Charmonium results at Belle

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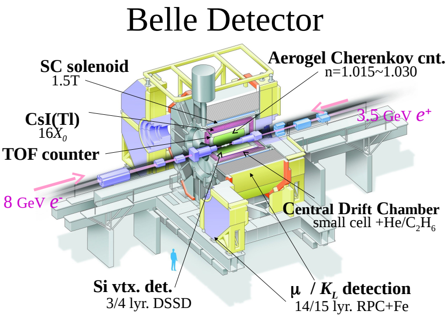
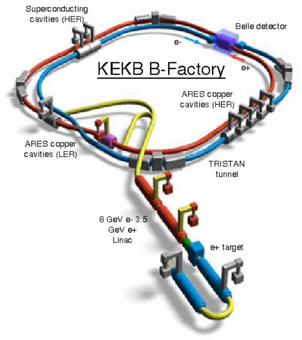
The Belle experiment

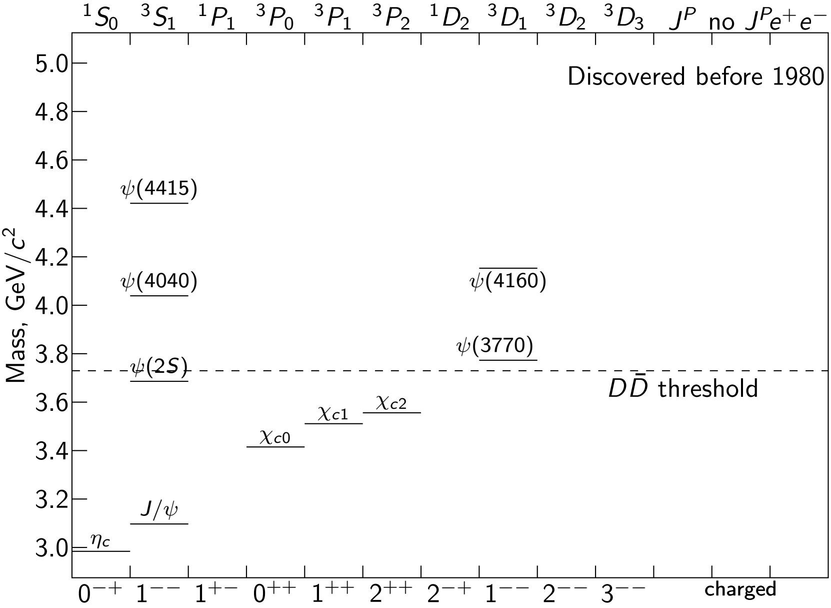




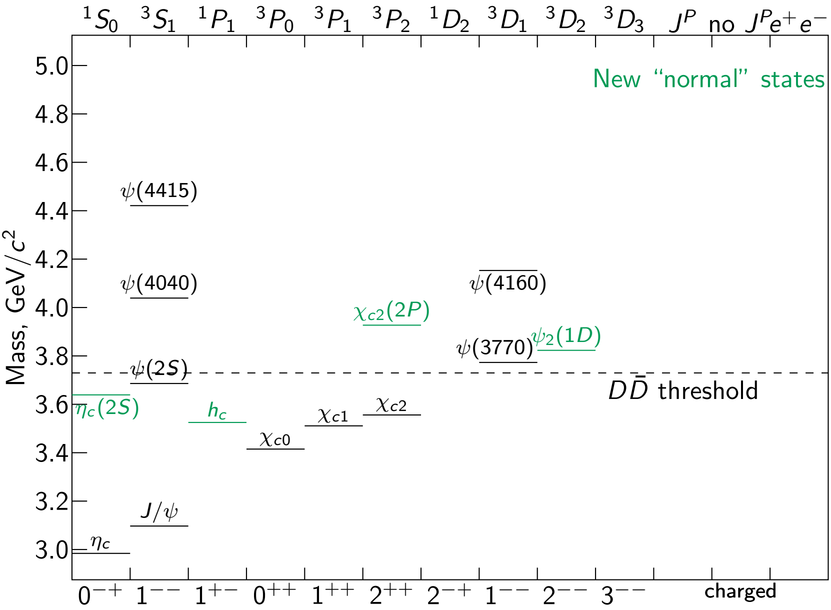
Charmonium production:

- From B decays - 711 fb^{-1}, 772×10^6 $B\bar{B}$ pairs.
- All energies (e.g. for double charmonium production): 980 fb^{-1}.

