Exotic spectroscopy at LHCb

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on behalf of the LHCb collaboration

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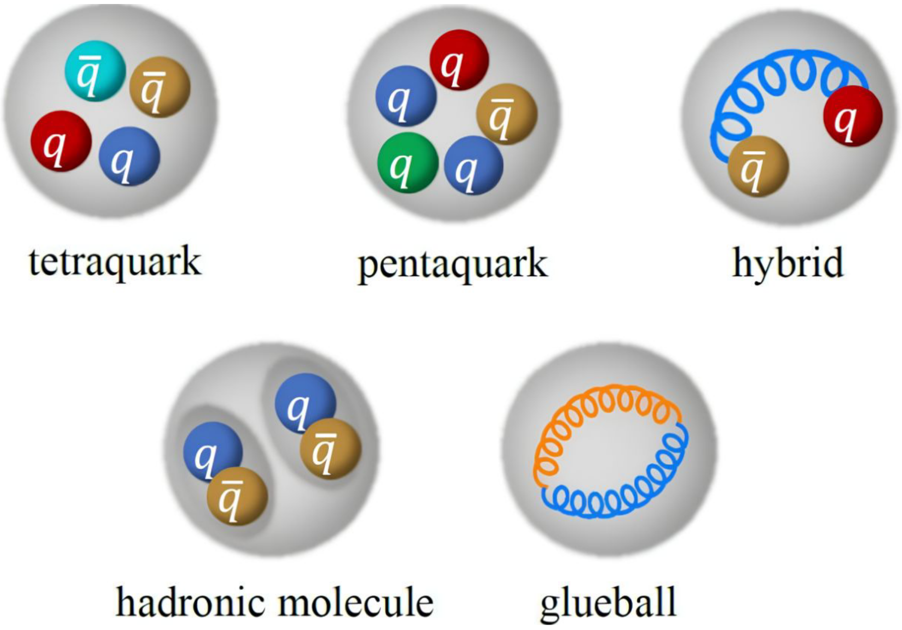
Introduction

Exotic hadrons

All states with internal structure different from conventional $\bar{q}q$ or qqq states

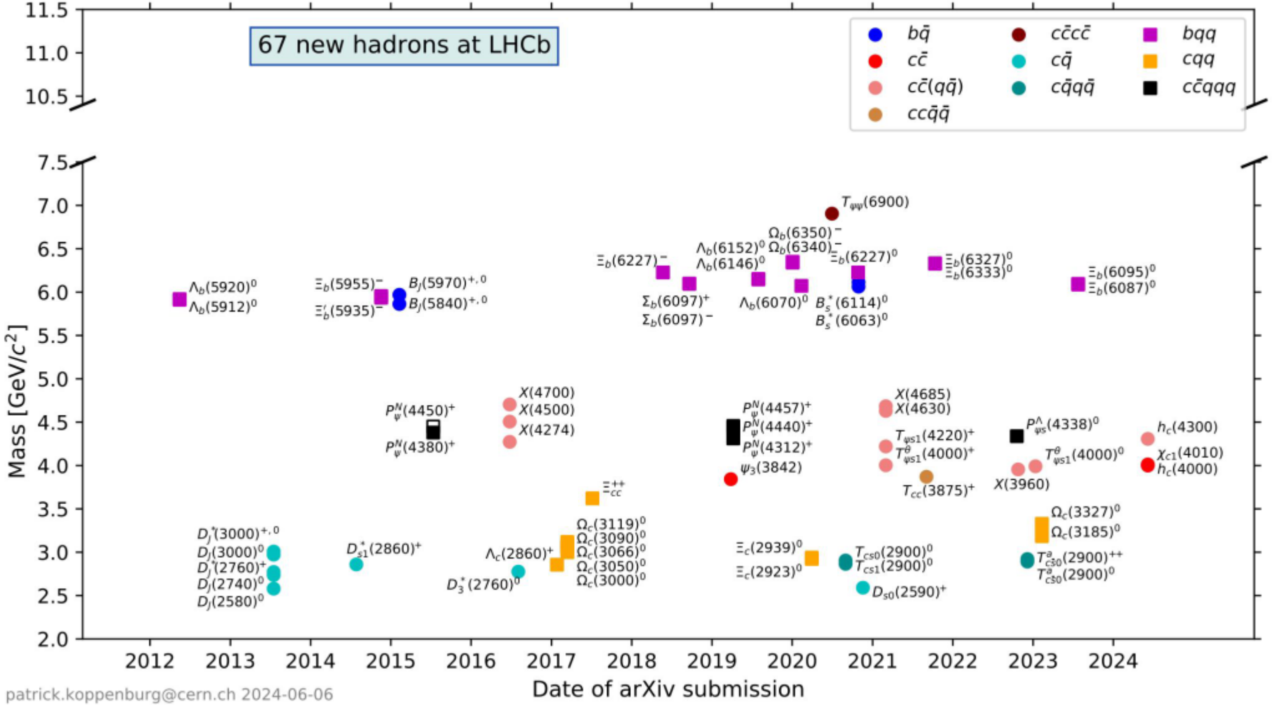
- **Glueballs**
  - No valence quarks, only gluons
- **Hadronic molecules**
  - Color-singlet hadrons bound by residual nuclear forces
- **Tetraquarks and Pentaquarks**
  - Bound state of quark and antiquark
- **Hadro-quarkonium**
  - $\bar{Q}Q$ core state bound to cloud of light quarks and gluons



