强相互作用和强子

I. 夸克模型

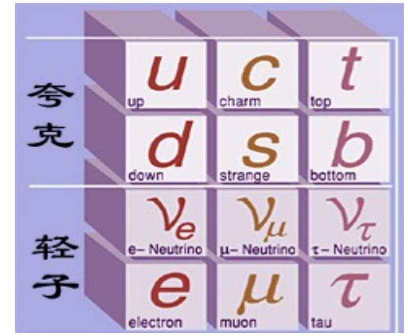
II. 强子和QCD

III. QCD和部分子

提纲

- 强子谱与量子色动力学
- LHCb实验上的强子谱研究
- 双粲重子
- 五夸克态
- 总结

夸克的味与色



- **味 (flavor) 区分不同种类的夸克**

	夸克	质量*（GeV/c^2)
轻味夸克	d	~0.005
	u	~0.002
	s	~0.093
重味夸克	c	~1.3
	b	~4.2
	t	~173

Just as ice cream has both color and flavour, so do quarks

- **色 (color) 强作用力的“荷”**

每个夸克有三种颜色，质量简并

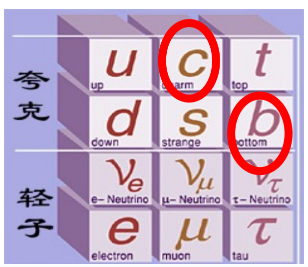
The u-, d-, and s-quark masses are estimates of so-called “current-quark masses,” in a mass-independent subtraction scheme such as $\overline{\rm MS}$ at a scale $\mu \approx 2$ GeV. The c- and b-quark masses are the “running” masses in the $\overline{\rm MS}$ scheme. This can be different from the heavy quark masses obtained in potential models.

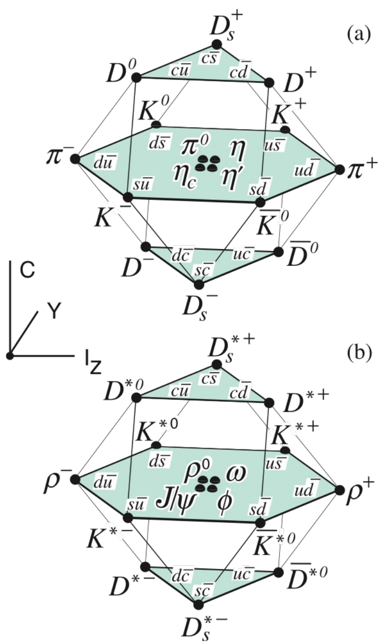
夸克模型

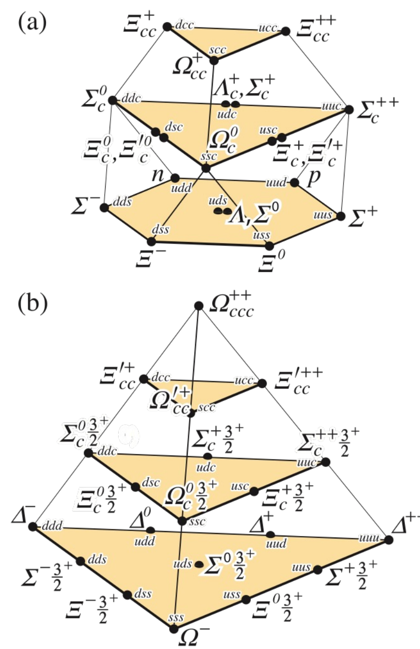
- **1964年夸克模型**

  介子： $q\bar{q}$　　　**重子：** qqq

- **逐渐扩展** $SU(3)_{uds} \rightarrow \begin{matrix} SU(4)_{udsc} \\ SU(4)_{udsb} \end{matrix} \rightarrow SU(5)_{udscb}$







量子色动力学

- 色自由度的实验证据

【1】 $e^+ + e^- \to \text{hadrons}$ 过程可以看成是

$$e^+ + e^- \to q + \bar{q} \qquad q, \bar{q} \to \text{hadrons}$$

定义：

$$R \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

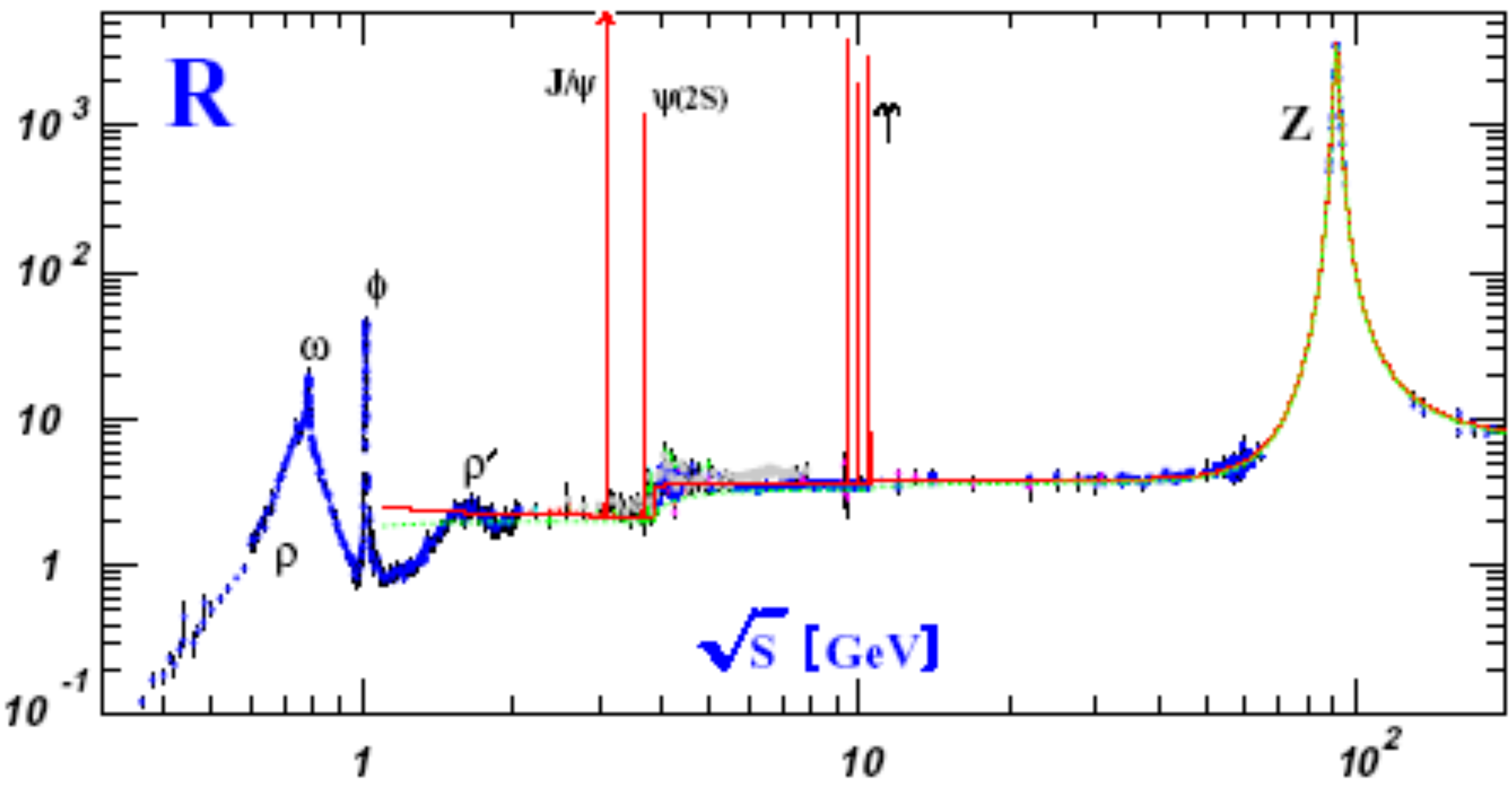
则在最低阶有：

$$R = N_C \sum_q e_q^2, \quad q = \text{u,d,s}, \cdots$$

因此：

$$\sqrt{s} < 3\ \text{GeV}, \quad R = N_C[(\frac{2}{3})^2 + (-\frac{1}{3})^2 + (-\frac{1}{3})^2] = N_C\,\frac{2}{3}$$

$$\sqrt{s} > 10\ \text{GeV}, \quad R = N_C[(\frac{2}{3})^2 + (-\frac{1}{3})^2 + (-\frac{1}{3})^2 + (\frac{2}{3})^2 + (-\frac{1}{3})^2] = N_C\,\frac{11}{9}$$



实验结果支持 $N_C = 3$！

【2】$\pi^0 \to 2\gamma$ 过程的分宽度

$$\Gamma_{\pi^0\to 2\gamma} = \frac{m_\pi^3}{64\pi}\left(\frac{2\alpha}{\pi f_\pi} N_C s\right)^2$$

$$s = (I_3)_u e_u^2 + (I_3)_d e_d^2 = \frac{1}{6}$$

实验值

$$\Gamma_{\pi^0\to 2\gamma} = (7.95 \pm 0.55)\ \ \mathrm{eV}$$

$$\Rightarrow N_C = 3.06 \pm 0.10$$

- $SU(3)$定域规范变换和QCD

自由夸克的拉氏量

$$L_0 = \bar{q}(i\gamma^\mu \partial_\mu - m)q, \qquad q = \begin{bmatrix} q_R \\ q_G \\ q_B \end{bmatrix}$$

仿照QED的情形，希望得到在定域变换

$$q(x) \to q'(x) = e^{i\alpha_a(x) I_a} q(x), \quad a = 1, \cdots, 8$$

下不变的拉氏量。引入协变导数

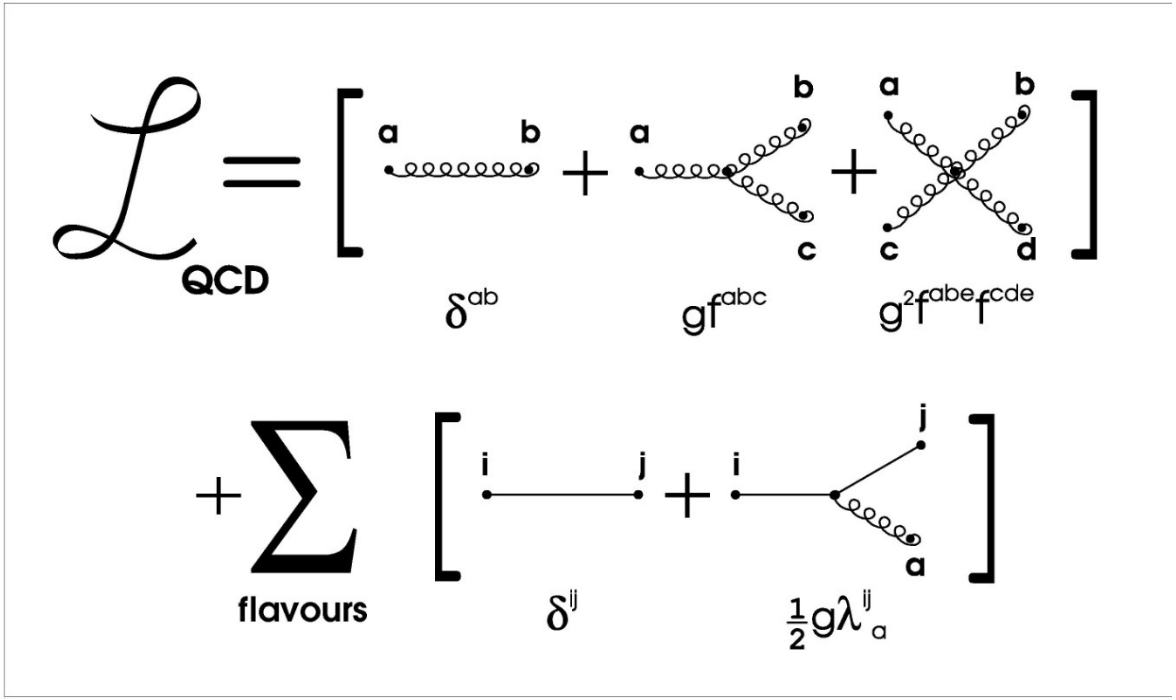
$$D_\mu \equiv \partial_\mu + igI_a G_{a\mu}$$

$$G_{a\mu} \to G_{a\mu} - \frac{1}{g}\partial_\mu \alpha_a(x) - f_{abc}\alpha_b G_{c\mu}$$

加入动能项，最后得到

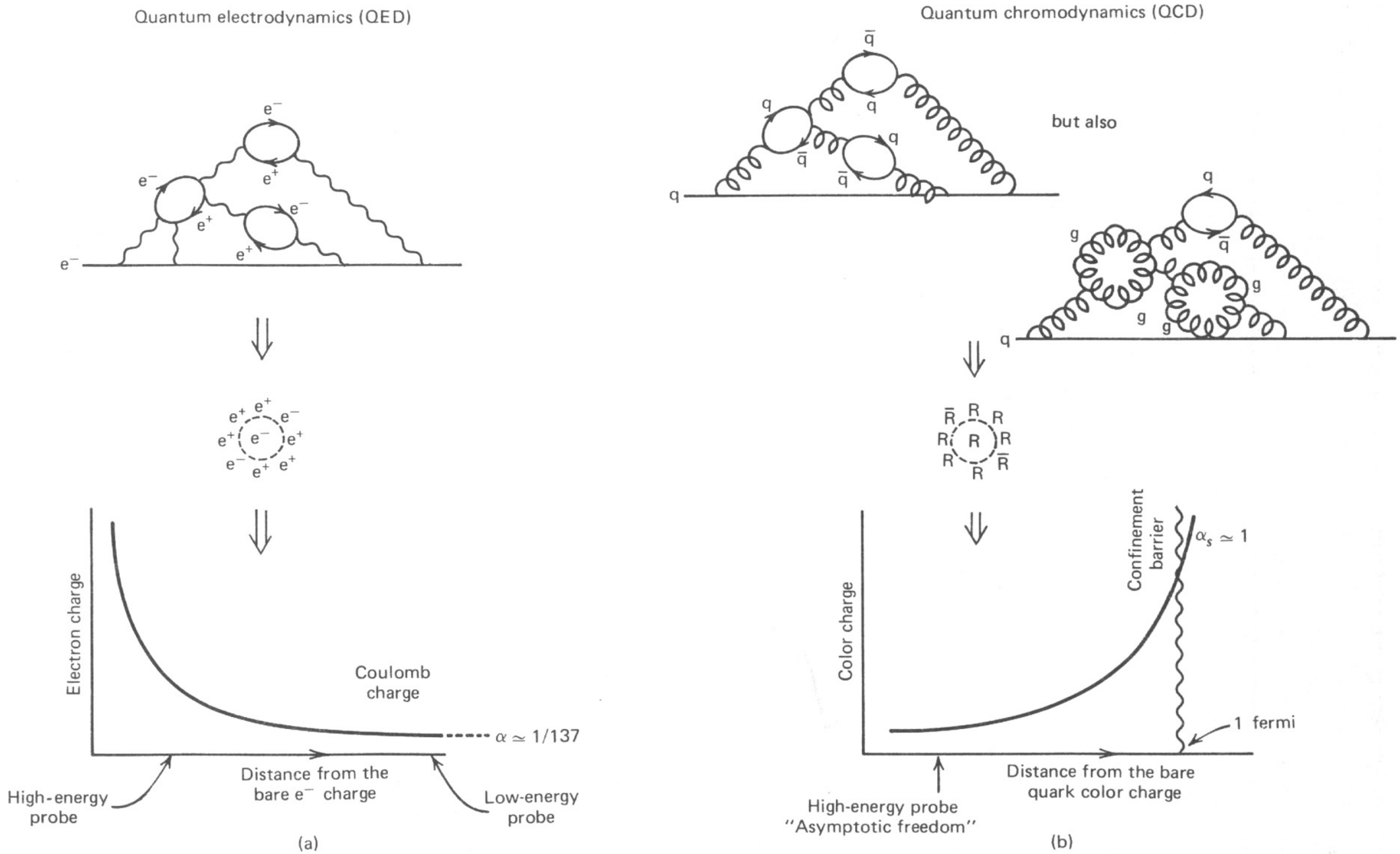
$$
\begin{aligned}
\mathcal{L}_{QCD} &= \bar{q}(i\gamma^{\mu}\partial_{\mu} - m)q \\
&\quad - g\bar{q}\gamma^{\mu}\frac{\lambda_a}{2}qG_{a\mu} - \frac{1}{4}G_{a\mu\nu}G_a^{\mu\nu} \\
G_{a\mu\nu} &= \partial_{\mu}G_{a\nu} - \partial_{\nu}G_{a\mu} + gf_{abc}G_{b\mu}G_{c\nu}
\end{aligned}
$$

