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Effects of Z_b states in $\Upsilon(3S,4S)$ dipion transitions

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We analyze the effects of the Z_b states in the dipion transitions from the $\Upsilon(3S,4S)$ to the lower Υ states. It is found that the Z_b's, together with the properly treated $\pi\pi$ final-state interaction, are essential to reproduce the double-bump structure in the dipion invariant mass distribution of the $\Upsilon(3S) \to \Upsilon(1S)\pi\pi$ transitions. We also point out that a reliable extraction of the $Z_b\Upsilon(nS)\pi$ coupling constants is crucial to finally settle the Z_b contributions to these transitions.

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Many decay processes of heavy quarkonia were reported soon after the discovery of the J/ψ. Among them, the transitions between two heavy quarkonia with the emission of two pions attracted special attention because the soft behavior of the pions, which are the pseudo-Goldstone bosons of the spontaneous breaking of chiral symmetry of quantum chromodynamics (QCD), is constrained by chiral symmetry. The QCD multipole expansion together with soft-pion theorems is the usual tool for such transitions [1, 2, 3], and the measured $\pi\pi$ invariant mass distributions for the processes $\psi' \to J/\psi\pi\pi$ and $\Upsilon(2S) \to \Upsilon(1S)\pi\pi$, both of which had a single peak toward the higher end of the phase space, could be well described within such a framework. However, the situation was changed due to the measurement of the dipion invariant mass distribution of the transition $\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$, which had an unusual double-bump structure. How to understand such a structure remained a puzzle since then, and many models were proposed (for references we refer to [4]). Among all the models, Voloshin proposed a very speculative one in 1980: the double-bump structure could be a consequence of the existence of an isovector $b\bar{b}q\bar{q}$ tetraquark state with quantum numbers $J^P = 1^+$ [5]. The model was refined in Ref. [6] considering also the $\pi\pi$ S-wave final-state interaction (FSI). Since there was no evidence for such a tetraquark state in the reported Dalitz plot and the state should not be too far from the $\Upsilon(3S)$, its mass was guessed to be in the region between 10.4 and 10.8 GeV. A good description of both the $\pi\pi$ invariant mass and the helicity angular distributions was obtained.

In 2011, the Belle Collaboration reported the observation of two charged bottomonium-like resonances $Z_b(10610)^\pm$ and $Z_b(10650)^\pm$ in five different decay modes of the $\Upsilon(5S)$: $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ $(n = 1,2,3)$ and $\Upsilon(5S) \to h_b(mP)\pi^+\pi^-$ $(m = 1,2)$ [7]. Their quantum numbers are $I^G(J^P) = 1^+(1^+)$, and their masses and widths have been determined to be $M_{Z_b(10610)} = (10607.4 \pm 2.0)$ MeV, $\Gamma_{Z_b(10610)} = (18.4 \pm 2.4)$ MeV, and $M_{Z_b(10650)} = (10652.2 \pm 1.5)$ MeV, $\Gamma_{Z_b(10650)} = (11.5 \pm 2.2)$ MeV, respectively. One sees that these properties are exactly those desired for the $b\bar{b}q\bar{q}$ isovector state in [5, 6]. Since the Z_b states were observed in both the $\Upsilon(3S)\pi$ and $\Upsilon(1S)\pi$ modes, they must contribute, though virtually, to the transitions $\Upsilon(3S) \to \Upsilon(1S)\pi\pi$. Furthermore, the branching fractions of the $Z_b(10610)$ and $Z_b(10650)$ decays into $\Upsilon(1S, 3S)\pi^+$ have been reported by the Belle Collaboration as well in Ref. [8, 9] where the Z_b states were observed to decay dominantly into open bottom channels, $B\bar{B}^* + c.c.$ and $B^*\bar{B}^*$ for the lighter and heavier Z_b state, respectively. Considering the lower $Z_b(10610)$ as an example, its branching fractions to the modes $\Upsilon(1S)\pi$ and $\Upsilon(3S)\pi$ in Ref. [8] are $(0.32 \pm 0.09)\%$ and $(2.15 \pm 0.56)\%$, respectively.[1] If we multiply these values with the Z_b width, the absolute value of the coupling constant for the $Z_b\Upsilon(nS)\pi$ vertex can be deduced. We obtain $C^{\text{naive}}_{31,Z_b(10610)} \simeq 0.01\,\text{GeV}^2$, the product of the couplings to the $3S$ and $1S$ states. One thus has the opportunity to quantitatively understand the contribution of the Z_b states to the transitions $\Upsilon(3S) \to \Upsilon(1S)\pi\pi$, which motivated us to revisit such transitions together with other analogous transitions between different Υ states by considering the Z_b states and $\pi\pi$ FSI simultaneously [4, 10]. Such an investigation will hopefully solve the double-bump puzzle.

For the transitions under consideration, the Υ states in the initial and final states have the same C-parity, then the C-parity of the dipion system much be positive. This constrains the two pions to be in even partial waves. For the transitions from the $3S$ to $1S$ state, $M_{\pi\pi}$ goes up to

[1] These numbers were used in our analysis. They were later on updated to larger values, $(0.60 \pm 0.18)\%$ and $(2.40 \pm 0.68)\%$, respectively, in [9]. Using these values will not change our conclusion in [4].

