High luminosity frontier experiments (LHC)

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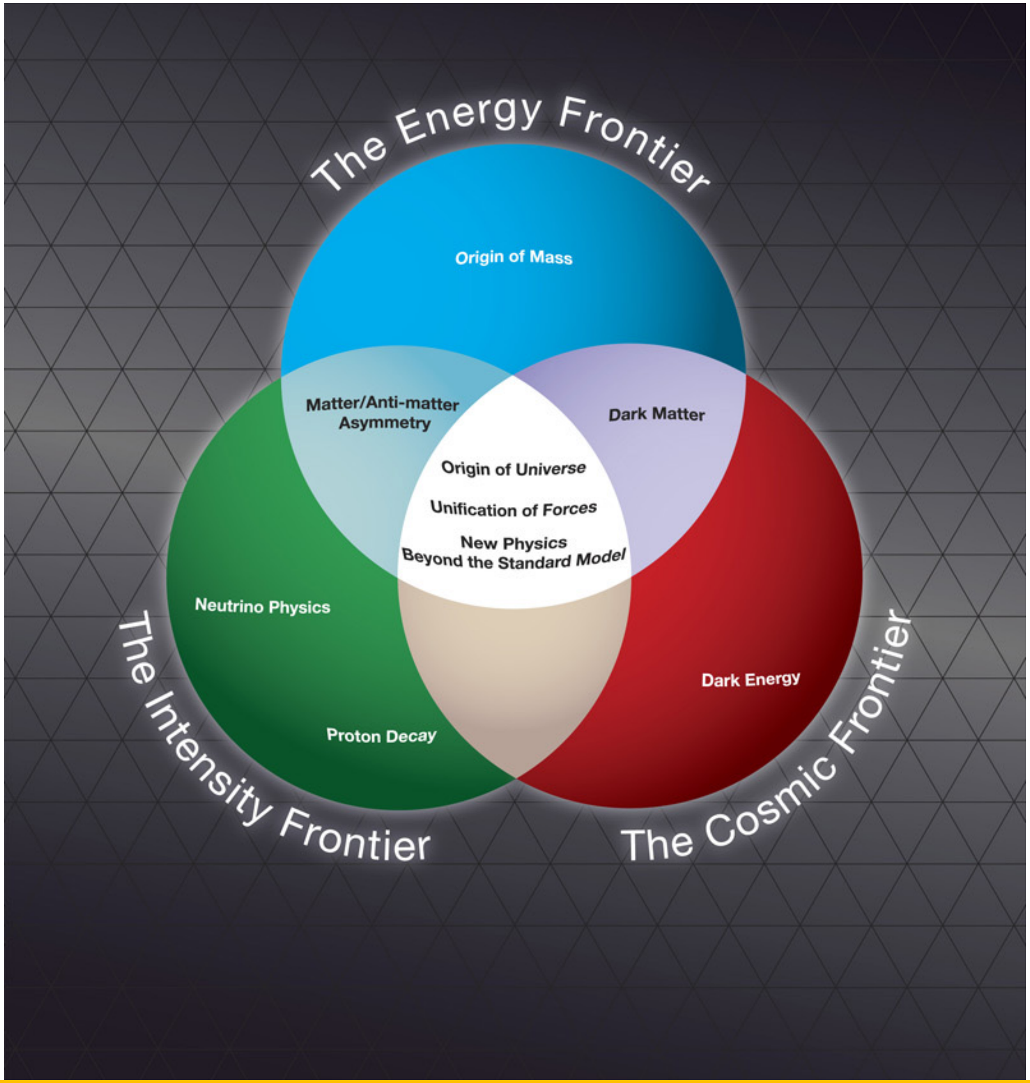
Content of this lecture

Lecture 1: physics motivation
Lecture 2: Detector

Not covered:
*reconstruction
*physics analysis
…



https://science.osti.gov/hep/About/Vision-for-HEP

大型强子对撞机（LHC）

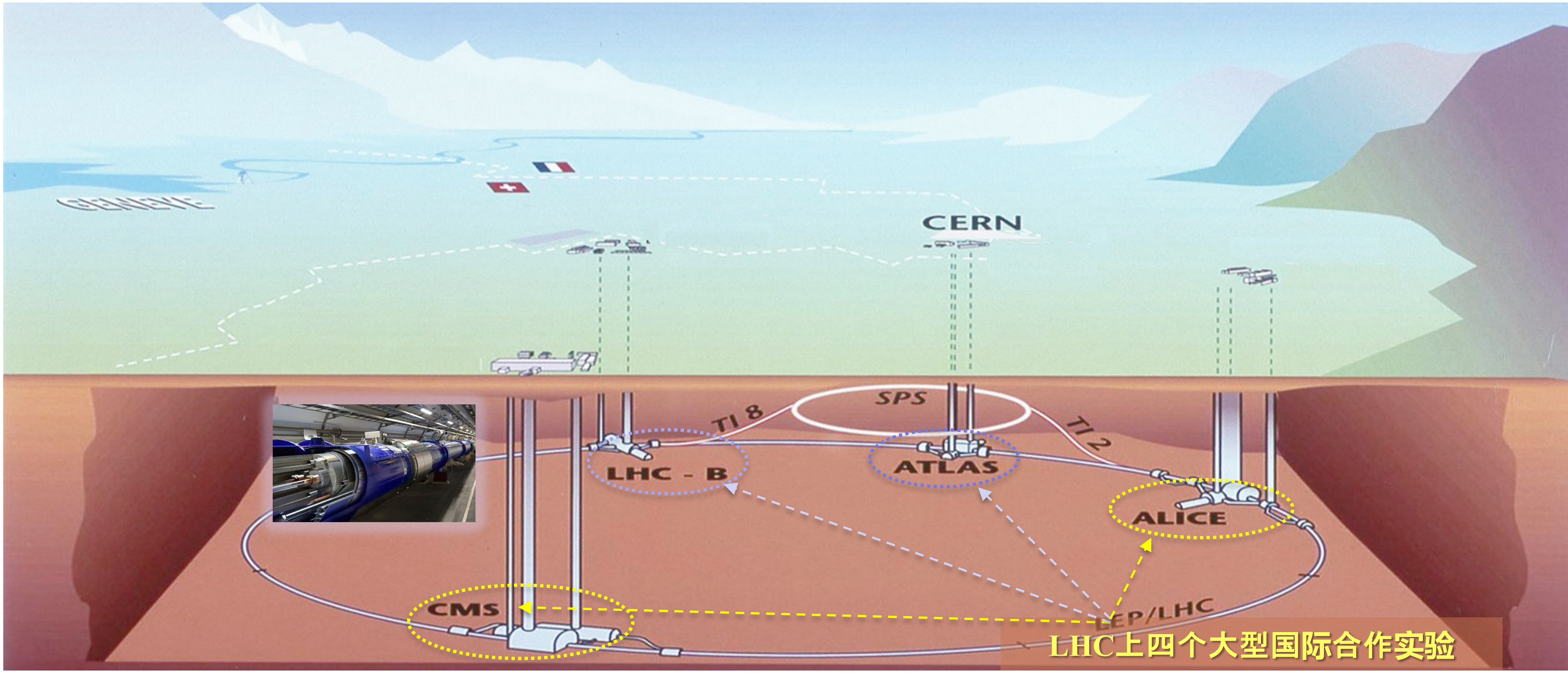
➢ **物质世界的根本问题：**

● 基本粒子质量起源？	● 标准模型是否准确？	● CP破坏怎么发生的？	● 超对称粒子是否存在？
● 暗物质是否存在？	● 早期宇宙物质特性如何？	● 额外维度是否存在？	● ……

➢ **研究手段：世界最高能量<u>对撞机LHC</u>：**

➢ ***p-p*对撞质心能量14TeV，隧道周长~27 公里，地下深度 ~100 米**

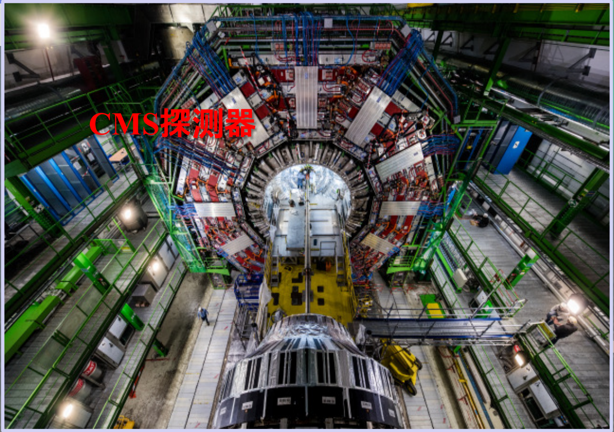
欧洲核子中心（CERN）



LHC上的大型粒子物理实验

大型粒子物理国际合作实验：

- 全球多国家、多学科合作，投资巨大，技术最先进
- 最深层物质世界研究，最先进成果

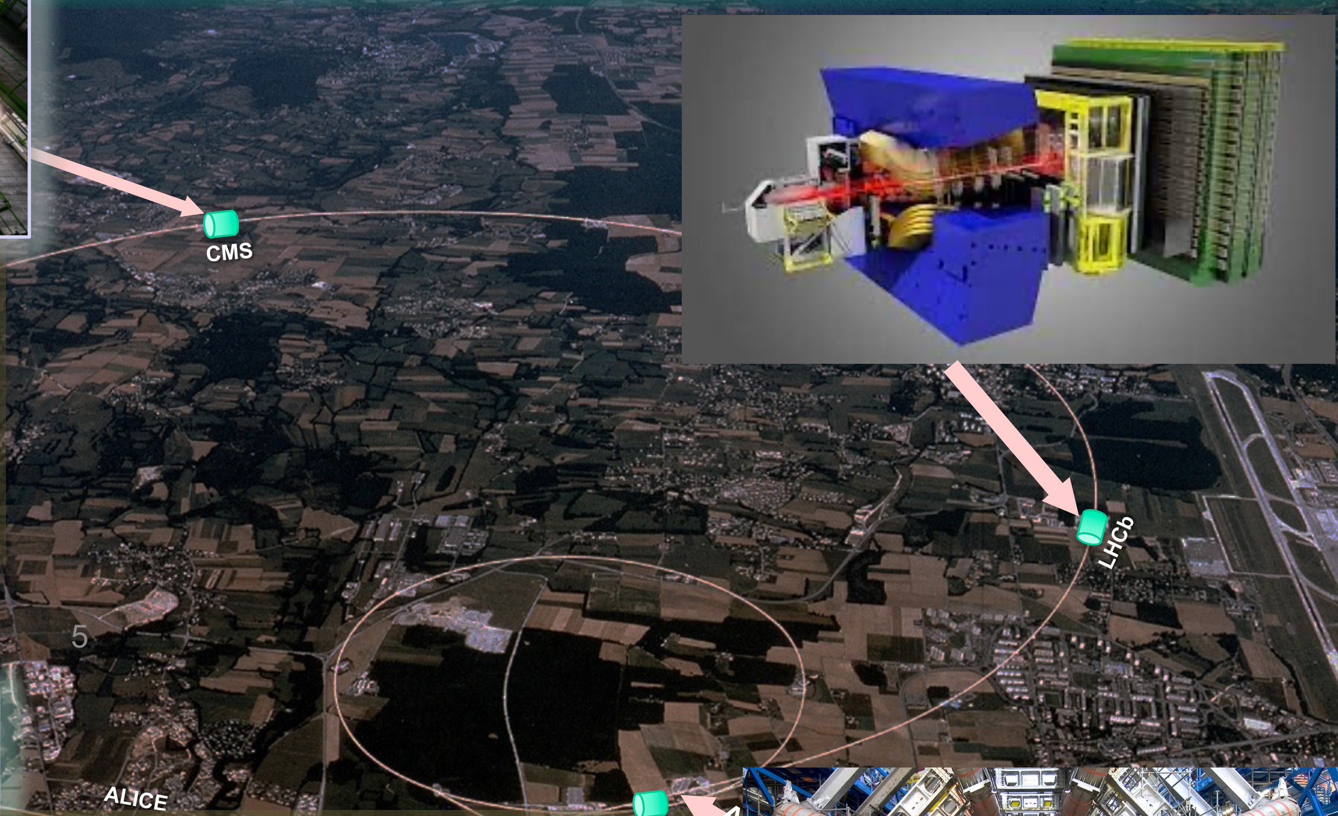


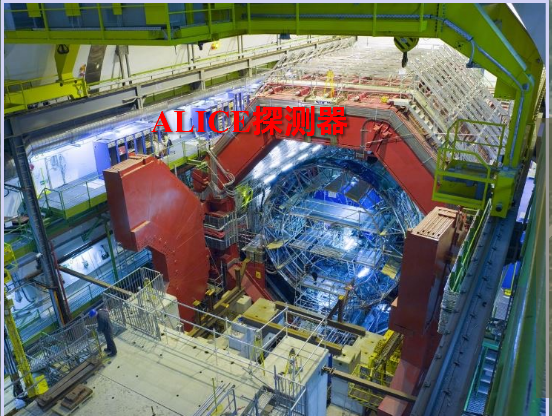
物理目标：

希格斯粒子性质研究，精确检验标准模型，寻找新物理…

国际合作组：

~40个国家，~200个大学和研究机构，~4000名科学家和工程技术人员





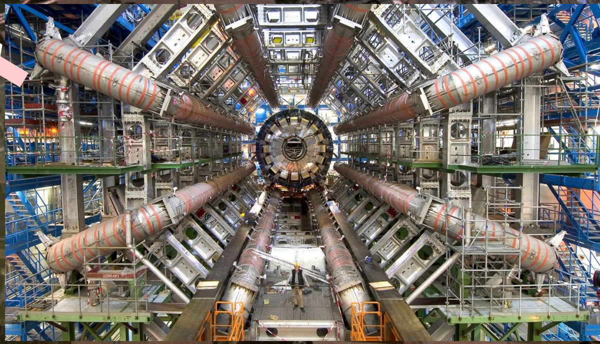
物理目标：

宇宙早期物质形态，夸克胶子等离子体性质…

国际合作组：

40个国家，172个大学和研究机构，

2000名科学家和工程技术人员



高能量/亮度前沿的主要实验设施

Z粒子等精确测量

欧洲 LEP

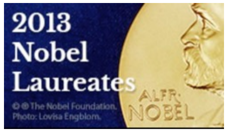
顶夸克

美国 Tevatron

上帝粒子

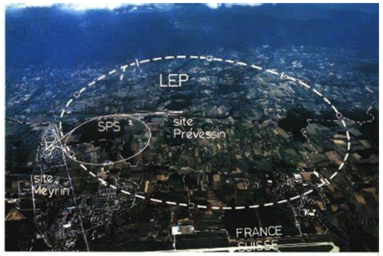
欧洲 LHC

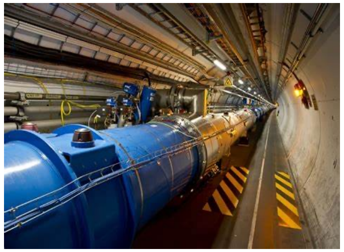
未来对撞机（中国/欧洲/日本）

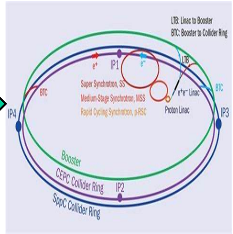


希格斯粒子精确测量

1980 2000 2020 2040



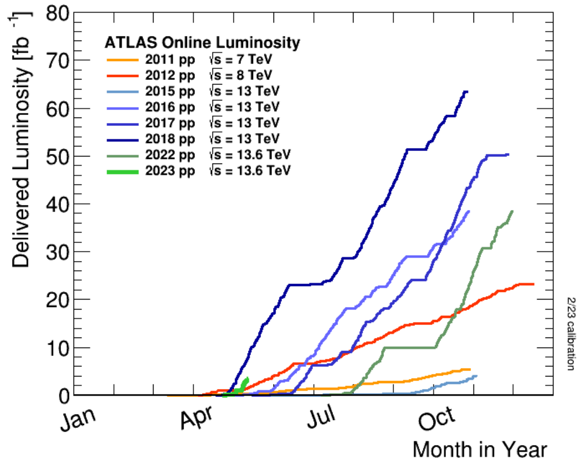


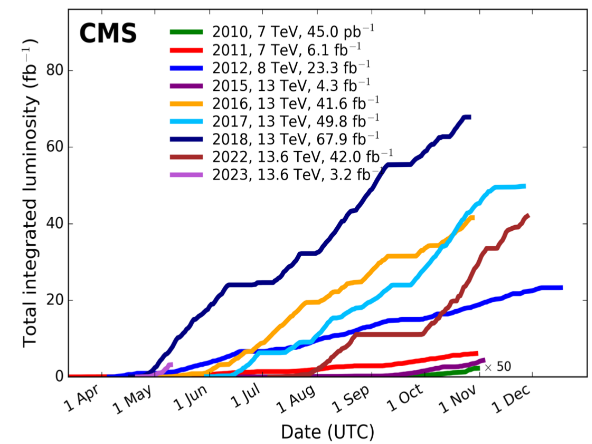


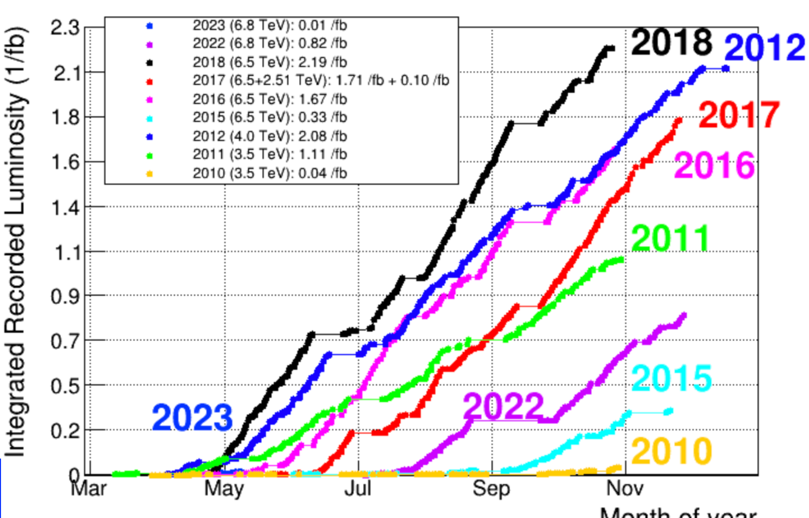
LHC运行情况

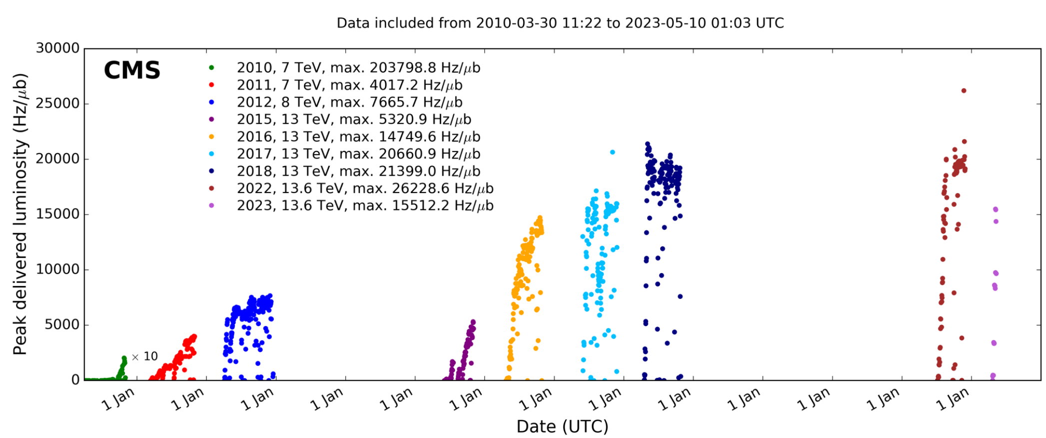
ATLAS Run-3 Detector Status (from May 2023)

Subdetector	Number of Channels	Approximate Operational Fraction
Pixels	92 M	95.3%
SCT Silicon Strips	6.3 M	98.4%
TRT Transition Radiation Tracker	350 k	94.9%
LAr EM Calorimeter	170 k	100%
Tile Calorimeter	5200	99.5%
Hadronic End-Cap LAr Calorimeter	5600	99.9%
Forward LAr Calorimeter	3500	99.8%
LVL1 Calo Trigger Legacy	7160	99.7%
LVL1 Calo Trigger Phase I	7160	100%
LVL1 Muon RPC Trigger	383 k	99.8%
LVL1 Muon TGC Trigger	312 k	100%
MDT Muon Drift Tubes	344 k	99.7%
MicroMegas NSW	2.1 M	98.0%
STGC NSW	358 k	95.0%
RPC Barrel Muon Chambers	383 k	90.1%
TGC End-Cap Muon Chambers	312 k	99.3%
ALFA	10 k	100%
AFP	430 k	98%
AFP TOF	2x16	100%
LUCID	2x12+8	100%
ZDC	2x(4+16)	100%

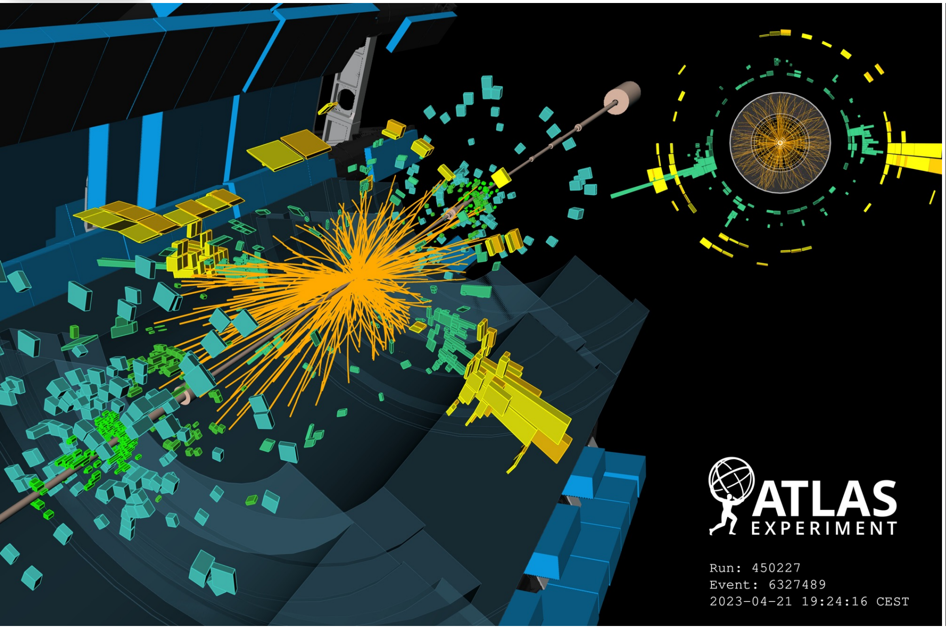


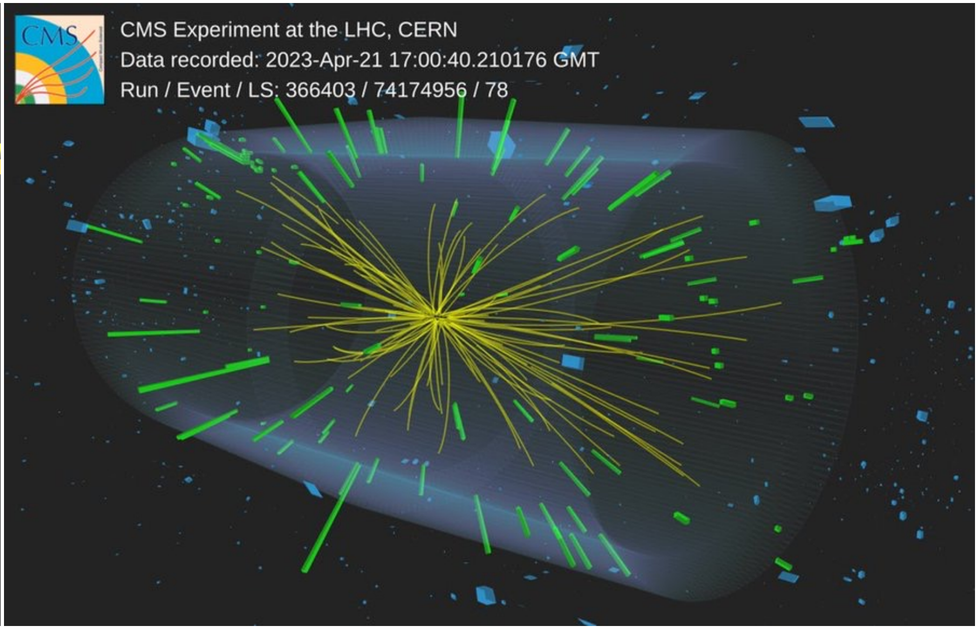


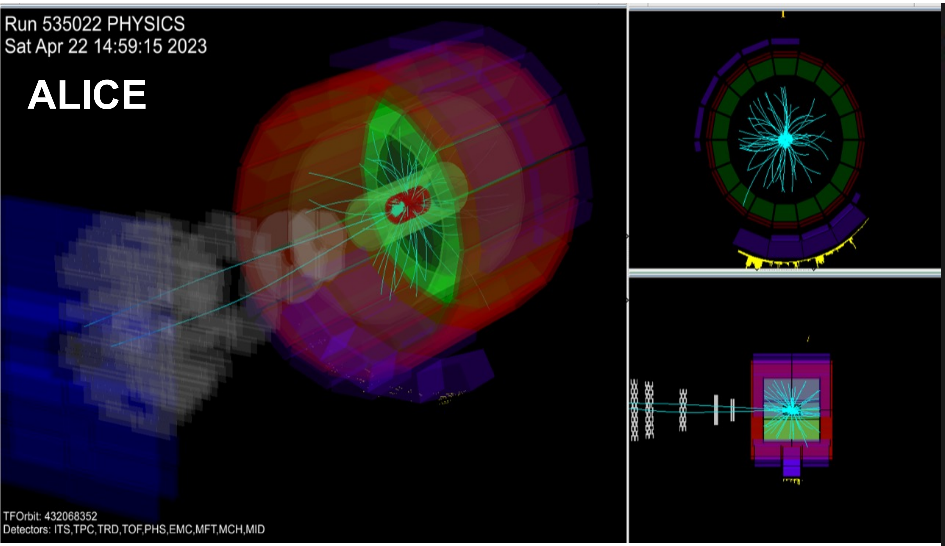


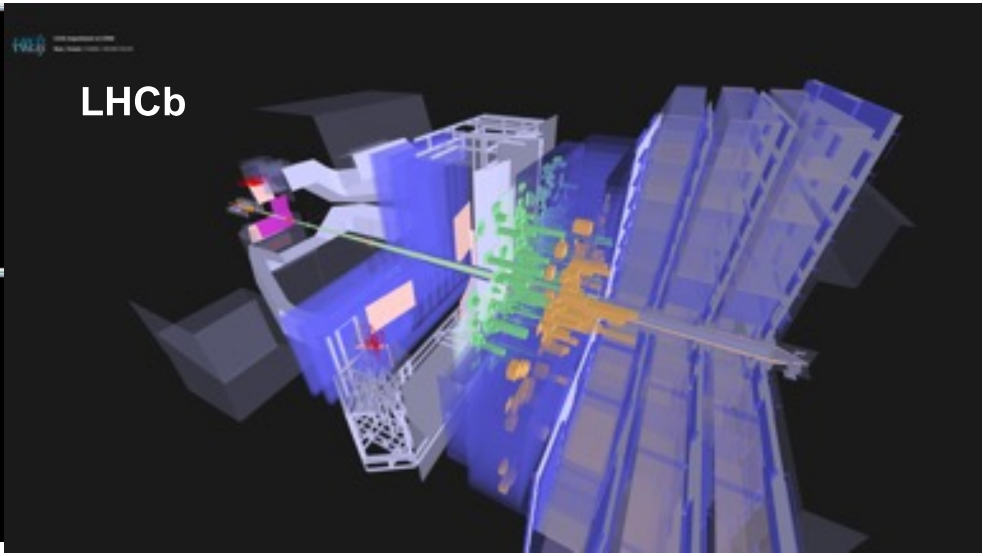


2023 Run started: First 13.6 TeV collisions Apr. 21



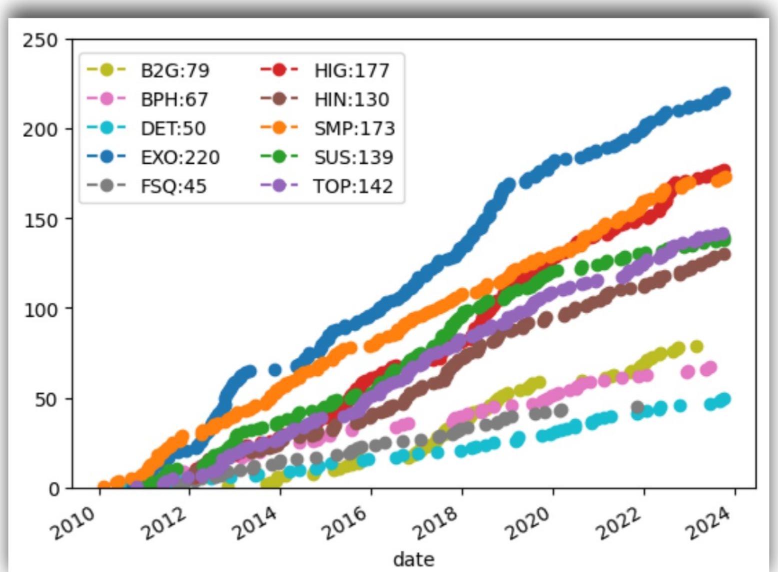


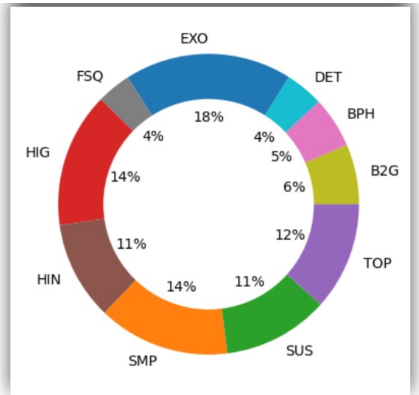


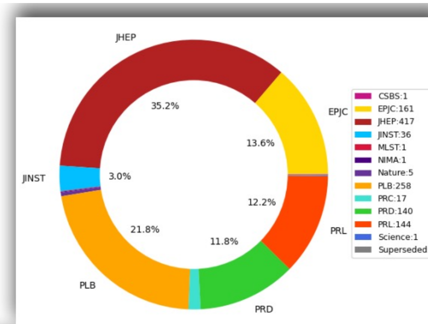


Publications ex. CMS experiment

1222 CMS papers based on collision data
1183 paper published (collision data)

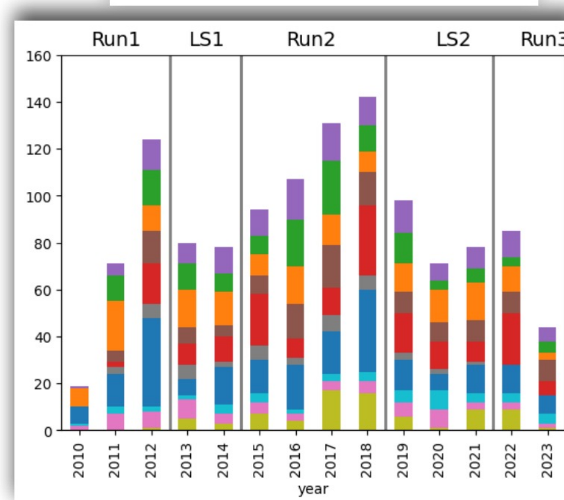






CMS titles
- 608 "Search"
- 56 "Observation"
- 21 "Evidence"
- 358 "Measurement"
- 45 "Study"

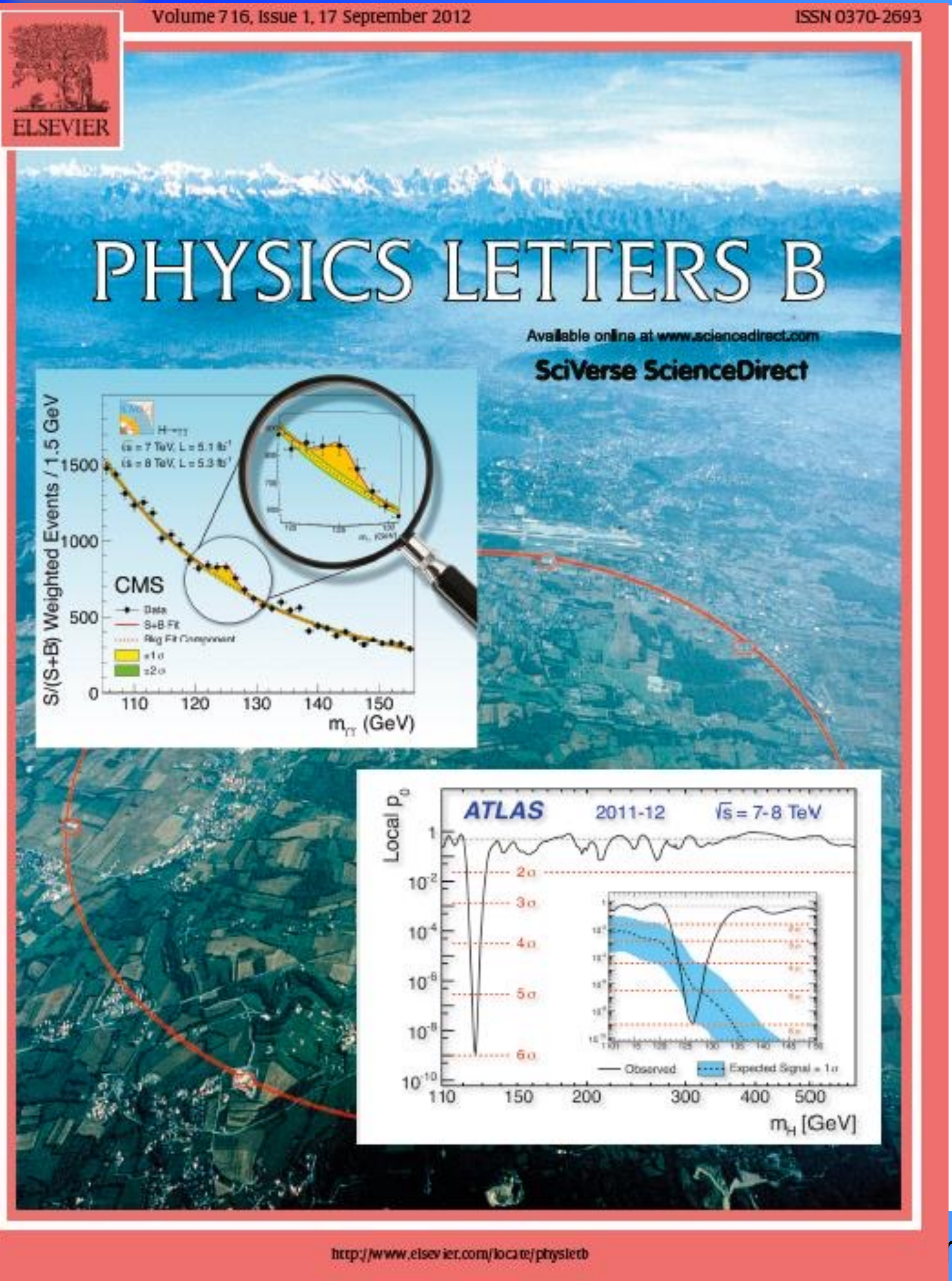
CMS with friends
- ATLAS: 6 (5 JHEP, 1 PRL)
- LHCb: 1 (Nature)
- TOTEM: 5 (1 JHEP, 3 EPJC, 1 JINST)

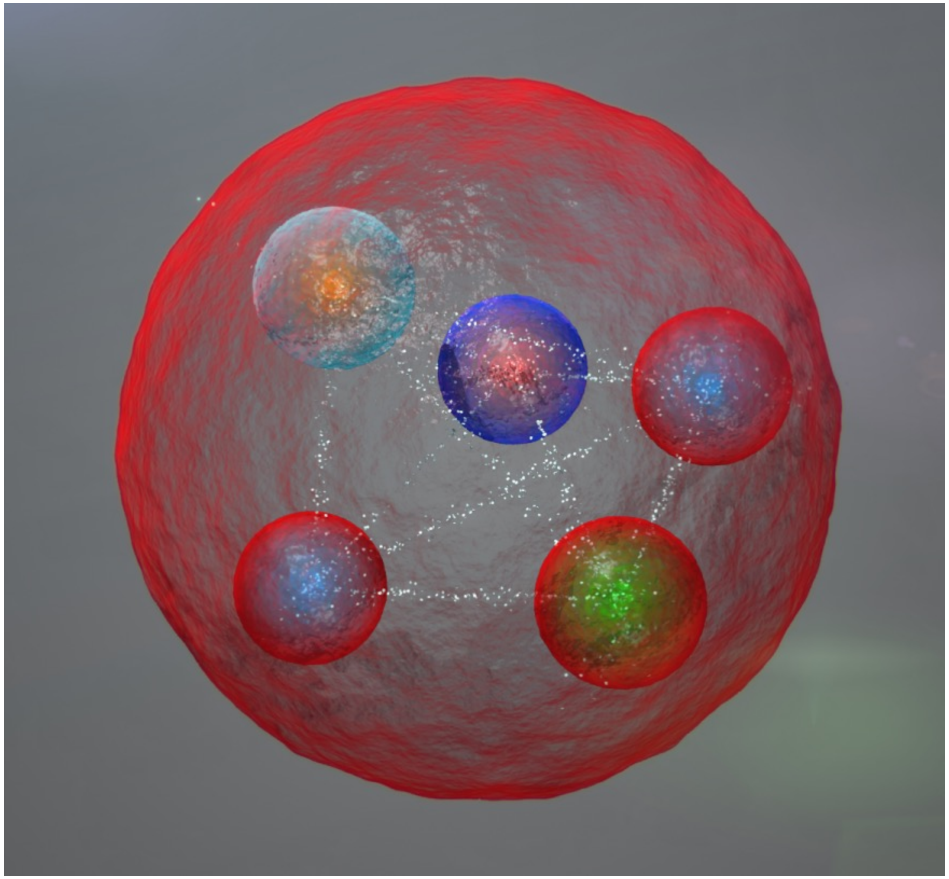


https://cms-results.web.cern.ch/cms-results/public-results/publications-vs-time/

ATLAS has similar publication profile
+ LHCb, ALICE

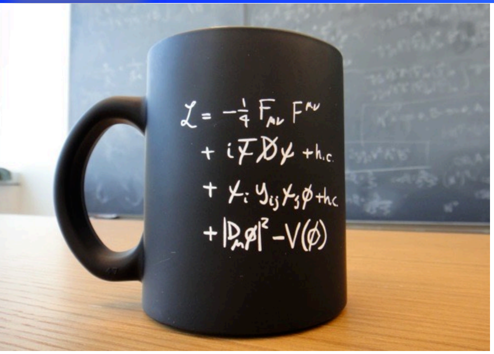
Selected highlights at LHC



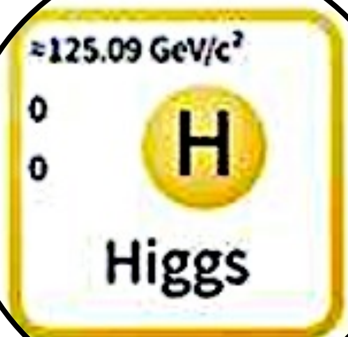


侧重介绍CMS/ATLAS实验

Higgs Physics opportunity at LHC



Higgs Boson: Origin of mass



Measurement of Higgs Mass, Width, CP etc

Couple to Bosons

- Higgs Mechanism
- Observed in **2012** when discover H

2013 Nobel Price

Couple to Fermions

- **Fifth force**
- **2018 observe couple to 3rd gen.**

Highlights of the Year

December 17, 2018 • *Physics* 11, 129

Physics picks its favorite stories from 2018.

Self Coupling

- **Sixth Force**
- HL LHC 2035

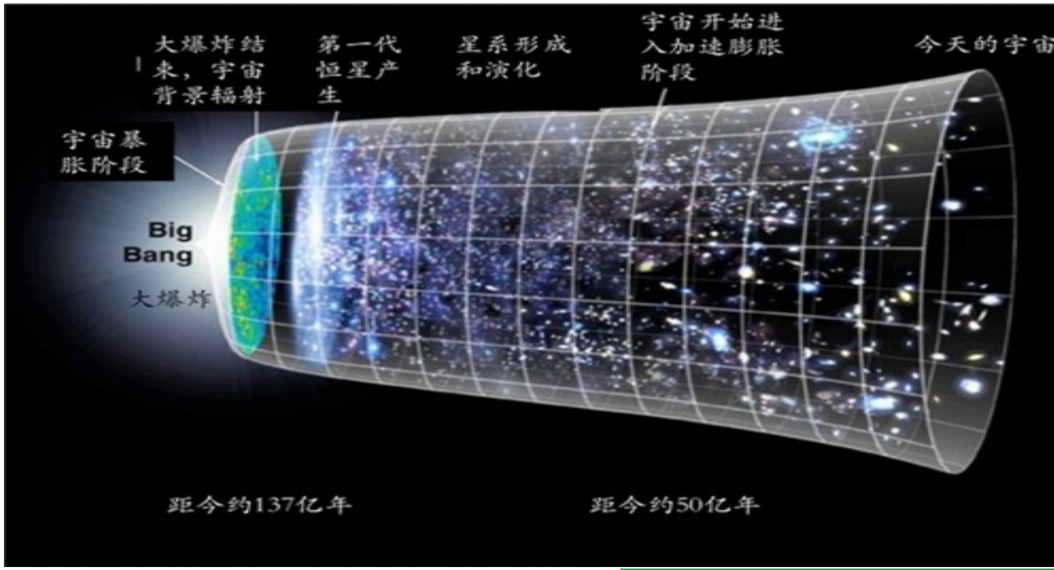
Is there PT

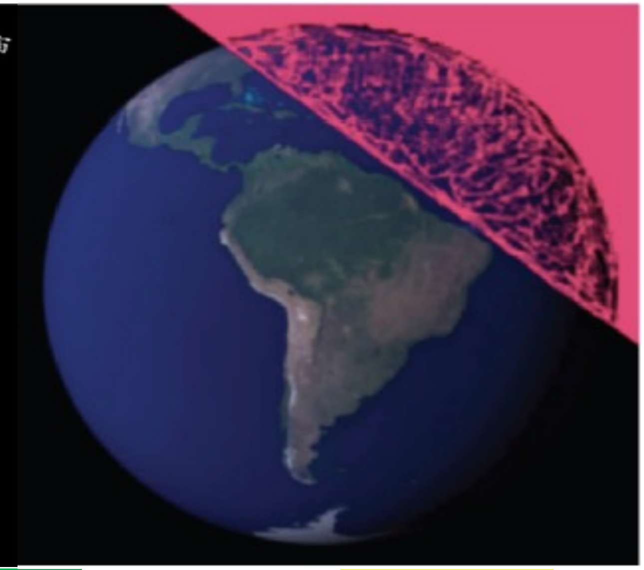
p-p collision can not be extreme acc.

CEPC ilc FCC hh ee he

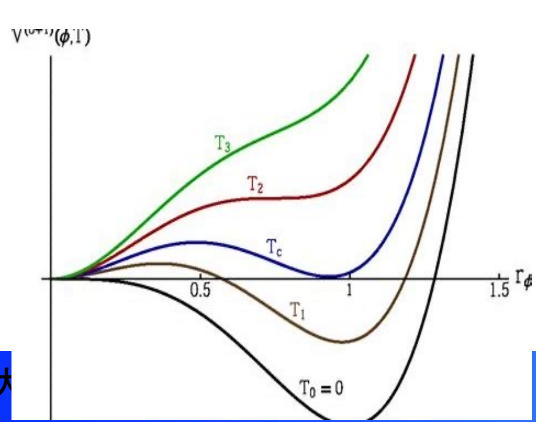
Why Higgs Properties/couplings so import

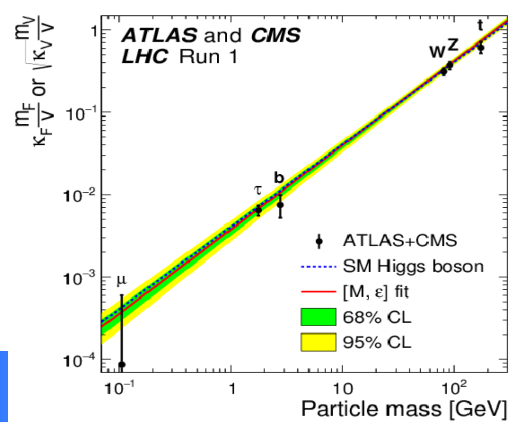
- Higgs: Link the past, current, and future of universe

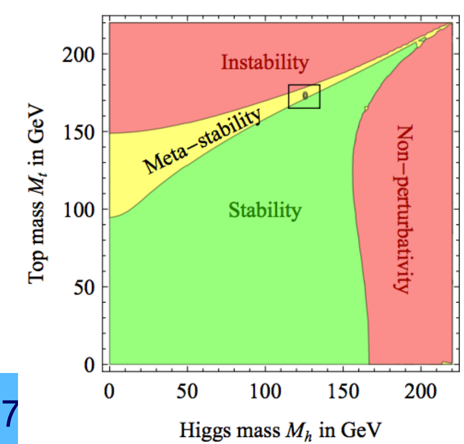




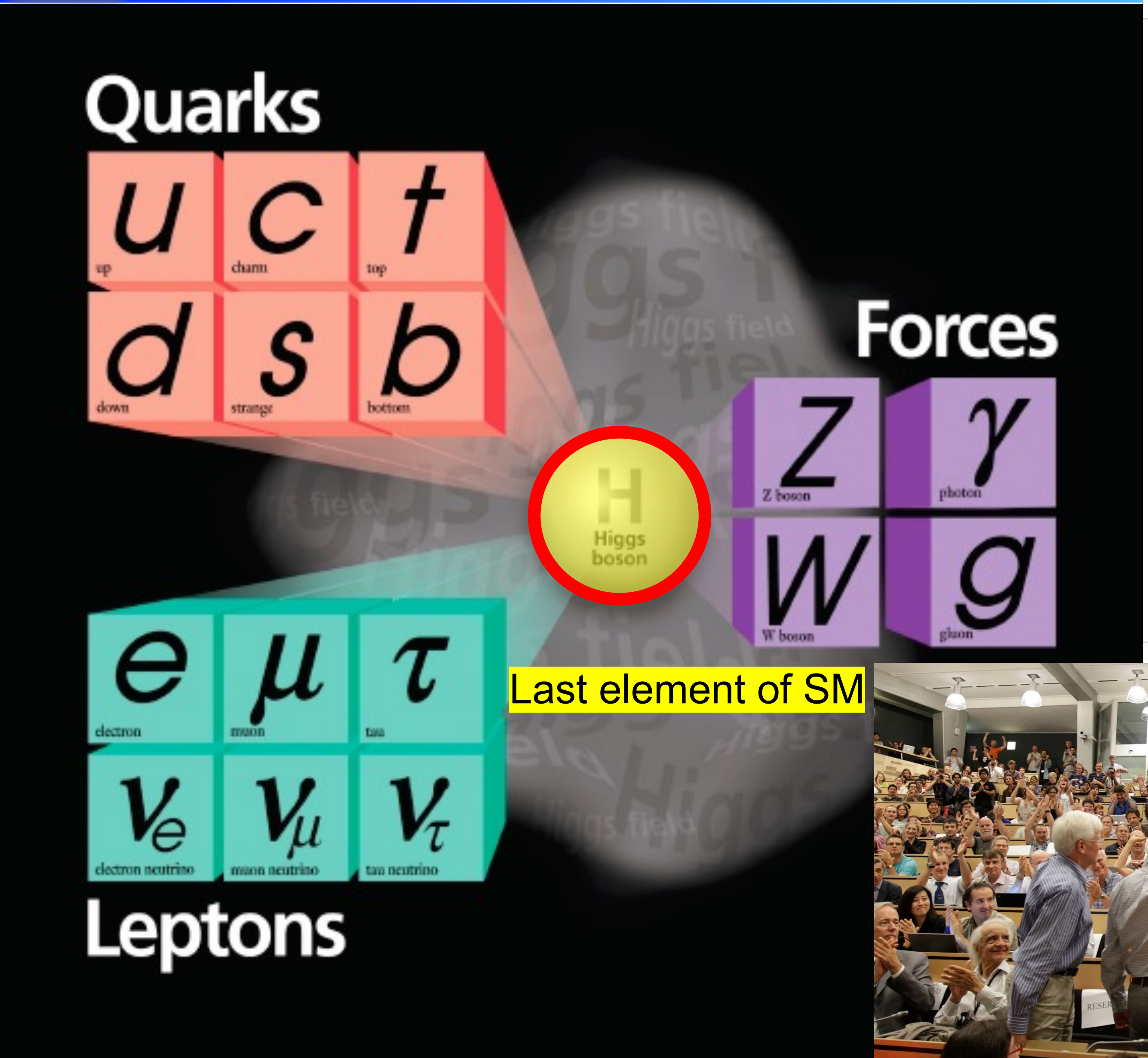
Phase Transition in early universe → Atom diameter；Mass of ele. particles → Vacuum Stability



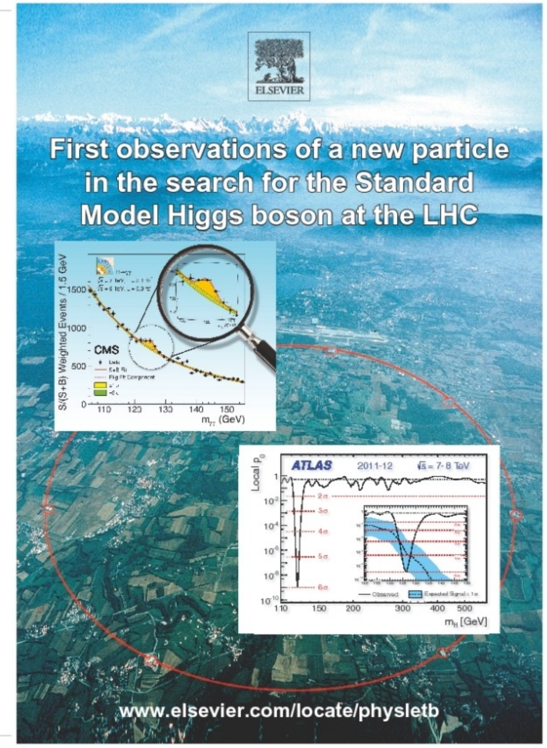




The Discovery of Higgs boson



Last element of SM



Observation of ttH production

4th June 2018, LHCP/PRL and others…

PHYSICAL REVIEW LETTERS

Observation of $t\bar{t}H$ Production

A. M. Sirunyan *et al.* (CMS Collaboration)
Phys. Rev. Lett. **120**, 231801 – P

Physics See Viewpoint: Sizing Up

Phys. Rev. Lett. 120, 231801

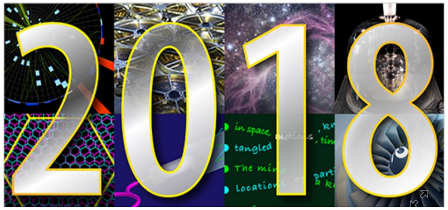
ABSTRACT

The observation of Higgs boson production in association with a top quark
based on a combined analysis of proton-proton collision data at center-of-
8, and 13 TeV, corresponding to integrated luminosities of up to 5.1, 19.7, a
The data were collected with the CMS detector at the CERN LHC. The resu
independent searches for Higgs bosons produced in association with a top
decaying to pairs of W bosons, Z bosons, photons, τ leptons, or bottom c
maximize sensitivity. An excess of events is observed, with a significance c
over the expectation from the background-only hypothesis. The correspon
from the standard model for a Higgs boson mass of 125.09 GeV is 4.2 star
combined best fit signal strength normalized to the standard model predict

Highlights of the Year

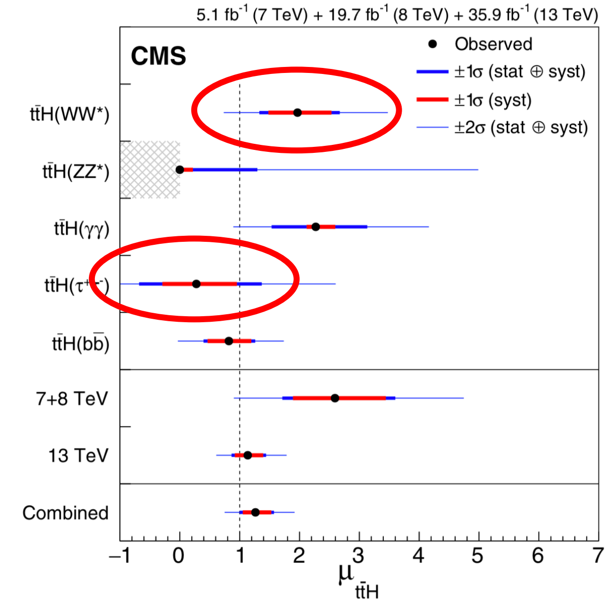
December 17, 2018 • *Physics* 11, 129

Physics picks its favorite stories from 2018.



The Higgs Shows up with the Heaviest Quarks

After detecting the Higgs boson in 2012, the next order of business was testing whether it behaves as expected. Two such experiments at CERN, which measured the interactions of the heaviest quarks with the Higgs, attained the gold standard of "5 sigma" statistical significance. Analyzing proton-proton collisions, CMS and ATLAS determined the interaction strength between the top quark and the Higgs boson by measuring how often the Higgs boson is produced with a top quark and a top antiquark (see Viewpoint: **Sizing up the Top Quark's Interaction with the Higgs**). The same collaborations later reported the first observation of the Higgs boson decaying into bottom quarks



Viewpoint: Sizing Up the Top Quark's Interaction with the Higgs

Matthew Reece, Department of Physics, Harvard University, 17 Oxford

Higgs boson comes out on top

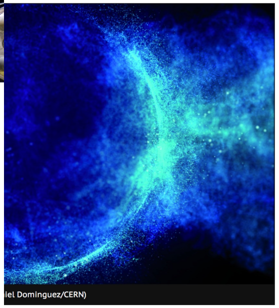
Media and Press Relations

The Higgs boson reveals its affinity for the top quark

04 Jun 2018

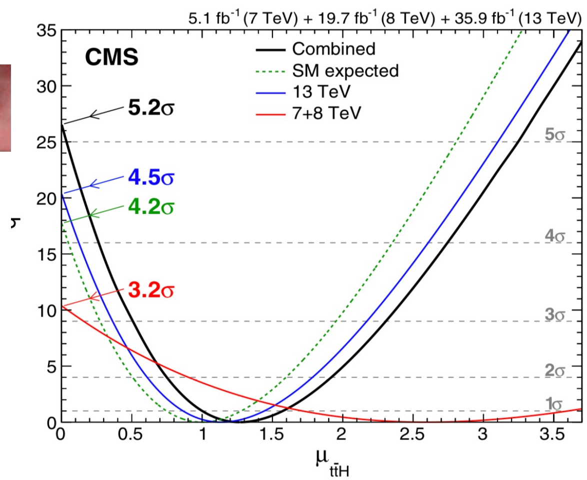
New results from the ATLAS and CMS experiments at the LHC reveal how strongly the Higgs boson interacts with the heaviest known elementary particle, the top quark, corroborating our understanding of the Higgs and setting constraints on new physics.

