XYZ at Belle

Jens Sören Lange[1,*] on behalf of the Belle collaboration

[1]Justus-Liebig-Universität Giessen, II. Physikalisches Institut, 35392 Giessen, Germany

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 dicussed.

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 $e^+e^-\to\gamma Y(4260)\to J/\psi\pi^+\pi^-$ by BaBar [3], Belle [4], CLEO–c [5] and in direct production in $e^+e^-\to Y(4260)$ 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 $D\overline{D}_1(2460)$ molecule and as a P-wave tetraquark [2]. In particular, the decay to $D^{(*)}\overline{D}^{(*)}$ 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 $[(c\overline{c})_8 g]$ 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 $B^+\to K^+Y(4260)$ with $Y(4260)\to J/\psi\pi^+\pi^-$. 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 $1.2<\mathcal{B}<2.9\times10^{-5}$.

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,

*e-mail: soeren.lange@exp2.physik.uni-giessen.de

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 Υ(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 $B^0 \rightarrow K^0_s Y(4260)$ 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 radius[1] of can be calculated in the Cornell potential $r \simeq 2.2$ 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±4 MeV and a width $\simeq$30 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 Υ(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 Υ(4S) resonance at $\sqrt{s}$=10.58 GeV. The particular situation kinematic situation at the Υ(4S) is, that the mass of the Υ(4S)) coincides very closely with the sum of the masses of the B meson and the $\overline{B}$ meson, the decay products of the Υ(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

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

[7] for $B^+ \to K^+ X(3872)$ with $X(3872) \to D^0 \overline{D}^0 \pi^0$ of $\mathcal{B}_{partial}$=(1.0±0.4)×10^{-4}. Thus, the measurement of $\mathcal{B}_{total}$ 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 $e^+e^- \to Z_c^+(3900)\pi^-$ at BESIII at $\sqrt{s}$=4.26 GeV [21]. In addition, the charged Z_b states have been observed in $e^+e^- \to Z_b^+\pi^-$ at Belle at higher $\sqrt{s}$=10.86 GeV in the bottomonium mass regime. Thus, it is intuitive to perform a search for $e^+e^- \to Z_c^+ Z_c^{(')-}$ 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. Υ(1S) and 158 Mill. Υ(2S) decays at $\sqrt{s}$=9.46 GeV and 10.02 GeV, respectively. Z_c^+ $Z_c^{(')-}$ 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 $\sigma \times \mathcal{B}(Z_c^+(3900) \to J/\psi\pi^+)$ 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 $\sigma(e^+e^- \to \Upsilon(5S))$=0.3 nb at $\sqrt{s}$=10.86 GeV and about a factor 10^4 smaller than $\sigma(e^+e^- \to$Y(4260))≃65 pb at $\sqrt{s}$=4.26 GeV, with $\Upsilon(5S) \to Z_b^{(')+}\pi^-$ and $Y(4260) \to Z_c^+(3900)\pi^-$.

6 Search for the P_s^+ pentaquark

The charmed pentaquark candidate $P_c^+ \to J/\psi p$ 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 $P_s^+ \to \phi p$ in $\Lambda_c \to [\phi p]\pi^0$. The search was performed at Belle [20] in a data set of 915 fb^{-1} with total 1.468.435±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±0.005 GeV/c^2 and a width of 0.022±0.012 GeV/c^2 leads to an upper limit of the product branching fraction of

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

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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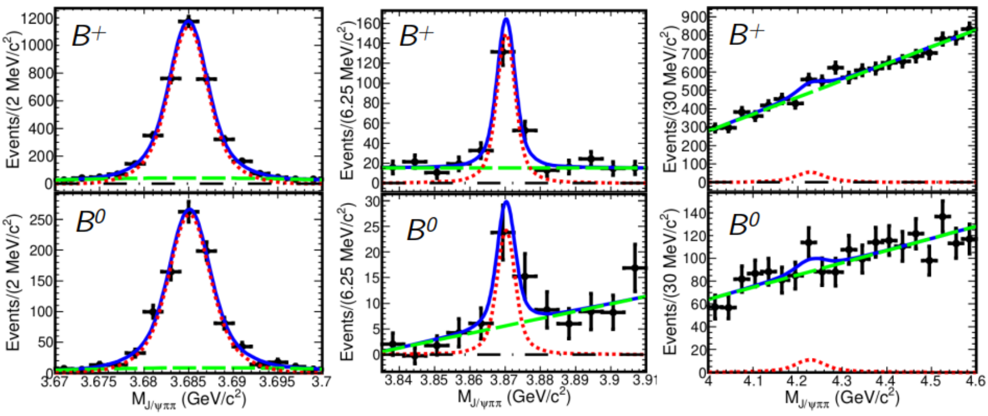

Figure 1. Invariant $m(J/\psi\pi^+\pi^-)$ mass distributions of $B^+ \to K^+ J/\psi\pi^+\pi^-$ decays (top) and $B^0 \to K_s^0 J/\psi\pi^+\pi^-$ decays (bottom) at Belle, using the complete recorded data set of 711 fb^{-1}. *Left:* zoom to mass region of ψ', *center:* zoom to mass region of $X(3872)$,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

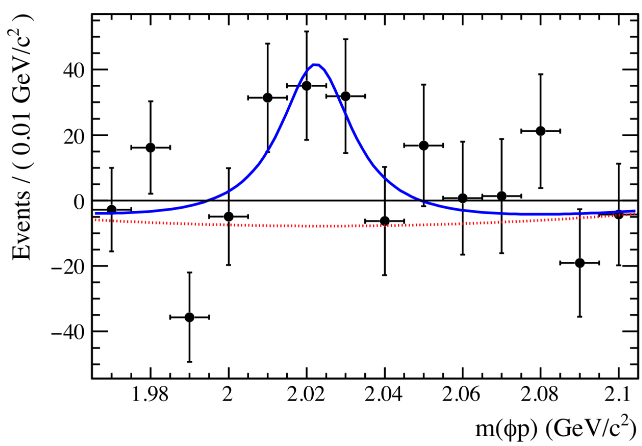

Figure 2. Invariant $m(\phi p)$ mass distributions in $\Lambda_c \to \phi p \pi^0$ decays in the search for the P_s^+ pentaquark state by Belle. For details about the background subtraction and the fit procedure see [20]. The red dotted line shows the phasespace distribution, which after background subtraction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

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