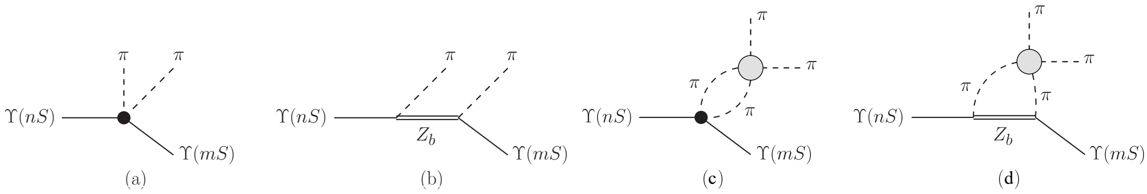

Figure 1: Mechanism considered for the $\Upsilon(3S) \to \Upsilon(1S)\pi\pi$. The gray circles represent the $\pi\pi$ FSI.

about 895 MeV. Therefore, one would expect the $f_0(500)$ to play a role and one has to take the $\pi\pi$ FSI into account. For $M_{\pi\pi} \lesssim 1\,\text{GeV}$, it is sufficient to consider only S and D waves. The $\pi\pi$ FSI is taken into account using dispersion relations constructed from analyticity and unitarity. The discontinuity along the right-hand cut starting from the two-pion threshold is obtained from unitarity, while the left-hand cut (LHC) is approximated through crossed-channel Z_b exchange. The mechanism considered here is depicted in Fig. 1. The solution of the dispersion relation with such a LHC contribution has been worked out in Ref. [11], and is used here. On the one hand, the dispersion integral contains subtraction polynomials in each partial wave. On the other hand, around the two-pion threshold, one can construct a chiral effective Lagrangian. The leading-order Lagrangian contains only two terms by further considering heavy-quark spin symmetry, which should be a rather good approximation for bottomonia. By matching the dispersive representation with the $\pi\pi$ FSI switched off to the chiral representation of the decay amplitude at low energies, the subtraction polynomials can be entirely written in terms of two low-energy constants in the chiral Lagrangian. The $\pi\pi$ phase shifts calculated in Refs. [12, 13] are used as inputs to the dispersion representation. For details of the amplitudes, we refer to [4].

First, we fit to the experimental data of the dipion invariant mass distribution and the helicity angular distribution for the $\Upsilon(3S) \to \Upsilon(1S)\pi\pi$ transitions measured by the CLEO Collaboration [14] without considering any Z_b contribution. The results are shown as the red curves in the upper panel of Fig. 2. It is clear that additional contributions need to be included. Then, both Z_b states are taken into account with the C_{31} coupling constants fixed to the values evaluated from the branching fractions in Ref. [8]. The best fit results are shown as the blue curves in the upper panel of Fig. 2. The difference from the red curves is small, and the data can still not be reproduced.

Finally, we try to fit to the data treating the coupling C_{31} as a free parameter. However, in this case, the two Z_b states can hardly be distinguished as their masses are larger than that of the $\Upsilon(3S)$ by more than 200 MeV. Thus, we include only the $Z_b(10610)$. The best fit results are shown in the lower panel of Fig. 2. One sees that the data can be rather well described. The resulting value for C_{31} is $(0.145 \pm 0.006)\,\text{GeV}^2$, one order of magnitude larger than the naive extraction mentioned above. This is in fact a welcome result. The reason is that the Z_b states are located very close to the $B^{(*)}\bar{B}^*$, and the nominal widths obtained from a fit with a Breit–Wigner form does not reflect their true decay properties. In particular, multiplying the nominal widths by the reported branching fraction does not gives the correct partial widths. As argued in the appendix of [4], the sum of the partial widths for all non-$(B\bar{B}^* + c.c.)$ decay modes should be larger than the nominal width of the $Z_b(10610)$. Then one would expect the value for C_{31} to be roughly one order of magnitude larger than the naive extraction of about 0.01 GeV^2, and the value obtained from fit is consistent with this.

