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Note on $X(3872)$ production at hadron colliders and its molecular structure*

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Abstract: The production of the $X(3872)$ as a hadronic molecule in hadron colliders is clarified. We show that the conclusion of Bignamini *et al.*, Phys. Rev. Lett. **103** (2009) 162001, that the production of the $X(3872)$ at high $p_{\rm T}$ implies a non-molecular structure, does not hold. In particular, using the well understood properties of the deuteron wave function as an example, we identify the relevant scales in the production process.

Keywords: $X(3872)$, hadronic molecules, exotic hadrons

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1 Introduction

A widespread argument against the interpretation of the $X(3872)$ as a hadronic molecule is its copious production at hadron colliders. Based on the inequality[1)]

$$\begin{aligned}\sigma(\bar{p}p\to X) &\sim \left|\int \mathrm{d}^3\boldsymbol{k}\langle X|D^0\bar{D}^{*0}(\boldsymbol{k})\rangle\langle D^0\bar{D}^{*0}(\boldsymbol{k})|\bar{p}p\rangle\right|^2\\ &\simeq \left|\int_{\mathcal{R}} \mathrm{d}^3\boldsymbol{k}\langle X|D^0\bar{D}^{*0}(\boldsymbol{k})\rangle\langle D^0\bar{D}^{*0}(\boldsymbol{k})|\bar{p}p\rangle\right|^2\\ &\leqslant \int_{\mathcal{R}} \mathrm{d}^3\boldsymbol{k}|\Psi(\boldsymbol{k})|^2\int_{\mathcal{R}} \mathrm{d}^3\boldsymbol{k}\left|\langle D^0\bar{D}^{*0}(\boldsymbol{k})|\bar{p}p\rangle\right|^2\\ &\leqslant \int_{\mathcal{R}} \mathrm{d}^3\boldsymbol{k}\left|\langle D^0\bar{D}^{*0}(\boldsymbol{k})|\bar{p}p\rangle\right|^2 \qquad (1)\end{aligned}$$

it is claimed in Ref. [1] that the fact that the $X(3872)$ was observed at high $p_{\rm T}$ at the Tevatron in $\bar{\rm p}$p collisions is inconsistent with the interpretation of $X(3872)$ as a $\mathrm{D}^0\bar{\mathrm{D}}^{0*}$+c.c. molecule. The whole argument depends crucially on the value of $\mathcal{R}$ which specifies the region where the bound state wave function "$\Psi(\boldsymbol{k})$ is significantly different from zero" [1]. In particular, if $\mathcal{R}$ is too small, the second line in Eq. (1) is significantly smaller than the first and the whole argument is invalidated. Using a Gaussian wave function in Ref. [1] a value $\mathcal{R}\simeq 35$ MeV, of the order of the binding momentum, was favored. The so-estimated upper bound, 0.071 nb, is three orders of magnitude smaller than the CDF measurement [2], see Table 1. The authors concluded that the empirical production rate at high $p_{\rm T}$ is inconsistent with a prominent $\mathrm{D}^0\bar{\mathrm{D}}^{*0}$ molecular nature of the $X(3872)$. In this short note we challenge the reasoning of Ref. [1] by showing that $\mathcal{R}$ should be significantly larger, which leads to cross section estimates for the production of a molecular $X(3872)$ that are consistent with both the CDF and CMS measurements.

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1) Throughout the paper, the required charge conjugation combinations are implicit.

2 The deuteron as an example

In order to quantify which values of $\mathcal{R}$ are appropriate to justify the approximation, we may assume that the production amplitude of $D\bar{D}^*$ pairs from $\bar{p}p$ collisions is (almost) a constant [3]. Then we are left with the wave function averaged in the $\mathcal{R}$ region: $\bar{\Psi}_\lambda(\mathcal{R}) \equiv \int_\mathcal{R} d^3\boldsymbol{k}\Psi_\lambda(\boldsymbol{k})$, where λ specifies a regulator that needs to be introduced to render the wave function well defined. To understand which value of $\mathcal{R}$ is appropriate to largely saturate $\bar{\Psi}_\lambda(\mathcal{R})$, we now switch to the deuteron, a well established molecular proton-neutron bound state with a binding momentum $\gamma_d \simeq 45$ MeV. In the case of the deuteron, as well as in that of the $X(3872)$, the range of forces is of $\mathcal{O}(M_\pi^{-1})$, the pion Compton wavelength. Figure 1 shows $\bar{\Psi}_\lambda(\mathcal{R})$ for the deuteron with two sets of wave functions, one generated from a potential with a short-range term and one-pion exchange (OPE) and the other without OPE [4]. For the former a Gaussian regulator is used and the small D-wave component is not shown. For the latter a sharp momentum space cut off is used for simplicity. One sees that $\bar{\Psi}_\lambda(\mathcal{R})$ is far from being saturated for $\mathcal{R} \simeq \gamma_d$ for all values of λ. A much larger value of $\mathcal{R} \sim 300$ MeV$\sim 2M_\pi$ needs to be taken for the second line in Eq. (1) to be a good approximation of the first. The same should also be true for the $X(3872)$ as a $D\bar{D}^*$ molecule, since the range of forces is the same. A similar value was also favored in Ref. [3] based on rescattering arguments. In fact, Ref. [1] noted that with such a value of $\mathcal{R}$ the upper bound becomes consistent with the CDF result.

