# MECHANISMS OF FULLY HEAVY TETRAQUARK PRODUCTION IN PROTON–PROTON COLLISIONS*

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We discuss the mechanism of production of the $X(6900)$ state discovered in the $J/\psi J/\psi$ channel by the LHCb Collaboration. Both single-parton scattering (SPS) and double-parton scattering (DPS) mechanisms are discussed. The cross section for the $c\bar{c}c\bar{c}$ system is calculated in the $k_{\mathrm{t}}$-factorization approach. We present distributions in invariant mass of the four quark system. The DPS contribution is almost two orders of magnitude larger than the SPS one. Imposing a mass window around the resonance position, we calculate the corresponding distribution in $p_{\mathrm{t},4c}$ — the potential tetraquark transverse momentum. The cross section for the $J/\psi J/\psi$ continuum is calculated. As for the signal, we include SPS (box diagrams) and DPS contributions. They are of similar size. We calculate in addition the $g^* g^* \to X(6900)$ mechanism in the $k_{\mathrm{t}}$-factorization approach. Then the $0^+$ assignment is preferred over the $0^-$ one.

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## 1. Introduction

Standard mesons are of the $q\bar{q}$ type as proposed by Zweig and Gell-Mann [1, 2]. Quarkonia are of the $Q\bar{Q}$ type. Jaffe proposed the existence of $q\bar{q}q\bar{q}$ tetraquarks and discussed it in the context of MIT bag model [3]. Some researchers considered $X(3870)$ discovered by the Belle Collaboration as the $q\bar{q}c\bar{c}$ tetraquark. Fully heavy tetraquarks were discussed in the literature in different theoretical approaches. Two years ago, the LHCb Collaboration announced a new $T_{4c}(6900)$ state which decays into the $J/\psi J/\psi$ channel [4]. This state was observed recently also by the CMS Collaboration [5]. The working hypothesis is that the state is a quantal state of the $c\bar{c}c\bar{c}$ system. The

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ground state $c\bar{c}c\bar{c}$ is at $M \sim 5.8$ GeV, decays *e.g.* as $T_{4c} \to \mu^+\mu^-\mu^+\mu^-$. The observed state is most probably an excited state of the $c\bar{c}c\bar{c}$ system. However, spin and parity remain unknown. Different models predict different $J^{PC}$ assignments, most often $0^+$, $1^+$, $2^+$, sometimes $0^-$. The decay branching fraction into $J/\psi J/\psi$ is most probably of the order of 50% (large), but is unknown. We believe that a new era has opened and the topic will be studied at the LHC Run 3 and HL-LHC. This state could be also studied in the future at the FCC. We argued that FCC may be even better for such studies. Theoretical studies concentrated (almost totally) on spectroscopy. In most of the models, the tetraquark is a diquark–antidiquark system $(cc)(\bar{c}\bar{c})$. But in principle, it could be also a genuine $c\bar{c}c\bar{c}$ system (relevant calculations are much more difficult). The decays were studied mostly for the ground-state fully heavy tetraquarks. The mechanism of the reaction was almost not studied. In our paper of a year ago [6], we discussed possible reaction mechanisms provided it is a $c\bar{c}c\bar{c}$ state.

## 2. Formalism

### *2.1. General idea*

The production mechanism of the $c\bar{c}c\bar{c}$ is much more complicated than for the production of $c\bar{c}$ states. One has to produce four (heavy) (anti)quarks in a narrow window of mass and close to each other in ordinary space.

The reaction mechanism for the $C = +1$ tetraquark production (the LHCb case) can be categorized as:

(a) $c\bar{c}c\bar{c}$ are produced in the color singlet state,

(b) $c\bar{c}c\bar{c}$ are produced in the color octet state and extra emission(s) of soft gluon(s) is(are) necessary to bring the $c\bar{c}c\bar{c}$ system to the color singlet state relevant for the tetraquark hadron.

