The doubly heavy particles: baryons, tetraquarks and pentaquarks

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09-13 November 2020

XXXII International Workshop on High Energy Physics - Hot Problems of Strong Interactions”

In collaboration with S. S. Agaev, H. Sundu, Y. Sarac, T. M. Aliev, M. Savci, N. Er, A. R. Olamaei, S. Rostami

…. will be discussed

1- Introduction

2- Doubly heavy baryons

3-Tetraquarks, Pentaquarks

4- Concluding notes

Introduction

QCD Lagrangian

The dynamics of the quarks and gluons are controlled by the quantum chromodynamics Lagrangian

$$\mathcal{L}_{QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + \sum_q \bar{\psi}_q (i \not{D} - m_q) \psi_q.$$

$$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu - g f^{abc} G^b_\mu G^c_\nu \,, \quad \text{gluon field-strength tensor}$$

$G^a_\mu(x)$ $\Rightarrow$ The gluon field

ψ_q $\Rightarrow$ quark fields

$$\not{D} = \gamma^\mu \mathcal{D}_\mu$$

$$\mathcal{D}_\mu = \partial_\mu + i \frac{g}{2} \lambda^a G^a_\mu$$

Nonperturbative methods in QCD

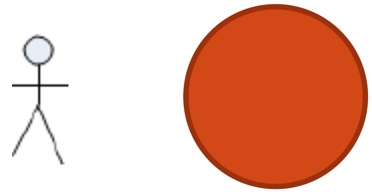
Hadrons are formed in low energies very far from perturbative regime. Therefore to calculate their parameters (properties) such as: mass, decay constant or residue lifetime, width as well as their decay properties (strong, weak and electromagnetic decays), we need some non-perturbarive methods.

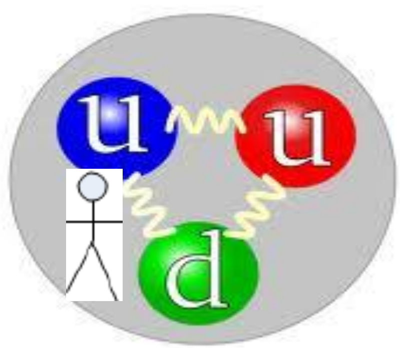
Some non-perturbative methods are:

- QCD sum rules
- Lattice QCD
- Heavy quark effective theory (HQET)
- Chiral perturbation theory,
- Soft-collinear effective theory
- Nambu-Jona-Lasinio model.
- Different relativistic and non-relativistic quark models

❑ QCD sum rules (SVZ)

hadron

Window1: 

Window2: 

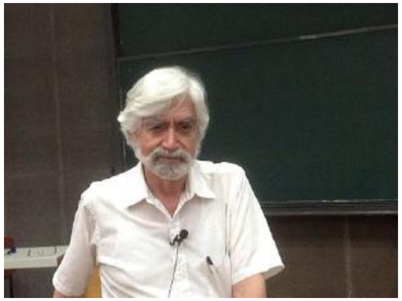
Matching: Window1 & Window2 ⇒ QCD sum rules for physical quantities

Hadrons: subatomic colorless particles made of quarks and gluons

Two main categories:
Standard Hadrons, Exotics

Quark Model: generally successful, there are puzzles regarding excited states in some channels

Murray Gell-Mann

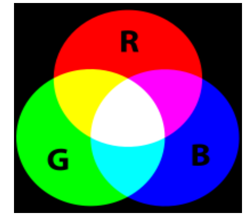


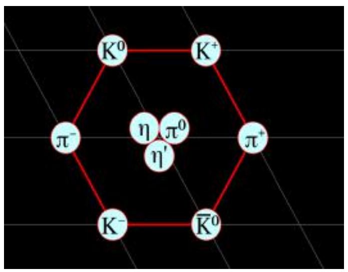
George Zweig

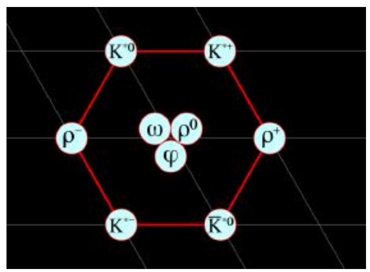
Standard Hadrons

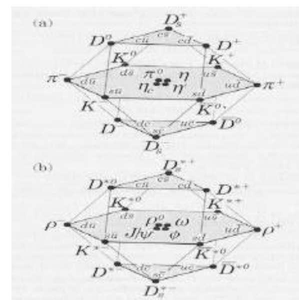
Mesons: one quark and one anti-quark (color+anticolor=white)

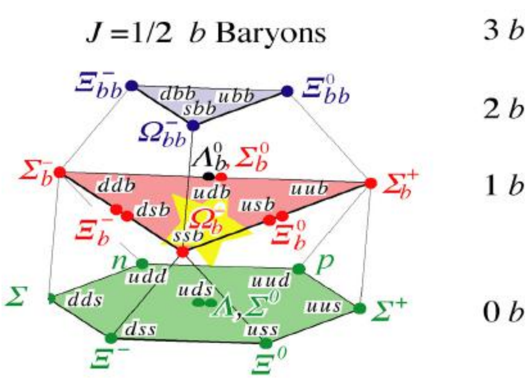
Baryons: 3 quarks or 3 anti-quarks

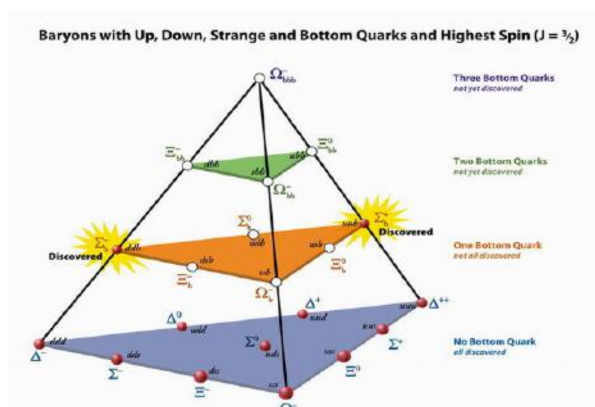






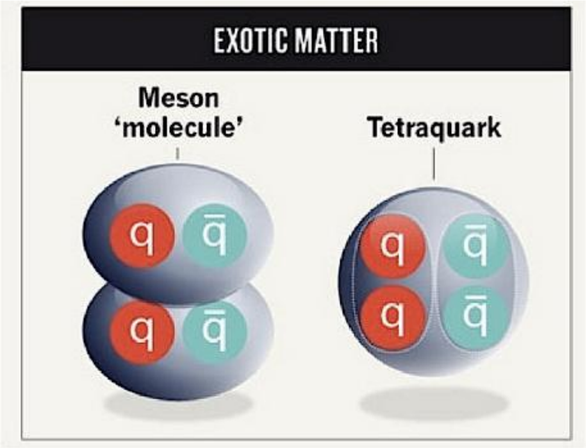




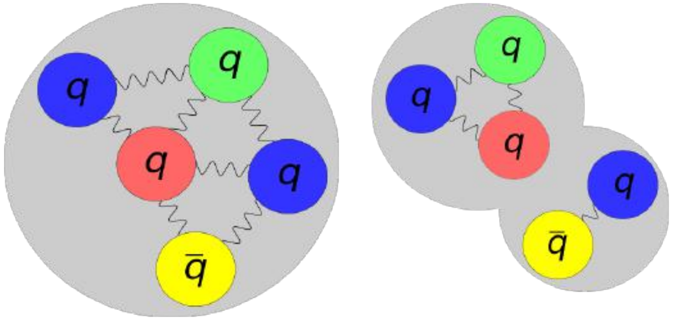


Exotics: non-conventional hadrons

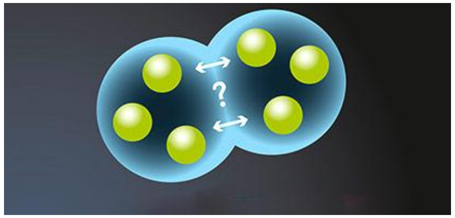
Tetraquarks



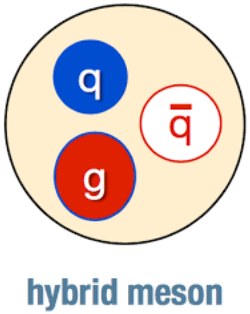
Pentaquarks



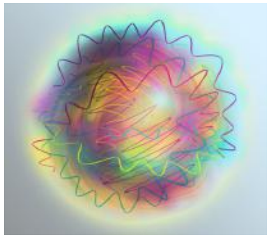
Hexaquarks, Dibaryons



Hybrids



Glueballs



Doubly heavy baryons

Doubly heavy baryons

QQ+q

spin 1/2

heavy diquark: spin 1

Doubly heavy baryons
with spin 3/2 or 1/2

with *

without *

Symmetric
Without prime

QQ'+q

spin 1/2

heavy diquark: spin 1 or 0

Doubly heavy
baryons with spin1/2

Doubly heavy baryons
with spin 3/2 or 1/2

Symmetric
Without prime

Anti-symmetric
Primed

T. M. Aliev, K. Azizi, M. Savci:

- *Nucl.Phys.A* 895 (2012) 59-70, e-Print: 1205.2873 [hep-ph]
- *Phys.Lett.B* 715 (2012) 149-151, e-Print: 1205.6320 [hep-ph]
- *J.Phys.G* 40 (2013) 065003, e-Print: 1208.1976 [hep-ph]
- *J.Phys.Conf.Ser.* 556 (2014) 1, 012016, Contribution to: BEACH 2014

