Hadron spectroscopy at LHCb

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on behalf of the LHCb collaboration

Large Hadron Collider Physics Conference
Belgrade
24/05/2023

Spectroscopy at LHCb

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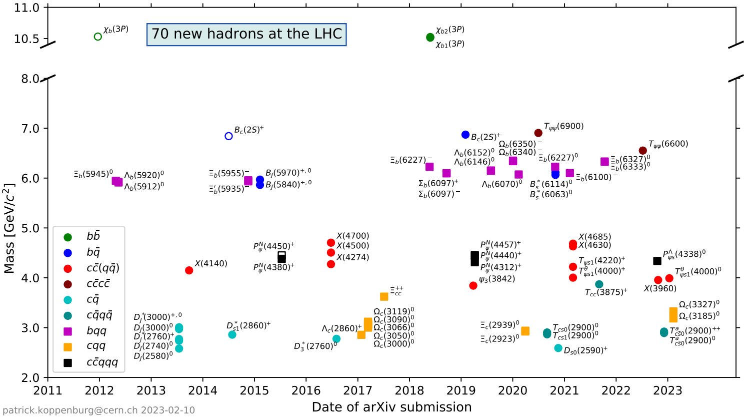
High luminosity, high b/c production cross-section, a unique dedicated design

LHCb: major player in the field of heavy hadron spectroscopy



From [P. Koppenburg]

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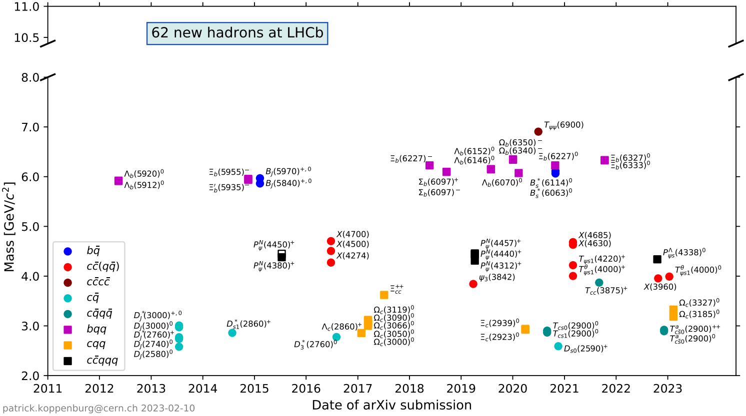

From [P. Koppenburg]

The spectroscopy programme

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Conventional heavy-hadron spectroscopy

- Excited open-flavour mesons: $B^{+,0}$, B_s^0, B_c^+, $D^{+,0}$, D_s^+...
- Excited conventional charmonia
- Excited baryons: Ξ_b^0, Λ_b^0, Σ_b^+, Ω_c^0, Ω_b^-...
- Discovery and searches of new particles and decay modes
- Precise mass, width, BR measurements and more

Exotic spectroscopy

- $\chi_{c1}(3872)$: production and decay, lineshape, mass
- Many other $c\bar{c}$ tetraquark candidates in various final states from b decays and primary vertex
- Exotic non-charmonia: charged states, cc, $cc\bar{c}\bar{c}$, open charm
- Pentaquark candidates
- Searches for unexpected contributions

Today: focus on most recent results

The LHCb experiment at CERN

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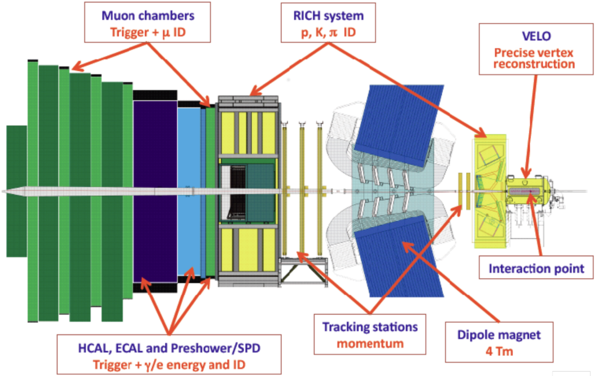
Single-arm spectrometer designed for high precision flavour physics measurements



Total recorded luminosity:

- Run 1: 1 fb^{-1} at $\sqrt{s} = 7$ TeV + 2 fb^{-1} at $\sqrt{s} = 8$ TeV
- Run 2: 6 fb^{-1} at $\sqrt{s} = 13$ TeV

