# CMS 探测器与升级简介

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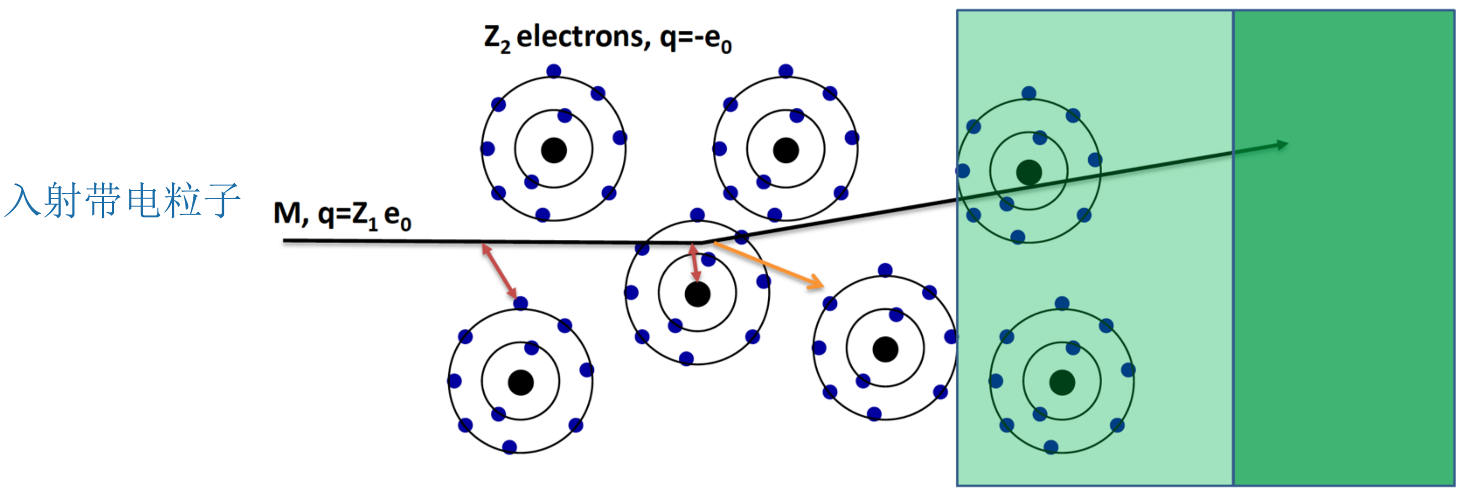
# 提纲

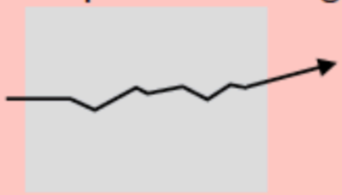
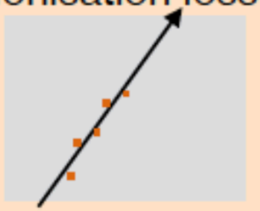
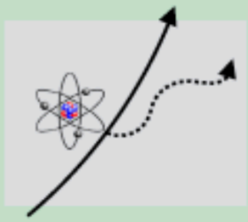
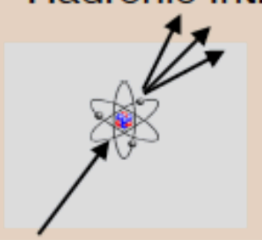
- 粒子探测基本原理回顾
- CMS探测器的整体设计思路
- CMS各子探测器简介与性能
- HL-LHC与探测器升级

# 粒子与物质相互作用(I)




- 与核外电子发生非弹性碰撞，入射粒子损失能量，引起原子激发或电离 → 电离能量损失
- 与原子核发生弹性、非弹性碰撞，产生多次散射（Multiple Scattering）；过程中还可能产生韧致辐射（Bremsstrahlung）→ 辐射能量损失
- 介质中粒子速度超过光速时产生切伦科夫光；当粒子穿过两种物质边界时有一定概率发出X-光（穿越辐射）。

# 粒子与物质相互作用(II)

| Type | particles | fund. parameter | characteristics | effect |
|---|---|---|---|---|
| Multiple Scattering  | all charged particle | radiation length $X$ | almost gaussian average effect 0 depends $\sim 1/\mathrm{p}$ | deflects particles, increases measurement uncertainty |
| Ionisation loss  | all charged particle | effective density $A/Z^* \rho$ | small effect in tracker, small dependence on $\mathrm{p}$ | increases momentum uncertainty |
| Bremsstrahlung  | all charged particle, dominant for e | radiation length $X$ | highly non-gaussian, depends | introduces measurement bias |
| Hadronic Int.  | all hadronic particles | nuclear interaction length $\Lambda$ | destroys particle, rather constant effect in $\mathrm{p}$ | main source of track reconstruction inefficiency |

# 电离能量损失与多次散射

Valid for heavy charged particles ($m_{incident}$>>$m_e$), e.g. proton, k, π, μ

$$-\left\langle \frac{dE}{dx} \right\rangle = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2} \left[ \ln\left(\frac{2m_e c^2 \beta^2 \gamma^2}{I^2} W_{max}\right) - 2\beta^2 - \delta(\beta\gamma) - \frac{C}{Z} \right]$$

$2\pi N_a r_e^2 m_e c^2$ =0.1535 MeV cm$^2$/g

$$\frac{dE}{dx} \propto \frac{Z^2}{\beta^2} \ln\left(a\beta^2\gamma^2\right)$$

**Fundamental constants**

$r_e$=classical radius of electron
$m_e$=mass of electron
$N_a$=Avogadro's number
c =speed of light

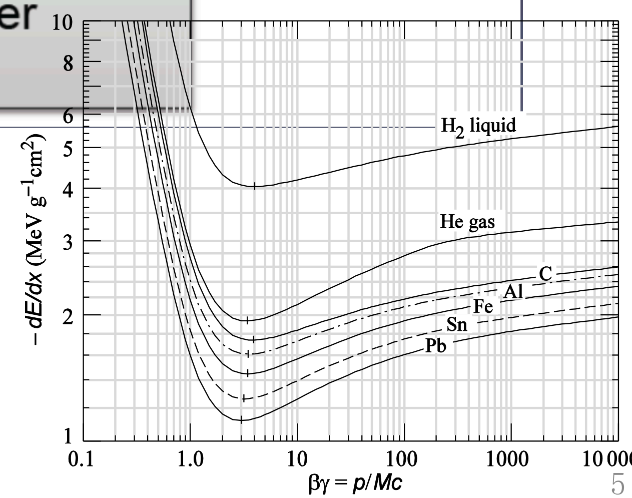
$$r_e = \frac{1}{4\pi\varepsilon_0} \frac{e^2}{m_e c^2}$$

**Absorber medium**

I = mean ionization potential
Z = atomic number of absorber
A = atomic weight of absorber
ρ = density of absorber
δ = density correction
C = shell correction

**Incident particle**

z = charge of incident particle
β = v/c of incident particle
γ = $(1-\beta^2)^{-1/2}$
$W_{max}$= max. energy transfer in one collision



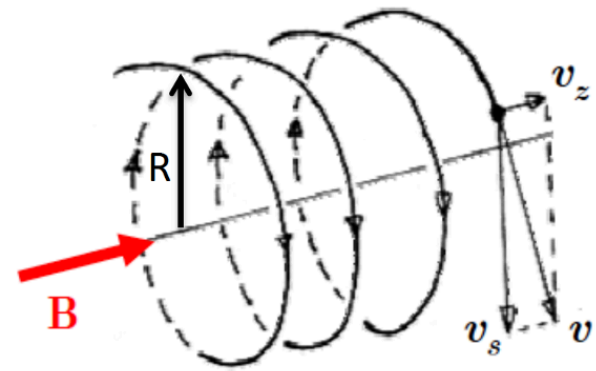

$$\theta_{rms}^{proj} = \sqrt{\langle\theta^2\rangle} = \frac{13.6\,\mathrm{MeV}}{\beta c p} z \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln(x/X_0)\right]$$

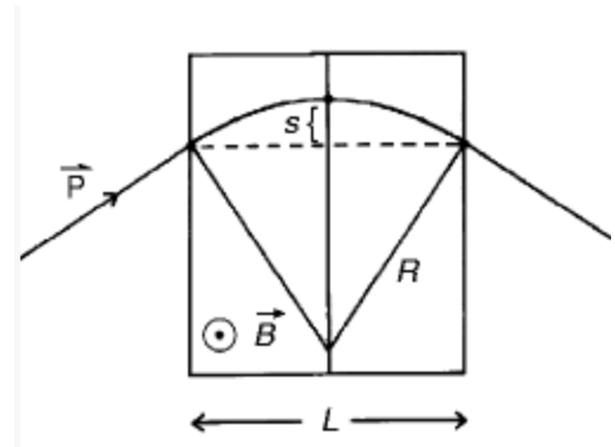
# 动量测量：带电粒子在磁场中的运动

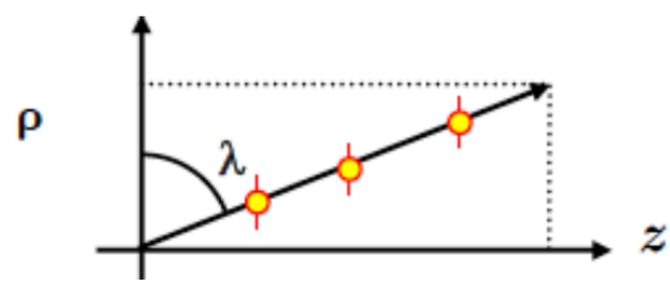
- 带电粒子在磁场中的运动：
  - $\frac{\mathrm{d}\vec{p}}{dt} = \vec{\mathrm{F}} = q\vec{v}\times\vec{B}$
- 在垂直磁场和速度的方向：

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

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



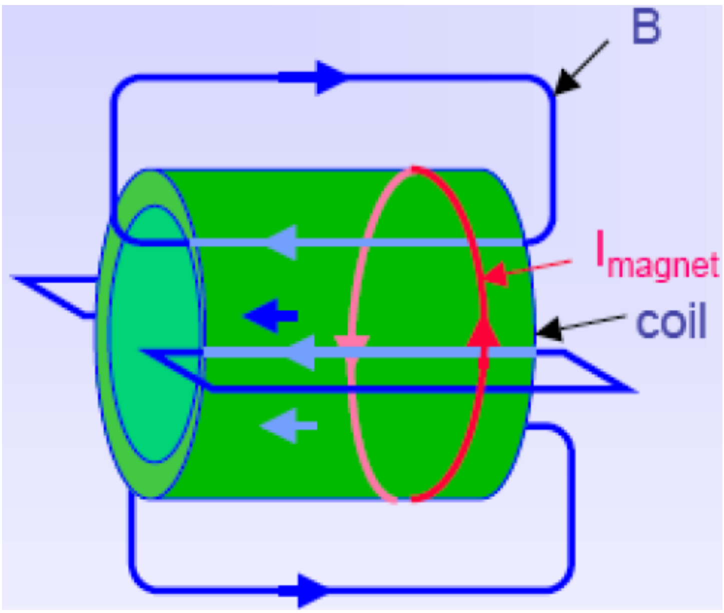



# Tracking in B-field

Spectrometer (measure momentum):

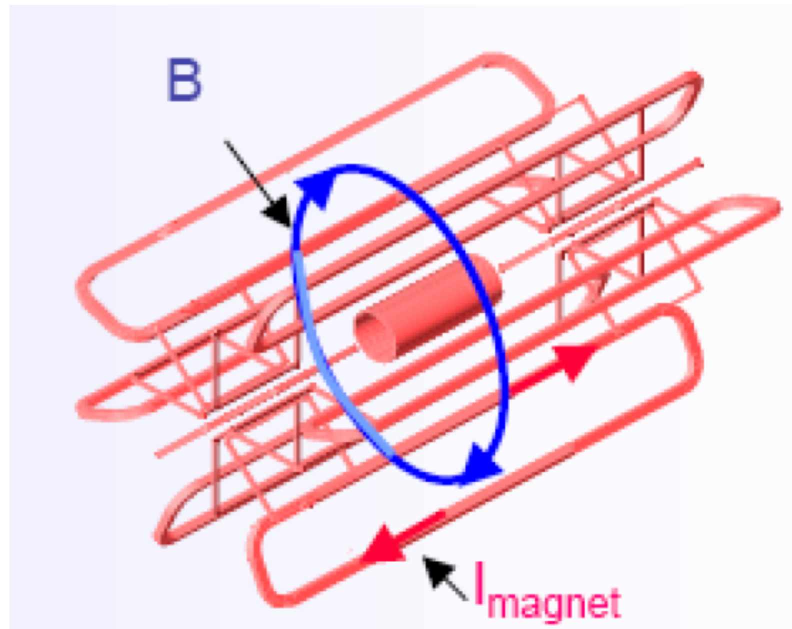
Tracking detector in magnetic field

$$\frac{d\mathbf{p}}{dt} = \frac{q}{c}\mathbf{v} \times \mathbf{B}$$




**Solenoid**

Uniform field; Vol. limited by cost




**Toroid**

Non-uniform field; Large volume

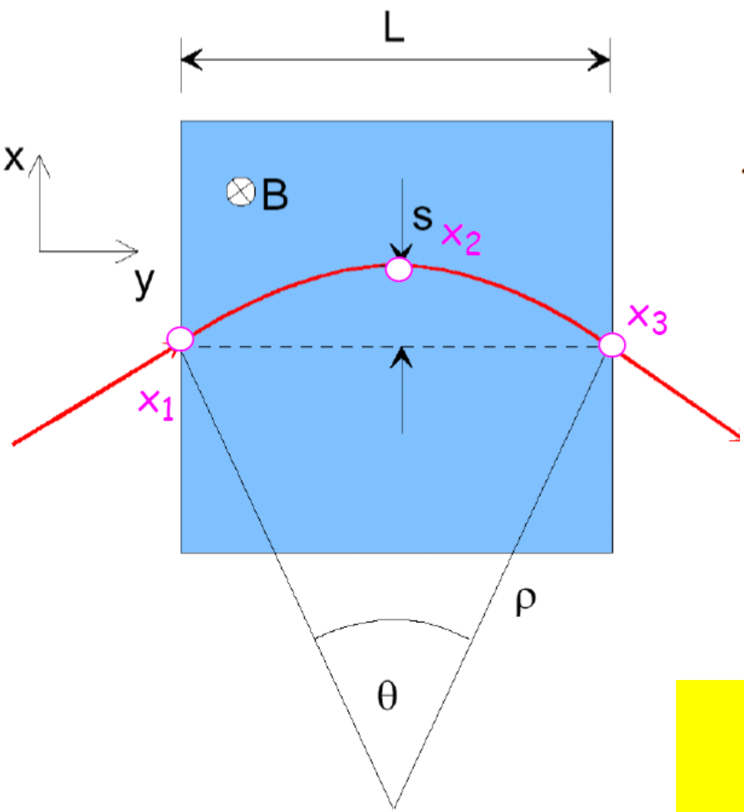
# Charge and Momentum

The momentum is measured
from the curvature ρ in B-field
Or from the sagitta s

Transverse momentum: $p_T = qB\rho$

$$p_T[GeV] = 0.3\ B[T]\ \rho[m]$$

$$\frac{L/2}{\rho} = \sin\frac{\theta}{2} \approx \frac{\theta}{2}\ (\text{for small } \theta) \Rightarrow \theta \approx \frac{L}{\rho} = \frac{0.3BL}{p_T}$$




$$s = \rho(1-\cos\frac{\theta}{2}) \approx \rho\left(1-(1-\frac{1}{2}\frac{\theta^2}{4})\right) = \rho\frac{\theta^2}{8} \approx \frac{0.3BL^2}{8p_T}$$

Example: 3 measurements

Design consideration

$$s = x_2 - (x_1+x_3)/2 \rightarrow ds = dx_2 - dx_1/2 - dx_3/2$$

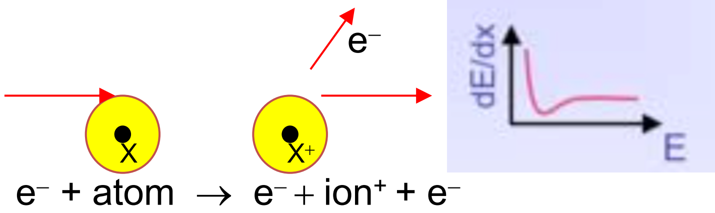
assume uncorrelated errors: $\sigma(x) \approx dx_i$

$$\sigma_s^2 = \sigma^2(x) + 2\frac{\sigma^2(x)}{4} = \frac{3}{2}\sigma^2(x)$$

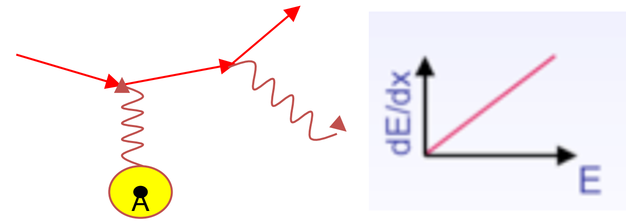
改善动量分辨： 增加L²B，减小$p_\perp$， $\delta s$
造价一般正比L³

# 粒子与物质相互作用(III)

- Electrons
  - Ionization (atomic electrons)



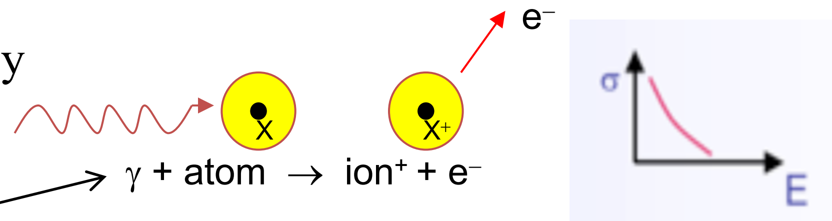

  - Bremsstrahlung (nuclear)



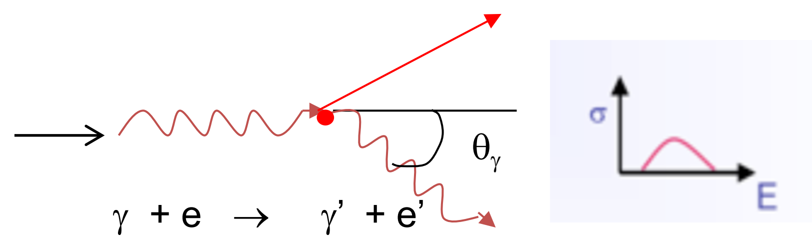

At high E, bremsstrahlung dominates

Critical energy, Ec ≈ 610 MeV/(Z + 1.24): energy at which the average energy losses by radiations equal those by ionization

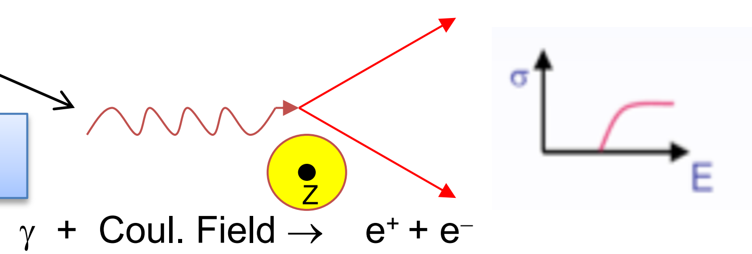
- Photons




  - Photoelectric effect (atomic electrons)
  - Compton scattering (atomic electrons)



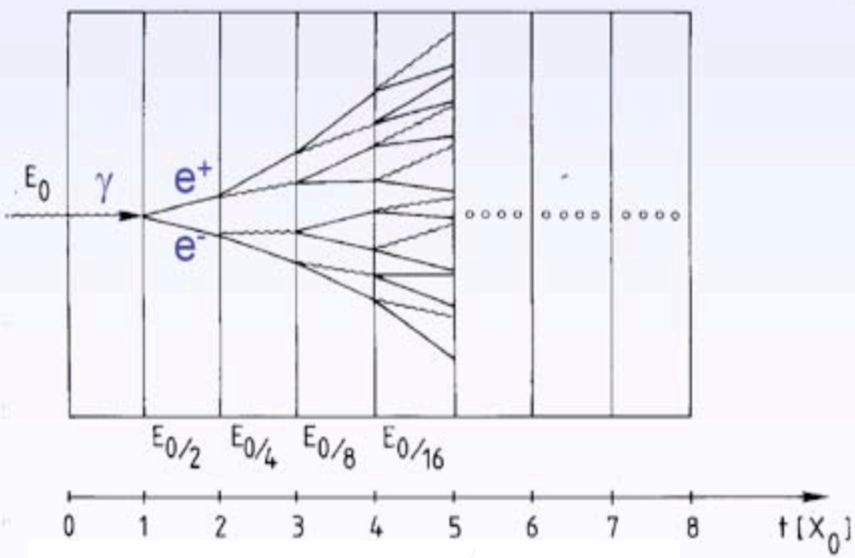

  - Pair-production (nucleus + electrons)

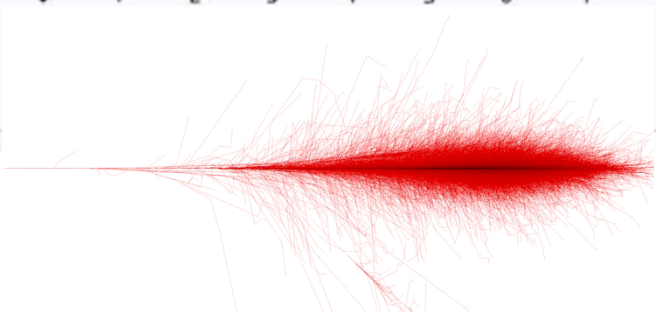



At high E, pair-production dominates

# 电磁簇射

## Simple qualitative model



- Consider only Bremsstrahlung and (symmetric) pair production.
- Assume: $X_0 \sim \lambda_{pair}$

$$N(t) = 2^t \qquad E(t)/\,particle = E_0 \cdot 2^{-t}$$

Process continues until $E(t) < E_c$

$$N^{total} = \sum_{t=0}^{t_{max}} 2^t = 2^{(t_{max}+1)} - 1 \approx 2 \cdot 2^{t_{max}} = 2\frac{E_0}{E_c}$$

$$t_{max} = \frac{\ln E_0/E_c}{\ln 2}$$

After $t = t_{max}$ the dominating processes are ionization, Compton effect and photo effect absorption of energy.

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

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

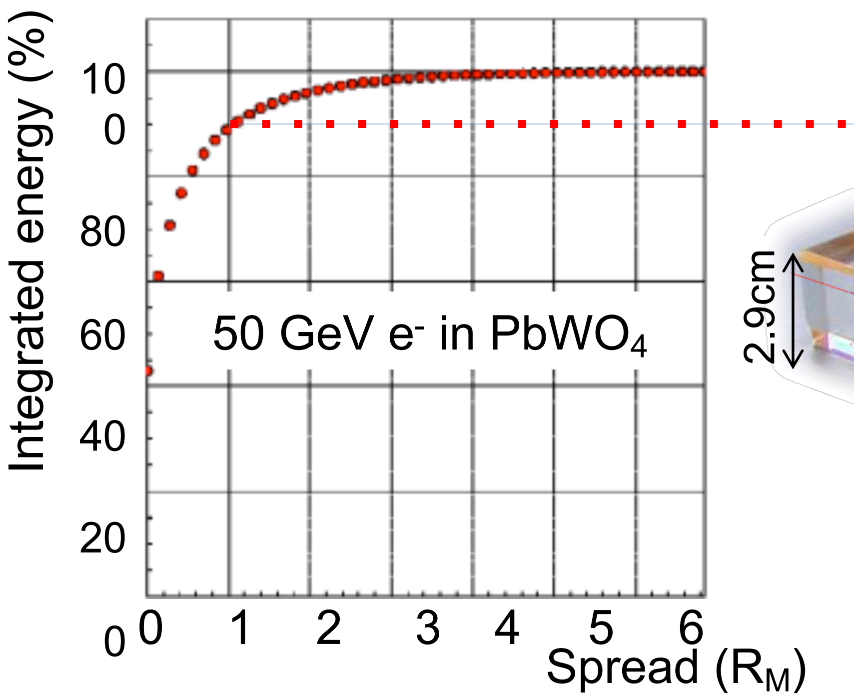
# 簇射的横向发展

Lateral spread of an em shower is dominated by two processes:

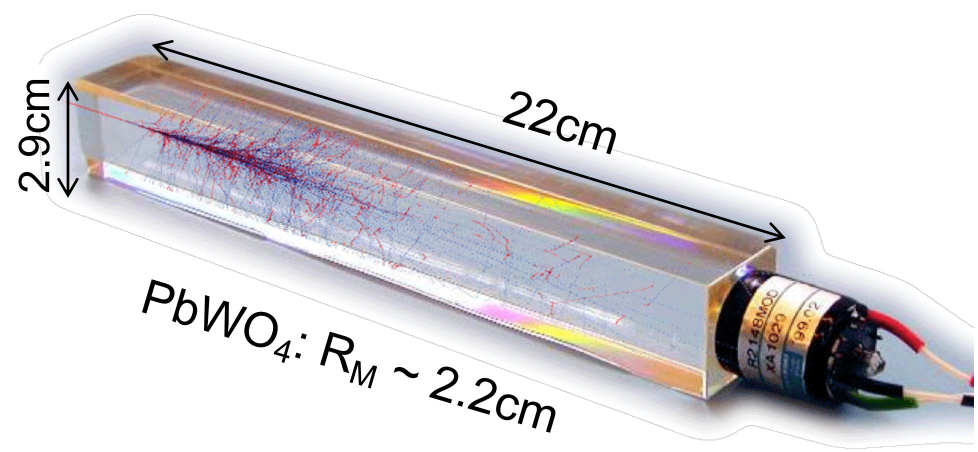
- Multiple scattering of electrons away from the shower axis
- Relatively long mean free path of photons

Molière radius: lateral spread for $E_C$ electrons after one $X_0$

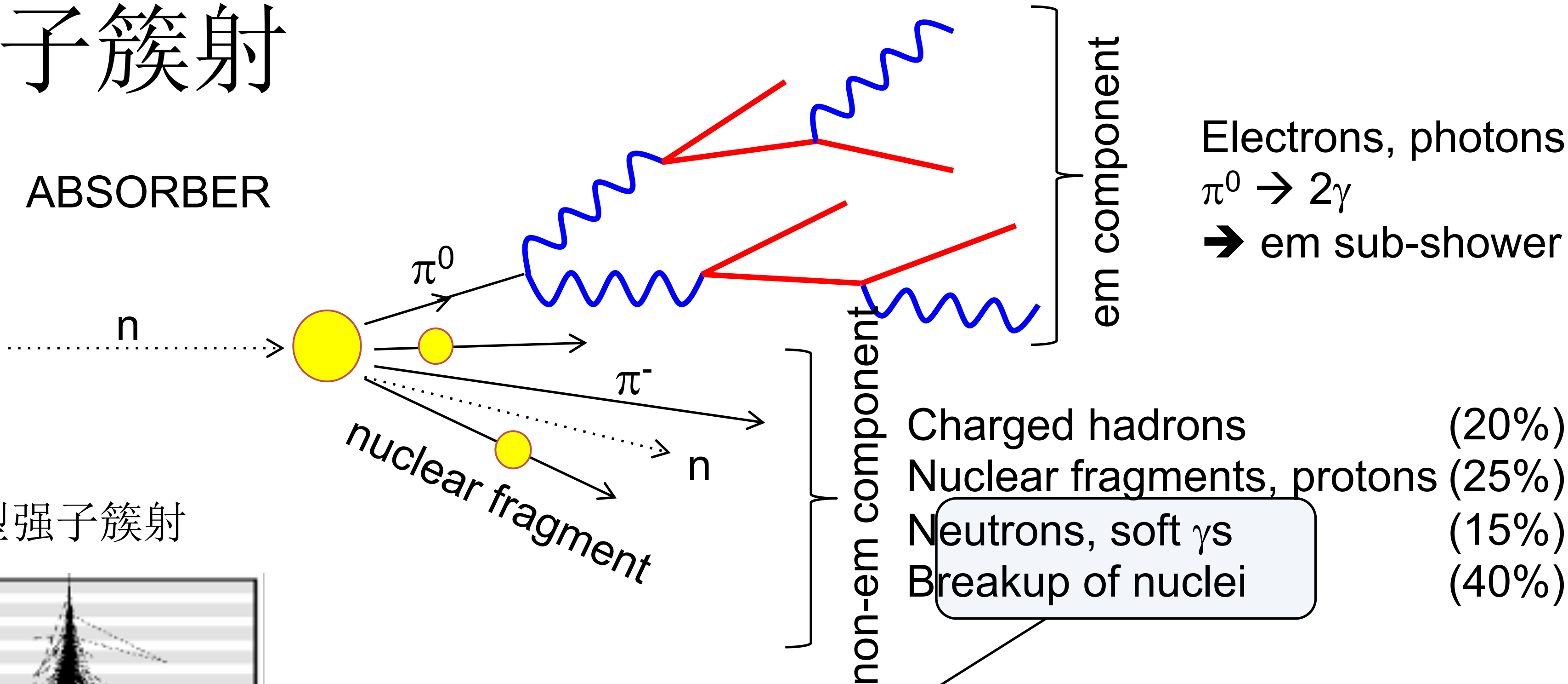
$$R_M = \frac{21\,MeV}{E_C} X_0 \approx 7\frac{A}{Z}$$



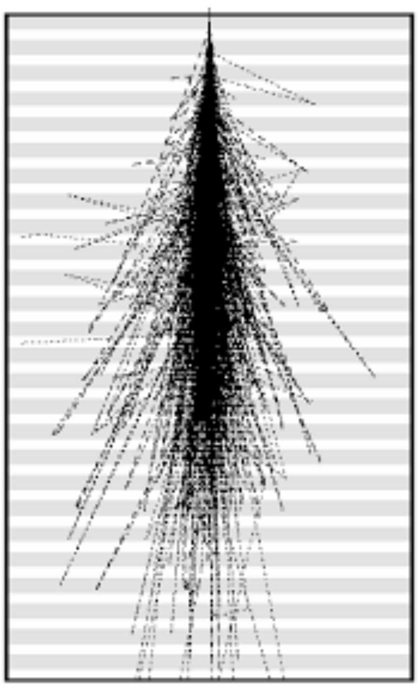

99% within 3.5 $R_M$
95% within 2 $R_M$
90% of shower energy within 1 $R_M$



# 强子簇射




典型强子簇射



Either not detected or often too slow to be within detector time window ➔ invisible energy

# 几个重要概念

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

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 $e$, $X_0 \sim A/Z^2$

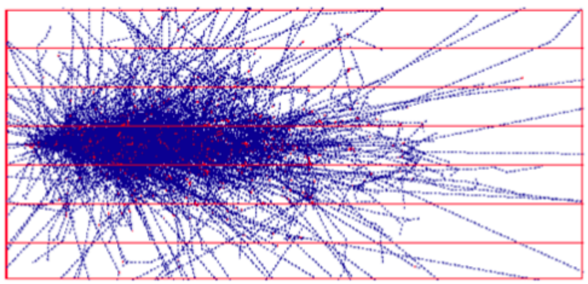
**Molière radius** ($R_M$): average lateral deflection of electrons of critical energy $E_c$ after traversing $1X_0$; 90% $E_0$ within $1R_M$, 95% within $3R_M$