用费曼图表示为：



- 跑动耦合常数

与QED不同，QCD具有反屏蔽效应，导致夸克禁闭和渐近自由（quark confinement and asymptotic freedom)

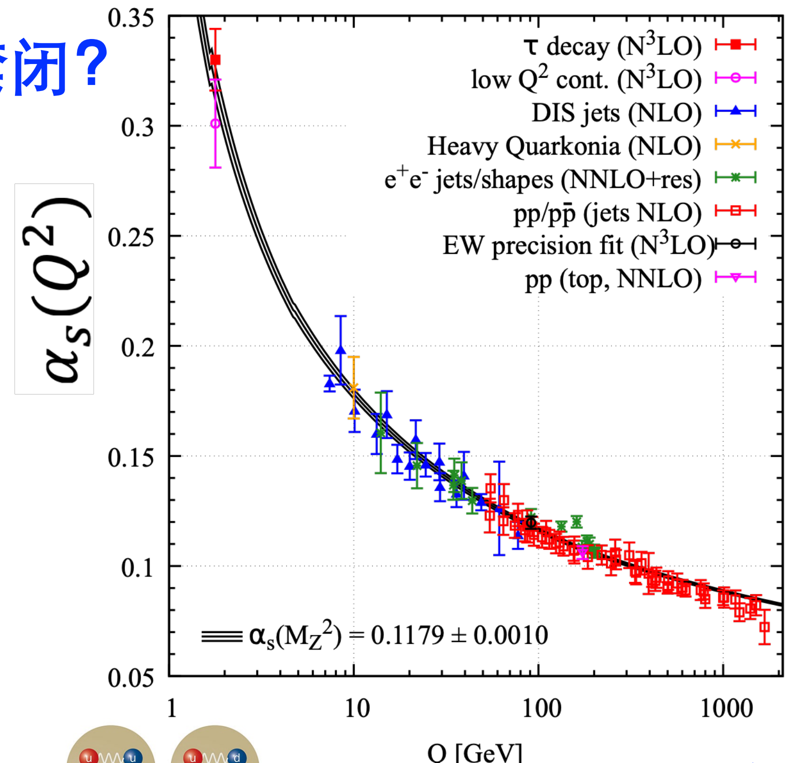


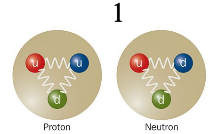
- 夸克模型提供强子分类，QCD描述夸克间强作用力
- $SU(3)_c$规范理论

$$\alpha_s = \frac{g^2}{4\pi}$$

$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1+\frac{7}{4\pi}\alpha_s(\mu^2)\ln\left(\frac{Q^2}{\mu^2}\right)}$$

夸克禁闭?





THE NOBEL PRIZE

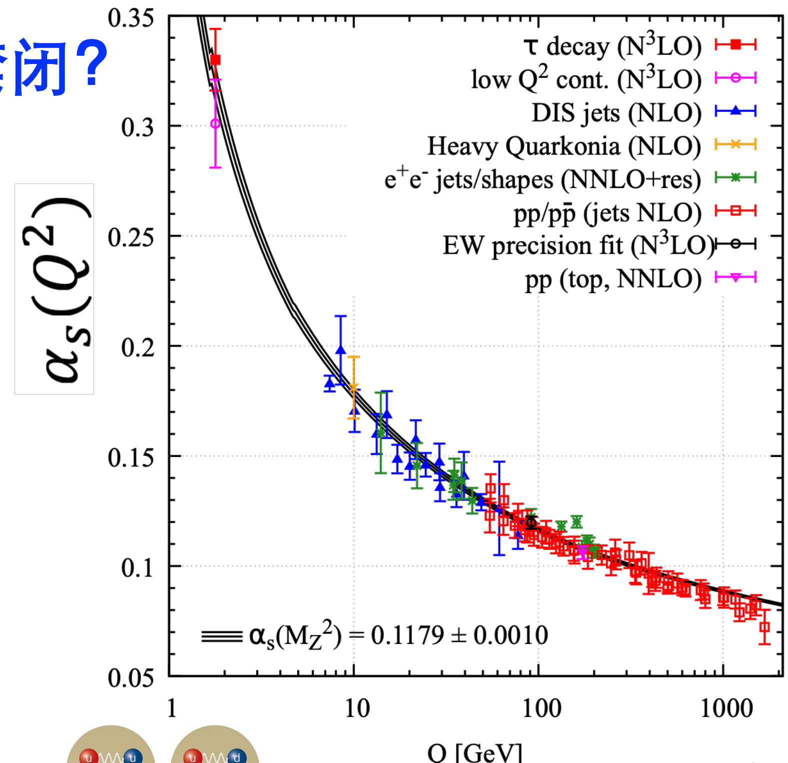
渐近自由

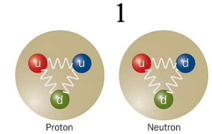
- 夸克模型提供强子分类，QCD描述夸克间强作用力
- $SU(3)_c$规范理论

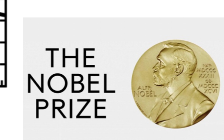
夸克禁闭?

We have something called a standard model, but its foundations are kind of scandalous. We have not known how to define an important part of it mathematically rigorously,...

-- Frank Wilczeck







渐近自由

强子谱和量子色动力学

- **强子谱对理解QCD有重要作用** **(类似光谱)**

方程式 (QCD)

↓

中间过程？？？

↓

标准答案 (实验结果)

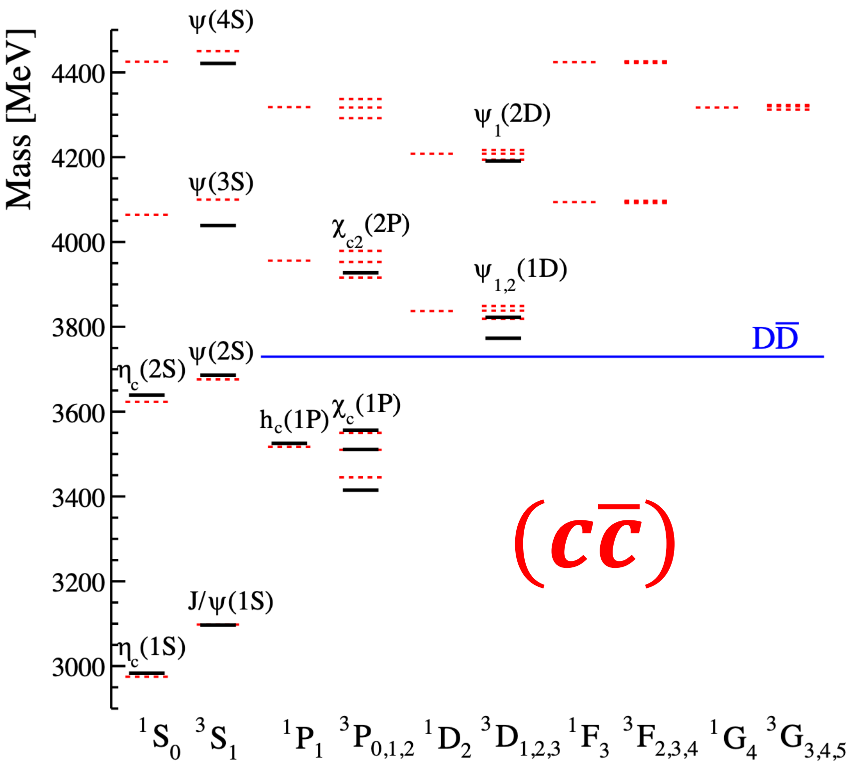
- 理论上研究QCD的解法（非线性、非微扰）
- 实验上提供更多的特例

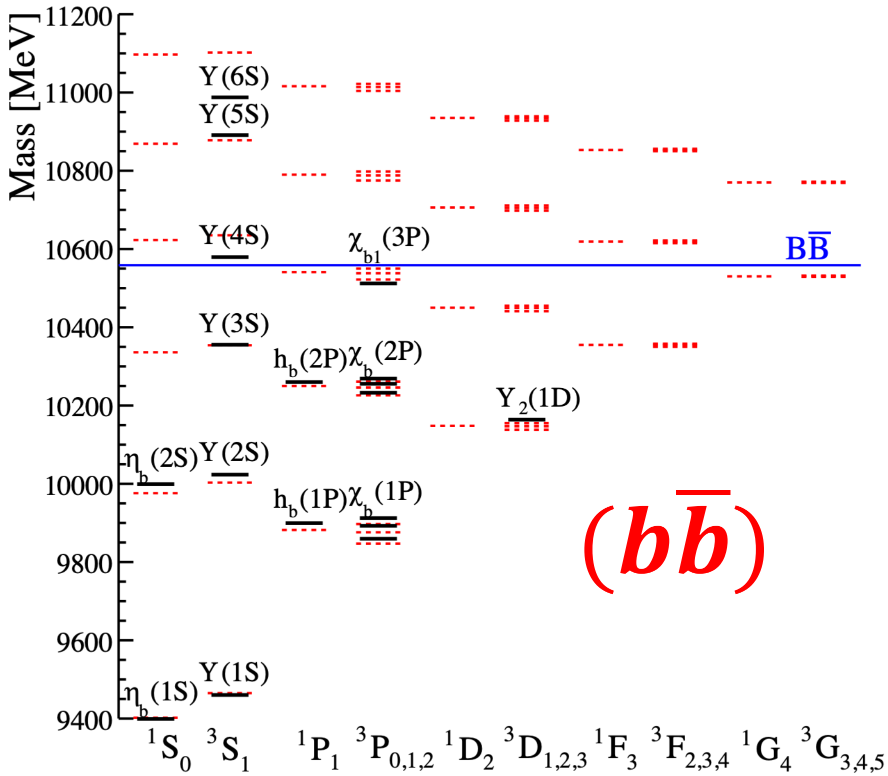
探究上帝如何解方程

重夸克偶素和重味强子

- 势模型+修正可以**系统地**描述重夸克偶素谱

$$V(r) = -\frac{\kappa}{r} + \sigma r$$

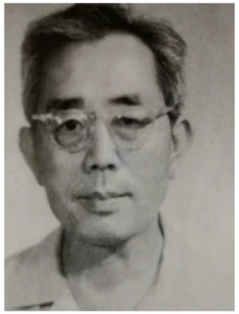


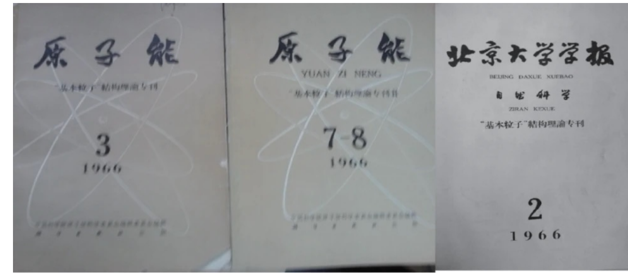


理论发展

- 重味强子的研究带动了理论/模型发展
  - 格点量子色动力学（Lattice QCD）
  - 非相对论量子色动力学（NRQCD）
  - 因子化 （QCD Factorization）
  - 求和规则 （QCD Sum Rule）
  - 重夸克有效理论 （HQEFT）
  - …
- 从层子模型开始，我国在强子谱理论研究上形成了深厚的学术传统；北京正反电子对撞机/北京谱仪的建造运行使我国在强子谱实验研究在国际上占有一席之地；一支高水平的理论和实验研究队伍。

层子模型




原子能
"基本粒子"結构理論专刊
3
1966
原子能
YUAN ZI NENG
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1966
北京大学学报
BEIJING DAXUE XUEBAO
自然科学
ZIRAN KEXUE
"基本粒子"結构理論专刊
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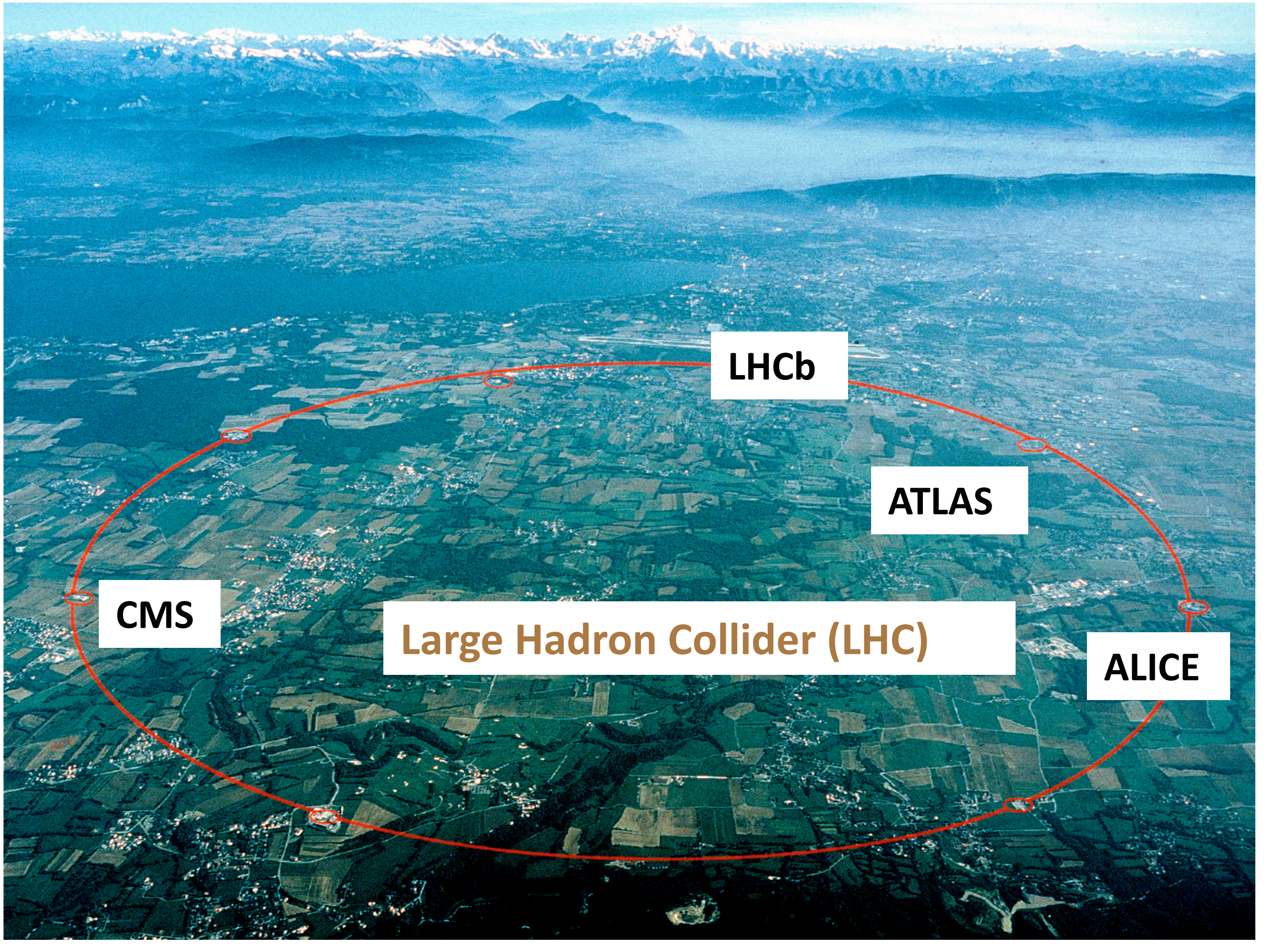
1966

大型强子对撞机



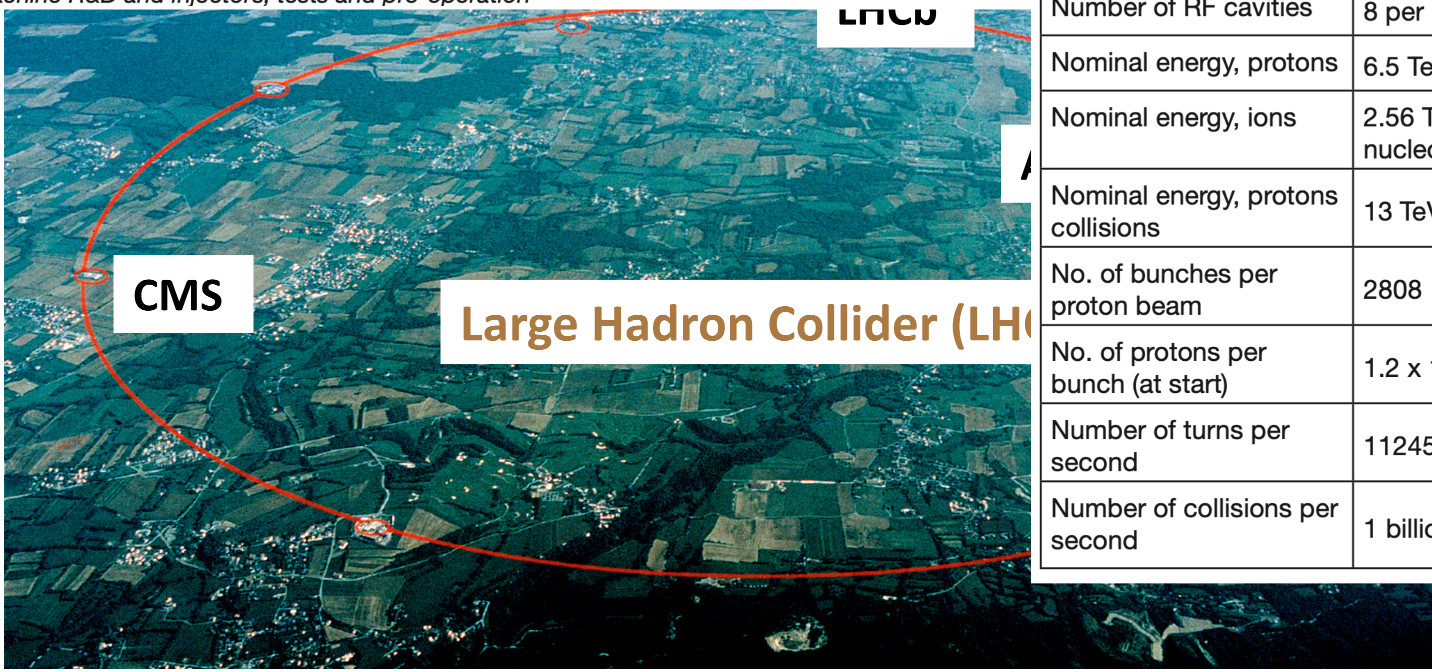
大型强子对撞机

HOW MUCH DOES THE LHC COST?