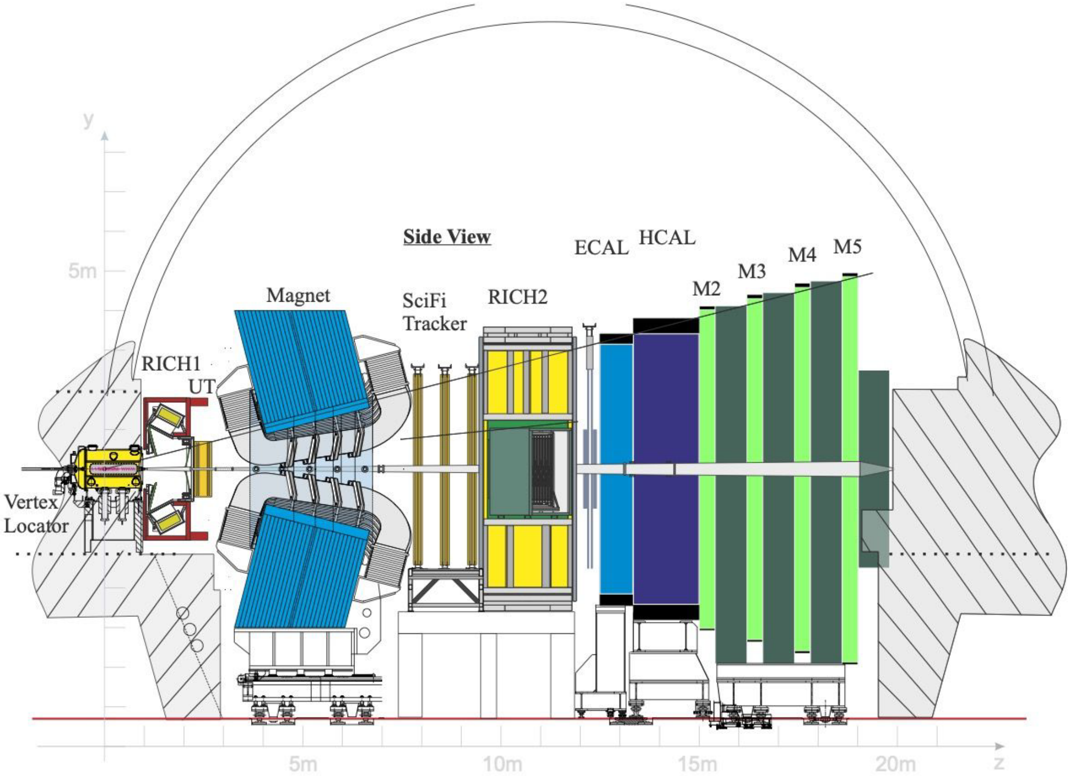
Exotic spectroscopy at LHCb

The X(3872), aka $\chi_{c1}(3872)$, is the first exotic candidate ever observed. [PhysRevLett 91, 262001 (2003)]

Many other exotic candidates have been discovered



The LHCb detector



[IJMPA 30 (2015) 1530022]

Run1: 7-8 TeV, 2011-2012

Run2: 13 TeV, 2015-2016-2017-2018

9 fb^{-1}, with $2< \eta <5$

Vertex reconstruction:

$\Delta IP = (15 + 29/p_T)\mu m$

Momentum resolution:

$\Delta p/p$ = ~0.5−1% (from 2 to 200 GeV)

Hadronic identification:

$\varepsilon_{K\to K}$ = ~95%, $\varepsilon_{K\to\pi}$ = ~10% (from 2 to 200 GeV)

Muon trigger efficiency:

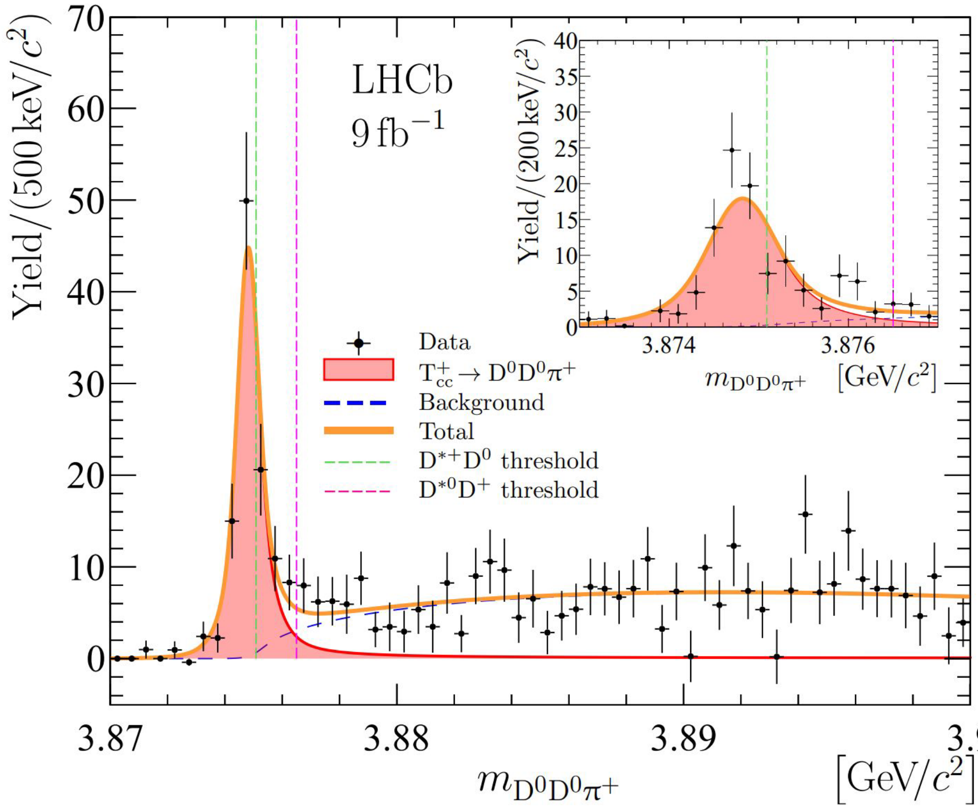
$\varepsilon > 90\%$

Latest exotic study at LHCb

Observation of a doubly charmed tetraquark

- Narrow peak in the $D^0D^0\pi^+$ spectrum just below the $D^{*+}D^0$ threshold
- $\delta m = -273 \pm 61 \pm 5\ ^{+11}_{-14}$ keV, wrt $D^{*+}D^0$ mass threshold
- $\Gamma = 410 \pm 165 \pm 43^{+18}_{-38}$ keV
- Minimal quark content $cc\bar{u}\bar{d}$
- Consistent with the T^+_{cc} isoscalar tetraquark
- $J^P = 1^+$

[Nature Physics 18, 751–754 (2022)]
[Nature Physics 13, 3351 (2022)]



