Production of Charged Heavy Quarkonium-Like States at the LHC and Tevatron

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Abstract We study prompt hadroproduction of the charged bottomonium-like states \(Z_b^{\pm}(10610)\) and \(Z_b^{\pm}(10650)\), and the charged charmonium-like states \(Z_c^{\pm}(3900)\) and \(Z_c^{\pm}(4020)\), at the Tevatron and the LHC, provided that these states are \(S\)-wave hadronic molecules. Using two Monte Carlo event generators, Herwig and Pythia, to simulate the production of heavy meson pairs, we derive an order-of-magnitude estimate of the production rates for these four particles. Our estimates yield a cross section at the nb level for the \(h_{\pi^\pm}c\overline{c}\) and \(cuc\bar{d}\) at the \(t\) level for the \(Z_{b,\pi^\pm}^\pm\) and \(D^*\bar{D}^*\) mass distributions. The masses and widths of these four states are collected in Table 1. Apparently all of them defy a standard bottomonium/charmonium assignment, as they should consist of at least four quarks, e.g. \(bubd\) or \(cuc\bar{d}\) for the positively charged states.

Due to the fact that the masses of the discovered states lie in the vicinity of meson-meson thresholds, it has been suggested that they are \(S\)-wave molecular states of heavy meson anti-heavy meson pairs with nearby thresholds, i.e. the \(B^*\bar{B}^*\) and \(B^*\bar{B}^*\) thresholds, respectively. The angular distribution analysis indicates that their quantum numbers are \(I^G(J^P) = 1^+(1^+)\). Recently, the BES-III and Belle Collaborations have studied the process \(e^+e^- \rightarrow \pi^+\pi^-J/\psi\) at the center-of-mass energy around 4.26 GeV, and found a charged charmonium-like state \(Z_c^{\pm}(3900)\), with the central value of the measured mass being about 20 MeV above the \(D\bar{D}^*\) threshold. The observation was confirmed later on by an analysis based on the CLEO data at the energy of 4.17 GeV. Just above the \(D^*\bar{D}^*\) threshold, there is evidence for another charged structure from the BESIII data in the \(h_{\pi^\pm}\) and \(D^*\bar{D}^*\) mass distributions. The masses and widths of these four states are collected in Table 1. Apparently all of them defy a standard bottomonium/charmonium assignment, as they should consist of at least four quarks, e.g. \(bubd\) or \(cuc\bar{d}\) for the positively charged states.

Table 1 Experimental data for the mass and width (in units of MeV) of the \(Z_b(10610), Z_b(10650), Z_c(3900)\), and \(Z_c(4020)\)

| State       | Mass (MeV) | Width (MeV) |
|-------------|------------|-------------|
| \(Z_b(10610)\) | 10 627.2 ± 0.2 | 10 652.2 ± 1.5 |
| \(Z_b(10650)\) | 3891.5 ± 3.5 | 4023.0 ± 2.3 |
| \(Z_c(3900)\) | 18.4 ± 2.4 | 11.5 ± 2.2 |
| \(Z_c(4020)\) | 39.2 ± 10.5 | 9.7 ± 3.2 |

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Hidden charm hadrons can be produced at $e^+e^-$ machines not only directly, but also in $B$ decays and radiative return studies. The study of bottom hadrons highly relies on direct measurements, most of which have been tuned to the center-of-mass energy of the masses of the $\Upsilon(4S)$ and the $\Upsilon(5S)$. The data set for the latter has much smaller statistics. The situation will be greatly improved in the future as the Super KEKB factory will provide a large amount of data.

On the other hand, since bottom and charm quarks will be abundantly produced at hadron colliders with very high luminosity like at the LHC and the Tevatron, hadroproduction processes can provide complementary and independent checks on these mysterious states, and help in understanding their underlying nature. Furthermore, the study of production rates of heavy hadronic molecules at hadron colliders can provide much information to understand the interplay of perturbative and non-perturbative QCD effects. For instance, the $X(3872)$, an ideal example of a loosely-bound hadronic molecule, can be copiously produced in high energy collisions at the Tevatron and LHC, for which different theoretical predictions were made in Refs. [22–25].

