



味物理与强子谱

杨振伟

清华大学工程物理系

清华大学高能物理研究中心

yangzhw@tsinghua.edu.cn

2019年7月17日



物理学家的目标

- 尝试理解并描述自然的**基本规律 (fundamental principles)**
- 极大与极小两个方向：**析理入微，见微知著**

➤ 极小

- 量子力学
- **粒子物理标准模型**

➤ 极大

- 广义相对论
- **宇宙大爆炸理论**

ABOUT 13.5 BILLION YEARS AGO, MATTER, energy, time and space came into being in what is known as the Big Bang. The story of these fundamental features of our universe is called physics.

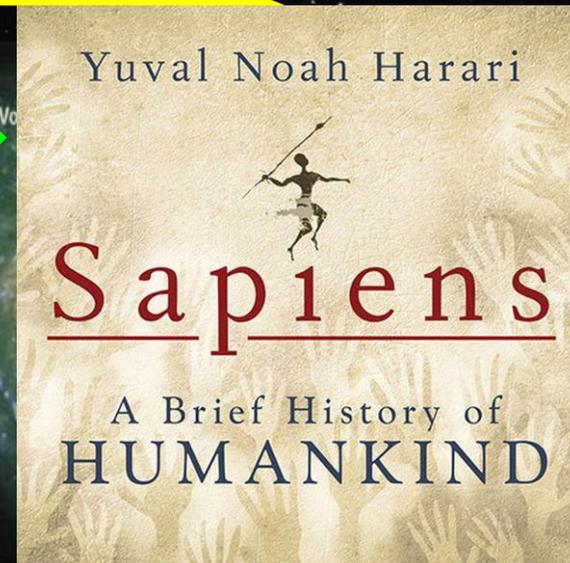
About 300,000 years after their appearance, matter and energy

1.54%

01:01

“大约135亿年前，**物质、能量、时间、空间**诞生于所谓的**宇宙大爆炸**。有关宇宙这些**基本特性的故事称为物理。**”

——《**人类简史**》



物理学家的目标

- 尝试理解并描述自然的**基本规律 (fundamental principles)**
- 极大与极小两个方向：**析理入微，见微知著**

➤ 极小

- 量子力学
- **粒子物理标准模型**

➤ 极大

- 广义相对论
- **宇宙大爆炸理论**

粒子物理研究世界的**基本组元**及其**相互作用**



基本粒子探索 和诺贝尔奖



Takaaki Kajita Arthur B. McDonald

2015



Francois Englert Peter W. Higgs

2013



Yoichiro Nambu Makoto Kobayashi Toshihide Maskawa

2008



David Gross David Politzer Frank Wilczek

2004



Murray Gell-Mann

1969



Sin-Itiro Tomonaga Julian Schwinger Richard P. Feynman

1965



Emilio Segrè Owen Chamberlain

1959



Chen Ning Yang Tsung-Dao Lee

1957



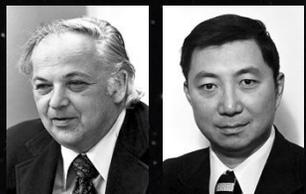
Hideki Yukawa

1949



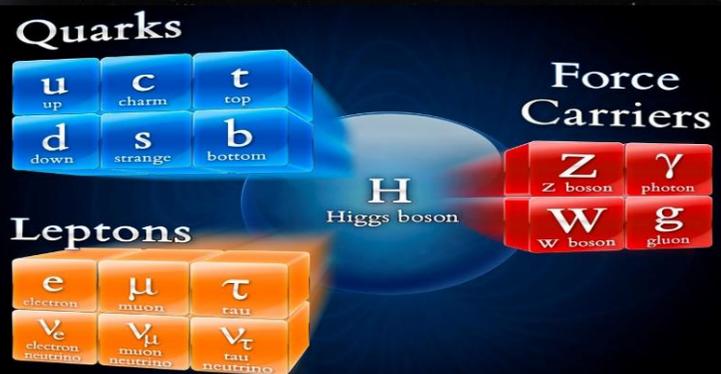
Raymond Davis Jr. Masatoshi Koshiba Riccardo Giacconi

2002



Burt Richter Sam Ting

1976



Joseph John Thomson

1906



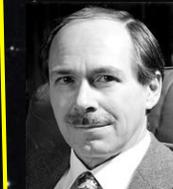
James Chadwick

1935



Carl David Anderson

1936



Gerard 't Hooft

1999



Martinus Veltman



Sheldon Glashow Abdus Salam Steven Weinberg

1979



James Watson Cronin Val Logsdon Fitch

1980



Carlo Rubbia Simon van der Meer

1984



Leon M. Lederman Melvin Schwartz Jack Steinberger

1988



Jerome Friedman Henry Kendall Richard Taylor

1990



Martin L. Perl Frederick Reines

1995

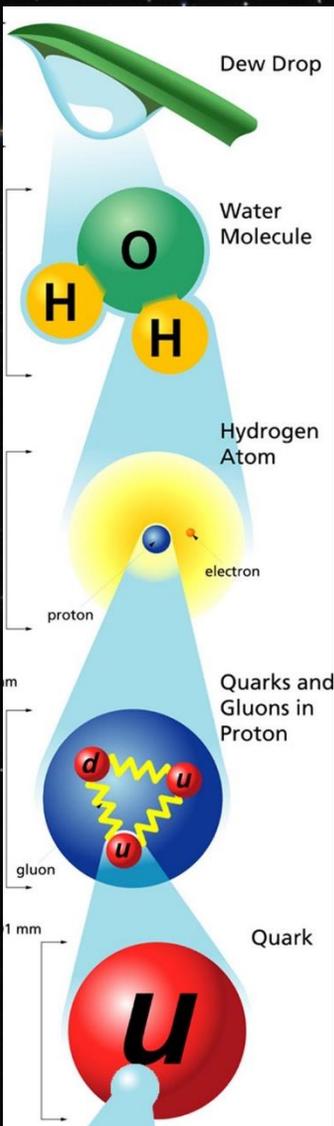
2019/7/17

杨振伟 清华大学高能物理研究中心

(C) Felton Péter | 2017

粒子物理标准模型

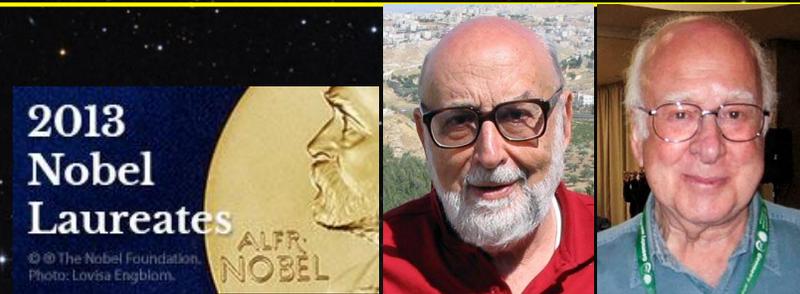
- 基本组元: **quarks (夸克)**、**leptons (轻子)**
- 力的媒介 (规范玻色子): γ (电磁力)、 W^\pm/Z^0 (弱力)、 g (强力)
- 希格斯玻色子——上帝粒子
 - 1964年Peter Higgs提出对称性自发破缺机制解释质量起源问题



基本组元



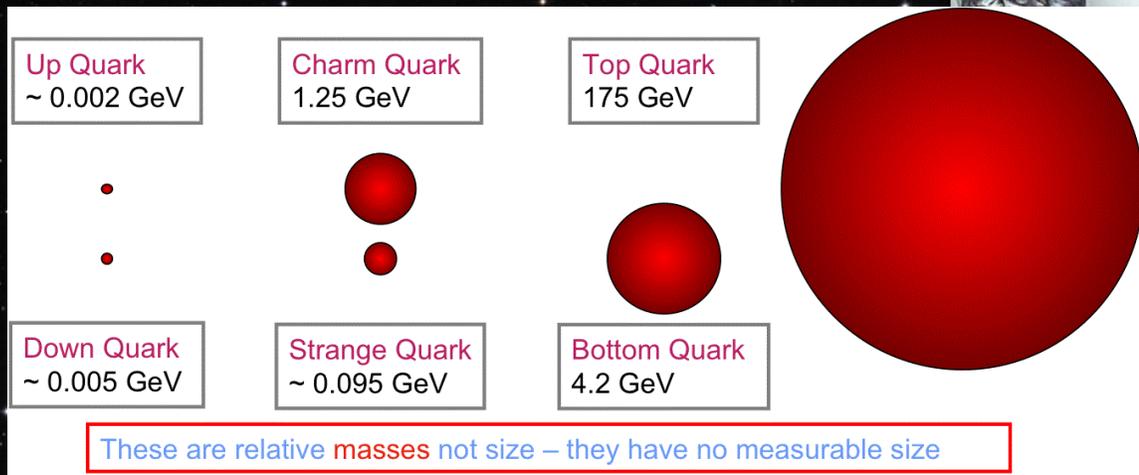
- 2012年7月4日, **欧洲核子研究中心**宣布在大型强子对撞机上发现了**希格斯玻色子**
- 2013年F. Englert和P. Higgs 被授予**诺贝尔物理奖**



新的启航

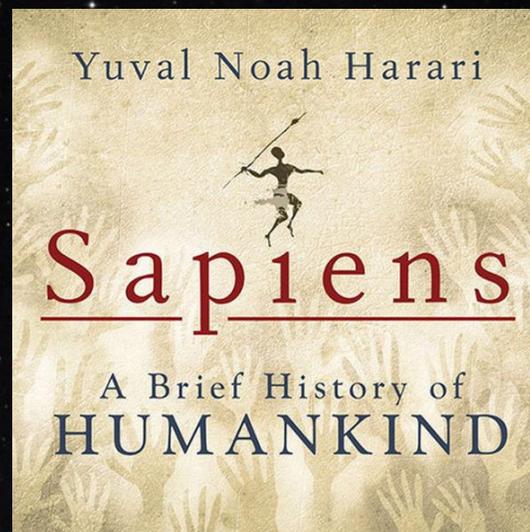


- 反物质世界哪去了？
- 暗物质、暗能量？
- 为什么存在三代轻子和夸克，质量差如此巨大？
- 作用力可以统一吗？



图示大小仅表示其质量的相对大小，与可测量的几何尺寸无关！

“..... Yet it is vital to ask questions for which no answers are available, otherwise we might be tempted to dismiss 60,000 of 70,000 years of human history with the excuse that ‘the people who lived back then did nothing of importance’ ”.
—*Sapiens* (《人类简史》) by Yuval Noah Harari

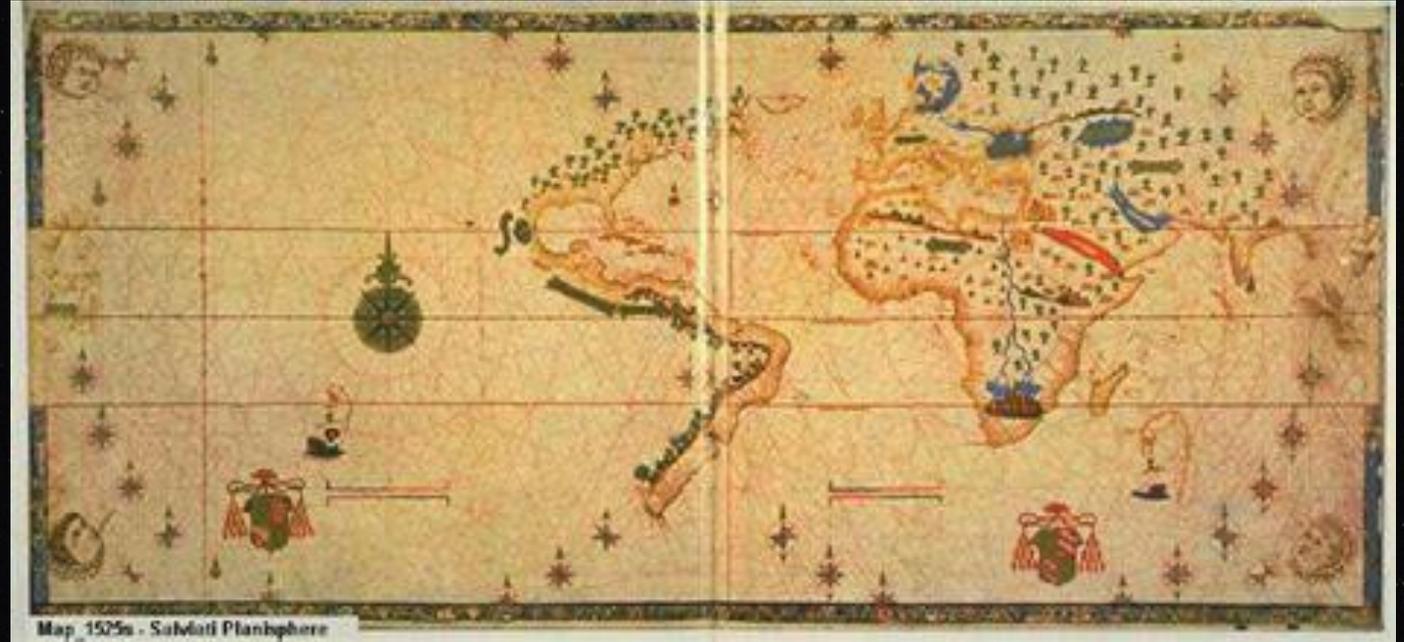


“承认无知” 与现代科学

1459年欧洲人的世界地图



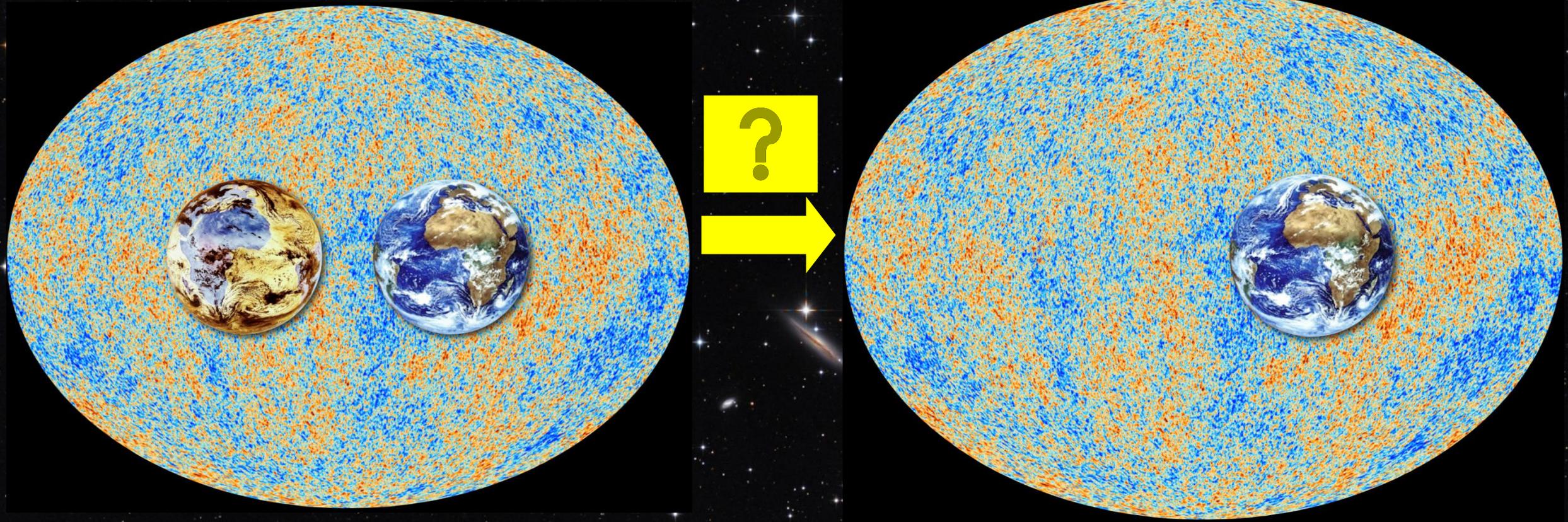
1525年欧洲人的世界地图



- 承认无知 (ignorance) 是现代科学发展的前提
- 通过新发现和数学推理获取新的知识，并转化为新技术和新力量

“知之为知之，不知为不知，是知也。”