Ξ_{bb}	9.96(0.90)
Ω_{bb}	9.97(0.90)
Ξ_{bc}	6.72(0.20)
Ω_{bc}	6.75(0.30)
Ξ_{cc}	3.72(0.20)
Ω_{cc}	3.73(0.20)
Ξ'_{bc}	6.79(0.20)
Ω'_{bc}	6.80(0.30)

Mass of the doubly heavy spin–1/2 baryons (GeV)

Selected for a Viewpoint in *Physics*

PRL **119,** 112001 (2017) PHYSICAL REVIEW LETTERS week ending 15 SEPTEMBER 2017

Observation of the Doubly Charmed Baryon Ξ_{cc}^{++}

R. Aaij *et al.*[*]

(LHCb Collaboration)

(Received 6 July 2017; revised manuscript received 2 August 2017; published 11 September 2017)

A highly significant structure is observed in the $\Lambda_c^+ K^- \pi^+ \pi^+$ mass spectrum, where the Λ_c^+ baryon is reconstructed in the decay mode $pK^-\pi^+$. The structure is consistent with originating from a weakly decaying particle, identified as the doubly charmed baryon Ξ_{cc}^{++}. The difference between the masses of the Ξ_{cc}^{++} and Λ_c^+ states is measured to be $1334.94 \pm 0.72(\text{stat.}) \pm 0.27(\text{syst.})\ \text{MeV}/c^2$, and the Ξ_{cc}^{++} mass is then determined to be $3621.40 \pm 0.72(\text{stat.}) \pm 0.27(\text{syst.}) \pm 0.14(\Lambda_c^+)\ \text{MeV}/c^2$, where the last uncertainty is due to the limited knowledge of the Λ_c^+ mass. The state is observed in a sample of proton-proton collision data collected by the LHCb experiment at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 1.7 fb^{-1}, and confirmed in an additional sample of data collected at 8 TeV.

DOI: 10.1103/PhysRevLett.119.112001

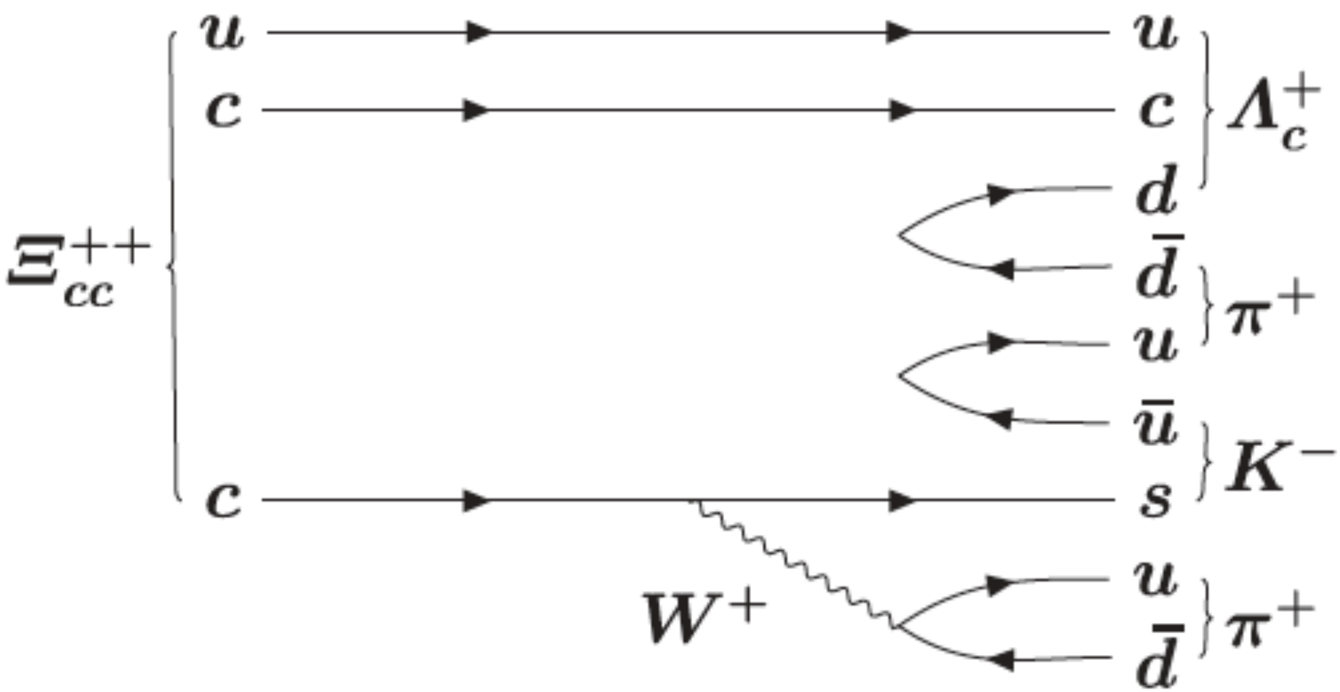


FIG. 1. Example Feynman diagram contributing to the decay $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$.

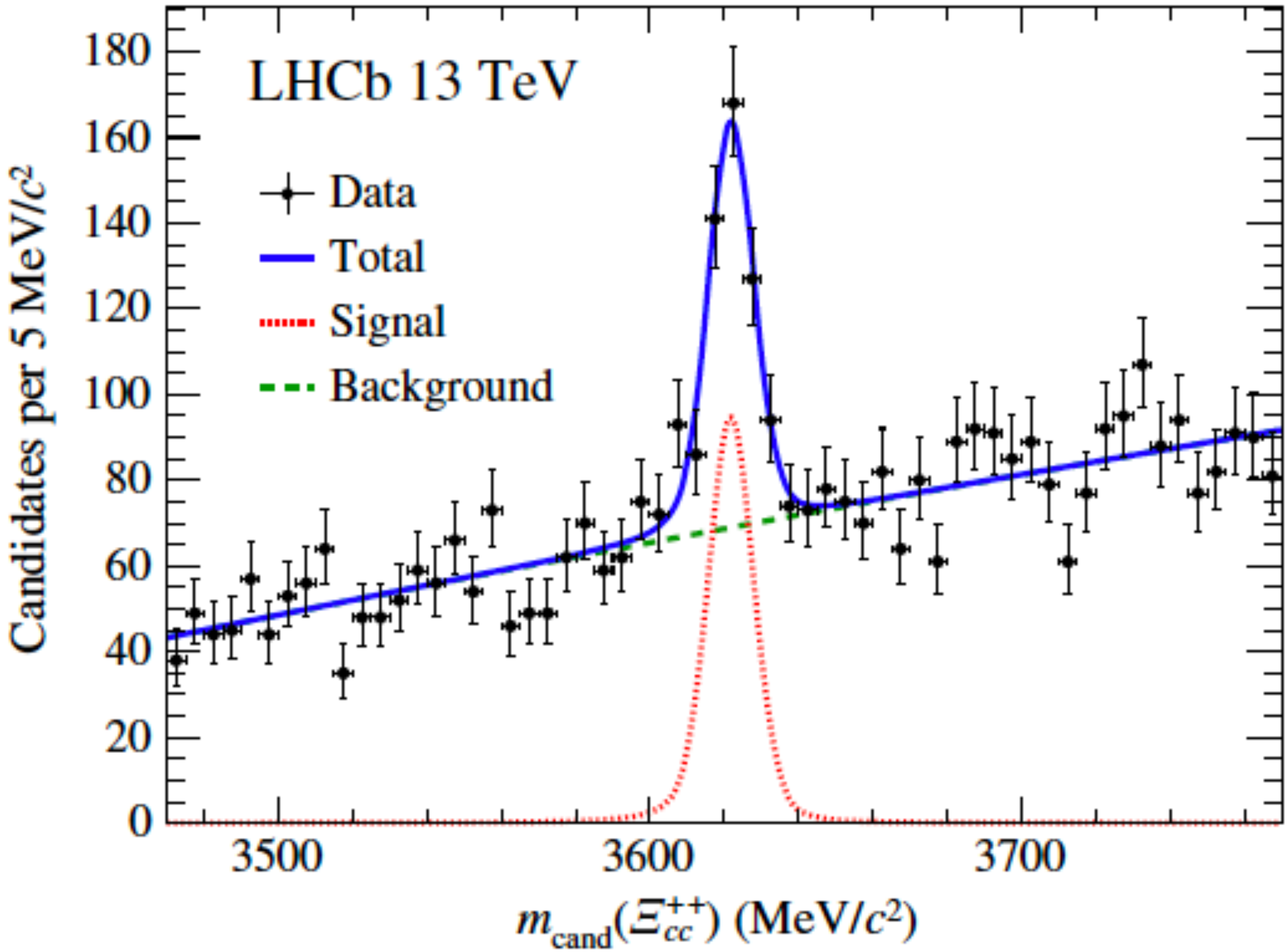


FIG. 3. Invariant mass distribution of $\Lambda_c^+ K^- \pi^+ \pi^+$ candidates with fit projections overlaid.

Was it a new discovery??????