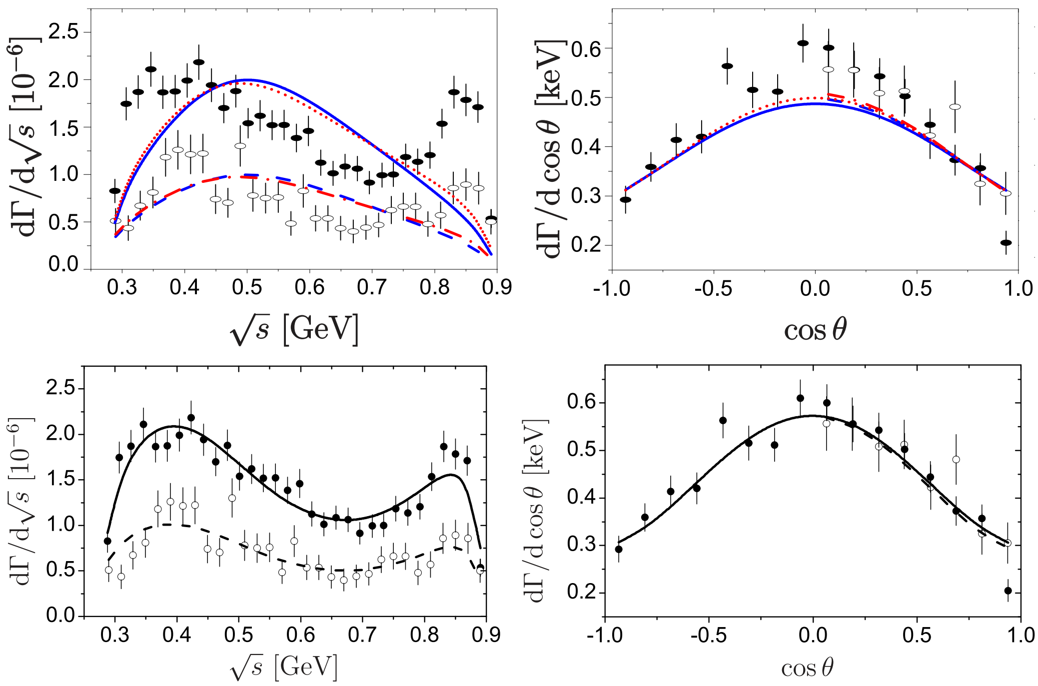

Figure 2: The best fit to the $\pi\pi$ invariant mass distribution (left) and the helicity angular distribution (right) for the decays $\Upsilon(3S) \to \Upsilon(1S)\pi\pi$ [14]. The solid and open circles denote the data for the $\Upsilon(1S)\pi^+\pi^-$ and $\Upsilon(1S)\pi^0\pi^0$ modes, respectively, with the curves our fitting results. Upper: red curves represent the best fit without any Z_b; blue curves represent the case considering both Z_b states with C_{31} fixed to the values calculated from the branching fractions in Ref. [8]. Lower: the case considering the $Z_b(10610)$ with C_{31} treated as a free parameter.

Therefore, considering both the Z_b exchange and the $\pi\pi$ FSI the double-bump structure in the $\pi\pi$ invariant mass distribution for the $\Upsilon(3S) \to \Upsilon(1S)\pi\pi$ as well as the angular distribution gets nicely explained. What remains to be checked is whether an updated analysis, which can be done using the framework detailed in [15], of the Belle data for the Z_b states in all observed channels from the $\Upsilon(5S)$ decays would result in a value of C_{31} consistent with the one required here.

We extend the above analysis to the dipion transitions from the $\Upsilon(4S)$ to $\Upsilon(1S)$ state [10]. These transitions are much more complicated for a dispersive analysis because the $\Upsilon(4S)$ is above the $B\bar{B}$ threshold and thus the LHC induced by intermediate bottom-meson loops should be taken into account. Such contributions are included as well as the Z_b and $\pi\pi$ FSI discussed above. Several different fits with or without the Z_b or/and bottom-meson loops are performed. It turns out that the used data [16, 17] are not sufficient for distinguishing the Z_b from the bottom-meson loops (Fig. 3 left), without knowing much about the $Z_b\Upsilon(nS)\pi$ couplings. Nevertheless, we expect that the $\pi\pi$ invariant mass distribution has a nontrivial structure at around 1 GeV, which turns out to be a dip in all our fits, due to the presence of the $f_0(980)$ in the coupled-channel ($\pi\pi$ and $K\bar{K}$) system, as already noticed in [18]. Such a nontrivial structure was not present in either the BaBar [16] or old Belle data [17]. However, the updated Belle data [19] indeed has a dip there (Fig. 3 right).

At last, we urge a reliable extraction of the $Z_b\Upsilon(nS)\pi$ coupling constants, which will be crucial

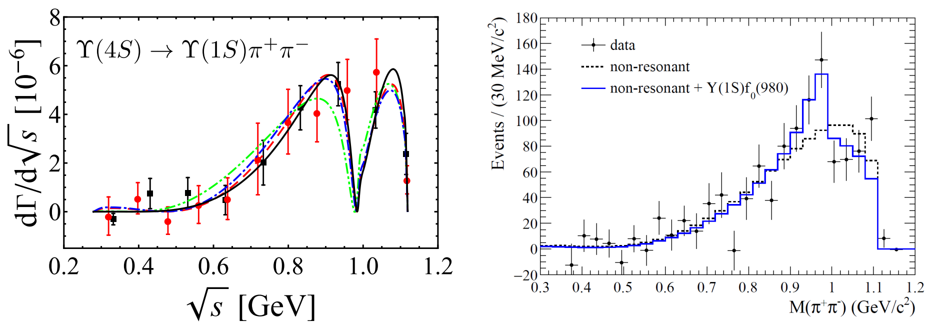

Figure 3: Left: different fits to the BaBar (squares) [16] and Belle (circles) [17] data of the $\pi\pi$ invariant mass distribution for the decay $\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$. Right: the updated Belle data [19].

to finally settle the Z_b contributions to the dipion transitions between different Υ states.

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