**Interaction length** ($\lambda_{int}$): 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 |
|---|---|---|---|---|---|
| $\lambda_{int}$ [cm] | 83.7 | 16.8 | 17.1 | 10.5 | 38.1 |
| $X_0$ [cm] | 14.0 | 1.76 | 0.56 | 0.32 | 18.8 |

# 量能器Calorimeter:全吸收与取样型

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

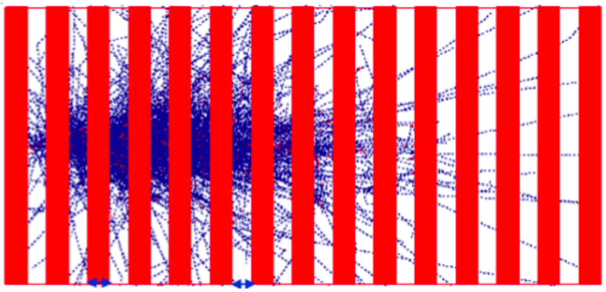


- Excellent energy resolution
- No information on longitudinal shower shape
- Cost

Examples

Flavor factories (small γ energies): KLOE, BESIII, CLEO_c, Belle(II), Babar
OPAL, Delphi, L3 (LEP)
ALICE PHOS & CMS ECAL

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

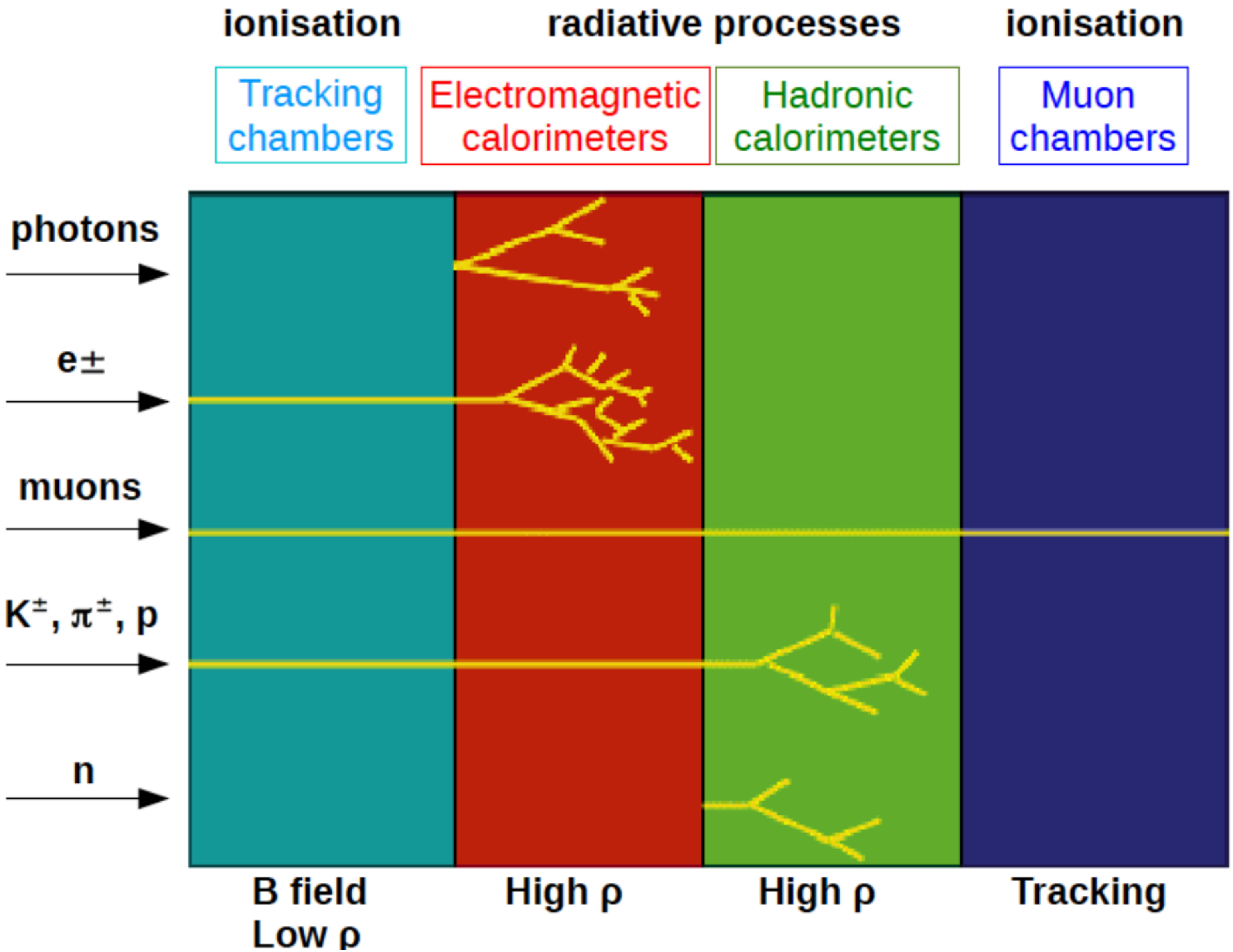


- Limited energy resolution
- Longitudinal segmentation: detailed shower shape information
- Cost

Examples

Aleph ECAL (LEP)
LHCb & ATLAS ECALs
All HCALs so far

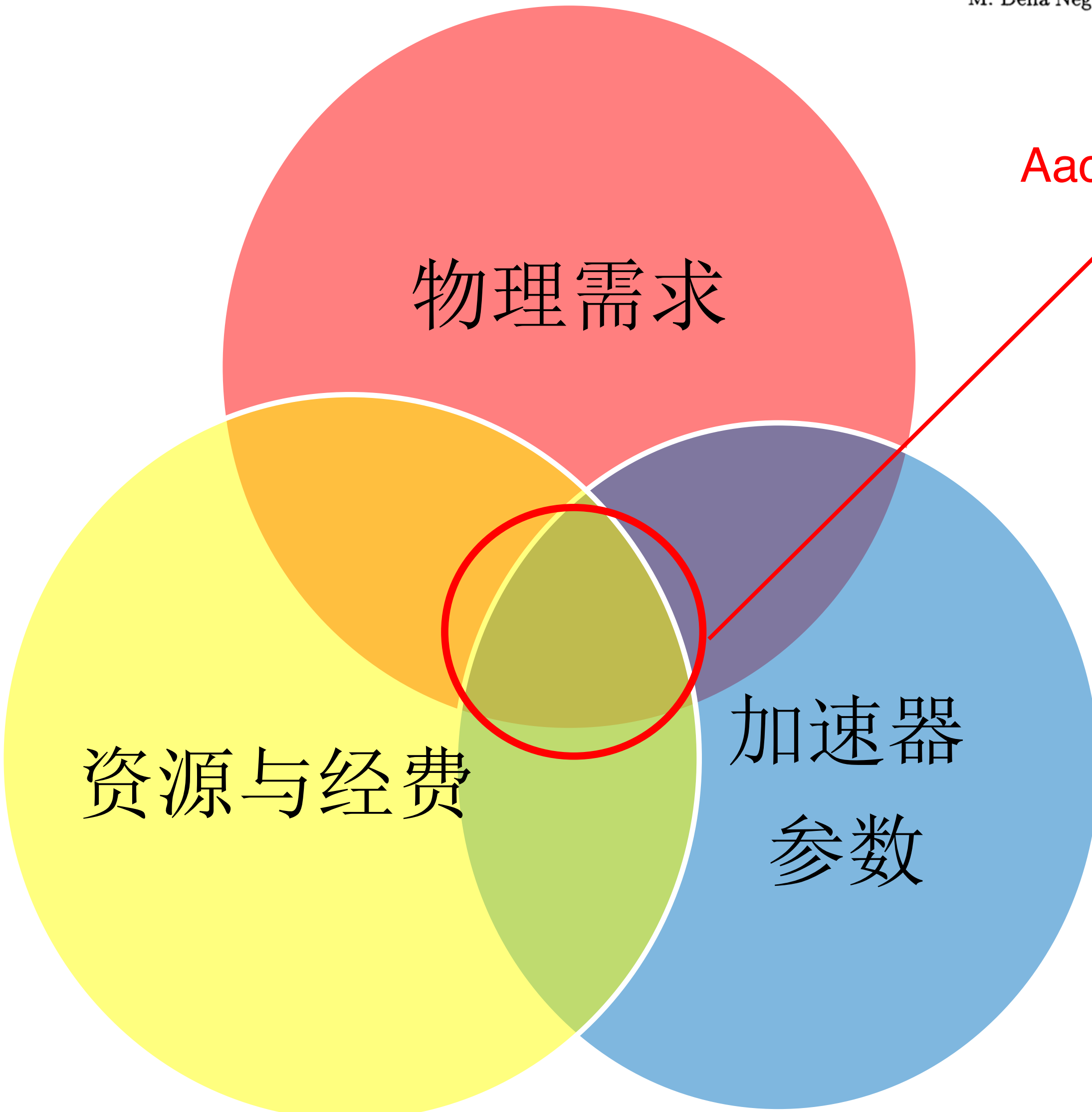
# 粒子探测器


ionisation
radiative processes
ionisation
Tracking chambers
Electromagnetic calorimeters
Hadronic calorimeters
Muon chambers
photons
e±
muons
K±, π±, p
n
B field
Low ρ
High ρ
High ρ
Tracking

# Requirements on CMS detector

- CMS探测对象：电子，光子，缪子，喷注等
- 性能要求
  - 在大空间范围，大动量范围内有好的单个mu鉴别和动量、角度分辨；好的的双mu质量分辩（1%@100GeV）；在<1TeV动量下有好的电荷符号鉴别（Muon探测器）
  - 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(内径迹探测器）
  - 好的电磁能量分辨率和双电子/光子质量分辨（1%@100GeV），$\pi$0 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探测器设计考虑



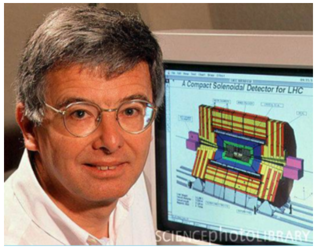

Compact Muon Solenoid

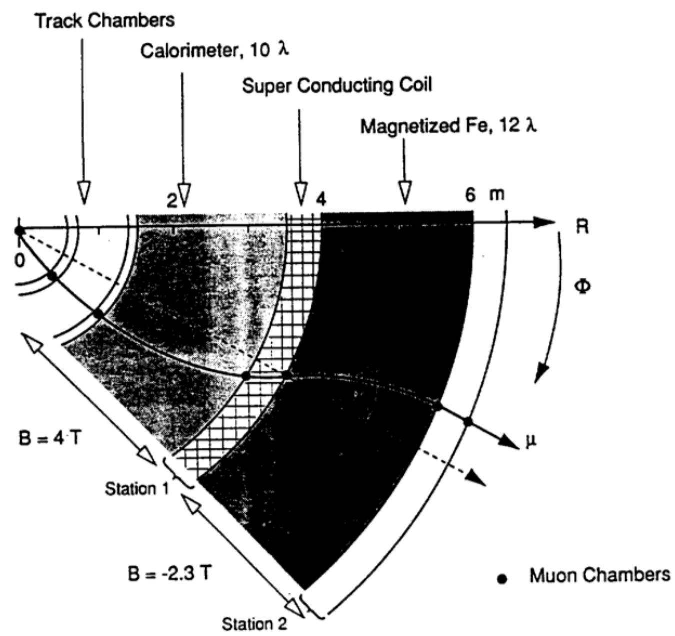
M. Della Negra, K. Eggert, M. Lanzagorta, M. Pimiä, F. Szoncso

presented by M. Pimiä

SEFT, University of Helsinki, Finland

Aachen WS 1990





# CMS Timeline

1984 Workshop on a Large Hadron Collider in the LEP tunnel, Lausanne.

1990 ECFA LHC Workshop, Aachen. First proposal of CMS.

1992 General Meeting on LHC, Evian les Bains. Letter of Intent of CMS.

1994 CMS Technical Proposal Approved.

1996 Approval to move to Construction (materials cost of <475 $MCHF_{1996}$)

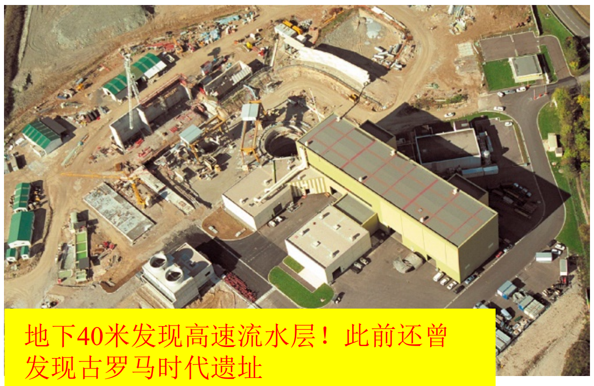
1998 Construction Begins (after approval of Technical Design Reports)

2008 CMS ready for First LHC Beams

2012 Higgs discovery.

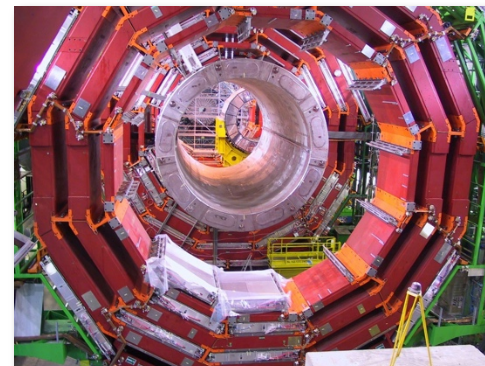

# CMS探测器的建造和安装

- 全世界40多个国家、~200个研究机构的~4000名科学家和工程技术人员分担各个子探测器的研发和生产任务。
- 建成的子探测器运到CERN进行组装测试、安装调试。

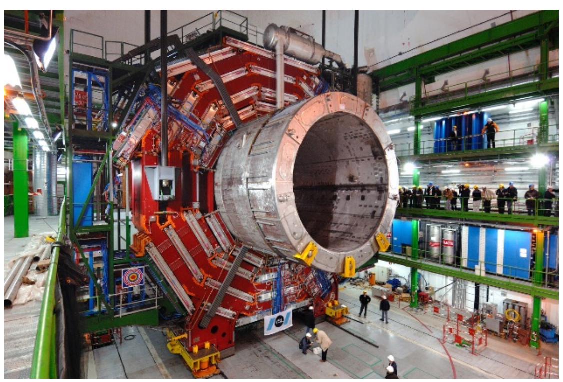



土建工程（2000年10月）

地下100米实验大厅（2004年）

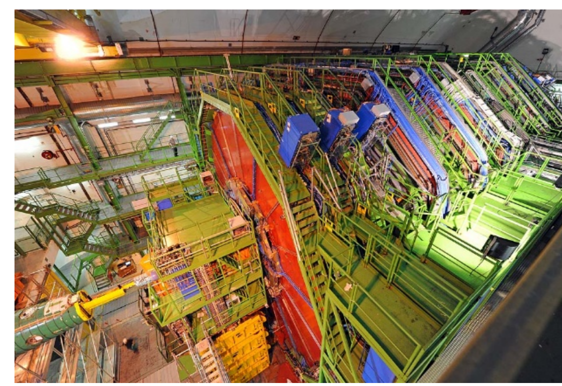


**地面探测器组装大厅（2006年2月）**



组装好的探测器被吊装到地下（**2007年2月**）

**在地下继续进行安装、接线等工作（2007年12月）**



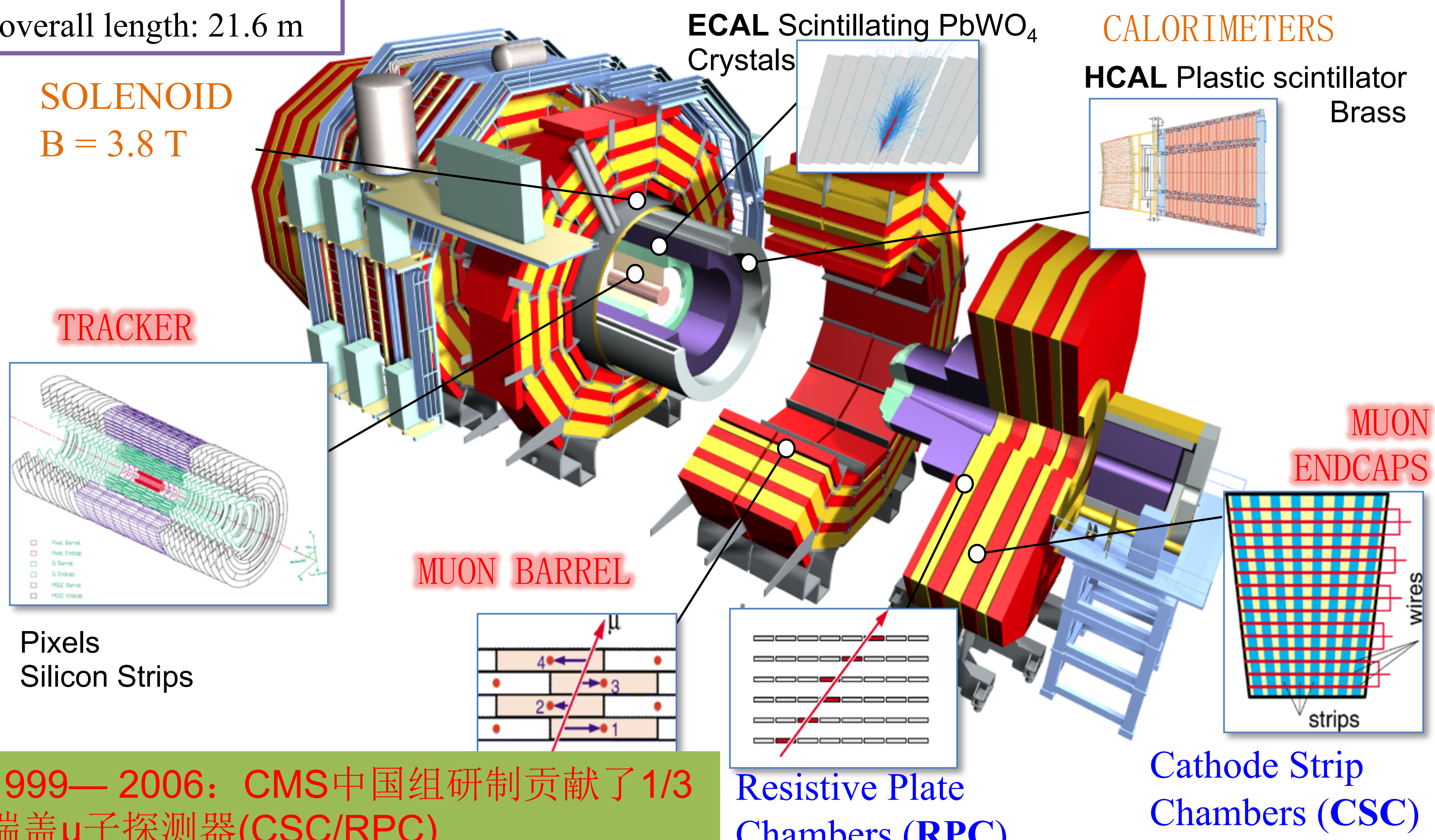
安装调试完成，准备取数

# CMS (Compact Muon Solenoid) 探测器

weight: 12500 t
overall diameter: 15 m
overall length: 21.6 m

人类建造最重的对撞机实验粒子探测器

JINST3,S08004(2008)

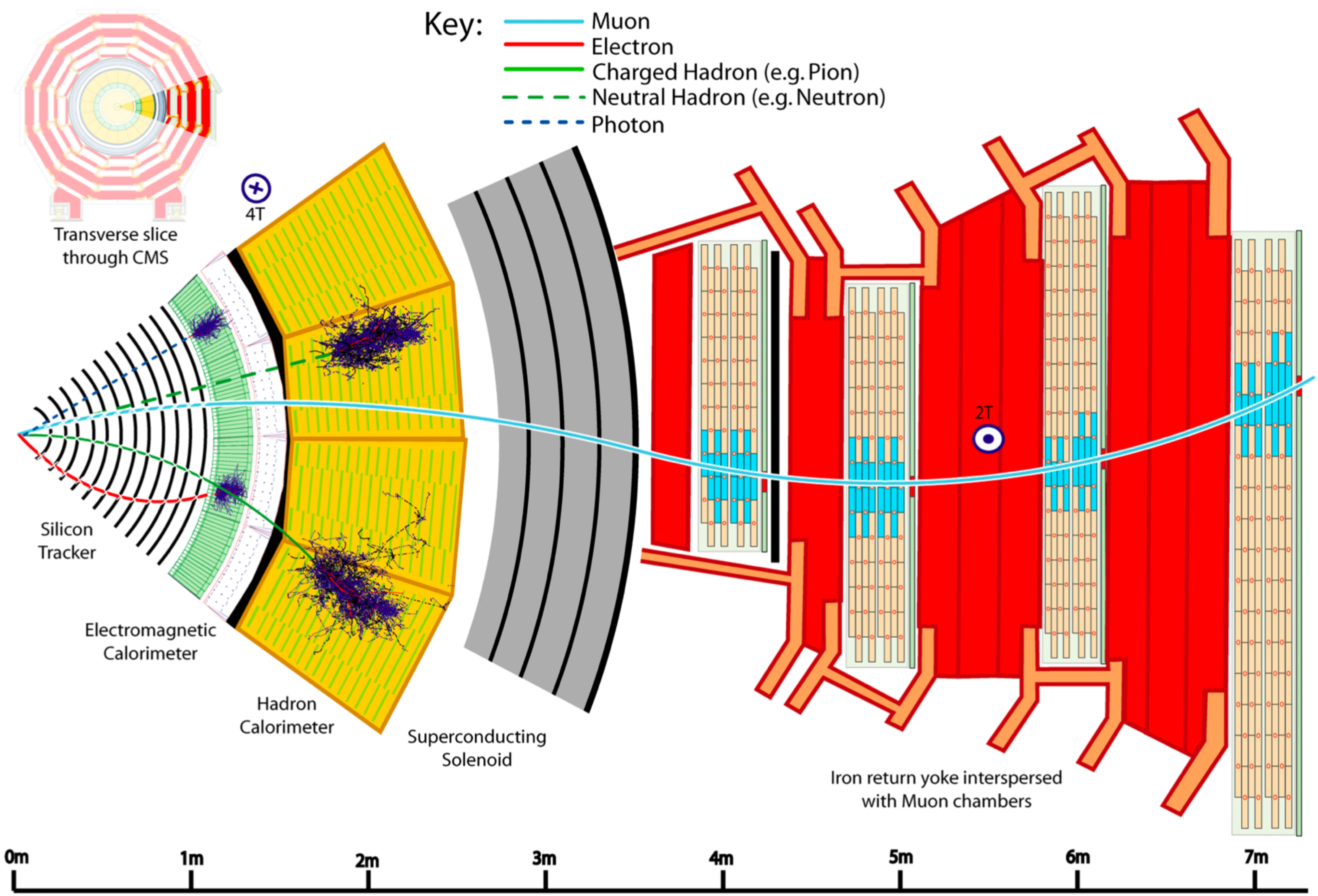



1999— 2006：CMS中国组研制贡献了1/3端盖μ子探测器(CSC/RPC)
2013—2019：参与并圆满完成I期升级

# ATLAS vs CMS 探测器

| | ATLAS | CMS |
|---|---|---|
| 谱仪磁场 | 2 T螺线管 + 环形线圈（桶部 0.5 T/端盖1 T） | 4T螺线管 + 磁轭 |
| 径迹探测系统 | 硅像素+ 硅微条 + TRT<br>$\sigma/p_T \approx 5\cdot10^{-4}\,p_T + 0.01$ | 硅像素+ 硅微条<br>$\sigma/p_T \approx 1.5\cdot10^{-4}\,p_T + 0.005$ |
| 电磁量能器 | 液氩+铅吸收体<br>$\sigma/E \approx 10\%/\sqrt{E} + 0.007$ | 钨酸铅晶体<br>$\sigma/E \approx 2.8\%/\sqrt{E} + 0.003$ |
| 强子量能器 | 铁+闪烁体/铜+液氩（10$\lambda$）<br>$\sigma/E \approx 50\%/\sqrt{E} + 0.03$ | 黄铜+闪烁体（7$\lambda$ + catcher）<br>$\sigma/E \approx 100\%/\sqrt{E} + 0.05$ |
| 缪子谱仪 | （径迹探测器 + 缪子探测器）<br>$\sigma/p_T \approx 2\%$ @50 GeV | （径迹探测器 + 缪子探测器）<br>$\sigma/p_T \approx 1\%$ @50 GeV |
| 触发系统 | L1 + HLT （L2 + EF） | L1 + HLT（L2+L3） |

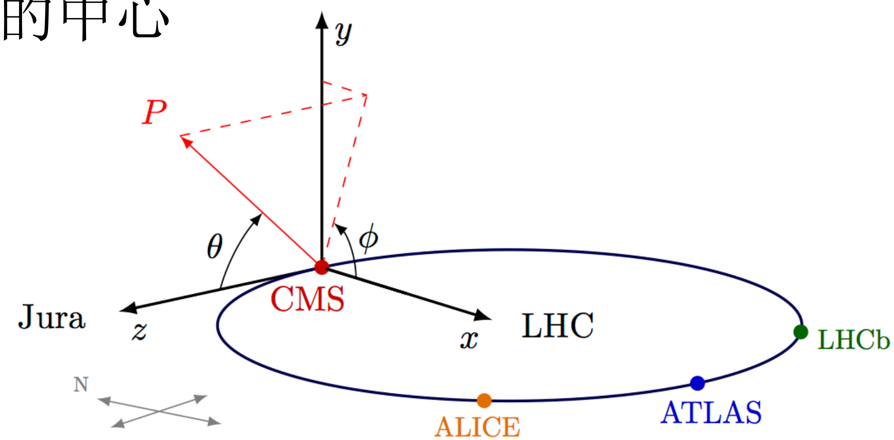
# CMS 探测器

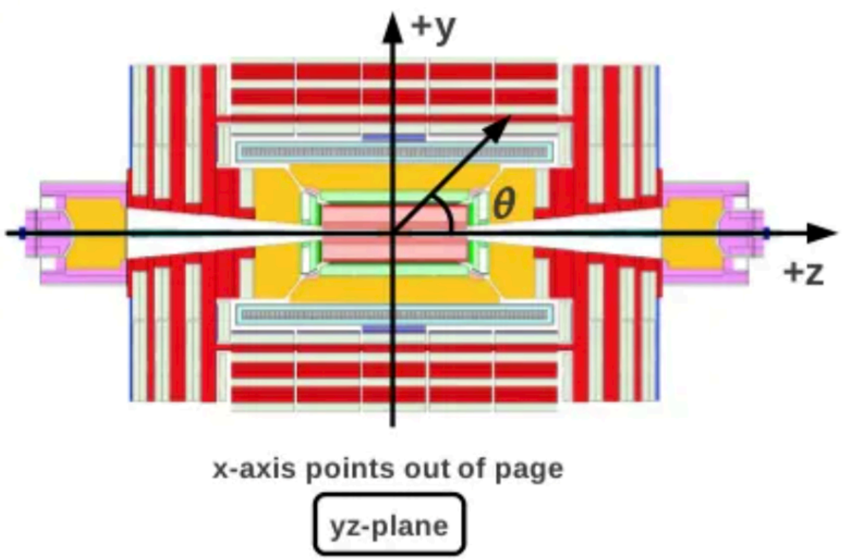


Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
Transverse slice through CMS
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0m
1m
2m
3m
4m
5m
6m
7m

# CMS cordinates

- *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
- $\theta$：极角
- $\eta = -ln[tan(\theta/2)]$：赝快度
- $\varphi$



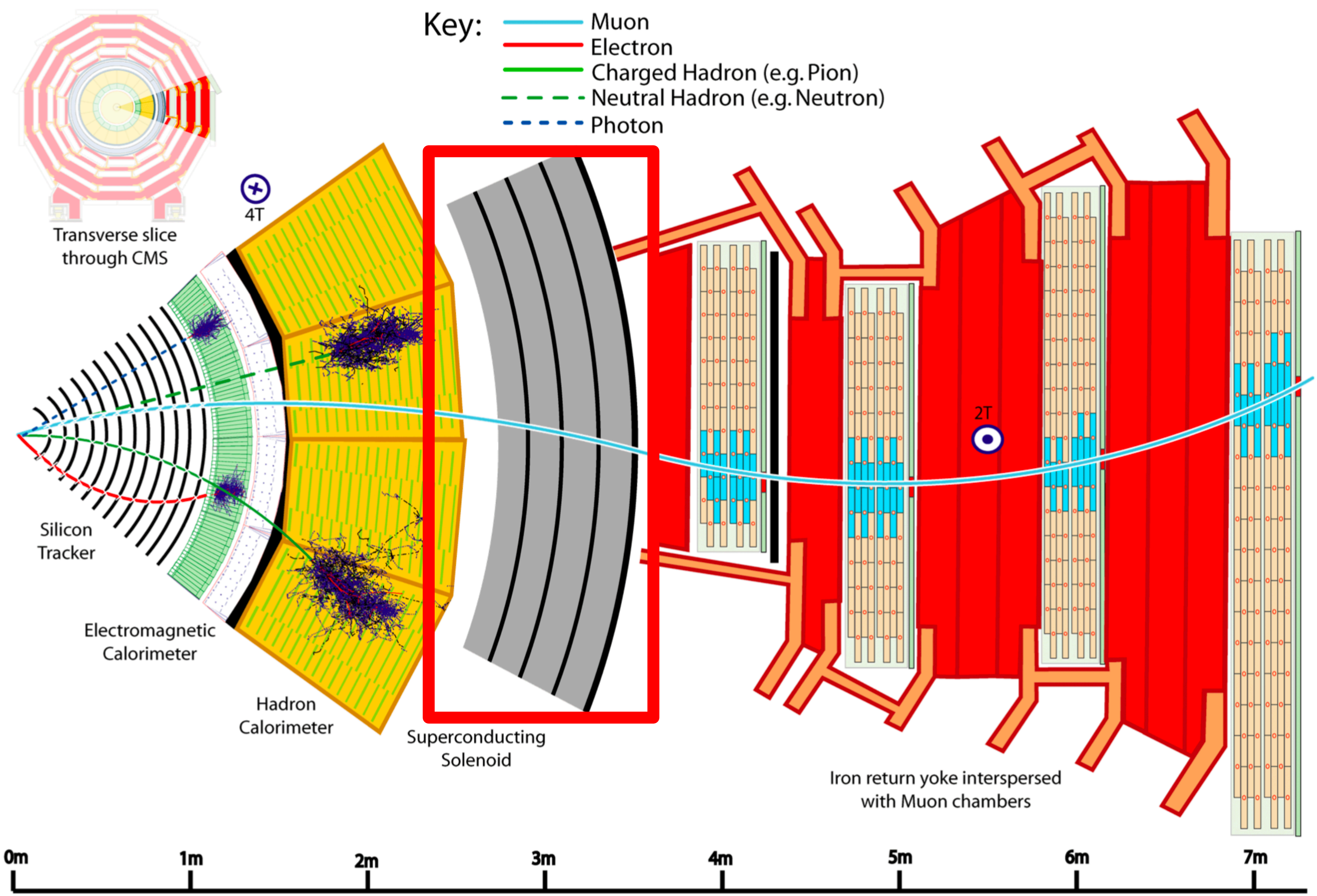





$$\eta = -\ln\left(\tan\left(\theta/2\right)\right) \qquad \Delta\phi = \phi_2 - \phi_1 \qquad \Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$

