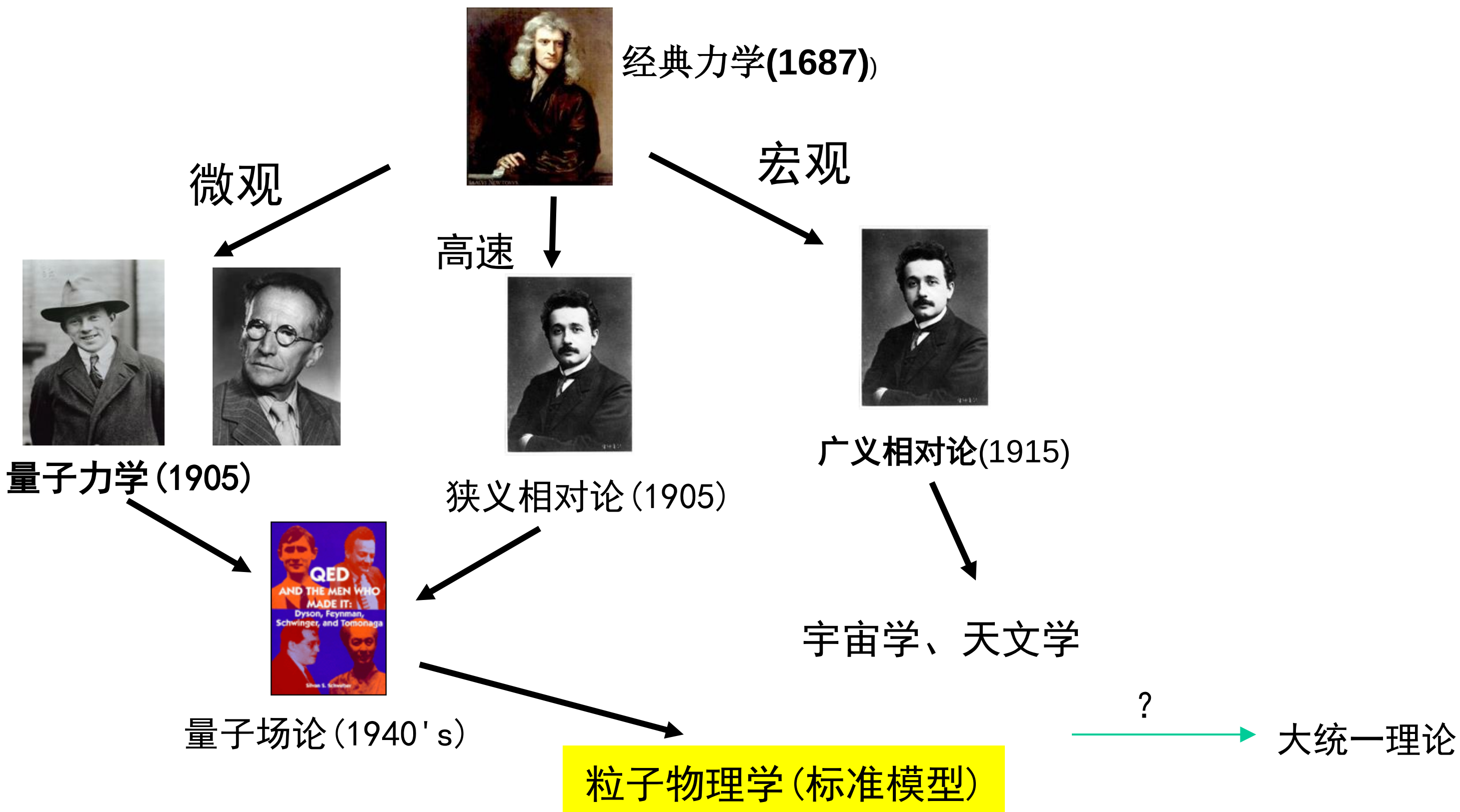
CMS实验简介

张华桥，高能物理研究所

报告内容

- 高能物理的研究对象和方法
- 为什么要建立LHC
- CMS实验和物理介绍
- 中国CMS介绍
- 小结

物理理论的关键发展图谱

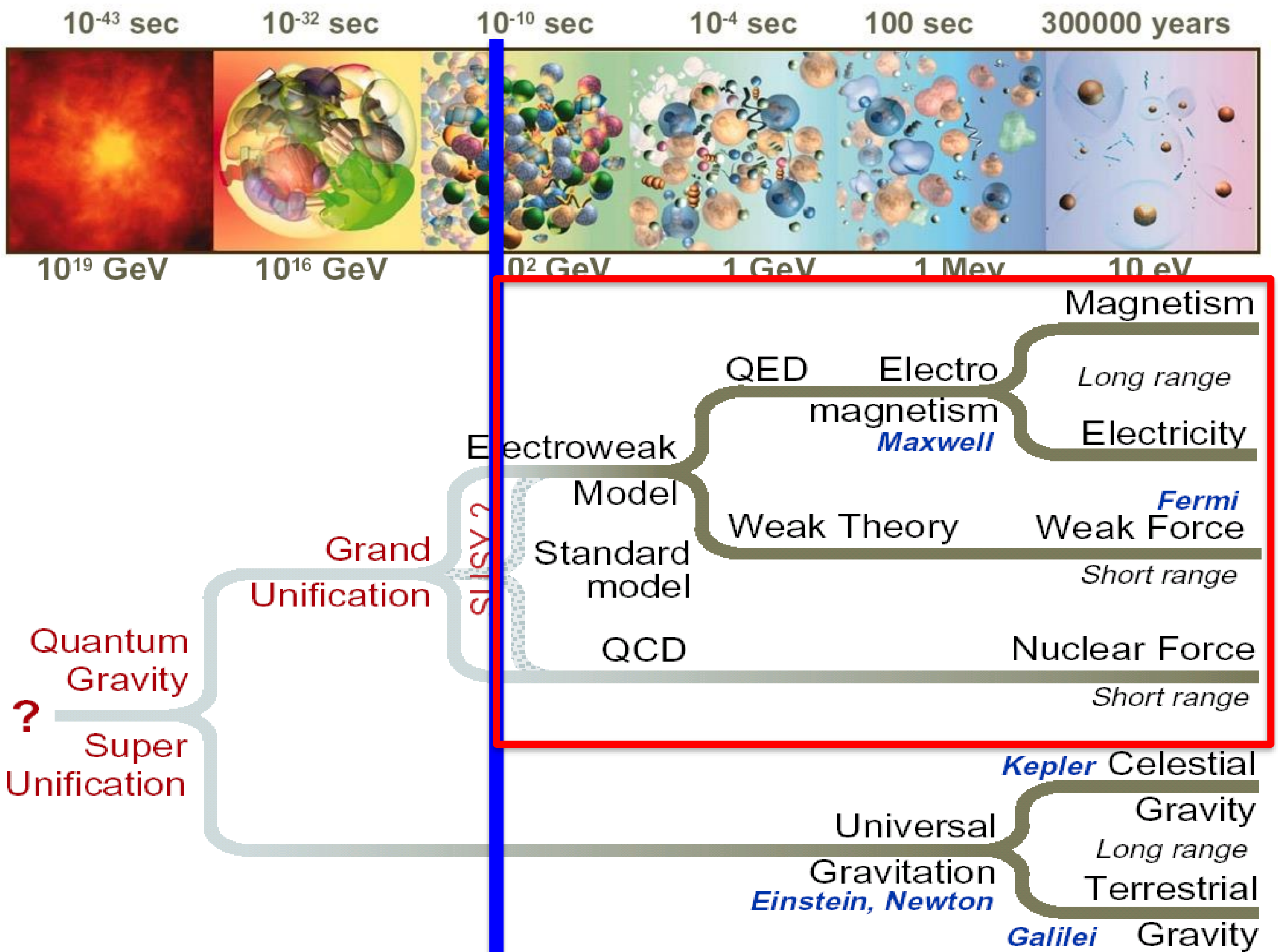


物理的研究范畴

上知天文，下知地理？

物质和宇宙

探索极大与极小的高能物理



大型强子对撞机(LHC)能量

探索宇宙的过去与未来...

奇点 → 基本粒子 → 原子核 电子 光子 → 星系 恒星 行星 → 生命

可观测宇宙：930亿光年

大坍塌？

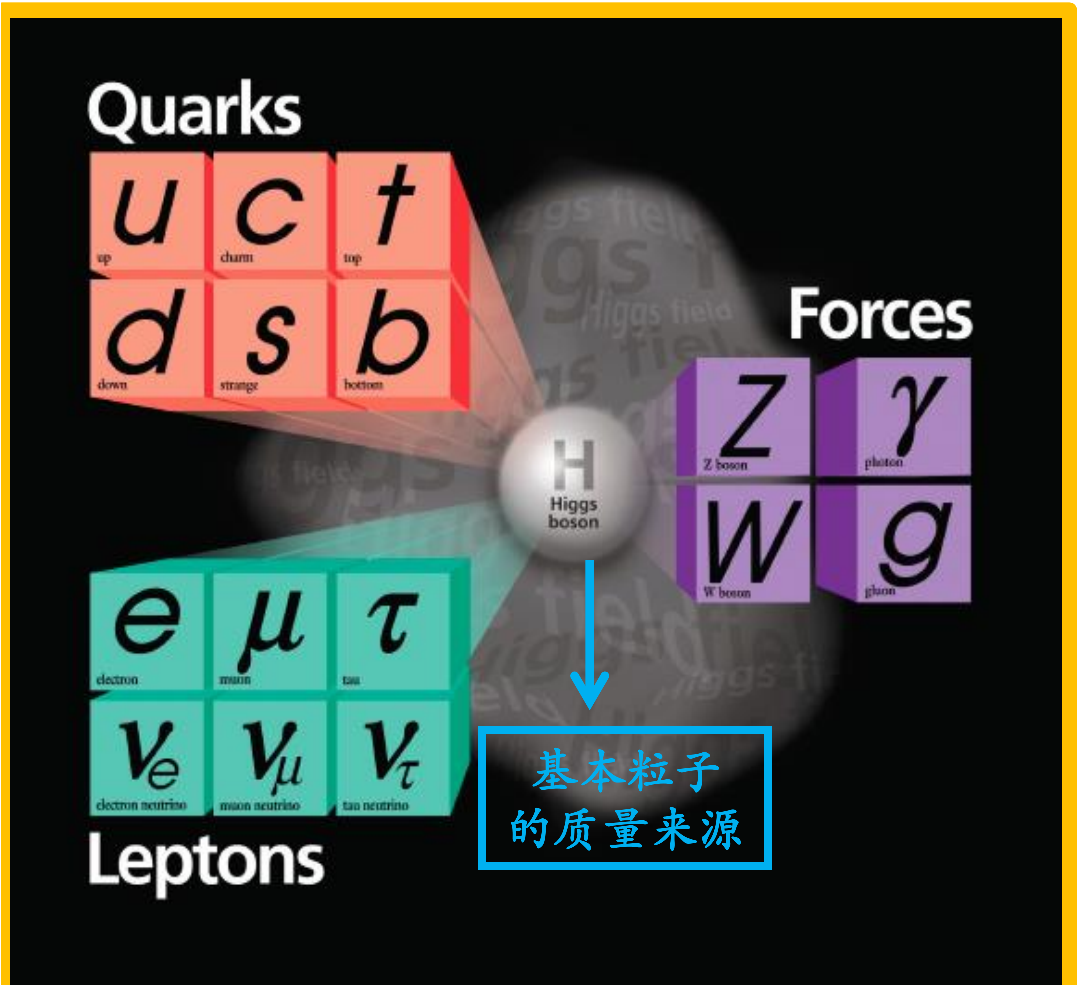
热寂？

真空衰变？

目前我们所知道的

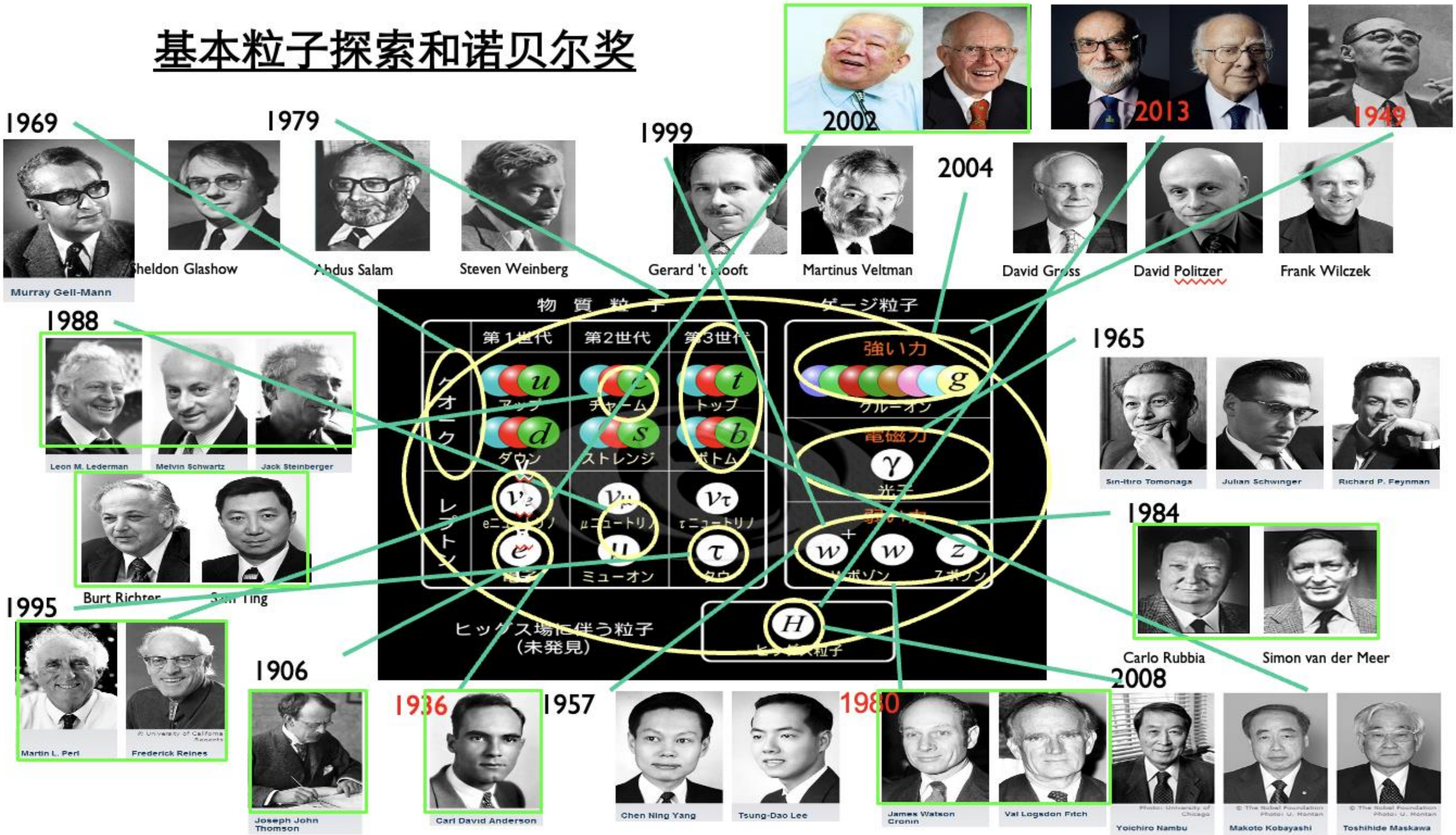
✦ 构成物质的基本单元:

粒子物理标准模型
电磁、弱相互作用



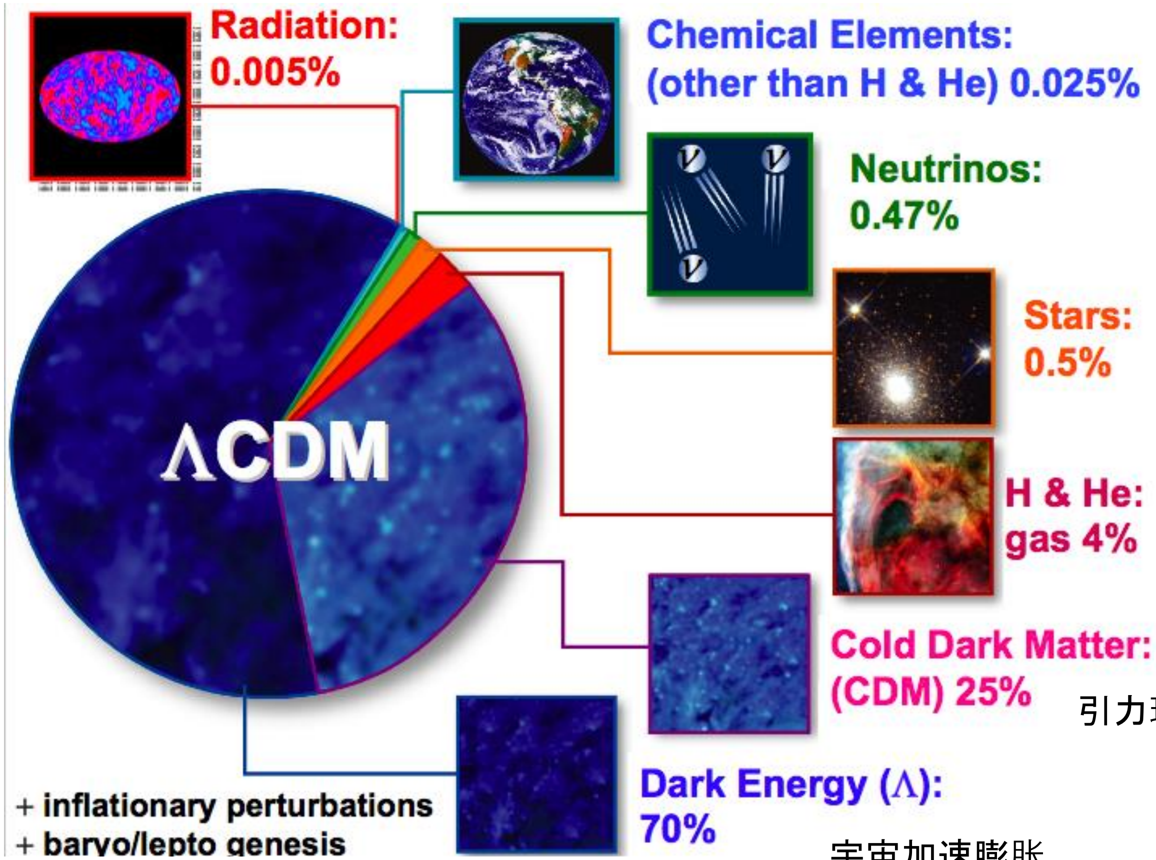
电磁相互作用：量子电动力学
强相互作用: 量子色动力学
弱相互作用：量子味动力学
引力：量子引力

基本粒子探索和诺贝尔奖



目前我们知道我们所不知道的...

