Charmed Baryons and Mesons

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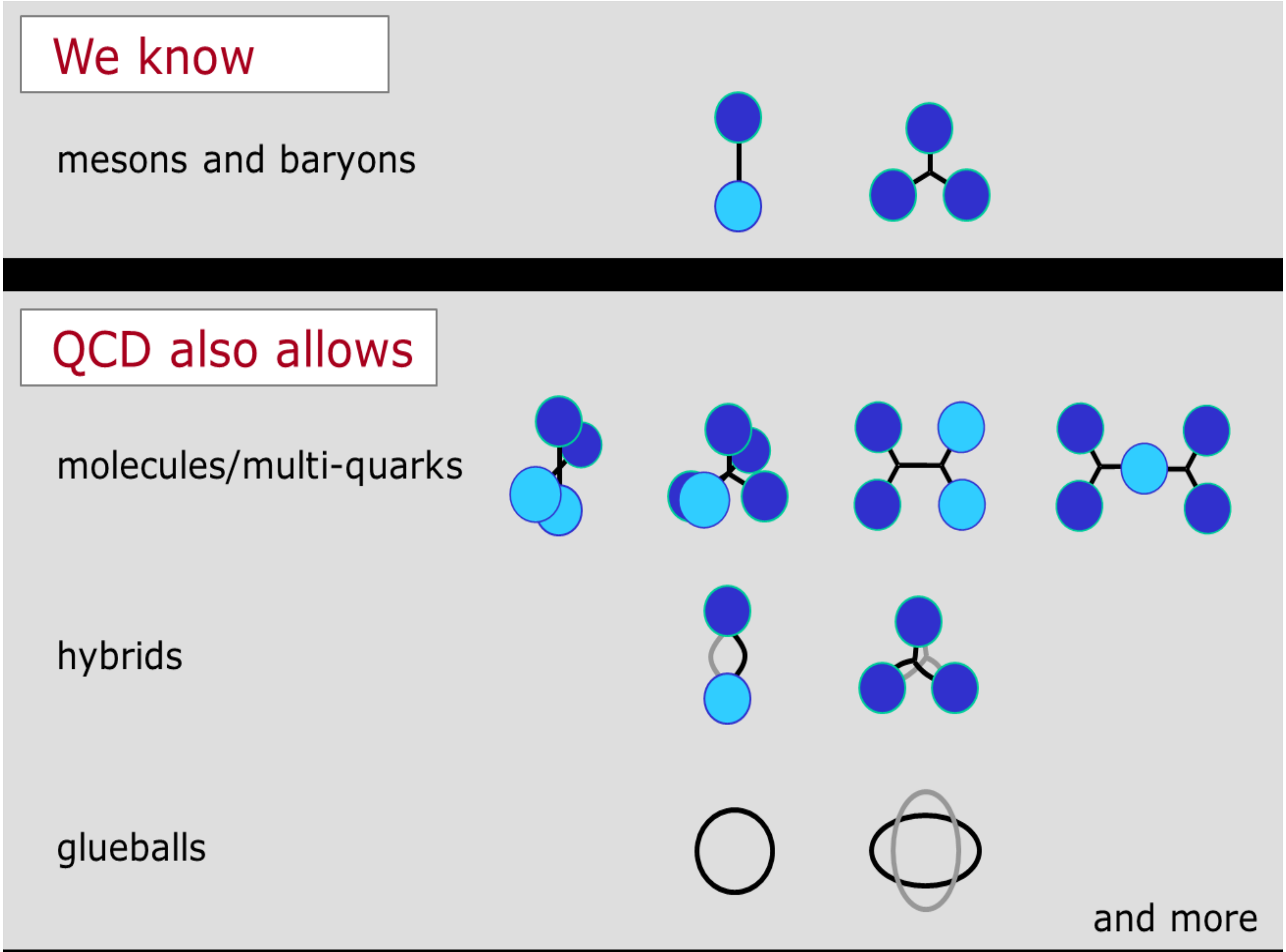
Outline

- 1. Charmed baryons
- 2. Charmed mesons
- 3. Discussions

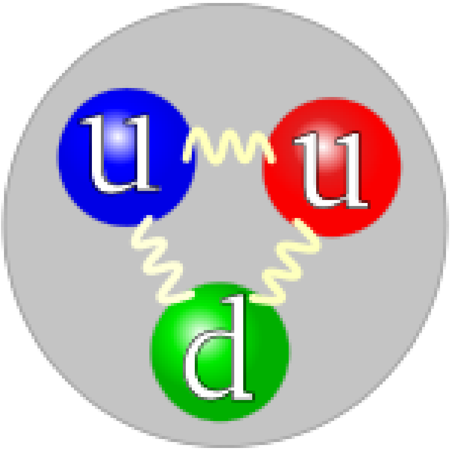
1. Charmed baryons

Quark Model



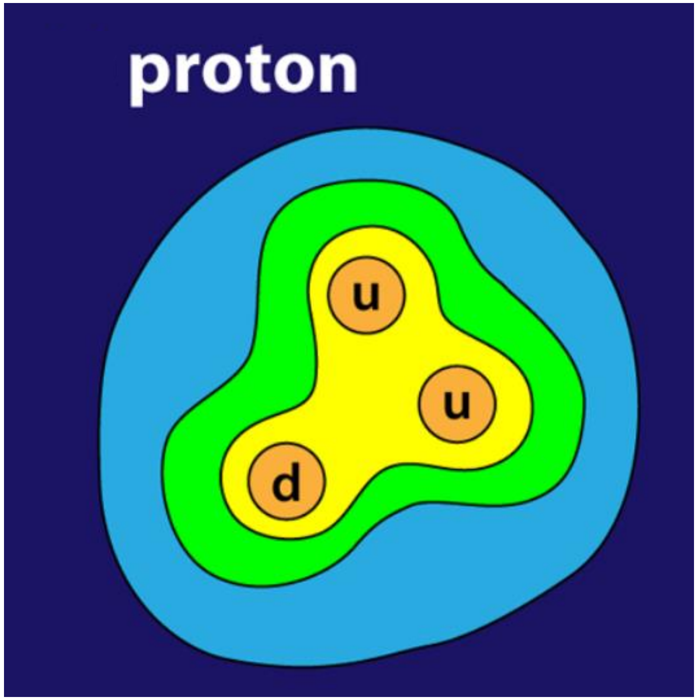
Baryons

Proton: 1919, E. Rutherford.
Hydrogen nucleus was proved to be present in other nuclei



