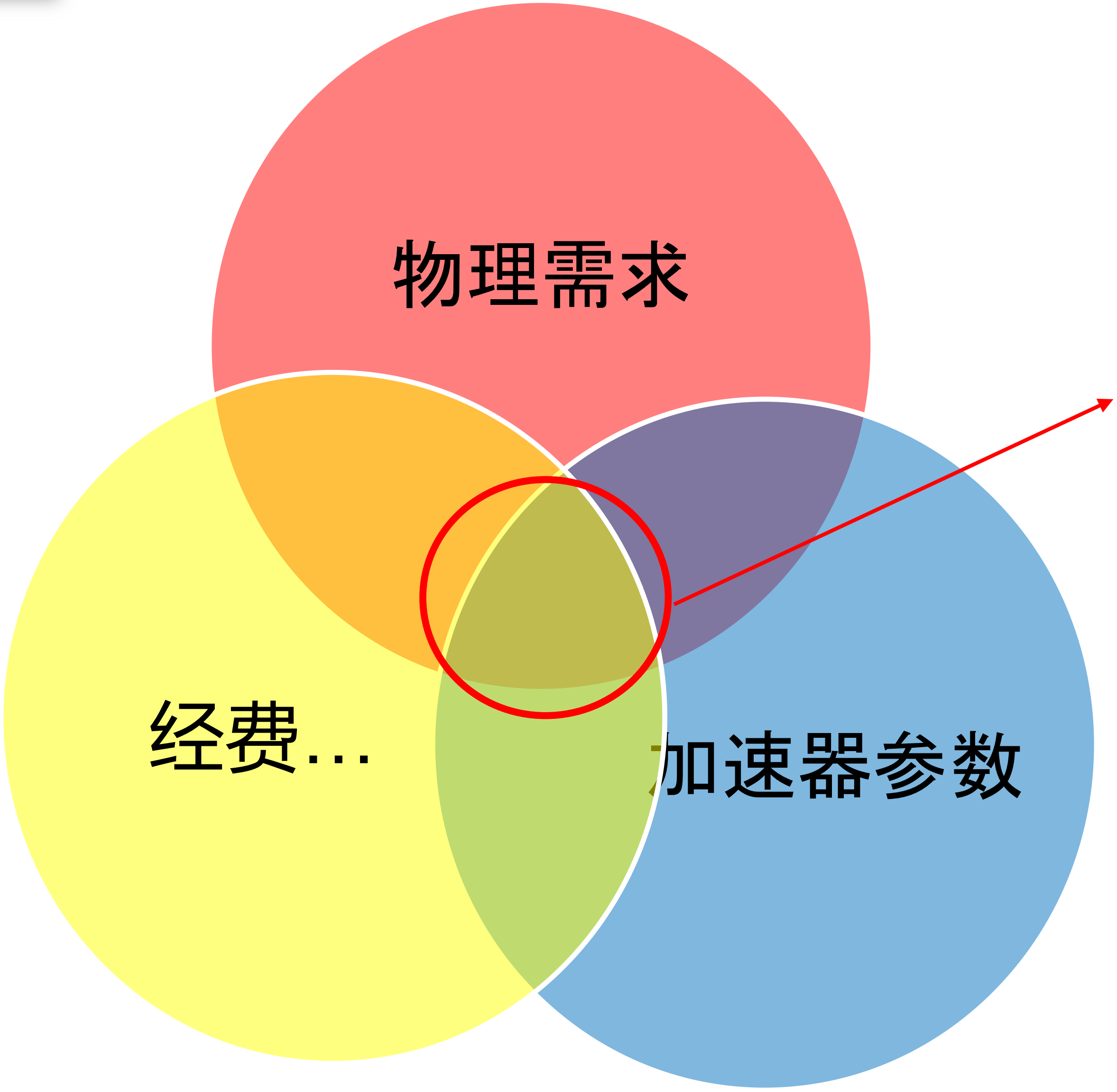
- CMS：Compact Muon Solenoid（紧凑谬子螺线管）
  - 1990 Aachen: 提出基于高磁场强度的紧凑性探测器设想
  - 1992 Evian：概念设计报告
  - 2008 首次LHC数据取数

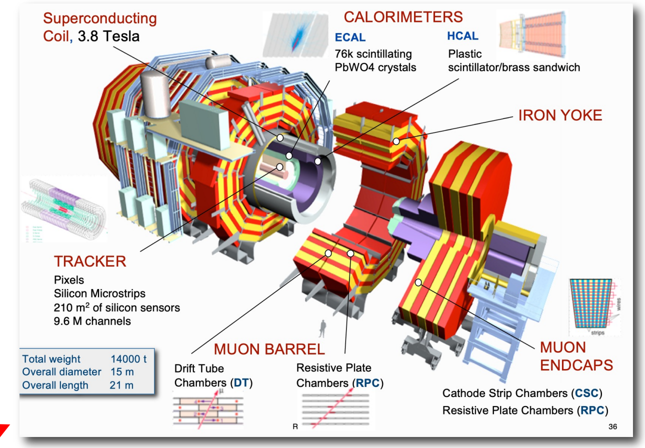


长：22米
直径：15米
重 14500吨

- 中国1990s加入CMS
- 1998与CMS签订正式合作，参与单位：高能所，北大，科大；后发展到清华，中山，北航，复旦，浙大，南师大
- 参与建造CSC/RPC，一期升级的CPPF触发电子学系统，以及二期升级到HGC，GEM，trigger，MTD等

为什么CMS探测器如此设计建造

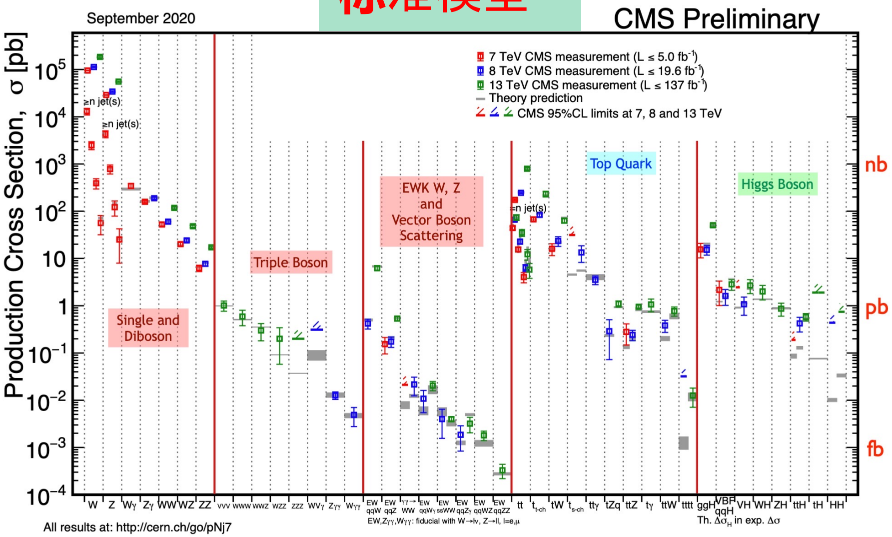




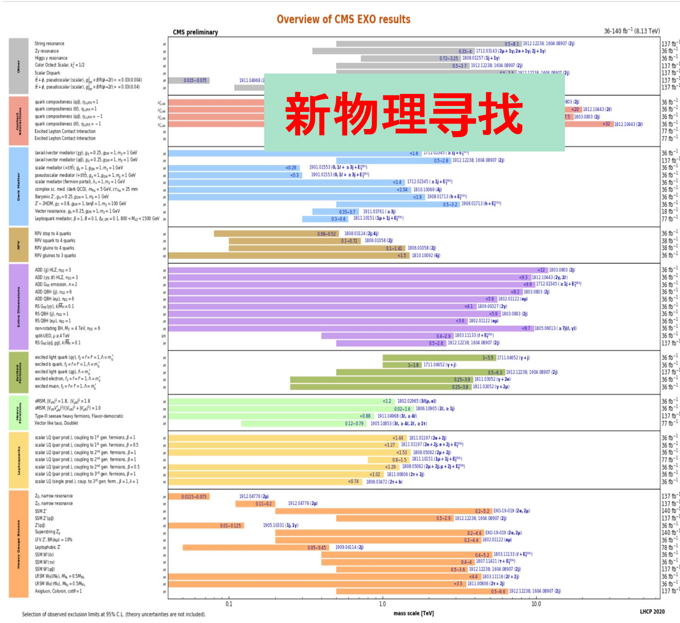
CMS 物理需求

- 物理目标

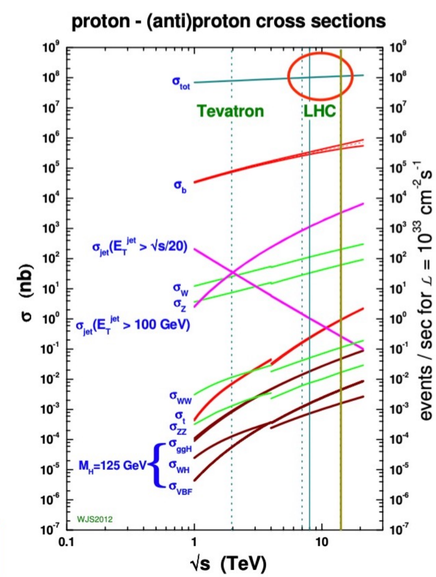
标准模型

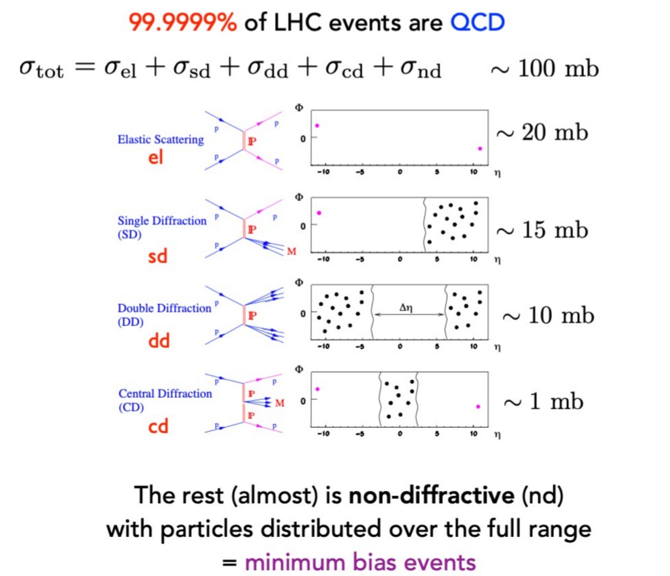


新物理寻找



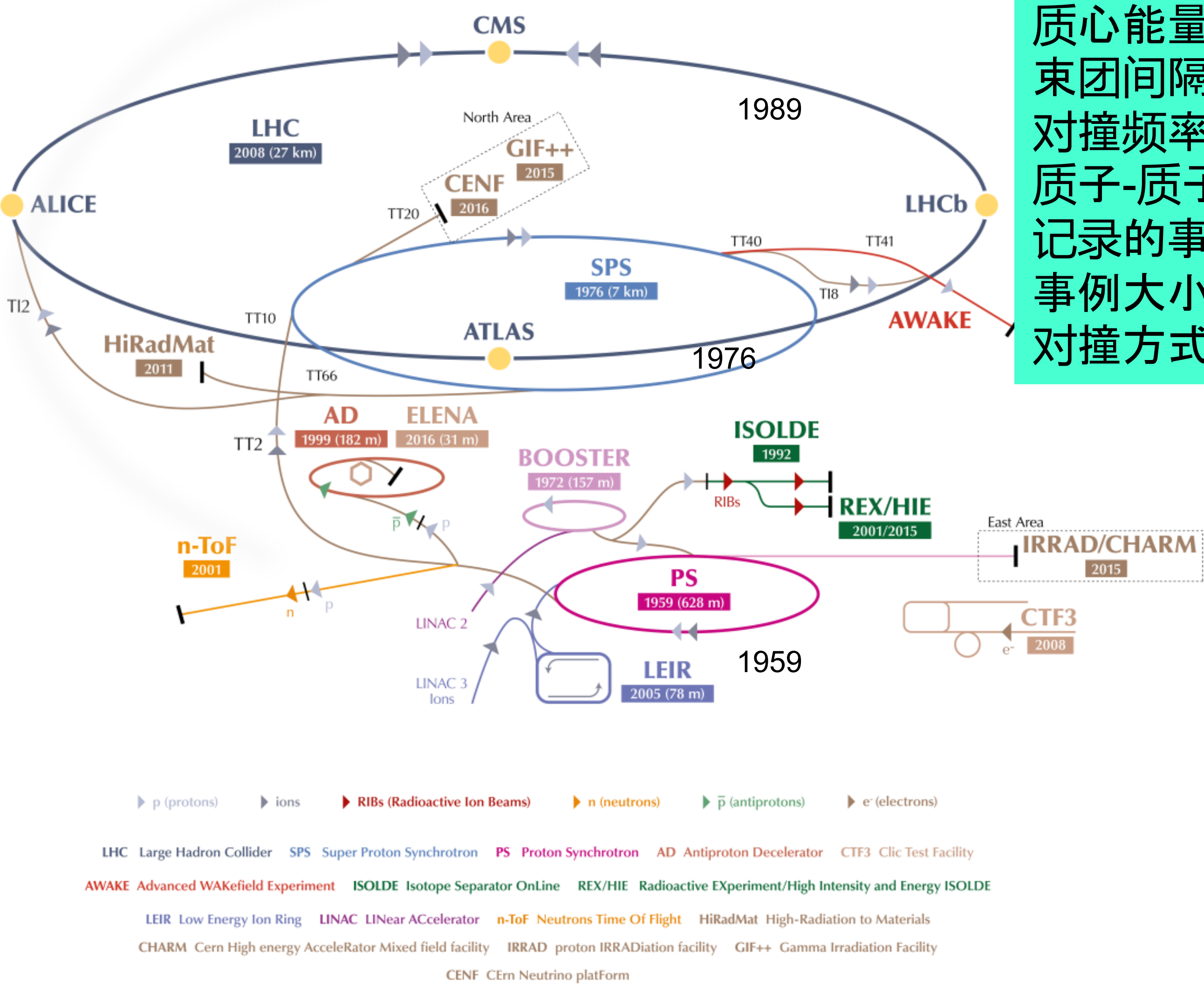
- 真实物理过程





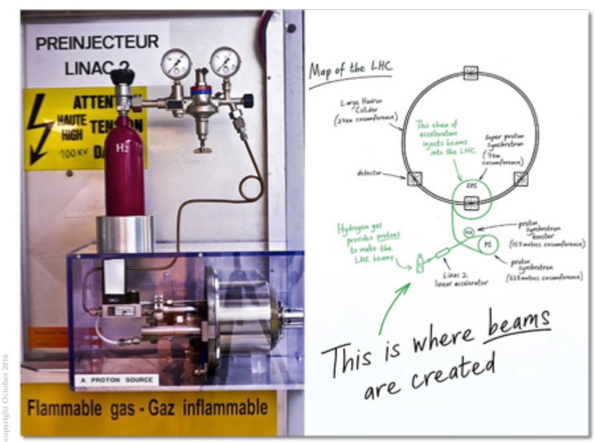
LHC和CERN

LHC 加速器系统



高能量前沿

质心能量：0.9,2.36,7,8，13/14 TeV
束团间隔: 50 - 25 纳秒
对撞频率: 2000万-4000万/ 秒
质子-质子对撞: 20亿次 /秒
记录的事例: ~1000 - 3000 / 秒
事例大小：1-2 MB
对撞方式：p-p;pb-pb;p-pb;Xe-Xe…

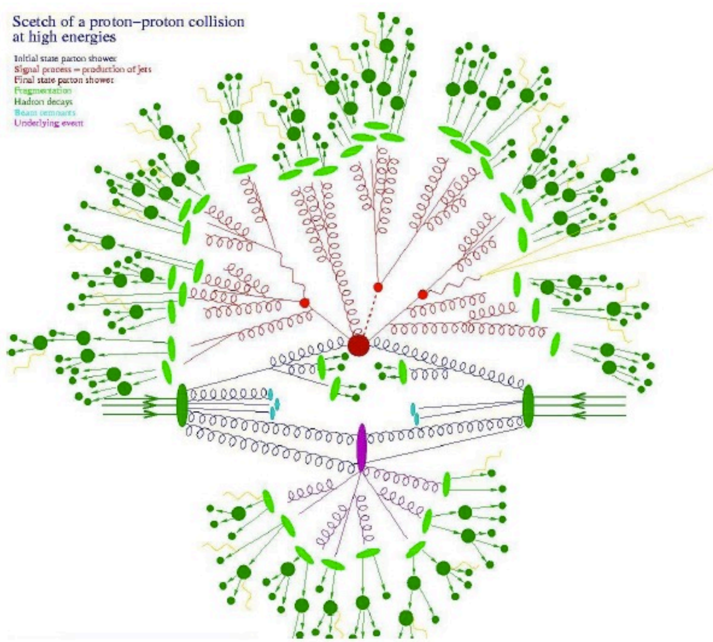


PS booster：1.4 GeV
PS: 25 GeV
SPS: 450 GeV
LHC: 6.5/7TeV

CMS 探测器面临的挑战

Proton bunch

Proton bunch



单个质子对的核反应

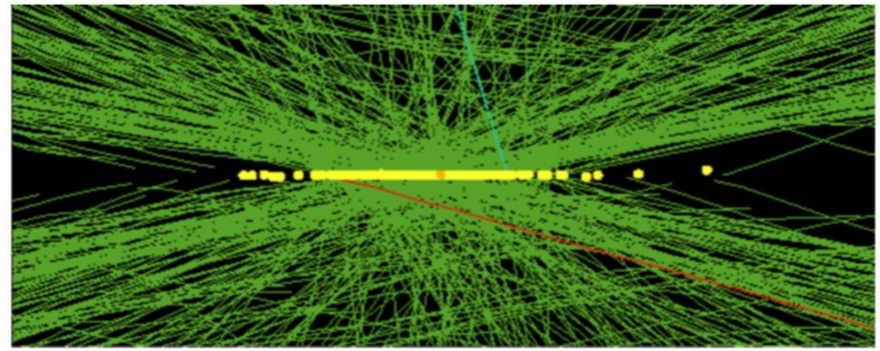
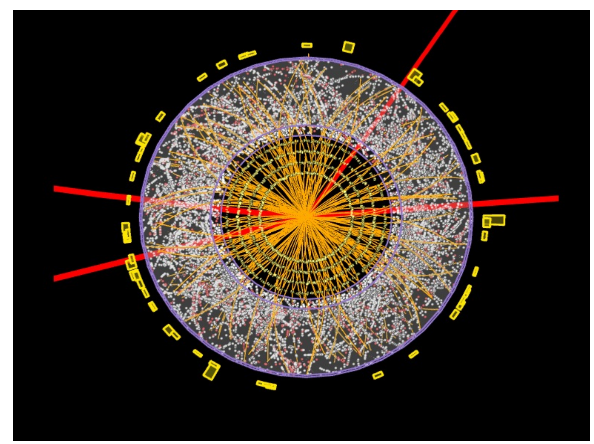


Figure 1.16: High pileup event with 78 reconstructed vertices taken in 2012

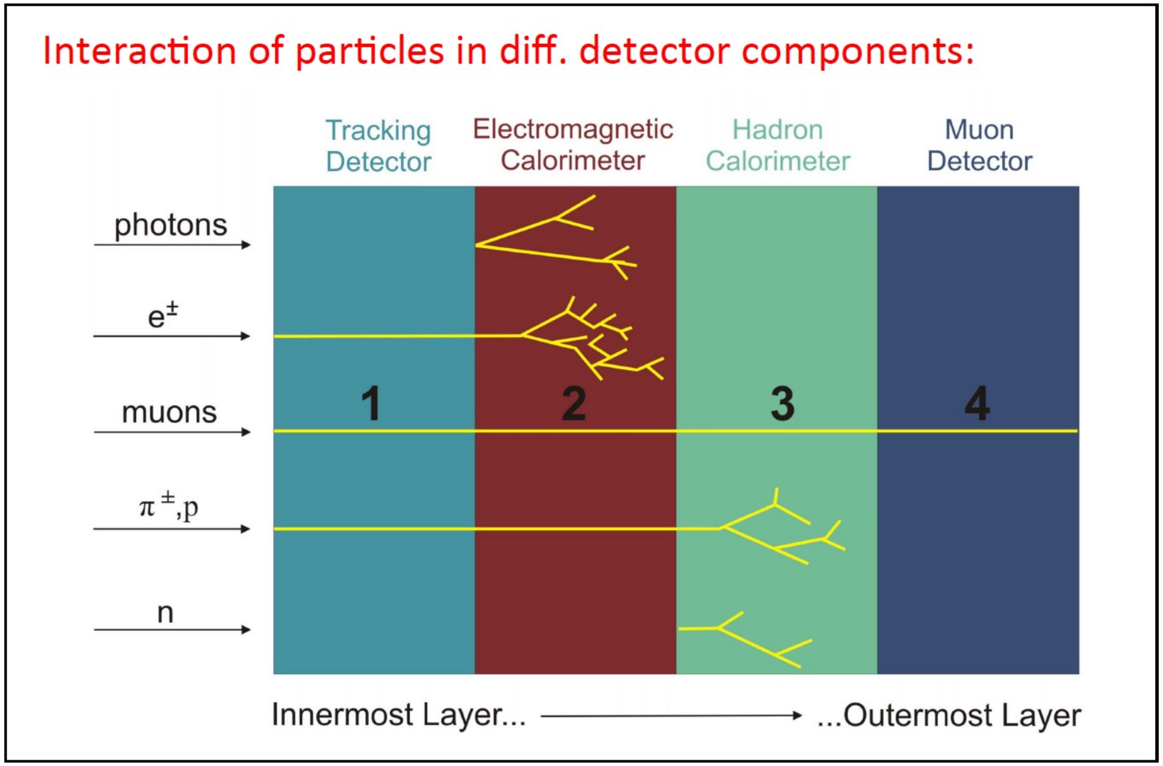
LHC CMS实验中的一次束团对撞



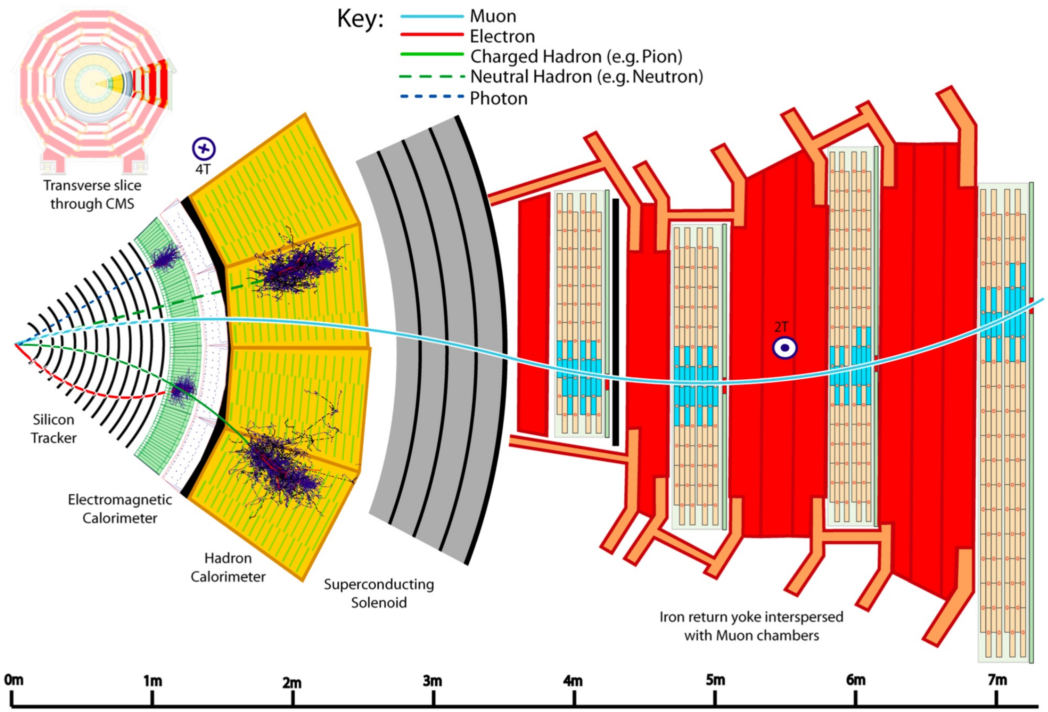
每秒对撞4000万次@～20年

- 借我一双慧眼，让我把这纷扰看的清清楚楚明明白白真真切切

- 粒子探测器的主要功能:
  - 记录径迹：利用带电粒子引起的电离或激发
  - 测量动量：利用带电粒子在磁场中的偏转
  - 测量能量：利用电磁或强子簇射
  - 鉴别粒子种类：利用不同粒子在电离能损、契伦科夫辐射、穿越辐射、飞行速度，簇射等方面的差异