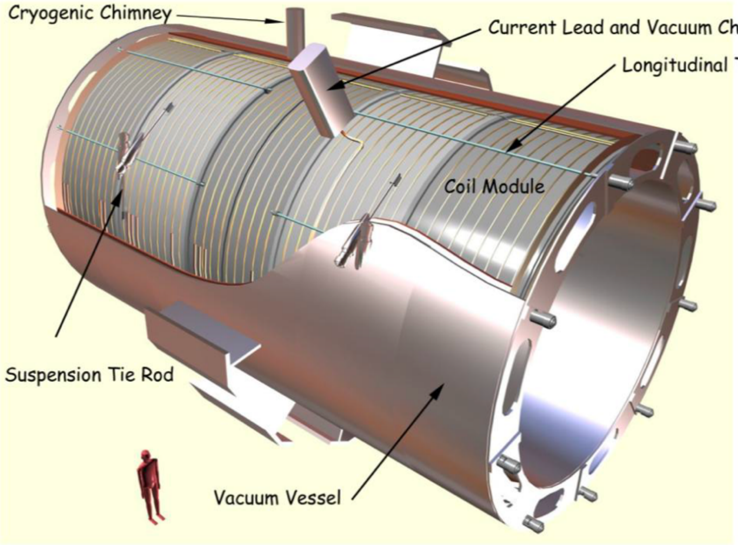
$$p_T = \sqrt{p_x^2 + p_y^2} \qquad \Delta\eta = \eta_2 - \eta_1 \qquad \Delta A = \Delta\phi \text{ or } \Delta R$$

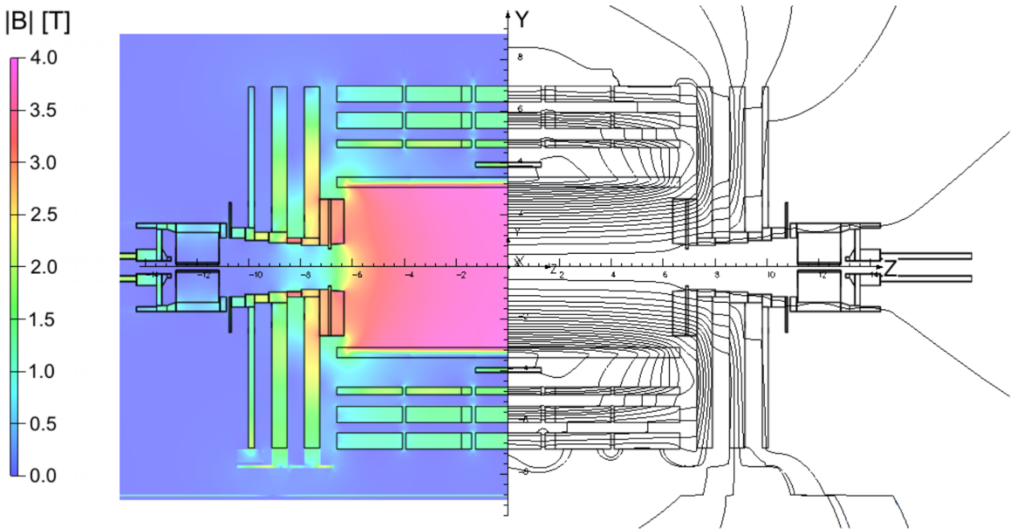
# CMS探测器：solenoid磁铁

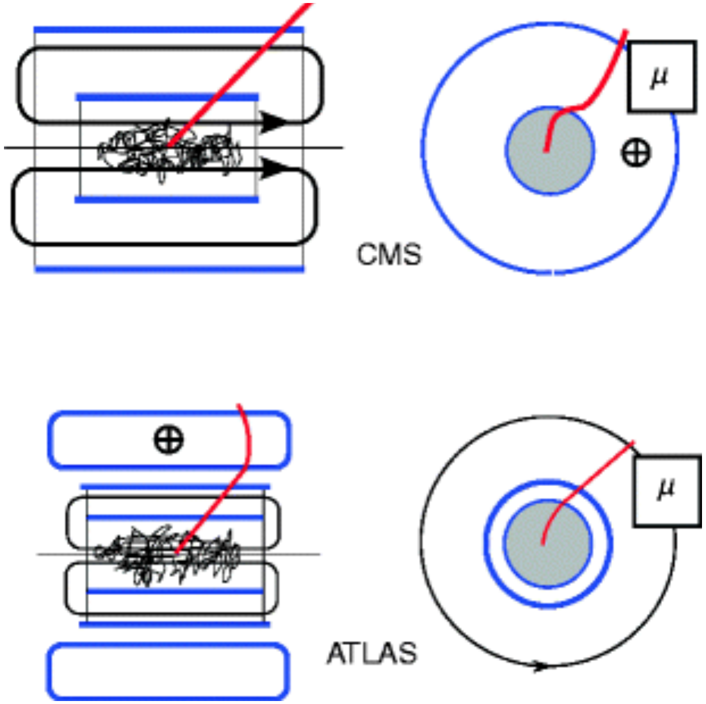


# CMS磁铁系统：solenoid

- 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



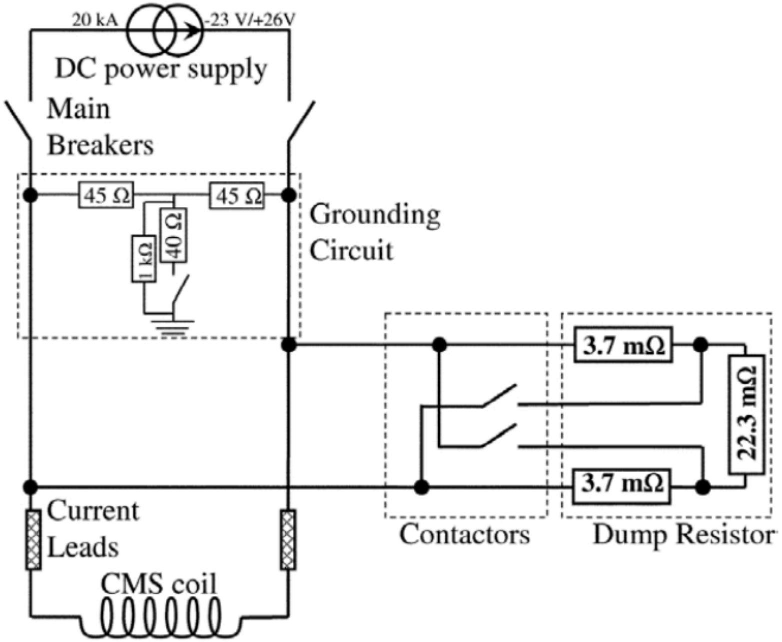



# CMS实验的超导螺线管磁铁参数

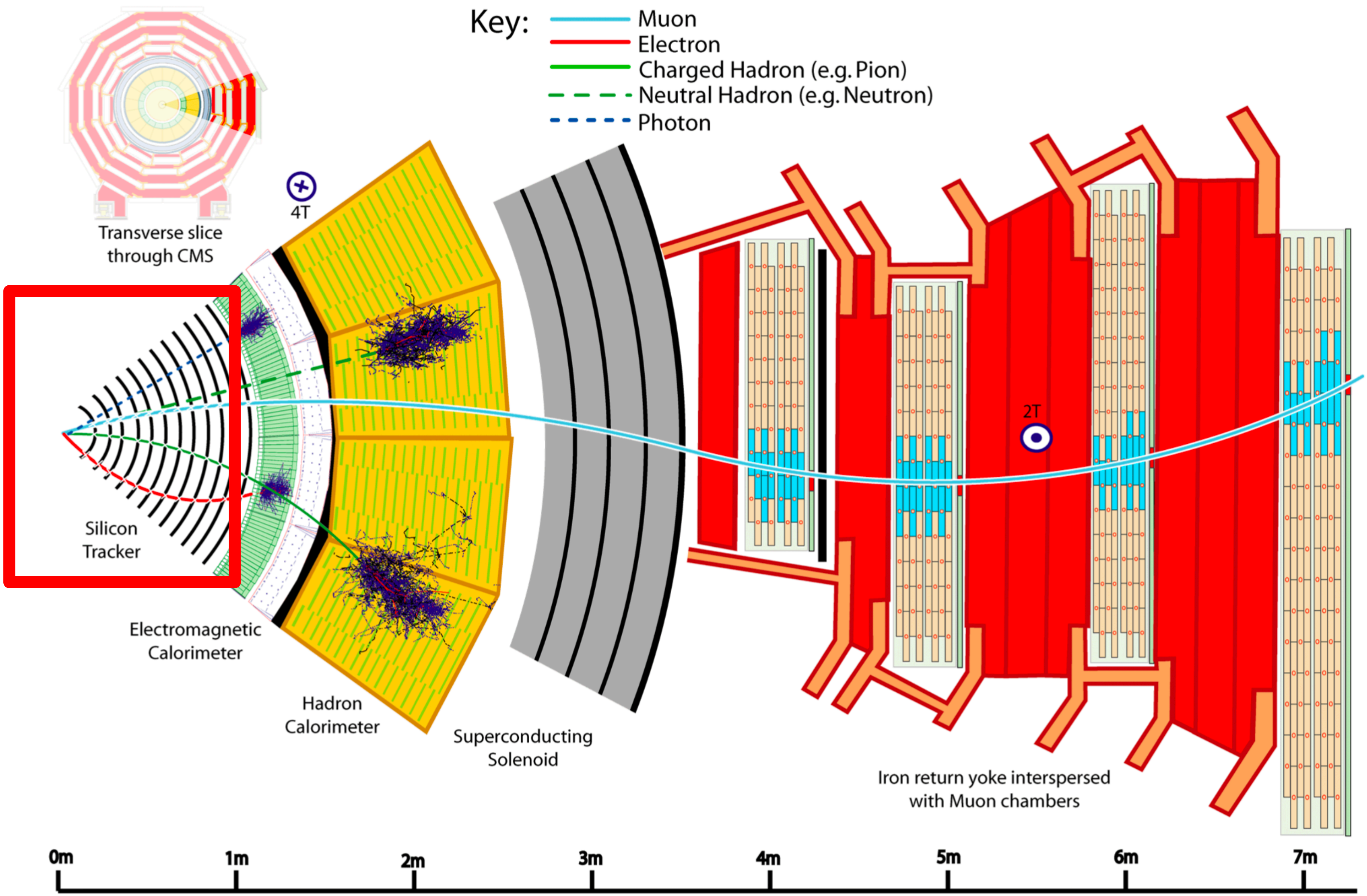
- 10 000 吨轭铁， 相当于2个埃菲尔铁塔
- 220吨 NbTi超导线材
- 运行温度1.8K, 电流 19.14 kA, 41.7 MA-turns, 总电感 14.2 H
- The ratio between stored energy and cold mass is high (11.6 KJ/kg)
- Large mechanical deformation (0.15%) during energizing
- 磁场4T， 直径6.3m， 长度 12.5m

$$W_m = \frac{1}{2}LI^2 = \frac{1}{2}BHSl = \frac{1}{2}BHV \quad \vec{\boldsymbol{B}} = \mu_0\vec{\boldsymbol{H}}$$

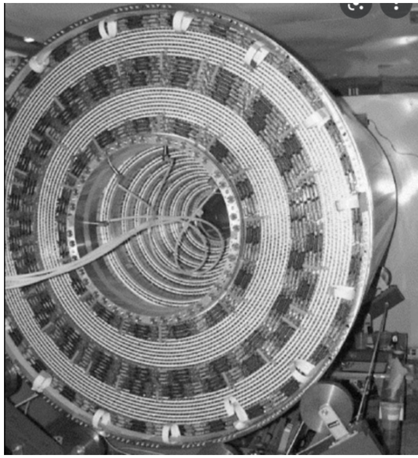
- 可以计算储能 W=2.6 GJ， 该能量可以熔化18吨黄金
- 失超时， 巨大能量瞬间释放破坏力巨大=>保护电路

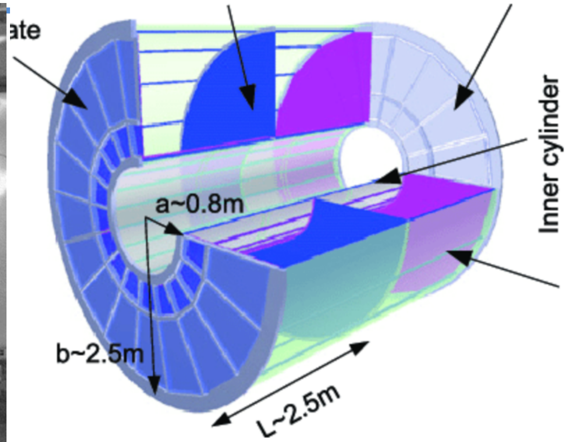


# CMS 探测器：内径迹探测器

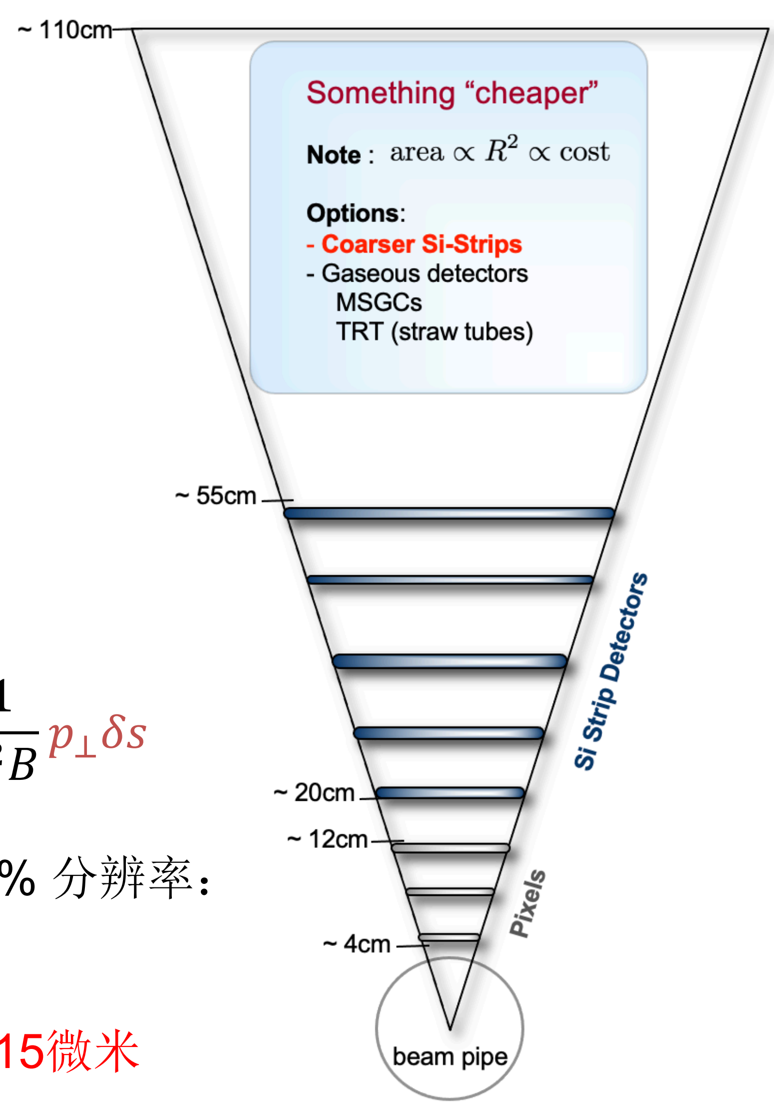


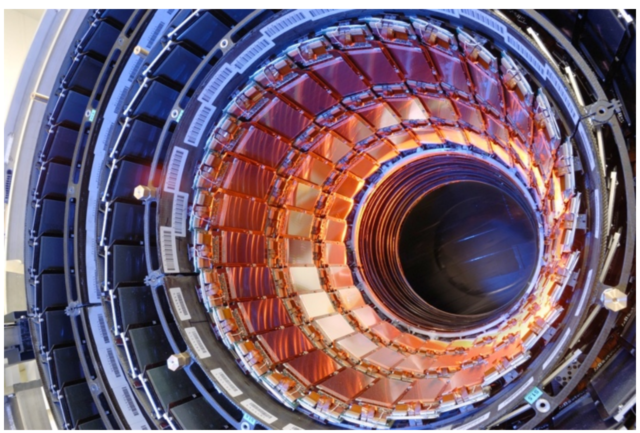
# 内径迹探测器






漂移室（BES，CLEO…）　　Alice时间投影室



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

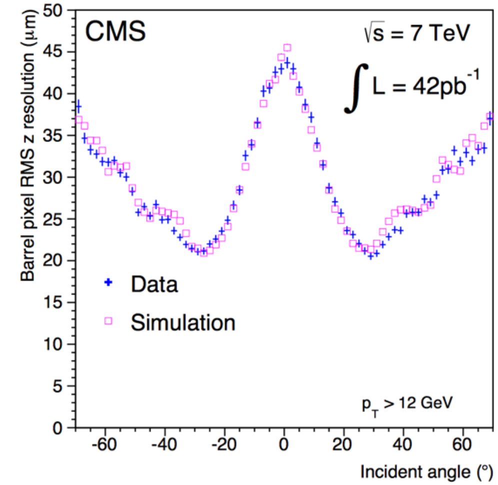
100 GeV $p_\perp$， 1% 分辨率：
L=1米，B～4T

➔位置分辨率～15微米

CMS： 全硅径迹探测器=pixel+strip

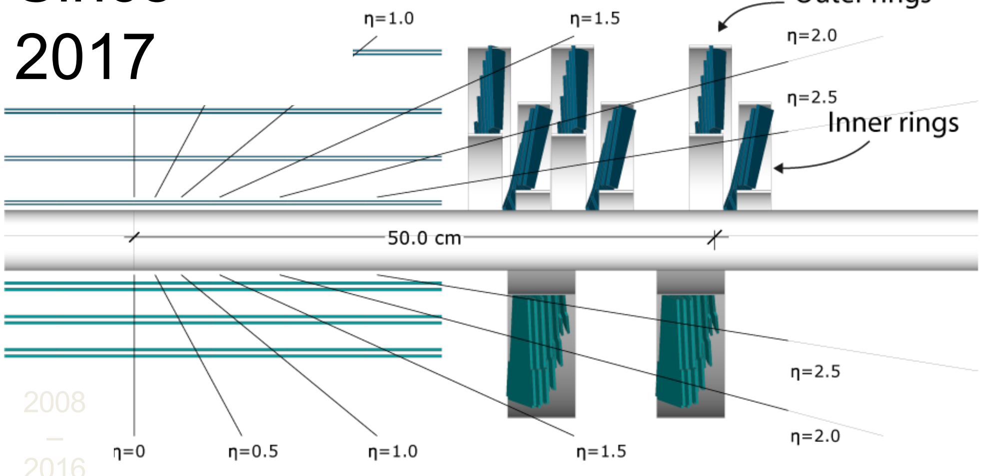
# Silicon Pixel 硅像素探测器

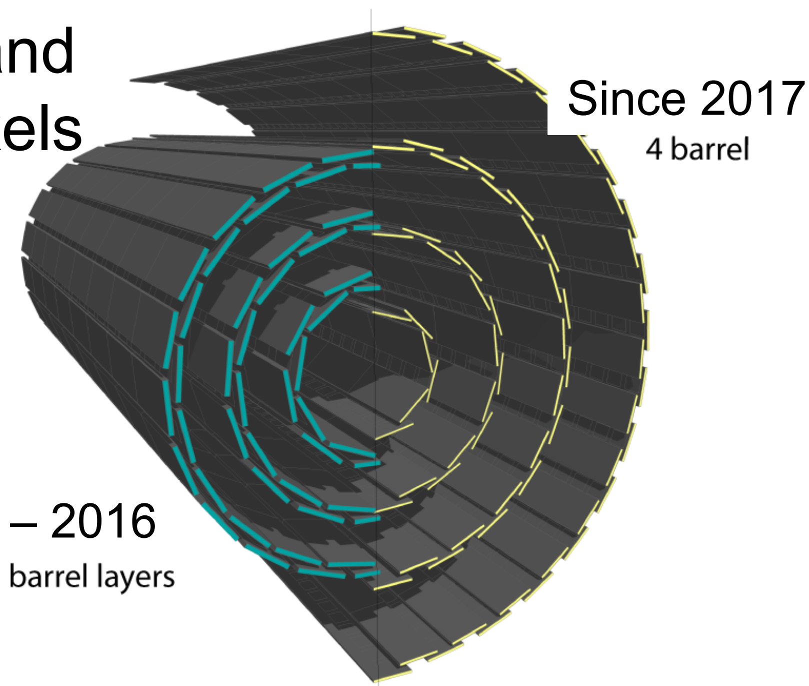
- 100X150 μm² 像素，工作在零下22度， n-in-p 型传感器
- 覆盖了|η|=2.5 的区域
  - 作为寻迹开始的种子，以及探测径迹的顶点参数
- 在半径 = 3cm处
  - 600 MHz/cm² （在LHC 瞬时峰亮度下 (L=2x10³⁴ cm)⁻²s⁻¹ ）
  - 抗辐照强度: 3x10¹⁴ $n_{eq}$/cm²/yr
  - 占空比: 10⁻³



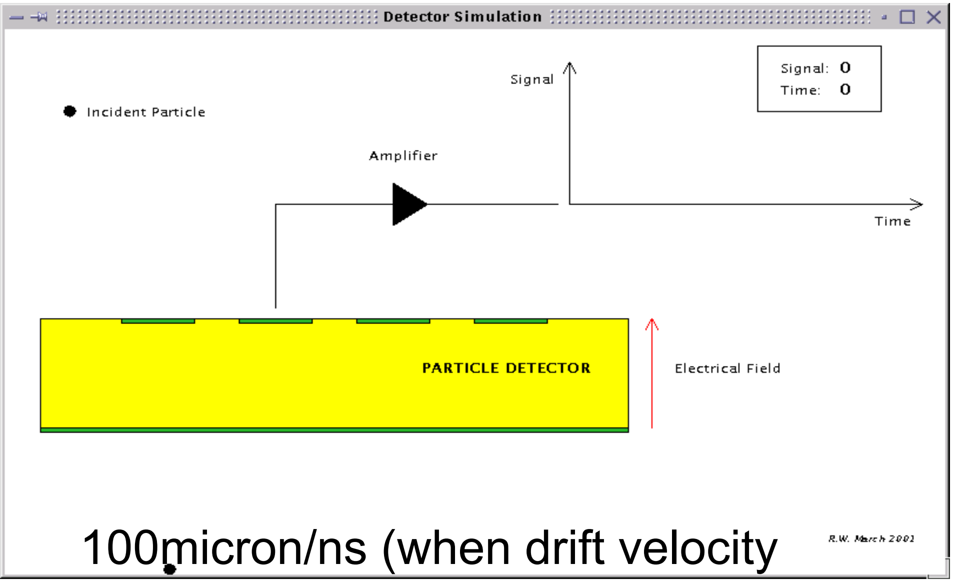

45M forward and
79M barrel pixels

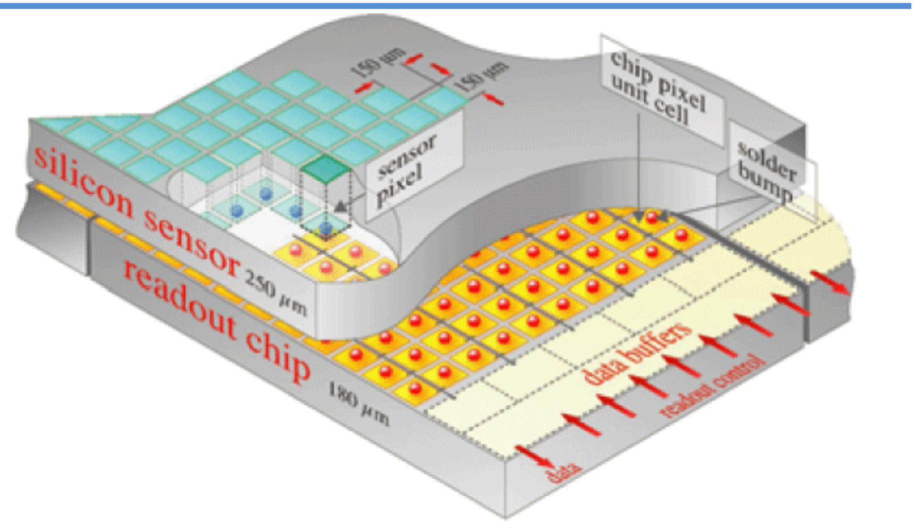
Since
2017



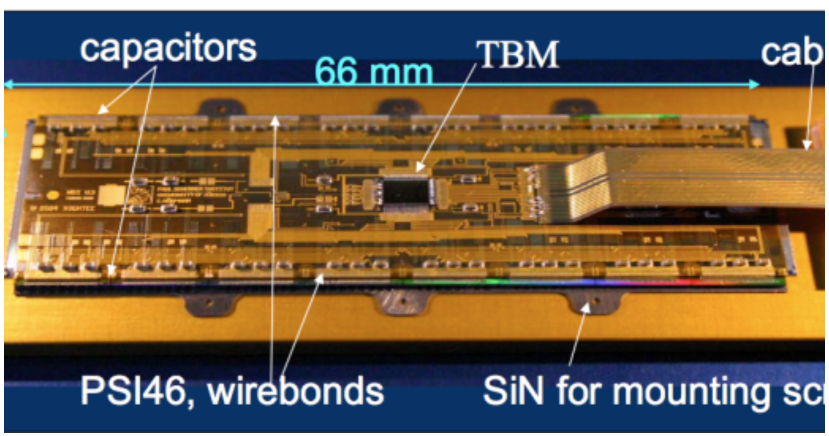



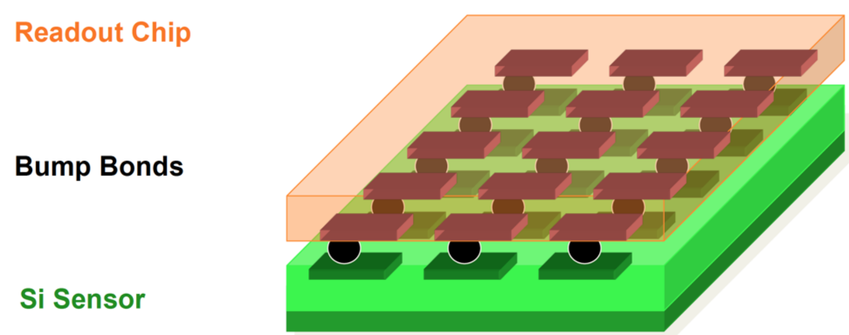
# Silicon Pixel 硅像素探测器



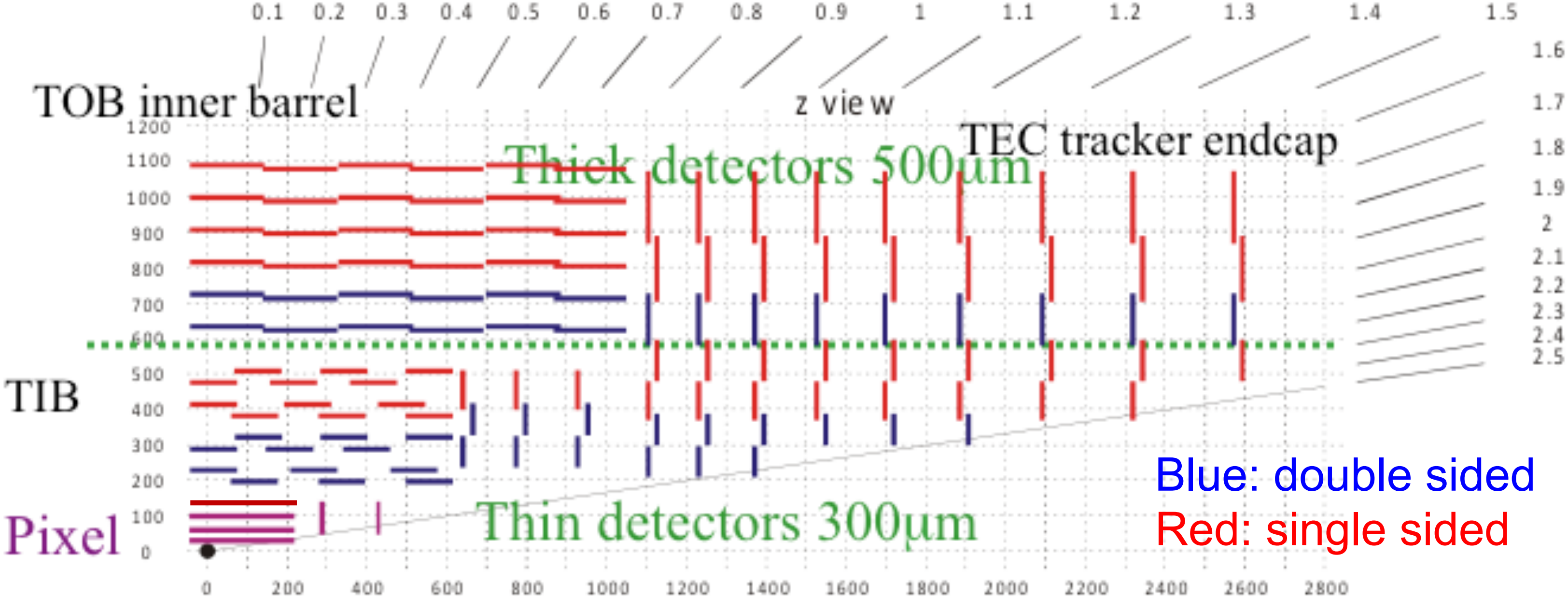

100micron/ns (when drift velocity saturated at ~30kV/mm E-field) and 73 e-h pair per micron for MIP



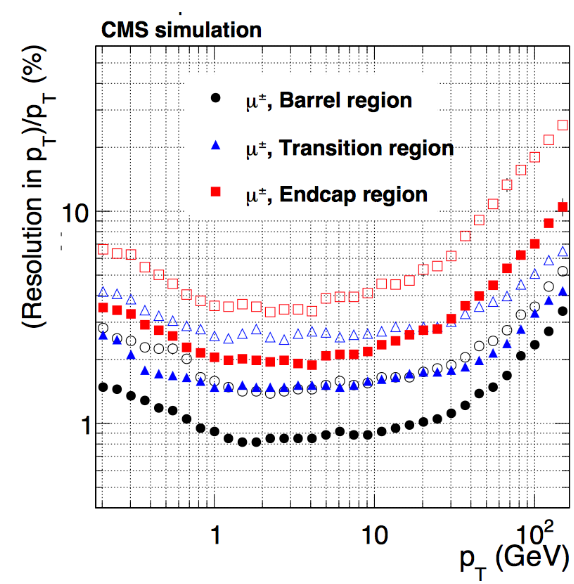




Each pixel cell in the sensor is connected to a pixel cell in the readout chip via a bump bond.

