Interference effects in the $X(4260)$ signal

Eef van Beveren*

Centro de Física Computacional, Departamento de Física, Universidade de Coimbra, P-3004-516 Coimbra, Portugal

George Rupp†

Centro de Física das Interacções Fundamentais, Instituto Superior Técnico, Technical University of Lisbon, P-1049-001 Lisboa, Portugal

We show that the long known puzzling branching ratios of open-charm decays in e^+e^- annihilation can be reasonably described with a simple form factor, which strongly suppresses open channels far above threshold. Application to the $e^+e^- \rightarrow J/\psi\pi\pi$ data on the $X(4260)$ enhancement recently reported by the *BABAR* Collaboration [B. Aubert (*BABAR* Collaboration), arXiv:0808.1543] allows a good fit with a simple nonresonant cusp structure around the $D_s^* D_s^*$ threshold. Moreover, we argue that a closer look at the data reveals an oscillatory pattern, which we model as an interference effect between a fast—OZI-allowed—and a slow—OZI-forbidden—$J/\psi f_0(980)$ mode. Other candidates for similar nonresonant enhancements are discussed.

Recently, the *BABAR* Collaboration presented new preliminary data for the reaction $e^+e^- \rightarrow J/\psi\pi^+\pi^-$ [1]. These data exhibit a much more pronounced peak in the $X(4260)$ [2] region than in the first *BABAR* observation of this structure [3], besides a rather constant signal for the remaining invariant masses [4]. The new experimental analysis of the $X(4260)$ using a nonrelativistic Breit-Wigner parametrization yielded a mass of $M = (4252 \pm 6^{+2}_{-3})$ MeV and a width of $\Gamma = (105 \pm 18^{+4}_{-6})$ MeV.

The $X(4260)$ enhancement was confirmed, and also seen in the processes $\pi^0\pi^0 J/\psi$ as well as $K^+K^- J/\psi$, by the CLEO Collaboration [5], whereas the Belle Collaboration observed a similar structure in $J/\psi\pi^+\pi^-$ [6]. On the theoretical side [7–9], a variety of model explanations have been suggested, such as a standard vector charmonium state $(4S)$ [10], a mesonic or baryonic molecule [11], a gluonic excitation (hybrid) [12], or a $cq\bar{c}\bar{q}$ state [13].

It was also noticed [14] that the Belle data [6] reveal a curious $\pi\pi$ mass spectrum in the $m_{\pi^+\pi^- J/\psi}$ invariant-mass region of 4.2–4.4 GeV, which was confirmed by the *BABAR* Collaboration in Ref. [1].

A remarkable aspect of this experimental observation is that the main signal of $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ coincides with the $D_s^* D_s^*$ threshold [4] and, furthermore, that very little $D\bar{D}$ production has been observed in the 4.26 GeV region [15]. Here, we shall first pay some attention to the latter phenomenon, then discuss the relation of the $X(4260)$ signal to the opening of $D_s^* D_s^*$, and finally present a possible explanation for the $\pi\pi$ mass spectrum.

It has been observed [15,16] that $D\bar{D}$ production in e^+e^- annihilation is suppressed at invariant masses far above the production threshold for $D\bar{D}$. Branching frac-

tions have been measured at 4.028 GeV with the SLAC/LBL magnetic detector at SPEAR [17]. The results suggest that the opening of a channel is followed by a rather fast fading out of the same channel at higher invariant masses. In Refs. [18,19], it was shown that this feature can be parametrized for the total cross section σ by a simple Gaussian form factor, which for P waves suggests the expression

$$\sigma \propto |pr_0| e^{-|pr_0|^2}, \qquad (1)$$

where p stands for the two-particle linear momentum and r_0 represents a distance parameter. In Table I, we show some results of formula (1) for the branching fractions of pairs of neutral charmed mesons at 4.028 GeV, produced in e^+e^- annihilation. We observe that expression (1) allows a reasonable agreement with experiment. This may explain why so few $D\bar{D}$ pairs are observed at 4.26 GeV [15], as this channel opens at 3.74 GeV. It supports the idea that channels get effectively damped at invariant masses far above their thresholds. This phenomenon may be understood as the manifestation of boost effects on the wave functions of

TABLE I. Branching fractions for $e^+e^- \rightarrow D^0 D^0$, $D^0 D^{*0}$, and $D^{*0} D^{*0}$ at 4.028 GeV, obtained by the use of formula (1), including the ratios which stem from the three-meson vertex couplings, viz. $PP{:}PV{:}VV = 1{:}4{:}7$ ($P =$ pseudoscalar, $V =$ vector meson), and compared to the results of Goldhaber *et al.* [17].

