Study of charmoniumlike states by amplitude analyses at Belle

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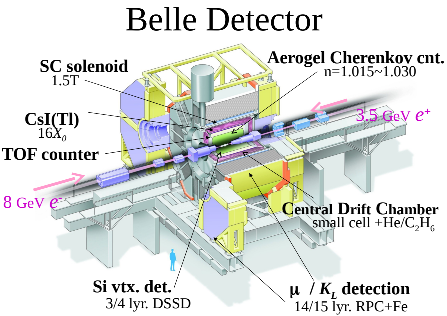
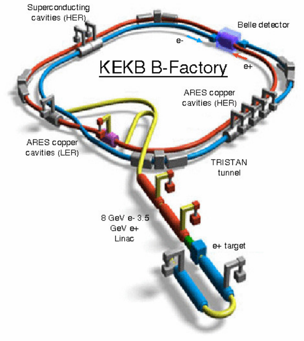
The Belle experiment

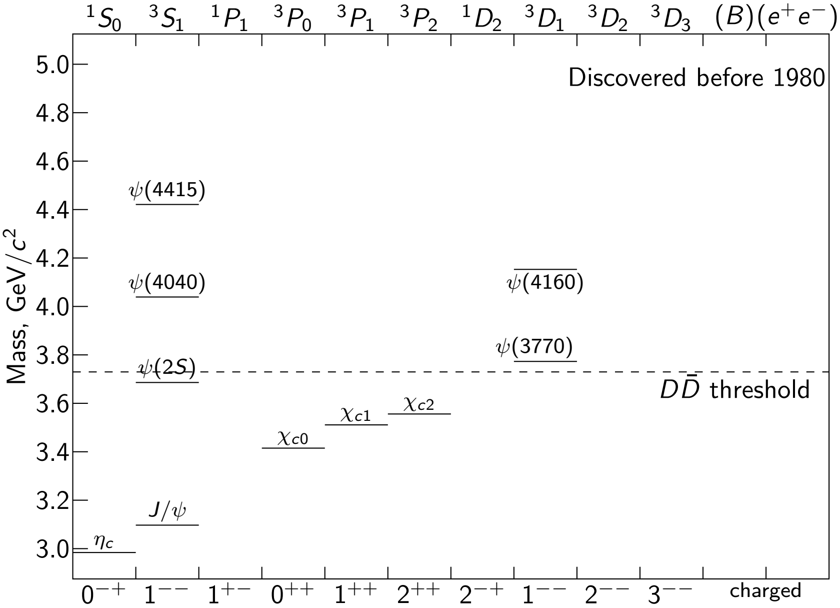




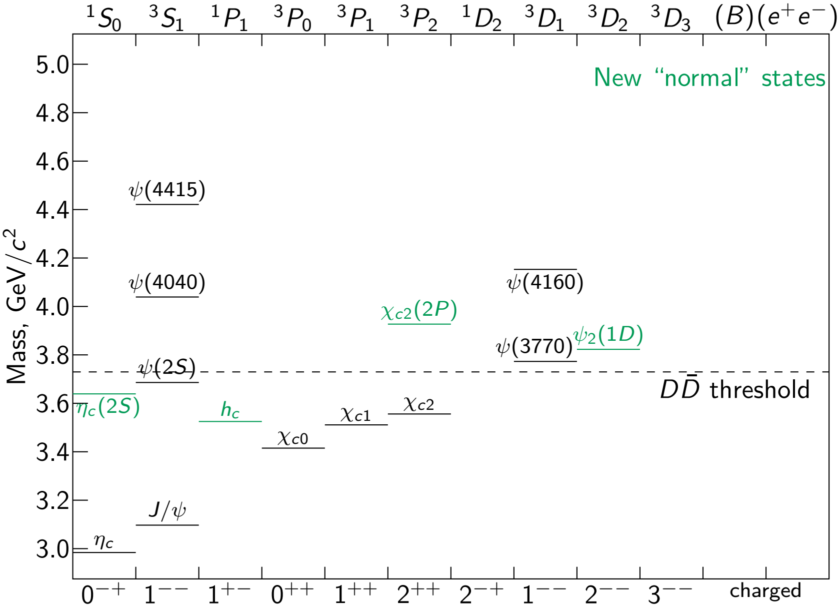
Charmonium production:

- From B decays - 711 fb^{-1}, 772×10^6 $B\bar{B}$ pairs.
- Double charmonium production (all energies): 980 fb^{-1}.