Geneva, 4 June 2018. The Higgs boson interacts only with massive particles, yet it was discovered in its decay to two massless photons. Quantum mechanics allows the Higgs to fluctuate for a very short time into a top quark and a top anti-quark, which promptly annihilate each other into a photon pair. The probability of this process occurring varies with the strength of the interaction (known as coupling) between the Higgs boson and top quarks. Its measurement allows us to indirectly infer the value of the Higgs-top coupling. However,



New results from the ATLAS and CMS experiments at the Large Hadron Collider (LHC) reveal how strongly the Higgs boson interacts with the heaviest known elementary particle, the top quark.

The Higgs boson interacts only with massive particles, yet it was initially discovered in its decay to two

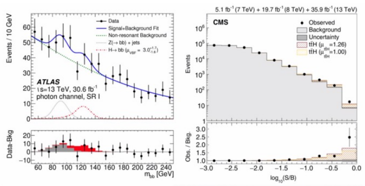


盘点2018 | 献给奋进中的高能人

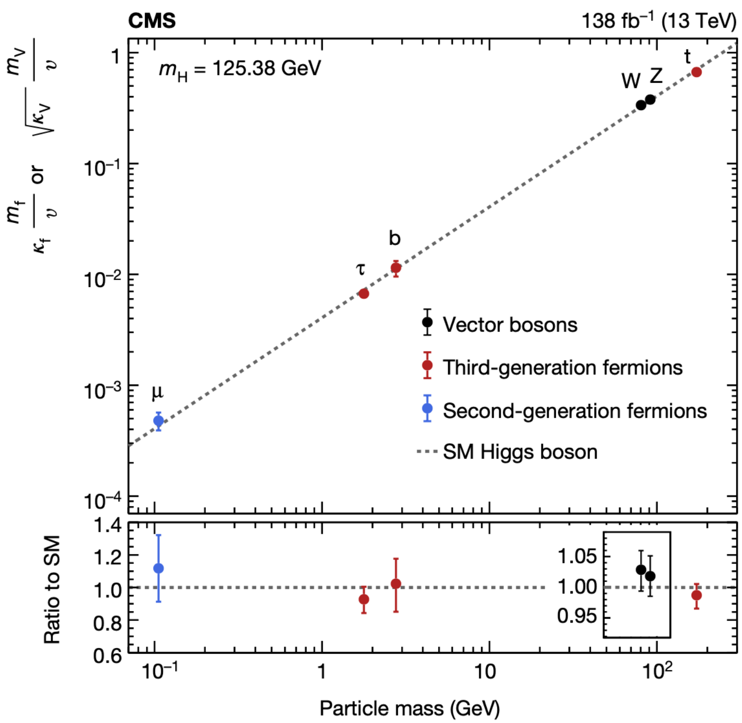
04

LHC发现Higgs与夸克耦合，高能所做关键贡献

填补了对Higgs认知的一大空白



Higgs coupling to Fermions



$$\mathcal{L}_{Yuk} = -\sum_{m,n=1}^{F}\Big[\Gamma^u_{mn}\bar{q}^0_{mL}\tilde{\phi}u^0_{nR} + \Gamma^d_{mn}\bar{q}^0_{mL}\phi d^0_{nR} + \Gamma^e_{mn}\bar{l}^0_{mn}\phi e^0_{nR} + \Gamma^\nu_{mn}\bar{l}^0_{mL}\tilde{\phi}\nu^0_{nR}\Big] + h.c.,$$

$$-\mathcal{L}_{Yuk} = \sum_i m_i\bar{\psi}_i\psi_i\left(1 + \frac{g}{2M_W}H\right) = \sum_i m_i\bar{\psi}_i\psi_i\left(1 + \frac{H}{\nu}\right)$$

$$m_F = \frac{v g_F}{\sqrt{2}}$$

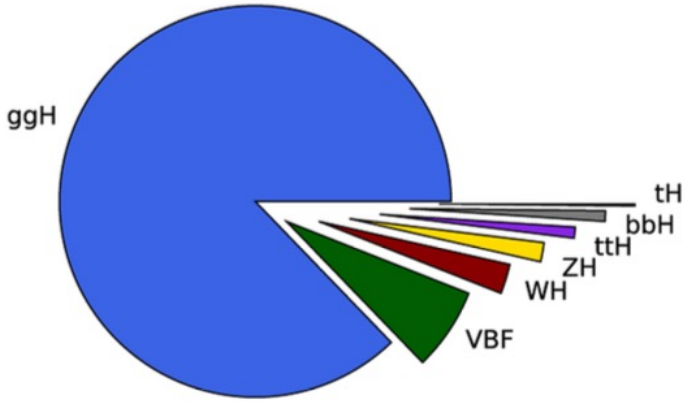
- Give mass to fermions (quarks/lepton)
- Coupling strength variations with a factor of ~10^6:
  - Only few mearsurable at LHC
- Unknown questions: CP properties of Yukawa interactions
- Different measurement strategies used at LHC

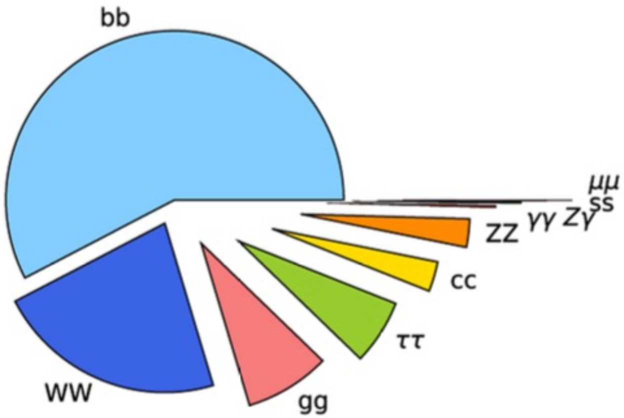
10 years after Higgs discovery, and beyond

Higgs Production and Decay

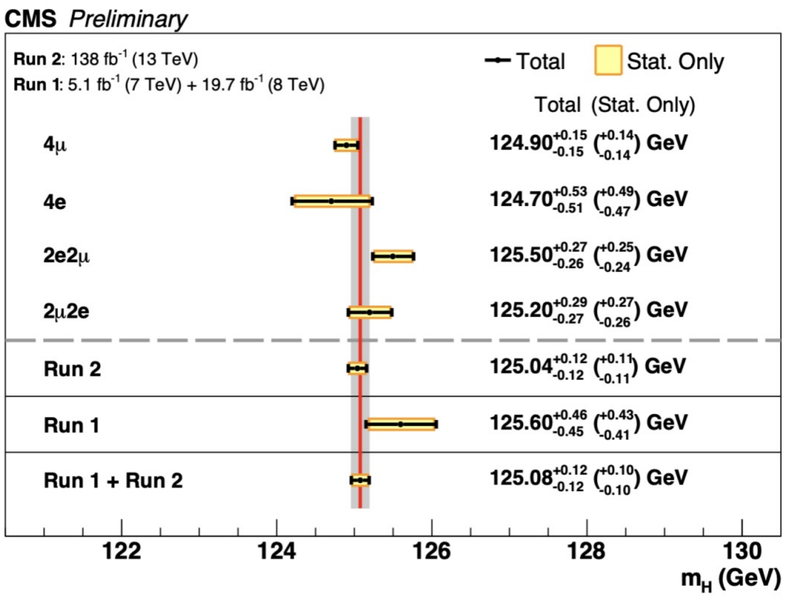
Production mode	Cross section (pb)
ggH	48.31 ± 2.44
VBF	3.771 ± 0.807
WH	1.359 ± 0.028
ZH	0.877 ± 0.036
ttH	0.503 ± 0.035
bbH	0.482 ± 0.097
tH	0.092 ± 0.008

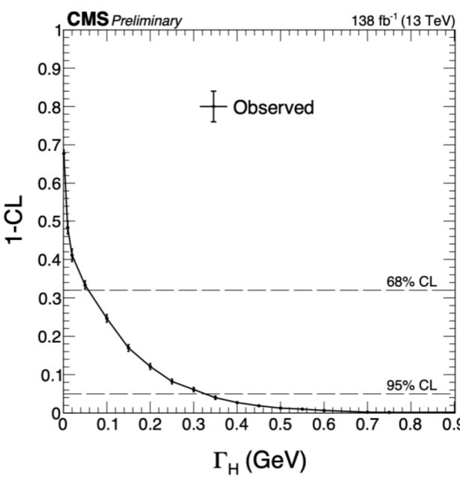
Decay channel	Branching fraction (%)
bb	57.63 ± 0.70
WW	22.00 ± 0.33
gg	8.15 ± 0.42
ττ	6.21 ± 0.09
cc	2.86 ± 0.09
ZZ	2.71 ± 0.04
γγ	0.227 ± 0.005
Zγ	0.157 ± 0.009
ss	0.025 ± 0.001
μμ	0.0216 ± 0.0004

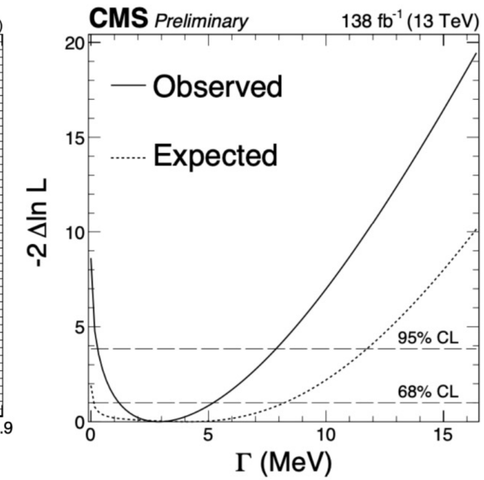




H→4l decay channel using the full Run2 LHC dataset







m_H = 125.08 ± 0.10 (stat) ± 0.05 (syst) GeV

Most precise single channel measurement to date!

On-shell Higgs width

95% CL upper limit:
0.33 GeV obs. (0.75 exp.)

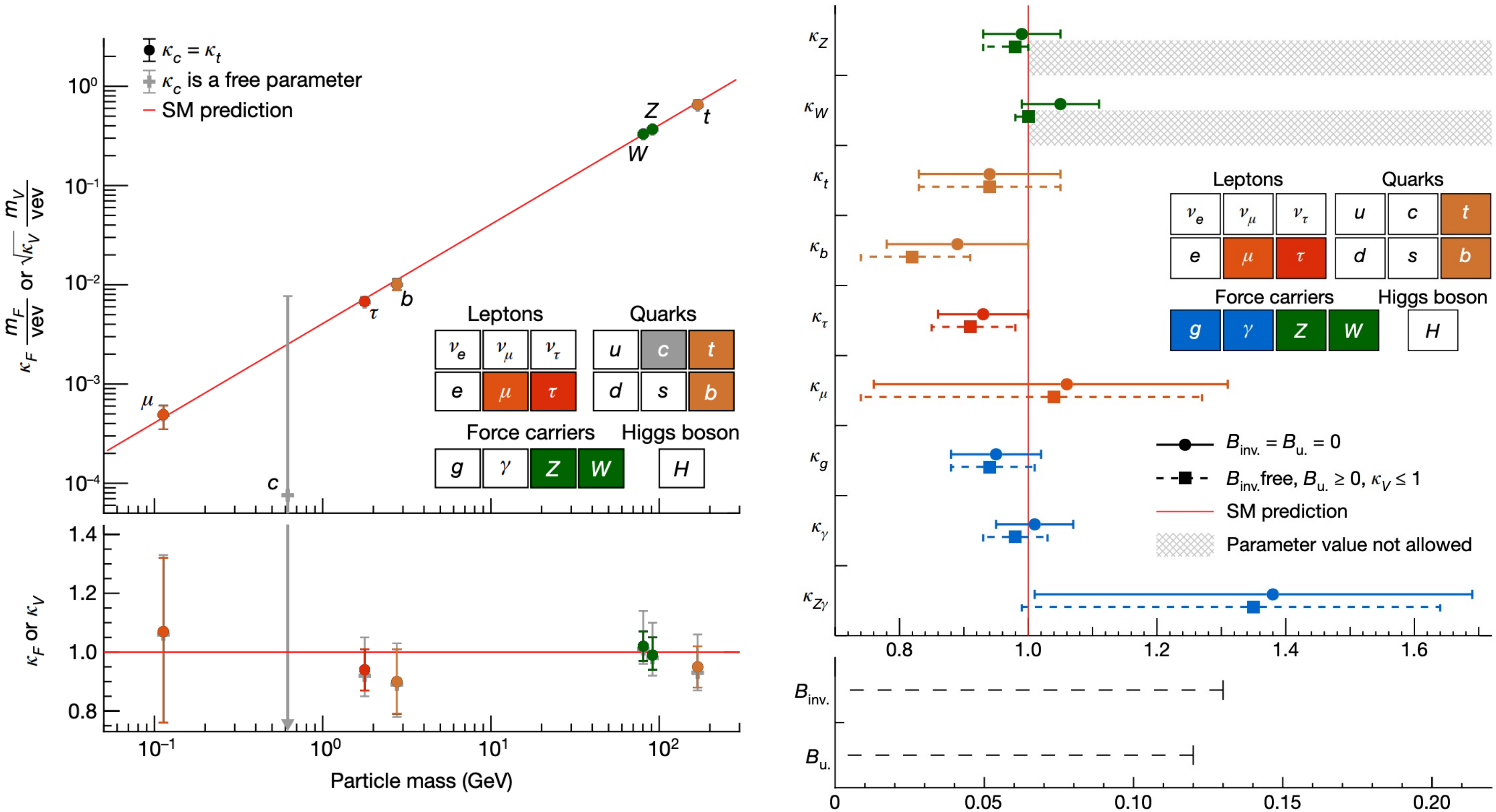
Off-shell Higgs width

Width: $\Gamma_H = 2.9^{+2.3}_{-1.7}$ MeV

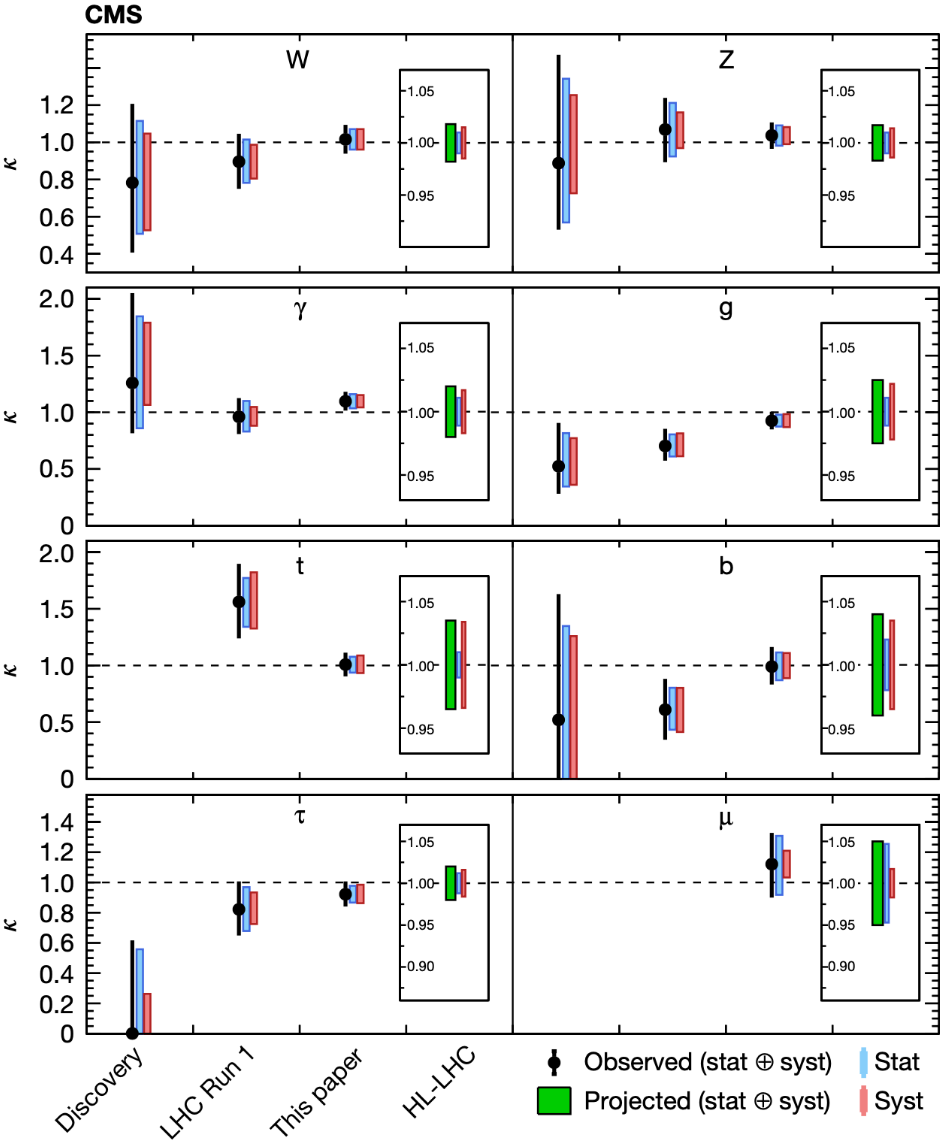
Consistent with SM and confirms previous results

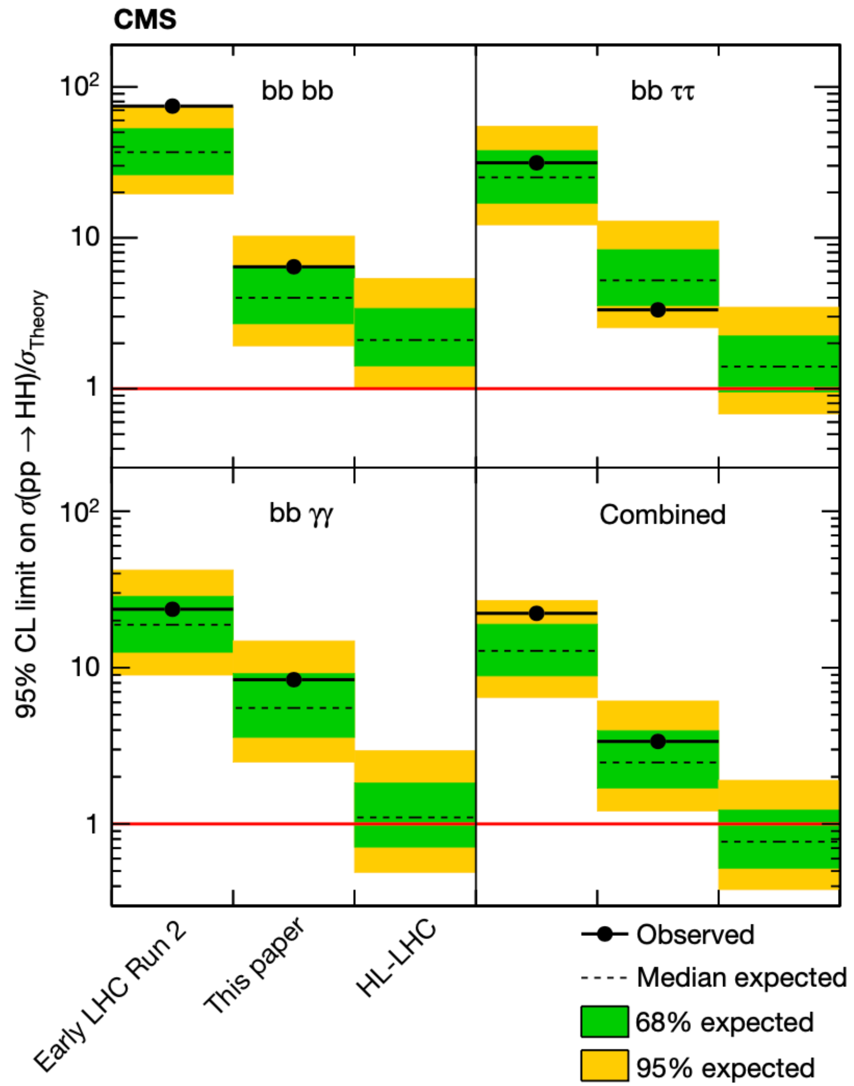
CMS-PAS-HIG-21-019

10 years after Higgs discovery, and beyond



10 years after Higgs discovery, and beyond





Top quark: the only "naked" quark

- Mass: ~172.5 GeV; the heaviest particle
- Lifetime: ~$4*10^{-25}$ Sec：
  - hadronization time ~$3*10^{-24}$ Sec
  - Decay before hadronization

"1夸克态"
"2夸克态"
"3夸克态"
"4夸克态"
"5夸克态"

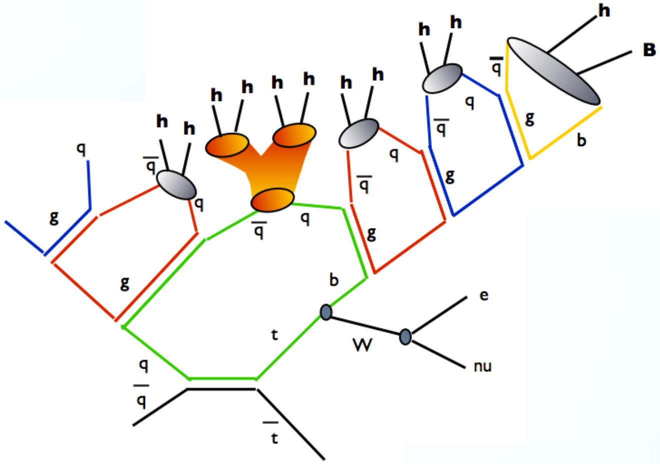
Nobel Prize 2008

Makoto Kobayashi

Toshihide Maskawa

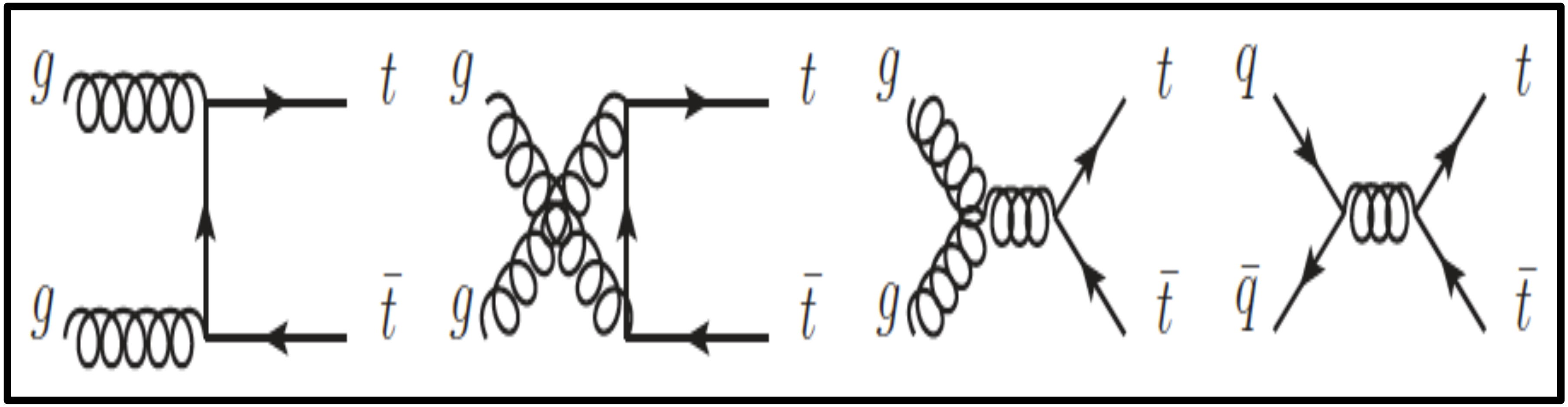
"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature."

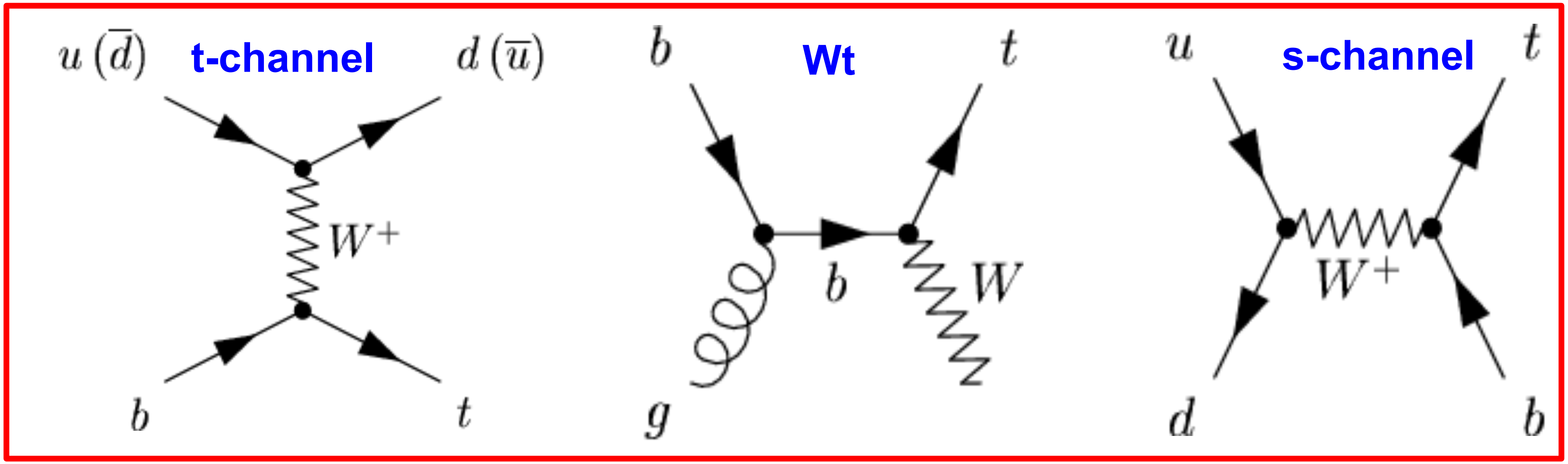
- Only place to study a "naked" quark properties
  - Mass
  - Spin
  - Polarization
  - Vtb
  - Charge



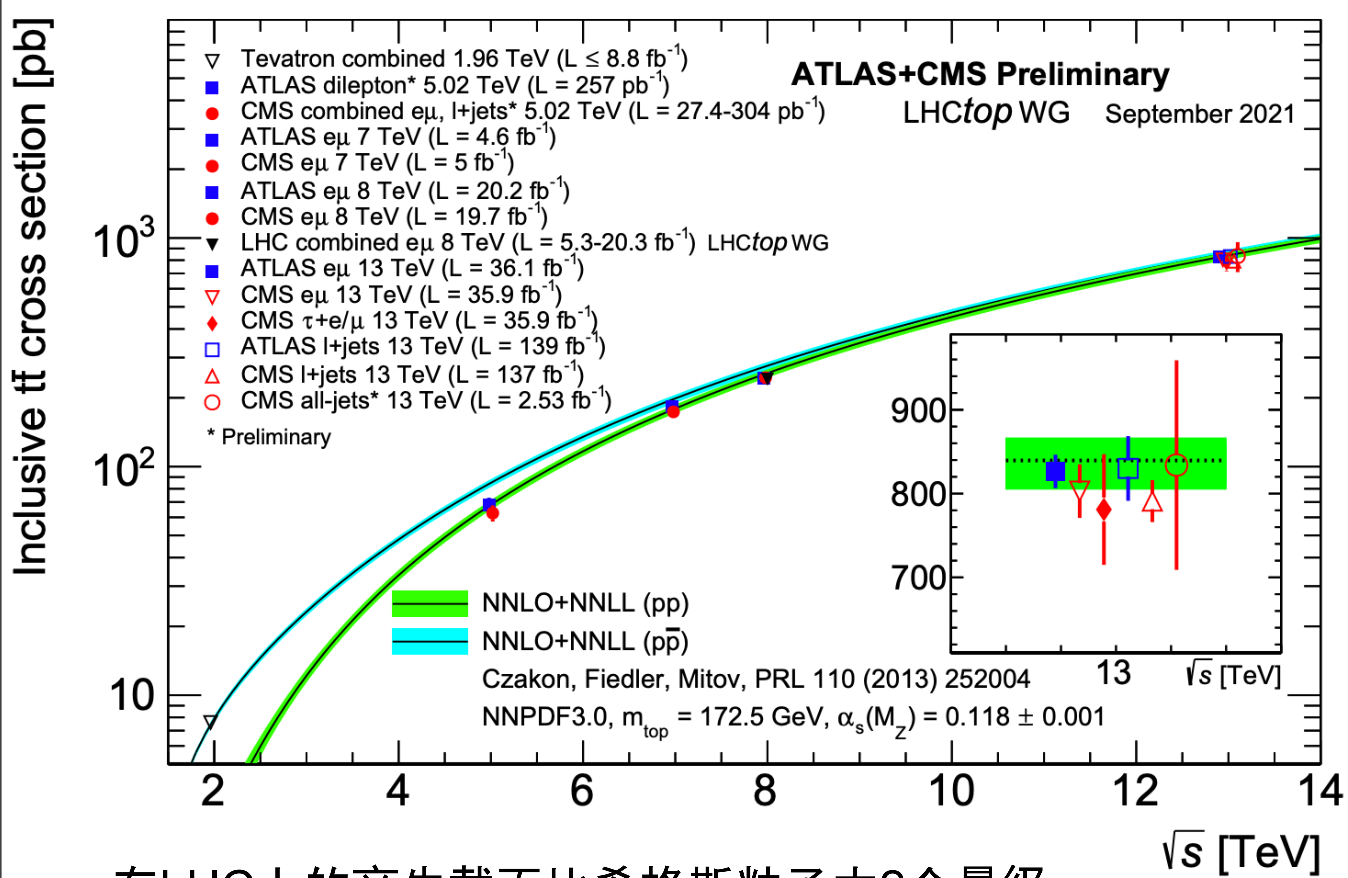
Top quark is a laboratory to precise test SM

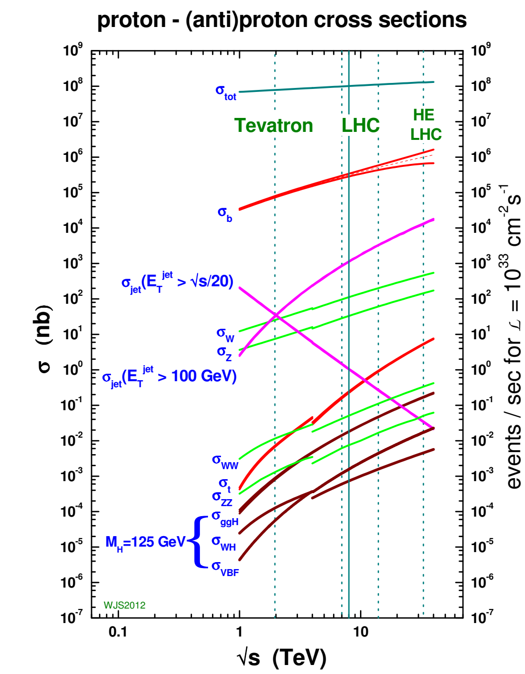
- 最重的基本粒子，在强子化之前衰变
- LHC有可以预计的未来最大的top样本





Pair production（强作用过程）



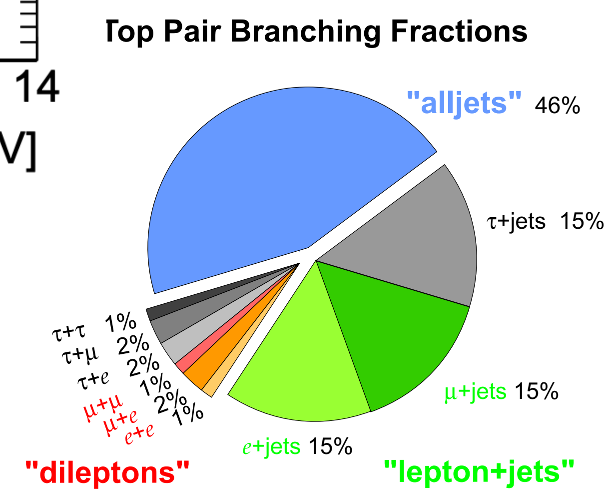


在LHC上的产生截面比希格斯粒子大2个量级

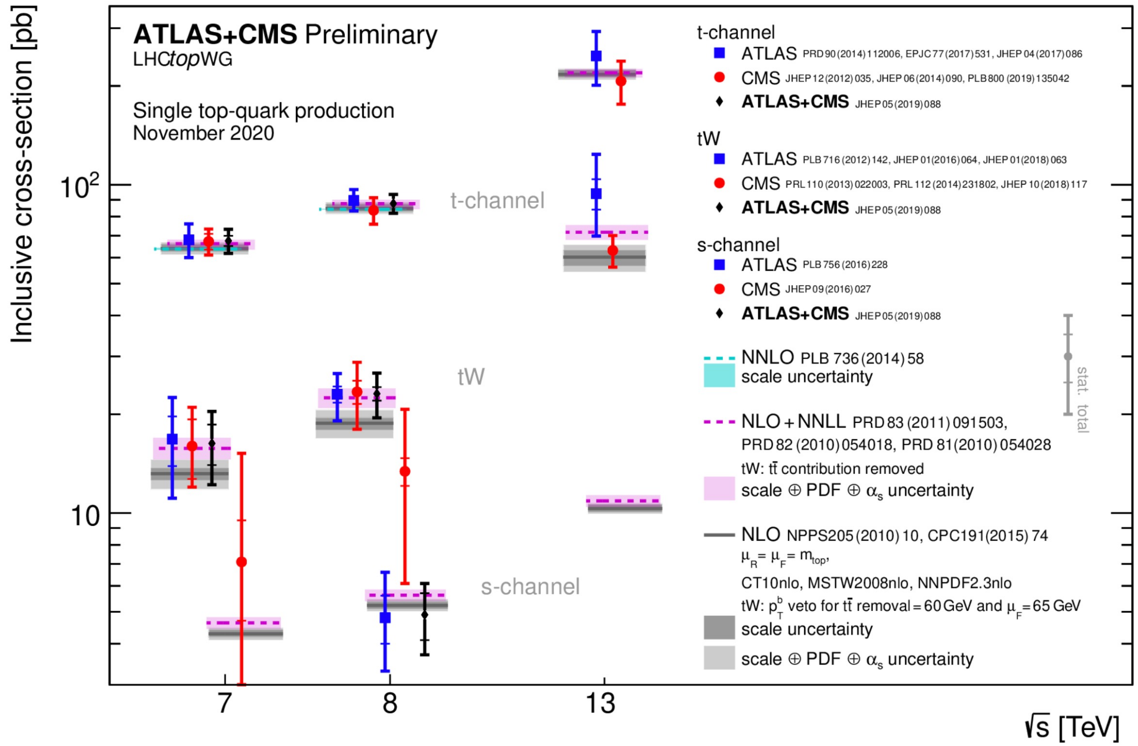
164^{+13}_{-10} pb @ 7TeV

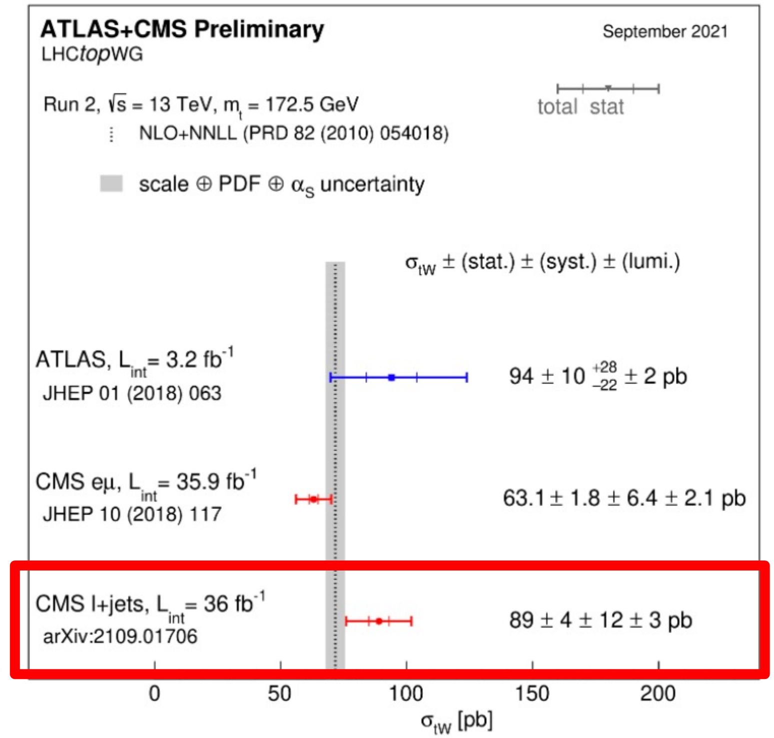
238^{+22}_{-24} pb @ 8TeV

830 pb @ 13TeV



Single production（电弱过程）



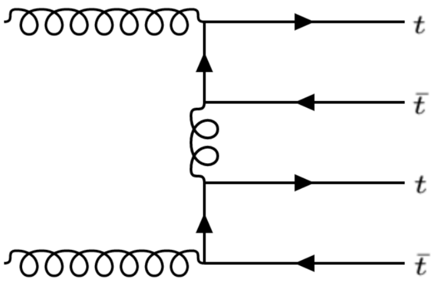


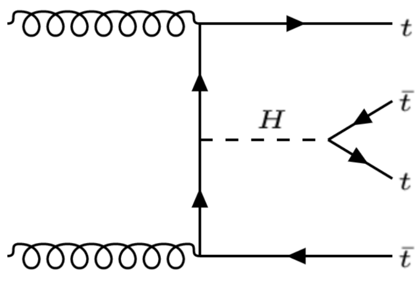
产生截面约为pair production的1/100 到1/4

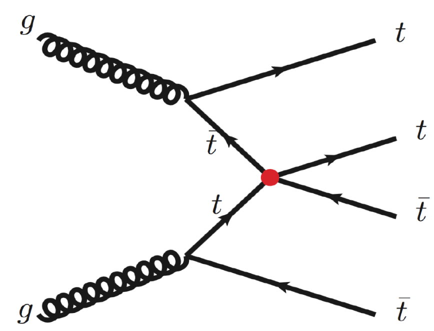
t-channel	tW	s-channel
$64.6^{+2.7}_{-2.0}$ pb @ 7TeV	15.7±1.1 pb @ 7TeV	4.6±0.2 pb @ 7TeV
$87.8^{+3.4}_{-1.9}$ pb @ 8TeV	22.4±1.5 pb @ 8TeV	5.6±0.2 pb @ 8TeV
First observation **2009 @ Tevatron**	First observation **2014 @ LHC**	First observation **2014 @ Tevatron**

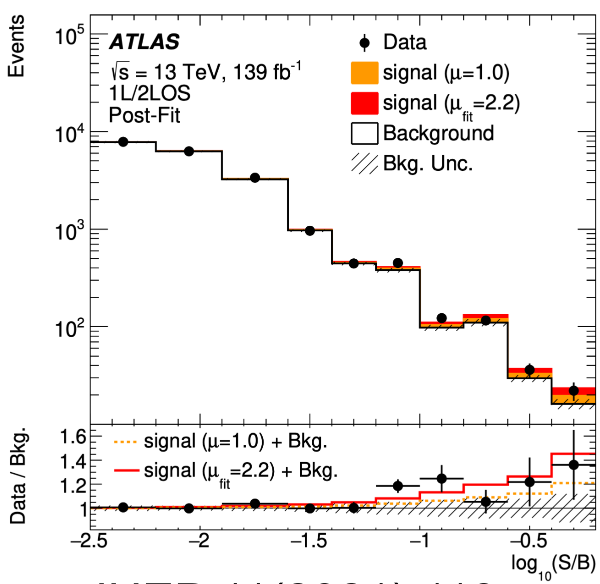
Four top production (ttH/是否混有新的作用？)

- SM 4 top theory prediction: 12fb (+- 20%) @ 13 TeV
- Observed（exp.) 4.3(2.4) sigma standard deviation









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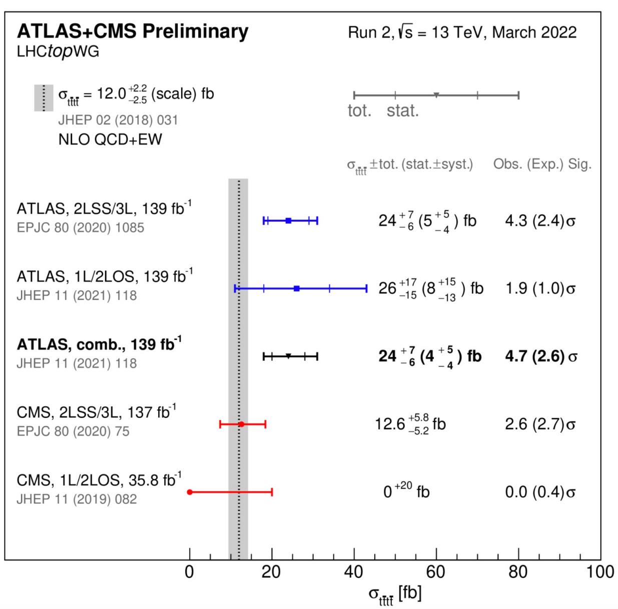
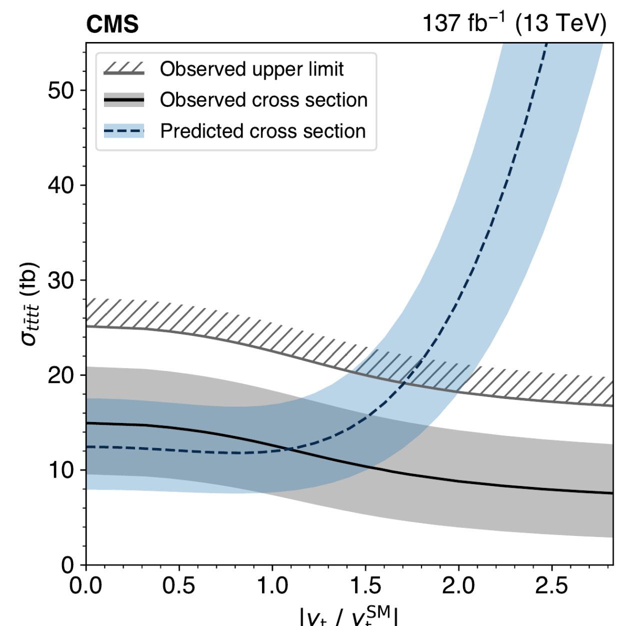


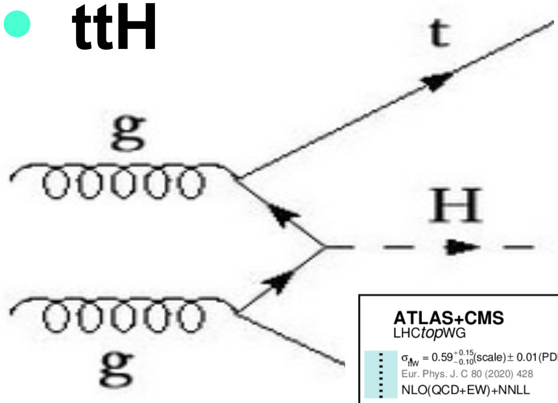


其他顶夸克的稀有伴随产生过程

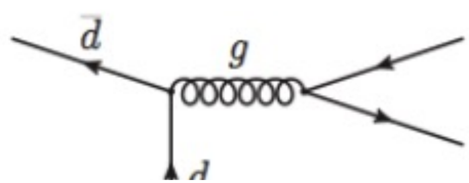
3top？新物理！

刚发现 4top

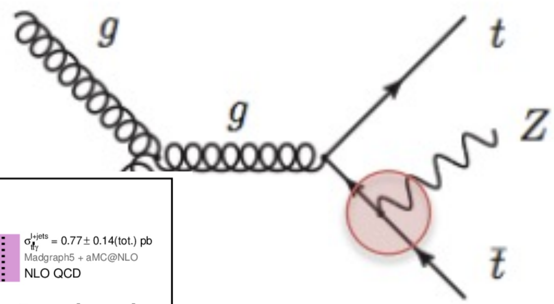
- **ttH**

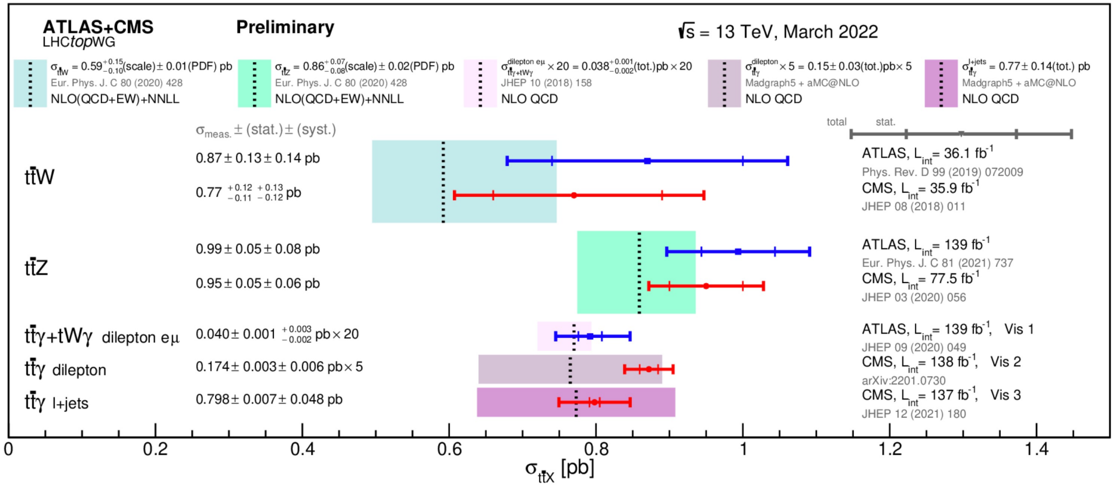


- **ttW**

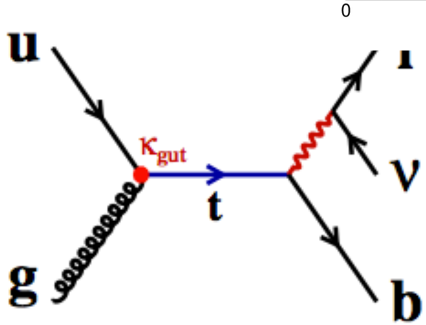


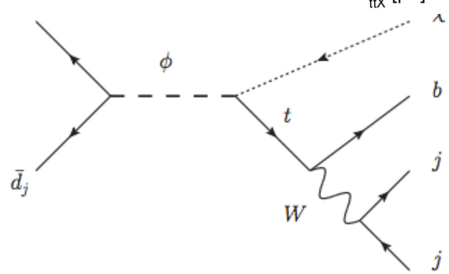
- **ttZ**

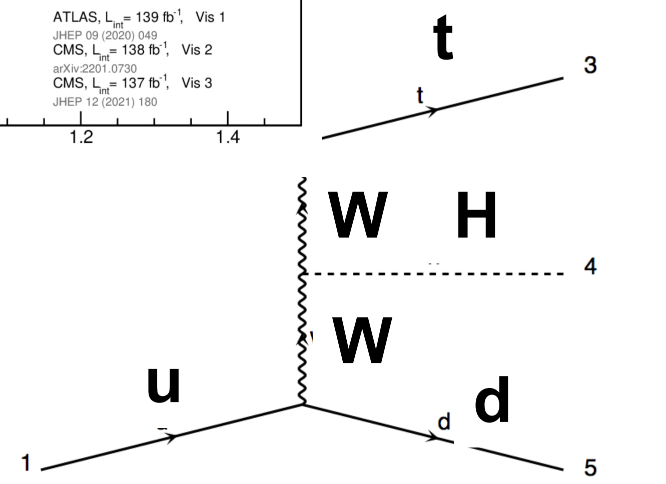




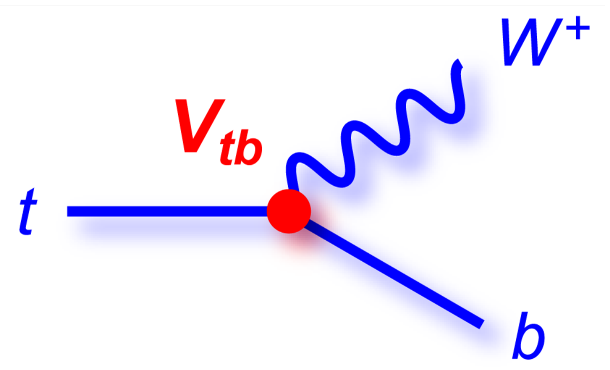
- **FCNC**

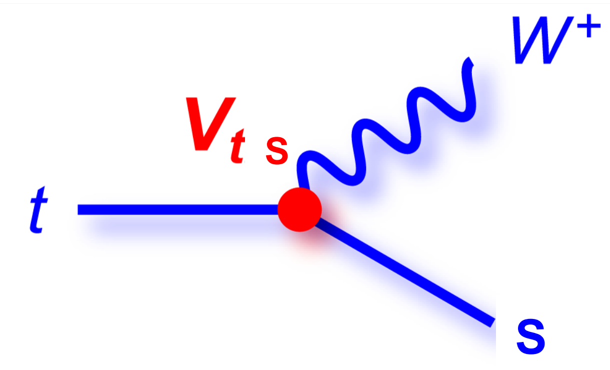


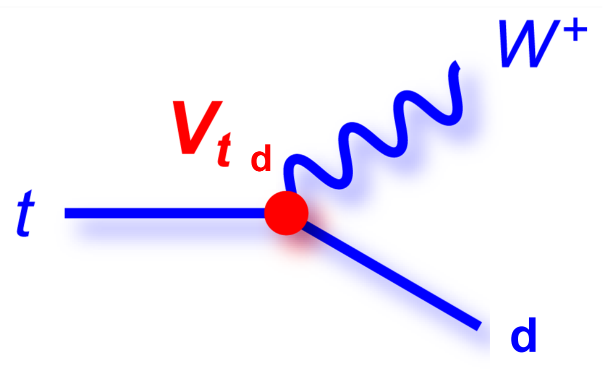




顶夸克的衰变

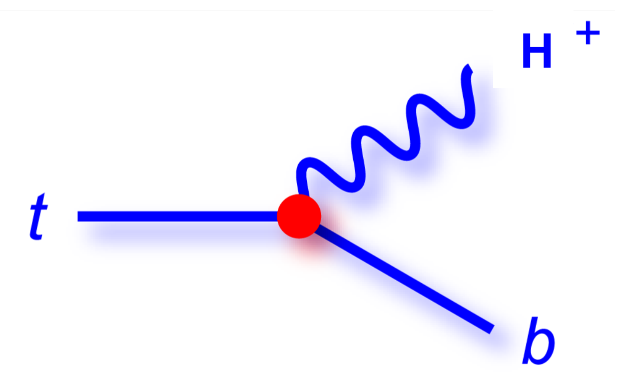


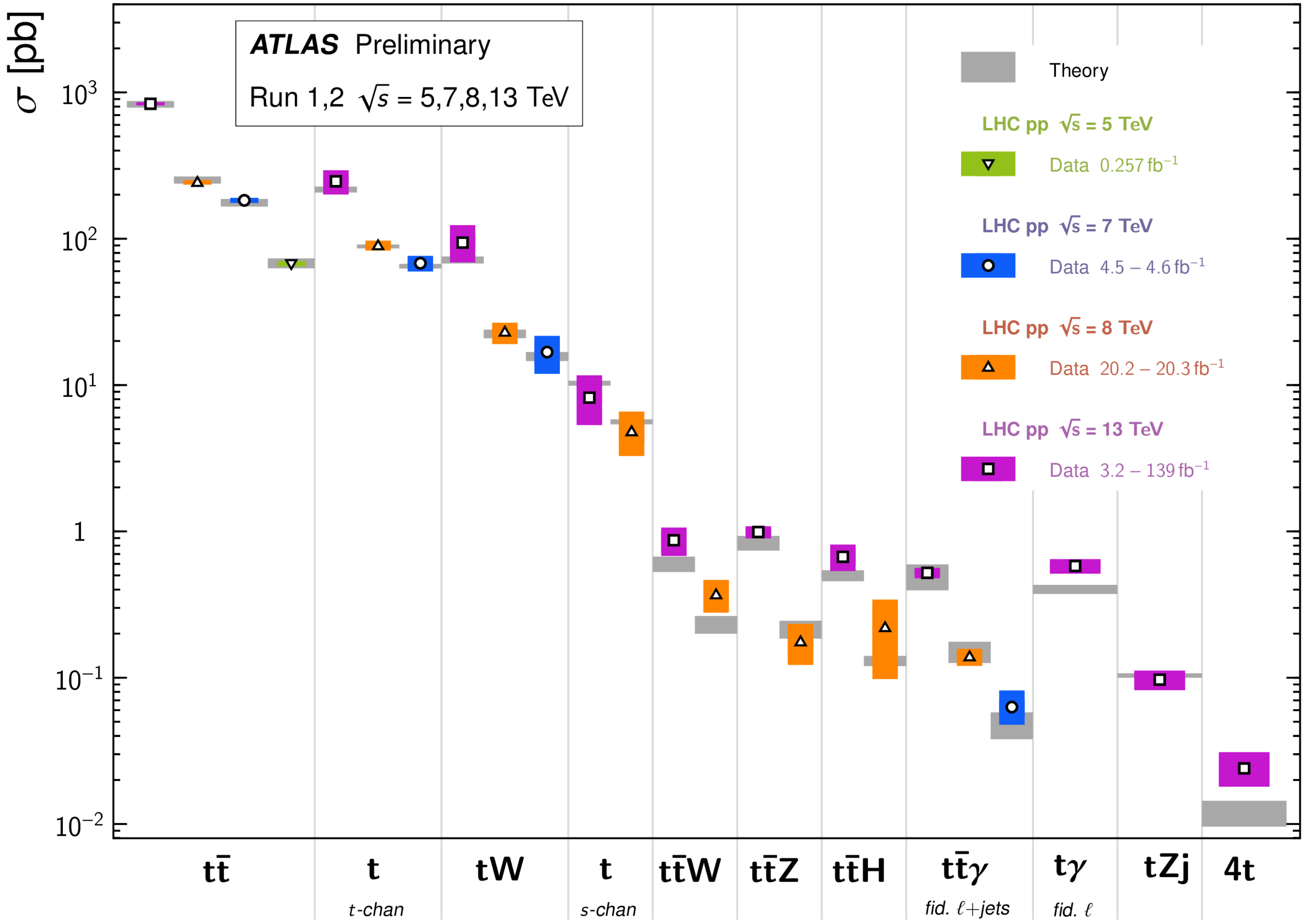




$Br(t \to bW^+) \simeq 0.998$ $Br(t \to sW^+) \simeq 0.0019$ $Br(t \to dW^+) \simeq 0.0001$

- Check top decay products properties
  - Top polarization/W helicity
  - Charge Higgs searches
- Check extra radiations
- With Top pair
  - Spin Correlations