- **Construction costs (MCHF)**

	Personnel	Materials	Total
LHC machine and areas*	1224	3756	4980
CERN share to detectors	869	493	1362
LHC computing (CERN share)	85	83	168
Total	2178	4332	6510

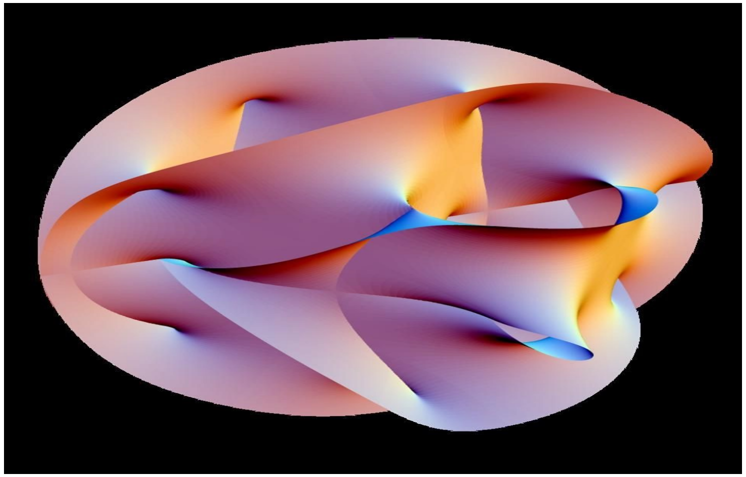
**Includes: Machine R&D and injectors, tests and pre-operation*



Quantity	Number
Circumference	26659 m
Dipole operating temperature	1.9 K (-271.3°C)
Number of magnets	9593
Number of main dipoles	1232
Number of main quadrupoles	392
Number of RF cavities	8 per beam
Nominal energy, protons	6.5 TeV
Nominal energy, ions	2.56 TeV/u (energy per nucleon)
Nominal energy, protons collisions	13 TeV
No. of bunches per proton beam	2808
No. of protons per bunch (at start)	1.2×10^{11}
Number of turns per second	11245
Number of collisions per second	1 billion

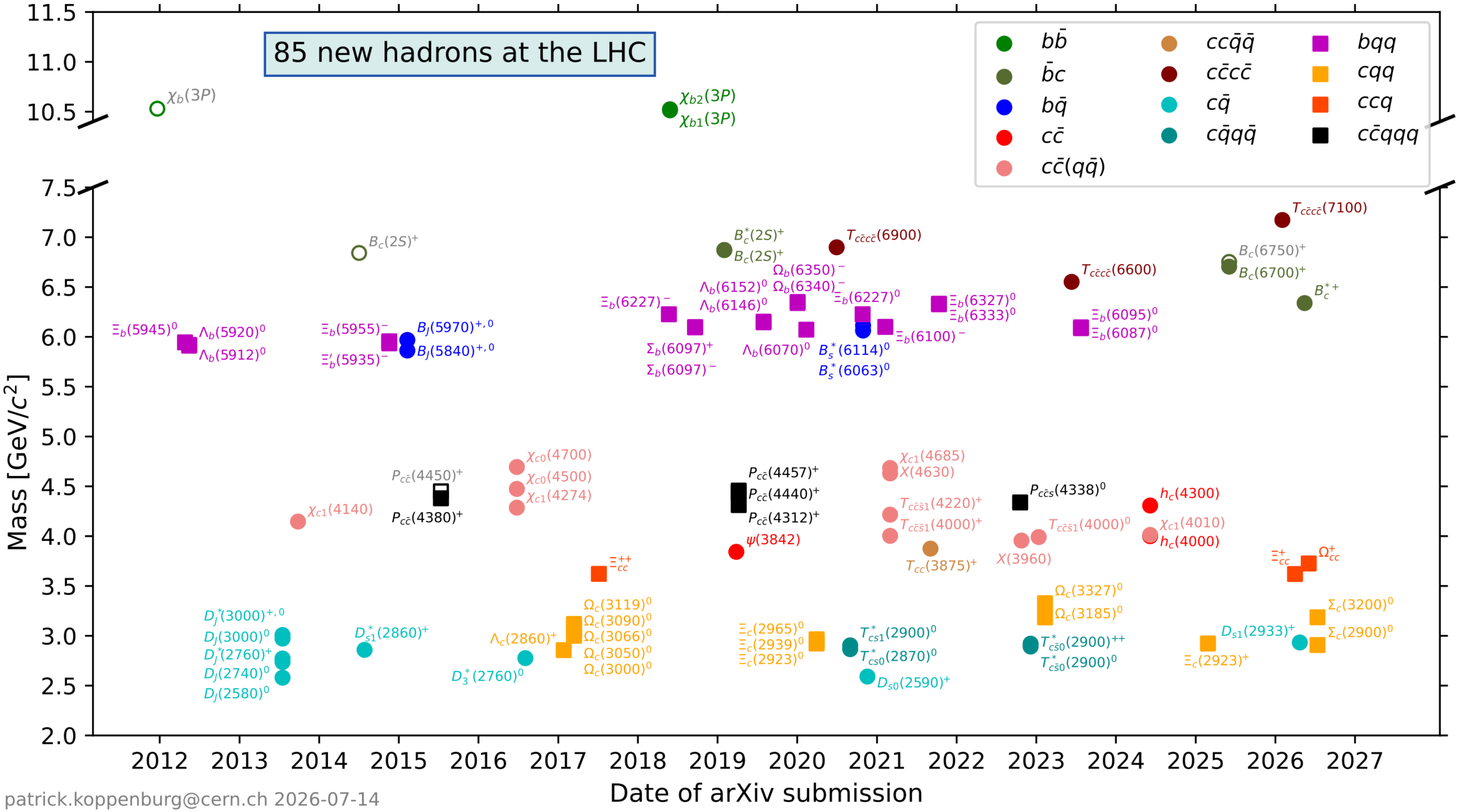
LHC的科学目标

- LHC的目标是大发现:
  - 希格斯物理（质量起源）
  - 正反物质不对称起源
  - 超出标准模型新物理
  - 夸克-胶子等离子体性质
  - …



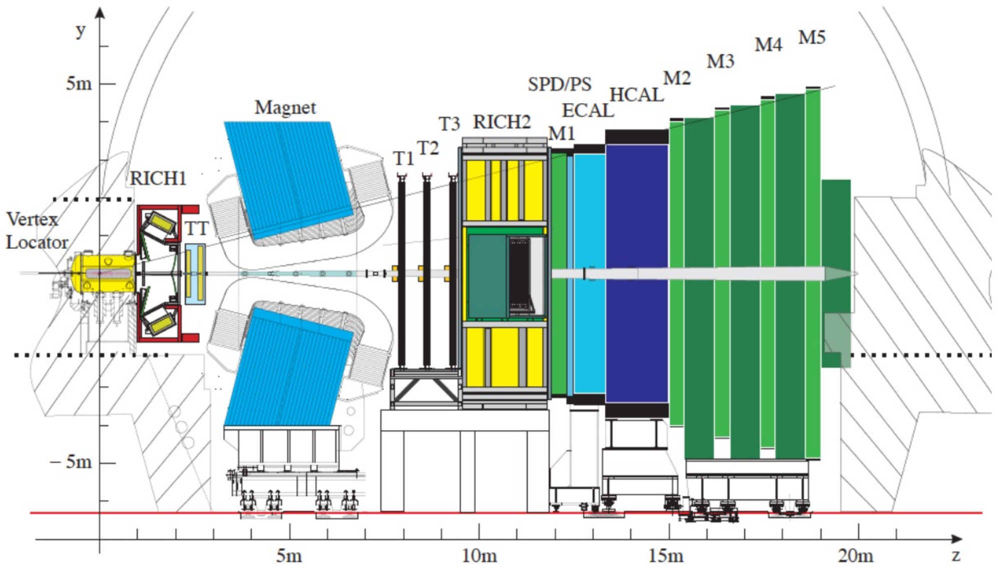
- 近年来，强子谱研究贡献了一系列小惊喜。

发现了85个新强子



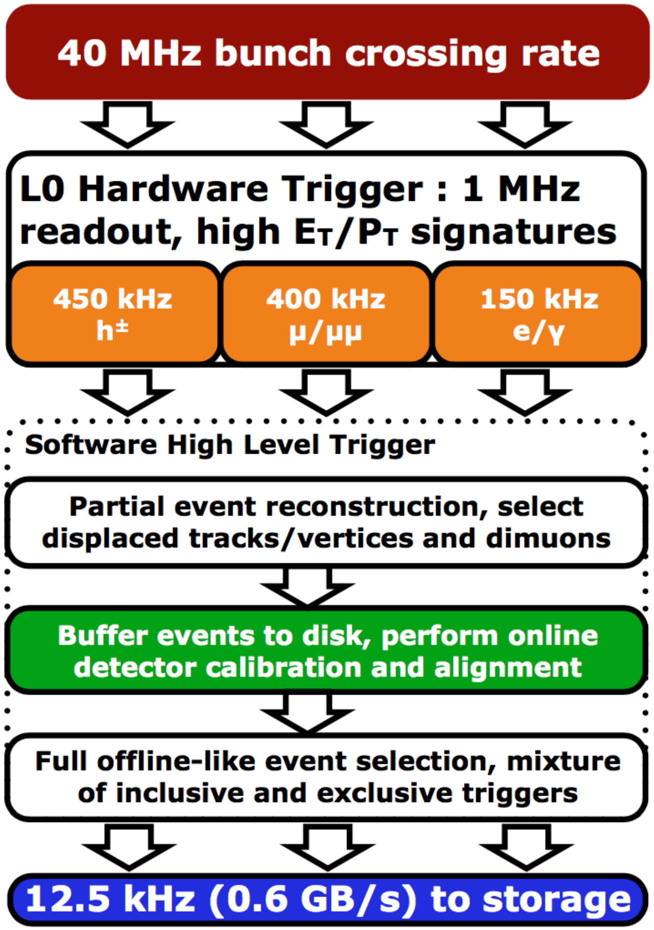
http://www.koppenburg.ch/particles.html

LHCb实验

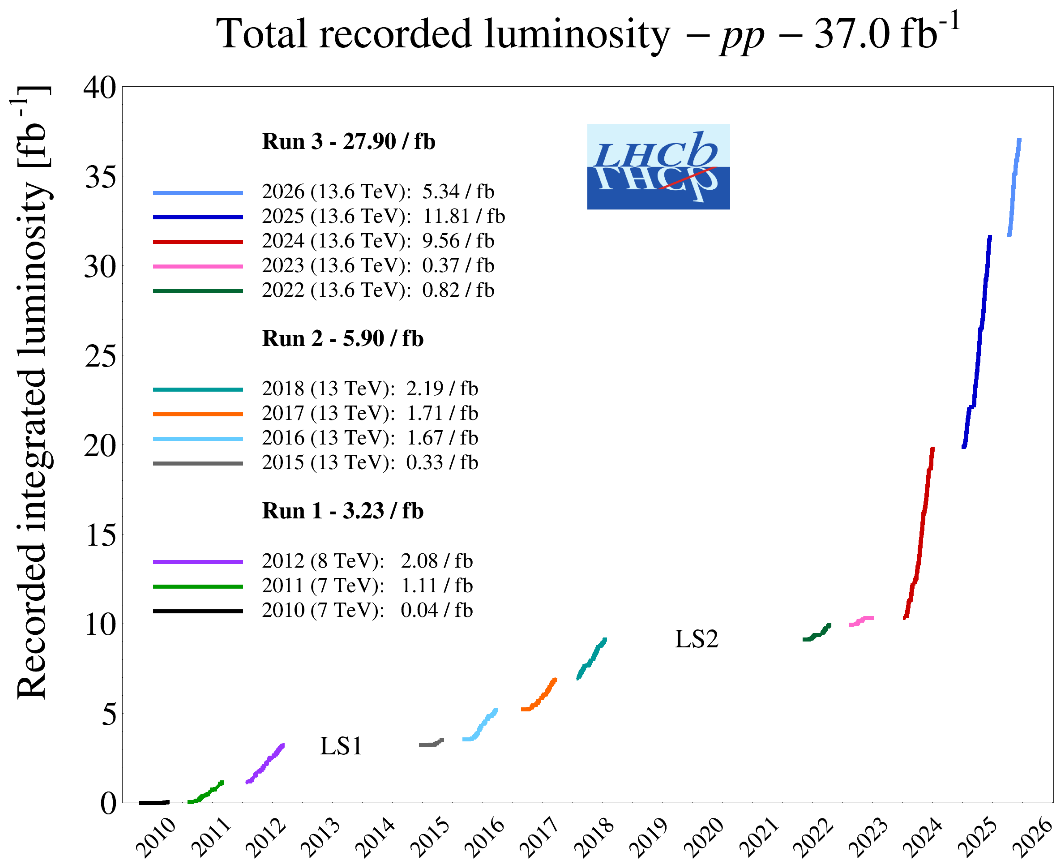


Vertex Locator	$\sigma_{\mathrm{PV},x/y} \sim 10\ \mu\mathrm{m}$, $\sigma_{\mathrm{PV},z} \sim 60\ \mu\mathrm{m}$
Tracking (TT, T1-T3)	$\Delta p/p$: 0.4% at 5 GeV/c, to 0.6% at 100 GeV/c
RICHs	$\varepsilon(K \to K) \sim 95\%$, mis-ID rate $(\pi \to K) \sim 5\%$
Muon system (M1-M5)	$\varepsilon(\mu \to \mu) \sim 97\%$, mis-ID rate $(\pi \to \mu) = 1-3\%$
ECAL	$\sigma_E/E \sim 10\%/\sqrt{E} \oplus 1\%$ (E in GeV)
HCAL	$\sigma_E/E \sim 70\%/\sqrt{E} \oplus 10\%$ (E in GeV)

LHCb实验



40 MHz bunch crossing rate
L0 Hardware Trigger : 1 MHz readout, high ET/PT signatures
450 kHz h±
400 kHz μ/μμ
150 kHz e/γ
Software High Level Trigger
Partial event reconstruction, select displaced tracks/vertices and dimuons
Buffer events to disk, perform online detector calibration and alignment
Full offline-like event selection, mixture of inclusive and exclusive triggers
12.5 kHz (0.6 GB/s) to storage



