

XYZ at Belle

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Abstract. Recent results of exotic states with heavy quarks, denoted as XYZ states, are presented. The results include searches for the $Y(4260)$ in B meson decays, a spin partner of $Y(4630)$, and the strange Pentaquark P_s^+ . An addition, the measurements of the absolute branching fraction of $X(3872)$ and search for double Z_c production is discussed.

1 Introduction

In recent years, numerous narrow states with heavy quarks (c, b) have been observed, which do not fit the expected properties for charmonium or bottomonium states from the Cornell potential [1]. For detailed information about the states, their discovery and their properties, we refer to the recent reviews [2]. Throughout this paper below, charge conjugated states and decay modes are implied.

2 $Y(4260)$ in B meson decays

The vector state $Y(4260)$ has been observed in the ISR (initial state radiation) process $e^+e^- \rightarrow \gamma Y(4260) \rightarrow J/\psi \pi^+ \pi^-$ by BaBar [3], Belle [4], CLEO-c [5] and in direct production in $e^+e^- \rightarrow Y(4260)$ at BESIII [6]. Up to date, in total four states $Y(4008)$, $Y(4260)$, $Y(4350)$ and $Y(4660)$ have been observed by several experiments, all of them carrying the quantum numbers $J^{PC}=1^{--}$. In addition, there are the well known conventional vector charmonium states $\psi(4040)$, $\psi(4140)$, $\psi(4400)$ [7] in the same mass regime, leading to a overpopulation of states and thus pointing to the exotic nature of the Y states.

In literature, the $Y(4260)$ has been discussed as a $D\bar{D}_1(2460)$ molecule and as a P -wave tetraquark [2]. In particular, the decay to $D^{(*)}\bar{D}^{(*)}$ has not been seen yet [7], although the phasespace is large. This observation can be explained in the context of a $[J/\psi f_0(980)]$ hadrocharmonium state (with dominant decays to "core" and "cloud" components) or of a $[(c\bar{c})_8 g]$ hybrid (with open charm decays being blocked by the gluon fluxtube) [2].

Searches for the $Y(4260)$ in B meson decays have started more than a decade ago by BABAR in the decay $B^+ \rightarrow K^+ Y(4260)$ with $Y(4260) \rightarrow J/\psi \pi^+ \pi^-$. In a data set of 211 fb^{-1} , 128 ± 42 signal events were observed [8], corresponding to a significance of 3.1σ , and being translated to a range of a branching fraction of $1.2 < \mathcal{B} < 2.9 \times 10^{-5}$.

Recently, the D0 experiment reported the surprising observation with 167 ± 41 signal events (4.3σ significance) in a data set of 10.4 fb^{-1} [9]. However, different from BABAR,

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b -flavoured hadrons (B , B_s , B^* , Λ_b , ...) were selected inclusively instead of B mesons, by requiring a $[J/\psi\pi^+\pi^-]$ system with a secondary vertex.

A search in Belle was performed [10], using the complete Belle $\Upsilon(4S)$ data set of 711 fb^{-1} and corresponding to a factor 3.3 more data than in case of $BABAR$. Scaling the signal and background yields would give $S/\sqrt{S+B}=5.7$, which would be a clear observation. In addition, neutral B decays with $B^0 \rightarrow K_s^0 Y(4260)$ were added to the analysis. Fig. 1 shows the $J/\psi\pi^+\pi^-$ invariant mass distributions for the three different mass regions around the ψ' , the $X(3872)$ and the $Y(4260)$. The first two served as control signals. For the $Y(4260)$, no signal was observed, with the measured branching fraction reaching the 10^{-6} level. The derived upper limit of 1.4×10^{-5} for the charged B meson decays is consistent with the $BABAR$ measurement.

