

Production mechanism of fully heavy tetraquarks in proton-proton collisions

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We discuss the production mechanism of fully charm tetraquark, observed last year by the LHCb at $M = 6.9$ GeV in the $J/\psi J/\psi$ channel. Both single parton scattering (SPS) and double parton scattering (DPS) mechanisms are considered. We calculate the distribution in the invariant mass of the four-quark system, M_{4c} , for SPS and DPS production of $c\bar{c}c\bar{c}$ in the k_t -factorization approach. We present transverse momentum distribution in $p_{t,4c}$ for $c\bar{c}c\bar{c}$ system in a mass window around tetraquark mass. The calculation of the SPS $g^*g^* \rightarrow T_{4c}(6900)$ fusion mechanism is performed in the k_T -factorization approach assuming different spin scenarios (0^+ and 0^-).

Keywords: Heavy tetraquark production mechanism; multiparton interactions.

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1. Introduction

The recent observation by the LHCb collaboration [1] of a sharp peak in the di- J/ψ channel at $M = 6.9$ GeV seems to strongly suggest the presence of a fully charm tetraquark, consisting of $c\bar{c}c\bar{c}$. A number of theoretical models for the spectroscopy of tetraquarks were developed. The most popular approach treats the fully heavy ($c\bar{c}c\bar{c}$, $b\bar{b}b\bar{b}$ or $c\bar{c}b\bar{b}$) tetraquark as a bound system of a color antitriplet diquark and color triplet antidiquark.

Assuming the peak observed by LHCb is indeed caused by a new state, models suggest that it is rather an excited state. However, the spin and parity of the state are not known at present.

Different J^{PC} combinations are possible in general [2–5], What is the mechanism of the fusion of four charm quarks/antiquarks is not clear in the moment. A large cross section for $c\bar{c}c\bar{c}$ production at the LHC due to double-parton scattering (DPS) mechanism was predicted in [6]. The contribution of the single parton scattering to the $c\bar{c}c\bar{c}$ production is much smaller [7–10]. The production of two J/ψ states was also studied at the LHC [11–14].

Recently, our group studied production of pseudoscalar [15] and scalar [16] charmonia via gluon-gluon fusion. We shall use the same formalism also in the context of the tetraquark production.

2. Sketch of the formalism

In Fig. 1 we show the dominant reaction mechanisms of $c\bar{c}c\bar{c}$ production: SPS type (left diagram) and DPS type (right diagram).

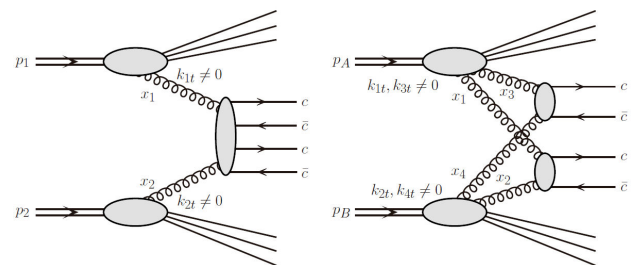


FIGURE 1. Two dominant reaction mechanisms of production of $c\bar{c}c\bar{c}$ non-resonant continuum. The left diagram represent the SPS mechanism (box type) and the left diagram the DPS mechanism.

In our recent study both the SPS and the DPS contributions are calculated in the framework of k_T -factorization [17].

In this approach the SPS cross section for $pp \rightarrow c\bar{c}c\bar{c} X$ reaction can be written as

$$\begin{aligned} d\sigma_{pp \rightarrow c\bar{c}c\bar{c} X} = & \int dx_1 \frac{d^2 k_{1t}}{\pi} dx_2 \frac{d^2 k_{2t}}{\pi} d\hat{\sigma}_{g^*g^* \rightarrow c\bar{c}c\bar{c}} \\ & \times \mathcal{F}_g(x_1, k_{1t}^2, \mu^2) \mathcal{F}_g(x_2, k_{2t}^2, \mu^2). \end{aligned} \quad (1)$$

Above $\mathcal{F}_g(x, k_t^2, \mu^2)$ is the unintegrated gluon distribution function (gluon uPDF).