In this paper, we will derive for the first time an estimate of the prompt production rates of these four charged hadrons not only directly, but also in proton-(anti)proton collisions at the LHC and Tevatron, assuming them to be hadronic molecules. ”Prompt” means that these states are not produced from the decays of particles of higher masses. The production of the $Z_b^+(10610), Z_b^+(10650), Z_c^+(3900)$ and $Z_c^+(4020)$, in proton-(anti)proton collisions at the LHC and Tevatron, was discussed in Ref. [26]. For the sake of simplicity, the four states will be abbreviated as $Z_Q$ with the mesonic constituents $H\bar{H}$, where the heavy quark is denoted as $Q$ and $H(\bar{H})$ represents the relevant heavy (anti-)meson.

2 Hadroproduction of Hadronic Molecules

The production rates of $S$-wave hadronic molecules can be quantitatively calculated under a few assumptions:

- The production rates of hadronic molecules satisfy the factorization ansatz, which will separate the formation of a molecule at long distance from the short-distance production of its constituents.

- A hadronic molecule can be formed only if its constituents are produced with a relative momentum less than some critical value.

These assumptions lead to the simplification that the production rates for $Z_Q$ can be expressed in terms of the cross sections for the inclusive production of $H\bar{H}$ (and charge conjugates). As a phenomenological and successful tool that has been utilized in many other processes, Monte Carlo (MC) event generators are able to simulate the hadronization of partons produced in the QCD processes, and therefore provide an estimate of the $pp/\bar{p} \rightarrow H\bar{H}$ inclusive cross sections.

At the energy region around the pole of a narrow resonance, the resonance will provide a dramatic energy dependence of the relevant differential cross sections. Around the $H\bar{H}$ threshold, one may neglect the impact of the inelastic channels and apply Watson’s theorem to relate the $H\bar{H}$ final-state-interaction (FSI) in the production to the $H\bar{H}$ scattering amplitude. Thus, when the relative momentum of the two constituents is small, the momentum dependence of the amplitude for the production of molecules arises from the $S$-wave scattering amplitude.

For a narrow resonance, it may be effectively described by a Breit–Wigner parameterization

$$f(E) = \frac{1}{8\pi m_{Z_Q} E^2 - m^2 + i m_{Z_Q} \Gamma_{Z_Q}(k)}, \quad (1)$$

where $g$ is the $Z_QH\bar{H}$ coupling constant, and $E$ is the energy of the two constituents. Assuming that the total width is saturated by the decay $Z_Q \rightarrow H\bar{H}$, we have

$$\Gamma_{Z_Q}(k) = \frac{|\vec{k}|}{8\pi m_{Z_Q}^2} g^2, \quad (2)$$

with $k$ the center-of-mass momentum of the $H$.

The factorization ansatz allows for the separation of the long-distance and short-distance contributions in the amplitudes for the production of the molecules. The latter is the same for the processes $pp/\bar{p} \rightarrow H\bar{H}$ and $pp/\bar{p} \rightarrow Z_Q$, while the long-distance factor can be deduced from the scattering amplitude given above. Following Ref. [24], we assume that beyond the resonance region, the production rate is given by the MC event generators. This is achieved by matching the production amplitude including the FSI effect to the MC one at an energy $E \approx E_\Lambda \equiv m_{Z_Q} + \Gamma_{Z_Q}$ as follows

$$\sigma(Z_Q) \approx K_{H\bar{H}} \int_0^\Lambda \frac{d\sigma_{H\bar{H}}^{MC}(k)}{dk} \frac{|f(E)|^2}{|f(E = E_\Lambda)|^2}, \quad (3)$$

where $d\sigma_{H\bar{H}}^{MC}(k)/dk$ is the differential cross section of the $H\bar{H}$ inclusive production, and $K_{H\bar{H}} \sim \mathcal{O}(1)$ is a normalization factor that is introduced to compensate the overall difference between the MC simulation and the experimental data. The cut-off $\Lambda$ in the momentum integration is the center-of-mass momentum evaluated at the energy value $E = E_\Lambda$. In case that the considered molecule is a bound state, the above formula can be reduced to the form derived for the process $pp \rightarrow X(3872)$ in Ref. [24].