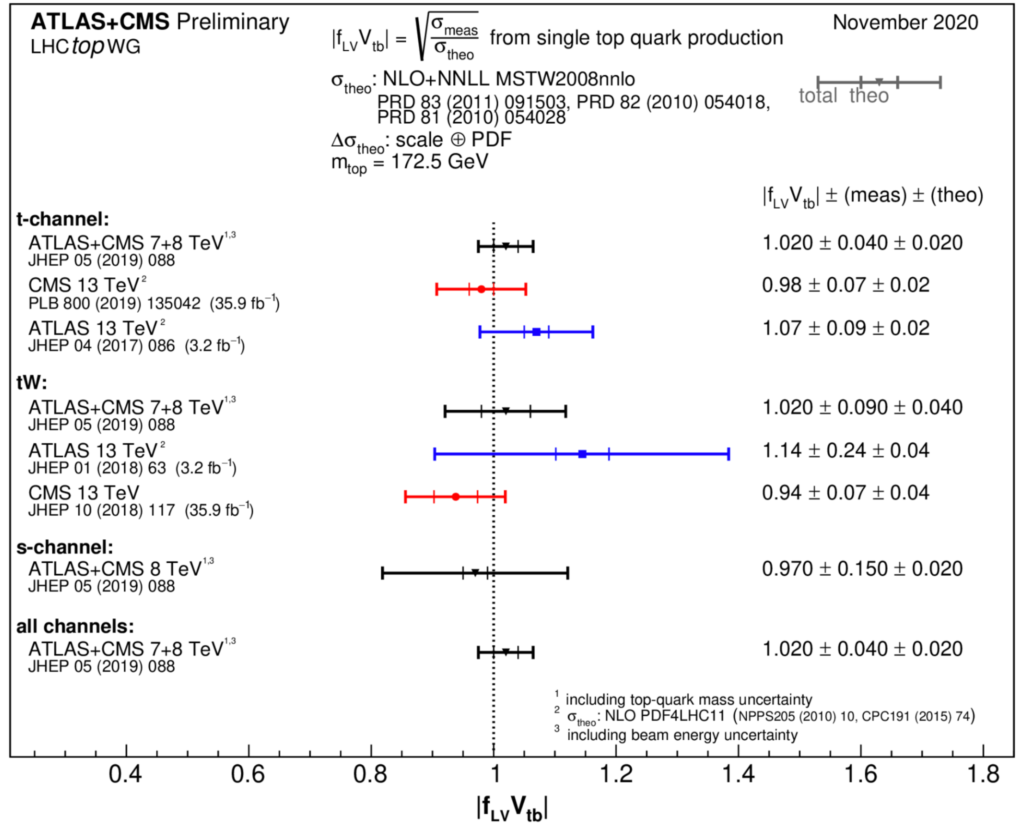
Top Quark Production Cross Section Measurements
Status: November 2022
ATLAS Preliminary
Run 1,2 $\sqrt{s}$ = 5,7,8,13 TeV
σ [pb]
10^3
10^2
10^1
1
10^{-1}
10^{-2}
Theory
LHC pp $\sqrt{s}$ = 5 TeV
Data 0.257 fb^{-1}
LHC pp $\sqrt{s}$ = 7 TeV
Data 4.5 – 4.6 fb^{-1}
LHC pp $\sqrt{s}$ = 8 TeV
Data 20.2 – 20.3 fb^{-1}
LHC pp $\sqrt{s}$ = 13 TeV
Data 3.2 – 139 fb^{-1}
$t\bar{t}$
t
t-chan
tW
t
s-chan
$t\bar{t}W$
$t\bar{t}Z$
$t\bar{t}H$
$t\bar{t}\gamma$
fid. ℓ+jets
$t\gamma$
fid. ℓ
tZj
4t

Vtb的精确(直接)测量

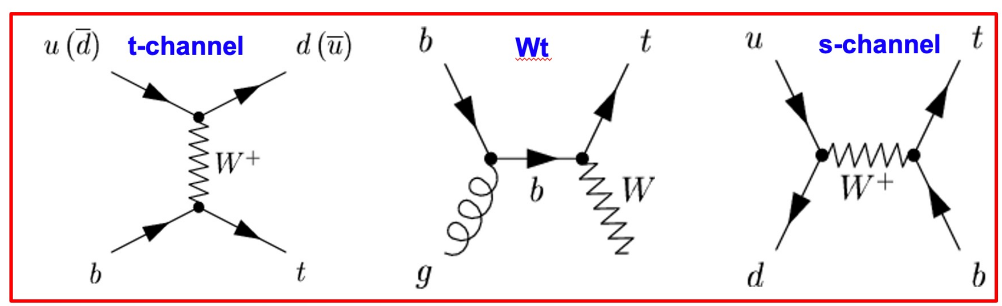
- CKM机制

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$



CKM矩阵给出了CP破坏的微观机制，提供正反物质不对称的来源



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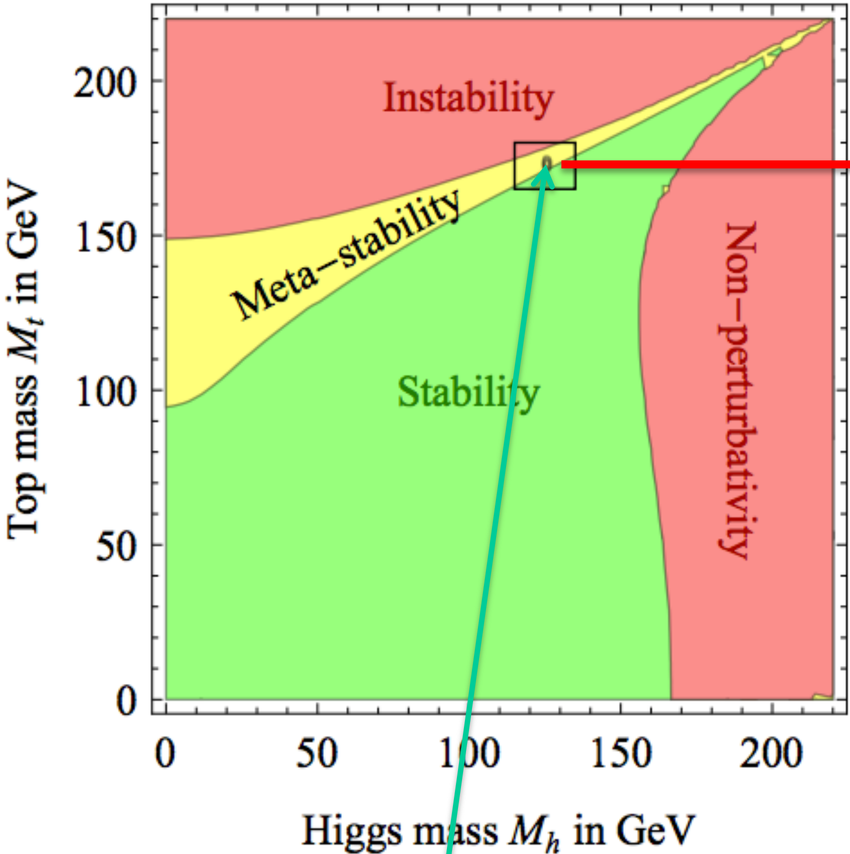
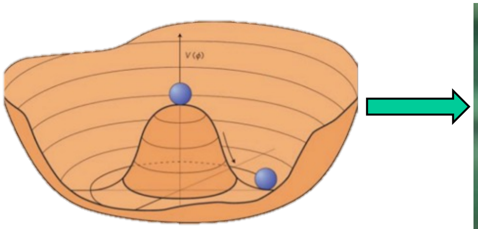
PRD 97, 056006 (2018)

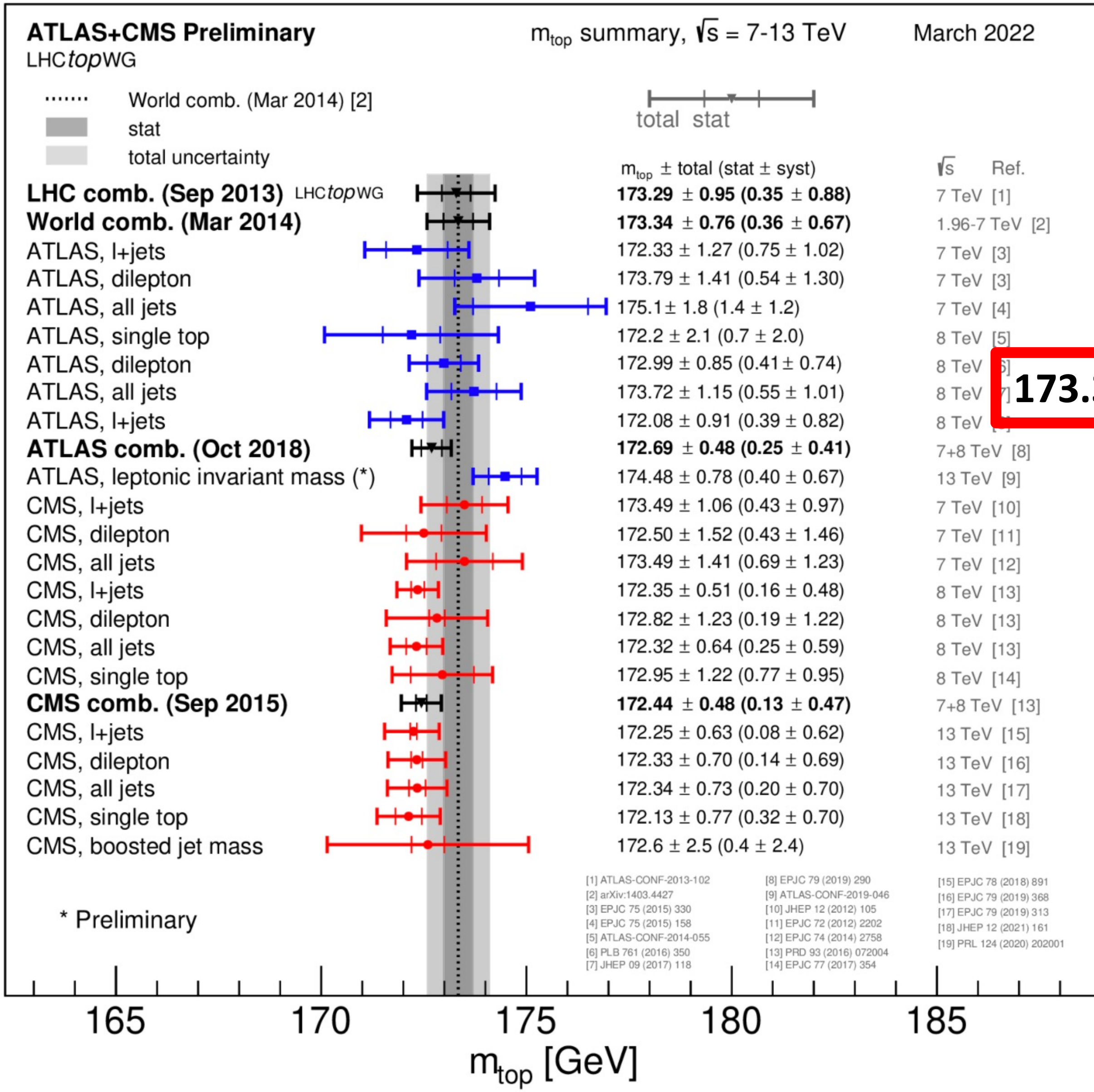
Metastable Universe?





Main uncertainties from Top-quark Mass

顶夸克质量测量结果



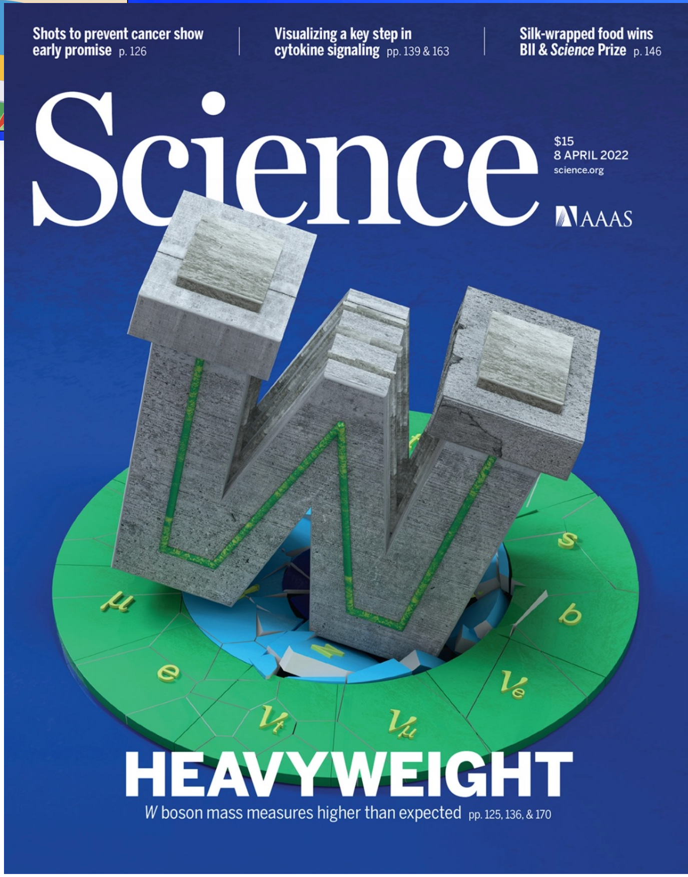
2014年世界平均

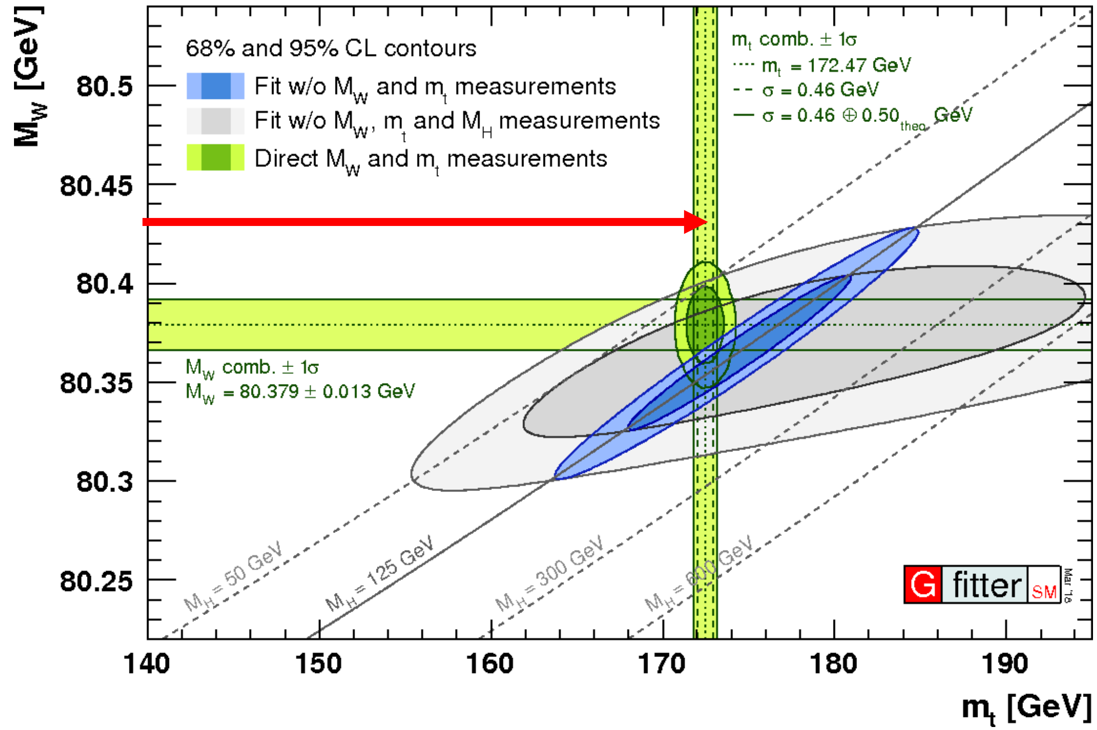
173.34±0.36(stat)±0.67(syst) GeV

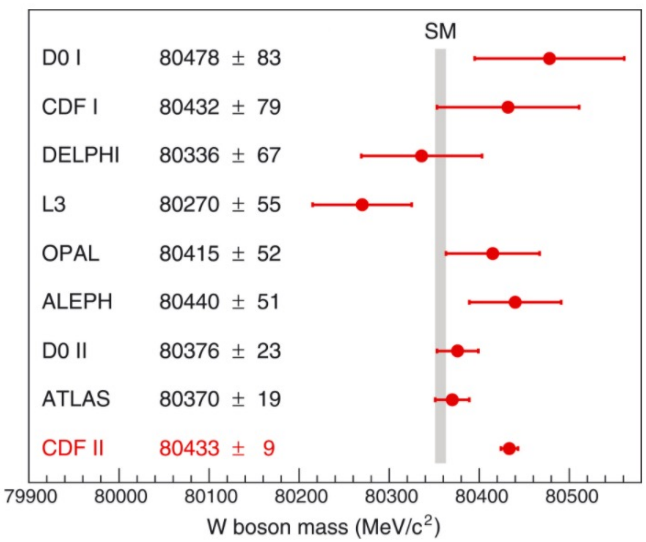
CMS最新实验测得的顶夸克质量下降到171.77+-0.38GeV
CMS-PAS-TOP-20-008

真空目前还稳定吗？

顶夸克质量(2)





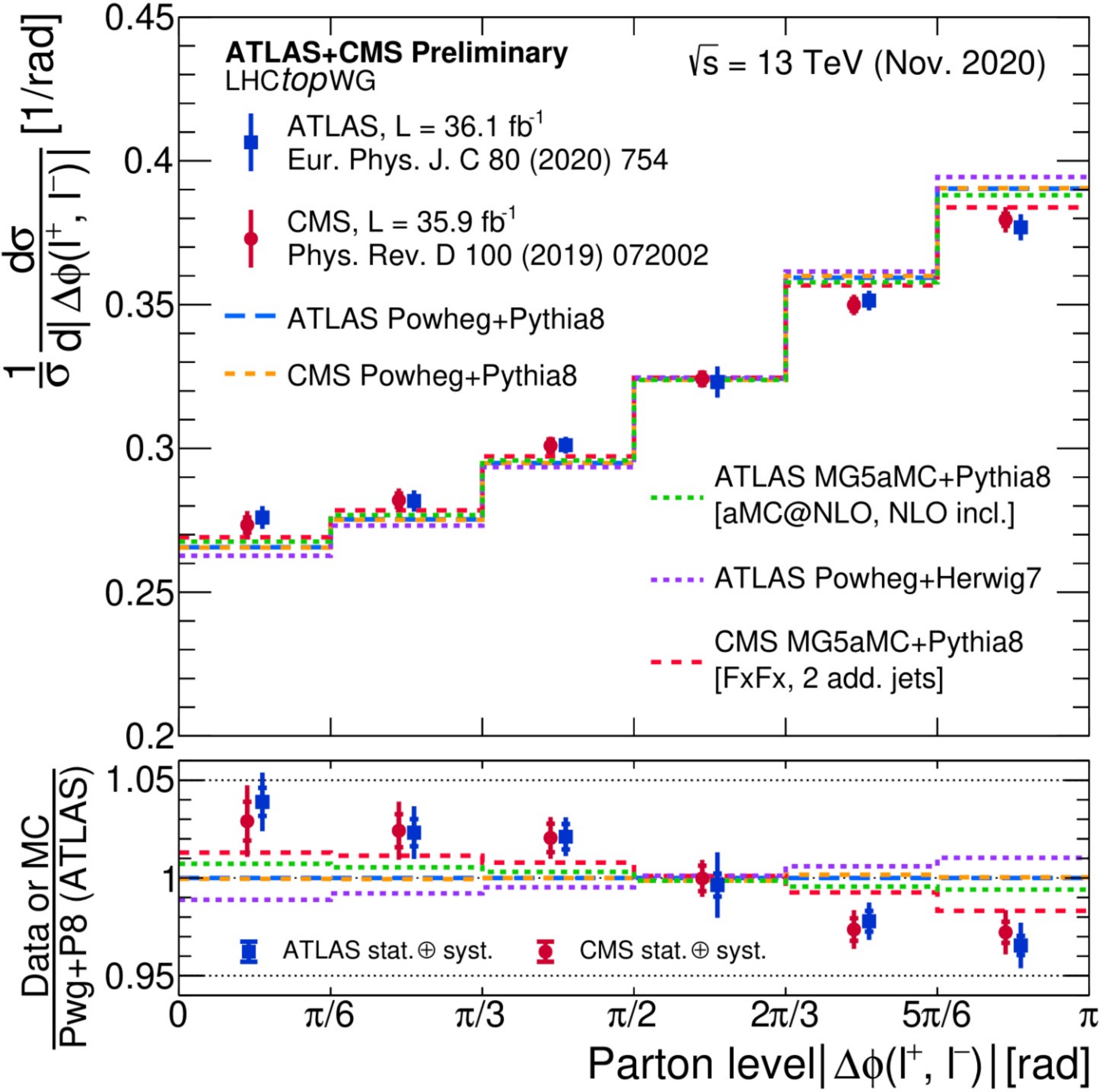


不是实验错了，就是新物理 --- 韩涛

粒子物理大厦将倾

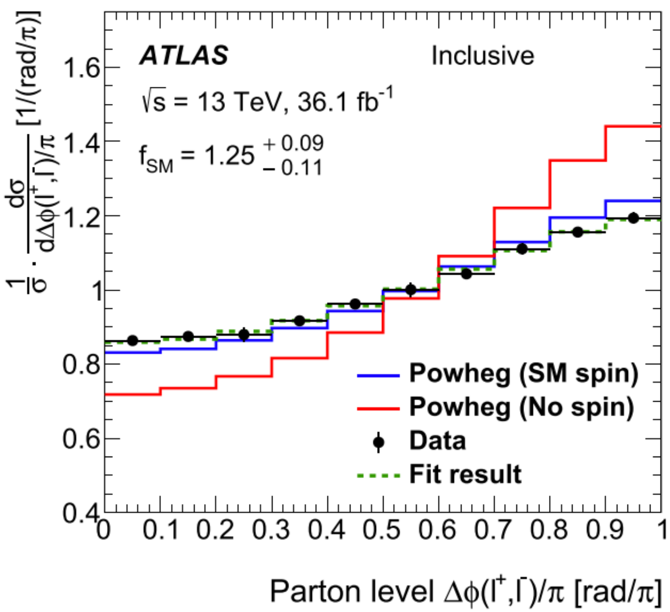
到底是W重了，还是top轻了？

ATLAS 最新的W质量偏差变小



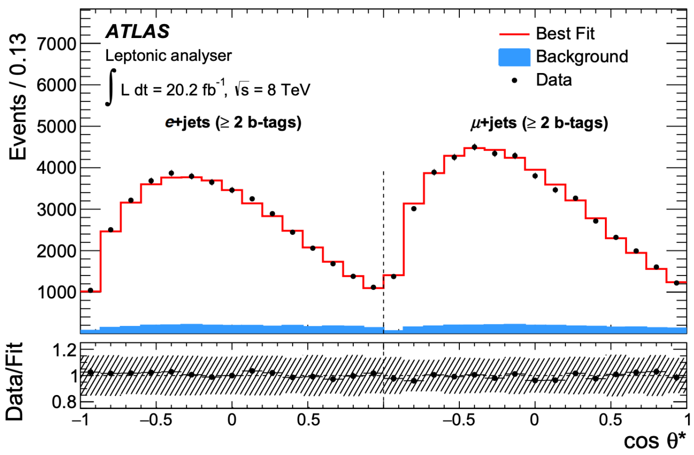
Top quark lifetime: $4*20^{-25}$
Hadronization time: $3*20^{-24}$
Spin decorrelation time ($\sim 10^{-21}$ s)

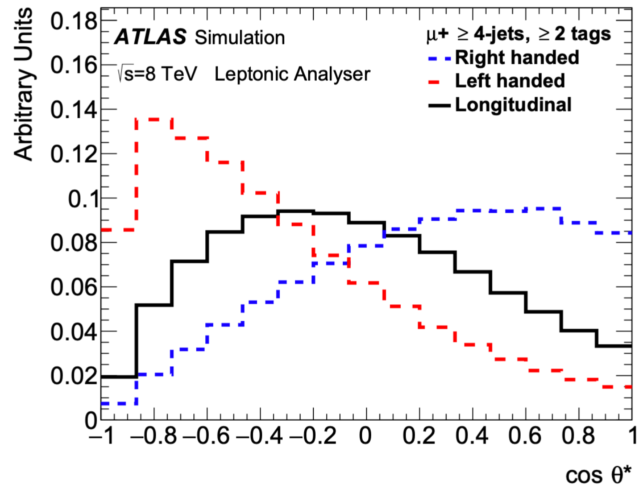
Dilepton angle in ttbar system preserve top spin information
Unfolding to partton level



probe of new physics in production

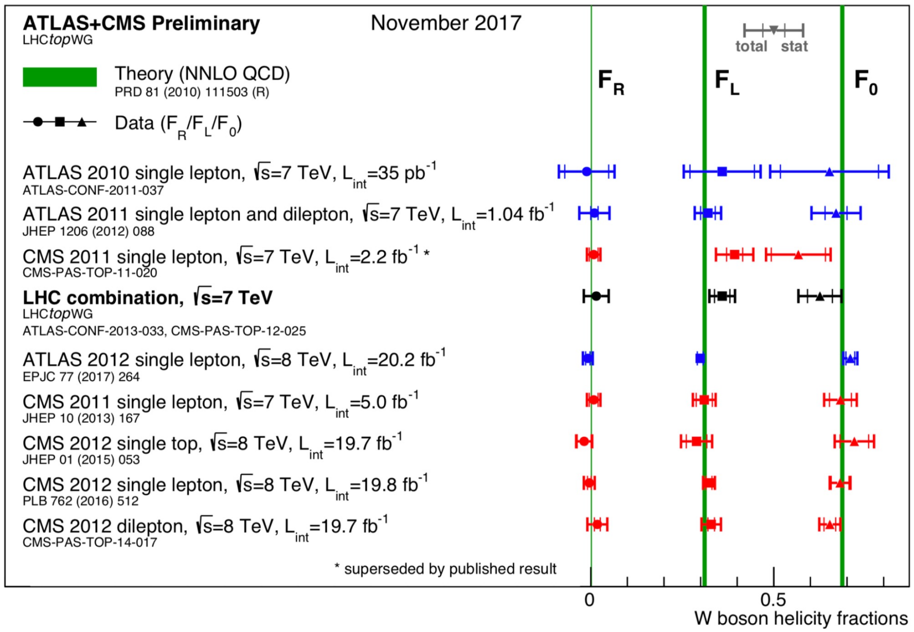
W helicity（螺旋性）



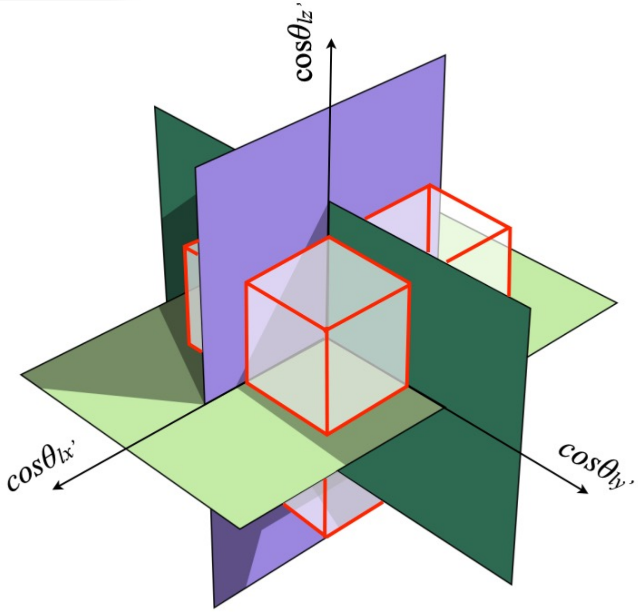


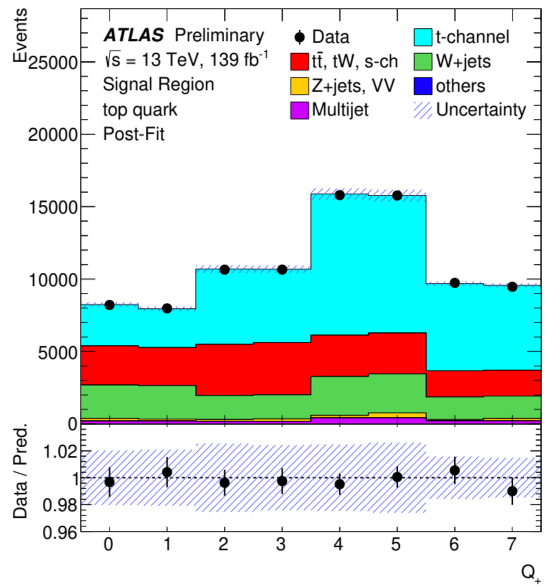
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \frac{3}{4}\left(1-\cos^2\theta^*\right)F_0 + \frac{3}{8}(1-\cos\theta^*)^2 F_L + \frac{3}{8}(1+\cos\theta^*)^2 F_R$$

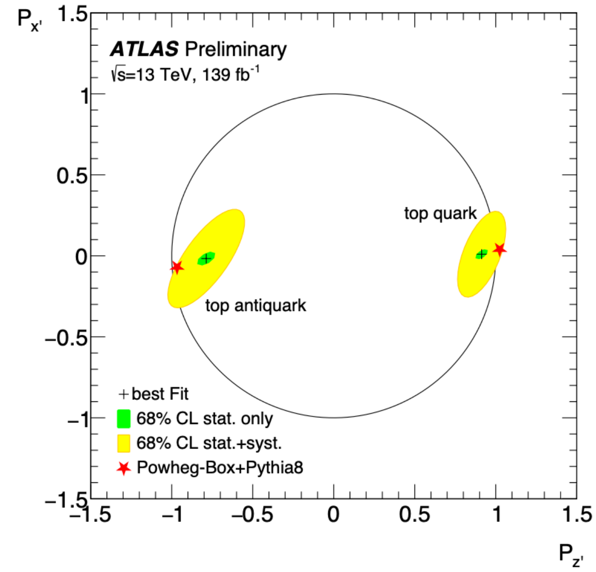
- Define θ^* in W rest frame
  - angle between charged lepton and the rev. b quark
- Fit θ^* distribution with 3 components: F_0, F_L, F_R
- Measured in single top and top pair events



W polarization



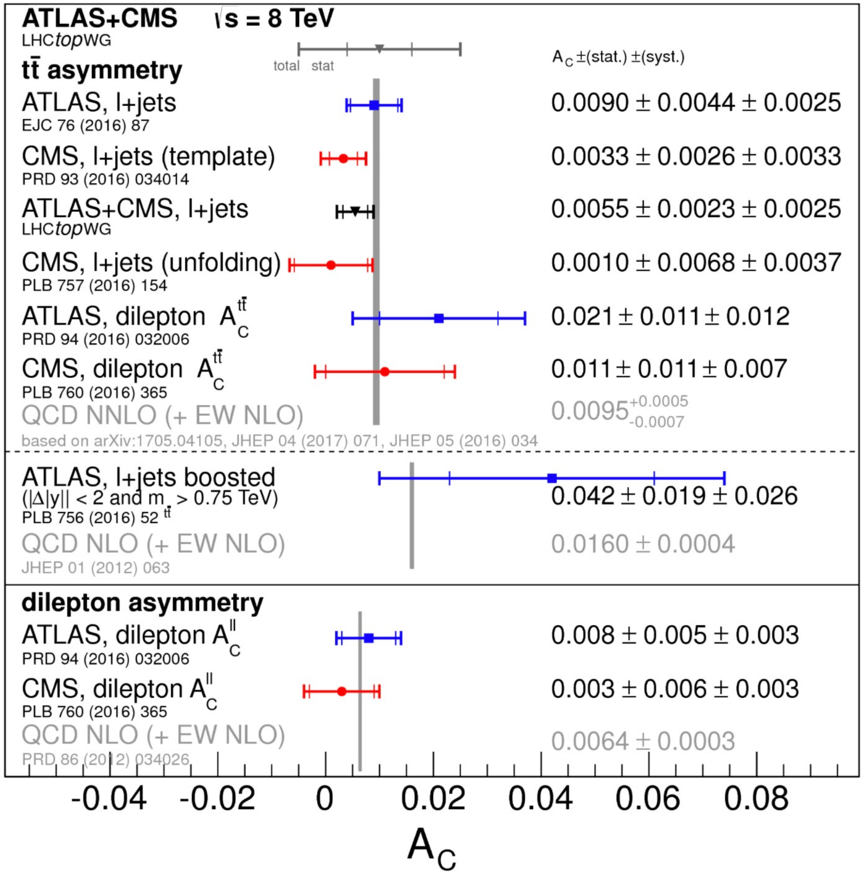


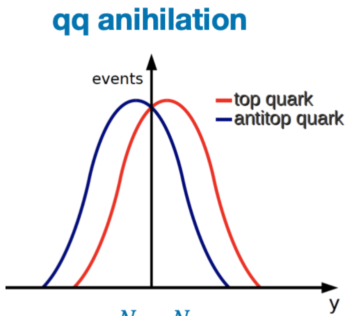


- Measured in single top t-channel (l+b+q+MET)
- Angles constructed using spectator jet in top quark rest frame
  - $\hat{z}$: direction of the momentum of the spectator quark, q' (FS light jet),
  - $\hat{y}$: $\hat{z} \times q$, q is the direction of the incoming light quark
- Octant variable constructed fitted by slicing phase space
- Strong polarization in z-direction(as expected), little in others

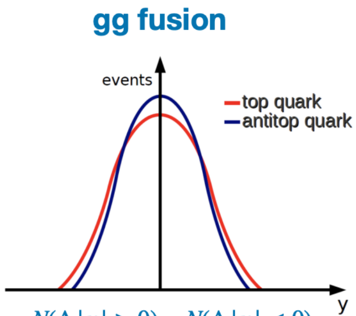
$$P_x = -0.02 \pm 0.20 \qquad P_y = -0.007 \pm 0.051 \qquad P_z = 0.91 \pm 0.10$$

Charge asymmetry in top-antitop system





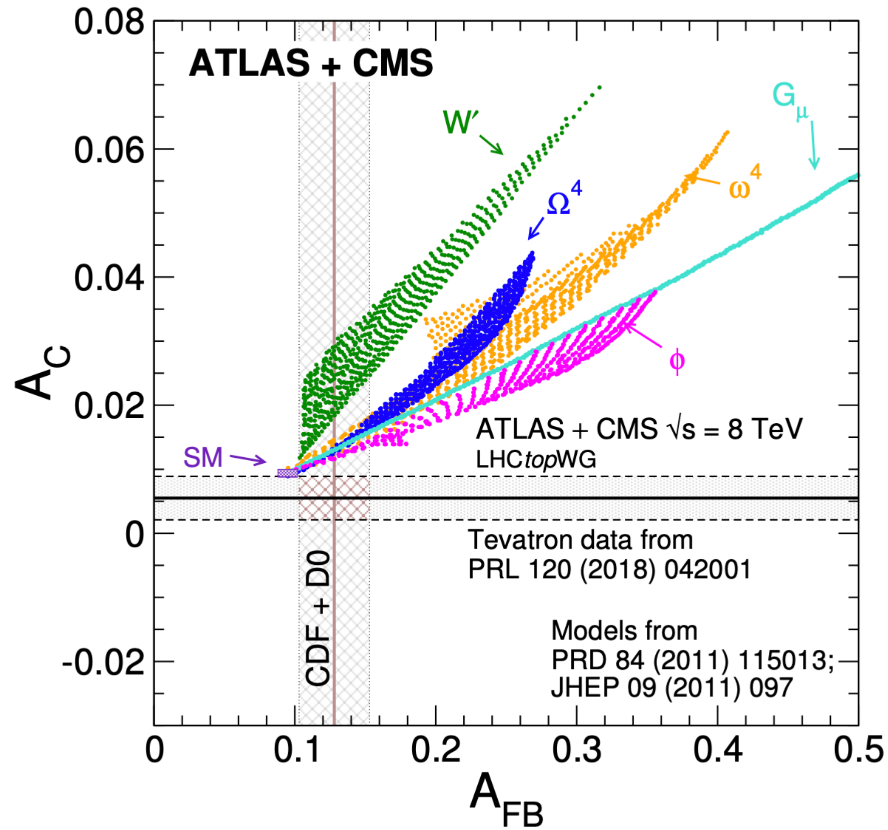
$$A_C = \frac{N_F - N_B}{N_F + N_B}$$

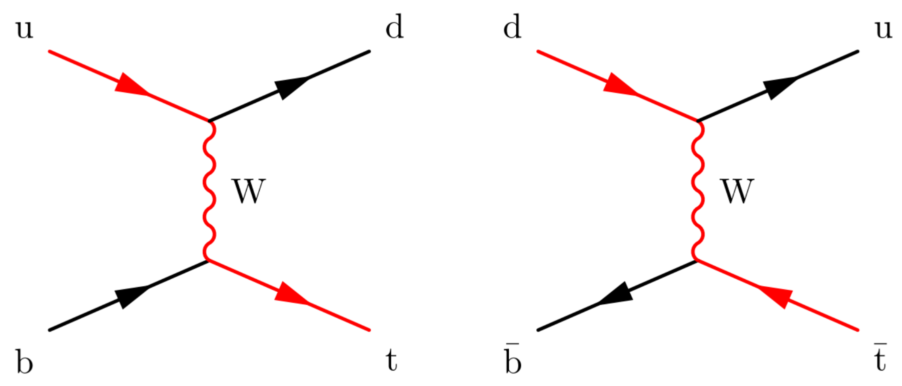


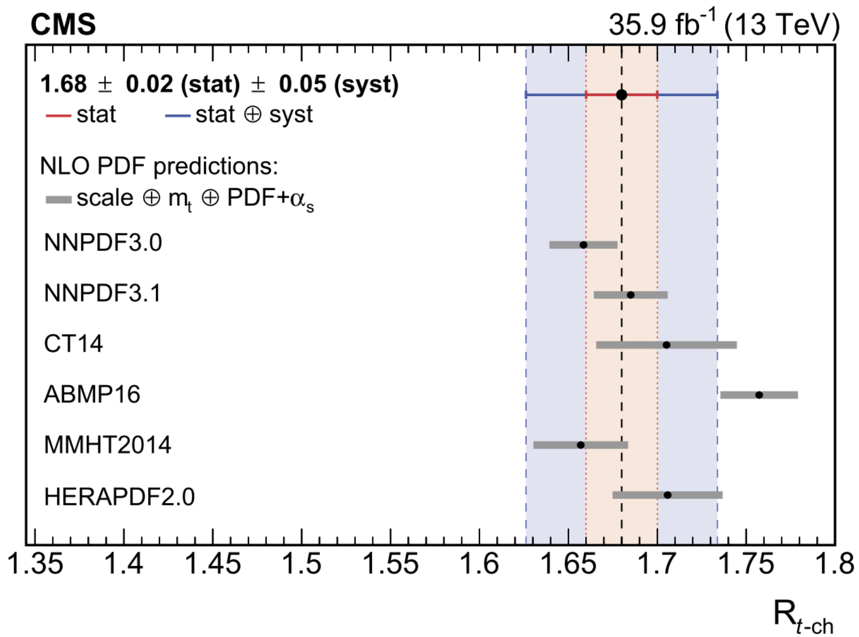
$$A_C = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}$$

$$A_C = \frac{N^{\Delta|y|>0} - N^{\Delta|y|<0}}{N^{\Delta|y|>0} + N^{\Delta|y|<0}} \quad \Delta|y| = |y_t| - |y_{\bar{t}}|$$

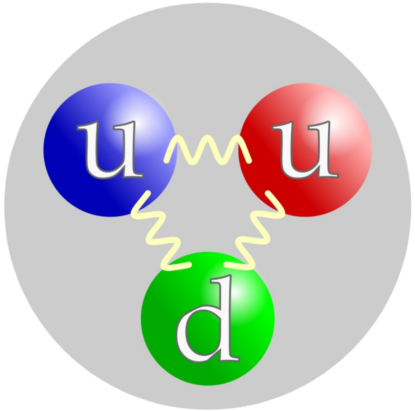
$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y_{t\bar{t}} > 0) - N(\Delta y_{t\bar{t}} < 0)}{N(\Delta y_{t\bar{t}} > 0) + N(\Delta y_{t\bar{t}} < 0)} \quad \Delta y_{t\bar{t}} = y_t - y_{\bar{t}}$$





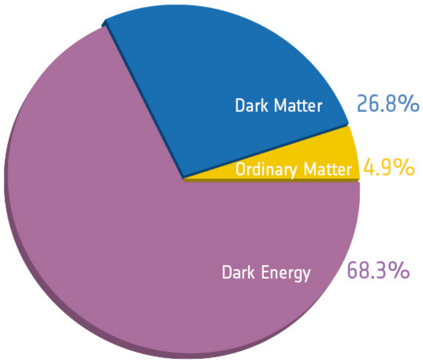


PLB 800 (2020) 135042

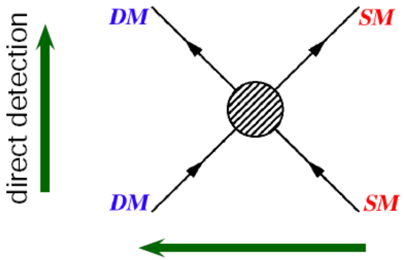


- Measure the ratio of top and anti-top t-channel production cross-section
  - Ratio of integrated u/d quark parton distribution function

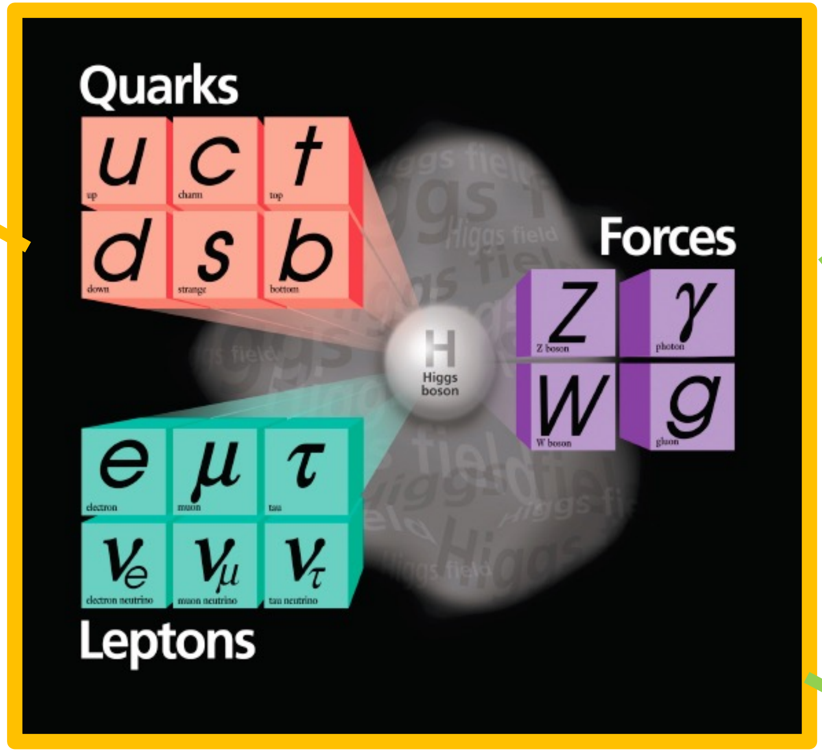
New physics opportunity at Energy Frontier



thermal freeze-out (early Univ.)
indirect detection (now)



production at colliders

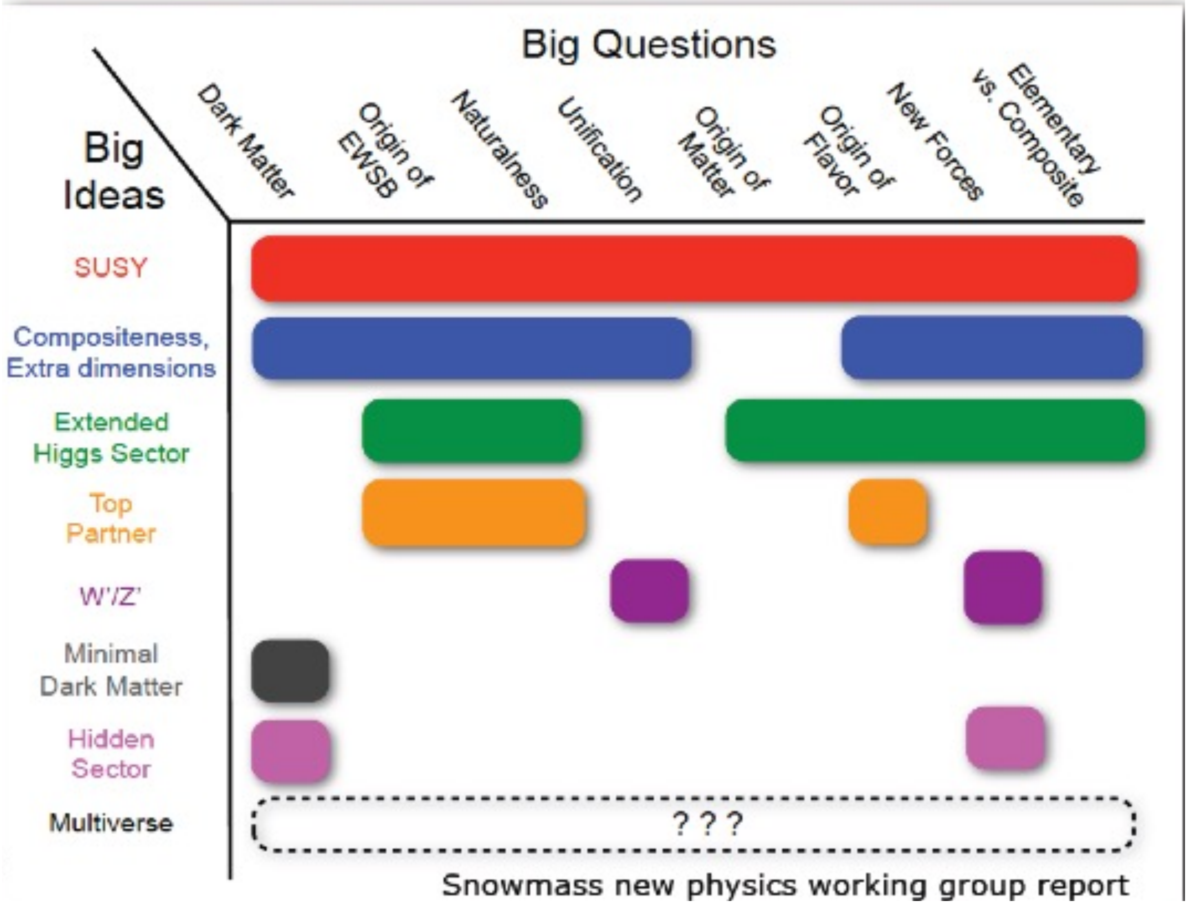


Direct search for new physics signals

Acc. Measurement for deviation of SM process

Why NP beyond SM?

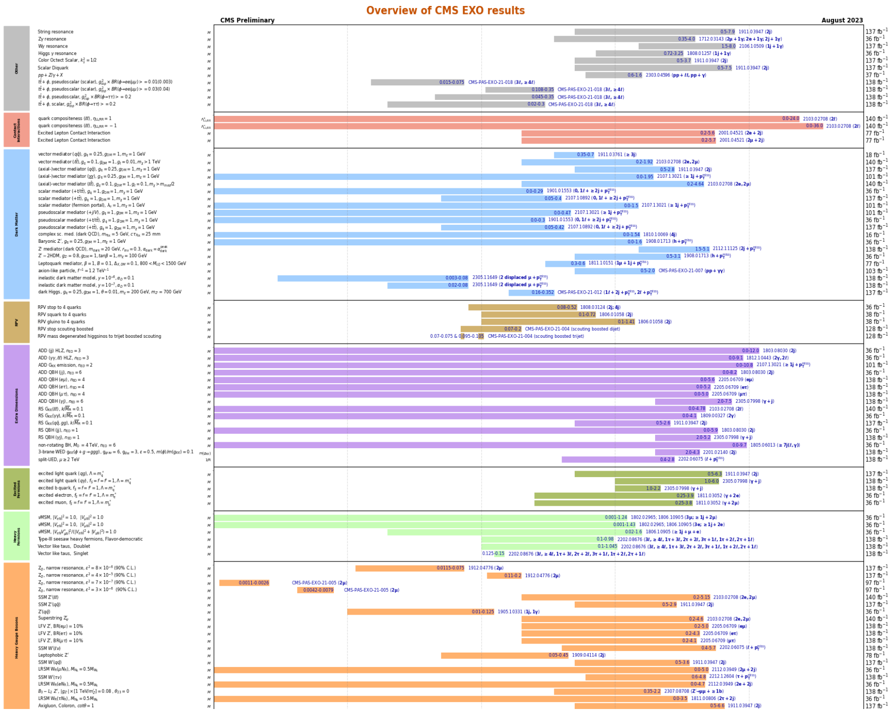
- Origin of flavor sym.
- Vacuum stability?
- Naturalness
- Dark Matter?
- CP violation?
- 。。。

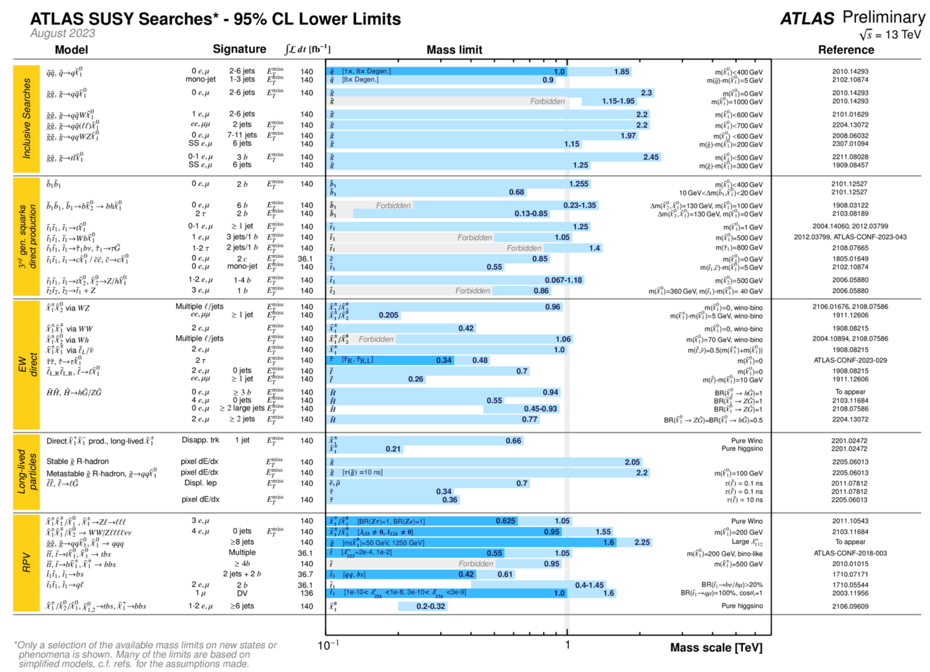


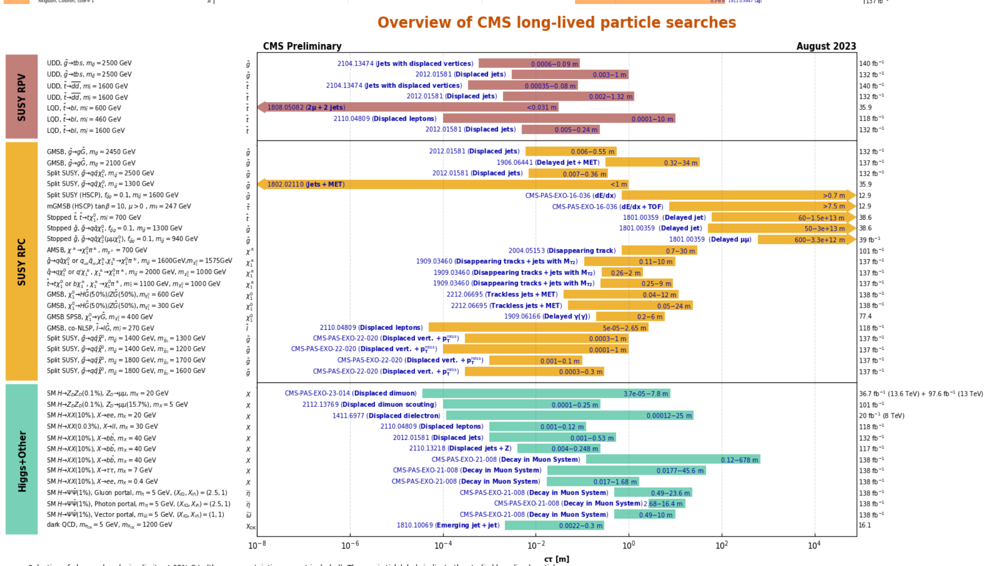
14 TeV Center of mass energy(highest manmade) provide unique opportunity

Advanced detector is the key to catch up these physics opportunity at LHC

Current status of new physics searches



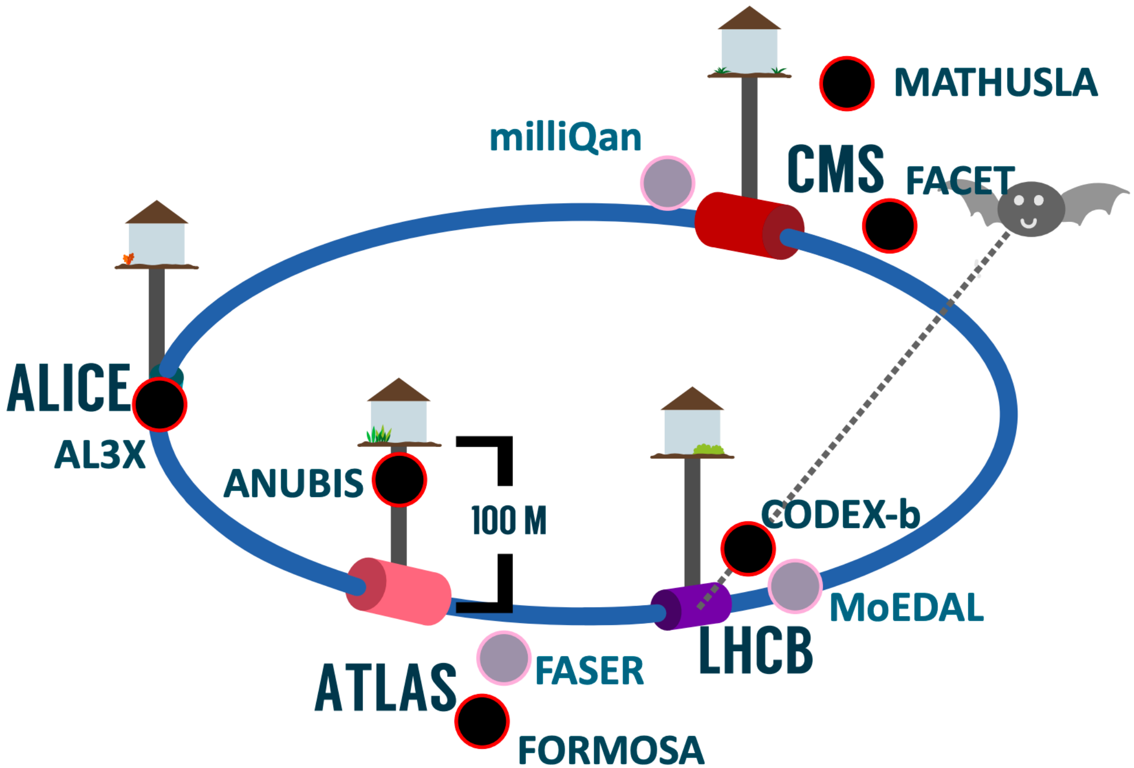




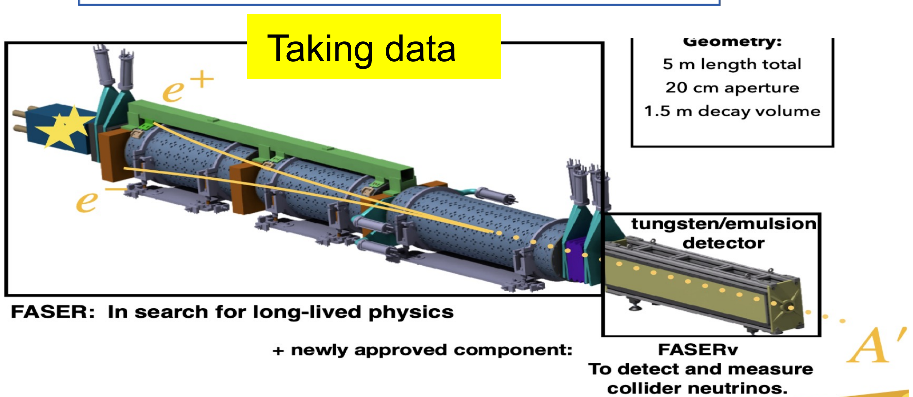
Exotics, SUSY, Long Lived Particles…

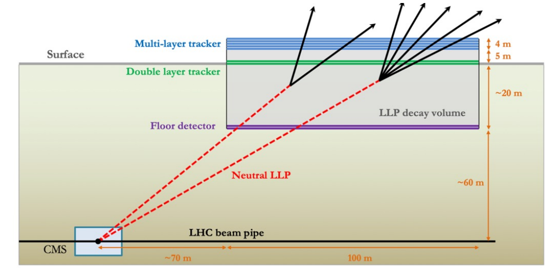
So far no hits yet
But still large phase space for new physics