The elementary cross section in Eq. (1) can be written as:

$$d\hat{\sigma}_{g^*g^* \rightarrow c\bar{c}c\bar{c}} = \frac{1}{(2!)^2} \prod_{l=1}^4 \frac{d^3\vec{p}_l}{(2\pi)^3 2E_l} (2\pi)^4 \times \delta^4 \left(\sum_{l=1}^4 p_l - k_1 - k_2 \right) \times \frac{1}{\text{flux}} |\mathcal{M}_{g^*g^* \rightarrow c\bar{c}c\bar{c}}(k_1, k_2, \{p_l\})|^2. \quad (2)$$

We consider also the calculation of the SPS-type signal as a fusion of two (off-shell) gluons for two different spin-parity assignments: 0^+ and 0^- of the tetraquark. The corresponding diagram is shown in Fig. 2.

In this context we use the formalism worked out recently for the inclusive production of pseudoscalar [15] and scalar [16] quarkonia. The off-shell gluon fusion cross sections is

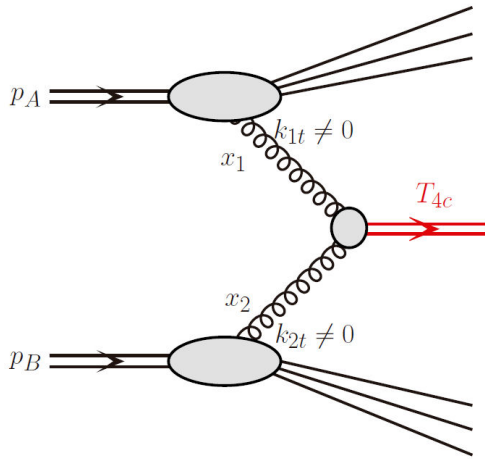


FIGURE 2. The mechanism of gluon-gluon fusion leading to the production of the $T_{4c}(6900)$ tetraquark.

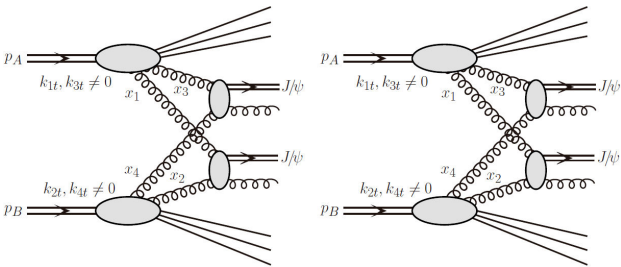


FIGURE 3. Two dominant reaction mechanisms of production of $J/\psi J/\psi$ nonresonant continuum. The left diagram represent the SPS mechanism (box type) and the right diagram the DPS mechanism.

proportional to a form-factor, which depends on the virtualities of gluons, $Q_i^2 = -k_i^2$:

$$d\sigma_{g^*g^* \rightarrow 0^-} \propto \frac{1}{k_{1t}^2 k_{2t}^2} (\vec{k}_{1t} \times \vec{k}_{2t})^2 F^2(Q_1^2, Q_2^2),$$

$$d\sigma_{g^*g^* \rightarrow 0^+} \propto \frac{1}{k_{1t}^2 k_{2t}^2} \left((\vec{k}_{1t} \cdot \vec{k}_{2t}) \times (M^2 + Q_1^2 + Q_2^2) + 2Q_1^2 Q_2^2 \right)^2 \times \frac{F^2(Q_1^2, Q_2^2)}{4X^2}, \quad (3)$$

with $X = (M^4 + 2(Q_1^2 + Q_2^2)M^2 + (Q_1^2 - Q_2^2)^2)/4$. Note that for the 0^+ assignment we use only the TT coupling, as in analogy with [16] we expect the LL contribution to be smaller.

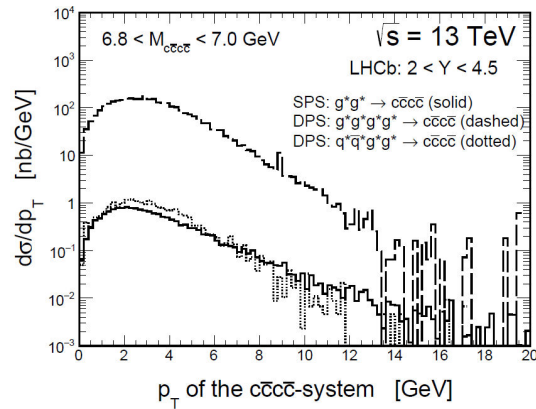


FIGURE 4. Distribution of $p_{t,4c}$ of four quark-antiquark system within invariant mass window ($M_R - 0.1\text{GeV}, M_R + 0.1\text{GeV}$). Here $\sqrt{s} = 13\text{ TeV}$ and average rapidity of quarks and antiquarks in the interval (2,4.5). The solid line is for SPS, the dashed line for $gggg \rightarrow c\bar{c}c\bar{c}$ DPS and the dotted line is for $q\bar{q}gg \rightarrow c\bar{c}c\bar{c}$ DPS contribution.