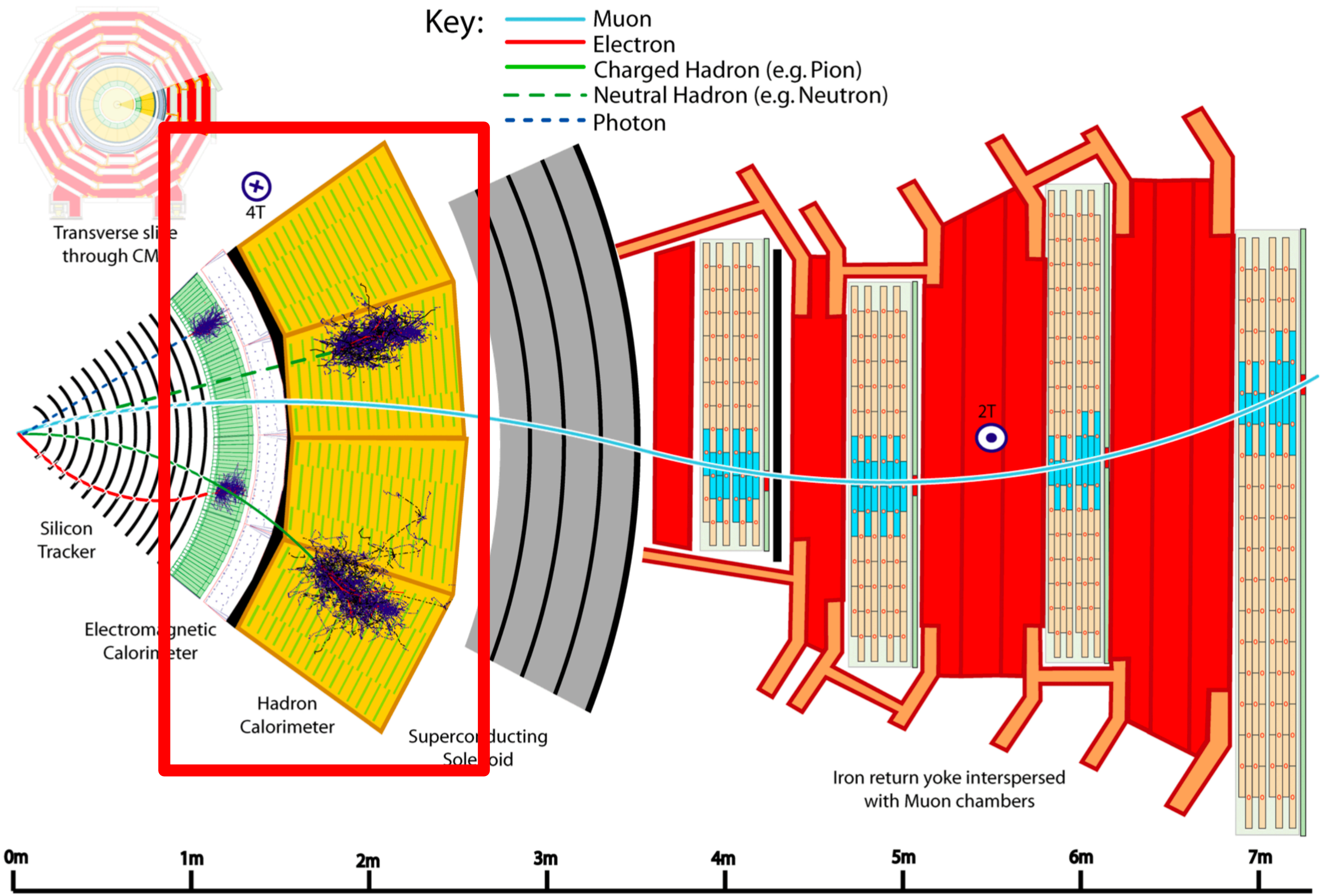
# 硅微条（Silicon strip）探测器




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



# CMS 探测器：量能器



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

# CMS量能器系统

Em Barrel : EB

Em Endcap : EE

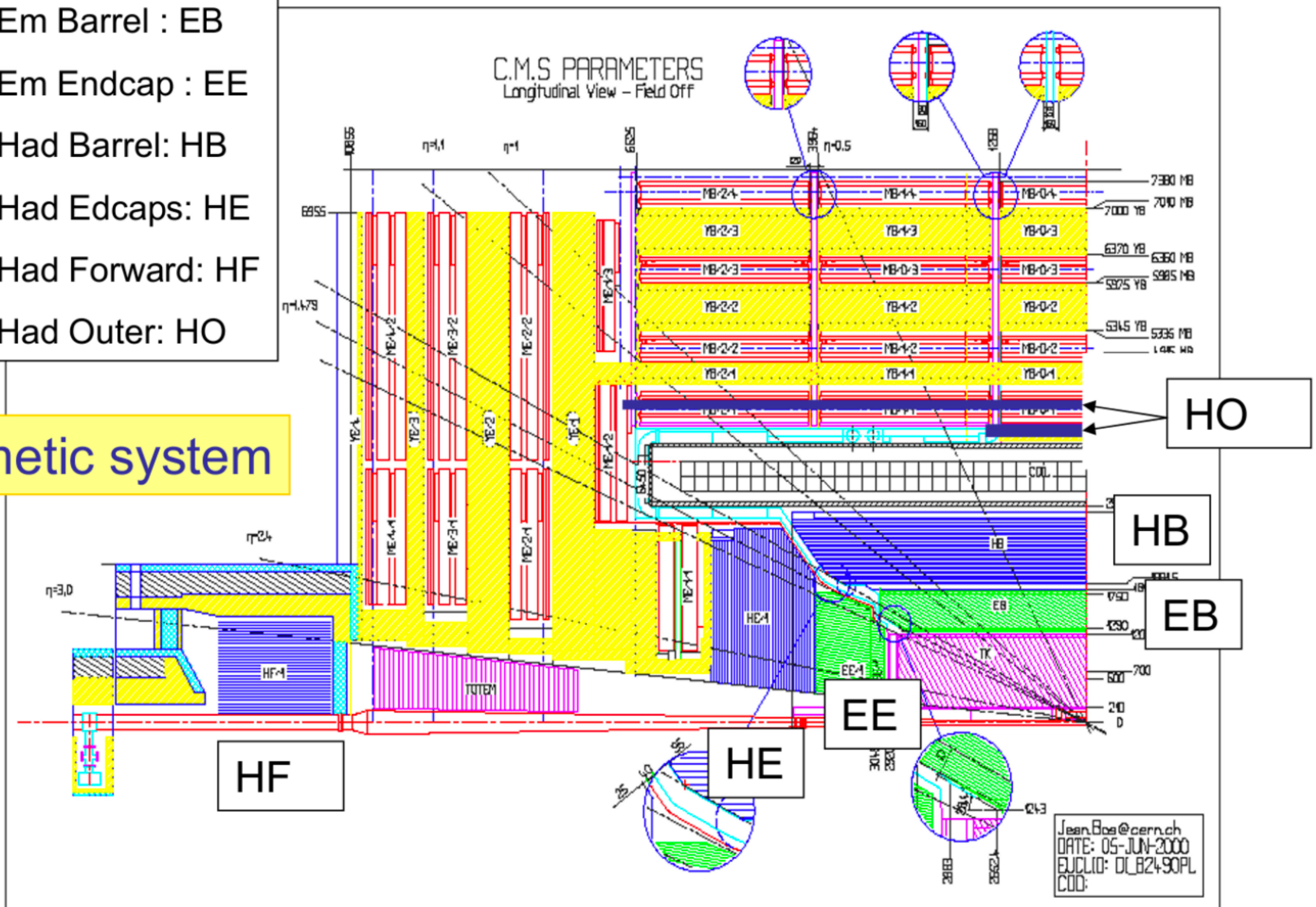
Had Barrel: HB

Had Edcaps: HE

Had Forward: HF

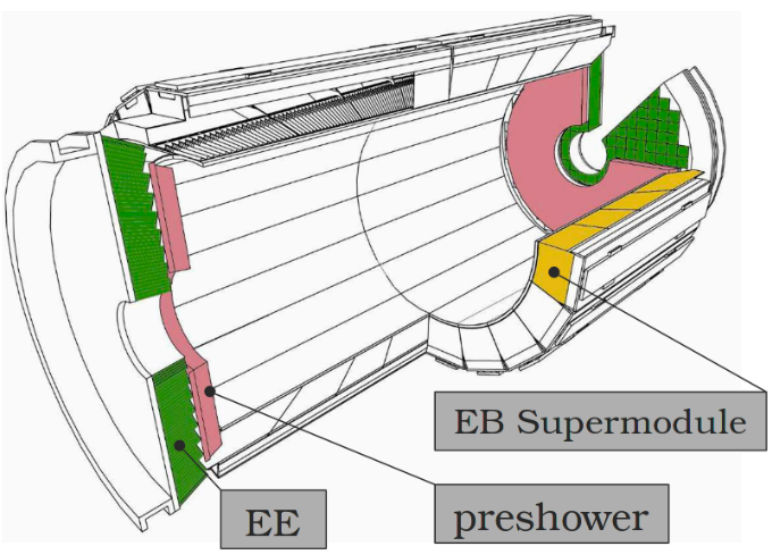
Had Outer: HO

Hermetic system



# 电磁量能器

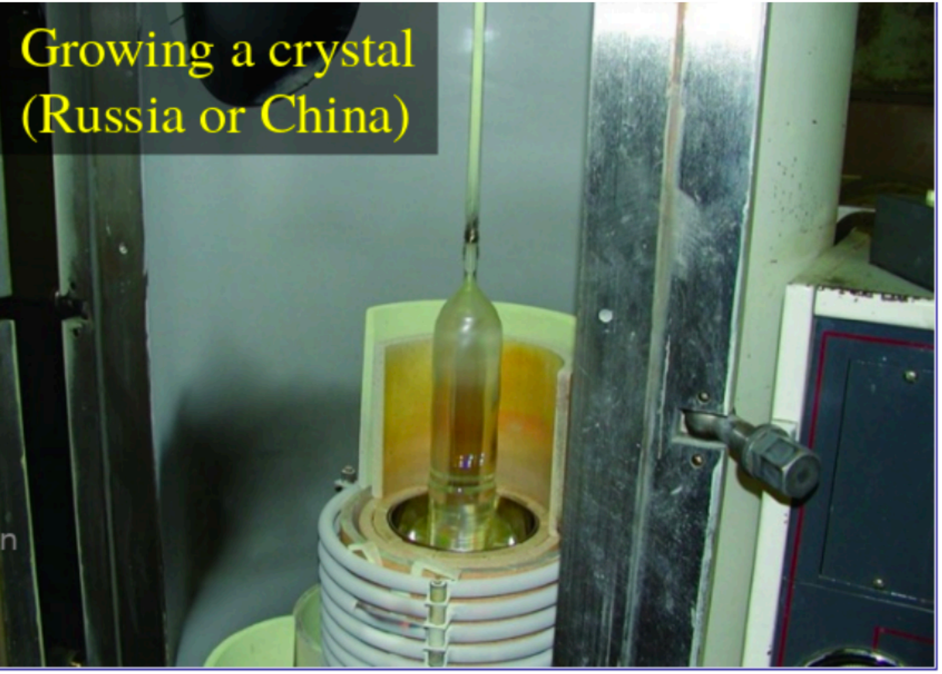
- **Homogeneous, hermetic, high granularity $PbWO_4$ crystal calorimeter**
  - density of 8.3 g/cm$^3$, radiation length 0.89 cm, Molière radius 2.2 cm, $\approx$ 80% of scintillating light in $\approx$ 25 ns, refractive index 2.2, light yield spread among crystals $\approx$ 10%
- **Barrel**: 61200 crystals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



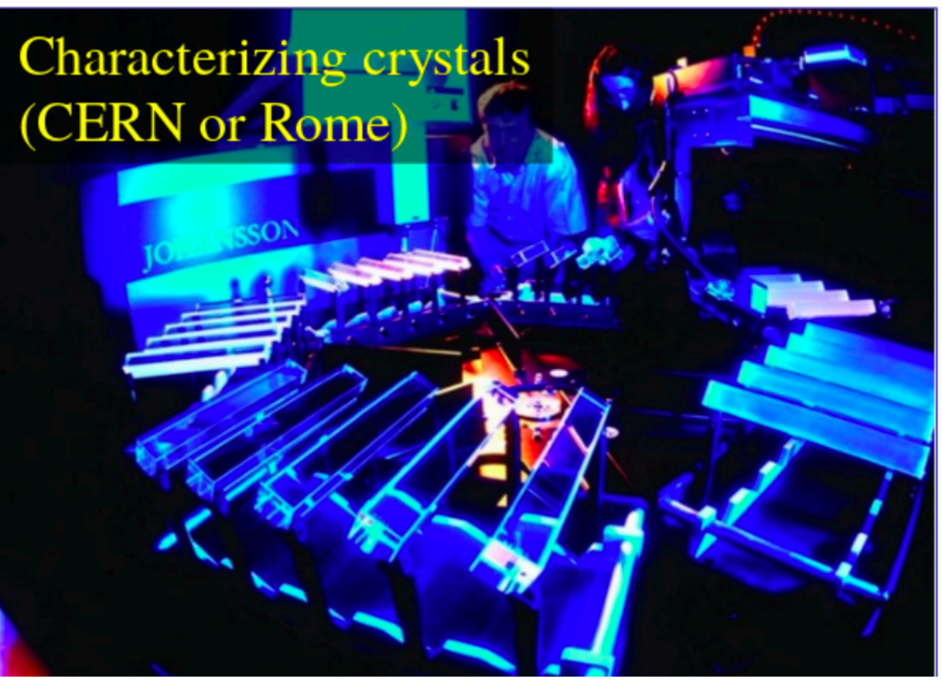

$$\frac{\sigma(E)}{E} = \frac{2.8\%}{\sqrt{E}} \oplus \frac{0.128}{E(GeV)} \oplus 0.3\%$$

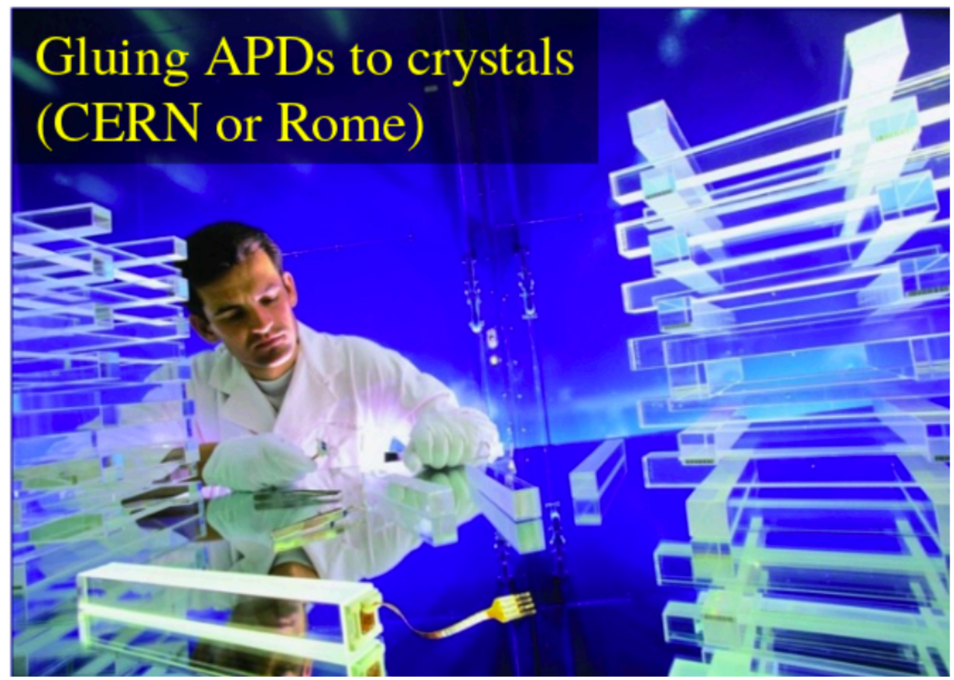
- Solenoidal magnetic field: 3.8 T
  ECAL fully contained in the coil
- CMS tracker coverage: $|\eta| < 2.5$

$2.2*2.2*23cm^3$,~$26X_0$


Growing a crystal
(Russia or China)


Before and after
cutting & polishing


Characterizing crystals
(CERN or Rome)


Gluing APDs to crystals
(CERN or Rome)

# 强子量能器

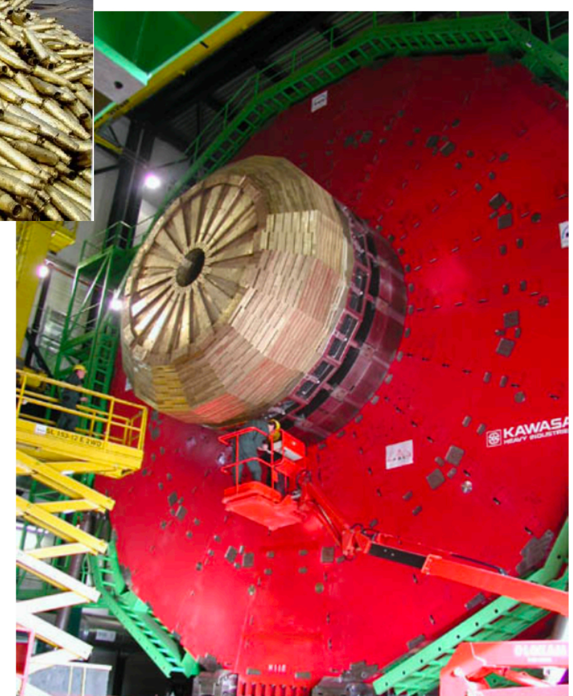
## Barrel (HB)

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

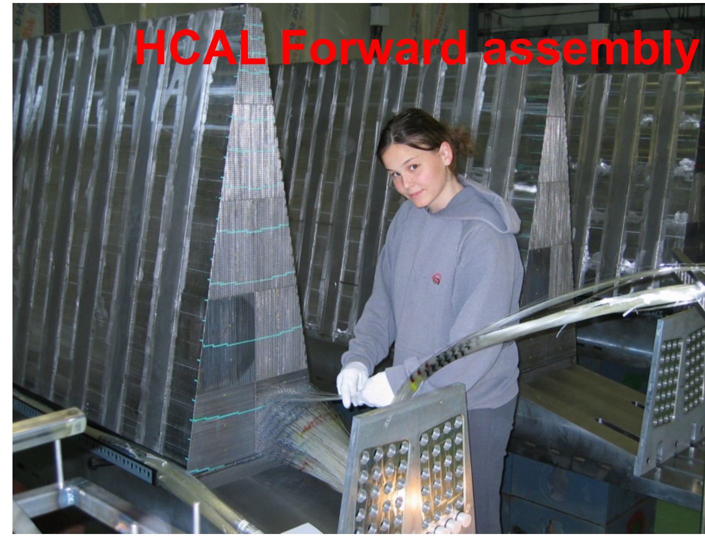
Fun fact: much of the brass came from old WWII shells from the Russian Navy!

## Endcap (HE)

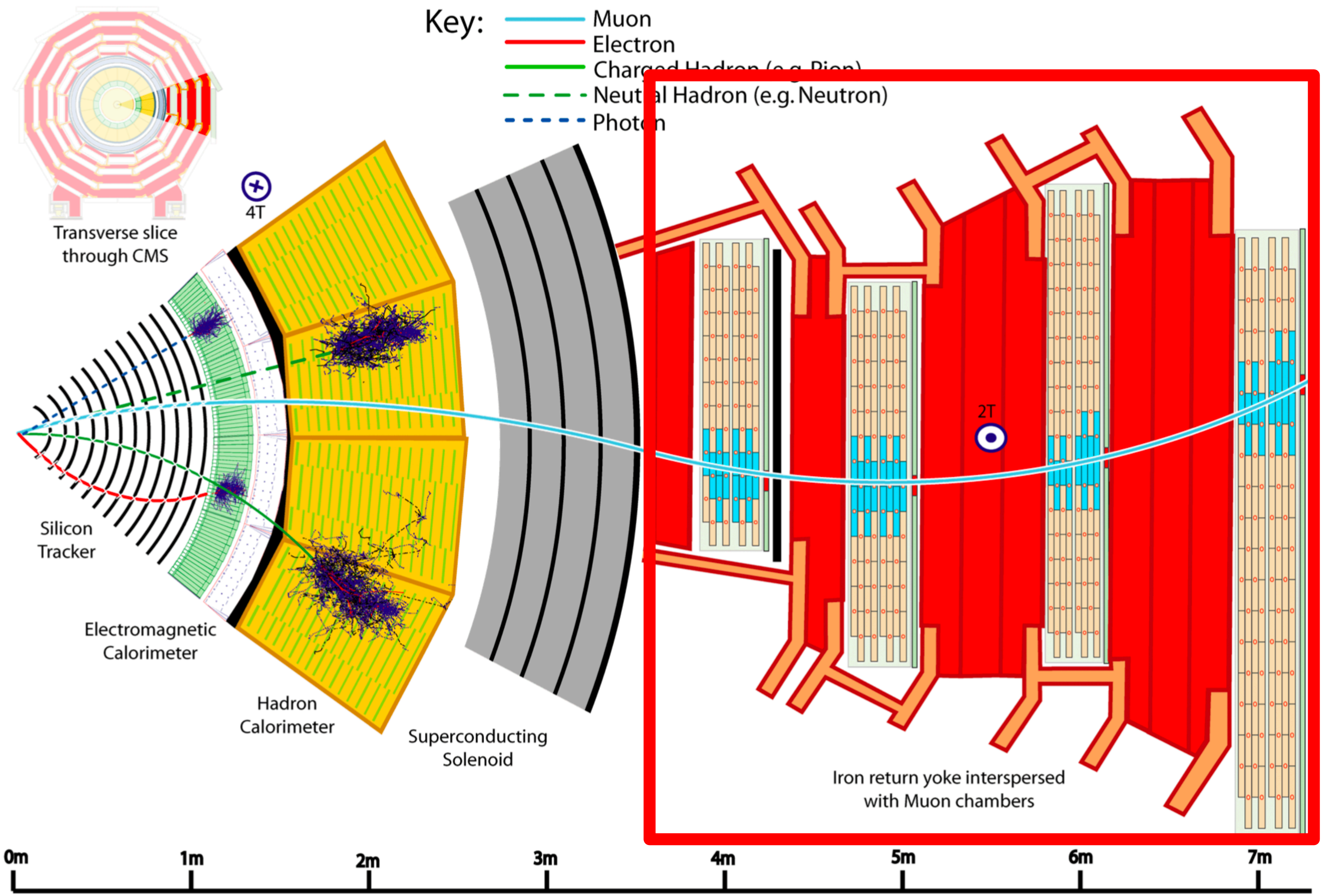
- Two brass/scintillator discs
- 19 longitudinal layers, 8 cm brass, 3.7 mm scintillator
- $1.3 < |\eta| < 3.0$



# CMS 强子量能器

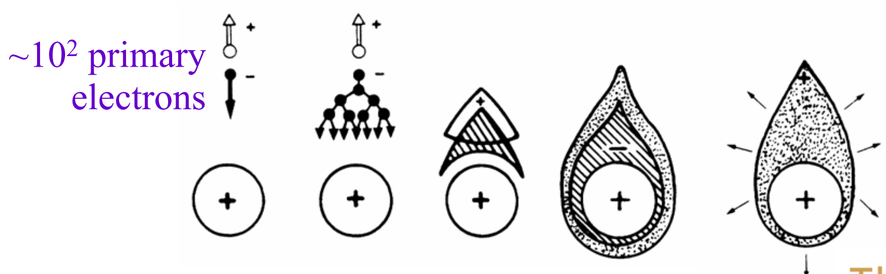




# CMS探测器：Muon系统

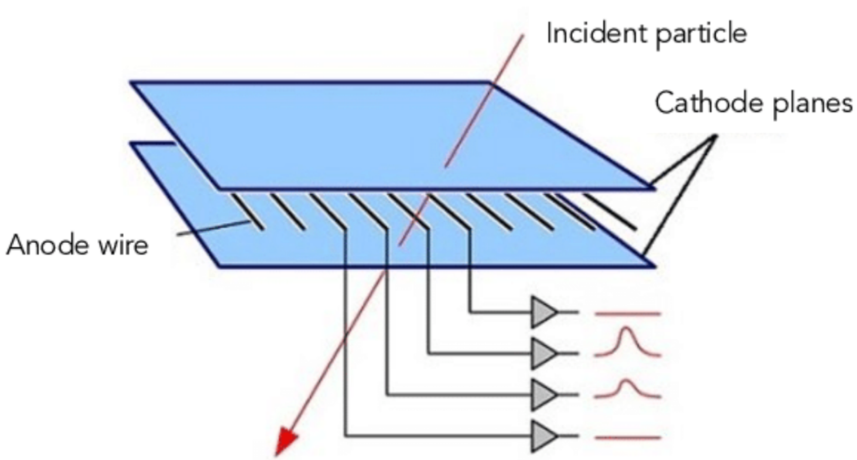


# CMS muon探测器

- 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




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




The Nobel Prize in Physics 1992

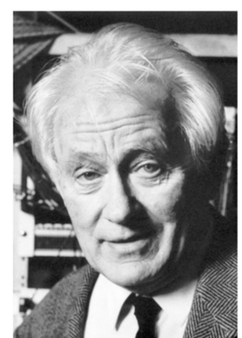


Photo from the Nobel Foundation archive.

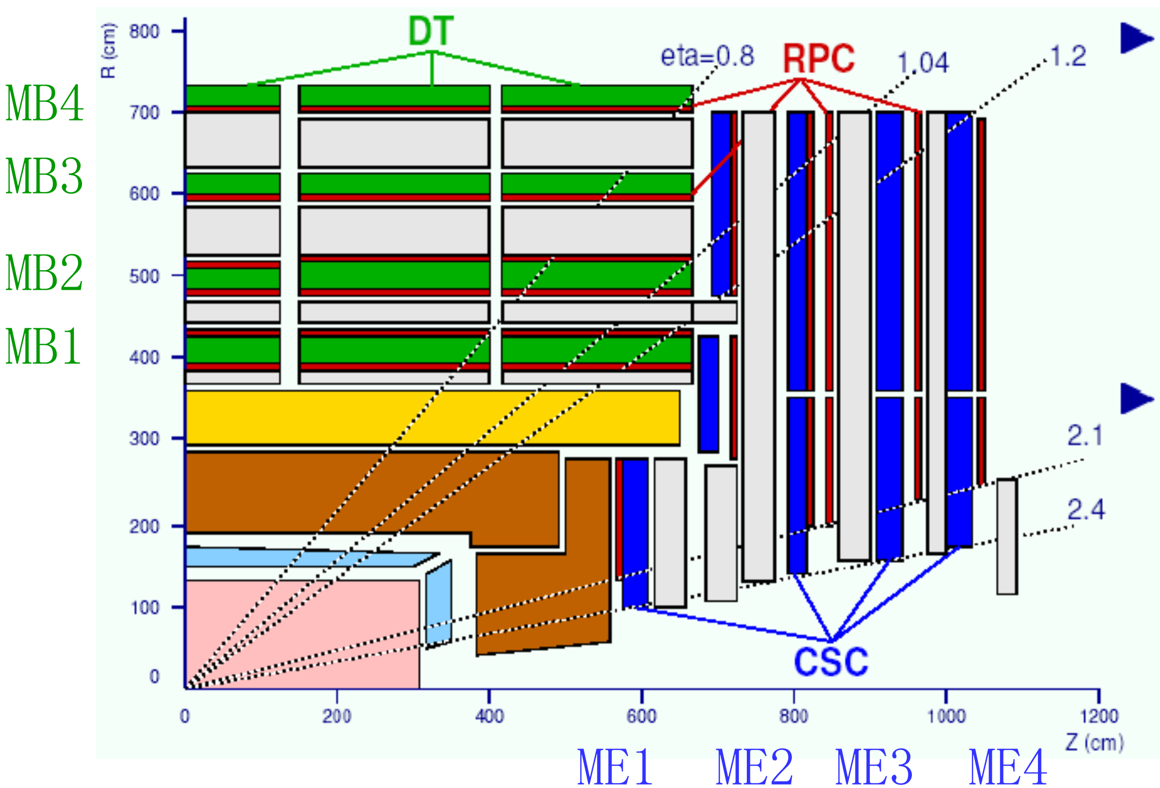
Georges Charpak

Prize share: 1/1

Gas detector：multiwire proportional chamber

# CMS muon探测器的组成

- 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

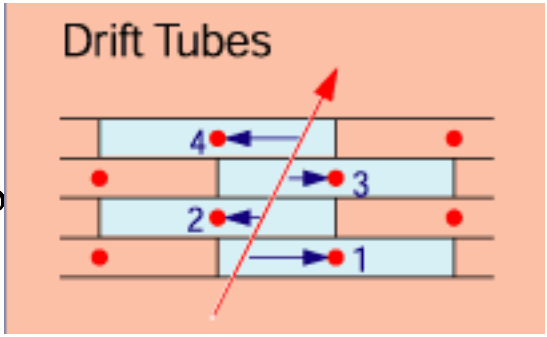
# CMS Drift Tubes (DT)

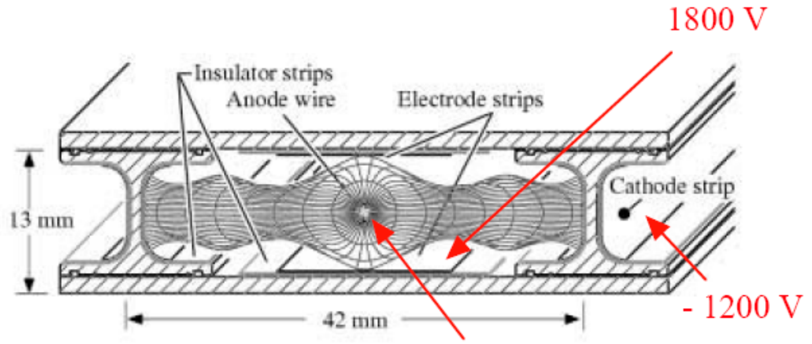
- **240 chambers in CMS <u>barrel</u>** – 5 wheels