New strange pentaquark candidate $P_{\psi_s}^{\Lambda}$

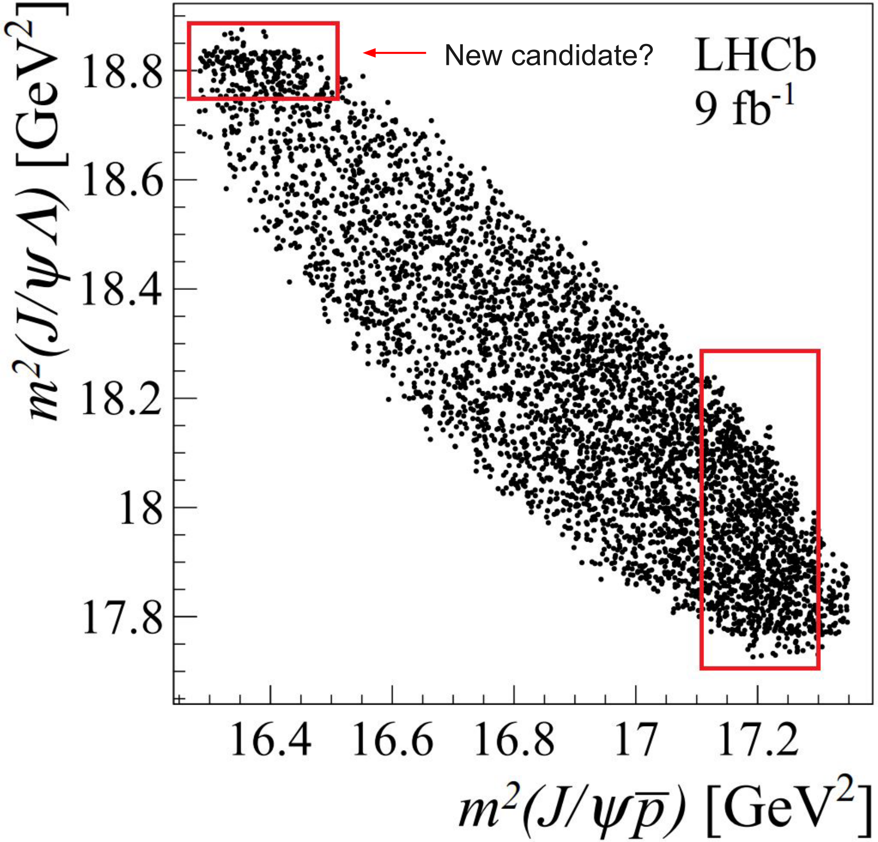
Amplitude analysis of $B^- \to J/\psi \Lambda \bar{p}$

- ~4400 events
- High signal purity (93%)
- $m_{B^-} = 5279.44 \pm 0.05 \pm 0.07$ MeV

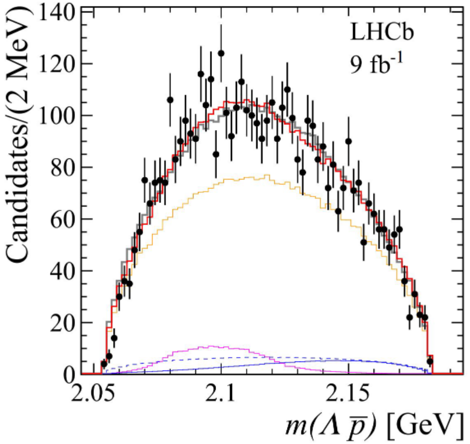
Model used:

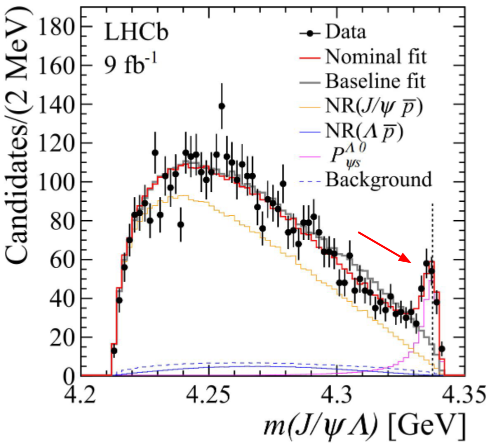
- NR($J/\psi \bar{p}$)
- NR($\Lambda \bar{p}$)
  - $K_4^*(2045)^-$, $K_2^*(2250)^-$, $K_3^*(2320)^-$ outside the phase space but can contribute
- Combinatorial background
- $P_{\psi_s}^{\Lambda} \to J/\psi \Lambda$ (**new**)

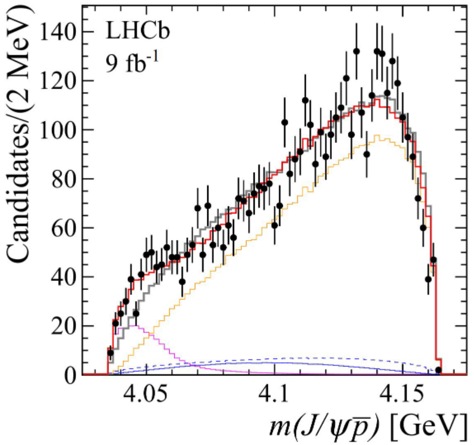
[PhysRevLett 131, 031901 (2023)]



New strange pentaquark candidate $P^{\Lambda}_{\psi_s}$







- Baseline model → χ^2/ndof = 120.8/47
- Default model → χ^2/ndof = 55.3/51
- m($P^{\Lambda}_{\psi_s}$) = 4338.2 ± 0.7 ± 0.4 MeV and Γ($P^{\Lambda}_{\psi_s}$) = 7.0 ± 1.2 ± 1.3 MeV
- J = 1/2 , odd parity preferred: $J^P = 1/2^+$ excluded at 90% C.L.
- First observation of a pentaquark with strange quark content: [ccud$\bar{s}$] , significance >10σ
- Very close to the $\Xi_c^+ D^-$ mass threshold