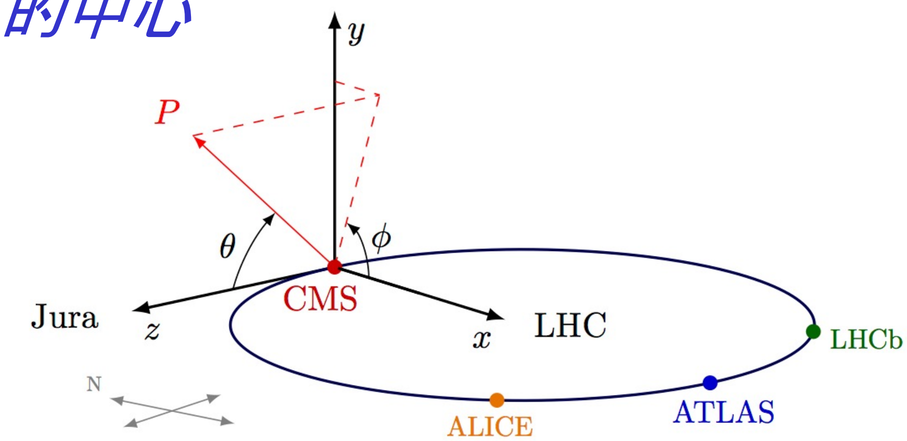


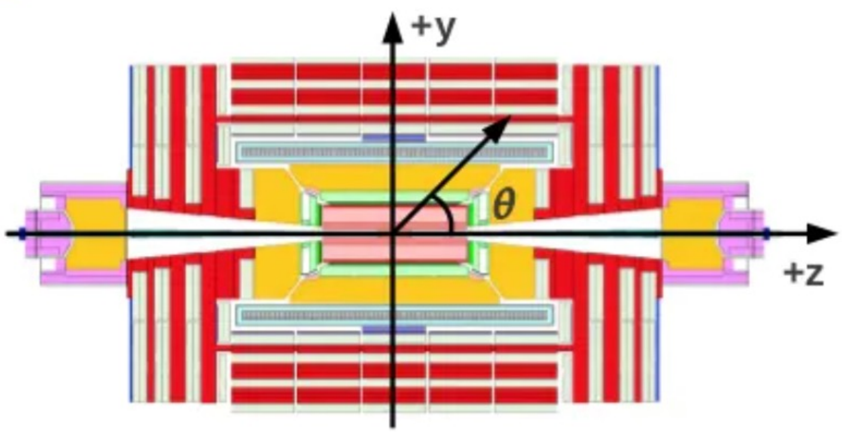
- CMS主要探测：电子，光子，μ子，喷注等(带电/中性粒子)
  - 在大空间范围，大动量范围内有好的单个μ子鉴别和动量、角度分辨；好的的双μ子质量分辨(1%@100GeV)；在<1TeV动量下有好的电荷符号鉴别
  - 好的带电径迹的动量分辨和重建效率，探测径迹的IP，鉴别b-喷注
  - 好的电磁能量分辨率和双电子/光子质量分辨(1%@100GeV)，π0 分辨，光子鉴别，孤立化鉴别（电磁量能器）
  - 好的丢失横动量和双喷注能量分辨(强子量能器)



CMS 坐标系系统

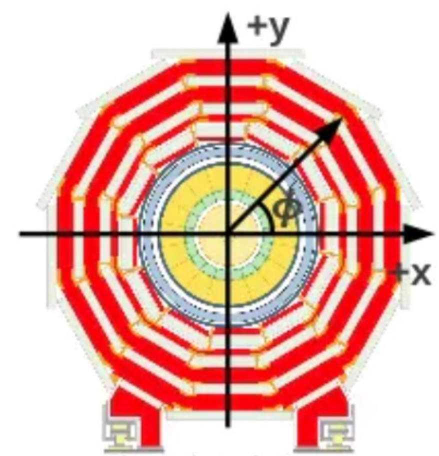
- *X轴：LHC环的平面内，指向LHC的中心*
- *Y轴：朝上垂直于LHC环的平面*
- *Z轴：和X，Y行成右手坐标系*
- *θ：极角*
- *η = −ln[tan(θ/2)]：赝快度*
- *φ*





x-axis points out of page

yz-plane



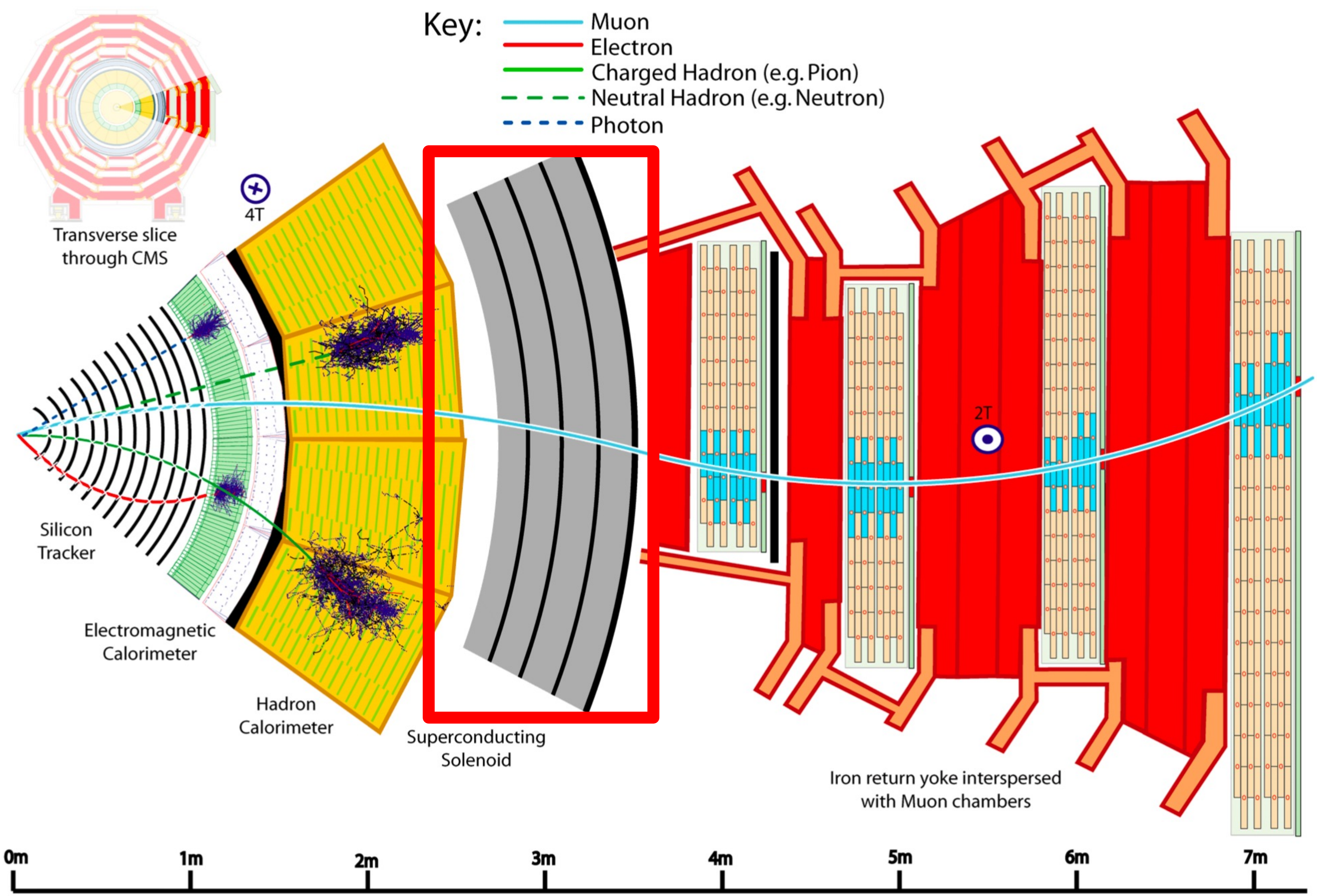
z-axis points into page

xy-plane

$$\eta = -\ln\left(\tan\left(\theta/2\right)\right) \qquad \Delta\phi = \phi_2 - \phi_1 \qquad \Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$

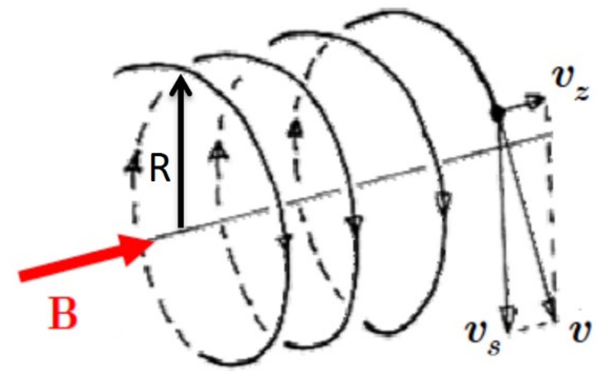
$$p_T = \sqrt{p_x^2 + p_y^2} \qquad \Delta\eta = \eta_2 - \eta_1 \qquad \Delta A = \Delta\phi \text{ or } \Delta R$$

CMS 探测器的设计：磁铁solenoid



带电粒子在磁场中的运动

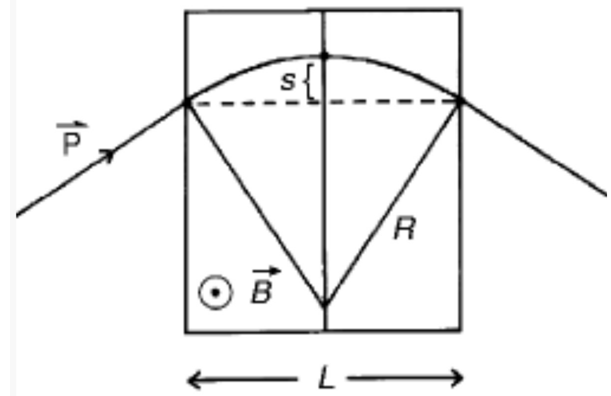
- 带电粒子在磁场中的运动：
  - $\frac{d\vec{p}}{dt} = \vec{F} = q\vec{v}\times\vec{B}$



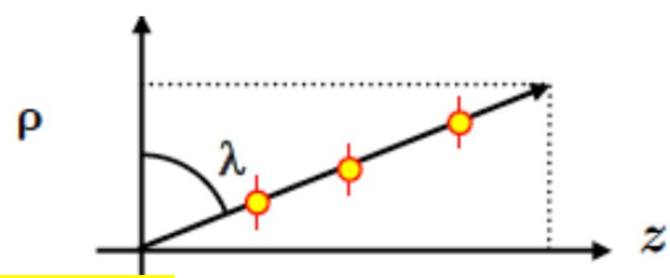
- 在垂直磁场和速度的方向：

$$R = \frac{p_\perp}{e\,B} = 3.3\,\mathrm{m}\cdot\frac{p_\perp/(\mathrm{GeV}/c)}{B/\mathrm{T}},$$

- 通过运动求解带电粒子横动量
  - s$= R - \sqrt{R^2 - \left(\frac{L}{2}\right)^2} \approx \frac{L^2}{8R}$
  - $p_\perp = \frac{0.3L^2B}{8s}$
  - $\frac{\delta p_\perp}{p_\perp} = \frac{8}{0.3}\frac{1}{L^2B}p_\perp\delta s = \frac{\delta s}{s}$

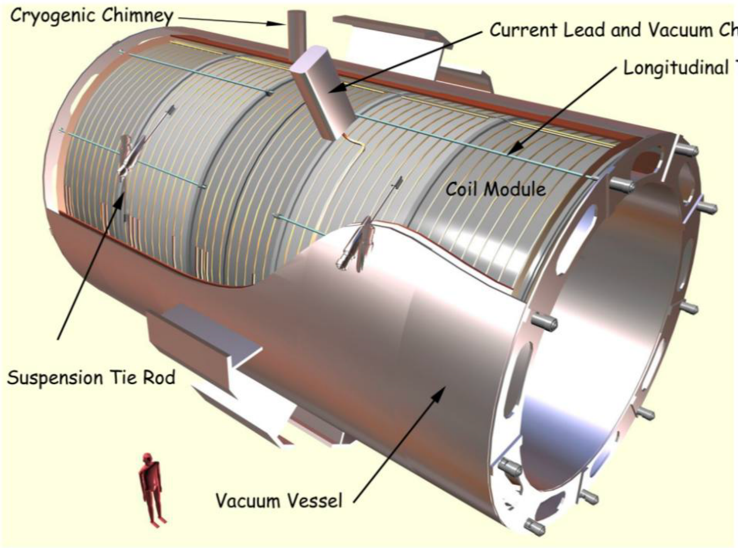


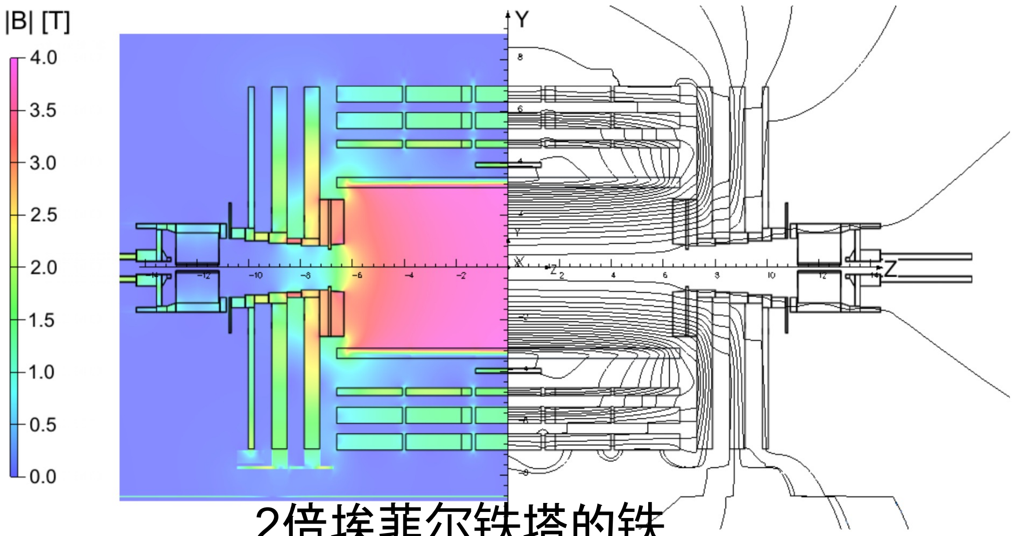
- 总动量的测量：
  - $p = \frac{p_\perp}{\cos\lambda}$



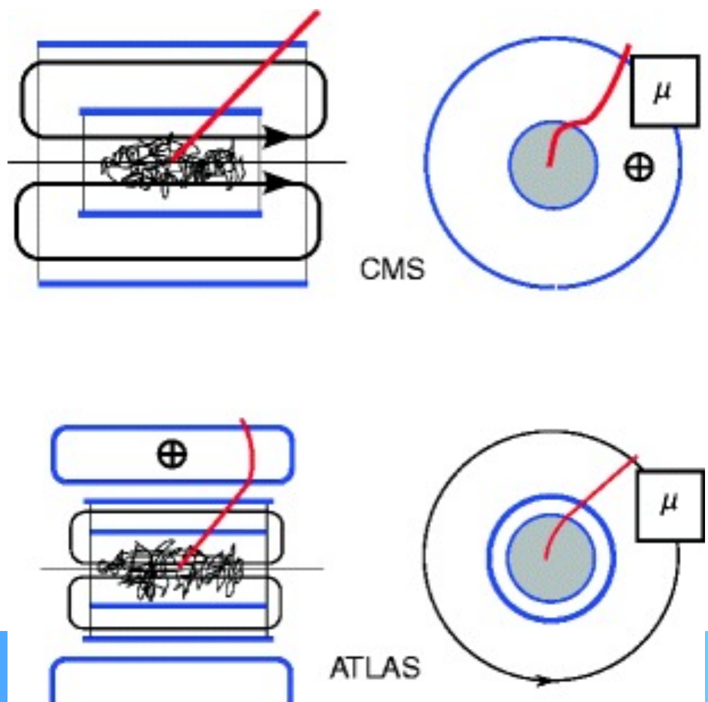
如何改善动量分辨率：增加L^2B，减小$p_\perp$，δs
造价一般正比L^3

- 铌钛合金@4.2K
- 20 kA @ 2179 圈
- 12米长，6米直径
  - 包住了量能器和内部径迹探测器
- 内部磁场3.8特斯拉，外部～2T
- 存储了2G焦耳的能量
  - 能融化18吨金

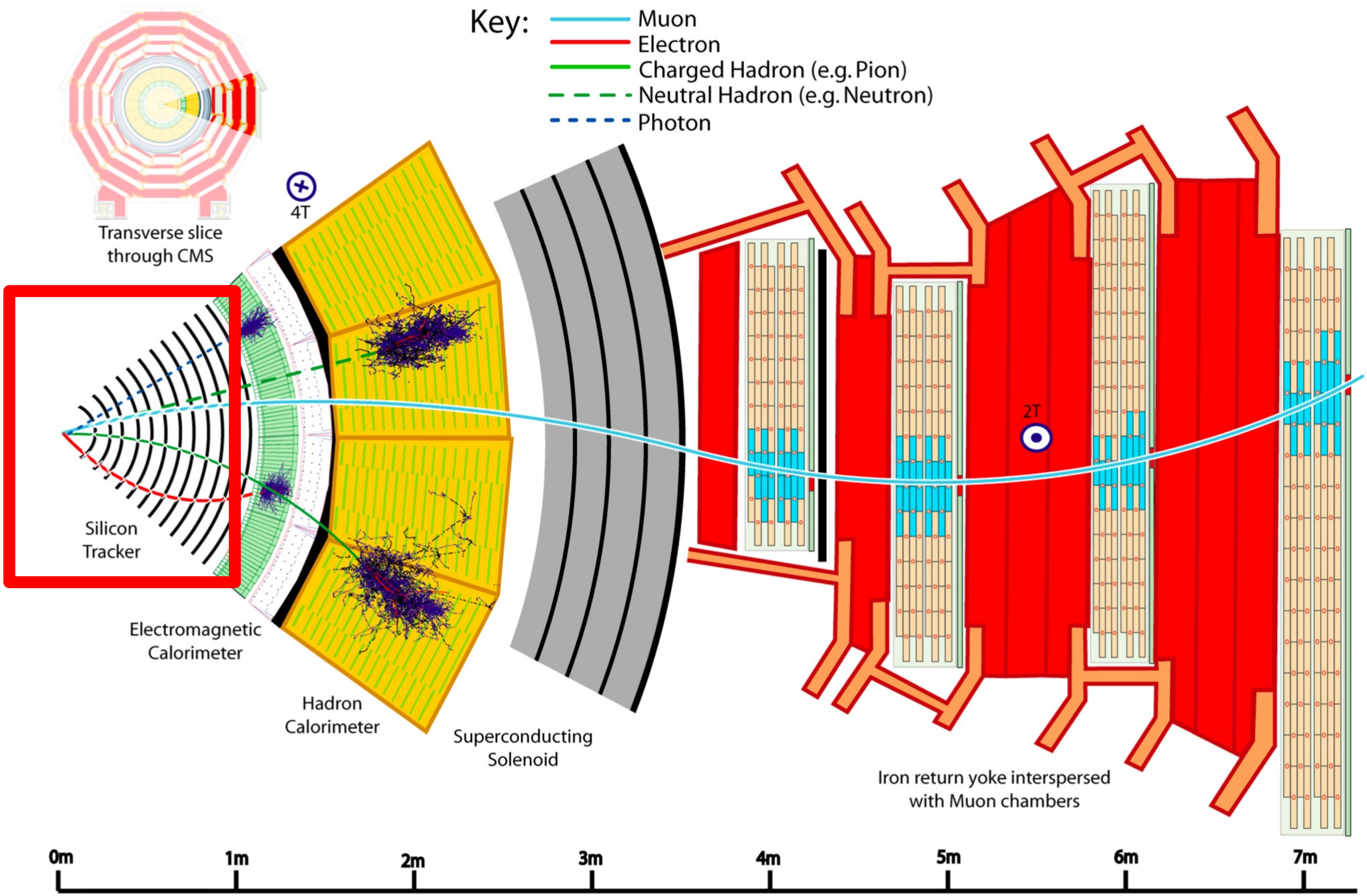




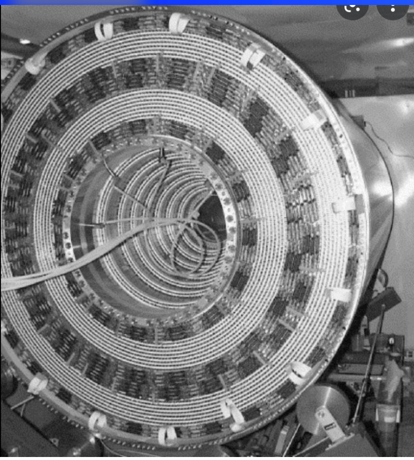
2倍埃菲尔铁塔的铁

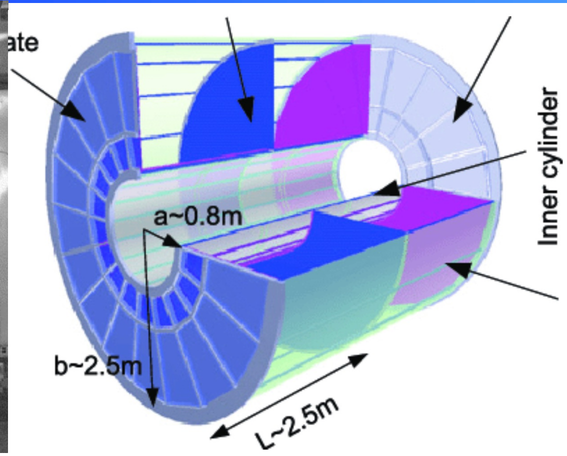


CMS 探测器的设计:内部径迹探测器

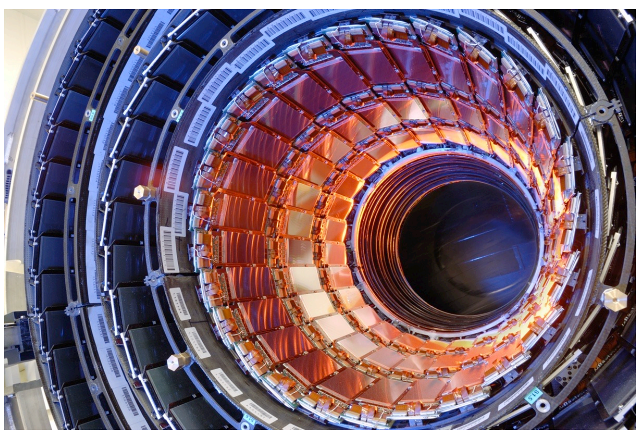


内部径迹探测器





漂移室（BES, CLEO…)　　　Alice时间投影室

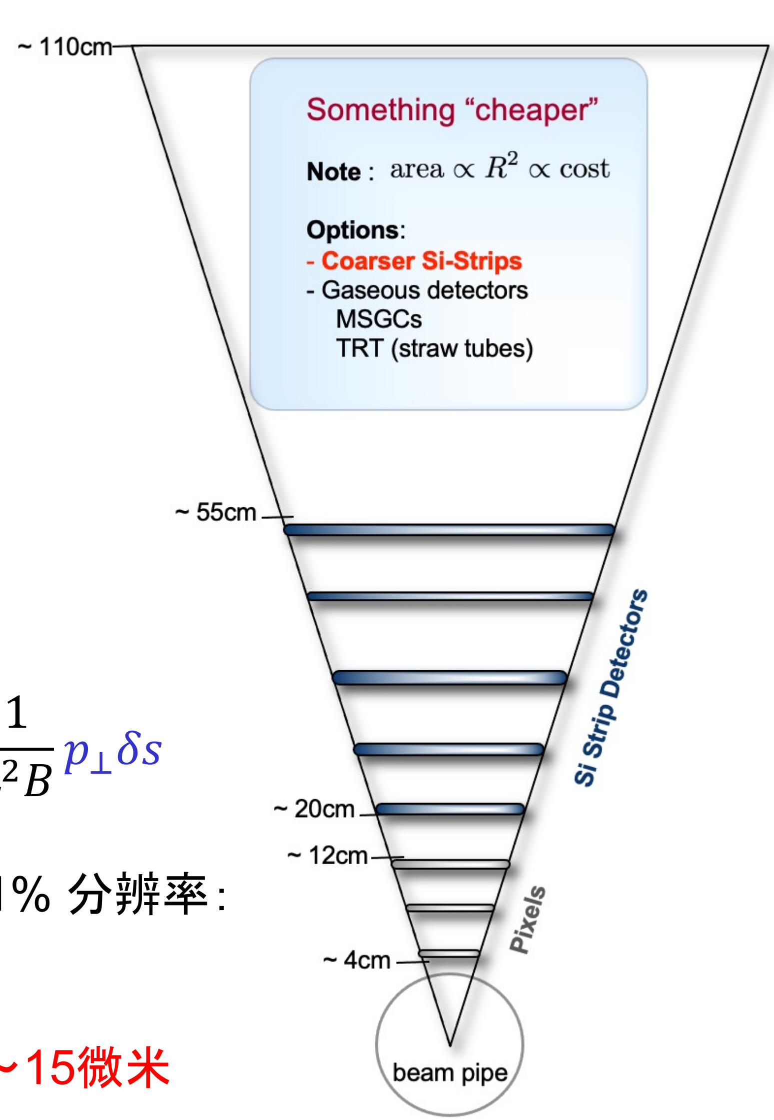


CMS：全硅径迹探测器

$$\frac{\delta p_\perp}{p_\perp} = \frac{8}{0.3}\frac{1}{L^2 B} p_\perp \delta s$$