Channels	$r_0 = 3.2$[a]	$r_0 = 3.8$[a]	Experiment [17]
$D^0 D^0 / D^0 D^{*0}$	0.021	0.007	0.05 ± 0.035
$D^0 D^0 / D^{*0} D^{*0}$	0.0023	0.0002	0.0016 ± 0.0014
$D^0 D^{*0} / D^{*0} D^{*0}$	0.11	0.033	0.031 ± 0.016

[a]Units of r_0: GeV^{-1}.

*eef@teor.fis.uc.pt
†george@ist.utl.pt

the produced mesons [20]. Consequently, near the $X(4260)$ we may restrict ourselves to the opening of the $D_s^* D_s^*$ channel. As for the possible alternatives in this energy region, the $DD_1(2420)$ [21] threshold at about 4.29 GeV lies somewhat too high, while the $DD_1(2430)$ channel, involving the very broad $D_1(2430)$ [2] resonance, cannot give rise to the rather sharp $X(4260)$ enhancement either. Also the suggested [21] $D^* D_0^*(2400)$ threshold at roughly 4.3–4.4 GeV [2], with the very broad scalar charm meson D_0^*, is way too smeared out to produce a narrow signal at about 4.25 GeV.

In Refs. [4,22], it was observed that $c\bar{c}$ resonances show up as dips in the $e^+ e^- \to \pi^+ \pi^- J/\psi$ cross section, and not as resonance peaks. Furthermore, in Ref. [4] we showed that also at the opening of channels, in particular, open-charm baryonic channels, dips appear in the $e^+ e^- \to \pi^+ \pi^- J/\psi$ cross section.

In fact, the overall aspect of the $J/\psi \pi\pi$ cross section appears to be rather constant (see below), with no obvious sign of the established and possible new $c\bar{c}$ resonances. So pion-pair creation does not seem to stem from the constituent $c\bar{c}$ system. Nevertheless, besides a $c\bar{c}$ component, we may assume the presence of glue [23,24]. The latter field will, in the periphery, absorb little of the $c\bar{c}$ oscillations and the corresponding resonances. Hence, anything created out of the surrounding glue will probably not display much of the charmonium structure and its spectrum. Thus, we may suppose that the pion pair stems from the glue, not from the strongly oscillating interior. This explains why a σ-like $\pi\pi$ structure can be formed that is not correlated with any $c\bar{c}$ resonances. Such a structure, being very broad, allows for a wide range of total two-pion masses at a slowly varying rate, and so shows up as an almost constant signal for a comparably wide range of total $J/\psi \pi\pi$ invariant masses. The peripheral, OZI-forbidden $\pi\pi$-creation process is depicted in Fig. 1.

However, at the opening of an open-charm decay channel, the dynamics of the system is dominated by string breaking through the creation of light quark-antiquark pairs. We have shown in Ref. [4] that such a process is substantially faster than peripheral pion-pair production. Hence, it eats up signal by premature decay into open-charm hadrons, thus leaving dips in the production cross section for $J/\psi \pi\pi$. Nonetheless, this is not the case at the $X(4260)$ enhancement, which certainly calls for an explanation.
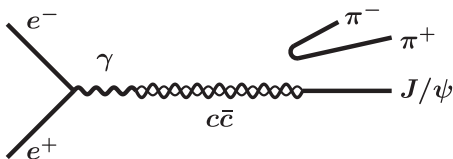

FIG. 1.   Peripheral creation of pion pairs in the gluon cloud surrounding $c\bar{c}$, for the reaction $e^+ e^- \to \pi^+ \pi^- J/\psi$.

In Ref. [4], we found that, except for the dips and the $X(4260)$ signal, the $e^+ e^- \to \pi^+ \pi^- J/\psi$ cross section is rather flat. This leaves us with the picture that the $c\bar{c}$ propagator, which is formed in $e^+ e^-$ annihilation, allows for the development of a pion pair as long as it is not resonating or near the opening of a threshold. Moreover, as the $c\bar{c}$ propagator dominantly couples to vector-vector (VV) open-charm pairs, almost 2 times more weakly to pseudoscalar-vector (PV), and 7 times more weakly to pseudoscalar-pseudoscalar (PP), it has to be expected that special phenomena may be observed at or just above the threshold of a VV open-charm pair. As we have argued above, open channels get damped quite fast at higher energies.