Proposed new LLP search detectors

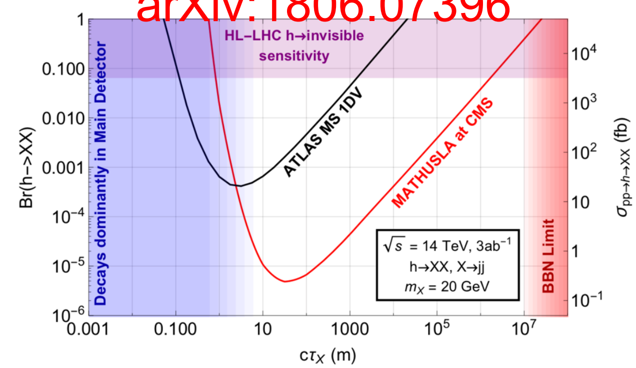


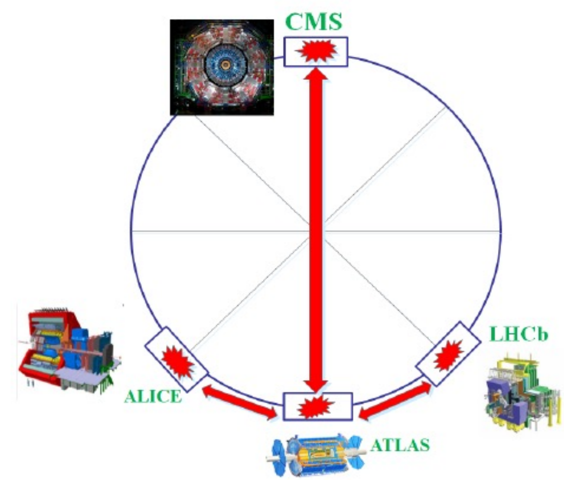
pp → LLP + X, LLP travels ~ 480m, LLP → $e^+e^-, \mu^+\mu^-, \pi^+\pi^-, \gamma\gamma, \ldots$





arXiv:1806.07396

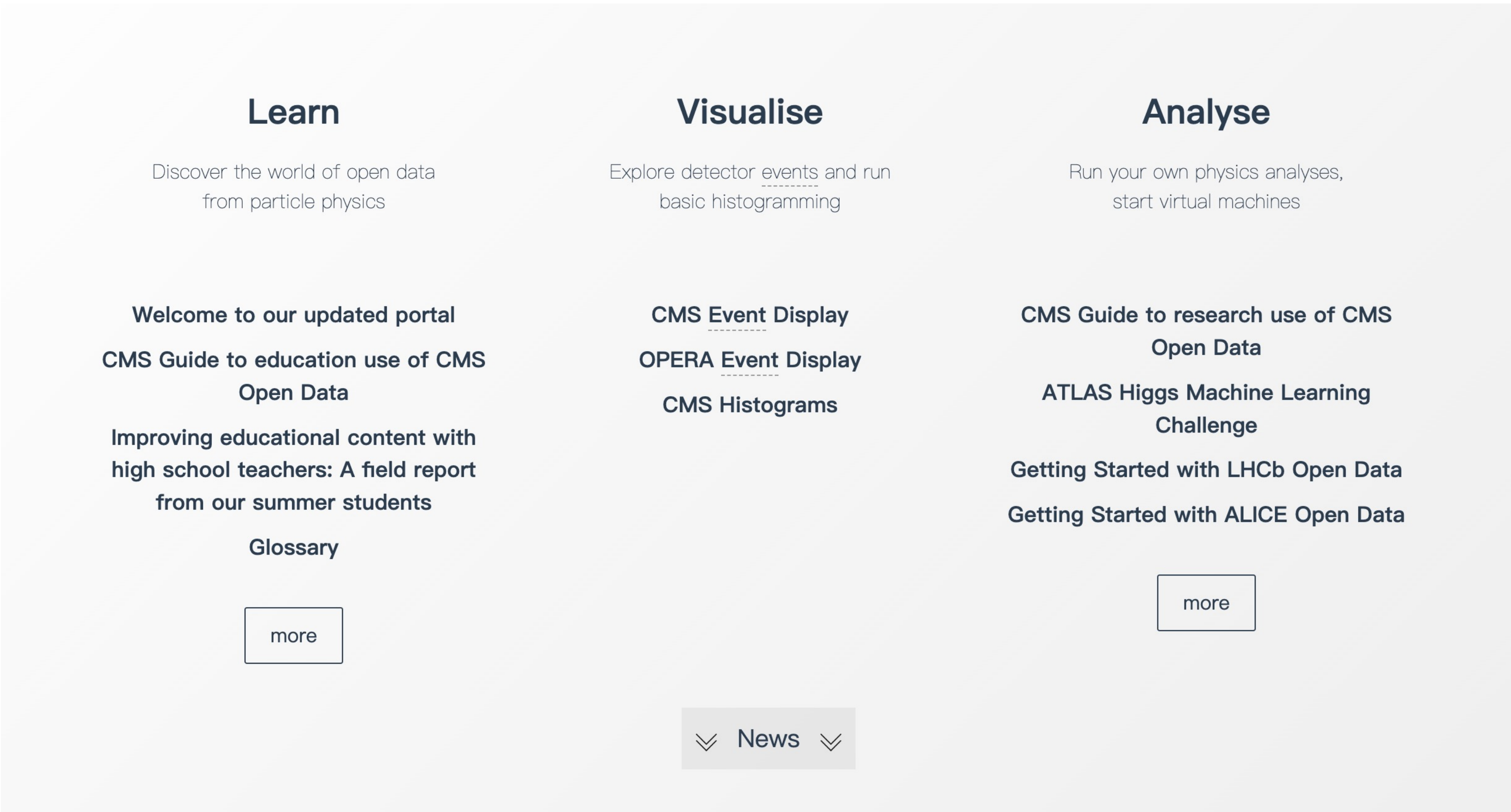




arXiv:2004.08820

CERN Open data

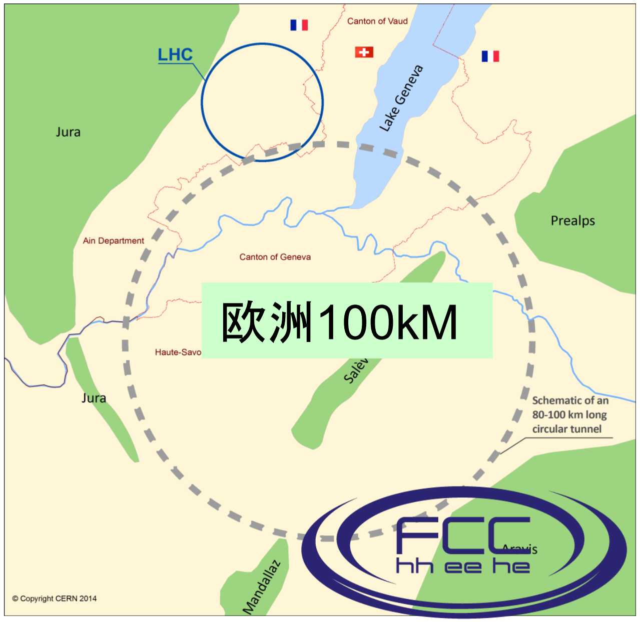
- Open collision data to public
- Detail tool/documentation for analysis these data



https://opendata.cern.ch/

物理展望

- 未来15年左右，LHC将新获取20倍现有数据的数据

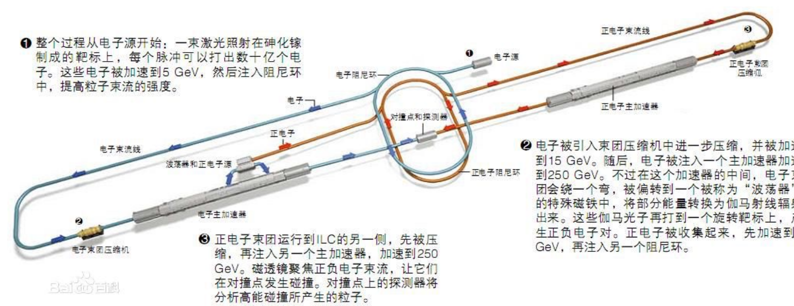


Future Collider Options for the US

P. C. Bhat*, S. Jindariani†, G. Ambrosio, G. Apollinari, S. Belomestnykh, A. Bross, J. Butler, A. Canepa, D. Elvira, P. Fox, Z. Gecse, E. Gianfelice-Wendt, P. Merkel, S. Nagaitsev, D. Neuffer, H. Piekarz, S. Posen, T. Sen, V. Shiltsev, N. Solyak, D. Stratakis, M. Syphers, G. Velev, V. Yakovlev, K. Yonehara, A. Zlobin

Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA

March 16, 2022

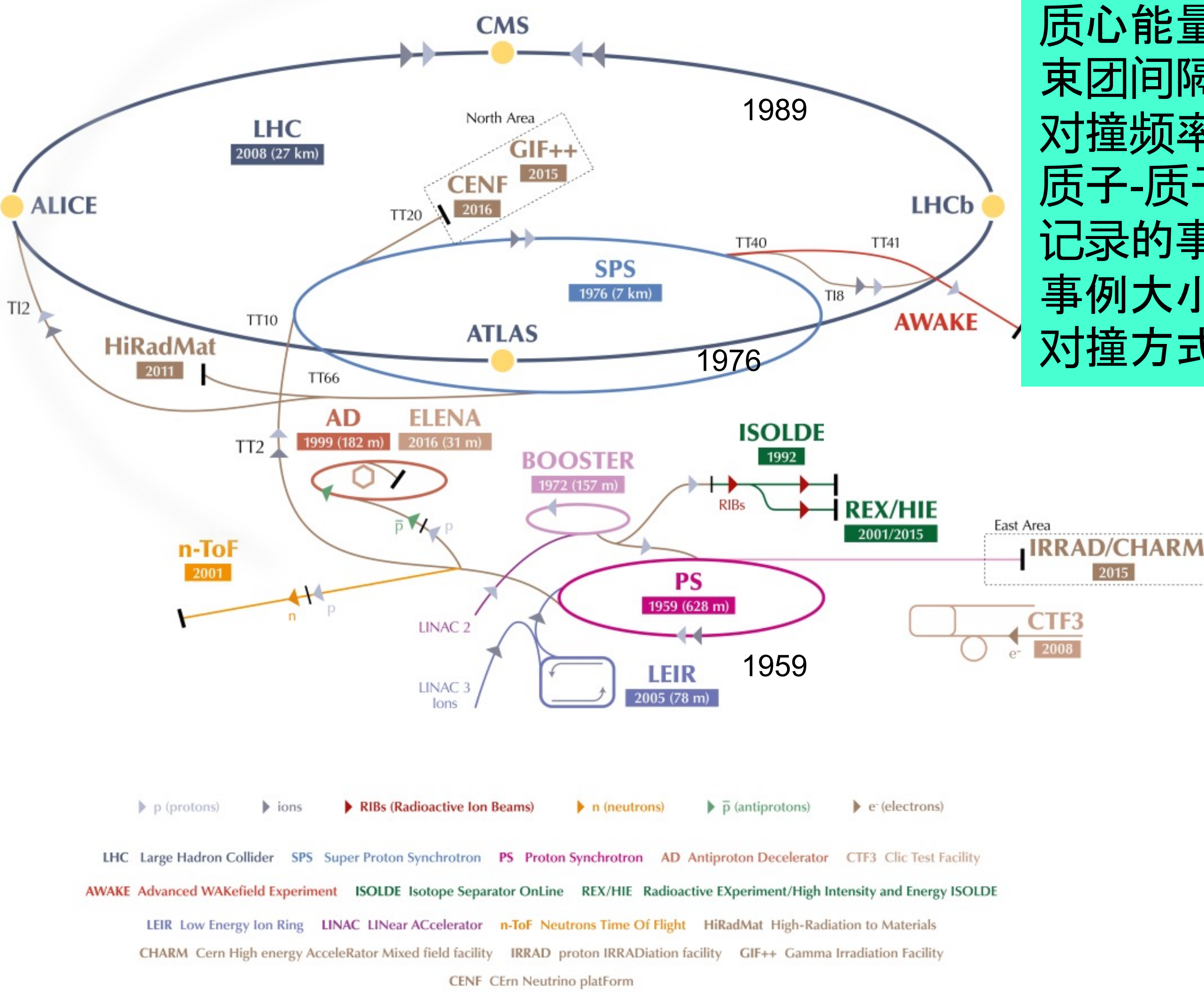


美国 snow mass 2022：正负电子/质子，谬子对撞机，直线对撞机

日本直线11-30Km

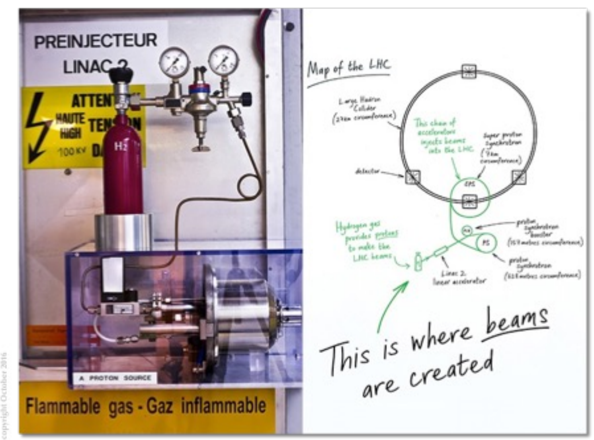
LHC和CERN

LHC 加速器系统



高能量前沿

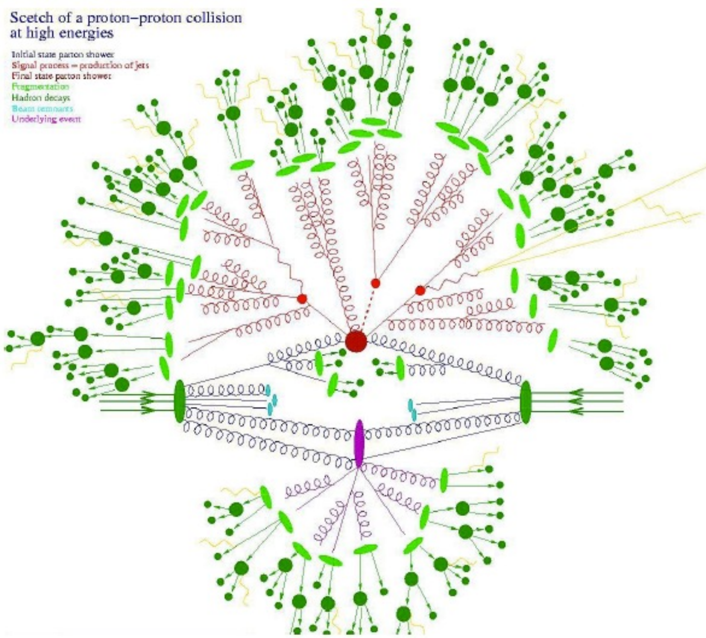
- 质心能量：0.9,2.36,7,8，13/14 TeV
- 束团间隔: 50 - 25 纳秒
- 对撞频率: 2000万-4000万/ 秒
- 质子-质子对撞: 20亿次 /秒
- 记录的事例: ~1000 - 3000 / 秒
- 事例大小：1-2 MB
- 对撞方式：p-p;pb-pb;p-pb;Xe-Xe…



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

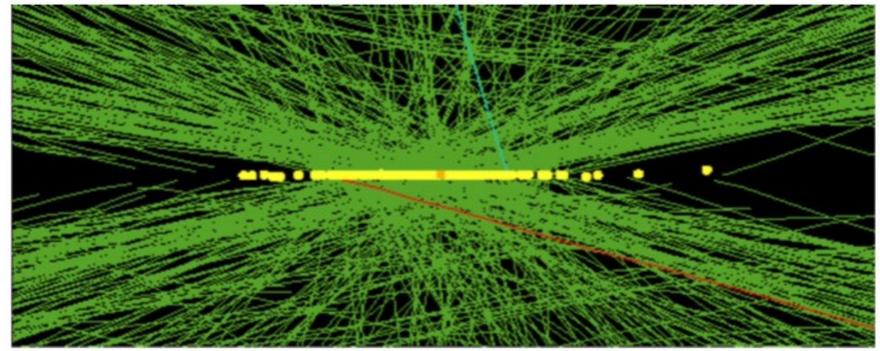
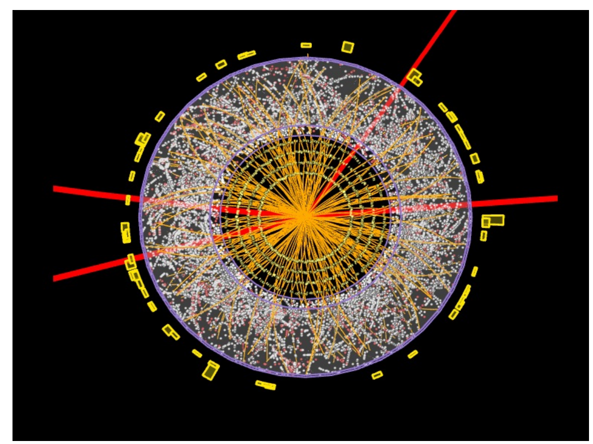


Figure 1.16: High pileup event with 78 reconstructed vertices taken in 2012

LHC CMS实验中的一次束团对撞

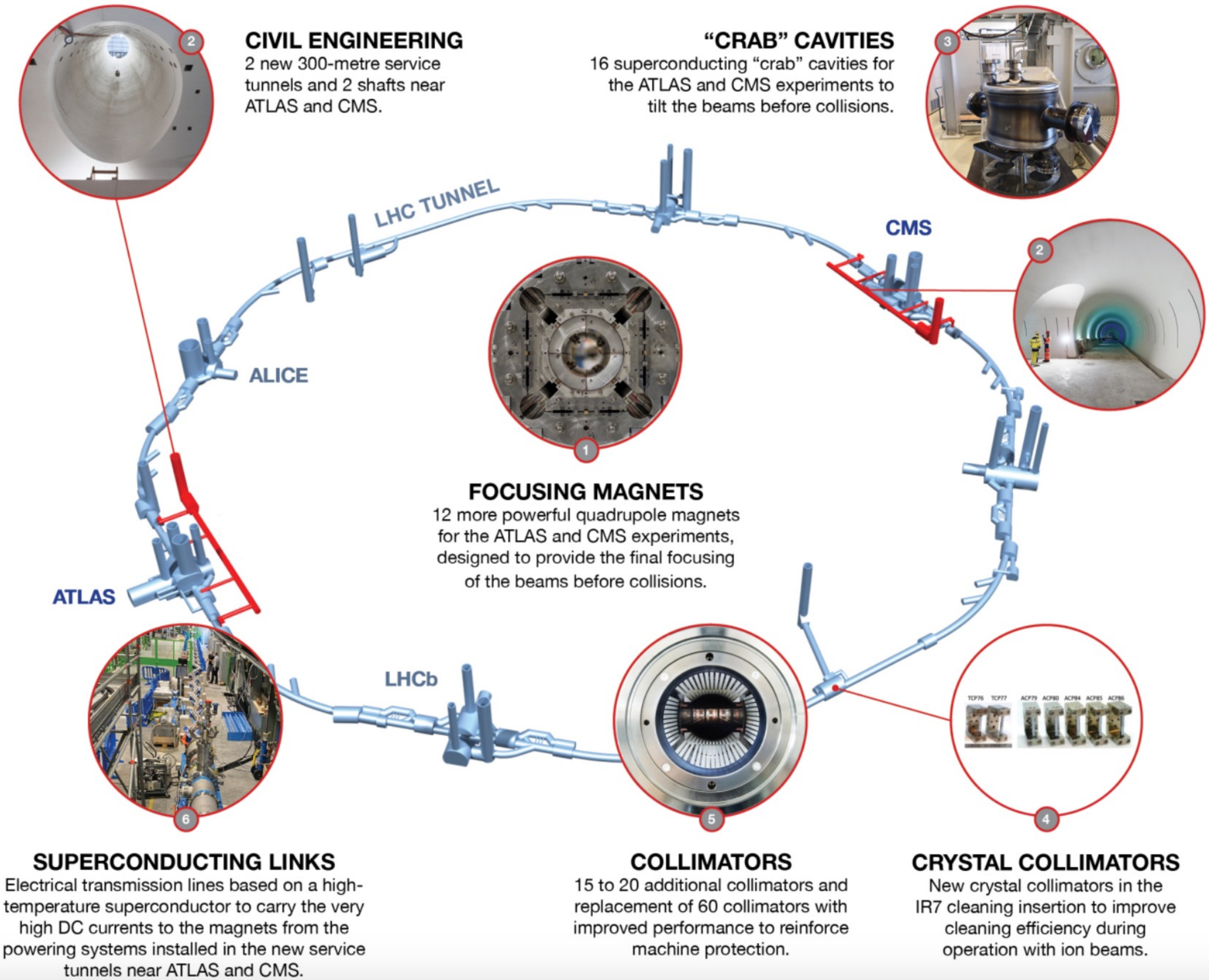


每秒对撞4000万次@～20年

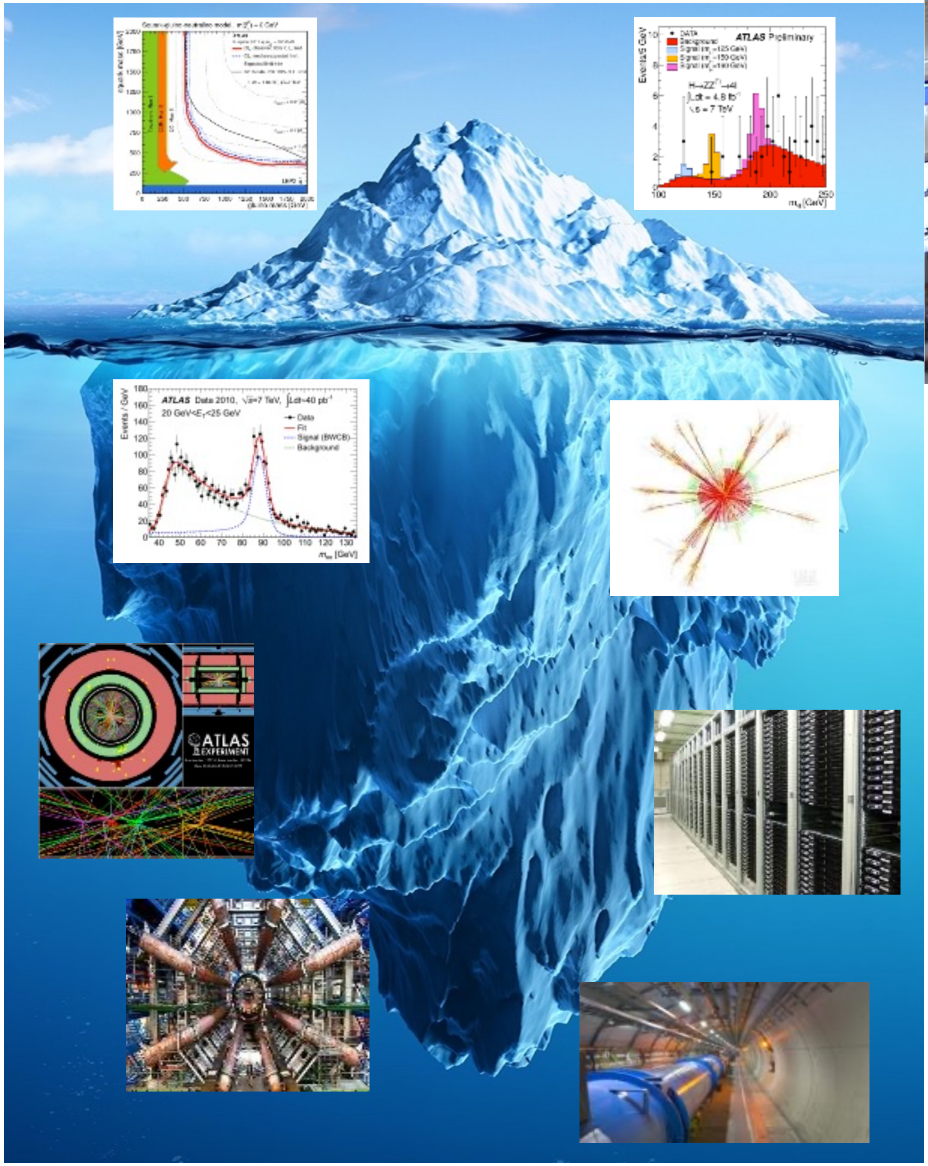
- 借我一双慧眼，让我把这纷扰看的清清楚楚明明白白真真切切

LHC phase II upgrade overview

NEW TECHNOLOGIES FOR THE HIGH-LUMINOSITY LHC

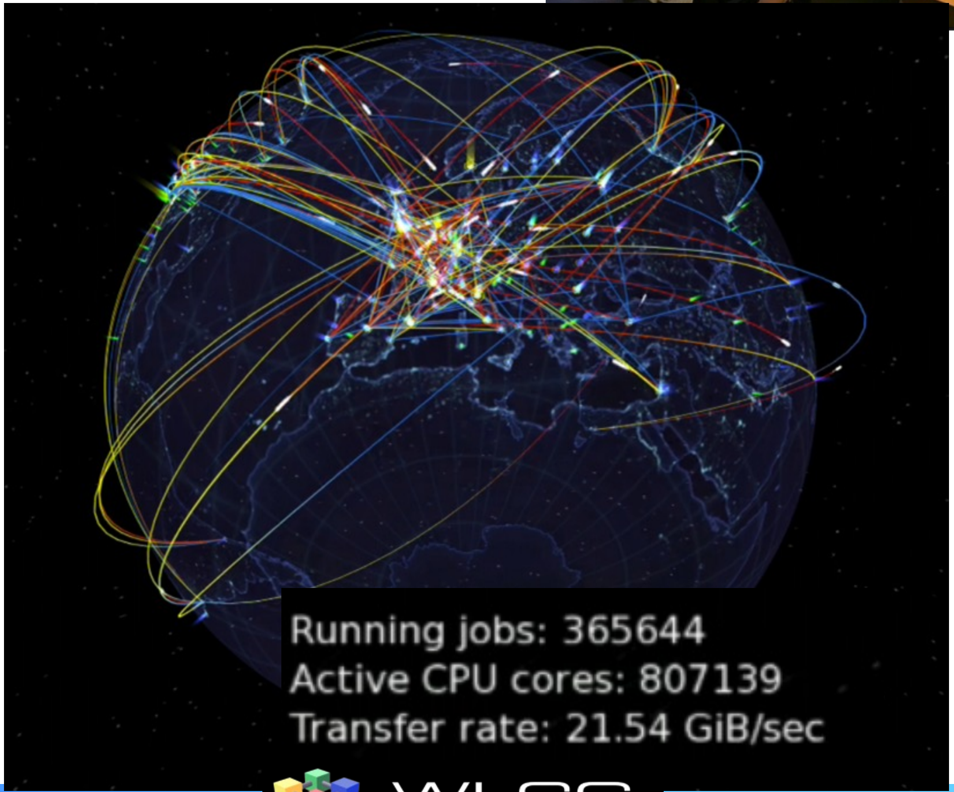


物理成果的背后



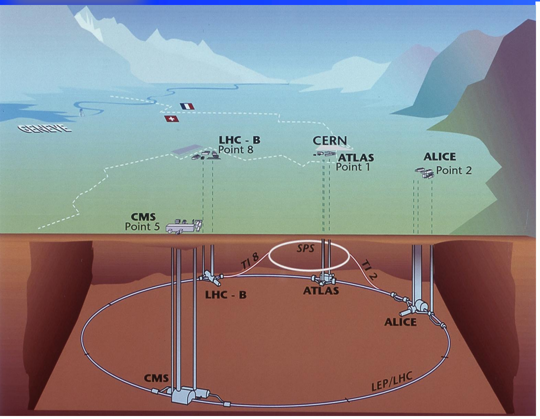
CMS运行控制室 - 值班监控等

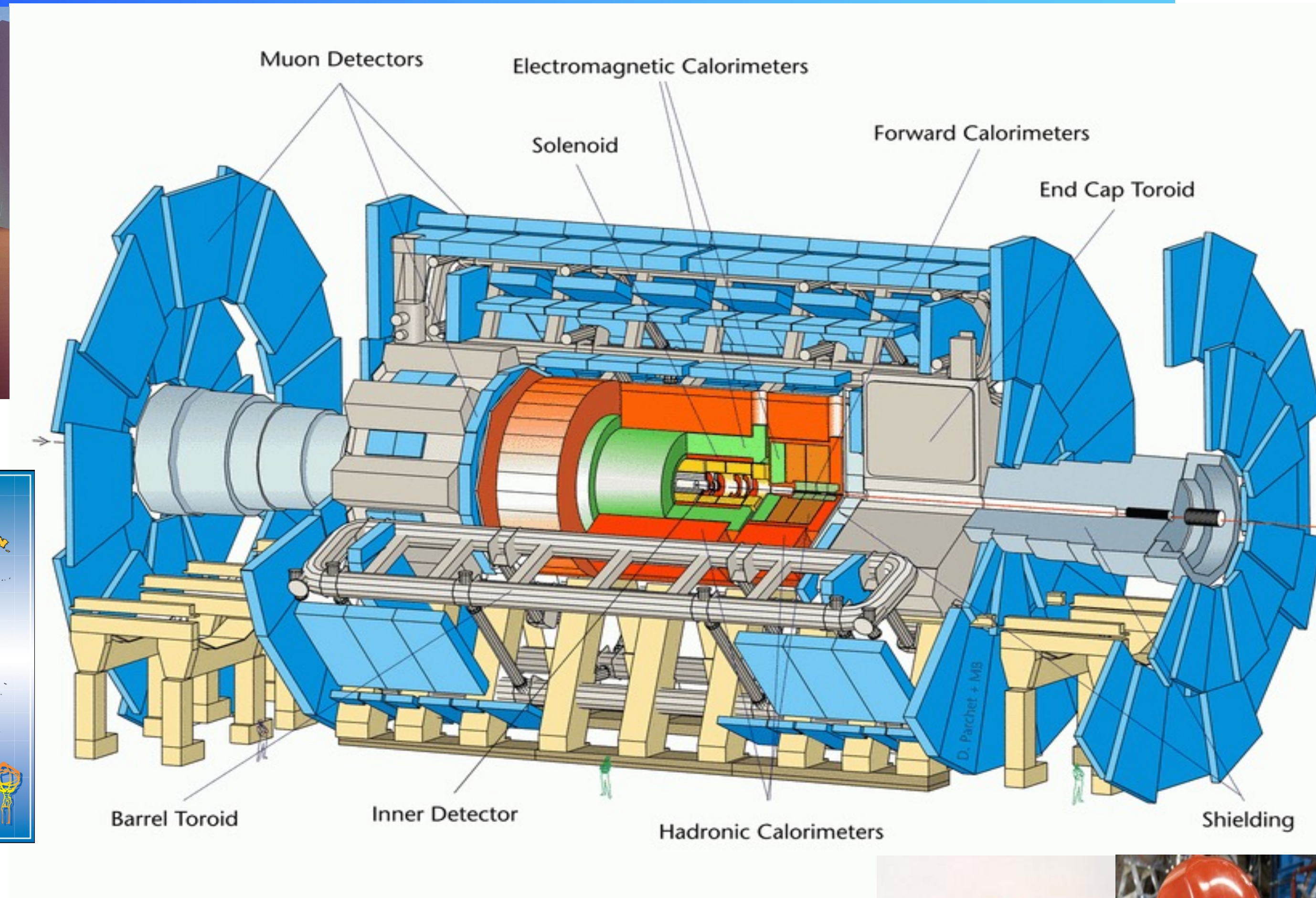
ATLAS运行控制室



WLCG
Worldwide LHC Computing Grid

ATLAS experiment

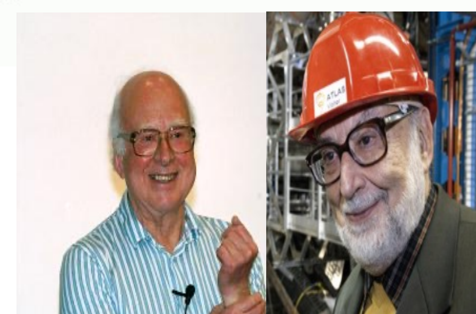




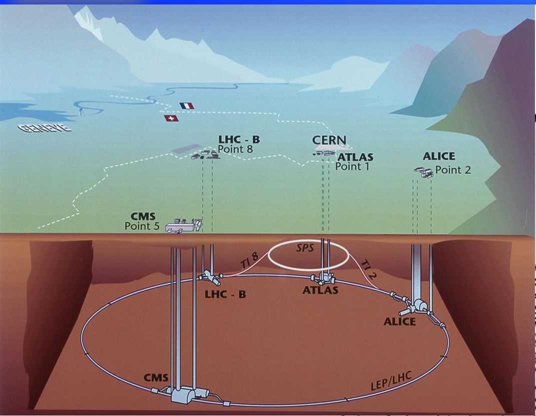
Largest detector

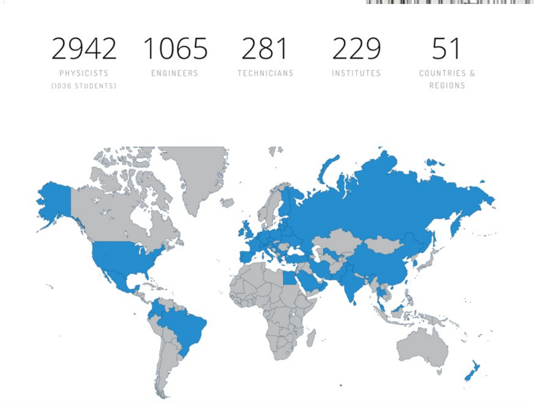
直径25米
长40米

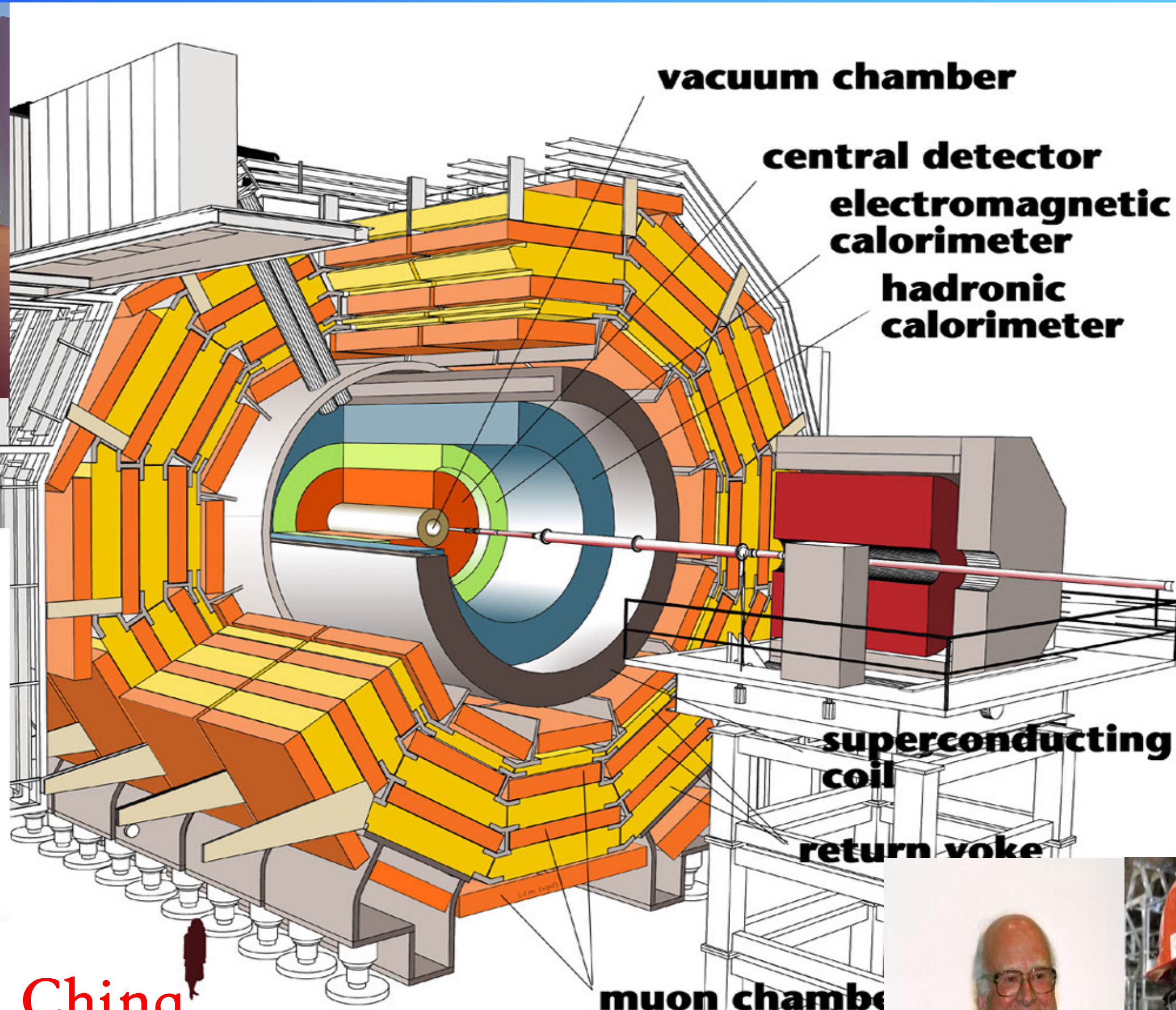
China
Muon/ITK/HGTD



CMS (compact muon solenoid) experiment







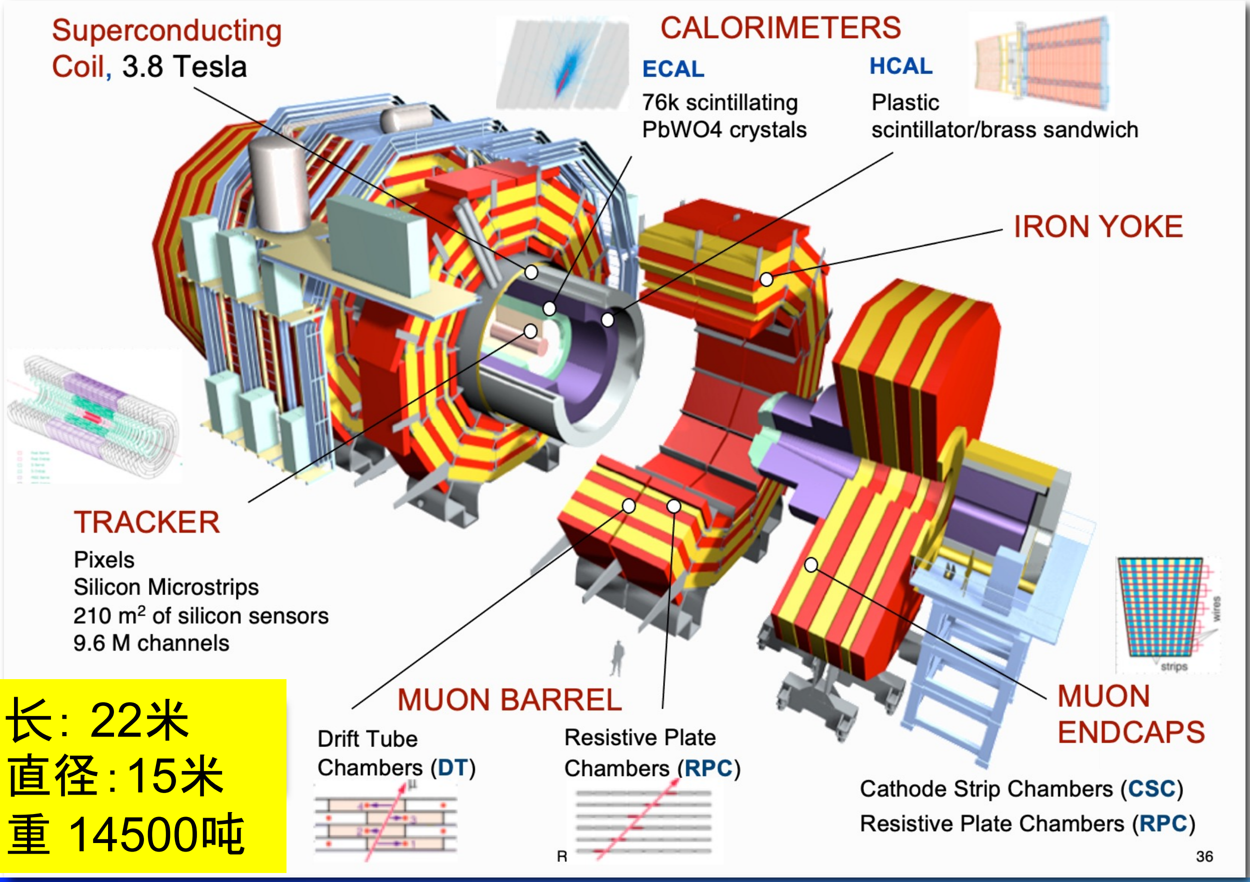
Heaviest detector

Detector characteristics

Width: 22m
Diameter: 15m
Weight: 14'500t

China
RPC/CSC
GEM/Trigger/HGCal

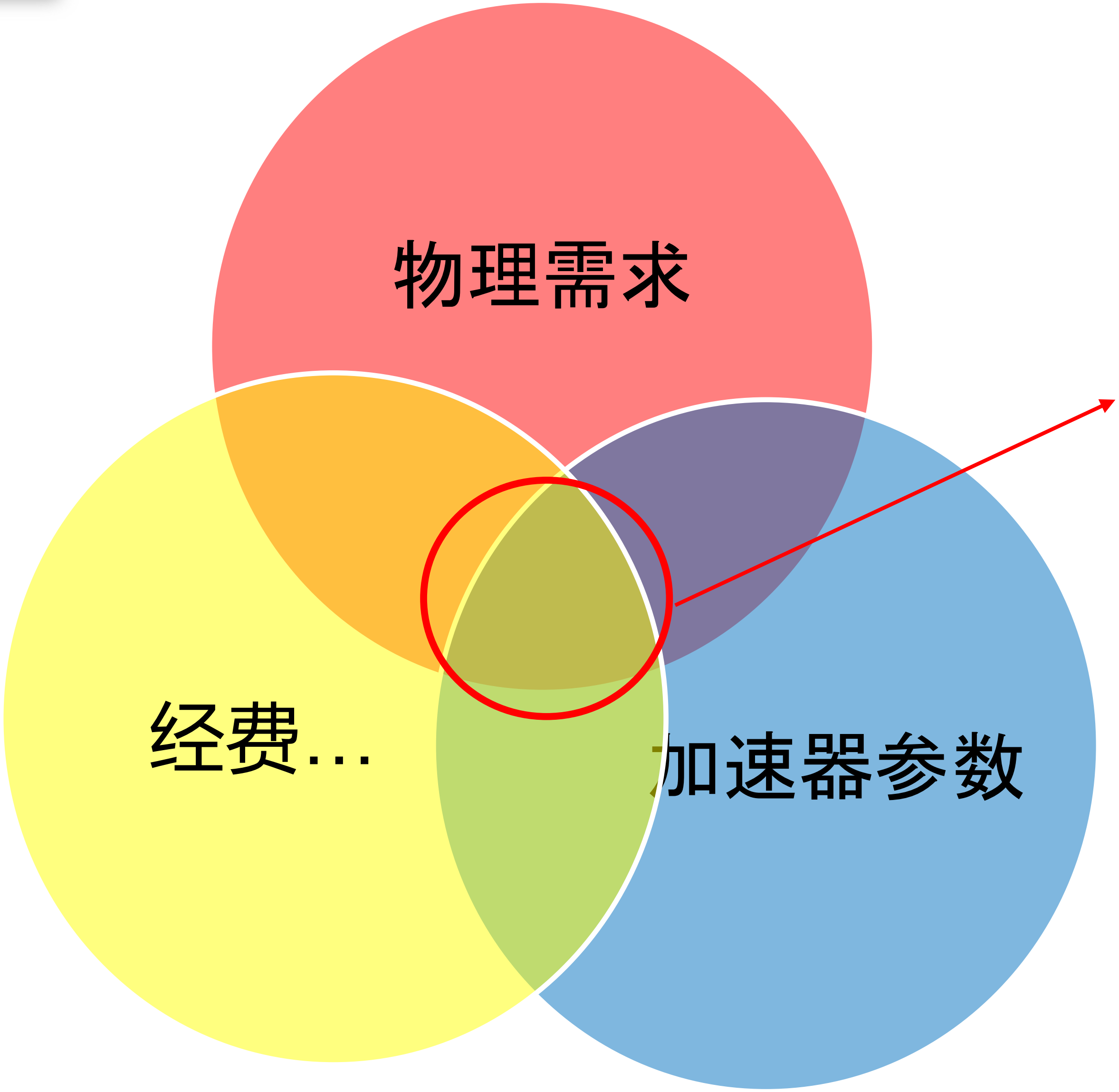
- CMS：Compact Muon Solenoid（紧凑谬子螺线管）
  - 1990 Aachen: 提出基于高磁场强度的紧凑性探测器设想
  - 1992 Evian：概念设计报告
  - 2008 首次LHC数据取数

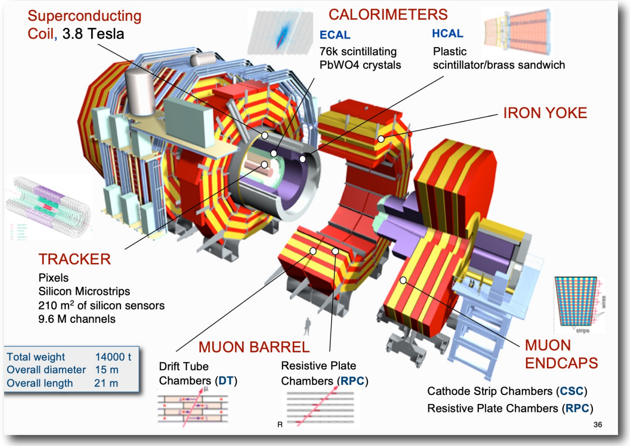


长：22米
直径：15米
重 14500吨

- 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，山大，华南师大
- 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

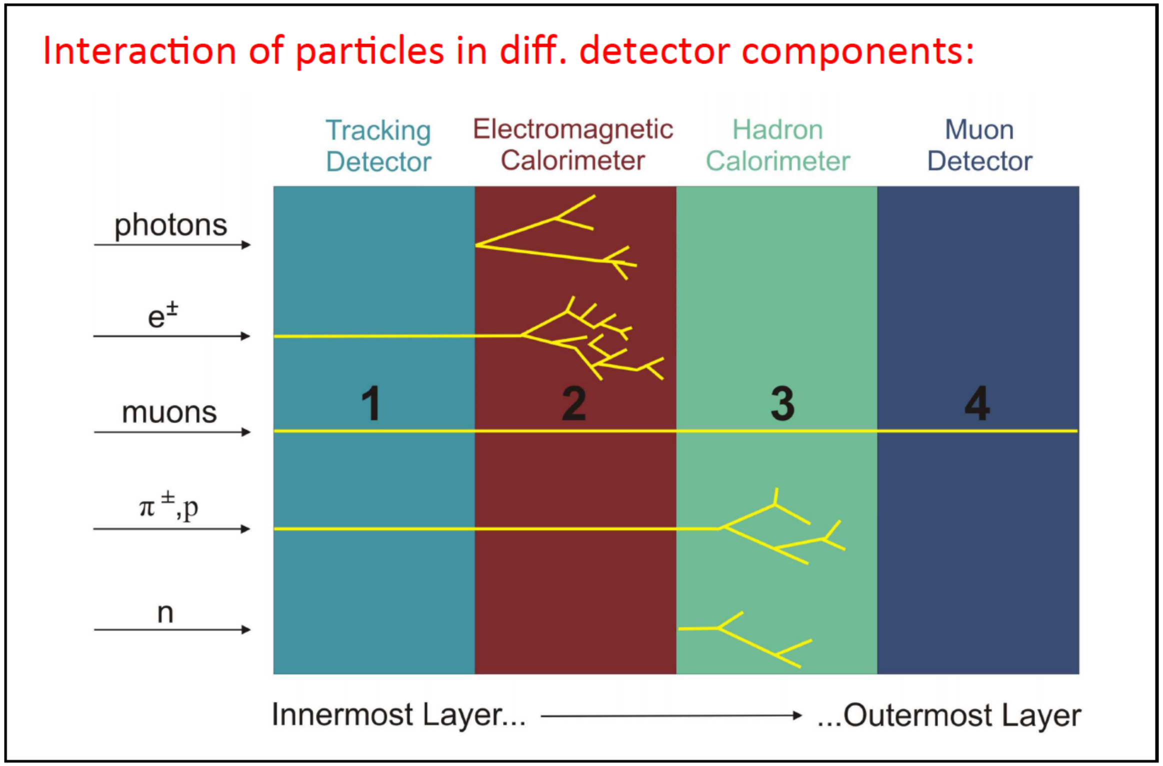
为什么CMS探测器如此设计建造





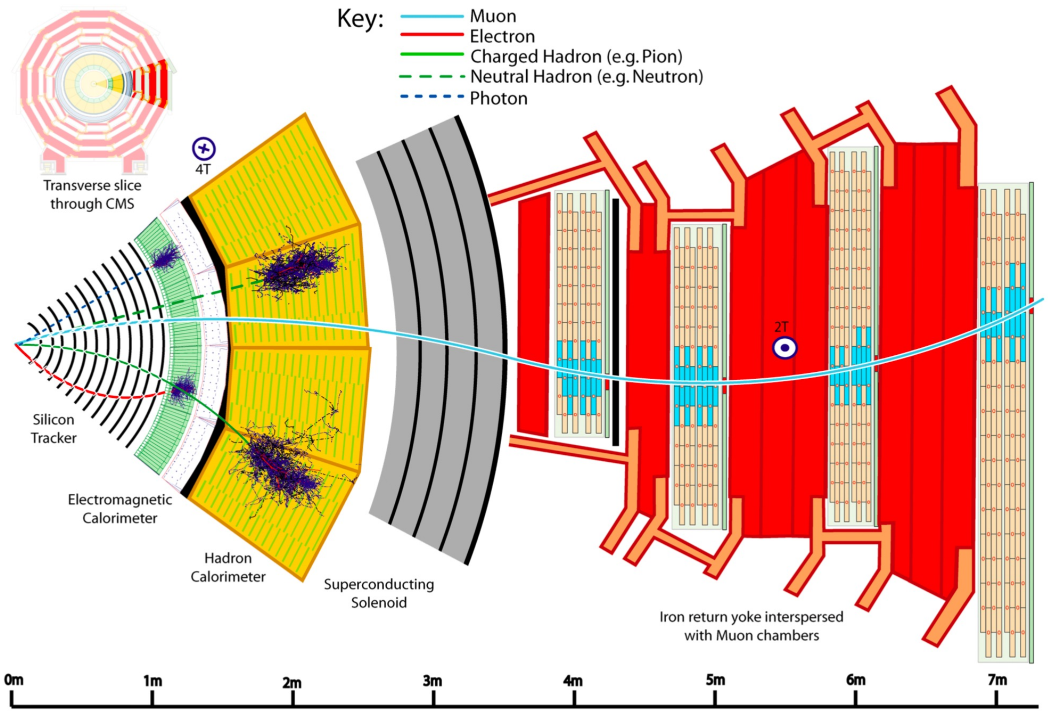
探测器的功能

- 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



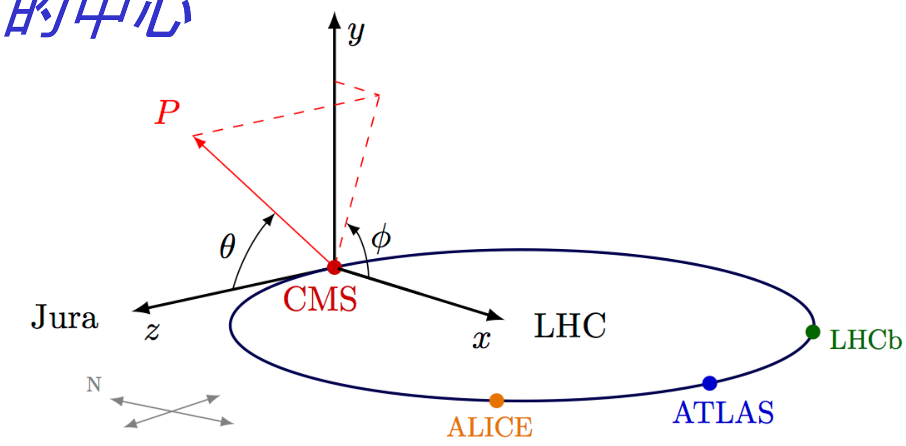
CMS探测器谱仪

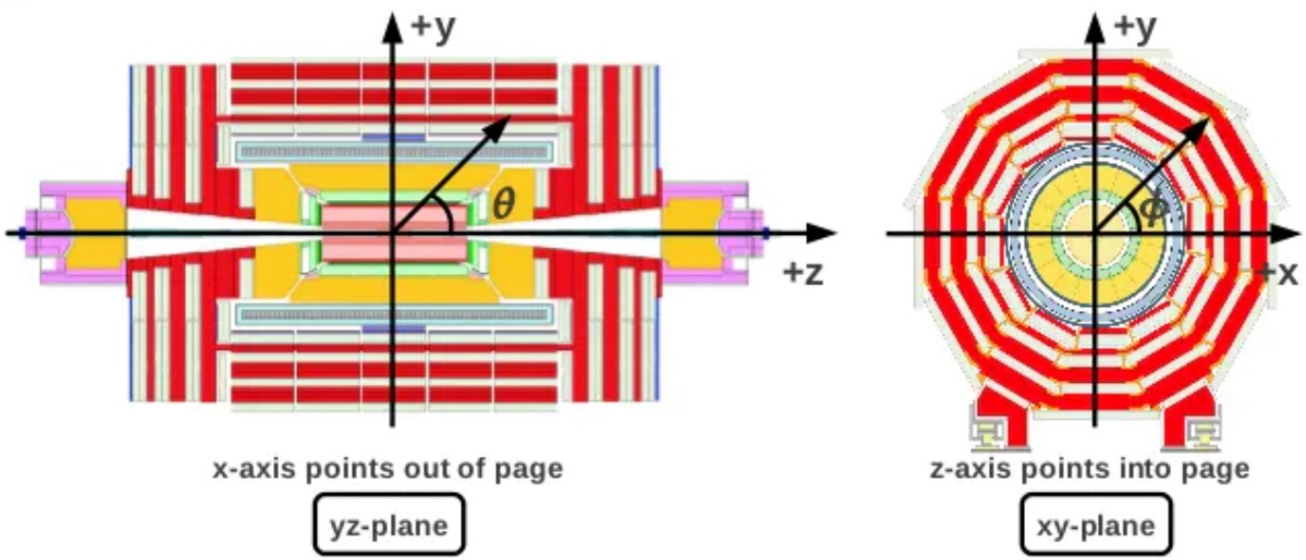
- CMS主要探测：电子，光子，谬子，喷注等（带电/中性粒子）
  - 在大空间范围，大动量范围内有好的单个谬子鉴别和动量、角度分辨；好的的双谬子质量分辩（1%@100GeV）；在<1TeV动量下有好的电荷符号鉴别
  - 好的带电径迹的动量分辨和重建效率，探测径迹的IP，鉴别b-喷注
  - 好的电磁能量分辨率和双电子/光子质量分辨（1%@100GeV），π0 分辨，光子鉴别，孤立化鉴别（电磁量能器）
  - 好的丢失横动量和双喷注能量分辨（强子量能器）