To form a molecular state, the constituents must move nearly collinear and have a small relative momentum. Such configurations can be realized in an inclusive QCD process, which contains a $Q\bar{Q}$ pair with approximately the same relative momentum in the final state. However, it is
necessary to stress that since the $Z_{Q}^{+}$ consist of at least four quarks, the final state must contain at least six quarks: $QQar{u}ar{d}d$ with $QQar{u}ar{d}$ (or charge conjugates) moving coherently. At the hadron level, the additional light quarks form one or more pions. These multiquark final states can be produced by the soft parton shower radiations in the $2 \rightarrow 3$ QCD events. The dominant partonic process is $gg \rightarrow Qar{Q}g$, as the gluon density at the LHC and Tevatron energy is much larger than those for quarks. Nevertheless, other contributing processes are also included in this analysis.

3 Results

We use Madgraph$^{[28]}$ to generate the $2 \rightarrow 3$ partonic events having $b\bar{b}$ (or $c\bar{c}$) in the final states, and then pass them to the MC event generators to hadronize. At the parton level, to increase the efficiency, we apply a cut $p_T > 2$ GeV for heavy quarks and light jets, $m_{bb} < 11$ GeV (corresponding to $k_{b\bar{b}} = 1.5$ GeV and $k_{b\bar{b}} = 1.4$ GeV at the hadron level), $m_{cc} < 5$ GeV (corresponding to $k_{D\bar{D}} = 1.6$ GeV and $k_{D\bar{D}} = 1.5$ GeV) and $\Delta R(b, \bar{b}) < 1$ ($\Delta R(c, \bar{c}) < 1$) with $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$, where $\Delta \phi$ is the azimuthal angle difference and $\Delta \eta$ is the pseudo-rapidity difference between the $Q$ and the $\bar{Q}$. Since additional light quark pairs are produced apart from the $QQ$ (corresponding to pion radiation at the hadron level), a too stringent cut on $m_{QQ}$ may underestimate the production rates of $HH$. On the other hand, this cut cannot be too large, otherwise the efficiency of the numerical calculation will be highly reduced. The above choice is a compromise and will not affect the $HH$ production rates in the region of interest for the study of molecular states. We choose Herwig$^{[29]}$ and Pythia$^{[30]}$ as the hadronization generators, whose output are further analyzed using the Rivet library$^{[31]}$ and at this step we select the heavy meson pair with the smallest invariant mass.

Table 2 Integrated normalized cross sections (in units of nb) for the reactions $pp/\bar{p} \rightarrow Z_{b}(10610), Z_{b}(10650), Z_{c}(3900)$, and $Z_{c}(4020)$ at the LHC and the Tevatron. Results are obtained using Herwig (Pythia). The rapidity range $|y| < 2.5$ has been assumed for the LHC experiments (ATLAS and CMS) at 7, 8, and 14 TeV, respectively, for the Tevatron experiments (CDF and D0) at 1.96 TeV, we use $|y| < 0.6$; the rapidity range 2.0 < $y$ < 4.5 is used for LHCb.