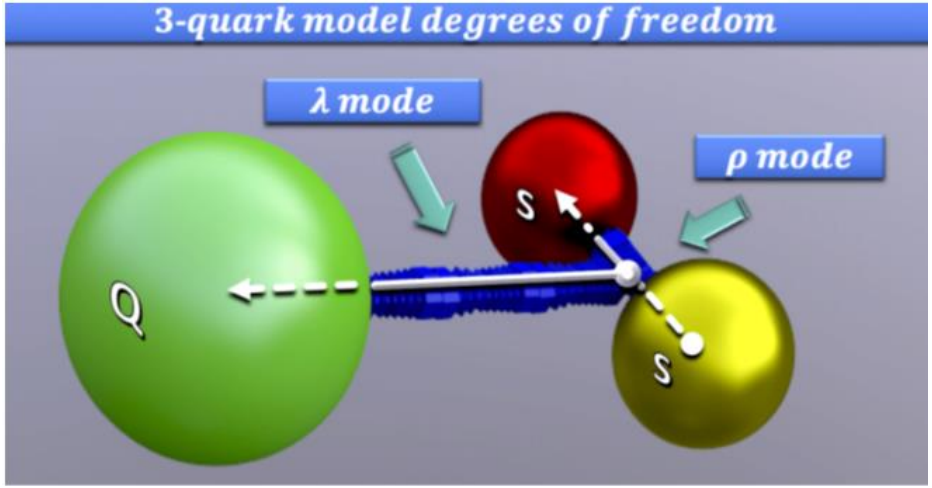
Quark Model

M. Gell-Mann, Phys. Lett. 8, 214 (1964)

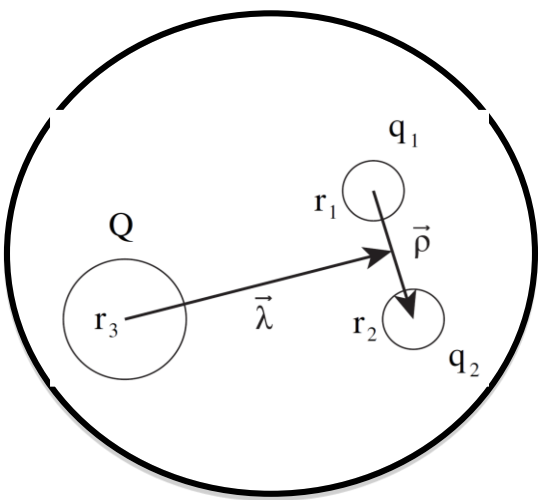


Baryon

Baryon is a resonance with three bodies



Jacobi coordinates



$$\vec{\rho} = \vec{r}_2 - \vec{r}_1$$

$$\vec{\lambda} = (\vec{r}_2 + \vec{r}_1)/2 - \vec{r}_3$$

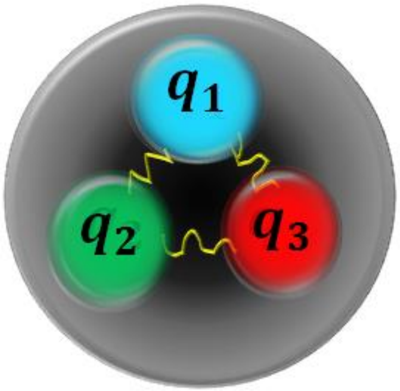
$s_\rho = s_1 + s_2 = 0,1$

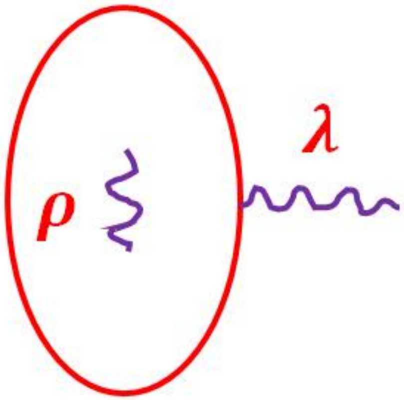
$L = L_\rho + L_\lambda = 0,1,2...$

$J_L = L + s_\rho = 0,1,2...$

$J = J_L + s_3 = 1/2, 3/2...$

Internal quantum numbers of Baryon





s_ρ: $s_\rho = s_1 + s_2 = 0,1$

L: $L = L_\rho + L_\lambda = 0,1,2\ldots$

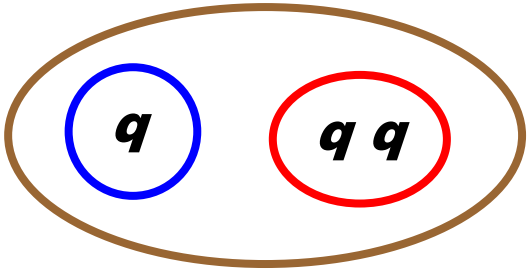
J_L: $J_L = L + s_\rho = 0,1,2\ldots$

J: $J = J_L + s_3 = 1/2, 3/2\ldots$

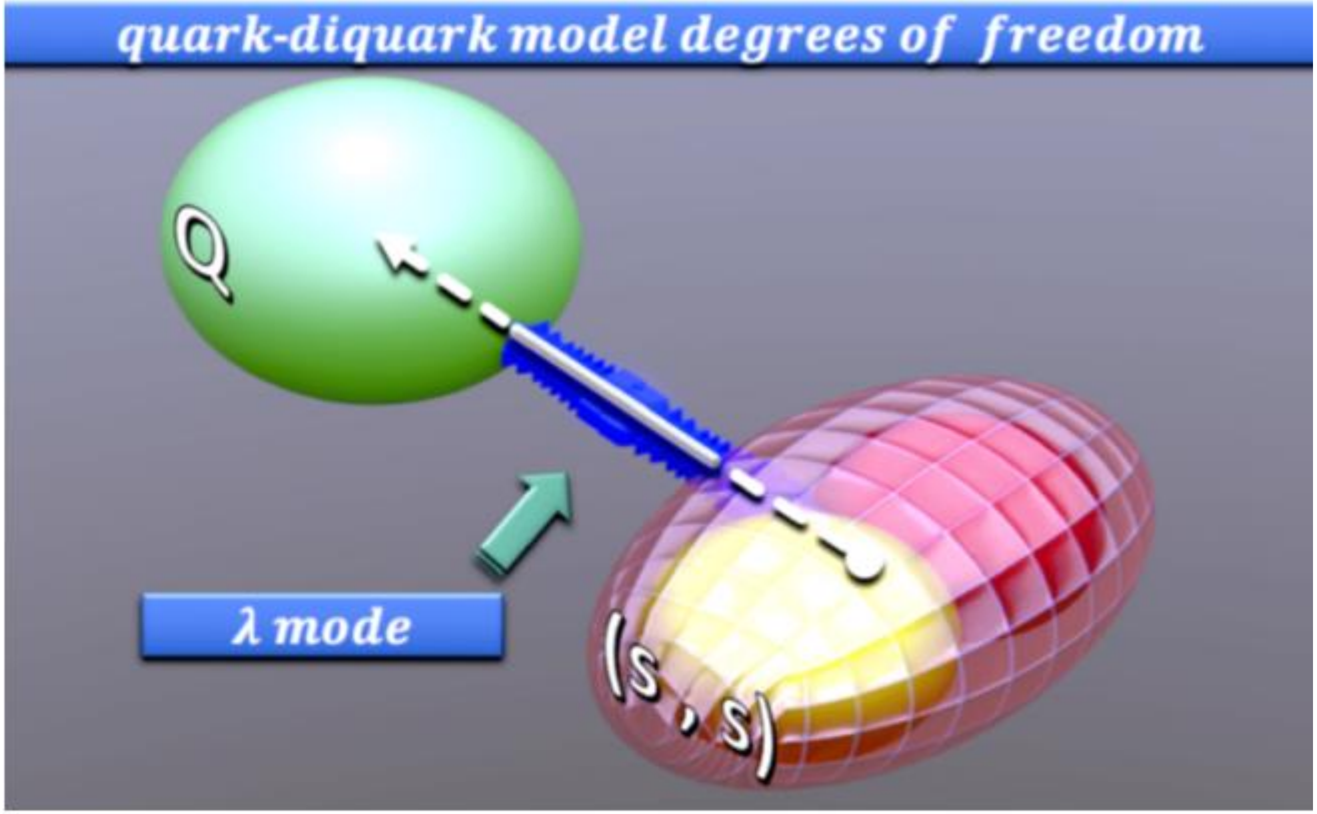
n	s_ρ	L_ρ	L_λ	L	J_L	J^P
1	0	0	0	0	0	$\frac{1}{2}^+$
1	1	0	0	0	1	$\frac{1}{2}^+, \frac{3}{2}^+$
1	0	1	0	1	1	$\frac{1}{2}^-, \frac{3}{2}^-$
1	1	1	0	1	0	$\frac{1}{2}^-$
1	1	1	0	1	1	$\frac{1}{2}^-, \frac{3}{2}^-$
1	1	1	0	1	2	$\frac{3}{2}^-, \frac{5}{2}^-$
…			$P=(-1)^L$			
…						

Baryon

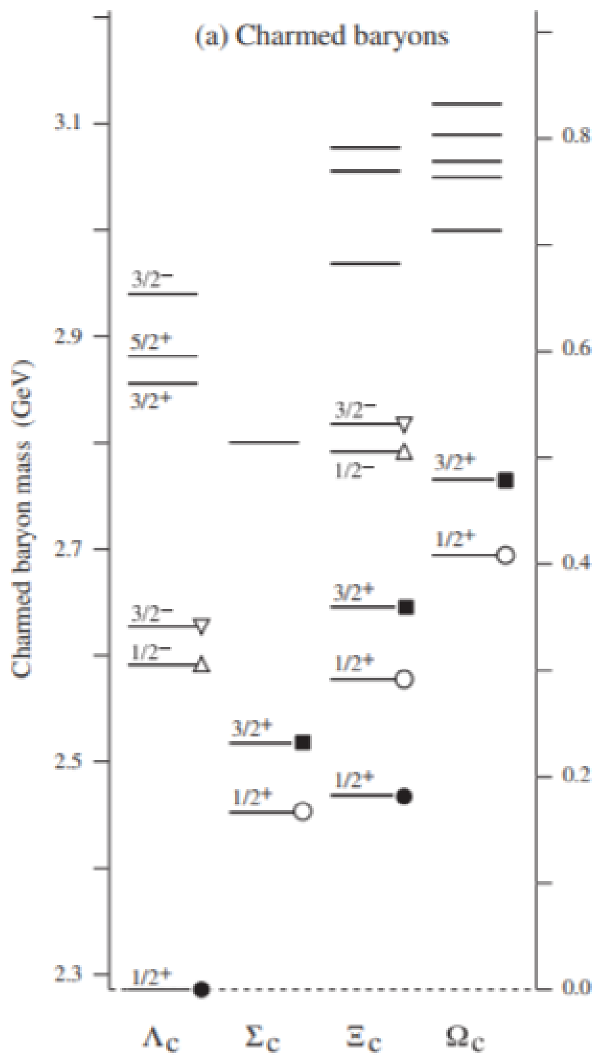
Baryon is a resonance with two bodies



Diquark



Charmed baryons: **There are now 36 established singly-charmed baryons (2020PDG). There were 17 known charmed baryons, and 4 other candidates not well enough established in 2010PDG.**



$\Lambda_c^+ = udc$, $\Sigma_c^{++} = uuc$, $\Sigma_c^+ = udc$, $\Sigma_c^0 = ddc$,
$\Xi_c^+ = usc$, $\Xi_c^0 = dsc$, $\Omega_c^0 = ssc$

Λ_c: two u, d quarks and one c quark; I = 0

J^P	Mass(expt.)
$\frac{1}{2}^+$	$\Lambda_c(2286)^+$
$\frac{1}{2}^-$	$\Lambda_c(2595)^+$
$\frac{3}{2}^-$	$\Lambda_c(2625)^+$
$?^?$	$\Lambda_c(2765)^+$ or $\Sigma_c(2765)$
$\frac{3}{2}^+$	$\Lambda_c(2860)^+$
$\frac{5}{2}^+$	$\Lambda_c(2880)^+$
$\frac{3}{2}^-$	$\Lambda_c(2940)^+$

Particle Data Group 2022

Only the J^P of $\Lambda_c(2880)^+$ has been measured!

$\Lambda_c(2910)$: $I(J^P)$ = ?(?$^?$),Belle, PRL.130,031901(2023)

A candidate heavy quark symmetry doublet partner to the $\Lambda_c(2940)$. Further study is needed to confirm whether this state is anexcited Λ_c or Σ_c

(Belle Collaboration)

(Received 19 June 2022; revised 31 July 2022; accepted 23 August 2022; published 20 January 2023)

We present the study of $\bar{B}^0 \to \Sigma_c(2455)^{0,++}\pi^\pm \bar{p}$ decays based on 772×10^6 $B\bar{B}$ events collected with the Belle detector at the KEKB asymmetric-energy e^+e^- collider. The $\Sigma_c(2455)^{0,++}$ candidates are reconstructed via their decay to $\Lambda_c^+\pi^\mp$ and Λ_c^+ decays to $pK^-\pi^+$, pK_S^0, and $\Lambda\pi^+$ final states. The corresponding branching fractions are measured to be $\mathcal{B}(\bar{B}^0 \to \Sigma_c(2455)^0\pi^+\bar{p}) = (1.09 \pm 0.06 \pm 0.07) \times 10^{-4}$ and $\mathcal{B}(\bar{B}^0 \to \Sigma_c(2455)^{++}\pi^-\bar{p}) = (1.84 \pm 0.11 \pm 0.12) \times 10^{-4}$, which are consistent with the world average values with improved precision. A new structure is found in the $M_{\Sigma_c(2455)^{0,++}\pi^\pm}$ spectrum with a significance of 4.2σ including systematic uncertainty. The structure is possibly an excited Λ_c^+ and is tentatively named $\Lambda_c(2910)^+$. Its mass and width are measured to be $(2913.8 \pm 5.6 \pm 3.8)$ MeV$/c^2$ and $(51.8 \pm 20.0 \pm 18.8)$ MeV, respectively. The products of branching fractions for the $\Lambda_c(2910)^+$ are measured to be $\mathcal{B}(\bar{B}^0 \to \Lambda_c(2910)^+\bar{p}) \times \mathcal{B}(\Lambda_c(2910)^+ \to \Sigma_c(2455)^0\pi^+) = (9.5 \pm 3.6 \pm 1.6) \times 10^{-6}$ and $\mathcal{B}(\bar{B}^0 \to \Lambda_c(2910)^+\bar{p}) \times \mathcal{B}(\Lambda_c(2910)^+ \to \Sigma_c(2455)^{++}\pi^-) = (1.24 \pm 0.35 \pm 0.10) \times 10^{-5}$. Here, the first and second uncertainties are statistical and systematic, respectively.

DOI: 10.1103/PhysRevLett.130.031901

Σ_c: two u, d quarks and one c quark; I = 1

J^P	Mass(expt.)
$\frac{1}{2}^+$	$\Sigma_c(2455)$
$\frac{3}{2}^+$	$\Sigma_c(2520)$
$?^?$	$\Sigma_c(2800)$

Particle Data Group 2022

Neither J nor P has been measured!

Ω_c: two *s* quarks and one *c* quark

J^P	Mass(expt.)
$\frac{1}{2}^+$	$\Omega_c(2695)$
$\frac{3}{2}^+$	$\Omega_c(2770)$
$?^?$	$\Omega_c(3000)$
$?^?$	$\Omega_c(3050)$
$?^?$	$\Omega_c(3065)$
$?^?$	$\Omega_c(3090)$
$?^?$	$\Omega_c(3120)$

Particle Data Group 2022

Neither J nor P has been measured!