SELEX result (2002-2005): 3518.9 +- 0.9 MeV

T. M. Aliev, K. Azizi, and M. Savcı, Nucl. Phys. A895, 59 (2012):

Mass should considerably be higher than the SELEX result

LHCb mass

$$3621.40 \pm 0.72(\text{stat.}) \pm 0.27(\text{syst.}) \pm 0.14(\Lambda_c^+)\ \text{MeV}/c^2$$

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2019 Review of Particle Physics.
M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018) and 2019 update.

Ξ_{cc}^{++} MASS

INSPIRE search

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
3621.2 ± 0.7	**OUR AVERAGE**				
$3620.6 \pm 1.5 \pm 0.4 \pm 0.3$	91	[1] AAIJ	2018BA	LHCB	pp at 13 TeV
$3621.40 \pm 0.72 \pm 0.27 \pm 0.14$	313	[2] AAIJ	2017BC	LHCB	pp at 13 TeV

[1] The third error in AAIJ 2018BA value is from the uncertainty of the Ξ_c^+ mass.

[2] The third error in AAIJ 2017BC value is from the uncertainty of the Λ_c^+ mass. The width of the signal is 6.6 ± 0.8 MeV, consistent with the experimental resolution.

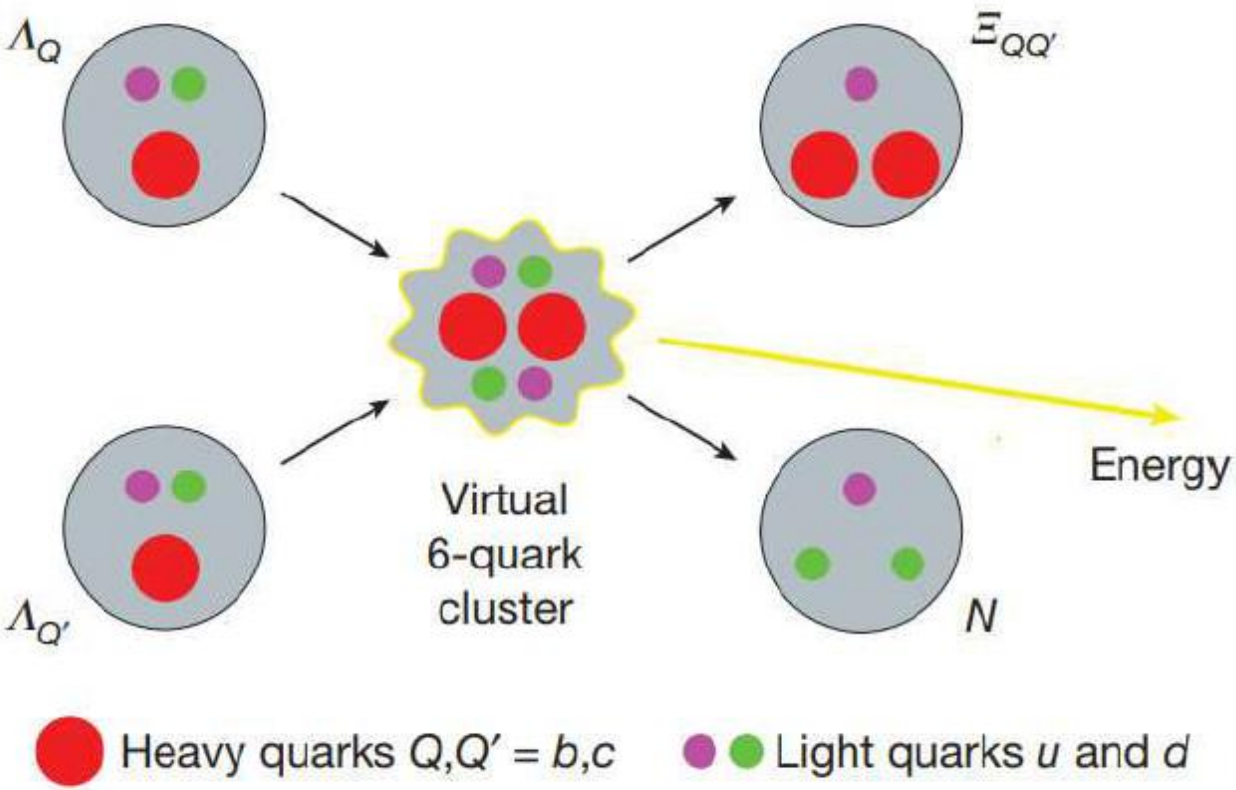
References:

AAIJ	2018BA	PRL 121 162002	First Observation of the Doubly Charmed Baryon Decay $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$
AAIJ	2017BC	PRL 119 112001	Observation of the Doubly Charmed Baryon Ξ_{cc}^{++}

Theoretical quark Fusion/S-Sexaquark as candidate for Dark Matter/QCD nature of Dark Energy

✓ **Theoretical quark Fusion:** *Nature* **551**, 89–91 (02 November 2017)

Theoretical quark fusion found to be more powerful than hydrogen fusion



Schematic depiction of quark-level exothermic fusion reactions $\Lambda Q \Lambda Q' \rightarrow \Xi QQ'N$, where $Q,Q' \in \{b, c\}$. Credit: (c) *Nature* (2017). DOI: 10.1038/nature24289

Null Result

Search for the doubly heavy Ξ_{bc}^0 baryon via decays to D^0pK^-

arXiv:2009.02481v1 [hep-ex] 5 Sep 2020

LHCb collaboration†

Abstract

A search for the doubly heavy Ξ_{bc}^0 baryon using its decay to the D^0pK^- final state is performed using proton-proton collision data at a centre-of-mass energy of 13 TeV collected by the LHCb experiment between 2016 and 2018, corresponding to an integrated luminosity of $5.4\,\mathrm{fb}^{-1}$. No significant signal is found in the invariant mass range from 6.7 to 7.2 GeV/c^2. Upper limits are set at 95% credibility level on the ratio of the Ξ_{bc}^0 production cross-section times its branching fraction to D^0pK^- relative to that of the $\Lambda_b^0 \to D^0pK^-$ decay. The limits are set as a function of the Ξ_{bc}^0 mass and lifetime hypotheses, in the rapidity range from 2.0 to 4.5 and in the transverse momentum region from 5 to 25 GeV/c. Upper limits range from 1.7×10^{-2} to 3.0×10^{-1} for the considered Ξ_{bc}^0 mass and lifetime hypotheses.

We need more information on different properties of these baryons

Strong Coupling Constants of the Doubly Heavy Spin-1/2 Baryons with Light Pseudoscalar Mesons

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[3] Department of Physics, Jahrom University, Jahrom, P. O. Box 74137-66171, Iran

[4] School of Particles and Accelerators, Institute for Research in Fundamental Sciences (IPM), P. O. Box 19395-5531, Tehran, Iran

- e-Print: 2008.12715 [hep-ph]
- *Eur.Phys.J.C* 80 (2020) 7, 613, e-Print: 2003.12723 [hep-ph]

$$\langle B_2(p,r)\mathcal{P}(q)|B_1(p+q,s)\rangle = g_{B_1 B_2 \mathcal{P}}\bar{u}(p,r)\gamma_5 u(p+q,s) ,$$

$$\eta^S = \frac{1}{\sqrt{2}}\epsilon_{abc}\Big\{(Q^{aT}Cq^b)\gamma_5 Q'^c + (Q'^{aT}Cq^b)\gamma_5 Q^c + t(Q^{aT}C\gamma_5 q^b)Q'^c + t(Q'^{aT}C\gamma_5 q^b)Q^c\Big\},$$

$$\eta^A = \frac{1}{\sqrt{6}}\epsilon_{abc}\Big\{2(Q^{aT}CQ'^b)\gamma_5 q^c + (Q^{aT}Cq^b)\gamma_5 Q'^c - (Q'^{aT}Cq^b)\gamma_5 Q^c + 2t(Q^{aT}C\gamma_5 Q'^b)q^c + t(Q^{aT}C\gamma_5 q^b)Q'^c - t(Q'^{aT}C\gamma_5 q^b)Q^c\Big\},$$

$$\Pi(p,q) = i \int d^4x e^{ipx} \langle \mathcal{P}(q)|\mathcal{T}\{\eta(x)\bar{\eta}(0)\}|0\rangle \ ,$$

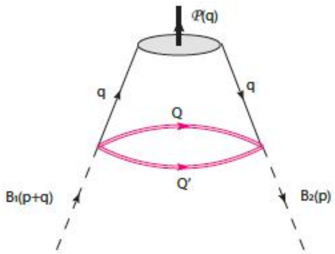

Figure 1: The leading order diagram contributing to $\Pi(p,q)$.

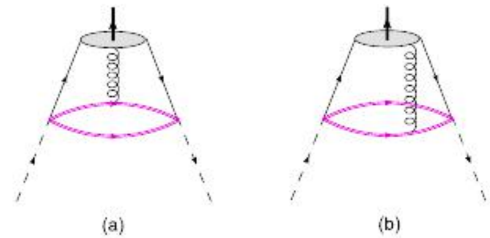

Figure 2: The one-gluon exchange diagrams.