There are two candidates for VV open-charm channels, viz. $D^* D^*$ and $D_s^* D_s^*$. Now, $D^* D^*$ decay results from the creation of $u\bar{u}$ and $d\bar{d}$ pairs, which, being a much faster process than peripheral pion-pair creation, eats up signal from $e^+ e^- \to \pi^+ \pi^- J/\psi$. So this might leave a dip in the cross section of this process [4]. We shall come back to this issue later on.

We now assume for the reaction $e^+ e^- \to \pi^+ \pi^- J/\psi$ the following scenario. When not near a resonance or an open-charm threshold, the pion pair is basically formed [25] in the gluon cloud, with the quantum numbers of the σ. However, near the $c\bar{c} \to D_s^* D_s^*$ threshold, the dynamics of the system is dominated by $s\bar{s}$ pair creation, which we reckon to be a much faster process than peripheral pion-pair creation. Consequently, we should expect a dip in the cross section. In order to explain the $X(4260)$ peak, we must assume that $s\bar{s}$ pair creation, besides allowing for the formation of the pair of D_s^* mesons, makes a process possible other than the creation of a pion pair from up and down quarks. Such a process exists, namely, the formation of $f_0(980)$ [26], which then couples to a pion pair, though not very strongly [27].

This may explain why the $J/\psi \pi\pi$ signal closely follows the rise and fall of the $D_s^* \bar{D}_s^*$ amplitude on top of the constant "background" of $J/\psi \pi\pi$, which stems from the processes originating in the surrounding glue.

In Fig. 2 we depict each of the three contributions: the almost constant peripheral production of pion pairs via sigmas, the dip which is caused by premature decay into D_s^* pairs, and the contribution to pion-pair production by $f_0(980)$'s which stem from the abundantly produced $s\bar{s}$ pairs. From Fig. 2 we may also infer that each of the two distinct processes occurs for roughly 50%. Experiment [1,3,6] seems to agree with this value, but for a definite conclusion we must await better statistics.

We thus have two processes of very different origin, which result in the same final state. Such a situation may give rise to interference effects in the $J/\psi \pi\pi$ production amplitude, and hence to observable oscillations, which indeed appear to be present in the data shown in Fig. 2. One mode is the relatively slow, OZI-forbidden process via
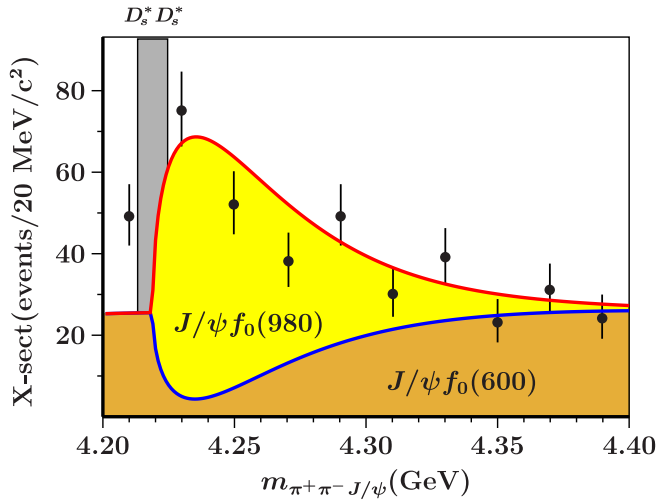
FIG. 2 (color online).   Schematic representation of the distinct contributions to the total cross section for e^+e^- annihilation into $J/\psi\,\pi^+\pi^-$. The vertical gray bar shows the region where the $D_s^*D_s^*$ threshold may be situated, according to the various results for the D_s^* mass, reported in Refs. [35–40]. The data are taken from Ref. [1].

the peripheral formation of up and down quarks, while the other mode is $J/\psi\,\pi\pi$ production through the formation of $f_0(980)$'s in an $s\bar{s}$-rich environment. Moreover, for the latter process we have an idea of the frequency of the $c\bar{c}$ oscillations, namely $\omega \sim 200$ MeV [28,29], which is equivalent to an oscillation period of $T \approx 5$ GeV^{-1}.

In the foregoing, we have taken the mass of the $D_s^*D_s^*$ threshold as a very rigorous boundary for the onset of the $X(4260)$ signal. This is, of course, correct for the onset of the dip. However, for $f_0(980)$ formation we are not bound by the $D_s^*D_s^*$ threshold, since $s\bar{s}$ creation will certainly be important already close to but below threshold, also because of the 40–100 MeV width [2] of the $f_0(980)$. The *BABAR* data indeed start to rise already some 40–50 MeV below threshold. Furthermore, the $J/\psi f_0$ system couples in an S wave to the $c\bar{c}$ vector propagator. Hence, the behavior will be different from the P-wave shape of Eq. (1).

