what's inside pentaquarks?

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what's inside pentaquarks?

Outline:

- Observation of a new state
- Brief history of exotics
- (un)Colored bound states
- Pentaquark models

OBSERVATION OF A NEW STATE

August 2015: observation of an exotic structure reported by the LHCb collaboration [Phys. Rev. Lett. 115, 072001]

- Two resonances with close masses
- Compatible with pentaquark states

PRL **115,** 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays

R. Aaij *et al.**

(LHCb Collaboration)

(Received 13 July 2015; published 12 August 2015)

Observations of exotic structures in the $J/\psi p$ channel, which we refer to as charmonium-pentaquark states, in $\Lambda_b^0 \to J/\psi K^- p$ decays are presented. The data sample corresponds to an integrated luminosity of 3 fb^{-1} acquired with the LHCb detector from 7 and 8 TeV pp collisions. An amplitude analysis of the three-body final state reproduces the two-body mass and angular distributions. To obtain a satisfactory fit of the structures seen in the $J/\psi p$ mass spectrum, it is necessary to include two Breit-Wigner amplitudes that each describe a resonant state. The significance of each of these resonances is more than 9 standard deviations. One has a mass of $4380 \pm 8 \pm 29$ MeV and a width of $205 \pm 18 \pm 86$ MeV, while the second is narrower, with a mass of $4449.8 \pm 1.7 \pm 2.5$ MeV and a width of $39 \pm 5 \pm 19$ MeV. The preferred J^P assignments are of opposite parity, with one state having spin 3/2 and the other 5/2.

DOI: 10.1103/PhysRevLett.115.072001 PACS numbers: 14.40.Pq, 13.25.Gv

Introduction and summary.—The prospect of hadrons with more than the minimal quark content ($q\bar{q}$ or qqq) was proposed by Gell-Mann in 1964 [1] and Zweig [2], followed by a quantitative model for two quarks plus

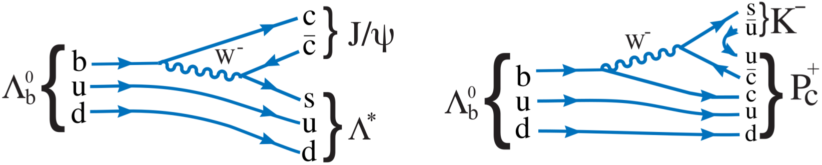
ascertain if the structures seen in Fig. 2(b) are resonant in nature and not due to reflections generated by the Λ^* states, it is necessary to perform a full amplitude analysis, allowing for interference effects between both decay

OBSERVATION OF A NEW STATE

The decay of the Λ_b^0 (ubd) baryon

$$\Lambda_b^0 \to J/\psi\, K^-\, p$$

is dominated by the resonances $\Lambda^* \;\to\; K^- p$ (left) but could have also exotic contribution resulting in a resonance in the $J/\psi p$ mass (right)



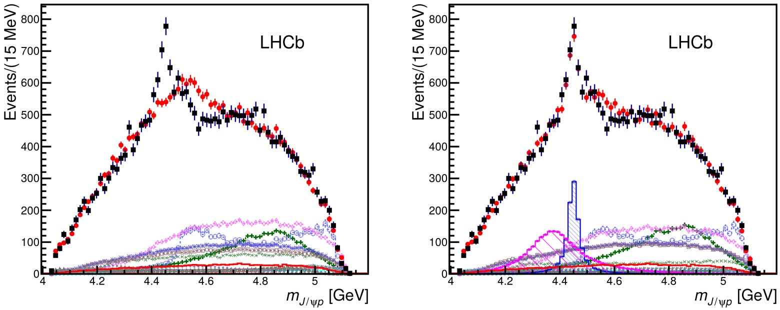
P_c^+ is a pentaquark with minimal content $c\bar{c}uud$ [Phys. Rev. Lett. 115, 072001]

OBSERVATION OF A NEW STATE

Found two resonances with best fit values

$$\mathcal{M} \simeq 4380\text{MeV} \;\; \Gamma \simeq 200\text{MeV} \qquad \mathcal{M} \simeq 4450\text{MeV} \;\; \Gamma \simeq 39\text{MeV}$$

with J^P assignments $3/2^-$ and $5/2^+$ respectively



Data (black) and fit (red) without (left) and with (right) P_c^+ resonances (blue and magenta points). Remaining dots represent contributions from known Λ^*. [Phys. Rev. Lett. 115, 072001]

A BRIEF HISTORY OF EXOTIC STATES

In 1964, both Gell-Mann and Zweig explicitly mentioned the possibility of multiquark states [Phys.Lett. 8 (1964) 214, CERN 8182/TH.401]

> 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 lowes baryon configuration (qqq) gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\bar{q})$ similarly give: just **1** and **8**.