Channel	$M^2(\mathrm{GeV}^2)$	s_0 (GeV^2)	s
		Decays to π	
$\Xi_{bb} \to \Xi_{bb}\pi^0$	$14 \le M^2 \le 18$	$105.3 \le s_0 \le 113.6$	
$\Xi_{bb} \to \Xi_{bb}\pi^\pm$	$14 \le M^2 \le 18$	$105.3 \le s_0 \le 113.6$	
$\Xi_{bc} \to \Xi_{bc}\pi^0$	$7 \le M^2 \le 10$	$49.3 \le s_0 \le 55$	
$\Xi_{bc} \to \Xi_{bc}\pi^\pm$	$7 \le M^2 \le 10$	$49.3 \le s_0 \le 55$	
$\Xi_{cc} \to \Xi_{cc}\pi^0$	$3 \le M^2 \le 6$	$15.4 \le s_0 \le 18.7$	
$\Xi_{cc} \to \Xi_{cc}\pi^\pm$	$3 \le M^2 \le 6$	$15.4 \le s_0 \le 18.7$	
$\Xi'_{bc} \to \Xi'_{bc}\pi^0$	$7 \le M^2 \le 10$	$50.3 \le s_0 \le 56.1$	
$\Xi'_{bc} \to \Xi'_{bc}\pi^\pm$	$7 \le M^2 \le 10$	$50.3 \le s_0 \le 56.1$	
$\Xi'_{bc} \to \Xi_{bc}\pi^0$	$7 \le M^2 \le 10$	$50.3 \le s_0 \le 56.1$	
$\Xi'_{bc} \to \Xi_{bc}\pi^\pm$	$7 \le M^2 \le 10$	$50.3 \le s_0 \le 56.1$	
		Decays to K	
$\Omega_{bb} \to \Xi_{bb}\bar{K}^0$	$14 \le M^2 \le 18$	$105.3 \le s_0 \le 113.6$	
$\Omega_{bb} \to \Xi_{bb}K^-$	$14 \le M^2 \le 18$	$105.5 \le s_0 \le 113.8$	
$\Omega_{bc} \to \Xi_{bc}\bar{K}^0$	$7 \le M^2 \le 10$	$49.7 \le s_0 \le 55.5$	
$\Omega_{bc} \to \Xi_{bc}K^-$	$7 \le M^2 \le 10$	$49.7 \le s_0 \le 55.5$	
$\Omega_{cc} \to \Xi_{cc}\bar{K}^0$	$3 \le M^2 \le 6$	$16.2 \le s_0 \le 19.6$	
$\Omega_{cc} \to \Xi_{cc}K^-$	$3 \le M^2 \le 6$	$16.2 \le s_0 \le 19.6$	
$\Omega'_{bc} \to \Xi'_{bc}\bar{K}^0$	$7 \le M^2 \le 10$	$50.4 \le s_0 \le 56.2$	
$\Omega'_{bc} \to \Xi'_{bc}K^-$	$7 \le M^2 \le 10$	$50.4 \le s_0 \le 56.2$	
		Decays to η	
$\Omega_{bb} \to \Omega_{bb}\eta$	$14 \le M^2 \le 18$	$105.3 \le s_0 \le 113.6$	
$\Omega_{bc} \to \Omega_{bc}\eta$	$7 \le M^2 \le 10$	$49.7 \le s_0 \le 55.5$	
$\Omega_{cc} \to \Omega_{cc}\eta$	$3 \le M^2 \le 6$	$16.2 \le s_0 \le 19.6$	
$\Omega'_{bc} \to \Omega'_{bc}\eta$	$7 \le M^2 \le 10$	$50.4 \le s_0 \le 56.2$	
		Decays to η'	
$\Omega_{bb} \to \Omega_{bb}\eta'$	$14 \le M^2 \le 18$	$105.3 \le s_0 \le 113.6$	
$\Omega_{bc} \to \Omega_{bc}\eta'$	$7 \le M^2 \le 10$	$49.7 \le s_0 \le 55.5$	
$\Omega_{cc} \to \Omega_{cc}\eta'$	$3 \le M^2 \le 6$	$16.2 \le s_0 \le 19.6$	
$\Omega'_{bc} \to \Omega'_{bc}\eta'$	$7 \le M^2 \le 10$	$50.4 \le s_0 \le 56.2$	

Channel	$M^2(\mathrm{GeV}^2)$	$s_0\ (\mathrm{GeV}^2)$	strong coupling constant
		Decays to π	
$\Xi_{bb} \to \Xi_{bb}\pi^0$	$14 \leq M^2 \leq 18$	$105.3 \leq s_0 \leq 113.6$	$17.63\,^{0.38}_{0.24}$
$\Xi_{bb} \to \Xi_{bb}\pi^\pm$	$14 \leq M^2 \leq 18$	$105.3 \leq s_0 \leq 113.6$	$24.93\,^{0.53}_{0.33}$
$\Xi_{bc} \to \Xi_{bc}\pi^0$	$7 \leq M^2 \leq 10$	$49.3 \leq s_0 \leq 55$	$3.76\,^{0.17}_{0.10}$
$\Xi_{bc} \to \Xi_{bc}\pi^\pm$	$7 \leq M^2 \leq 10$	$49.3 \leq s_0 \leq 55$	$5.32\,^{0.24}_{0.14}$
$\Xi_{cc} \to \Xi_{cc}\pi^0$	$3 \leq M^2 \leq 6$	$15.4 \leq s_0 \leq 18.7$	$5.27\,^{0.97}_{0.70}$
$\Xi_{cc} \to \Xi_{cc}\pi^\pm$	$3 \leq M^2 \leq 6$	$15.4 \leq s_0 \leq 18.7$	$7.45\,^{1.37}_{0.98}$
$\Xi'_{bc} \to \Xi'_{bc}\pi^0$	$7 \leq M^2 \leq 10$	$50.3 \leq s_0 \leq 56.1$	$7.84\,^{0.24}_{0.24}$
$\Xi'_{bc} \to \Xi'_{bc}\pi^\pm$	$7 \leq M^2 \leq 10$	$50.3 \leq s_0 \leq 56.1$	$11.08\,^{0.33}_{0.34}$
$\Xi'_{bc} \to \Xi_{bc}\pi^0$	$7 \leq M^2 \leq 10$	$50.3 \leq s_0 \leq 56.1$	$0.62\,^{0.14}_{0.13}$
$\Xi'_{bc} \to \Xi_{bc}\pi^\pm$	$7 \leq M^2 \leq 10$	$50.3 \leq s_0 \leq 56.1$	$0.89\,^{0.20}_{0.19}$
		Decays to K	
$\Omega_{bb} \to \Xi_{bb}\bar{K}^0$	$14 \leq M^2 \leq 18$	$105.3 \leq s_0 \leq 113.6$	$22.36\,^{1.30}_{0.91}$
$\Omega_{bb} \to \Xi_{bb}K^-$	$14 \leq M^2 \leq 18$	$105.5 \leq s_0 \leq 113.8$	$22.90\,^{1.31}_{0.91}$
$\Omega_{bc} \to \Xi_{bc}\bar{K}^0$	$7 \leq M^2 \leq 10$	$49.7 \leq s_0 \leq 55.5$	$4.04\,^{0.42}_{0.25}$
$\Omega_{bc} \to \Xi_{bc}K^-$	$7 \leq M^2 \leq 10$	$49.7 \leq s_0 \leq 55.5$	$4.05\,^{0.42}_{0.25}$
$\Omega_{cc} \to \Xi_{cc}\bar{K}^0$	$3 \leq M^2 \leq 6$	$16.2 \leq s_0 \leq 19.6$	$5.76\,^{1.40}_{0.80}$
$\Omega_{cc} \to \Xi_{cc}K^-$	$3 \leq M^2 \leq 6$	$16.2 \leq s_0 \leq 19.6$	$5.78\,^{1.42}_{0.84}$
$\Omega'_{bc} \to \Xi'_{bc}\bar{K}^0$	$7 \leq M^2 \leq 10$	$50.4 \leq s_0 \leq 56.2$	$11.11\,^{1.20}_{0.76}$
$\Omega'_{bc} \to \Xi'_{bc}K^-$	$7 \leq M^2 \leq 10$	$50.4 \leq s_0 \leq 56.2$	$11.14\,^{1.19}_{0.75}$
		Decays to η	
$\Omega_{bb} \to \Omega_{bb}\eta$	$14 \leq M^2 \leq 18$	$105.3 \leq s_0 \leq 113.6$	$17.20\,^{0.75}_{0.75}$
$\Omega_{bc} \to \Omega_{bc}\eta$	$7 \leq M^2 \leq 10$	$49.7 \leq s_0 \leq 55.5$	$3.36\,^{0.25}_{0.15}$
$\Omega_{cc} \to \Omega_{cc}\eta$	$3 \leq M^2 \leq 6$	$16.2 \leq s_0 \leq 19.6$	$4.14\,^{0.90}_{0.48}$
$\Omega'_{bc} \to \Omega'_{bc}\eta$	$7 \leq M^2 \leq 10$	$50.4 \leq s_0 \leq 56.2$	$8.38\,^{0.64}_{0.42}$
		Decays to η'	
$\Omega_{bb} \to \Omega_{bb}\eta'$	$14 \leq M^2 \leq 18$	$105.3 \leq s_0 \leq 113.6$	$9.54\,^{0.90}_{0.77}$
$\Omega_{bc} \to \Omega_{bc}\eta'$	$7 \leq M^2 \leq 10$	$49.7 \leq s_0 \leq 55.5$	$1.78\,^{0.24}_{0.18}$
$\Omega_{cc} \to \Omega_{cc}\eta'$	$3 \leq M^2 \leq 6$	$16.2 \leq s_0 \leq 19.6$	$1.80\,^{0.80}_{0.80}$
$\Omega'_{bc} \to \Omega'_{bc}\eta'$	$7 \leq M^2 \leq 10$	$50.4 \leq s_0 \leq 56.2$	$4.43\,^{0.76}_{0.62}$