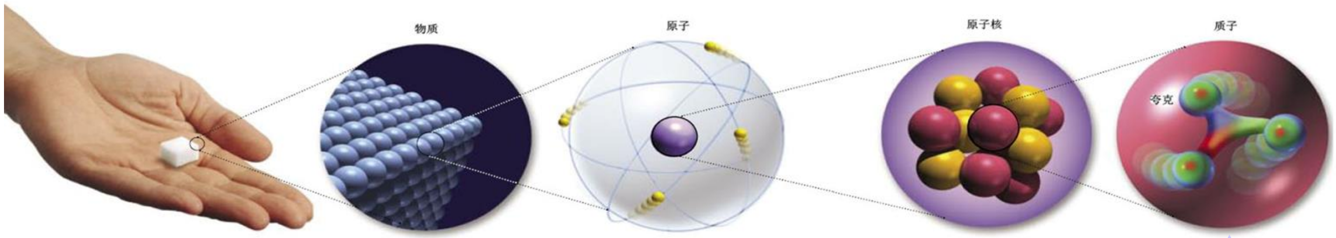
Λ为宇宙学常数，解释暗能量的项
CDM = 冷暗物质
ΛCDM为尝试解释宇宙微波背景辐射、宇宙大尺度结构以及宇宙加速膨胀的超新星观测的最简单的模型



引力现象

宇宙加速膨胀

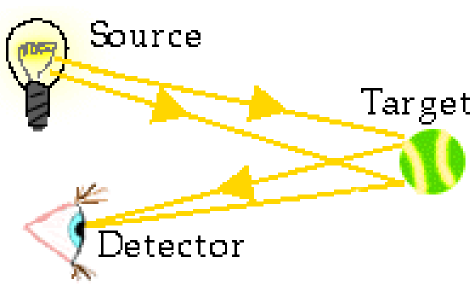
我们的研究逻辑

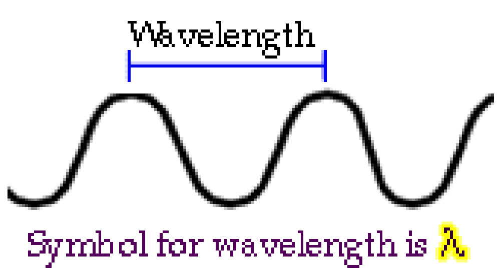


凝聚态物理 化学 材料科学 | 原子分子物理 | 原子核物理 | 粒子物理

keV | 10MeV | 10GeV

But, how to see smaller things?



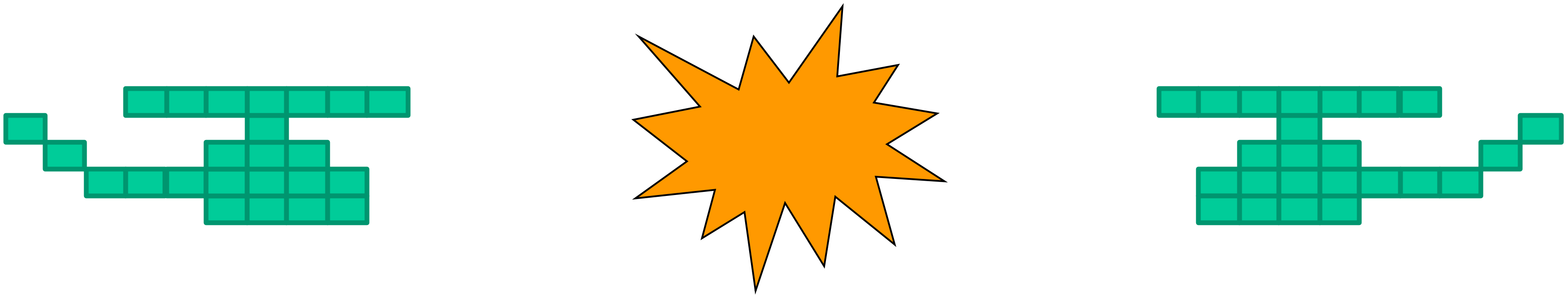


$$d \sim \frac{\hbar c}{E}$$

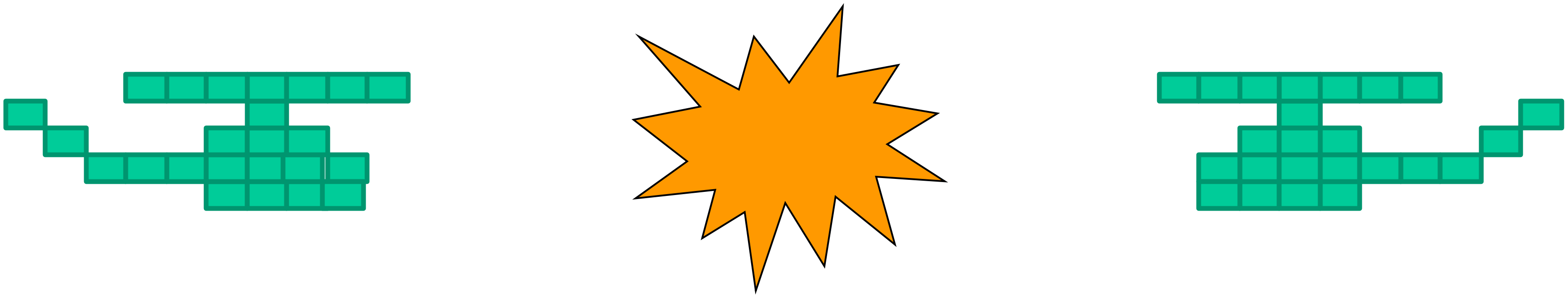
LHC～TeV

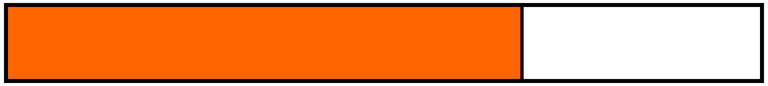
10^{-19}m

Smash things together, see what happens!



Accelerator Energy





Accelerator Energy

The interesting things (the dinosaurs!) disappear almost instantly. We “see” the resulting particles – so we have to be like detectives – look at the evidence to see what happened…….

Accelerator Energy

近年来高能量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

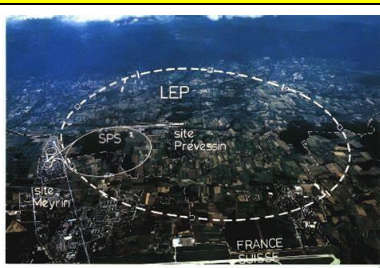
上帝粒子

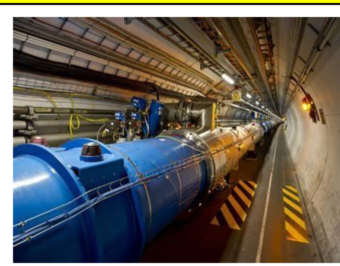
欧洲 LHC

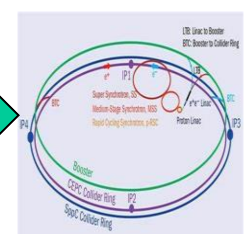
未来对撞机（中国/欧洲/日本）

希格斯粒子精确测量

1980 2000 2020 2040







大型强子对撞机(LHC)

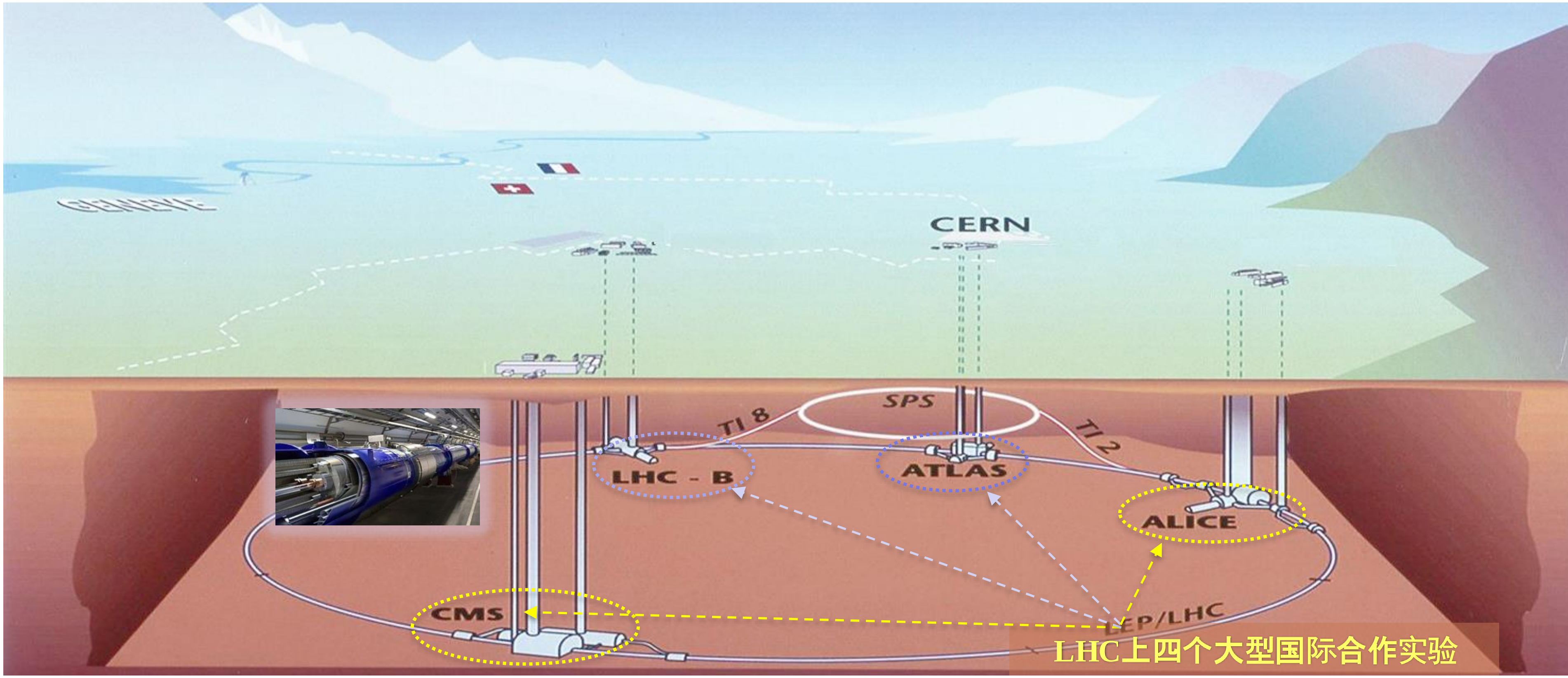
➢ 物质世界的根本问题:

- **希格斯粒子**性质如何？
- 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:世界最高能量对撞机LHC:

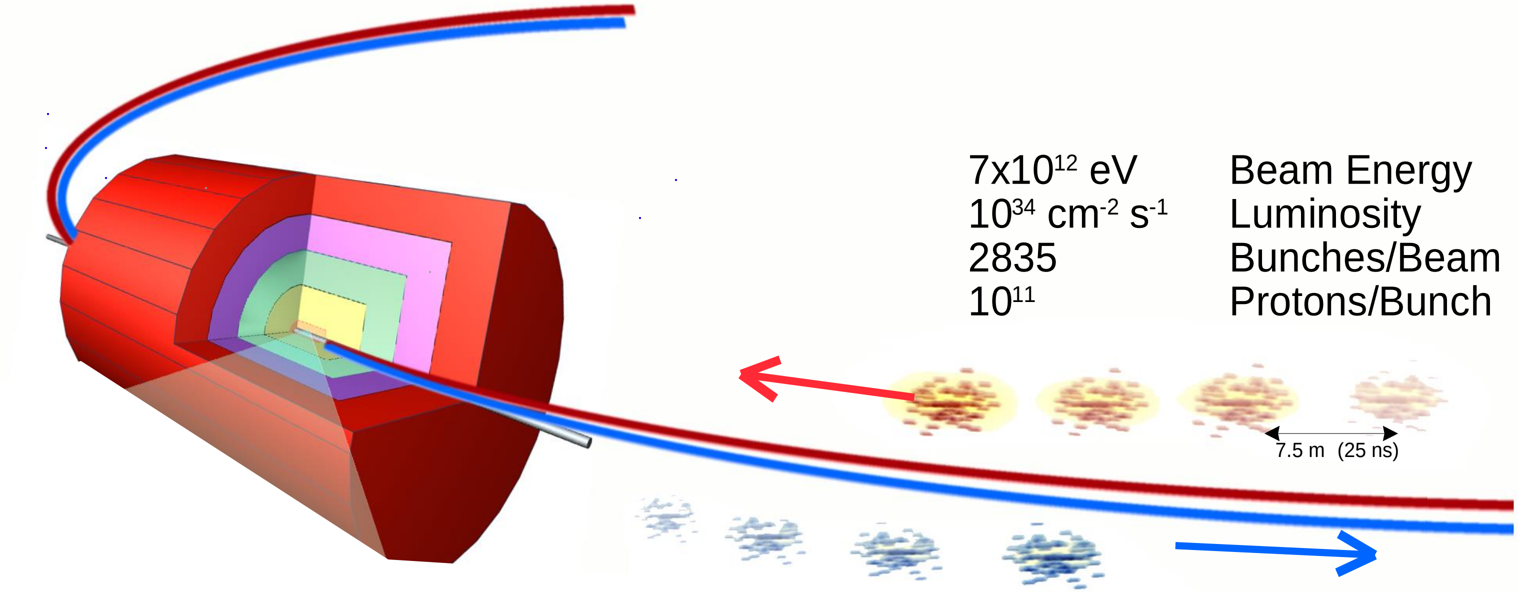
➢ *p-p*对撞质心能量14TeV，隧道周长~27 公里，地下深度 ~100 米

欧洲核子中心(CERN)



The Large Hadron Collider at CERN, Geneva, Switzerland

The Environment: Collisions at LHC



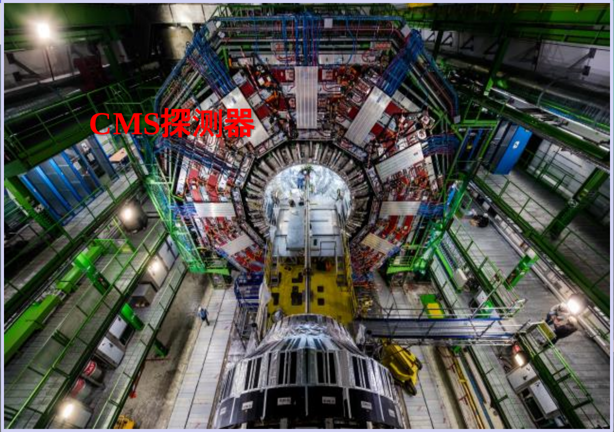
7×10^{12} eV	Beam Energy
10^{34} cm^{-2} s^{-1}	Luminosity
2835	Bunches/Beam
10^{11}	Protons/Bunch