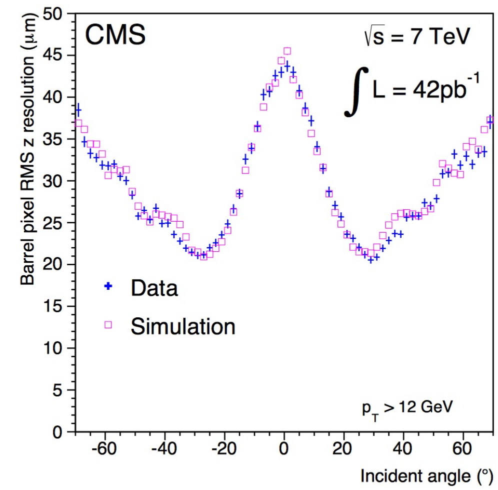
100 GeV $p_\perp$，1% 分辨率：
L=1米，B～4*T*

➔位置分辨率～15微米



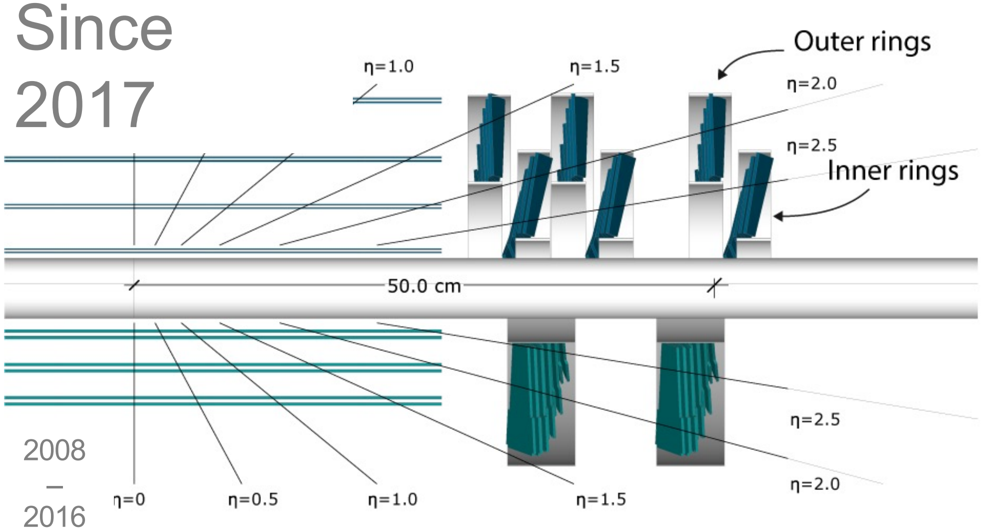
CMS 像素探测器

- 100X150 μm² 像素，工作在零下22度，n-in-p 型传感器
- 覆盖了|η|=2.5 的区域
  - 作为寻迹开始的种子，以及探测径迹的顶点参数
- 在半径 = 3cm处
  - 600 MHz/cm²（在LHC 瞬时峰亮度下 ($L=2x10^{34}$ $cm)^{-2}s^{-1}$ ）
  - 抗辐照强度: $3x10^{14}$ $n_{eq}/cm^2/yr$
  - 占空比: 10^{-3}

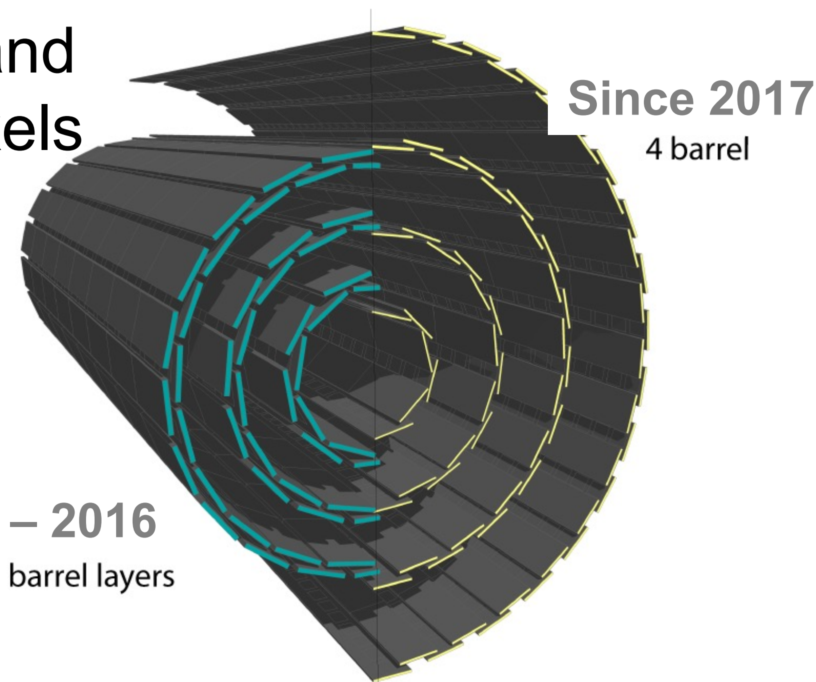


45M forward and
79M barrel pixels

Since 2017



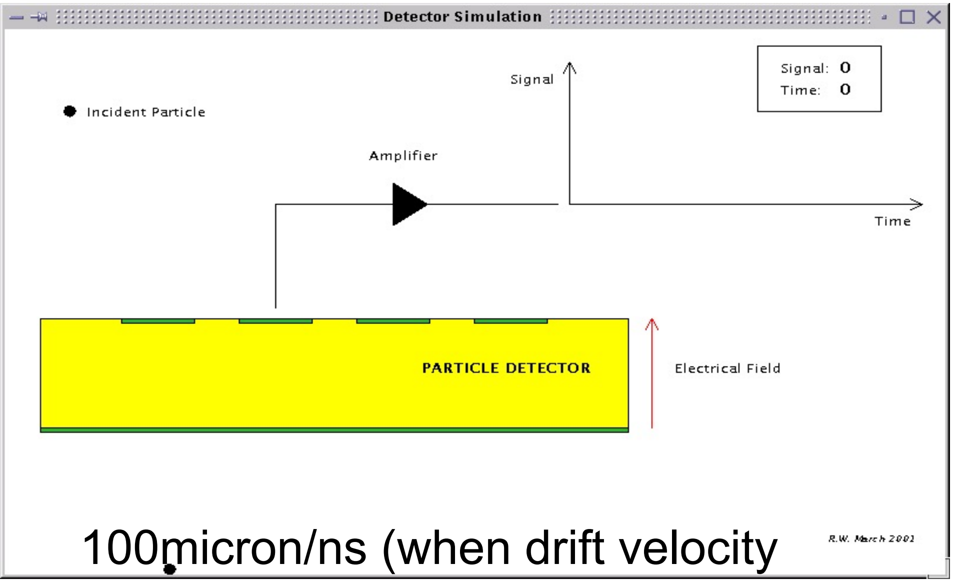
2008 – 2016

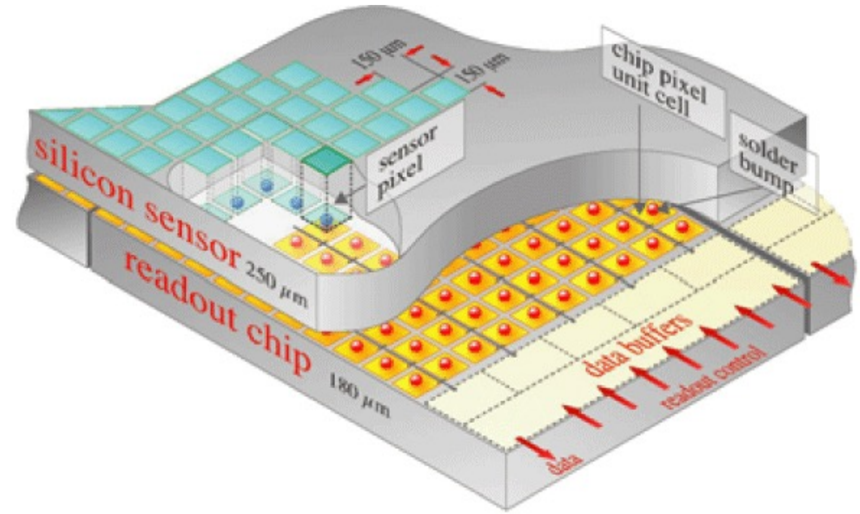


Since 2017
4 barrel

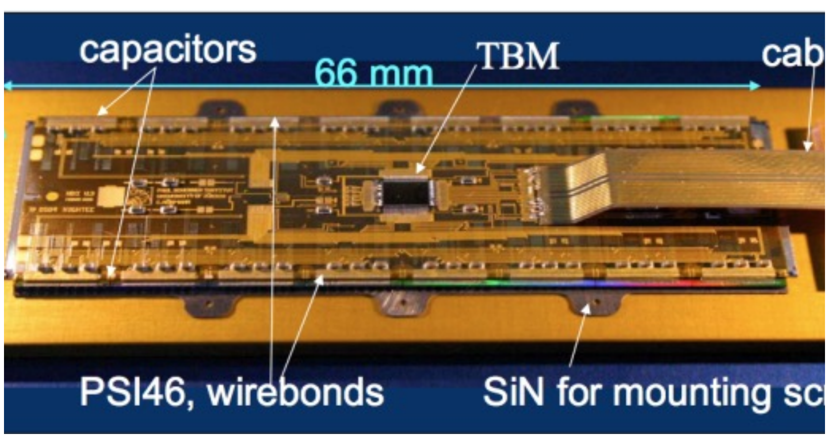
2008 – 2016
3 barrel layers

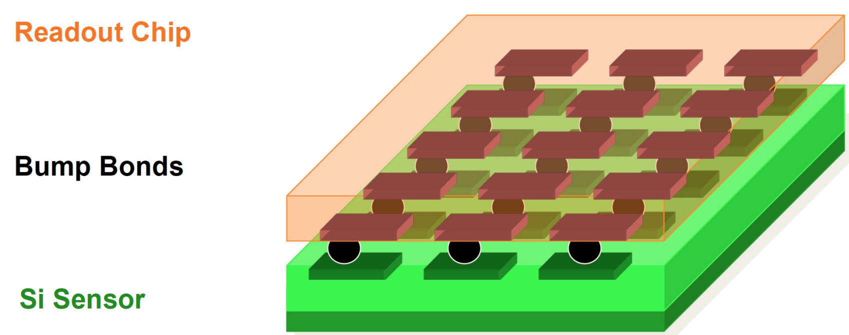
Silicon Pixel



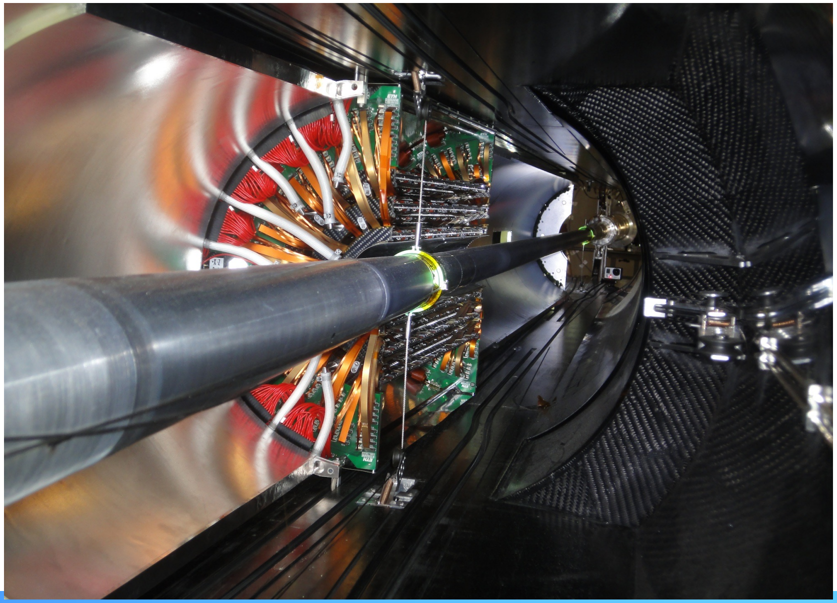


100micron/ns (when drift velocity saturated at ~30kV/mm E-field) and 73 e-h pair per micron for MIP

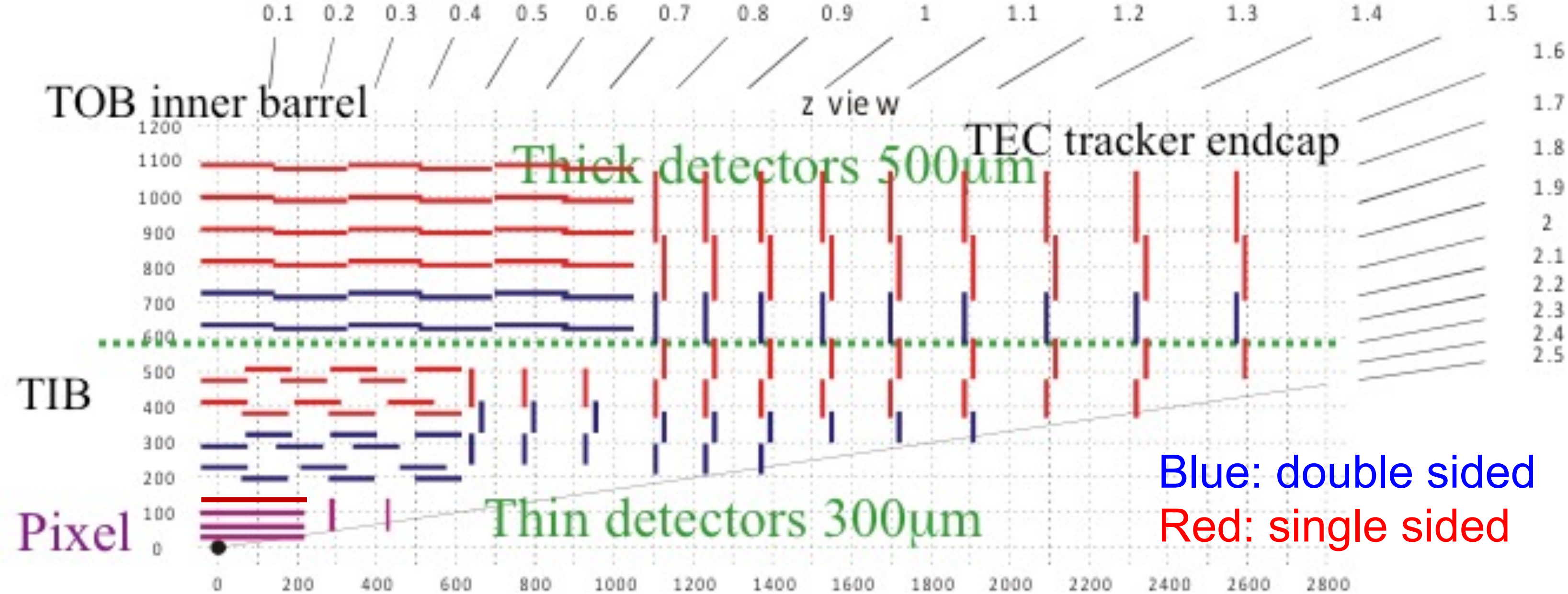




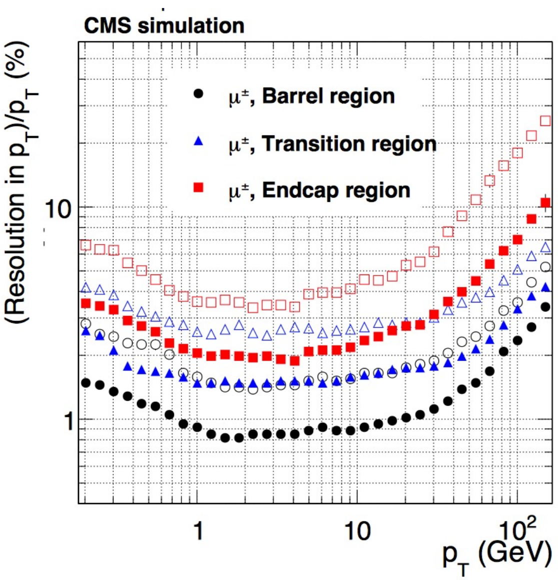
Each pixel cell in the sensor is connected to a pixel cell in the readout chip via a bump bond.

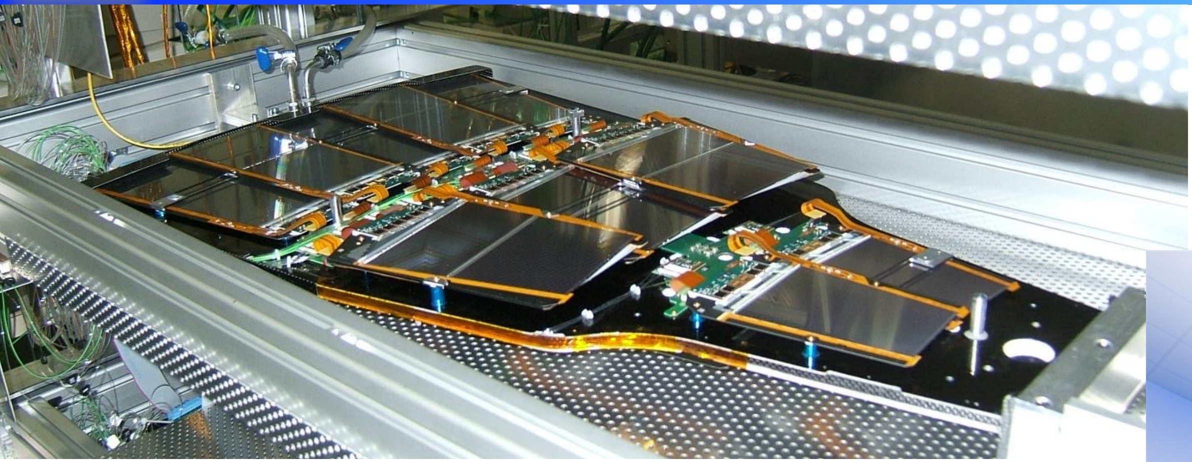


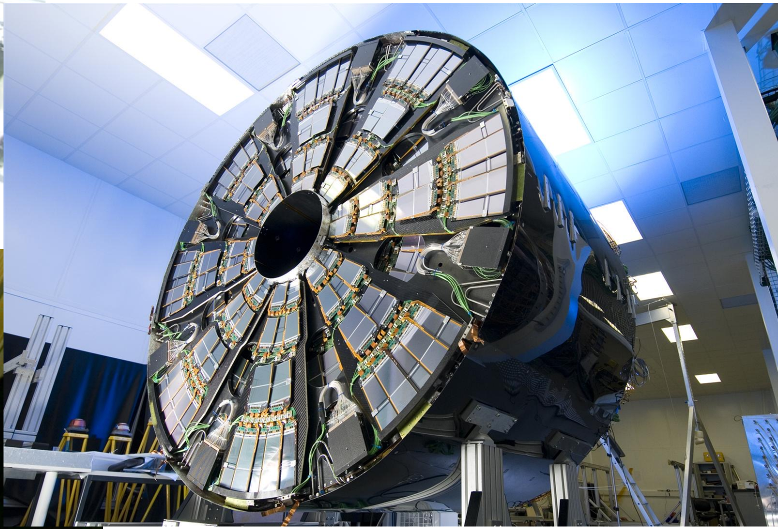
硅微条(Silicon strip)探测器

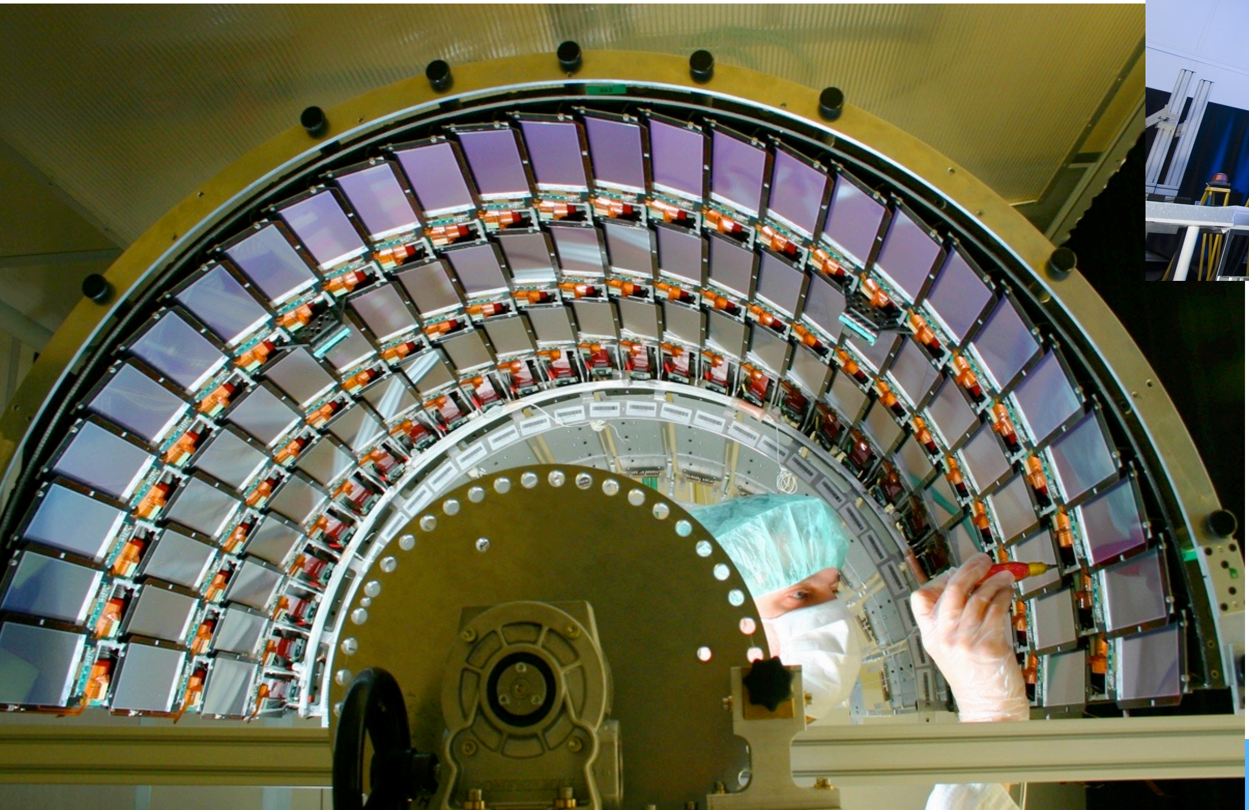


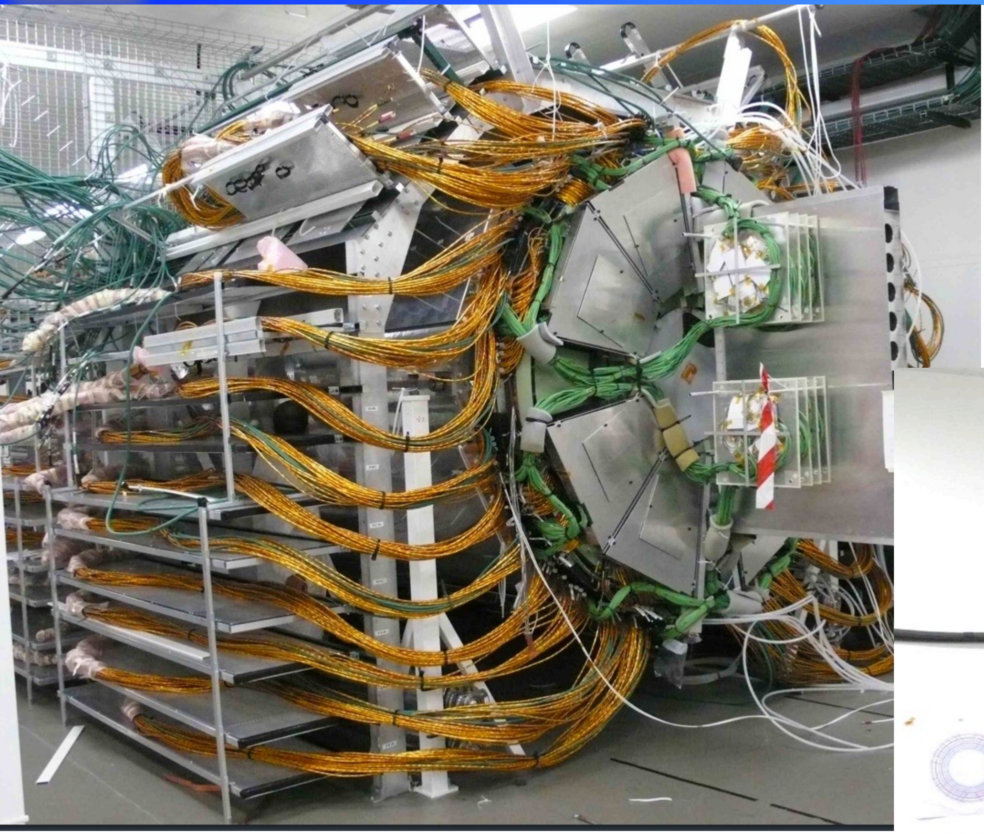
- Sensor Technology p-in-n
- Design occupancy 1-3% - resolve & isolate tracks
  - Outer cell size ~20cm x 100-200μm
  - Inner cell side ~10cm x 80μm
- Operation -20C
- Signal / noise ~20 (above 10 after radiation)
- Radiation tolerance ~1.5x10[14] n_{eq}