[JINST 3 (2008) S08005], [IJMPA 30 (2015) 1530022]

CONVENTIONAL HEAVY HADRON SPECTROSCOPY

Search for $\Xi_c^{0**} \to \Lambda_c^+ K^-$

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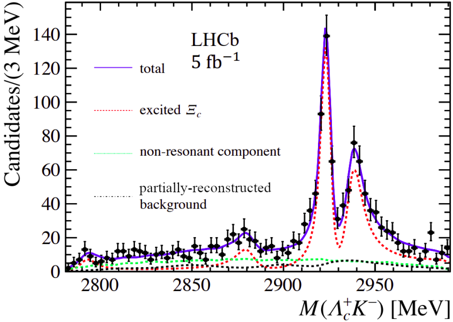
Prompt $\Lambda_c^+ K^-$ already studied by LHCb, new states observed:

- $\Xi_c(2923)^0$, $\Xi_c(2939)^0$

Study of the decay $B^- \to \Lambda_c^+ \overline{\Lambda}_c^- K^-$ also looking for exotics

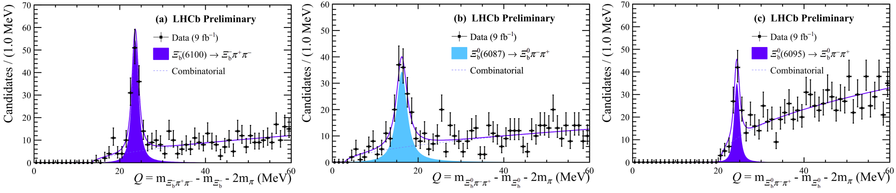


- $\Xi_c(2790)^0$: evidence of new decay mode
- $\Xi_c(2880)^0$: evidence of new state
- $\Xi_c(2923)^0$, $\Xi_c(2939)^0$ confirmed
- No structures found in $\overline{\Lambda}_c^- K^-$ and $\Lambda_c^+ \overline{\Lambda}_c^-$ spectra

[PRL 124 (2020) 222001], [arXiv:2211.00812], submitted to Phys. Rev. D

New excited Ξ_b baryons

New excited Ξ_b baryons are observed in the $\Xi_b^-\pi^+\pi^-$ and $\Xi_b^0\pi^+\pi^-$ final states decaying mainly through the intermediate Ξ_b^{*0}, $\Xi_b^{\prime -}$ and Ξ_b^{*-} states



Ξ_b^{*0} mass window | $\Xi_b^{\prime -}$ mass window | Ξ_b^{*-} mass window

- $\Xi_b(6100)^-$: confirmed previous CMS observation [PRL 126 (2021) 252003]
- New states: $\Xi_b(6087)^0$ and $\Xi_b(6095)^0$
- Similarity of decay pattern with *c*-baryon system suggests P-wave states
- Additional studies required to measure quantum numbers

[LHCb-PAPER-2023-008] in preparation

Search for $\Xi_{bc}^+ \to J/\psi \Xi_c^+$

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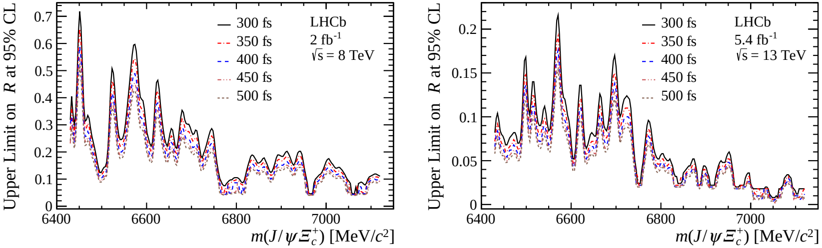
First search of the Ξ_{bc} baryon, mass expected in range $[6700, 7029]$ MeV$/c^2$
No excess larger than 3σ is observed, upper limits are set on the production ratio with respect to $B_c^+ \to J/\psi D_s^+$



[arXiv:2204.09541], submitted to Chin. Phys. C

EXOTIC SPECTROSCOPY

Observation of $B_s^0 \to \chi_{c1}(3872)\pi^+\pi^-$

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First observation of the decay $B_s^0 \to \chi_{c1}(3872)\pi^+\pi^-$