At present, it is not possible to model such a highly complex system since, moreover, the $c\bar{c}$ resonances will play an important role [30], too. Hence, in order to account for interference, we simply modify the S-wave equivalent of the distribution in Eq. (1) by adding to the main signal an interference term

$$[1 + \alpha \cos(\{m_{\pi^+\pi^-J/\psi} - 2m_{D_s^*}\}\Delta T)]e^{-|pr_0|^2}, \quad (2)$$

with $4p^2 = m_{\pi^+\pi^-J/\psi}^2 - 4m_{D_s^*}^2$. The main signal has been explained in Ref. [4]. It consists of a constant term and a very wide bell-shaped contribution, which for the new *BABAR* data has its maximum at 4.35 GeV, and a width of 750 MeV. Here, we choose the constant contribution

somewhat smaller than in Ref. [4], in an attempt to average over the maxima and minima in the signal.

In Fig. 3(a), we show the resulting amplitude over a wide energy range, using $r_0 = 2.5$ GeV^{-1} above threshold, $r_0 = 4.2$ GeV^{-1} below, and for the moment $\alpha = 0$. On the other hand, in Fig. 3(b) we depict the amplitude in the energy interval of 4.1–4.4 GeV, but now for $\alpha = 0.4$ and $\Delta T = 85$ GeV^{-1}, and the same values for r_0. With this parametrization we clearly obtain the expected $D_s^*D_s^*$ threshold cusp [31] in the cross section for e^+e^- annihilation into $J/\psi\,\pi^+\pi^-$. Also the interference pattern peaks at threshold and agrees to a reasonable degree with the data. Consequently, the *BABAR* data seem to confirm our picture for the $X(4260)$ signal as consisting of two pro-
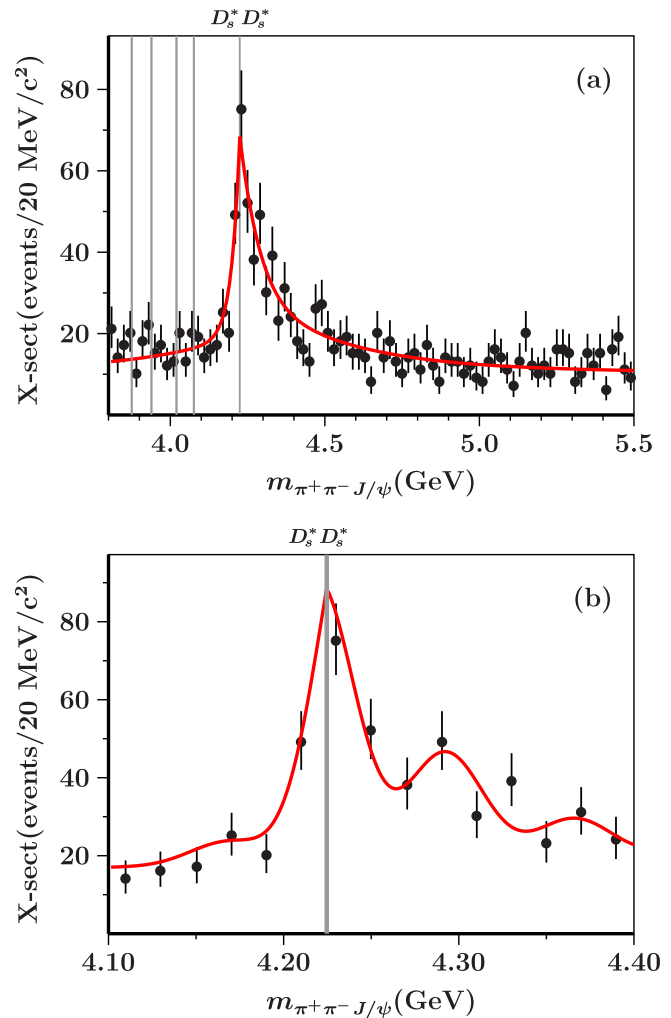

FIG. 3 (color online).   The new preliminary *BABAR* data [1] for e^+e^- annihilation into $J/\psi\,\pi^+\pi^-$ in the invariant-mass region from 3.8 GeV to 5.5 GeV (a) and from 4.1 GeV to 4.4 GeV (b). In (a), where no interference is considered, we observe the $D_s^*D_s^*$ threshold cusp in $J/\psi\,\pi\pi$. In (b) an additional interference effect is introduced as given by Eq. (2), with $\alpha = 0.4$ and $\Delta T = 85$ GeV^{-1}. The vertical gray lines represent the various open-charm thresholds.