3 Search for a spin partner of the $Y(4630)$

The $Y(4630)$ was discovered in ISR as well and thus also represents a vector state with $J^{PC}=1^{--}$. Along with the $Y(4660)$ mentioned above in Sec. 2, it represents the highest charmed XYZ state with charm observed so far. If being a pure $c\bar{c}$ state, the radius¹ of can be calculated in the Cornell potential $r \approx 2.2 \text{ fm}$, far beyond string breaking limit outside the confinement region. In addition, it is the only XYZ state observed so far decaying into baryons. It was recognized early, that the $Y(4660)$, decaying to $J/\psi\pi^+\pi^-$ and already mentioned above, and the $Y(4630)$, decaying to $\Lambda_c^+\Lambda_c^-$, may represent same state [11]. In the hadrocharmonium model, the $X(3872)$ can be interpreted as a $[J/\psi\rho^0]$ state, the $Y(4260)$ as a $[J/\psi f_0(980)]$ state and the $Y(4630)$ as a $[\psi' f_0(980)]$ state. The latter one would imply the existence of a $[\eta_c(2S) f_0(980)]$ partner state, called the Y_η , with a mass of $4613 \pm 4 \text{ MeV}$ and a width $\approx 30 \text{ MeV}$, whereas the width is dominated by the $\eta_c(2S)$. With $L=0$, the quantum numbers would be $J^{PC}=0^{-+}$, and thus it can not be produced in ISR. Therefore a search in B meson decays was performed with the complete Belle $\Upsilon(4S)$ data set of 711 fb^{-1} [13]. No signal was observed yet, leading to an upper limit of $\mathcal{B}(B^+ \rightarrow K^+ Y_\eta) \times \mathcal{B}(Y_\eta \rightarrow \Lambda_c^+ \Lambda_c^-) < 2.0 \times 10^{-4}$.

4 Absolute branching fraction of the $X(3872)$

The $X(3872)$ has been observed in five different decays [7]. However, all branching fractions are only established as lower limits [7], because the total branching fraction \mathcal{B}_{total} , being required as normalisation, is not known. There is a way to measure \mathcal{B}_{total} at B factories, which operate with e^+e^- collisions at the $\Upsilon(4S)$ resonance at $\sqrt{s}=10.58 \text{ GeV}$. The particular situation kinematic situation at the $\Upsilon(4S)$ is, that the mass of the $\Upsilon(4S)$ coincides very closely with the sum of the masses of the B meson and the \bar{B} meson, the decay products of the $\Upsilon(4S)$. Therefore, the two B mesons are almost at rest in the center-of-mass (cms) system. One of the two B mesons can now be tagged, with a hierarchical full reconstruction of 1104 hadronic decays [15]. The other, remaining B meson could be decay into a K meson and a charmonium or charmonium-like, exotic state $X_{c\bar{c}}$. Due to the peculiar kinematic situation, the missing mass m_{miss} of the K meson can be utilized for the measurements of total cross sections of any $X_{c\bar{c}}$, and in particular the $X(3872)$. The missing mass is calculated as $m_{miss}(K) = \sqrt{(p_{e^+e^-}^* - p_{tag}^* - p_K^*)^2/c^2}$ with cms momenta of the e^+e^- collision system, the tagging side and the K meson, respectively. The recently measured value is $\mathcal{B}_{total} = 1.2 \pm 1.1 \pm 0.1 \times 10^{-4}$ [14], leading to an upper limit of $\mathcal{B}_{total} < 2.6 \times 10^{-4}$. Interestingly, this value almost reaches the value of the highest known partial product branching fraction

¹In the Cornell potential, the radius can be approximated by the turning point of the wavefunction.

[7] for $B^+ \rightarrow K^+ X(3872)$ with $X(3872) \rightarrow D^0 \bar{D}^0 \pi^0$ of $\mathcal{B}_{\text{partial}} = (1.0 \pm 0.4) \times 10^{-4}$. Thus, the measurement of $\mathcal{B}_{\text{total}}$ is in close reach for the ongoing data taking at Belle II.

5 Double Z_c production

The charged Z_c states have been observed in $e^+e^- \rightarrow Z_c^+(3900)\pi^-$ at BESIII at $\sqrt{s}=4.26$ GeV [21]. In addition, the charged Z_b states have been observed in $e^+e^- \rightarrow Z_b^+\pi^-$ at Belle at higher $\sqrt{s}=10.86$ GeV in the bottomonium mass regime. Thus, it is intuitive to perform a search for $e^+e^- \rightarrow Z_c^+ Z_c^{(\prime)-}$ pair production at such higher cms energies of $\sqrt{s}=10.52$ GeV, 10.58 GeV and 10.86 GeV, using the complete Belle data set. This search was performed at Belle [23], adding even 102 Mill. $\Upsilon(1S)$ and 158 Mill. $\Upsilon(2S)$ decays at $\sqrt{s}=9.46$ GeV and 10.02 GeV, respectively. $Z_c^+ Z_c^{(\prime)-}$ refer to any possible combination of the $Z_c(3900)$ and the $Z_c(4200)$ states. No signal was observed, resulting, as an example, in an upper limit on the product branching fraction $\sigma \times \mathcal{B}(Z_c^+(3900) \rightarrow J/\psi \pi^+)$ of 2.3 fb for the $Z_c(3900)Z_c(3900)$ combination. The order of magnitude of these upper limits is about a factor of 10^6 smaller than typical cross sections of $\sigma(e^+e^- \rightarrow \Upsilon(5S))=0.3$ nb at $\sqrt{s}=10.86$ GeV and about a factor 10^4 smaller than $\sigma(e^+e^- \rightarrow Y(4260)) \simeq 65$ pb at $\sqrt{s}=4.26$ GeV, with $\Upsilon(5S) \rightarrow Z_b^{(\prime)+}\pi^-$ and $Y(4260) \rightarrow Z_c^+(3900)\pi^-$.