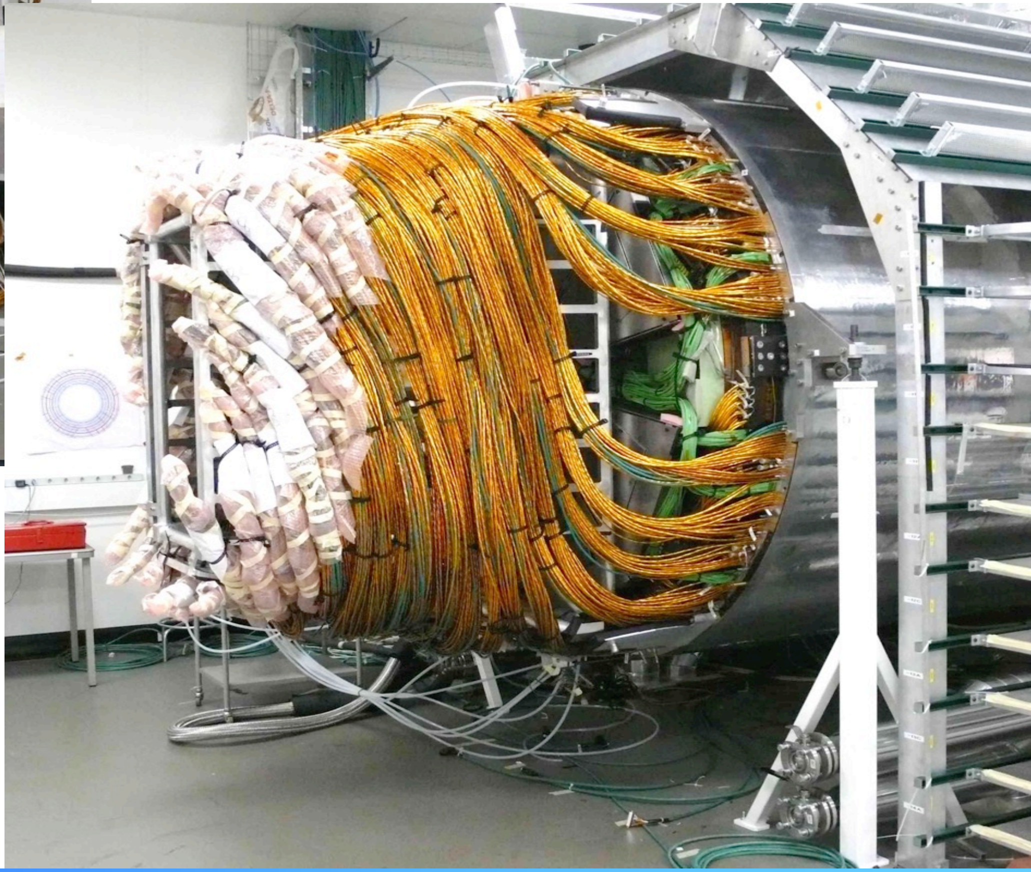










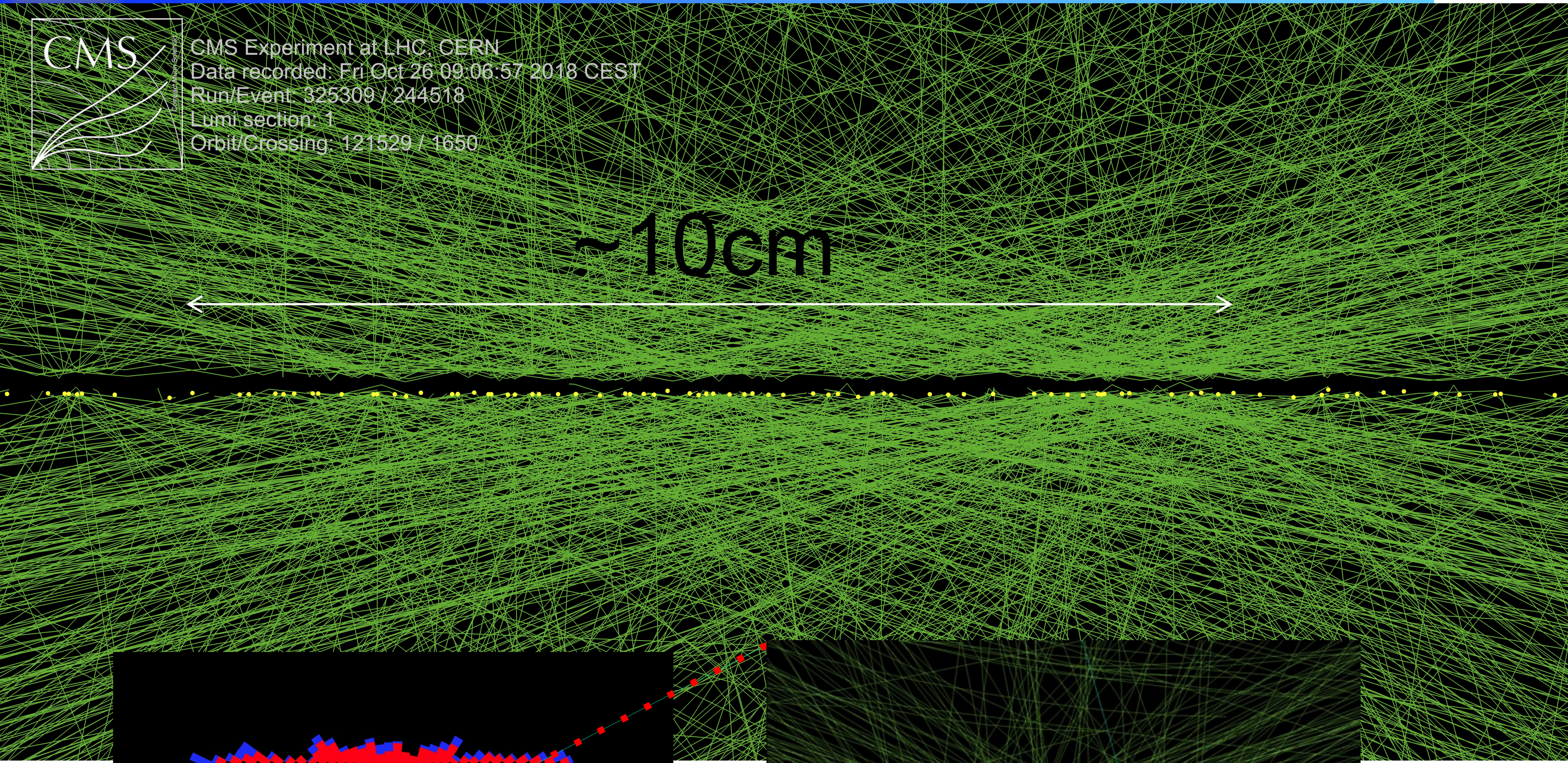


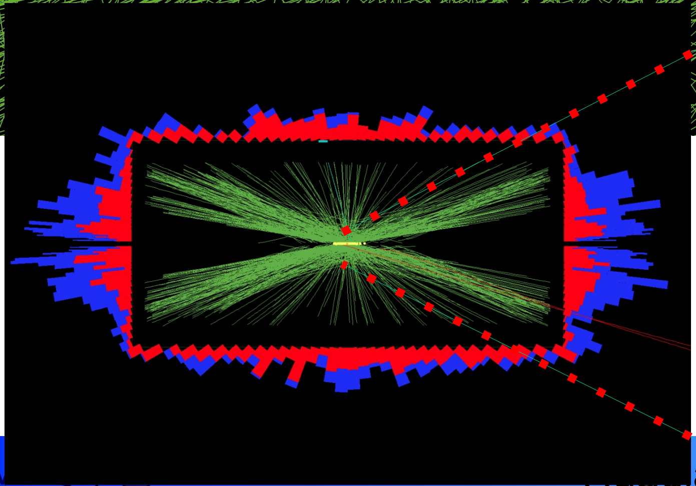
安装tracker时的问题

- 6.5 tons
- 100 MCHF
- 2000 man years
- 100 m deep shaft below
- Not insured ;-)

On one hook!

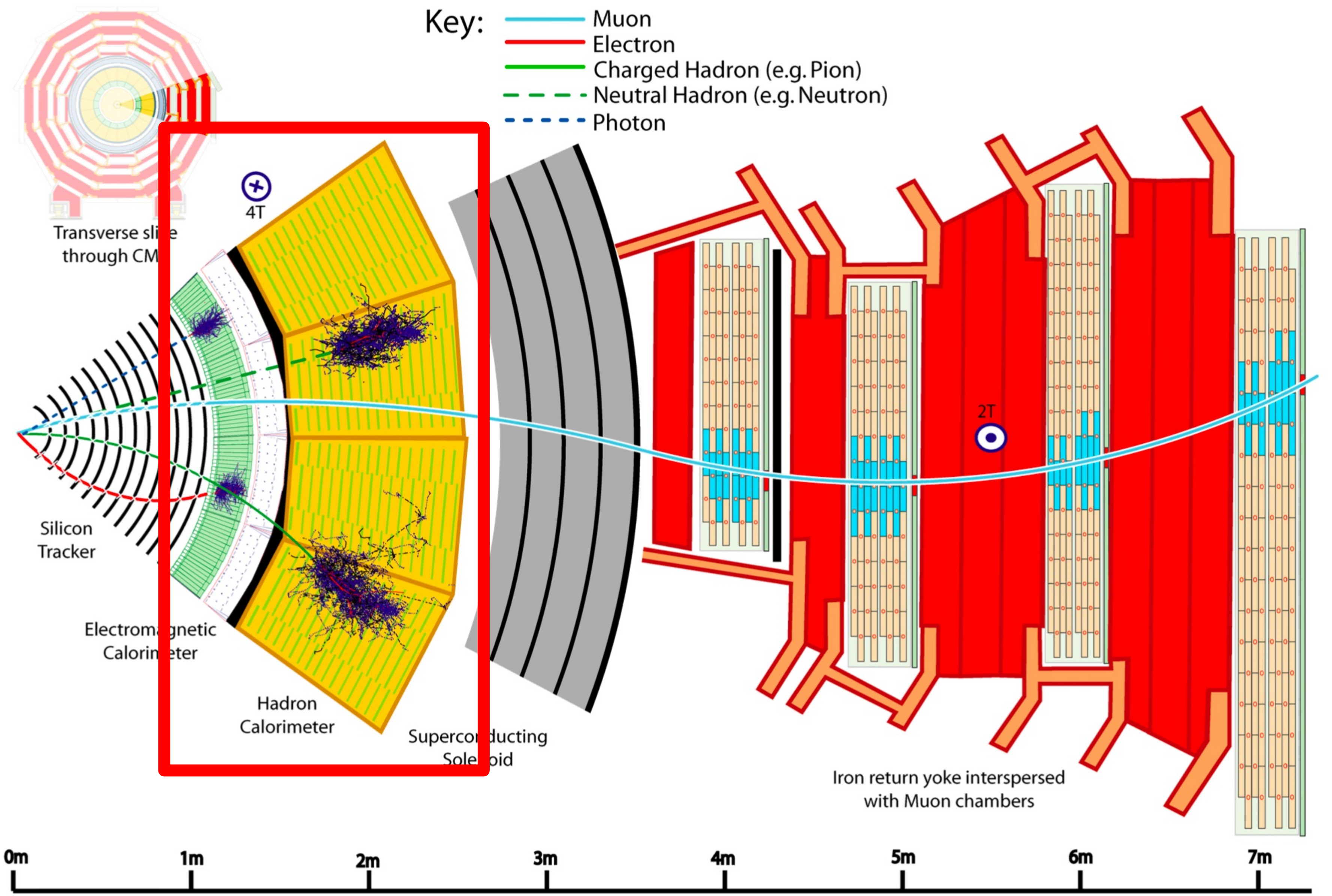
- Several frightened physicists





136 reconstructed vertices
in a special run in 2018

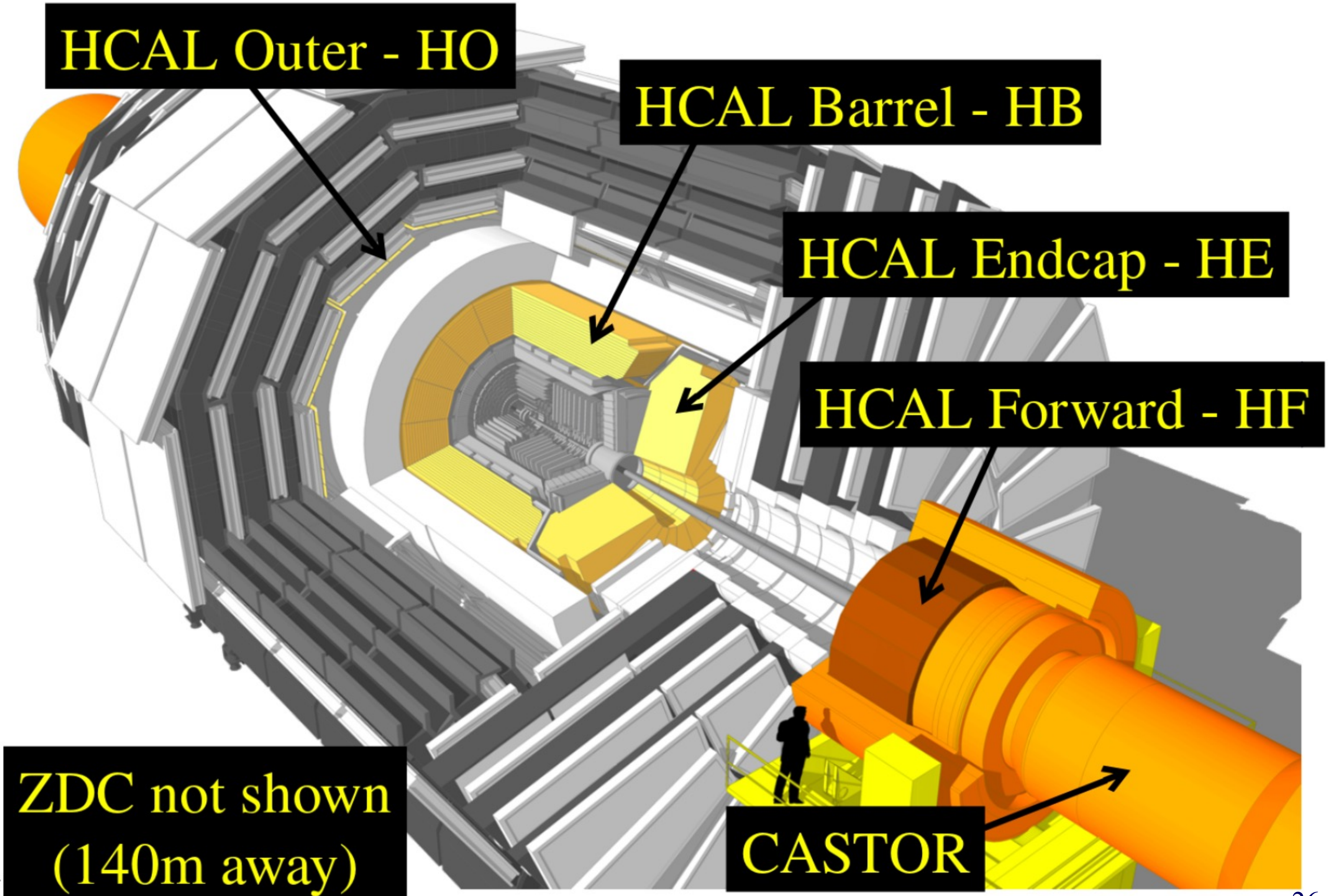
确实值这
个价格！


Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
Transverse slice through CMS
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
2T
Iron return yoke interspersed with Muon chambers
0m
1m
2m
3m
4m
5m
6m
7m

量能器

- 量能器Calorimeter

- 测量粒子的能量（tracker测粒子的“横”动量）
- 量能器的特点：
  - 探测粒子种类多：既能探测带电粒子又能探测中性粒子。
  - 能量测量精度随能量升高而改善，与其它探测器不同。
  - 对于电子、μ、强子具有不同的响应特征，可以提供粒子鉴别的信息。
  - 可以分割为小单元，从而精确给出入射粒子的位置和方向，簇射形状。
  - 量能器的几何尺寸随入射粒子能量的增加呈对数增长，而磁谱仪的几何尺寸随动量的方根增长。所以在高能条件下，量能器可以有较小的尺寸。
  - 量能器的时间响应可以很快（100ns），可以在高计数率环境下工作。
  - 可以利用能量沉积组成事例选择的触发信号，对感兴趣的事例进行选择。如中性触发。


HCAL Outer - HO
HCAL Barrel - HB
HCAL Endcap - HE
HCAL Forward - HF
ZDC not shown
(140m away)
CASTOR

Em Barrel : EB

Em Endcap : EE

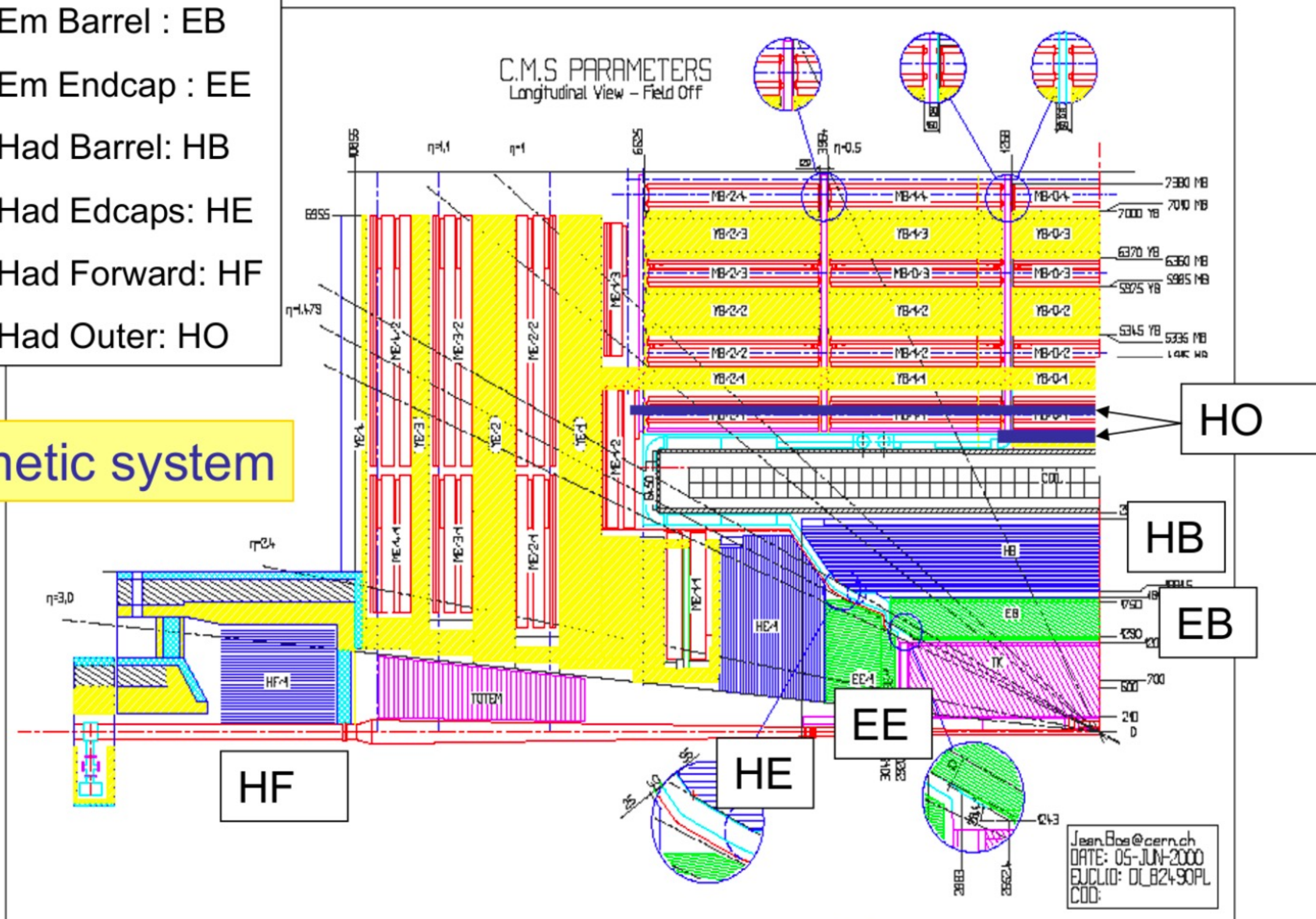
Had Barrel: HB

Had Edcaps: HE

Had Forward: HF

Had Outer: HO

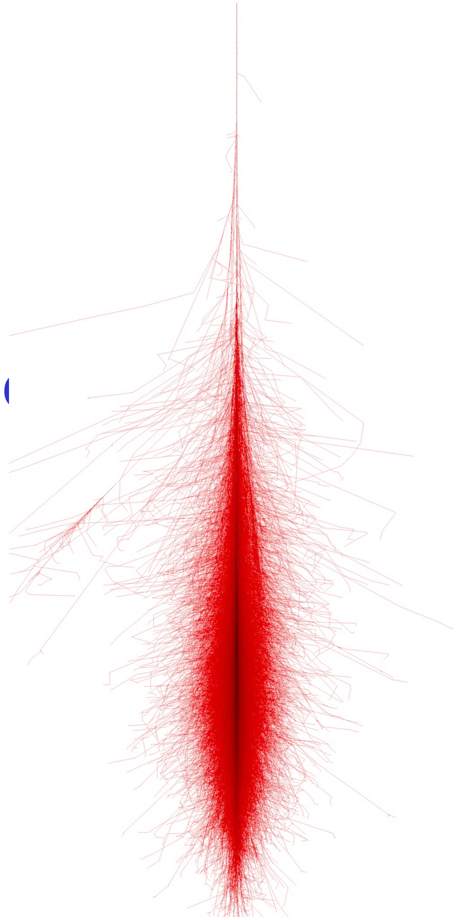
Hermetic system



- Electrons and photons, a "self-contained" case:
  - Above 1 GeV: bremsstrahlung ($1e^{\pm} \to 1\gamma$) and pair production ($1\gamma \to 1e^+ + 1e^-$)
  - Below 1 GeV: ionization, photoelectric, Compton
  - Critical energy, $E_c \approx 610\ \mathrm{MeV}/(Z + 1.24)$: energy at which the average energy losses by radiations equal those by ionization
- A cascade process ("shower") develops until the energy of charged secondaries is degraded to the regime dominated by ionization loss (i.e. no production of new particles)

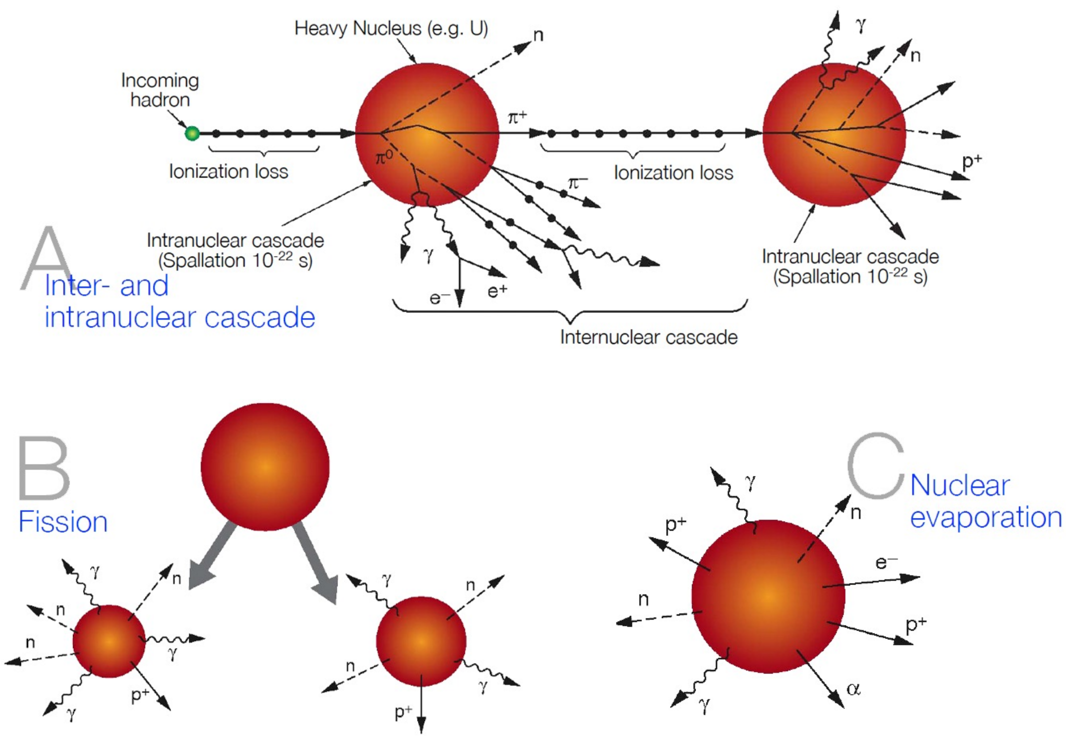
$$\frac{\delta E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

典型电磁簇射

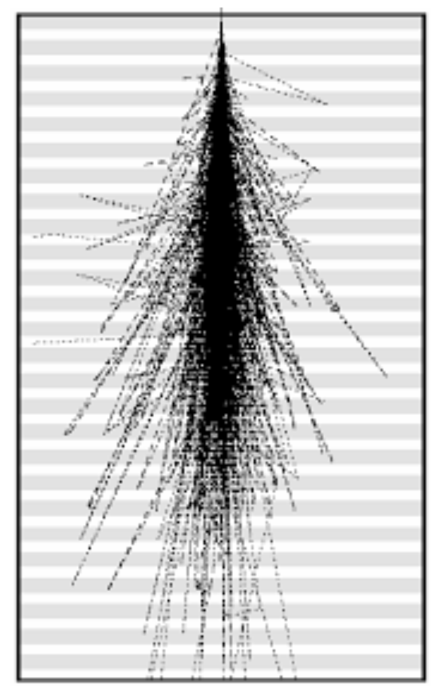


强子量能器

- Hadrons, a complex case:
  - multi-particle production, typically mesons(π±,π0,K,...)
- N.B. π0 → γγ ⇒ electromagnetic component!
  - nuclei break up leading to spallation neutrons/protons



典型强子簇射



$$\frac{dE}{dx} = -\frac{E}{X_0}$$

longitudinal development

$$\frac{dE}{dt} \propto E_0 t^{\alpha} e^{\beta t}$$

e.m case, E. Longo (active CMS member! Rome group), I. Sestili, NIM 128 (1975)

Radiation length (X_0): thickness of material that reduces the mean energy of a beam of high energy electrons by a factor e, $X_0 \sim A/Z^2$

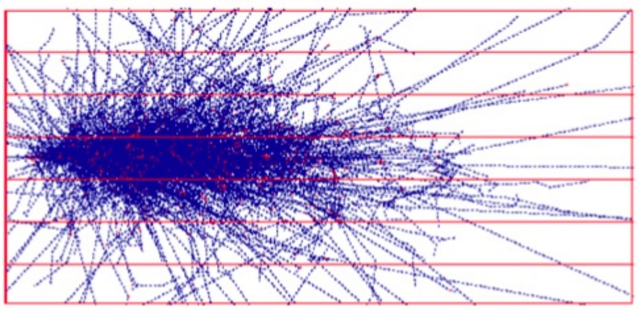
Molière radius (R_M): average lateral deflection of electrons of critical energy E_c after traversing $1X_0$; 90% E_0 within $1R_M$, 95% within $3R_M$