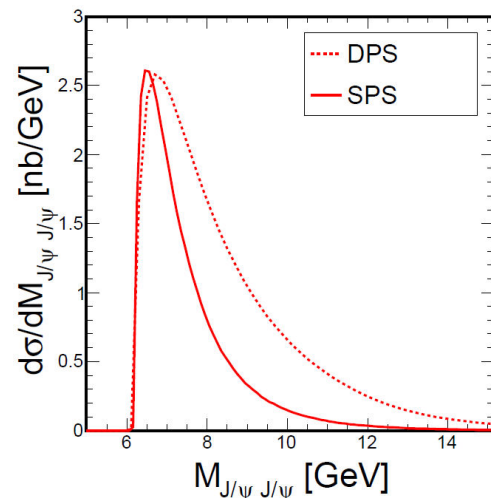


FIGURE 5. Distribution in invariant mass of the $J/\psi J/\psi$ system for SPS (solid line) and DPS (dashed line). In this calculation $\sqrt{s} = 13\text{ TeV}$ and we assumed that both J/ψ mesons have rapidity in the (2,4.5) interval.

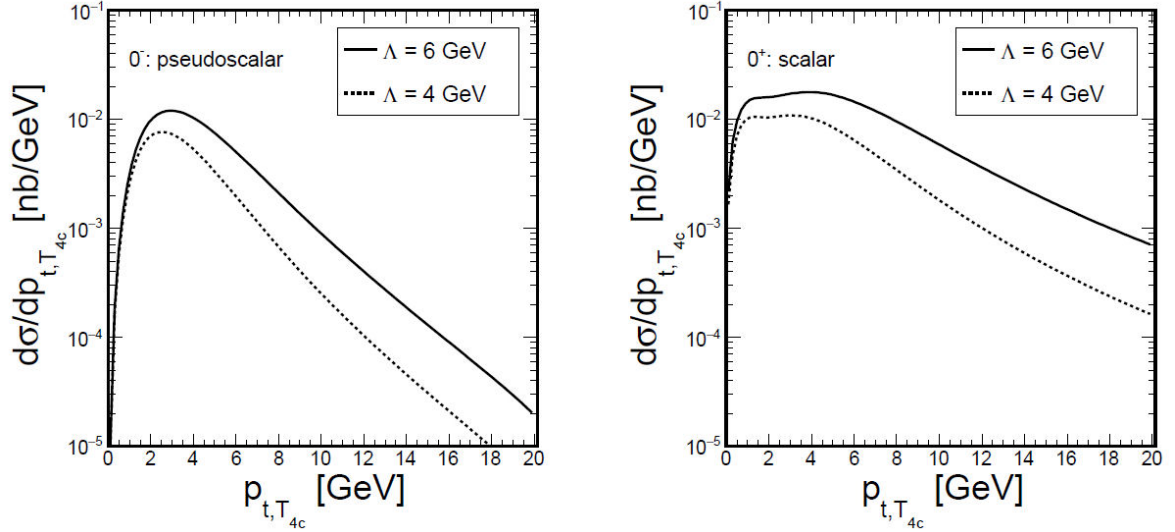


FIGURE 6. Transverse momentum distribution of the $T_{4c}(6900)$ tetraquark for the 0^- (left panel) and 0^+ (right panel) assignments. Here $\sqrt{s} = 13$ TeV. We show results for the KMR UGDF and $\Lambda = 6$ GeV (solid line) and $\Lambda = 4$ GeV (dashed line).