反物质去哪儿了？





屈原 (约前340—前278年)



Leon Lederman
(1922.7.15-2018.10.3)
2019/7/17

天问

【先秦】屈原

曰：遂古之初，谁传道之？

上下未形，何由考之？

冥昭瞢闇，谁能极之？

冯翼惟像，何以识之？

明明闇闇，惟时何为？

阴阳三合，何本何化？

圜则九重，孰营度之？

惟兹何功，孰初作之？

请问远古开始之时，
谁将此态流传导引？
天地尚未成形之前，
又从哪里得以产生？

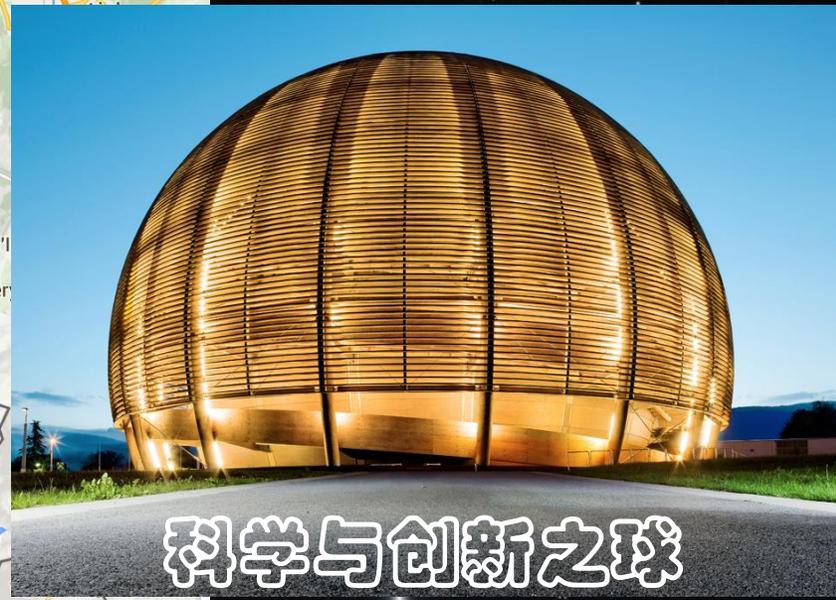
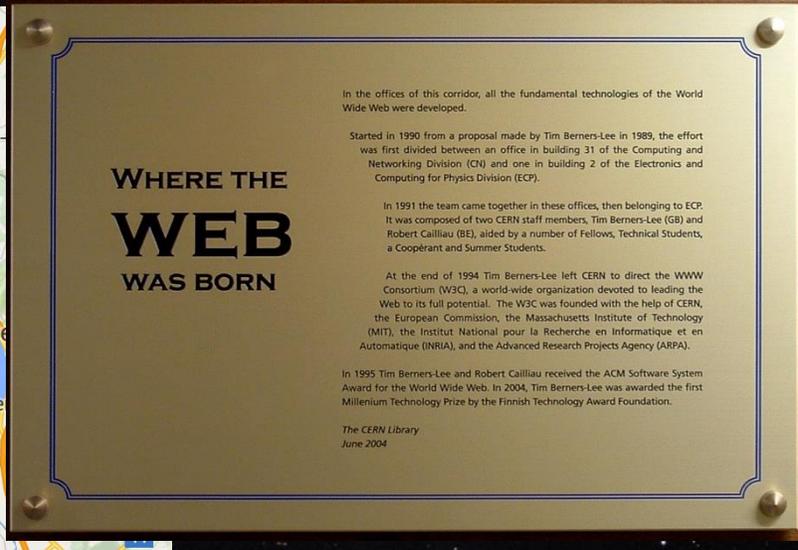
明暗不分浑沌一片，
谁能探究根本原因？
迷迷濛濛这种现象，
怎么识别将它认清？

白天光明夜晚黑暗，
究竟它是为何而然？
阴阳参合而生宇宙，
哪是本体哪是演变？

天的体制传为九重。
有谁曾去环绕量度？
这是多么大的工程。
是谁开始把它建筑？

**约2300年后， Leon Lederman:
If the Universe is the answer, what is the question?**

欧洲核子研究中心(CERN)



大型强子对撞机 (LHC)

目前全球能量最高的对撞机

- 束流能量: 6.5 TeV
- 对撞频率: 40 MHz
- 瞬时亮度: $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

LHC beauty experiment

大型强子对撞机之“美味”实验

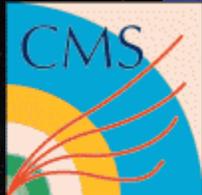
日内瓦机场

欧洲核子
研究中心

LHCb
THCP

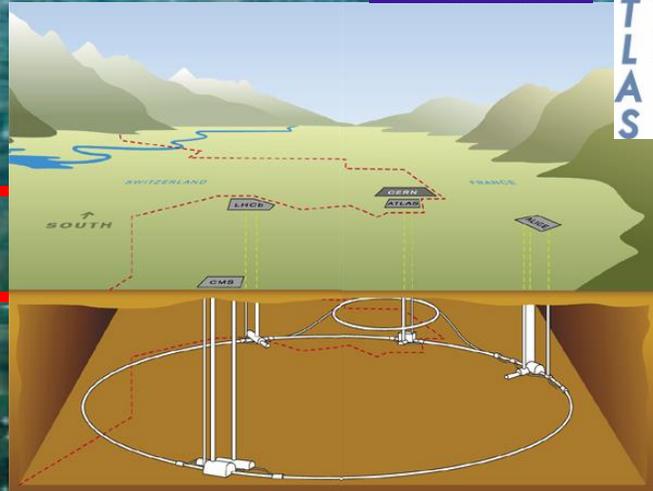
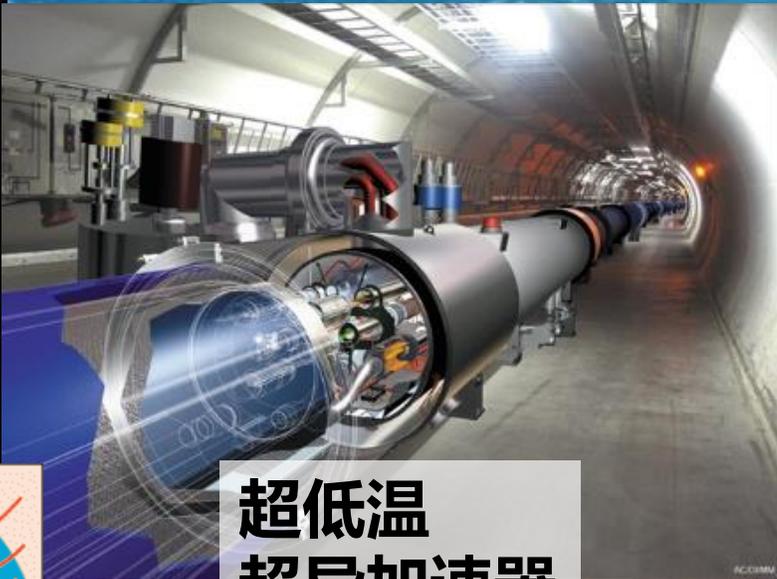


超低温
超导加速器



几十至
一百米

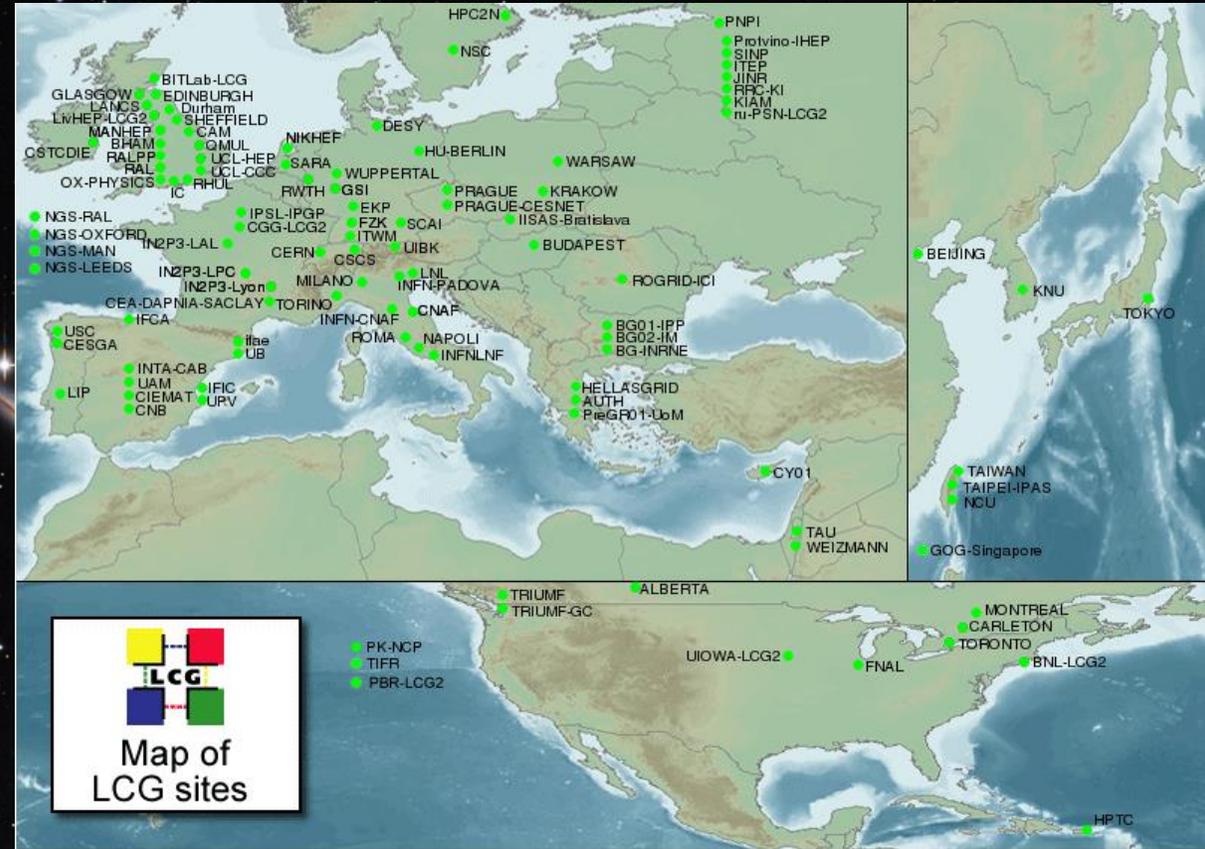
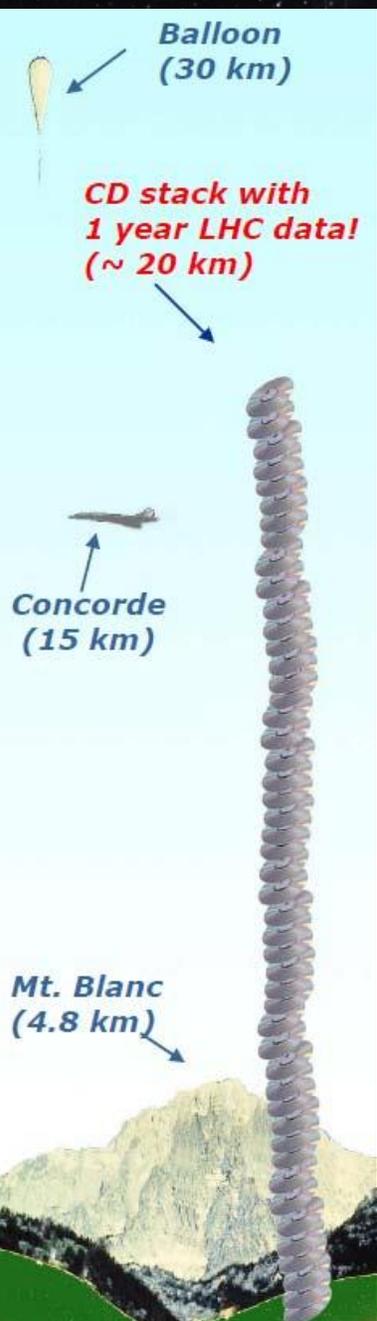
LHC隧道



大型强子对撞机上的数据处理

- 每天约 1000 TB
- 一年数据约等于20 km高的CD

这是1990's的设计规划!



什么是“味”？



精制牛肉末210g 风味水豆豉210g (酸辣味) 番茄辣酱210g 香辣酱200g

红油腐乳260g 风味腐乳260g 辣三丁油辣椒210g 香辣菜188g

8个口味任选5瓶备注好

默认发货：2瓶牛肉末+1瓶风味水豆豉+1瓶番茄辣酱+1瓶香辣酱

为什么是“味”？

[孙子兵法·势篇](#) 百度汉语

作者：孙武

孙子曰：凡治众如治寡，分数是也；斗众如斗寡，形名是也；三军之众，可使必受敌而无败者，奇正是也；兵之所加，如以礮投卵者，虚实是也。

凡战者，以正合，以奇胜。

故善出奇者，无穷如天地，不竭如江海。

终而复始，日月是也。

死而更生，四时是也。

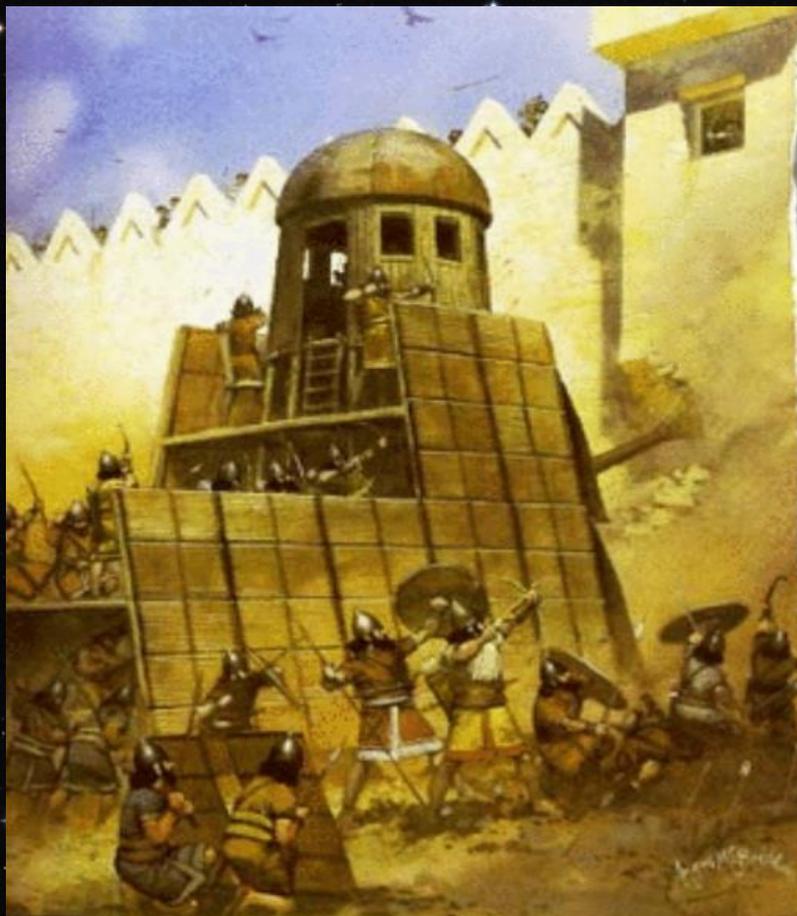
声不过五，五声之变，不可胜听也；色不过五，五色之变，不可胜观也；味不过五，五味之变，不可胜尝也；战势不过奇正，奇正之变，不可胜穷也。