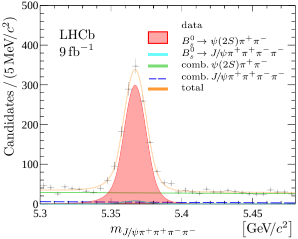
Significance $>7\sigma$

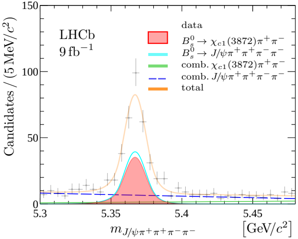
BR ratio with respect to $B_s^0 \to \psi(2S)\pi^+\pi^-$ measured

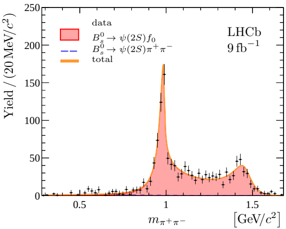
Using the known B_s^0 and $\psi(2S)$ BRs:

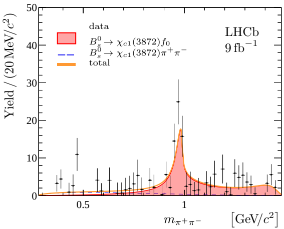
$$\mathcal{B}(B_s^0 \to \chi_{c1}(3872)\pi^+\pi^-) \times \mathcal{B}(\chi_{c1}(3872) \to J/\psi\pi^+\pi^-) = (1.6 \pm 0.3 \pm 0.1 \pm 0.3) \times 10^{-6}$$

Dipion system found to proceed through a coherent sum of the $f_0(980)$ and $f_0(1500)$ states





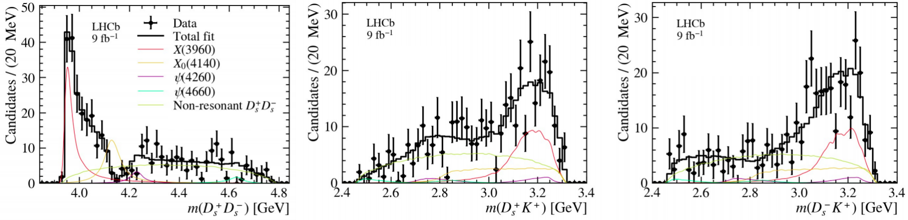




[arXiv:2302.10629], submitted to JHEP

Observation of $X(3960)$

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



- Threshold enhancement in the $D_s^+ D_s^-$ mass spectrum
- $X(3960)$ (14σ) and $X_0(4140)$ (3.9σ) both with preferred $J^{PC} = 0^{++}$
- Alternatively, the dip can be explained by $J/\psi\phi \to D_s^+ D_s^-$ rescattering
- $X(3960)$ state could be the same as $\chi_{c0}(3930)$ observed in $D^+ D^-$?
- $\frac{\Gamma(X \to D^+ D^-)}{\Gamma(X \to D_s^+ D_s^-)} = 0.29 \pm 0.09 \pm 0.10 \pm 0.08$
- Incompatible with the suppression of $s\bar{s}$ pair from vacuum (wrt $u\bar{u}$ or $d\bar{d}$) and the smaller phase-space volume of $D_s^+ D_s^-$
- Exotic candidate with minimal quark content $[c\bar{c}s\bar{s}]$

[arXiv:2210.15153], submitted to Phys. Rev. Lett.

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

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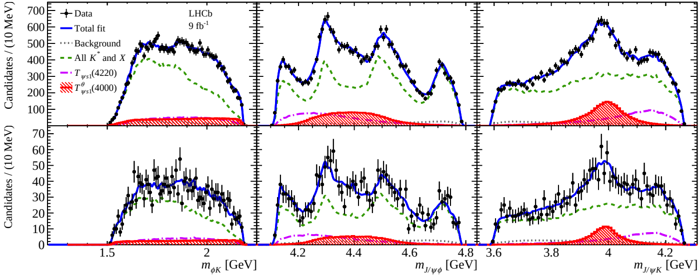
Amplitude analysis of $B^0 \to J/\psi \phi K_s^0 \Longrightarrow$ search for the isospin partners of the $T_{\psi s}^{\theta +}$ states observed in the $B^+ \to J/\psi \phi K^+$ channel



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

$B^0 \to J/\psi \phi K_s^0$

- Amplitude model includes 9 excited K states, excited charmonia and the known $J/\psi \phi$ exotics
- Evidence for a new state $T_{\psi s1}^{\theta}(4000)^0$ at 4σ
- Mass difference between $T_{\psi s1}^{\theta 0}$ and $T_{\psi s1}^{\theta +}$ is $\Delta M = 12^{+11+6}_{-10-4}$ MeV which is consistent with the two states being isospin partners

[PRL 127 (2021) 082001], [arXiv:2301.04899], submitted to Phys. Rev. Lett.