Strong interaction of doubly heavy spin-3/2 baryons with light vector mesons

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• e-Print: 2011.02919 [hep-ph]

$$\langle B_2^*(p,r)V(q) \mid B_1^*(p+q,s)\rangle = \bar{u}_\alpha(p,r)\left\{ g^{\alpha\beta}\left[\not{\varepsilon} g_1 + 2(p.\varepsilon)\frac{g_2}{m_1+m_2}\right] + \frac{q^\alpha q^\beta}{(m_1+m_2)^2}\left[\not{\varepsilon} g_3 + 2(p.\varepsilon)\frac{g_4}{m_1+m_2}\right]\right\} u_\beta(p+q,s)$$

Vertex	g_1	g_2	g_3	g_4
$\Xi^*_{bb}\Xi^*_{bb}\rho^0$	$45.8^{2.5}_{2.0}$	$164.1^{5.9}_{2.0}$	162.6^{24}_{20}	$24.8^{4.1}_{3.6}$
$\Xi^*_{bc}\Xi^*_{bc}\rho^0$	$12.3^{0.4}_{0.3}$	$35.3^{1.0}_{0.7}$	$43.3^{8.1}_{6.5}$	$6.9^{0.8}_{0.8}$
$\Xi^*_{cc}\Xi^*_{cc}\rho^0$	$4.5^{0.5}_{0.4}$	$8.98^{1.4}_{1.3}$	$11.5^{0.7}_{0.5}$	$1.6^{0.04}_{0.04}$
$\Xi^*_{bb}\Xi^*_{bb}\rho^\pm$	$64.8^{3.5}_{2.8}$	$232.04^{8.4}_{5.6}$	$229.9^{34.5}_{29.2}$	$35.2^{5.8}_{5.2}$
$\Xi^*_{bc}\Xi^*_{bc}\rho^\pm$	$17.4^{0.6}_{0.4}$	$49.8^{1.5}_{1.1}$	$61.2^{11.4}_{9.3}$	$9.7^{1.2}_{1.1}$
$\Xi^*_{cc}\Xi^*_{cc}\rho^\pm$	$6.3^{0.7}_{0.6}$	$12.7^{2}_{1.8}$	$16.3^{1.0}_{0.7}$	$2.3^{0.06}_{0.06}$
$\Xi^*_{bb}\Xi^*_{bb}\omega$	$56.7^{2.9}_{2.3}$	$207.5^{6.9}_{4.5}$	$200.9^{30.1}_{25.5}$	$34.2^{6.0}_{5.2}$
$\Xi^*_{bc}\Xi^*_{bc}\omega$	$15.27^{2.9}_{2.3}$	$44.44^{1.1}_{0.9}$	53.46^{10}_{8}	$9.70^{1.4}_{1.3}$
$\Xi^*_{cc}\Xi^*_{cc}\omega$	$5.6^{0.7}_{0.6}$	$11.3^{1.8}_{1.7}$	$14.2^{0.9}_{0.6}$	$2.2^{0.06}_{0.07}$
$\Omega^*_{bb}\Omega^*_{bb}\phi$	$62.7^{1.6}_{1.2}$	$215.5^{7.2}_{4.8}$	264.9^{44}_{37}	$33.1^{3.3}_{3.2}$
$\Omega^*_{bc}\Omega^*_{bc}\phi$	$14.2^{0.2}_{0.1}$	$37.3^{0.5}_{0.6}$	$60.2^{12.1}_{9.8}$	$5.2^{0.7}_{1.2}$
$\Omega^*_{cc}\Omega^*_{cc}\phi$	$6.5^{0.8}_{0.8}$	$10.1^{1.9}_{1.8}$	$18.5^{1.7}_{1.2}$	$1.5^{0.4}_{0.6}$
$\Omega^*_{bb}\Xi^*_{bb}K^{*0}$	$71.5^{3.3}_{2.6}$	251.8^{9}_{6}	262.8^{4}_{3}	$25.3^{1.6}_{1.7}$
$\Omega^*_{bc}\Xi^*_{bc}K^{*0}$	$18.1^{0.4}_{0.2}$	$49.0^{1.0}_{0.9}$	64.7^{12}_{10}	$3.9^{1.0}_{1.6}$
$\Omega^*_{cc}\Xi^*_{cc}K^{*0}$	$7.4^{0.8}_{0.7}$	$13.1^{2.0}_{2.0}$	$18.5^{1.4}_{1.0}$	$1.0^{0.5}_{0.6}$
$\Xi^*_{bb}\Omega^*_{bb}\bar{K}^{*0}$	$72.7^{3.4}_{2.7}$	$251.6^{9.1}_{6.2}$	262.6^{41}_{35}	$25.3^{1.6}_{1.7}$
$\Xi^*_{bc}\Omega^*_{bc}\bar{K}^{*0}$	$18.2^{0.4}_{0.2}$	$49.0^{1.1}_{0.9}$	$64.7^{12.5}_{10.2}$	$4.0^{1.0}_{1.6}$
$\Xi^*_{cc}\Omega^*_{cc}\bar{K}^{*0}$	$7.6^{0.8}_{0.8}$	$13.1^{2.1}_{2.0}$	$18.4^{1.4}_{1.0}$	$1.1^{0.5}_{0.6}$

Tetraquarks, Pentaquarks

Some Candidates:

X (3872): 2003 Belle

D_{sJ}(2632): 2004 Fermilab SELEX

Z(4430): 2007 Belle

Y(4140) : 2009 Fermilab, 2012 CMS, 2013 D0,
Belle did not found, LHCb ?

Zc(3900): 2013 BESIII, Belle

Z(4430):2014 LHCb

X(5568): February 2016 D0, LHCb and CMS did not found.

X(4274), X(4500) and X(4700): June 2016 LHCb

X_0(2900): 2020 LHCb

For a history on theoretical studies see for instance:

Phys.Rev. D93 (2016) no.7, 074002 ;
Phys.Rev. D93 (2016) no.11, 114036 .

Despite a lot of theoretical and experimental studies on exotic states their structure and quark organizations remain unclear.

Zc(3900): 2013 BESIII, Belle

Its mass and width was available from the experiment

PHYSICAL REVIEW D **93,** 074002 (2016)

Strong $Z_c^+(3900) \to J/\psi\pi^+;\ \eta_c\rho^+$ decays in QCD

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(Received 14 January 2016; published 1 April 2016)

The widths of the strong decays $Z_c^+(3900) \to J/\psi\pi^+$ and $Z_c^+(3900) \to \eta_c\rho^+$ are calculated. To this end, the mass and decay constant of the exotic $Z_c^+(3900)$ state are computed by means of a two-point sum rule. The obtained results are then used to calculate the strong couplings $g_{Z_cJ/\psi\pi}$ and $g_{Z_c\eta_c\rho}$ employing QCD sum rules on the light cone supplied by a technique of the soft-meson approximation. We compare our predictions on the mass and decay widths with available experimental data and other theoretical results.

DOI: 10.1103/PhysRevD.93.074002

THE MASS AND DECAY CONSTANT OF THE Z_c STATE

$$\Pi_{\mu\nu}(q) = i \int d^4 x e^{iq\cdot x} \langle 0|\mathcal{T}\{J_\mu^{Z_c}(x) J_\nu^{Z_c\dagger}(0)\}|0\rangle, \qquad (1)$$

where the interpolating current with required quantum numbers $J^{PC} = 1^{+-}$ is given by the following expression:

$$J_\nu^{Z_c}(x) = \frac{i\epsilon\tilde{\epsilon}}{\sqrt{2}}\{[u_a^T(x)C\gamma_5 c_b(x)][\bar{d}_d(x)\gamma_\nu C\bar{c}_e^T(x)]$$
$$-[u_a^T(x)C\gamma_\nu c_b(x)][\bar{d}_d(x)\gamma_5 C\bar{c}_e^T(x)]\}. \qquad (2)$$

Here we have introduced the shorthand notations $\epsilon = \epsilon_{abc}$ and $\tilde{\epsilon} = \epsilon_{dec}$. In Eq. (2) a, b, c, d, e are color indexes and C is the charge conjugation matrix.