$\Omega_c(3185)$: I(J^P) = ?(?$^?$) , PRL.131,131902(2023)

$\Omega_c(3327)$: I(J^P) = ?(?$^?$)   PRL.131,131902(2023)

Observation of New Ω_c^0 States Decaying to the $\Xi_c^+ K^-$ Final State

R. Aaij *et al.* (LHCb Collaboration)

Phys. Rev. Lett. **131**, 131902 – Published 26 September 2023

Article | References | Citing Articles (6) | PDF | HTML | Export Citation

ABSTRACT

Two new excited states, $\Omega_c(3185)^0$ and $\Omega_c(3327)^0$, are observed in the $\Xi_c^+ K^-$ invariant-mass spectrum using proton-proton collision data collected by the LHCb experiment, corresponding to an integrated luminosity of $9\ \mathrm{fb}^{-1}$. Five previously observed excited Ω_c^0 states are confirmed, namely $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3065)^0$, $\Omega_c(3090)^0$, and $\Omega_c(3119)^0$. The masses and widths of these seven states are measured with the highest precision to date.

Ξ_c: one u or d quark, one c quark and one strange quark

J^P	Mass(expt.)
$\frac{1}{2}^+$	$\Xi_c(2470)$
$\frac{1}{2}^+$	$\Xi_c'(2579)$
$\frac{3}{2}^+$	$\Xi_c(2645)^+$
$\frac{1}{2}^-$	$\Xi_c(2790)^+$
$\frac{3}{2}^-$	$\Xi_c(2815)^+$
$?^?$	$\Xi_c(2930)$
$?^?$	$\Xi_c(2970)^+$
$?^?$	$\Xi_c(3055)^+$
$?^?$	$\Xi_c(3080)^+$
$?^?$	$\Xi_c(3123)^+$(KATO 14 finds no evidence)

Particle Data Group 2022

J and P have not been measured!

Ξ_c(2882): I(J^P) = ?(?$^?$) , PRD.108,012020(2023)

Ξ_c(2923): I(J^P) = ?(?$^?$)   PRL.124,222001(2020); PRD.108,012020(2023)

Ξ_c(2930) state observed at the BABAR and Belle experiments is resolved into two narrower states, Ξ_c(2923) and Ξ_c(2939) .

Study of the $B^- \to \Lambda_c^+ \bar{\Lambda}_c^- K^-$ decay

R. Aaij *et al.* (LHCb Collaboration)

Phys. Rev. D **108**, 012020 – Published 27 July 2023

Article | References | No Citing Articles | PDF | HTML | Export Citation

ABSTRACT

The decay $B^- \to \Lambda_c^+ \bar{\Lambda}_c^- K^-$ is studied in proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 13$ TeV using data corresponding to an integrated luminosity of 5 fb^{-1} collected by the LHCb experiment. In the $\Lambda_c^+ K^-$ system, the $\Xi_c(2930)^0$ state observed at the *BABAR* and Belle experiments is resolved into two narrower states, $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$, whose masses and widths are measured to be $m(\Xi_c(2923)^0) = 2924.5 \pm 0.4 \pm 1.1$ MeV, $m(\Xi_c(2939)^0) = 2938.5 \pm 0.9 \pm 2.3$ MeV, $\Gamma(\Xi_c(2923)^0) = 4.8 \pm 0.9 \pm 1.5$ MeV, $\Gamma(\Xi_c(2939)^0) = 11.0 \pm 1.9 \pm 7.5$ MeV, where the first uncertainties are statistical and the second systematic. The results are consistent with a previous LHCb measurement using a prompt $\Lambda_c^+ K^-$ sample. Evidence of a new $\Xi_c(2880)^0$ state is found with a local significance of 3.8σ, whose mass and width are measured to be $2881.8 \pm 3.1 \pm 8.5$ MeV and $12.4 \pm 5.3 \pm 5.8$ MeV, respectively. In addition, evidence of a new decay mode $\Xi_c(2790)^0 \to \Lambda_c^+ K^-$ is found with a significance of 3.7σ. The relative branching fraction of $B^- \to \Lambda_c^+ \bar{\Lambda}_c^- K^-$ with respect to the $B^- \to D^+ D^- K^-$ decay is measured to be $2.36 \pm 0.11 \pm 0.22 \pm 0.25$, where the first uncertainty is statistical, the second systematic and the third originates from the branching fractions of charm hadron decays.

TABLE II. Measured masses, widths and significance of excited Ξ_c^0 states.

State	Mass (MeV)	Width (MeV)	Significance
$\Xi_c(2880)^0$	$2881.8 \pm 3.1 \pm 8.5$	$12.4 \pm 5.2 \pm 5.8$	3.8σ
$\Xi_c(2923)^0$	$2924.5 \pm 0.4 \pm 1.1$	$4.8 \pm 0.9 \pm 1.5$	$>10\sigma$
$\Xi_c(2939)^0$	$2938.5 \pm 0.9 \pm 2.3$	$11.0 \pm 1.9 \pm 7.5$	$>10\sigma$

TABLE III. Systematic uncertainties on the masses and widths of the $\Xi_c(2923)^0$, $\Xi_c(2939)^0$ and $\Xi_c(2880)^0$ states. Values are given in MeV.

	$\Xi_c(2923)^0$		$\Xi_c(2939)^0$		$\Xi_c(2880)^0$	
Source	Mass	Width	Mass	Width	Mass	Width
Model assumption	0.8	1.4	1.9	7.0	8.4	4.1
Lineshape formalism	0.7	0.1	1.3	0.8	1.1	0.0
Bias correction	0.2	0.4	0.4	2.1		
Momentum scale	0.0		0.1		0.0	
Mass constraint	0.1	0.1	0.1	0.5	0.1	0.4
Background	0.1	0.3	0.2	0.8	0.7	4.0
Total	1.1	1.5	2.3	7.5	8.5	5.8

Our attempts: flux Tube model

1, Bing Chen, Deng-Xia Wang and Ailin Zhang, J^P assignments of Λ^+_c baryons, Chin. Phys. C 33, 1327 (2009).
2, Deng-Xia Wang, Xue-Feng Li and Ailin Zhang, Spectrum of baryons with one charm quark, AIP Conf. Proc. 1388, 318(2011) .
3, Bing Chen, Ke-Wei Wei and Ailin Zhang, Assignments of Λ_Q and Ξ_Q baryons in the heavy quark-light diquark picture, Eur. Phys. J. A51, 82(2015) .

Relativistic flux tube model

Charmed Baryons

TABLE 2. Spectrum of Λ_c (GeV) with parameters $\sigma = 0.999$ GeV^2, $M_c = 1.474$ GeV, $m_d = 0.548$ GeV and $a = 0.059$ GeV^2.

candidates	J^P ([3])	j^P (ours)	mass (expt.)	mass (ours)
$\Lambda_c(2595)^+$	$\frac{1}{2}^-$	$\frac{1}{2}^-$	2.595	2.577
$\Lambda_c(2625)^+$	$\frac{3}{2}^-$	$\frac{3}{2}^-$	2.628	2.660
$\Lambda_c(2765)^+$ or $\Sigma_c(2765)^+$	$?^?$	$\frac{3}{2}^+$	2.767	2.780
$\Lambda_c(2880)^+$	$\frac{5}{2}^+$	$\frac{5}{2}^+$	2.882	2.880
$\Lambda_c(2940)^+$	$?^?$	$\frac{5}{2}^-$	2.939	2.949
?	$?^?$	$\frac{7}{2}^-$	?	3.089

TABLE 3. Spectrum of Ξ_c (GeV) with parameters $\sigma = 0.999$ GeV^2, $M_c = 1.655$ GeV, $m_d = 0.468$ GeV and $a = 0.059$ GeV^2.

Candidates	J^P ([3])	j^P (ours)	mass (expt.)	mass (ours)
Ξ_c^+	$\frac{1}{2}^+$	$\frac{1}{2}^+$	2.468	-
Ξ_c^0	$\frac{1}{2}^+$	$\frac{1}{2}^+$	2.470	-
$\Xi_c(2790)$	$\frac{1}{2}^-$	$\frac{1}{2}^-$	2.791	2.776
$\Xi_c(2815)$	$\frac{3}{2}^-$	$\frac{3}{2}^-$	2.819	2.829
$\Xi_c(2980)$	$?^?$	$\frac{3}{2}^+$	2.968	2.979
$\Xi_c(3077)$	?	$\frac{5}{2}^+$	3.079	3.068
?	?	$\frac{5}{2}^-$	?	3.149

Relativistic flux tube model

The following energy ε and the angular momentum L of a hadron system were derived rigorously from the Wilson area law in QCD

$$\varepsilon = \sum_{i=1}^{2}\left[\frac{m_i}{\sqrt{1-(\omega r_i)^2}} + \frac{T}{\omega}\int_0^{\omega r_i}\frac{du}{\sqrt{1-u^2}}\right]$$

$$L = \sum_{i=1}^{2}\left[\frac{m_i \omega r_i^2}{\sqrt{1-(\omega r_i)^2}} + \frac{T}{\omega^2}\int_0^{\omega r_i}\frac{u^2 du}{\sqrt{1-u^2}}\right]$$

The spin-dependent terms

$$H_{so} = \frac{4}{3}\frac{\alpha_s}{r^3}\frac{1}{m_d m_Q}\mathbf{S}_Q\cdot\mathbf{L}.$$

$$\frac{1}{r} = \frac{\omega}{v_1+v_2} = \frac{1}{v_1+v_2}\sqrt{\frac{\sigma}{8L}}.$$

For heavy light hadrons with radial and orbital excitation,

$$(\varepsilon - m_Q)^2 = \frac{1}{2}\sigma(\lambda n + L) + (m_d + \zeta_Q)^2$$

$$H_{nL}^{so} = \frac{1}{3 \times 2^{5/2}} \frac{\alpha_s}{(v_1 + v_2)^3} \left(\frac{\sigma}{\lambda n + L} \right)^{3/2} \frac{1}{m_d m_Q} \hat{s}_Q \cdot \hat{L}$$

Reproduce the Regge trajectories behavior of different hadrons!

Our predictions are cited by LHCb collaboration for the first observation of $\Lambda_c(2860)^+$. In order to compare the observed data with theoretical prediction, the LHCb collaboration took use of our results as the theoretical input in JHEP 1705 (2017) 030.

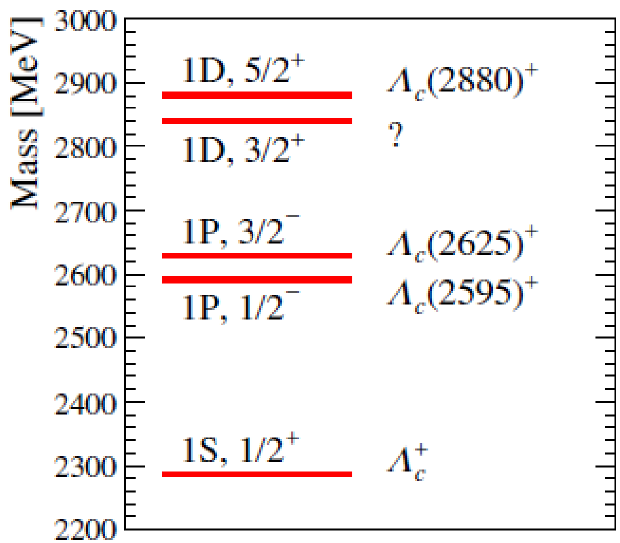


Figure 1. Expected spectrum of the Λ_c^+ ground state and its orbital excitations from a study based on the nonrelativistic heavy quark-light diquark model [21], along with the observed resonances corresponding to those states [23].