CMS 坐标系系统

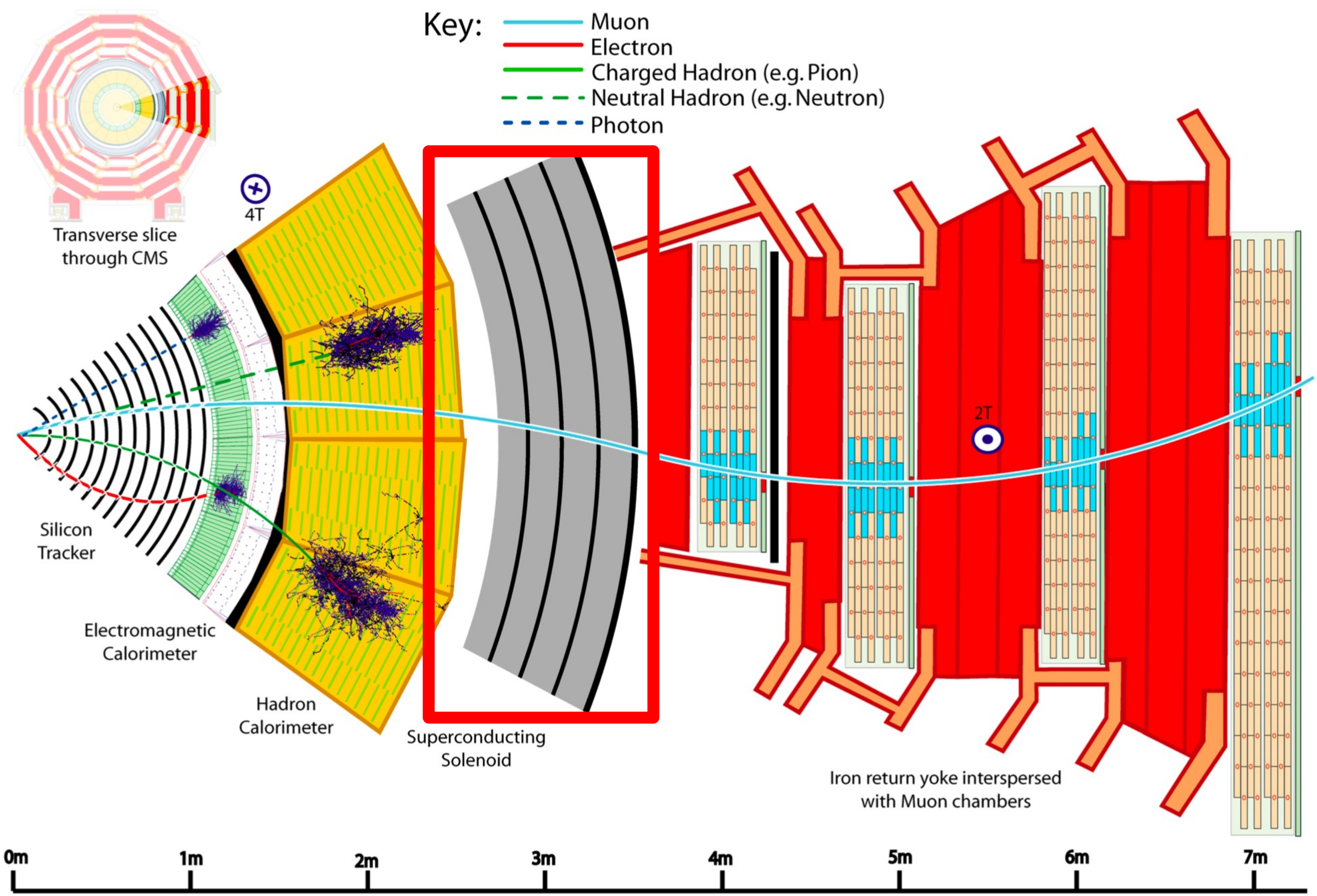
- *X轴：LHC环的平面内，指向LHC的中心*
- *Y轴：朝上垂直于LHC环的平面*
- *Z轴：和X，Y行成右手坐标系*
- *θ：极角*
- *η = −ln[tan(θ/2)]：赝快度*
- *φ*





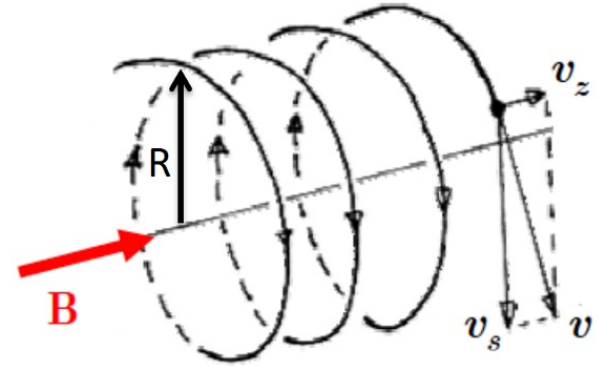
$$\eta = -\ln\left(\tan\left(\theta/2\right)\right) \qquad \Delta\phi = \phi_2 - \phi_1 \qquad \Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$

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

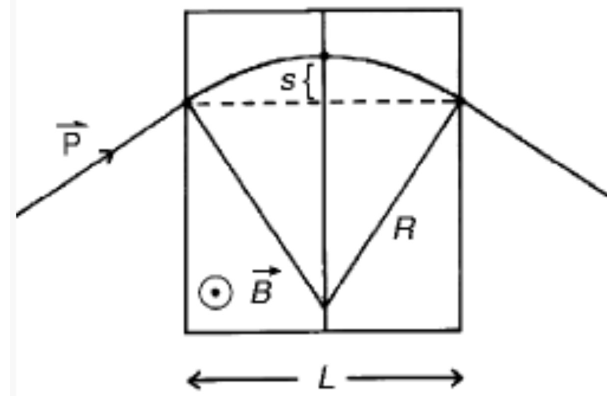

Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Transverse slice through CMS
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0m
1m
2m
3m
4m
5m
6m
7m

- 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：

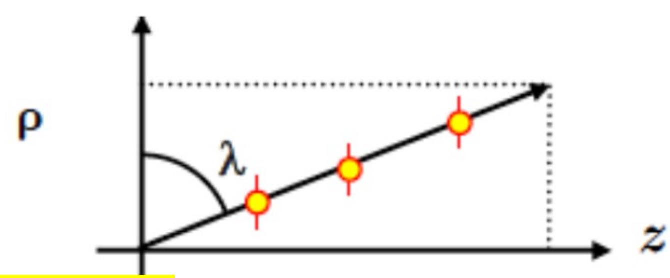
$$R = \frac{p_\perp}{e\,B} = 3.3\ \mathrm{m} \cdot \frac{p_\perp/(\mathrm{GeV}/c)}{B/\mathrm{T}},$$



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



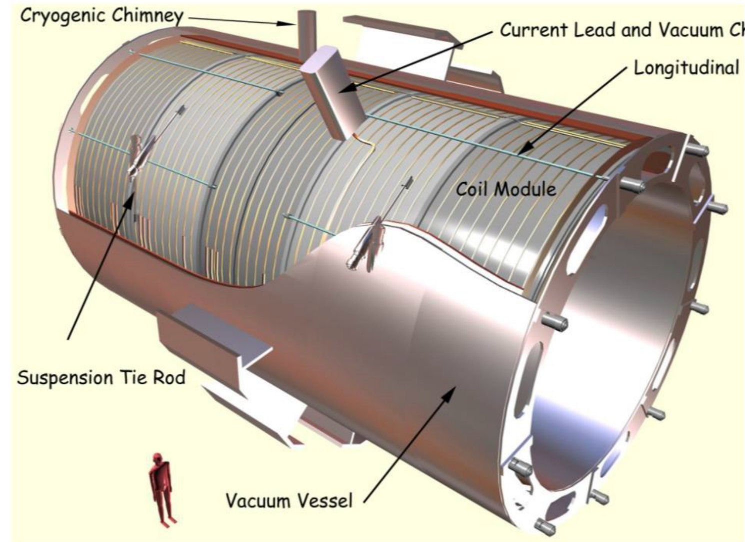
- 总动量的测量：
  - $p = \frac{p_\perp}{\cos\lambda}$

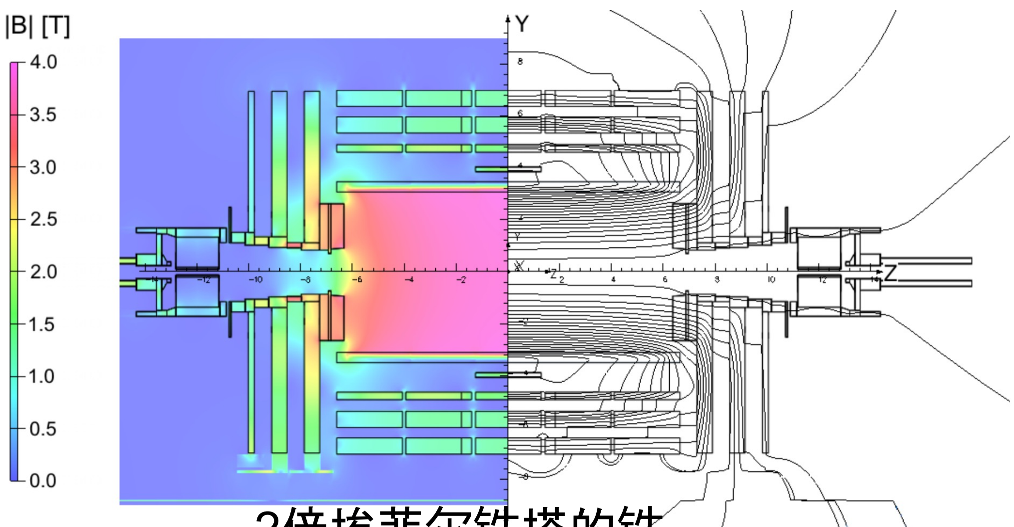


如何改善动量分辨率：增加L^2B，减小$p_\perp$，δs
造价一般正比L^3

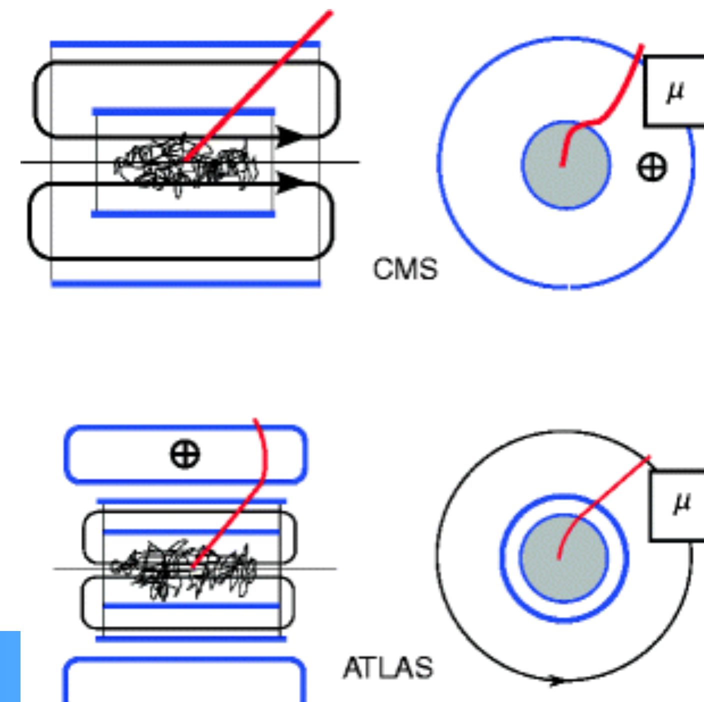
CMS磁铁系统：solenoid

- 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
- 存储了2G焦耳的能量
  - 能融化18吨金

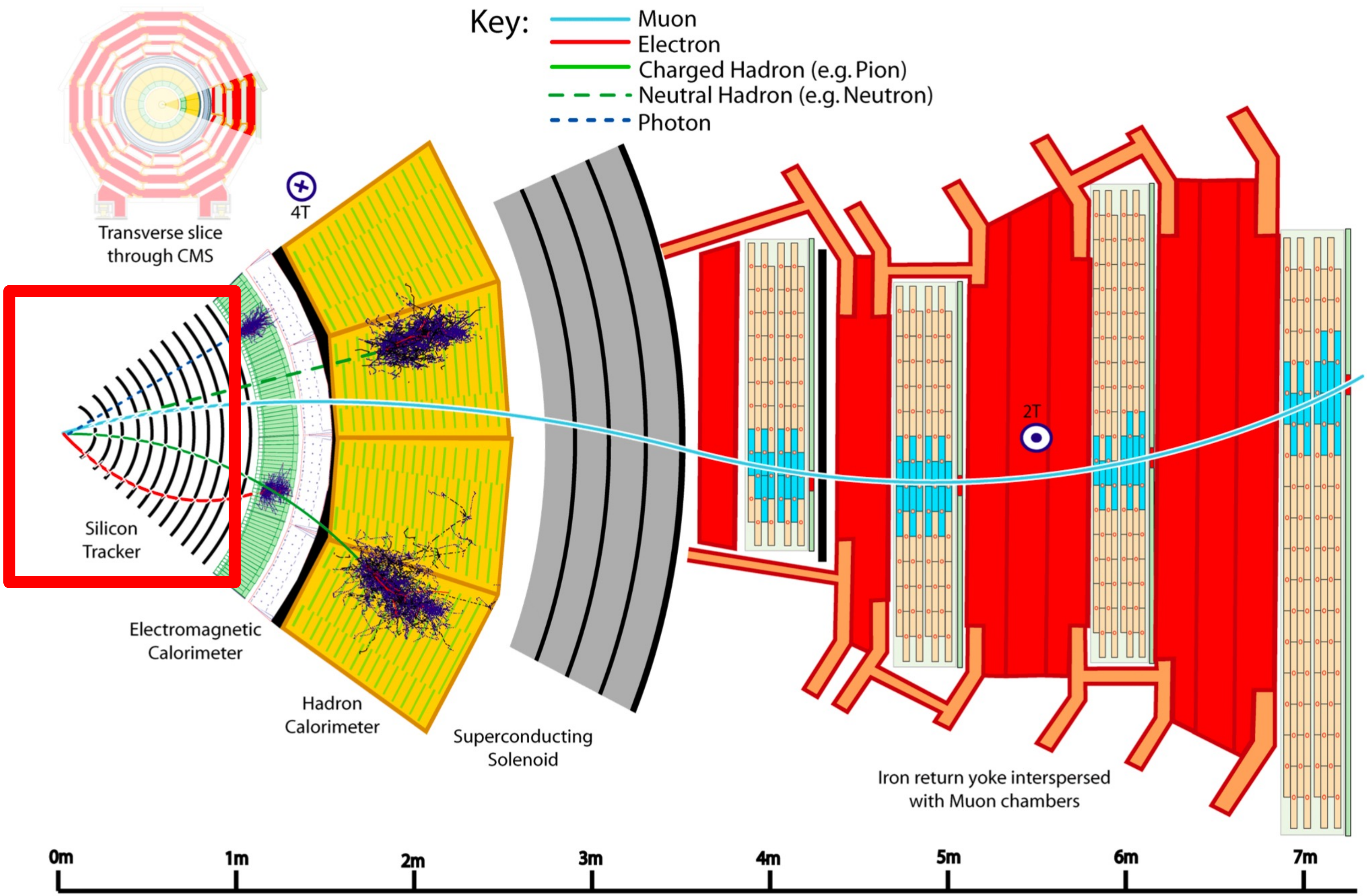


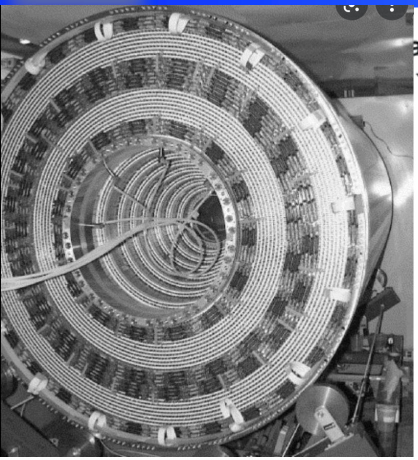


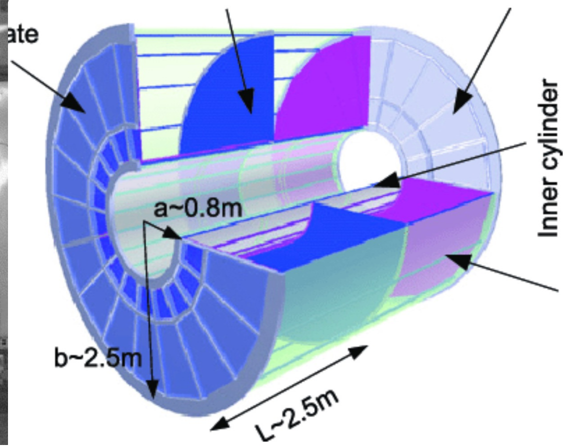
2倍埃菲尔铁塔的铁



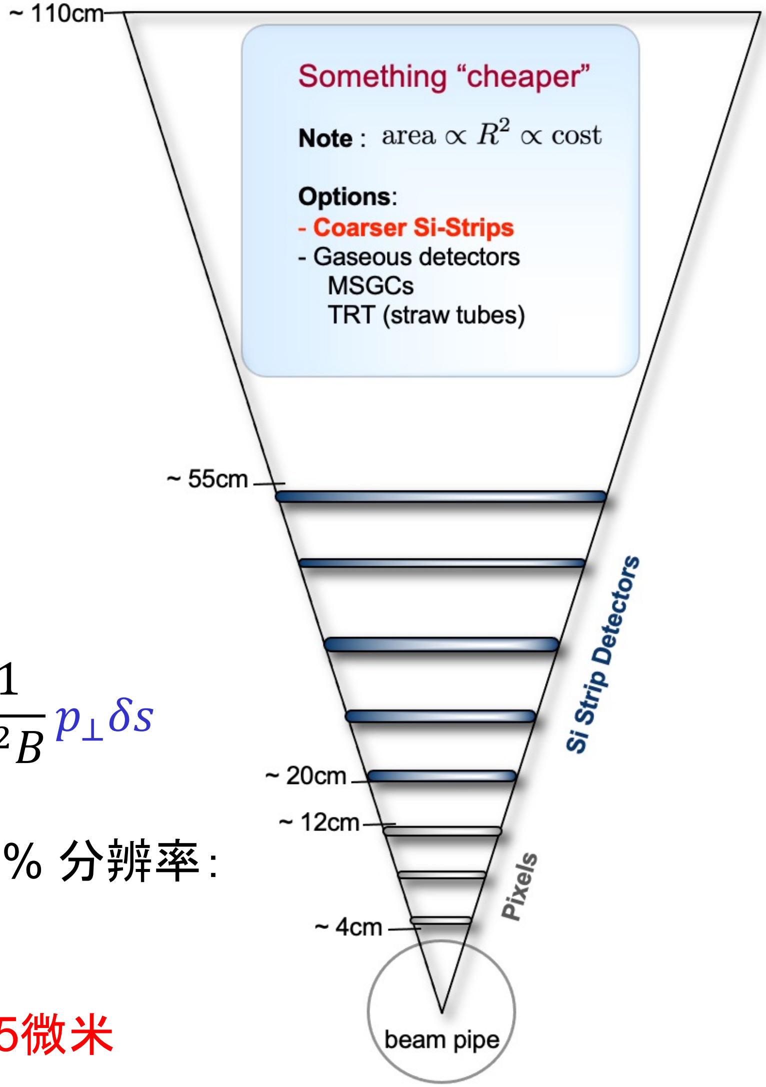
CMS 探测器的设计：内部径迹探测器

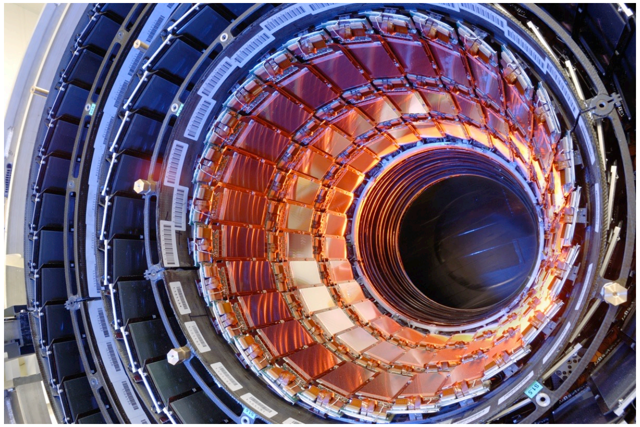






漂移室(BES, CLEO…)　　Alice时间投影室





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

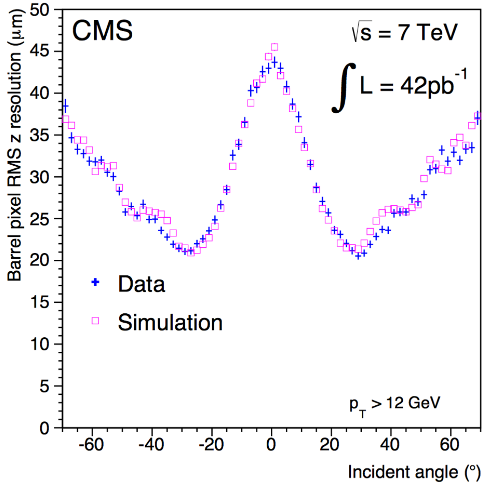
100 GeV $p_\perp$, 1% 分辨率:
L=1米, B～4T

➔位置分辨～15微米

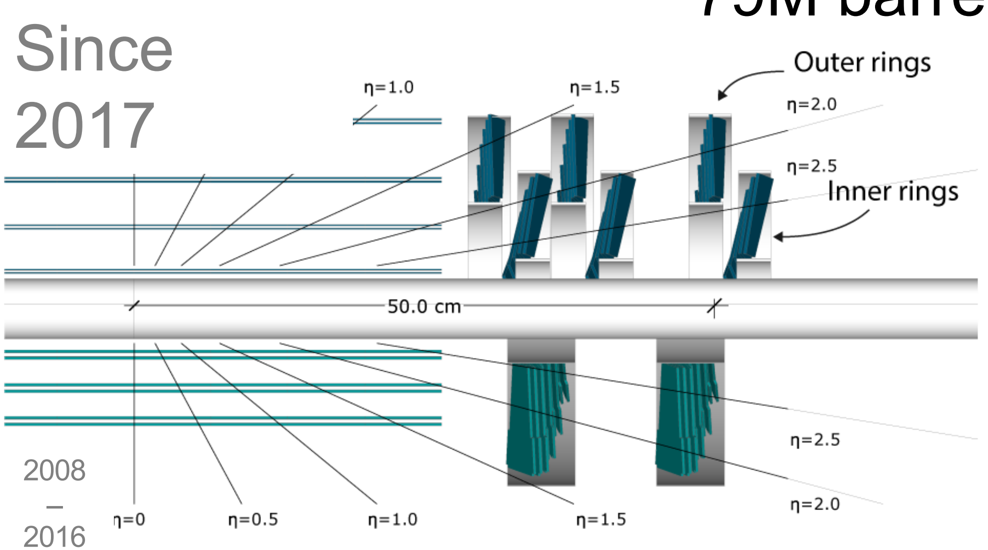
CMS: 全硅径迹探测器

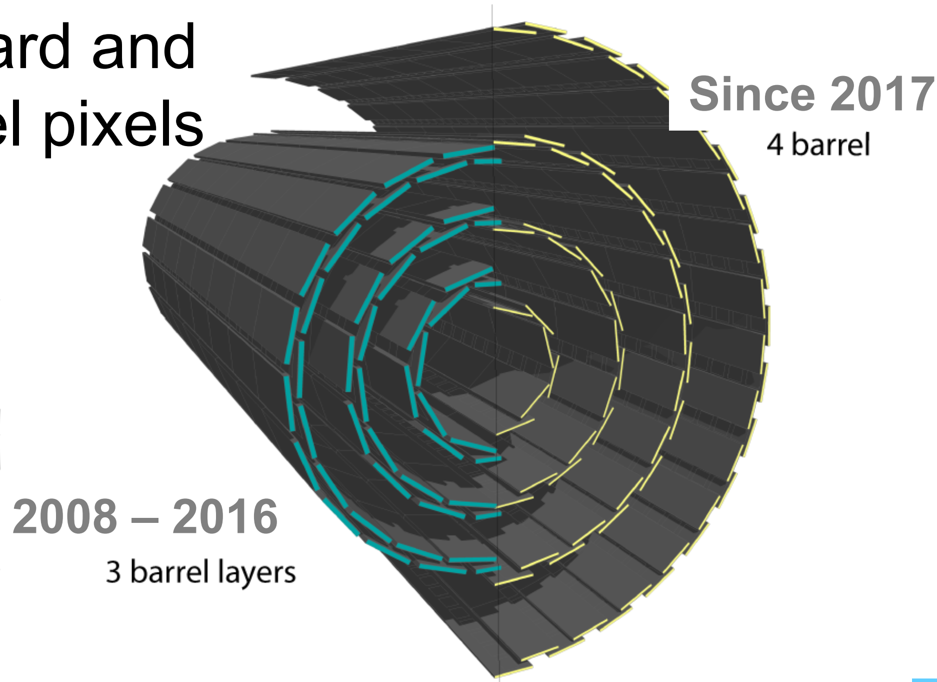
CMS 像素探测器

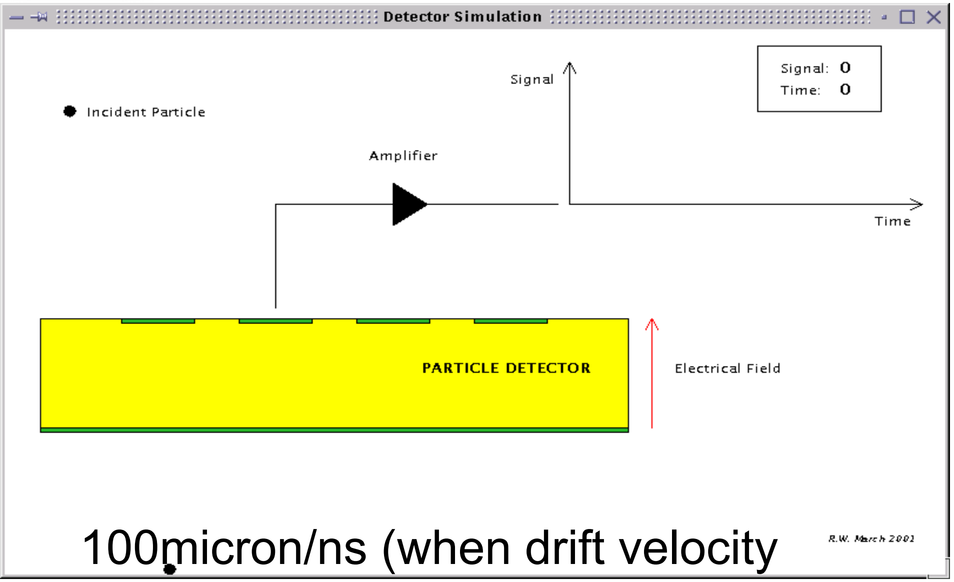
- 100X150 □m² 像素，工作在零下22度，n-in-p 型传感器
- 覆盖了|η|=2.5 的区域
  - 作为寻迹开始的种子，以及探测径迹的顶点参数
- 在半径 = 3cm处
  - 600 MHz/cm²（在LHC 瞬时峰亮度下 (L=2x10³⁴ cm)⁻²s⁻¹ ）
  - 抗辐照强度: 3x10¹⁴ n_eq/cm²/yr
  - 占空比: 10⁻³

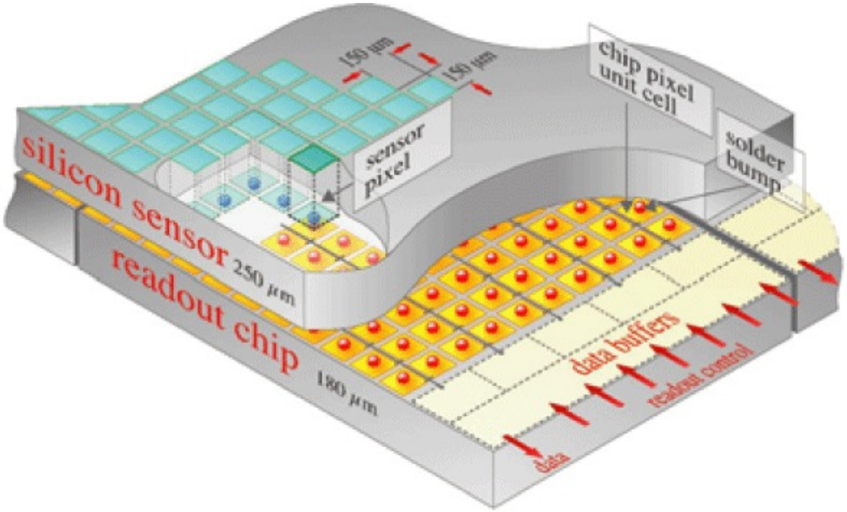


45M forward and
79M barrel pixels

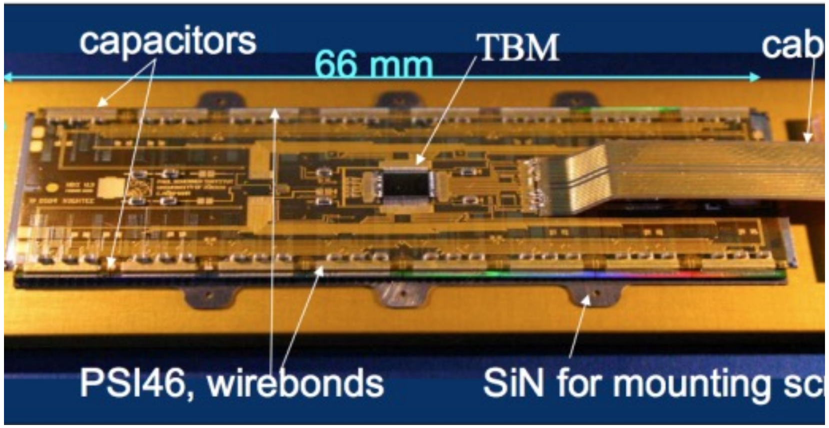


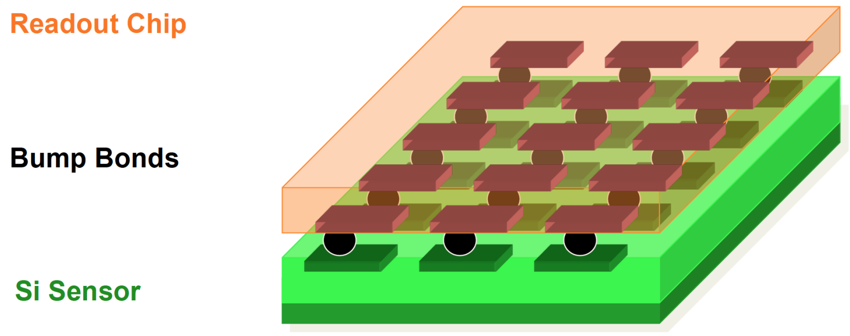




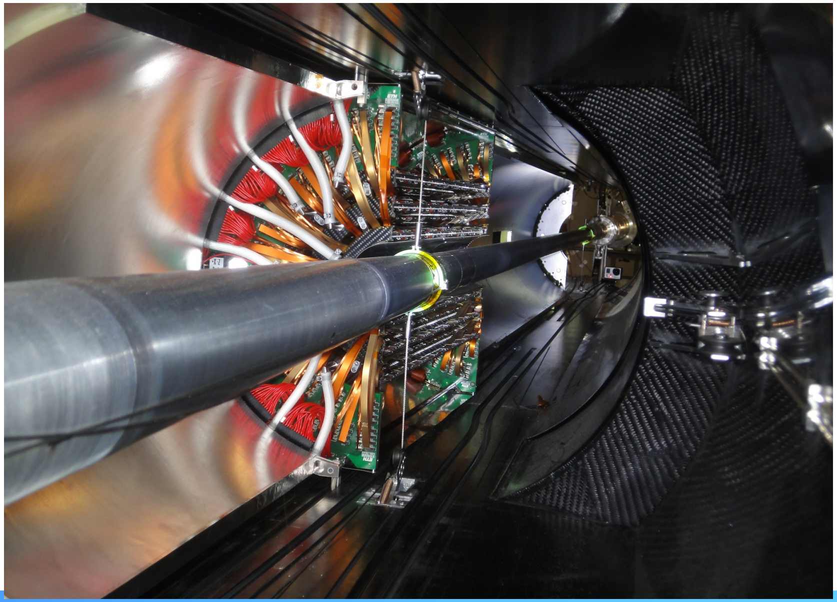


100micron/ns (when drift velocity saturated at ~30kV/mm E-field) and 73 e-h pair per micron for MIP

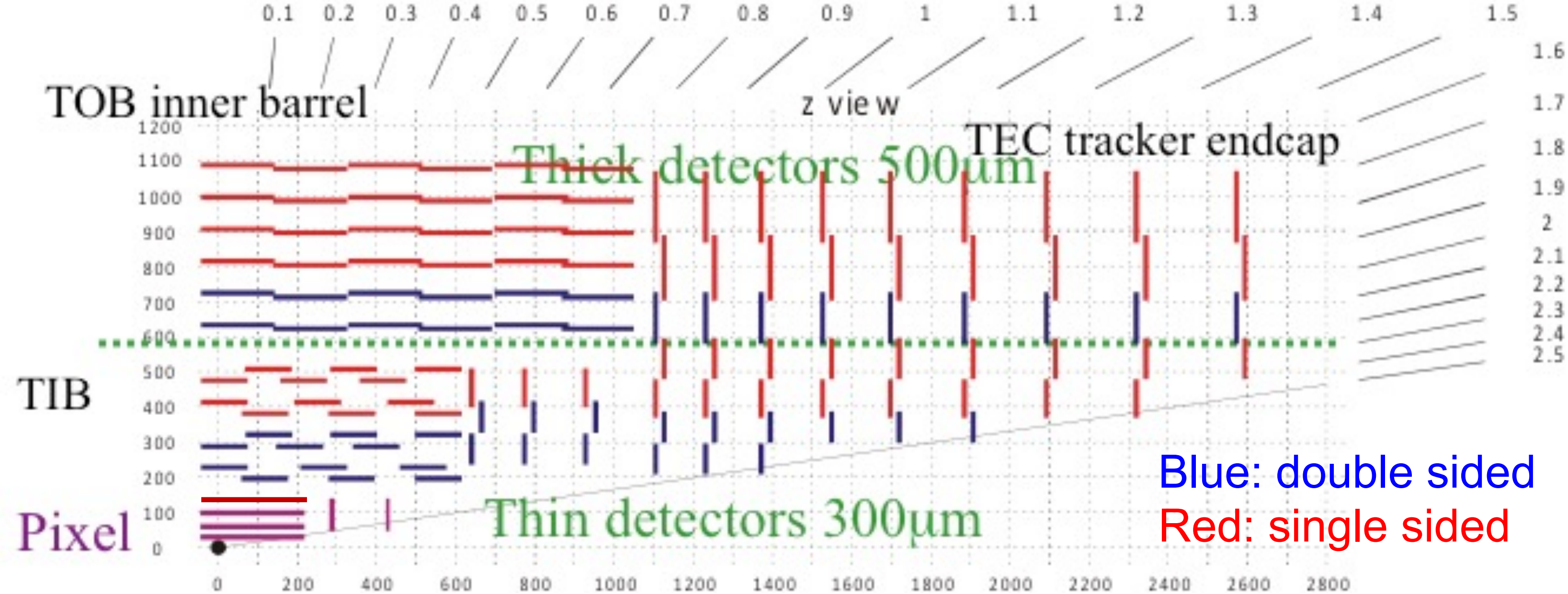




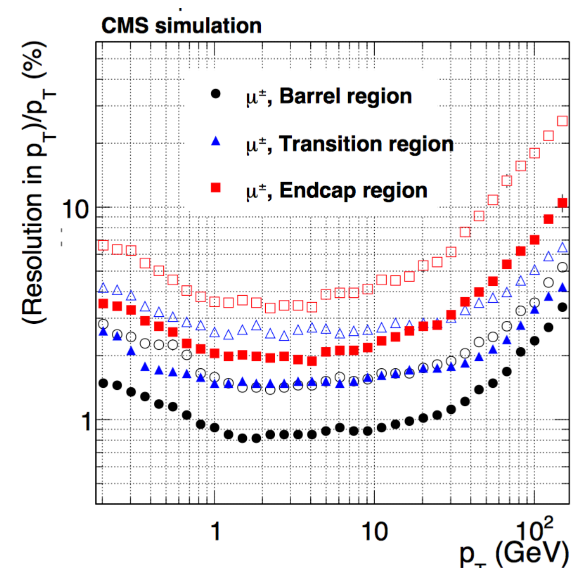
Each pixel cell in the sensor is connected to a pixel cell in the readout chip via a bump bond.

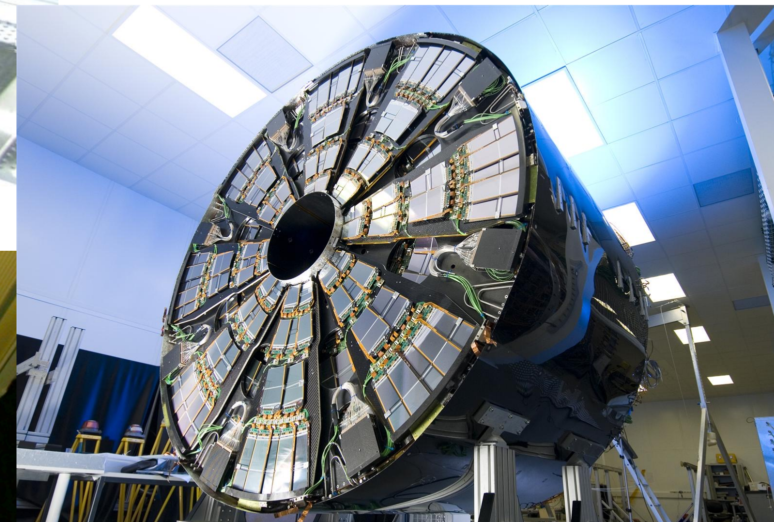


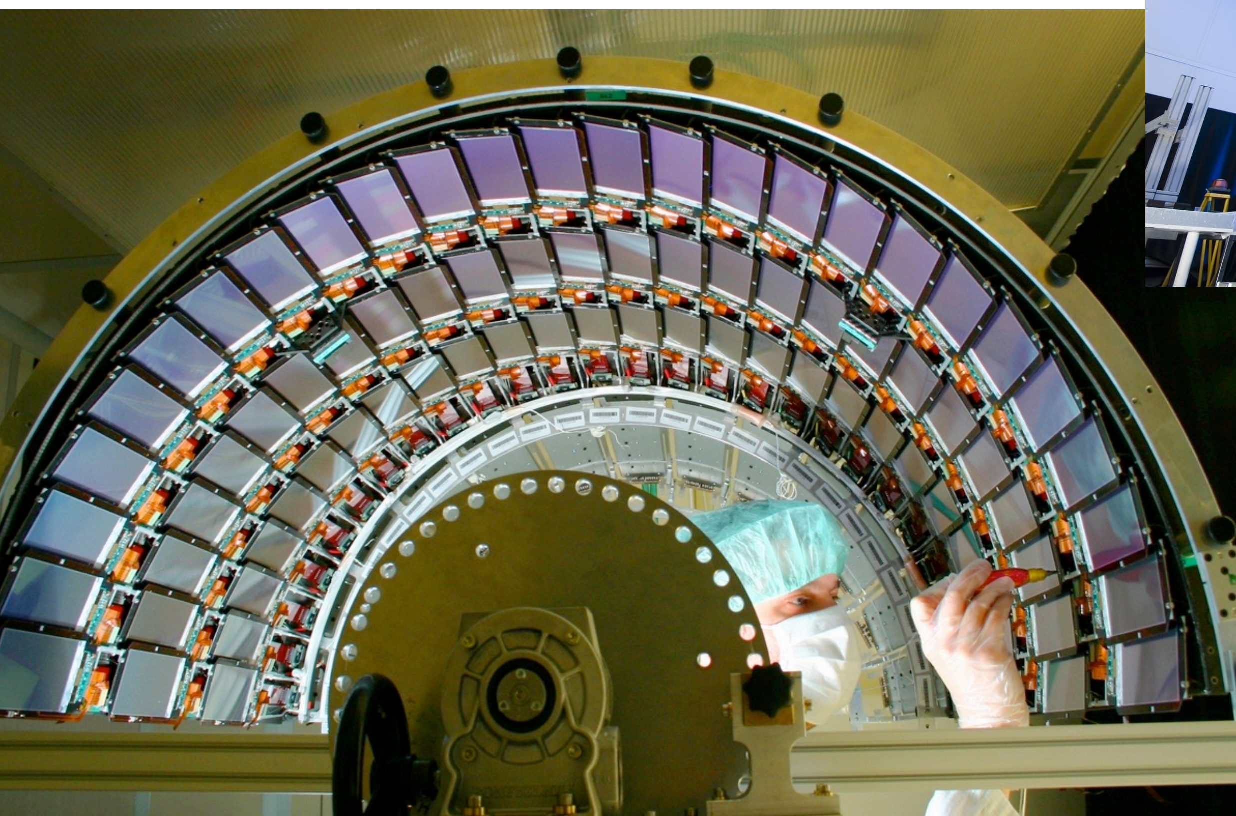
硅微条(Silicon strip)探测器

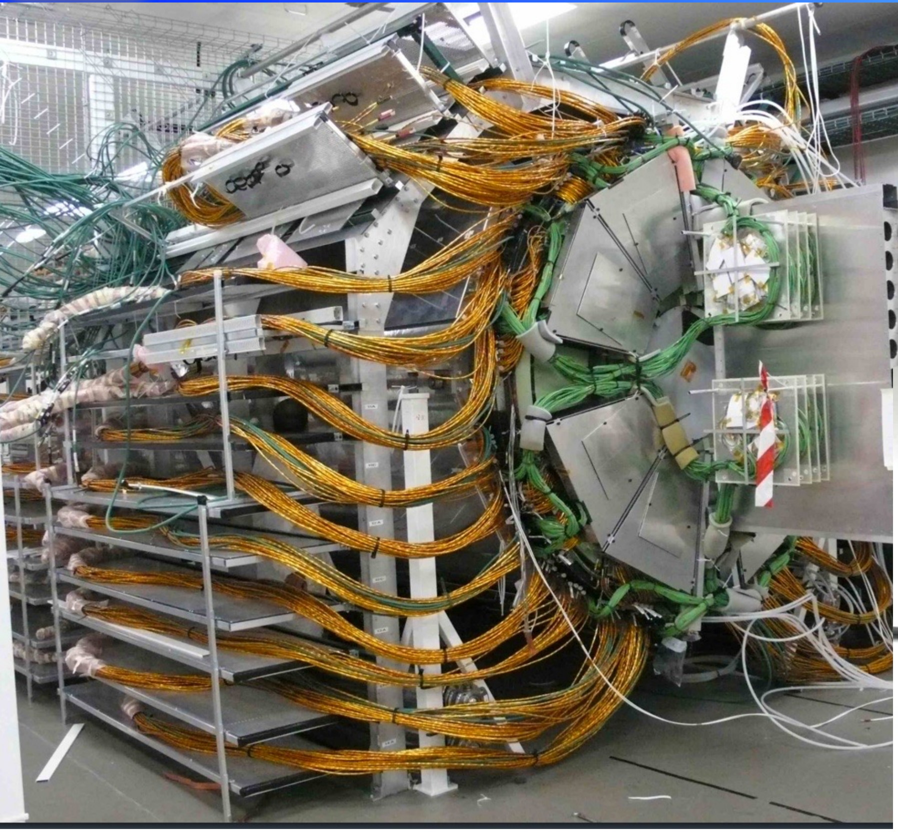


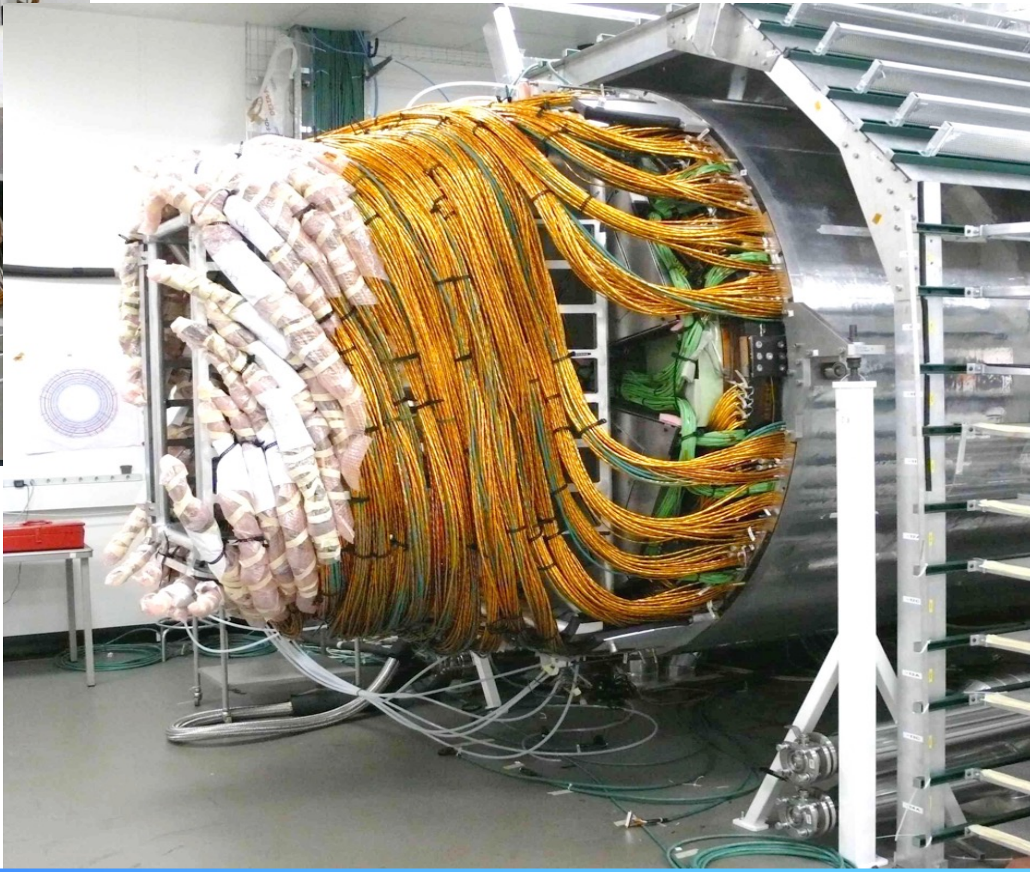
- Sensor Technology p-in-n
- Design occupancy 1-3% - resolve & isolate tracks
  - Outer cell size ~20cm x 100-200□m
  - Inner cell side ~10cm x 80□m
- Operation -20C
- Signal / noise ~20 (above 10 after radiation)
- Radiation tolerance ~1.5x10^{14} n_{eq}









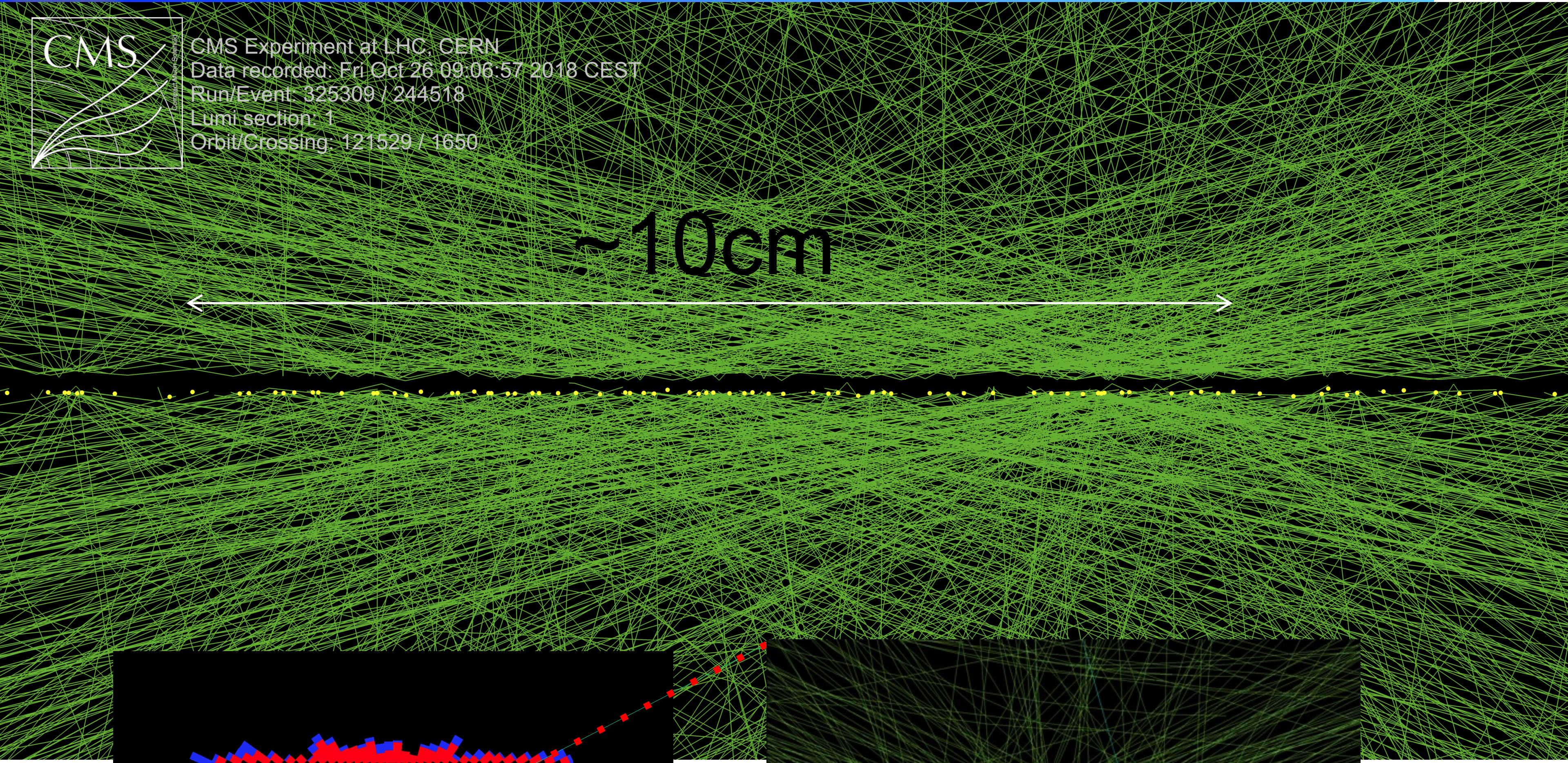


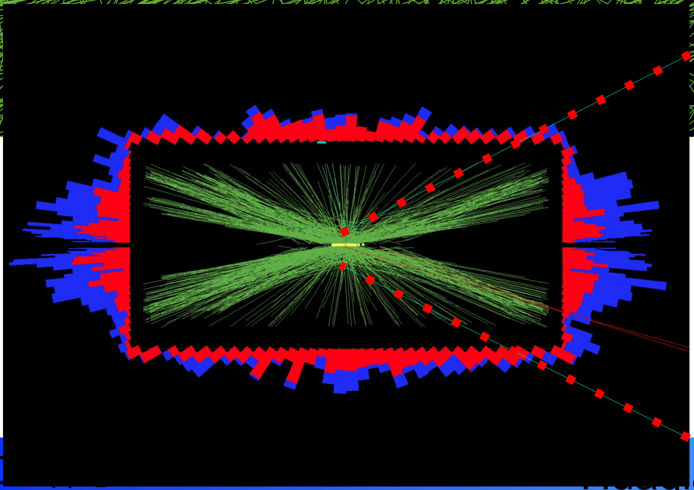
安装tracker时的问题

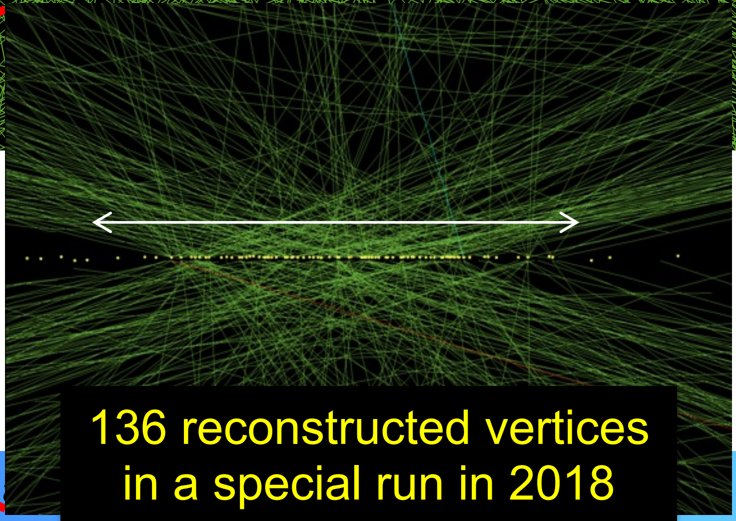
- 6.5 tons
- 100 MCHF
- 2000 man years
- 100 m deep shaft below
- Not insured ;-)

On one hook!