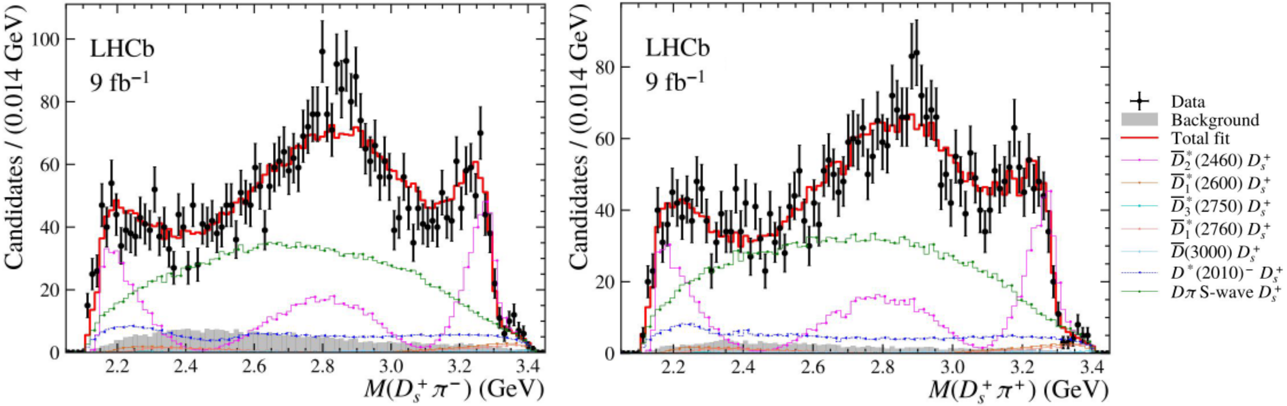
[PhysRevLett 131, 031901 (2023)]

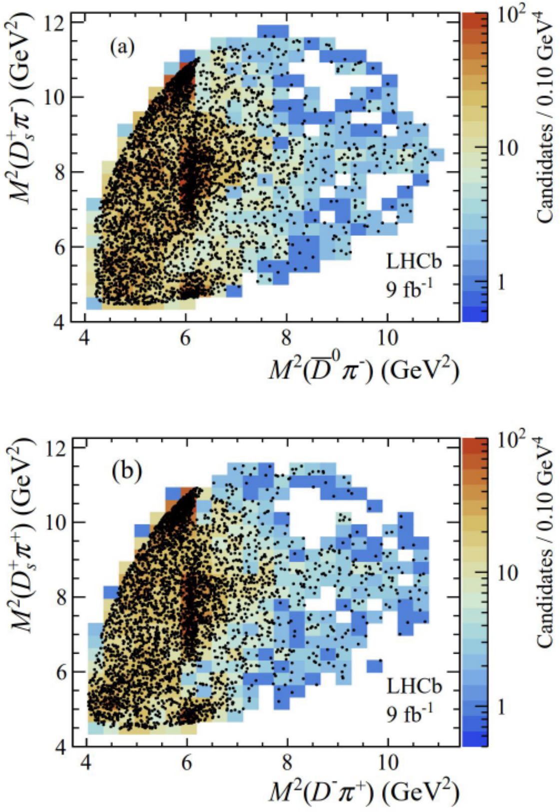
Doubly charged tetraquark and neutral partner

Joint amplitude analysis of two channels (related by isospin symmetry)

- $B^0 \to \overline{D}^0 D_s^+ \pi^-$ ~ 4000 events
- $B^+ \to D^- D_s^+ \pi^-$ ~ 3750 events

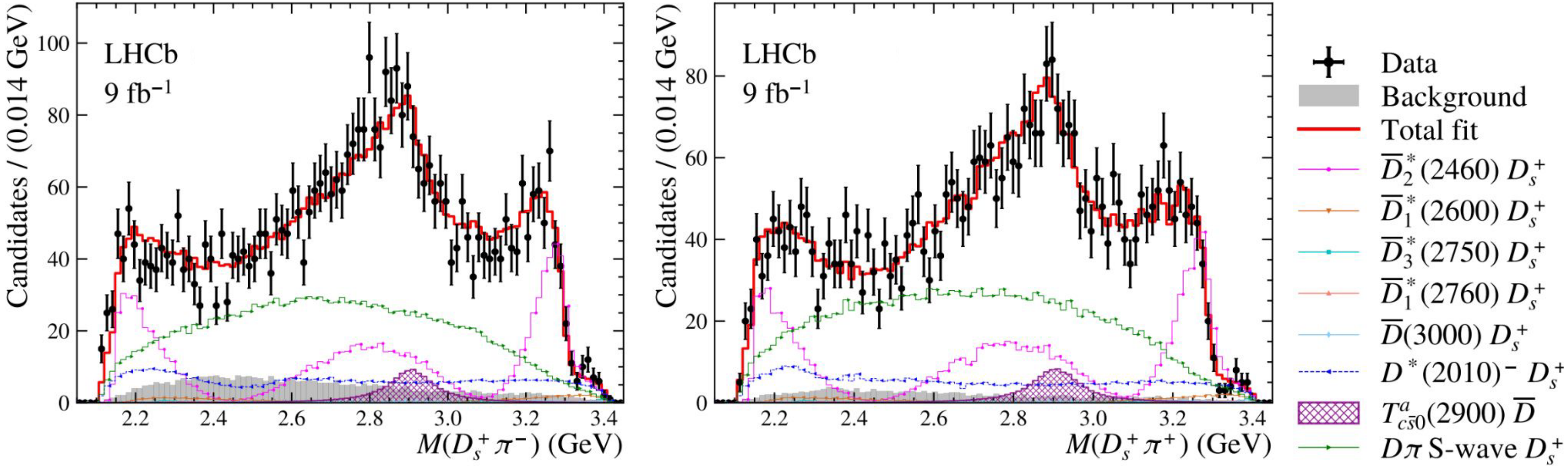
Fit with only $\overline{D}^*$ gives no satisfactory description





[PhysRevLett 131, 041902 (2023)] [PhysRevLett 108, 012017 (2023)]

Doubly charged tetraquark and neutral partner



- Peaking structure well described by adding a $J^P = 0^+$ state $T_{cs0}(2900)^{++/0}$ (**new**)
- m = 2908 ± 11 ± 20 MeV, Γ= 136 ± 23 ± 11 MeV
- Significance >9σ
- $J^P = 0^+$ favoured by >7.5σ

[PhysRevLett 131, 041902 (2023)] [PhysRevLett 108, 012017 (2023)]