[21] B. Chen, K.-W. Wei and A. Zhang, *Investigation of Λ_Q and Ξ_Q baryons in the heavy quark-light diquark picture*, Eur. Phys. J. **A 51** (2015) 82 [arXiv:1406.6561] [INSPIRE].

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Bottom baryons (2015)

Table 6. The predicted masses of the Λ_b^0 baryons (in MeV). We also collect the experimental values [1] and pther theoretical results [9, 50, 51] for comparison.

$J^P(nL)$	Exp. [1]	This work	Ref. [9]	Ref. [50]	Ref. [51]
$\frac{1}{2}^+(1S)$	5619.4	5619	5620	5612	5585
$\frac{1}{2}^-(1P)$	5912.0	5911	5930	5939	5912
$\frac{3}{2}^-(1P)$	5919.8	5920	5942	5941	5920
$\frac{3}{2}^+(1D)$		6147	6190	6181	6145
$\frac{5}{2}^+(1D)$		6153	6196	6181	6165
$\frac{5}{2}^-(1F)$		6346	6408	6206	6205
$\frac{7}{2}^-(1F)$		6351	6411		6360
$\frac{7}{2}^+(1G)$		6523	6598	6433	6445
$\frac{9}{2}^+(1G)$		6526	6599		6580

Table 7. The predicted masses of the Ξ_b^0 baryons (in MeV). We also collect the experimental values [1] and other theoretical results [9, 50] for comparison.

$J^P(nL)$	Exp. [1]	This work	Ref. [9]	Ref. [50]
$\frac{1}{2}^+(1S)$	5795.8	5801	5803	5806
$\frac{1}{2}^-(1P)$		6097	6120	6090
$\frac{3}{2}^-(1P)$		6106	6130	6093
$\frac{3}{2}^+(1D)$		6344	6366	6311
$\frac{5}{2}^+(1D)$		6349	6373	6300
$\frac{5}{2}^-(1F)$		6555	6577	
$\frac{7}{2}^-(1F)$		6559	6581	
$\frac{7}{2}^+(1G)$		6743	6760	
$\frac{9}{2}^+(1G)$		6747	6762	

LHCb Collaboration (2019)

PHYSICAL REVIEW LETTERS **123**, 152001 (2019)

Observation of New Resonances in the $\Lambda_b^0\pi^+\pi^-$ System

R. Aaij *et al.**
(LHCb Collaboration)

(Received 6 August 2019; revised manuscript received 27 August 2019; published 11 October 2019)

We report the observation of a new structure in the $\Lambda_b^0\pi^+\pi^-$ spectrum using the full LHCb data set of pp collisions, corresponding to an integrated luminosity of 9 fb^{-1}, collected at $\sqrt{s} = 7, 8$, and 13 TeV. A study of the structure suggests its interpretation as a superposition of two almost degenerate narrow states. The masses and widths of these states are measured to be $m_{\Lambda_b(6146)^0} = 6146.17 \pm 0.33 \pm 0.22 \pm 0.16$ MeV, $m_{\Lambda_b(6152)^0} = 6152.51 \pm 0.26 \pm 0.22 \pm 0.16$ MeV, $\Gamma_{\Lambda_b(6146)^0} = 2.9 \pm 1.3 \pm 0.3$ MeV, $\Gamma_{\Lambda_b(6152)^0} = 2.1 \pm 0.8 \pm 0.3$ MeV,with a mass splitting of $\Delta m = 6.34 \pm 0.32 \pm 0.02$ MeV, where the first uncertainty is statistical, the second systematic. The third uncertainty for the mass measurements derives from the knowledge of the mass of the Λ_b^0 baryon. The measured masses and widths of these new excited states suggest their possible interpretation as a doublet of $\Lambda_b(1D)^0$ states.

DOI: 10.1103/PhysRevLett.123.152001

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1P Ξ_b in the channel of $\Xi'_b(5945)\,\pi$?

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Relativistic quark-diquark model, light diquark

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Nonrelativistic quark model Hamiltonian, similar to that used by Isgur and Karl

[51]. S. Capstick, N. Isgur, Baryons in a relativized quark model with chromodynamics, Phys. Rev. D 34, 2809 (1986).

Relativized quark model

模型计算，

实验数据，

相互作用，禁闭势？

Our attempts: hadronic decays

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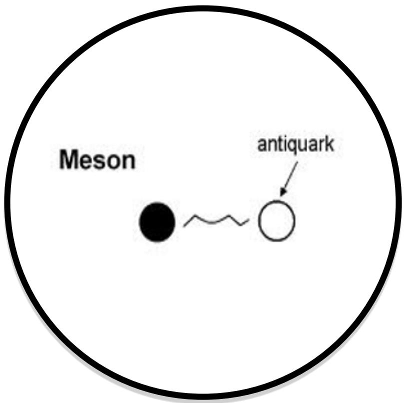
ρ Excitation in Λ_Q baryons

λ Excitation?

Model dependent!

2. Charmed mesons



Two kinds of classification schemes of D_s, nonrelativistic $n\ ^{2S+1}L_J$ or the heavy quark symmetric nj^P eigenstates in quark model

n: radial excited numbers
P: parity
C: charge conjugate
(only neutral mesons have definite C)

Heavy-light systems:

Heavy quark symmetry,
Chiral symmetry

Nonrelativistic:

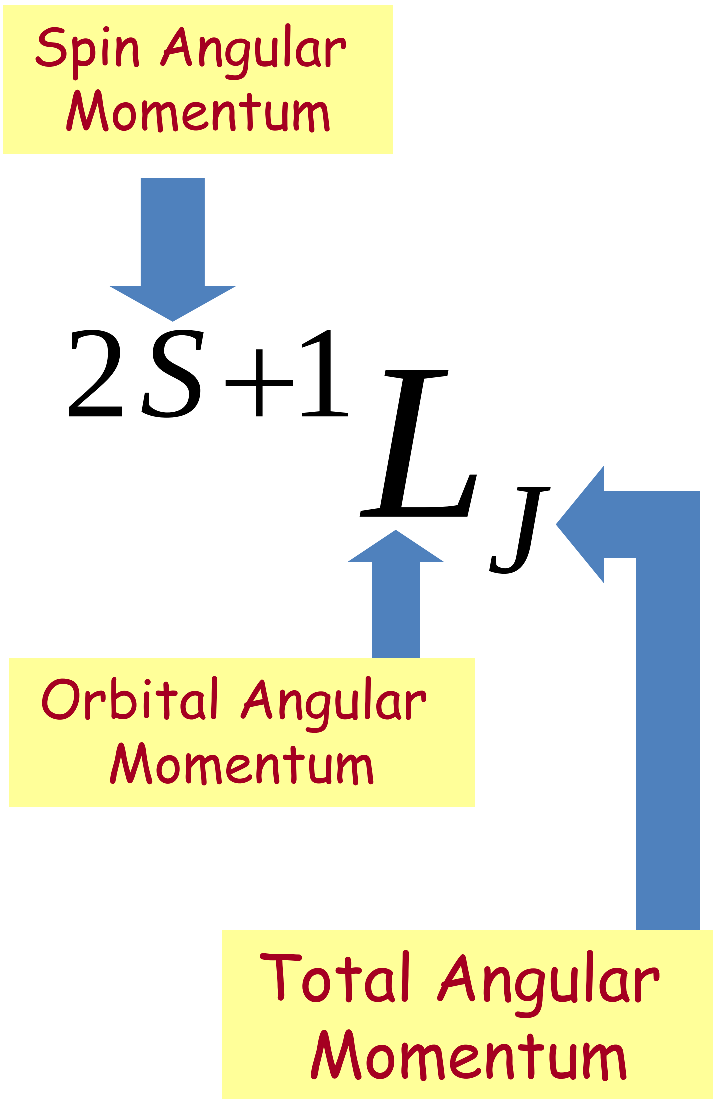
$$n^{2S+1}L_J$$

Heavy quark symmetric:

$$nj^P$$

$$\left|J = L, j_q = L + \frac{1}{2}\right\rangle = \sqrt{\frac{J+1}{2J+1}}|J = L, S = 0\rangle + \sqrt{\frac{J}{2J+1}}|J = L, S = 1\rangle$$

$$\left|J = L, j_q = L - \frac{1}{2}\right\rangle = -\sqrt{\frac{J}{2J+1}}|J = L, S = 0\rangle + \sqrt{\frac{J+1}{2J+1}}|J = L, S = 1\rangle.$$



natural parity

$$J^P = 0^+, 1^-, 2^+, \cdots$$

$$P = (-1)^J$$

unnatural parity

$$J^P = 0^-, 1^+, 2^-, \cdots$$

D mesons

S-wave and P-wave D mesons are believed established

States	J^P	$n^{2S+1}L_J$	j^P	PDG2020 notes
$D^{\pm}$	0^-	1^1S_0	$\frac{1}{2}^-$	
$D^*(2010)^{\pm}$	1^-	1^3S_0	$\frac{1}{2}^-$	J, P need confirmation
$D_0^*(2300)^{\pm}$	0^+	1^3P_0	$\frac{1}{2}^+$	J, P need confirmation
$D_1(2420)^0$	1^+	mixing	$\frac{1}{2}^+$	
$D_1(2430)^0$	1^+	mixing	$\frac{3}{2}^+$	Omitted form summary table
$D_2^*(2460)^0$	2^+	1^3P_2	$\frac{3}{2}^+$	$J^P = 2^+$ assignment strongly favored

$D_1(2420)^{\pm}$

$I(J^P) = \frac{1}{2}(?^?)$
I needs confirmation.

OMITTED FROM SUMMARY TABLE
Seen in $D^*(2007)^0\pi^+$. $J^P = 0^+$ ruled out.

Spin-orbit interaction

$$Q_{low} = \sin\theta\ {}^3P_1 + \cos\theta\ {}^1P_1$$
$$Q_{high} = \cos\theta\ {}^3P_1 - \sin\theta\ {}^1P_1$$

$\theta_0 \approx -35.3°$ and $\theta \approx 38°$

Higher excited D have been observed

Higher excited D mesons

◇ **Quantum numbers for D(2550), D^*_J(2600), D(2740), and D(2750) are determined by LHCb Collaboration in 2020.**

In PDG 2022, they are denoted with D_0(2550), D^*_1(2600), D_2(2740), and D^*_3(2750)

PHYSICAL REVIEW D **101,** 032005 (2020)

Determination of quantum numbers for several excited charmed mesons observed in $B^- \to D^{*+}\pi^-\pi^-$ decays

R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 15 November 2019; accepted 23 January 2020; published 20 February 2020)

A four-body amplitude analysis of the $B^- \to D^{*+}\pi^-\pi^-$ decay is performed, where fractions and relative phases of the various resonances contributing to the decay are measured. Several quasi-model-independent analyses are performed aimed at searching for the presence of new states and establishing the quantum numbers of previously observed charmed meson resonances. In particular the resonance parameters and quantum numbers are determined for the $D_1(2420)$, $D_1(2430)$, $D_0(2550)$, $D_1^*(2600)$, $D_2(2740)$ and $D_3^*(2750)$ states. The mixing between the $D_1(2420)$ and $D_1(2430)$ resonances is studied and the mixing parameters are measured. The dataset corresponds to an integrated luminosity of 4.7 fb^{-1}, collected in proton-proton collisions at center-of-mass energies of 7, 8 and 13 TeV with the LHCb detector.