## 3. Mechanisms of $c\bar{c}c\bar{c}$ production

Let us first consider the $c\bar{c}c\bar{c}$ production. Two different mechanisms are shown in Fig. 1. In the $k_{\mathrm{t}}$-factorization approach, the SPS cross section for $pp \to c\bar{c}c\bar{c}\,X$ reaction can be written as (see Ref. [7])

$$\mathrm{d}\sigma_{pp\to c\bar{c}c\bar{c}\,X} = \int \mathrm{d}x_1 \frac{\mathrm{d}^2k_{1\mathrm{t}}}{\pi} \mathrm{d}x_2 \frac{\mathrm{d}^2k_{2\mathrm{t}}}{\pi} \mathcal{F}_g\left(x_1, k_{1\mathrm{t}}^2, \mu^2\right) \mathcal{F}_g\left(x_2, k_{2\mathrm{t}}^2, \mu^2\right) \mathrm{d}\hat{\sigma}_{g^*g^*\to c\bar{c}c\bar{c}} \,. \tag{1}$$

In the formula above, $\mathcal{F}_g(x, k_{\mathrm{t}}^2, \mu^2)$ is the unintegrated or transverse momentum-dependent gluon distribution function.

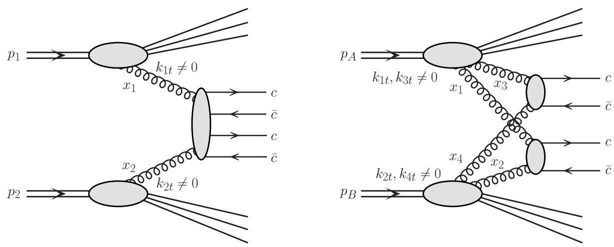


Fig. 1. Two dominant reaction mechanisms of production of $c\bar{c}c\bar{c}$ nonresonant continuum. The left diagram represents the SPS mechanism and the right diagram, the DPS mechanism.

In phenomenological studies, one usually follows the assumption of the factorization of the DPS cross section. Within the factorized ansatz, the differential cross section for the $pp \to c\bar{c}c\bar{c}\ X$ reaction within the DPS mechanism can be expressed as (see Refs. [8, 9])

$$\frac{\mathrm{d}\sigma^{\mathrm{DPS}}(pp \to c\bar{c}c\bar{c}\ X)}{\mathrm{d}\xi_1 \mathrm{d}\xi_2} = \frac{m}{\sigma_{\mathrm{eff}}} \frac{\mathrm{d}\sigma^{\mathrm{SPS}}(pp \to c\bar{c}\ X)}{\mathrm{d}\xi_1} \frac{\mathrm{d}\sigma^{\mathrm{SPS}}(pp \to c\bar{c}\ X)}{\mathrm{d}\xi_2}\,, \quad (2)$$

where $\xi_1$ and $\xi_2$ stand for generic phase-space kinematical variables for the first and second scattering, respectively, and $m = 0.5$ is the combinatorial factor that includes identity of the two subprocesses. Here, we use the world-average value of $\sigma_{\mathrm{eff}} = 15$ mb provided by several world experiments.

The $c\bar{c}c\bar{c} \to T_{4c}(6900)$ transition can be written as follows:

$$\frac{\mathrm{d}\sigma_{T_{4c}}}{\mathrm{d}^3\vec{P}_{T_{4c}}} = F_{T_{4c}} \int\limits_{M_{T_{4c}}-\Delta M}^{M_{T_{4c}}+\Delta M} \mathrm{d}^3\vec{P}_{4c}\, \mathrm{d}M_{4c} \frac{\mathrm{d}\sigma_{c\bar{c}c\bar{c}}}{\mathrm{d}M_{4c}\mathrm{d}^3\vec{P}_{4c}} \delta^3\left(\vec{P}_{T_{4c}} - \frac{M_{T_{4c}}}{M_{4c}}\vec{P}_{4c}\right)\,. \quad (3)$$

## 4. Results for signal and background

In Fig. 2, we show $c\bar{c}c\bar{c}$ invariant mass (left panel) and transverse momentum (right panel) distribution for the LHCb acceptance. Imposing a cut on invariant mass (a window around $M_{\mathrm{R}} = 6900$ MeV), we can build any distribution relevant for the $X(6900)$.