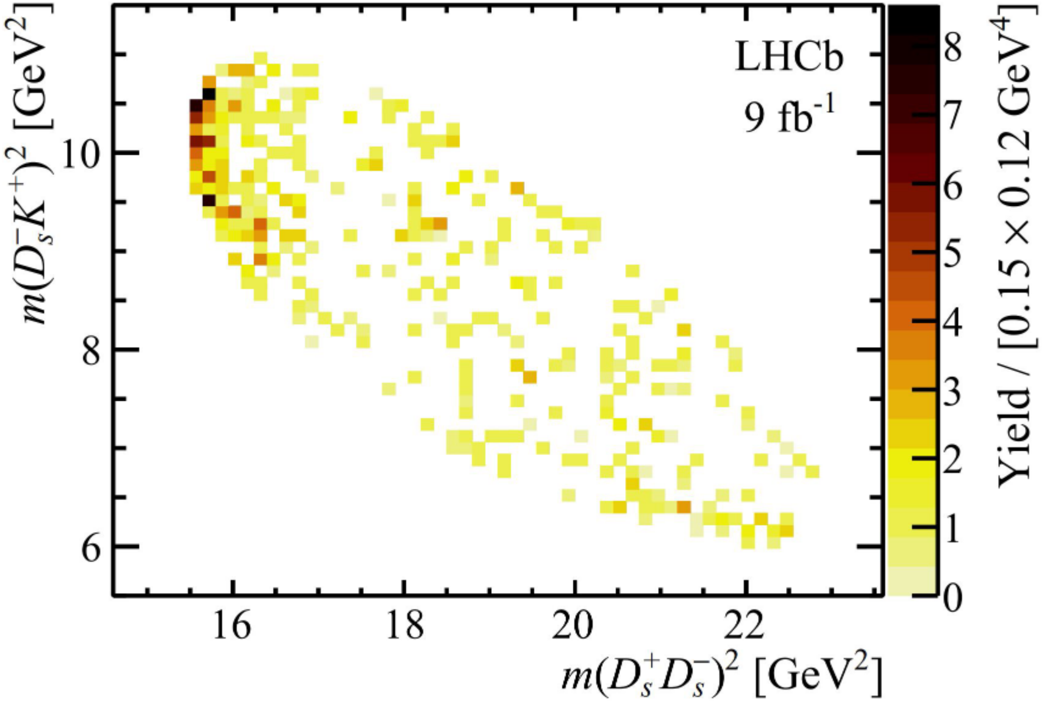
X(3960) observation

Amplitude analysis of $B^+ \to D_s^+ D_s^- K^+$

- 360 events
- Threshold enhancement in the $D_s^+ D_s^-$ mass spectrum

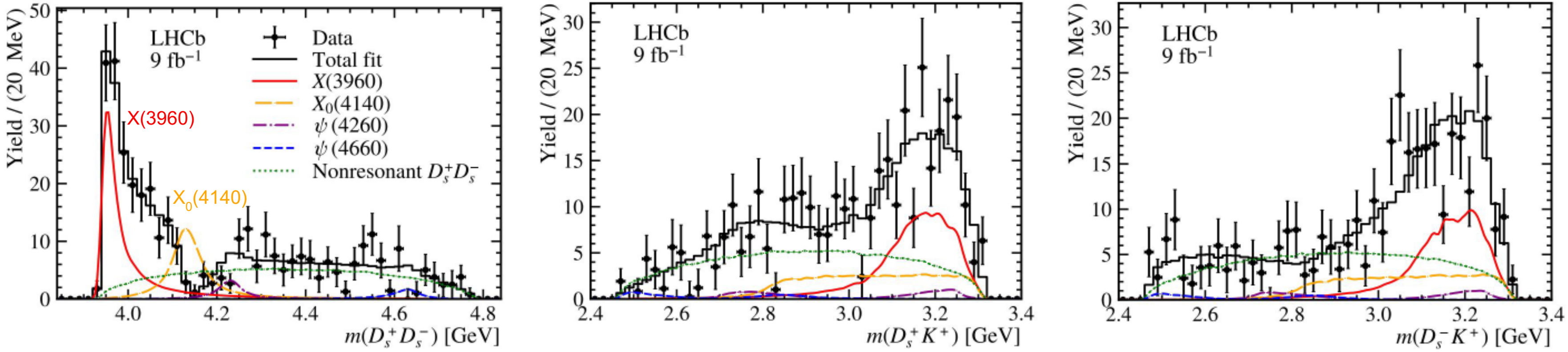
Model used:

- $\psi(4260)$, $\psi(4660)$ ($J^{PC} = 1^{--}$) (**known**)
- $X(3960)$, $X_0(4140)$ ($J^{PC} = ?^{??}$) (**new**)
- $NR(D_s^+ D_s^- K^+)$



[PhysRevLett 131, 071901 (2023)]

X(3960) observation



- m(X(3960)) = 3956 ± 5 ± 10 MeV, Γ(X(3960))= 43 ± 13 ± 8 MeV, significance > 12σ
- X_0(4140) describe the dip near 4140 MeV, significance = 3.9σ. The dip can be described also with $J/\psi\phi \to D_s^+D_s^-$ rescattering
- Both with preferred $J^{PC} = 0^{++}$
- X(3960) exotic candidate with minimal quark content [$c\bar{c}s\bar{s}$]

[PhysRevLett 131, 071901 (2023)]