- Several frightened physicists



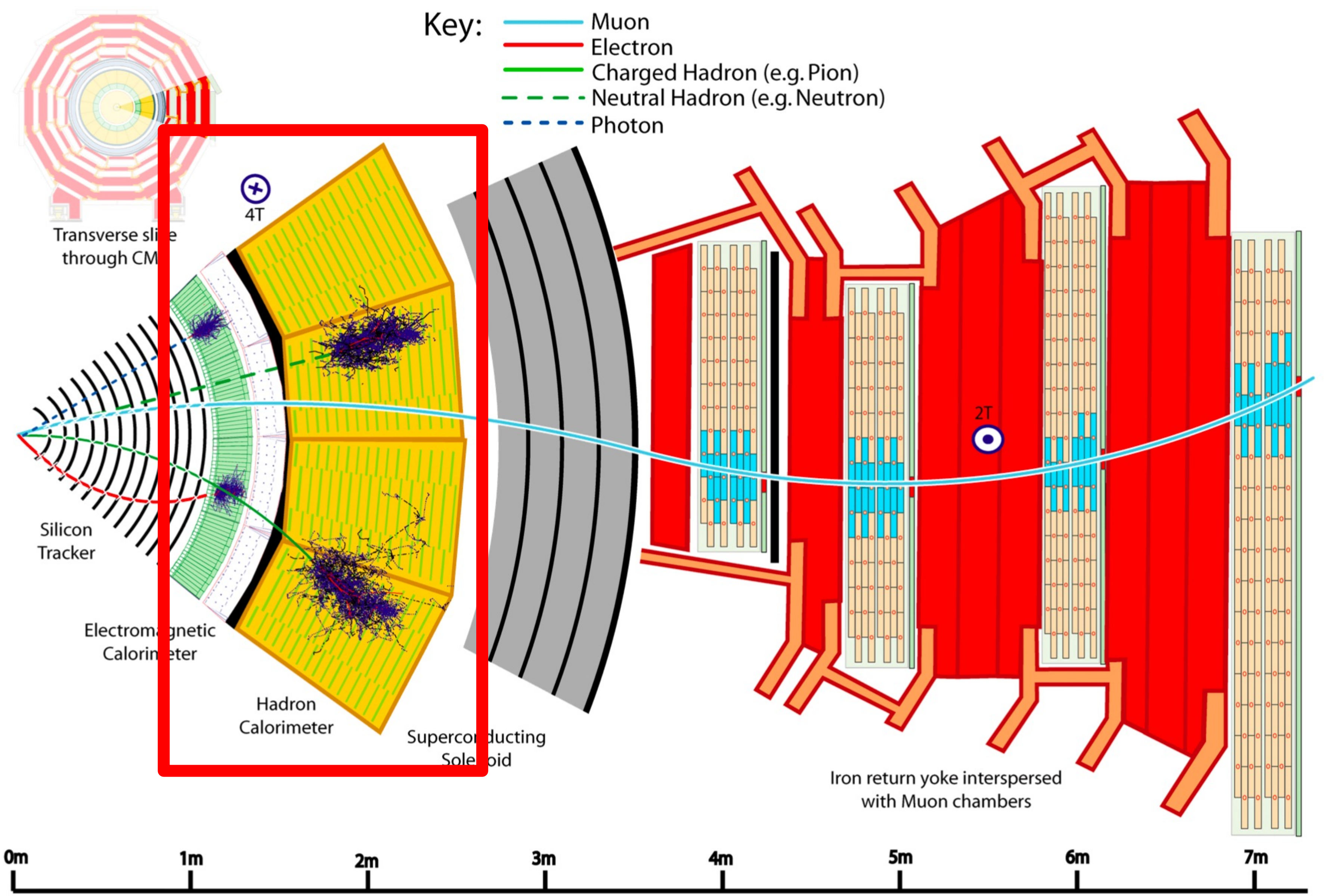




136 reconstructed vertices in a special run in 2018

确实值这个价格！

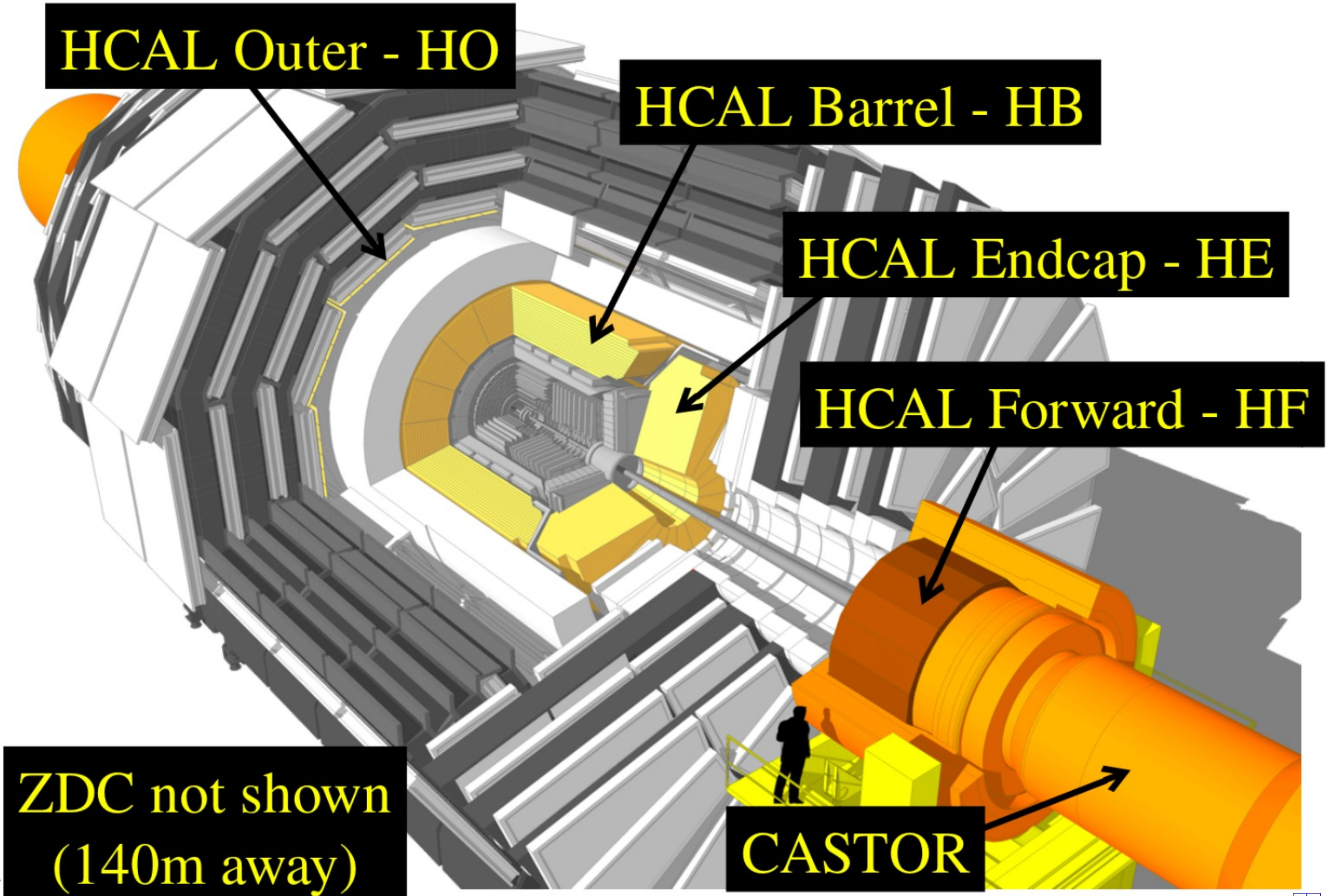
CMS 探测器的设计：量能器



量能器

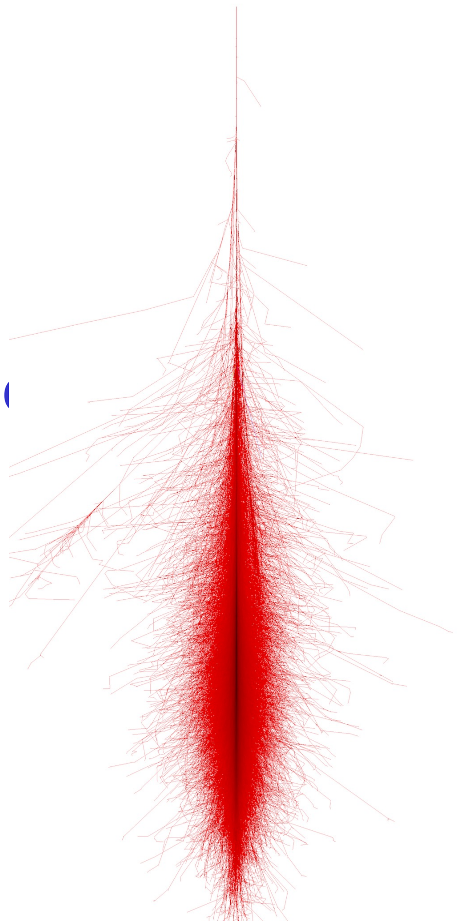
- 量能器Calorimeter

- 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、□、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

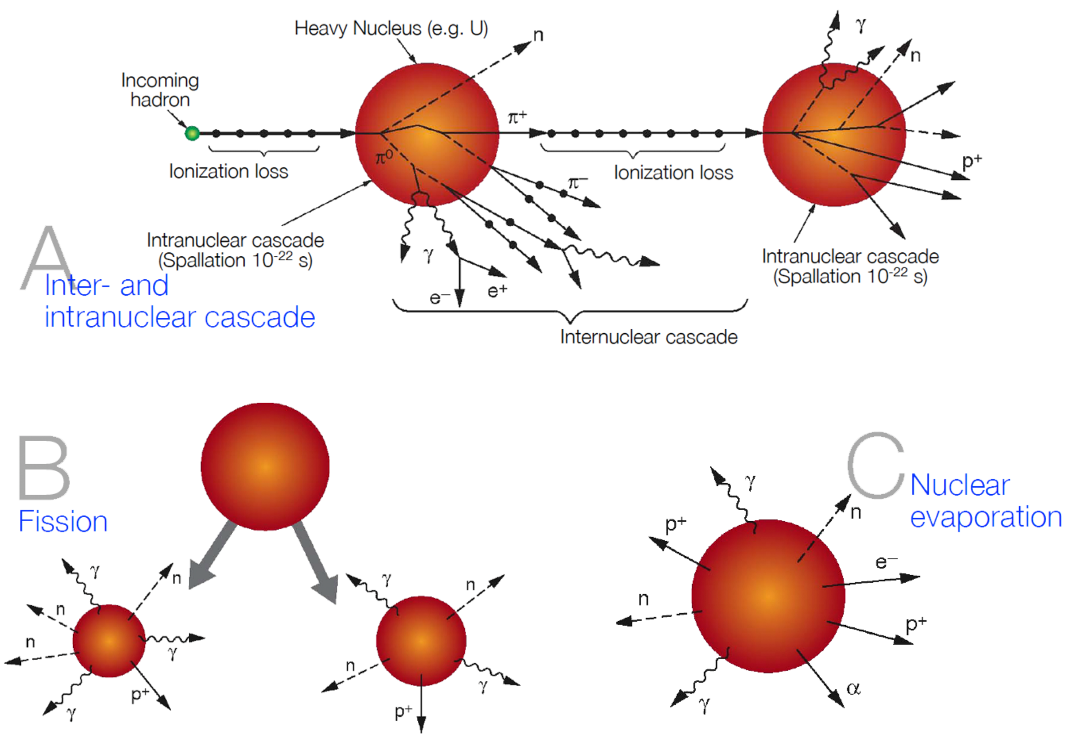
- Electrons and photons, a “self-contained” case:
  - Above 1 GeV: bremsstrahlung (1e± → 1γ) and pair production (1γ → 1e+ + 1e−)
  - Below 1 GeV: ionization, photoelectric, Compton
  - Critical energy, Ec ≈ 610 MeV/(Z + 1.24): energy at which the average energy losses by radiations equal those by ionization
- 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)

典型电磁簇射

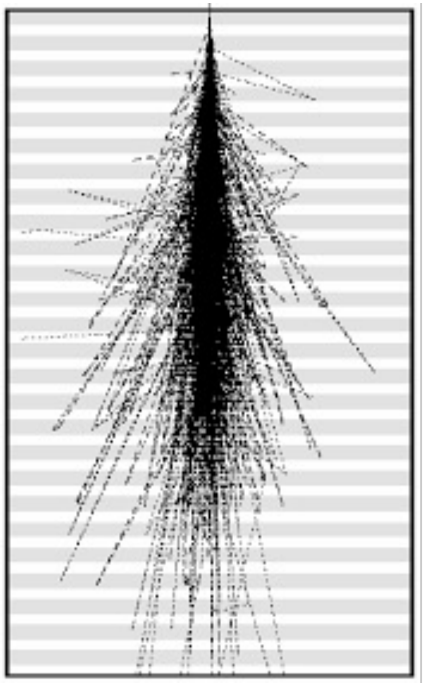


$$\frac{\delta E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

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

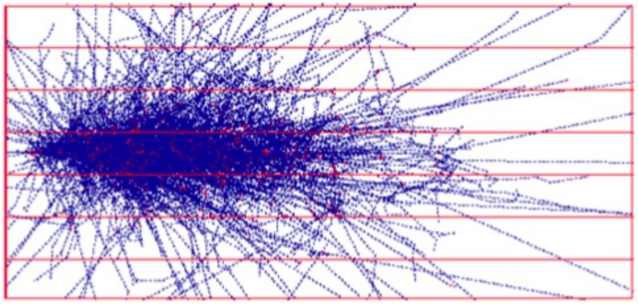
Molière radius (R_M): average lateral deflection of electrons of critical energy E_c after traversing $1X_0$; 90% E_0 within $1R_M$, 95% within $3R_M$

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

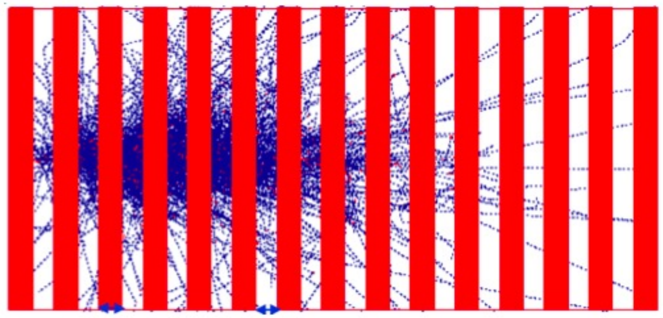
典型量能器的设计

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



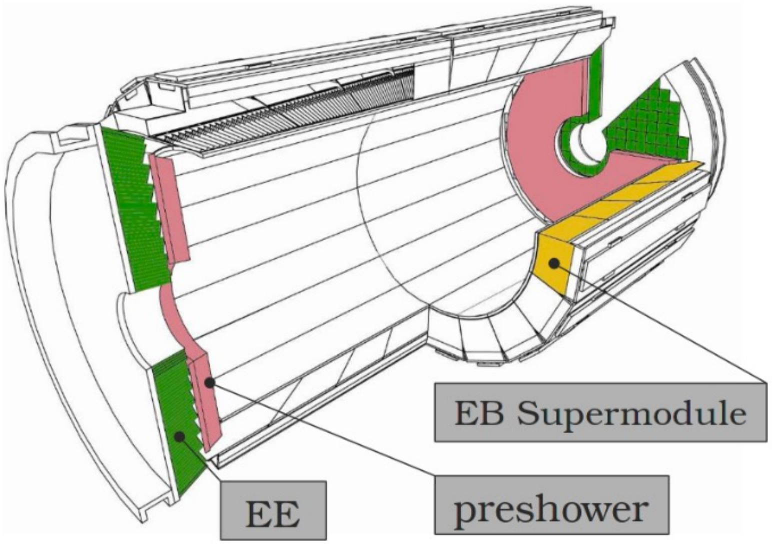
- Excellent energy resolution
- No information on longitudinal shower shape
- Cost

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



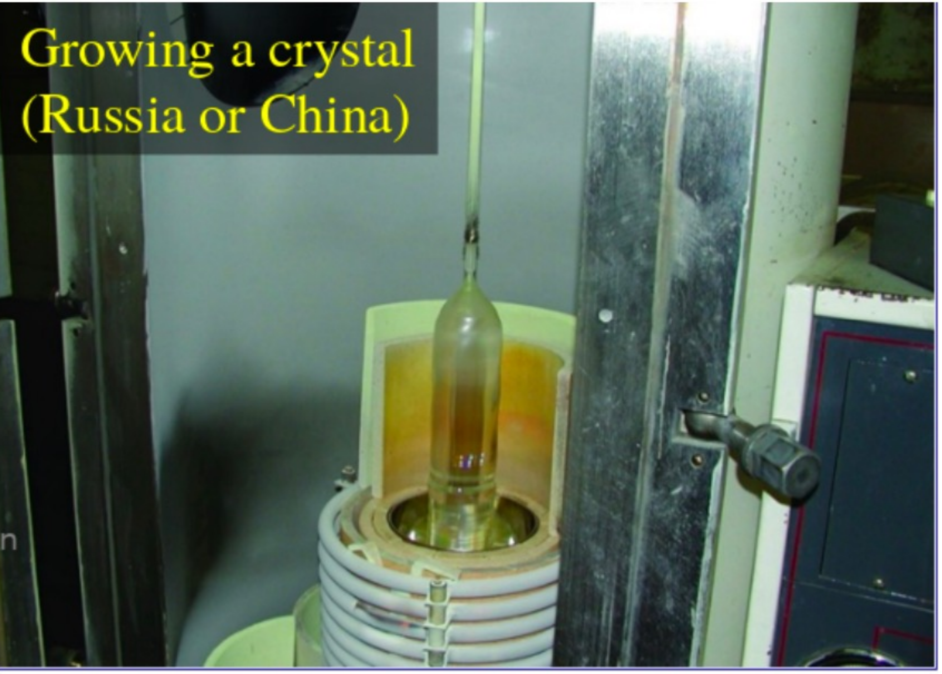
- Limited energy resolution
- Longitudinal segmentation: detailed shower shape information
- Cost

- **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, $1.65 < |\eta| < 2.6$

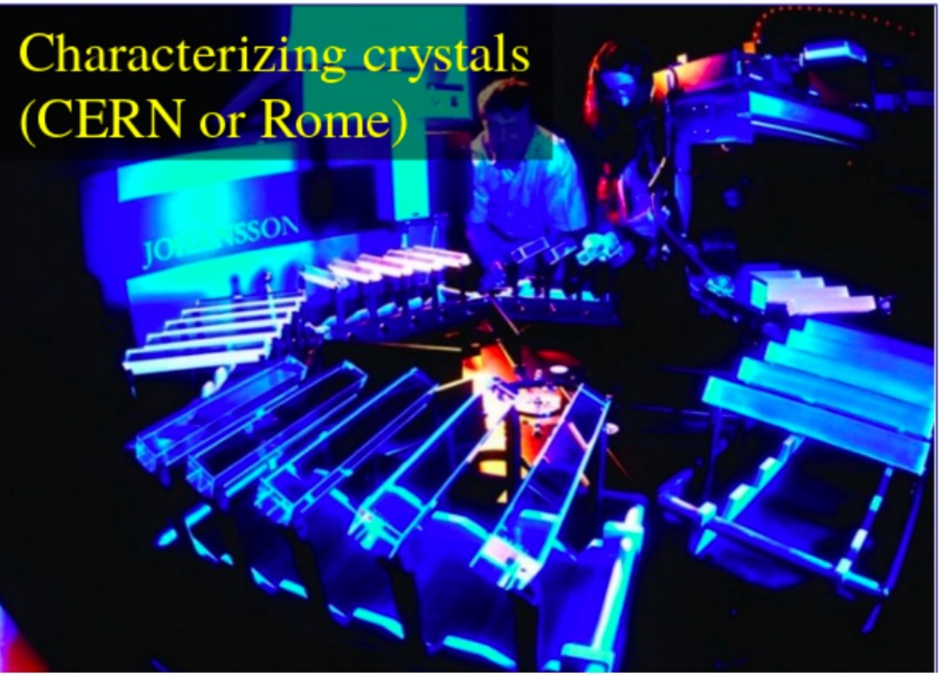


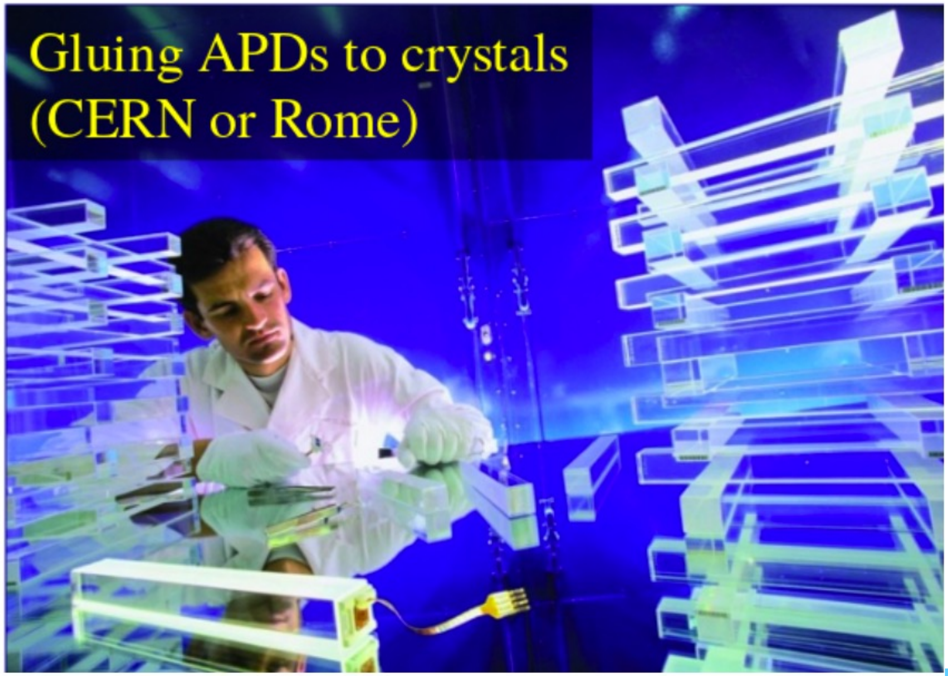
- Solenoidal magnetic field: 3.8 T
  ECAL fully contained in the coil
- CMS tracker coverage: $|\eta| < 2.5$

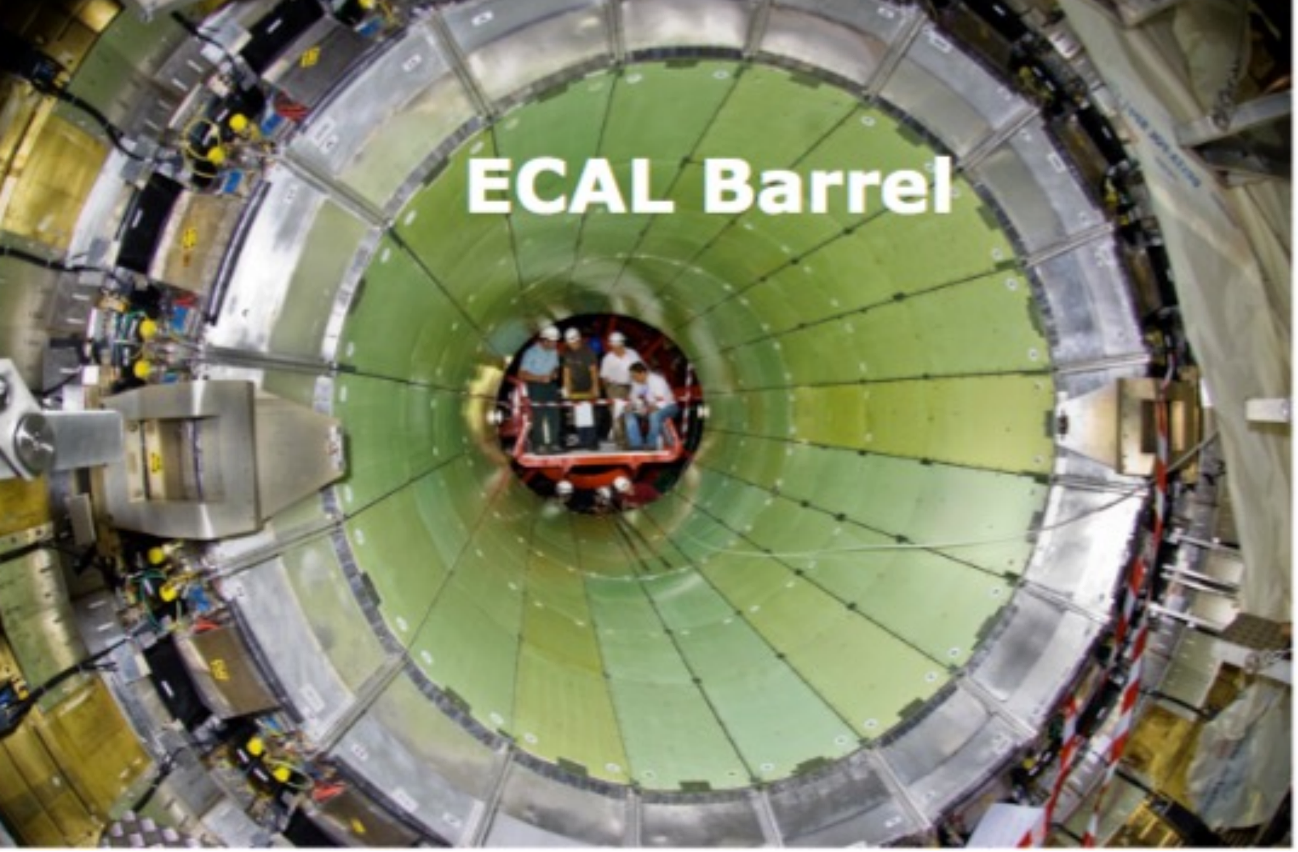
2.2*2.2*23cm^3,~26X0

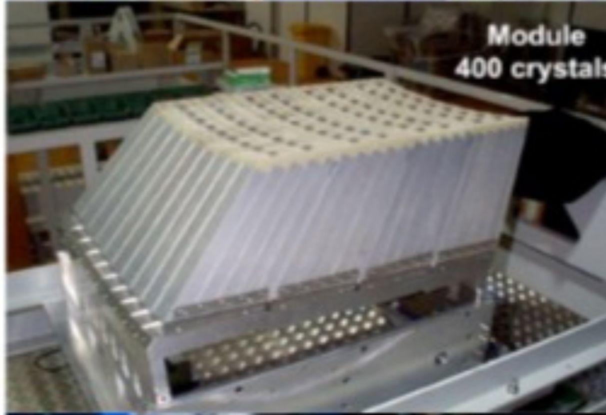

Growing a crystal
(Russia or China)

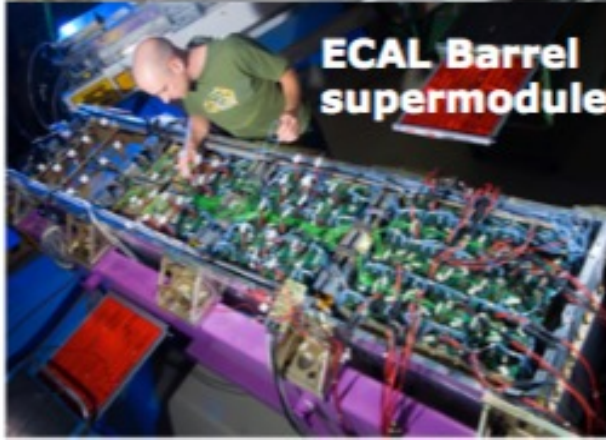

Before and after
cutting & polishing


Characterizing crystals
(CERN or Rome)

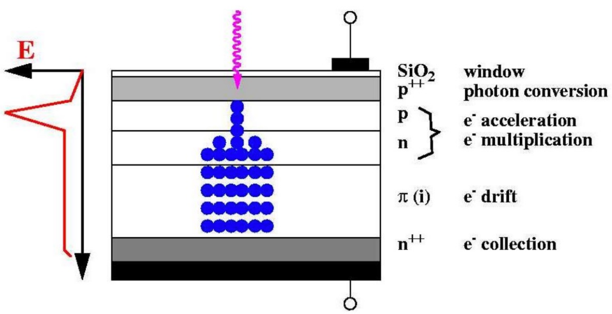

Gluing APDs to crystals
(CERN or Rome)


ECAL Barrel

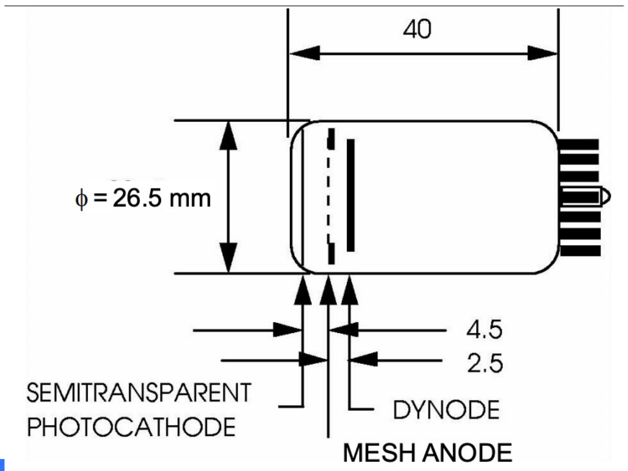

Module
400 crystals

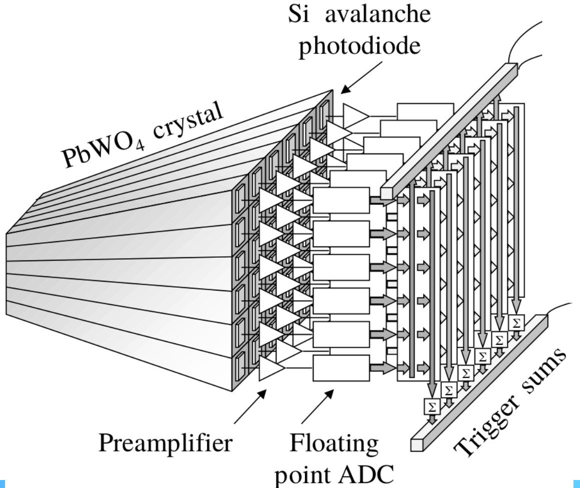

ECAL Barrel
supermodule

APD


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

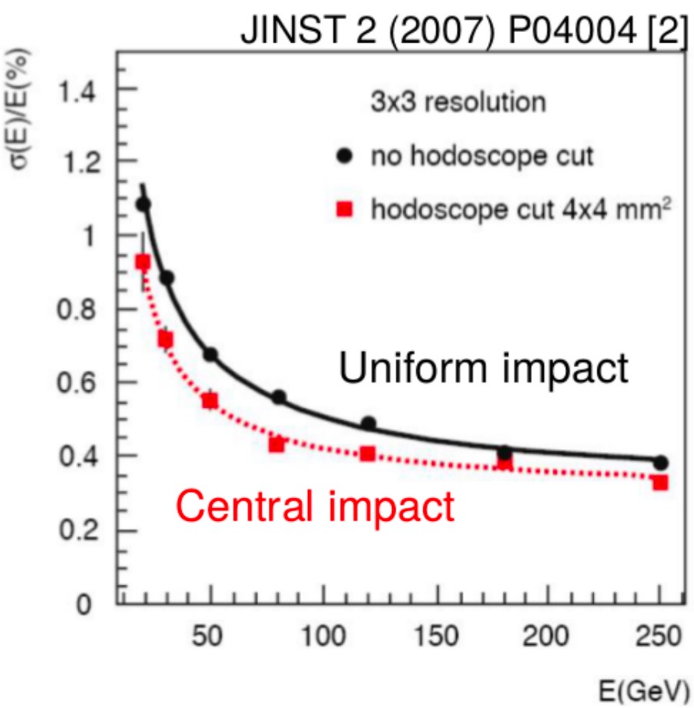
VPT


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

CMS电磁量能器的性能

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



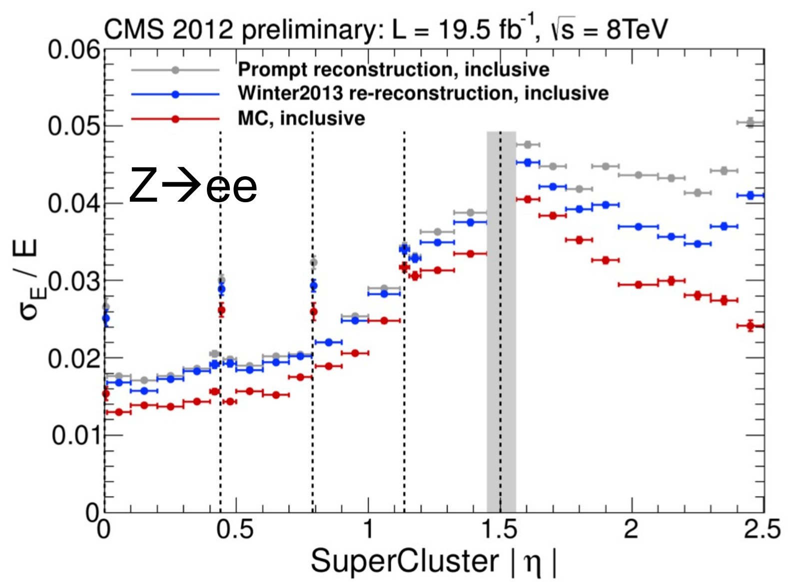
Energy resolution

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…)



Barrel (HB)

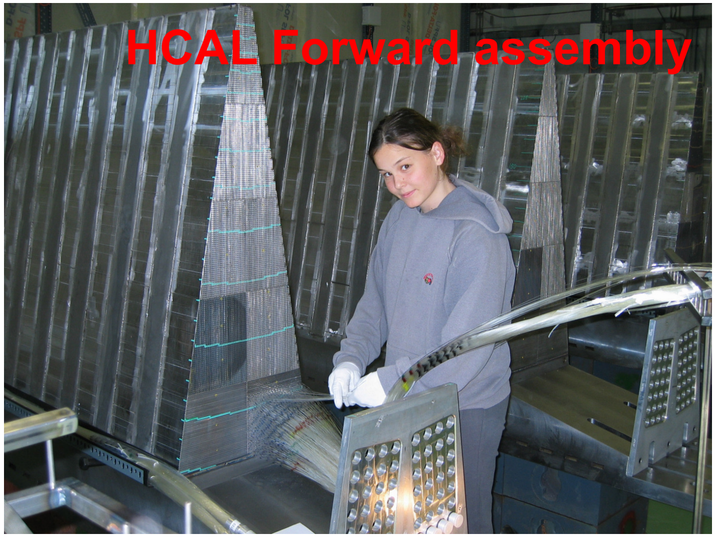
- 36 brass/scintillator wedges
- 17 longitudinal layers, 5 cm brass, 3.7 mm scintillator
- $|\eta| < 1.3$

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

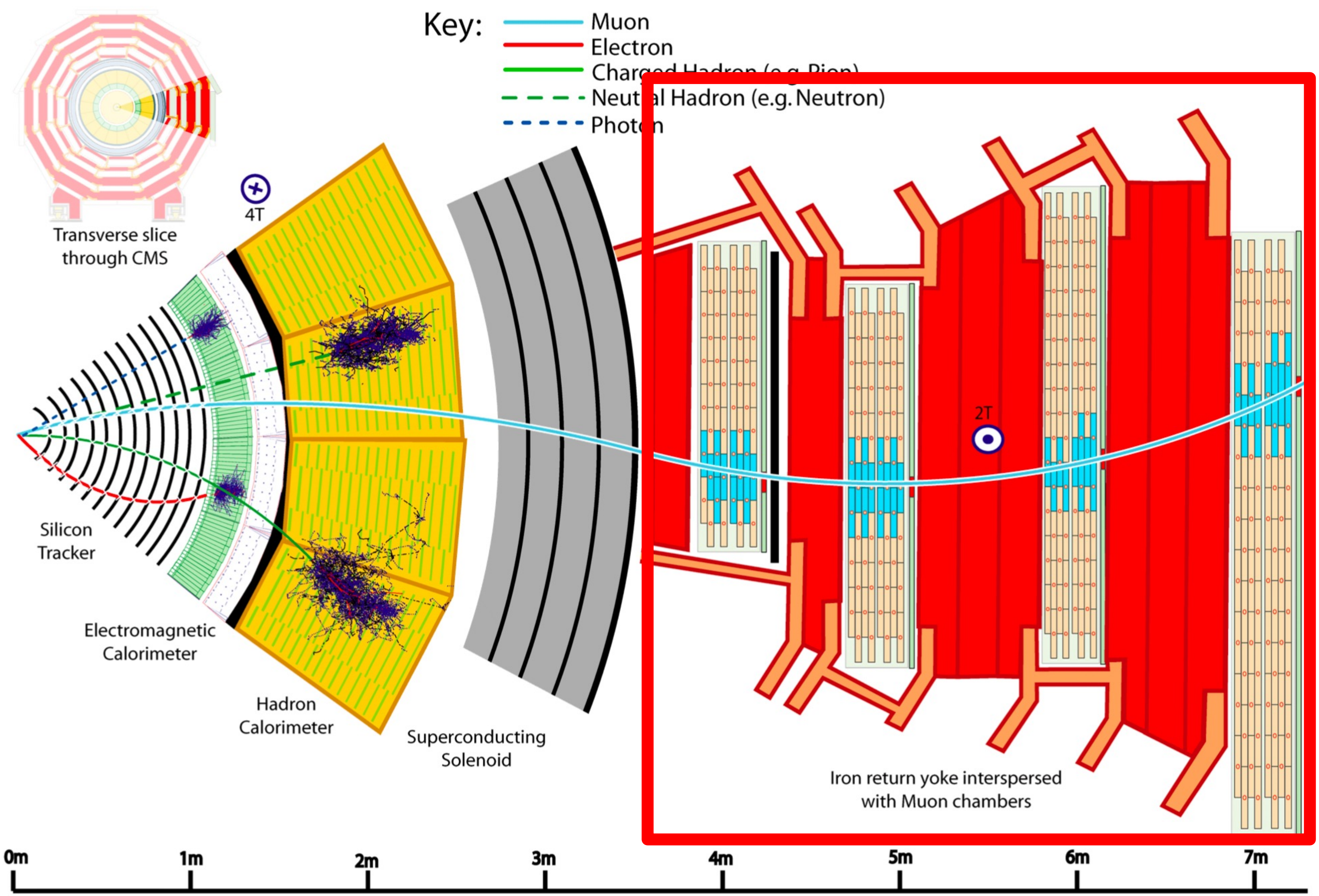
Endcap (HE)

- 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

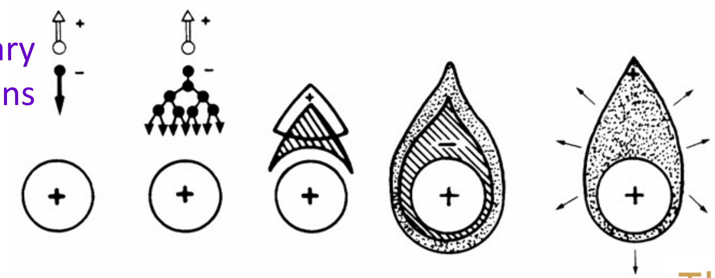


CMS 探测器的设计：缪子探测器

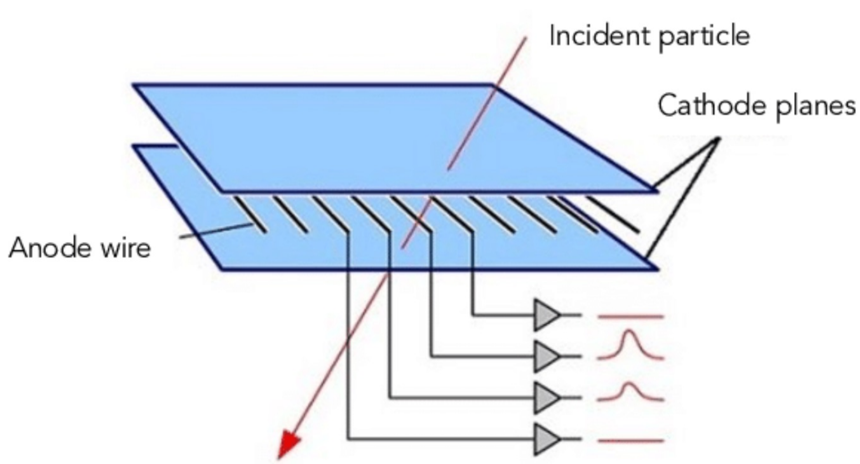


- Muon detectors are on the outside, so must be large
- Economics: use gas detectors to cover a large surface area
  - Need amplification of the electron ionization signal within the gas volume
  - Factors of 10^5-10^7 are typical, using wires or parallel plates

~10^2 primary electrons



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



The Nobel Prize in Physics 1992

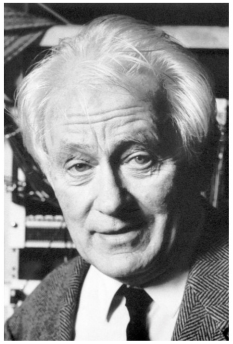
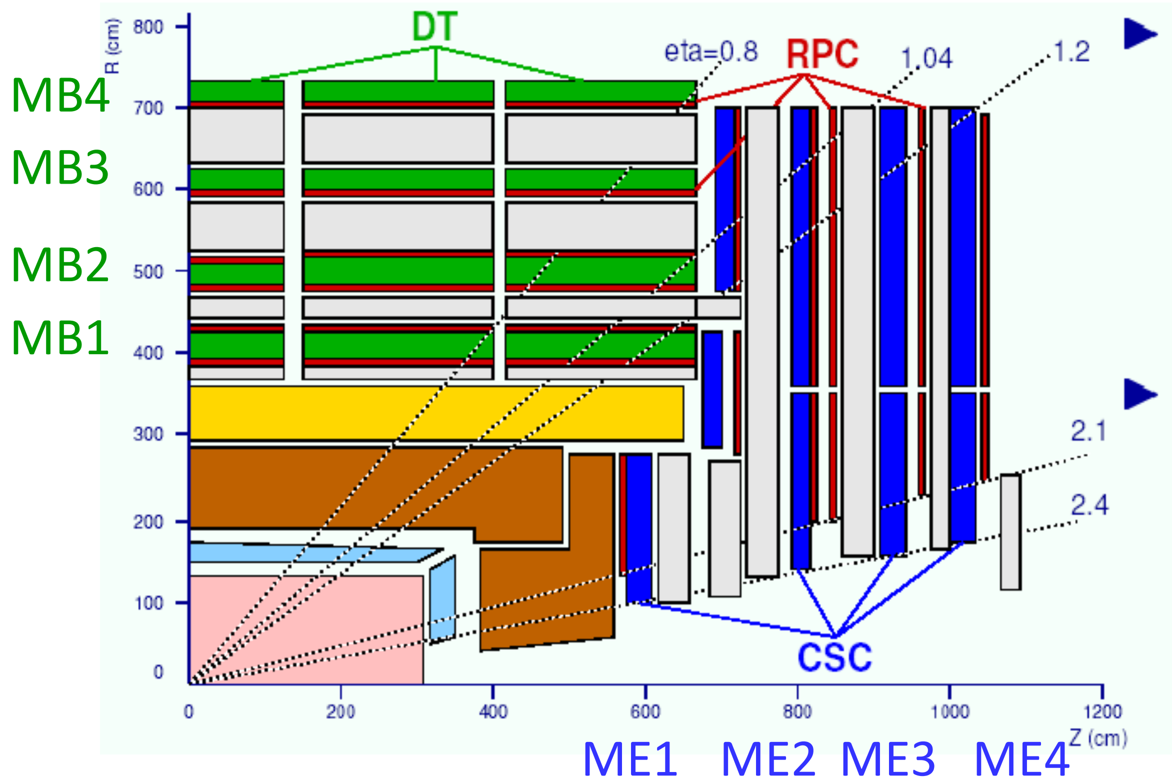


Photo from the Nobel Foundation archive.
Georges Charpak
Prize share: 1/1

Gas detector: multiwire proportional chamber

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 < | η| < 1.2

5 wheels / 4 stations instrumented with DTs and RPCs

Endcap: 0.9 < | η| < 2.4

3 discs / 4 stations instrumented with CSCs and RPCs

Spatial precision

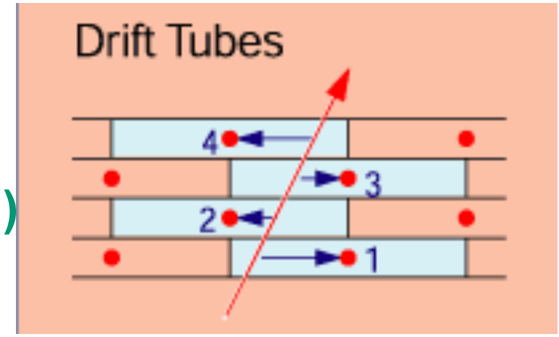
75-150 □m /station

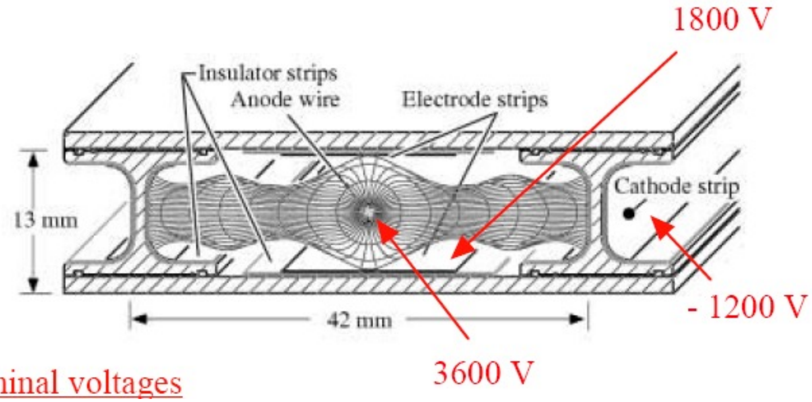
CMS Drift Tubes (DT)

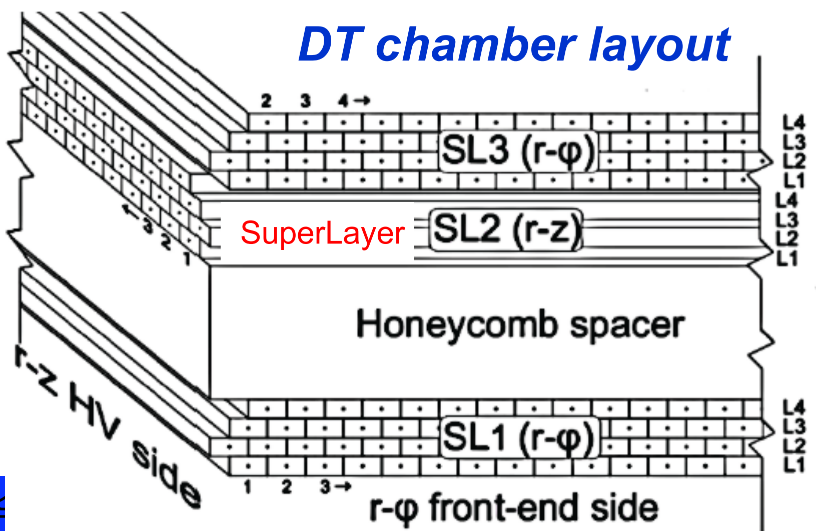
- **240 chambers in CMS <u>barrel</u>** – 5 wheels
- Drift time measurement, gives **distance (d)** to wire to **~250 μm accuracy**

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

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



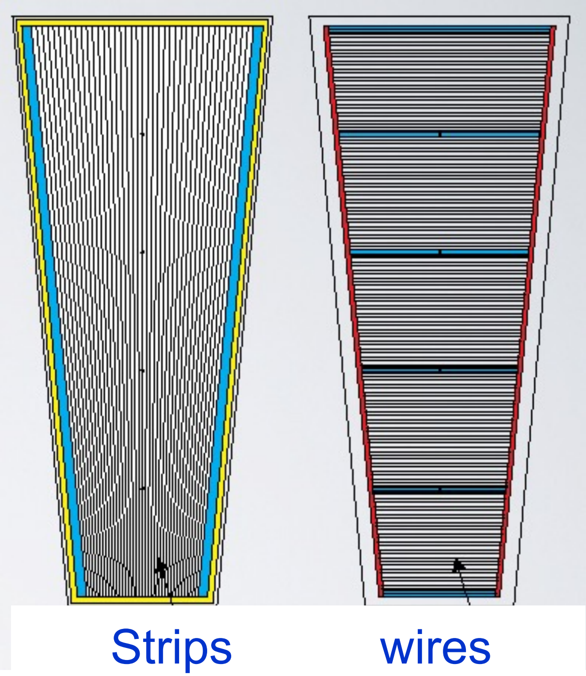


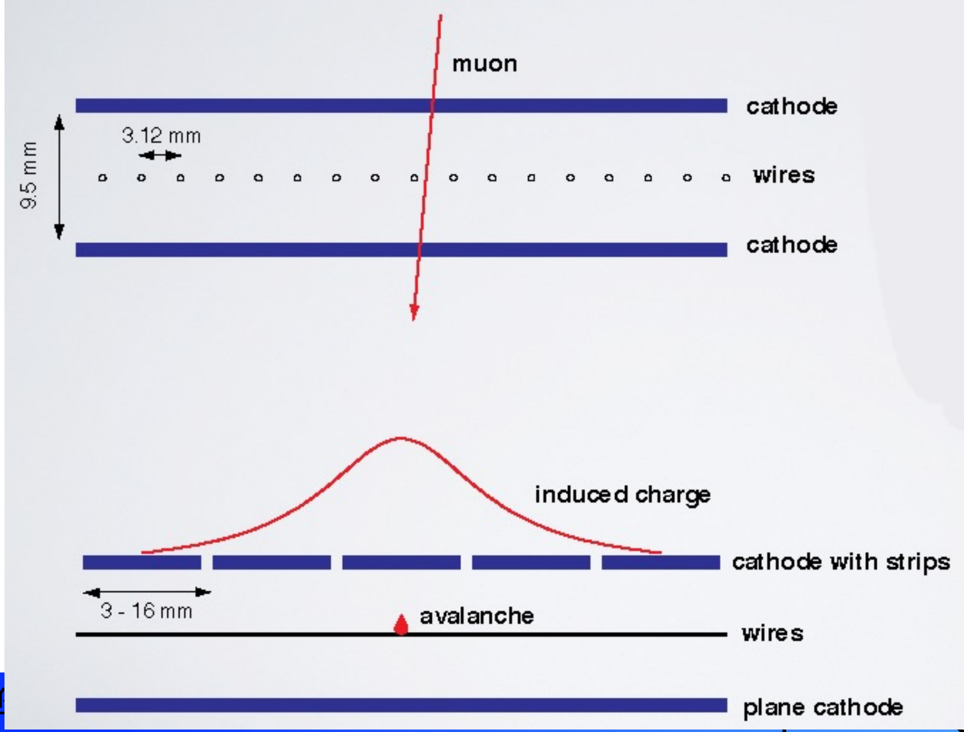


CMS Cathode Strip Chambers (CSC)

IHEP

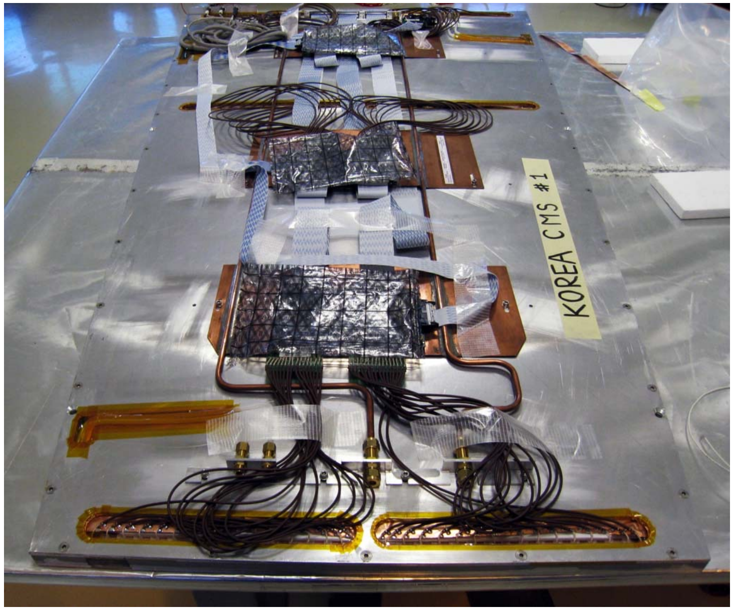
- **540 trapezoidal chambers in CMS <u>endcaps</u>**
- Electrons drift to wires, **induce** opposite charge on perpendicular cathode strips
- Precise ~2% interpolation of cathode charge on ~cm strips gives ~200 μm accuracy
- 6 layers: precision *ϕ* from cathode strips, coarse ***r*** and timing from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



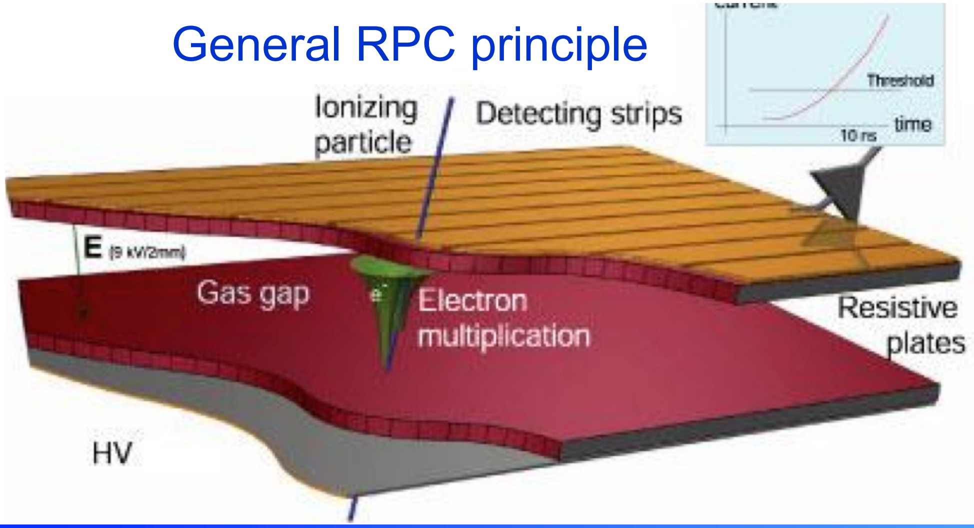


CMS Resistive Plate Chambers (RPC)