Total recorded luminosity – pp – 37.0 fb-1
Recorded integrated luminosity [fb-1]
Run 3 - 27.90 / fb
2026 (13.6 TeV): 5.34 / fb
2025 (13.6 TeV): 11.81 / fb
2024 (13.6 TeV): 9.56 / fb
2023 (13.6 TeV): 0.37 / fb
2022 (13.6 TeV): 0.82 / fb
Run 2 - 5.90 / fb
2018 (13 TeV): 2.19 / fb
2017 (13 TeV): 1.71 / fb
2016 (13 TeV): 1.67 / fb
2015 (13 TeV): 0.33 / fb
Run 1 - 3.23 / fb
2012 (8 TeV): 2.08 / fb
2011 (7 TeV): 1.11 / fb
2010 (7 TeV): 0.04 / fb
LHCb
LS1
LS2
0
5
10
15
20
25
30
35
40
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026

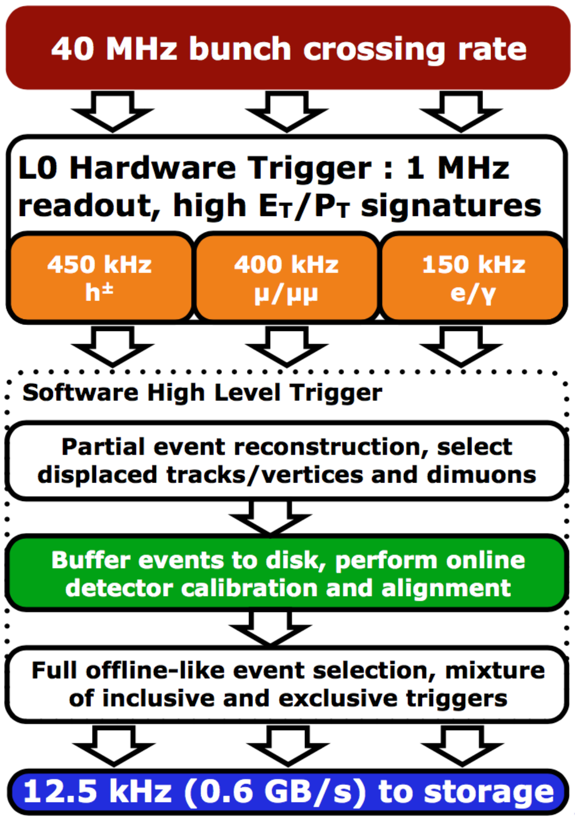
LHCb实验的科学目标

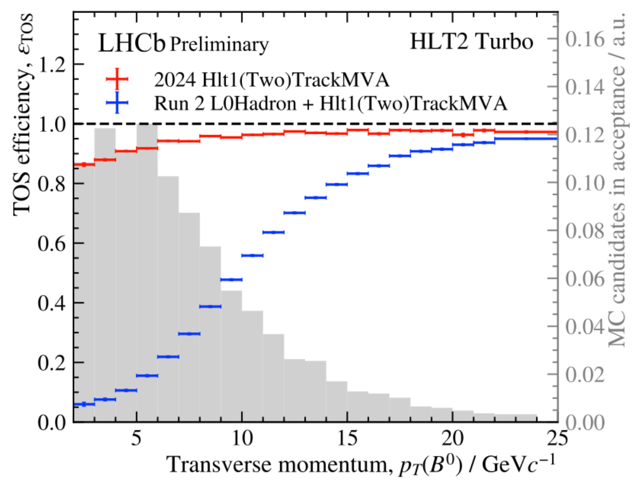
- LHCb 既定科学目标和扩展
  - 理解正反物质不对称 （CP破坏过程精确测量）
  - 间接发现新物理（强子稀有衰变过程寻找）
  + 理解强相互作用机制 （强子谱和重味强子的产生机制）
  + 冷核物质的性质，夸克-胶子等离子体

- 强子谱研究
  - 强子谱研究一般在低能粒子物理/核物理实验开展
  - 对含重夸克强子的理论预言更精确，LHC上容易产生

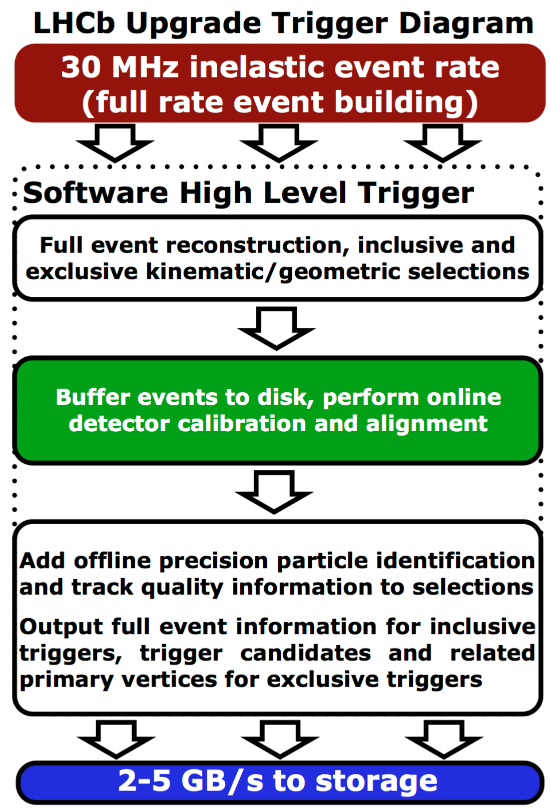
LHCb Upgrade

RUN1/RUN2



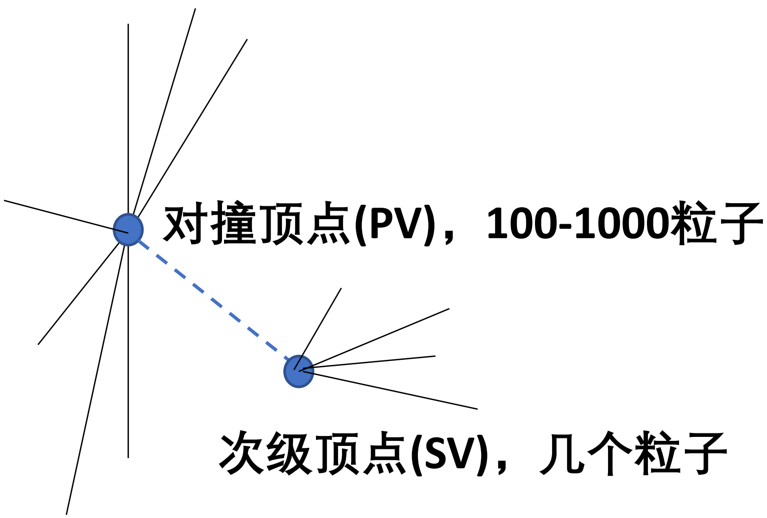


RUN3



重味强子探测

- 每次对撞探测器记录100-1000个末态粒子，如何从中重建出一个重味强子?



核心是降低多重组合!

√ 动量分辨
  → 提高质量分辨率

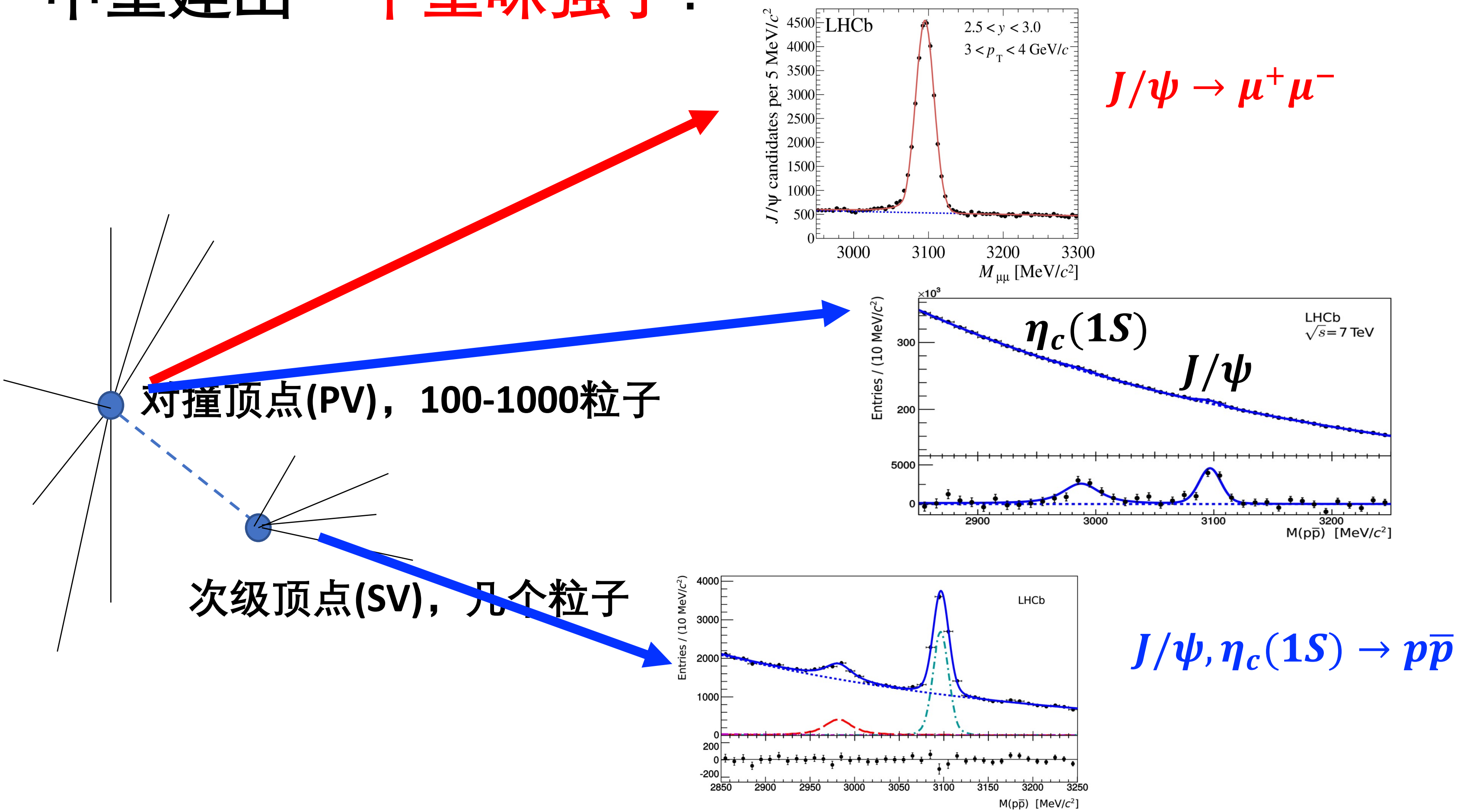
√ 粒子鉴别 ($e/\mu/\pi/K/p$ ...)
  → 减少误组合

√ 衰变顶点
  → 弱衰变粒子
  → 从b/c强子末态衰变中重建

√ 算法（神经网络/机器学习）

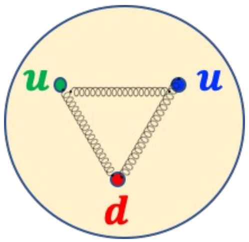
重味强子探测

- 每次对撞探测器记录100-1000个末态粒子，如何从中重建出一个重味强子?

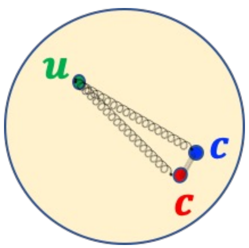


双粲重子

- 双粲重子有独特结构



已发现重子：夸克间近似等间距

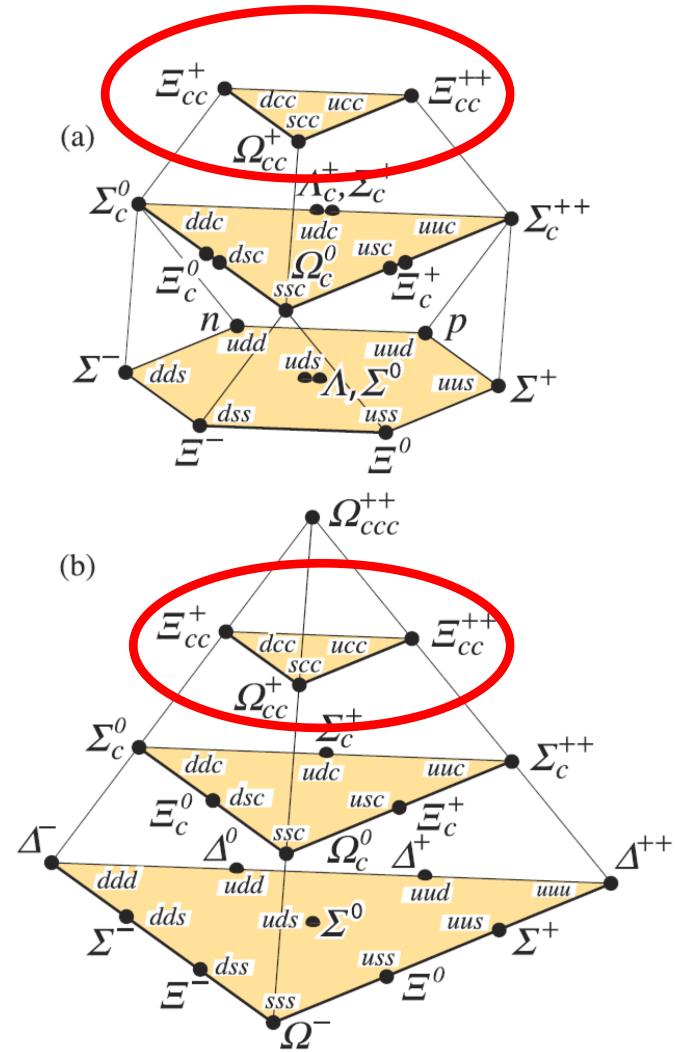


“hydrogen atom of the baryon system”

双粲重子：两个c-夸克很近

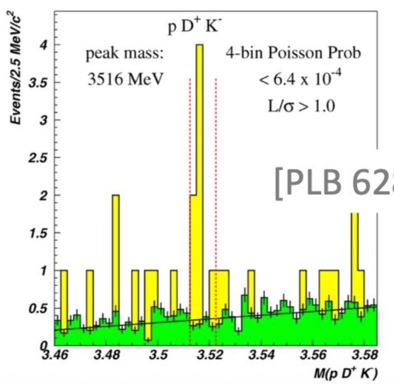
- 检验HQEFT, …

- *cc* 结合能，寿命, …



检验 SELEX 结果?