Great progresses in the study of $q\bar{q}$ and qqq hadrons

- theoretically: QCD, quark models, etc.
- experimentally: a full zoo of particles

but still no exotic states (at least prior to the January 2003)!

A BRIEF HISTORY OF EXOTIC STATES

Finally two important steps in 2003

- $\Theta^+(1540)$ by LEPS Collaboration [Phys.Rev.Lett. 91 (2003) 012002] first observation compatible with a light pentaquark, great theoretical impact but not confirmed and then forgotten
- observation of $X(3872)$ at Belle [Phys. Rev. Lett. 91 (2003) 262001]

and then other evidences in the following years

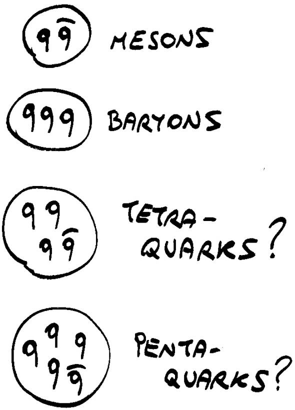
State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3872)$	3871.52±0.20	1.3±0.6	$1^{++}/2^{-+}$	$B \to K(\pi^+\pi^- J/\psi)$	Belle [85, 86] (12.8), *BABAR* [87] (8.6)	2003	OK
		(<2.2)		$p\bar{p} \to (\pi^+\pi^- J/\psi) + ...$	CDF [88–90] (np), DØ [91] (5.2)		
				$B \to K(\omega J/\psi)$	Belle [92] (4.3), *BABAR* [93] (4.0)		
				$B \to K(D^{*0}\bar{D}^0)$	Belle [94, 95] (6.4), *BABAR* [96] (4.9)		
				$B \to K(\gamma J/\psi)$	Belle [92] (4.0), *BABAR* [97, 98] (3.6)		
				$B \to K(\gamma\psi(2S))$	*BABAR* [98] (3.5), Belle [99] (0.4)		
$X(3915)$	3915.6 ± 3.1	28±10	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle [100] (8.1), *BABAR* [101] (19)	2004	OK
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [102] (7.7)		
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [103] (6.0)	2007	NC!
				$e^+e^- \to J/\psi\ (...)$	Belle [54] (5.0)		
$G(3900)$	3943 ± 21	52±11	1^{--}	$e^+e^- \to \gamma(D\bar{D})$	*BABAR* [27] (np), Belle [21] (np)	2007	OK
$Y(4008)$	4008^{+121}	226±97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	Belle [104] (7.4)	2007	NC!

[Eur.Phys.J. C71 (2011) 1534]

A BRIEF HISTORY OF EXOTIC STATES

Meanwhile, theoretical development

- possible description of tetraquark $q^2\bar{q}^2$ state[Phys. Rev. D (1977) 15, 267]
- first "pentaquark" in the literature as baryon $q^4\bar{q}$ [Phys.Lett.B 195 (1987) 484]
- and so on various model proposed



Open questions:
structure of these exotic states?
why they are so rare?

(UN)COLORED BOUND STATES

A quick recall: properties of quarks

- six flavours: u, d, s, c, b, t
- $\frac{1}{2}$ spin particles with electric charge $+\frac{2}{3}e$ or $-\frac{1}{3}e$
- color charged, fondamental representation of $SU(3)_C$

Confinement postulate:

all states and observables are color-singlet

So $q\bar{q}$ and qqq, $qq\bar{q}\bar{q}$ (and so on) are allowed while q, qq or $qq\bar{q}$ missed.

$$qq:\ 3\otimes 3 = \bar{3}\oplus 6$$

$$q\bar{q}:\ 3\otimes\bar{3} = 1\oplus 8$$

$$qqq:\ 3\otimes 3\otimes 3 = 1\oplus 8\oplus 8\oplus 10$$

$$qq\bar{q}\bar{q}:\ 3\otimes 3\otimes\bar{3}\otimes\bar{3} = 1\oplus 1\oplus 4\cdot 8\oplus 10\oplus\ldots$$

...

(UN)COLORED BOUND STATES

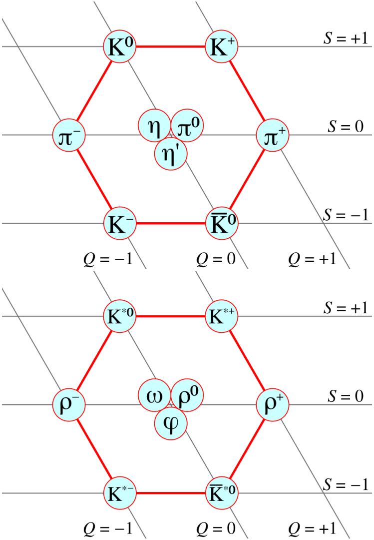
With light quarks patterns described by (approximate) flavour symmetry:

$SU(N_F)_F$ with N_F light flavors

- $m_u \simeq m_d \rightarrow SU(2)$
- $m_d \simeq m_u \simeq m_s \rightarrow SU(3)$

States have defined charge Q, isospin I_z, strangeness S...