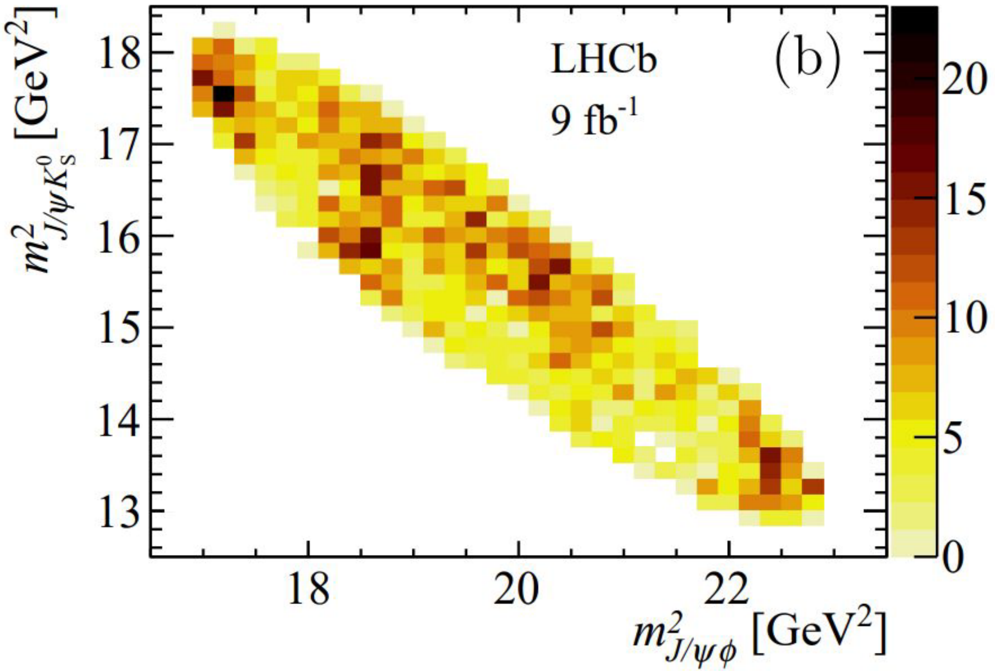
Evidence for a $J/\psi K_s^0$ structure

Amplitude analysis of $B^0 \rightarrow J/\psi\phi K_s^0$

- ~1900 events
- Search for the isospin partners of the $T_{\psi_{s1}}^{\theta+}$ states observed in the $B^+ \rightarrow J/\psi\phi K^+$ decay [PhysRevLett 127, 082001 (2021)]

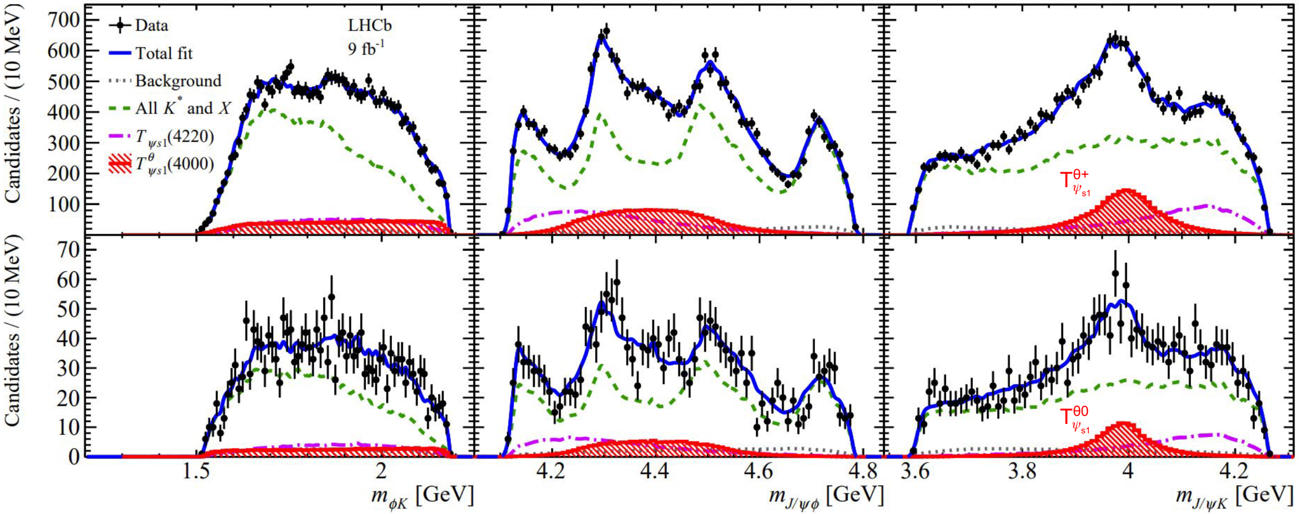
Model used:

- 9 excited K states
- 7 X ($J/\psi\phi$ exotic states)
- $T_{\psi_{s1}}(4220)$
- $T_{\psi_{s1}}^{\theta 0}(4000)$ (**new**)
- NR($J/\psi\phi$)



[PhysRevLett 131, 131901 (2023)]

Evidence for a $J/\psi K^0_s$ structure



$B^+ \rightarrow J/\psi\phi K^+$

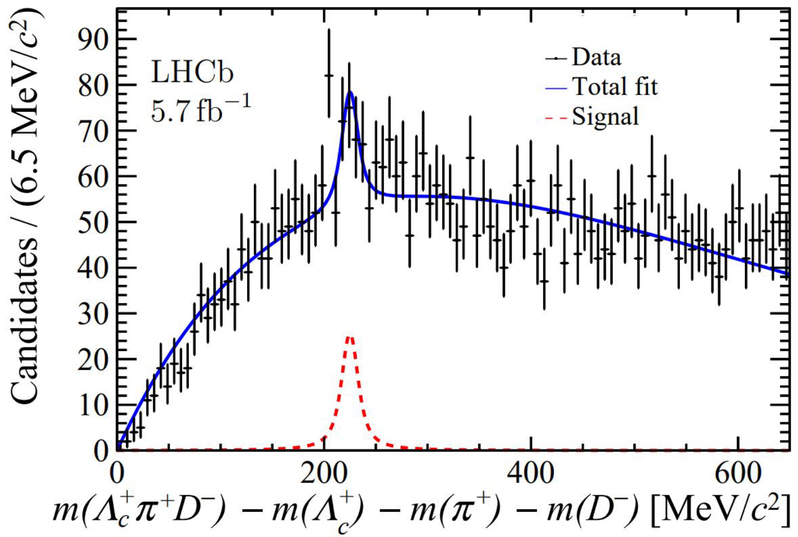
$B^0 \rightarrow J/\psi\phi K^0_s$

- Simultaneous fit to the two channel because of the small sample size
- $M(T^{\theta 0}_{\psi_{s1}}(4000)) = 3991^{+12}_{-10}{}^{+9}_{-17}$ MeV, $\Gamma(T^{\theta 0}_{\psi_{s1}}(4000)) = 105^{+29}_{-25}{}^{+17}_{-23}$ MeV, significance = 4.0σ
- Mass difference between neutral and charged state $\Delta M = -12^{+11}_{-10}{}^{+6}_{-4}$ MeV, consistent with the two states being isospin partners
- With isospin symmetry imposed significance = 5.4σ

[PhysRevLett 131, 131901 (2023)]

Prompt pentaquarks in charm final states

- Mass of observed pentaquarks is close to some hadron-hadron threshold
- Search for pentaquark decays into a range of $\Sigma_c\overline{D}$, $\Lambda_c^+\overline{D}$, $\Sigma_c D$ and $\Lambda_c^+ D$
- 42 different modes are tested
  - ▷ Simultaneous extended maximum likelihood fit to signal region and sideband region
  - ▷ Scan of the Q-value in 4 MeV steps up to 600 MeV to search for peaks
  - ▷ No clear signal observed, upper limits are set as function of Q-value
  - ▷ Signal model based on the known pentaquark states is also fitted, the signal yield is found to be consistent with zero in all cases