TABLE II. Experimental data and theoretical predictions for the mass of Z_c state.

	m_{Z_c} (MeV)
BESIII [26]	3899 ± 6
Belle [27]	3895 ± 8
Present work	3900 ± 210
Z. Wang, T. Huang [32]	3910^{+110}_{-90}

For the decay constant we get

$$f_{Z_c} = (0.46 \pm 0.03) \times 10^{-2}\ \mathrm{GeV}^4.$$

Main input to analyze its strong, weak and electromagnetic decays

To calculate its width we consider its dominant decays

THE STRONG VERTICES $Z_c J/\psi\pi$ AND $Z_c\eta_c\rho$

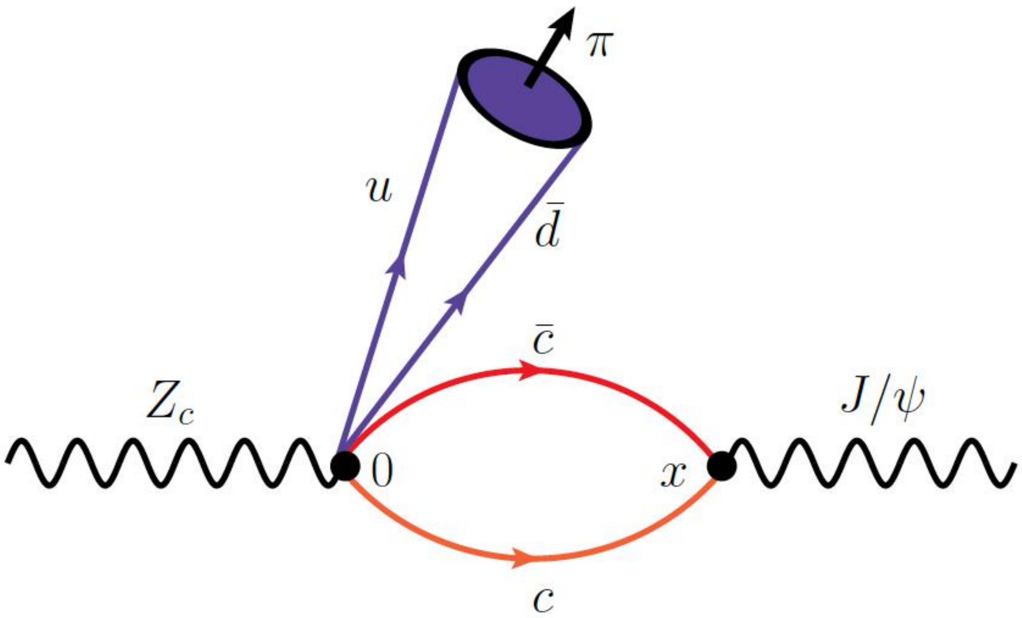

FIG. 1. Sample diagram for the decay $Z_c \to J/\psi\pi$.

$$\langle J/\psi(p)\pi(q)|Z_c(p')\rangle = [(p \cdot p')(\varepsilon^* \cdot \varepsilon') - (p \cdot \varepsilon')(p' \cdot \varepsilon^*)] g_{Z_c J/\psi\pi},$$

Considering the transitions $Z_c \to J/\psi\pi$ and $Z_c \to \eta_c\rho$ as dominant channels we obtain for the total width of Z_c

$$\Gamma_{Z_c} = 65.7 \pm 10.6 \text{ MeV},$$

Belle Data 63 ± 35 MeV

BESIII Data 46 ± 22 MeV

Comparision of the theoretical results on both the mass and width with the experimental data results in:

Z_c(3900) can be considered as a hidden charm axial vector tetraquark

PHYSICAL REVIEW D **101,** 074037 (2020)

Properties of $Z_c(3900)$ tetraquark in a cold nuclear matter

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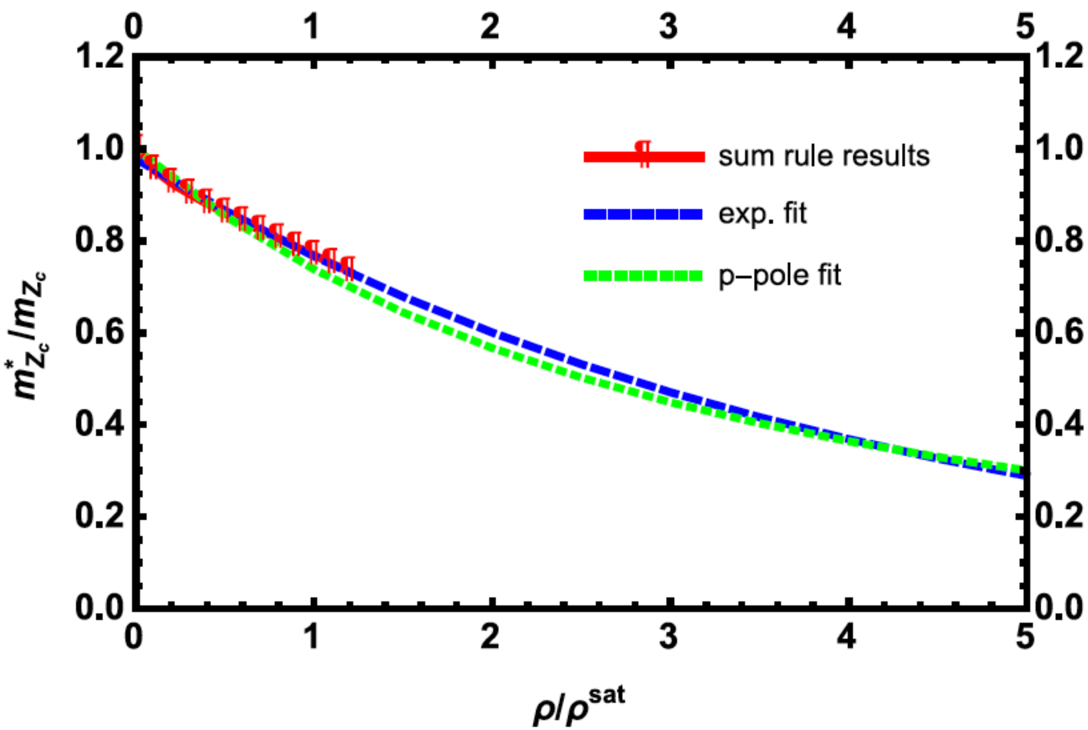
(Received 25 January 2020; accepted 13 April 2020; published 27 April 2020)

$$\Pi_{\mu\nu}(p) = i \int d^4 x e^{ip\cdot x} \langle \psi_0 | \mathcal{T}[J_\mu(x) J_\nu^\dagger(0)] | \psi_0 \rangle,$$

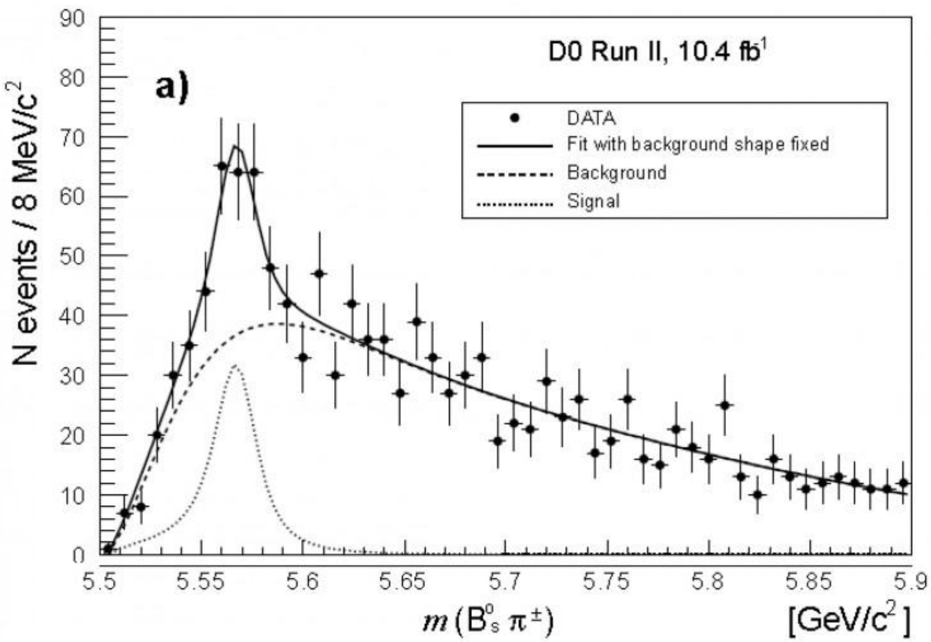


Fermilab: http://news.fnal.gov/2016/02/dzero-discovers-a-new-particle-consistent-with-a-tetraquark/

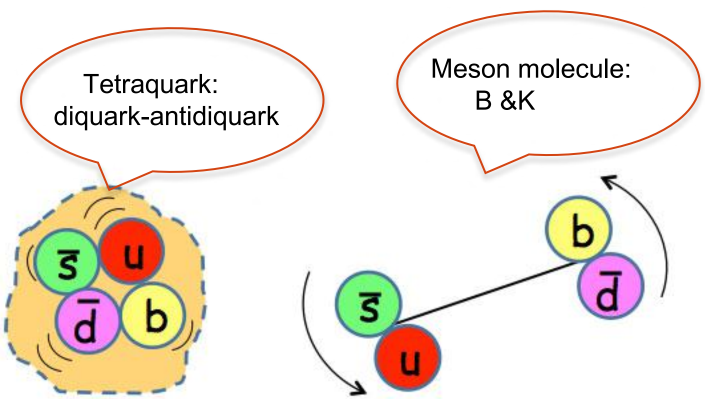
February 25, 2016

D0 discovers a new particle consistent with a tetraquark: X(5568)

(with 5.1 standard deviation significance)



Only particle made of four different quark flavors



$J^{PC}=0^{++}$

$X(5568) \rightarrow B^0_s\pi^\pm,\ B^0_s \rightarrow J/\psi\phi,\ J/\psi \rightarrow \mu^+\mu^-,\ \phi \rightarrow K^+K^-$

based on $p\bar{p}$ collision data at $\sqrt{s} = 1.96$ TeV

First version of D0 Paper: arxiv: 1602.07588v1

Observation of a new $B_s^0\pi^\pm$ state

We report the observation of a narrow structure, $X(5568)$, in the decay sequence $X(5568) \to B_s^0\pi^\pm$, $B_s^0 \to J/\psi\phi$, $J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$. This is the first observation of a hadronic state with valence quarks of four different flavors. The mass and natural width of the new state are measured to be $m = 5567.8 \pm 2.9\,(\text{stat})^{+0.9}_{-1.9}\,(\text{syst})\ \text{MeV}/c^2$ and $\Gamma = 21.9 \pm 6.4\,(\text{stat})^{+5.0}_{-2.5}\,(\text{syst})\ \text{MeV}/c^2$, and the significance including look-elsewhere effect and systematic uncertainties is 5.1σ. The observation is based on $10.4\ \text{fb}^{-1}$ of $p\overline{p}$ collision data at $\sqrt{s} = 1.96$ TeV collected by the D0 experiment at the Fermilab Tevatron collider.