◇ $D^*(2640)^\pm$

Citation: R.L. Workman *et al.* (Particle Data Group), Prog.Theor.Exp.Phys. **2022**, 083C01 (2022) and 2023 update

$D^*(2640)^\pm$

$I(J^P) = \frac{1}{2}(?^?)$

OMITTED FROM SUMMARY TABLE

Seen in Z decays by ABREU 98M. Not seen by ABBIENDI 01N and CHEKANOV 09. Needs confirmation.

Mass: 2637±2±6 MeV
Decay width: <15 MeV

$D^*(2640)^+$ DECAY MODES

$D^*(2640)^-$ modes are charge conjugates of modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D^*(2010)^+\pi^+\pi^-$	seen

♢ $D^*_1(2760)$ natural parity

$$e^+e^- \to c\bar{c} \to D^{(*)}\pi X,$$

$$pp \to D^+\pi^- X,\ pp \to D^0\pi^+ X,\ pp \to D^{*+}\pi^- X,$$

Observed also in exclusive B decay by LHCb collaboration

$$B^- \to D^+K^-\pi^-$$

Mass: $2781 \pm 18 \pm 11 \pm 6$ MeV;

Decay width: $177 \pm 32 \pm 20 \pm 7$ MeV;

$$1^3D_1(c\overline{q})$$

◊ $D^*_3(2760)$

$$e^+e^- \to c\bar{c} \to D^{(*)}\pi X,$$

$$pp \to D^+\pi^- X,\ pp \to D^0\pi^+ X,\ pp \to D^{*+}\pi^- X,$$

Observed also in exclusive B decay by LHCb collaboration

$$B^0 \to \bar{D}^0\pi^+\pi^-$$

Mass: $2798 \pm 7 \pm 1 \pm 7$ MeV;

Decay width: $105 \pm 18 \pm 6 \pm 23$ MeV;

$$1^3D_3(c\bar{q})$$

◇ D(3000)^0

$$e^+e^- \to c\bar{c} \to D^{(*)}\pi X,$$

$$pp \to D^+\pi^- X,\ pp \to D^0\pi^+ X,\ pp \to D^{*+}\pi^- X,$$

$D^{*+}\pi^-$

Mass: 3214±29±49 MeV
Decay width: 186±38±72 MeV

2P, 3S, and 1F ?

$D^*(2760)$命名的演化：

- $D^*(2760)$(Babar 2010)->

Inclusive production:

$e^+e^- \rightarrow c\bar{c} \rightarrow D^{(*)}\pi X$, where X is any additional system.

$m(D^+\pi^-)$

modeled with relativistic BW functions

(BaBar, PRD82,111101(R)(2010))

演化2：

◇ **$D^*_J(2760)$(LHCb 2013)**

inclusive reactions:

$$pp \to D^+\pi^- X,\ pp \to D^0\pi^+ X,\ pp \to D^{*+}\pi^- X,$$

$m(D^+\pi^-)$= parameterized with a relativistic Breit-Wigner，lineshape

The $D^*_J(2760)^0$ is observed in the $D^{*+}\pi^-$ and $D^+\pi^-$ decay modes with consistent parameters. We also observe the $D^*_J(2760)^+$ in the $D^0\pi^+$ final state which can be identified as a $J^P = 1^-$ state (LHCb, JHEP09,145(2013)).

measure their angular distributions， -> natural parity states.

$D^*_J(2760)$(LHCb 2013)

演化3：

- **$D^*_J(2760)$**
  The spin of the $D^*_J(2760)$ state has not been determined previously. From the pp collision data, $B^- \longrightarrow D^+K^-\pi^-$, $D^*_J(2760)$ state is determined to have spin 1(LHCb, PRD91,092002(2015)). An amplitude analysis of the resonant structure+Dalitz plot

$D^*_1(2760)$(LHCb 2015)->

◇ **D^*_3(2760), (LHCb 2015)->**

From the pp collision data, $B^0 \to \bar{D}^0 \pi^+ \pi^-$, A resonant structure at m($\bar{D}^0 \pi^-$) ≈2.8 GeV/c^2 is confirmed and its spin-parity is determined for the first time as $J^P=3^-$ (LHCb, PRD92,032002(2015)). Dalitz plot.

$D(2750)$ PDG2012 J^P=??)->

$D(2750)$(PDG2016 $J^P=3^-$)->

$D^*_3(2750)$(PDG2018)

Citation: C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016)

$D(2750)$ $I(J^P) = \frac{1}{2}(3^-)$

OMITTED FROM SUMMARY TABLE

J^P determined by AAIJ 15Y from the Dalitz plot analysis of $B^0 \rightarrow \overline{D}^0 \pi^+ \pi^-$ decays. J^P consistent with natural parity (AAIJ 13CC).

Citation: M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018)

$D_3^*(2750)$ $I(J^P) = \frac{1}{2}(3^-)$

OMITTED FROM SUMMARY TABLE

J^P determined by AAIJ 15Y from the Dalitz plot analysis of $B^0 \rightarrow \overline{D}^0 \pi^+ \pi^-$ decays. J^P consistent with natural parity (AAIJ 13CC).

$D_J(2750)$ seen in the $D^*\pi$ final state and some number of natural parity states collectively labeled the $D_J^*(2760)$ which has recently been resolved by LHCb into two states with $J^P = 1^-$ and 3^- labeled the $D_1^*(2760)$ [9] and $D_3^*(2760)$ [10] seen in the $D\pi$ final state. The states

PHYSICAL REVIEW D **91**, 092002 (2015)

First observation and amplitude analysis of the $B^- \to D^+K^-\pi^-$ decay

R. Aaij *et al.*[*]
(LHCb Collaboration)
(Received 11 March 2015; published 5 May 2015)

The $B^- \to D^+K^-\pi^-$ decay is observed in a data sample corresponding to 3.0 fb^{-1} of pp collision data recorded by the LHCb experiment during 2011 and 2012. Its branching fraction is measured to be $\mathcal{B}(B^- \to D^+K^-\pi^-) = (7.31 \pm 0.19 \pm 0.22 \pm 0.39) \times 10^{-5}$ where the uncertainties are statistical, systematic and from the branching fraction of the normalization channel $B^- \to D^+\pi^-\pi^-$, respectively. An amplitude analysis of the resonant structure of the $B^- \to D^+K^-\pi^-$ decay is used to measure the contributions from quasi-two-body $B^- \to D_0^*(2400)^0K^-$, $B^- \to D_2^*(2460)^0K^-$, and $B^- \to D_J^*(2760)^0K^-$ decays, as well as from nonresonant sources. The $D_J^*(2760)^0$ resonance is determined to have spin 1.

DOI: 10.1103/PhysRevD.91.092002 PACS numbers: 13.25.Hw, 14.40.Lb

PHYSICAL REVIEW D **92**, 032002 (2015)

Dalitz plot analysis of $B^0 \to \bar{D}^0\pi^+\pi^-$ decays

R. Aaij *et al.*[*]
(LHCb Collaboration)
(Received 8 May 2015; published 7 August 2015)

The resonant substructures of $B^0 \to \bar{D}^0\pi^+\pi^-$ decays are studied with the Dalitz plot technique. In this study a data sample corresponding to an integrated luminosity of 3.0 fb^{-1} of pp collisions collected by the LHCb detector is used. The branching fraction of the $B^0 \to \bar{D}^0\pi^+\pi^-$ decay in the region $m(\bar{D}^0\pi^\pm) > 2.1\ \mathrm{GeV}/c^2$ is measured to be $(8.46 \pm 0.14 \pm 0.29 \pm 0.40) \times 10^{-4}$, where the first uncertainty is statistical, the second is systematic and the last arises from the normalization channel $B^0 \to D^*(2010)^-\pi^+$. The $\pi^+\pi^-$ S-wave components are modeled with the isobar and K-matrix formalisms. Results of the Dalitz plot analyses using both models are presented. A resonant structure at $m(\bar{D}^0\pi^-) \approx 2.8\ \mathrm{GeV}/c^2$ is confirmed and its spin-parity is determined for the first time as $J^P = 3^-$. The branching fraction, mass and width of this structure are determined together with those of the $D_0^*(2400)^-$ and $D_2^*(2460)^-$ resonances. The branching fractions of other $B^0 \to \bar{D}^0h^0$ decay components with $h^0 \to \pi^+\pi^-$ are also reported. Many of these branching fraction measurements are the most precise to date. The first observation of the decays $B^0 \to \bar{D}^0f_0(500)$, $B^0 \to \bar{D}^0f_0(980)$, $B^0 \to \bar{D}^0\rho(1450)$, $B^0 \to D_3^*(2760)^-\pi^+$ and the first evidence of $B^0 \to \bar{D}^0f_0(2020)$ are presented.