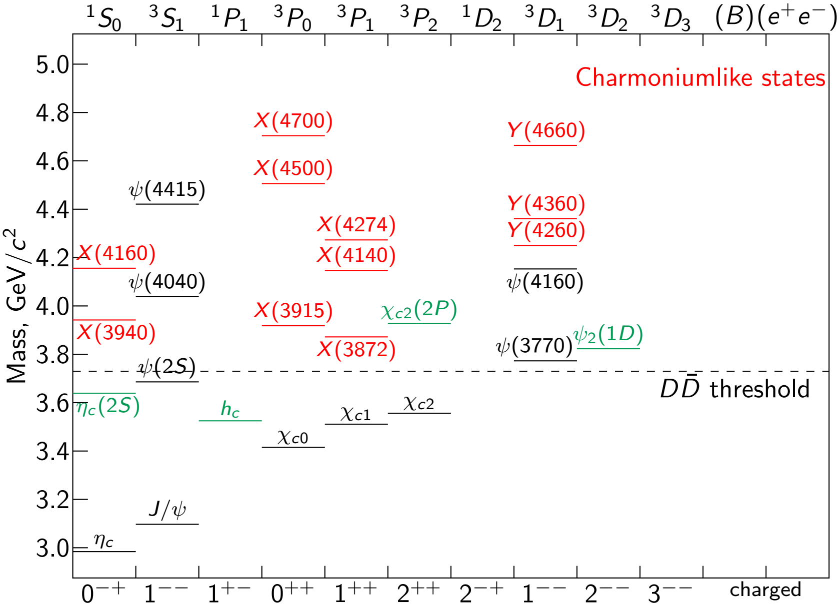
Charmonium states



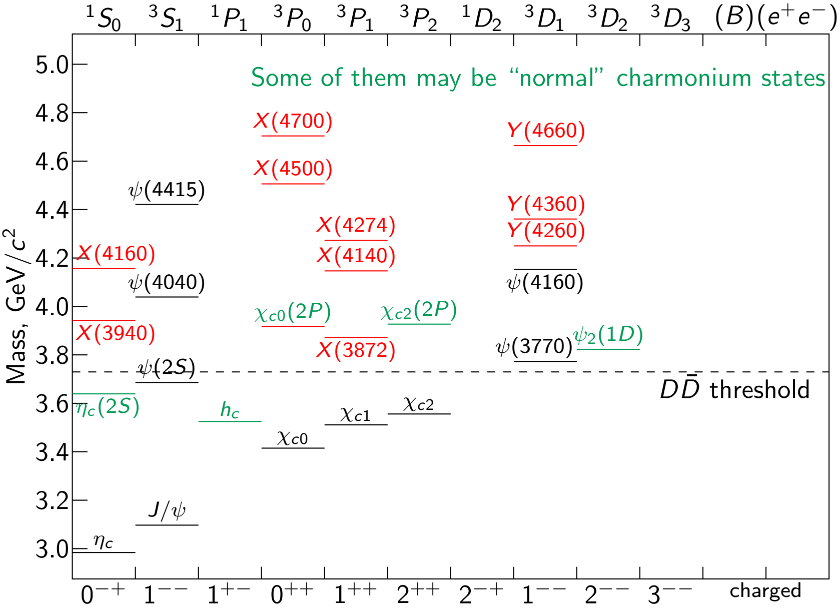
Charmonium states



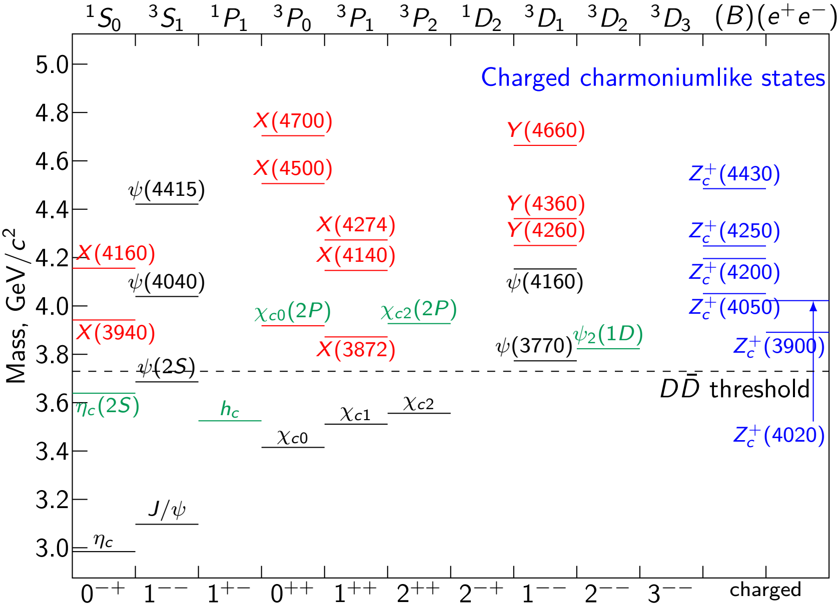
Charmonium states



Charmonium states



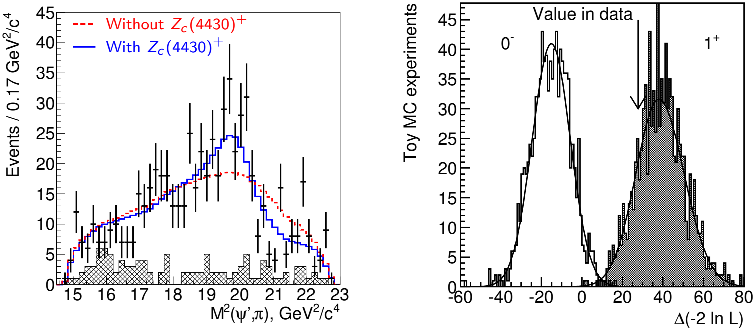
Charmonium states



Charged Z_c^+ states

$Z_c(4430)^+$ quantum numbers

PRD **88**, 074026 (2013)