LHCb (5-6 months later): No significant excess is found.

arxiv: 1608.00435, Phys. Rev. Lett. 117, 152003 (2016)

Later: very similar conclusions were drawn by CMS

The CMS Collaboration, CMS PAS BPH-16-002.

Final version of D0 Paper: arxiv: 1602.07588v5

Phys. Rev. Lett. 117, 022003 (2016)

Evidence for a $B_s^0\pi^\pm$ State

We report evidence for a narrow structure, $X(5568)$, in the decay sequence $X(5568) \to B_s^0\pi^\pm$, $B_s^0 \to J/\psi\phi$, $J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$. This is evidence for the first instance of a hadronic state with valence quarks of four different flavors. The mass and natural width of this state are measured to be $m = 5567.8 \pm 2.9\,(\text{stat})^{+0.9}_{-1.9}\,(\text{syst})$ MeV$/c^2$ and $\Gamma = 21.9 \pm 6.4\,(\text{stat})^{+5.0}_{-2.5}\,(\text{syst})$ MeV$/c^2$. If the decay is $X(5568) \to B_s^*\pi^\pm \to B_s^0\gamma\pi^\pm$ with an unseen γ, $m(X(5568))$ will be shifted up by $m(B_s^*) - m(B_s^0) \sim 49$ MeV$/c^2$. This measurement is based on 10.4 fb^{-1} of $p\overline{p}$ collision data at $\sqrt{s} = 1.96$ TeV collected by the D0 experiment at the Fermilab Tevatron collider.

Further experimental analyses are needed

In theoretical side, however, a close and compress competition was started after D0 announcement on 25 February 2016

PHYSICAL REVIEW D **93,** 074024 (2016)

Mass and decay constant of the newly observed exotic $X(5568)$ state

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(Received 27 February 2016; published 20 April 2016)

The mass and decay constant of the $X(5568)$ state newly observed by the D0 Collaboration are computed within the two-point sum rule method using the diquark-antidiquark interpolating current. In calculations, the vacuum condensates up to eight dimensions are taken into account. The obtained result for the mass of the $X(5568)$ state is in a nice agreement with the experimental data.

DOI: 10.1103/PhysRevD.93.074024

We adopted

quantum numbers $J^{\mathrm{PC}} = 0^{++}$

diquark-antidiquark $[su][\overline{b}\,\overline{d}]$

$$J^{X_b}(x) = \varepsilon^{ijk}\varepsilon^{imn}[s^j(x)C\gamma_\mu u^k(x)][\overline{b}^m(x)\gamma^\mu C\overline{d}^n(x)].$$

Results:

$$\boxed{m_{X_b} = (5584 \pm 137)\ \mathrm{MeV}.}$$

agrees with experimental data of the D0 Collaboration

$$\boxed{5567.8 \pm 2.9\ (\mathrm{stat})^{+0.9}_{-1.9}\ (\mathrm{syst})\ \mathrm{MeV}/c^2}$$

For decay constant we get

$$\boxed{f_{X_b} = (0.24 \pm 0.02) \times 10^{-2}\ \mathrm{GeV}^4.}$$

Its width in the same picture

PHYSICAL REVIEW D **93,** 114007 (2016)

Width of the exotic $X_b(5568)$ state through its strong decay to $B_s^0\pi^+$

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(Received 1 March 2016; revised manuscript received 21 April 2016; published 7 June 2016)

The width of the newly observed exotic state $X_b(5568)$ is calculated via its dominant strong decay to $B_s^0\pi^+$ using the QCD sum rule method on the light cone in conjunction with the soft-meson approximation. To this end, the vertex $X_bB_s\pi$ is studied and the strong coupling $g_{X_bB_s\pi}$ is computed employing for $X_b(5568)$ state the interpolating diquark-antidiquark current of the $[su][\bar{b}\,\bar{d}]$ type. The obtained prediction for the decay width of $X_b(5568)$ is confronted and a nice agreement found with the experimental data of the D0 Collaboration.

DOI: 10.1103/PhysRevD.93.114007

$$\boxed{\Gamma(X_b \to B_s^0\pi^+) = (22.4 \pm 9.2)\ \mathrm{MeV},}$$

which is in a good consistency with the experimental data of the D0 Collaboration.

$$\boxed{\Gamma = 21.9 \pm 6.4(\mathrm{stat})^{+5.0}_{-2.5}(\mathrm{syst})\ \mathrm{MeV}}$$

PHYSICAL REVIEW D **93,** 094006 (2016)

Charmed partner of the exotic $X(5568)$ state and its properties

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(Received 4 March 2016; revised manuscript received 26 April 2016; published 6 May 2016)

The mass, decay constant, and width of a hypothetical charmed partner X_c of the newly observed exotic $X_b(5568)$ state are calculated using the technique of the QCD sum rule method. The $X_c = [su][\bar{c}\,\bar{d}]$ state with $J^P = 0^+$ is described, employing two types of the diquark-antidiquark interpolating currents. The evaluation of the mass m_{X_c} and decay constant f_{X_c} is carried out utilizing the two-point sum rule method by including vacuum condensates up to eight dimensions. The widths of the decay channels $X_c \to D_s^- \pi^+$ and $X_c \to D^0 K^0$ are also found. To this end, the strong couplings $g_{X_c D_s \pi}$ and $g_{X_c DK}$ are computed by means of QCD sum rules on the light-cone and soft-meson approximation.

$$m_{X_c} = (2590 \pm 60)\ \text{MeV},$$

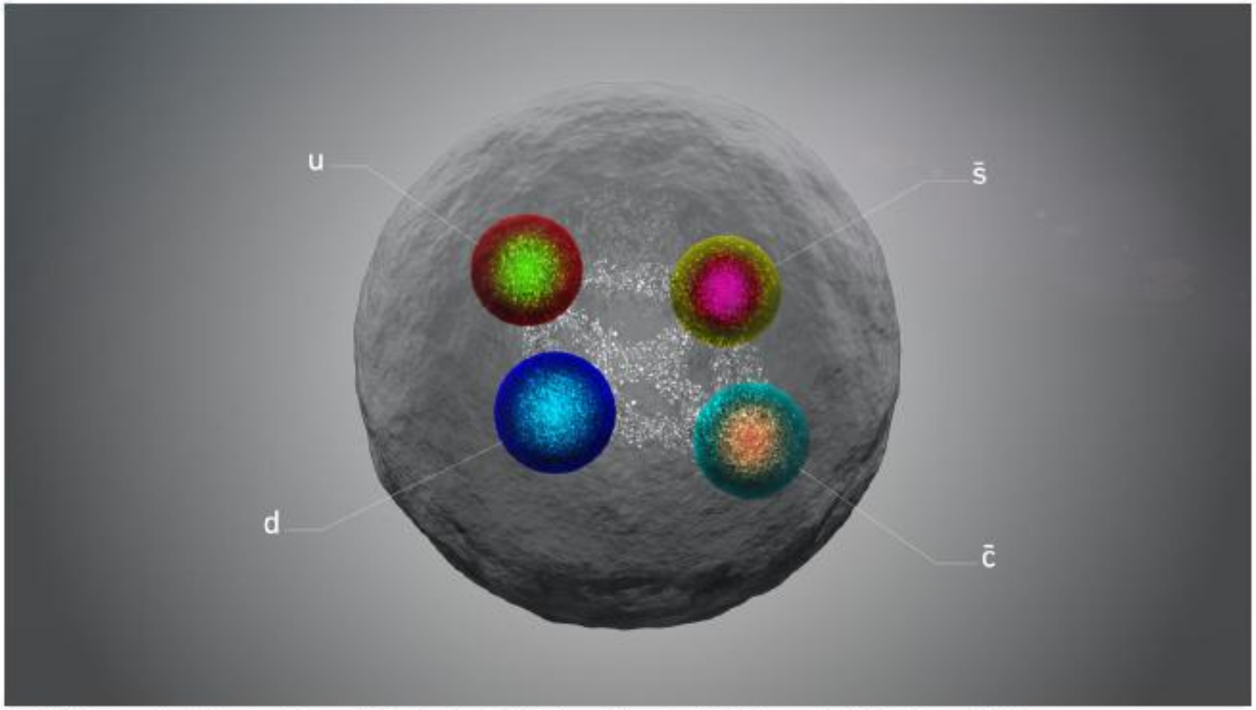
$$m_{X_c} = (2634 \pm 62)\ \text{MeV},$$