DOI: 10.1103/PhysRevD.92.032002 PACS numbers: 14.40.Lb, 14.40.Be, 14.40.Nd

♢ PDG2020

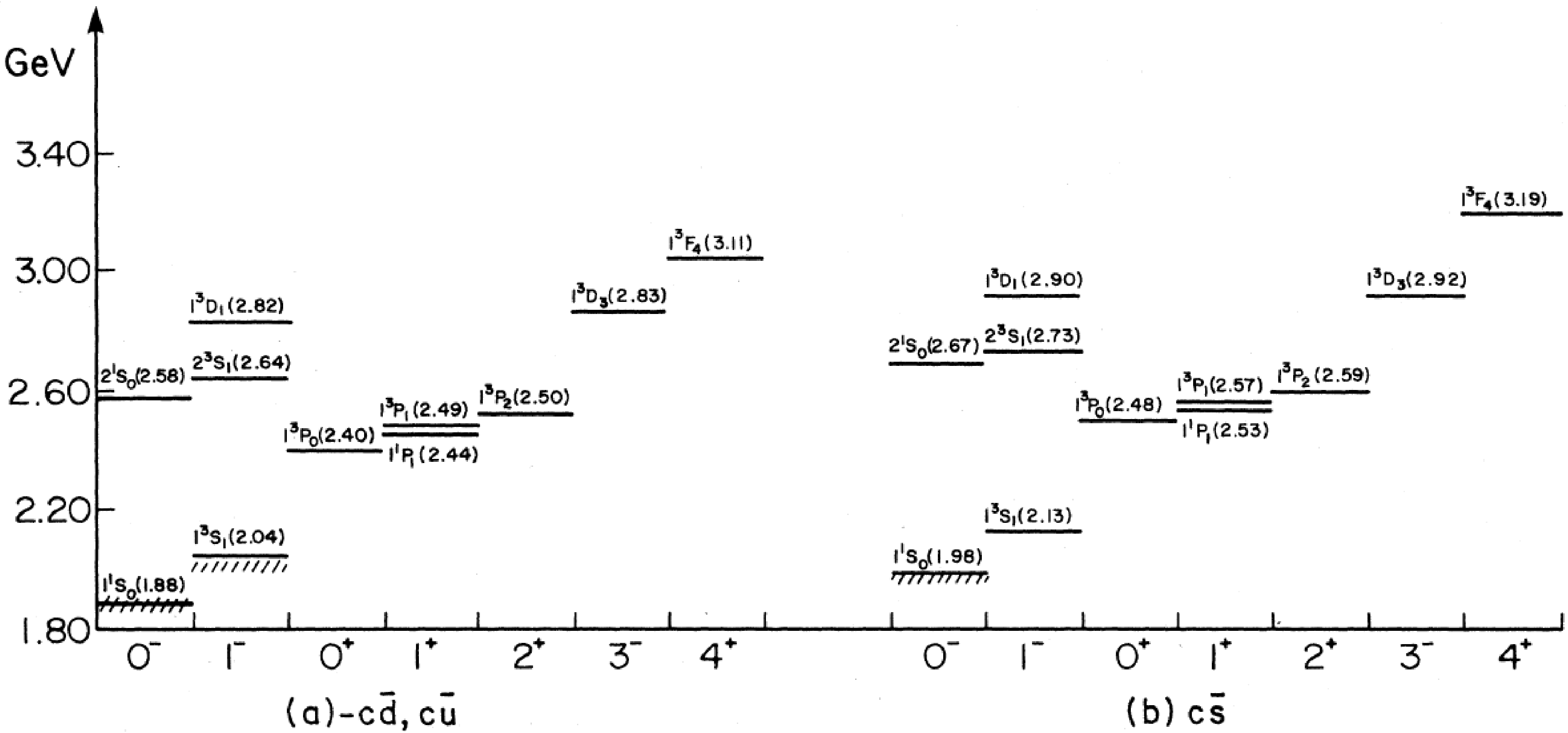
$D^+ = c\,\bar{d}$, $D^0 = c\,\bar{u}$, $\bar{D}^0 = \bar{c}\,u$, $D^- = \bar{c}\,d$, similarly for D^*'s

See related reviews:

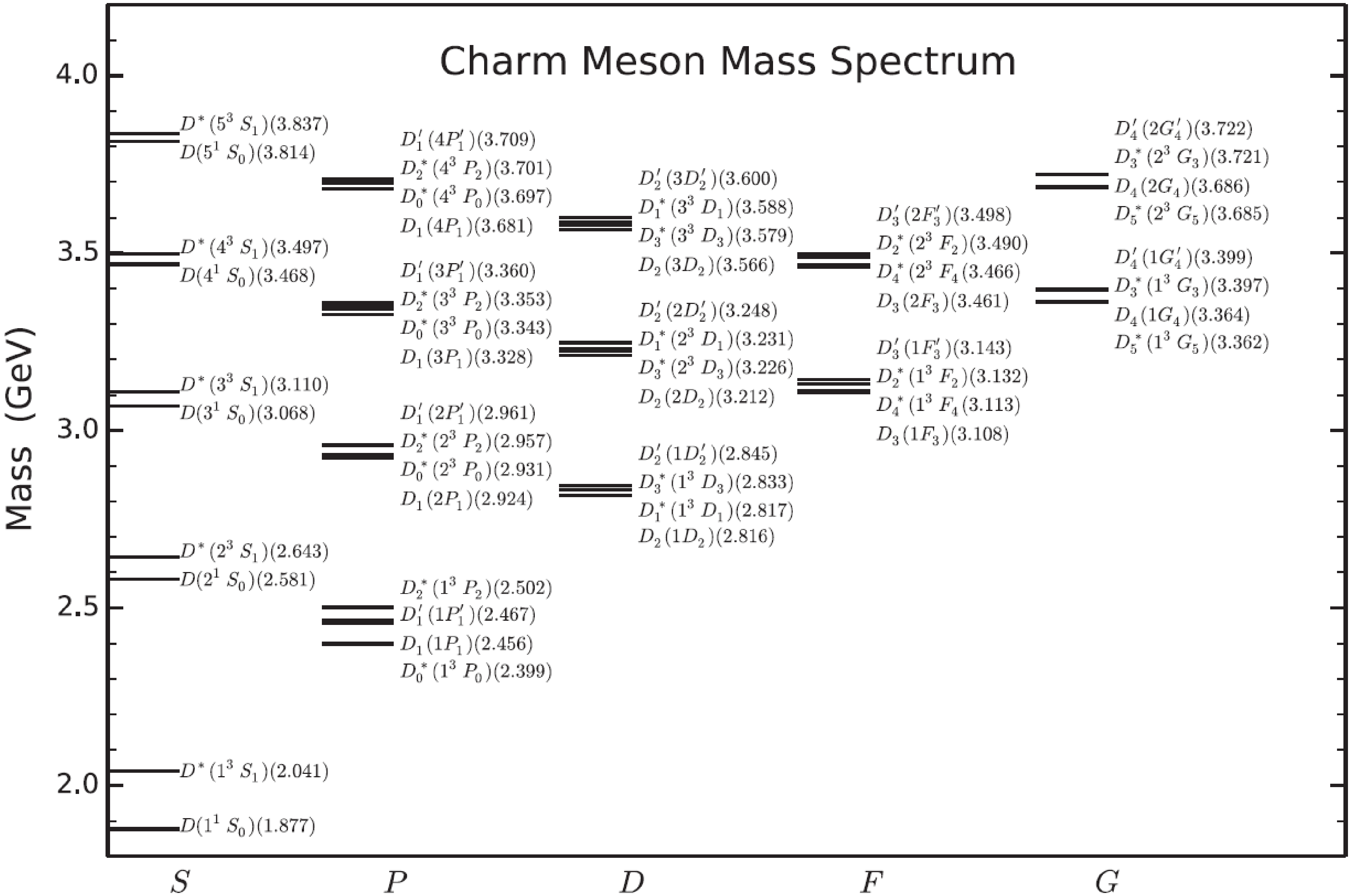
- Review of Multibody Charm Analyses
- $D^0 - \bar{D}^0$ Mixing

• $D^{\pm}$	$1/2(0^-)$
• D^0	$1/2(0^-)$
• $D^*(2007)^0$	$1/2(1^-)$
• $D^*(2010)^{\pm}$	$1/2(1^-)$
• $D_0^*(2300)^0$ was $D_0^*(2400)^0$	$1/2(0^+)$
$D_0^*(2300)^{\pm}$ was $D_0^*(2400)^{\pm}$	$1/2(0^+)$
• $D_1(2420)^0$	$1/2(1^+)$
$D_1(2420)^{\pm}$	$1/2(?^?)$
$D_1(2430)^0$	$1/2(1^+)$
• $D_2^*(2460)^0$	$1/2(2^+)$
• $D_2^*(2460)^{\pm}$	$1/2(2^+)$
$D(2550)^0$	$1/2(?^?)$
$D_J^*(2600)$ was $D(2600)$	$1/2(?^?)$
$D^*(2640)^{\pm}$	$1/2(?^?)$
$D(2740)^0$	$1/2(?^?)$
$D_3^*(2750)$	$1/2(3^-)$
$D(3000)^0$	$1/2(?^?)$

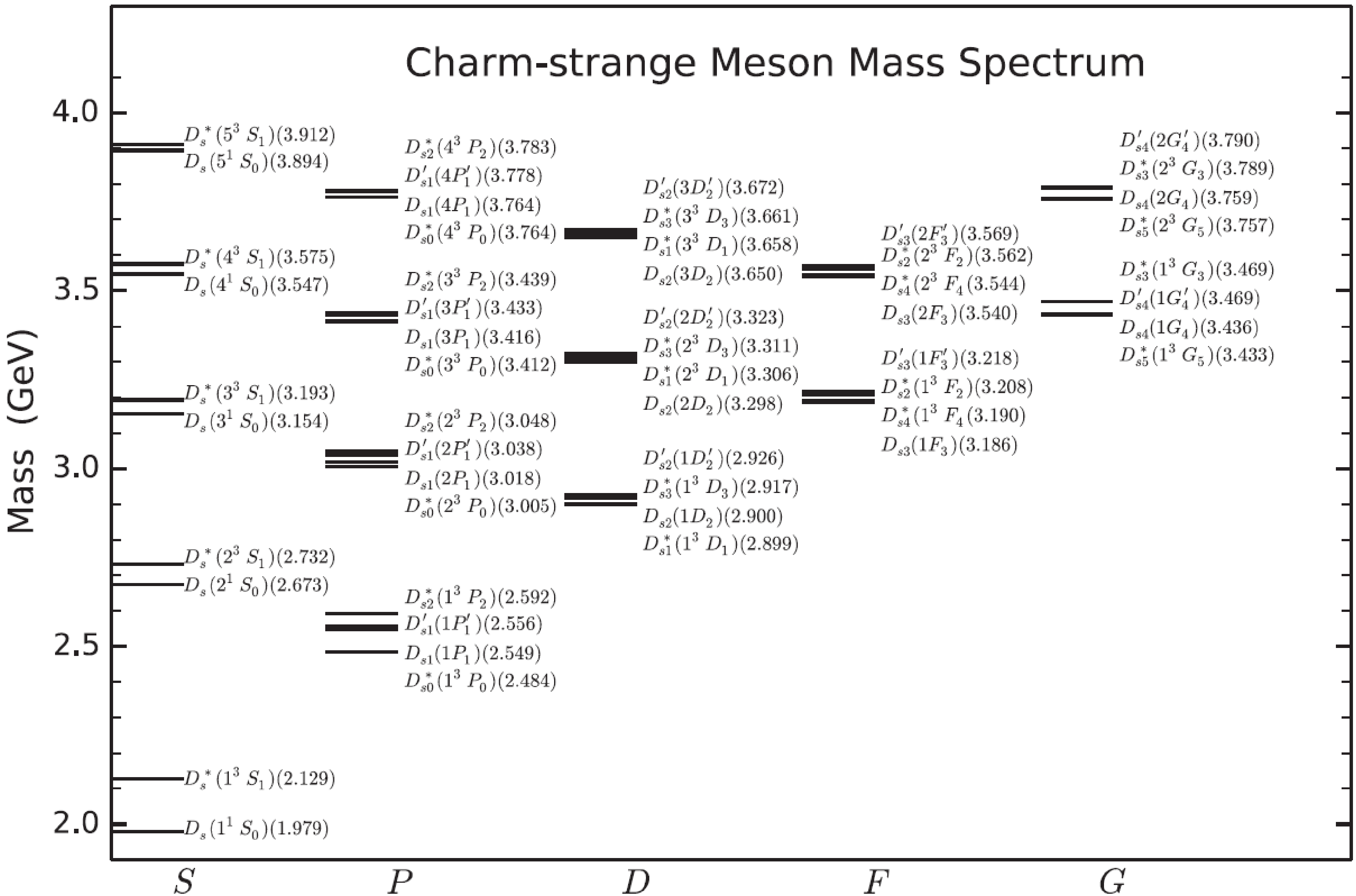
Charm mesons mass spectrum in the relativistic quark model (S. Godfrey and N. Isgur, PRD32, 189 (1985))