奇正相生，如循环之无端，孰能穷之哉！

正：直接测量

奇：间接测量

直接测量 —— 间接测量



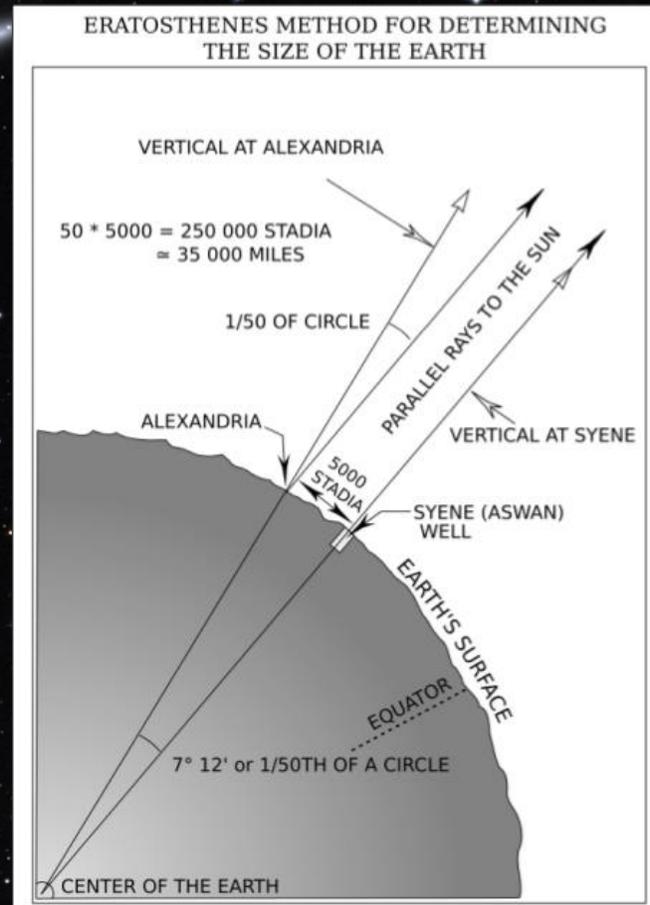
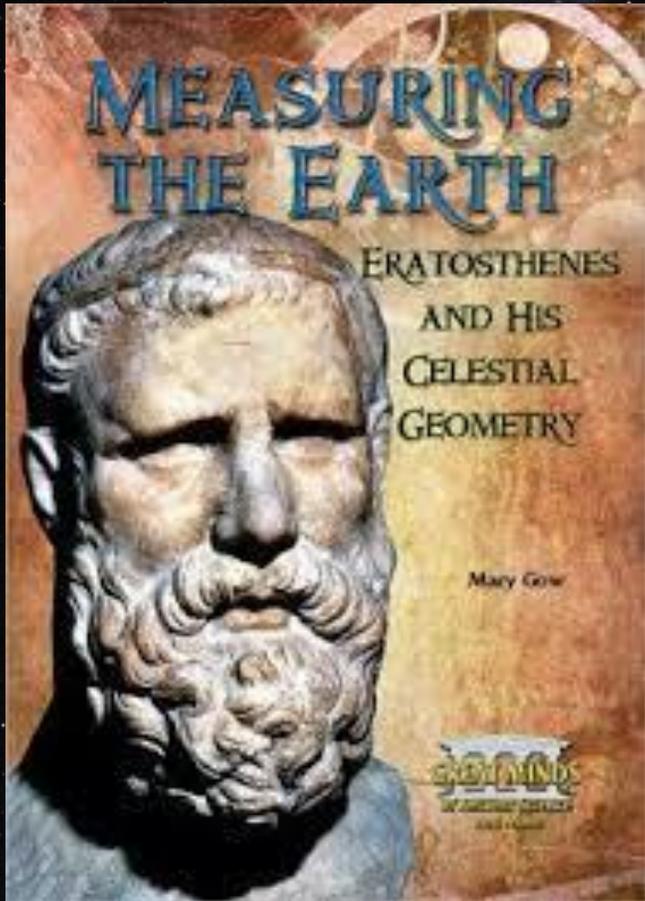
**直接测量：能量足以击穿城墙
(足以直接产生新粒子)**



**间接测量：间接攻入城内
(能量无需太高，在圈图出现即可)
可探索能量远高于加速器能量的物理**

远古时期的间接测量

- 埃拉托斯特尼 (Eratosthenes, 前276-前195)
 - 间接测量地球周长: 46100公里 (与现代值差15%)



约2200年后直接观测



粲夸克的预言

➤ $K^0 \rightarrow \mu^+ \mu^-$ 衰变分支比异常之小

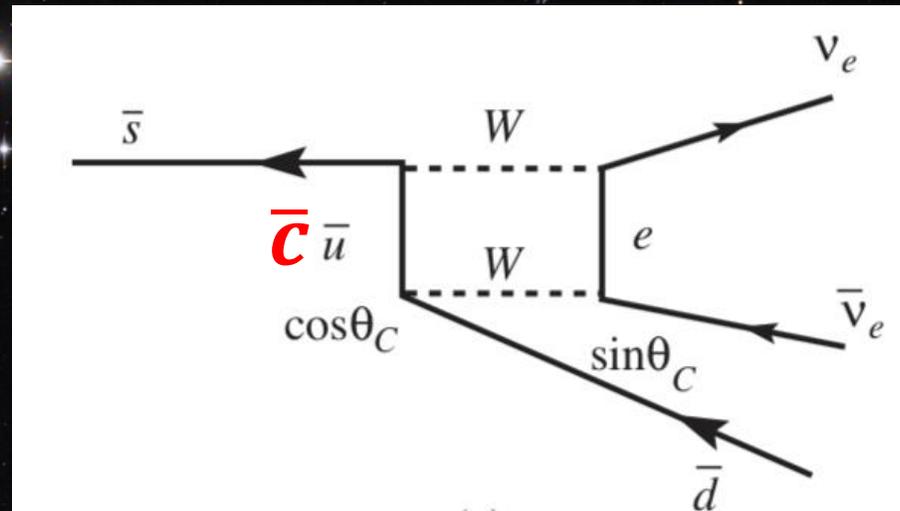
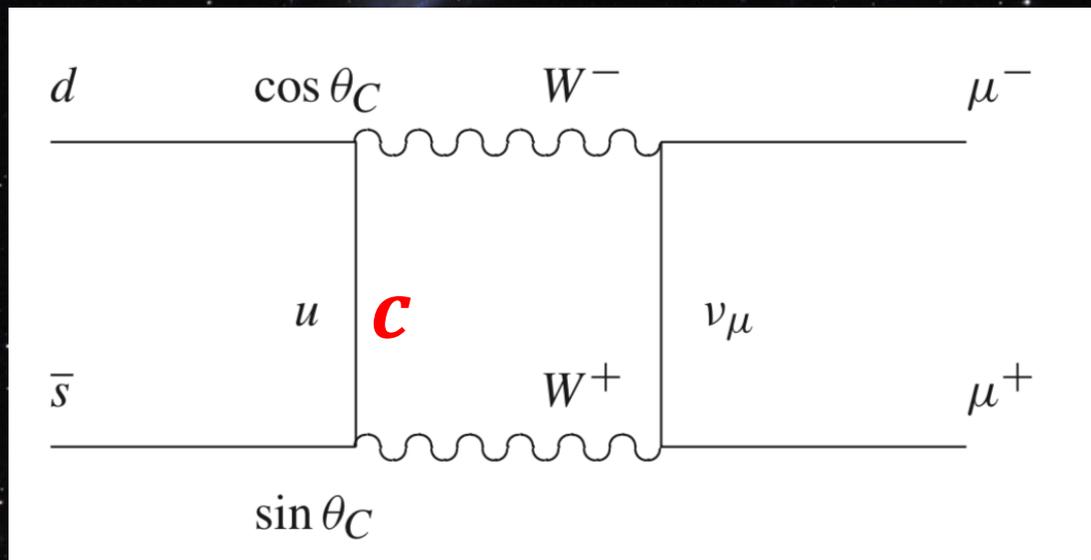
- 最新结果大约 $10^{-9} - 10^{-8}$ 量级

➤ 1964年预言存在“粲”夸克

- 质量 $1.5 - 2.0 \text{ GeV}$!

$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu_e \bar{\nu}_e) = (1.5_{-0.9}^{+1.3}) \times 10^{-10}$$

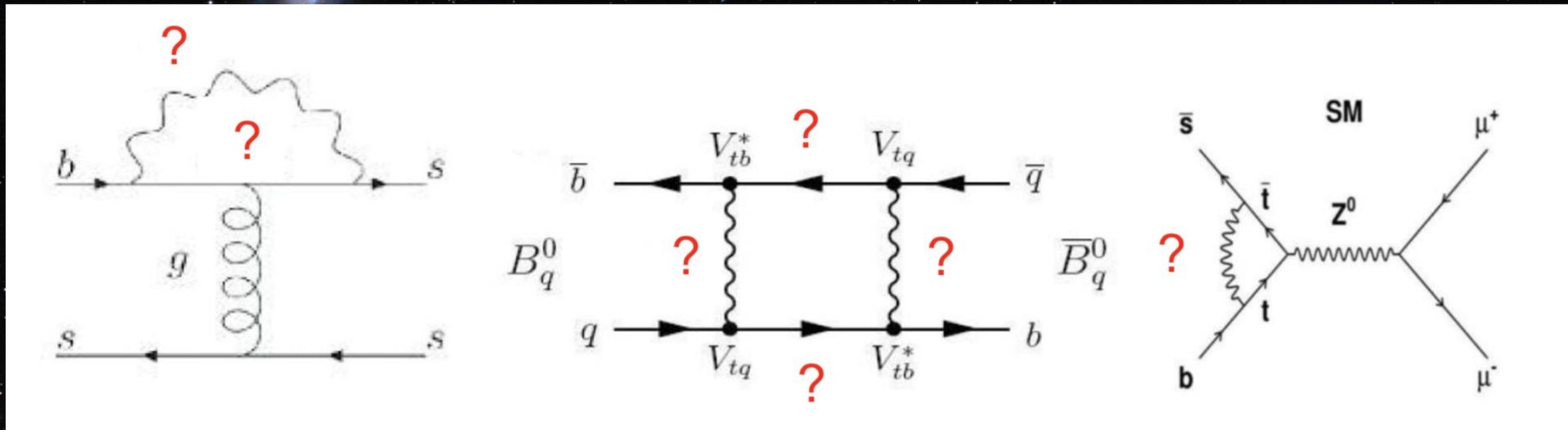
$$\mathcal{B}(K^+ \rightarrow \pi^0 \nu_e e^+) = (4.98 \pm 0.07) \times 10^{-2}$$



间接测量

➤ 费曼图的内线如果有“未知”粒子的贡献，会改变反应截面的大小

- 往往需要精确测量



LHCb实验

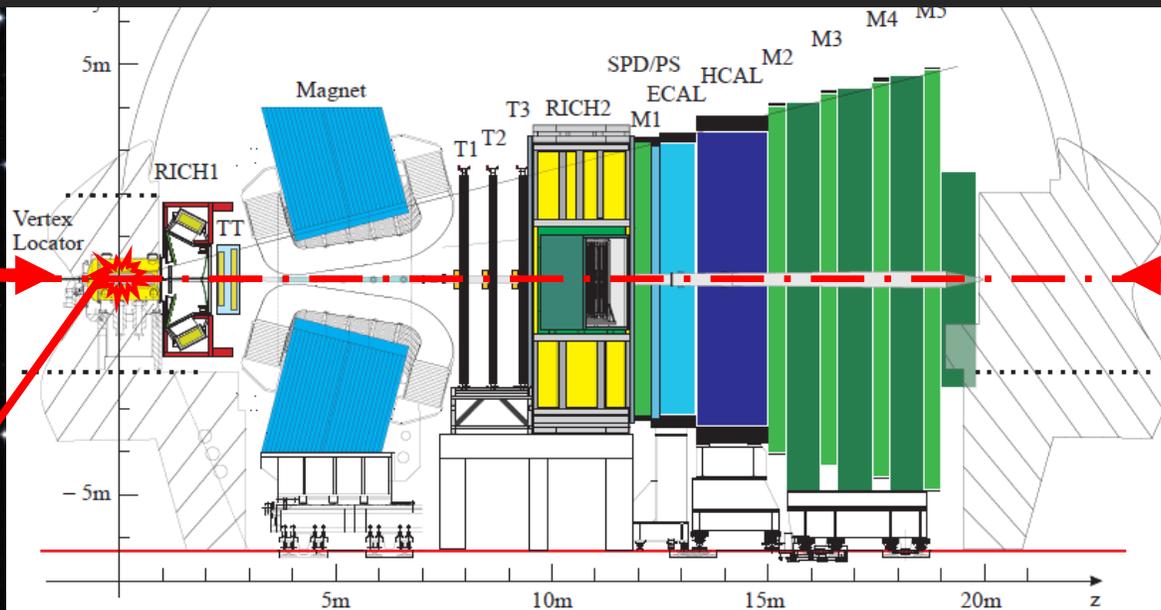
LHCb 探测器

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

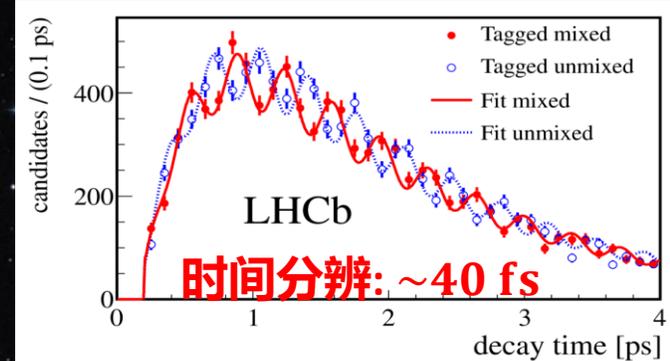
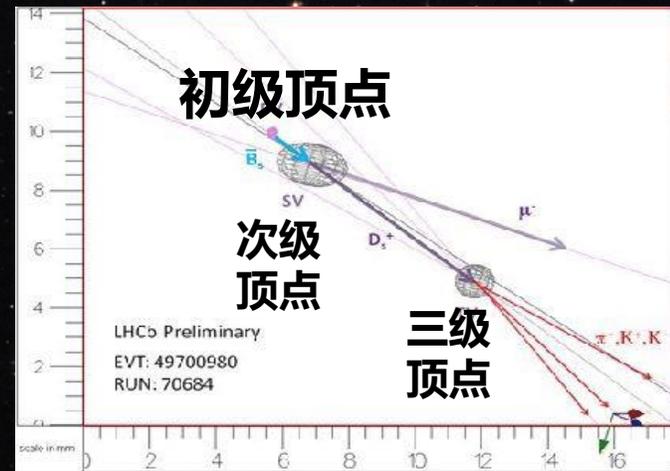
Designed for precise measurements of heavy flavor hadrons
with unique acceptance: $2 < \eta < 5$

束流1

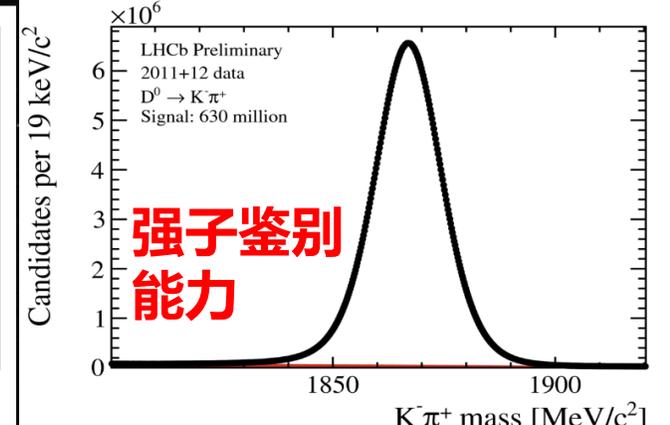
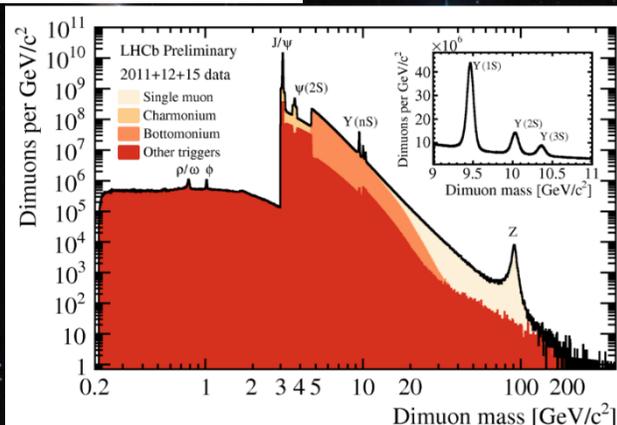
Collision point
对撞点