New open-charm tetraquarks

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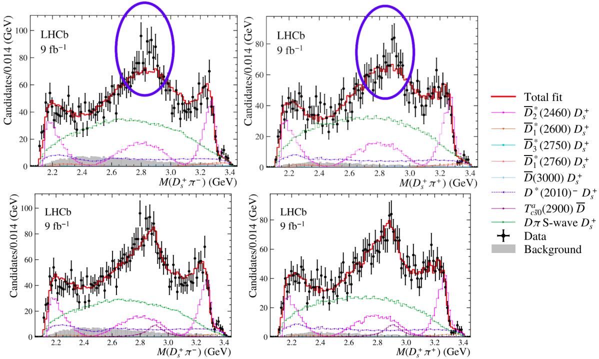
Two T_{cs} states ($X_0(2900)$ and $X_1(2900)$) observed in $B^+ \to D^+ D^- K^+$ amplitude analysis: first discovery of open-charm tetraquarks $[cs\bar{u}\bar{d}]$

$\Longrightarrow$ study of the $B^0 \to \bar{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ channels

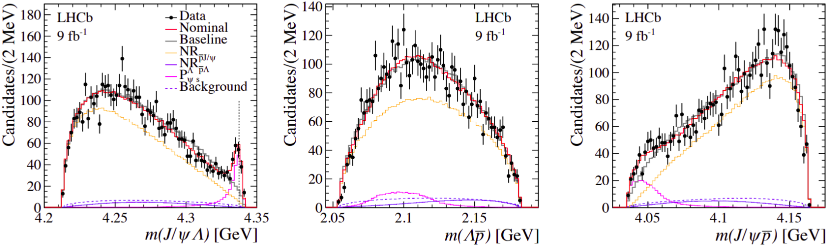


- Joint amplitude analysis linked through isospin symmetry
- Two new states necessary (9σ) to describe the peaking structure
- $T^a_{c\bar{s}0}(2900)^0$ and $T^a_{c\bar{s}0}(2900)^{++}$, $J^P = 0^+$ favoured by $>7.5\sigma$

[PRL 125 (2020) 242001], [PRD 102 (2020) 112003], [arXiv:2212.02716] sub. to PRL

New pentaquarks: $P^{\Lambda}_{\psi s}$

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



- Observation of a narrow pentaquark state with high significance
- $J = \frac{1}{2}$, odd parity preferred: $J^P = \frac{1}{2}^+$ escluded at 90% CL
- First observation of a pentaquark with strange quark content: $[c\bar{c}uds]$
- Very close to the $\Xi_c^+ D^-$ mass threshold
- Furthermore, most precise single measurement of B^- mass

$$m_{B^-} = 5279.44 \pm 0.05 \pm 0.07 \text{ MeV}$$

[arXiv:2210.10346], submitted to Phys. Rev. Lett.

CONCLUSIONS AND PROSPECTS

Conclusions

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- Heavy meson spectroscopy is an extremely rich and productive field, both for conventional and exotic states
- New conventional and exotic hadrons are discovered every year
- LHCb has established itself to be a major player due to high luminosity, high b/c production cross-section and a unique, dedicated design
- Spectroscopy of heavy hadrons is crucial to understand QCD dynamics and binding rules
- Many excitation spectra are still mostly unexplored territory
- New "non-conventional" exotic states have been discovered recently

Prospects for Run 3

- Run 3 started with an upgraded detector and a software-only trigger, with improvements on hadronic triggers
- LHC experiments will be the only explorers of the B_c^+ spectrum in the near future and LHCb will play a major role in it
- Heavy baryon spectroscopy already started in Run 2
- Run 3: access to bc tetraquarks and pentaquarks and $b\bar{b}$ spectroscopy
- Confirm new pentaquarks and measure their properties
- For Runs 1-2 exotic hadron searches rely on J/ψ for reconstruction
- In Run 3, with the removal of the L0 trigger, fully-hadronic final states will be accessible allowing studies on open-flavour exotic states