Interaction length (λ_{int}): average distance a high energy hadron has to travel inside a medium before a nuclear interaction occurs, $\lambda_{int} = A/N_A\sigma_{int} \propto A^{1/3} \gg X_0$

	LAr	Fe	Pb	U	C
λ_{int} [cm]	83.7	16.8	17.1	10.5	38.1
X_0 [cm]	14.0	1.76	0.56	0.32	18.8

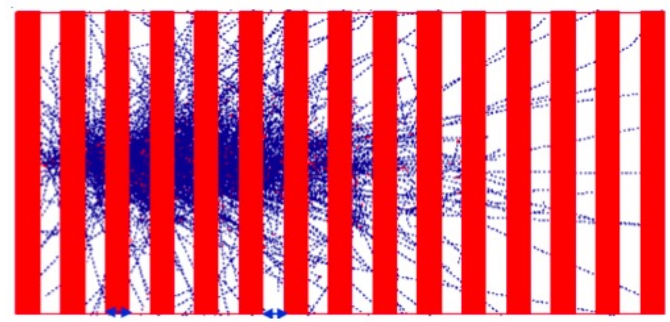
典型量能器的设计

Homogeneous calorimeters: all the energy is deposited in the active medium



- Excellent energy resolution
- No information on longitudinal shower shape
- Cost

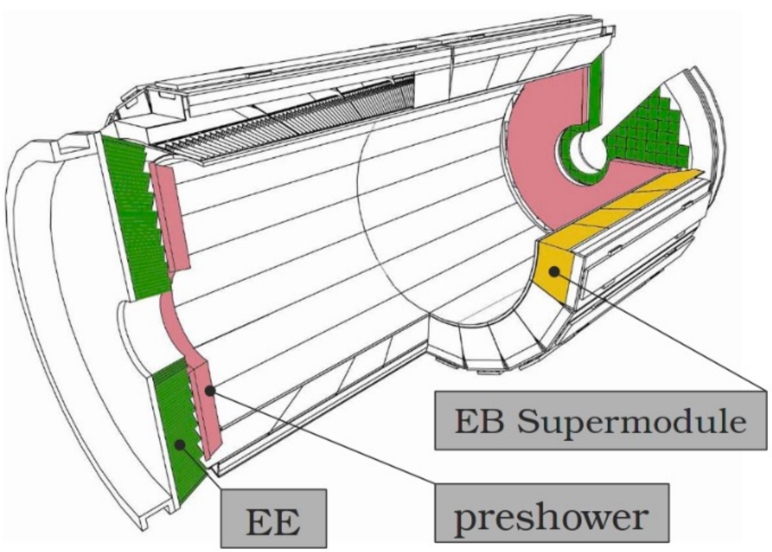
Sampling calorimeters: the shower is sampled by layers of active medium (low-Z) alternated with dense radiator (high-Z)



- Limited energy resolution
- Longitudinal segmentation: detailed shower shape information
- Cost

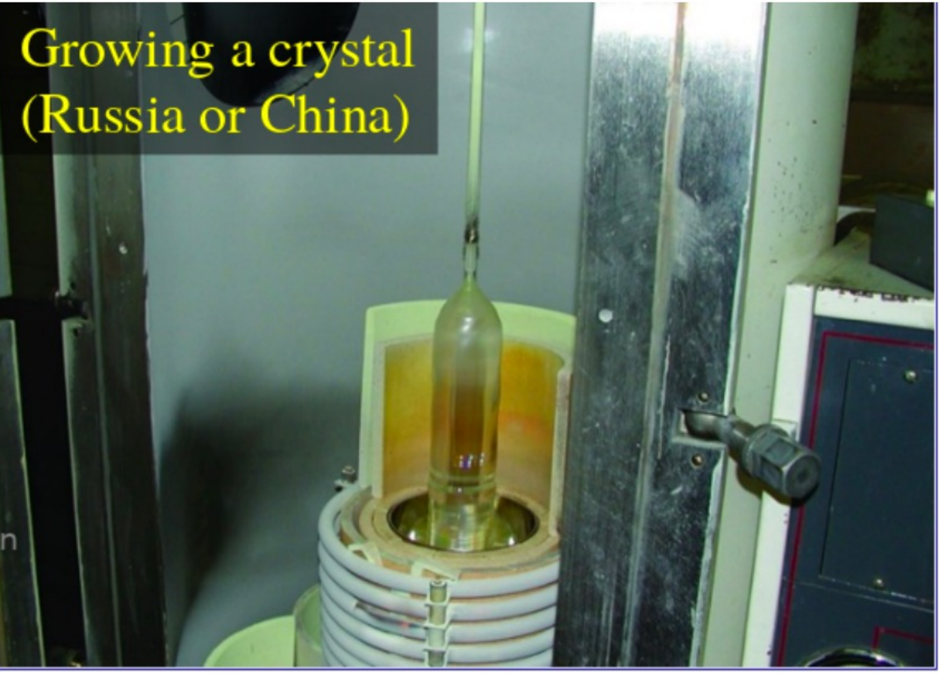
CMS 电磁量能器

- **Homogeneous, hermetic, high granularity $PbWO_4$ crystal calorimeter**
  - density of 8.3 g/cm^3, radiation length 0.89 cm, Molière radius 2.2 cm, $\approx$ 80% of scintillating light in $\approx$ 25 ns, refractive index 2.2, light yield spread among crystals $\approx$ 10%
- **Barrel**: 61200 crystals in 36 super-modules, **Avalanche Photo-Diode (APD)** readout — $|\eta| < 1.48$,
- **Endcaps**: 14648 crystals in 4-Dees, **Vacuum Photo-Triode (VPT)** readout — $1.48 < |\eta| < 3.0$,
- **Preshower** (endcaps only): $3X_0$ of Pb/Si strips, — $1.65 < |\eta| < 2.6$

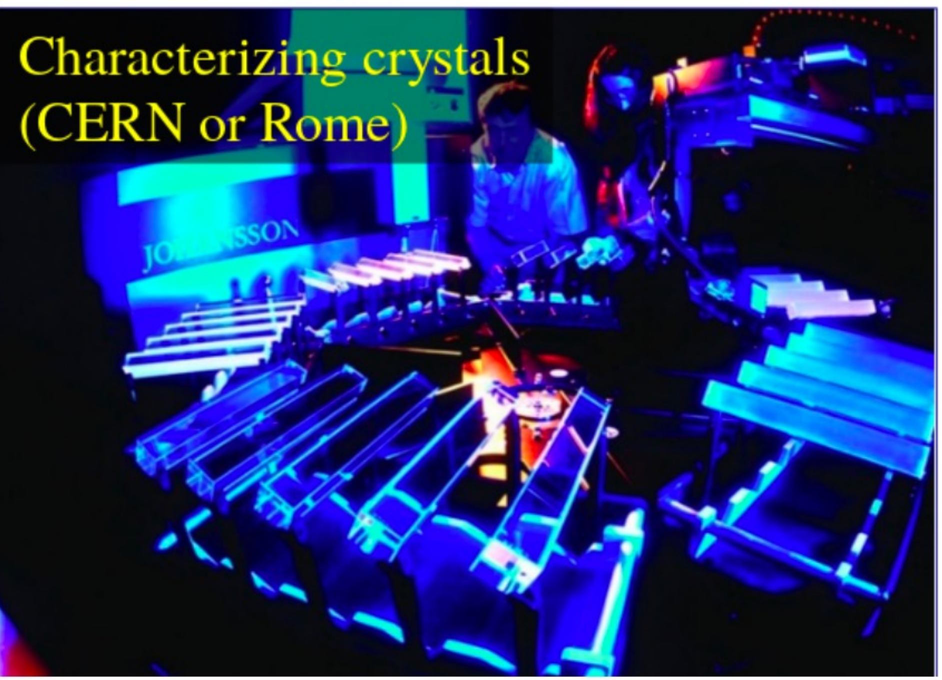


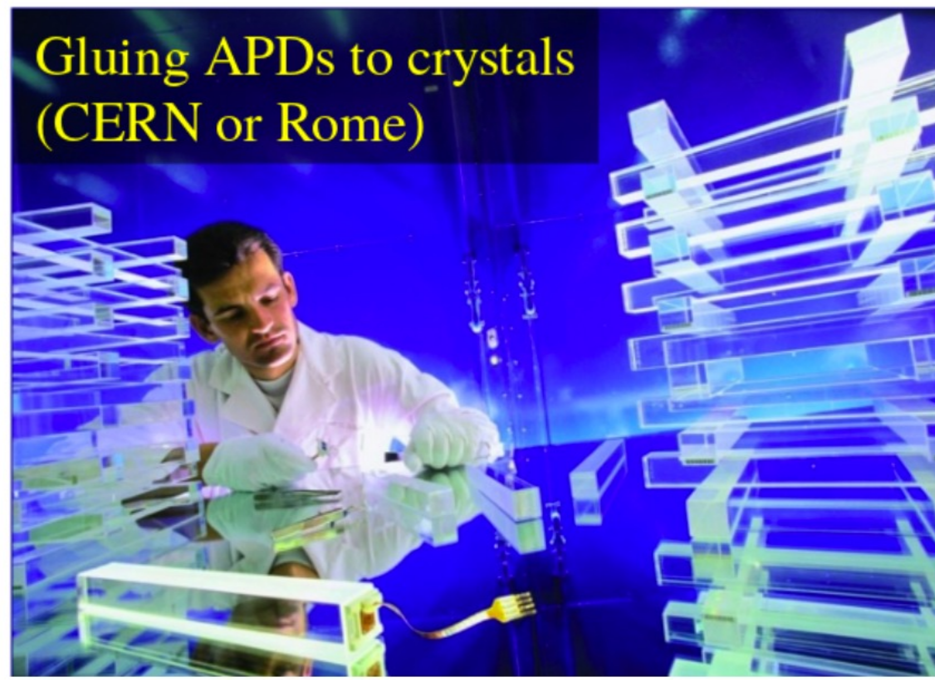
- Solenoidal magnetic field: 3.8 T
  ECAL fully contained in the coil
- CMS tracker coverage: $|\eta| < 2.5$

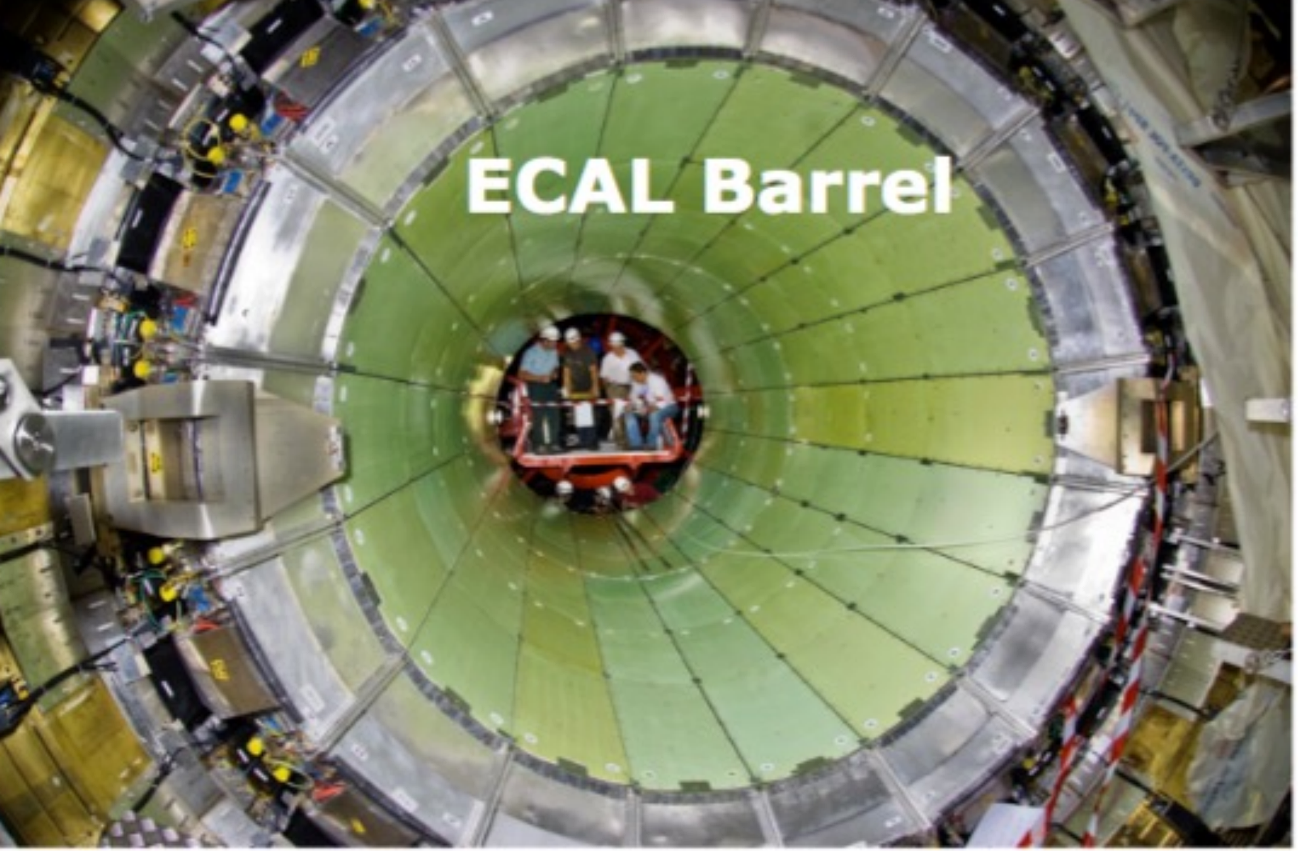
2.2*2.2*23cm^3,~26X0

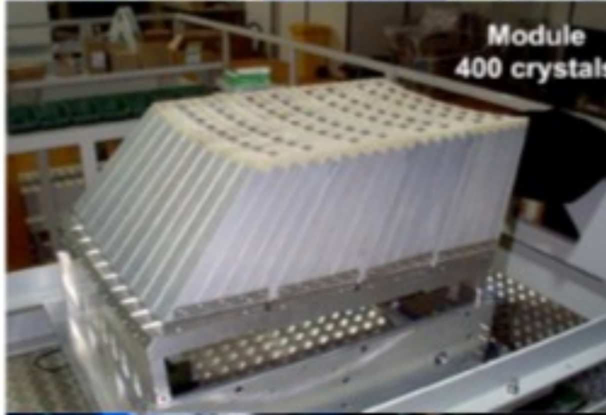

Growing a crystal (Russia or China)

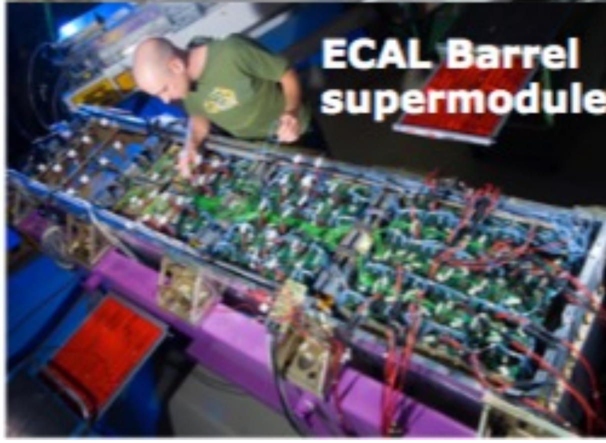

Before and after cutting & polishing


Characterizing crystals (CERN or Rome)

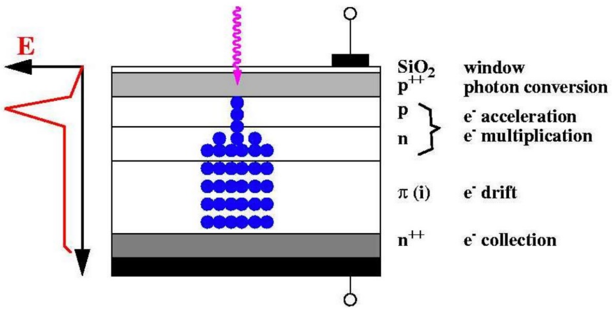

Gluing APDs to crystals (CERN or Rome)


ECAL Barrel

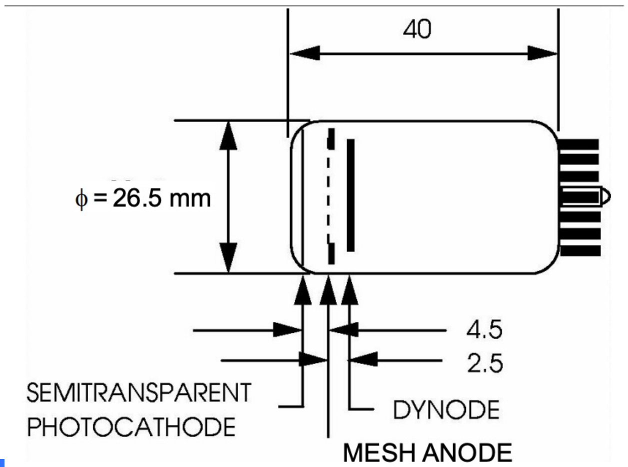

Module
400 crystals

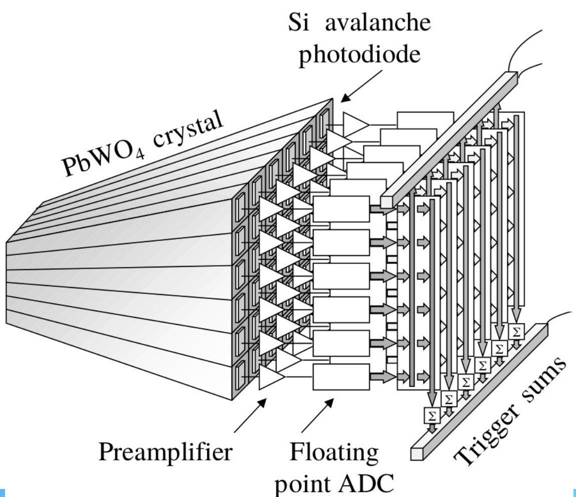

ECAL Barrel
supermodule

APD

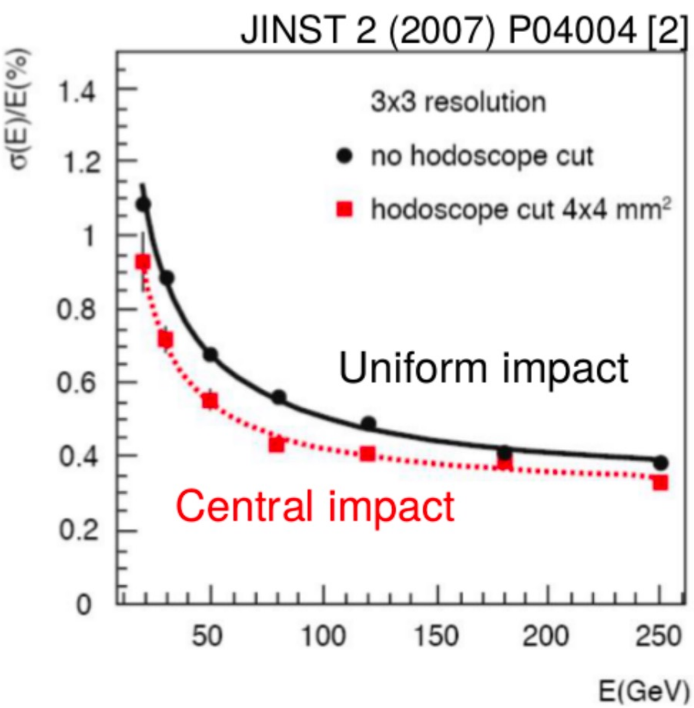

E
SiO_2 window
p^{++} photon conversion
p
n
e⁻ acceleration
e⁻ multiplication
π (i) e⁻ drift
n^{++} e⁻ collection

VPT


40
ϕ = 26.5 mm
4.5
2.5
SEMITRANSPARENT
PHOTOCATHODE
DYNODE
MESH ANODE


Si avalanche
photodiode
$PbWO_4$ crystal
Preamplifier
Floating
point ADC
Trigger sums

- Perfect calibration, no magnetic field, no material upstream, negligible irradiation, controlled environment



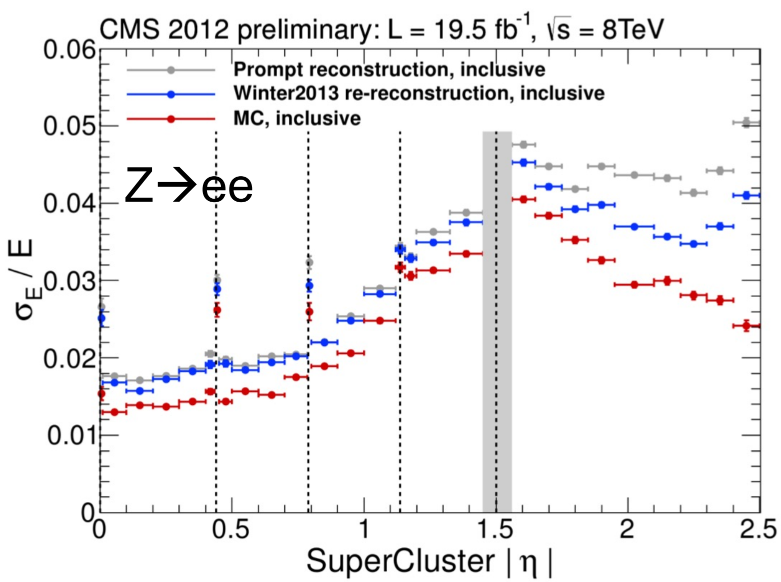
Energy resolution

central impact, 3×3 barrel crystals [?][?]:

$$\frac{\sigma(E)}{E} = \frac{2.8\%}{\sqrt{E}} \oplus \frac{0.128}{E(GeV)} \oplus 0.3\%$$

- constant term to be kept $\ll 1\%$

真实探测的性能受到探测器响应的变化(温度，辐照，老化)，物理过程(堆积事例，重叠...)



CMS 强子量能器

Barrel (HB)

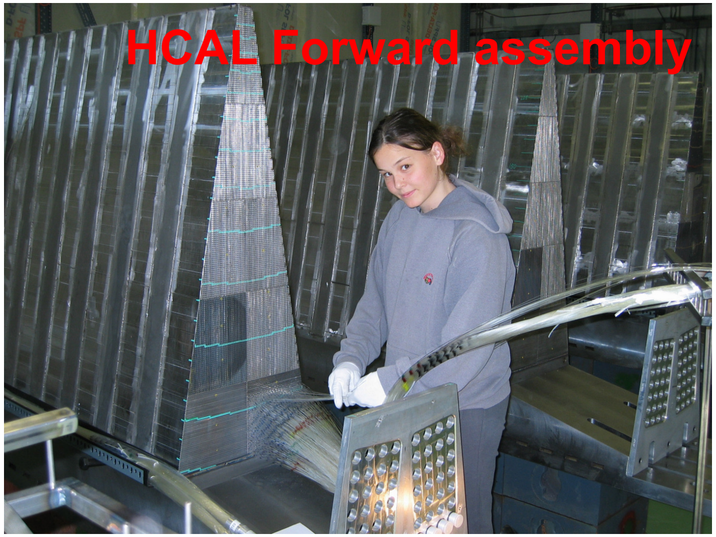
- 36 brass/scintillator wedges
- 17 longitudinal layers, 5 cm brass, 3.7 mm scintillator
- $|\eta| < 1.3$

Fun fact: much of the brass came from old WWII shells from the Russian Navy!