束流2

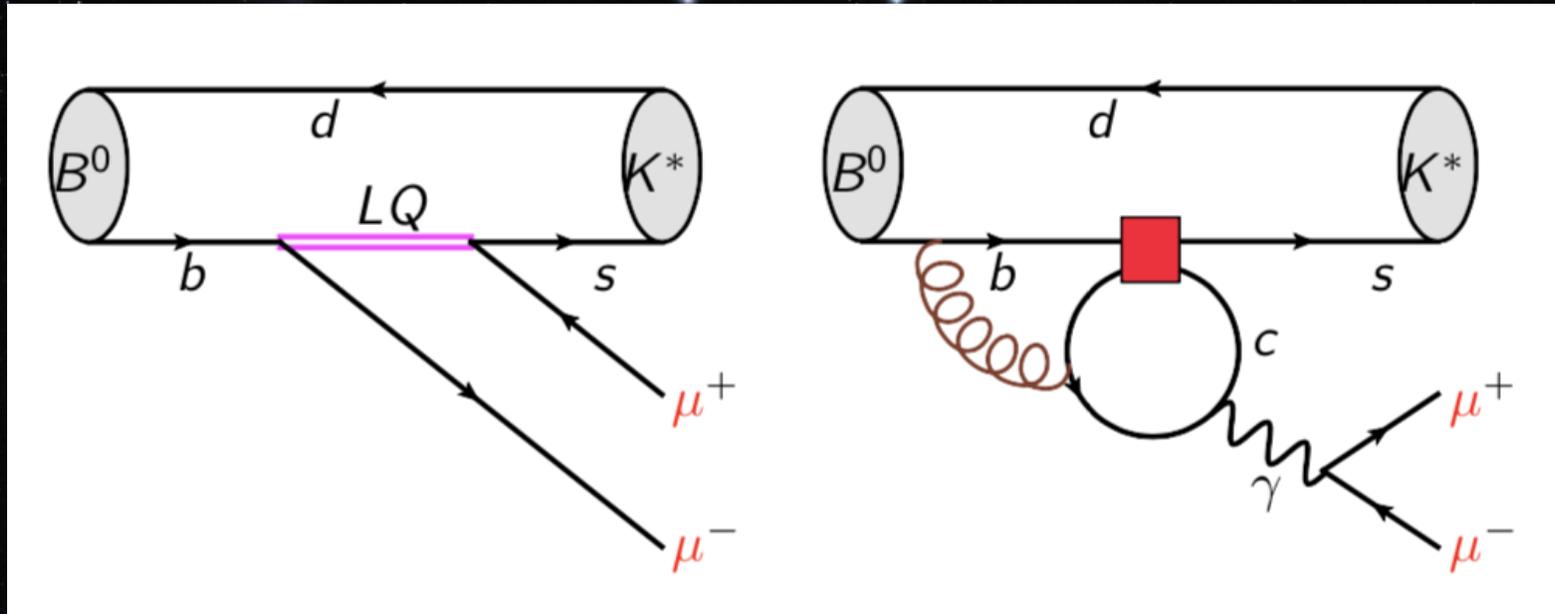


- 顶点精度: $\sigma_{IP} = 20 \mu\text{m}$
- 时间分辨率: $\sigma_\tau = 45 \text{ fs}$ for $B_s^0 \rightarrow J/\psi\phi$ or $D_s^+\pi^-$
- 动量分辨率: $\Delta p/p = 0.4 \sim 0.6\%$ (5 - 100 GeV/c)
- 质量分辨率: $\sigma_m = 8 \text{ MeV}/c^2$ for $B \rightarrow J/\psi X$ ($m_{J/\psi}$)
- 强子鉴别: $\epsilon(K \rightarrow K) \sim 95\%$ misID $\epsilon(\pi \rightarrow K) \sim 5\%$
- 缪子鉴别: $\epsilon(\mu \rightarrow \mu) \sim 97\%$ misID $\epsilon(\pi \rightarrow \mu) \sim 1 - 3\%$
- 电磁量能器: $\Delta E/E = 1 \oplus 10\%/\sqrt{E(\text{GeV})}$



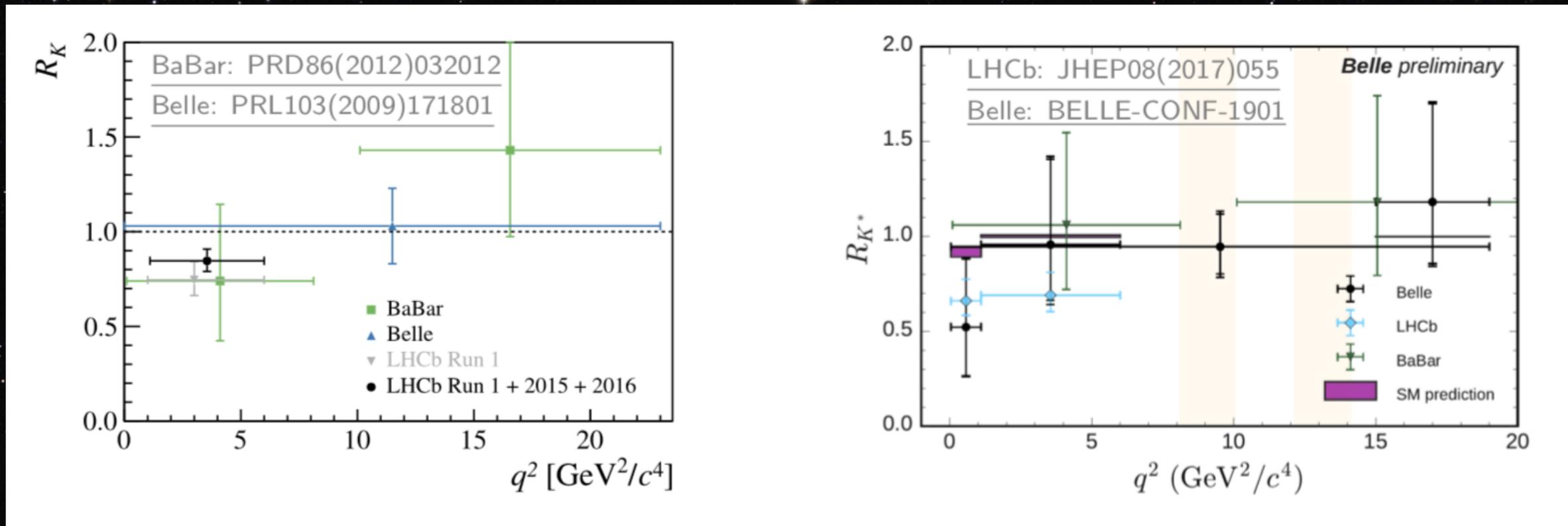
轻子普适性检验

➤ 除了质量，轻子的相互作用性质完全相同



$$R_{K^{(*)}} = \frac{\mathcal{B}(B \rightarrow K^{(*)} \mu^+ \mu^-)}{\mathcal{B}(B \rightarrow K^{(*)} e^+ e^-)} \stackrel{\text{SM}}{=} 1.0$$

$$R_{K^{(*)}}$$



➤ LHCb结果低于标准模型预言值 $2.0 - 2.5\sigma$



从元素周期表谈起。。。

元素周期表

原子一直以来被认为是物质世界不可再分割的基本单元

Periodic Table of the Elements

1 IA 11A H Hydrogen 1.008	2 IIA 2A Be Beryllium 9.012											13 IIIA 3A B Boron 10.811	14 IVA 4A C Carbon 12.011	15 VA 5A N Nitrogen 14.007	16 VIA 6A O Oxygen 15.999	17 VIIA 7A F Fluorine 18.998	18 VIIIA 8A He Helium 4.003	
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 Al Aluminum 26.982	6 Si Silicon 28.086	7 P Phosphorus 30.974	8 S Sulfur 32.066	9 Cl Chlorine 35.453	10 Ne Neon 20.180	
11 Na Sodium 22.990	12 Mg Magnesium 24.305	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 8	10 VIII 8	11 IB 1B	12 IIB 2B	13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948	
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.933	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.732	32 Ge Germanium 72.61	33 As Arsenic 74.922	34 Se Selenium 78.09	35 Br Bromine 79.904	36 Kr Krypton 84.80	
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.29	
55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71 Lanthanide Series	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018	
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103 Actinide Series	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown	
		57 La Lanthanum 138.906	58 Ce Cerium 140.115	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.966	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.930	68 Er Erbium 167.26	69 Tm Thulium 168.934	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967		
		89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]		

门捷列夫的元素周期表 (1869.03.06)



门捷列夫

I	II	III	IV	V	VI	VII	VIII		
H 1.01									
Li 6.94	Be 9.01	B 10.8	C 12.0	N 14.0	O 16.0	F 19.0			
Na 23.0	Mg 24.3	Al 27.0	Si 28.1	P 31.0	S 32.1	Cl 35.5			
K 39.1	Ca 40.1		Ti 47.9	V 50.9	Cr 52.0	Mn 54.9	Fe 55.9	Co 58.9	Ni 58.7
Cu 63.5	Zn 65.4			As 74.9	Se 79.0	Br 79.9			
Rb 85.5	Sr 87.6	Y 88.9	Zr 91.2	Nb 92.9	Mo 95.9		Ru 101	Rh 103	Pd 106
Ag 108	Cd 112	In 115	Sn 119	Sb 122	Te 128	I 127			
Ce 133	Ba 137	La 139		Ta 181	W 184		Os 194	Ir 192	Pt 195
Au 197	Hg 201	Tl 204	Pb 207	Bi 209					
			Th 232			U 238			

- 50多种化学元素呈现出一定的周期性
- “缺失”的元素尚未被发现

**一个重要问题：
为什么会存在这样的
周期性？**

化学元素为什么呈现出周期性？

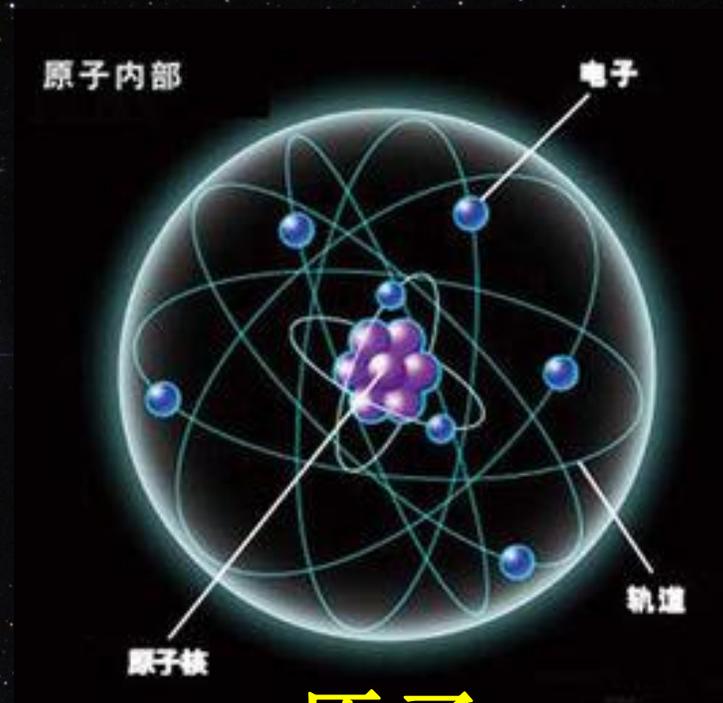
- 1869年门捷列夫总结元素的化学性质提出元素周期表
- 1911年卢瑟福根据散射实验结果提出原子模型
 - 原子由原子核和核外电子构成
 - 亚原子：比原子更深层次的结构
- 量子力学的建立（1900-1930）
 - 核外电子壳层结构，最外层电子主导原子的化学性质

组成：原子核+核外电子

规律：量子力学

电磁理论

→ 化学键，周期表

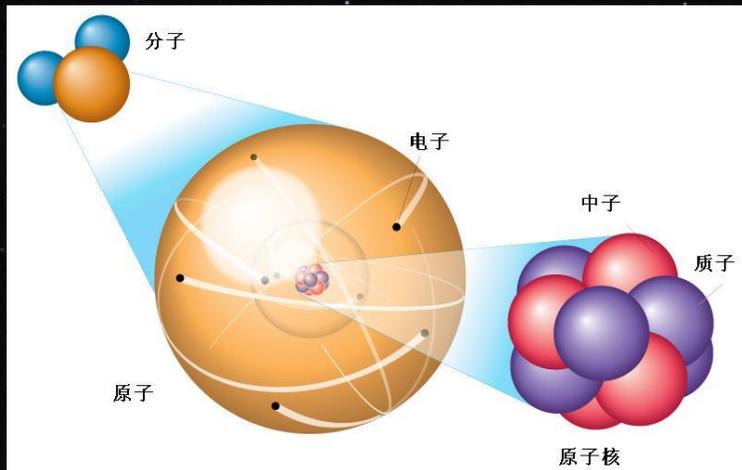


原子

元素周期表及其背后物理规律带来的启示

- 100 种元素 + 周期性变化的性质
 - ? 内部结构
- 基本粒子 间具有简单的 相互作用
- 量子力学原理 + 基本粒子的相互作用规律
 - 元素的性质
 - 元素间的复杂相互作用
 - ...

强子：新的“元素”



- 原子核是可分的，由**质子(p)**和**中子(n)**组成！

- 质子 p 、中子 n 、电子 e → 组成原子核与原子
- 外加 π 介子（传递核力的相互作用）
看起来是完美的

- 实验发现意外多的“基本粒子”

$p, n, \Sigma, \Lambda, \Xi, \Delta, \dots$

$\pi, K, \rho, \omega, \phi, \eta, \dots$

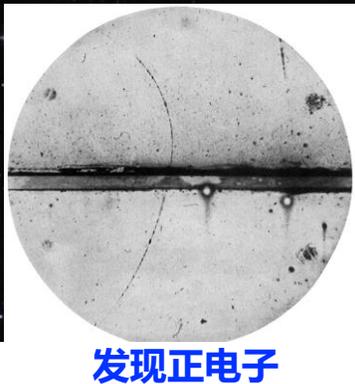
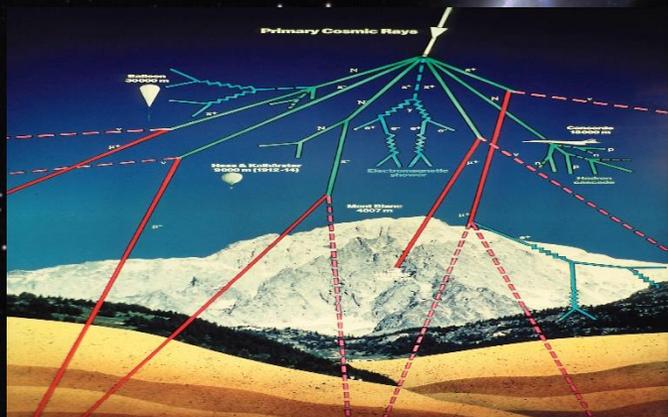
统称为“强子”

- 核子（质子+中子）间作用力具有复杂形式

粒子发现的三个时代

➤ 农业时代

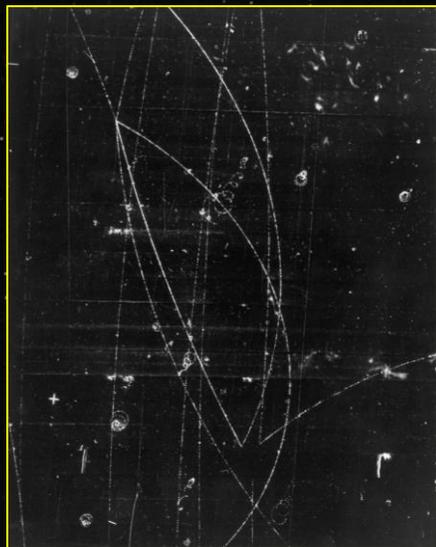
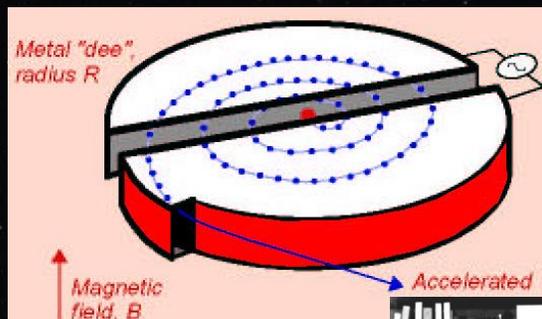
- 靠天吃饭
- 宇宙射线或放射性