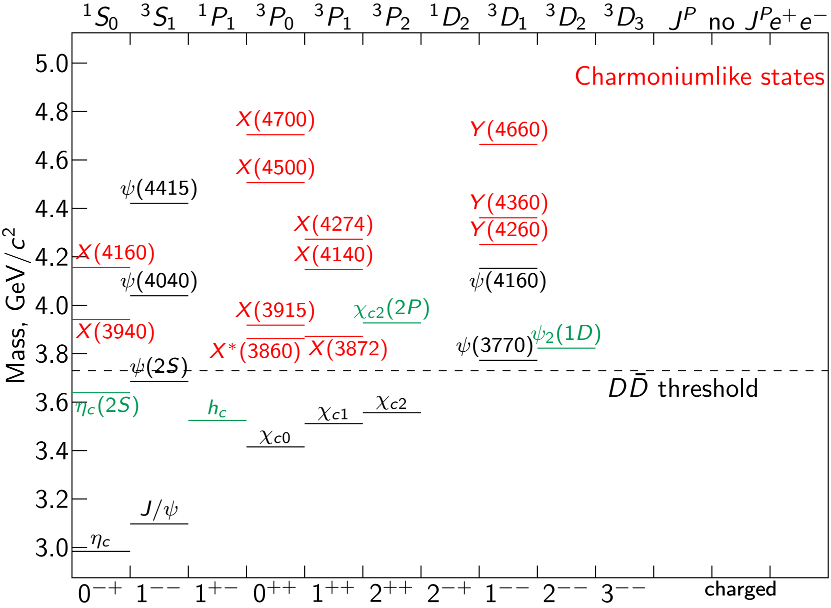
Charmonium states



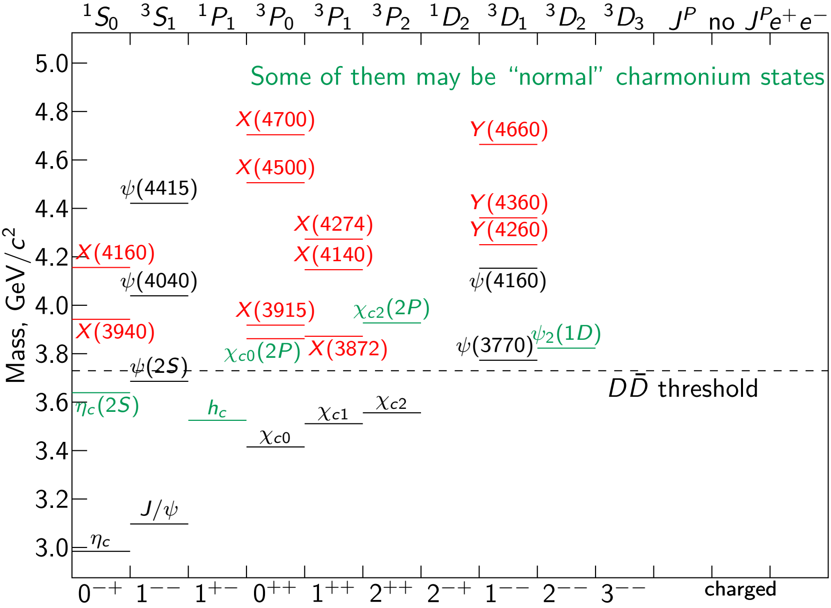
Charmonium states



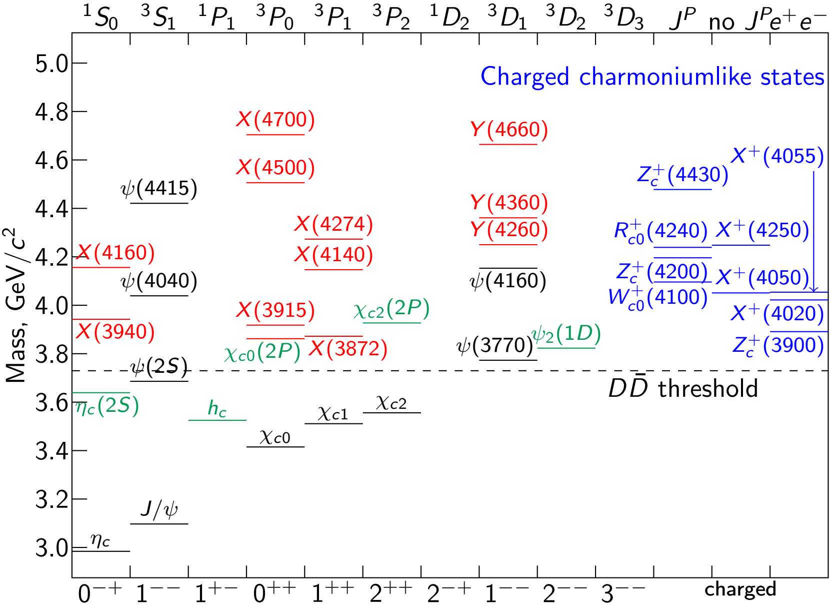
Charmonium states



Charmonium states



Charmonium states



Alternative $\chi_{c0}(2P)$ candidate in $e^+e^- \to J/\psi D\bar{D}$

Reconstruction

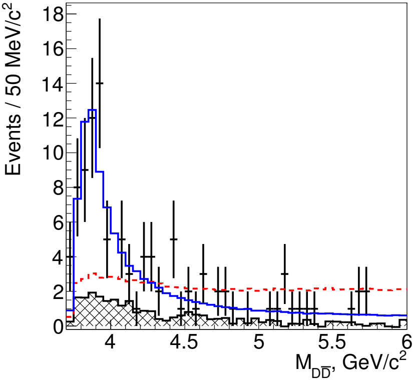
PRD **95**, 112003 (2017)

- $J/\psi \to e^+e^-, \mu^+\mu^-$.
- One D is reconstructed, the other is identified by the recoil mass ($M_{\mathrm{rec}}(J/\psi, D)$). Both D^0 and D^+ are used.
- $D^0 \to K^-\pi^+, K_S^0\pi^+\pi^-, K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-$ (4 channels).
- $D^+ \to K_S^0\pi^+, K^-\pi^+\pi^+, K_S^0\pi^+\pi^0, K^-\pi^+\pi^+\pi^0, K_S^0\pi^+\pi^+\pi^-$ (5 channels).
- Separation of signal and background using the MLP neural network.
- Global optimization of the selection requirements for (4 variables per D channel: signal regions in $M_{J/\psi}$, M_D, $M_{\mathrm{rec}}(J/\psi, D)$ and MLP output cutoff value).

