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# Is the $X(3872)$ molecular hypothesis compatible with CDF data?

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The $X(3872)$ is universally accepted to be an exotic hadron. In this letter we assume that the $X(3872)$ is a $D^0\bar{D}^{*0}$ molecule, as claimed by many authors, and attempt an estimate of its prompt production cross section at Tevatron. A comparison with CDF data allows to draw some qualitative conclusions about this statement.

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## 1. *Introduction*

Since the discovery of the $X(3872)$ resonance by Belle [1] it was soon realized that this particle could not have been identified as a standard charmonium excitation [2]. The mass of the $X$ being so close to the $D^0\bar{D}^{*0}$ threshold suggested that it could be a neat example of a hadron molecule [3]. Nevertheless the case of the $X(3872)$ is rather peculiar, since the $D^0\bar{D}^{*0}$ molecule constituting the $X(3872)$ would be an extremely weakly bound system and it seems odd that it could be produced promptly (*i.e.* not from $B$ decay) in a high energy hadron collision. This was one of the motivations to consider the possibility that the $X(3872)$ could be, instead of a molecule, a 'point-like' hadron resulting from the binding of a diquark and an antidiquark [4].

In this contribution we give a review of a recent study, which tries to analyze quantitatively the viability of the molecular hypothesis. Using standard Monte Carlo tools as Herwig [5] and Pythia [6], and the most recent CDF data, we estimate an *upper bound* for the theoretical cross section and a *lower bound* for the experimental one, for the $X(3872)$ prompt production process at the Tevatron, assuming the molecular hypothesis. The comparison of the two bounds allows to estimate to which extent the production of $X(3872)$ is exclusively due to the formation of a molecular bound-state.

## 2. *CDF data on prompt* $X(3872)$ *production*

The CDF collaboration measured the fraction of promptly produced $X(3872)$, $83.9\pm5.3\%$ [7], the yields of $\psi(2S)\to J/\psi\pi^+\pi^-$ and $X(3872)\to J/\psi\pi^+\pi^-$ candidates, using nearly identical selection criteria, as well as the measurement of the prompt fraction of $\psi(2S)$ candidates. From these we can roughly estimate, taking from [8] the $\mathrm{B}(\psi(2S)\to J/\psi\pi^+\pi^-)$:

$$\frac{\sigma(p\bar{p}\to X(3872)+\mathrm{All})_{\mathrm{prompt}}\times\mathscr{B}(X(3872)\to J/\psi\pi^+\pi^-))}{\sigma(p\bar{p}\to\psi(2S)+\mathrm{All})}=4.7\pm0.8\% \tag{2.1}$$

where the uncertainty includes statistical and systematic uncertainties. The acceptance of the $\psi(2S)$ and $X(3872)$ candidates is not specified in [7], but from the CDF II detector geometry and the indicated candidates selection, we can conservatively assume that the above ratio applies for $p_\perp > 5$ GeV and $|y| < 1$.

To derive an absolute $X(3872)$ cross section, we use the recently published [9] $\psi(2S)$ Run II prompt differential cross-section measurement integrating from $p_T > 5$ and taking $\mathrm{B}(\psi(2S)\to\mu^+\mu^-)$ from [8]: $\sigma(p\bar{p}\to\psi(2S)+\mathrm{All}) = 67\pm9$ nb for $p_\perp(\psi(2S)) > 5$ GeV, $|y(\psi(2S))| < 0.6$.

Assuming that both $X(3872)$ and $\psi(2S)$ have the same rapidity distribution in the range $|y| < 1$, we can finally estimate a lower bound on the prompt production cross section of $X(3872)$ as:

$$\sigma(p\bar{p}\to X(3872)+\mathrm{All})^{\mathrm{min}} > \sigma(p\bar{p}\to X(3872)+\mathrm{All})\times\mathscr{B}(X(3872)\to J/\psi\pi^+\pi^-) = 3.1\pm0.7\text{ nb} \tag{2.2}$$

in $p_\perp(X) > 5$ GeV and $|y(X)| < 0.6$.