发现正电子

➤ 工业时代

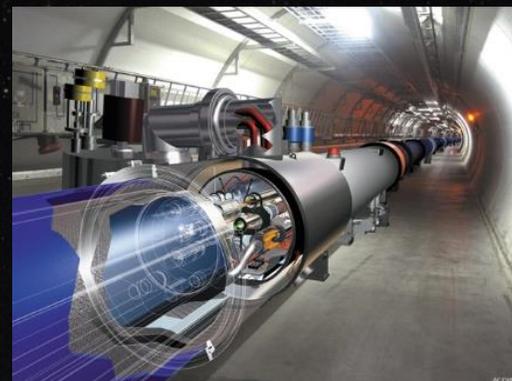
- 加速器时代



➤ 信息时代

- 计算机技术的应用

网格计算
WWW协议
触摸屏技术



(C) Ferrón Páter | 2017

急速膨胀的“粒子动物园”

Mesons
π^-, π^0, π^+
K^0, K^+
K^-, \bar{K}^0
η
ρ^-, ρ^0, ρ^+
ω
K^{*0}, K^{*+}
K^{*-}, \bar{K}^{*0}
η'
ϕ

Baryons
p, n
Λ
$\Sigma^-, \Sigma^0, \Sigma^+$
$\Delta^-, \Delta^0, \Delta^+, \Delta^{++}$
Ξ^-, Ξ^0
$\Sigma^{*-}, \Sigma^{*0}, \Sigma^{*+}$
Ξ^{*-}, Ξ^{*0}

人们意识到这些粒子不可能都是基本粒子.....
 → 夸克模型

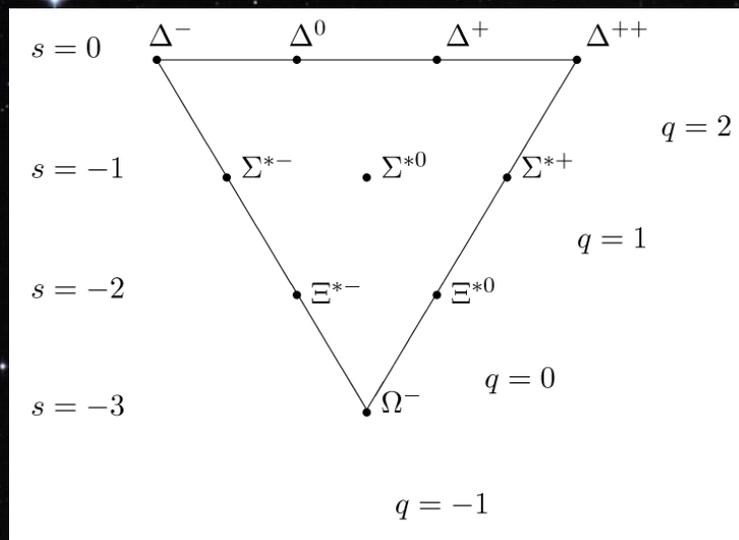
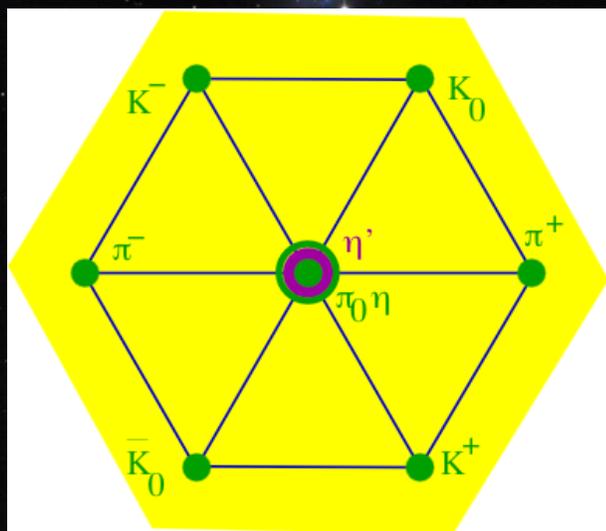
..... I have heard it said that « the finder of a new elementary particle used to be rewarded by a Nobel Prize, but such a discovery now ought to be punished by a \$10,000 fine ». — Lamb 1955

	1895	X-ray produced by Wilhe
	1897	Electron discovered by
	1899	Alpha particle discover
	1900	Gamma ray (a high-ene
	1911	Atomic nucleus identifi
	1919	Proton discovered by E
	1932	Neutron discovered by J
	1932	Antielectron (or positro
	1937	Muon (or mu lepton) di mistaken for the pion un
	1947	Pion (or pi meson) disc
	1947	Kaon (or K meson), the
	1947	Λ^0 discovered during a s
	1955	Antiproton discovered b
	1956	Electron antineutrino o decay) ^[18] At the time it v
	1962	Muon neutrino (or mu
	1964	Xi baryon discovery at B

夸克模型：一场认识的革命

探索自然界物质基本结构的进程中有很多里程碑式的发现

- 盖尔曼和茨威格提出的**夸克模型**是最重要里程碑之一
- 对强作用物质的基本结构产生了革命性的突破



The Nobel Prize in Physics 1969



Murray Gell-Mann

... "for his contributions and discoveries concerning the classification of elementary particles and their interactions".

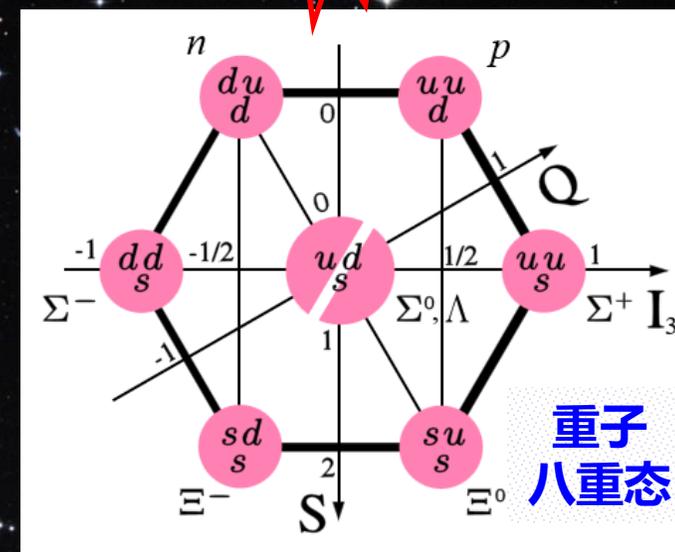
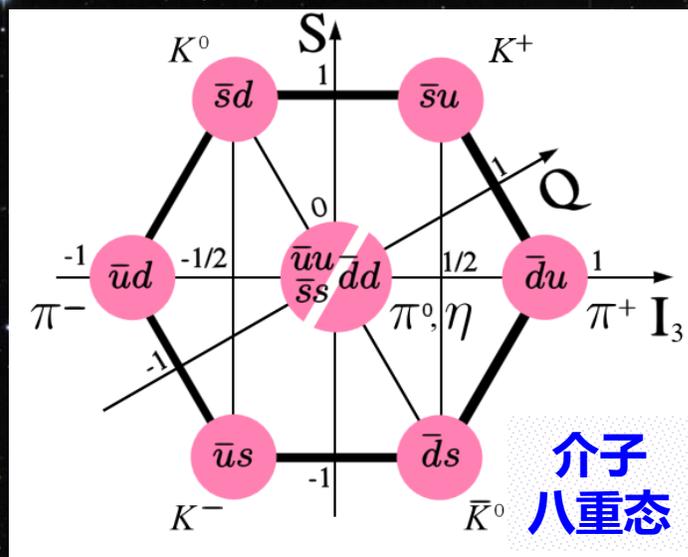
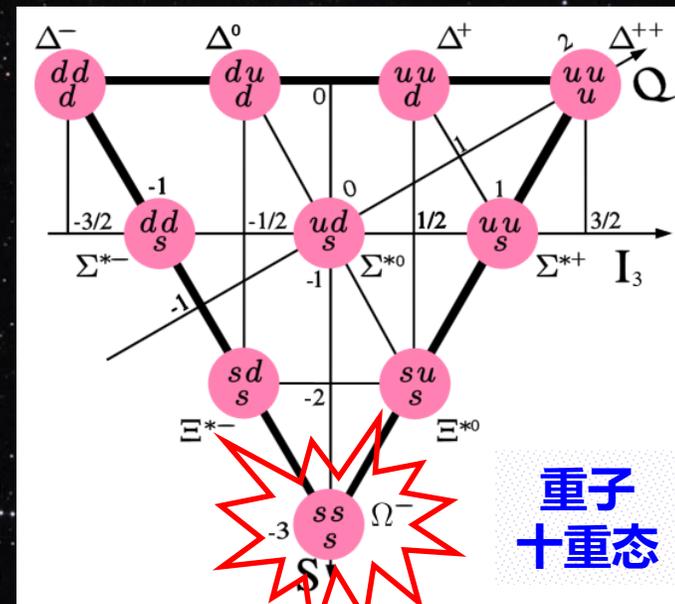
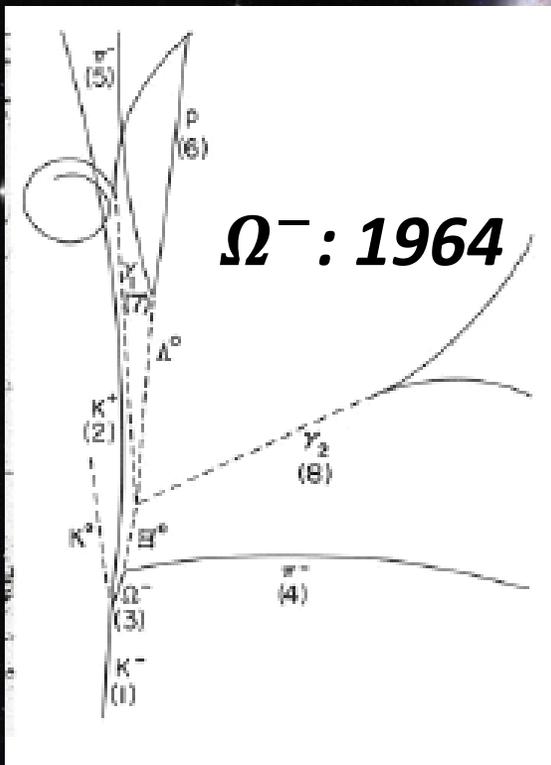
夸克模型: SU(3)

- 强子由不可见的夸克组成 (u, d, s)
- 介子 ($q\bar{q}'$) 和 重子 ($qq'q''$) 是 SU(3) 多重态

上夸克 下夸克 奇异夸克



新的“元素周期表”：已发现的强子漂亮地排在周期表中，并预言新强子



夸克模型：SU(4)

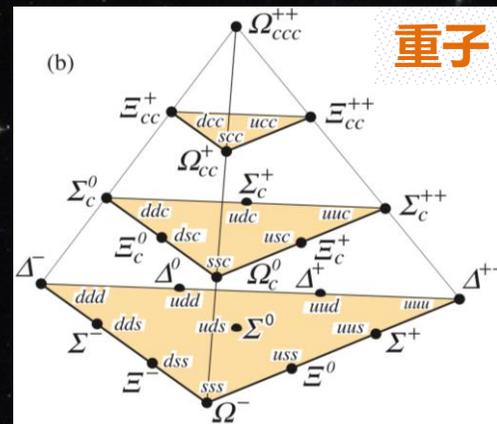
➤ 1974年11月丁肇中等人发现 J/ψ 粒子，夸克家族扩展为 (u, d, s, c) ，强子“周期表”变成 SU(4) 多重态：**粒子物理“十一月革命”**

➤ 粲量子数 $C = 0$ 和 1 的基态强子均被发现

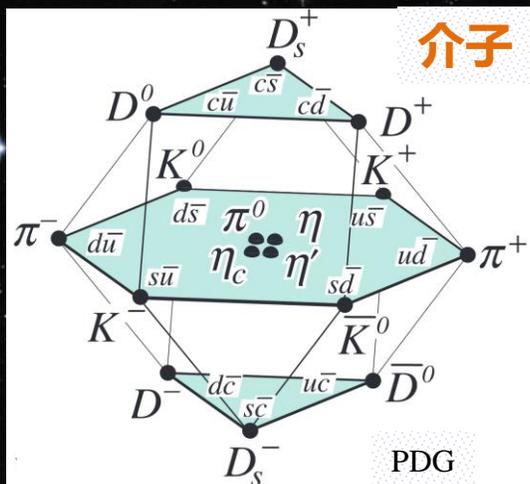
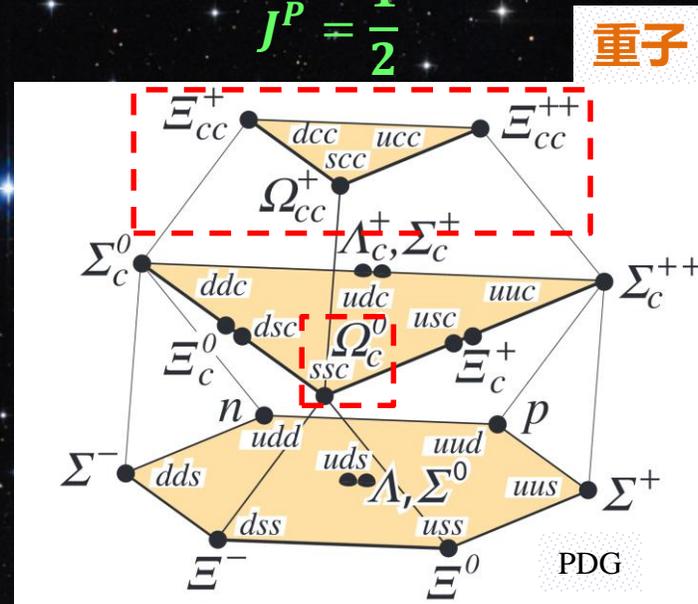
➤ $C = 2$ 的强子一直没有确切的实验证据

- 同位旋二重态: $\Xi_{cc}^+(ccd)$ 和 $\Xi_{cc}^{++}(ccu)$
就像质子(uud)和中子(ddu)构成同位旋二重态
- 同位旋单态: $\Omega_{cc}^+(ccs)$

$$J^P = \frac{3}{2}^+$$



$$J^P = \frac{1}{2}^+$$



强子谱研究的两个方向

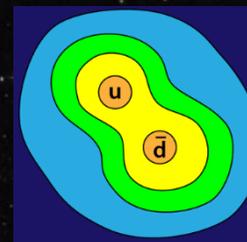
➤ 普通强子 ($q\bar{q}$ 和 qqq)

- 寻找尚未找到的基态, 例如
 - ✓ 含多个重夸克的强子: $\Xi_{cc}, \Omega_{cc}, \Xi_{bc}, \dots$
- 寻找激发态

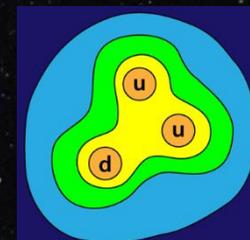
➤ 奇特强子

- 夸克模型预言存在奇特强子
 - ✓ 四夸克态 $qq\bar{q}\bar{q}$
 - ✓ 五夸克态 $qqqq\bar{q}$
 - ✓ 混杂态 $q\bar{q}g \dots$
 - ✓ 胶球: 由胶子构成的共振态