- Drift time measurement, gives **distance (d)** to wire to **~250 µm accuracy**

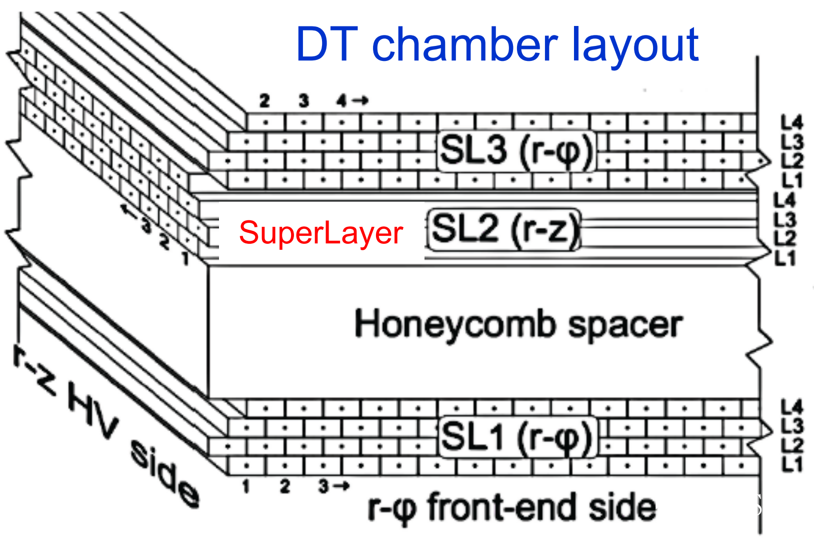
  **$d = (T - T_0) \times V_{drift}$**

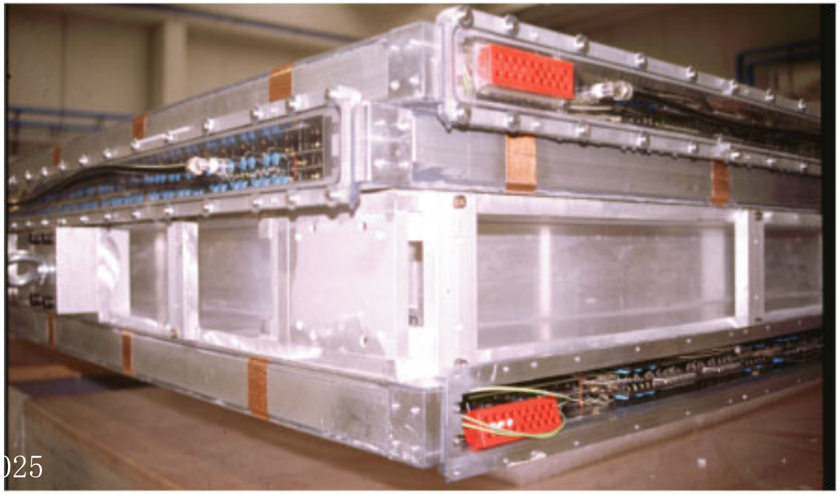
- **4** stations
  - **12** layers per station in groups of 4
    - 8 axial (r-ϕ), 4 longitudinal (r-z)



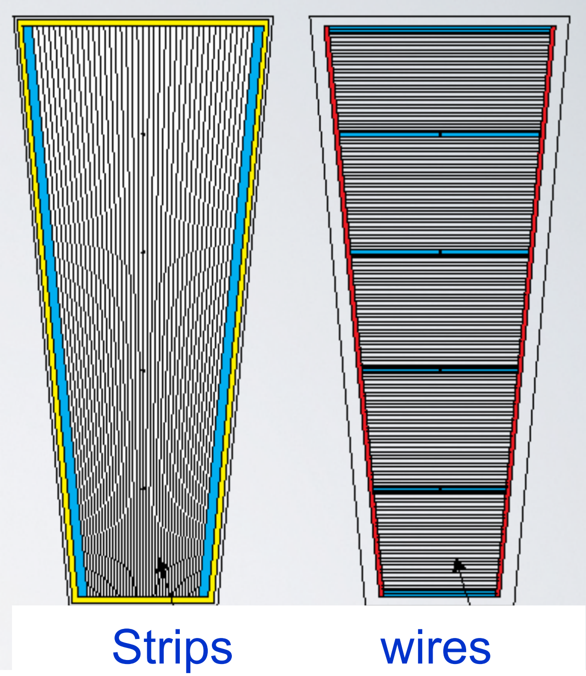

Nominal voltages

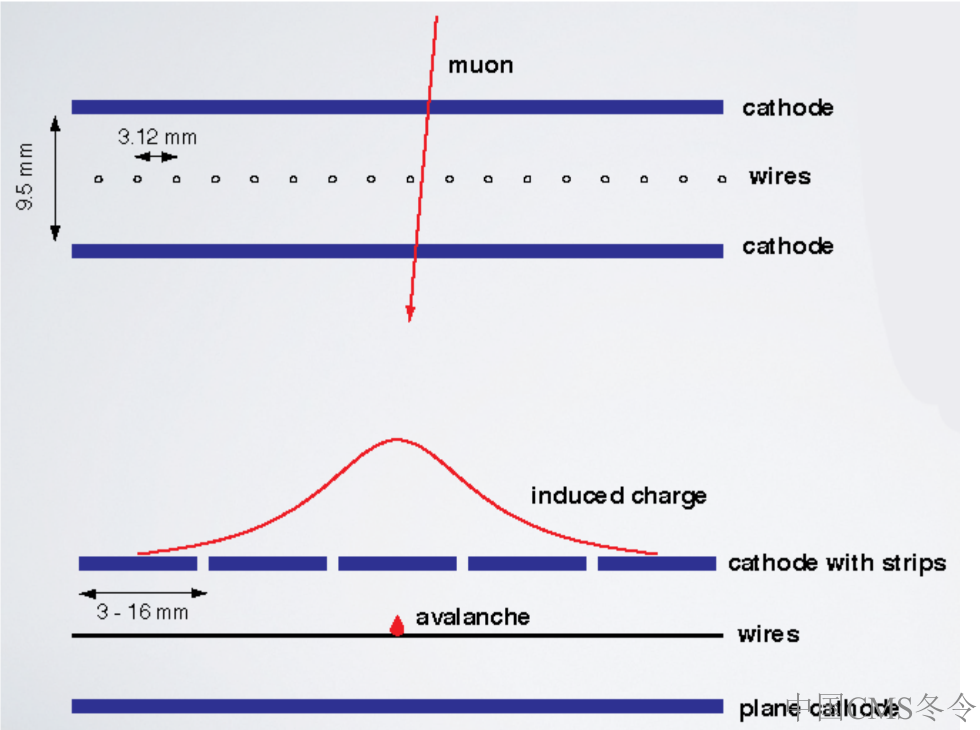


# CMS Cathode Strip Chambers (CSC) IHEP

- **540 trapezoidal chambers in CMS <u>endcaps</u>**
- 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

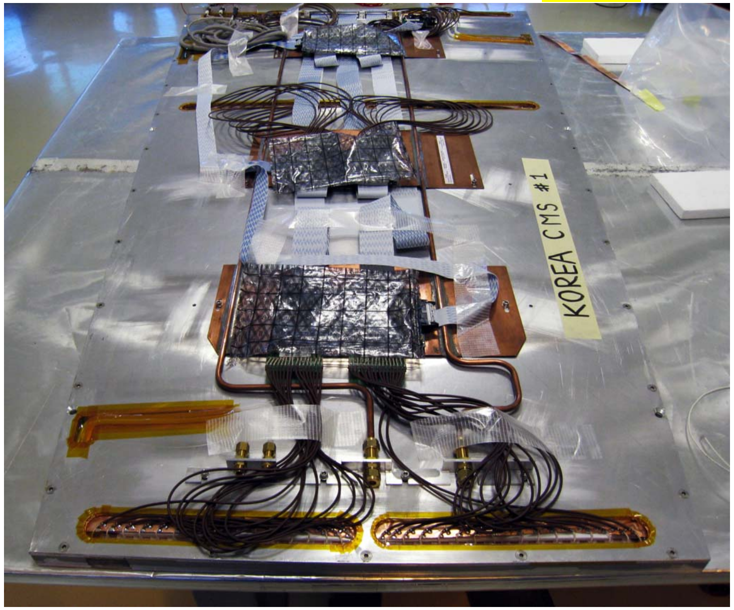


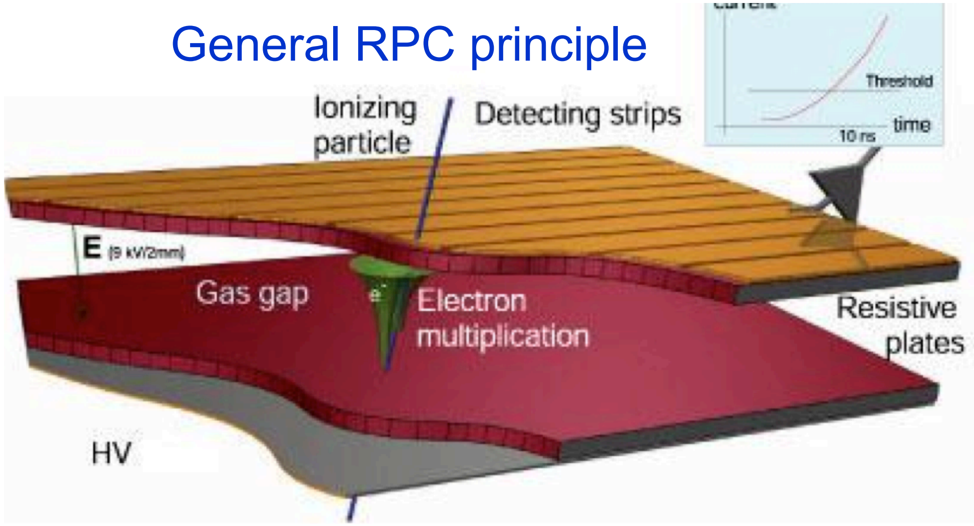

# CMS Resistive Plate Chambers (RPC)

PKU

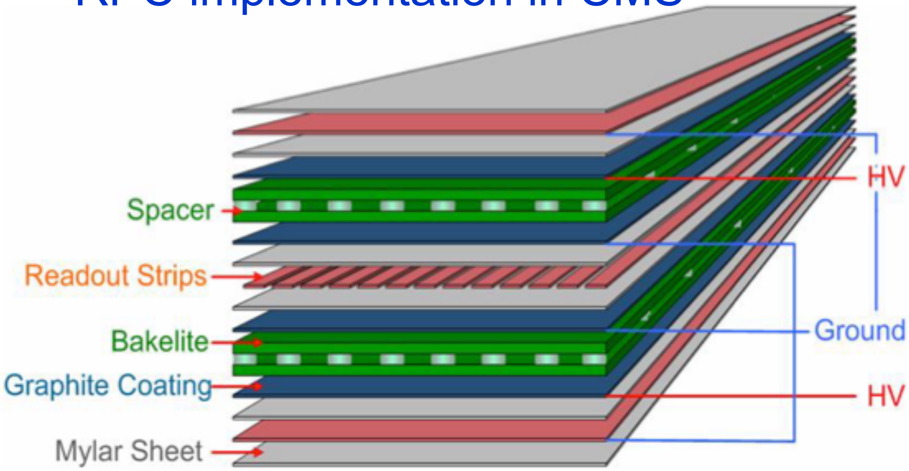
- **480 barrel** and **576 endcap** chambers
- Charge induced onto external strips
  - Resistive layer (Bakelite plastic) with $\rho \sim 10^{10}$ $\Omega$cm is transparent to signal as if infinite, quenches avalanche as if conducting
- Spatial resolution 0.8-1.2 centimeters
- Double gap, each 2 mm,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




General RPC principle




RPC implementation in CMS



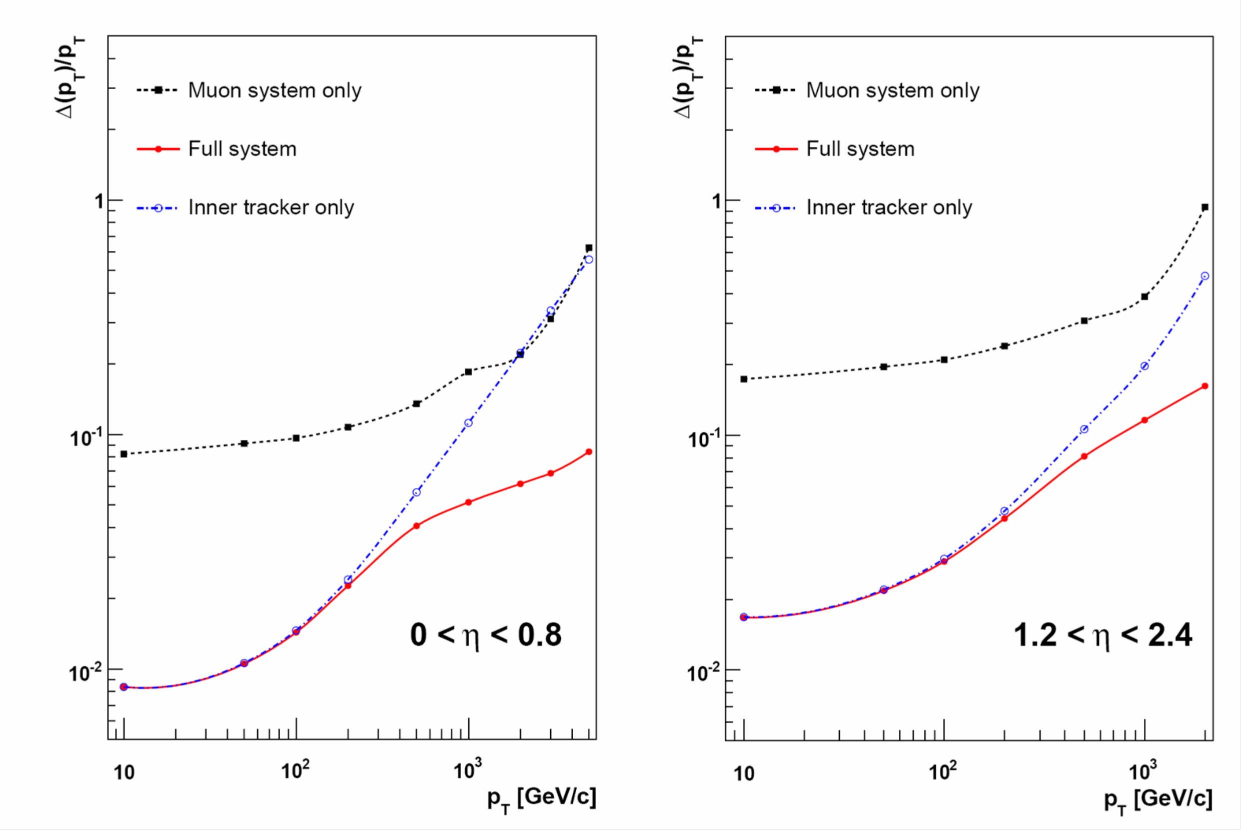
# Muon探测器性能

- 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

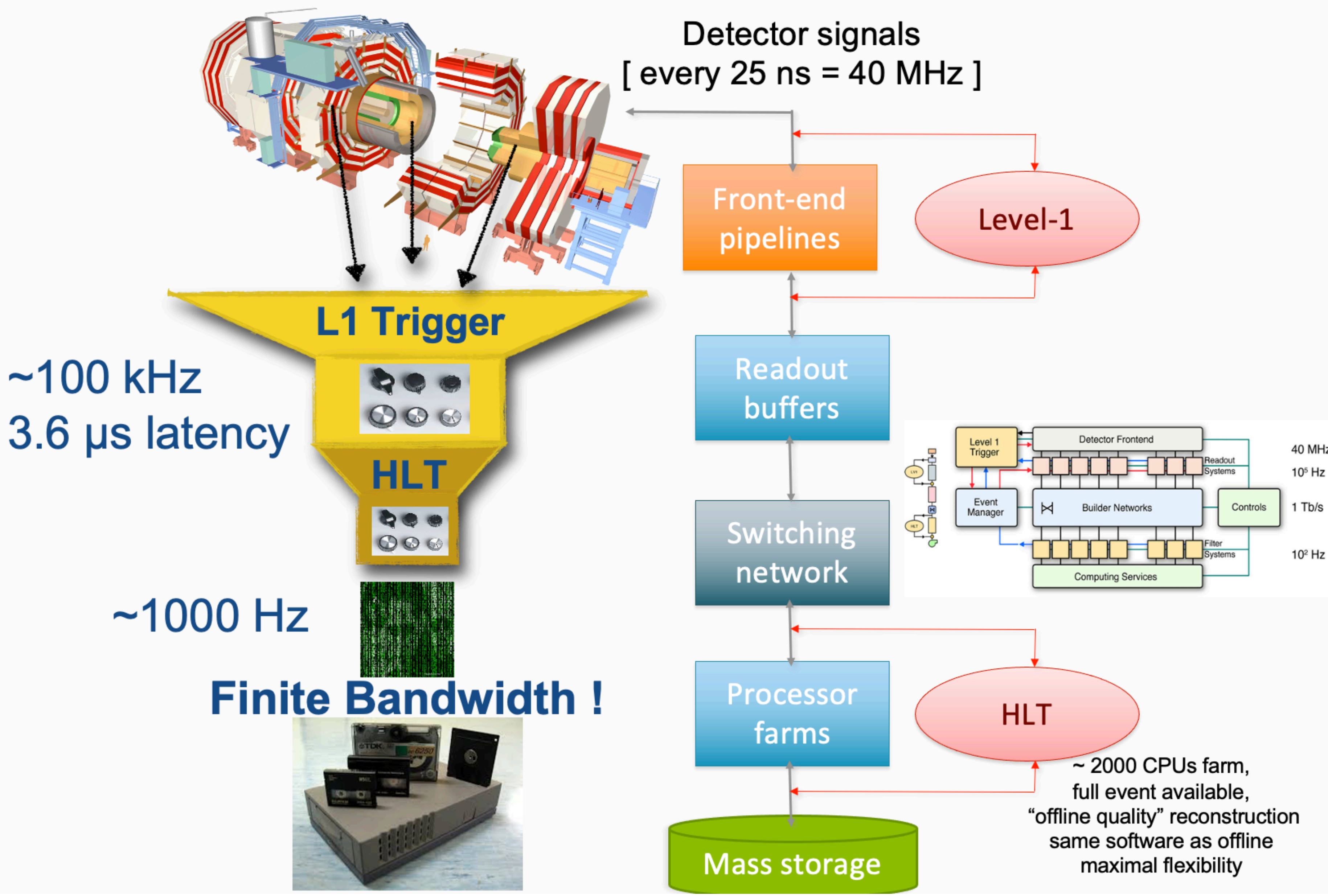
The μ measurements improve the momentum resolution for $p_T > 200$ GeV/c if the DT/CSC chambers are properly aligned

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

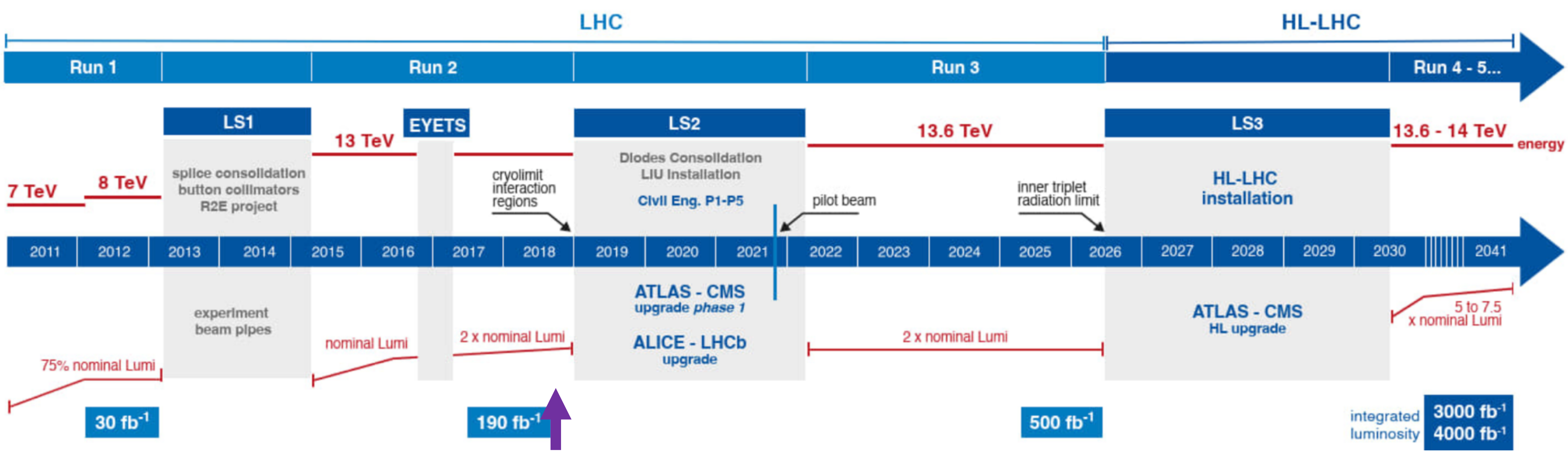


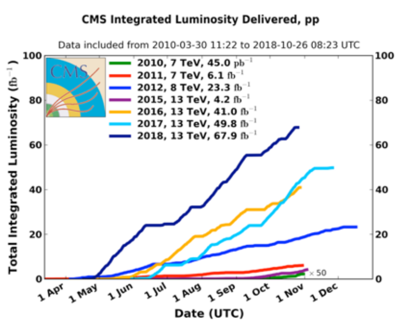
# CMS触发和数据获取系统



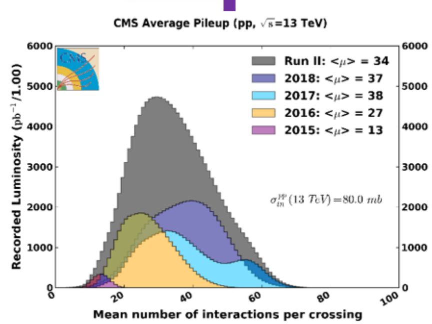
# High Lumi-LHC upgrade

Phase-II upgrade of CMS matches HL-LHC and provide bases for future physics until 2040s

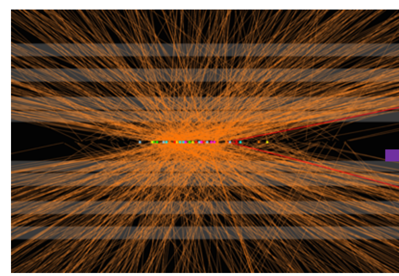



Peak Lumi.
～2x10$^{34}$cm$^{-2}$s$^{-1}$



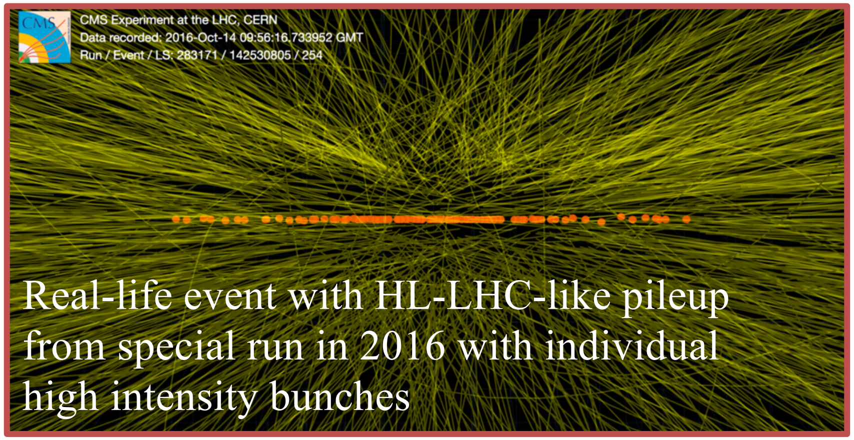

Run II Mean Pileup
34 interactions/Xing



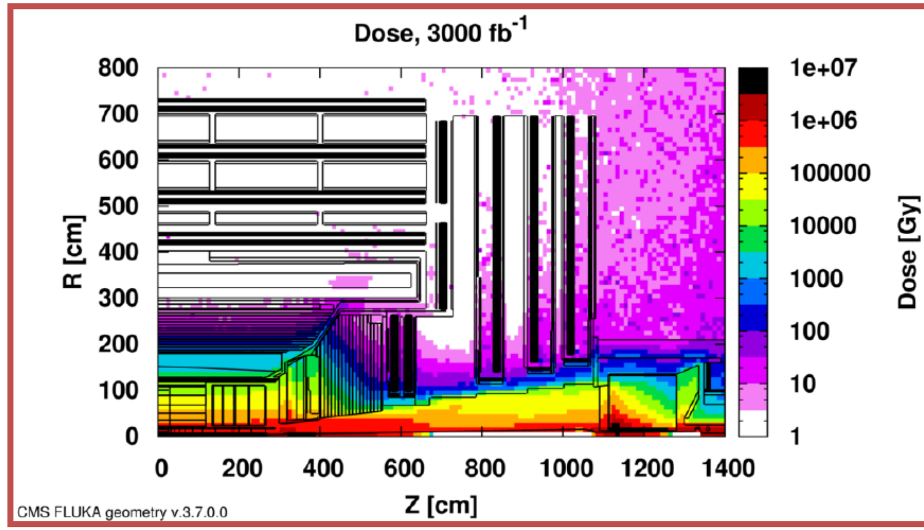
A Z->μμ event with 28 vertices

- Stable running in two decades
- Instant lumi 5-7.5 times higher
- 3000-4000 fb$^{-1}$
- <PU>=140-200

# HL-LHC: challenges and CMS solution




Real-life event with HL-LHC-like pileup from special run in 2016 with individual high intensity bunches



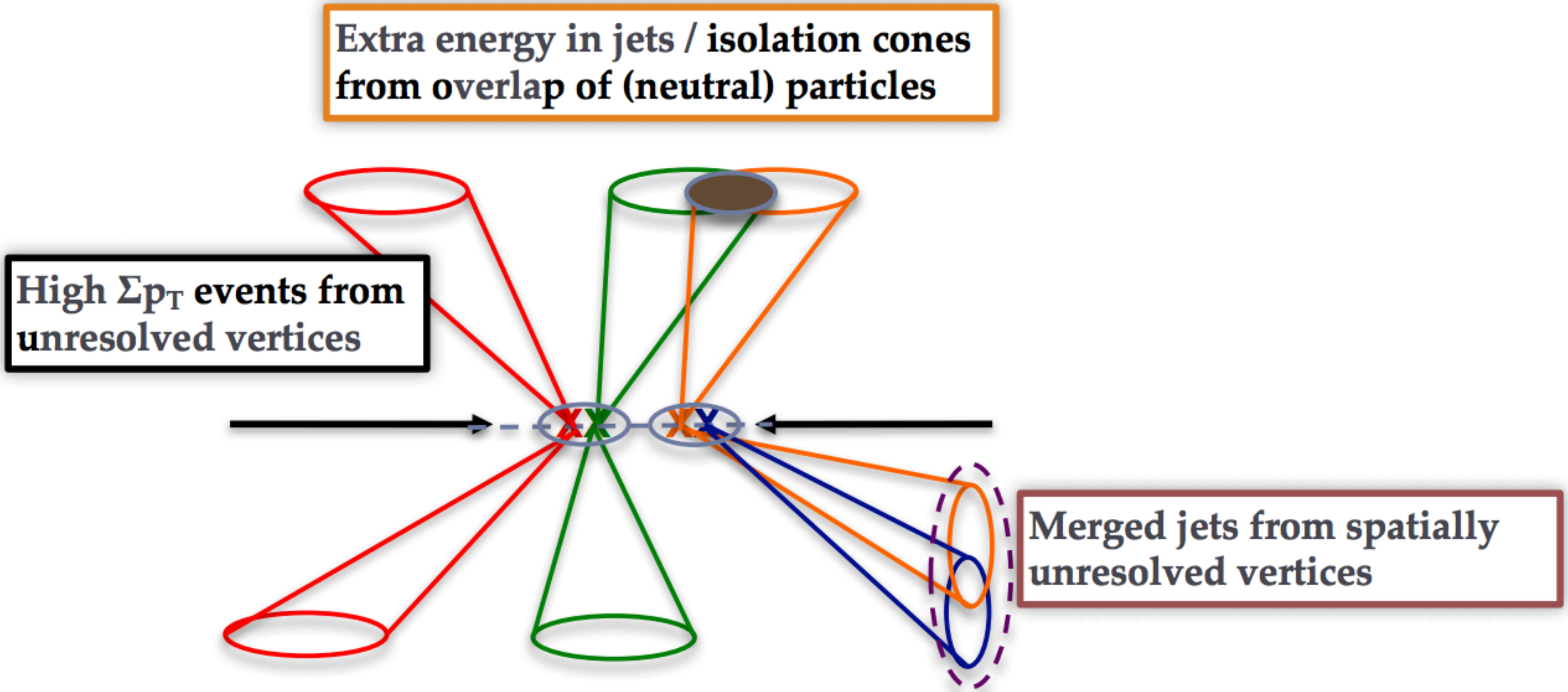

- **Expected pileup** (PU): ~140 -200 (nominal-1.5xnorm)
- Motivates/requires:
  - Improved granularity wherever possible
  - Novel approaches to in-time Pile Up mitigation: Precision Timing detectors (30ps)
  - A complete renovation of the Trigger and DAQ systems for better selectiveness, despite the high PU.

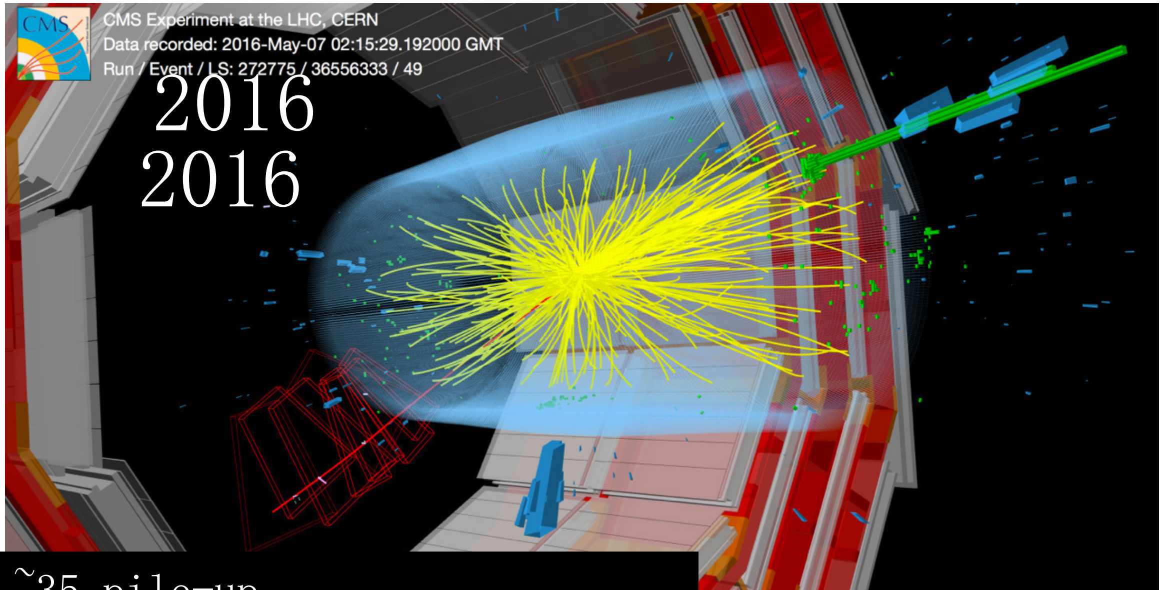
需承受>$10^{16}$等效MeV中子/cm$^2$辐照
局部区域吸收剂量~10MGy, 1Gy=1J/kg

- **Radiation damage / accumulated dose** in detectors and on-board electronics may result in a progressive degradation of the performance.
- Maintain detector performance in harsh conditions:
  - The complete replacement of the Tracker and Endcap Calorimeter systems.
  - Major electronics overhaul and consolidation of the Barrel Calorimeters and Muon systems

CMS 探测器II期升级: 2019-2026年, 匹配高亮度LHC升级, 是未来物理研究的基础!