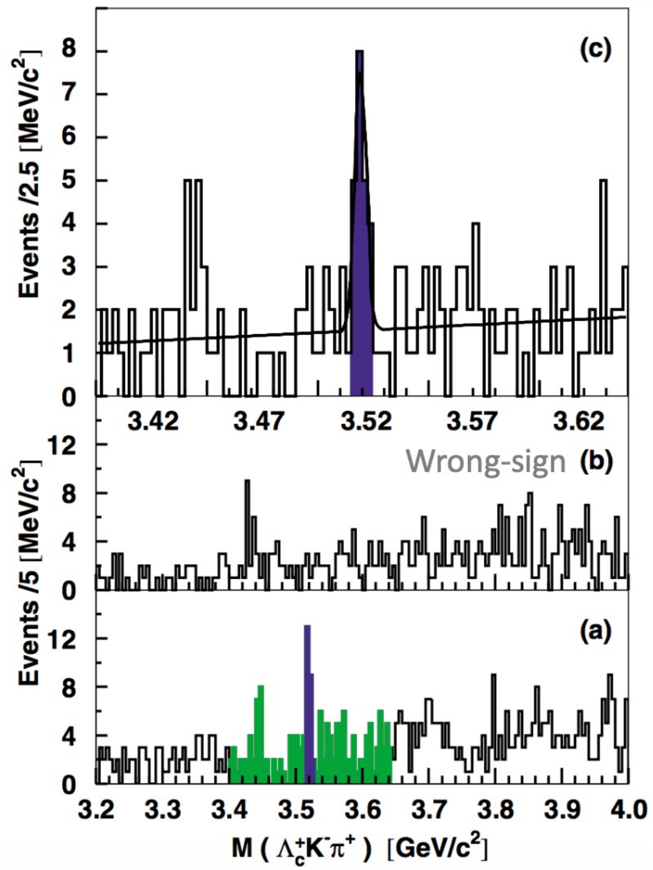
- SELEX claimed $\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$ (6.3σ)
  - M: 3519±1 MeV
  - τ: <33 fs @90%CL
  - σ_{prod}: 20% Λ_c^+ from Ξ_{cc}^{+}
- Also $\Xi_{cc}^{+} \to pD^+K^-$



[PLB 628 (2005)18]

[PRL 89 (2002) 112001]

矩形选择



检验 SELEX 结果？

9.6 前上交

10008405－3907－59

国家自然科学基金资助项目批准通知

清华大学　高原宁同志：

根据《国家自然科学基金条例》的规定和专家评审意见，国家自然科学基金委员会决定资助您的申请项目。请您登录科学基金项目管理 ISIS 网络信息系统（https://isis.nsfc.gov.cn），获取《国家自然科学基金资助项目研究计划书》（以下简称计划书）。您登录该系统的用户名和密码以电子邮件方式发送至您在申请书中填写的电子邮箱。

请您按照本通知的研究期限、资助金额和修改意见填写计划书，要求纸质原件（一式两份）和电子文档同时报送（请保证电子文档和纸质文件内容一致）。电子文档由申请人上传到科学基金网络信息系统（https://isis.nsfc.gov.cn），或用电子邮件发送到：report@pro.nsfc.gov.cn 信箱，电子文档报送截止日期为 9 月 12 日；纸质原件送所在单位审核盖章后，由依托单位在 9 月 12 日前统一报送；如对批准意见有异议，须在上述日期前提出；未说明理由逾期不报计划书者，视为自动放弃接受资助。

国家自然科学基金委员会数学物理科学部

国家自然科学基金委员会

数理科学部

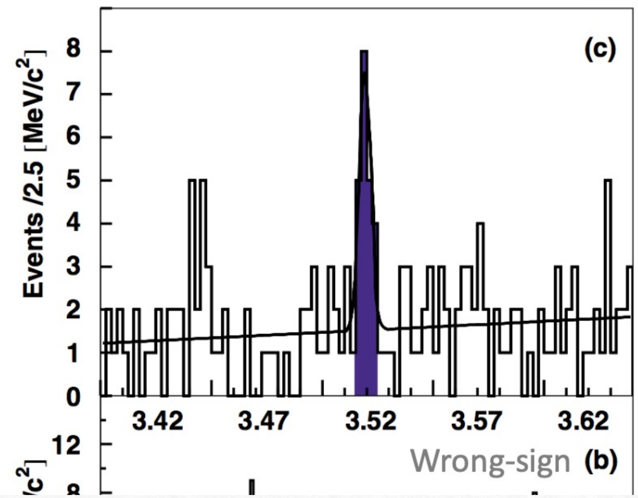
2010 年 8 月 18 日

附：批准意见表（见背面）

$\Xi^{-}\pi^{+}$ (6.3σ)

[PRL 89 (2002) 112001]

矩形选择



附：批准意见表

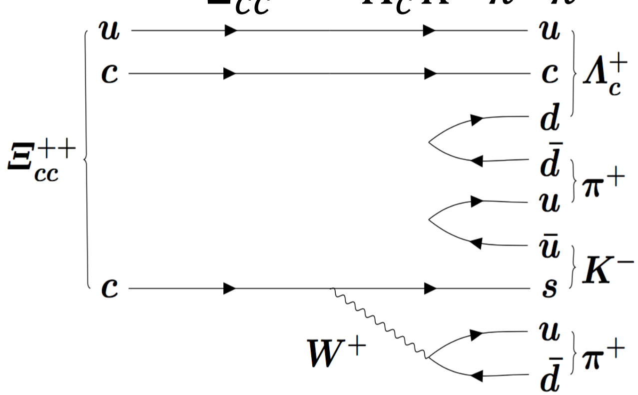
项目批准号	11075084	归口管理部门	数理科学部	资助领域分类代码	A050202
项目名称	双重味重子的实验研究				
资助类别	面上项目	亚类说明			
附注说明					
项目负责人	高原宁	依托单位	清华大学		
资助金额	52.00 万元	研究期限	2011.01 至 2013.12		

Ξ_{cc}^{++}的实验发现

LHCb, PRL 119 (2017) 112001

- **2017年LHCb发现Ξ_{cc}^{++}**

$$\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$$

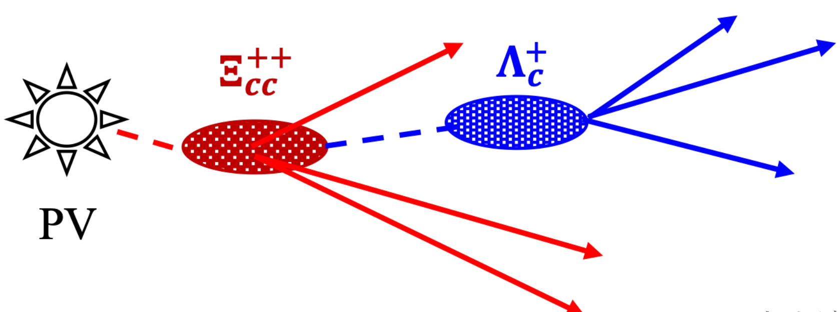


The LHCb Chinese scientists played a crucial role in the observation of the new particle. They are being rewarded for a long standing and highly recognized experimental effort.

A group of Chinese theorists provided also fundamental inputs to drive the analysis to the right direction and gave key suggestions to achieve this result.

Giovanni Passaleva （LHCb Spokesperson)

$$\Xi_{cc}^{++} \rightarrow K^- \pi^+ \pi^+ \Lambda_c^+ (\rightarrow p K^- \pi^+)$$



Ξ_{cc}^{++}的实验发现

LHCb, PRL 119 (2017) 112001

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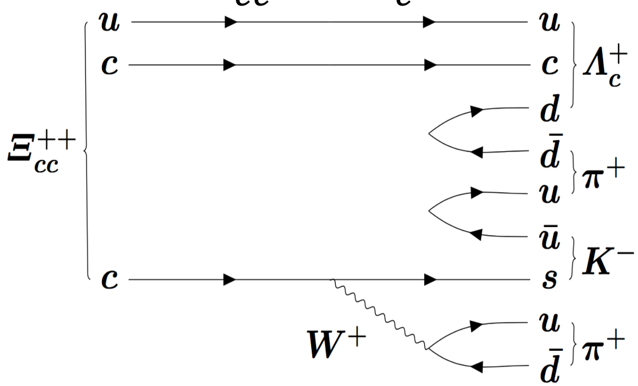
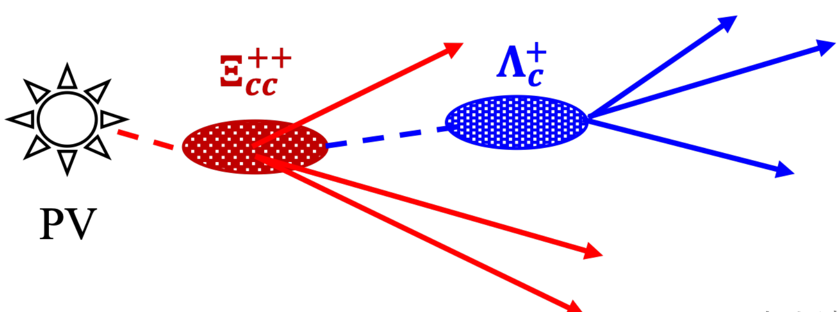
$$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$$

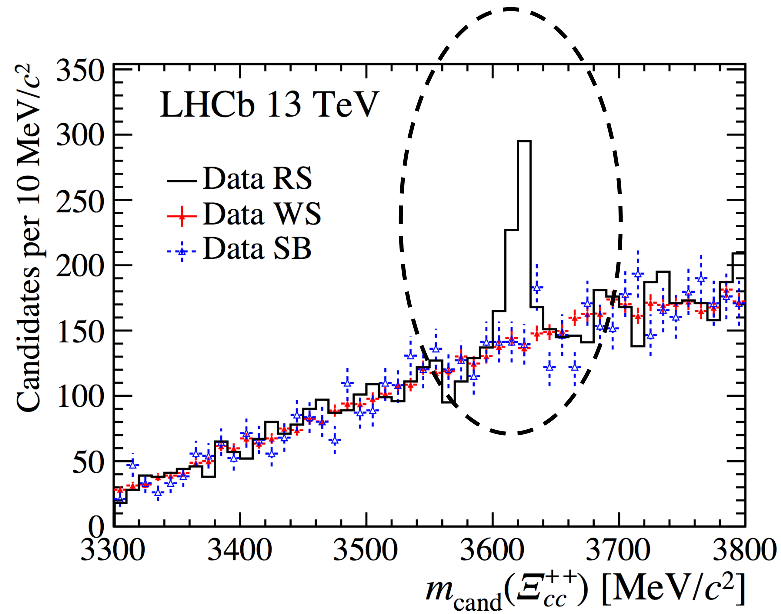


$$m(\Xi_{cc}^{++}) - m(\Lambda_c^+)$$

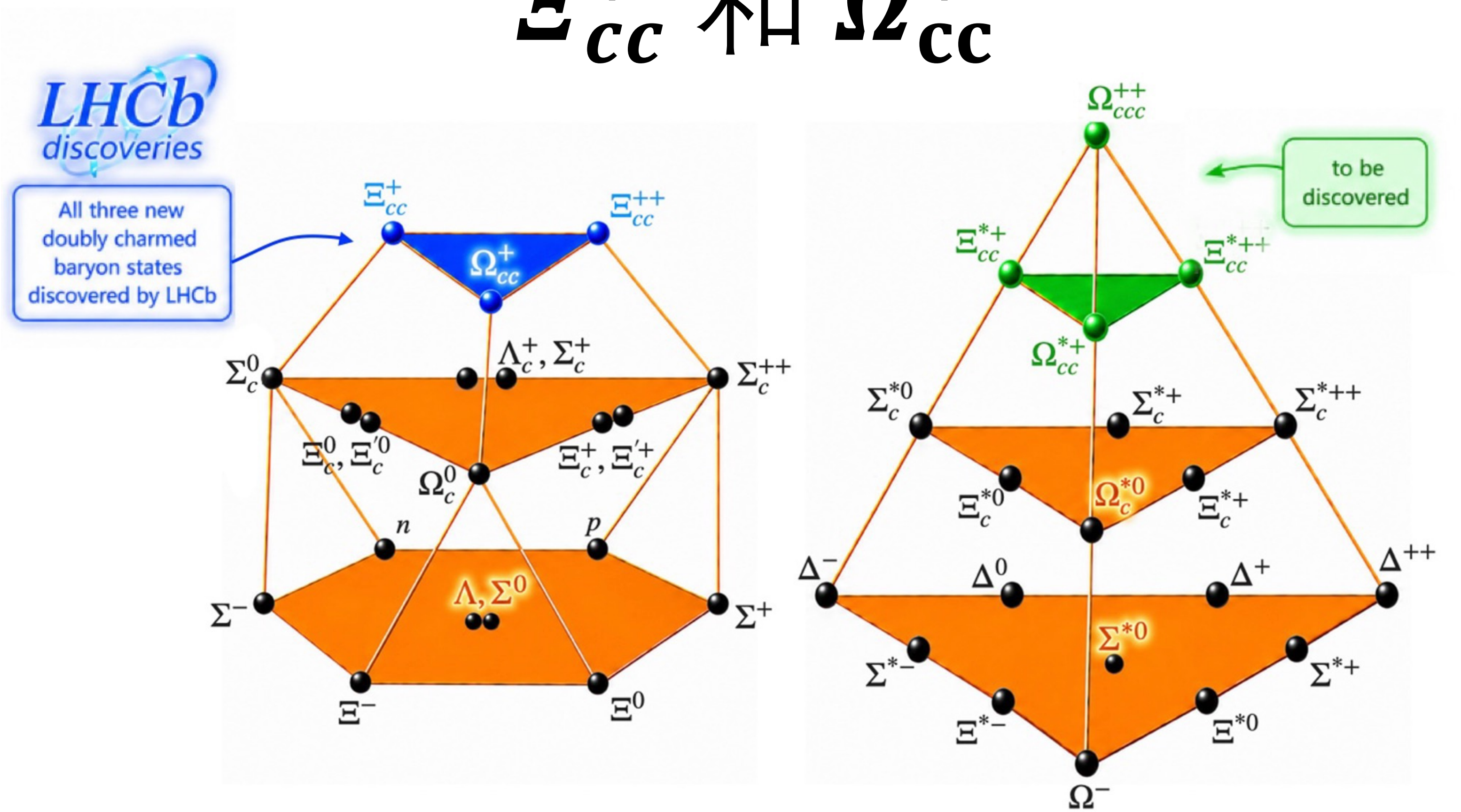
$$= 1134.94 \pm 0.72(stat) \pm 0.27(syst)\ \mathrm{MeV}$$

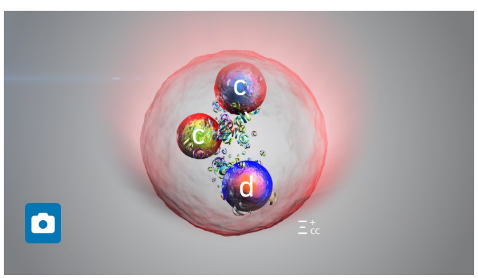
$$\Xi_{cc}^{++} \to K^- \pi^+ \pi^+ \Lambda_c^+ (\to p K^- \pi^+)$$





Ξ_{cc}^{+} 和 Ω_{cc}^{+}



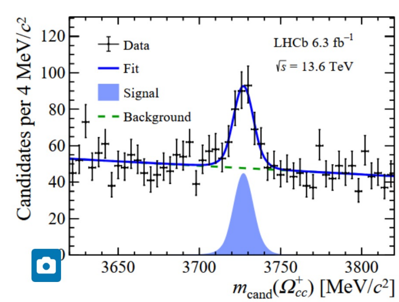


CONFERENCE LATEST POSTS OTHER PHYSICS RESULTS

Observation of the doubly charmed heavy proton Ξ_{cc}^{+}.

17/03/2026 BOLEK PIETRZYK

Today at the Rencontres de Moriond Electroweak meeting, the upgraded LHCb experiment at CERN announced its first particle discovery: a new kind of heavy proton-like particle known as the Ξcc⁺….



CONFERENCE LATEST POSTS OTHER PHYSICS RESULTS

Observation of the doubly charmed baryon Ω_{cc}^{+}

03/06/2026 BOLEK PIETRZYK

In a major new discovery, LHCb has announced the observation of the doubly charmed Ωcc+ baryon at the Beauty 2026 conference in Maastricht. With this...

多夸克奇特粒子

常规粒子

介子：*π*, *K*, *ρ*, …

$q\bar{q}$

+

$Q\bar{Q}$

↓

$q\bar{q}Q\bar{Q}$

四夸克态

重子：*p*, *n*, *Δ*, *Λ*, …

qqq

+

$Q\bar{Q}$

↓

$qqqQ\bar{Q}$

五夸克态

奇特粒子

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

Multiquark states have been discussed since the 1st page of the quark model

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone [4]. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means

ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\bar{q})$ similarly gives just **1** and **8**.

3

http://cds.cern.ch/record/352337/files/CERN-TH-401.pdf

Multiquark states have been discussed since the quark model was proposed

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

8182/TH.401
17 January 1964

Both mesons and baryons are constructed from a set of three fundamental particles called aces. The aces break up into an isospin doublet and singlet. Each ace carries baryon number $\frac{1}{3}$ and is consequently fractionally charged. SU_3 (but not the Eightfold Way) is adopted as a higher symmetry for the strong interactions. The break[illegible] symmetry is assumed to be universal, being due t[illegible]differences among the aces. Extensive space-time a[illegible] theoretic structure is then predicted for both mesons and baryons, in agreement with existing experimental information. An experimental search for the aces is suggested.

5) In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}A$ and AAA, that is, "deuces and treys".