7 TeV Proton Proton
colliding beams

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

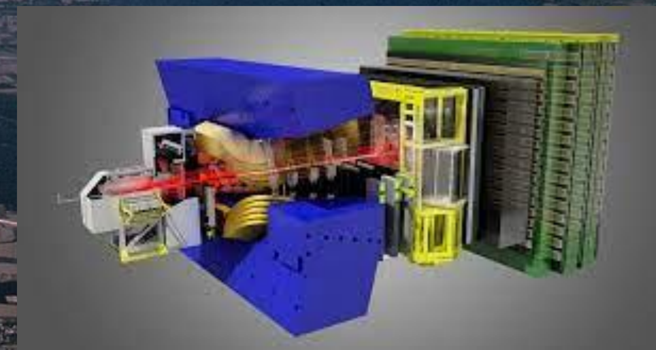


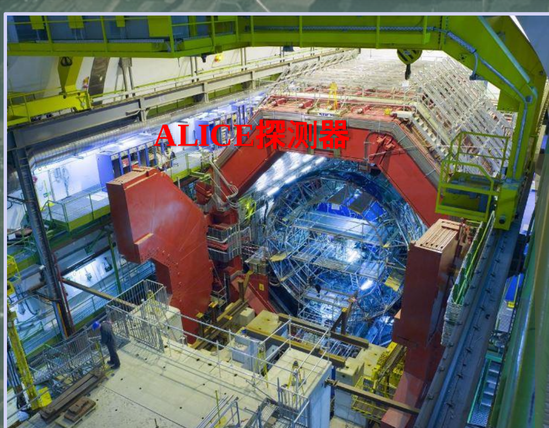
物理目标：

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



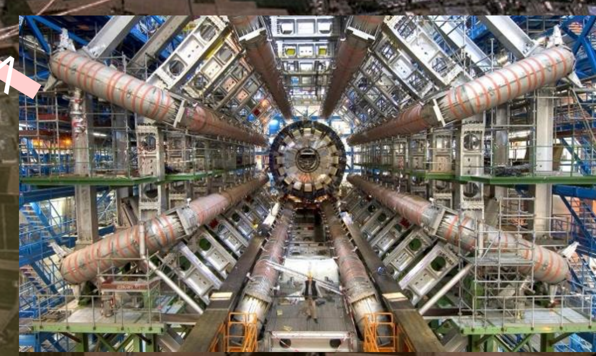


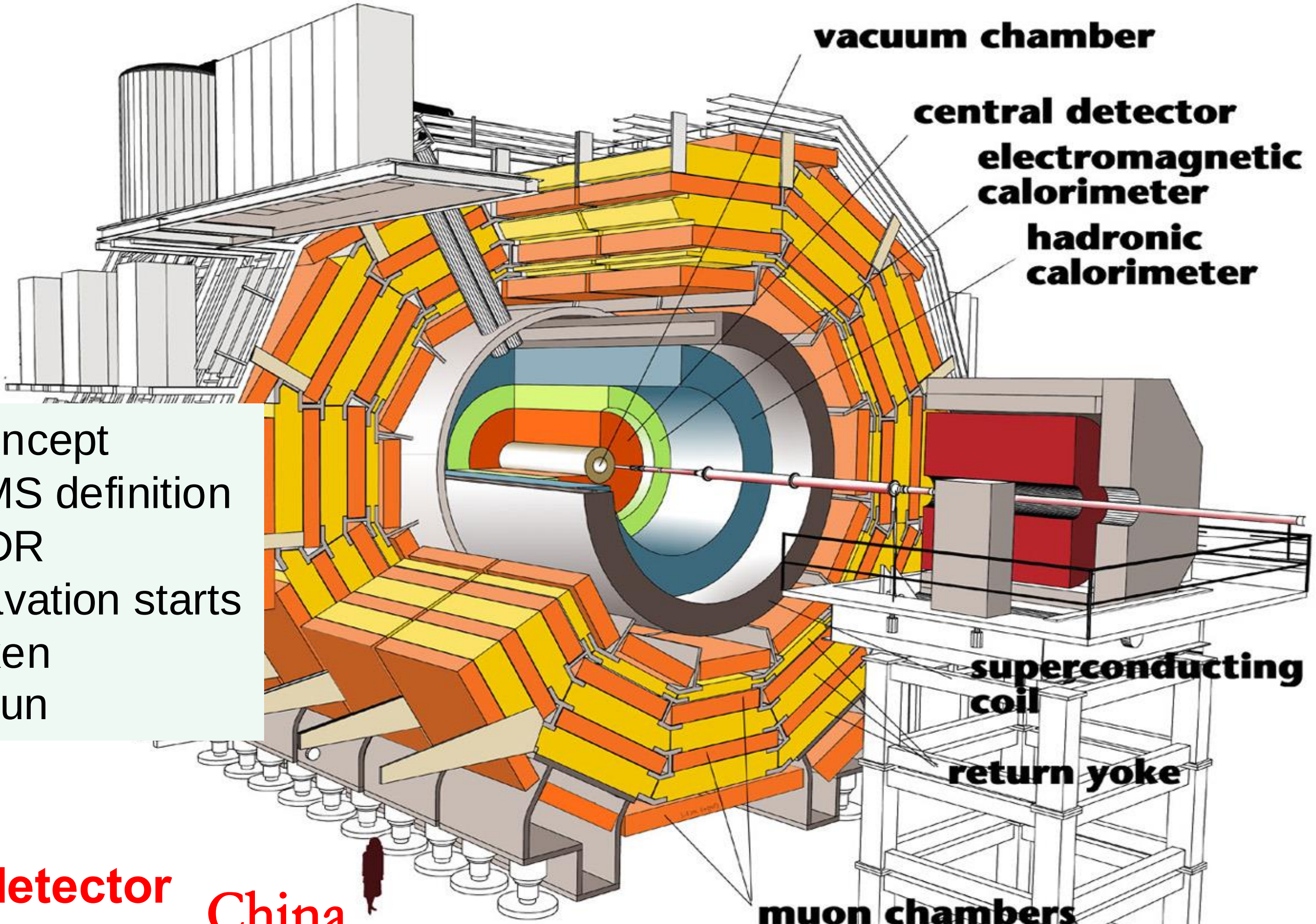
物理目标：

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





1990: CMS concept
1992: LHC/CMS definition
1994: CMS TDR
1998: P5 excavation starts
2010: data taken
2041: End of run

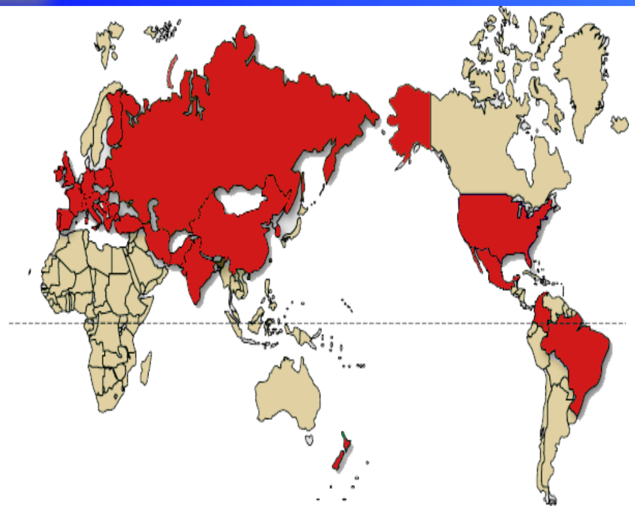
Heaviest detector

Detector characteristics

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

China
RPC/CSC
GEM/Trigger/HGCal/MTD

CMS collaboration in 2024



The CMS experiment has **5969** active members from **254** institutes coming from **58** countries.

CMS members

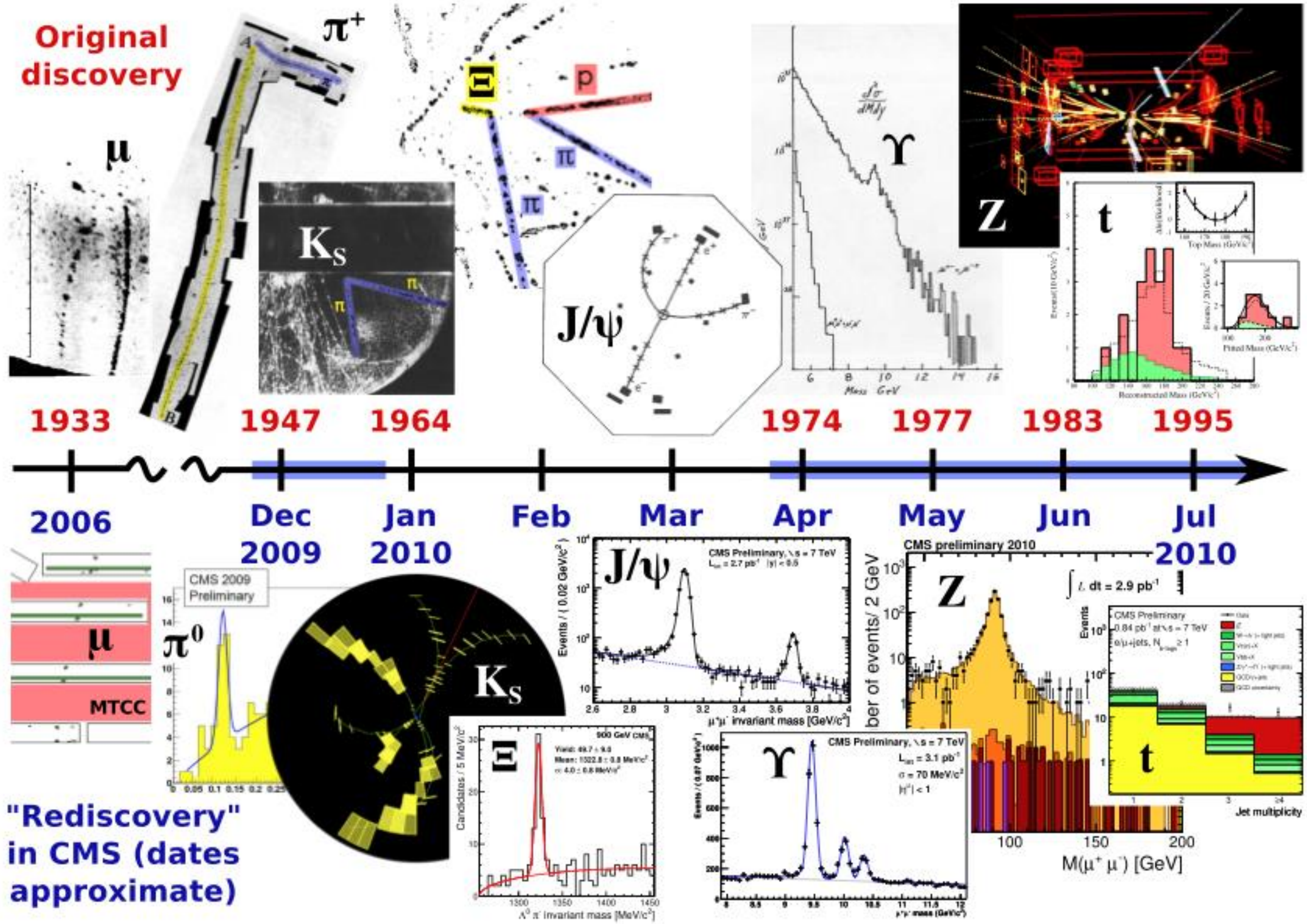
216 Full Members

28 Associate Members

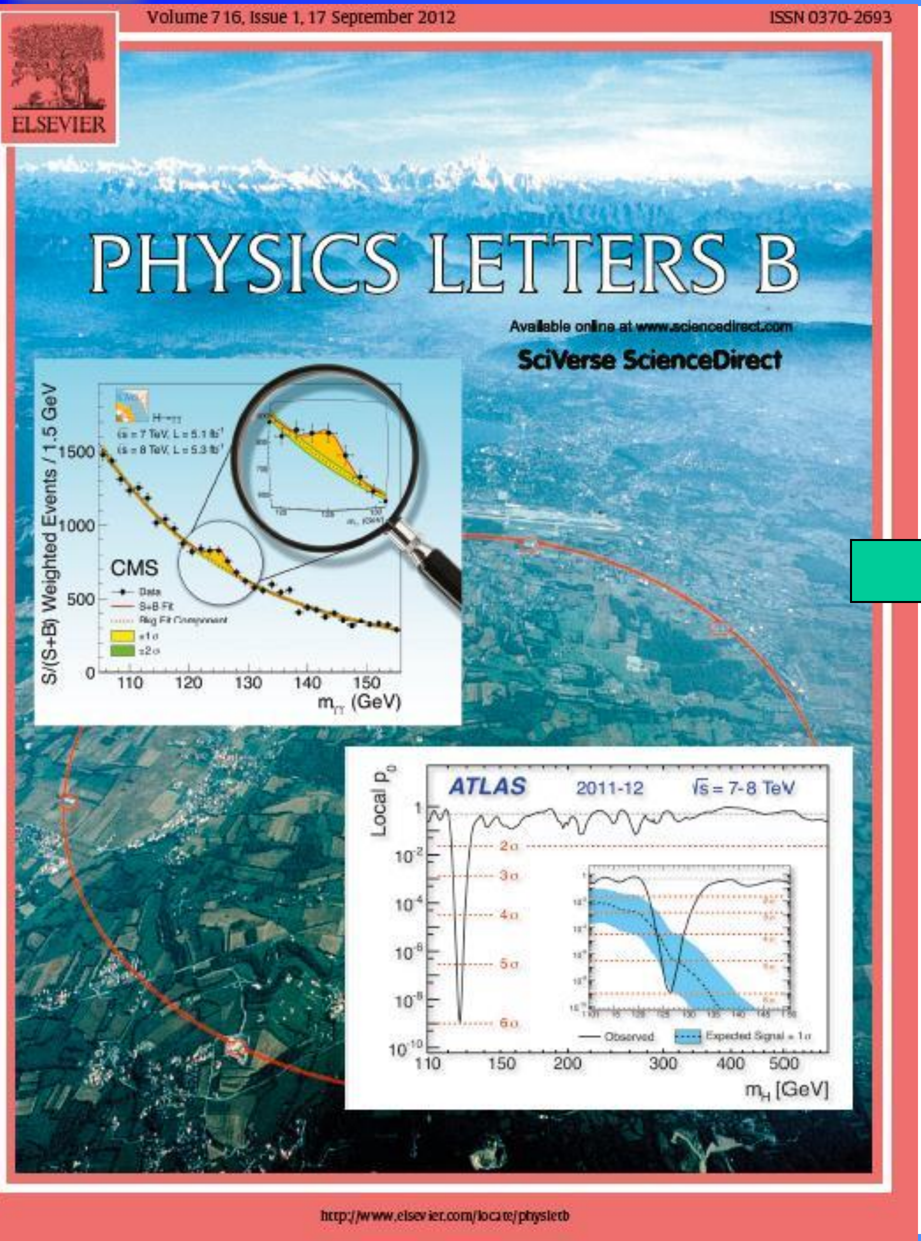
10 Cooperating Members

2070	1194	1354	985	251	110
Phd Physicists	Physics Doctoral Students	Non Doctoral Students	Engineers	Technicians	Administratives
(401 women 1669 men)	(327 women 867 men)	(371 women 983 men)	(148 women 837 men)	(22 women 229 men)	(70 women 40 men)

Re-discovery at LHC



New discovery at LHC: The Higgs



The Nobel Prize in Physics 2013
François Englert, Peter Higgs

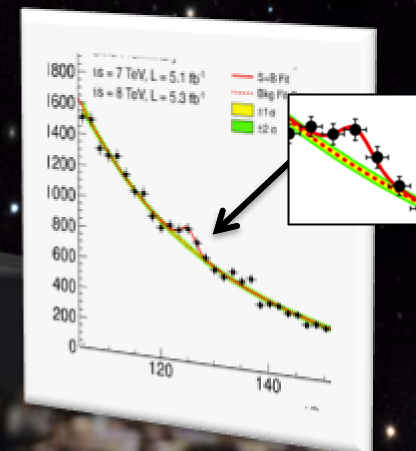
The Nobel Prize in Physics 2013

Photo: A. Mahmoud
François Englert
Prize share: 1/2

Photo: A. Mahmoud
Peter W. Higgs
Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