# Impacts on Physics

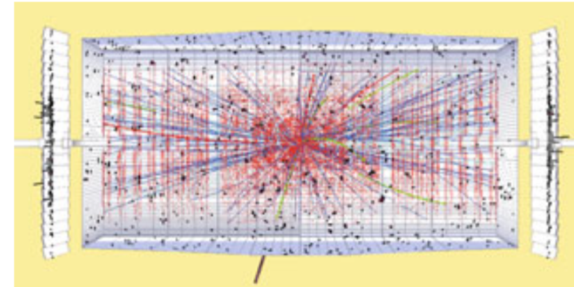




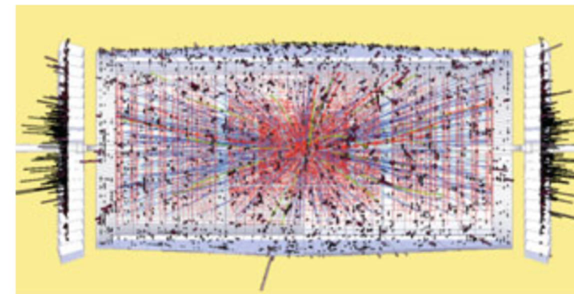

2016

2016

LHC nominal: $10^{34}$ cm$^{-2}$ s$^{-1}$

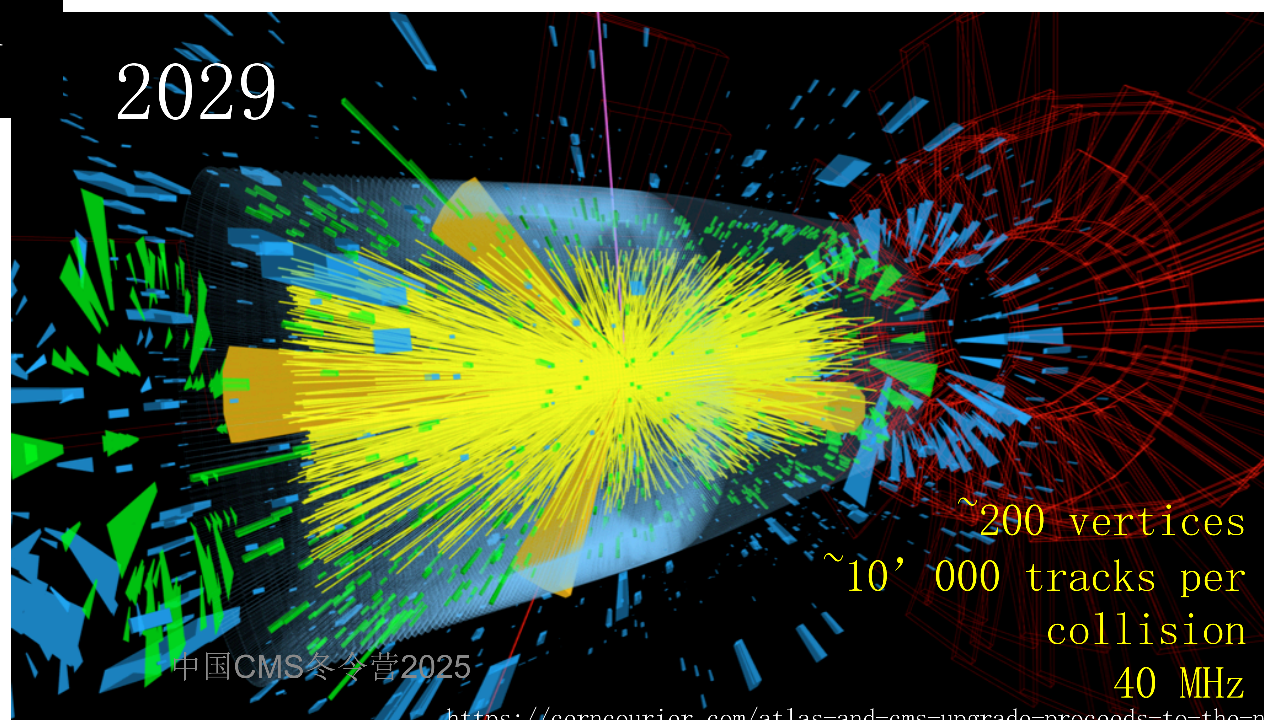


HL-LHC: $10^{35}$ cm$^{-2}$ s$^{-1}$



~35 pile-up
~2’ 000 tracks per collision bunch (40 MHz)

2029



Higgs boson produced in the VBF process on top of 200 pile-up collisions. The efficient identification of the forward jets accompanying this process requires association of the calorimeter energy deposits with charged tracks.

~200 vertices
~10’ 000 tracks per collision
40 MHz



https://cerncourier.com/atlas-and-cms-upgrade-proceeds-to-the-ne

# CMS探测器 II期升级项目

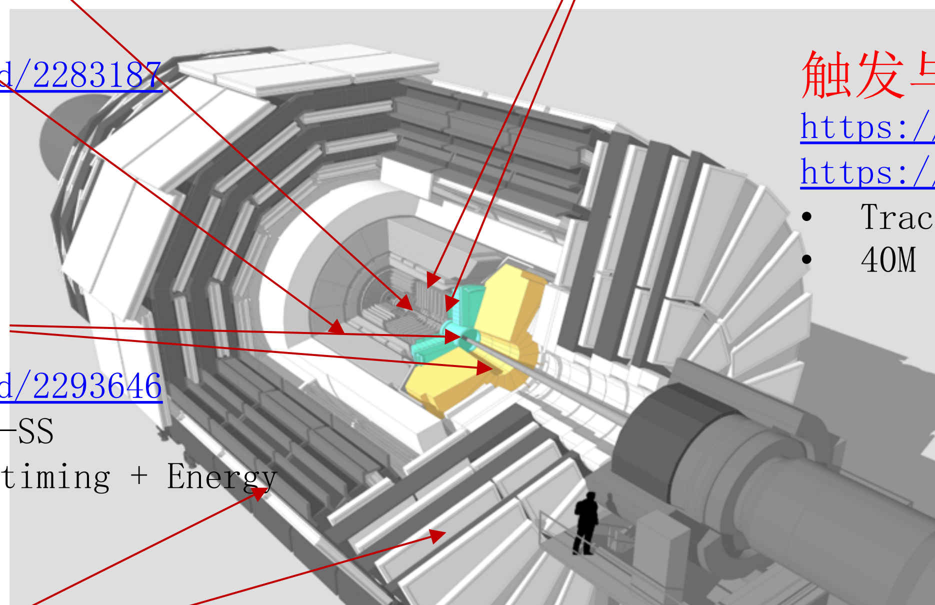
各主要项目TDR
背后是>5-10年
R&D,都已获
LHCC批准

## 硅径迹探测器：
https://cds.cern.ch/record/2272264
- Si-strips and Pixels increased granularity
- Tracking in L1-Trigger
- Coverage extended to |eta|~3.8

## 桶部量能器：
https://cds.cern.ch/record/2283187
- New ECAL/HCAL readout

## MIP 时间探测器：
https://cds.cern.ch/record/2296612
- ~30ps timing resolution
- Barrel: Crystals + SiPMs
- Endcap layer: LG Avalanche Diodes

## 触发与数据获取系统：
https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193
- Tracks in L1
- 40M → 750k(PF-like) → 7.5k



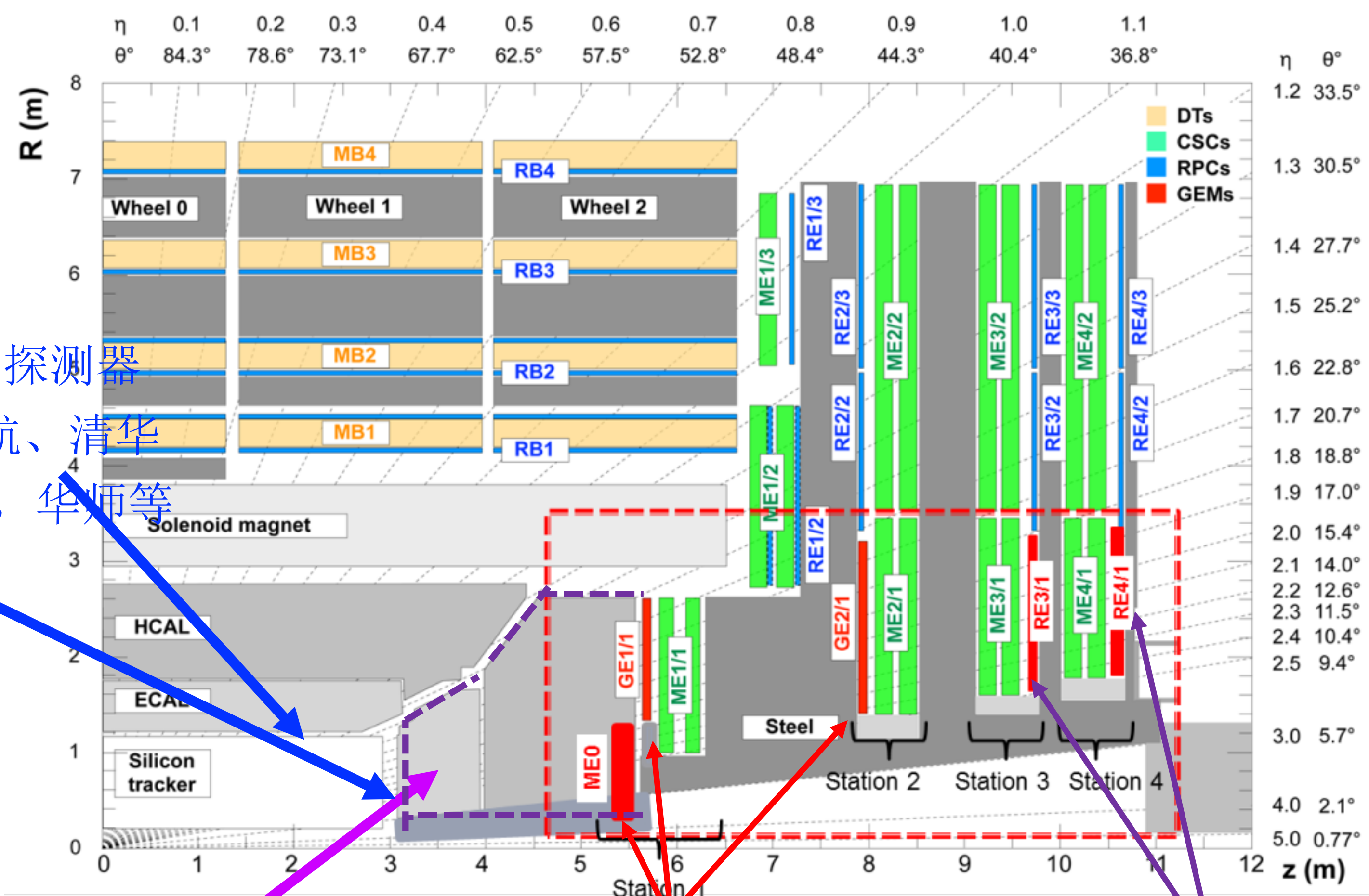
## 端部量能器：
https://cds.cern.ch/record/2293646
- Si, Scint+SiPM in Pb-W-SS
- 3D position + precise timing + Energy

## 束流、亮度监测与通用设施
https://cds.cern.ch/record/2020886

## Muon探测器系统：
https://cds.cern.ch/record/2283189
- New FE/BE readout for DT/CSC
- New GEM/RPC 1.4 <|eta|<2.4: GE1/1, GE2/1
- Coverage extended to |eta|~3:ME0

总造价（预算）：2.83亿瑞士法郎

# 中国组参与的CMS II期探测器升级




MTD时间探测器

北大、北航、清华

科大, 山大，华师等

端部量能器升级

高能所、浙大、清华、复旦

端盖μ子探测器升级，GEM

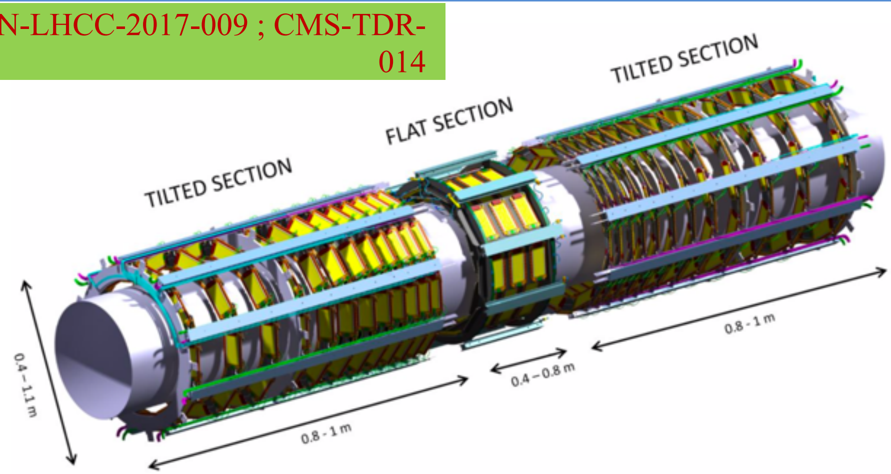
北大、清华、中山、北航

iRPC后端电子学及触发

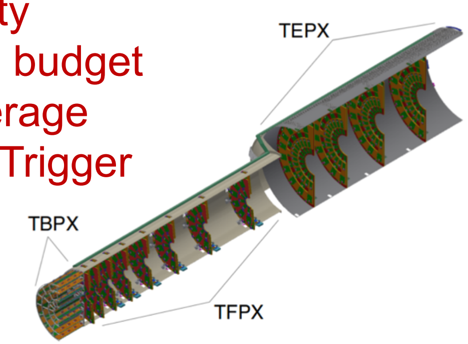
高能所

# Tracker Upgrade: layout and material

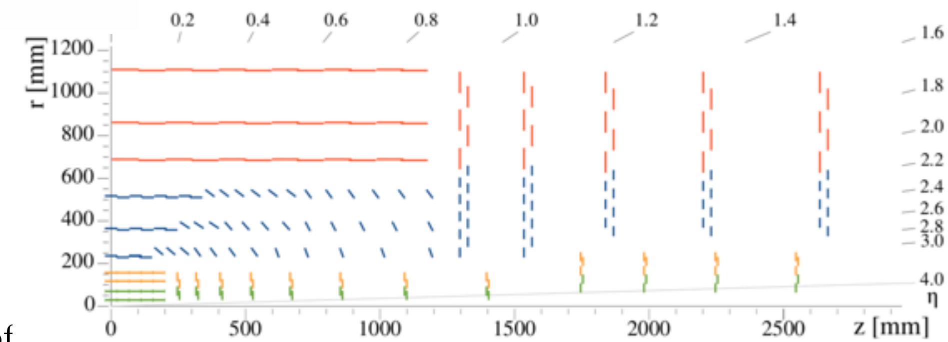
CERN-LHCC-2017-009 ; CMS-TDR-014

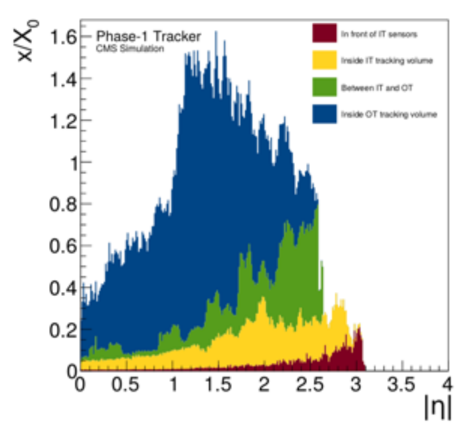


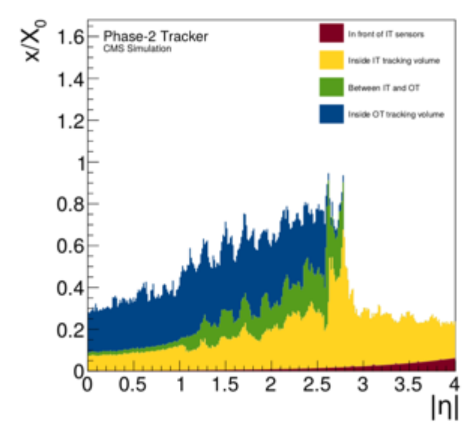

- More granularity
- Lower material budget
- Extended coverage
- Tracking in L1 Trigger



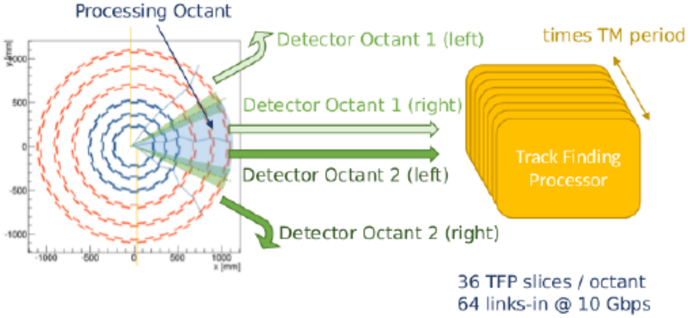

- **Inner tracker**:
  - Increased granularity with occupancy at per mille level: pixel size ~ 25 × 100 μm² or 50 × 50 μm²
  - Coverage up to η ~ 4, with ~4.9 m² active area
  - Layout: 4 barrel layers, 8 small disks, 4 large discs per side
  - Mechanics and support: simple structure for easy installation and removal → potential replacement of inefficient parts possible!
- **Outer tracker**:
  - Layout: 6 barrel layers, 5 discs per endcap
  - 9.5 million channels:
    - ~ 200 m² of active silicon sensors → 44M strips and 174M macro pixels (r < 60 cm)
  - Vastly **reducing** material:
    - light-weight mechanics and modules
    - improved routing of services
    - tilted barrel section



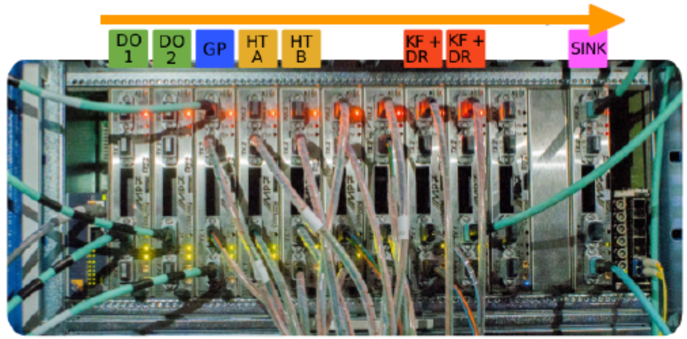



# Tracks into L1 Trigger

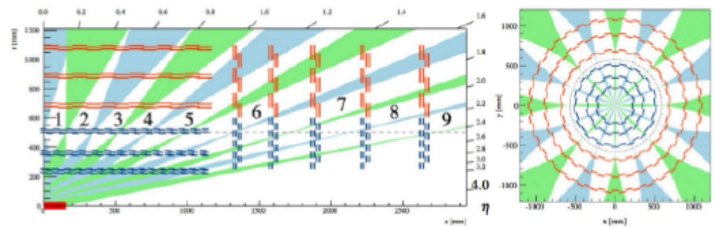



FPGA-based Hardware Demonstrator



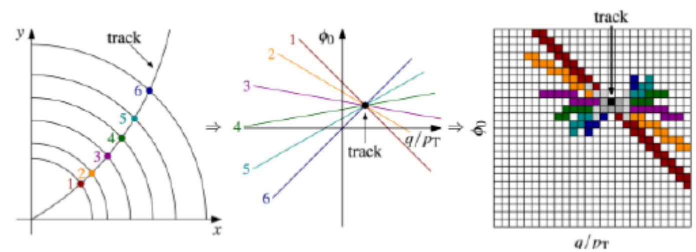

## Geometric Processor GP

Processes stub data, sub-divides octant into 36 sub-sectors



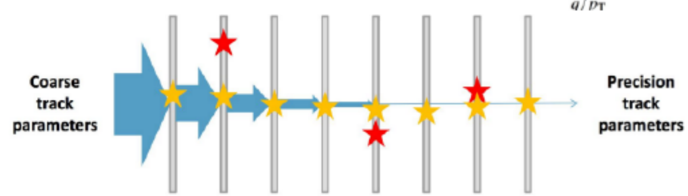
## Hough Transformation HT

Track finder, identifies groups of stubs consistent with a track in r-φ



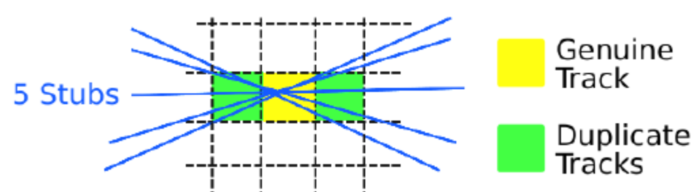

## Kalman Filter KF

Candidate cleaning and precision fitting




## Duplicate Removal DR

Uses fit information to remove duplicate tracks generated by the HT



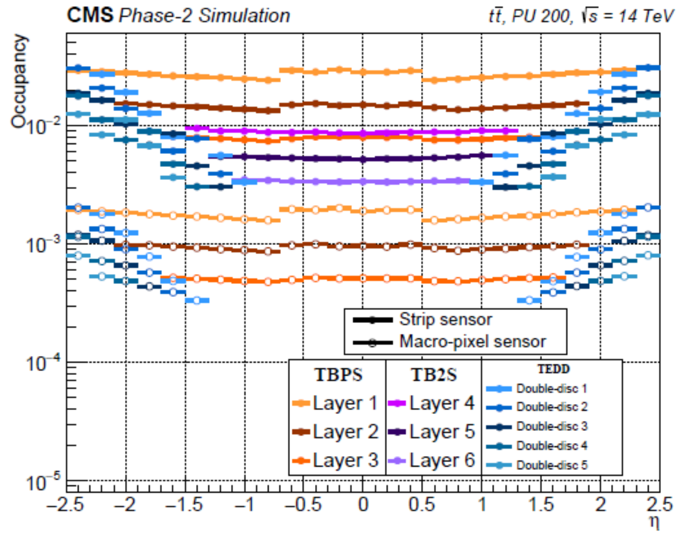

Data flow

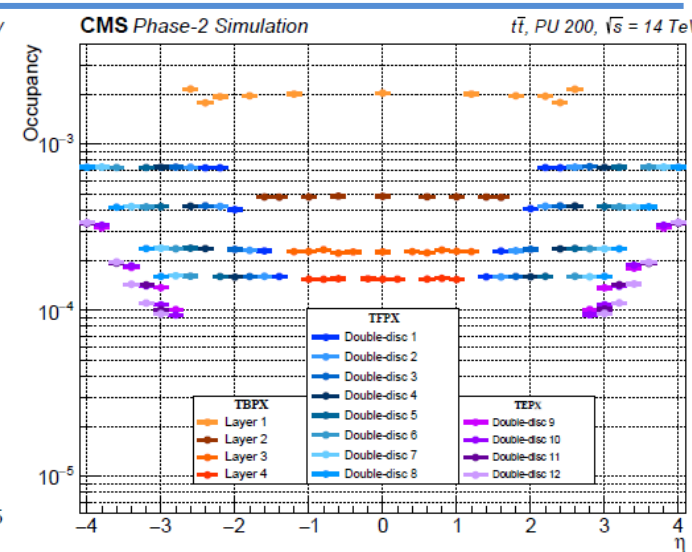
# Expected performance

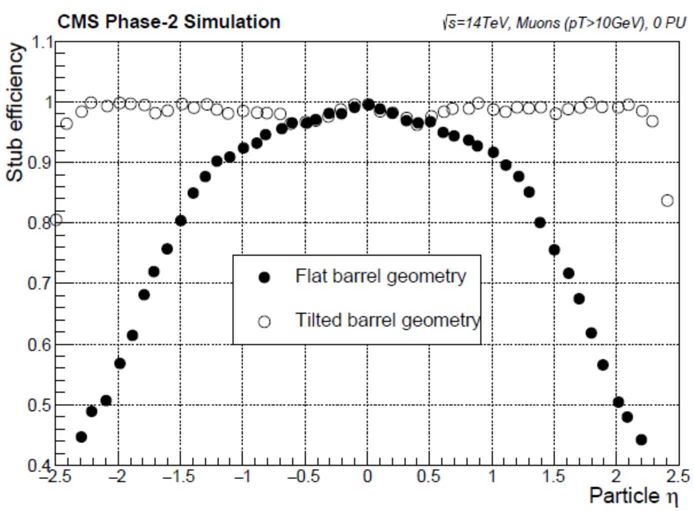
**Occupancy will not exceed 3%**

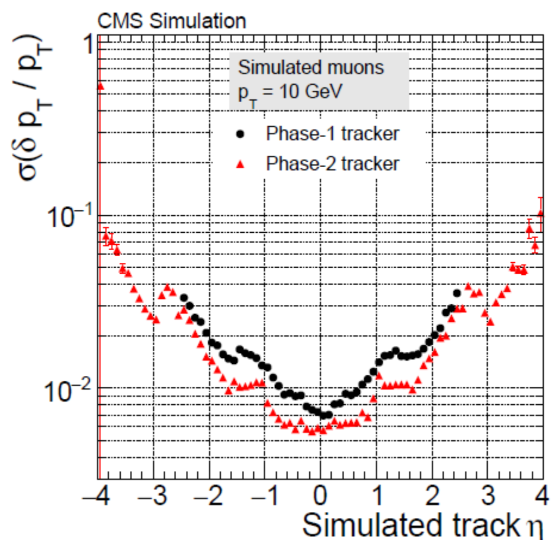
**Resolution:**

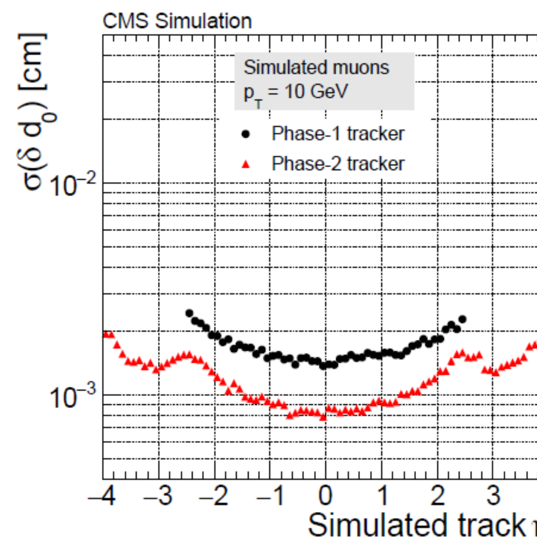
- ✓ Deteriorates at higher η due to shorter lever arm
- ✓ Below 10µm in centre, 20µm at edge



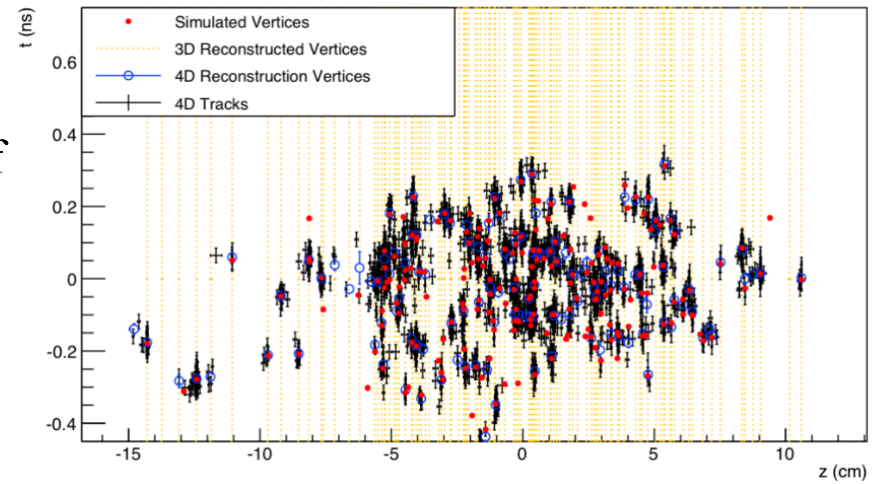



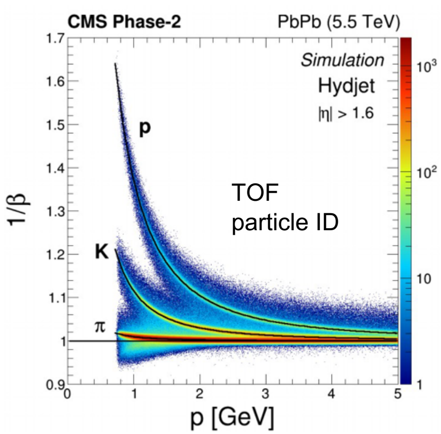



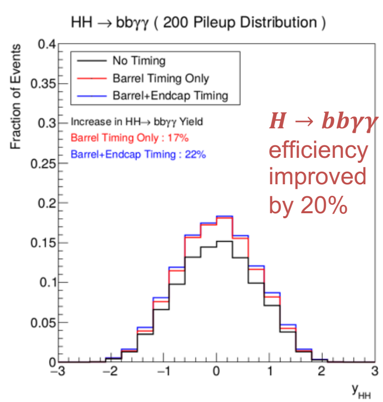



# MIP Timing Detector

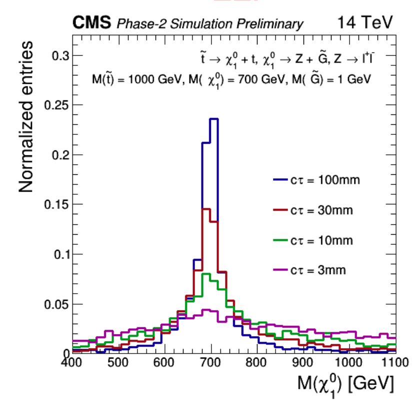
- **Time information** improves the quality of the reconstruction of physics objects.
  - Track time association allows to remove spurious pile-up tracks from reconstruction,
  - Impact on fake jet reconstruction, lepton isolation and ID, b-tagging, $p_T^{miss}$ resolution.
  - Also adding the possibility to perform Time-Of-Flight particle identification
- Impact on the reach of physics analysis: both SM and BSM



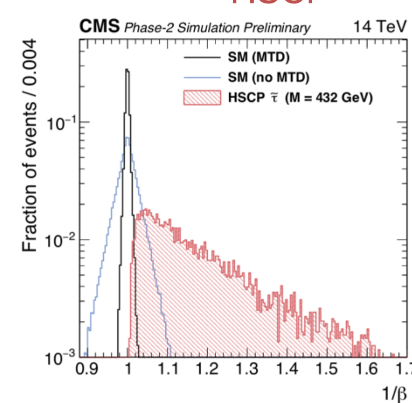




LLP




HSCP

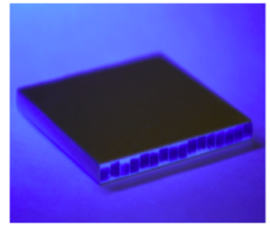



Improve HH sensitivity by 20%

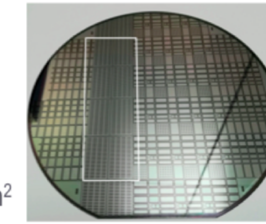
Improve single Higgs precision by 20-30%