But is difficult to find a model describing states with light quarks



Pseudo-scalar and vector mesons “nonets”

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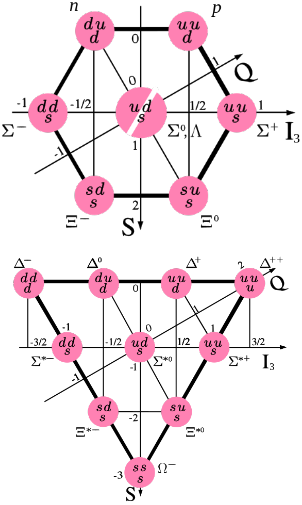


Baryon octet and decuplet

(UN)COLORED BOUND STATES

$n\,^{2s+1}\ell_J$	J^{PC}	$c\bar{c}$	$b\bar{b}$
$1\,^1S_0$	0^{-+}	$\eta_c(1S)$	$\eta_b(1S)$
$1\,^3S_1$	1^{--}	$J/\psi(1S)$	$\Upsilon(1S)$
$1\,^1P_1$	1^{+-}	$h_c(1P)$	
$1\,^3P_0$	0^{++}	$\chi_{c0}(1P)$	$\chi_{b0}(1P)$
$1\,^3P_1$	1^{++}	$\chi_{c1}(1P)$	$\chi_{b1}(1P)$
$1\,^3P_2$	2^{++}	$\chi_{c2}(1P)$	$\chi_{b2}(1P)$
$1\,^3D_1$	1^{--}	$\psi(3770)$	
$2\,^1S_0$	0^{-+}	$\eta_c(2S)$	
$2\,^3S_1$	1^{--}	$\psi(2S)$	$\Upsilon(2S)$
$2\,^3P_{0,1,2}$	$0^{++},1^{++},2^{++}$		$\chi_{b0,1,2}(2P)$

Charmonium ($c\bar{c}$) mass spectrum
[PDG, Chin. Phys. C 38, 090001 (2014)]

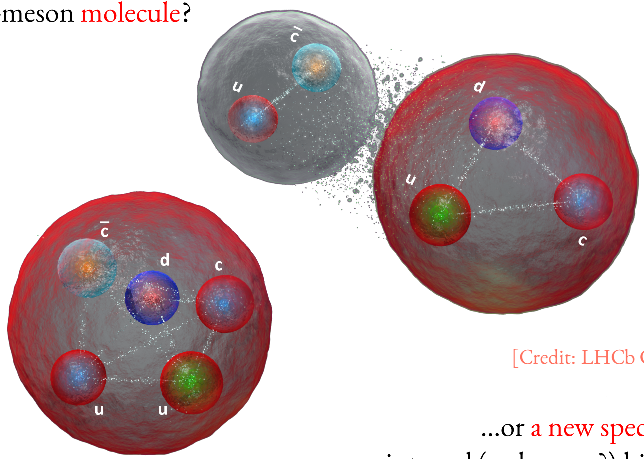
With heavy quarks $Q = c, b$ the pattern is more "familiar"

Good effective description in terms of NR potential models:

- two-body $Q\bar{Q}$ bound state
- description in terms of radial exitation n, total spin S, orbital L and total J angular momentums
- usual spectroscopic notation $n\,^{2S+1}J_L$

PENTAQUARK MODELS

Is the pentaquark a baryon-meson molecule?



[Credit: LHCb C., CERN]

...or a new species with internal (unknown?) bindings?

PENTAQUARK MODELS: MOLECULE

P_C^+ structure is *uudcc̄*, then two sub-possibilities:

uud baryon (p,Δ^+,...) plus a $c\bar{c}$ heavy meson

- addition of masses do not provide anything close to $m_{P_C^+}$ values
- needs to combine a $c\bar{c}$ 1P-state, but sum of masses exceeds too much

[arXiv:1507.0469]

open charm combination: $u\bar{c}$+*cud* or $d\bar{c}$+*cuu*

- very close to $\bar{D}^*\Sigma_c$ or $\bar{D}^*\Sigma_c^*$ threshold
- problem with quantum numbers: do not fit the LHCb assignments of J^P

[Phys. Rev. D 92, 094003 (2015)]

PENTAQUARK MODELS: NEW STATE

First possibility: uncorrelated quark models

general aspects: [Nucl.Phys.Proc. 142 (2005) 343]