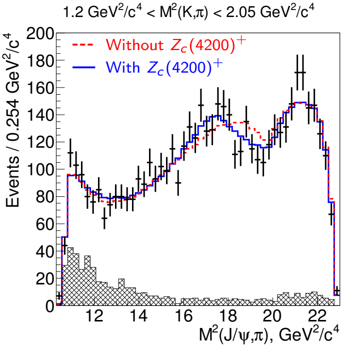


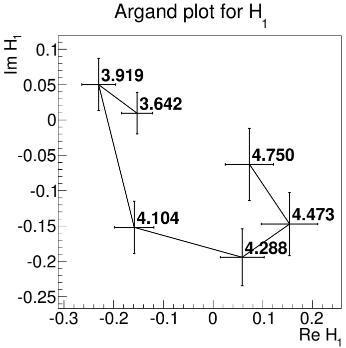
Full 4-dimensional amplitude analysis of $\bar{B}^0 \to \psi(2S)K^-\pi^+$.
Result: $J^P = 1^+$ is preferred, 0^-, 1^-, 2^- and 2^+ hypotheses are excluded at the levels of 3.4σ, 3.7σ, 4.7σ and 5.1σ, respectively.
Parameters: $M = 4485^{+22+28}_{-22-11}$ MeV$/c^2$, $\Gamma = 200^{+41+26}_{-46-35}$ MeV.