Charm mesons mass spectrum in the relativized quark model (S. Godfrey and K. Moats, PRD93, 034035 (2016))



Charm mesons mass spectrum in the relativized quark model (S. Godfrey and K. Moats, PRD93, 034035 (2016))



Possible assignments of D mesons

$c\bar{u}$, $c\bar{d}$	J^P	j^P	$n^{2S+1}L_J$	GI	GM	PE	SZ
$D_0^*(2300)$	0^+	$\frac{1}{2}^+$	1^3P_0	2.40	2.399	2.377	2.37
$D_1(2420)$	1^+	$(\frac{3}{2}^+)$	1^3P_1	2.49	2.456	2.417	2.408
$D_1(2430)$	1^+	$(\frac{1}{2}^+)$	1^1P_1	2.44	2.467	2.490	2.446
$D_2^*(2460)$	2^+	$\frac{3}{2}^+$	1^3P_2	2.50	2.502	2.460	2.484
$D_1^*(2760)$	1^-	$\frac{3}{2}^-$	1^3D_1	2.82	2.817	2.795	2.623
?	2^-	$(\frac{5}{2}^-)$	1^3D_2	-	2.816	2.775	2.699
$D_2(2740)$	2^-	$(\frac{3}{2}^-)$	1^1D_2	-	2.845	2.833	2.737
$D_3^*(2750)$	3^-	$\frac{5}{2}^-$	1^3D_3	2.83	2.833	2.799	2.813
$D_0(2550)$	0^-	$\frac{1}{2}^-$	2^1S_0	2.58	2.581	2.589	-
$D_1^*(2600)$	1^-	$\frac{1}{2}^-$	2^3S_1	2.64	2.643	2.692	-

Red: to be confirmed

GI: S. Godfrey and N.Isgur, Phys. Rev. D32, 189 (1985)

GM: S. Godfrey and K. Moats, Phys. Rev. D93, 034035 (2016)

PE: M.Di Pierro and E. Eichten, Phys. Rev. D64, 114004 (2001)

SZ: Hong-Yun Shan and Ailin Zhang, Chin. Phys. C 34, 16 (2010).

D_s mesons

S-wave and P-wave D_s mesons are also believed established

Table 2: S−wave and P−wave D_s.

States	J^P	$n^{2S+1}L_J$	j^P	PDG2020 notes
$D_s^{\pm}$	0^-	1^1S_0	$\frac{1}{2}^-$	The parity given is that expected of a $c\bar{s}$ ground state
$D_s^{\star\pm}$	1^-	1^3S_0	$\frac{1}{2}^-$	J^P =?$^?$, consistent with 1^-
$D_{s0}^{\star}(2317)^{\pm}$	0^+	1^3P_0	$\frac{1}{2}^+$	J, P need confirmation
$D_{s1}(2460)^{\pm}$	1^+	mixing	$\frac{1}{2}^+$	
$D_{s1}(2536)^{\pm}$	1^+	mixing	$\frac{3}{2}^+$	J, P need confirmation
$D_{s2}^{\star}(2573)$	2^+	1^3P_2	$\frac{3}{2}^+$	consistent with 2^+

Higher excited D_s mesons have been observed

Higher excited D_s mesons

◇ $D^*_{s1}(2700)$ $I(J^P) = 0(1^-)$

$D_{s1}(2700)^{\pm}$ was first observed by Belle(K. Abe, *et al.*, Belle Collaboration, hep-ex/0608031) in

$$B^+ \to \bar{D}^0 D_{sJ} \to \bar{D}^0 D^0 K^+$$

with $M = 2715 \pm 11^{+11}_{-14}$ and $\Gamma = 115 \pm 20^{36}_{-32}$ MeV. The mass and the decay width change a little in their published version(J. Brodzicka *et al.*, Belle Collaboration, Phys. Rev. Lett. **100**, 092001 (2008))

Mass: $2708.3^{+4.0}_{-3.4}$ MeV
Decay width: 120 ± 11 MeV

$$2^3S_1(c\bar{s})$$

Higher excited D mesons

$I(J^P) = 0(1^-)$ $1^3D_1(s\bar{c})$

◇ $D^*_{s1}(2860)$

$$e^+e^- \to D^0K^+X, \qquad D^0 \to K^-\pi^+, \qquad (1)$$

$$e^+e^- \to D^0K^+X, \qquad D^0 \to K^-\pi^+\pi^0, \qquad (2)$$

$$e^+e^- \to D^+K^0_SX, \qquad D^+ \to K^-\pi^+\pi^+, \qquad K^0_S \to \pi^+\pi^-. \qquad (3)$$

Mass: 2859±12±24 MeV
Decay width: 120±23±77 MeV

$\Gamma(D^*K)/\Gamma(DK)$ Γ_4/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.10±0.15±0.19	3122	[1] AUBERT	09AR	BABR	$e^+e^- \to D^{(*)}KX$

[1] From the average of the corresponding ratios with $D^{(*)0}K^+$ and $D^{(*)+}K^0_S$.

$\Gamma(D^{*0}K^+)/\Gamma(D^0K^+)$ Γ_5/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.04±0.17±0.20	2241	[1] AUBERT	09AR	BABR	$e^+e^- \to D^{(*)}KX$

[1] From the $D^{*0}K^+$ and D^0K^+, where $D^{*0} \to D^0\pi^0$.

$\Gamma(D^{*+}K^0_S)/\Gamma(D^+K^0_S)$ Γ_6/Γ_3

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.38±0.35±0.49	881	[1] AUBERT	09AR	BABR	$e^+e^- \to D^{(*)}KX$

◇ $D^*_{s3}(2860)$ $I(J^P) = 0(3^-)$ $1^3D_3(s\bar{c})$

$$e^+e^- \to D^0K^+X, \quad D^0 \to K^-\pi^+, \quad (1)$$

$$e^+e^- \to D^0K^+X, \quad D^0 \to K^-\pi^+\pi^0, \quad (2)$$

$$e^+e^- \to D^+K^0_SX, \quad D^+ \to K^-\pi^+\pi^+, \quad K^0_S \to \pi^+\pi^-. \quad (3)$$

Mass: 2860.5±2.6±6.5 MeV
Decay width: 53±7±7 MeV

PRL **113,** 162001 (2014) PHYSICAL REVIEW LETTERS week ending 17 OCTOBER 2014

Observation of Overlapping Spin-1 and Spin-3 $\bar{D}^0K^-$ Resonances at Mass 2.86 GeV/c^2

R. Aaij *et al.*[*]
(LHCb Collaboration)
(Received 30 July 2014; published 14 October 2014)

The resonant substructure of $B^0_s \to \bar{D}^0K^-\pi^+$ decays is studied using a data sample corresponding to an integrated luminosity of 3.0 fb^{-1} of pp collision data recorded by the LHCb detector. An excess at $m(\bar{D}^0K^-) \approx 2.86$ GeV/c^2 is found to be an admixture of spin-1 and spin-3 resonances. Therefore, the $D^*_{sJ}(2860)^-$ state previously observed in inclusive $e^+e^- \to \bar{D}^0K^-X$ and $pp \to \bar{D}^0K^-X$ processes consists of at least two particles. This is the first observation of a heavy flavored spin-3 resonance, and the first time that any spin-3 particle has been seen to be produced in B decays. The masses and widths of the new states and of the $D^*_{s2}(2573)^-$ meson are measured, giving the most precise determinations to date.

DOI: 10.1103/PhysRevLett.113.162001 PACS numbers: 14.40.Lb, 13.25.Hw

collaborations. More recently the LHCb collaboration has measured the properties of the $D^*_{sJ}(2860)^-$ more precisely and found that it is comprised of two overlapping states, the $D^*_{s1}(2860)^-$ and $D^*_{s3}(2860)^-$ with $J^P = 1^-$ and 3^- respectively [13,14]. With this new information it was argued that

◇ PDG2020

CHARMED, STRANGE MESONS ($C = S = \pm 1$)

$D_s^+ = c\,\bar{s}$, $D_s^- = \bar{c}\,s$, similarly for D_s^*'s

See related reviews:

D_s^+ Branching Fractions

Leptonic Decays of Charged Pseudoscalar Mesons

•	$D_s^{\pm}$	$0(0^-)$
•	$D_s^{*\pm}$	$0(?^?)$
•	$D_{s0}^*(2317)^{\pm}$	$0(0^+)$
•	$D_{s1}(2460)^{\pm}$	$0(1^+)$
•	$D_{s1}(2536)^{\pm}$	$0(1^+)$
•	$D_{s2}^*(2573)$	$0(2^+)$
•	$D_{s1}^*(2700)^{\pm}$	$0(1^-)$
	$D_{s1}^*(2860)^{\pm}$	$0(1^-)$
	$D_{s3}^*(2860)^{\pm}$	$0(3^-)$
	$D_{sJ}(3040)^{\pm}$	$0(?^?)$

命名的演化：

- $D_{SJ}(2860)$(BaBar 2006)->

  $D^*_{SJ}(2860)$(LHCb 2012，PDG2010-2014)->

  $D^*_{s1}(2860)$，$D^*_{s3}(2860)$(LHCb 2014,PDG2016)

◇ $D_{sJ}(3040)$ $I(J^P) = 0(?^?)$

$$e^+e^- \longrightarrow D^{*0}K^+X$$
$$e^+e^- \longrightarrow D^{*+}K_S^0X$$
$$e^+e^- \longrightarrow D^{*+}K_S^0X$$
$$e^+e^- \longrightarrow D^{*+}K_S^0X$$
$$e^+e^- \longrightarrow D^{*+}K_S^0X$$

BaBar

Mass: $3044 \pm 8^{+30}_{-5}$ **MeV**

Decay width: $239 \pm 35^{+46}_{-42}$ **MeV**

Our work(Nucl. Phys. A 1048, 122893(2024)): $j^P=1^-$, mixing of spin singlet and spin triplet. radial excitation of $D_{s1}(2536)$

Possible assignments of D_s mesons

$c\bar{s}$	J^P	j^P	$n^{2S+1}L_J$	GI	GM	PE	SZ
$D^{\star}_{s0}(2317)^{\pm}$	0^+	$\frac{1}{2}^+$	1^3P_0	2.48	2.484	2.487	2.478
$D_{s1}(2536)^{\pm}$	1^+	$(\frac{3}{2}^+)$	1^3P_1	2.57	2.549	2.535	2.516
$D_{s1}(2460)^{\pm}$	1^+	$(\frac{1}{2}^+)$	1^1P_1	2.53	2.556	2.605	2.554
$D_{s2}(2573)^{\pm}$	2^+	$\frac{3}{2}^+$	1^3P_2	2.59	2.592	2.581	2.592
$D^*_{s1}(2860)$	1^-	$\frac{3}{2}^-$	1^3D_1	2.90	2.899	2.913	2.714
?	2^-	$(\frac{5}{2}^-)$	1^3D_2	-	2.900	2.900	2.789
?	2^-	$(\frac{3}{2}^-)$	1^1D_2	-	2.926	2.953	2.827
$D^*_{s3}(2860)$	3^-	$\frac{5}{2}^-$	1^3D_3	2.92	2.917	2.925	2.903
$D_{s0}(2590)$	0^-	$\frac{1}{2}^-$	2^1S_0	2.67	2.673	2.700	-
$D^*_{s1}(2700)$	1^-	$\frac{1}{2}^-$	2^3S_1	2.73	2.732	2.806	-

Our attempts: Charmed mesons

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Quark dynamics?