Resulting sample: 103 events with $24.9 \pm 1.1 \pm 1.6$ background events.

Signal fit results

PRD **95**, 112003 (2017)



Red dashed line - only background and nonresonant amplitudes, blue solid line - X^*, $J^{PC} = 0^{++}$.

A new charmoniumlike state $X^*(3860)$ is observed (6.5σ with systematic error). Parameters: $M = 3862^{+26}_{-32}{}^{+40}_{-13}$ MeV$/c^2$, $\Gamma = 201^{+154}_{-67}{}^{+88}_{-82}$ MeV.

Systematic uncertainties

PRD **95**, 112003 (2017)

Global significance is determined from $\Delta(-2\ln L)$ distributions.

Model	Significance (global)
Default (constant nonresonant)	8.5σ
NRQCD nonresonant	7.6σ
$M_{D\bar{D}}^{-4}$ nonresonant	6.5σ
Background mass calculation	8.4σ
Optimization ($a = 4$)	8.1σ
Optimization ($a = 6$)	8.1σ

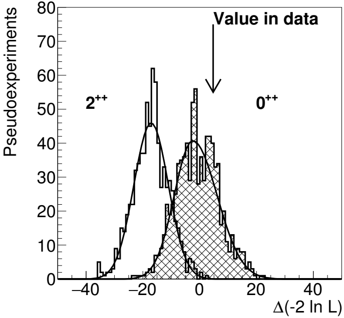
The minimal significance is $6.5\sigma \Rightarrow$ the $X^*(3860)$ is observed.