The J^P measurement was confirmed by LHCb in PRL **112**, 222002 (2014) with much higher significance.

$Z_c(4200)^+$ in $\bar{B}^0 \to J/\psi K^- \pi^+$

PRD **90**, 112009 (2014)





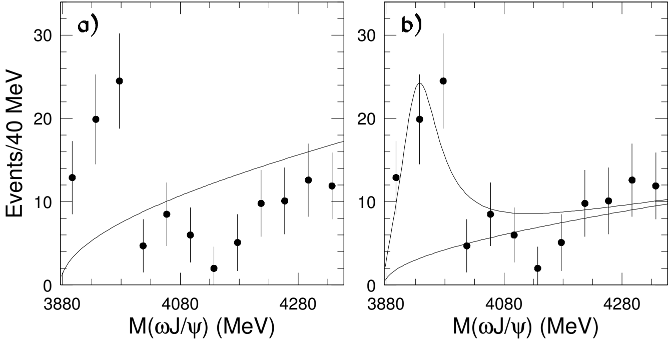
A new state $Z_c(4200)^+$ was observed with $M = 4196^{+31}_{-17}{}^{+29}_{-13}$ MeV$/c^2$, $\Gamma = 370^{+70}_{-70}{}^{+70}_{-132}$ MeV, 6.2σ. $J^P = 1^+$ is preferred, 0^-, 1^-, 2^-, 2^+ are excluded at the levels of 6.1σ, 7.4σ, 4.4σ and 7.0σ, respectively. Evidence for $Z_c(4430)^+ \to J/\psi \pi^+$ was found.

The $Z_c(4200)^+$ is not confirmed, but it may be the same state as the $Z_c(4240)^+$ found by LHCb in $\bar{B}^0 \to \psi(2S) K^- \pi^+$ (if it has $J^P = 1^+$ that is excluded at 1σ only).

$X^*(3860)$ in $e^+e^- \to J/\psi D\bar{D}$

Motivation

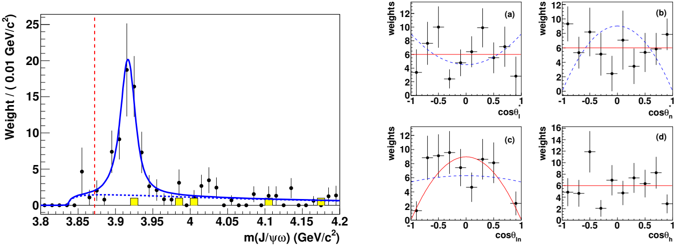
The $X(3915)$ was seen by fisrt seen by Belle in $B \to J/\psi\omega K$ [PRL **94**, 182002 (2005)]:



Then the $X(3915)$ was seen by BaBar in the same decay mode [PRD **82**, 011101 (2010)].

Motivation

It was also seen by Belle [PRL **104**, 092001 (2010)] and BaBar [PRD **86**, 072002 (2012)] in $\gamma\gamma \to J/\psi\omega$. The BaBar analysis measured $J^P = 0^+$:



Resulting identification was: $X(3915) = \chi_{c0}(2P)$

But this identification is doubtful because of: low width; $\chi_{c0}(2P) \to J/\psi\omega$ is OZI-suppressed; the difference between the $X(3915)$ and $\chi_{c2}(2P)$ masses is too small, ... [see F. K. Guo and U. G. Meissner, PRD **86**, 091501 (2012), S. L. Olsen PRD **91**, 057501 (2015)].

An alternative $\chi_{c0}(2P)$ candidate is searched for in the process $e^+e^- \to J/\psi D\bar{D}$.