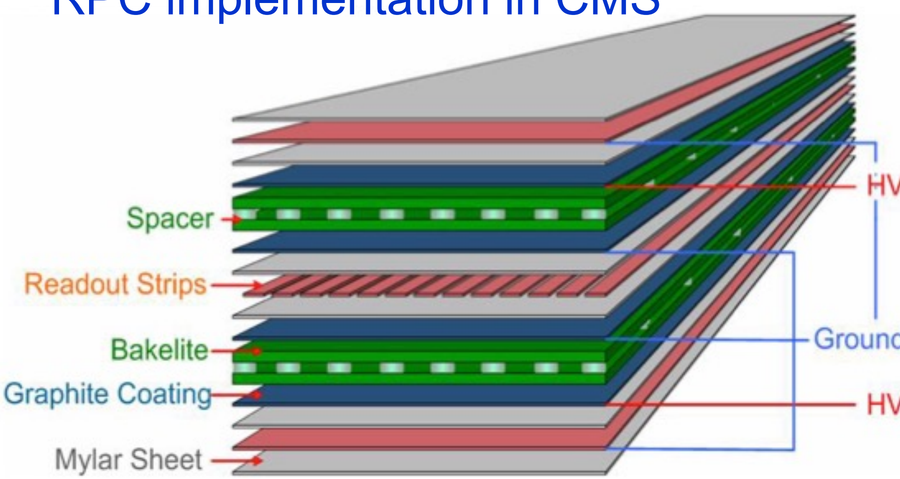
- **480 barrel** and **576 endcap** chambers
- Charge induced onto external strips
  - Resistive layer (Bakelite plastic) with $\rho \sim 10^{10}$ Ωcm is transparent to signal as if infinite, quenches avalanche as if conducting
- Spatial resolution 0.8-1.2 centimeters
- Double gap, each 2 mm, 9.6 kV,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



General RPC principle

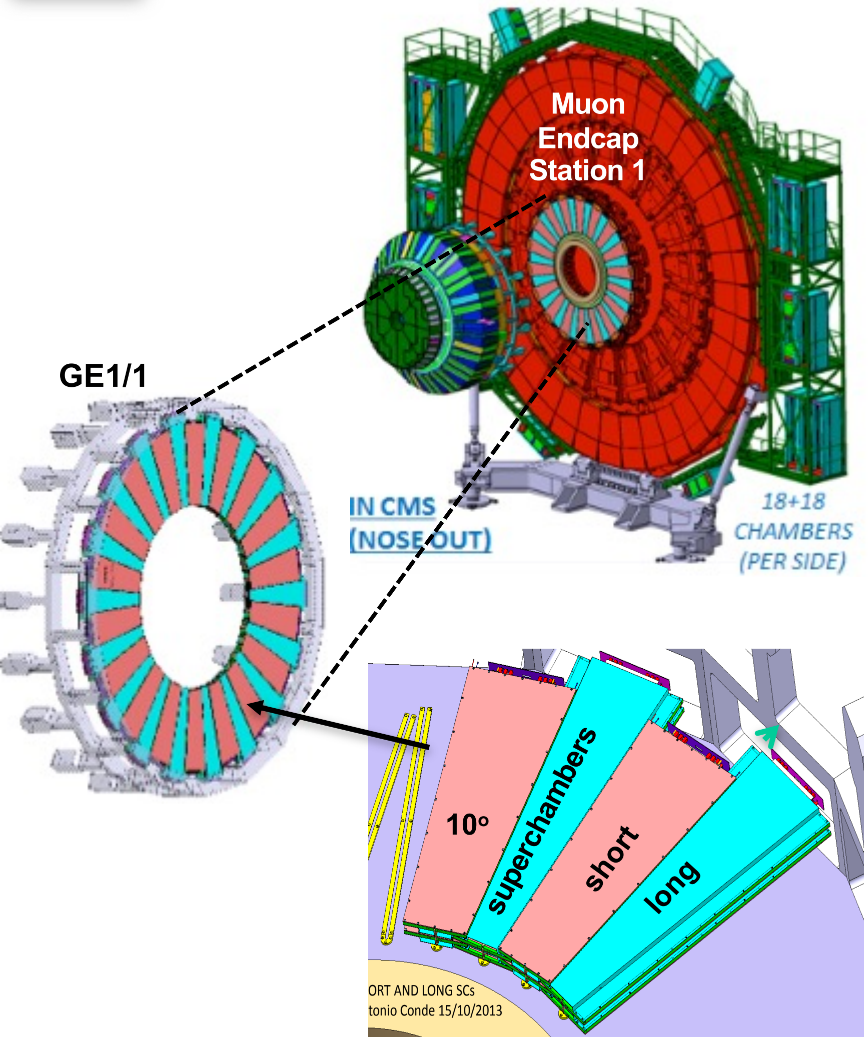


RPC implementation in CMS



New Micro-Pattern Gas Detectors (MPGD):GEM

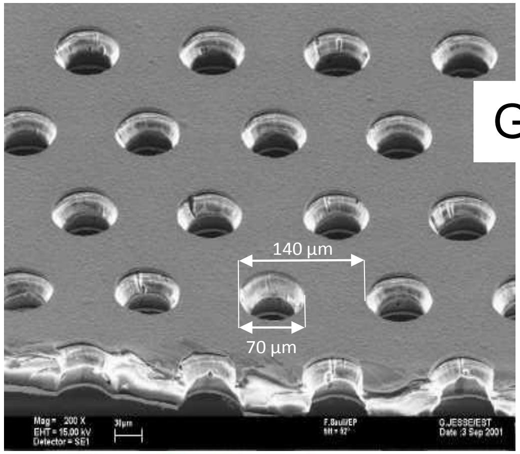
PKU

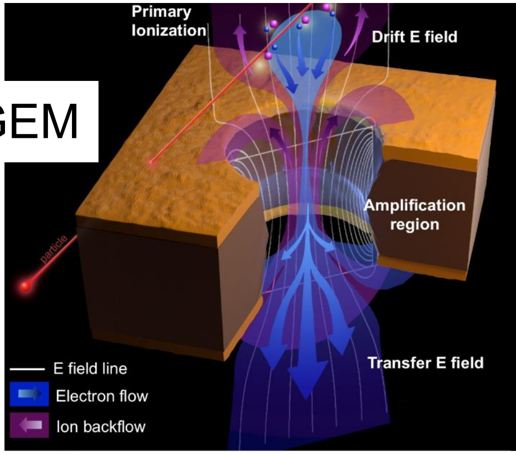


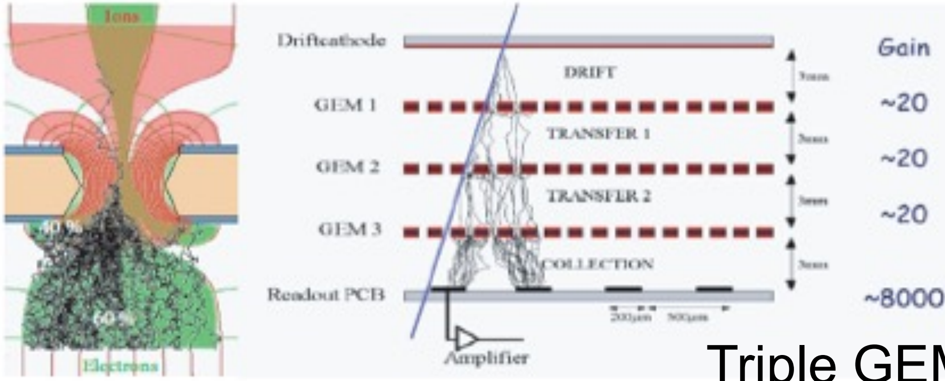
Long (1.5<|η|<2.2) and short (1.6<|η|<2.2) version

36 superchambers in each endcap

GEM: Gas Electron Multiplier



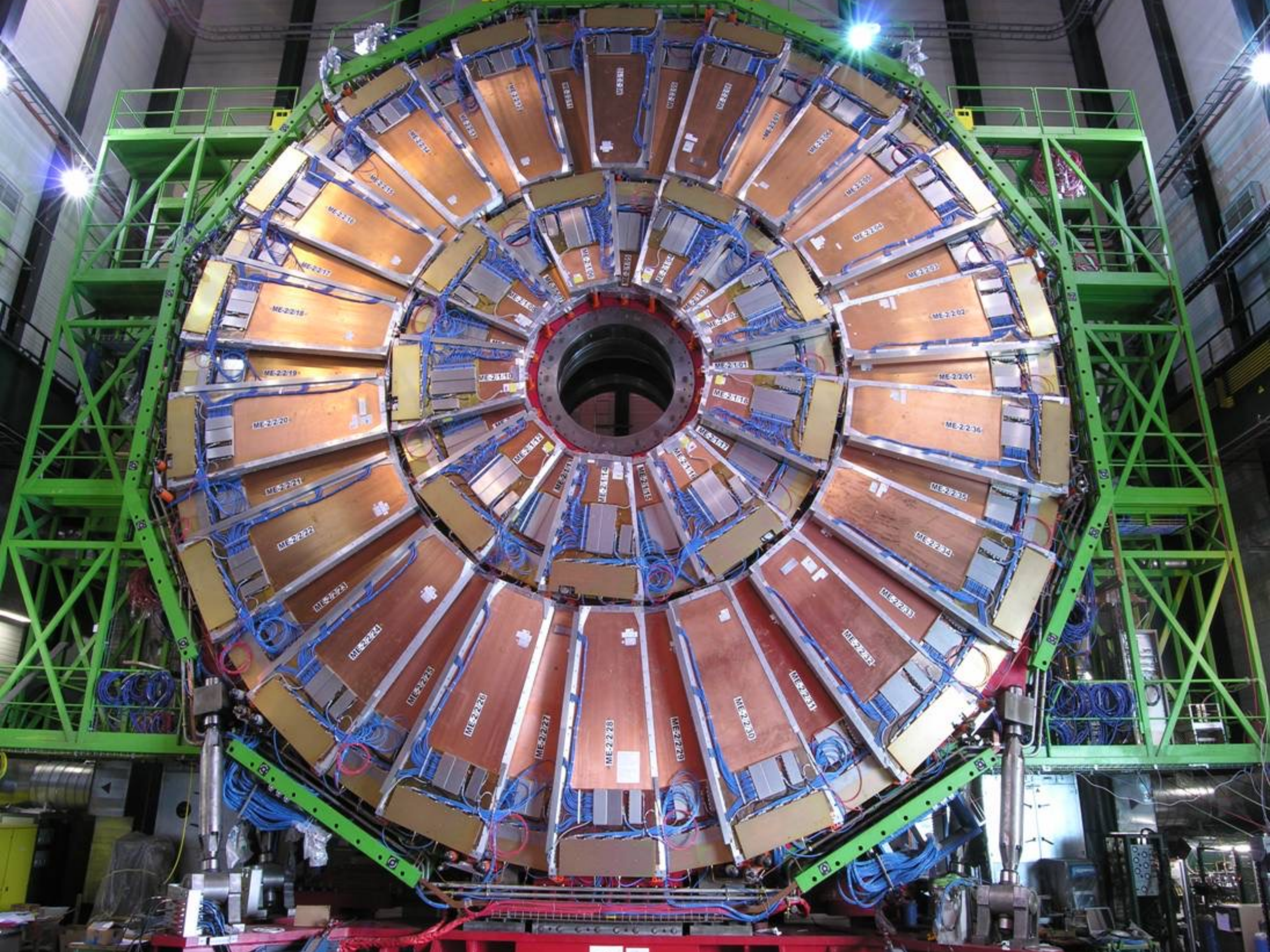




Triple GEM

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

Installation in LS2 – first half installed in October 2019!

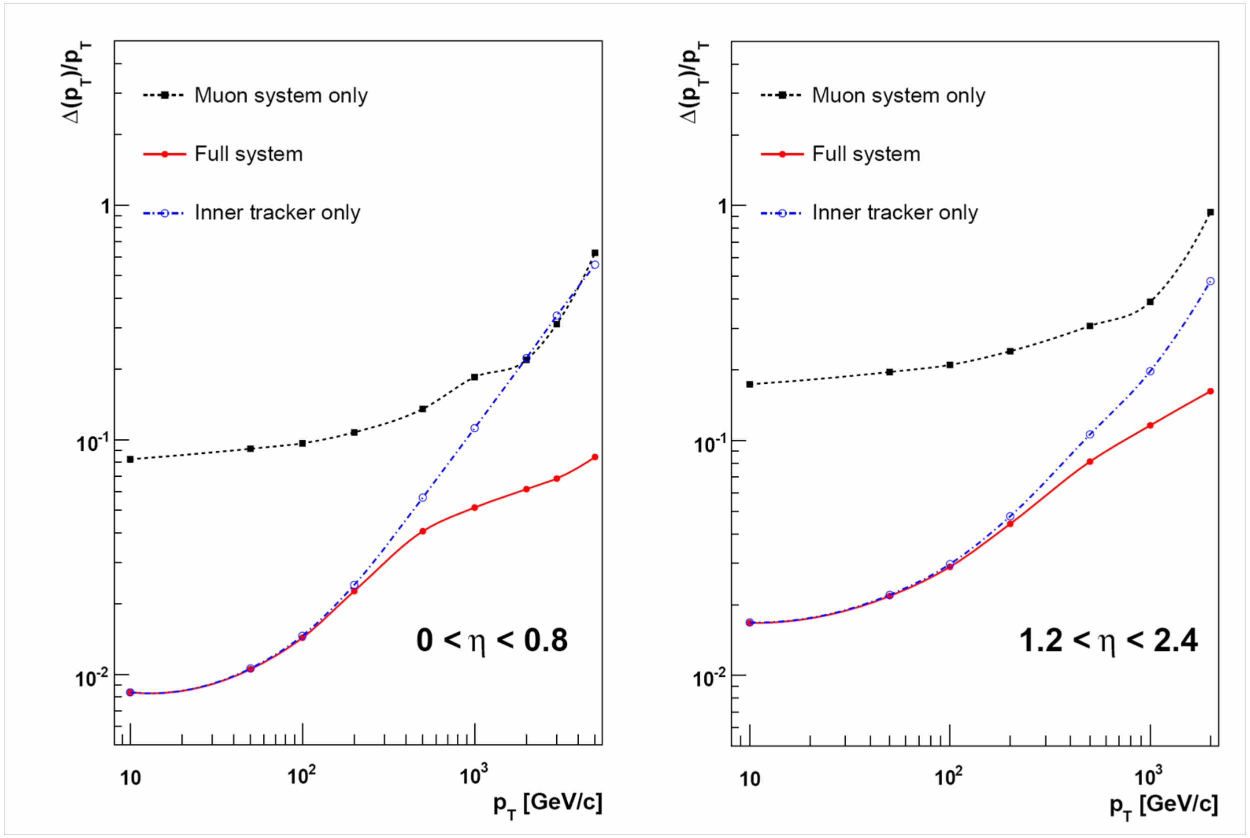

ME-2/2/17
ME-2/2/18
ME-2/2/19
ME-2/2/20
ME-2/2/21
ME-2/2/22
ME-2/2/23
ME-2/2/24
ME-2/2/26
ME-2/2/27
ME-2/2/28
ME-2/2/29
ME-2/2/30
ME-2/2/31
ME-2/2/32
ME-2/2/33
ME-2/2/34
ME-2/2/35
ME-2/2/36
ME-2/2/01
ME-2/2/02
ME-2/1/01
ME-2/1/16
ME-2/1/17

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

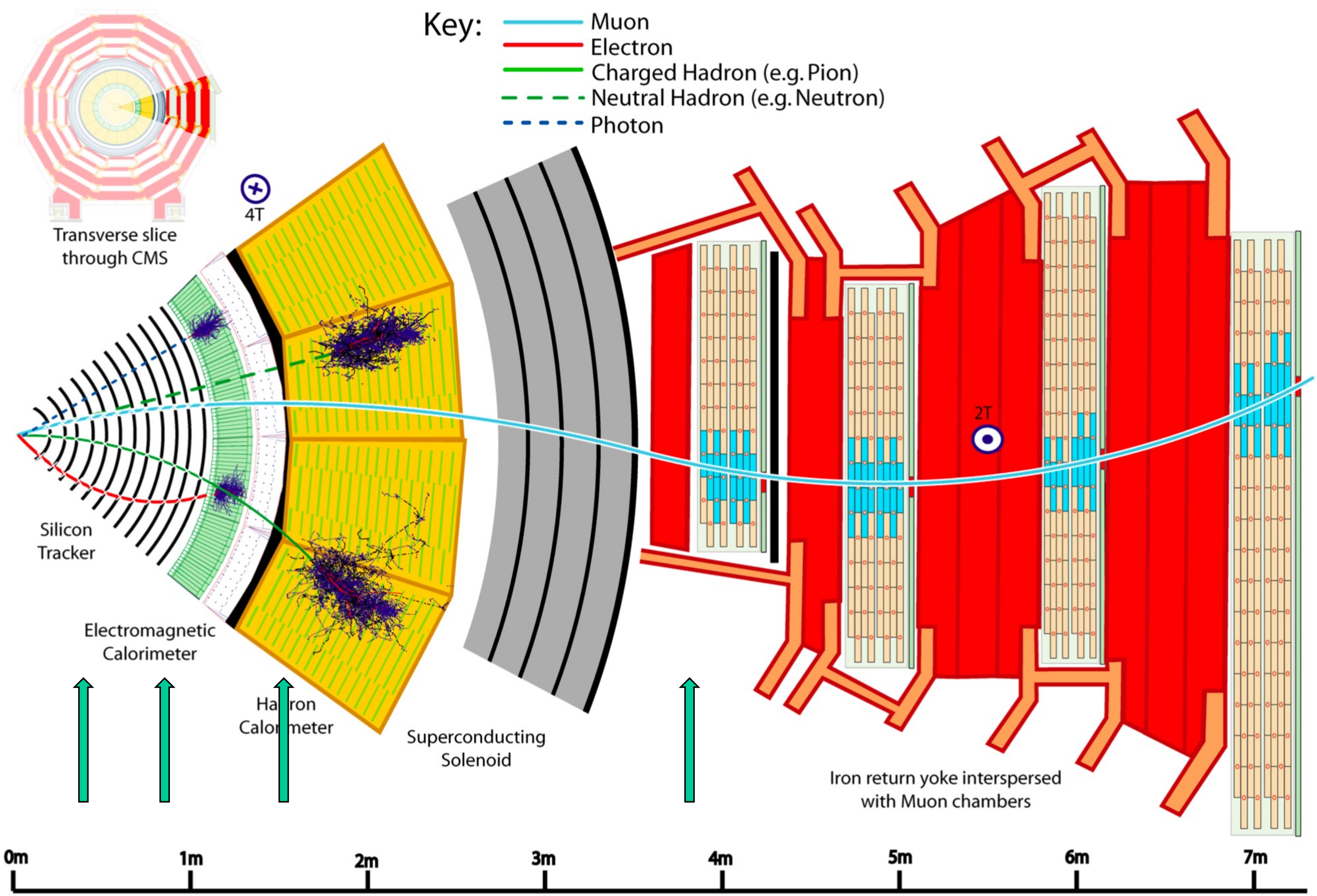
The measurements improve the momentum resolution for p_T > 200 GeV/c if the DT/CSC chambers are properly aligned

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 m** level

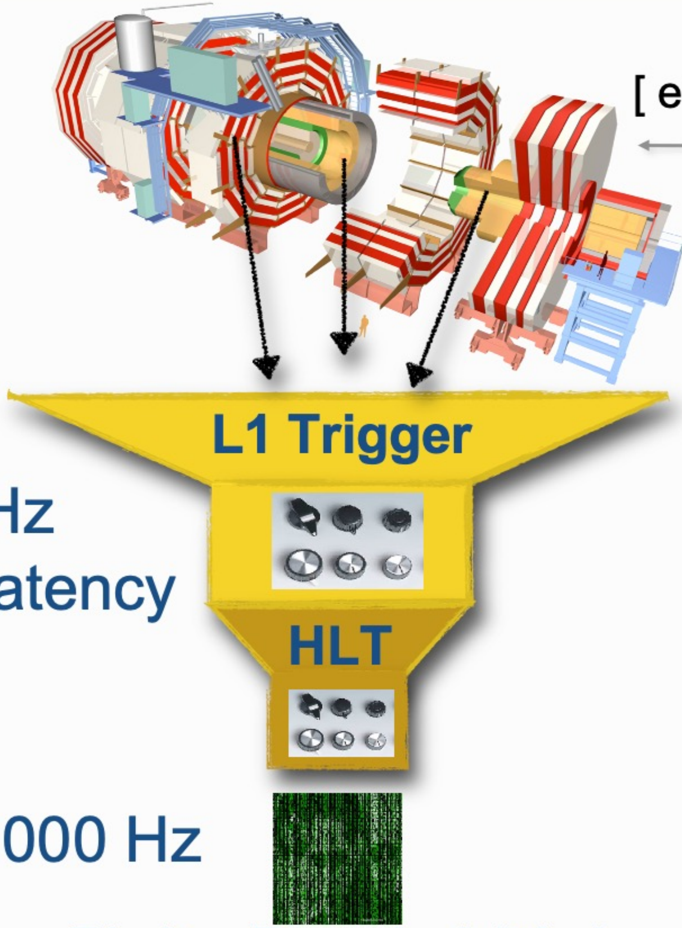


CMS 探测器的设计:触发与数据获取



CMS触发和数据获取系统

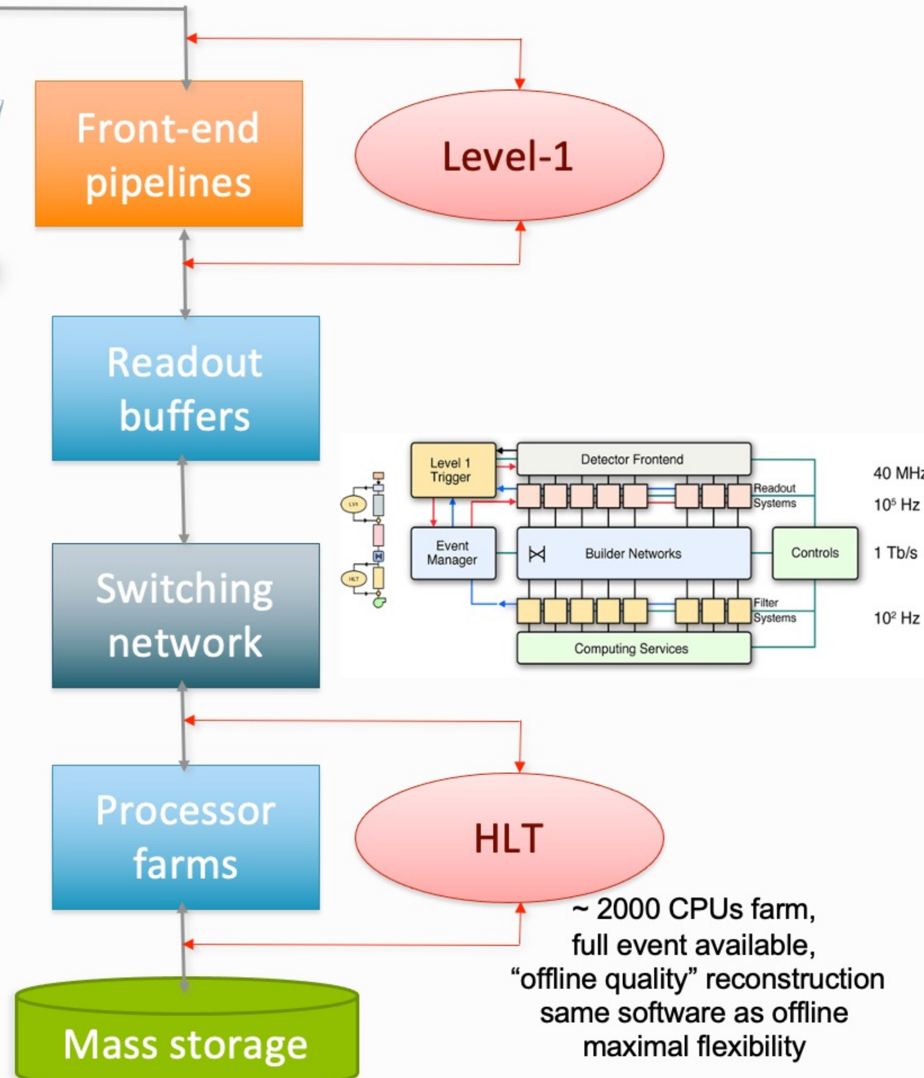
Detector signals
[every 25 ns = 40 MHz]



~100 kHz
3.6 μs latency

~1000 Hz

Finite Bandwidth !

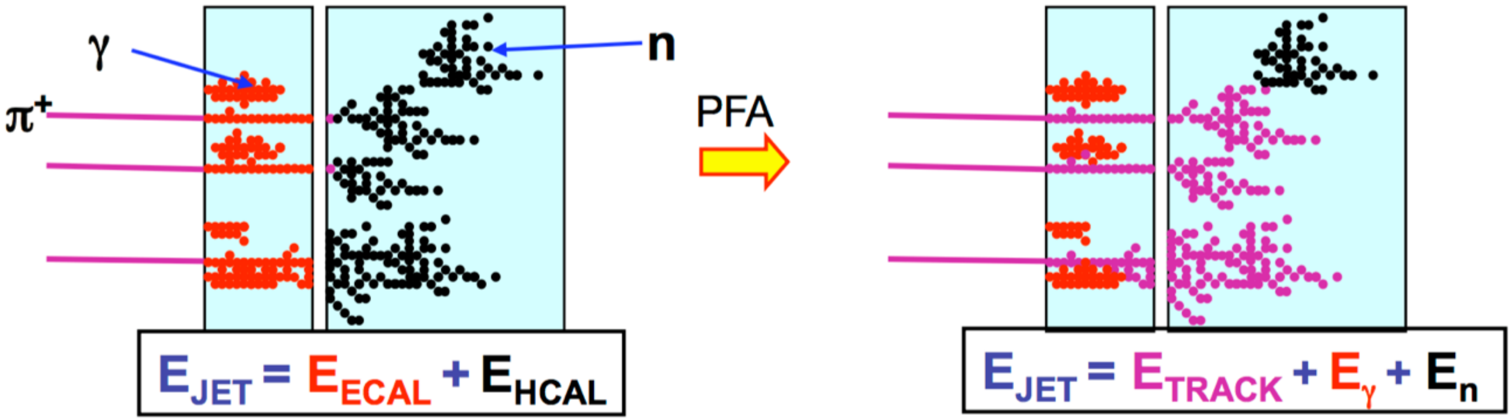


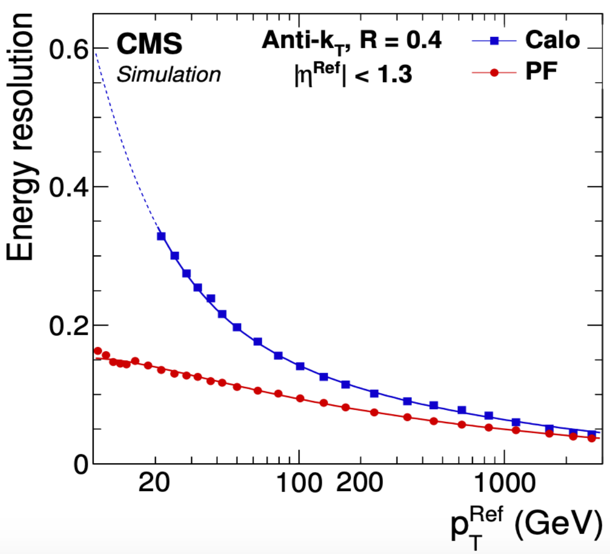
CMS探测器与ATLAS的比较

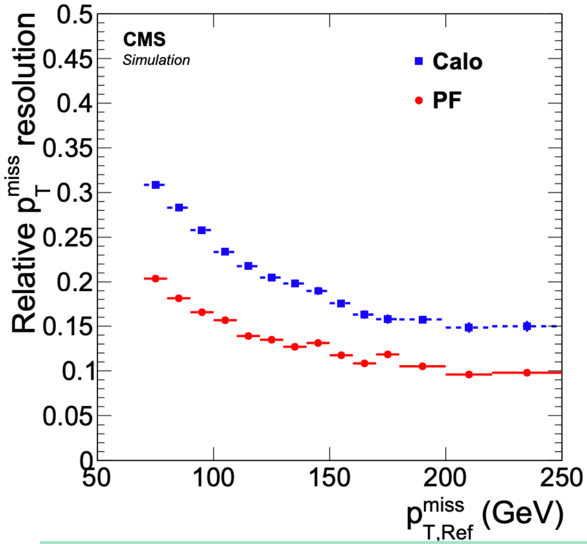
	ATLAS ≡ A Toroidal LHC ApparatuS	CMS ≡ Compact Muon Solenoid
MAGNET (S)	Air-core toroids + solenoid in inner cavity 4 magnets Calorimeters in field-free region	Solenoid Only 1 magnet Calorimeters inside field
TRACKER	Si pixels+ strips TRT → particle identification B=2T $\sigma/p_T \sim 3\times10^{-4}\, p_T \oplus 0.01$	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

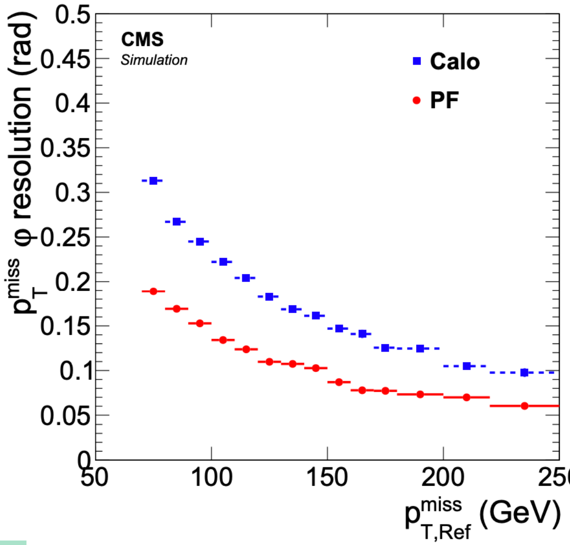
Use best meas. of individual particle in a jet (MET), ==> Particle Flow Algorithm

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









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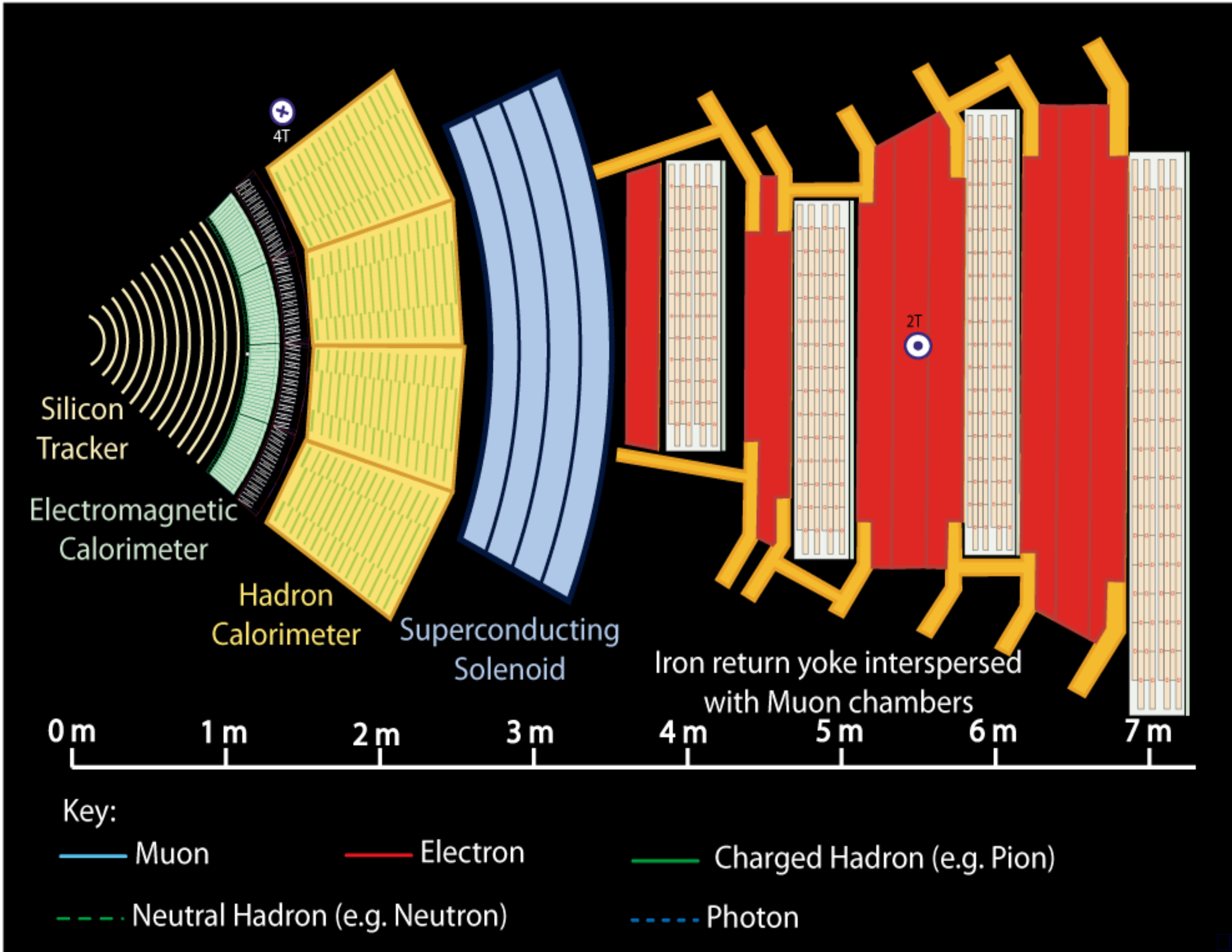
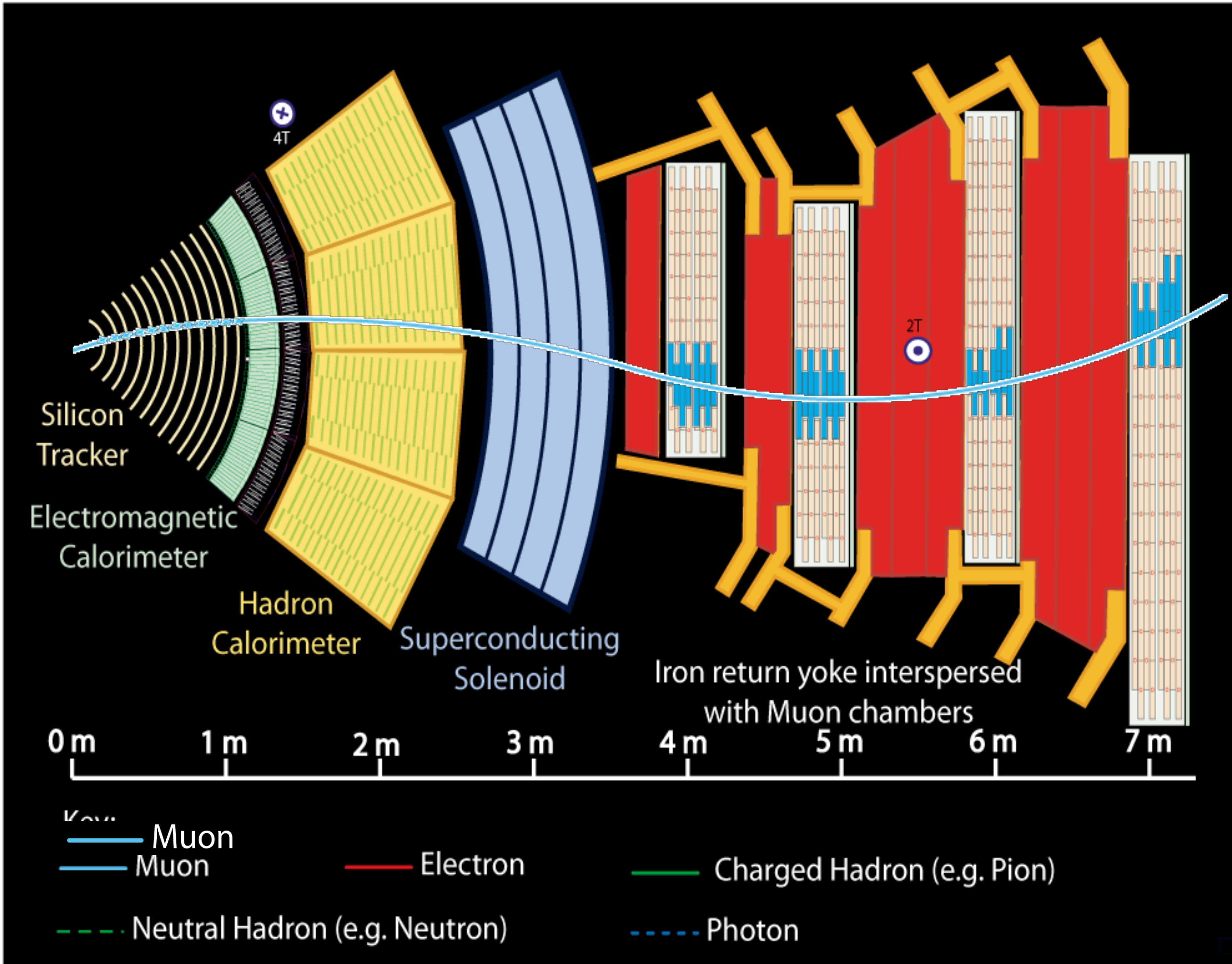

4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon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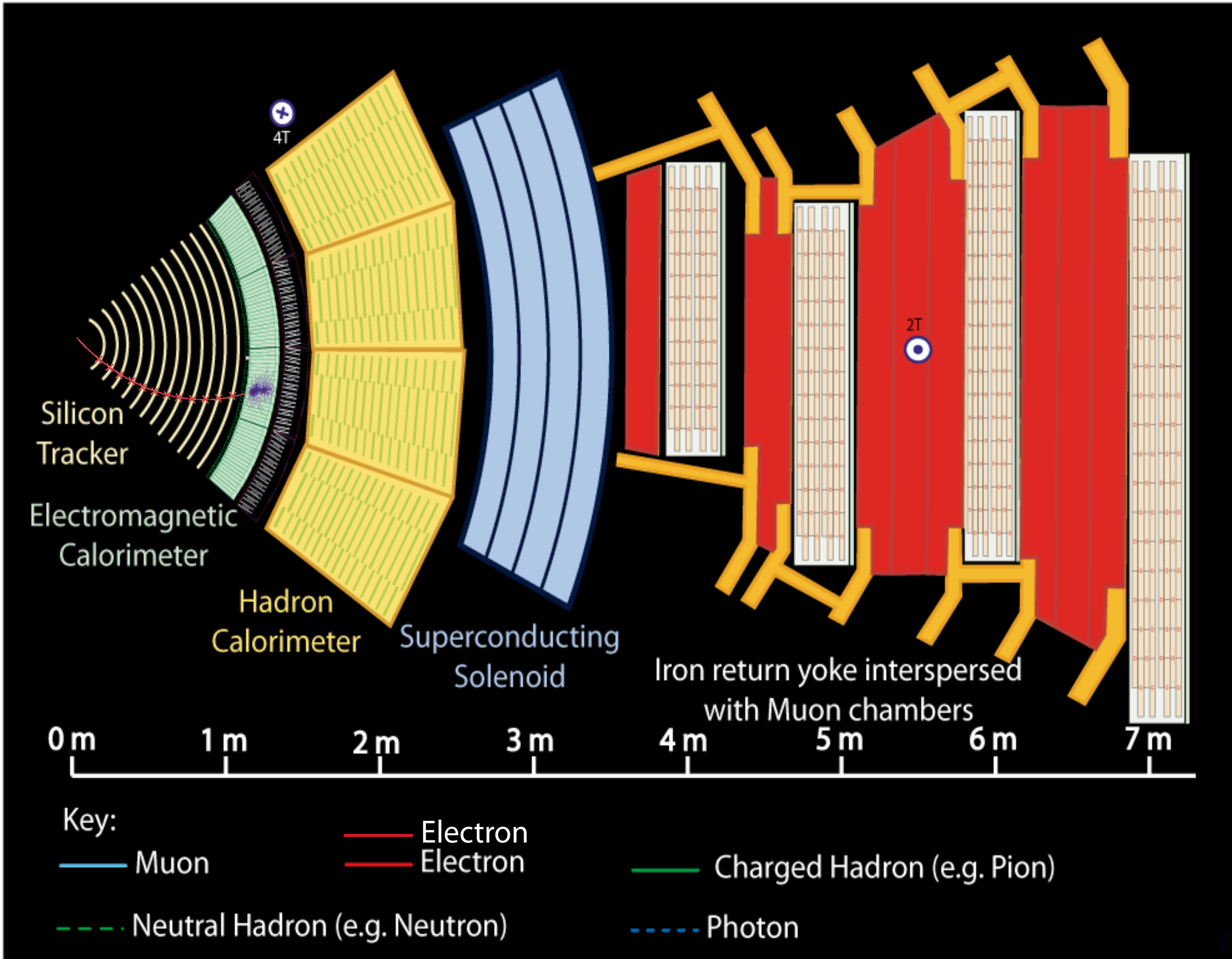
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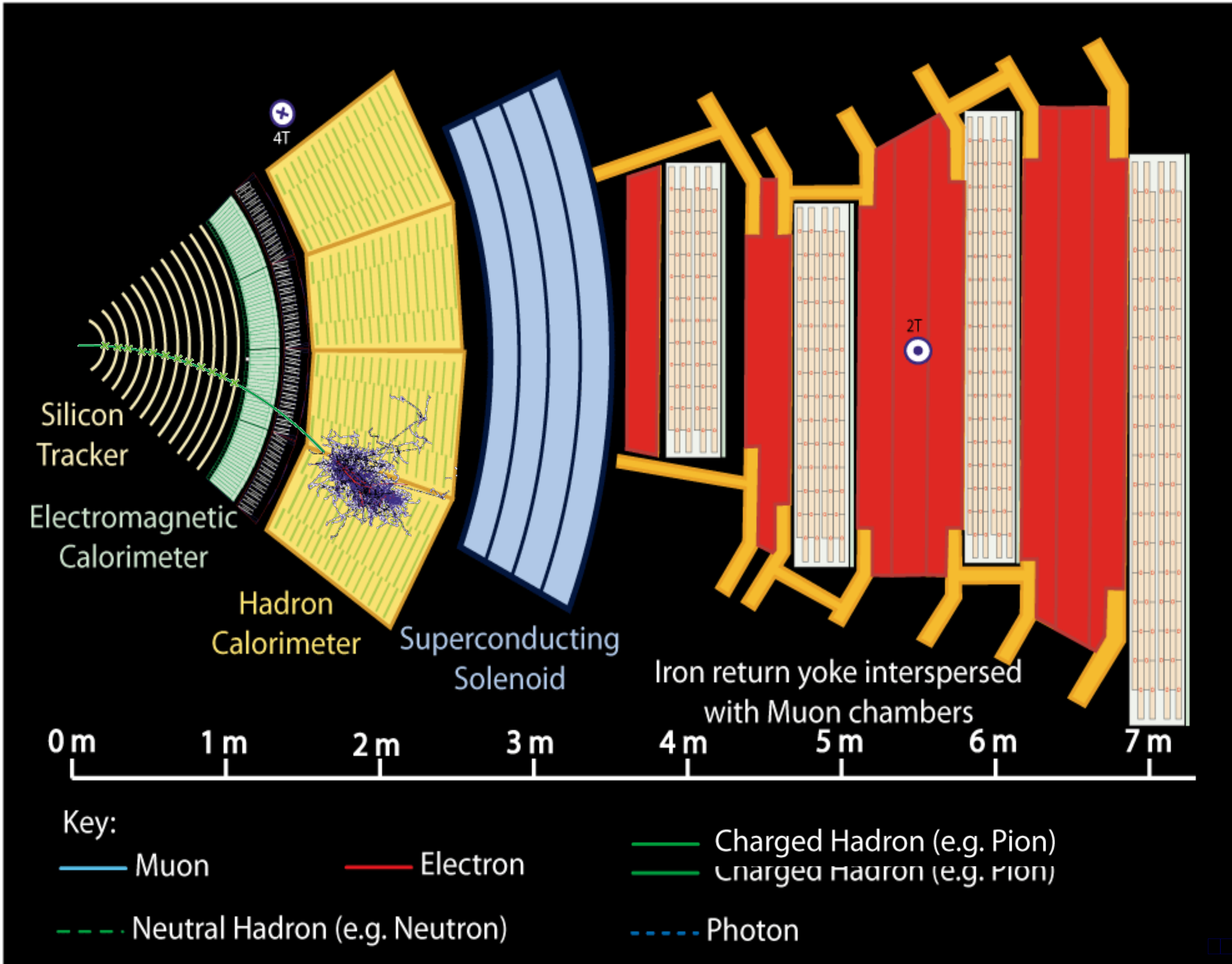
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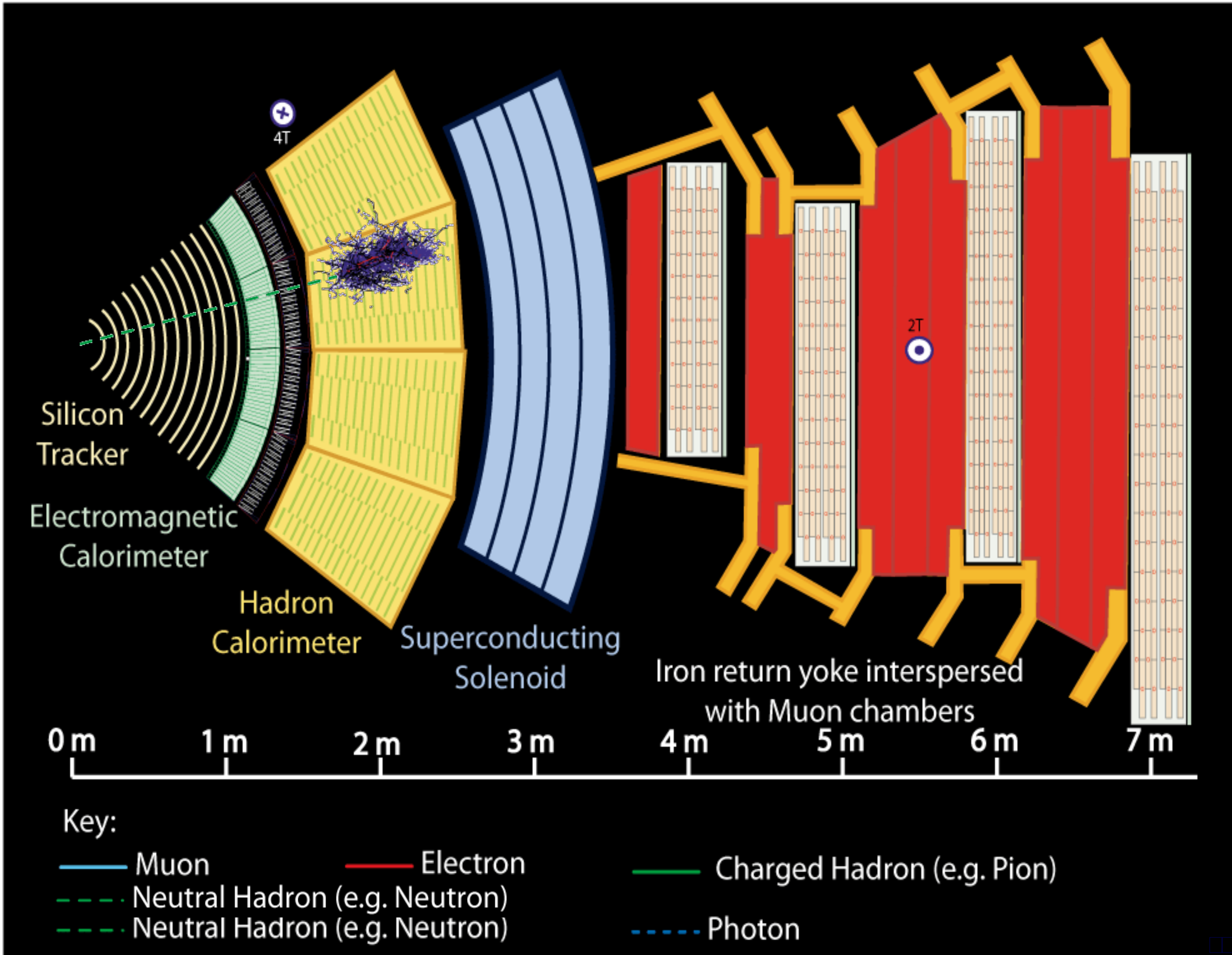
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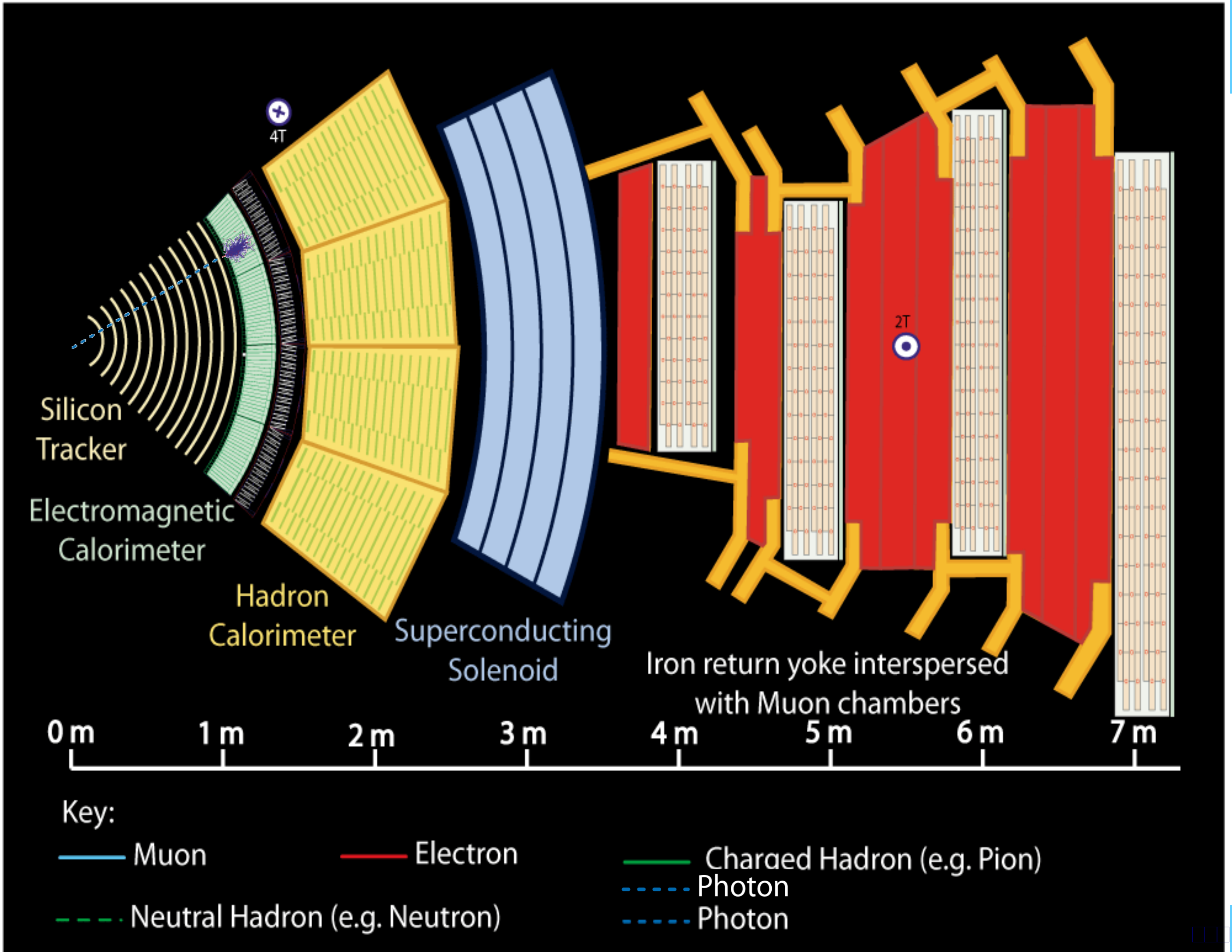
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7 m
Key:
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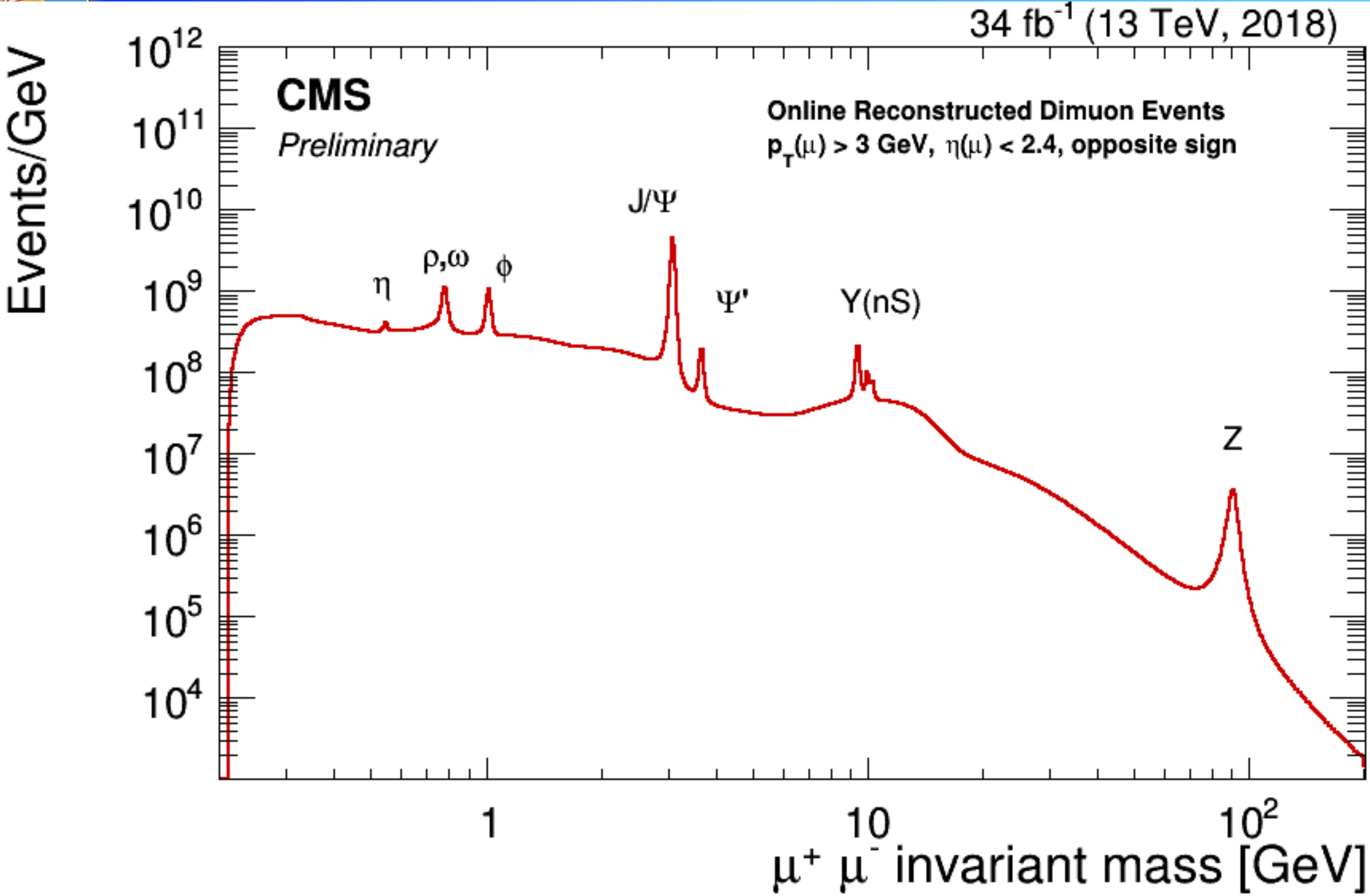
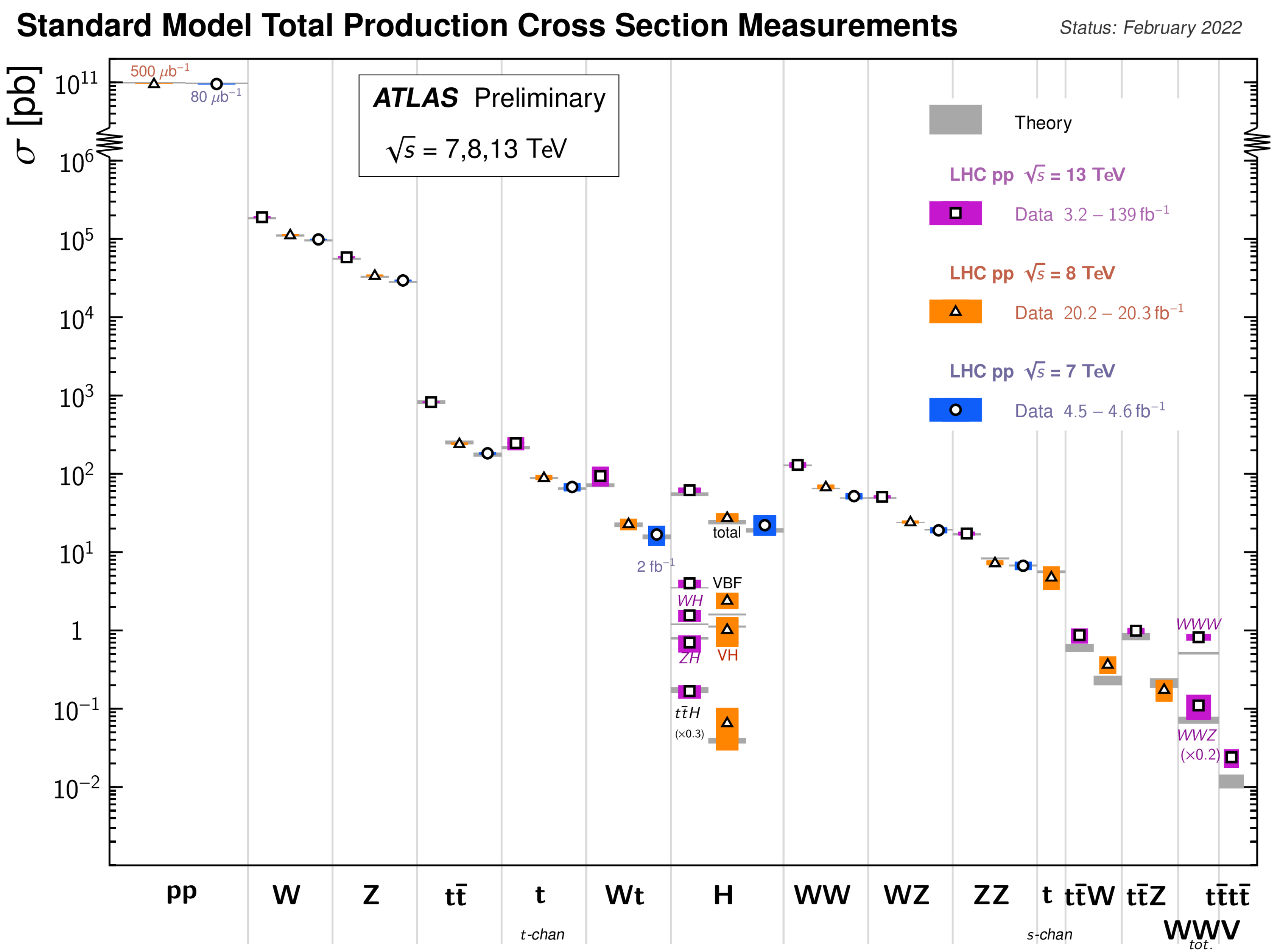
Electron
Charged Hadron (e.g. Pion)
Photon
Neutral Hadron (e.g. Neutron)
Photon