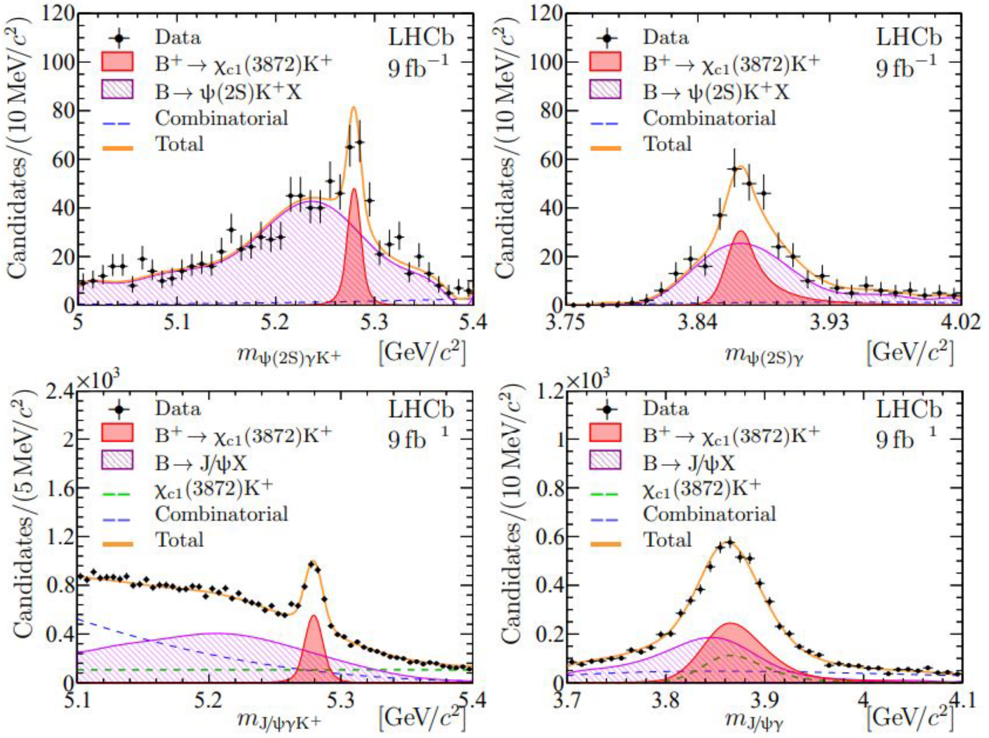
[arXiv:2404.07131]

$\chi_{c1}(3872)$ nature using radiative decays

$B^+ \to \chi_{c1}(3872)K^+$ decay to measure the ratio:

$$\mathscr{R}_{\psi\gamma} \equiv \frac{\Gamma_{\chi_{c1}(3872)\to\psi(2S)\gamma}}{\Gamma_{\chi_{c1}(3872)\to J/\psi\gamma}}$$

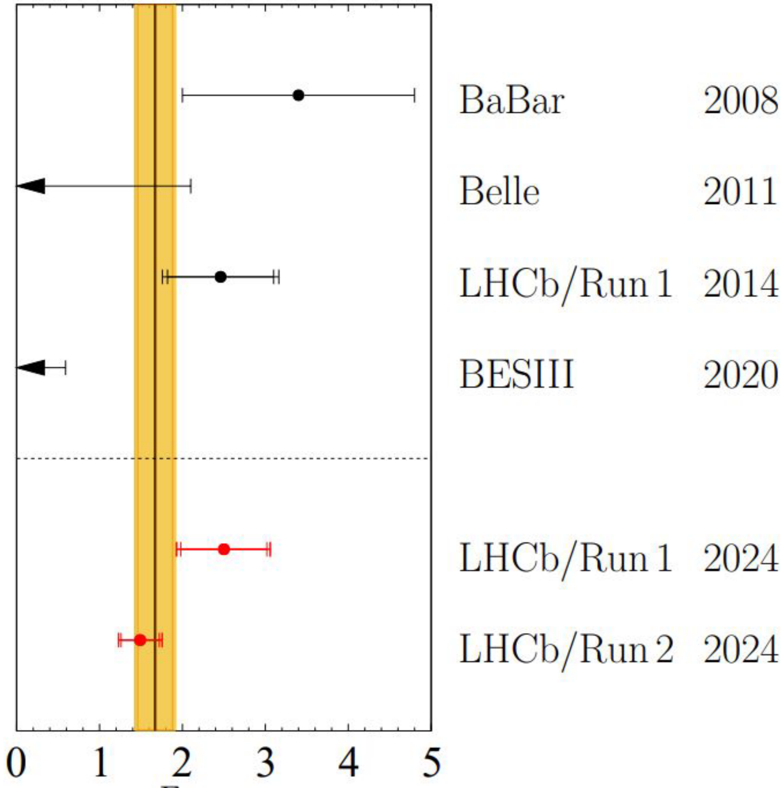
- Different theoretical prediction depending on the model
- Allow us to study the nature of $\chi_{c1}(3872)$
- $\chi_{c1}(3872) \to \psi(2S)\gamma$ first observation



[arXiv:2406.17006]

$\chi_{c1}(3872)$ nature using radiative decays

- $\chi_{c1}(3872) \to \psi(2S)\gamma$ observed with 5.3σ and 6.7σ for Run1 and Run2
- $\mathscr{R}_{\psi\gamma} = 1.67 \pm 0.21 \pm 0.12 \pm 0.04$
- Strong argument in favour of a compact component in the $\chi_{c1}(3872)$ structure
- Notably in tension with the upper limit set by the BESIII collaboration