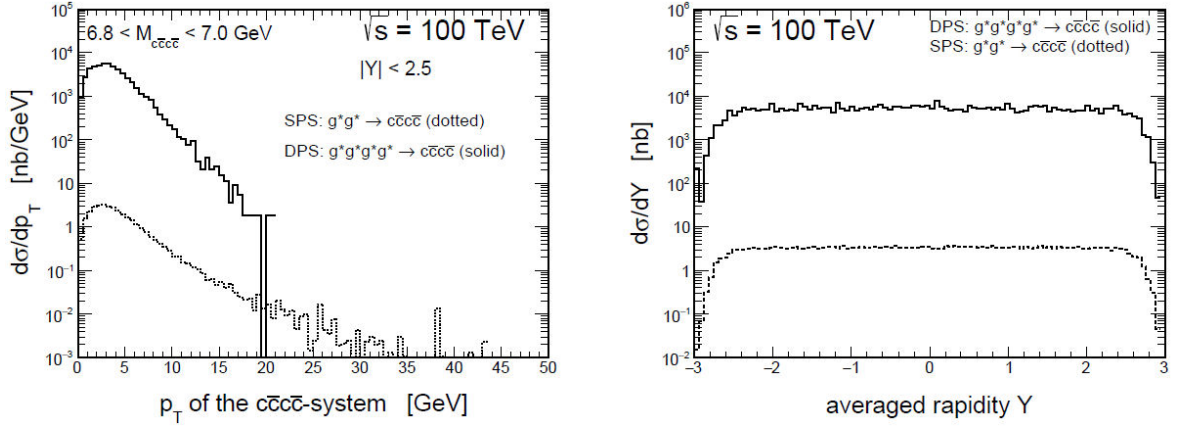


FIGURE 7. Transverse momentum (left) and rapidity (right) distributions of the $T_{4c}(6900)$ tetraquark for $\sqrt{s} = 100$ TeV.

The mechanisms of the background productions are shown in Fig. 3.

3. Results

In Fig. 4 we present distribution in $p_{t,4c}$ of four quark-antiquark system within invariant mass window ($M_R - 0.1\text{GeV}, M_R + 0.1\text{GeV}$). In a naive coalescence model this corresponds to the distribution of the tetraquark.

In Fig. 5 we show distribution in $M_{J/\psi J/\psi}$ for the two background mechanisms shown in Fig. 3. We see that in the vicinity of the tetraquark mass the SPS contribution is similar to the DPS one so both of them must be included in the evaluation of the background.

The transverse momentum distribution of the $T_{4c}(6900)$ tetraquark produced in a single particle mechanism is shown in Fig. 6.

Since the ratio of signal-to-background improves with

transverse momentum of the tetraquark [1] and knowing relatively well the behaviour of the SPS and DPS background [17] we can conclude that the 0^- assignment is disfavoured by the LHCb experimental results.

Finally, predictions of the cross sections for future FCC experiments are shown in Fig. 7. The contribution of the SPS and DPS mechanisms are shown separately. The dominance of the DPS over SPS mechanism is even larger than for the LHC. Since the cross sections are large such processes could be studied in detail at the future experiments at FCC.

4. Conclusions

In our recent paper [17] we have considered several aspects related to the production of $T_{4c}(6900)$ tetraquark observed recently by the LHCb collaboration in the $J/\psi J/\psi$ channel and the $J/\psi J/\psi$ background.

While the background distributions can in our opinion be reliably calculated, it is not the case for the signal. In the discussed naive coalescence model we have adjusted a normalization factor C responsible for the formation probability $P_{T_{4c}}$ and decay branching fraction $Br(T_{4c}(6900) \rightarrow J/\psi J/\psi)$. We have obtained $C = 10^{-4}$ for the DPS and $C = 10^{-2}$ for the SPS production of $c\bar{c}c\bar{c}$.

We have considered also more explicitly the SPS mechanism of the resonance production via gluon-gluon fusion in the k_T -factorization approach. Also, in this case the normalization, related to the underlying formation process and/or wave function of the tetraquark and the decay branching fraction $T_{4c} \rightarrow J/\psi J/\psi$ must be adjusted to the experimental

signal-to-background ratio. In this study we have considered two examples of the 0^+ and 0^- assignment. The current data seem to exclude the 0^- assignment as the final result contradicts qualitatively to the transverse momentum dependence of the signal-to-background ratio as observed by the LHCb collaboration [1].

Acknowledgements

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