# MIP Timing Detector

**BTL: LYSO bars + SiPM readout:**
- TK / ECAL interface: $|\eta| < 1.45$
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 $m^2$; 332k channels
- Fluence at 4 $ab^{-1}$: $2 \times 10^{14}\ n_{eq}/cm^2$



**ETL: Si with internal gain (LGAD):**
- On the CE nose: $1.6 < |\eta| < 3.0$
- Radius: 315 < R < 1200 mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~14 $m^2$; ~8.5M channels
- Fluence at 4 $ab^{-1}$: up to $2 \times 10^{15}\ n_{eq}/cm^2$



Thin layer between tracker and calorimeters

Hermetic coverage for $|\eta| < 3.0$

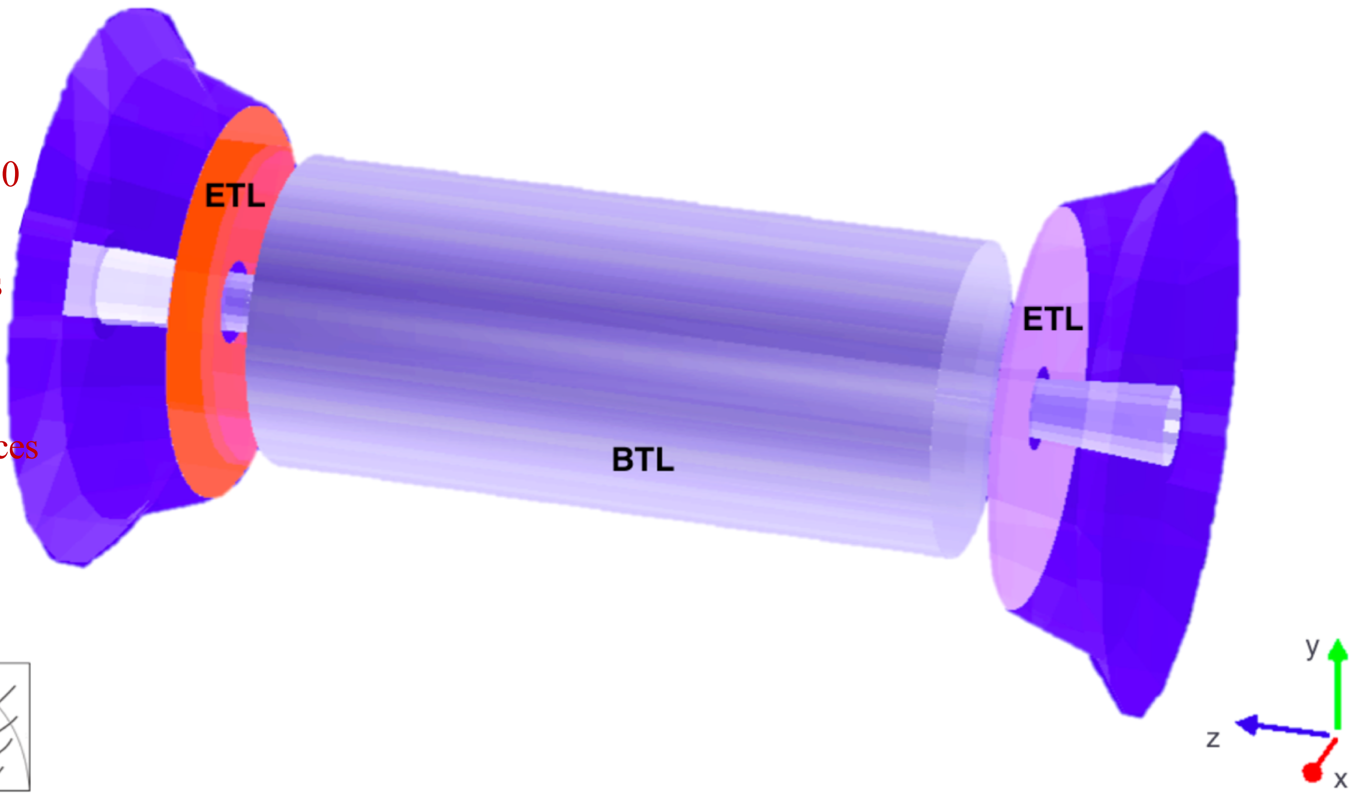
Feature:

MIP Time resolution 30-50 ps

4D vertex reconstruction

Expand physics at HL-LHC:

- Reduction of pile-up enhances quality of reconstruction
- Mass reconstruction of the long-lived particle

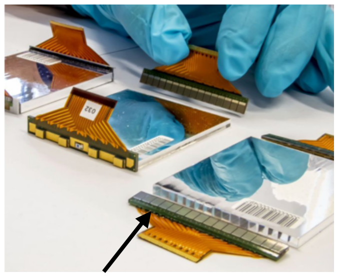


# MTD Technology

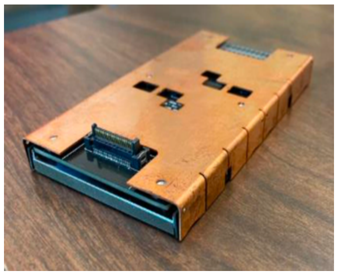
**BTL:** first HEP experiment "PET-like" system

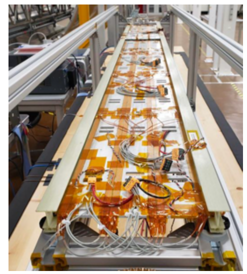
thin layer of LYSO:Ce crystal bars + SiPM + thermal electric coolers providing $\sigma_t \simeq$ **30/60 ps** before/after irradiation

16 LYSO bars polished on both ends (56 x 3 x 3.75 mm$^3$) per module ($\simeq$ 21000)

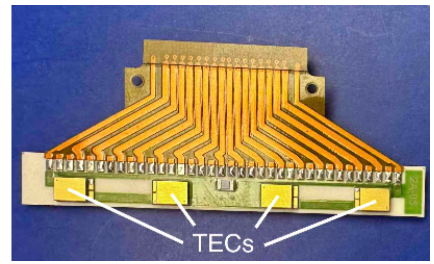


SiPM on both sides

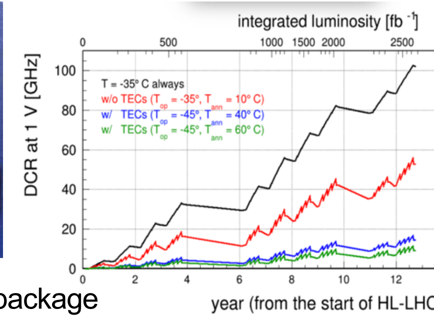




24 modules readout unit grouped in trays

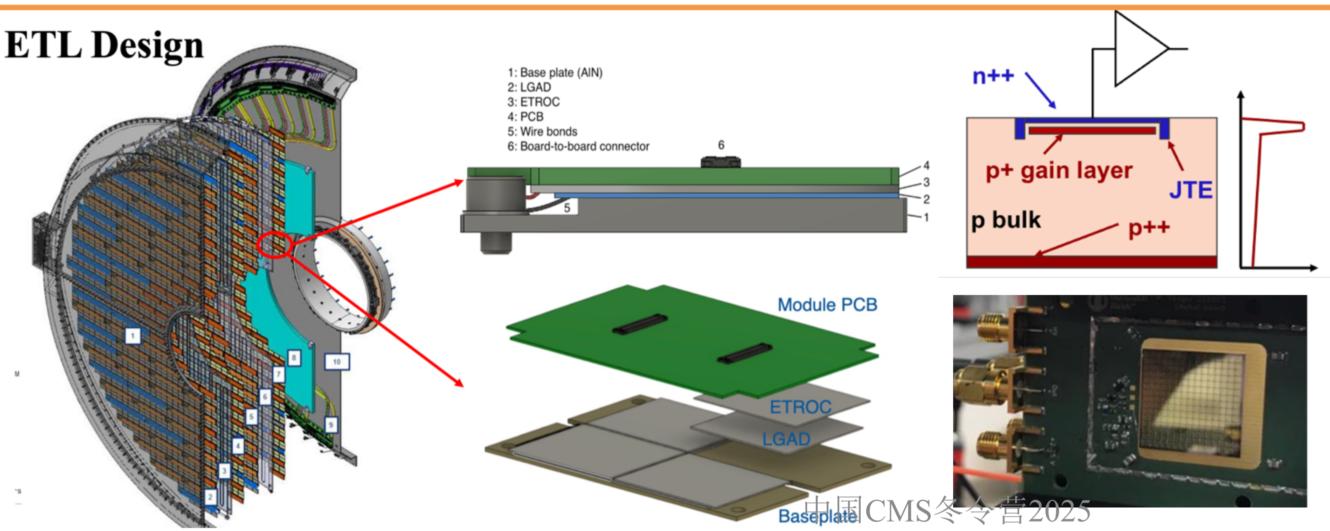



Company delivers SiPM+TEC package




**ETL:** first use (ATLAS&CMS) of Low Gain Avalanche photo Diodes (LGAD) on large scale readout by dedicated ASIC

1.6 < $|\eta|$ < 3 , 2 double sided thin layers with 1.3 x 1.3 mm$^2$ pads providing 8.5 M channels $\sigma_t \simeq$ **35 ps /track**

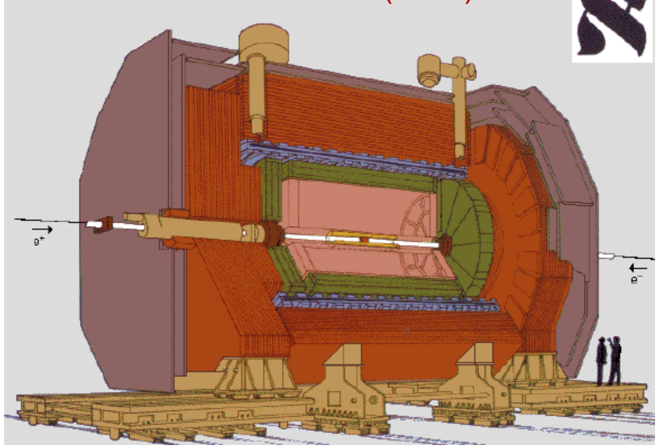



LGADs is a new technology

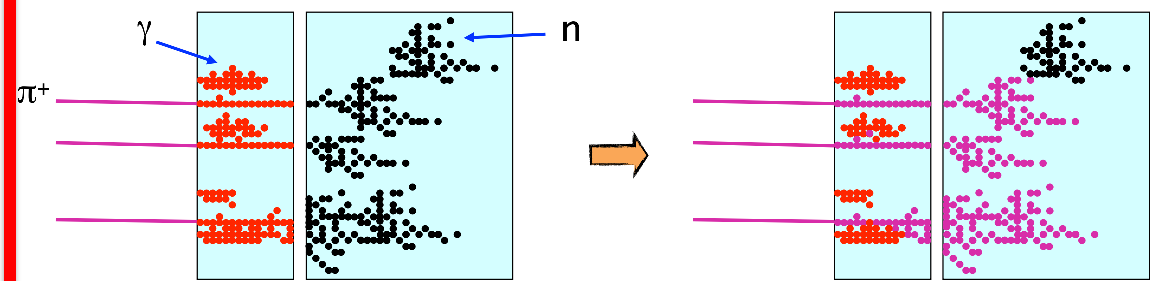
Lots of next-gen R&D is ongoing

# CMS端部量能器升级

Nucl.Instrum.Meth. A360 (1995) 481

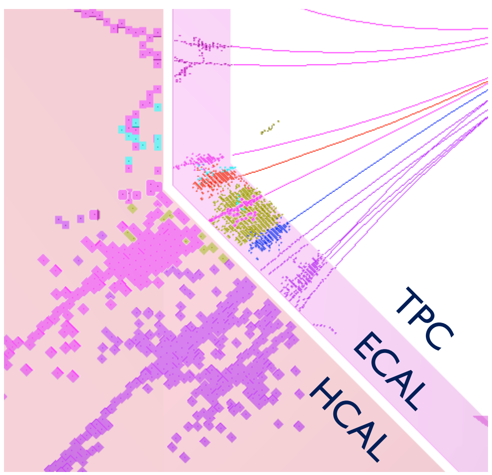


## 传统事例重建vs粒子流算法

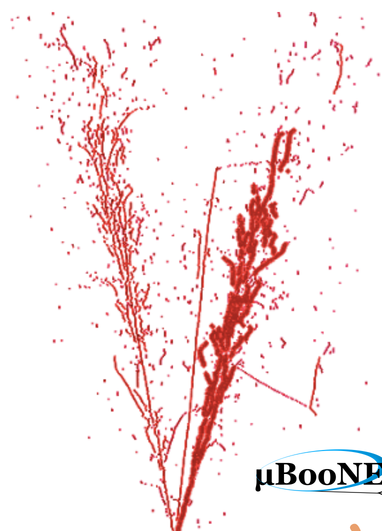



$E_{JET} = E_{ECAL} + E_{HCAL}$ $E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

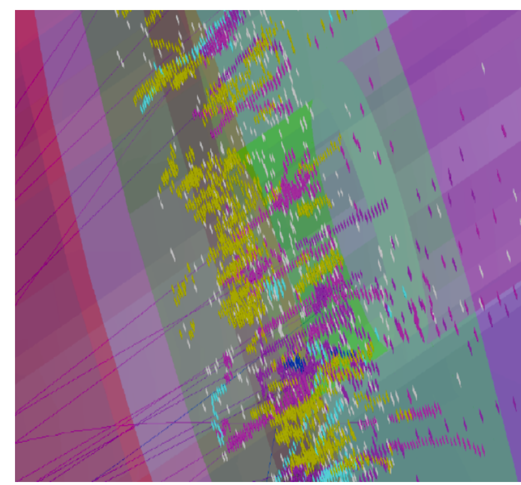
NIMA.2009.09.009, NIMA.2012.10.038




arXiv:1307.7335, 1506.05348



LHCC-P-008

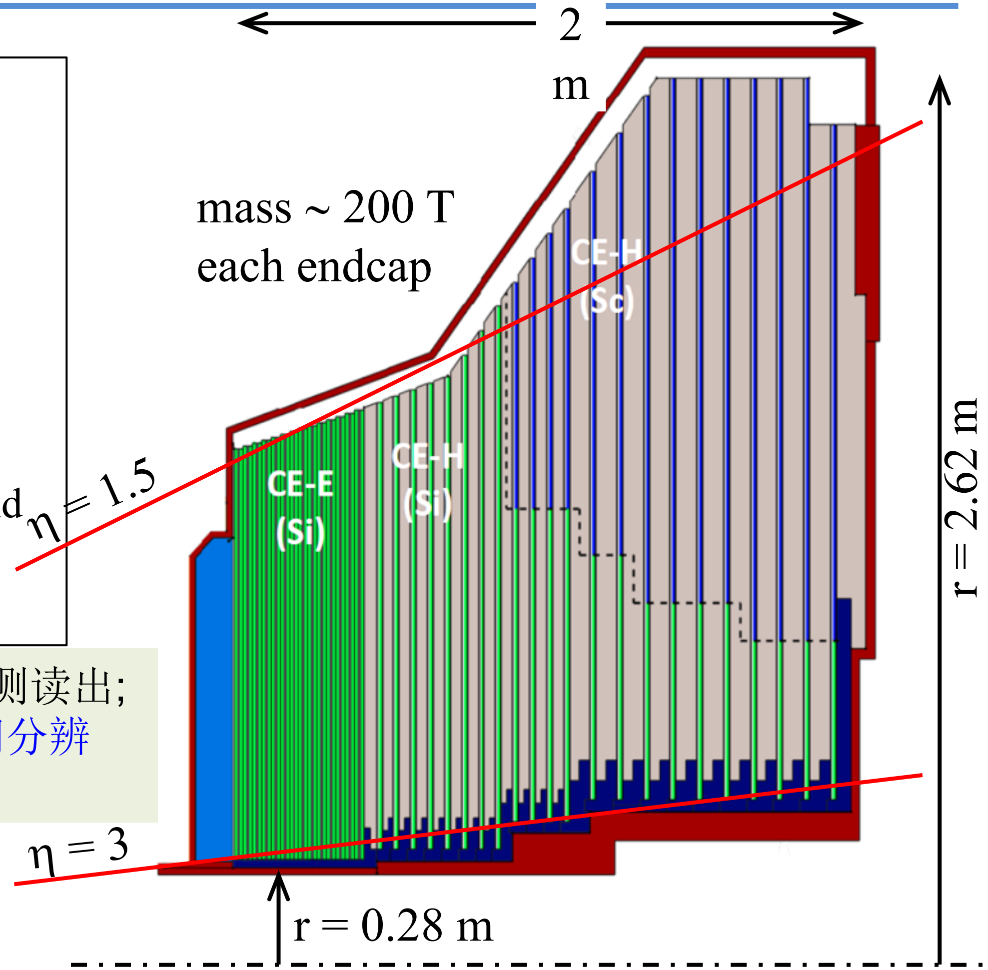


JINST 12 (2017) no.10, P10003

# 高粒度量能器HGCal

Key Parameters :

- HGCAL covers $1.5 < \eta < 3.0$
- Full system maintained at -30°C
- ~640 $m^2$ of silicon sensors
- ~370 $m^2$ of scintillators
- 6.1M Si channels, 0.5 or 1.1 $cm^2$ cell size (6M)
  240k scint-tile channels ($\eta-\phi$)
  - Data readout from all layers
  - Trigger readout from alternate layers in CE-E and all in CE-H
- ~31k Si modules (incl. spares)



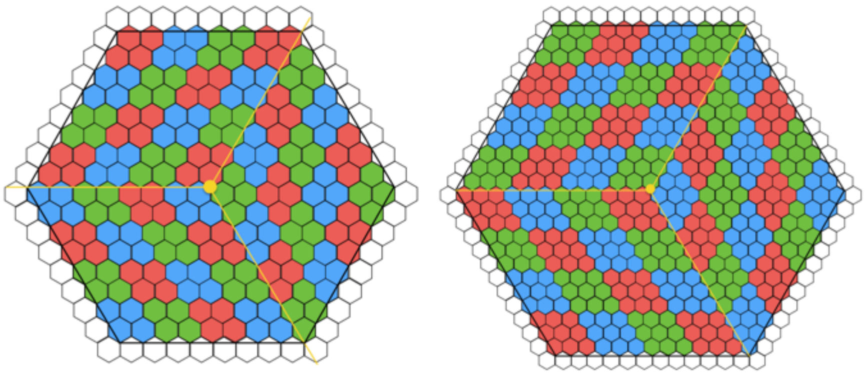

challenges:
2MGy does
140 pileup
220kW heat load
640$m^2$ silicon sensor
…

1立方厘米单个探测读出;
能量，位置，时间分辨
5D量能器

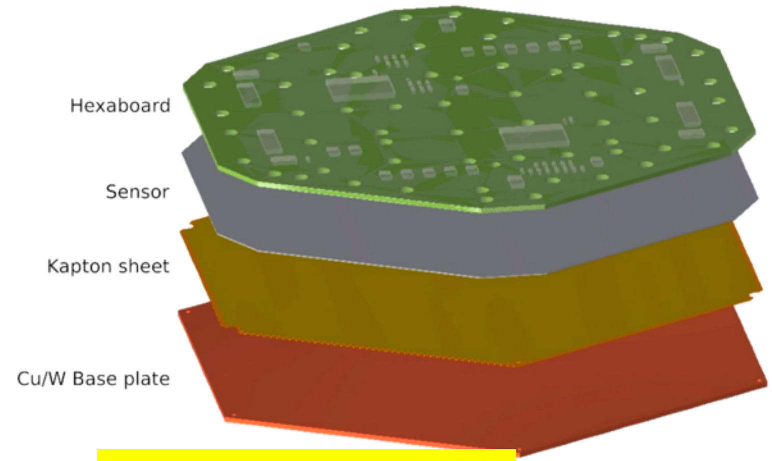
Electromagnetic calorimeter (CE-E): Si, Cu/CuW/Pb absorbers, 28 layers, 25.5 $X_0$ & ~1.7λ
Hadronic calorimeter (CE-H): Si & scintillator, steel absorbers, 22 layers, ~9.5λ (including CE-E)

# 高粒度量能器的设计

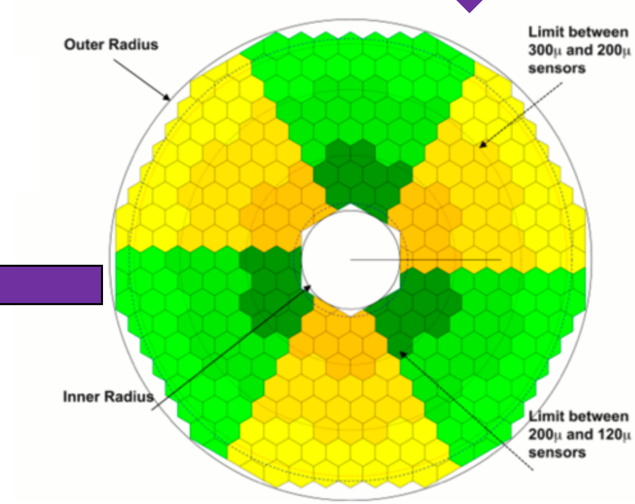
8inch， 1.18cm$^2$（192） / 0.52cm$^2$（432）



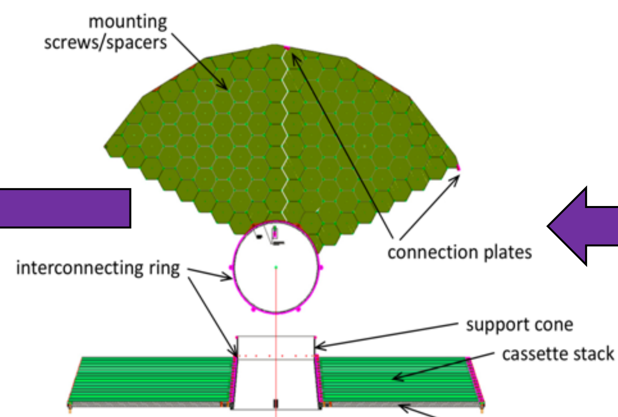
Sensors (Hexagon)



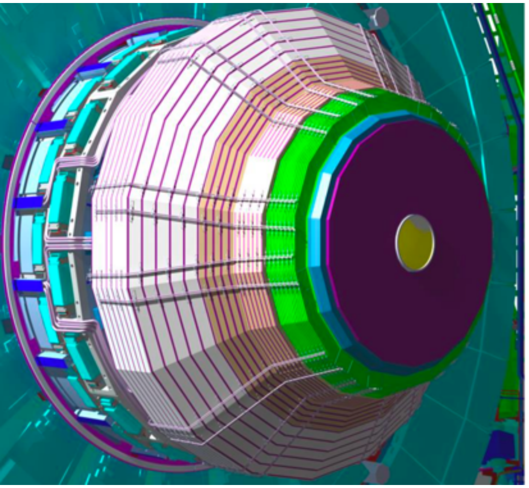

Module Assembly




Tiling

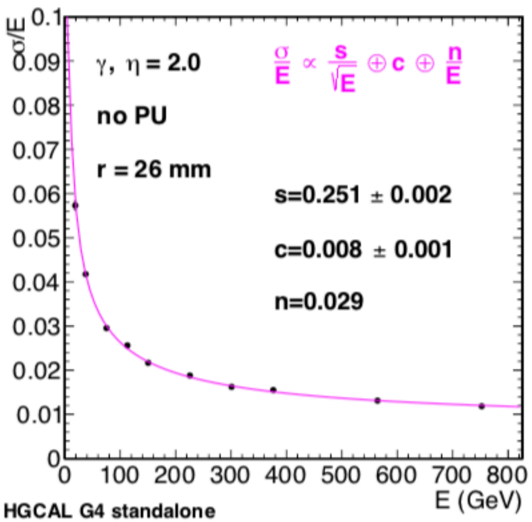


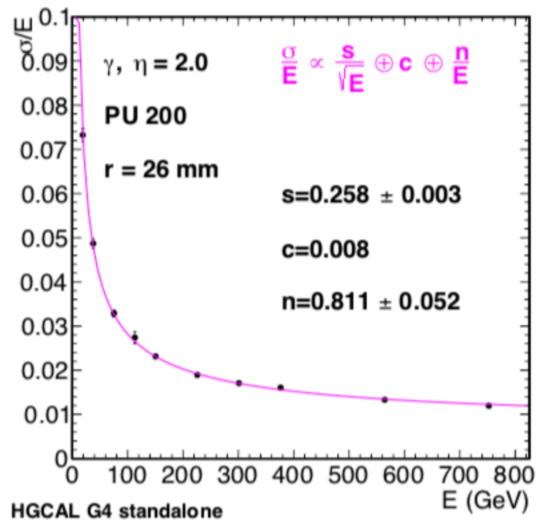

Stacking

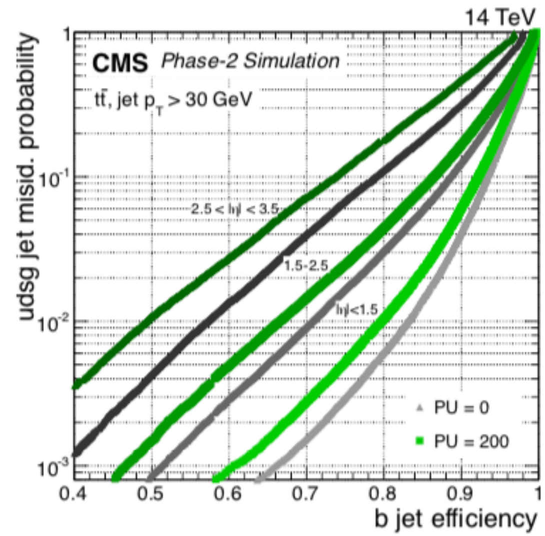


28层Ecal，24层HCal

# CMS-HGCAL预期性能与物理

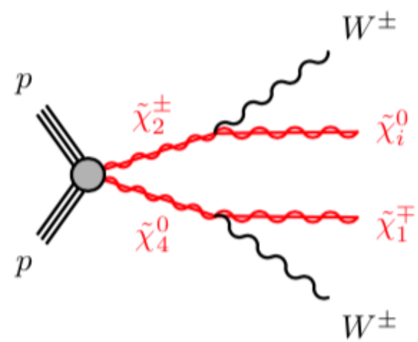


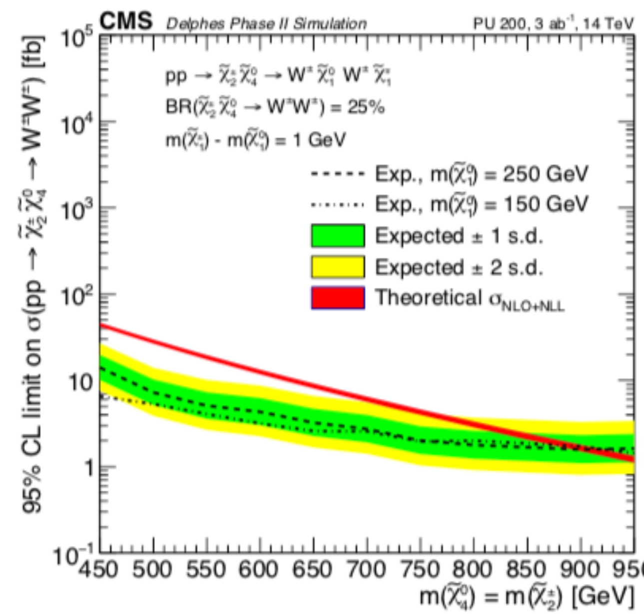



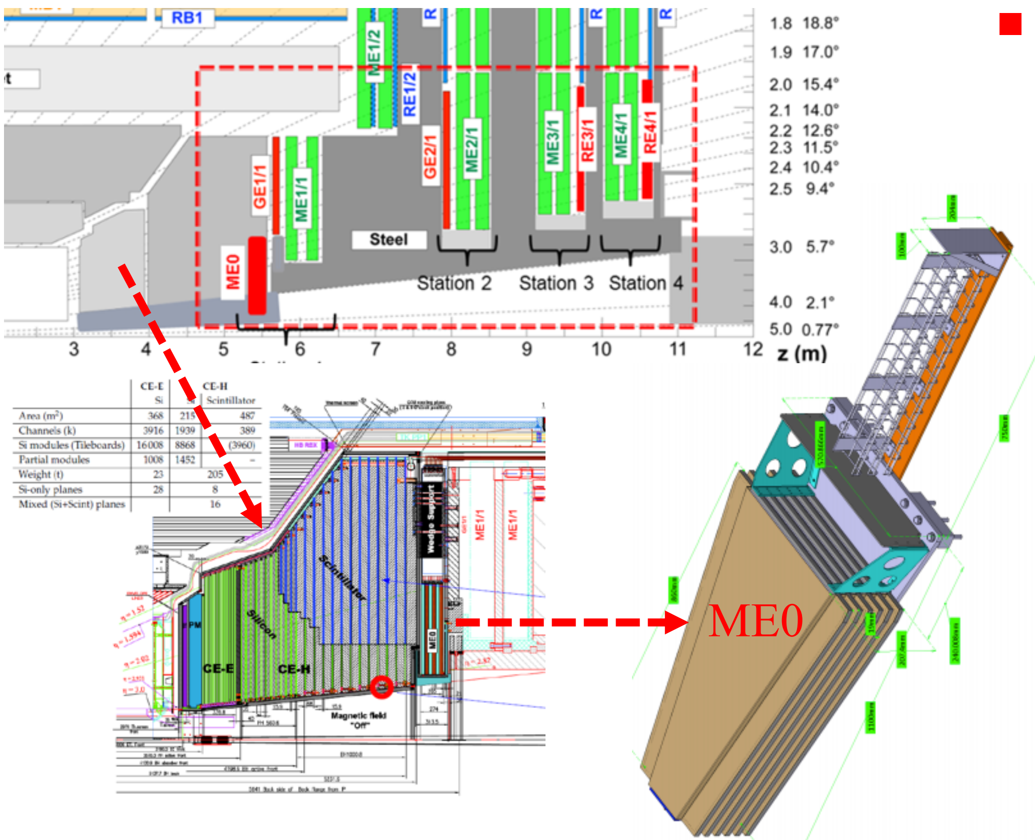

改善光子和喷注末态重要物理：

- H → γγ, H → ττ in the VBF
- HH→ bbττ
- Search for electroweakinos with SS leptons
- Search for FCNC in t→qγ
- Physics with boosted objects



# Muon Challenges: ME0 as example

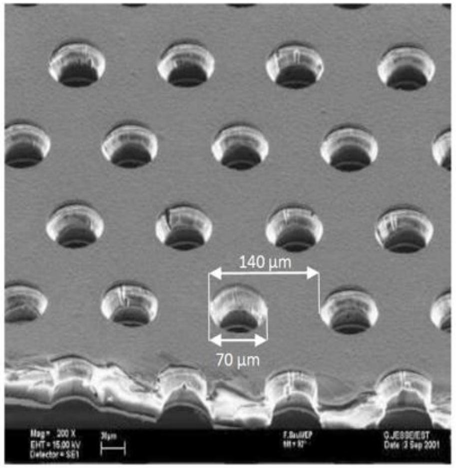



| | CE-E | CE-H | |
|---|---|---|---|
| | Si | Si | Scintillator |
| Area ($m^2$) | 368 | 215 | 487 |
| Channels (k) | 3916 | 1939 | 389 |
| Si modules (Tileboards) | 16008 | 8868 | (3960) |
| Partial modules | 1008 | 1452 | – |
| Weight (t) | 23 | 205 | |
| Si-only planes | 28 | 8 | |
| Mixed (Si+Scint) planes | | 16 | |