Two of these 10,000 people presented results…

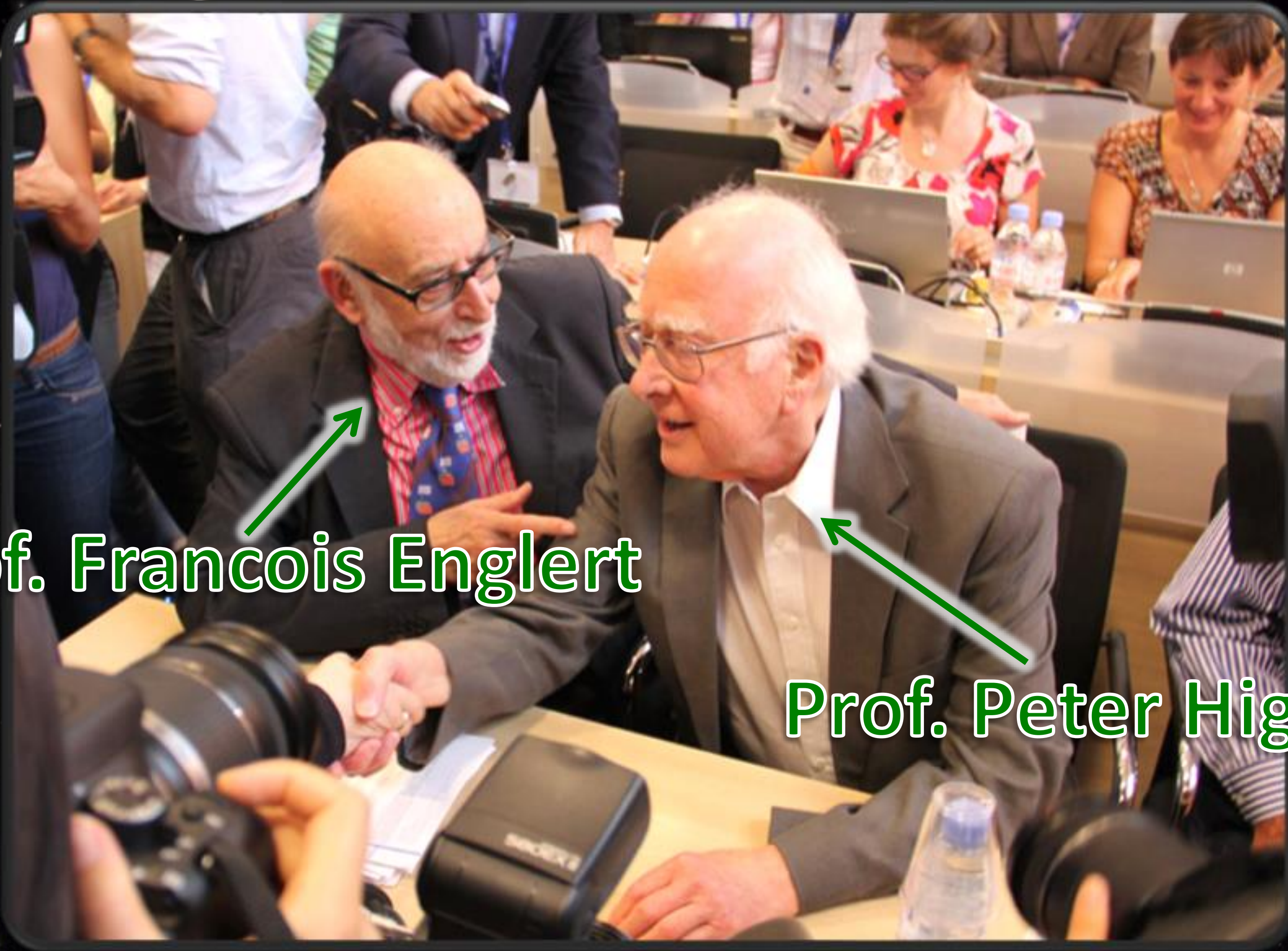


Fabiola Gianotti
ATLAS Spokesperson 2010-2012

Joe Incandela
CMS Spokesperson 2012-2013

...that made a lot of physicists VERY happy...

...including these two guys!



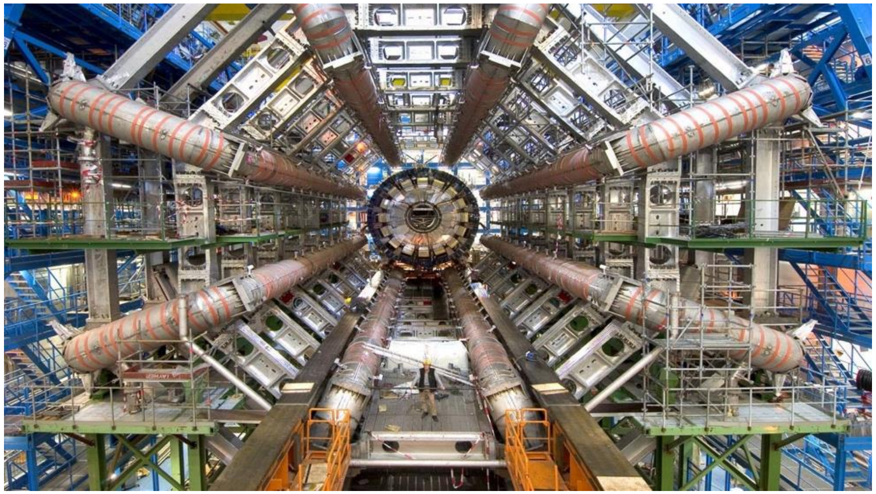
As well as the world's media

Estimated worldwide audience

1,000,000,000 people!!

Higgs粒子的发现：历史性的重大事件

全球上万名科学家与工程师三十多年的努力，其中具有极为丰富的科学、工程、管理、国际合作、文化等内涵



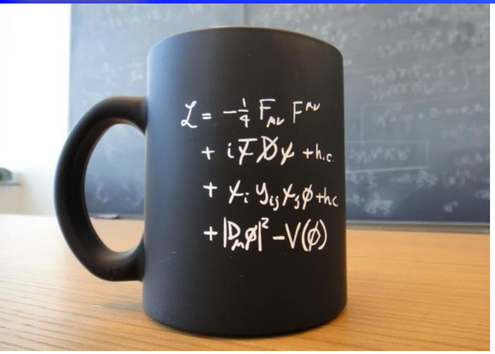
社会影响：

全球上千家媒体的报道；

对人类生活和社会发展产生了重大推动作用：

在此过程中 发明了**World-Wide-Web 和网页浏览器**

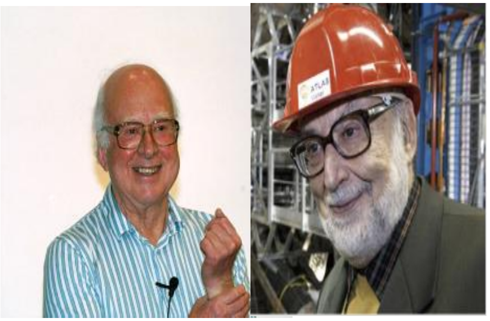
Higgs Physics opportunity at LHC



Higgs Boson: Origin of mass

Couple to Bosons

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



2013 Nobel Price

Highlights of the Year

December 17, 2018 • *Physics* 11, 129

Physics picks its favorite stories from 2018.

Couple to Fermions

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

Measurement of Higgs Mass, Width, CP etc

Self Coupling

- **Sixth Force**
- HL LHC 2035

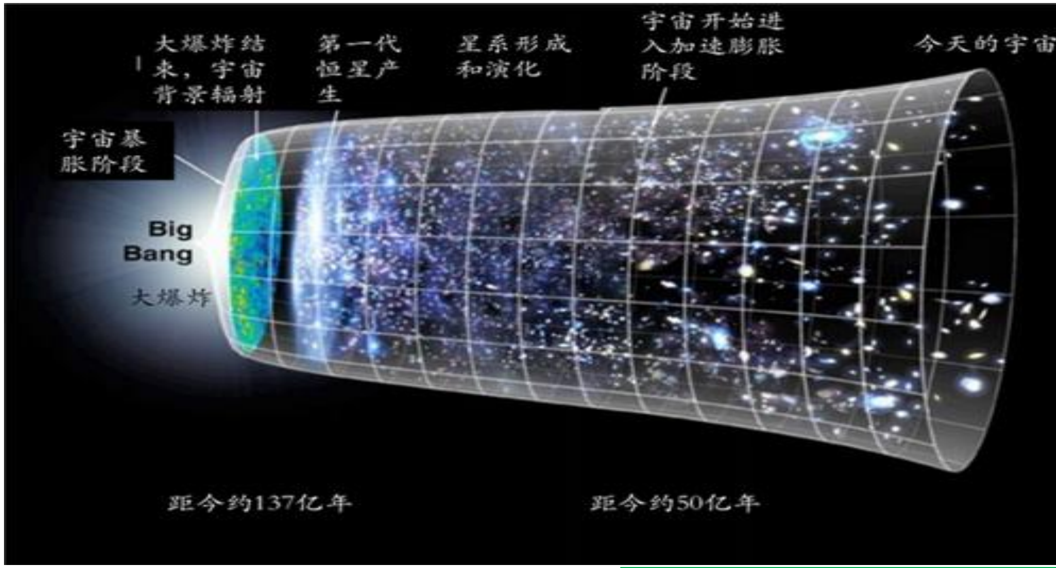
Is there PT

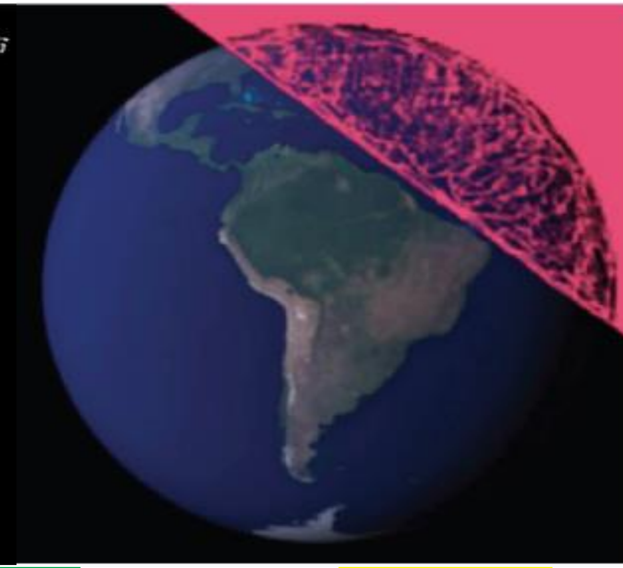
p-p collision can not be extreme acc.

CEPC ilc FCC hh ee he

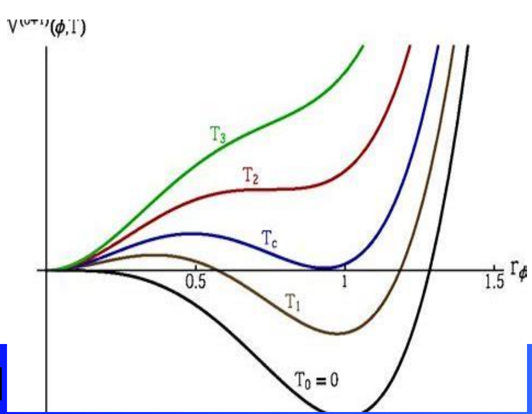
Why Higgs Properties/couplings so import

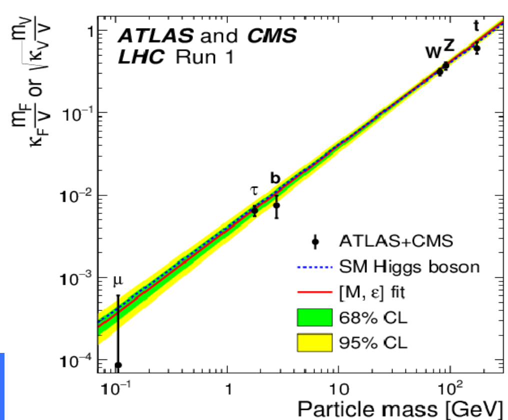
- Higgs: Link the past, current, and future of universe

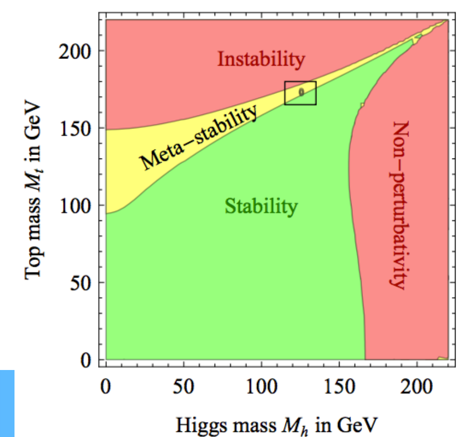




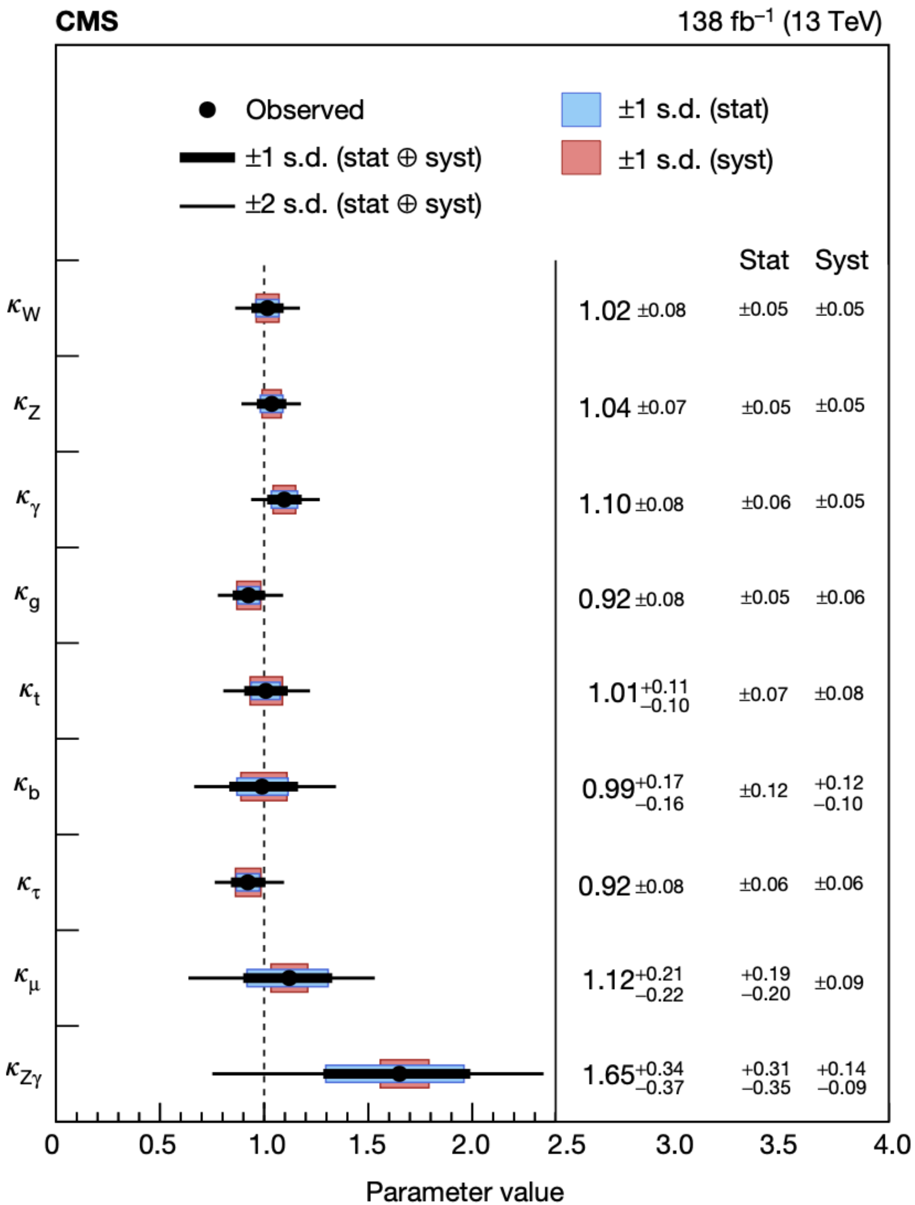
Phase Transition in early universe → Atom diameter ; Mass of ele. particles → Vacuum Stability