In [6], we discussed also background, see Fig. 3. Here, the SPS and DPS contributions give the cross sections of similar size. In the left panel of Fig. 4, we show the invariant mass distribution of the background, $J/\psi J/\psi$ continuum, for SPS and DPS separately. As for the signal, in the right panel of Fig. 4, we show the transverse momentum distribution of the background in the chosen region of the resonance. Since the background is absolutely normalized, one can use it to extract an unknown normalization of the signal in order to reproduce the signal-to-background ratio known from experiment.

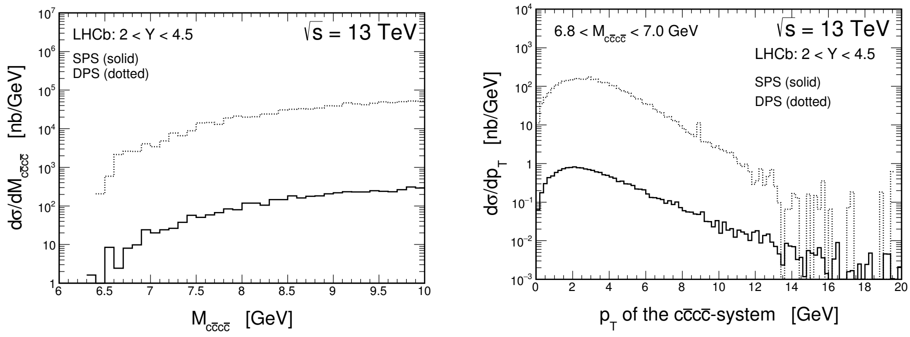


Fig. 2. Distribution of invariant mass (left panel) and $p_{\mathrm{t},4c}$ (right panel) of the $c\bar{c}c\bar{c}$ system. Here, each quark/antiquark rapidity is contained in the rapidity interval (2,4.5). The solid line is for SPS and the dashed line, for DPS contributions.

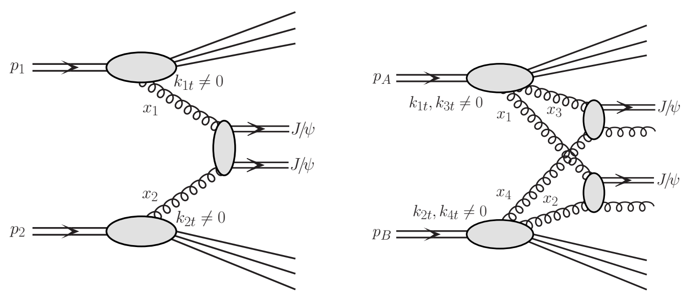


Fig. 3. Two dominant reaction mechanisms of production of $J/\psi J/\psi$ nonresonant continuum. The left diagram represents the SPS mechanism (box type) and the right diagram, the DPS mechanism.

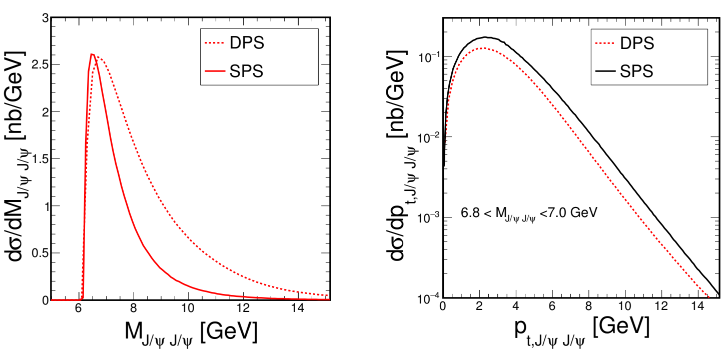


Fig. 4. Distribution in invariant mass (left panel) and transverse momentum within the invariant mass window ($M_{\mathrm{R}} - 0.1$GeV, $\mathrm{M}_{\mathrm{R}} + 0.1$GeV) (right panel) of the $J/\psi J/\psi$ system for SPS (solid line) and DPS (dashed line).