| $Z_{b}$ | $Z_{b}$ | $Z_{c}$ | $Z_{c}$ |
|-----|-----|-----|-----|
| Tevatron | 0.26 (0.47) | 0.06 (0.17) | 11 (13) | 1.7 (2.0) |
| LHC 7 | 4.8 (8.0) | 1.2 (3.0) | 187 (211) | 29 (31) |
| LHCb 7 | 0.76 (1.3) | 0.18 (0.47) | 33 (39) | 5.5 (5.8) |
| LHC 8 | 5.9 (9.5) | 1.4 (3.5) | 220 (240) | 34 (36) |
| LHCb 8 | 0.9 (1.4) | 0.22 (0.56) | 40 (48) | 6.3 (6.9) |
| LHC 14 | 11 (17) | 2.6 (6.5) | 382 (423) | 61 (63) |
| LHCb 14 | 1.9 (3.0) | 0.52 (1.2) | 84 (88) | 14 (14) |

Fig. 1 Differential cross sections $d\sigma/dk$ (in units of nb/GeV) for the inclusive processes $pp \rightarrow B^{+}\bar{B}^{*0}$, $pp \rightarrow B^{+}\bar{B}^{0}$ (the upper two panels) and $pp \rightarrow D^{+}\bar{D}^{*0}$, $pp \rightarrow D^{+}\bar{D}^{0}$ (the lower two panels) at the LHC with $\sqrt{s} = 8$ TeV. The kinematic cuts used are $|y| < 2.5$ and $p_T > 5$ GeV, which lie in the phase-space regions of the ATLAS and CMS detectors.
Based on the data sample collected at 7 TeV, the inclusive differential cross sections for $pp \to BB$ have been measured by the CMS Collaboration.\cite{32} It is found that the cross sections are substantial at small values of $\Delta \phi$ and $\Delta R$, in the same kinematics region considered in this work. We wish to point out that the simulation in Pythia is in qualitative consistency with the experimental data for most observables for the $BB$ angular correlation.\cite{32}

The overall agreement may, at least qualitatively, verify $K_{BB} \sim K_{B^*B^*} \sim 1$ for the current analysis, as our main concern is to estimate the production cross sections at the order-of-magnitude level.

We have generated $10^7$ partonic events, based on which we show the differential distribution $d\sigma/dk$ (in units of nb/GeV) for the inclusive processes $pp \to BB^*$ (upper left panel) and $pp \to B^*B^*$ (upper right panel) at the LHC collider with $\sqrt{s} = 8$ TeV in Fig. 1. The lower panels correspond to the distributions for the $pp \to DD^*$ (left) and the $pp \to D^*D^*$ (right). The kinematic cuts are chosen in accordance with the default choice of the CMS/ATLAS measurements: $p_T > 5$ GeV and $|y| < 2.5$.

Using Eq. (3), we show the integrated cross sections for the production of molecules in Table 2. We also modify the rapidity range to $2.0 < y < 4.5$ in order to match the specifics of the LHCb detector. For the Tevatron experiments (CDF and D0) at 1.96 TeV, we use $|y| < 0.6$, which is the choice for the measurement of the $p_T \to X$ (3872).

The charged $Z_b(10610)$ and $Z_b(10650)$ have a large decay branching fraction into $Y(nS)\pi^\pm$, and thus can be reconstructed in the $(\mu^+\mu^-)\pi^\pm$ final states. Using the decay branching fractions,\cite{33,34} we find that the cross sections for the $pp \to Z_b(10610)^\pm \to Y(2S)\pi^\pm \to \mu^+\mu^-\pi^\pm$ and the $pp \to Z_b(10610)^\pm \to Y(3S)\pi^\pm \to \mu^+\mu^-\pi^\pm$ can reach $O(10 \text{ pb})$ at the LHC. To estimate the number of events, we take the integrated luminosity of 22 fb$^{-1}$ collected by ATLAS in 2012\cite{35} (similar for CMS\cite{36}), and this yields $O(10^5)$ events for these processes, respectively. At the Tevatron and LHCb, the number of events is smaller by about one order-of-magnitude. The $Z_c(3900)$ and $Z_c(4020)$ will be more copiously produced, since the cross sections for the $pp \to Z_c(3900)$ and $pp \to Z_c(4020)$ are larger by a factor of 20–30 than those for the $Z_b(10610)$ and $Z_b(10650)$. The differences between the results derived from the two MC events reflect the hadronic uncertainties.