普通强子

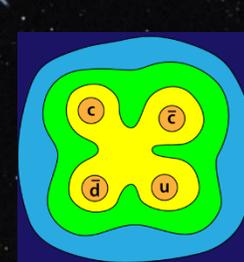


$q\bar{q}$

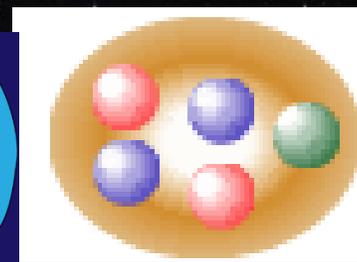


qqq

奇特强子

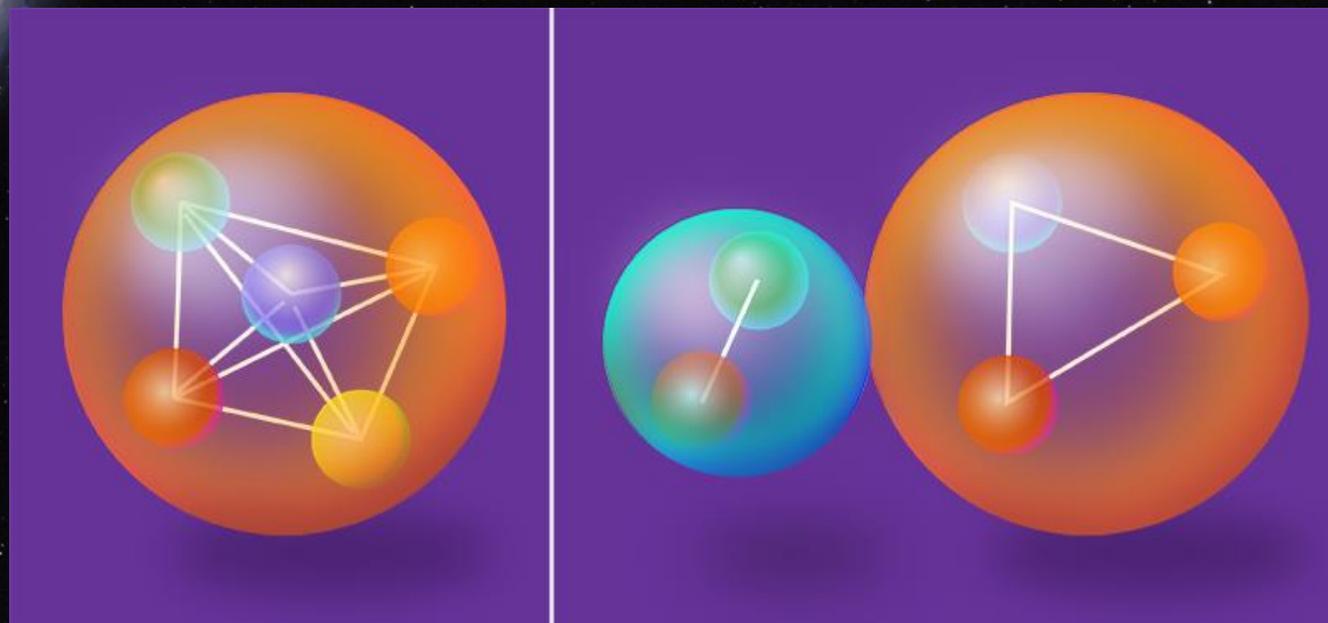


$qq\bar{q}\bar{q}$



$qqqq\bar{q}$

五夸克态的发现



五夸克态的发现

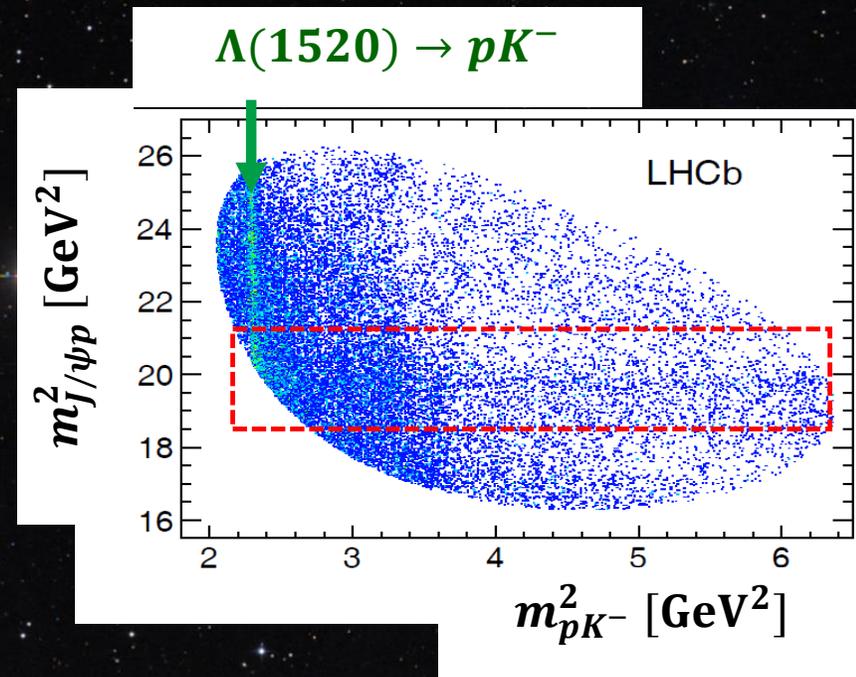
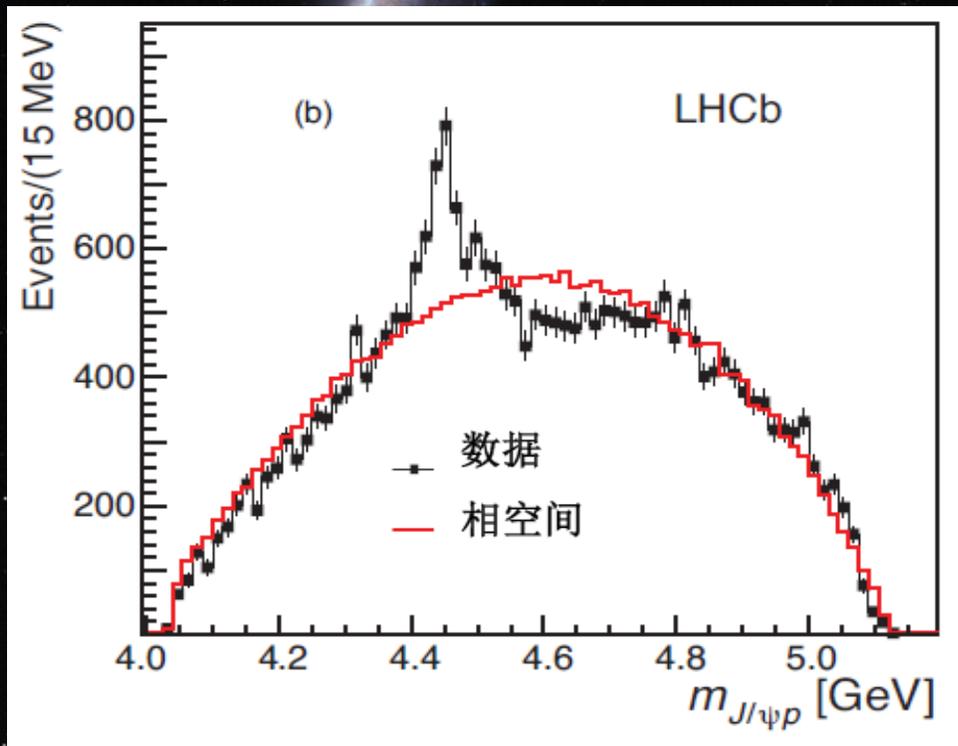
- 1964 年 **Gell-Mann** 提出夸克模型时预言了 “五夸克态” 存在的可能
- 50 多年来，实验上一直没有确切的证据
- **LHCb** 发现五夸克态是个意外
 - 我们没有寻找五夸克态
 - 是五夸克态自己进入到我们的视野。。。

意料之外的质量谱结构

➤ 一幅让粒子物理与核物理学家兴奋的图

• **五夸克态** 衰变成 J/ψ 介子和 质子?

$$P_c^+ \rightarrow J/\psi + p$$



谱分析发现五夸克态

➤ 拟合发现存在两个 P_c^+ 共振态

- $P_c(4450)^+$: 12σ
- $P_c(4380)^+$: 9σ

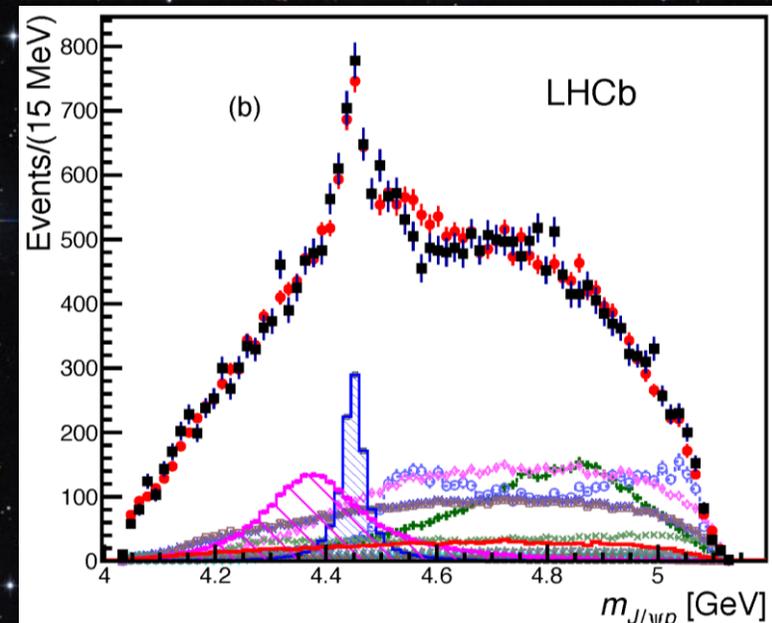
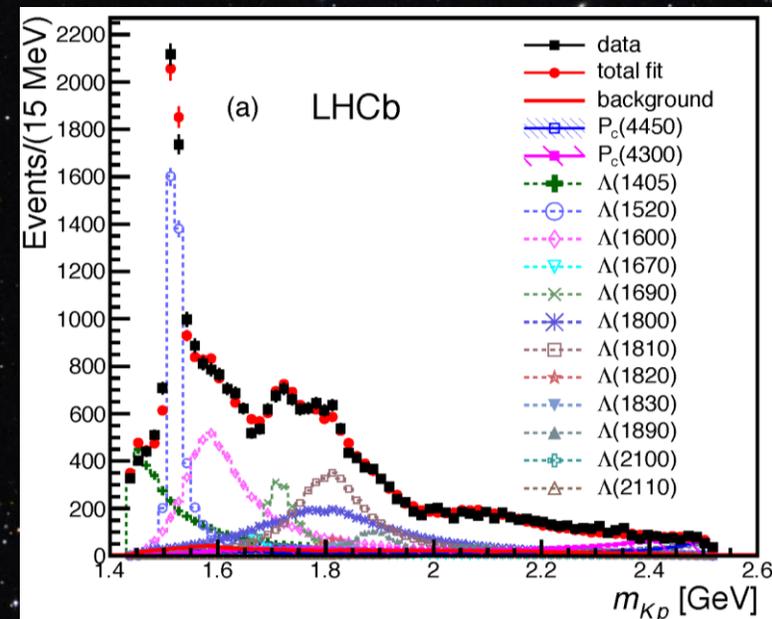
➤ 最佳拟合结果给出 $J^P = (3/2^-, 5/2^+)$

- $J^P = (3/2^+, 5/2^-)$ & $(5/2^+, 3/2^-)$ 的可能未被排除

共振态	质量 (MeV)	宽度 (MeV)	百分比 (%)
$P_c(4380)^+$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	$8.4 \pm 0.7 \pm 4.2$
$P_c(4450)^+$	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$	$4.1 \pm 0.5 \pm 1.1$

$$\mathcal{B}(\Lambda_b^0 \rightarrow P_c(4380)^+ K^-) \mathcal{B}(P_c^+ \rightarrow J/\psi p) = (2.66 \pm 0.22 \pm 1.33_{-0.38}^{+0.48}) \times 10^{-5}$$

$$\mathcal{B}(\Lambda_b^0 \rightarrow P_c(4450)^+ K^-) \mathcal{B}(P_c^+ \rightarrow J/\psi p) = (1.30 \pm 0.16 \pm 0.35_{-0.18}^{+0.23}) \times 10^{-5}$$



➤ 2015年7月14日提交到预印本arXiv.org
和 **Phys. Rev. Lett.**

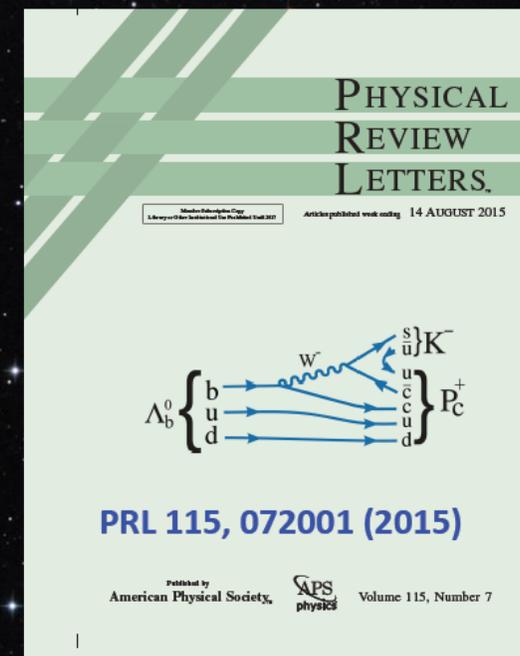
➤ 2015年8月14日发表，并得到封面推荐和
专论报道

➤ “**Breakthroughs of the Year**” in 2015
by **Physics World (IOP)**

【英国《物理世界》2015年度十大突破】

➤ “**Highlights of the Year**” in 2015 by
Physics (APS)

【美国《物理》2015年度八大重要进展】



科学界和媒体的广泛关注

- Inspire-HEP 引用560次 (2018年5月11日)
- 国内外科学媒体 (如Nature) 和大众媒体 (如央视) 的报道

诺贝尔物理奖获得者(2004)
Frank Wilczek (MIT教授)
在当日的评论:

“It’s about the most exciting discovery in QCD I could imagine,” says Frank Wilczek, of the Massachusetts Institute of Technology, and himself an architect of QCD. “To me the deep message is that ‘diquarks’ [hypothetical quark pairs] are a useful organizing principle within hadrons,” he says, adding that the scene is now set for rapid progress: “It’s like a phoenix rising from the ashes.”