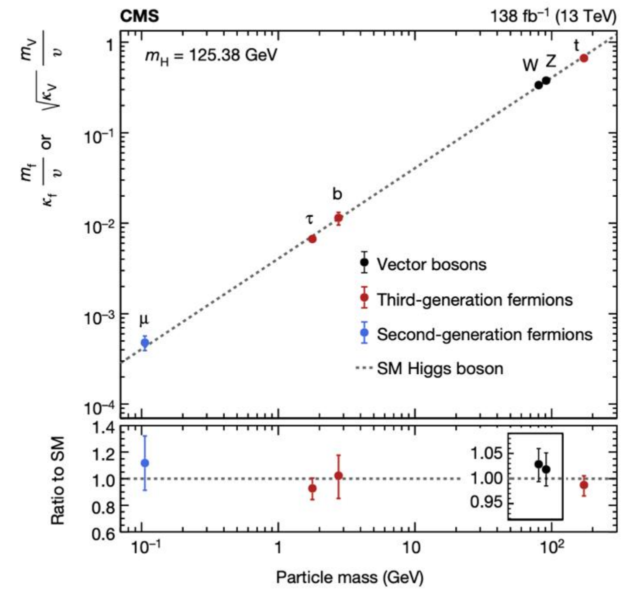


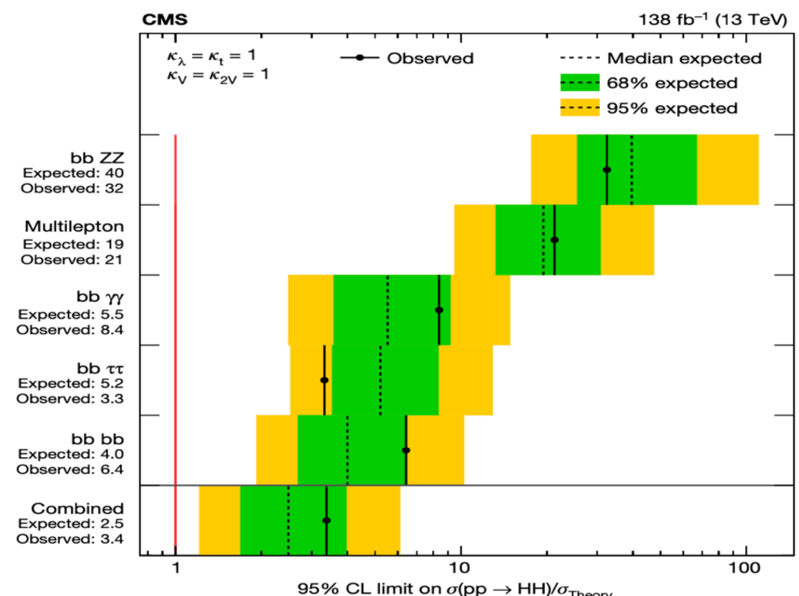




Knowledge about Higgs







- Mass: ~172.5 GeV; the heaviest particle

Nobel Prize 2008

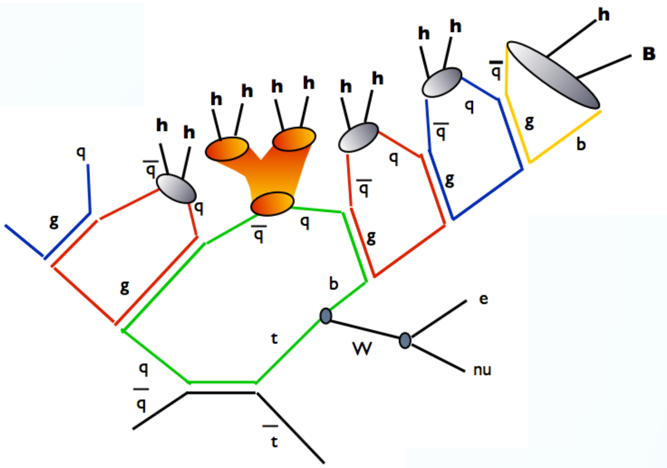
Makoto Kobayashi

Toshihide Maskawa

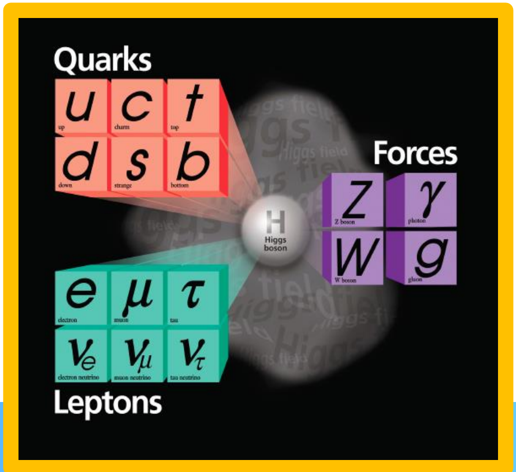
- Lifetime: $\sim 4*10^{-25}$ Sec:
  - hadronization time $\sim 3*10^{-24}$ Sec
  - Decay before hadronization

“1夸克态”
“2夸克态”
“3夸克态”
“4夸克态”
“5夸克态”

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



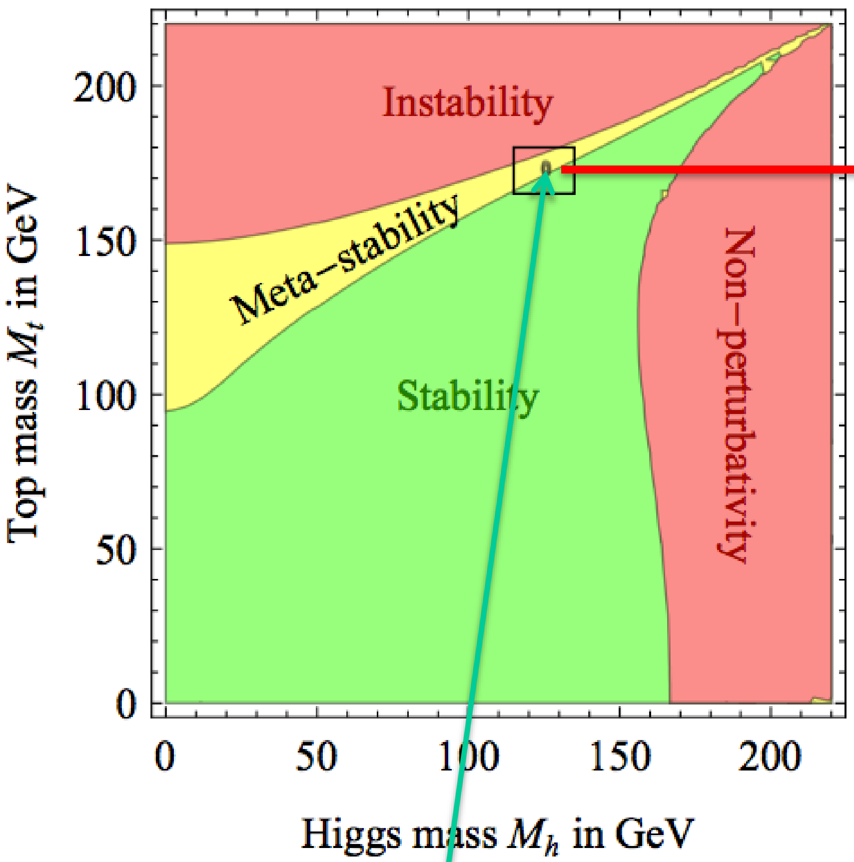
"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature."



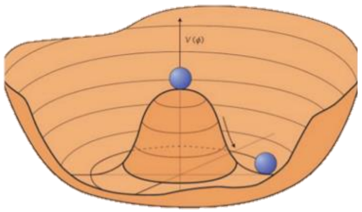
Top quark is a laboratory to precise test SM

JHEP 08 (2012) 098
PRD 97, 056006 (2018)

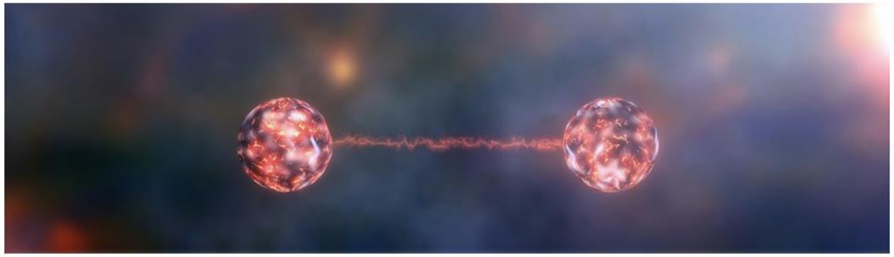
Metastable Universe?



Main uncertainties from Top-quark Mass

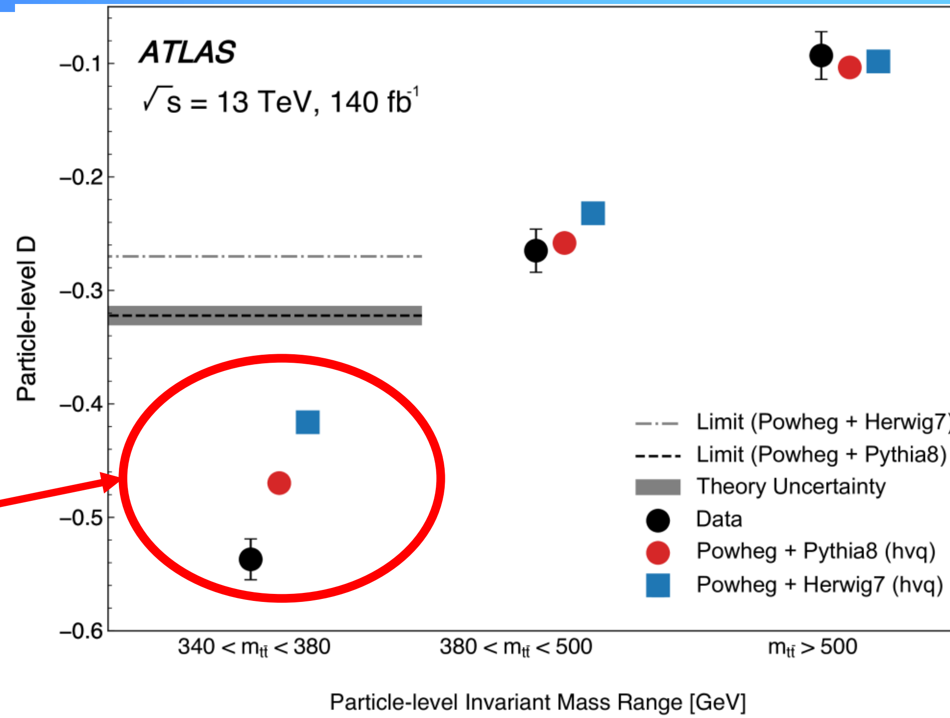


Ttbar entanglement and threshold structure

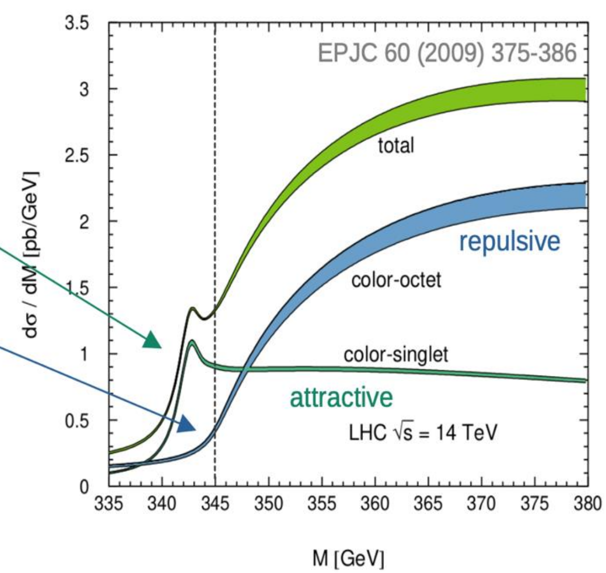


$$|\psi\rangle = |a_1\rangle_A \otimes |b_1\rangle_B + |a_2\rangle_A \otimes |b_2\rangle_B$$

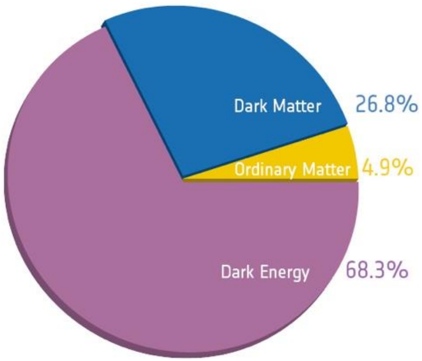
Observe Quantum entanglement



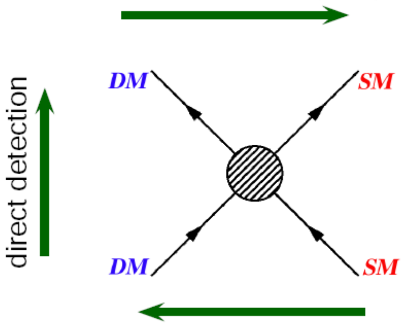
- Color-singlet ($^1S_0^{[1]}$) - attractive
  → Peak below the $t\bar{t}$ threshold
- Color-octet ($^1S_0^{[8]}$ or $^3S_1^{[8]}$) - repulsive
  → Suppressed below the $t\bar{t}$ threshold
- Lineshape and width not exactly known - but below experimental resolution



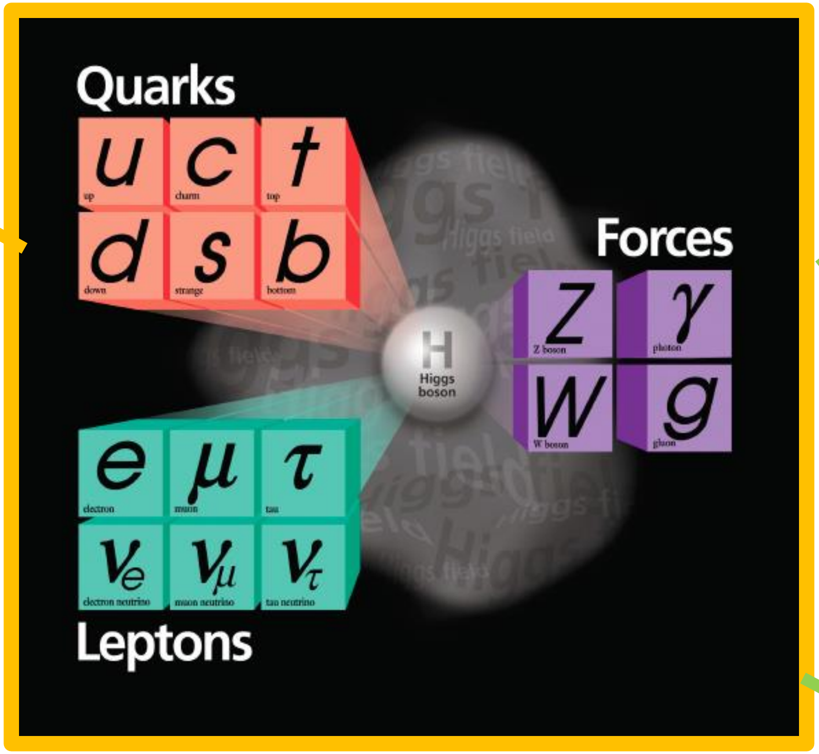
New physics opportunity at Energy Frontier



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



production at colliders

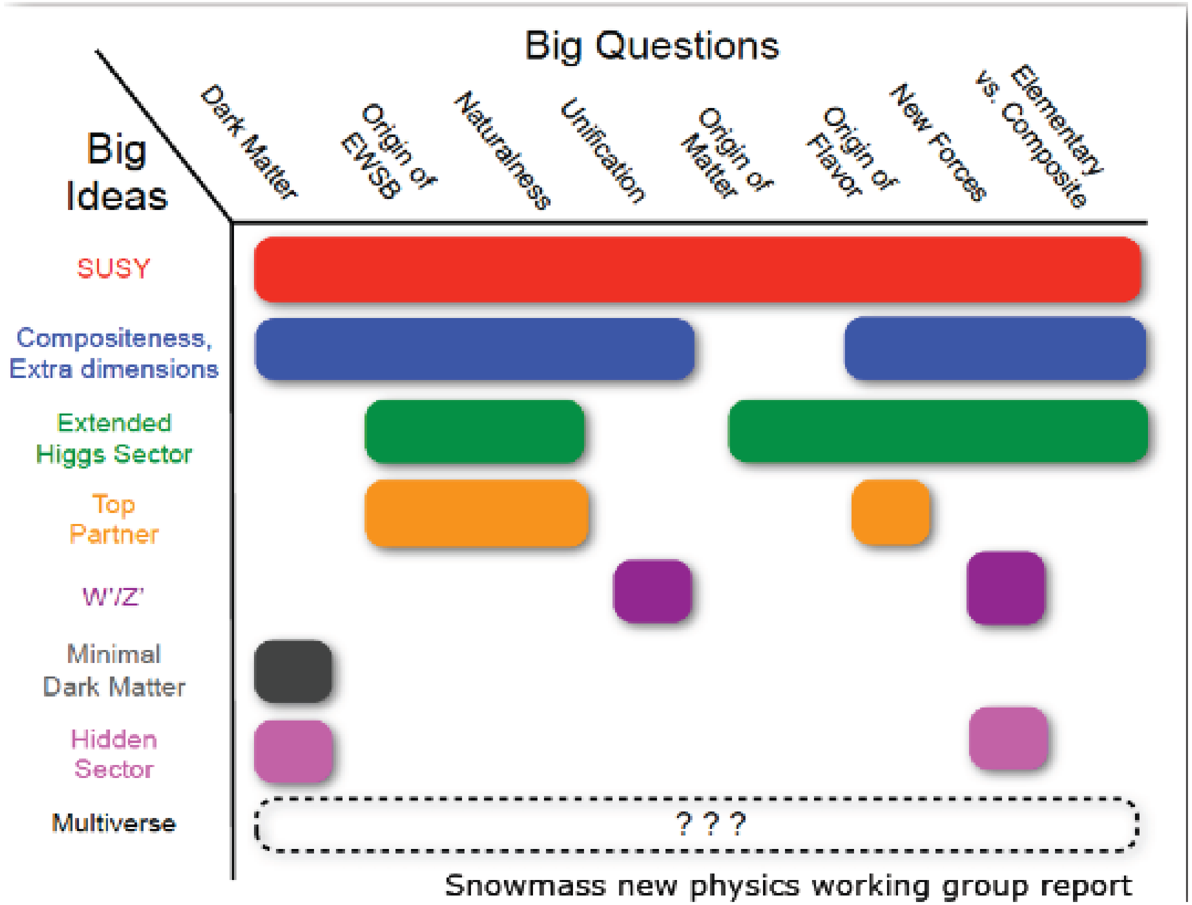


Direct search for new physics signals

Acc. Measurement for deviation of SM process

Why NP beyond SM?
- Origin of flavor sym.
- Vacuum stability?
- Naturalness
- Dark Matter?
- CP violation?
- 。。。