Error source	Mass	Width
Nonresonant amplitude model	${}^{+40.2}_{-0.0}$	${}^{+0.0}_{-82.0}$
Signal model	${}^{+0.0}_{-10.2}$	${}^{+0.0}_{-4.0}$
Fit bias	—	${}^{+32.6}_{-0}$
Optimization	${}^{+0.0}_{-3.1}$	${}^{+71.1}_{-0.0}$
Background mass calculation	${}^{+0.0}_{-7.9}$	${}^{+40.0}_{-0.0}$
D mass	± 0.2	—
Total	${}^{+40.2}_{-13.3}$	${}^{+87.9}_{-82.1}$

Comparison of $J^{PC} = 0^{++}$ and 2^{++}

PRD **95**, 112003 (2017)

Toy MC pseudoexperiments are generated in accordance with the fit results with $J^{PC} = 0^{++}$ and 2^{++} and fitted by both hypotheses. Result:



The $J^{PC} = 2^{++}$ hypothesis is excluded at the level of 3.8σ for the default model (shown in the histogram) and 2.5σ with systematic uncertainty. The confidence level of the $J^{PC} = 0^{++}$ hypothesis is 77% (default model).

Cross section measurement

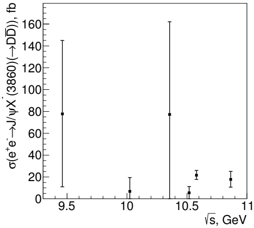
PRD **95**, 112003 (2017)

The Born cross section of $e^+e^- \to J/\psi X^*(3860)(\to D\bar{D})$ is measured at each energy point:

Data set	Energy, GeV	$\sigma^{(\mathrm{Born})}_{e^+e^- \to J/\psi X^*(3860)(\to D\bar{D})}$, fb
$\Upsilon(1S)$	9.46	$77\,^{+66}_{-66}\,^{+9}_{-7}$
$\Upsilon(2S)$	10.02	$6.9\,^{+12.6}_{-12.6}\,^{+0.9}_{-0.7}$
$\Upsilon(3S)$	10.36	$77\,^{+85}_{-85}\,^{+11}_{-8}$
Continuum	10.52	$5.5\,^{+5.7}_{-5.7}\,^{+0.7}_{-0.5}$
$\Upsilon(4S)$	10.58	$21.7\,^{+3.9}_{-4.3}\,^{+2.9}_{-2.1}$
$\Upsilon(5S)$	10.87	$17.9\,^{+7.2}_{-7.3}\,^{+2.4}_{-1.8}$

NRQCD [PRD **77**, 014002 (2008)] (usually smaller than measured cross sections):

$$\sigma_{e^+e^- \to J/\psi \chi_{c0}(2P)}(10.6\ \mathrm{GeV}) = 9.1\ \mathrm{fb}$$



$X^*(3860)$ and $\chi_{c0}(2P)$

PRD **95**, 112003 (2017)

- Quantum numbers: $J^{PC} = 0^{++}$.
- Production: in S-wave. Same for $\chi_{c0}(1P)$, measured in PRD **70**, 071102 (2004).
- The $\chi_{c0}(2P)$ mass in Ebert-Faustov-Galkin model [PRD **67**, 014027 (2003)]: 3854 MeV$/c^2$, in Godfrey-Isgur model [PRD **32**, 189 (1985)]: 3916 MeV$/c^2$.
- Mass difference (potential models: $\sim 0.6 - 0.9$): $r_c = (m_{\chi_{c2}(2P)} - m_{\chi_{c0}(2P)})/(m_{\chi_{c2}(1P)} - m_{\chi_{c0}(1P)}) = 0.46^{+0.25}_{-0.34}$
- Decay: $\chi_{c0}(2P)$ should primarily decay to $D\bar{D}$ (observation mode for the $X^*(3860)$) and not $J/\psi\omega$.
- The $X^*(3860)$ agrees with the peak in $\gamma\gamma$ data ($M = 3837.6 \pm 11.5$ MeV$/c^2$, $\Gamma = 221 \pm 19$ MeV).

The $X^*(3860)$ is a better $\chi_{c0}(2P)$ candidate than the $X(3915)$.