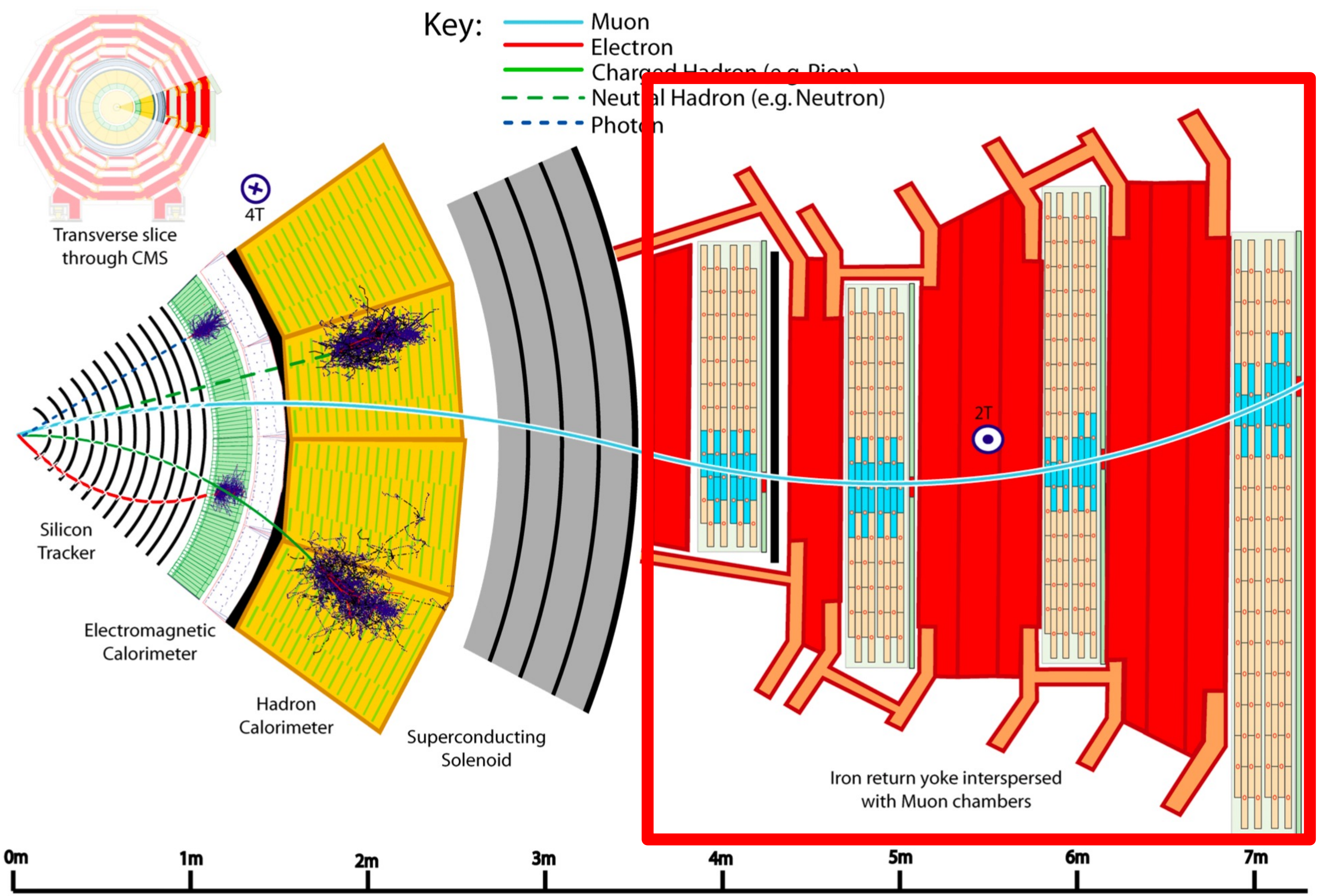
Endcap (HE)

- Two brass/scintillator discs
- 19 longitudinal layers, 8 cm brass, 3.7 mm scintillator
- $1.3 < |\eta| < 3.0$

CMS 强子量能器

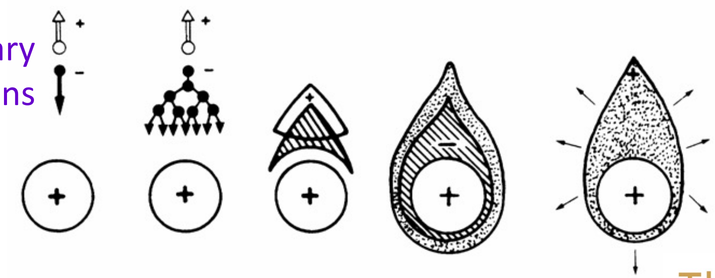


CMS 探测器的设计:缪子探测器

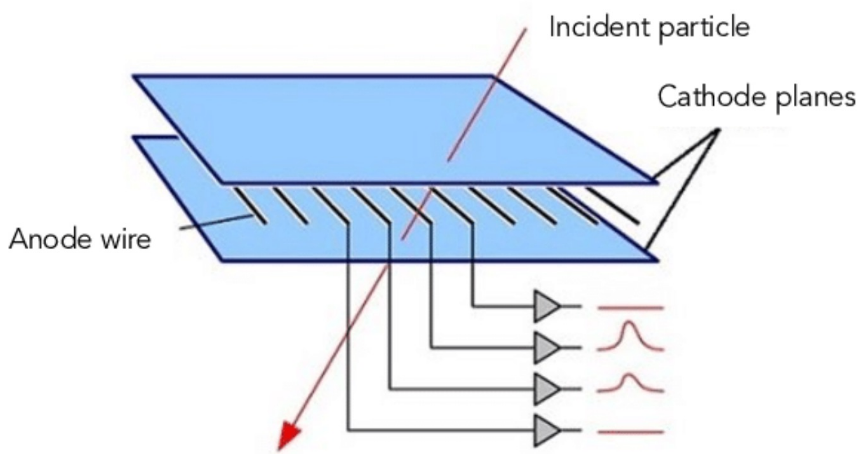


- Muon detectors are on the outside, so must be large
- Economics: use gas detectors to cover a large surface area
  - Need amplification of the electron ionization signal within the gas volume
  - Factors of 10^5-10^7 are typical, using wires or parallel plates

~10^2 primary electrons



~ 10^5 – 10^7 gas amplification
~10^7 – 10^9 electrons
~1-100 pC



The Nobel Prize in Physics 1992

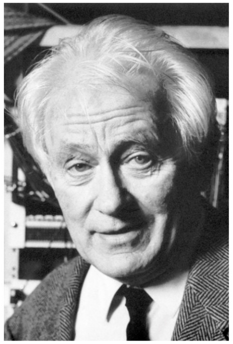
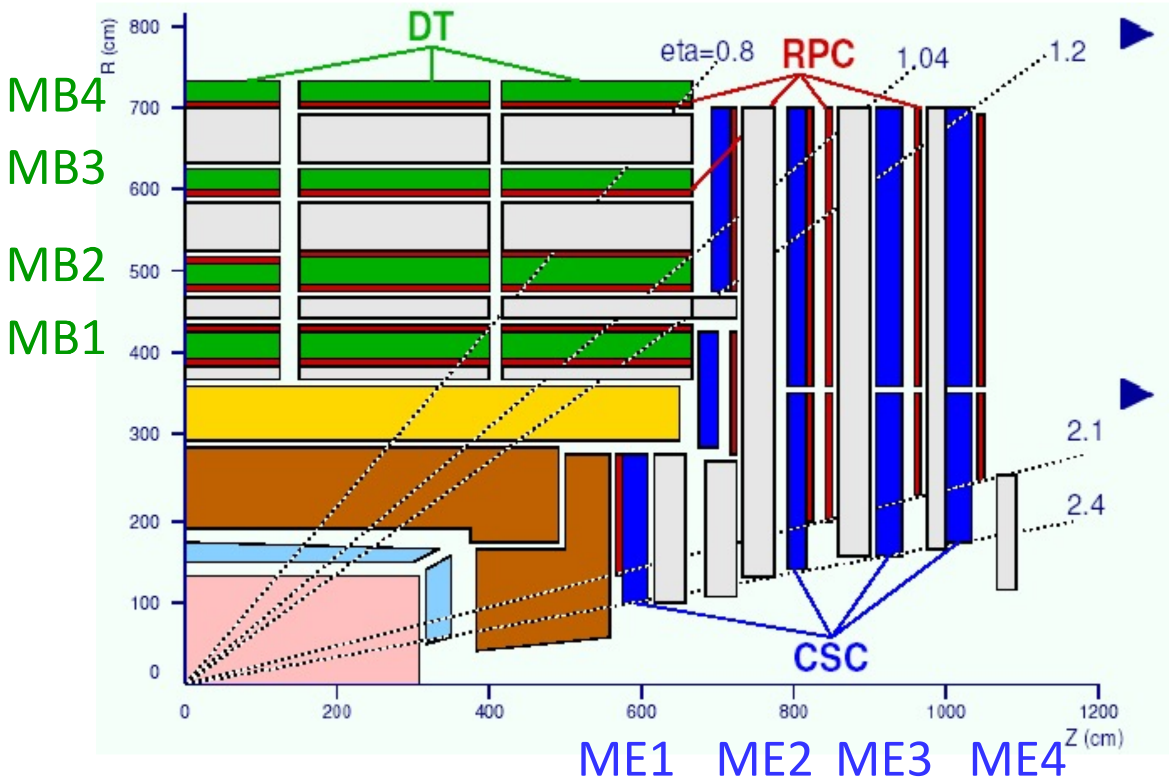


Photo from the Nobel Foundation archive.
Georges Charpak
Prize share: 1/1

Gas detector: multiwire proportional chamber

- Four types of detector(since 2019, adding GEM):
  - Precise position measurement and triggering by Drift Tubes (DT) in the barrel, and Cathode Strip Chambers (CSC) in the endcap
  - Redundant triggering by Resistive Plate Chambers (RPC)
  - Adding Gas Electron Multiplier (GEM) in LS2 since 2019



Barrel: $0 < |\eta| < 1.2$

5 wheels / 4 stations instrumented with DTs and RPCs

Endcap: $0.9 < |\eta| < 2.4$

3 discs / 4 stations instrumented with CSCs and RPCs

Spatial precision

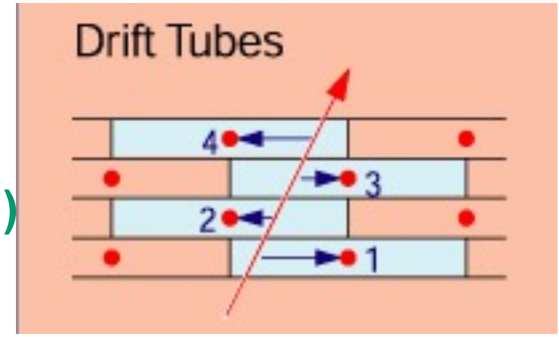
75-150 μm /station

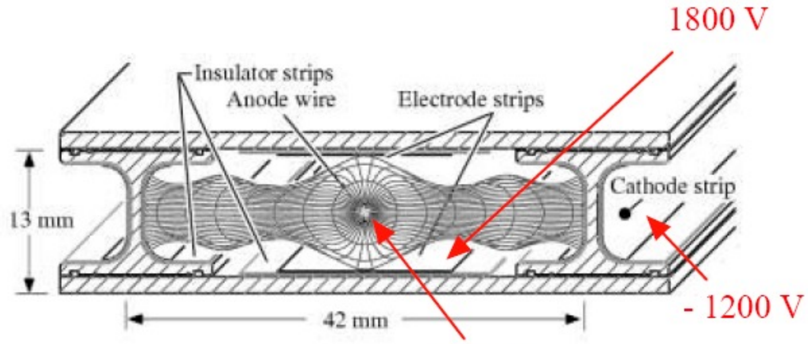
CMS Drift Tubes (DT)

- **240 chambers in CMS barrel** – 5 wheels
- Drift time measurement, gives **distance (d)** to wire to **~250 µm accuracy**

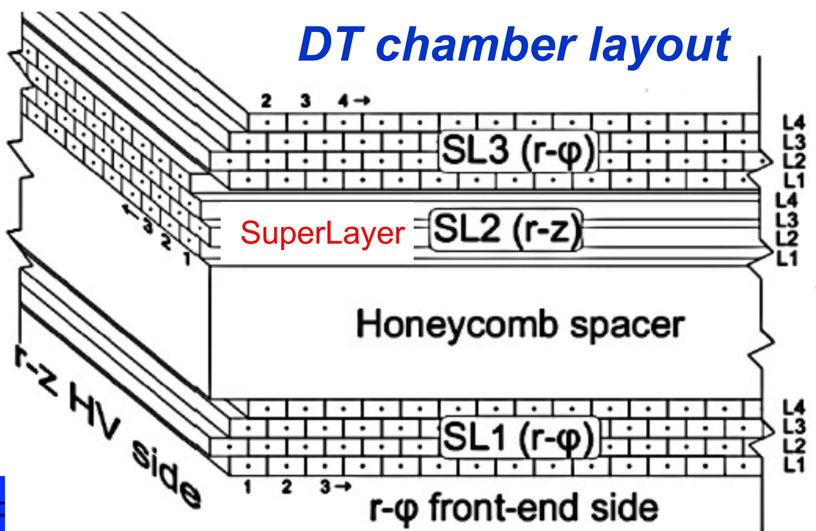
  $$d = (T - T_0) \times V_{drift}$$

- **4** stations
  - **12** layers per station in groups of 4
    - 8 axial (r-ϕ), 4 longitudinal (r-z)





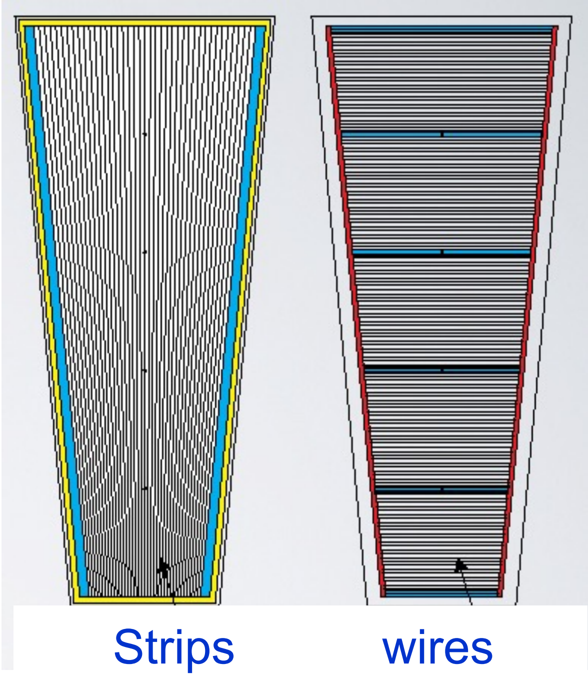
Nominal voltages

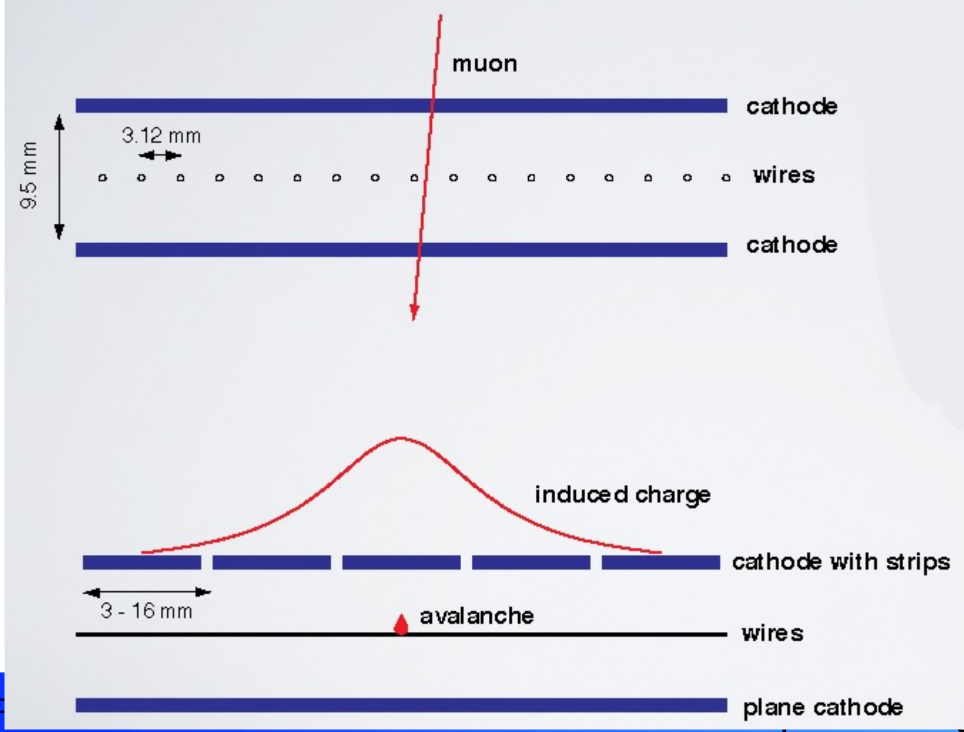


CMS Cathode Strip Chambers (CSC)

IHEP

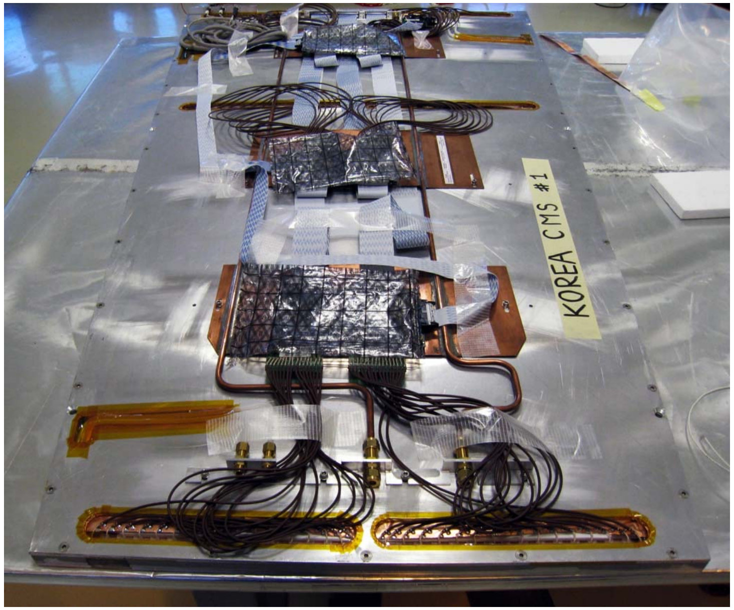
- **540 trapezoidal chambers in CMS endcaps**
- Electrons drift to wires, **induce** opposite charge on perpendicular cathode strips
- Precise ~2% interpolation of cathode charge on ~cm strips gives ~200 μm accuracy
- 6 layers: precision ϕ from cathode strips, coarse ***r*** and timing from anode wires



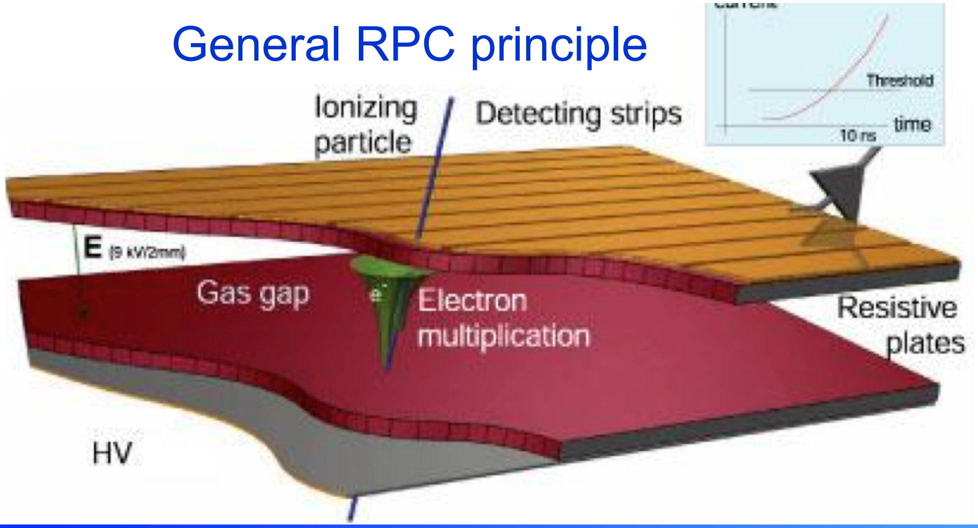


CMS Resistive Plate Chambers (RPC)

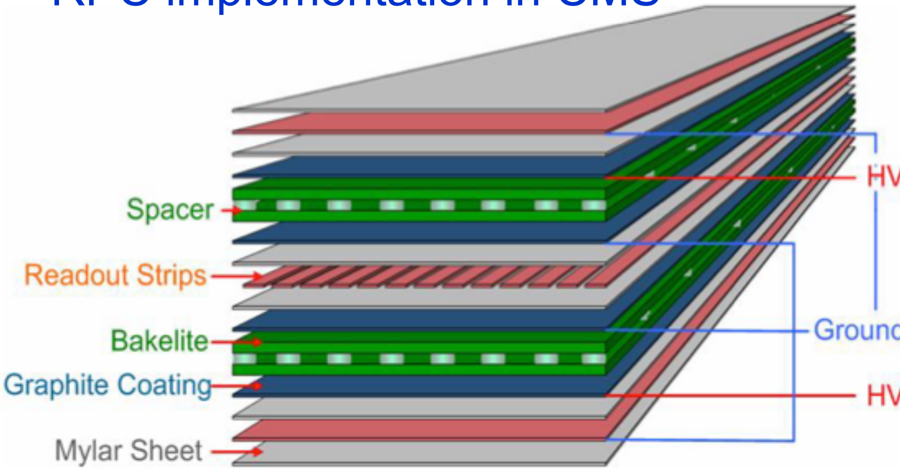
- **480** **barrel** and **576** **endcap** chambers
- Charge induced onto external strips
  - Resistive layer (Bakelite plastic) with $\rho \sim 10^{10}$ Ωcm is transparent to signal as if infinite, quenches avalanche as if conducting
- Spatial resolution 0.8-1.2 centimeters
- Double gap, each 2 mm, 9.6 kV, for high ε
- Fast - triggering



General RPC principle



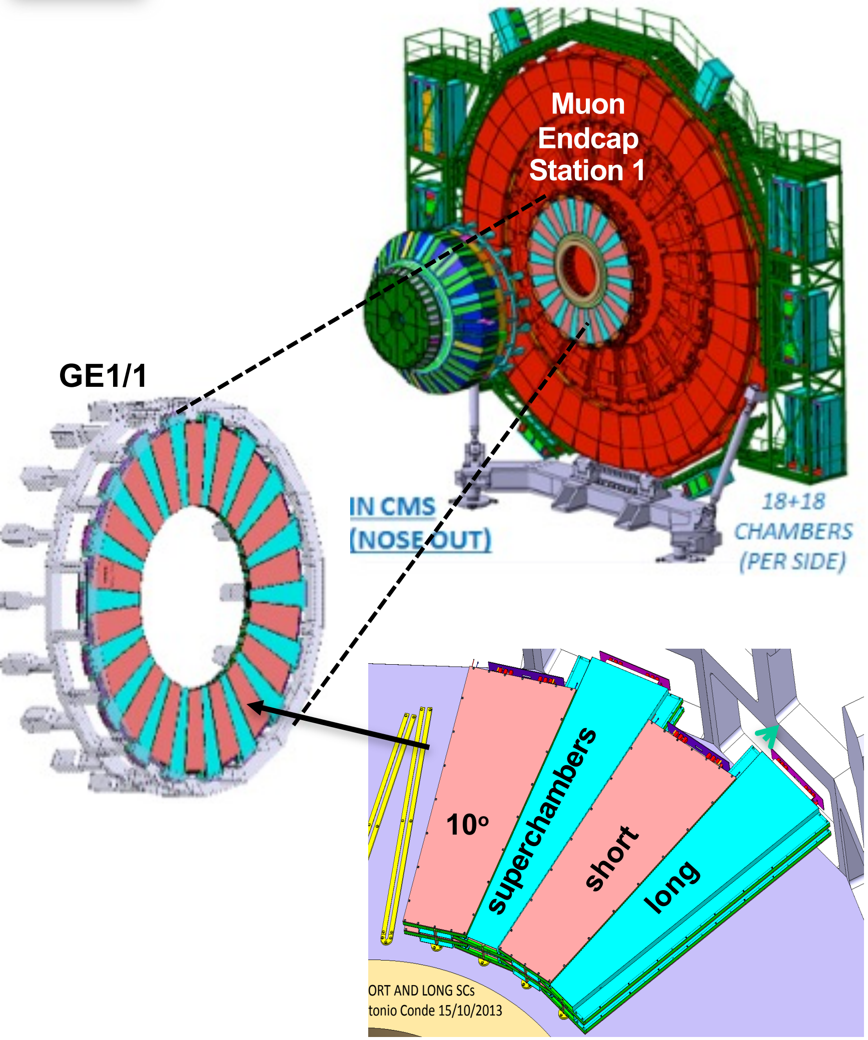
RPC implementation in CMS

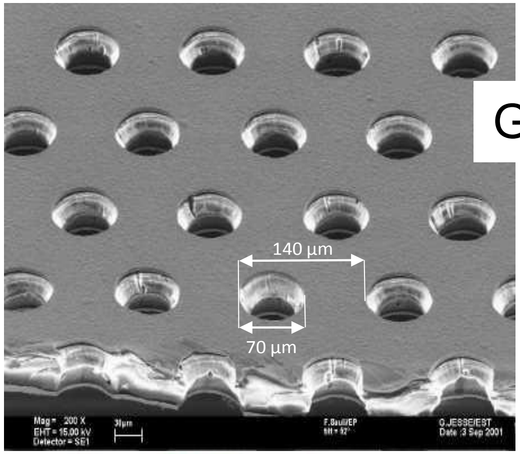


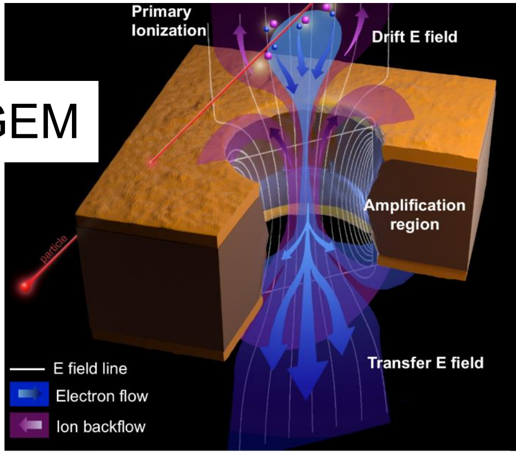
New Micro-Pattern Gas Detectors (MPGD):GEM