6 Search for the P_s^+ pentaquark

The charmed pentaquark candidate $P_c^+ \rightarrow J/\psi p$ has been observed in Λ_b decays at LHCb [16]. For Belle (II), the Λ_b is outside the kinematically accessible range. However, Λ_c baryons are produced copiously and provide a suitable data set for the search for the strange partner of the P_c^+ , called P_s^+ , in the decay $P_s^+ \rightarrow \phi p$ in $\Lambda_c \rightarrow [\phi p]\pi^0$. The search was performed at Belle [20] in a data set of 915 fb^{-1} with total $1.468.435 \pm 4816$ Λ_c candidates. Fig. 2 shows the background subtracted $m(\phi p)$ distribution. Each data point corresponds to a fitted yield of a 2D fit. For details about the background subtraction and the fit procedure see [20]. No significant signal is observed. The fit result of 77.6 ± 28.1 P_s events at a mass of $2.025 \pm 0.005 \text{ GeV}/c^2$ and a width of $0.022 \pm 0.012 \text{ GeV}/c^2$ leads to an upper limit of the product branching fraction of

$$\mathcal{B}(\Lambda_c^+ \rightarrow P_s^+ \phi) \times \mathcal{B}(P_s^+ \rightarrow \phi p) < 8.3 \times 10^{-5}.$$

The determined upper limit for P_s^+ is still about a factor of 6 higher than measured branching fraction for the P_c^+ at LHCb.

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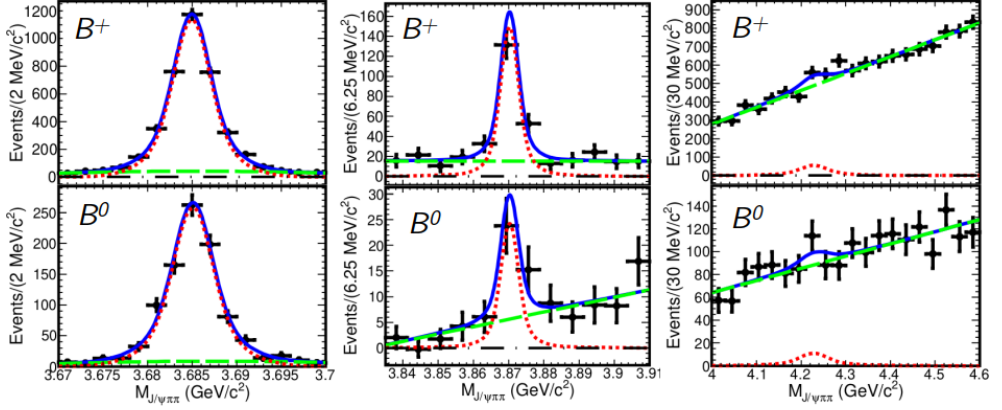


Figure 1. Invariant $m(J/\psi\pi^+\pi^-)$ mass distributions of $B^+\rightarrow K^+J/\psi\pi^+\pi^-$ decays (top) and $B^0\rightarrow K_s^0J/\psi\pi^+\pi^-$ decays (bottom) at Belle, using the complete recorded data set of 711 fb^{-1} . *Left:* zoom to mass region of ψ' , *center:* zoom to mass region of $X(3872)$, and *right:* zoom to mass region of $Y(4260)$.