Absolute branching fractions of $B^+ \to X_{c\bar{c}} K^+$

Branching fractions of $B^+ \to X_{c\bar{c}} K^+$

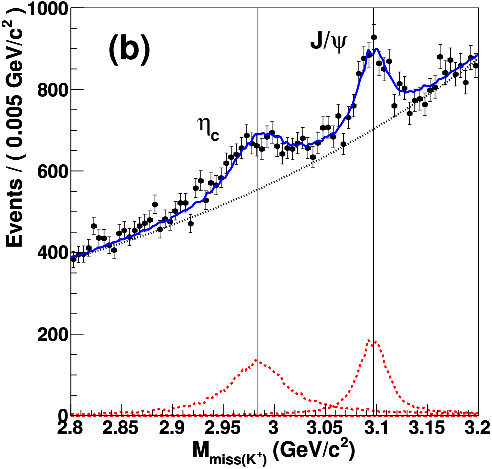
PRD **98**, 012005 (2018)

One B is fully reconstructed using a large set of final states, this defines the momentum of another B. The branching fractions are extracted from the fit to the recoil mass to the K^+. Results:

Mode	Yield	Signif.	$\mathcal{B}$ (10^{-4})	World average $\mathcal{B}$ (10^{-4})
η_c	2590 ± 180	14.2	$12.0 \pm 0.8 \pm 0.7$	9.6 ± 1.1
J/ψ	1860 ± 140	13.7	$8.9 \pm 0.6 \pm 0.5$	10.26 ± 0.031
χ_{c0}	430 ± 190	2.2	$2.0 \pm 0.9 \pm 0.1$ (< 3.3)	$1.50^{+0.15}_{-0.14}$
χ_{c1}	1230 ± 180	6.8	$5.8 \pm 0.9 \pm 0.5$	4.79 ± 0.23
$\eta_c(2S)$	1050 ± 240	4.1	$4.8 \pm 1.1 \pm 0.3$	3.4 ± 1.8
$\psi(2S)$	1410 ± 210	6.6	$6.4 \pm 1.0 \pm 0.4$	6.26 ± 0.24
$\psi(3770)$	-40 ± 310	-	$-0.2 \pm 1.4 \pm 0.0$ (< 2.3)	4.9 ± 1.3
$X(3872)$	260 ± 230	1.1	$1.2 \pm 1.1 \pm 0.1$ (< 2.6)	(< 3.2)
$X(3915)$	80 ± 350	0.3	$0.4 \pm 1.6 \pm 0.0$ (< 2.8)	-

Fit result in the J/ψ region.

PRD **98**, 012005 (2018)

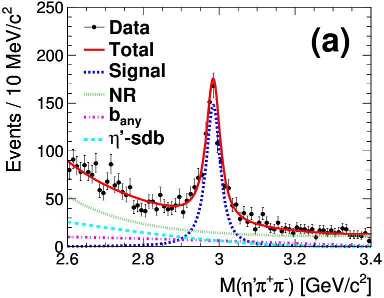


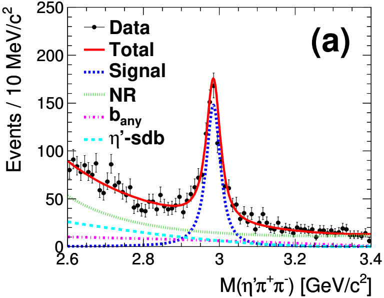
Signal shape from MC, background - exponential of a second-order polynomial.

Two-photon production of the $\eta_c(1S)$ and $\eta_c(2S)$

$\eta_c(1S)$ and $\eta_c(2S)$ mass distributions

PRD **98**, 072001 (2018)





$\eta_c(1S)$ and $\eta_c(1S)$ are reconstructed in $\eta'\pi^+\pi^-$ decay modes, with $\eta' \to \eta\pi^+\pi^-$ (shown above) or $\eta'\gamma\rho$.
This decay mode is observed for the first time for the $\eta_c(2S)$ with 5.5σ significance.