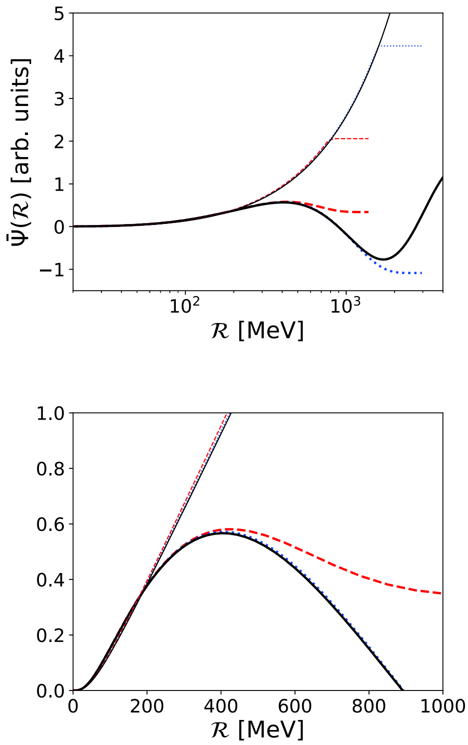

Fig. 1. (color online) Estimate of $\bar{\Psi}_\lambda(\mathcal{R})$ for various deuteron wave functions. Results for λ=0.8, 1.6, and 4 GeV are shown as red (dashed), blue (dotted) and black (solid) curves, respectively. The thick (thin) lines depict the results with (without) OPE. The bottom panel is a zoom in a linear scale to the relevant $\mathcal{R}$ region.

At the same time Fig. 1 illustrates that, within a hadronic theory, the wave function at short distances is not a well defined object — it is scheme- and regulator-dependent. This can be seen from the S-wave deuteron wave function calculated using different potentials as well as different values for the regulator shown in Fig. 2 (for more details, we refer to Ref. [4]). Although the wave functions are very different at short distances, their long-distance tails are universal. In fact, the importance of this tail is a direct measure of the molecular admixture in the wave function — for a recent review on hadronic molecules see Ref. [5]. A production process sensitive to such tails is, e.g., the reaction $Y(4260) \to \gamma X(3872)$ — because of this feature it is possible to predict the rate for this reaction [11] starting from the known rate for $Y(4260) \to \pi Z_c(3900)$, assuming that the $Y(4260)$ and the $Z_c(3900)$ are $D_1(2420)\bar{D}$ and isovector $D\bar{D}^*$ hadronic molecules, respectively, as proposed in Ref. [12].

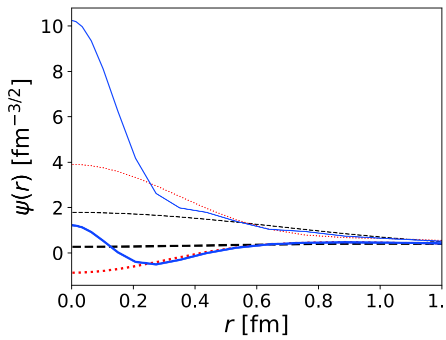

Fig. 2. (color online) The S-wave wave function of the deuteron calculated using an OPE potential with a cutoff λ [4]. Results for $\lambda = 0.8, 1.6$ and 4 GeV are shown as red (dashed), blue (dotted) and black (solid) curves, respectively. The thick (thin) lines depict the results with (without) OPE. The wave functions have been normalized so that the magnitudes of the tails agree.

There are various reactions that are sensitive to the short range structure of the wave function which, as demonstrated above, is regulator-dependent — in particular they are not sensitive to the molecular component. Since within a consistent field theory, observables cannot be sensitive to the regulator employed, there must be an additional short range operator of unknown strength at the leading order, that absorbs the regulator dependence. As a result, contrary to the transitions mentioned in the previous paragraph, the hadronic theory is not predictive for those reactions. Example of those are not only radiative decays of $X(3872)$ to vector states [13] but also the production reactions discussed in this note.

Table 1. Estimated inclusive cross sections compared with the CDF [2] and CMS [6] measurements converted into cross sections [10]. Results outside (inside) brackets are obtained using Herwig (Pythia) with the same kinematical cuts as in Ref. [10].

$\sigma(\mathrm{p\bar{p}/p} \to \mathrm{X})$ [nb]	Exp.	Λ=0.1 GeV	Λ=0.5 GeV	Λ=1.0 GeV
Tevatron	37-115	0.07 (0.05)	7 (5)	29 (20)
LHC-7	13-39	0.12 (0.04)	13 (4)	55 (15)

3 Cross section estimates

However, at least in the theory with OPE, the wave function at short distances is bounded and one may use renormalisation group and naturalness arguments to claim that its typical values may still be used to estimate the order-of-magnitude of the corresponding contribution. To be more quantitative, in Table 1 we present the cross section estimates for inclusive $X(3872)$ production compared with the CDF [2] and CMS [6] measurements by computing the short-distance $\mathrm{D\bar{D}^*}$ production with the Monte Carlo event generators Pythia [7] and Herwig [8] and the long-distance part using an effective field theory treating the $X(3872)$ as a hadronic molecule following Refs. [3, 9, 10, 14]. A Gaussian regulator with a cutoff Λ, which roughly amounts to $2\sqrt{2/\pi}\mathcal{R}\simeq 1.6\mathcal{R}$, is used. The results with $\Lambda = 0.1$ GeV, with only neutral charmed mesons included, are much smaller than the data. However, the order-of-magnitude estimated cross sections become consistent with measurements when a larger cutoff of [0.5,1.0] GeV, roughly corresponding to $\mathcal{R}\in[0.3,0.6]$ GeV, is used. Notice that for such a large cutoff, the $\mathrm{D^+D^{*-}}$ channel with a binding momentum of 126 MeV becomes dynamical and has been included. Its inclusion has led to an enhancement of about a factor of three. It is apparent that the order-of-magnitude estimates are consistent with the CDF and CMS measurements.

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