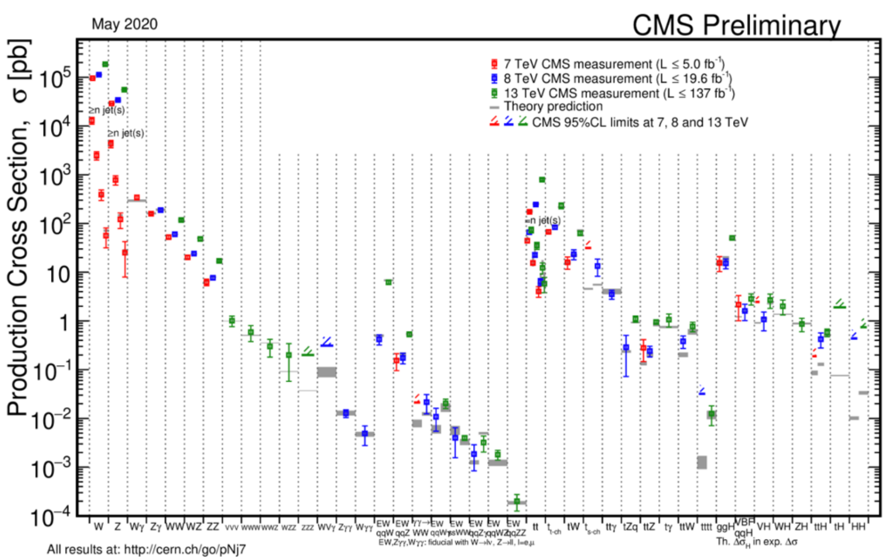
New physics opportunity at Energy Frontier

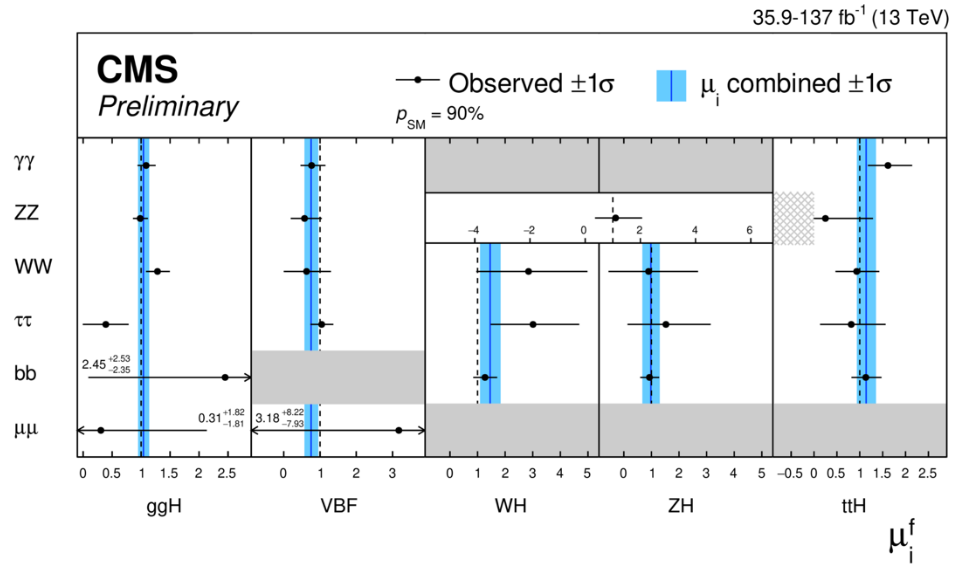


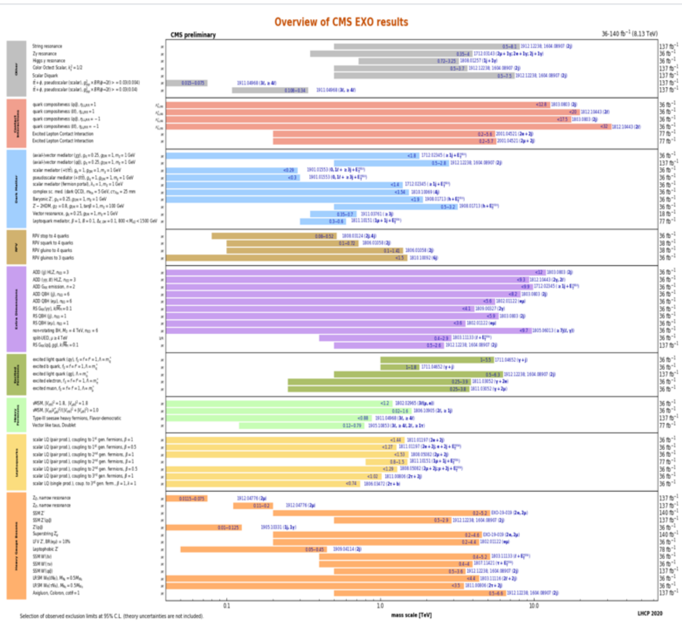
14 TeV Center of mass energy(highest manmade) provide unique opportunity

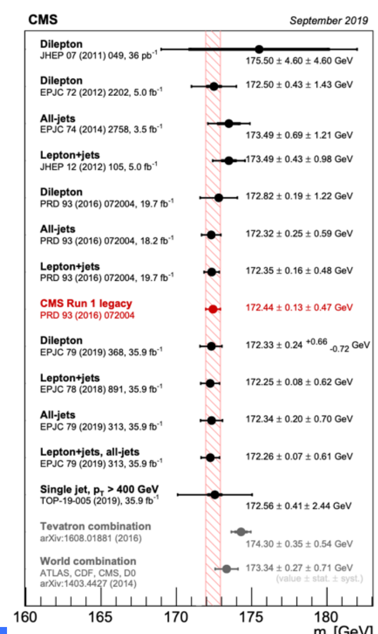
Advanced detector is the key to catch up these physics opportunity at LHC