$\eta_c(1S)$ and $\eta_c(2S)$ parameters

PRD **98**, 072001 (2018)

Numerical results:

	$\eta_c(1S)$		$\eta_c(2S)$	
	$\gamma\rho$	$\eta\pi^+\pi^-$	$\gamma\rho$	$\eta\pi^+\pi^-$
n_s	1728^{+69}_{-68}	945^{+38}_{-37}	65^{+14}_{-13}	41^{+9}_{-8}
M (MeV/c^2)	$2984.6 \pm 0.7 \pm 2.2$		$3635.1 \pm 3.7 \pm 2.9$	
Γ (MeV)	$30.8^{+2.3}_{-2.2} \pm 2.5$		11.3 [fixed]	
$\Gamma_{\gamma\gamma}\mathcal{B}$ (eV)	$65.4 \pm 2.6 \pm 6.9$		$5.6^{+1.2}_{-1.1} \pm 1.1$	

Cross sections of $\gamma\gamma \to \eta'\pi^+\pi^-$ in non-η_c regions are also measured.

A multichannel multivariate algorithm for the η_c selection for further studies in B decays is currently in development.

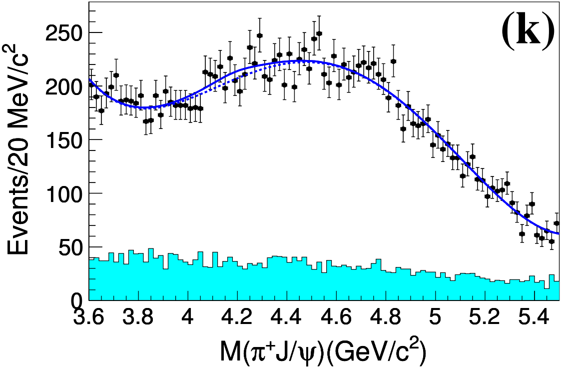
Search for $\Upsilon(1S, 2S) \to Z_c^+ \bar{Z}_c^-$

Analysis method and results

- Data samples: $\Upsilon(1S)$, $\Upsilon(2S)$ decays; e^+e^- annihilation at $\sqrt{s} = 10.52, 10.58, 10.867$ GeV.
- Partial reconstruction: one Z_c^+ is reconstructed, another is identified by the recoil mass.
- Z_c^+ states included into the search: $Z_c^+(3900) \to J/\psi\pi^+$, $Z_c^+(4200) \to J/\psi\pi^+$, $Z_c^+(4050) \to \chi_{c1}\pi^+$, $Z_c^+(4250) \to \chi_{c1}\pi^+$, $Z_c^+(4055) \to \psi(2S)\pi^+$, $Z_c^+(4430) \to \psi(2S)\pi^+$.
- No significant signal is found for any Z_c^+ combination at any energy. Upper limits to the $\Upsilon(1S)$, $\Upsilon(2S)$ branching fraction or the production cross section are set.

Example fit result

PRD **97**, 112004 (2017)



$e^+e^- \to Z_c^+(4200)\bar{Z}_c^-(4200)$ at the $\Upsilon(4S)$ energy.

Signal PDF - Breit-Wigner convolved with the resolution; background PDF - sum of Chebyshev polynomials (in this case, up to third order).

Thank you for attention!

BACKUP

Signal fit

$$S(\Phi) = \sum_{\substack{\lambda_{\rm beam}=-1,1 \\ \lambda_{\ell\ell}=-1,1}} \left| \sum_{X^*} A_{\lambda_{\rm beam}\,\lambda_{\ell\ell}}(\Phi) A_{X^*}(M_{D\bar{D}}) \right|^2, \quad (1)$$

Here, $A_{\lambda_{\rm beam}\,\lambda_{\ell\ell}}(\Phi)$ is the signal amplitude calculated using the helicity formalizm (the phase space Φ is 6-dimensional). For resonance, A_{X^*} = relativistic Breit-Wigner. For nonresonant amplitude, $A_{X^*} = \sqrt{F_{D\bar{D}}(M_{D\bar{D}})}$, where $F_{D\bar{D}}(M_{D\bar{D}})$ is the nonresonant amplitude form factor ($F_{D\bar{D}} = 1$ by default). Alternatives: mass dependence of NRQCD prediction for $e^+e^- \to \psi\chi_c$ [PRD **77**, 014002 (2008)], $F_{D\bar{D}} = M_{D\bar{D}}^{-4}$ [Victor Chernyak, based on PLB **612**, 215 (2005)].