4

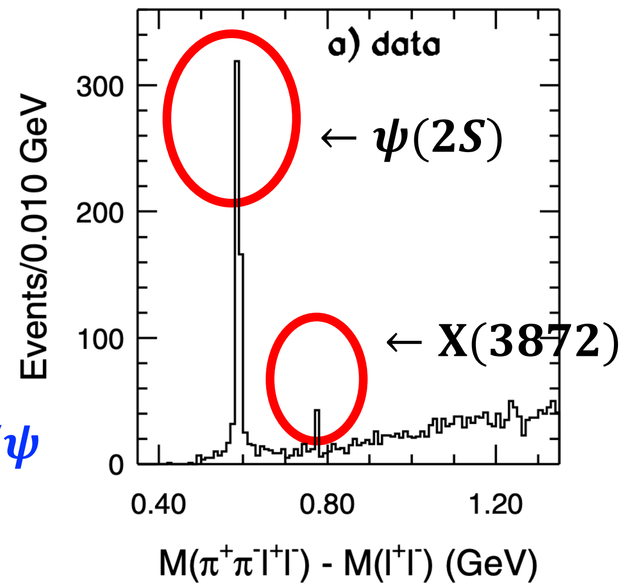
类粲偶素

- 历史性的突破 Belle, PRL 91 (2003) 262001

  $X(3872)$ 或 $\chi_{c1}(3872)$

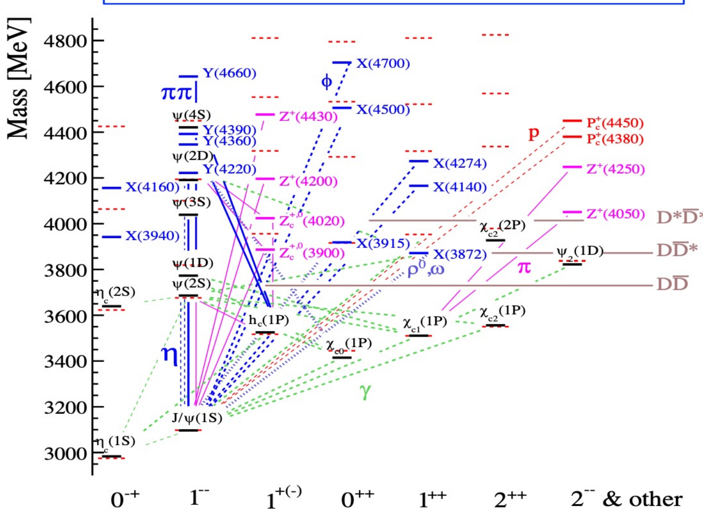
$B \to KX(3872)$,

$X(3872) \to \pi\pi J/\psi$

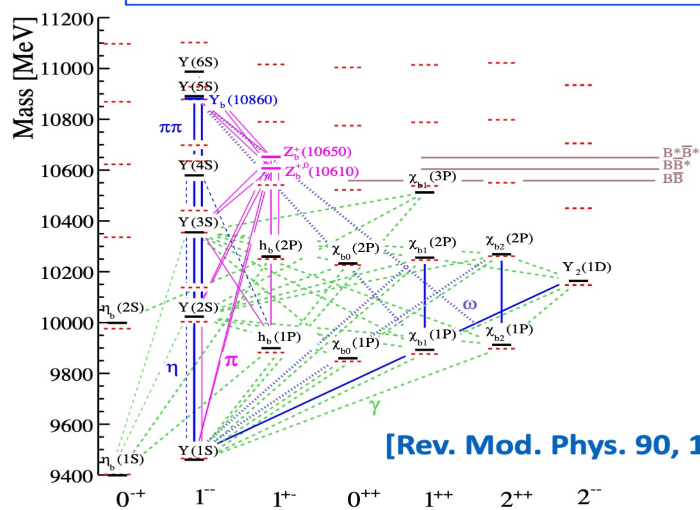


- 一系列新发现的开端

Charmonium ($c\bar{c}$)-like spectrum



Bottomonium ($b\bar{b}$)-like spectrum

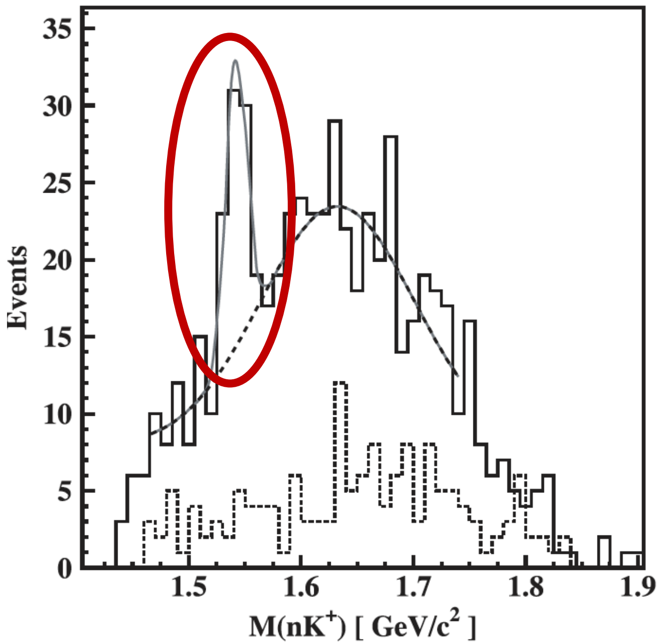


[Rev. Mod. Phys. 90, 15003 (2018)]

Θ(1540)

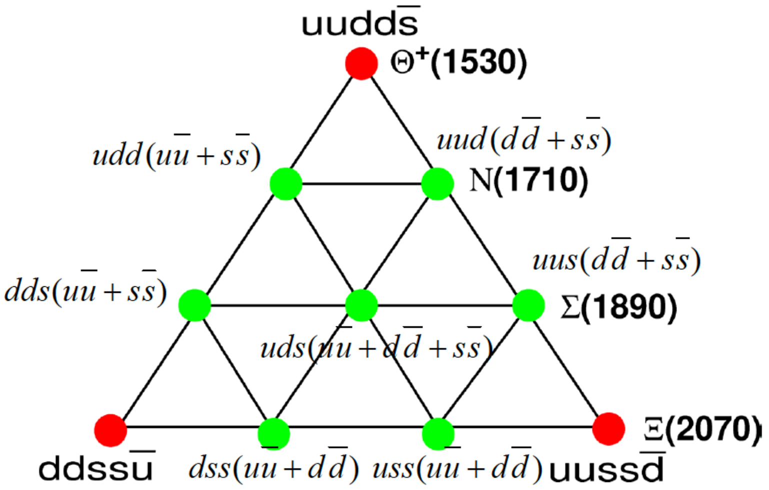
- LEPS 实验 @ SPring-8

$$\gamma d \to K^+K^-pn$$



$$m_\Theta = 1540 \pm 10\ \mathrm{MeV}$$

- 五夸克理论预言（之一）



Summary of Positive Results

Experiment	Mass(MeV)	Width(MeV)	Reaction	Production	
SPring-8	1540±10	< 25	γn	nK^+	hep-ex/0301020, PRL
DIANA	1539±2	< 9	K^+Xe	$nK^+ \to pK_s^0$	hep-ex/0304040, ?
CLAS-1	1542±5	< 21	γd	nK^+	hep-ex/0307018, PRL
SAPHIR	1540±4 ± 2	< 25	γp	nK^+	hep-ex/0307083, PLB
ITEP	1533±5	< 20	$\nu CC, \overline{\nu} CC$	pK_s^0	hep-ex/0309042, ?
CLAS-2	1555±10	< 26	γp	nK^+	hep-ex/0311046, PRL
ALICE	1532±-	$< -$	CC	pK_s^0	Proc. Mong. Acad Sci.
HERMES	1528±2.6±2.1	$17 \pm 9 \pm 3$	γd	pK_s^0	hep-ex/0312044, PLB
COSY-TOF	1530±5	$< 18 \pm 4$	pp	$\Sigma^+ pK_s^0$	hep-ex/0403011
SVD-2	1526±3±3	< 24	pN	pK_s^0	hep-ex/0401024
JINR-1	1545.1±12.0	16.3 ± 3.6	pC_3H_3	pK_s^0	hep-ex/0403044
ZEUS	$1521.5 \pm 1.5^{+2.8}_{-1.7}$	$6.1 \pm 1.6^{+2.0}_{-1.4}$	ep	$pK_s^0, \overline{p}K_s^0$	hep-ex/0403051
JINR-2	1541±4	8 ± 4	np	nK^+	hep-ex/0404003
NA49	1535±-	$-$	pp	pK_s^0	http://na49info.cern.ch

Summary of Negative Results

Experiment	$\Theta^+(1540)$ $(uudd\bar{s})$	$\Xi^{--}(1862)$ $(ddss\bar{s})$	$D^{*-}p(3100)$ $(uudd\bar{c})$	Reaction
→ HERA-B	NO	NO		$pA \to \Theta^+ X,\ \Xi^{--}X$
E690	NO	NO		$pp \to \Theta^+ X,\ \Xi^{--}X$
CDF	NO	NO	NO	$p\bar{p} \to \Theta^+ X,\ \Xi^{--}X,\ \Theta^c X$
HyperCP	NO			$\pi, K, p \to \Theta^+ X$
BaBar	NO	NO		$e^+e^- \to \Theta^+ X,\ \Xi^{--}X$
ZEUS	yes	NO	NO	$ep \to \Theta^+ X,\ \Xi^{--}X,\ \Theta^c X$
ALEPH	NO	NO	NO	$e^+e^- \to \Theta^+ X$
DELPHI	NO			$e^+e^- \to \Sigma^+ K^0 p$
→ PHENIX	NO			$AuAu \to \Theta^+ X$
FOCUS			NO	$\gamma A \to \Theta^c X$
→ BES	NO			$e^+e^- \to J/\Psi \to \Theta^+ \overline{\Theta^-}$

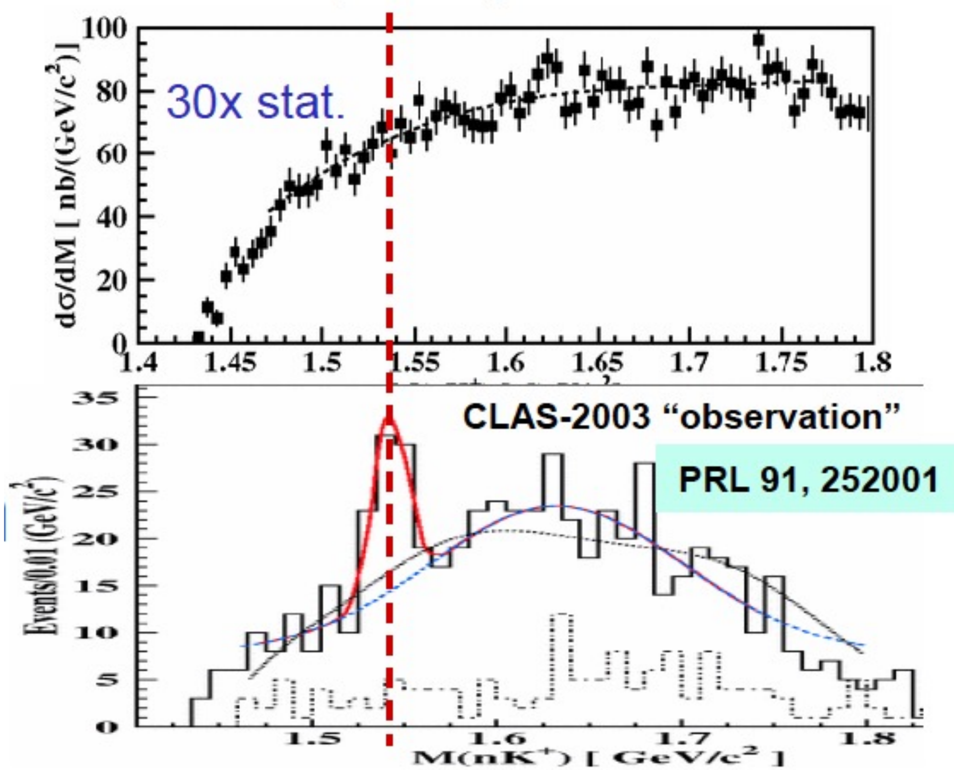
0 null results published, only 3 on arXiv so far

⇒ need null results to be published

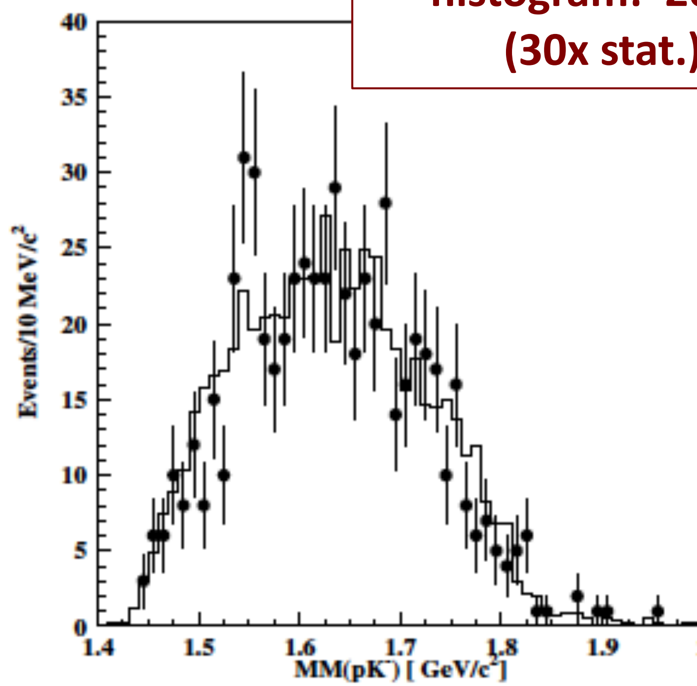
“被遗弃的”五夸克态

JLab CLAS-2006 PRL 96, 212001

$$\gamma d \to p K^- K^+ n$$



JLAB-CLAS
- points: 2003
- histogram: 2006
(30x stat.)



“被遗弃的”五夸克态

Recent reviews:

- **K. H. Hicks, Eur. Phys. J. H37, 1 (2012);**
- **T. Liu, Y. Mao, B.-Q. Ma, Int. J. Mod. Phys. A29, 1430030 (2014).**

C. G. Wohl in PDG2008:

The only advance in particle physics thought worthy of mention in the American Institute of Physics “Physics News in 2003” was a false alarm. *The whole story - the discoveries themselves, the tidal wave of papers by theorists and phenomenologists that followed, and the eventual “undiscovery”* - is a curious episode in the history of science.

$\Theta(1540)^{+}$ $\quad I(J^P) = 0(?^?)$ Status: *

OMITTED FROM SUMMARY TABLE

PENTAQUARK UPDATE

Written February 2006

In 2003, the field of baryon spectroscopy was almost revolutionized by experimental evidence for the existence of baryon states constructed from five quarks (actually four quarks and an antiquark) rather than the usual three quarks. In a 1997 paper [1], considering only u, d, and s quarks, Diakonov *et*

...

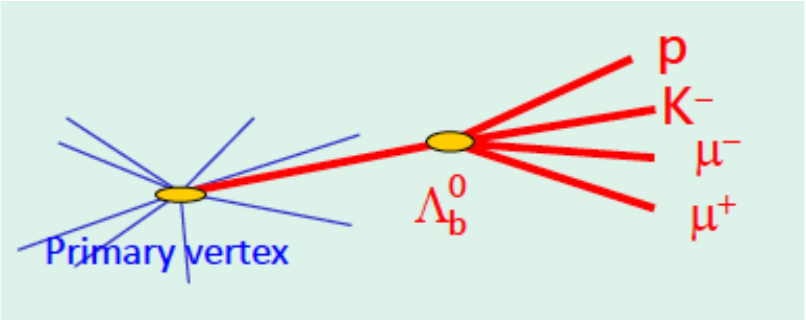
To summarize, with the exception described in the previous paragraph, there has not been a high-statistics confirmation of any of the original experiments that claimed to see the Θ^+; there have been two high-statistics repeats from Jefferson Lab that have clearly shown the original positive claims in those two cases to be wrong; there have been a number of other high-statistics experiments, none of which have found any evidence for the Θ^+; and all attempts to confirm the two other claimed pentaquark states have led to negative results. The conclusion that pentaquarks in general, and the Θ^+, in particular, do not exist, appears compelling.