Inclusive production in e⁺e⁻ and pp collisions

$$e^+e^- \to c\bar{c} \to D^{(*)}\pi X,$$

$$pp \to D^+\pi^- X,\ pp \to D^0\pi^+ X,\ pp \to D^{*+}\pi^- X,$$

In inclusive decays, the spin and parity are difficult to determine. Analyses of resonances produced directly from e^+e^- and pp collisions do not allow determination of the quantum numbers of the produced states, but can distinguish whether or not they have natural spin parity

Exclusive B decays

$$B^0 \to \bar{D}^0\pi^+\pi^-$$

$$B^- \to D^+K^-\pi^-$$

In a charmed-strange meson sector, it was found that $D^*_{sJ}(2860)$ produced in e^+e^- and pp collisions by *BABAR* and LHCb, respectively, consists of $D^*_{s1}(2860)$ and $D^*_{s3}(2860)$ [6,7]. Similarly, $D^*(2760)$ produced in e^+e^- and pp collisions consists of $D^*_1(2760)$ and $D^*_3(2760)$

Mixing

Physical states may not be the $^{2S+1}L_J$ or the j^P eigenstates!

Antisymmetric piece of the spin-orbit interaction:

$$^3L_J - ^1L_J$$

Color hyperfine interaction:

$$^3L_J - ^3L'_J$$

Dynamical mixing between 2^3S_1 and 1^3D_1 charmed mesons

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In charmed D and D_s mesons sector, the matrix of a Hamiltonian in a quark potential model is computed in the 2^3S_1 and 1^3D_1 subspace. The masses of four mixed states of 2^3S_1 and 1^3D_1 denoted with $D_1^*(2635)$, $D_1^*(2739)$, $D_{s1}^*(2715)$ and $D_{s1}^*(2805)$ are obtained. It is an off-diagonal part of the spin-orbit tensor interaction that causes the mixing between the 2^3S_1 and 1^3D_1 states. The mixing angles between the 2^3S_1 and 1^3D_1 states are tiny. Under the mixing, a $^3P_0$ model is employed to compute the hadronic decay widths of all OZI-allowed decay channels of the four mixed states. The two light mixed states $D_1^*(2635)$ and $D_{s1}^*(2715)$ are close in mass to $D_J^*(2600)$ and $D_{s1}^*(2700)$, while the two heavy mixed states $D_1^*(2739)$ and $D_{s1}^*(2805)$ are lighter in mass than $D(2750)$ and $D_{s1}^*(2860)$. The mixing angles obtained from dynamical interaction are inconsistent with the mixing angles obtained from hadronic decay. Based on mass spectra and hadronic decay analyses, $D_J^*(2600)$, $D(2750)$, $D_{s1}^*(2700)$, and $D_{s1}^*(2860)$ are impossibly the mixed states of 2^3S_1 and 1^3D_1 at the small mixing angles. The inconsistence implies that $D_1^*(2760)$ and $D_{s1}^*(2860)$ have not been properly resolved from present experimental data, or there exist large unknown off-diagonal interactions that result in large mixing angles.

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$$M(D_1^{*L}) = 2635.16\ \text{MeV},$$
$$M(D_1^{*H}) = 2738.51\ \text{MeV},$$
$$\theta_{c\bar{q}} \approx 0.12^\circ.$$
$$M(D_{s1}^{*L}) = 2714.76\ \text{MeV},$$
$$M(D_{s1}^{*H}) = 2805.49\ \text{MeV},$$
$$\theta_{c\bar{s}} \approx 0.18^\circ.$$

Based on mass spectra and hadronic decay analyses, $D_J^*(2600)$ and $D(2750)$ are impossibly the mixed D mesons of 2^3S_1 and 1^3D_1 at a tiny mixing angle $\theta \approx 0.12°$, $D_{s1}^*(2700)$ and $D_{s1}^*(2860)$ are impossibly the mixed D_s mesons of 2^3S_1 and 1^3D_1 at $\theta \approx 0.18°$ either.

In order to identify $D_J^*(2600)$, $D(2750)$, $D_{s1}^*(2700)$, and $D_{s1}^*(2860)$, it is important to fix the accurate masses and J^P numbers both from inclusive e^+e^- and pp collisions, and from exclusive B decays in experiment. So far, the resolve of $D^*(2760)$ and $D_{sJ}^*(2860)$ is not sufficient for the identification of D_1^{*H} and D_{s1}^{*H}. In fact, the mass and decay data of D_1^{*H} and D_{s1}^{*H} has not been definitely fixed in experiments.

3. Discussions

1, Glueball candidate: X(2370)

1980s

E(1420), $\psi \to \gamma E(1420)$, SLAC, Phys. Lett. B97, 329 (1980).

$\eta(1405)$: $I^G(J^{PC})=0^+(0^{-+})$

2000s,

X(1835): PDG: $J/\psi(1S) \to \gamma X(1835) \to \gamma\pi^+\pi^-\eta'$, BES, Phys.Rev.Lett. 95 (2005) 262001.

X(1835): $I^G(J^{PC})=0^+(0^{-+})$.

2020s,

X(2370): $X(2370) \to \pi^+\pi^-\eta'$, BESIII, Phys. Rev. Lett. 106 (2011) 072002.

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Instanton and higher-loop perturbative contributions to the QCD sum-rule analysis of pseudoscalar gluonium

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Abstract

Instanton effects and three-loop perturbative contributions are incorporated into QCD sum-rule analyses of pseudoscalar ($J^{PC} = 0^{-+}$) gluonium. Gaussian sum-rules are shown to be superior to Laplace sum-rules in optimized predictions for pseudoscalar gluonium states in the presence of instanton contributions. The Gaussian sum-rule analysis yields a pseudoscalar mass of (2.65 ± 0.33) GeV and width bounded by $\Gamma < 530$ MeV. The Laplace sum-rules provide corroborating evidence in support of the ≈ 2.7 GeV mass scale.

2, X(3872): $I^G(J^{PC})=0^+(1^{++})$.

2003,

X(3872): Belle, Phys.Rev.Lett. 91 (2003) 262001.

$\chi_{c1}(3872) \to \pi^+\pi^- J/\psi(1S)$
$\chi_{c1}(3872) \to \gamma\chi_{c1}$
$\chi_{c1}(3872)$ MASS FROM $J/\psi X$ MODE
$\chi_{c1}(3872)$ WIDTH
$B^+ \to \chi_{c1}(3872) K^+$

Molecule, tetraquark, charmonium(χ_{c1} (2P)), hybrid

Model or interaction!

R. Aaij et al., LHCb collaboration, arXiv：2406.17006

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Probing the nature of the $\chi_{c1}(3872)$ state using radiative decays

LHCb collaboration[†]

文献
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Abstract

The radiative decays $\chi_{c1}(3872) \to \psi(2S)\gamma$ and $\chi_{c1}(3872) \to J/\psi\gamma$ are used to probe the nature of the $\chi_{c1}(3872)$ state using proton-proton collision data collected with the LHCb detector, corresponding to an integrated luminosity of $9\,\text{fb}^{-1}$. Using the $B^+ \to \chi_{c1}(3872)K^+$ decay, the $\chi_{c1}(3872) \to \psi(2S)\gamma$ process is observed for the first time and the ratio of its partial width to that of the $\chi_{c1}(3872) \to J/\psi\gamma$ decay is measured to be

$$\frac{\Gamma_{\chi_{c1}(3872)\to\psi(2S)\gamma}}{\Gamma_{\chi_{c1}(3872)\to J/\psi\gamma}} = 1.67 \pm 0.21 \pm 0.12 \pm 0.04\,,$$

where the first uncertainty is statistical, the second systematic and the third is due to the uncertainties on the branching fractions of the $\psi(2S)$ and J/ψ mesons. The measured ratio makes the interpretation of the $\chi_{c1}(3872)$ state as a pure $D^0\overline{D}^{*0} + \overline{D}^0D^{*0}$ molecule questionable and strongly indicates a sizeable compact charmonium or tetraquark component within the $\chi_{c1}(3872)$ state.

The closeness of the mass of the $\chi_{c1}(3872)$ state [50, 51] to the $D^0\overline{D}^{*0}$ threshold, its narrow width [35, 50, 51], quantum numbers of $J^{PC} = 1^{++}$ [45, 47] and a large coupling to the $D^0\overline{D}^{*0}$ system [18, 23, 24, 29, 35] provide natural arguments to support the interpretation of the $\chi_{c1}(3872)$ state as a loosely-coupled $D^0\overline{D}^{*0} + \overline{D}^0 D^{*0}$ molecular state [58–62], in which the colourless open-charm mesons are spatially well separated. However, the expected production cross-section for such a molecular object in high-energy hadron collisions is too small to explain the observed production of the $\chi_{c1}(3872)$ state [63–66]. In fact, the measured production cross-section, transverse momentum and rapidity spectra of the $\chi_{c1}(3872)$ state are close to those observed for conventional charmonium states [36, 40, 41, 44, 53]. Alternative hypotheses for the nature of the $\chi_{c1}(3872)$ state include a charmonium $\chi_{c1}(2P)$ state [67–70], its virtual companion [71] or its mixture with a hadronic molecule [70, 72]; a hadro-charmonium state [73]; a hybrid meson [74, 75] or a tetraquark [76, 77]. A large isospin violation in $\chi_{c1}(3872)$ decays [54] strongly disfavors the interpretation of the $\chi_{c1}(3872)$ particle as a pure charmonium state.

Experimental studies of the $\chi_{c1}(3872)$ lineshape in the $J/\psi\pi^+\pi^-$ [50] and $D^0\overline{D}^{*0}$ [29] final states, and the combined analysis of the two final states [35] provide important information about the parameters of the low-energy $D^0\overline{D}^{*0}$ scattering amplitude, namely the scattering length and the effective range. These parameters, if measured precisely, provide crucial information about the internal structure of the $\chi_{c1}(3872)$ state. The sign of the scattering

3, Where is the diquark (signal)?

Diquark signal in experiment?

Belle Collaboration

Production cross sections of hyperons and charmed baryons from e^+e^- annihilation near $\sqrt{s} = 10.52$~GeV

Belle Collaboration • M. Niiyama (Kyoto U. (main)) Show All(169)

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We measure the inclusive production cross sections of hyperons and charmed baryons from e^+e^- annihilation using a 800 fb^{-1} data sample taken near the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy e^+e^- collider. The feed-down contributions from heavy particles are subtracted using our data, and the direct production cross sections are presented for the first time. The production cross sections divided by the number of spin states for $S = -1$ hyperons follow an exponential function with a single slope parameter except for the $\Sigma(1385)^+$ resonance. Suppression for $\Sigma(1385)^+$ and $\Xi(1530)^0$ hyperons is observed. Among the production cross sections of charmed baryons, a factor of 3 difference for Λ_c^+ states over Σ_c states is observed. This observation suggests a diquark structure for these baryons.

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Thanks !