Voir en [français]

LHCb discovers first "open-charm" tetraquark

The particle, which has been called X(2900), was detected by analysing all the data LHCb has recorded so far from collisions at CERN's Large Hadron Collider

21 AUGUST, 2020 | By Achintya Rao



An artist's impression of the new tetraquark showing the individual constituent particles (Image: Daniel Dominguez/CERN)

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2020-159
LHCb-PAPER-2020-025
September 1, 2020

September 1 2020

Amplitude analysis of the $B^+ \to D^+ D^- K^+$ decay

LHCb collaboration†

The LHCb collaboration recently announced about observation of two resonant structures $X_0(2900)$ and $X_1(2900)$ (hereafter X_0 and X_1, respectively) in the invariant $D^- K^+$ mass distribution of the decay $B^+ \to D^+ D^- K^+$ [1]. The collaboration extracted their masses and widths, as well as determined their spin-parities. Thus, it was proved that the X_0 is the scalar resonance $J^{\mathrm{P}} = 0^+$ with parameters

$$\begin{aligned} m_0 &= (2866.3 \pm 6.5 \pm 2.0)\ \mathrm{MeV}, \\ \Gamma_0 &= (57.2 \pm 12.2 \pm 4.1)\ \mathrm{MeV}, \end{aligned} \quad (1)$$

whereas X_1 is the vector state $J^{\mathrm{P}} = 1^-$ and has the mass and width

$$\begin{aligned} m_1 &= (2904.1 \pm 4.8 \pm 1.3)\ \mathrm{MeV}, \\ \Gamma_1 &= (110.3 \pm 10.7 \pm 4.3)\ \mathrm{MeV}. \end{aligned} \quad (2)$$

New scalar resonance $X_0(2900)$ as a $\overline{D}^* K^*$ molecule: Mass and width

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[5] *Department of Physics, Kocaeli University, 41380 Izmit, Turkey*

(ΩDated: September 1, 2020)

arXiv:2008.13027 **[hep-ph]**

$X_0(2900)$ $\overline{D}^* K^*$

$$J(x) = [\overline{s}_a(x)\gamma_\mu d_a(x)][\overline{c}_b(x)\gamma^\mu u_b(x)],$$

$$m = (2868 \pm 198) \text{ MeV},$$
$$f = (3.0 \pm 0.7) \times 10^{-3} \text{ GeV}^4.$$

$$\Gamma\left[X_0 \to D^- K^+\right] = (49.6 \pm 9.3) \text{ MeV}.$$

In a good agreement with LHCb data

Pentaquarks:

Pentaquarks have a long experimental history:

K. Azizi, Y. Sarac, H. Sundu, Phys. Rev. D 95, 094016 (2017) [arXiv:1612.07479]

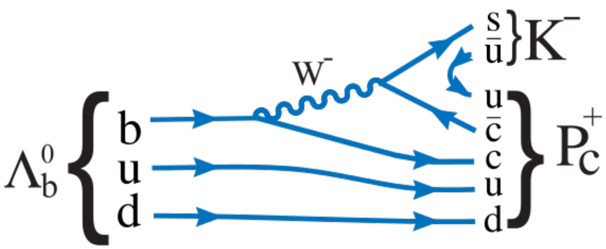
LHCb Pentaquarks, 2015:P_c (4380) and P_c(4450)

R. Aaij et al. [LHCb Collaboration], Phys. Rev. Lett.115, 072001 (2015).

The LHCb collaboration[1]

Abstract

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.



LHCb Pentaquarks, 2015

PHYSICAL REVIEW D **95**, 094016 (2017)

Analysis of $P_c^+(4380)$ and $P_c^+(4450)$ as pentaquark states in the molecular picture with QCD sum rules

K. Azizi,[1] Y. Sarac,[2] and H. Sundu[3]

We consider them as meson-baryon moleculs

THE PENTAQUARK $P_c^+(4380)$ STATE WITH $J = 3/2$

$$J_\mu^{\bar{D}^*\Sigma_c} = [\bar{c}_d\gamma_\mu d_d][\epsilon_{abc}(u_a^T C\gamma_\theta u_b)\gamma^\theta\gamma_5 c_c].$$

THE PENTAQUARK $P_c^+(4450)$ STATE WITH $J = 5/2$

admixture of

$$J_{\mu\nu}^{\bar{D}\Sigma_c^*} = [\bar{c}_d\gamma_\mu\gamma_5 d_d][\epsilon_{abc}(u_a^T C\gamma_\nu u_b)c_c] + \{\mu \leftrightarrow \nu\},$$
$$J_{\mu\nu}^{\bar{D}^*\Lambda_c} = [\bar{c}_d\gamma_\mu u_d][\epsilon_{abc}(u_a^T C\gamma_\nu\gamma_5 d_b)c_c] + \{\mu \leftrightarrow \nu\}.$$

TABLE II. The results of QCD sum rules calculations for the mass and residue of the pentaquark states.

J^P	m (GeV)	λ (GeV^6)
$\frac{3}{2}^+$	4.24 ± 0.16	$(0.59 \pm 0.07) \times 10^{-3}$
$\frac{3}{2}^-$	4.30 ± 0.10	$(0.94 \pm 0.05) \times 10^{-3}$
$\frac{5}{2}^+$	4.44 ± 0.15	$(1.01 \pm 0.23) \times 10^{-3}$
$\frac{5}{2}^-$	4.20 ± 0.15	$(0.51 \pm 0.09) \times 10^{-3}$

Exp. data $4380 \pm 8 \pm 29$ MeV

$4449.8 \pm 1.7 \pm 2.5$ MeV

Hidden Bottom Pentaquark States with Spin 3/2 and 5/2

K. Azizi,[1] Y. Sarac,[2] and H. Sundu[3]

Phys. Rev. D 96, 094030 (2017)

J^P	m (GeV)	λ (GeV^6)
$\frac{3}{2}^+$	$11.29^{+0.92}_{-1,01}$	$(2.89^{+0.52}_{-0,61}) \times 10^{-2}$
$\frac{3}{2}^-$	$11.46^{+0.87}_{-0,87}$	$(4.82^{+0.85}_{-0,99}) \times 10^{-2}$
$\frac{5}{2}^+$	$11.27^{+0.97}_{-0,98}$	$(5.58^{+1.49}_{-1,64}) \times 10^{-2}$
$\frac{5}{2}^-$	$10.59^{+0.98}_{-0,97}$	$(0.65^{+0.17}_{-0,15}) \times 10^{-2}$

TABLE II: The results of QCD sum rules calculations for the mass and residue of the bottom pentaquark states.

The LHCb searches for these states, as well.

PHYSICAL REVIEW LETTERS **122,** 222001 (2019)

Editors' Suggestion   Featured in Physics

Observation of a Narrow Pentaquark State, $P_c(4312)^+$, and of the Two-Peak Structure of the $P_c(4450)^+$

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(Received 6 April 2019; published 5 June 2019)

A narrow pentaquark state, $P_c(4312)^+$, decaying to $J/\psi p$, is discovered with a statistical significance of 7.3σ in a data sample of $\Lambda_b^0 \to J/\psi p K^-$ decays, which is an order of magnitude larger than that previously analyzed by the LHCb Collaboration. The $P_c(4450)^+$ pentaquark structure formerly reported by LHCb is confirmed and observed to consist of two narrow overlapping peaks, $P_c(4440)^+$ and $P_c(4457)^+$, where the statistical significance of this two-peak interpretation is 5.4σ. The proximity of the $\Sigma_c^+ \bar{D}^0$ and $\Sigma_c^+ \bar{D}^{*0}$ thresholds to the observed narrow peaks suggests that they play an important role in the dynamics of these states.

DOI: 10.1103/PhysRevLett.122.222001

Properties of $P_c(4312)$ pentaquark

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(Dated: November 7, 2020)

We present an analysis of the newly observed pentaquark $P_c(4312)^+$ to enlighten its quantum numbers. To do that, the QCD sum rule approach is used. This particle is close to $\Sigma_c^{++}\bar{D}^-$ threshold and has a small width, and this supports its possibility of being a molecular state. To this end, we consider an interpolating current in the molecular form and analyze both the positive and negative parity states with spin-$\frac{1}{2}$. Our mass result supports that, the quantum numbers of the observed state is consistent with $J^P = \frac{1}{2}^-$.

$$J = \left[\epsilon^{abc}(u_a^T C\gamma_\mu u_b)\gamma^\mu\gamma_5 c_c\right]\left[\bar{c}_d\gamma_5 d_d\right],$$

Resonance		This work (MeV)	Experiment (MeV)
$P_c(4312)$	Mass	4322.39 ± 342.03	$4311.9 \pm 0.7^{+6.8}_{-0.6}$
	J^P	$\frac{1}{2}^-$	-

arXiv:2011.05828 **[hep-ph],** Submitted to PRD

Concluding notes

- We have made a good progress on the identification of doubly heavy baryons in the experiment: we hope we will observe more states predicted by the quark model

- Although we have recorded good experimental and theoretical progresses on tetraquarks states, the nature and quantum numbers of most candidates have not been exactly fixed.

- We need more theoretical and experimental studies on the discovered pentaquark states to clarify their nature and internal quark-gluon organization.


Thank You