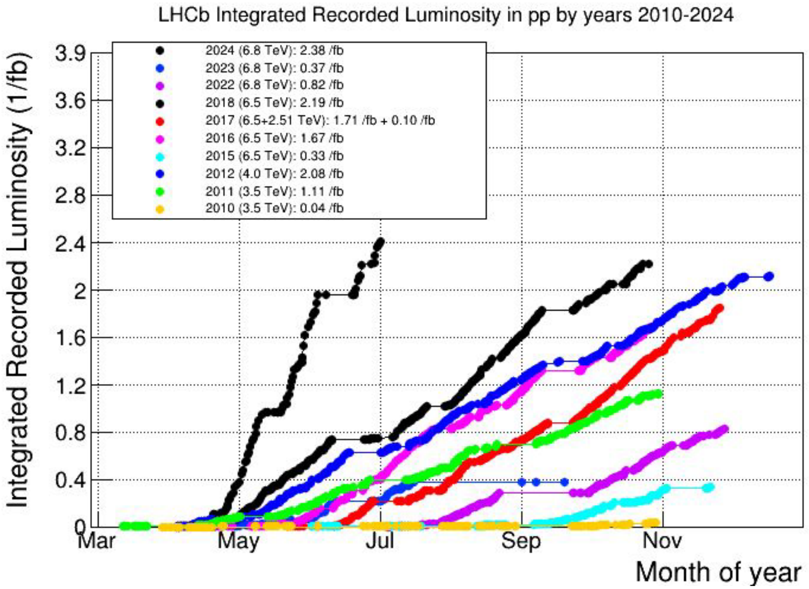
$$\mathscr{R}_{\psi\gamma} = \frac{\Gamma_{\chi_{c1}(3872)\to\psi(2S)\gamma}}{\Gamma_{\chi_{c1}(3872)\to J/\psi\gamma}}$$

[arXiv:2406.17006]

Future prospects and conclusions

Future prospects

- Many new states are expected and predicted (for example T_{bc}, T_{bb} based on the existence of T_{cc})
  - ▷ T_{bb} should be stable, binding energy order of 100 MeV
  - ▷ Production mechanism?
- In Run 3, with the removal of the L0 trigger, fully-hadronic final states are accessible allowing studies on open-flavour exotic states
- Prompt pentaquark production still unobserved



[Eur. Phys. J. A 56, 177 (2020)] [PhysRevLett 102, 094516 (2020)]
[Physics Letters B 814, 136095 (2021)]

Conclusions

- Heavy hadron spectroscopy is a highly rich and productive field, with new exotic hadrons being discovered every year
- The spectroscopy of heavy hadrons is essential for a better understanding of the dynamics and binding rules of QCD
- Largely unexplored territory
- Collaboration between the experimental and theoretical communities is essential

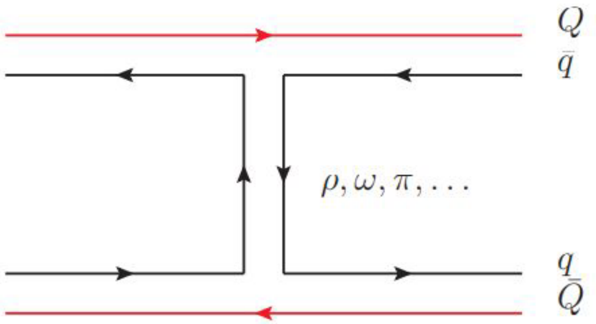
Thanks for your attention

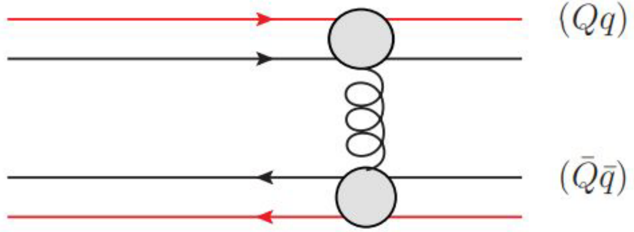
Models for multiquark states

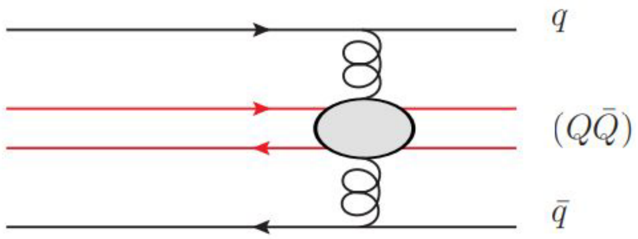
Hadronic molecule:
- Low binding energy, narrow states
- Only S-wave, few states predicted
- Independently decaying components
- Mass close to two-body threshold

Compact multiquark:
- Tightly bound states
- Large prompt production at high p_T
- Rich isospin splitting (charged states)

Hadro-quarkonium:
- Open heavy flavour decays suppressed
- Binded quarkonium and light quarks
- No requirements on mass
- Not clear whether binding can happen







$\chi_{c1}(3872)$ nature using radiative decays

Reference	$\mathscr{R}_{\psi\gamma}$	
T. Barnes and S. Godfrey	5.8	$c\bar{c}$
T. Barnes, S. Godfrey and S. Swanson	2.6	$c\bar{c}$
F. De Fazio	(1.64 ± 0.25)	$c\bar{c}$
B.-Q. Li and K. T. Chao	1.3	$c\bar{c}$
Y. Dong *et al.*	$1.3 - 5.8$	$c\bar{c}$
A. M. Badalian *et al.*	(0.8 ± 0.2)	$c\bar{c}$
J. Ferretti, G. Galata and E. Santopinto	6.4	$c\bar{c}$
A. M. Badalian, Yu. A. Simonov and B. L. G. Bakker	2.4	$c\bar{c}$
W. J. Deng *et al.*	1.3	$c\bar{c}$
F. Giacosa, M. Piotrowska and S. Goito	5.4	$c\bar{c}/vc$
E. S. Swanson	0.38 %	$D\bar{D}^*$
Y. Dong *et al.*	0.33 %	$D\bar{D}^*$
D. P. Rathaud and A. K. Rai	0.25	$D\bar{D}^*$
R. F. Lebed and S. R. Martinez	0.33 %	$D\bar{D}^*$
B. Grinstein, L. Maiani and A. D. Polosa	3.6 %	$D\bar{D}^*$
F.-K. Guo *et al.*	$0.21(g_2'/g_2)^2$	$D\bar{D}^*$
D. A.-S. Molnar, R. F. Luiz and R. Higa	$2 - 10$	$D\bar{D}^*$
E. Cincioglu *et al.*	< 4	$D\bar{D}^*$
S. Takeuchi, M. Takizawa and K. Shimizu	$1.1 - 3.4$	$D\bar{D}^*$
B. Grinstein, L. Maiani and A. D. Polosa	$> (0.95^{+0.01}_{-0.07})$	$c\bar{c}q\bar{q}$