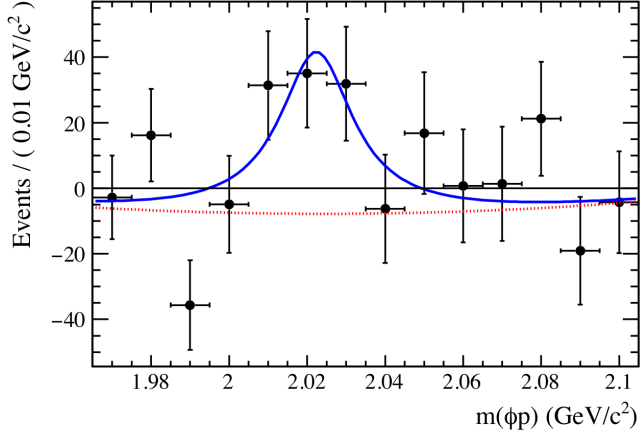


Figure 2. Invariant $m(\phi p)$ mass distributions in $\Lambda_c\rightarrow\phi p\pi^0$ decays in the search for the P_s^+ pentaquark state by Belle. For details about the background subtraction and the fit procedure see [20]. The red dotted line shows the phasespace distribution, which after background subtraction exhibits a negative fluctuation.

References

- [1] E. Eichten, K. Gottfried, T. Kinoshita, K. D. Lane, T.-M. Yan, Phys. Rev. **D17**, 3090 (1978)
- [2] A. Esposito, A. Pilloni, A. D. Polosa, Phys. Rep. **668**, 1 (2016); R. F. Lebed, R. E. Mitchell, E. S. Swanson, Prog. Part. Nucl. Phys. **93**, 143 (2017); A. Ali, J. S. Lange, S. Stone, Prog. Part. Nucl. Phys. **97**, 123 (2017); S. L. Olsen, T. Skwarnicki, D. Zieminska, Rev. Mod. Phys. **90**, 015003 (2018); F.-K. Guo, C. Hanhart, U.-G. Meißner, Q. Wang, Q. Zhao, B. S. Zou, Rev. Mod. Phys. **90**, 015004 (2018)
- [3] B. Aubert et al. (Babar Collaboration), Phys. Rev. Lett. **95**, 142001 (2005)
- [4] C. Z. Yuan et al. (Belle Collaboration), Phys. Rev. Lett. **99**, 182004 (2007)
- [5] Q. He et al. (CLEO-c Collaboration), Phys. Rev. **D74**, 091104 (2006)
- [6] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. Lett. **118**, 092001 (2017)
- [7] M. Tanabashi et al. (Particle Data Group), Phys. Rev. **D98**, 030001 (2018)
- [8] B. Aubert et al. (BaBar Collaboration), Phys. Rev. **D73**, 011101 (2006)
- [9] V. M. Abazov et al. (D0 Collaboration), Phys. Rev. **D98**, 052010 (2018)
- [10] R. Garg, V. Bhardwaj, J. B. Singh, et al. (Belle Collaboration), Phys. Rev. **D99**, 071102 (2019)
- [11] F.-K. Guo, J. Haidenbauer, C. Hanhart, U.-G. Meißner, Phys. Rev. **D82**, 094008 (2010)
- [12] S. Dubynskiy, M. B. Voloshin, Phys. Lett. **B666**, 344 (2008)
- [13] Y. B. Li, C. P. Shen, et al. (Belle Collaboration), Eur. Phys. J. **C78**, 252 (2018)
- [14] Y. Kato, T. Iijima, et al. (Belle Collaboration), Phys. Rev. **D97**, 012005 (2018)
- [15] M. Feindt, F. Keller, M. Kreps, T. Kuhr, S. Neubauer, D. Zander, A. Zupanc, NIM **A654**, 432 (2011)
- [16] R. Aaij et al. (LHCb Collaboration), Phys. Rev. Lett. **115**, 072001 (2015)
- [17] B. Aubert et al. (BABAR Collaboration), Phys. Rev. **D74**, 091103 (2006)
- [18] C. P. Shen et al. (Belle Collaboration), Phys. Rev. **D80**, 031101 (2009)
- [19] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. **D91**, 052017 (2015)
- [20] B. Pal, A. J. Schwartz, et al. (Belle Collaboration), Phys. Rev. **D96**, 051102 (2017)
- [21] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. Lett. **110**, 252001 (2013)
- [22] A. Bondar et al. (Belle Collaboration), Phys. Rev. Lett. **108**, 122001 (2011)
- [23] S. Jia, C. P. Shen, C. Z. Yuan, et al. (Belle Collaboration), Phys. Rev. **D97**, 112004 (2018)