### *4.1. $g^* g^* \to T_{4c}(6900)$ resonance production*

The off-shell gluon–gluon fusion cross sections are proportional to a form-factor, which depends on the virtualities of gluons, $Q_i^2 = -k_i^2$,

$$\begin{aligned} \mathrm{d}\sigma_{g^*g^*\to 0^-} &\propto \frac{1}{k_{1\mathrm{t}}^2 k_{2\mathrm{t}}^2} \left(\vec{k}_{1\mathrm{t}} \times \vec{k}_{2\mathrm{t}}\right)^2 F^2\left(Q_1^2, Q_2^2\right) , \\ \mathrm{d}\sigma_{g^*g^*\to 0^+} &\propto \frac{1}{k_{1\mathrm{t}}^2 k_{2\mathrm{t}}^2} \left(\left(\vec{k}_{1\mathrm{t}} \cdot \vec{k}_{2\mathrm{t}}\right)\left(M^2 + Q_1^2 + Q_2^2\right) + 2Q_1^2 Q_2^2\right)^2 \frac{F^2\left(Q_1^2, Q_2^2\right)}{4X^2} , \end{aligned} \tag{4}$$

with $X = (M^4 + 2(Q_1^2 + Q_2^2)M^2 + (Q_1^2 - Q_2^2)^2)/4$. For the $0^+$ assignment, we use only the TT coupling as, in analogy with [10], we expect the LL contribution to be smaller.

At present, the $g_{ggT_{4c}}$ coupling constants are in both cases roughly adjusted to get the signal-to-background ratio of the order of one. In our calculation in [6], we used the nonfactorizable monopole form factor

$$F\left(Q_1^2, Q_2^2\right) = \frac{\Lambda^2}{\Lambda^2 + Q_1^2 + Q_2^2} , \tag{5}$$

where $Q_1^2$ and $Q_2^2$ are gluon virtualities. For the tetraquark, one may expect naively $\Lambda \sim m_{T_{4c}}$ or $\Lambda \sim 4m_c$.

In [6], we considered only $0^+$ and $0^-$ ($C = 1$) spin-parity assignments (see Fig. 5). Other assigments ($1^+$, $2^+$, *etc.*) will be considered in the future.

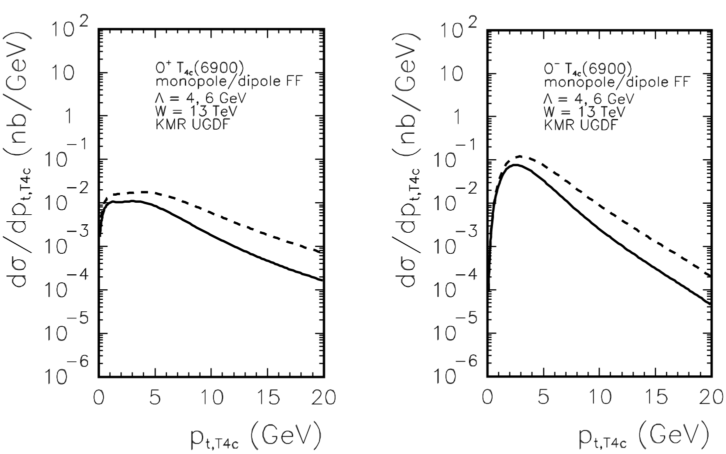


Fig. 5. Transverse momentum distribution of the $T_{4c}(6900)$ tetraquark for the $0^+$ (left panel) and $0^-$ (right panel) assignments. We show results for the KMR UGDF and $\Lambda = 6$ GeV (dashed line) and $\Lambda = 4$ GeV (solid line).

## 5. Conclusions

In Ref. [6], we considered several aspects of the production of $T_{4c}(6900)$ tetraquark (called signal) observed recently by the LHCb Collaboration in the $J/\psi J/\psi$ channel and the $J/\psi J/\psi$ background. Both for the signal and the background the SPS and DPS mechanisms were considered.

At the moment, the formation probability cannot be calculated from first principles. Similar situation is for the branching fraction into the $J/\psi J/\psi$ channel. Thus at the moment, the product of the two unknowns can be only roughly adjusted to the current signal-to-background ratio.

We have considered also more explicitly the SPS mechanism of the resonance production via gluon–gluon fusion in the $k_{\rm t}$-factorization approach with modern UGDFs. In this study, we have considered two examples of the $0^+$ and $0^-$ assignments. The current data prefer the $0^+$ assignment and seem to exclude the $0^-$ assignment.

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