The production rates for $Z_b$ states at the LHC predicted in this work, of the order a few nb, are much larger than those non-prompt rates from the decays of the $Y(5S)$ or an exotic candidate $Y_b(10890)$.\cite{26,37} The cross section for the latter process $pp \to Y(5S) \to Z_b\pi$ is predicted to be at the pb level,\cite{36} and this finding can be examined in future experiments.

The search for these molecular states at hadron colliders does not only depend on the production rates, but also on the non-resonant background contributions. If the statistical fluctuation of the background is comparable or even larger than the signal, one can hardly observe the desired state. To investigate this issue, we take the $Z_c^\pm$ as an example, and assume that it will be reconstructed in $J/\psi\pi^\pm$ final states. To the best of our knowledge, there is currently no available calculation of the cross section $pp/\bar{p} \to J/\psi\pi^\pm$. Nevertheless, the following relation trivially holds:

$$\sigma(pp \to \psi\pi^\pm + \text{anything}) < \sigma(pp \to \psi + \text{anything}) \cdot (4)$$

Thus the cross section $\sigma(pp \to \psi + \text{anything})$ can serve as an upper bound for the background. This cross section has been measured by various experiments. For instance, the cross section for prompt production rates at $\sqrt{s} = 7$ TeV as measured by the ATLAS Collaboration is\cite{38}

$$\sigma(pp \to \psi(\rightarrow \mu^+\mu^-) + \text{anything}) = (81^{+27}_{-22}) \text{ nb}, \quad (5)$$

where $p_T > 7$ GeV and $|y| < 2.4$. Our results in Table 2 show that the cross section of $pp \to Z_c(3900)$ at $\sqrt{s} = 7$ TeV is about 200 nb. Using the integrated luminosity in 2012, 22 fb$^{-1}$,\cite{35} we have an estimate for the signal/background ratio

$$\frac{S}{\sqrt{B}} \sim \frac{200 \times 22 \times 10^6 \times 10\% \times 5.9\%}{81 \times 22 \times 10^6} \sim 600, \quad (6)$$

where 5.9% is the branching fraction of the $J/\psi \to \mu^+\mu^-$\cite{33} and 10% is a rough estimate for the branching fraction of the $Z_c(3900)^\pm \to J/\psi\pi^\pm$. This should be reasonable given the measured ratio\cite{39}

$$\frac{\Gamma(Z_c(3885) \to DD^*)}{\Gamma(Z_c(3900) \to J/\psi\pi)} = 6.2 \pm 1.1 \pm 2.7, \quad \text{if the } Z_c(3885) \text{ can be identified with the } Z_c(3900).$$

In addition, the signal/background ratio can be further enhanced in the data analysis by employing suitable kinematics cuts, which can greatly suppress the background, and accumulating a large number of events. Although the above estimate is very rough, we believe that it indicates the promising potential for observing the discussed molecular states at hadron colliders, and a search for them would be valuable to understand the nature of these particles.

4 Summary

In conclusion, we have studied the prompt production of charged bottomonium-like and charmonium-like states discovered in $e^+e^-$ annihilation experiments, the $Z_b(10610)$, $Z_b(10610)$, $Z_c(3900)$, and $Z_c(4020)$ states, at the Tevatron and the LHC. These four particles are candidates of hadronic molecules formed of a pair of heavy mesons. We have used two Monte Carlo event generators, Herwig and Pythia, to simulate the hadronization, based
on which we found that the inclusive cross sections for the $pp/\bar{p} \to Z_0(10610)/Z_0(10650)$ are of the order of nb, and results for the $Z_0(3900)$ and $Z_0(4020)$ are larger by a factor of $20-30$. Taking into account the current integrated luminosities at the LHC, the number of events has been estimated. Measurements at hadron colliders will supplement the studies performed at electron-positron colliders, and thus allow to explore the nature of these four exotic states.

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