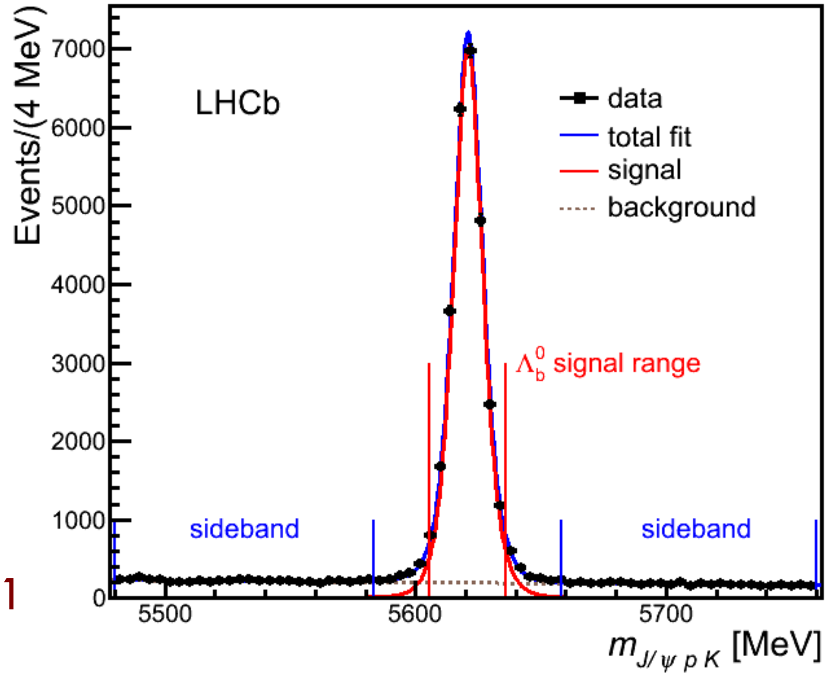
$\Lambda_b^0 \to J/\psi p K^-$ 简史（1）

- $\Lambda_b^0 = (udb)$
- 作为“CP测量道”的本底而最早引起关注

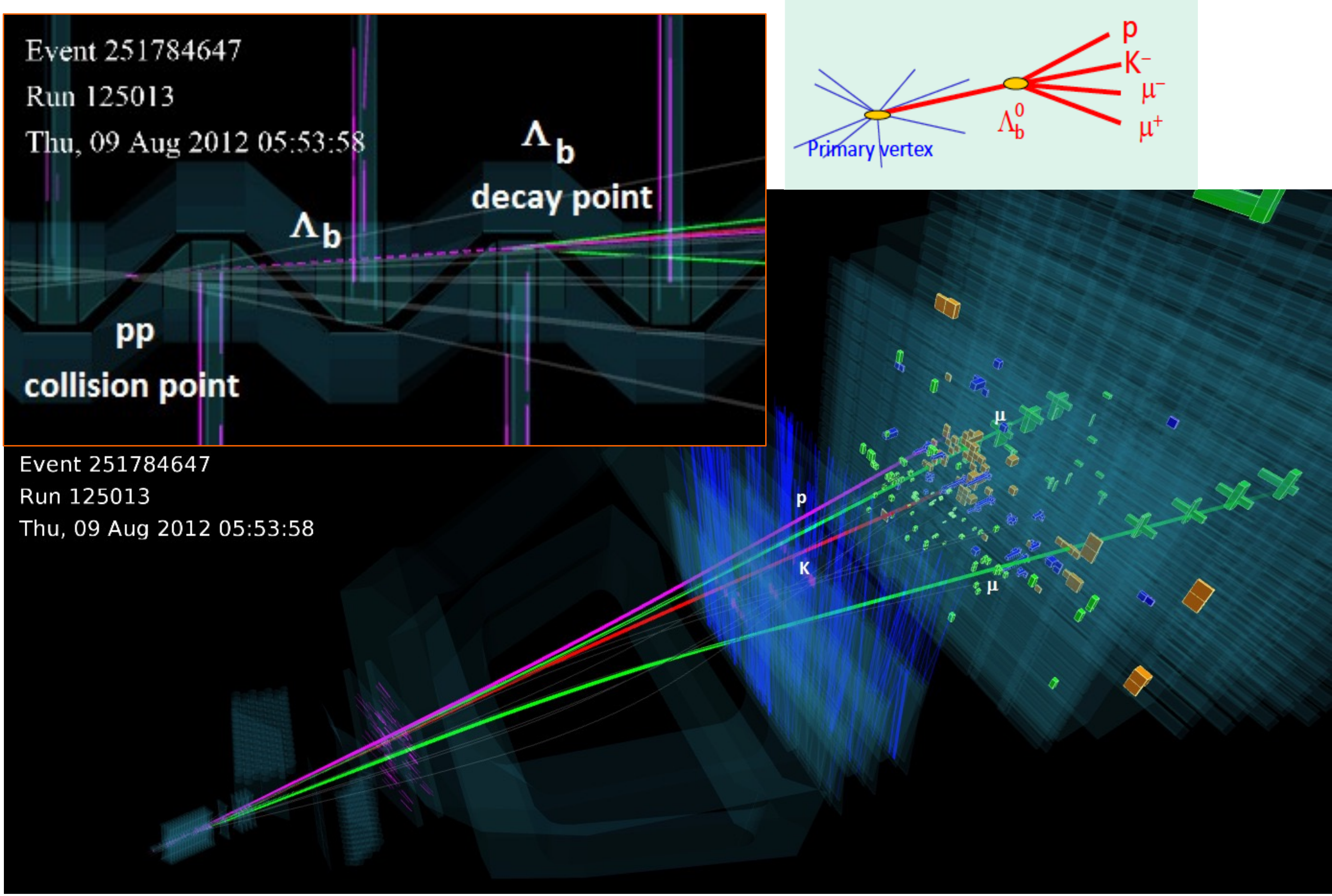
$\Lambda_b^0 \to J/\psi p K^-$ →p误判为K→ $B^0 \to J/\psi K^+ K^-$

- 发现有可观的信号





~26000 signals in 3 fb^{-1}



Event 251784647
Run 125013
Thu, 09 Aug 2012 05:53:58
Λ_b
decay point
Λ_b
pp
collision point
p
K^-
μ^-
μ^+
Λ_b^0
Primary vertex
Event 251784647
Run 125013
Thu, 09 Aug 2012 05:53:58
μ
p
K
μ

$\Lambda_b^0 \to J/\psi p K^-$ 简史（2）

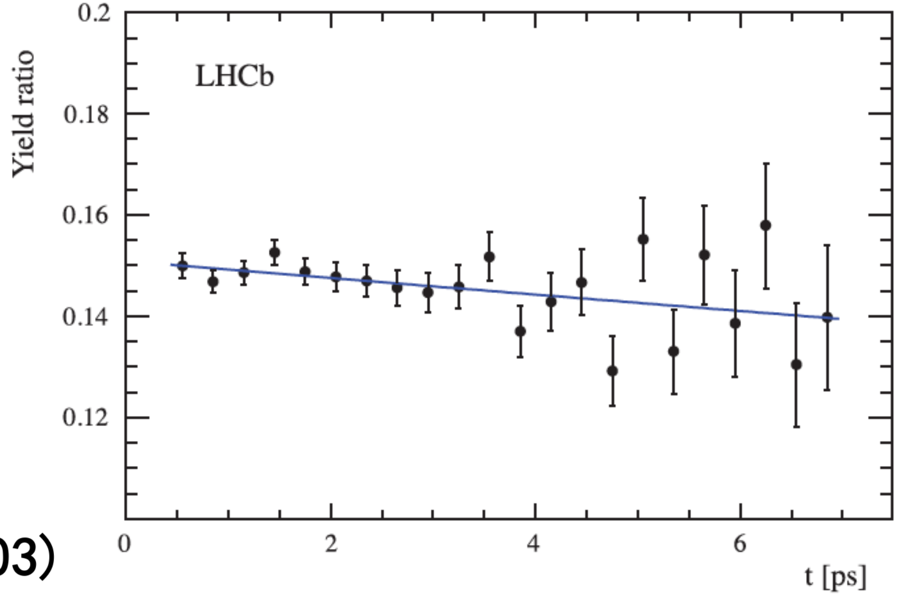
- 用于测量 Λ_b^0寿命

PLB 734, 122 (2014)

$$\frac{\tau_{\Lambda_b^0}}{\tau_{B^0}} = 0.974 \pm 0.006 \pm 0.004$$

- Consistent with HQET predictions

(was 0.798 ± 0.052 in 2002–2003)

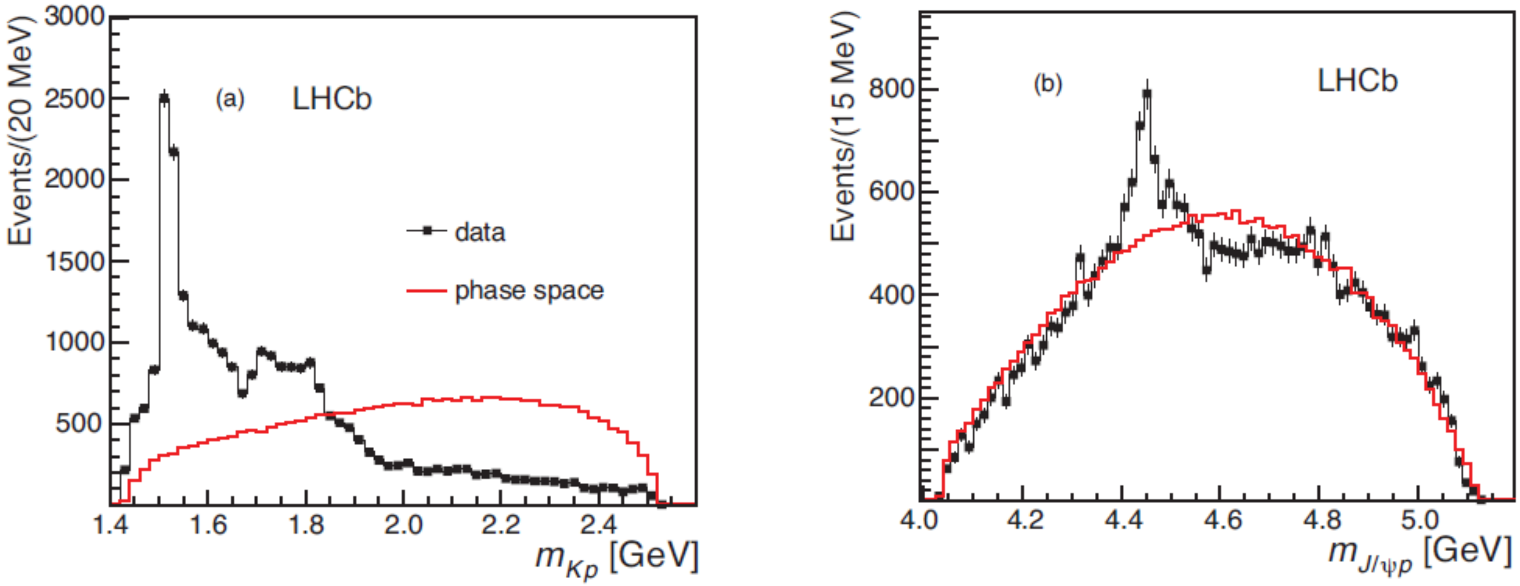


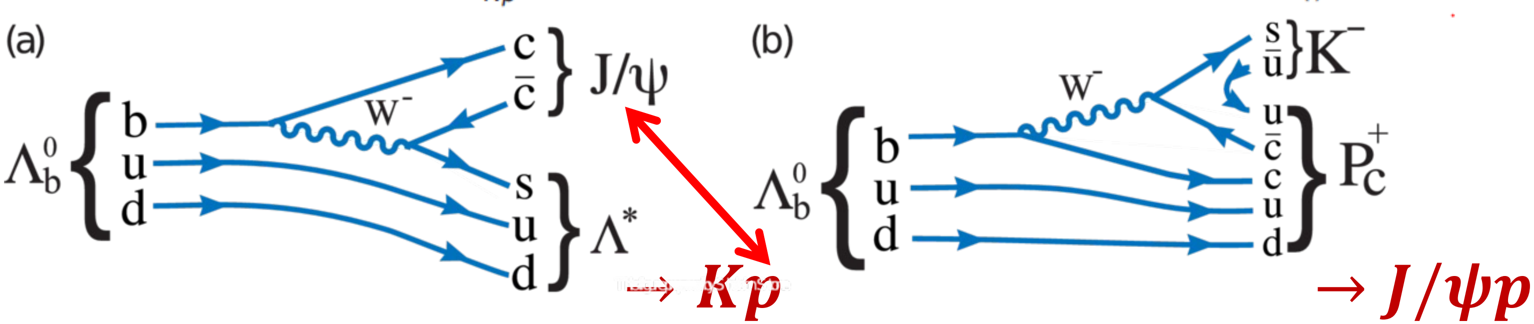
- 作为 $\Lambda_b^0 \to J/\psi p \pi^-$过程的本底重新被研究

JHEP 07, 103 (2014)

$\Lambda_b^0 \to J/\psi p K^-$ 简史（3）

- 多次发现奇怪结构，但以为是“共振态反射”