【Nature 523, 267–268】

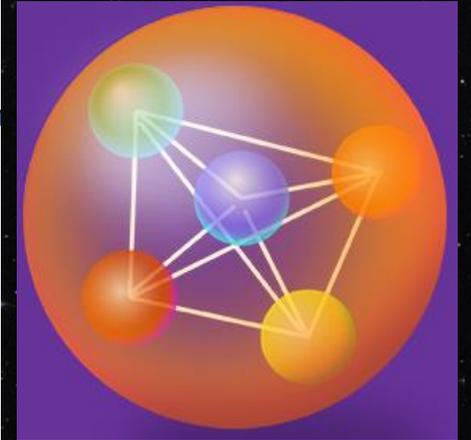
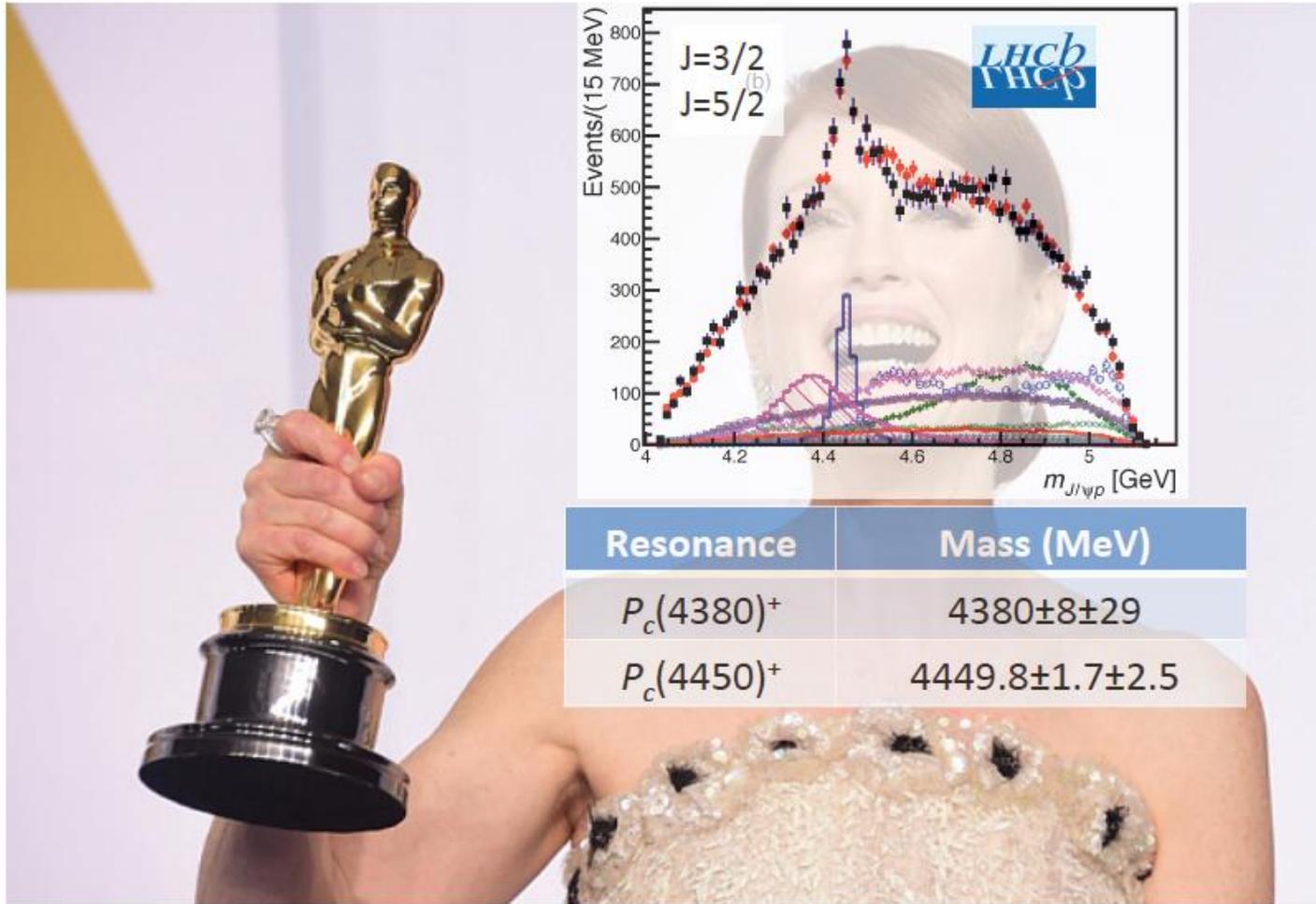


Summary talk of Hadron 2015 by Prof. Stephan Paul

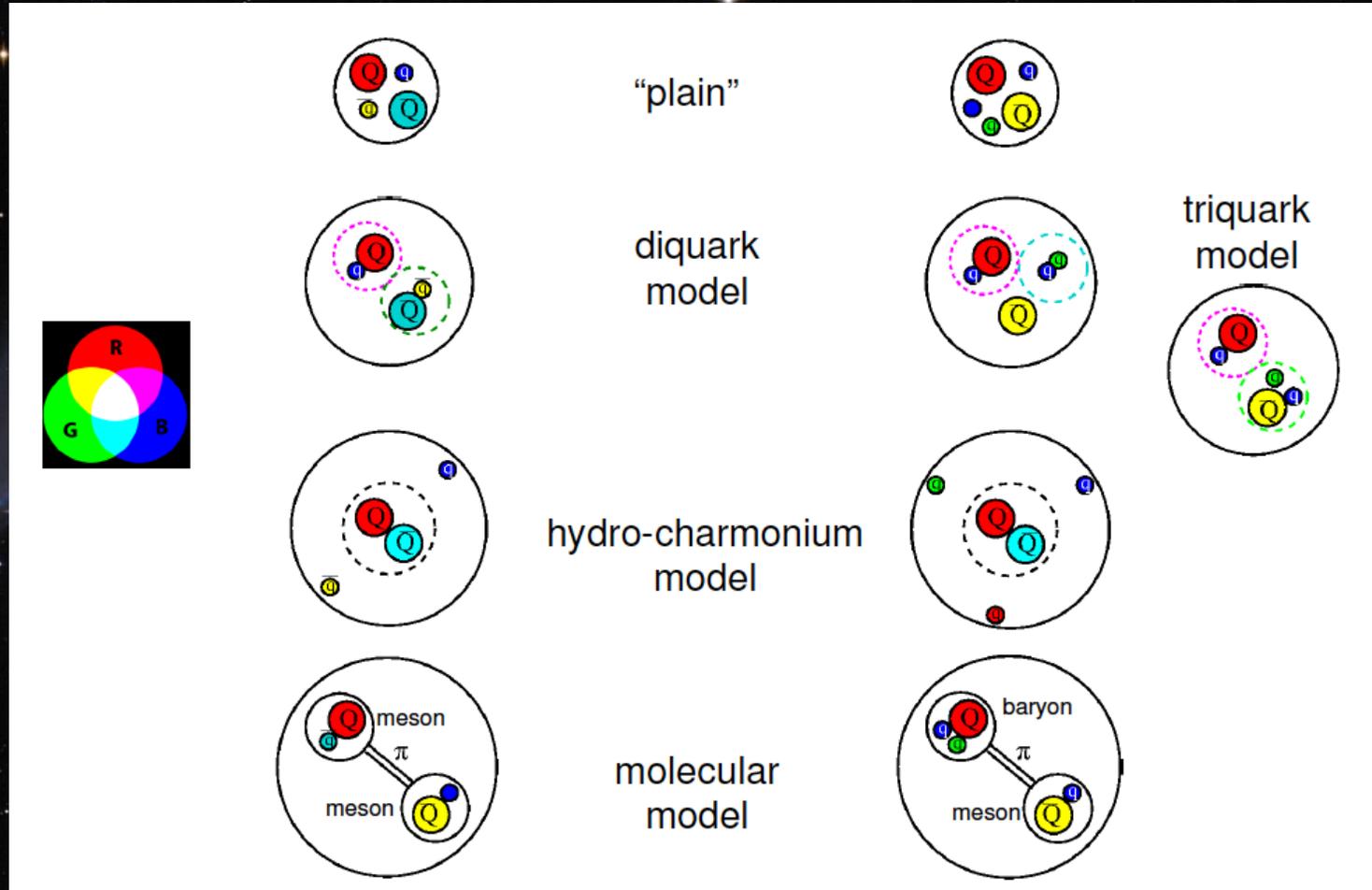


and the winner is....XYZP

Exzellenzcluster Universe



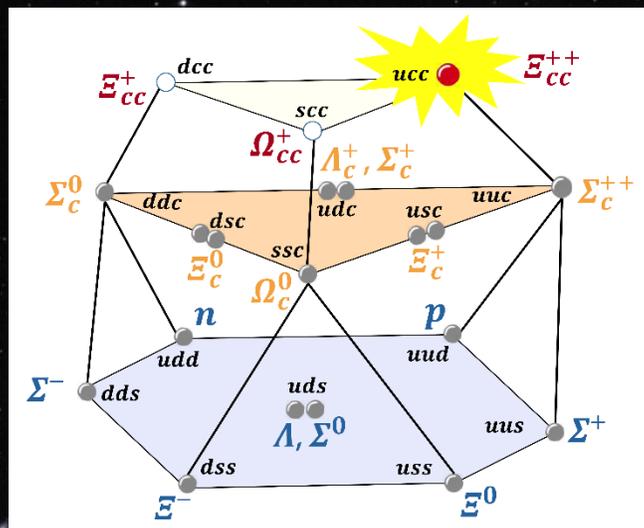
奇特粒子的内部结构?



需要理论与实验的密切配合，才能最终理解其内部结构。

双粲重子 Ξ_{cc}^{++} 的发现

..... 始于 2010



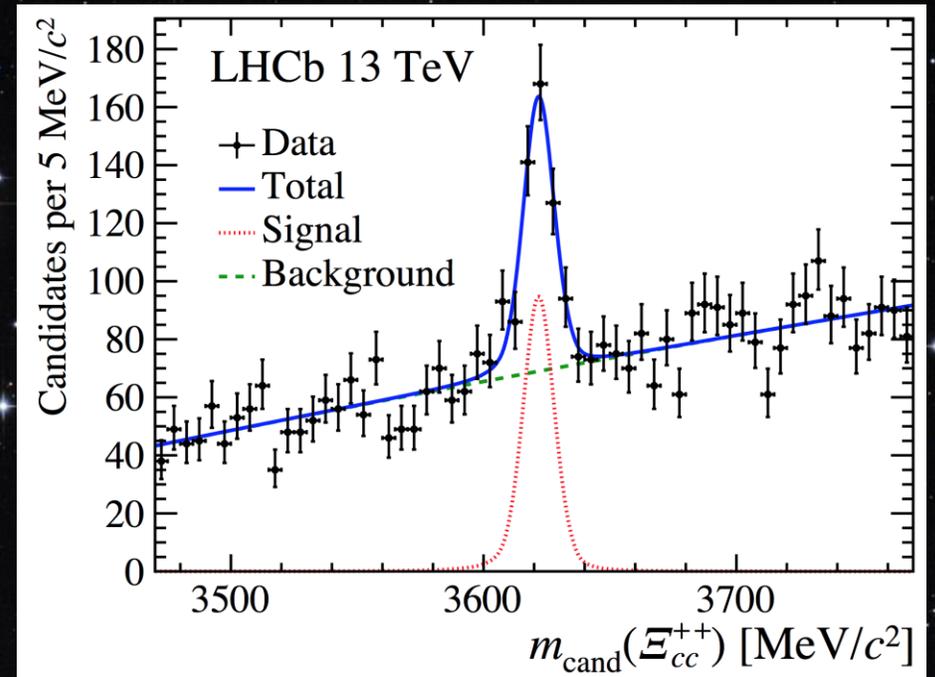
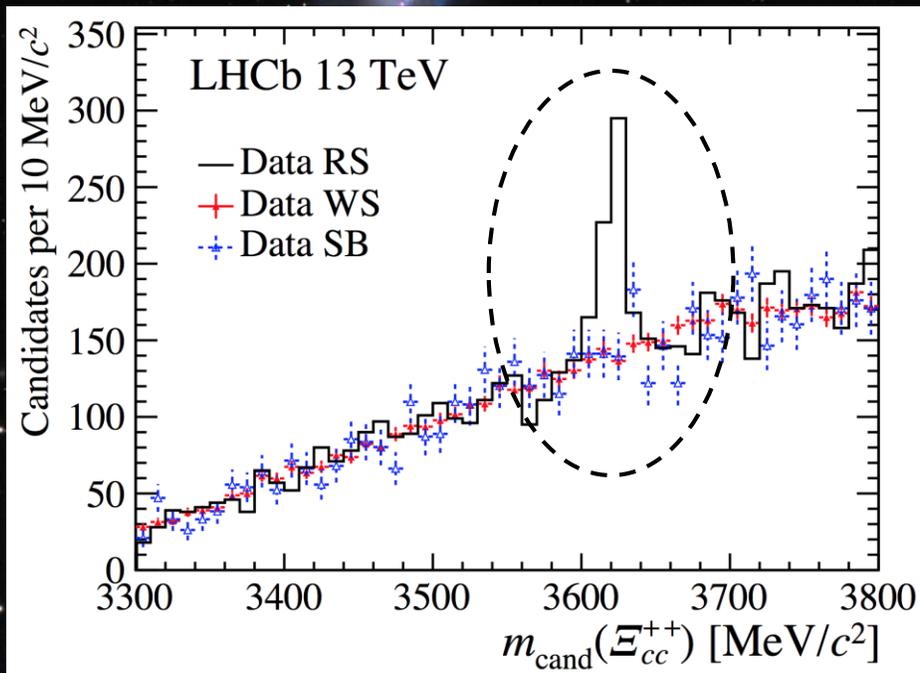
始于2010，成于2016年

- 盲分析：尽量确保排除人为干扰
- 人工神经网络：事例筛选最优化

在 $m \simeq 3620 \text{ MeV}/c^2$ 处发现显著信号峰

$$N_{\text{sig}} = 313 \pm 33$$
$$m = 3621.80 \pm 0.72 \text{ MeV}/c^2$$
$$\sigma = 6.63 \pm 0.82 \text{ MeV}/c^2$$

信号显著度超过 12σ



Highlighted by PRL editors as "Editors' suggestion"

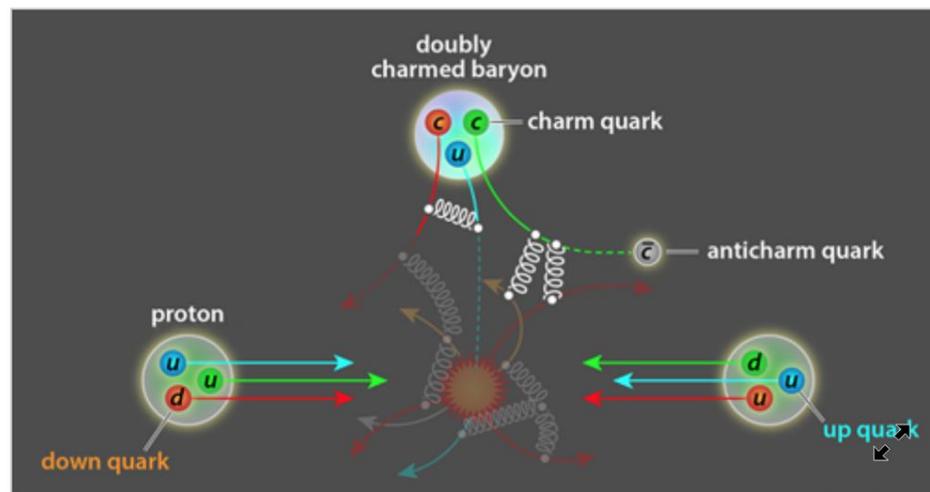
Viewpoint: A Doubly Charming Particle

Raúl A. Briceño, Department of Physics, Old Dominion University, Norfolk, VA 23529, USA and Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA

“倍加迷人的粒子”

September 11, 2017 • *Physics* 10, 100

High-precision experiments at CERN find a new baryon containing two charm quarks.



APS/Alan Stonebraker

Figure 1: The LHCb Collaboration has provided evidence for a doubly charmed baryon called Ξ_{cc}^{++} [1]. The baryon is formed when two charm quarks, produced in high-energy proton-proton collisions, join a light quark.

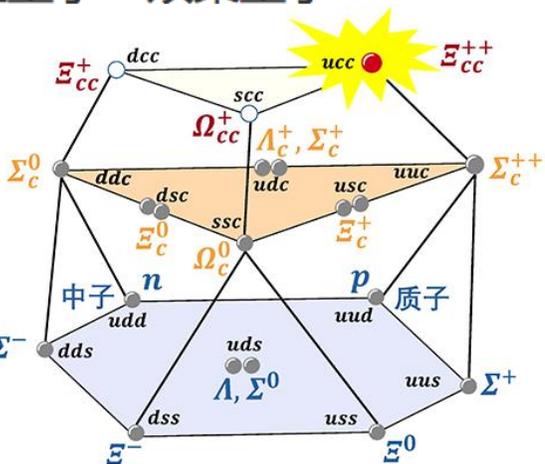
国内外媒体报道

我国科学家牵头首次发现新型重子 “双粲重子”

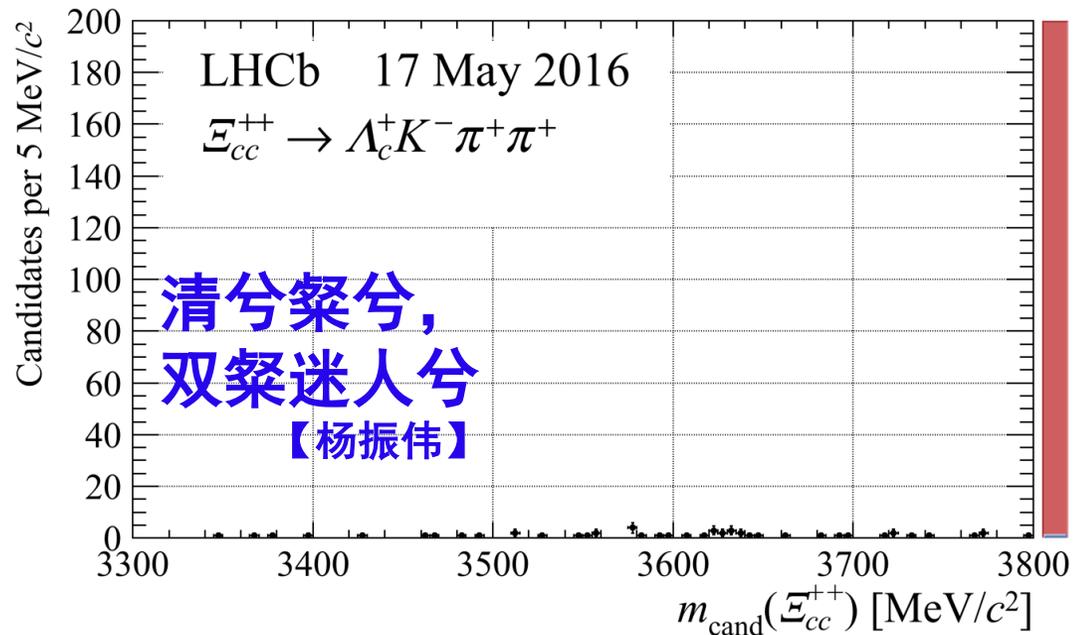
科技频道 来源：科技日报 2017年07月07日 09:22

原标题：我国科学家牵头发现新型重子

科技日报北京7月6日电（记者操秀英）北京撞机（LHC）上的实验组宣布首次发现双粲重子 Σ_c^{++} 研究论文提交至《物理评论快报》。



LHCb中国组负责人，清华大学高原宁教授介绍道，按照夸克模型分类，重子由三个夸克组成，熟知的质子和中子是最常见的重子。自然界中存在六种不同夸克：u, d, s, c, b, t。前三种较轻，后三种较重。理论预期存在很多种具有不同组分的重子。此前发现的重子最多含有一个重夸克，但此次发现的重子含有两个重夸克。这次发现的重子含有两个c夸克（粲夸克）和一个u夸克（上夸克），带两个单位电荷。



SCIENCE

Demystifying Science: What is Xicc++ ?