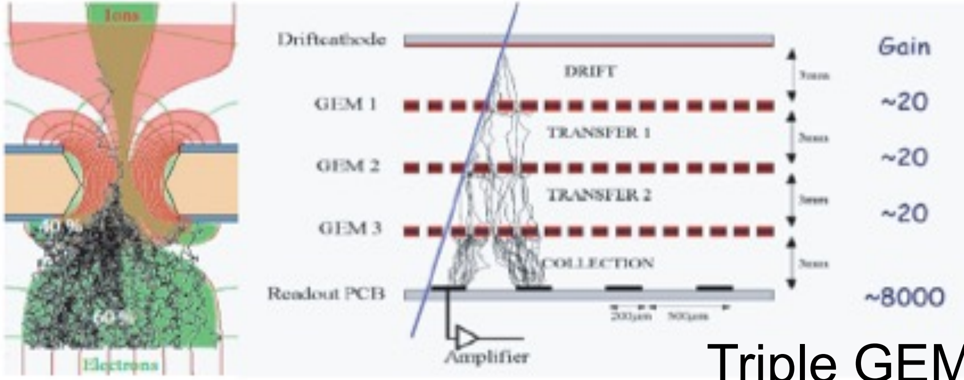
PKU

GEM: Gas Electron Multiplier









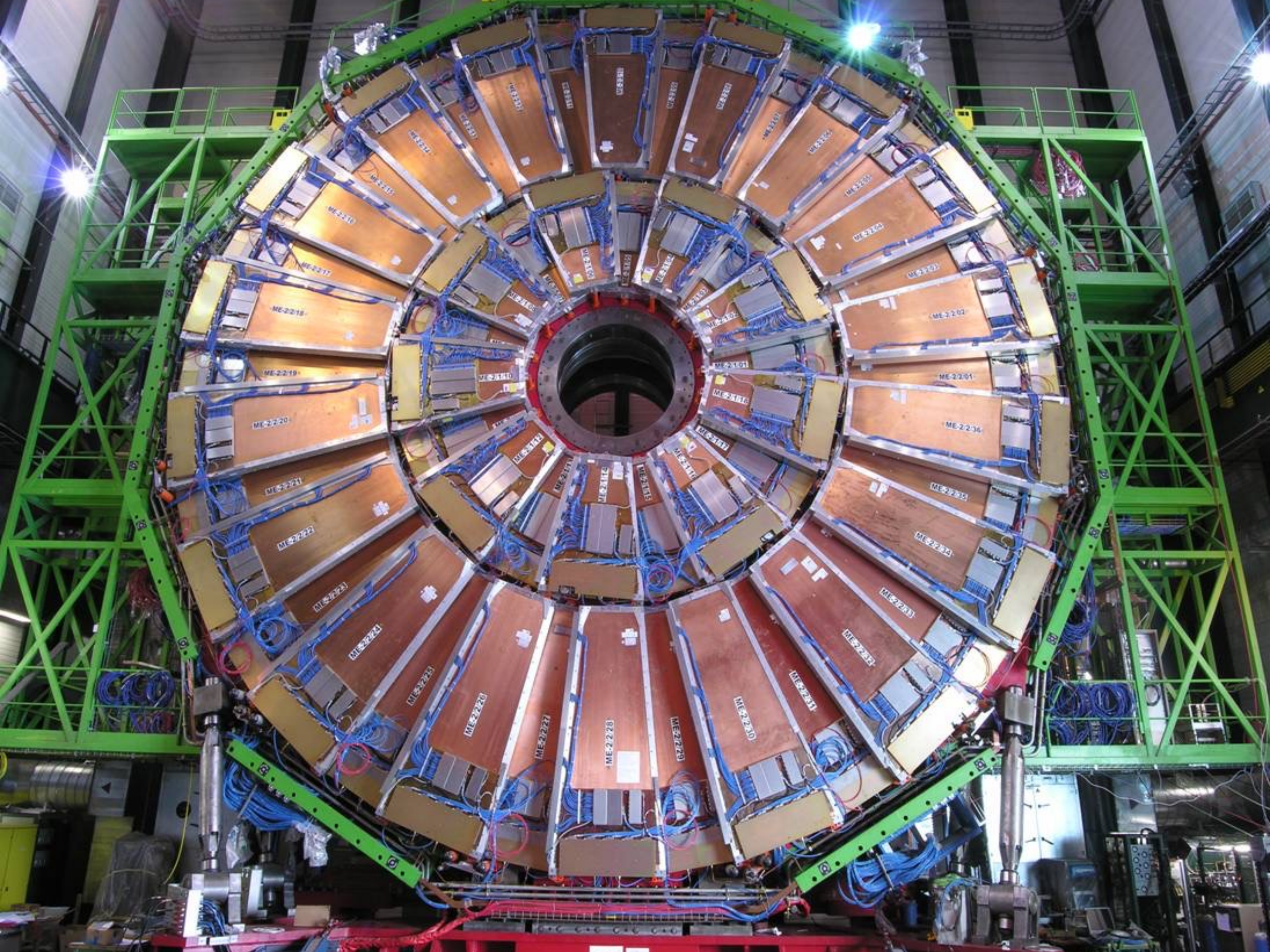
Triple GEM

Long (1.5<|η|<2.2) and short (1.6<|η|<2.2) version

36 superchambers in each endcap

- Decouple amplification and detection
- **High spatial and good time resolution**

Installation in LS2 – first half installed in October 2019!



ME-2/2/18
ME-2/2/20
ME-2/2/02
ME-2/2/01
ME-2/2/36

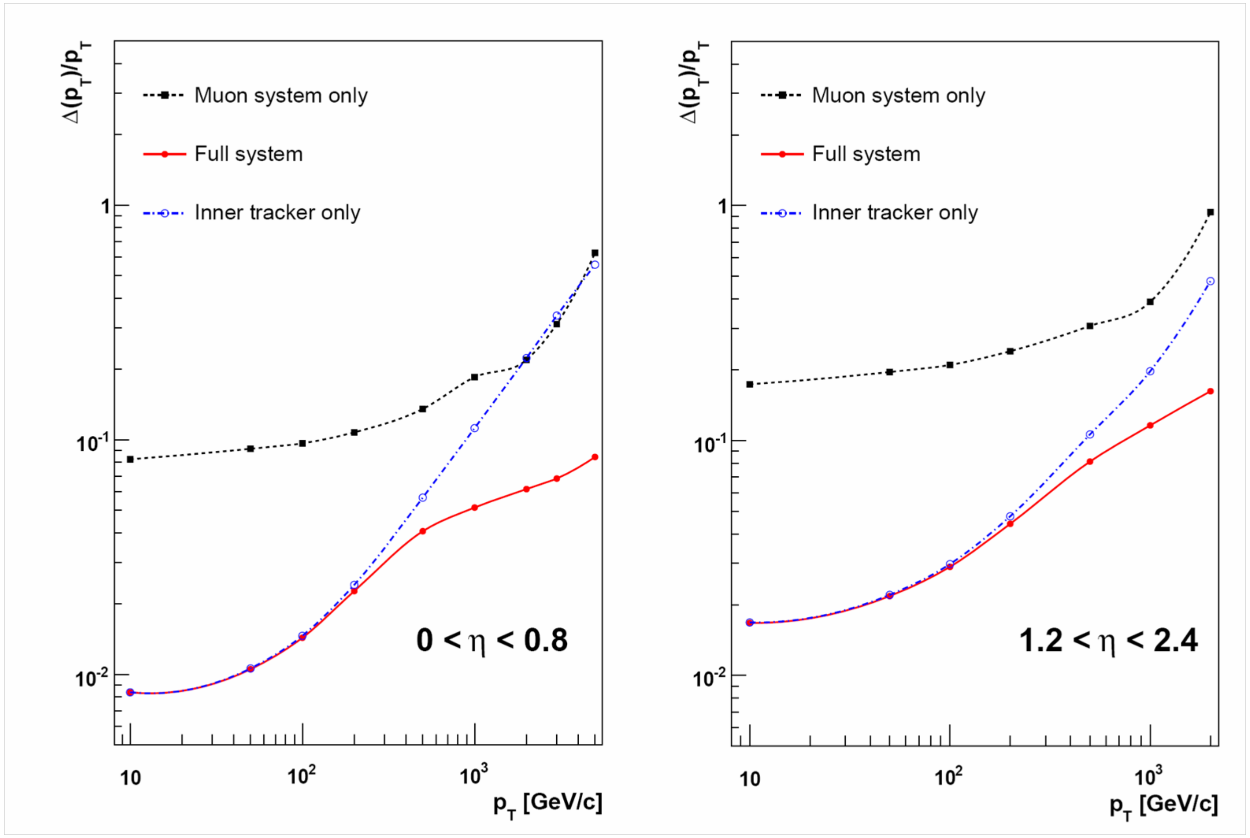
Muon探测器性能

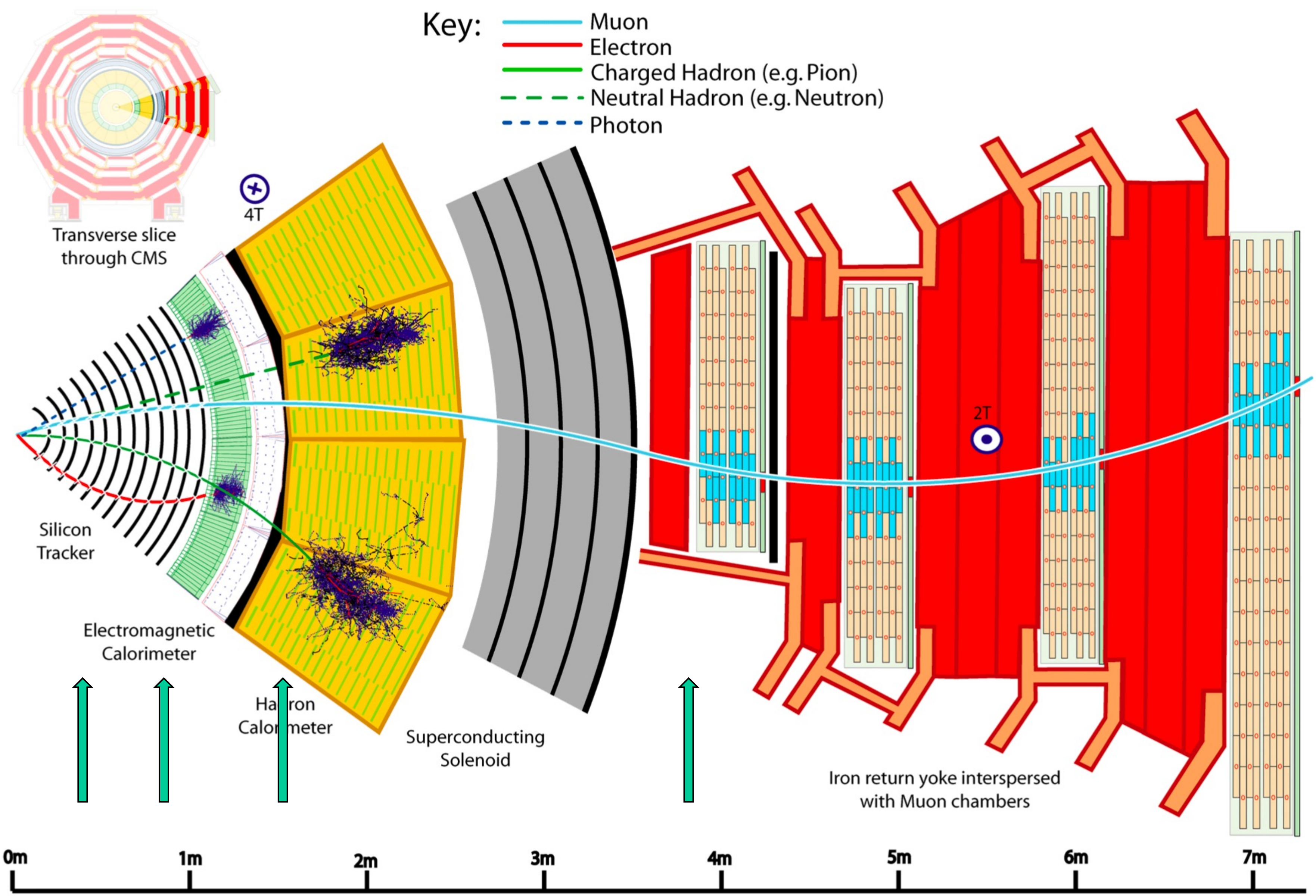
- The spatial resolution per chamber was
  - 80-120 μm in the DTs,
  - 40-150 μm in the CSCs,
  - 0.8-1.2 centimeters in the RPCs

The μ measurements improve the momentum resolution for p_T > 200 GeV/c if the DT/CSC chambers are properly aligned

Especially for p_T>1 TeV

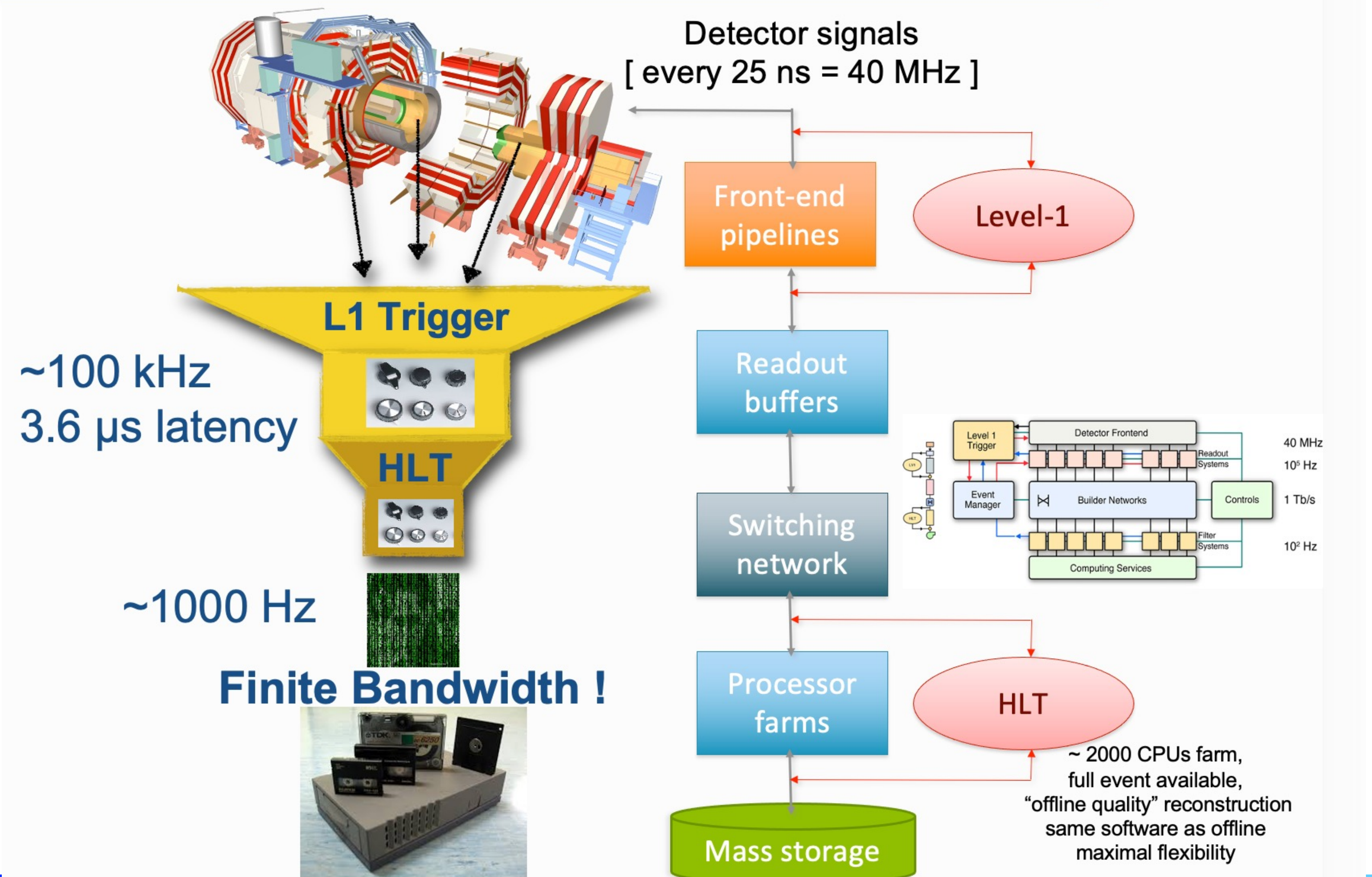
Alignment is done with hardware sensors to **<1 mm** level, then track-based correction to chamber positions to **~10 μm** level





Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
Transverse slice through CMS
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0m
1m
2m
3m
4m
5m
6m
7m

CMS触发和数据获取系统



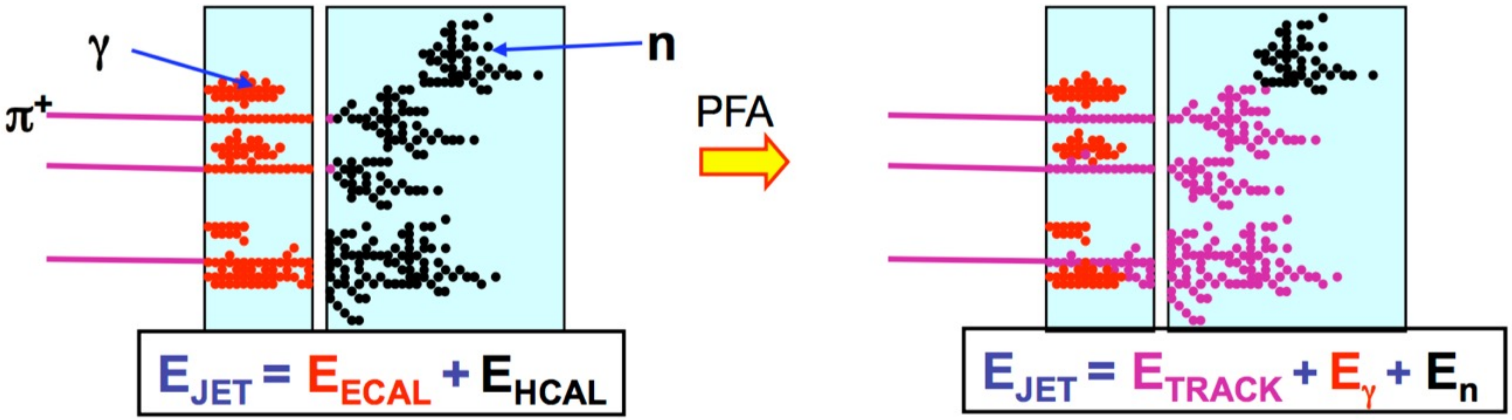
CMS探测器与ATLAS的比较

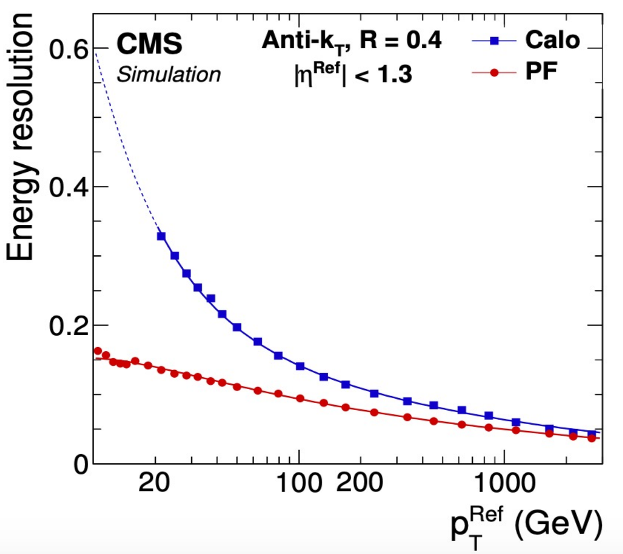
	ATLAS ≡ A Toroidal LHC ApparatuS	CMS ≡ Compact Muon Solenoid
MAGNET (S)	Air-core toroids + solenoid in inner cavity 4 magnets Calorimeters in field-free region	Solenoid Only 1 magnet Calorimeters inside field
TRACKER	Si pixels+ strips TRT → particle identification B=2T $\sigma/p_T \sim 3\times10^{-4}\ p_T \oplus 0.01$	Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5\times10^{-4}\ p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E} + 0.007$ longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 3\%/\sqrt{E} + 0.003$ no longitudinal segm.
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. (~7 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air → $\sigma/p_T \sim$ 2%(@50GeV) to 10% (@1 TeV) standalone	Fe → $\sigma/p_T \sim$ 1% (@50 GeV) to 10% (@1 TeV) combining with tracker

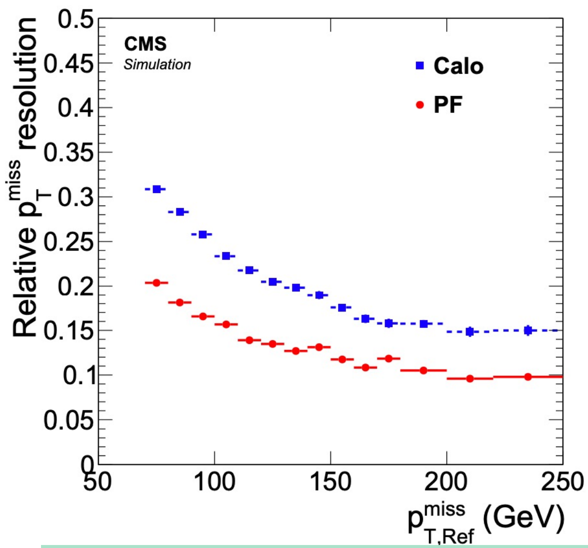
粒子流算法（Particle Flow Algorithm）

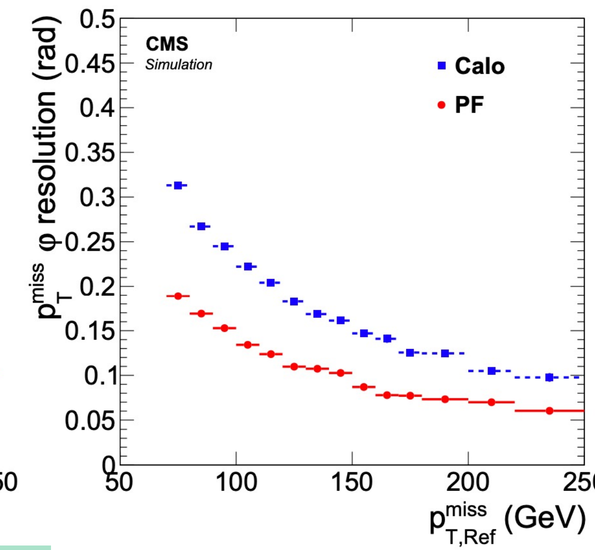
Use best meas. of individual particle in a jet (MET), ==> Particle Flow Algorithm