BACKUP

Study of the $B^+ \to J/\psi\eta^{(\prime)}K^+$ decay

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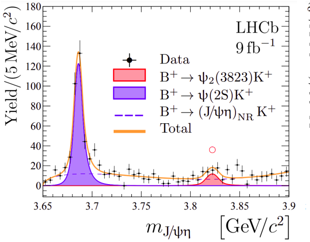
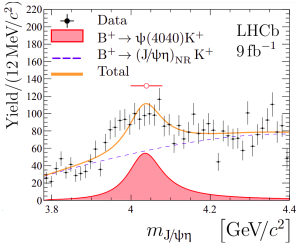
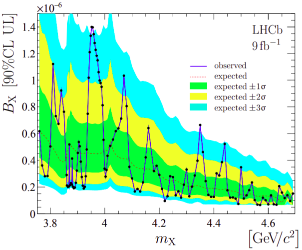
Search for charmonia and charmonia-like exotics decaying into $J/\psi\eta$







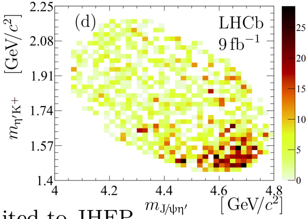
Only contribution found: $\psi_2(3823)$ and $\psi(4040)$

Limits at 90% CL set on $\mathcal{B}(X \to J/\psi\eta)$ scanning $m_X \in [3750, 4700]$ GeV$/c^2$

Searches also in the $B^+ \to J/\psi\eta' K^+$

no obvious unknown structure observed

amplitude analysis necessary



[JHEP 2022 (2022) 46], [arXiv:2303.09443], submited to JHEP

ω contribution in $\chi_{c1}(3872) \to \pi^+\pi^- J/\psi$

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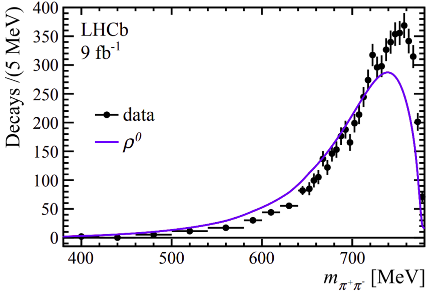
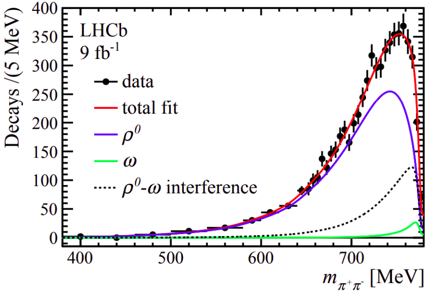
Study of the resonant $\pi^+\pi^-$ structure in the $\chi_{c1}(3872)$ "golden channel"



Using a single Breit-Wigner with a Blatt-Weisskopf radius of 1.45 GeV^{-1}



Adding an ω contribution with a 2-channel K-matrix model

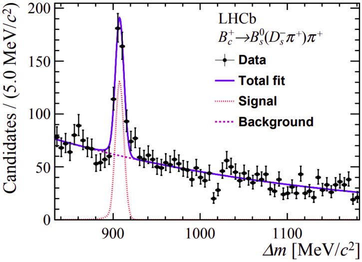
Ratio of couplings

$$\frac{g_{\chi_{c1}(3872)\to\rho J/\psi}}{g_{\chi_{c1}(3872)\to\omega J\psi}} = 0.29 \pm 0.04$$

is one order of magnitude larger than expected for pure $c\bar{c}$ states

[arXiv:2204:12597], submitted to PRL

B_c^+ - B_s^0 mass difference



$$\Delta m = 907.75 \pm 0.37 \pm 0.27 \text{ MeV}/c^2$$

[JHEP 07 (2020) 123]

Observation of new excited B_s^0 states

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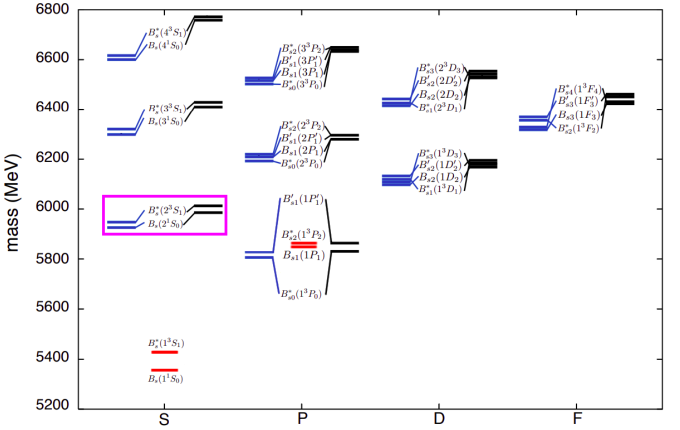
The B_s^0 excitation spectrum is mostly inexplored as well