JULY 09, 2017 04:02 IST
UPDATED: JULY 09, 2017 00:42 IST

SHARE ARTICLE PRINT | A | A | A

...w kind of quark, or a subatomic particle, that is a

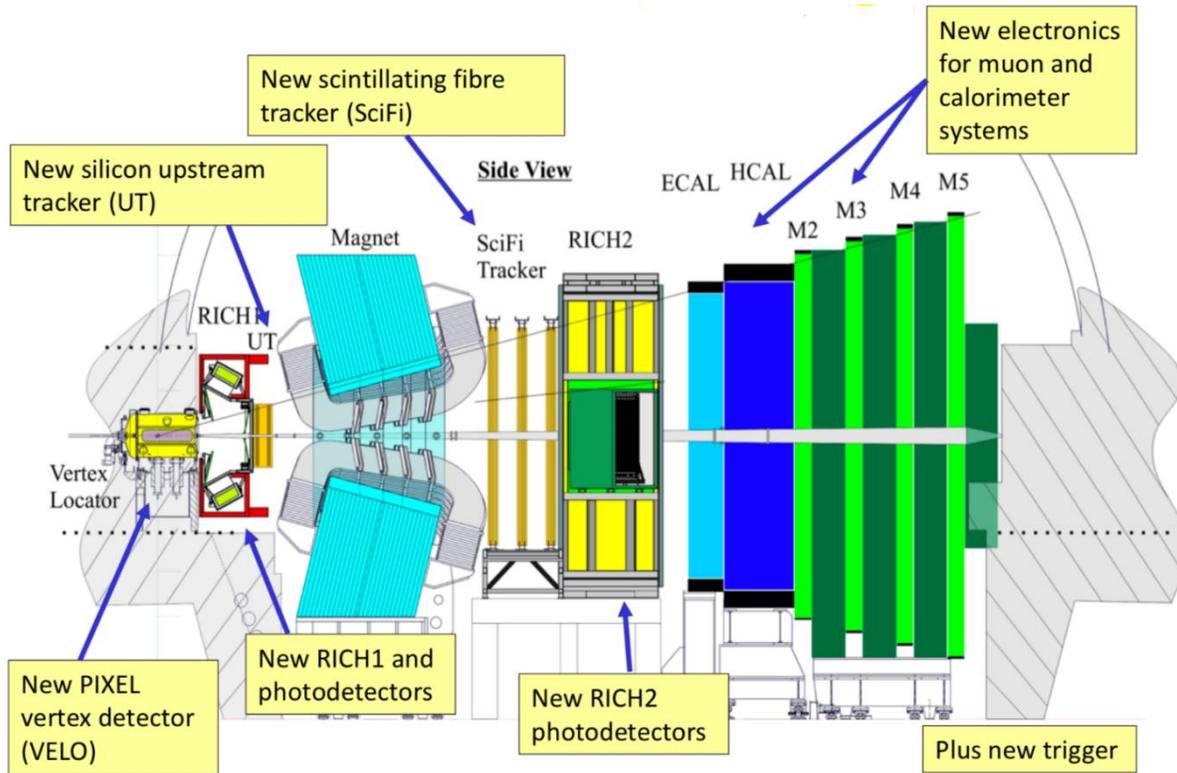
2017年度中国科学十大进展

Prospects



LHCb Upgrade (2019-2020)

[[LHCB-TDR-017](#)]



CERN-LHCC-2012-007

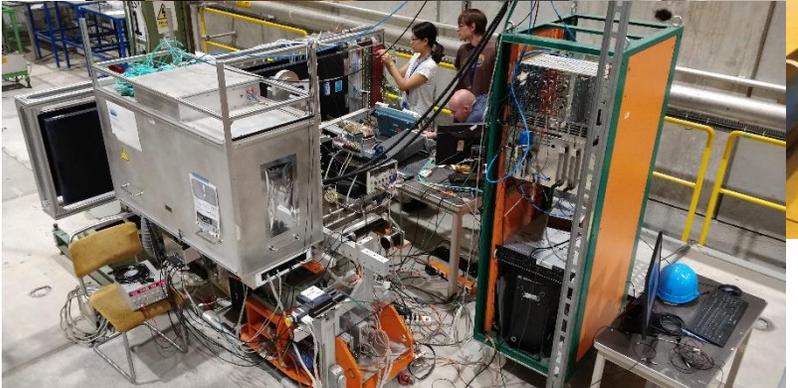
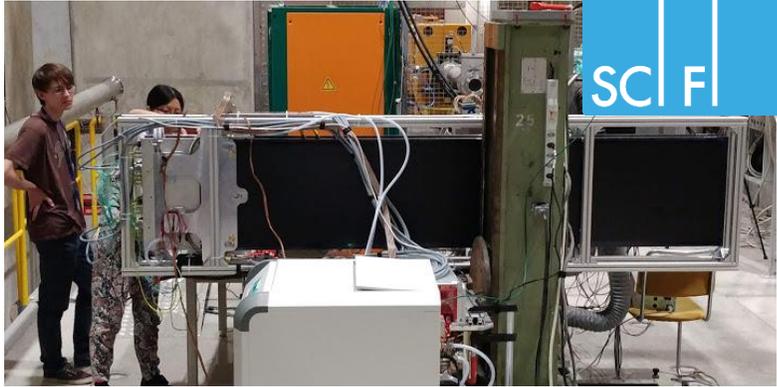
- **Increase luminosity to $2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$**
 - 5 times larger than current maximum instantaneous luminosity
- **All sub-detectors read out at 40 MHz for a full software trigger**
 - Record with 10 GB/s
- **All subdetector apart from muon and calorimeter systems will be fully replaced**

Scintillating Fibre (SciFi) tracker installation

SCI FI



Scintillating Fibre (SciFi) tracker installation

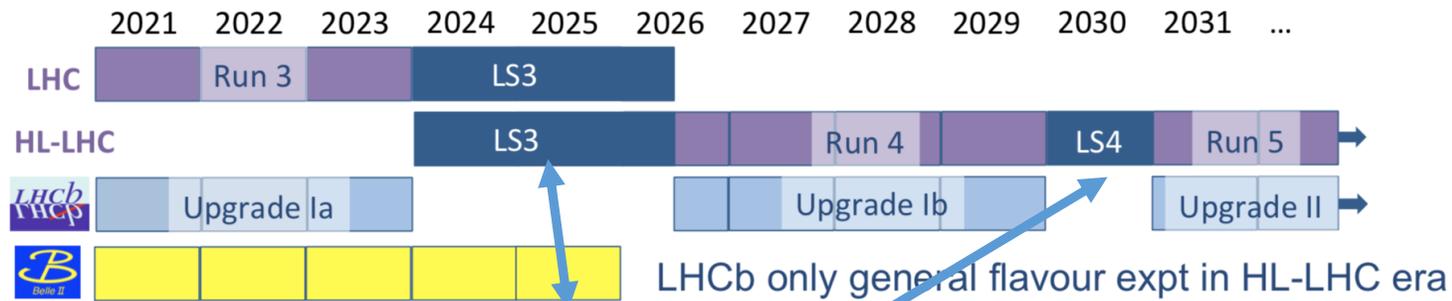


2019/05/30

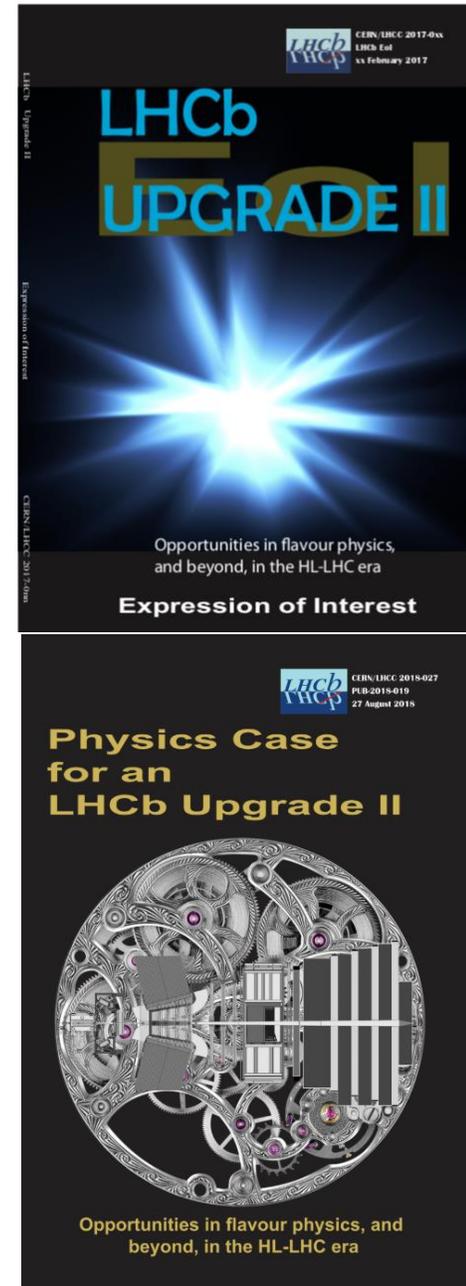
Zhenwei Yang, Center for High Energy Physics, Tsinghua

LHCb Upgrade 2

- Upgrade 2 proposed to take full profit of HL-LHC
 - $\mathcal{L} = 1 - 2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, 10 times larger than Upgrade 1
 - Aiming at 300 fb^{-1} after Run5



- Consolidate in **LS3**
- Major upgrade in **LS4**
- EOI submitted in 2017 (CERN-LHCC-2017-003)
- Physics document submitted in 2018 (arXiv:1808.08865)

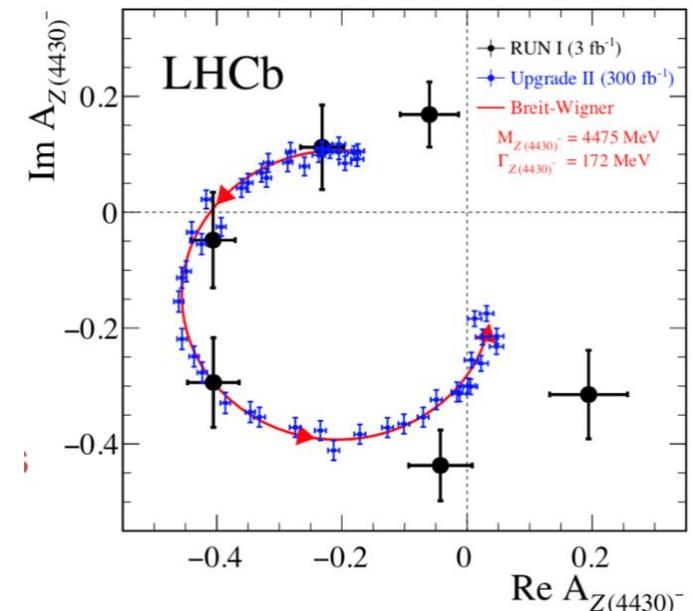


Physics case: hadron spectroscopy

arXiv:1808.08865

- Much more b - and c -hadrons would be produced with the Upgrade
- A gold mine of hadron spectroscopy studies
 - Observation of new states
 - Precision determination of the characteristics of observed hadrons
 - Understand the nature of these states and strong interactions

Decay mode	LHCb			Belle II
	23 fb ⁻¹	50 fb ⁻¹	300 fb ⁻¹	50 ab ⁻¹
$B^+ \rightarrow X(3872)(\rightarrow J/\psi \pi^+ \pi^-) K^+$	14k	30k	180k	11k
$B^+ \rightarrow X(3872)(\rightarrow \psi(2S)\gamma) K^+$	500	1k	7k	4k
$B^0 \rightarrow \psi(2S) K^- \pi^+$	340k	700k	4M	140k
$B_c^+ \rightarrow D_s^+ D^0 \bar{D}^0$	10	20	100	—
$\Lambda_b^0 \rightarrow J/\psi p K^-$	340k	700k	4M	—
$\Xi_b^- \rightarrow J/\psi \Lambda K^-$	4k	10k	55k	—
$\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$	7k	15k	90k	<6k
$\Xi_{bc}^+ \rightarrow J/\psi \Xi_c^+$	50	100	600	—



Physics cases: RD and CPV

± 10.0	± 2.6	± 90	LHCb Current	$\pm 33.0 \times 10^{-4}$	± 5.4	± 49	$\pm 28.0 \times 10^{-5}$	LHCb Current
± 3.6 ± 2.2	± 0.50 ± 0.72	± 34	Belle II ATLAS/CMS LHCb 2025	$\pm 10.0 \times 10^{-4}$	± 1.5 ± 1.5	± 14	$\pm 35.0 \times 10^{-5}$ $\pm 4.3 \times 10^{-5}$	Belle II ATLAS/CMS LHCb 2025
± 0.70 R_K [%]	± 0.20 $R(D^*)$ [%]	± 21 ± 10 $\frac{B(B^0 \rightarrow \mu^+ \mu^-)}{B(B_s^0 \rightarrow \mu^+ \mu^-)}$ [%]	HL-LHC	$\pm 3.0 \times 10^{-4}$ a_{SI}^S	± 0.35 γ [°]	± 22 ± 4 ϕ_S [mrad]	$\pm 1.0 \times 10^{-5}$ A_Γ	HL-LHC



总结

➤ 《粒子物理的实验根基》, Robert Cahn and Gerson Goldhaber

neutral atom has, as well, Z electrons, each with a mass only $1/1836$ that of a proton. The chemical properties of the atom are determined by Z ; atoms with equal Z but differing A have the same chemistry and are known as isotopes.

This school-level description did not exist at all in 1895. Atoms were the creation of chemists and were still distrusted by many physicists. Electrons, protons, and neutrons were yet to be discovered. Atomic spectra were well studied, but presented a bewildering catalog of lines connected, at best, by empirical rules like the Balmer formula for the hydrogen atom. Cathode rays had been studied, but many regarded them as uncharged, electromagnetic waves. Chemists had determined the atomic weights of the known elements and Mendeleev had produced the periodic table, but the concept of atomic number had not yet been developed.

THE EXPERIMENTAL
FOUNDATIONS OF
PARTICLE PHYSICS

Second Edition

ROBERT N. CAHN
Lawrence Berkeley National Laboratory

GERSON GOLDHABER
*Lawrence Berkeley National Laboratory and
University of California at Berkeley*

➤ 我们可能正在接近与1895或1964年类似的年代

**“Measure what is measurable,
and make measurable what is not so.” ——Galileo**
“可测者，测之；不可测者，使之可测。”



问题

➤ 如何探测肉眼不可见的粒子？

➤ 如何判断探测到的粒子是电子还是其他类型的粒子？



谢谢!