Standard candle

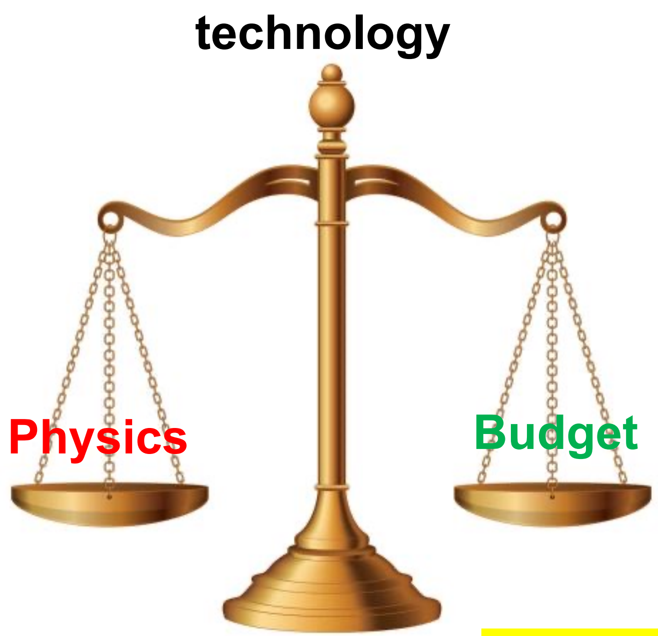


Physics results

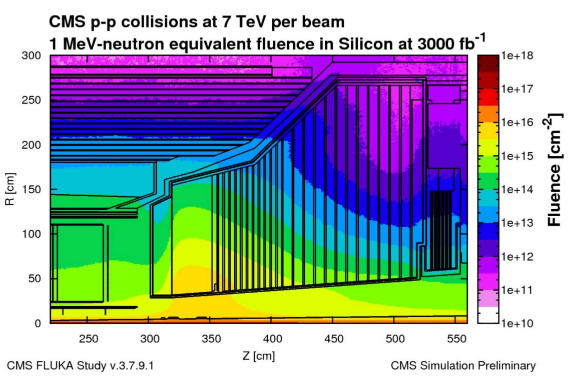


Challenge of HL-LHC

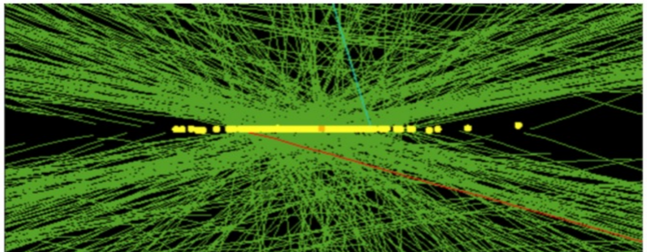
- Success LHC, upgrade needed for rich physics programs
  - 10 times more data
  - Higher center of mass energy
- Challenges
  - 10 times more radiations…
  - Pileup, event rates
  - Limited budget



Radiation damage



Pileup challenge



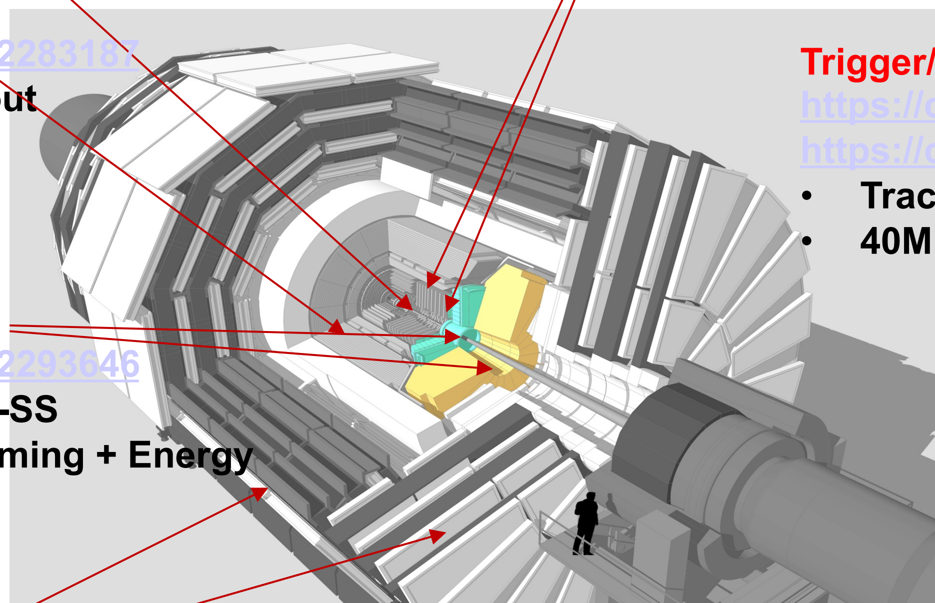
Event rates capability

Overview of CMS phase II upgrade

Tracker: https://cds.cern.ch/record/2272264
- Si-strips and Pixels increased granularity
- Tracking in L1-Trigger
- Coverage extended to |eta|~3.8

MIP Timing detector: https://cds.cern.ch/record/2296612
- ~30ps timing resolution
- Barrel: Crystals + SiPMs
- Endcap layer: LG Avalanche Diodes

Barrel Calorimeter: https://cds.cern.ch/record/2283187
- New ECAL/HCAL readout



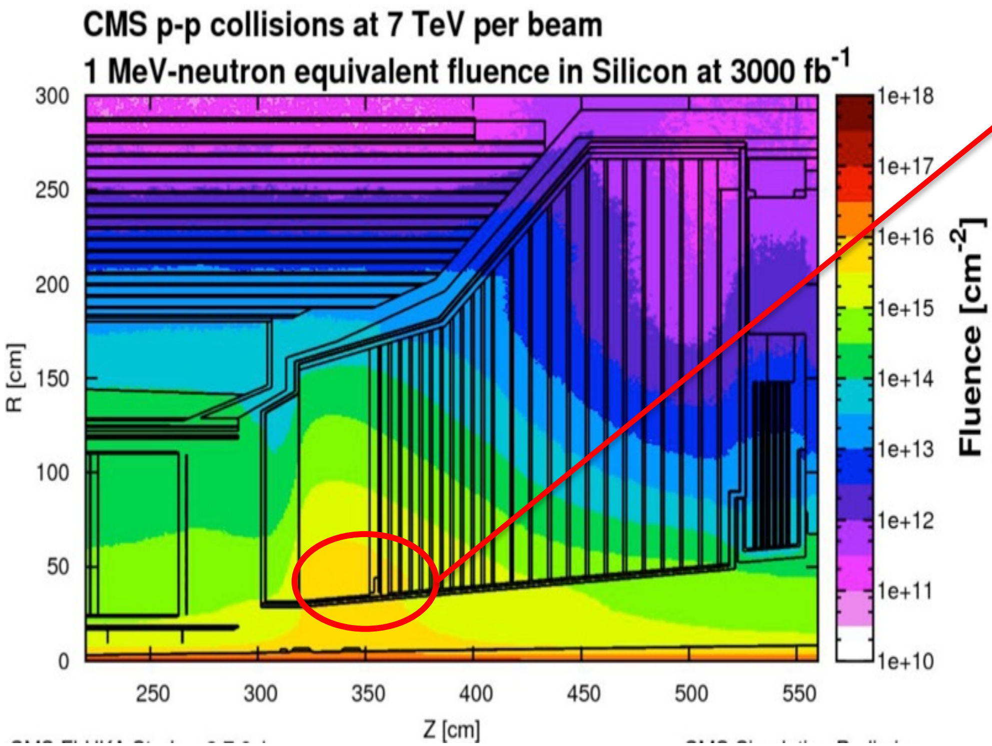
Trigger/DAQ: https://cds.cern.ch/record/2283192 https://cds.cern.ch/record/2283193
- Tracks in L1
- 40M → 750k(PF-like) → 7.5k

Calorimeter Endcap: https://cds.cern.ch/record/2293646
- Si, Scint+SiPM in Pb-W-SS
- 3D position + precise timing + Energy

Muon system: https://cds.cern.ch/record/2283189
- New FE/BE readout for DT/CSC
- New GEM/RPC 1.4 <|eta|<2.4
- Coverage extended to |eta|~3

Beam/Luminosity and common Infrastructure https://cds.cern.ch/record/2020886

CMS端盖量能器升级挑战

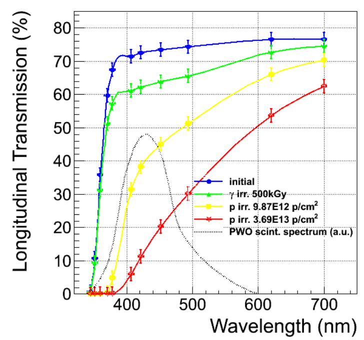


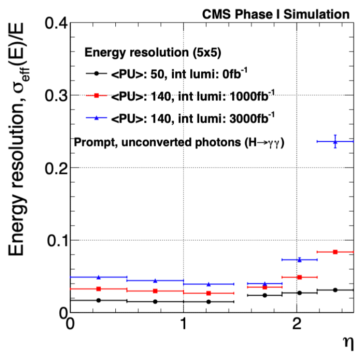
CMS @ HL-LHC:

~1x10^{16} 1 MeV n_{eq} /cm^{-2}

2 MGy 吸收剂量

140-200 堆积事例





现有量能器外推到HL-LHC的性能

有限的升级经费…

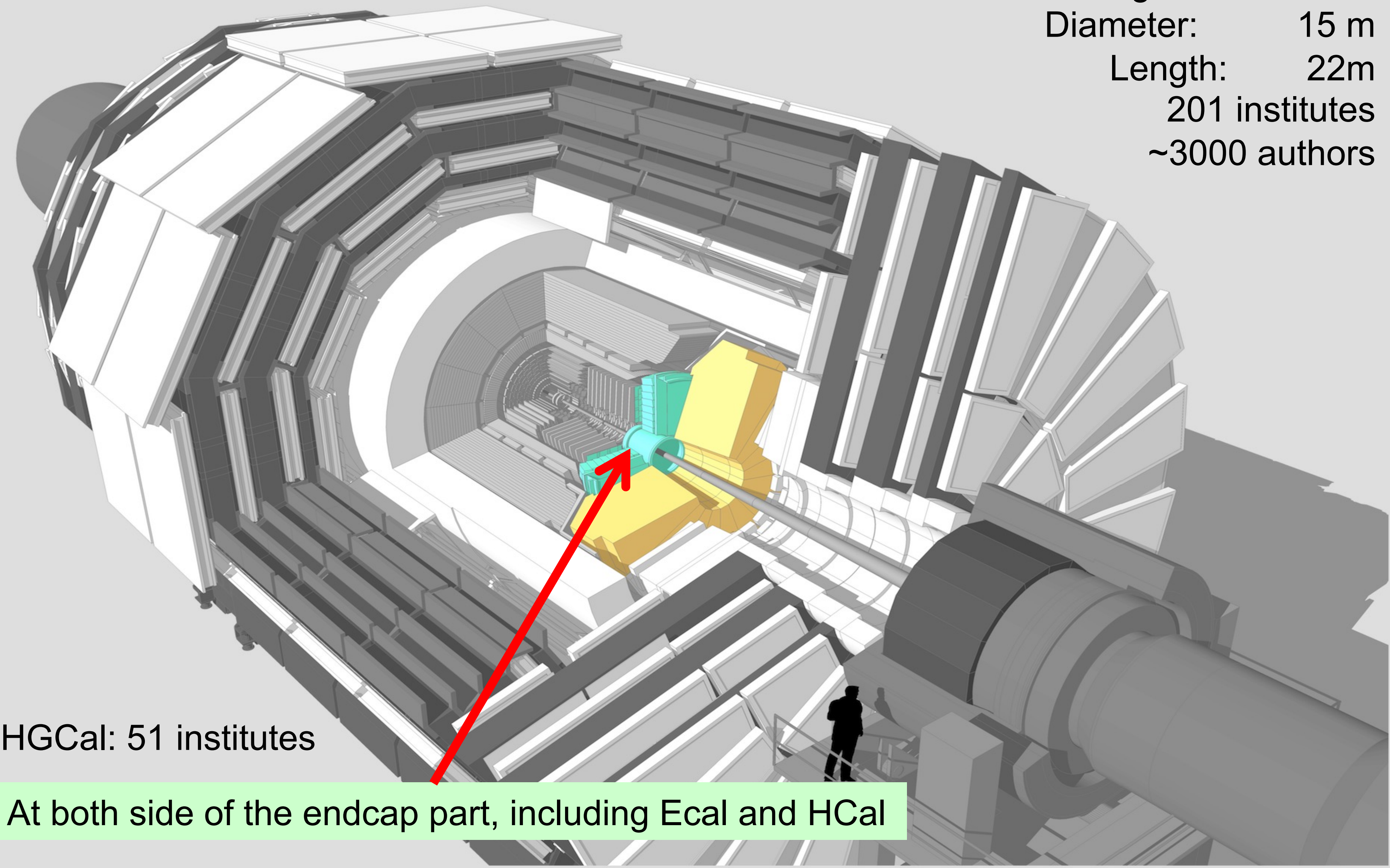
- 抗辐照是必须满足的
  - 多种方案竞争
- 物理的需求：喷注的能量分辨，堆积事例效应…

最终胜出者：

高粒度量能器方案
CMS HGCal

CMS实验中的高粒度量能器

Total weight: 14000 tons
Diameter: 15 m
Length: 22m
201 institutes
~3000 authors



HGCal: 51 institutes

At both side of the endcap part, including Ecal and HCal

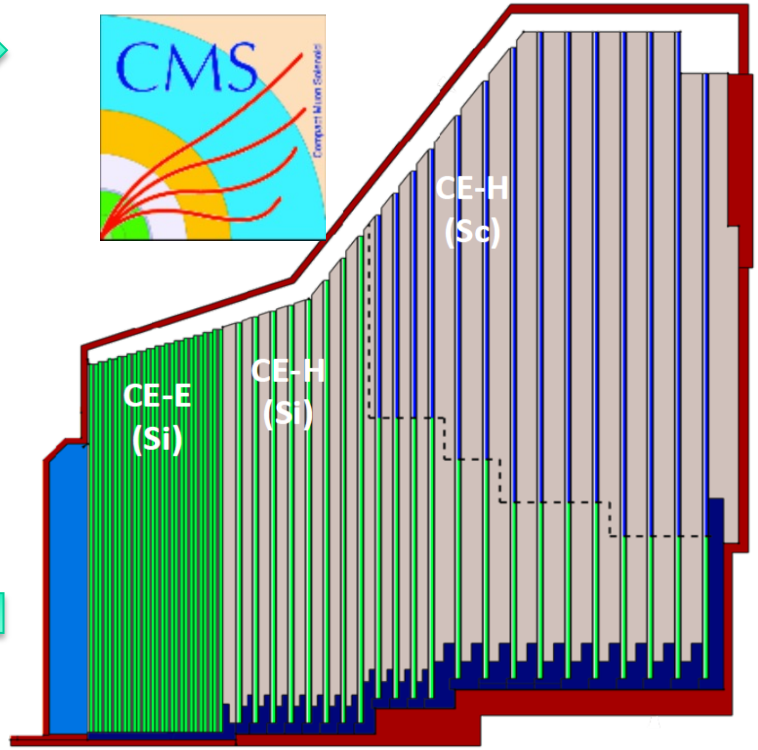
CMS 高粒度量能器项目技术特点

法国/葡萄牙/日本/英国

～20年的研发，未正式建造

同样技术

CMS 高粒度量能器
第一个大规模建造的此类探测器



空间项
目等

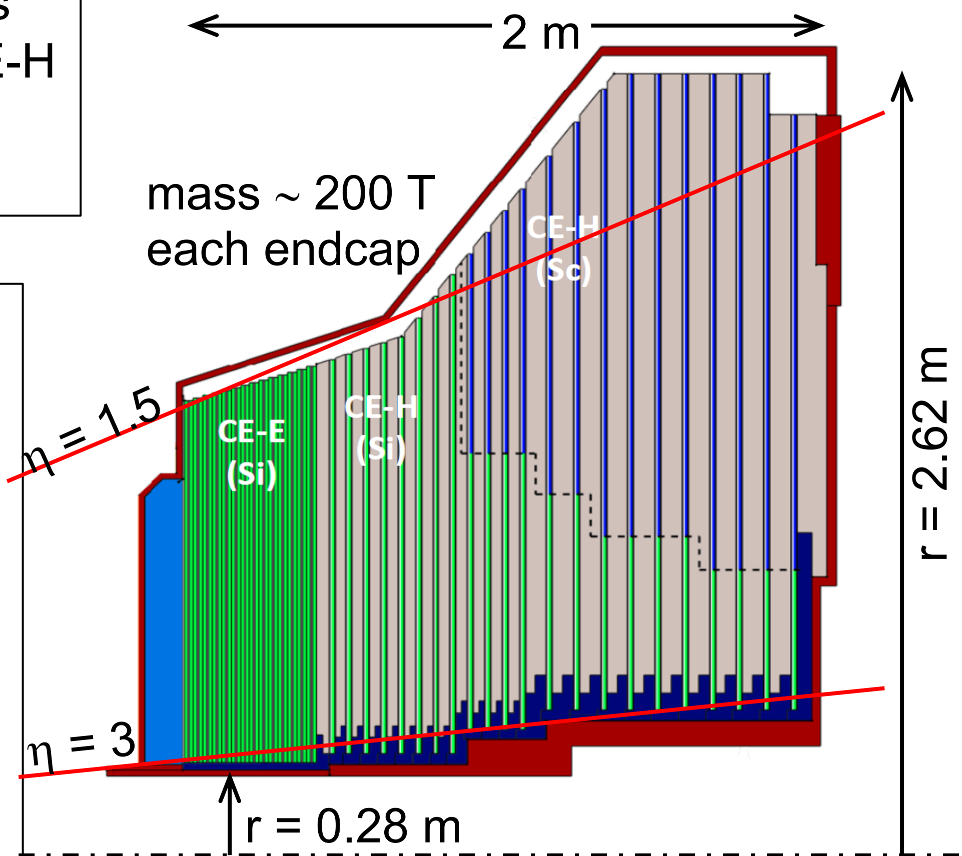
其他未来高能物理实验

优点：可以达到1立方厘米一个探测读出
很好的能量，位置，时间分辨率：5D量能器
抗辐照性能好：10^{16} MeV 中子/厘米^2

CMS HGCAL: a 50-layer sampling calorimeter

Active Elements:
- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- Scintillating tiles with SiPM readout in low-radiation regions of CE-H

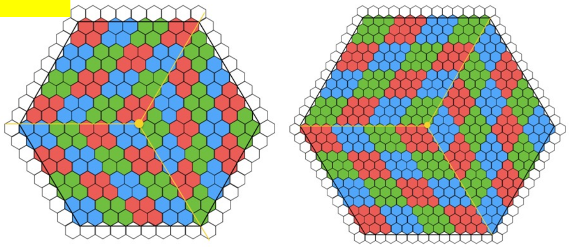
Key Parameters: (updated from TDR)
- HGCAL covers 1.5 < |η| < 3.0
- **Full system maintained at -30°C**
- **~620m²** of silicon sensors
- **~370m²** of scintillators
- 6M Si channels, 0.5 or 1.1 cm² cell size
  - Data readout from all layers
  - Trigger readout from alternate layers in CE-E and all layers in CE-H
- ~28000 Si modules including spares



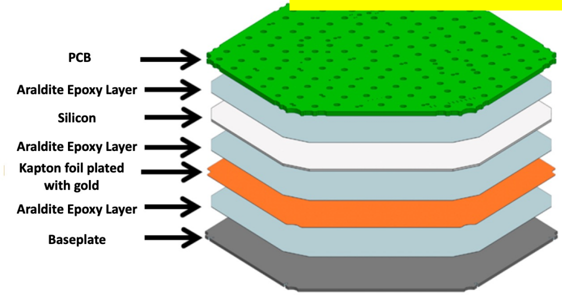
Electromagnetic calorimeter (**CE-E**): **Si**,Cu/CuW/Pb absorbers,26 layers,25.5 X_0 & ~1.7λ
Hadronic calorimeter (**CE-H**): **Si** & **scintillator**, steel absorbers, 21 layers, ~9.5λ

The HGCAL detector

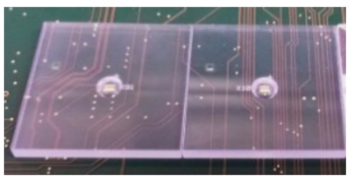
Si Sensor 8inch, 1.18cm^2（192）/ 0.52cm^2（432）

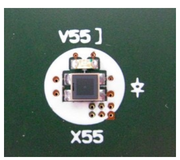


Silicon Module



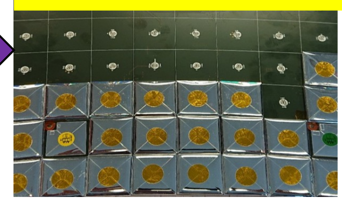
Sci. tile

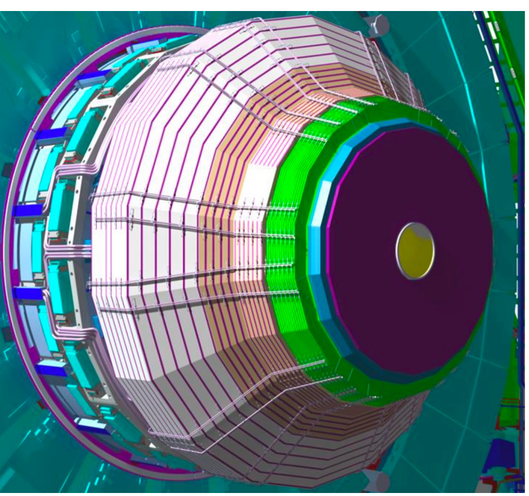


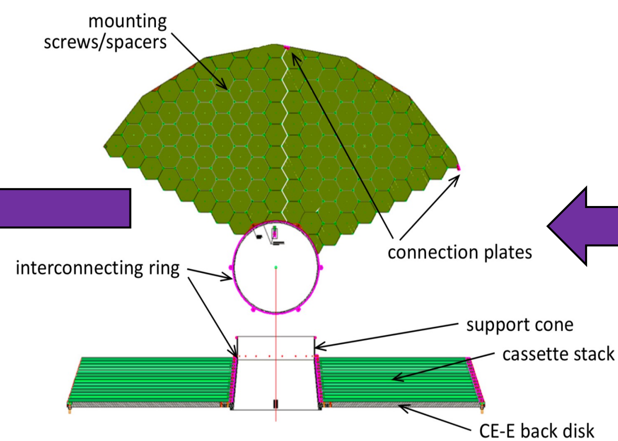


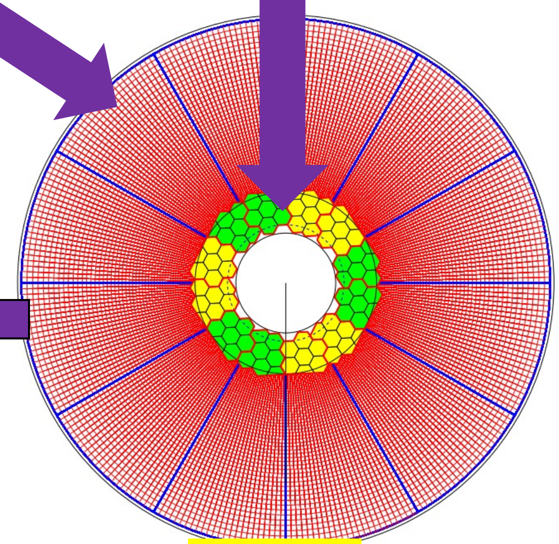
Scintillator + SiPMs

Tile module







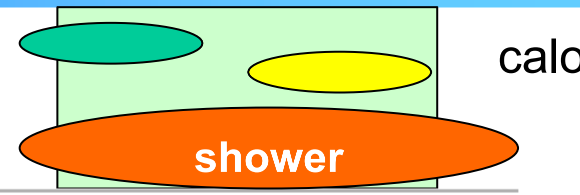


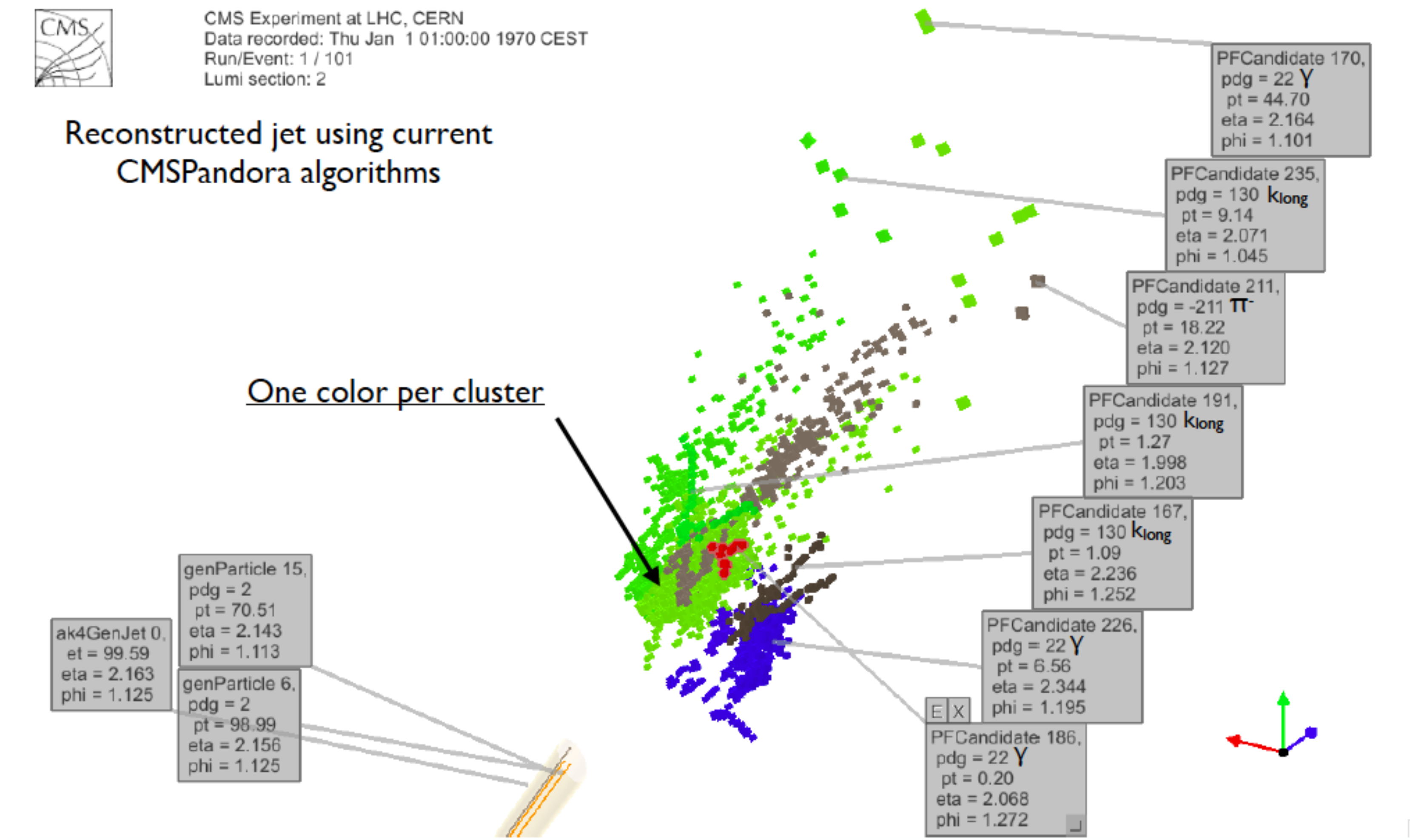
Stacking

Tiling

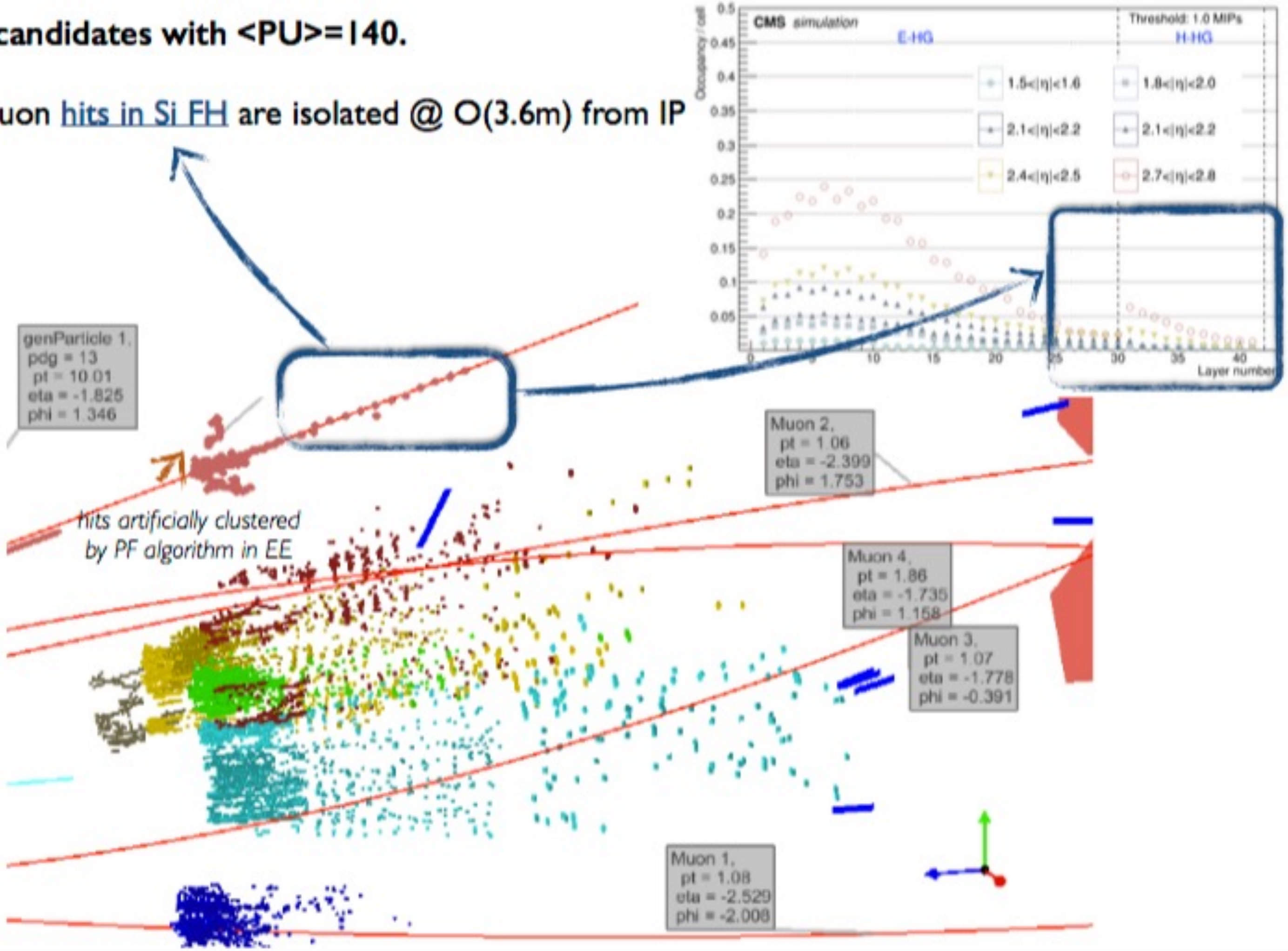
Advantage of CMS HGCal（1）

- 3D positioning
  - Full shower shape reco.: PID，Energy Calib

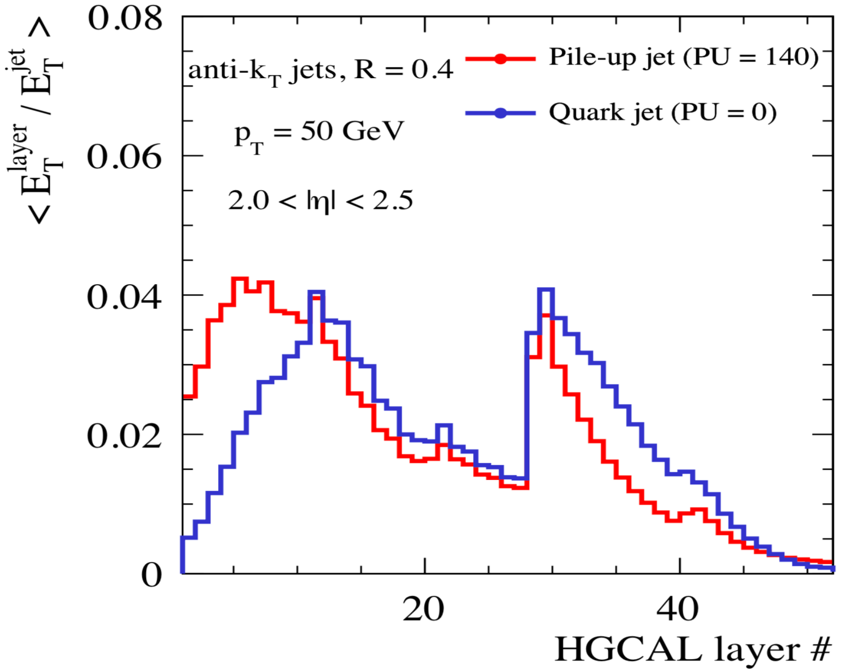


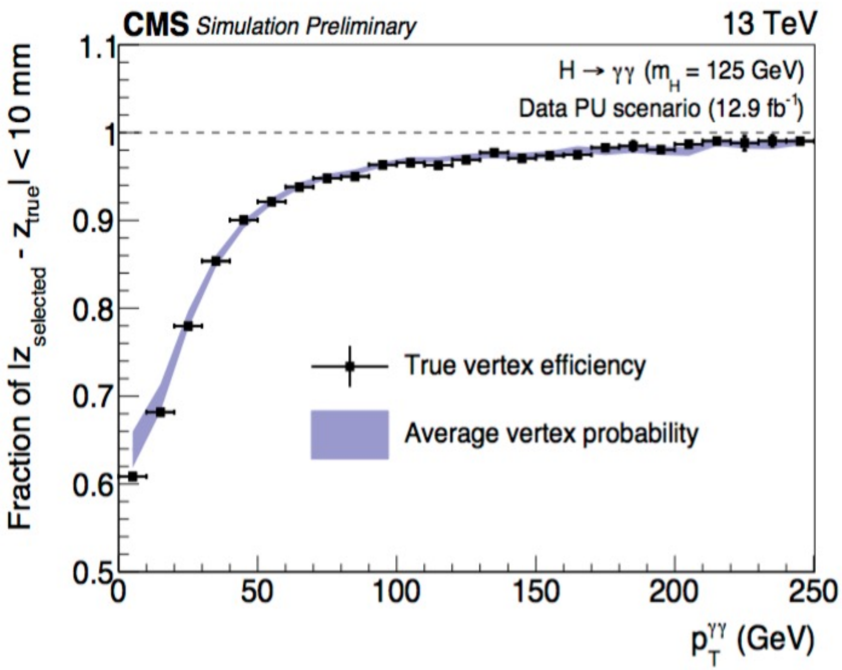


- 3D positioning
  - Full shower shape reco.: muon tag
    - Muon candidates with <PU>=140.
    - True muon hits in Si FH are isolated @ O(3.6m) from IP



- 3D positioning
  - Full shower shape reco.: pileup mitigation back pointing etc

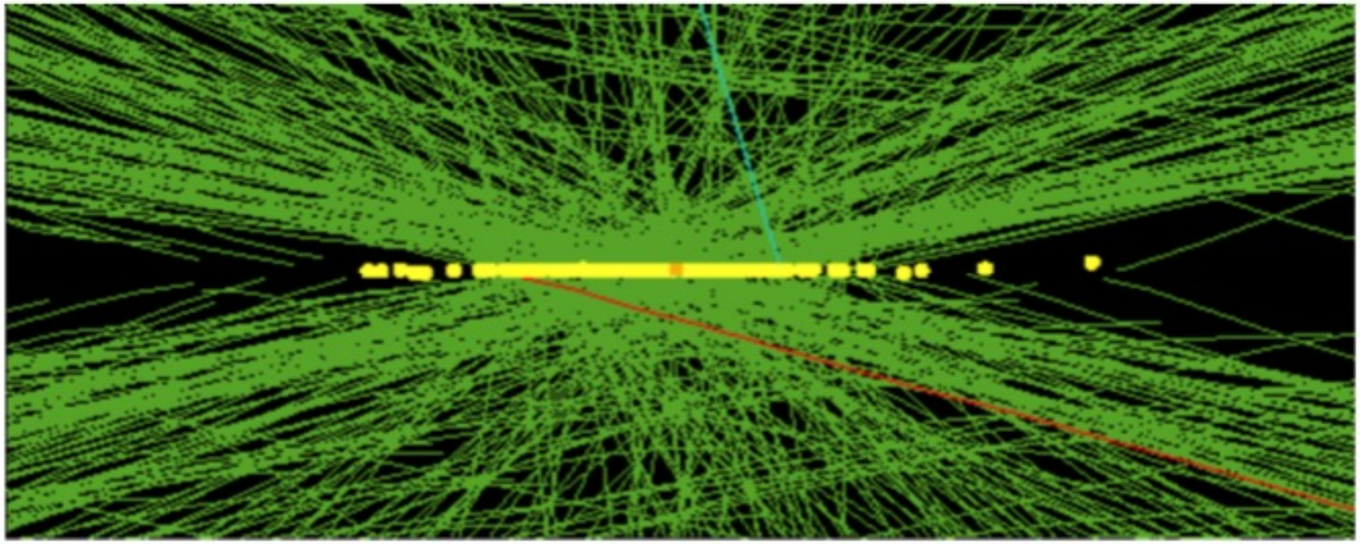




- Pileup Energy deposite first few layers
- Energy barycenter of each layer pointing back to IP
  - Complementary for IP ID

Advantage of CMS HGCal（4）

- Accurate time information
  - New dimension for calor.



78→200 PU

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

- Particle from different IP has different arrival time w.r.t. ref.:
  - HGC time resolution ~50ps，which light travels ~1.5cm
  - The size of HGC cell is around 1 cm^3
  - For particles from same IP, The difference of arrival time and difference of psudo-rapidility indicates the position of IP

Platform for advanced algorithms

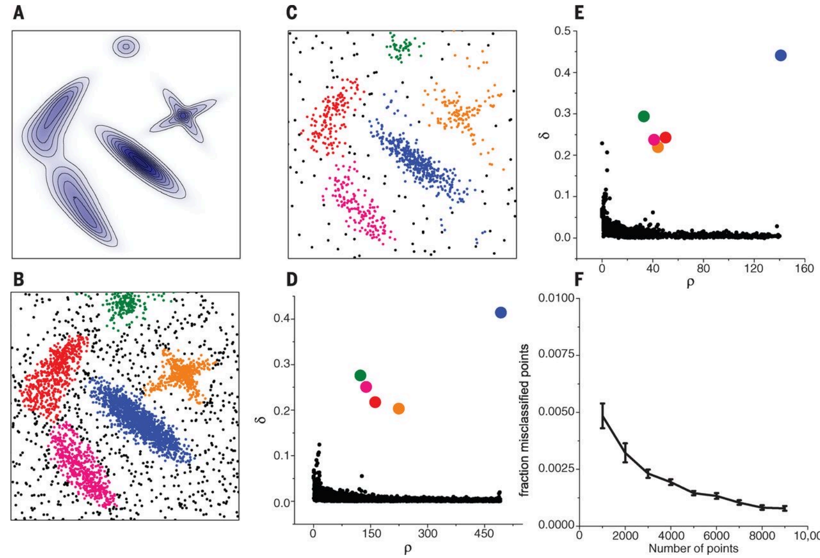
- Computing vision
- GPU Trigger
- Machine Learning
- PFA with time
- …

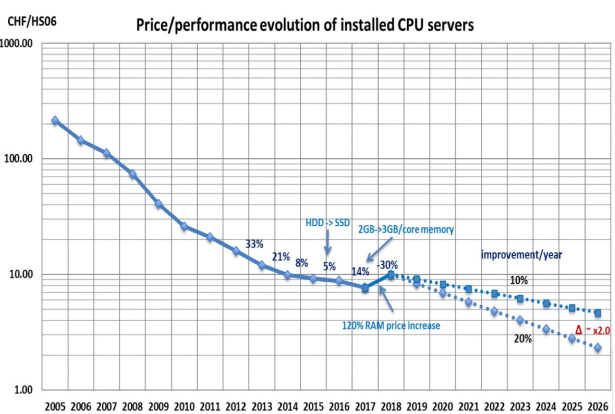
Physics Results

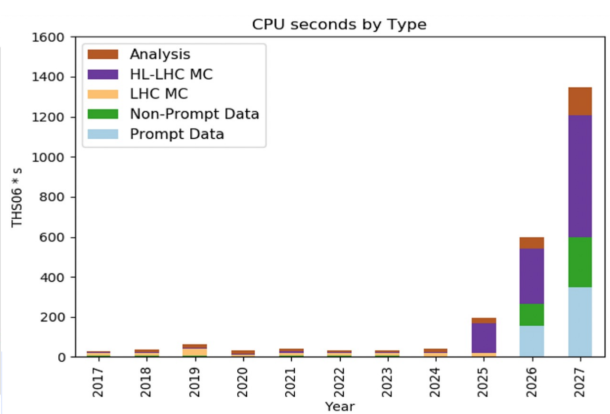
Clustering by fast search and find of density peaks

Alex Rodriguez, Alessandro Laio
+ See all authors and affiliations

Science 27 Jun 2014:
Vol. 344, Issue 6191, pp. 1492-1496
DOI: 10.1126/science.1242072



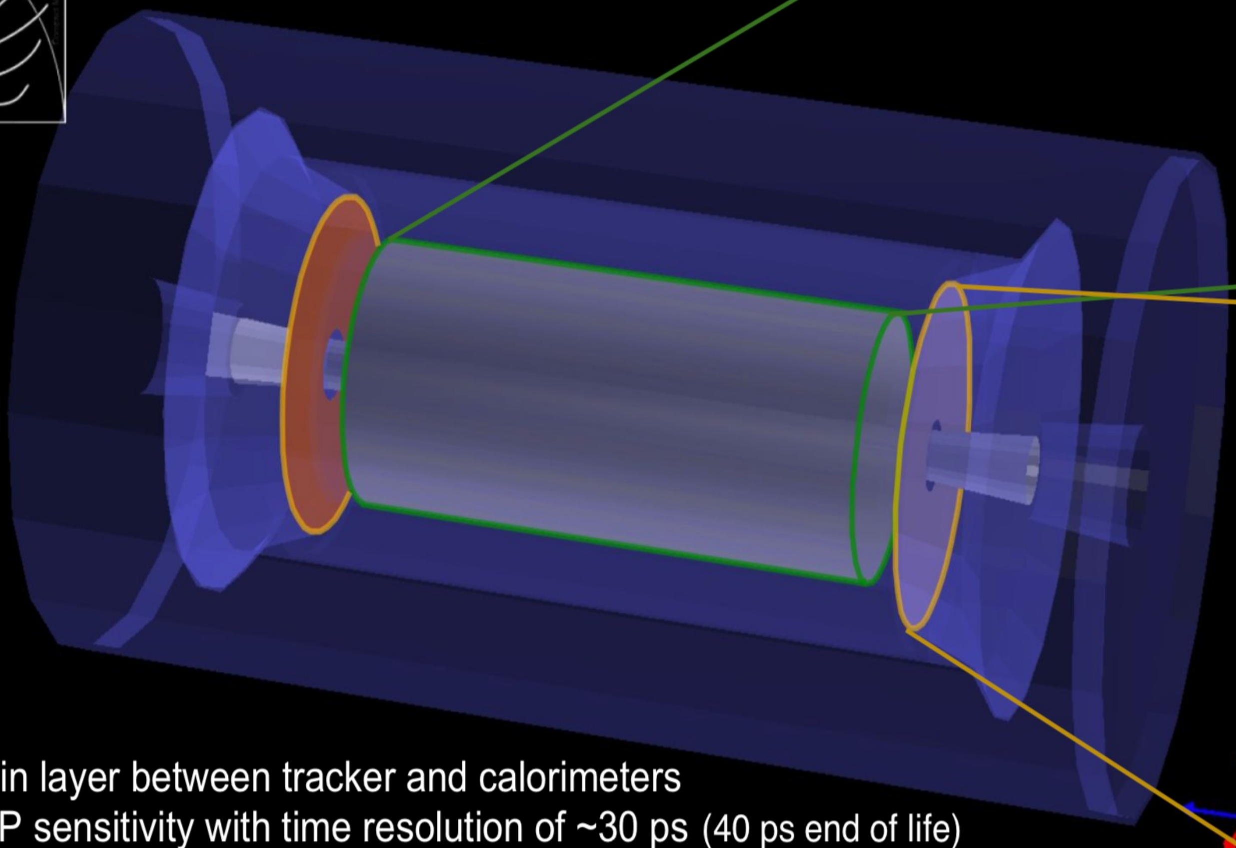




Mip Timing Detector overview

Calorimeter upgrades:

- Precision timing of **showers**
- Provide precision timing on high energy photons in ECAL Barrel
- All photons and high energy hadrons in HGCal Endcap



BARREL

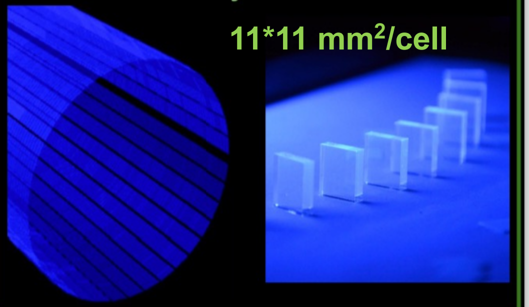
TK/ECAL interface ~ 25 mm thick

Surface ~ **40** m^2

Radiation level ~ $2x10^{14}$ n_{eq}/cm^2

Sensors: **LYSO crystals + SiPMs**

11*11 mm^2/cell



ENDCAPS

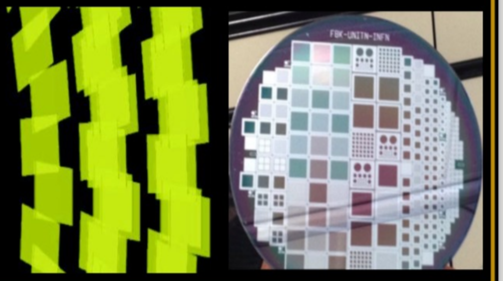
On the CE nose ~ 42 mm thick

Surface ~ **12** m^2

Radiation level ~ $2x10^{15}$ n_{eq}/cm^2

Sensors: **Si with internal gain (LGAD)**

1*3 mm^2/cell

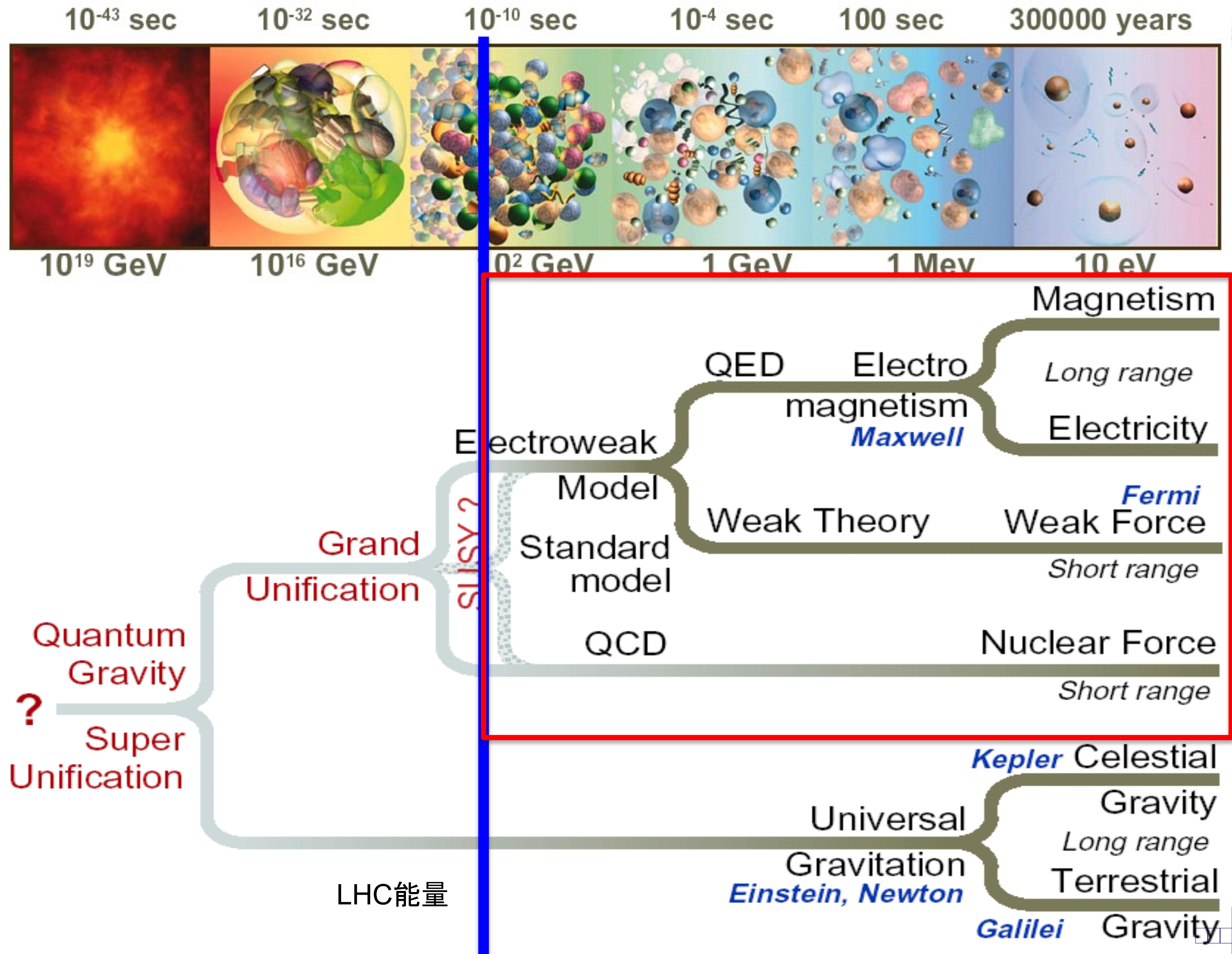


- Thin layer between tracker and calorimeters
- MIP sensitivity with time resolution of ~30 ps (40 ps end of life)
- Hermetic coverage for |η|<3

总结

- LHC 提供了独一无二的高能量实验平台，为研究基本物质世界的运动规律提供了条件
- 高亮度LHC升级超出现有探测器的设计，所采用的新探测器技术代表了未来探测的发展方向
- 欢迎大家来LHC/CMS/IHEP交流，迎接高亮度LHC的挑战，探寻高能量前沿的未知之谜

bakup



10-43 sec
10-32 sec
10-10 sec
10-4 sec
100 sec
300000 years
1019 GeV
1016 GeV
102 GeV
1 GeV
1 Mev
10 eV
Magnetism
QED
Electro magnetism
Maxwell
Long range
Electricity
Electroweak
Model
Standard model
Weak Theory
Fermi
Weak Force
Short range
QCD
Nuclear Force
Short range
Grand Unification
SUSY?
Quantum Gravity
?
Super Unification
Kepler
Celestial Gravity
Long range
Universal Gravitation
Einstein, Newton
Terrestrial
Galilei
Gravity
LHC能量