- Only ground state + three excited states observed
- First radial excitation (B_s^{*0}) and first orbital excitations (B_{s1}^0, B_{s2}^{*0})
- This analysis: observation of two new states



Adapted from [PRD 94 (2016) 054025]

$B^+ \to J/\psi \phi K^+$ fit results

J^P	Contribution		Significance $[\times\sigma]$	M_0 [MeV]	Γ_0 [MeV]	FF [%]
1^+	$2^1\mathrm{P}_1$	$K(1^+)$	4.5 (4.5)	$1861 \pm 10\,^{+16}_{-46}$	$149 \pm 41\,^{+231}_{-23}$	
	$2^3\mathrm{P}_1$	$K'(1^+)$	4.5 (4.5)	$1911 \pm 37\,^{+124}_{-48}$	$276 \pm 50\,^{+319}_{-159}$	
	$1^3\mathrm{P}_1$	$K_1(1400)$	9.2 (11)	1403	174	$15 \pm 3\,^{+3}_{-11}$
2^-	$1^1\mathrm{D}_2$	$K_2(1770)$	7.9 (8.0)	1773	186	
	$1^3\mathrm{D}_2$	$K_2(1820)$	5.8 (5.8)	1816	276	
1^-	$1^3\mathrm{D}_1$	$K^*(1680)$	4.7 (13)	1717	322	$14 \pm 2\,^{+35}_{-8}$
	$2^3\mathrm{S}_1$	$K^*(1410)$	7.7 (15)	1414	232	$38 \pm 5\,^{+11}_{-17}$
2^-	$2^3\mathrm{P}_2$	$K_2^*(1980)$	1.6 (7.4)	$1988 \pm 22\,^{+194}_{-31}$	$318 \pm 82\,^{+481}_{-101}$	$2.3 \pm 0.5 \pm 0.7$
0^-	$2^1\mathrm{S}_0$	$K(1460)$	12 (13)	1483	336	$10.2 \pm 1.2\,^{+1.0}_{-3.8}$
2^-		$X(4150)$	4.8 (8.7)	$4146 \pm 18 \pm 33$	$135 \pm 28\,^{+59}_{-30}$	$2.0 \pm 0.5\,^{+0.8}_{-1.0}$
1^-		$X(4630)$	5.5 (5.7)	$4626 \pm 16\,^{+18}_{-110}$	$174 \pm 27\,^{+134}_{-73}$	$2.6 \pm 0.5\,^{+2.9}_{-1.5}$
0^+		$X(4500)$	20 (20)	$4474 \pm 3 \pm 3$	$77 \pm 6\,^{+10}_{-8}$	$5.6 \pm 0.7\,^{+2.4}_{-0.6}$
		$X(4700)$	17 (18)	$4694 \pm 4\,^{+16}_{-3}$	$87 \pm 8\,^{+16}_{-6}$	$8.9 \pm 1.2\,^{+4.9}_{-1.4}$
		$\mathrm{NR}_{J/\psi\phi}$	4.8 (5.7)			$28 \pm 8\,^{+19}_{-11}$
1^+		$X(4140)$	13 (16)	$4118 \pm 11\,^{+19}_{-36}$	$162 \pm 21\,^{+24}_{-49}$	$17 \pm 3\,^{+19}_{-6}$
		$X(4274)$	18 (18)	$4294 \pm 4\,^{+3}_{-6}$	$53 \pm 5 \pm 5$	$2.8 \pm 0.5\,^{+0.8}_{-0.4}$
		$X(4685)$	15 (15)	$4684 \pm 7\,^{+13}_{-16}$	$126 \pm 15\,^{+37}_{-41}$	$7.2 \pm 1.0\,^{+4.0}_{-2.0}$
1^+		$Z_{cs}(4000)$	15 (16)	$4003 \pm 6\,^{+4}_{-14}$	$131 \pm 15 \pm 26$	$9.4 \pm 2.1 \pm 3.4$
		$Z_{cs}(4220)$	5.9 (8.4)	$4216 \pm 24\,^{+43}_{-30}$	$233 \pm 52\,^{+97}_{-73}$	$10 \pm 4\,^{+10}_{-7}$