Charged tracks：Tracker（60%）；photons：ECAL（30%）；Neutral hadrons (10%)：HCAL









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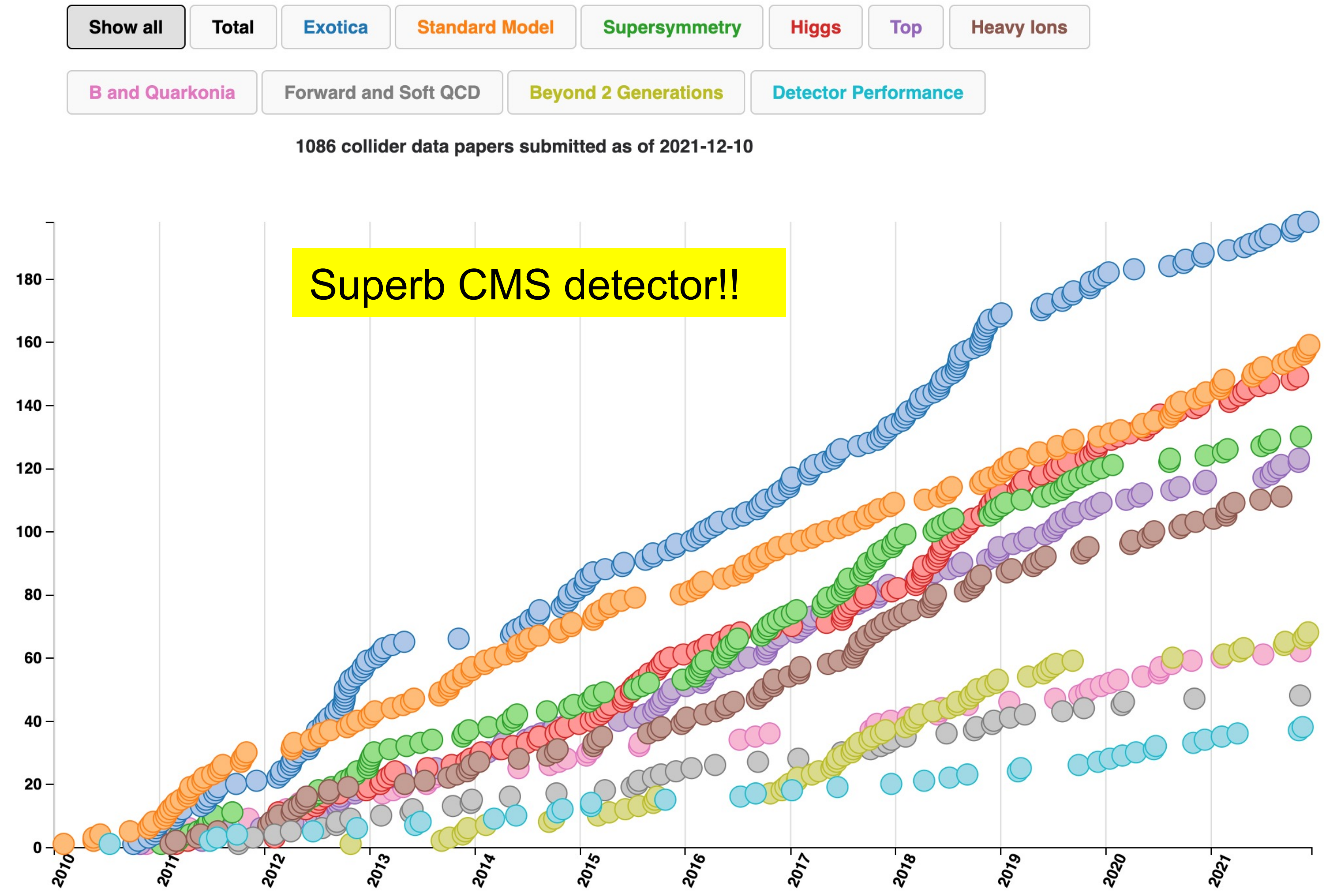
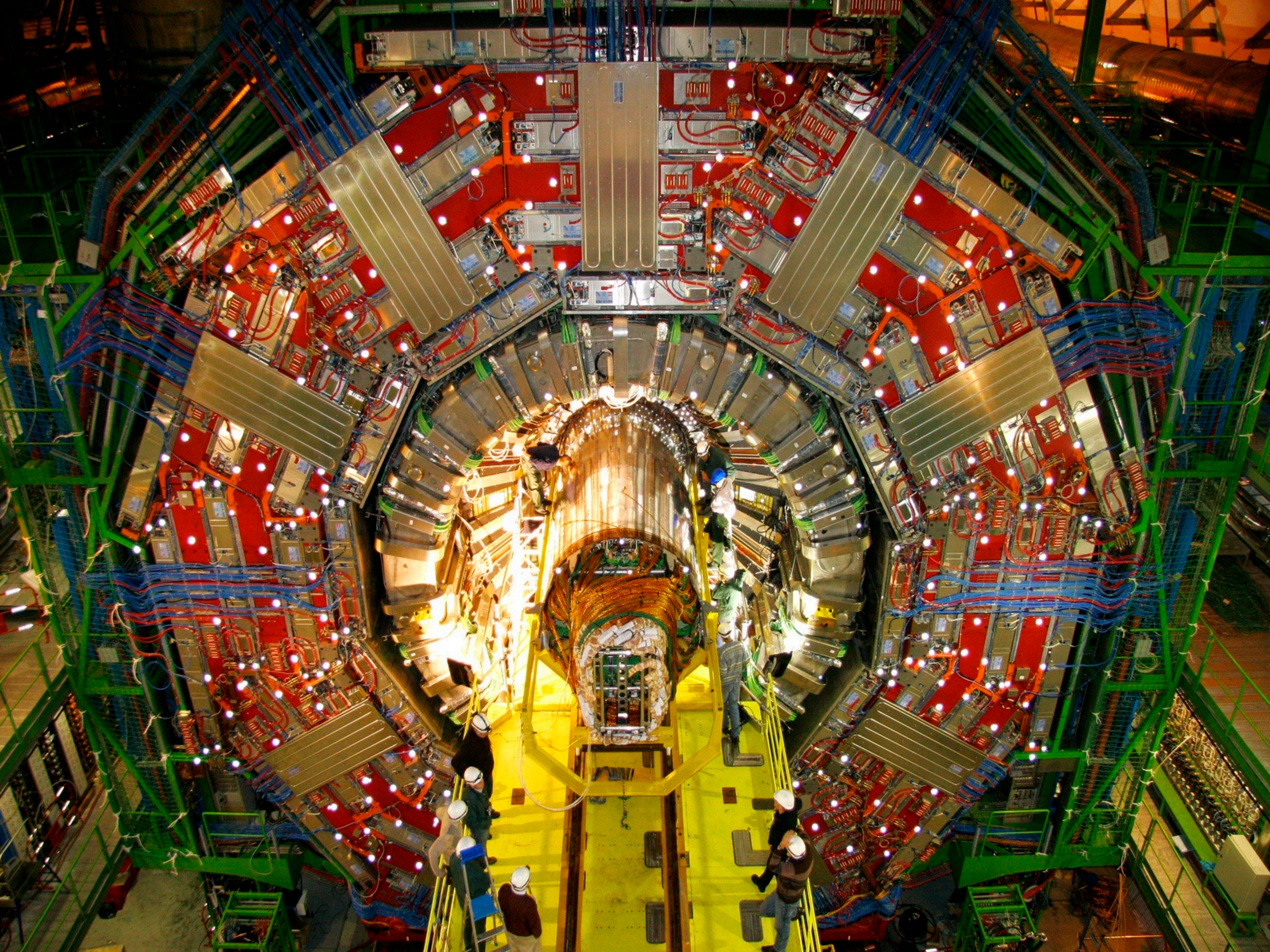
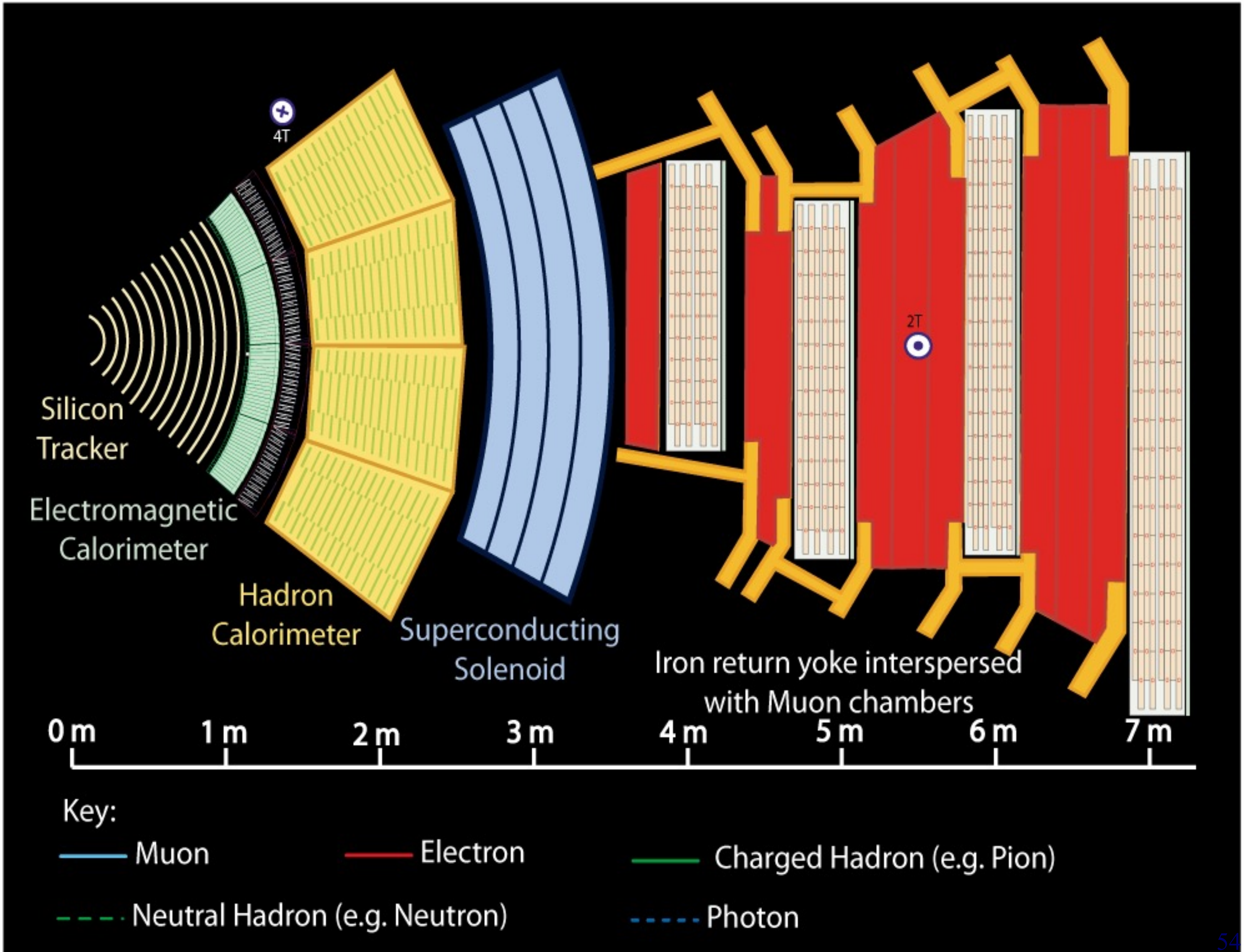
Welcome to CMS

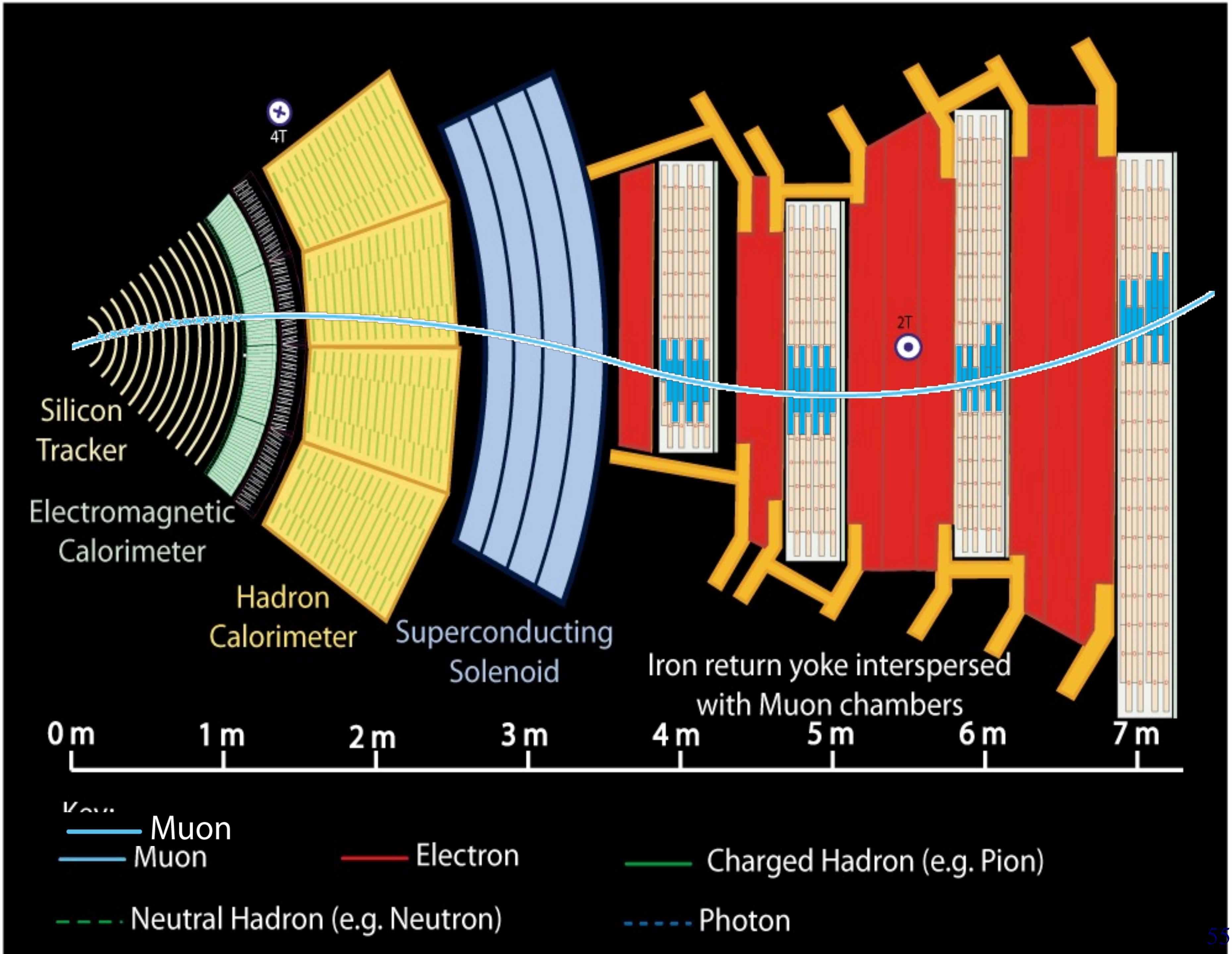


所有这些产出都依赖我们的CMS探测器
更好的物理成果==》CMS 探测器 phase II 升级



bakup


4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon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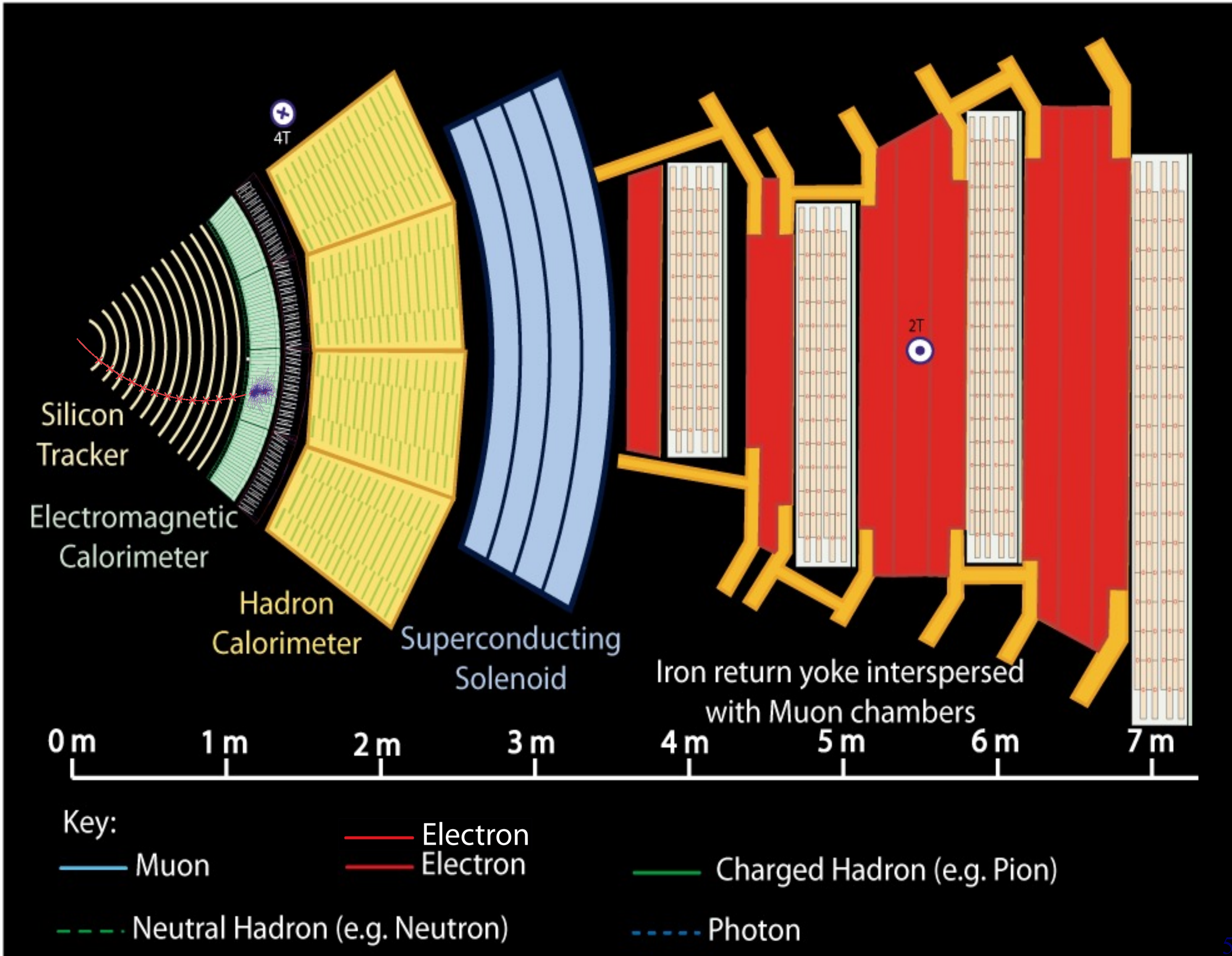
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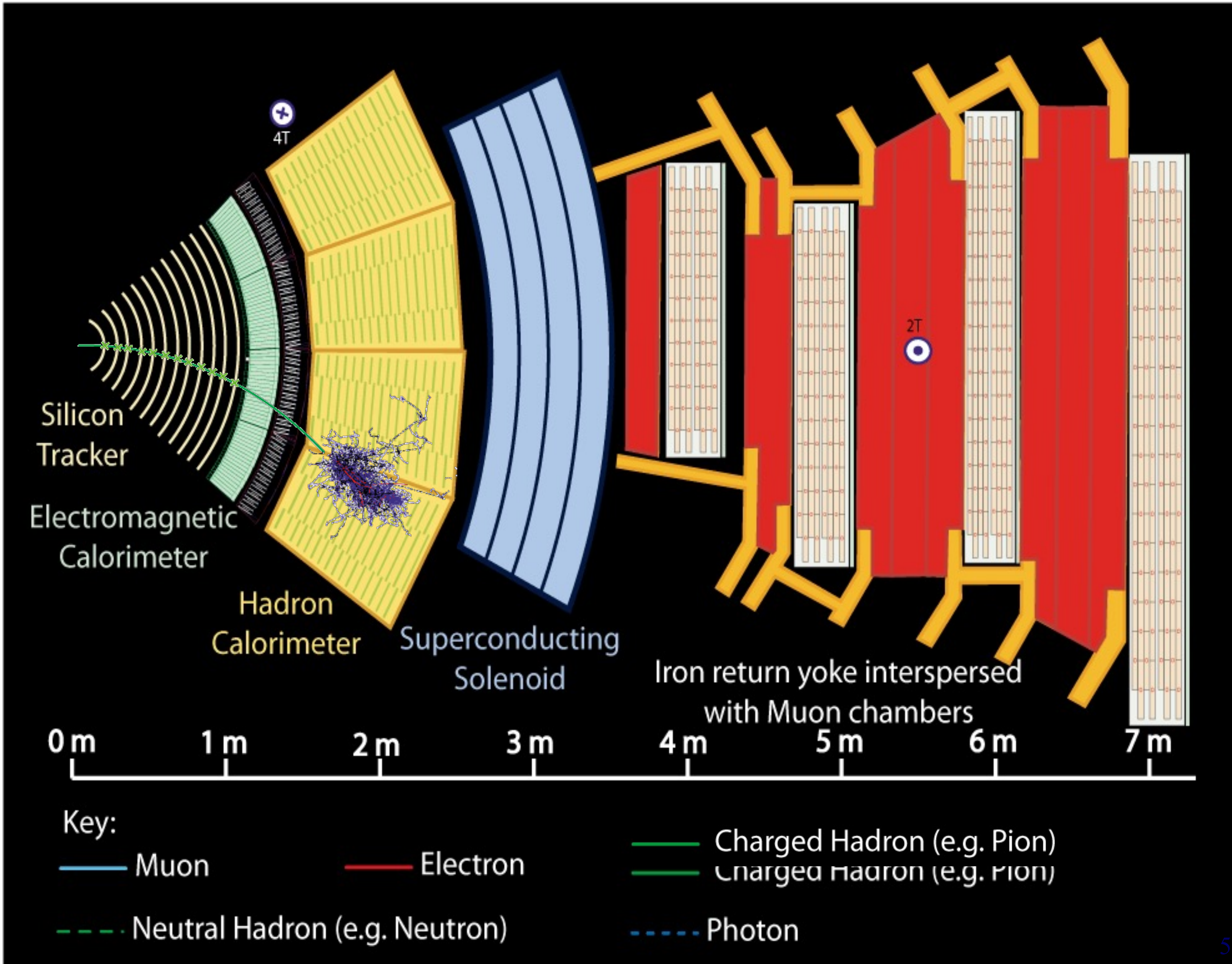
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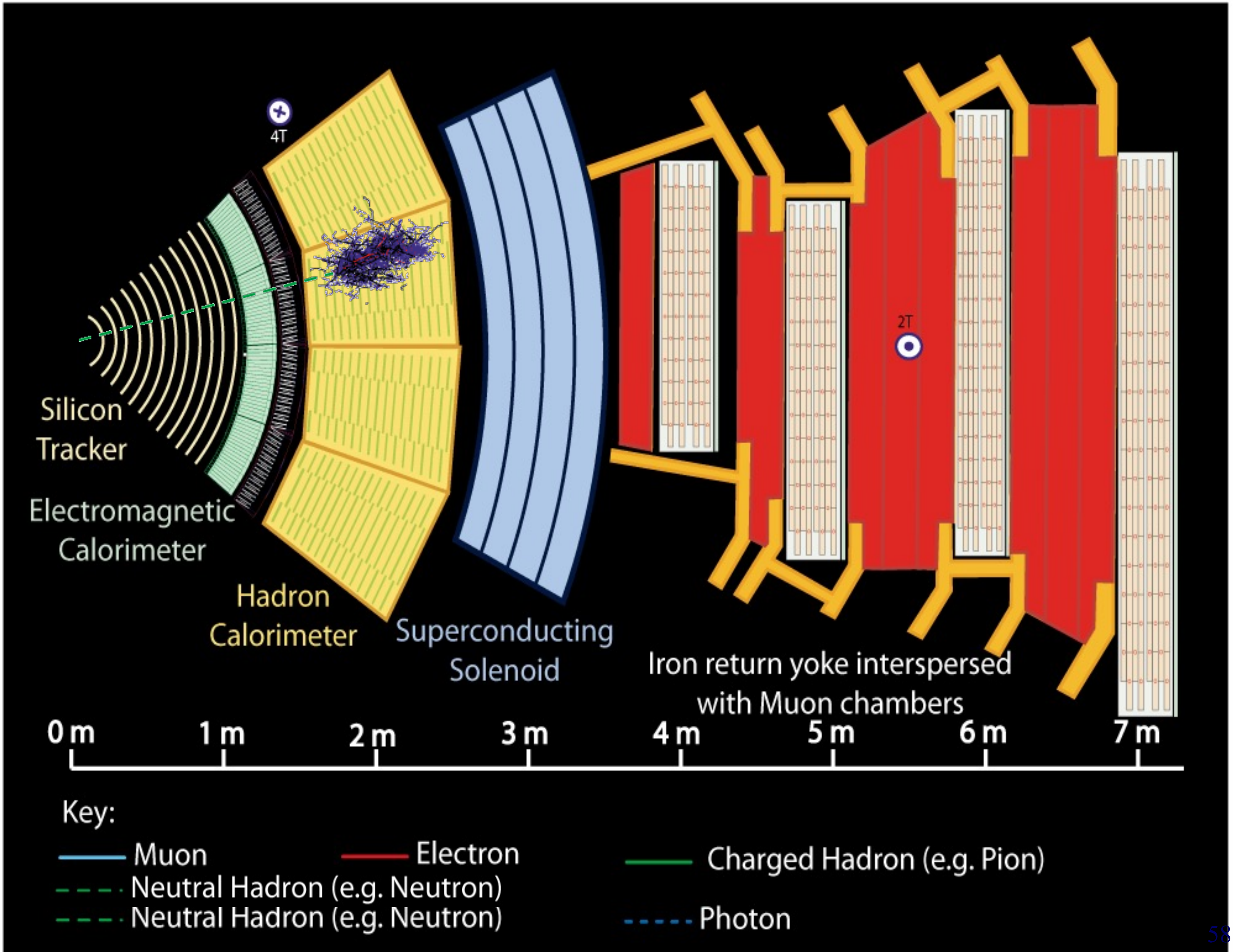
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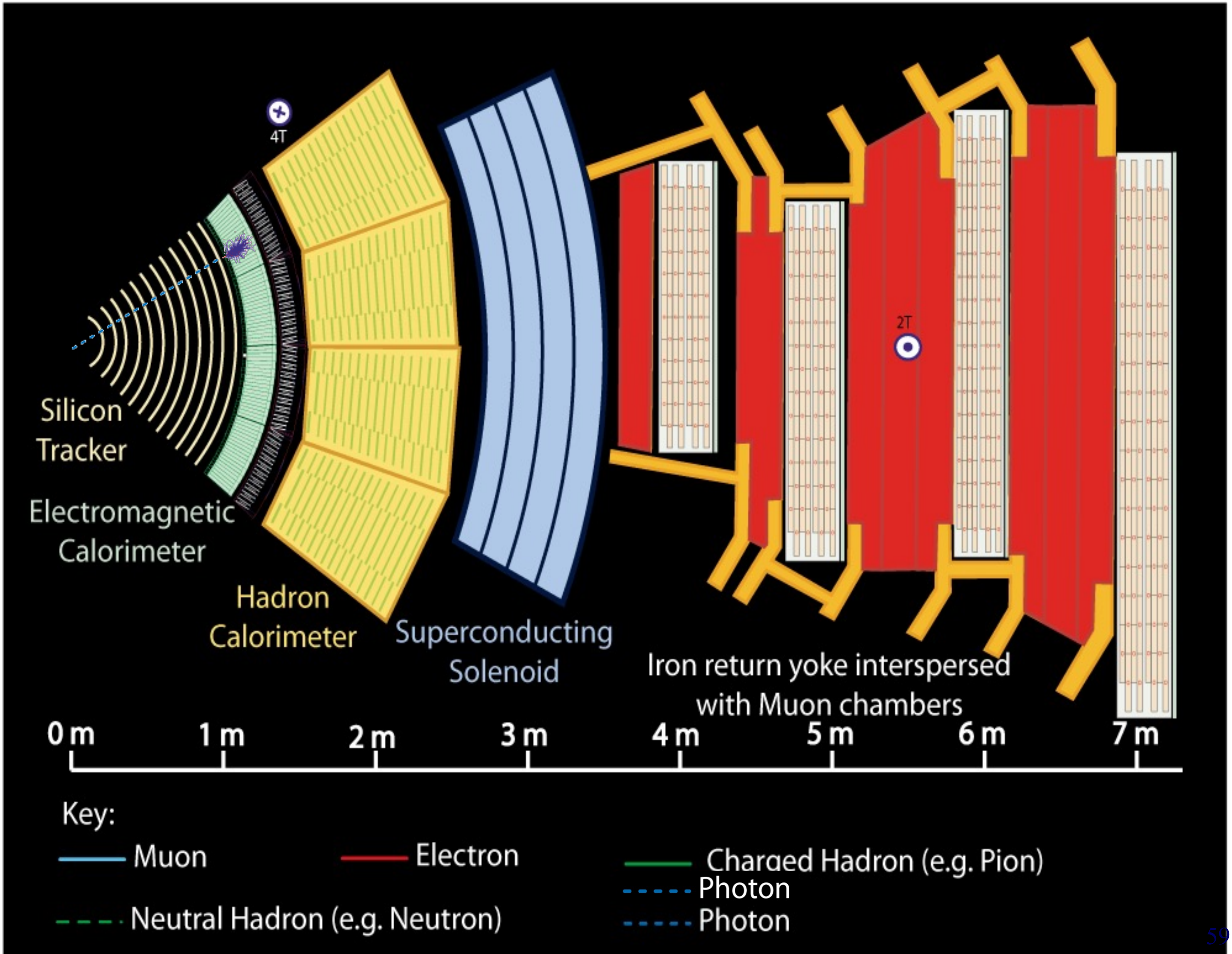

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