Reconstruction

PRD **95**, 112003 (2017)

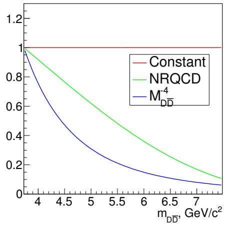
- $J/\psi \to e^+e^-, \mu^+\mu^-$.
- One D is reconstructed, the other is identified by the recoil mass ($M_{\rm rec}(J/\psi, D)$). Both D^0 and D^+ are used.
- $D^0 \to K^-\pi^+, K_S^0\pi^+\pi^-, K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-$ (4 channels).
- $D^+ \to K_S^0\pi^+, K^-\pi^+\pi^+, K_S^0\pi^+\pi^0, K^-\pi^+\pi^+\pi^0, K_S^0\pi^+\pi^+\pi^-$ (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, $M_{\rm rec}(J/\psi, D)$ and MLP output cutoff value).

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

Signal fit

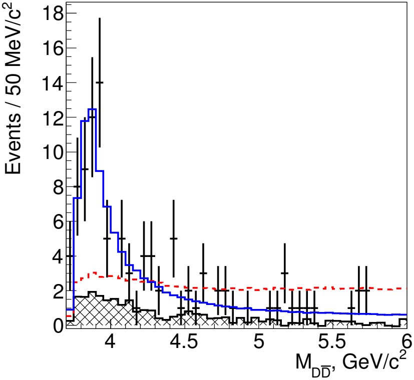
$$S(\Phi) = \sum_{\substack{\lambda_{\text{beam}}=-1,1 \\ \lambda_{\ell\ell}=-1,1}} \left| \sum_{X^*} A_{\lambda_{\text{beam}}\,\lambda_{\ell\ell}}(\Phi) A_{X^*}(M_{D\bar{D}}) \right|^2, \qquad (1)$$

Here, $A_{\lambda_{\text{beam}}\,\lambda_{\ell\ell}}(\Phi)$ 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)].



Signal fit results

PRD **95**, 112003 (2017)



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

Signal fit results

Fit results in the default model. For the 2^{++} hypothesis, there are three solutions (fit is started 1000 times from random initial values in order to check for that).

J^{PC}	Mass, MeV/c^2	Width, MeV	Significance (Wilks)
0^{++}	3862^{+26}_{-32}	201^{+154}_{-67}	9.1σ
2^{++}	3879^{+20}_{-17}	171^{+129}_{-62}	8.0σ
2^{++}	3879^{+17}_{-17}	148^{+108}_{-50}	8.0σ
2^{++}	3883^{+26}_{-24}	227^{+201}_{-125}	8.0σ

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

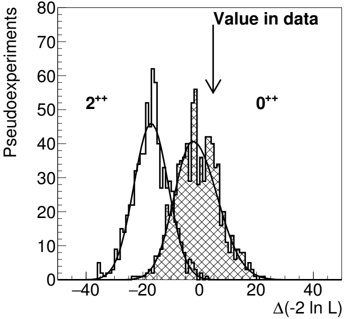
The minimal significance is $6.5\sigma \Rightarrow$ the $X^*(3860)$ is observed.

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).

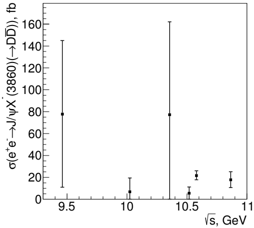
Cross section measurement

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	$\sigma^{(\text{Born})}_{e^+e^- \to J/\psi X^*(3860)(\to D\bar{D})}$, 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): $\sigma_{e^+e^- \to J/\psi \chi_{c0}(2P)}(10.6\text{ GeV}) = 9.1$ fb



Conclusions and discussion

- 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.
- The $J^{PC} = 0^{++}$ hypothesis is favored over the 2^{++} hypothesis at the level of 2.5σ.

$X^*(3860)$ 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 $X(3915)$.

Thank you for attention!