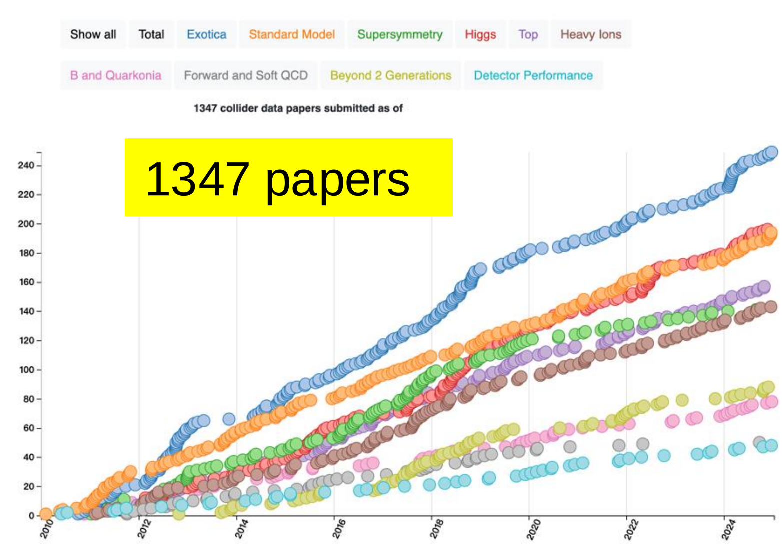
Exellent physics outcome of CMS



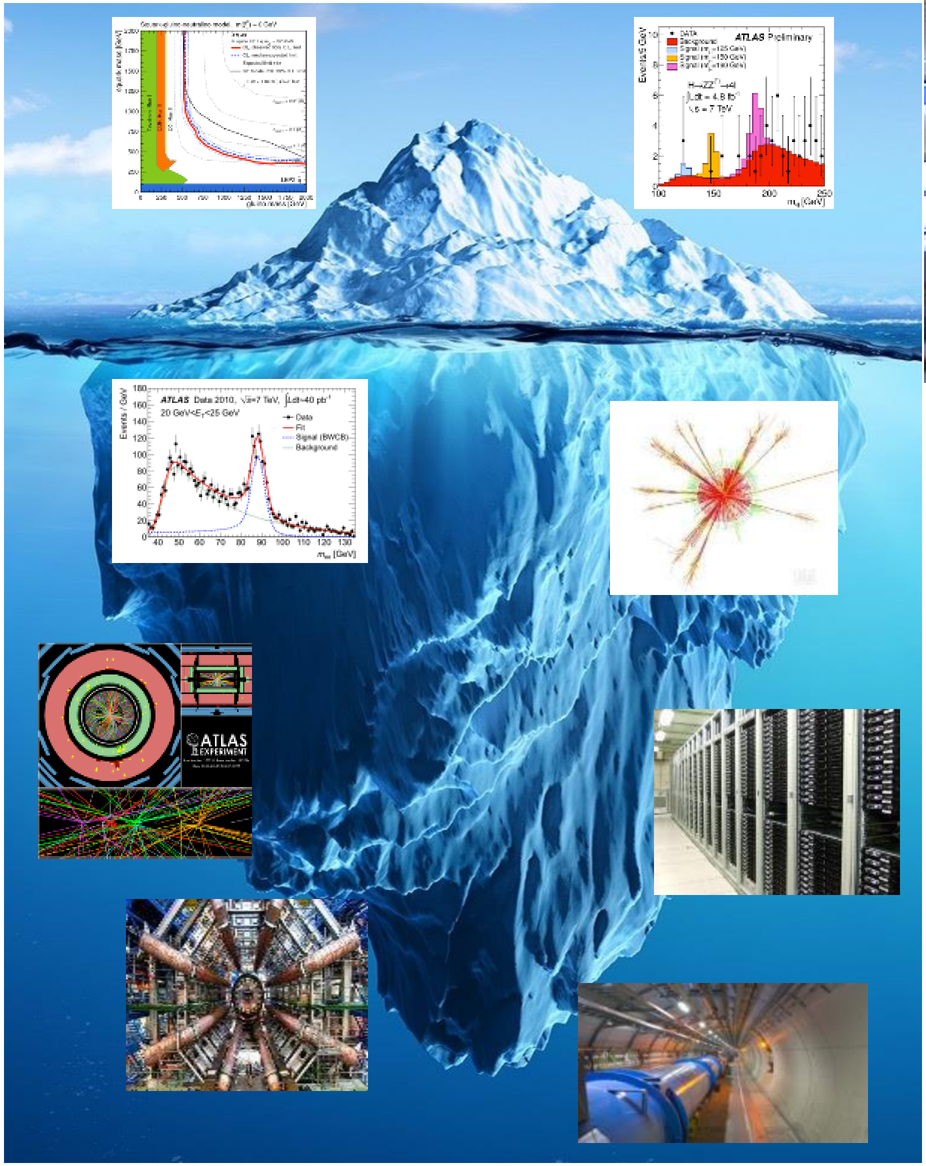






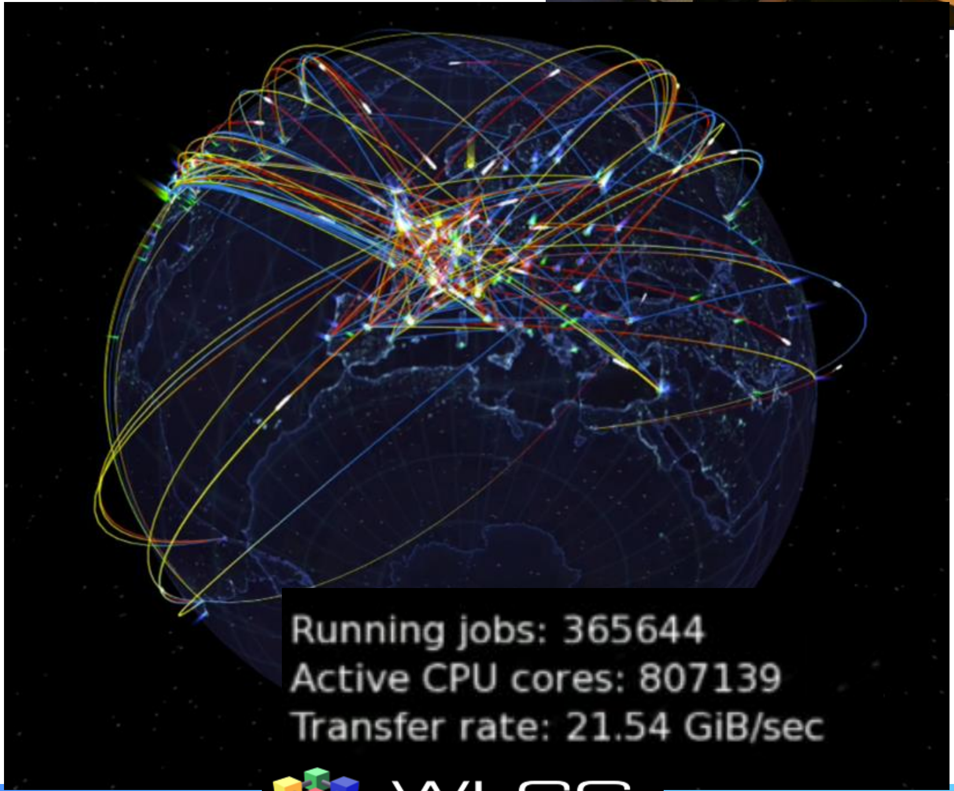


物理成果的背后



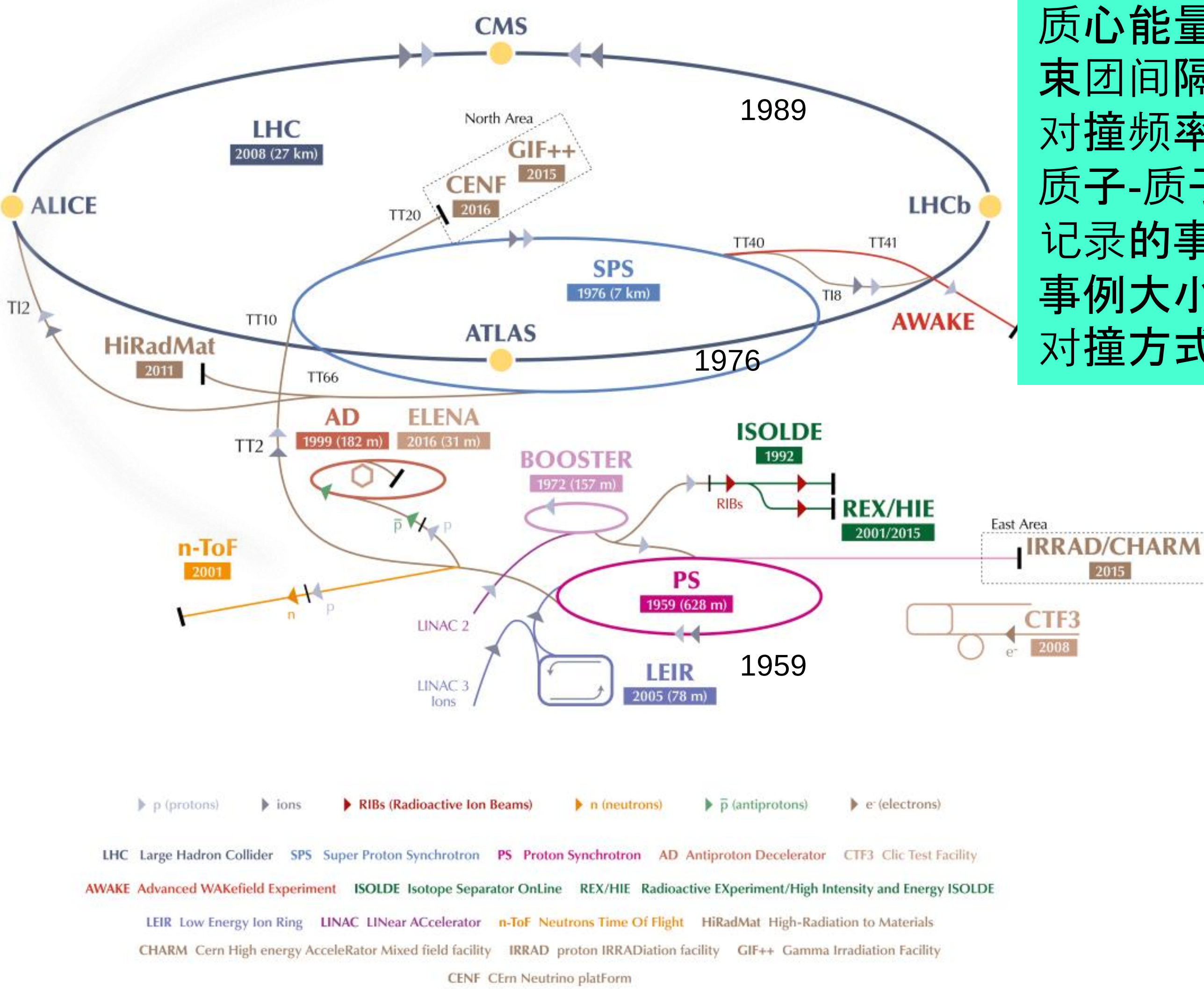
CMS运行控制室 - 值班监控等

ATLAS运行控制室



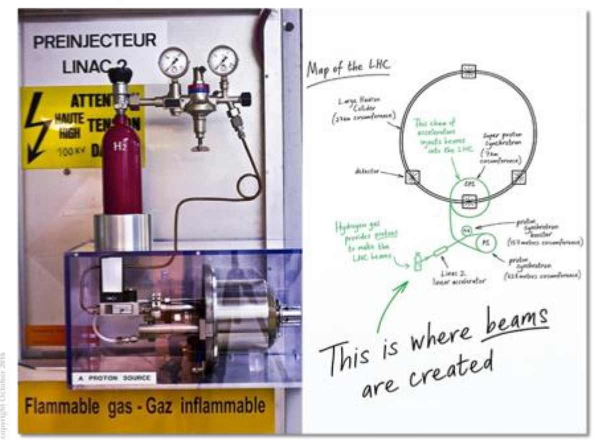
WLCG Worldwide LHC Computing Grid

LHC 加速器系统



高能量前沿

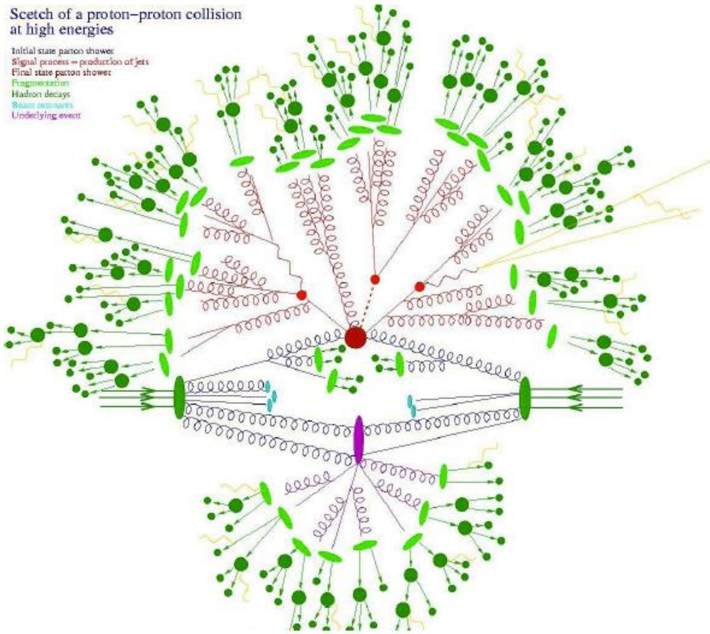
质心能量：0.9,2.36,7,8，13/14 TeV
束团间隔: 50 - 25 纳秒
对撞频率: 2000万-4000万/ 秒
质子-质子对撞: 20亿次 /秒
记录的事例: ~1000 - 3000 / 秒
事例大小：1-2 MB
对撞方式：p-p;pb-pb;p-pb;Xe-Xe…



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

CMS 探测器面临的挑战

Proton bunch　　Proton bunch



单个质子对的核反应

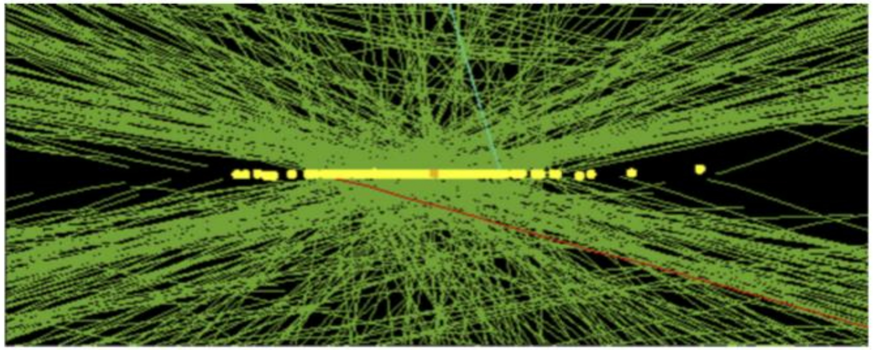
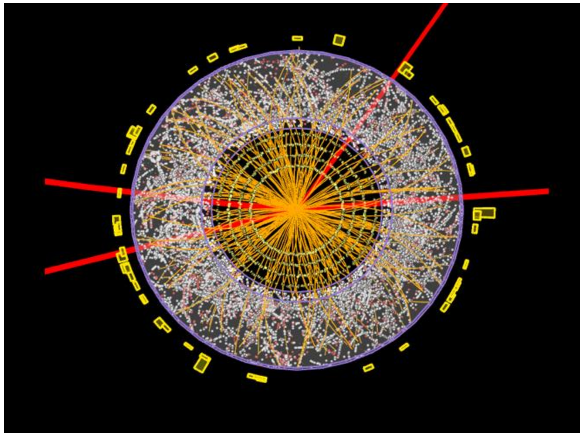


Figure 1.16: High pileup event with 78 reconstructed vertices taken in 2012

LHC CMS实验中的一次束团对撞

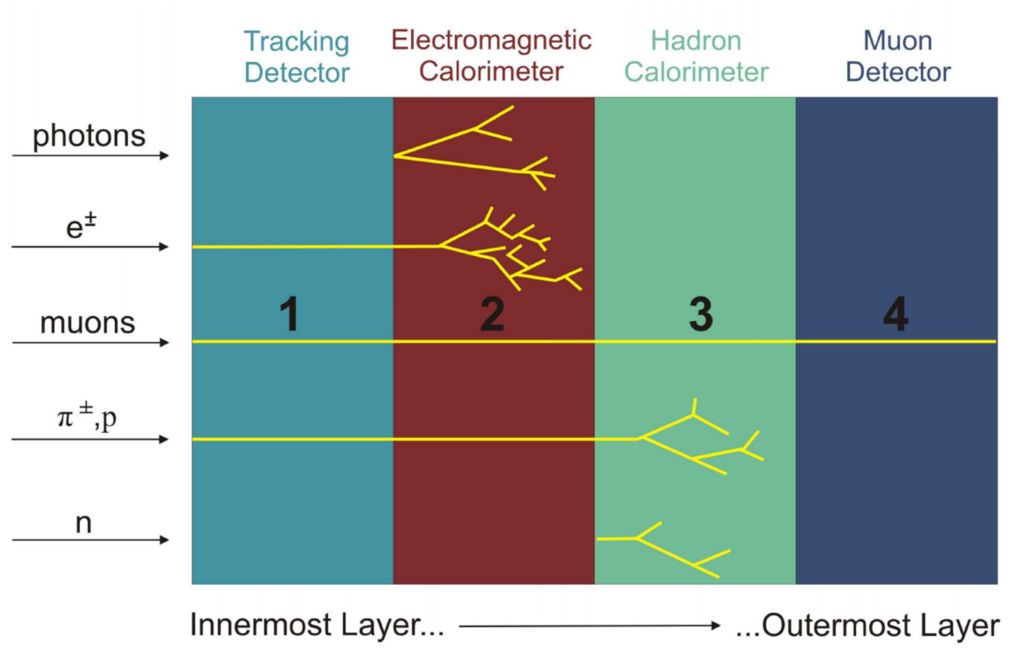


每秒对撞4000万次@～20年

- 借我一双慧眼，让我把这纷扰看的清清楚楚明明白白真真切切

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

Interaction of particles in diff. detector components:



探测器眼中的世界

- 光子的能量探测
- 电子的能量探测

电磁相互作用

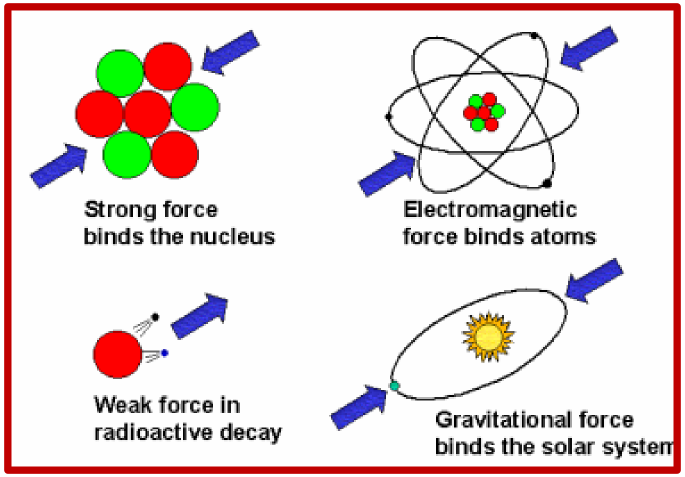
- 强子(由夸克通过强相互作用组成的物质)的能量探测
  - 质子，中子的能量探测
  - K介子，pi介子的能量探测