cesses, each with its own characteristic frequency. Furthermore, we find from expression (2) that peripheral pion-pair creation oscillates with a period of about 85 GeV^{-1}, which is 17 times slower than pion-pair production via $s\bar{s}$. This looks like a reasonable factor for the suppression of OZI-forbidden hadronic decays relative to OZI-allowed ones. Also note that, except at the opening of the $c\bar{c} \to D_s^* D_s^*$ channel, there is no specific peak position associated with either of the two phenomena. Hence, in this scenario the $X(4260)$ enhancement does not represent a new kind of resonance.

Let us now further discuss the $D^* D^*$ channel. In this case, the relevant pair creations from string breaking are $u\bar{u}$ and $d\bar{d}$, which then couple to the σ. Consequently, the situation is comparable to the $X(4260)$ signal. In fact, the Belle Collaboration did observe a similar structure [6], just above the $D^* D^*$ threshold, but not confirmed by the *BABAR* Collaboration [1]. However, there is an important difference between the mass of the latter signal and of the $X(4260)$. Namely, the $X(4260)$ comes right in between the two $c\bar{c}$ vector states $\psi(4160)$ and $\psi(4415)$. So the amplitude for open-charm production is close to a minimum here, which is favorable for the observation of other phenomena, as explained above. On the other hand, the Belle signal at 4050 MeV comes almost on top of the $\psi(4040)$, and so may be subject to destructive interference. Nonetheless, this might be settled with better statistics in the future.

Other open-charm channels that, in principle, could play a role in the relevant energy domain are $D^0 D_1(2420)^0$, with threshold at 4287.1 ± 1.5 MeV and a total width of 20.4 ± 1.7 MeV, and $D^{\pm} D_1(2420)^{\mp}$, with threshold at 4292.9 ± 3.6 MeV and a total width of 25 ± 6 MeV. However, as we have argued in Ref. [32], the narrow axial-vector meson $D_1(2420)^0$, partner of the broad $D_1(2430)^0$ resonance, must be such a combination of $^3P_1$ and $^1P_1$ that it almost completely decouples from $D^* \pi$. For exactly the same reason, the $D^0 D_1(2420)^0$ and, by isospin symmetry, $D^{\pm} D_1(2420)^{\mp}$ channels also decouple from vector $c\bar{c}$. Moreover, $^1S_0 + ^1P_1$ couples 7 times more weakly to $J^{PC} = 1^{--}$ than $^3S_1 + ^3S_1$ (VV), with $^1S_0 + ^3P_1$ coupling

twice as strongly as $^1S_0 + ^1P_1$. Hence, and in agreement with the data, the signals of the $D^0 D_1(2420)^0$ and $D^{\pm} D_1(2420)^{\mp}$ channels in $J/\psi \pi^+ \pi^-$ should be negligible. The corresponding channels containing the broad axial-vector partners, which do couple to vector charmonium, are not likely to be visible because of the large widths.

Actually, as one may notice from Fig. 3(a), the *BABAR* data display small enhancements exactly at the openings of the P-wave channels, which are indicated in the figure. These channels are below or just at (for $D_s D_s^*$) the $J/\psi f_0(980)$ threshold; hence they do not have enough phase space for the phenomenon described here.

A number of narrow open-charm S-wave channels open at 4431 ± 3 MeV, namely $D_s D_{s1}(2460)^0$, $D^{*0} D_1(2420)^0$, $D^{*\pm} D_1(2420)^{\mp}$, and $D_s^* D_{s0}^*(2317)$. However, their threshold energies coincide with the negative interference of the $\psi(4S)$ resonance, which peaks at 4421 ± 4 MeV.

In Ref. [4], we showed that the cross section for $e^+ e^-$ annihilation into $J/\psi \pi^+ \pi^-$ consists of a constant signal plus and a very wide bell-shaped structure, which has its maximum at about 4.35 GeV. The latter extremely broad structure is supported by a very recent detailed three-body calculation for $J/\psi \pi^+ \pi^-$ [33], to be published soon. In the foregoing, we have shown that in the 4.26 GeV region there additionally appears to be an interference structure. We believe a 10 MeV binning of the data could shed some more light on the picture for the $X(4260)$ enhancement proposed here.

The fundamental implications of the interference effects observed here between equal final states but with different creation mechanisms are not yet clear to us. Nevertheless, similar effects might be observable for the $X(4140)$ enhancement in $J/\psi \phi$ [34].

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