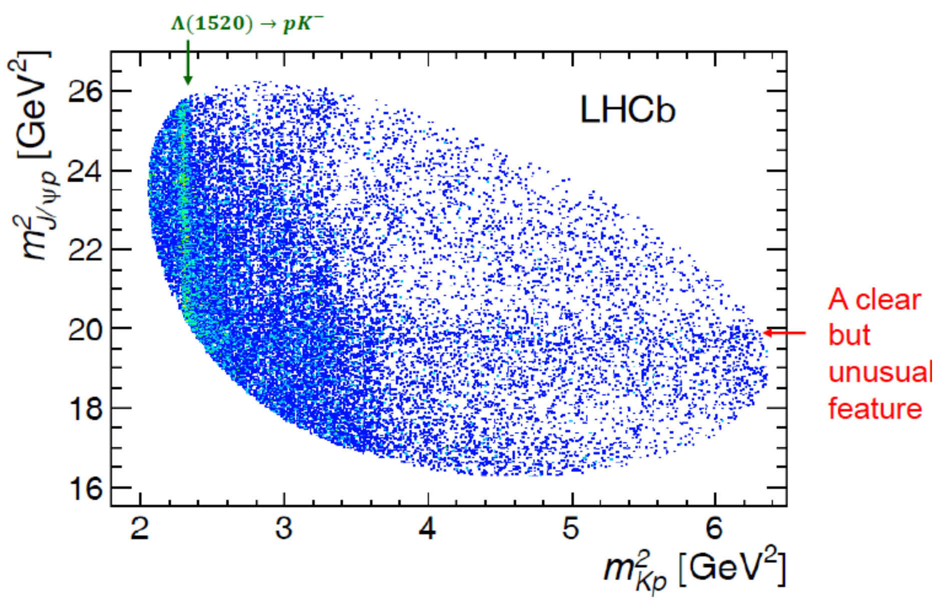


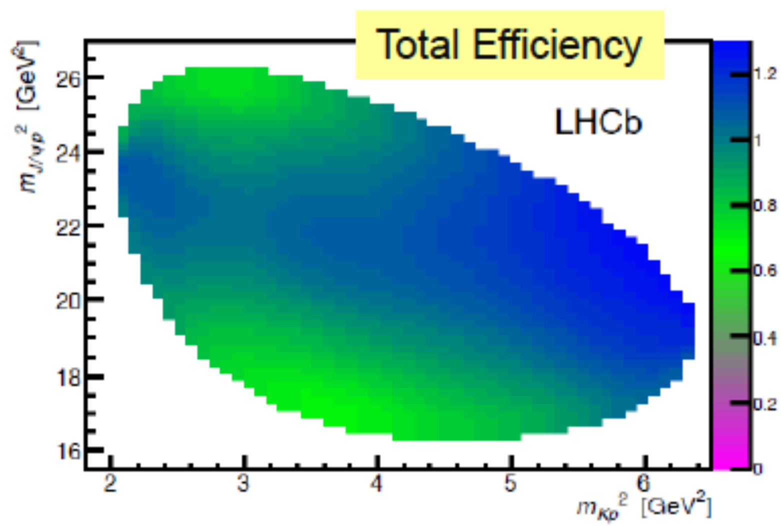


$\Lambda_b^0 \to J/\psi p K^-$ 简史（4）

- 用来测量 Λ_b^0 的产生截面，再次被研究…

  - Dalitz plot: 1D → 2D



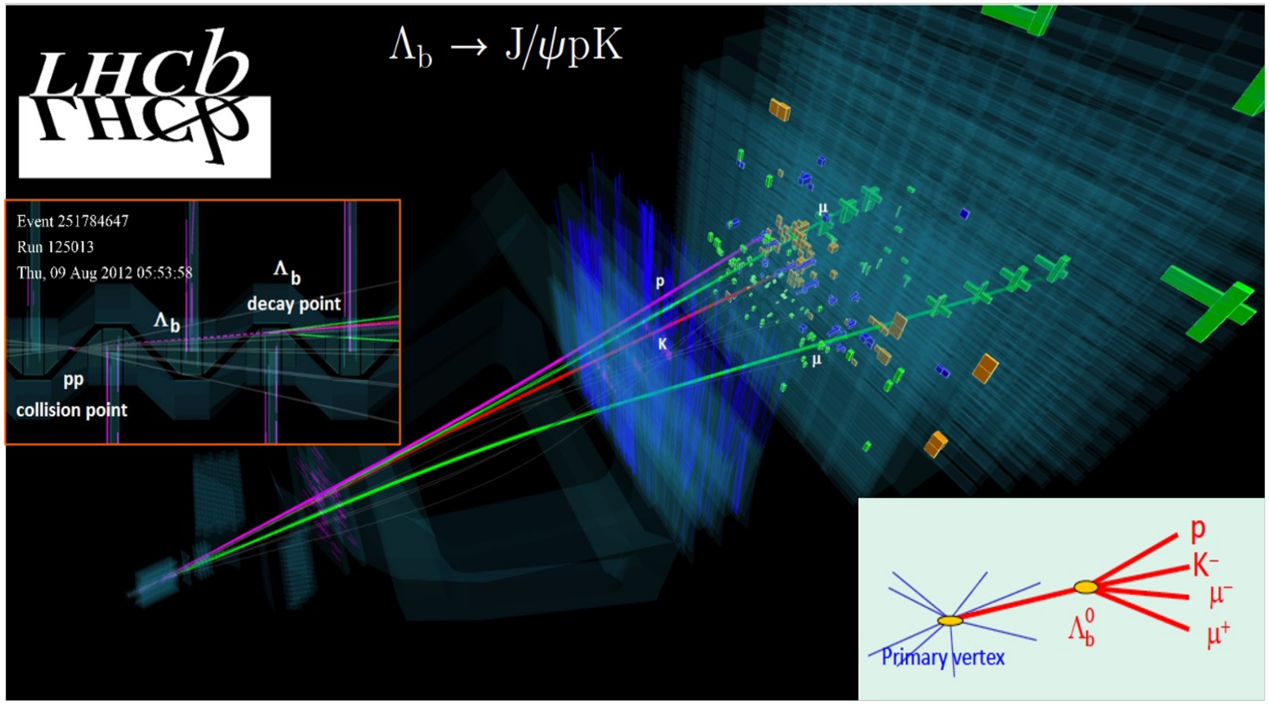


五夸克态的研究

- **2015年LHCb实验首次发现五夸克态**

LHCb, PRL 115 (2015) 072001

LHCb, CPC 40 (2016) 011001



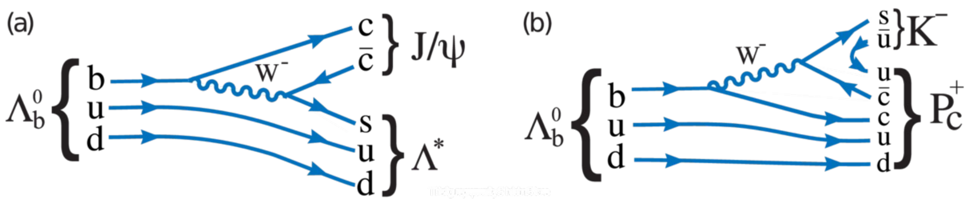
五夸克态的研究

- **2015年LHCb实验首次发现五夸克态**

$$\Lambda_b^0 \rightarrow J/\psi\Lambda^*, \Lambda^* \rightarrow pK^-$$
$$\rightarrow K^- P_c^+, P_c^+ \rightarrow J/\psi p$$

LHCb, PRL 115 (2015) 072001

LHCb, CPC 40 (2016) 011001



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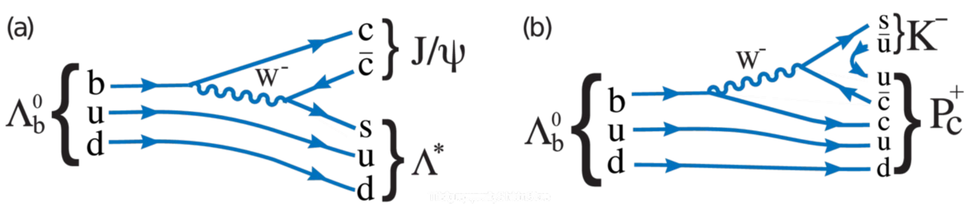
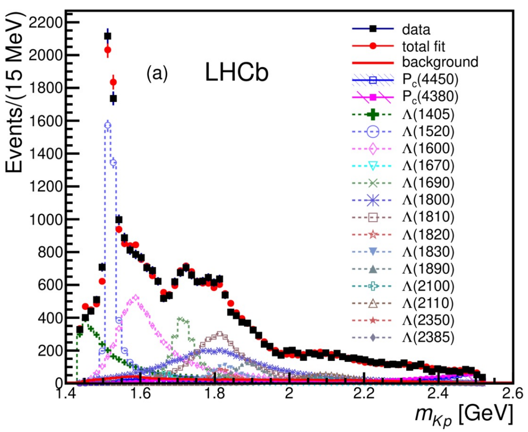
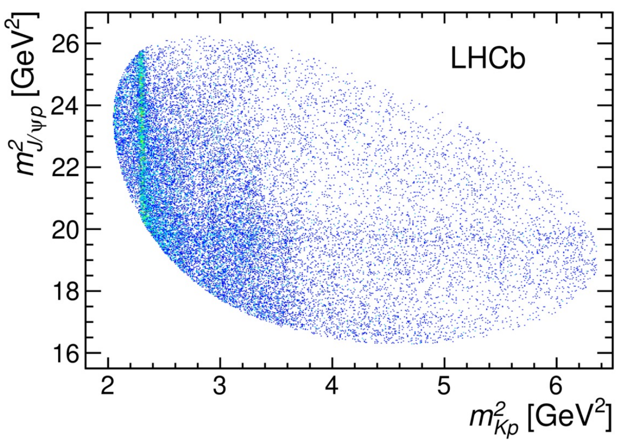
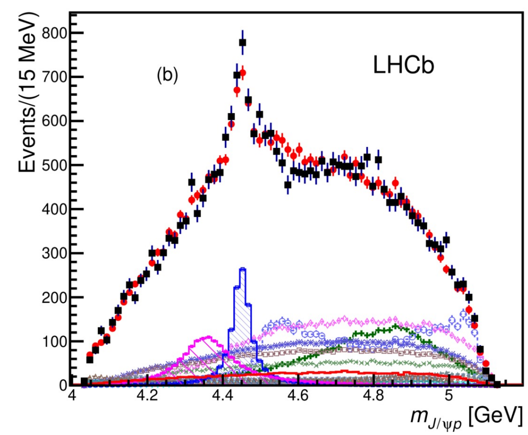








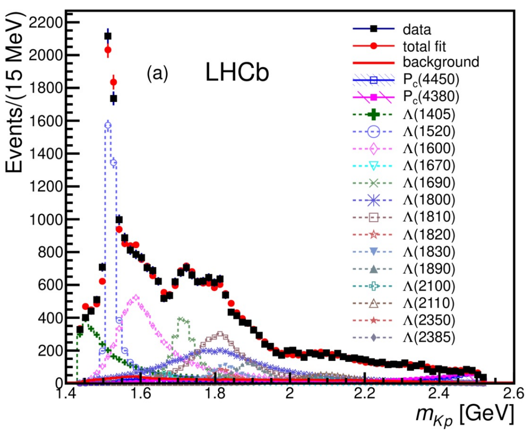
五夸克态的研究

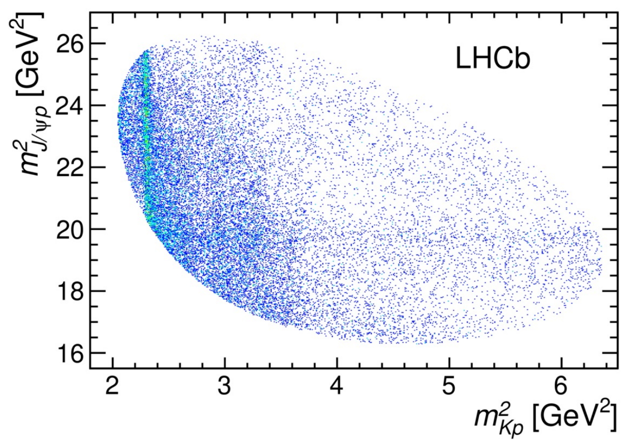
- **2015年LHCb实验首次发现五夸克态**

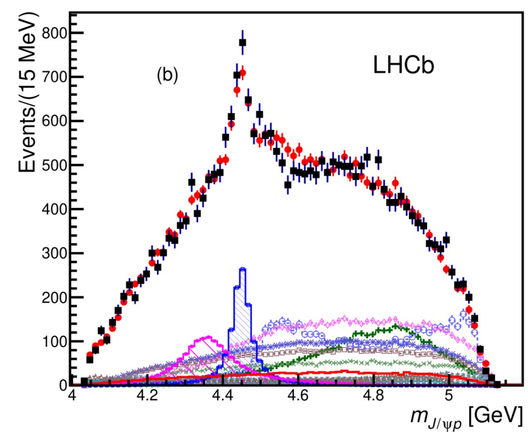
LHCb, PRL 115 (2015) 072001

LHCb, CPC 40 (2016) 011001

	$P_c(4380)^+$	$P_c(4450)^+$
J^P	$\frac{3}{2}^-$	$\frac{5}{2}^+$
Mass $[\mathrm{MeV}/c^2]$	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
Width $[\mathrm{MeV}]$	$205 \pm 18 \pm 86$	$39 \pm 5 \pm 19$
Significance	9σ	12σ



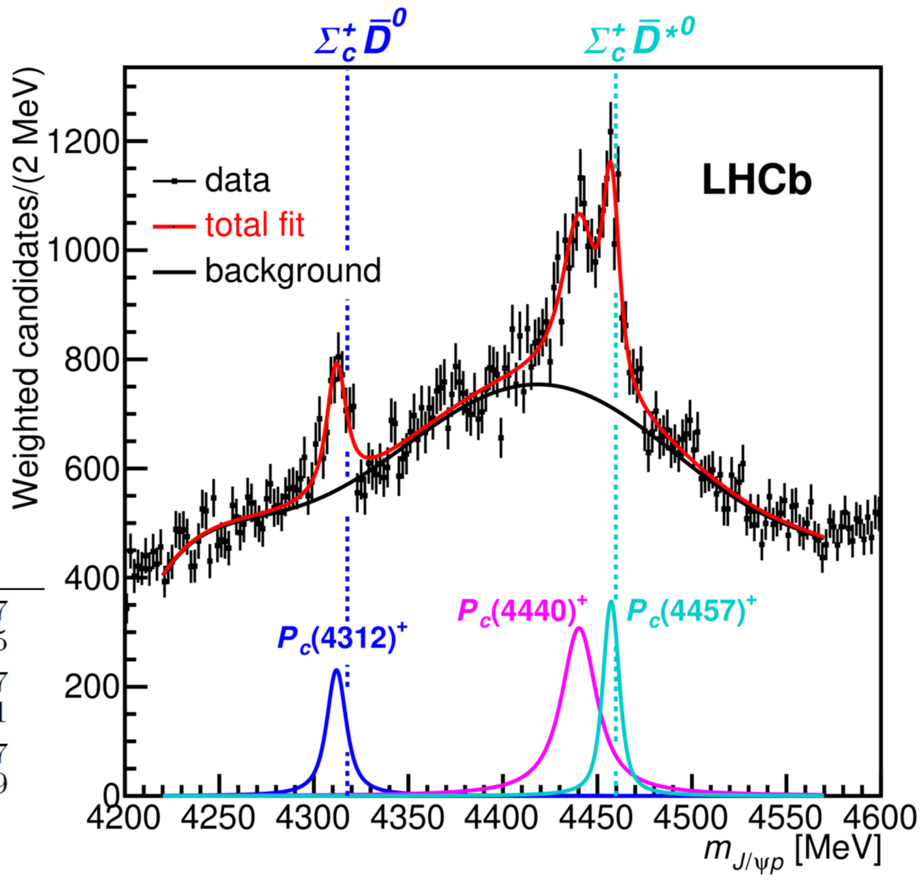




五夸克态的研究

- **2019年更新结果**
  - 更多的数据
  - 优化的事例选择

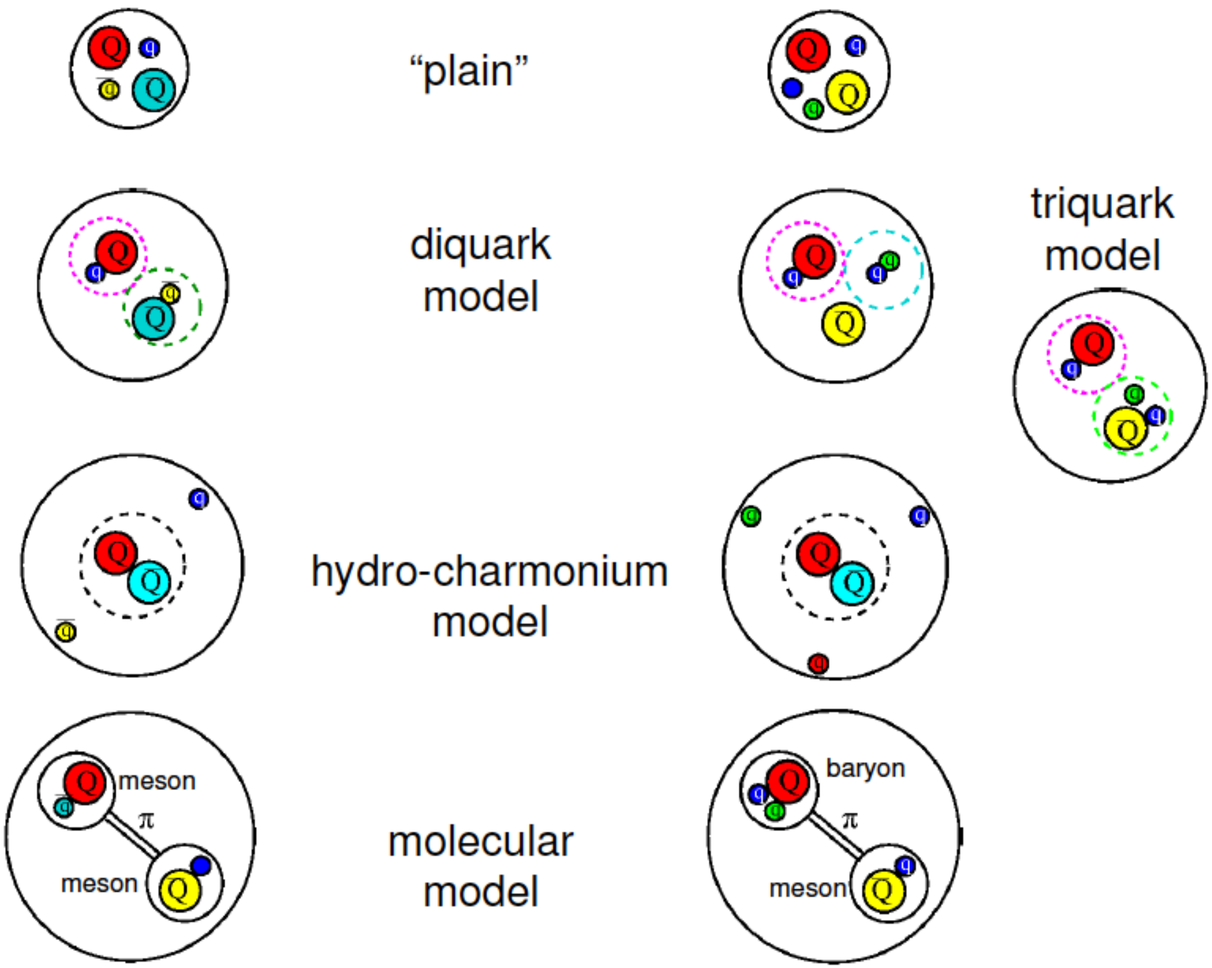
LHCb, PRL 122 (2019) 222001



State	M [MeV]	Γ [MeV]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$

奇特粒子的内部结构?


R
G
B


“plain”
diquark
model
triquark
model
hydro-charmonium
model
meson
π
meson
molecular
model
baryon
π
meson

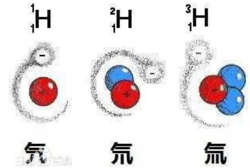
粒子物理

核物理(强作用力化学)

夸克和胶子如何组成强子

核力（强子间作用力）性质

$\boldsymbol{p, n}$

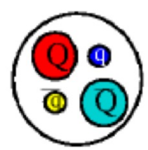


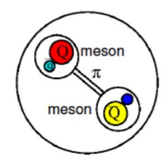
原子核

$\boldsymbol{\Lambda, \Sigma, \ldots, \Xi_{cc}^{++}}$

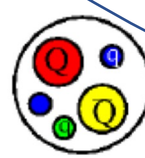
超核，…

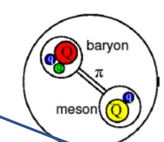
$\boldsymbol{X, Y, Z}$





五夸克态





总 结

- 重味强子谱研究为理解QCD的非微扰特性提供了独特的视角和大量的实验信息
- 四夸克态和五夸克态的发现为强子谱研究打开了一扇新的大门
- 高能强子对撞机/正负电子对撞机的实验和互动、理论探索不断推动强子谱研究

理解强相互作用的本质依然任重道远