强相互作用

- 中微子的能量探测（仅参与弱相互作用）

弱相互作用

- 引力波的探测？



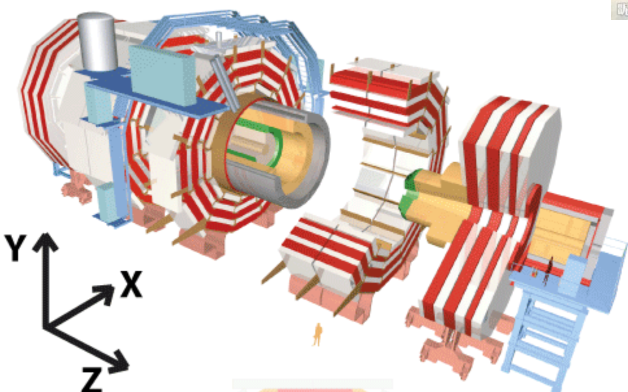
相比眼睛/照相机，探测器：

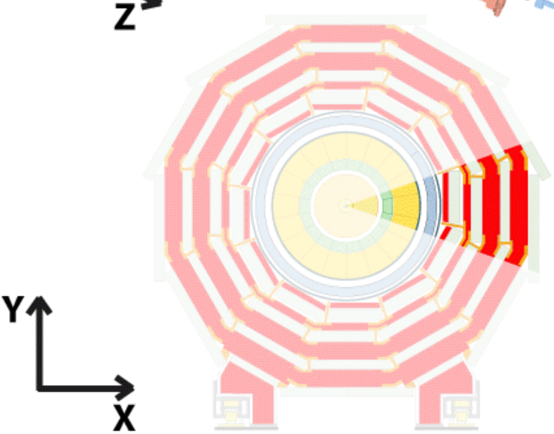
- 测量的能量范围要宽广数十个量级
- 能看到粒子种类也更多（更多维度）

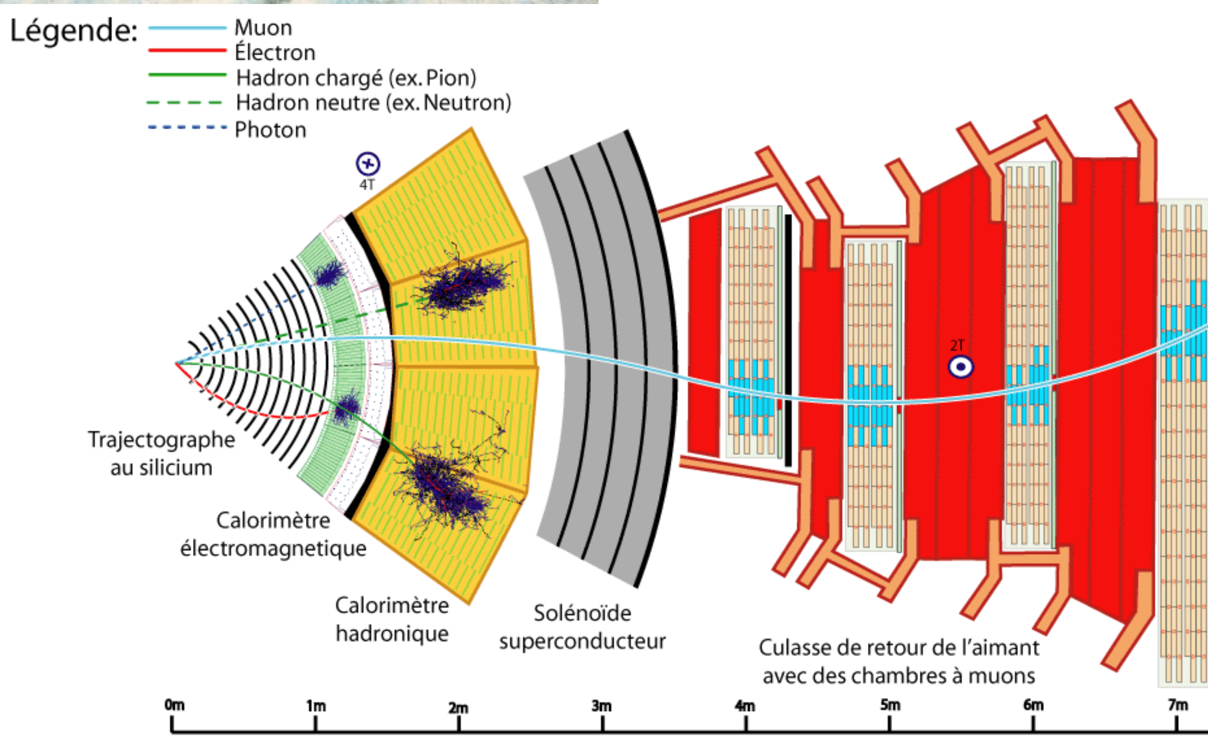
探测器眼中的世界更精彩

CMS detector

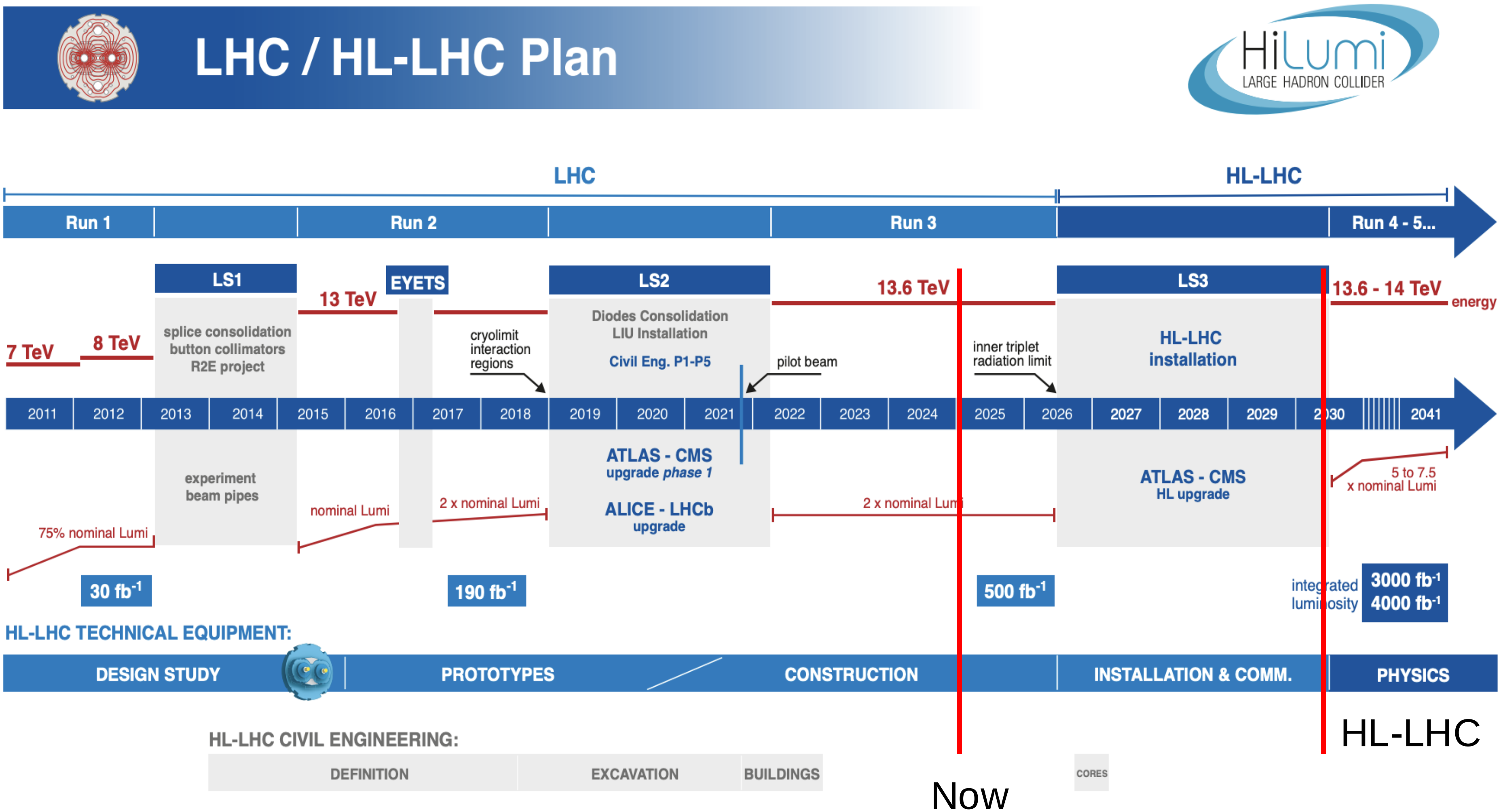
Particle flow rec.
lepton, hadron, jets





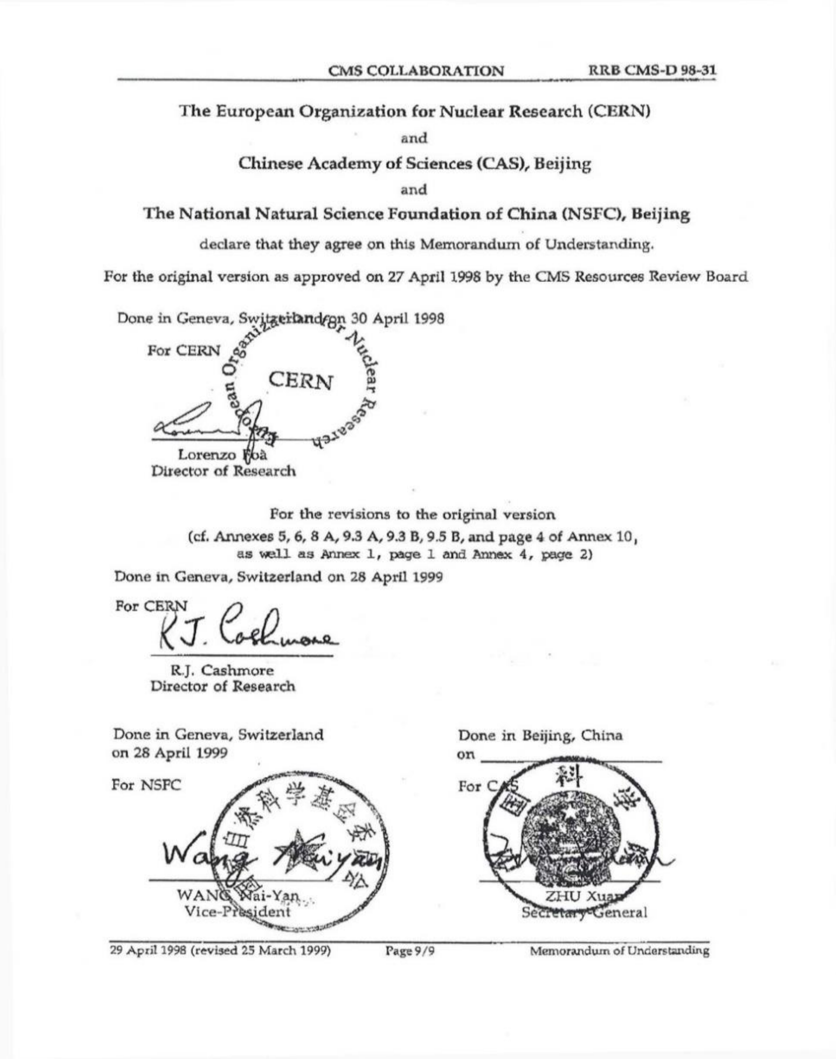


LHC/CMS operation time line



CMS China

中国参加CMS实验合作



CMS COLLABORATION RRB CMS-D 98-31

The European Organization for Nuclear Research (CERN)

and

Chinese Academy of Sciences (CAS), Beijing

and

The National Natural Science Foundation of China (NSFC), Beijing

declare that they agree on this Memorandum of Understanding.

For the original version as approved on 27 April 1998 by the CMS Resources Review Board

Done in Geneva, Switzerland on 30 April 1998

For CERN

Lorenzo Foà
Director of Research

For the revisions to the original version
(cf. Annexes 5, 6, 8 A, 9.3 A, 9.3 B, 9.5 B, and page 4 of Annex 10, as well as Annex 1, page 1 and Annex 4, page 2)

Done in Geneva, Switzerland on 28 April 1999

For CERN

R.J. Cashmore
Director of Research

Done in Geneva, Switzerland on 28 April 1999

For NSFC

WANG Nai-Yan
Vice-President

Done in Beijing, China on

For CAS

ZHU Xuan
Secretary-General

29 April 1998 (revised 25 March 1999) Page 9/9 Memorandum of Understanding

在科技部的协调下，1998年NSFC和中科院代表中国与CERN签订CMS合作备忘录。中国组包括高能所，科大和北京大学。项目长期得到了科技部、基金委和科学院的联合支持。

中国CMS发展历程

九十年代

北京大学（1996）
中科院高能所
中国科技大学
国内首次加入CMS合作组

2000-2008

探测器研发建造
国内首次成功研制国际领先探测器技术，（高能所CSC，北大RPC）
并按期高质量完成探测器生产组装任务

2009-2012

LHC首次对撞
Run1数据采集
功课重要物理课题，获得丰硕的的优秀物理成果
培养大量高能物理人才

2013-现在

清华大学（2014）
北京航空航天大学（2015）
中山大学（2017）
浙江大学（2019）
复旦大学（2019）
南京师范大学/山东大学/华南师范大学（2023）
相继加入CMS合作组开足马力，全面展开探测器升级、物理课题研究继续培养下一代高能物理人才

CMS中国组人员统计

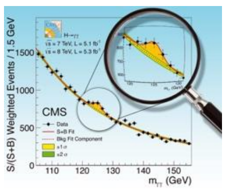
- 11个单位，约160人队伍
- 现有署名作者52人（去年41），占CMS签名人数~2%

单位	教职工	博士后	研究生	总人数	作者数
高能所	19	6	20	45	16
北大	8	6	30	44	17
北航	2	1	4	7	3
清华	2	0	8	10	3
中山	1	0	3	4	1
浙大	1	0	7	8	3
南师	5	0	12	17	5
复旦	1	0	3	4	1
中科大	2	3	4	9	2
山大	2	0	3	5	0
华南师大	2	1	3	6	1
总计	**45**	**17**	**97**	**159**	**52**

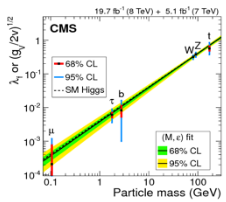
中国参与CMS的情况

共享合作组物理文章成果，以1%的硬件投入，2%的人员投入，主导了～5%的重要成果

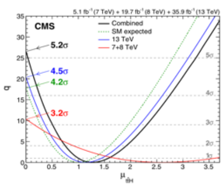
2012

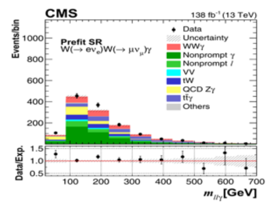


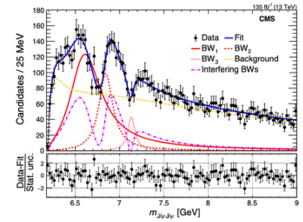
2015



2018







。。。

1990s

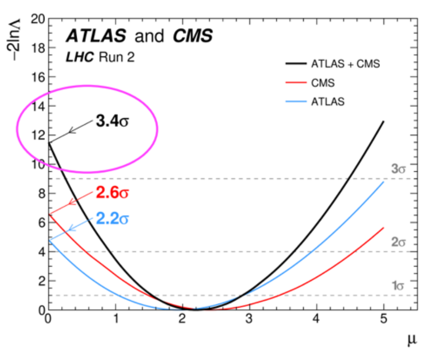
CMS建造 | run1 | 0期升级 | run2 | 一期升级 | run3 | 二期升级 | 高亮度LHC run

建造CSC
RPC

CSC/RPC
建造CPPF

HGCal/GEM/
Trigger/MTD

Zgamma实验证据



- 最近亮点成果

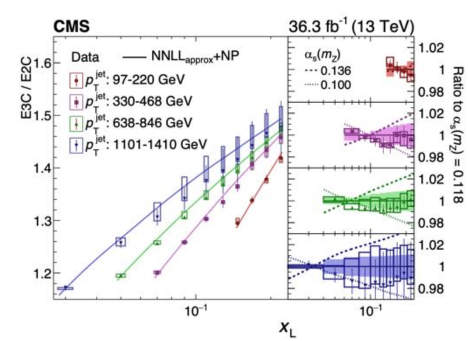

4 2024年3月28日 星期四

国 际 WORLD

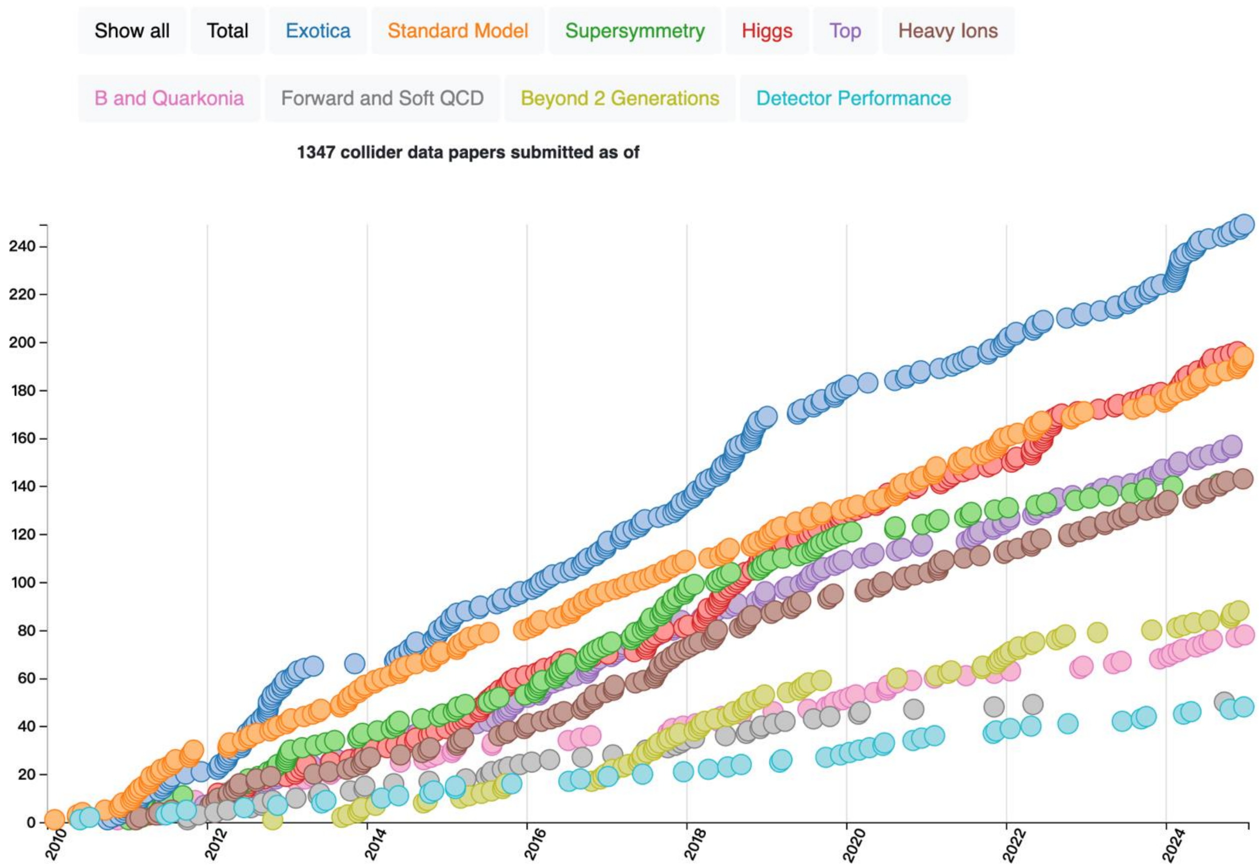
质子对撞中首次观察到光子变陶子

为探索新物理现象提供途径

喷注内部能量关联

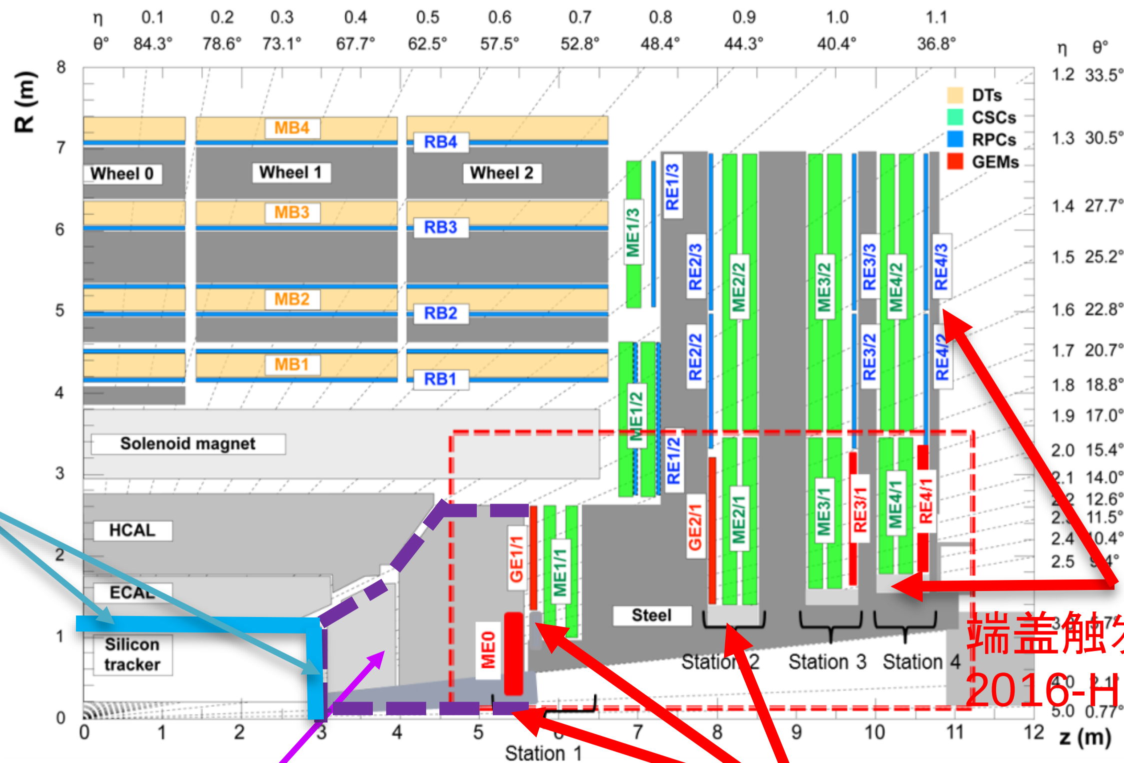


文章发表



2024年：
CMS合作组发表
~100篇文章，其中,
中国组做出主要贡献：
~11篇（~10%）

中国参与CMS实验探测器二期升级项目



MIP时间探测器
2021-HLLHC

端盖触发探测器
2016-HLLHC

端盖高粒度量能器:
2016-HLLHC

端盖GEM探测器
2016-HLLHC

51

硬件贡献约3M CHF，占比～1%；


科学思想+技术平台

总结

- 微观世界的物质组成与运动规律的探测是物质世界的重要方向
- 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极好的条件
  - 我们从哪里来，将到哪里去？
  - 世界的组成，跨国际，跨文化的合作…
- LHC，特别是高亮度LHC升级所采用的新探测器技术代表了未来探测的发展方向
  - 技术挑战，数据挑战，物理挑战
- 欢迎大家加入CMS，共同探寻高能量前沿的未知之谜

THANK YOU