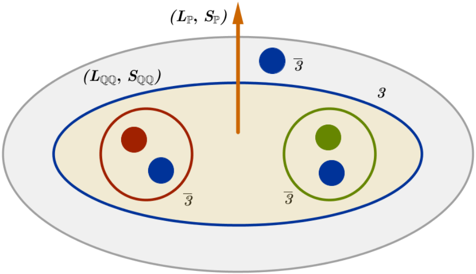
- quarks in the system interact together, each one with the others
- hadrons are made by filling q and $\bar{q}$ orbitals in a mean field or a potential or… (model dependent)
- ground state recipe: all constituents in the lowest orbital
- mass spectrum built from orbital excitations

a common problem: very large multiplicity of states

PENTAQUARK MODELS: NEW STATE

Idea: using diquarks [qq], sub-units of two quarks in $\bar{3}$ color triplet

[a review: Nucl.Phys.Proc. 142 (2005) 343]



Diquark – Diquark – Antiquark Model of Pentaquarks

pentaquark interpretation: $qqqq\bar{q} = [qq][qq]\bar{q}$

- two P_c^+ as orbital excitations [Phys.Lett. B 749 (2015) 289]
- lower multiplicity

CONCLUSIONS

- The LHCb observation of P_C^+ revives the attention on exotic pentaquark states
- Both new and old-fashioned models are proposed
- Need for new evidences in order to discern and make clear constraints on theoretical models

what's inside pentaquarks?

BACKUP: LHCb OBSERVATION

Observation of two resonances at LHCb [Phys. Rev. Lett. 115, 072001]

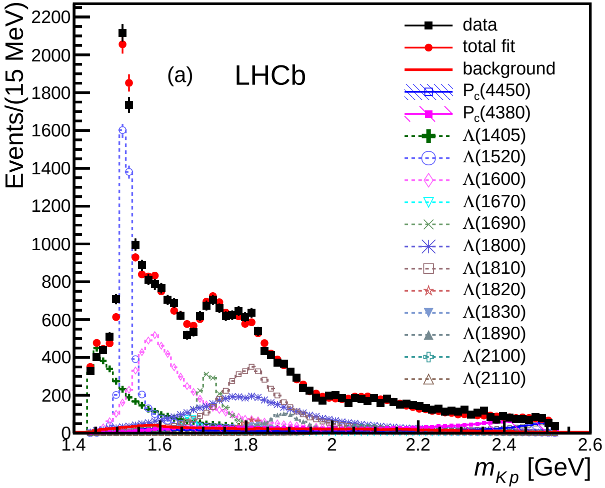
$$\mathcal{M} = 4380 \pm 8 \pm 29\text{MeV} \qquad \Gamma = 205 \pm 18 \pm 36\text{MeV}$$
$$\mathcal{M} = 4449.8 \pm 1.7 \pm 2.5\text{MeV} \qquad \Gamma = 39 \pm 5 \pm 19\text{MeV}$$

with preferred assignment $J^P = (3/2^-, 5/2^+)$ but also inverted parities and $(5/2^+, 3/2^-)$ are plausible.

Some details:

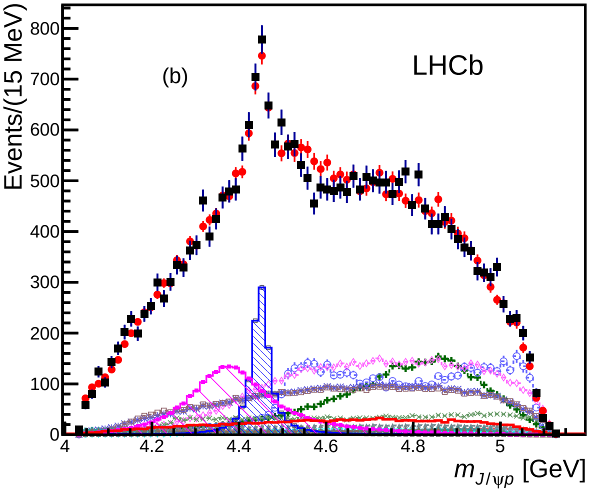
- integrated luminosity $\int L dt = 3\ \text{fb}^{-1}$
- $\sqrt{s} = 7 - 8$ TeV in pp collisions
- used 14 $\Lambda*$ resonances ($\mathcal{M}_{\Lambda*}$ from $\sim$ 1400 MeV to $\sim$ 2350 MeV)

BACKUP: LHC*b* OBSERVATION



Invariant mass combinations from $\Lambda_b^0 \to J/\psi K^- p$ decay

BACKUP: LHC*b* OBSERVATION



Invariant mass combinations from $\Lambda_b^0 \to J/\psi K^- p$ decay