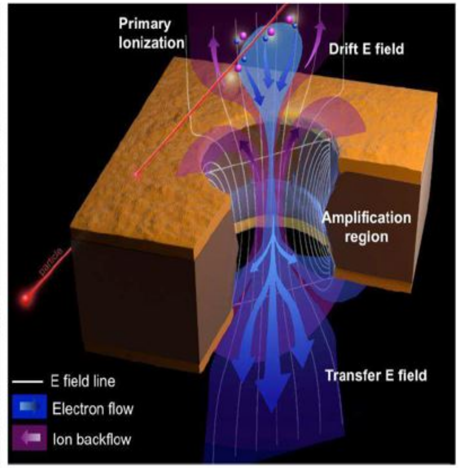
- 6-Layer Triple-GEM stack installed behind HGCAL (complex environment)
  - 2 $x$ 18 stacks (20°) covering $2.0 < \eta < 2.8$

- Requirements:
  - 97% module efficiency
  - $< 500\mu$rad resolution
  - 8-10 ns time resolution
  - $\leq 15\%$ gain uniformity
  - Work in high rate environment: 50kHz/cm$^2$
  - Survive harsh radiation environment: 280mC/cm$^2$
  - Discharge rate that does not impede performance or operation

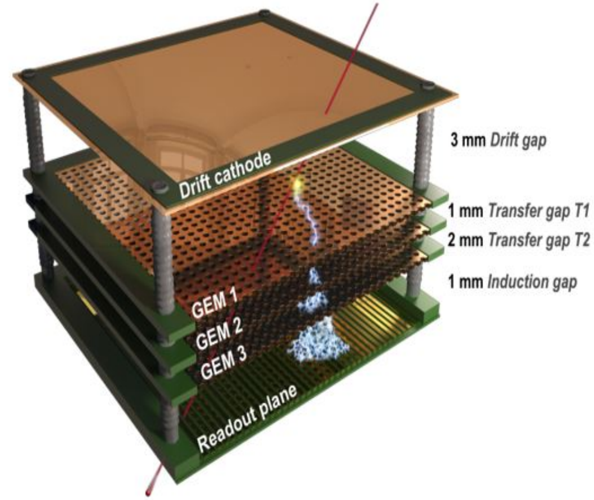
# CMS 端盖μ子探测器 GEM




GEM 微孔膜结构




在电场中的气体放大机制




三层膜GEM探测器结构

GEM工作机制：

粒子射入探测器，在漂移区产生的电离电子在电场作用下，穿过多层强电场微孔膜，在收集电极产生级联放大的信号。

GEM: Gaseous Electron Multiplier (气体电子倍增器）

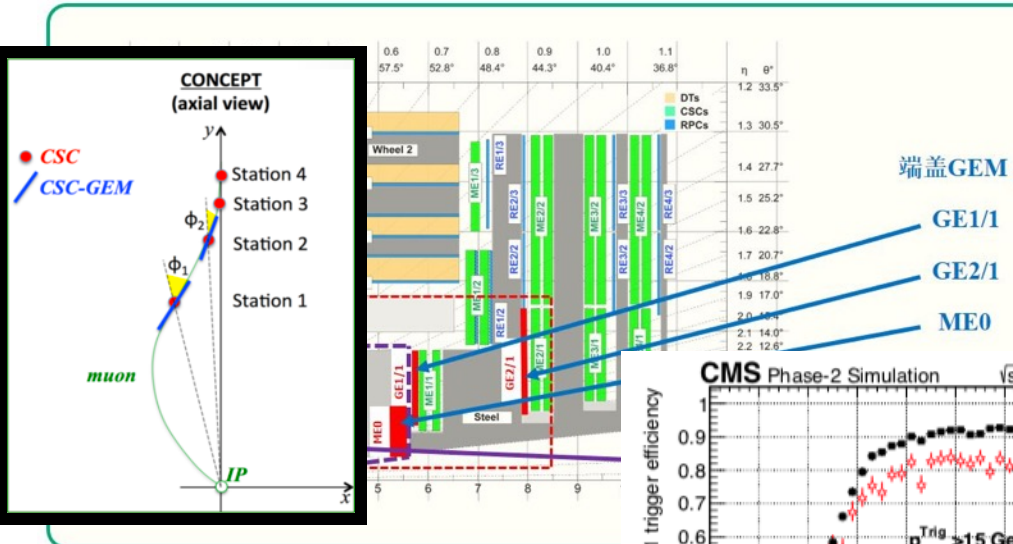
- CMS内圈μ子探测器工作在极强辐照环境中，将采用GEM（气体电子倍增器）技术。优点：结构简单，时间、空间、计数率性能优异。

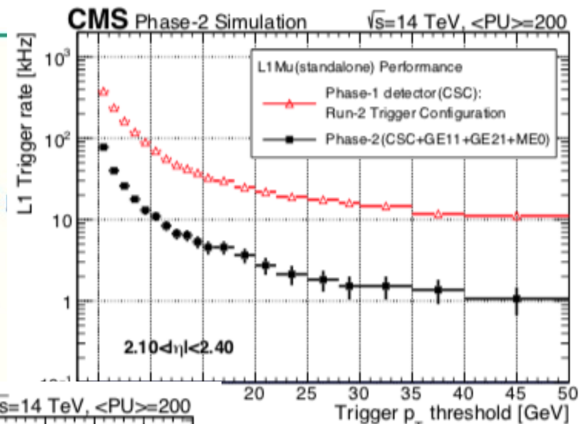
→大面积GEM技术在高能对撞实验中的首次大规模应用

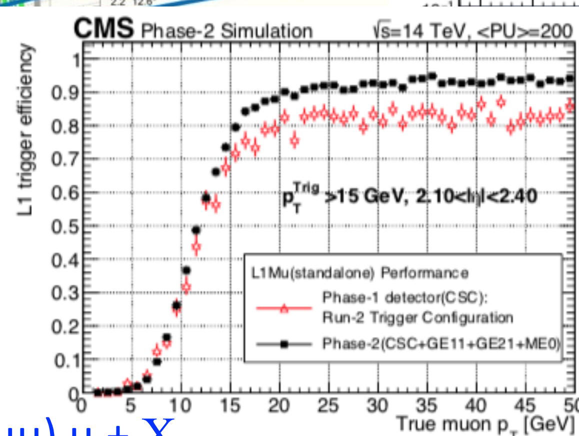
# CMS-GEM性能与未来物理研究

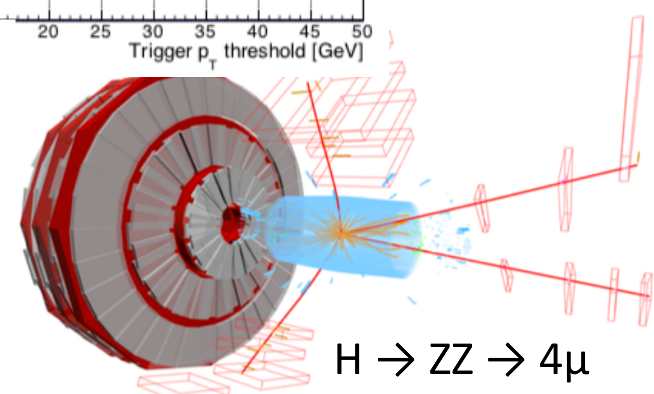
- CMS-GEM不仅提供触发，且高空间分辨能力可提供μ子径迹重建。

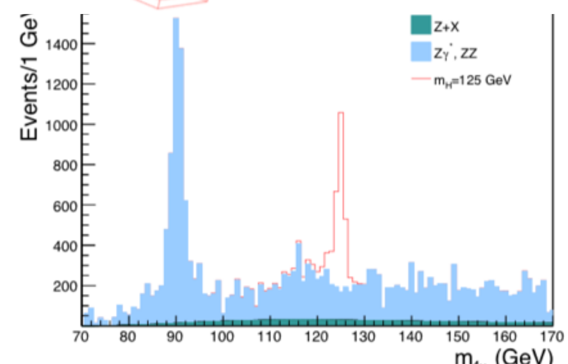
→保证高亮度运行时μ子触发效率，且大大提高新物理发现潜力



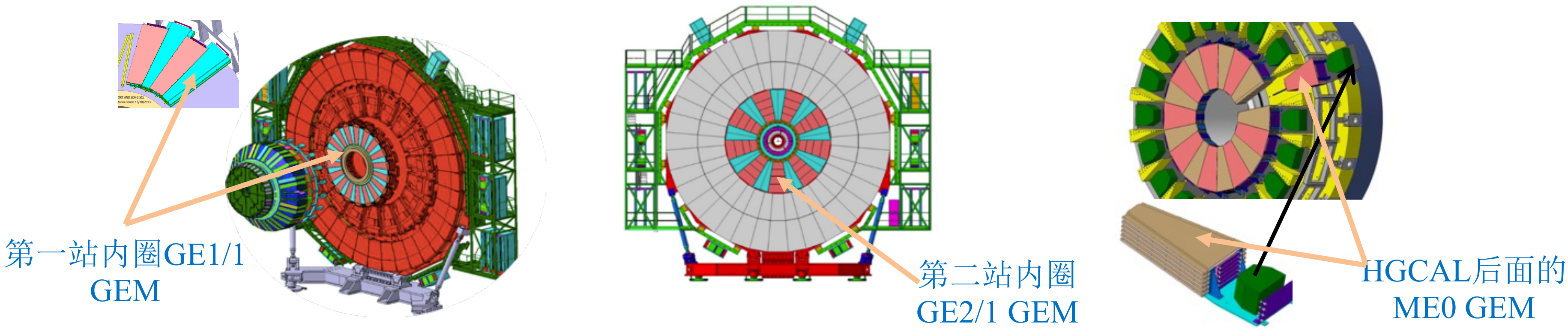




改善多μ子末态重要物理：

- H → ZZ → 4μ，H → 2μ
- Top quark mass in t → J/ψ(μμ) μ + X
- Double-parton scattering in pp → W+W+
- $B_{(s)}$→ μ μ, LFV decays τ → 3μ
- Precise electroweak mixing angle with Drell-Yan events
- BSM with two SS leptons, displaced muons, HSCP

# CMS-GEM探测器分阶段项目与中国组贡献



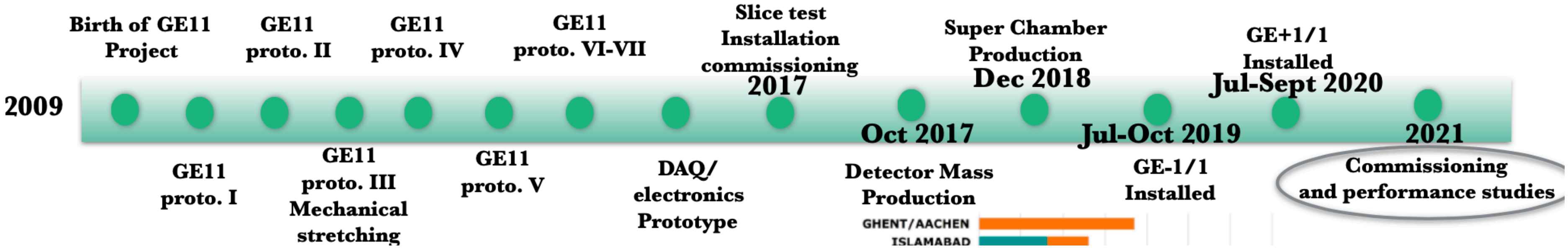

| 升级探测器 | | GE1/1 | GE2/1 | ME0 |
|---|---|---|---|---|
| 探测器个数* | | 288（=2×36×4） | 288（=2×18×8） | 216（=2×18×6） |
| **计划** | 预研 | 2013-2017 | 2014-2022 | 2014-2023 |
| | 批量生产 | 2017-2019 | 2022-2028 | 2024-2026 |
| | 安装调试 | 2018-2021 | 2029-(?) | 2027-2029 |
| **中国组任务** | | 全部前端电子板GEB生产测试，在CERN的探测器组装测试、安装调试 | 设计研发及生产测试全部GEB，在北大生产1/8 GEM探测器，在CERN进行组装测试、安装调试 | 设计研发及生产测试全部GEB，在北大生产~1/5 GEM探测器，在CERN进行组装测试、安装调试 |

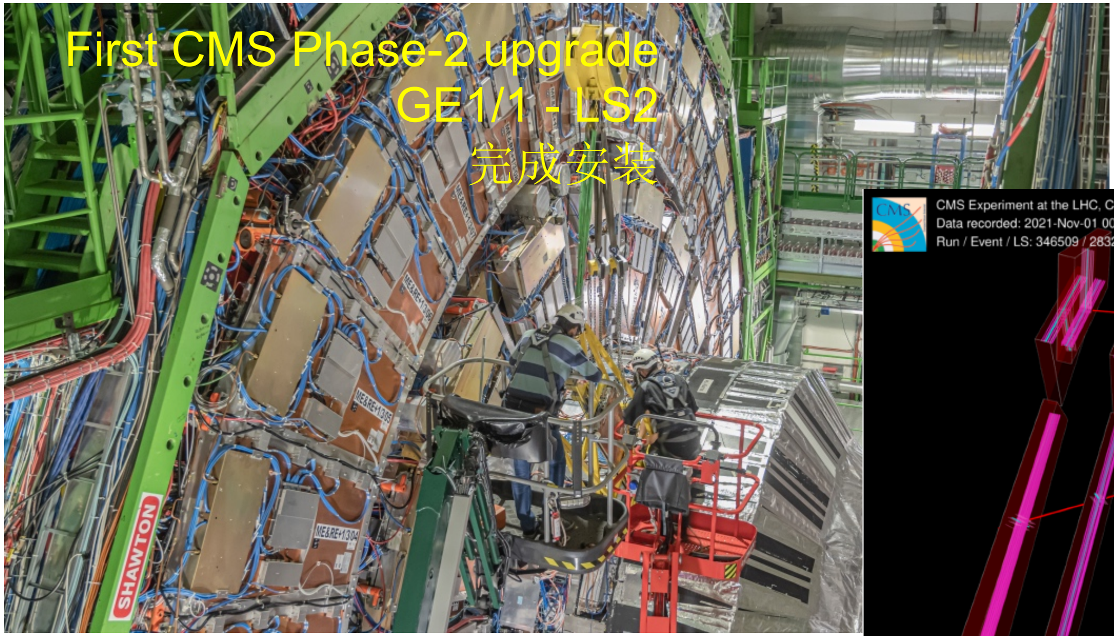
*（总探测器个数=端部数×每个端部module数×每个module探测器个数）

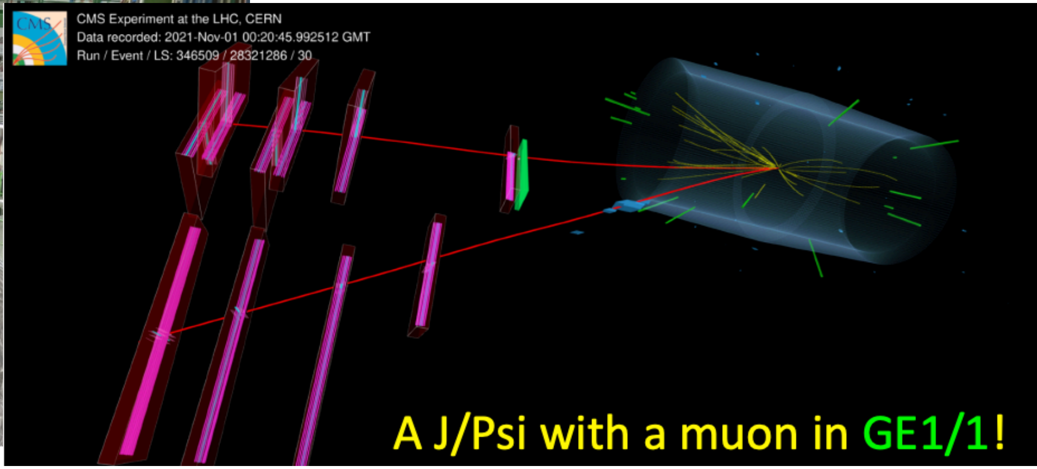
中国组还将负责GEM-FR4框架和超级模块结构部件生产

# GE1/1 探测器已经成功运行

NIMA 972 (2020) 164104



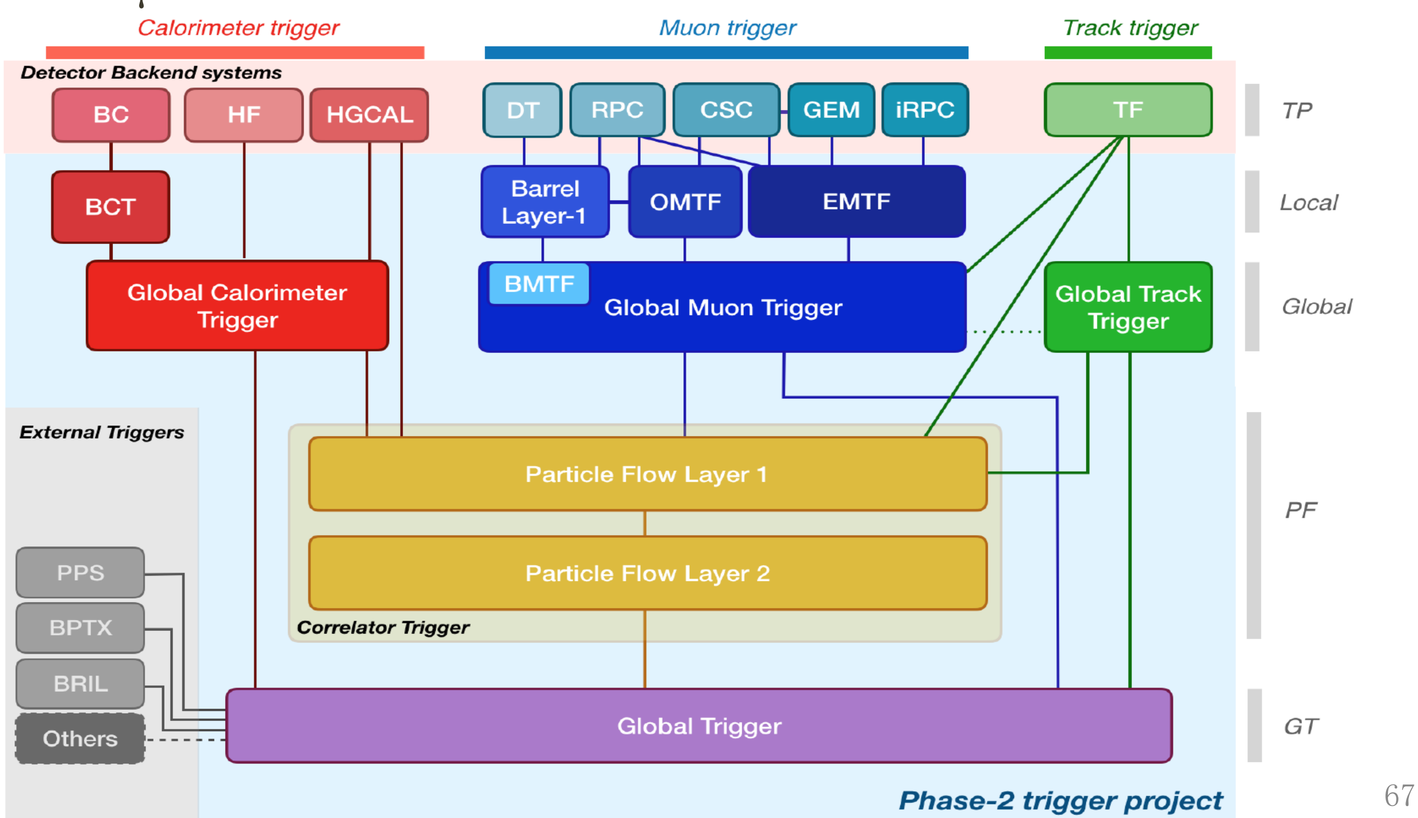



# Phase-II trigger upgrade

- Retain two-level trigger approach
  - ✓ Level-1 + High-Level Trigger
- L1 Key parameters
  - ✓ Rate: 100 kHz ⟶ 750 kHz
  - ✓ Latency: 3.8 µs ⟶ 12.5 µs
- Inputs
  - ✓ Calorimeters
  - ✓ Muon System
  - ✓ Outer Tracker

**Four independent trigger processing paths**

- ✓ Sophisticated FPGA-based algorithms: using particle-flow (PF) or ML approaches.
- ✓ Increase trigger acceptance&physics sensitivity, while maintaining Run-2 thresholds.
- ✓ Scouting into HL-LHC data @ 40 MHz: storing only high-level information



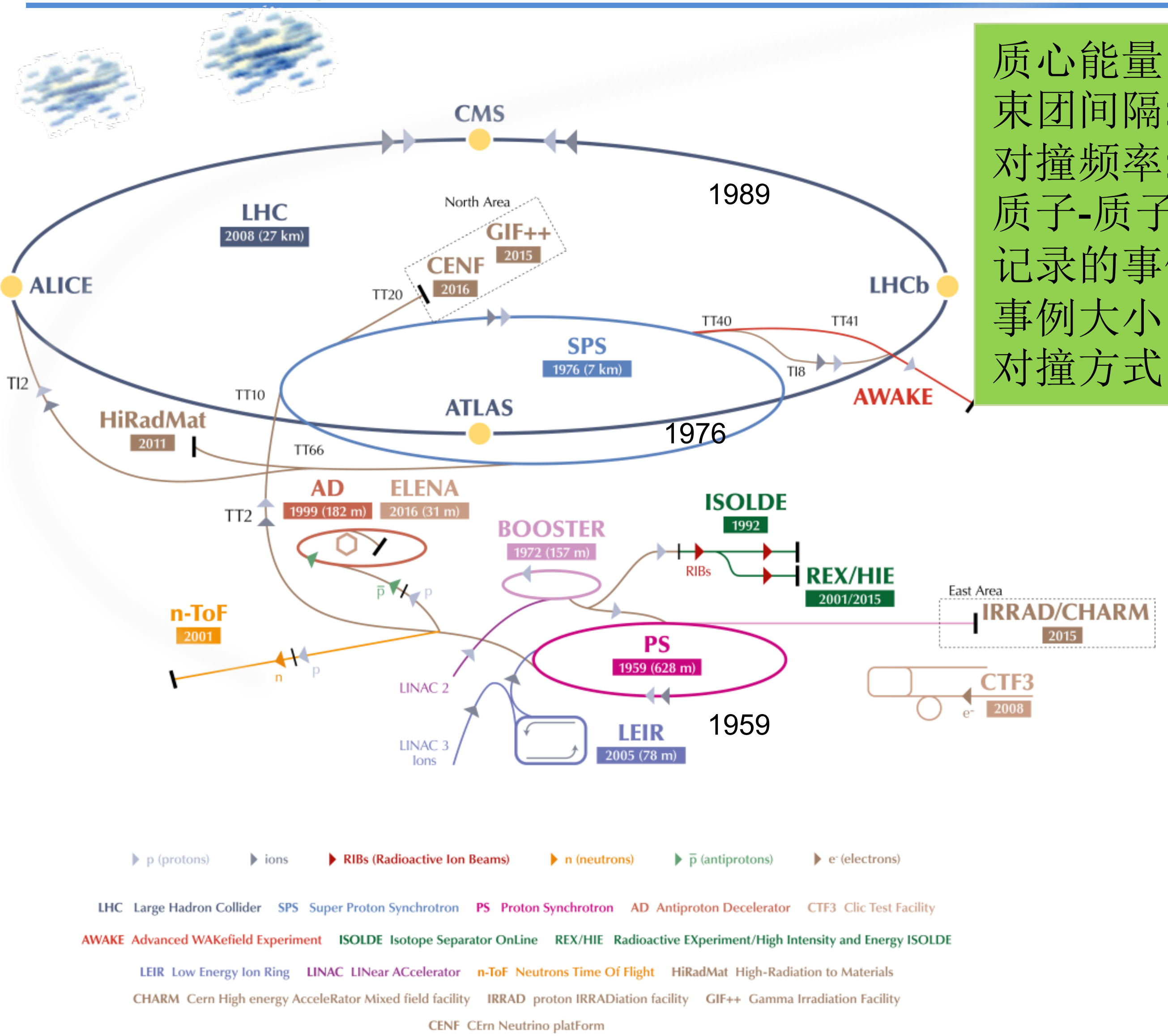
# Summary

- CMS detector (design, R&D, building, commissioning and operation) has been a great success story
- It laid down the basis of excellent physics results (>1300 publications after 15 years)
- To meet the challenges of HL-LHC and maintain physics potential, CMS needs Phase-II upgrade，with important contributions from CMS-China
  - MTD, HGCAL, GEM, PRC electronics

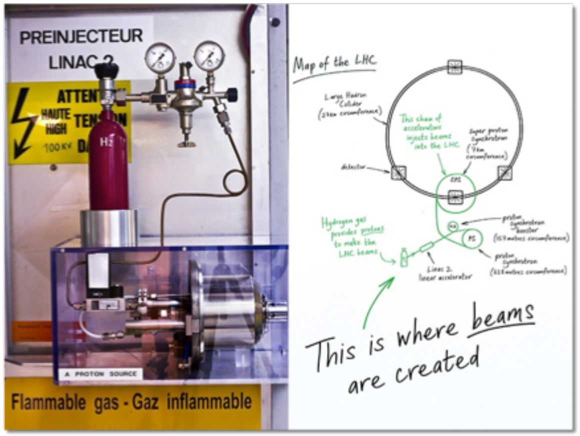
***Let us Build the future for CMS***

# 附录

# LHC 加速器参数




质心能量： 0.9,2.36,7,8,13/13.6 TeV
束团间隔: 50 - 25 纳秒 (bunch train)
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

# 量能器:全吸收与取样型

## Homogeneous

- Advantages
  - See all charged particles in the shower → best statistical precision (lowest stochastic term)
    ➔ minimizes detector contribution to measured particle widths
  - Same response from everywhere → good linearity (in principle)
- Disadvantages
  - Limited segmentation
  - Relatively high cost
- Examples
  - Flavor factories (small γ energies): KLOE, BESIII, CLEO_c, Belle(II), Babar
  - OPAL, Delphi, L3 (LEP)
  - ALICE PHOS & CMS ECAL

## Sampling

- Advantages
  - Relatively low cost
  - Transverse & longitudinal segmentation possibilities
    ➔ can significantly help to suppress background
- Disadvantages
  - Only part of the shower is seen → higher stochastic (sampling) term
- Examples
  - Aleph ECAL (LEP)
  - LHCb & ATLAS ECALs
  - All HCALs so far

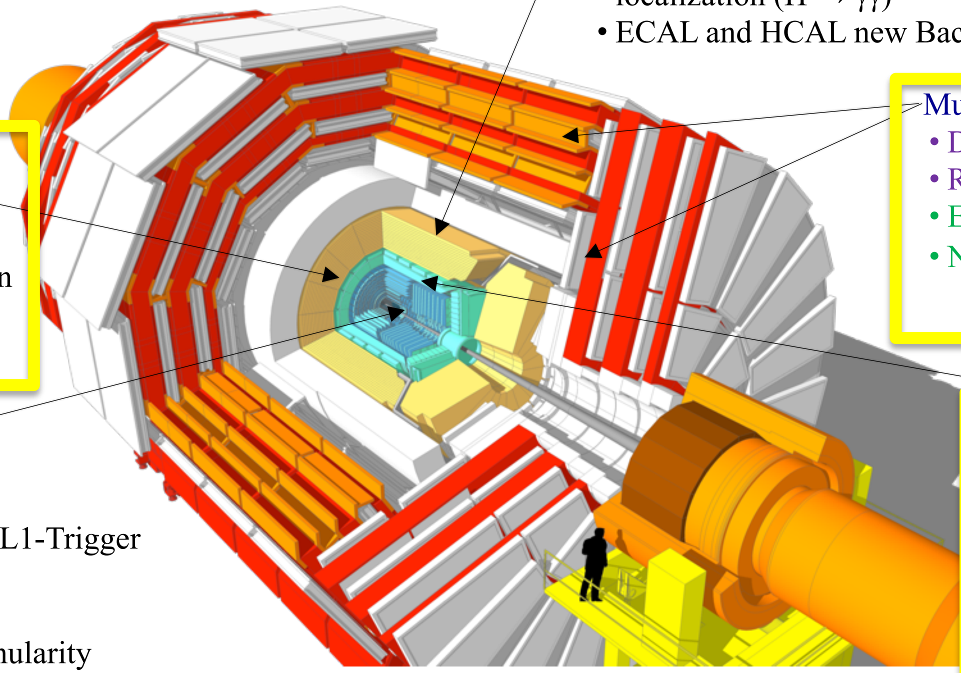
# CMS Phase-II upgrade

Replacements of existing system
Electronics upgrade/replacement
New detector

L1-Trigger/HLT/DAQ
- Tracks in L1-Trigger at 40 MHz
- PFlow-like selection 750 kHz output
- HLT output 7.5 kHz

Barrel Calorimeters*
- ECAL crystal granularity readout at 40 MHz
- Precision timing for e/γ at 30 GeV, for vertex localization ($H \rightarrow \gamma\gamma$)
- ECAL and HCAL new Back-End boards

Calorimeter Endcap
- 3D showers imaging for pattern recognition
- Precision timing for PU mitigation
- Si, Scint+SiPM in Pb/W-SS



Muon systems
- DT & CSC new FE/BE readout
- RPC back-end electronics
- Extended GEM coverage to $\eta \simeq 3$
- New GEM/RPC $1.6 < \eta < 2.4$

Tracker
- $P_T$ module design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$
- Much reduced material budget
- Si-Strip and Pixels increased granularity

MIP Timing Detector
- Precision timing for PU mitigation
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

Projects with major CMS-China contributions

# 中国组参加探测器升级的意义

## 重要升级系统

硅径迹探测器、μ 子探测器、量能器和相关电子学和事例触发等

## 采用新一代粒子探测技术

- 大面积的抗辐照、高空间分辨硅探测器
- 大面积、高计数率、高效率的新型μ 子探测器
- 高粒度高能量分辨量能器
- 高致密度ASIC 芯片
- 先进事例触发、数据获取与计算技术

→代表当今世界探测技术最前沿，可以跟踪掌握这些技术、打破禁运、推动我国在这些关键材料、技术和方法的发展，并辐射至其他领域。

→人才培养和个人发展

# 选择题

1. CMS超导螺线管磁铁在正常运行时储能多少？
   A. $2.6x10^9$J
   B. $2.6x10^{10}$J
   C. $2.6x10^{11}$J
   D. $2.6x10^{12}$J
2. 目前的CMS缪子探测器使用了几种探测技术？
   A. 2 种
   B. 3 种
   C. 4 种
   D. 5 种