## 3. *Estimating an upper bound for* $\sigma_{\rm th}$

Assuming that $X(3872)$ is an $S$-wave bound state of two $D$ mesons, namely a $1/\sqrt{2}(D^0\bar{D}^{*0}+\bar{D}^0D^{*0})$ molecule and using the Schwartz inequality, the $X(3872)$ prompt production cross section at the Tevatron can be written as:

$$\begin{aligned}\sigma(p\bar{p}\to X(3872)) &\simeq \left|\int_{\mathscr{R}} d^3\mathbf{k}\langle X|D\bar{D}^*(\mathbf{k})\rangle\langle D\bar{D}^*(\mathbf{k})|p\bar{p}\rangle\right|^2 \\ &\leq \int_{\mathscr{R}} d^3\mathbf{k}|\langle D\bar{D}^*(\mathbf{k})|p\bar{p}\rangle|^2 \sim \sigma(p\bar{p}\to X(3872))^{\rm max} \end{aligned} \tag{3.1}$$

where $\mathbf{k}$ is the relative 3-momentum between the $D$ and $D^*$ mesons, $\psi(\mathbf{k})=\langle X|D\bar{D}^*(\mathbf{k})\rangle$ is some normalized bound state wave function characterizing the $X(3872)$ and $\mathscr{R}$ is the integration region where $\psi(\mathbf{k})$ is significantly different from zero. The matrix element $\langle D\bar{D}^*(\mathbf{k})|p\bar{p}\rangle$ can be computed using standard Monte Carlo programs like Herwig and Pythia, generating $2\to 2$ QCD events and choosing the events containing $D^0\bar{D}^{*0}$ pairs. The region $\mathscr{R}$ in (3.1) can be estimated assuming a naive gaussian Ansatz for the bound state wave function and a strong interaction Yukawa potential between the two $D$ mesons: given that the binding energy $\mathscr{E}_0$ is $\mathscr{E}_0 \sim M_X - M_D - M_{D^*} \sim -0.25\pm 0.40$ MeV we find that $r_0\sim 8$ fm ($8.6\pm1.1$ fm) and applying the (minimal) uncertainty principle relation, we get the gaussian momentum spread $\Delta p\sim 12$ MeV. Given the very small binding energy we can estimate $k$ to be of the order of the center of mass momentum $k\simeq 27$ MeV and so we can restrict the integration region to a ball $\mathscr{R}$ of radius[1] of about 35 MeV.

## 4. *Results*

We have used Herwig and Pythia to simulate hadron final states from $2\to 2$ QCD parton processes reaching a Monte Carlo luminosity $\mathscr{L}\sim 100$ nb$^{-1}$. In Figs. 3 and 4 in [10] we show the integrated cross section as a function of the relative momentum in the $D^0\bar{D}^{*0}$ molecule obtained using Herwig and Pythia respectively. To get the minimal experimental value of $\sigma\sim 3.1\pm0.7$ nb we need to include $D^0\bar{D}^{*0}$ configurations having up to $k_{\rm rel}=205\pm20$ MeV for Herwig and up to $k_{\rm rel}=130\pm15$ MeV for Pythia. Molecule candidates in the ball of relative momenta $\mathscr{R}$ can account only for 0.071 nb for Herwig and for 0.11 nb for Pythia.

We studied also the contribution of $gc\bar{c}$ events with one gluon at $p_\perp>5$ GeV recoiling from the $c\bar{c}$ pair, which in turn can hadronize into open charm mesons very close in phase space, using ALPGEN [11]. The results obtained point at a definitely negligible contribution from these configurations, being in the range of few picobarns.

## 5. *Conclusions*

Assuming the $D^0\bar{D}^{*0}$ molecular hypothesis for the nature of the $X(3872)$, we have estimated an upper bound for the theoretical prompt production cross section of that particle at CDF. Averaging the results obtained with Pythia and Herwig we find this to be approximately 0.085 nb in the most

[1]Which corresponds to a $k_0$ of the Gaussian at $\sim 27$ MeV and a spread of $+12$ MeV.



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reasonable region of center of mass relative momenta $[0,35]$ MeV of the open charm meson pair constituting the molecule. This value has to be compared with the lower bound on the experimental cross section, namely $3.1\pm0.7$ nb, extracted from CDF data. The intuitive expectation that $S-$wave resonant scattering is unlikely to allow the formation of a loosely bound $D^0\bar{D}^{*0}$ molecule in high energy hadron collision is confirmed by this analysis.

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