

## Production mechanism of fully heavy tetraquarks in proton-proton collisions

---

Antoni Szczurek,<sup>a,b,\*</sup> Rafał Maciuła<sup>b</sup> and Wolfgang Schäfer<sup>b</sup>

<sup>a</sup>*Institute of Nuclear Physics,  
ul. Radzikowskiego 152, PL-31-342 Kraków, Poland*

<sup>b</sup>*College of Natural Sciences, Institute of Physics,  
ul. Pigońia 1, PL-35-959 Rzeszów, Poland*

*E-mail:* [antoni.szczurek@ifj.edu.pl](mailto:antoni.szczurek@ifj.edu.pl)

We discuss the production mechanism of fully charm tetraquark, observed recently 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  $cc\bar{c}\bar{c}$  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  $0^-$ ).

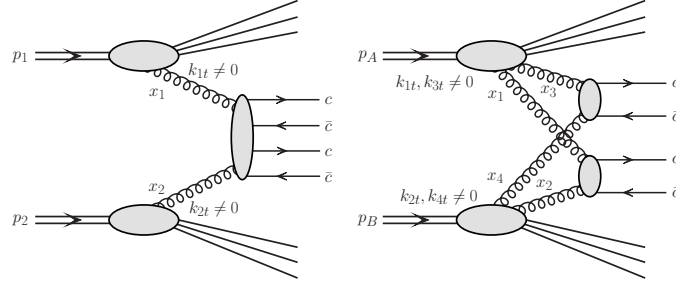
\*\*\* *The European Physical Society Conference on High Energy Physics (EPS-HEP2021), \*\*\**

\*\*\* *26-30 July 2021 \*\*\**

\*\*\* *Online conference, jointly organized by Universität Hamburg and the research center DESY \*\*\**

---

\*Speaker



**Figure 1:** Two dominant reaction mechanisms of production of  $c\bar{c}c\bar{c}$  nonresonant continuum. The left diagram represent the SPS mechanism (box type) and the left diagram the DPS mechanism.

## 1. Introduction

The recent observation by the LHCb collaboration [1] of a sharp peak in the di- $J/\psi$  channel at  $M = 6.9$  GeV seems to strongly suggest the presence of a fully charm tetraquark, consisting of  $cc\bar{c}\bar{c}$ . A number of theoretical models for the spectroscopy of tetraquarks were developed. The most popular approach treats the fully heavy ( $cc\bar{c}\bar{c}$ ,  $bb\bar{b}\bar{b}$  or  $c\bar{c}b\bar{b}$ ) tetraquarks 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  $J/\psi$  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  $cc\bar{c}\bar{c}$  production: SPS type (left diagram) and DPS type (right diagram).

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

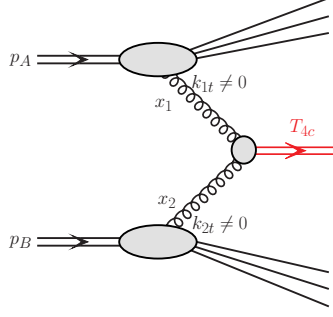
In this approach the SPS cross section for  $pp \rightarrow c\bar{c}c\bar{c} X$  reaction can be written as

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

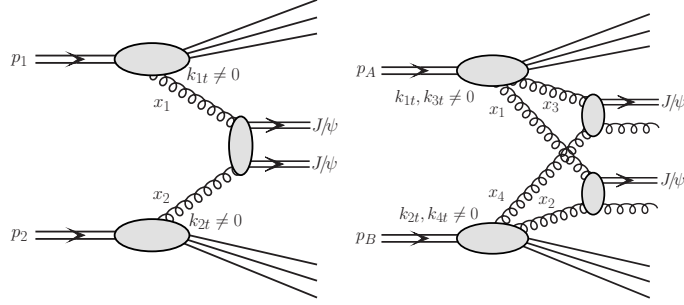
Above  $\mathcal{F}_g(x, k_t^2, \mu^2)$  is the unintegrated gluon distribution function (gluon uPDF).

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

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



**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.

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

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

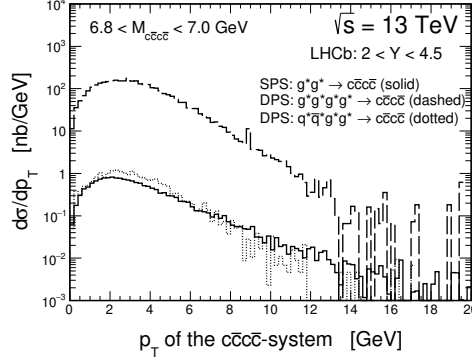
$$d\sigma_{g^*g^* \rightarrow 0^+} \propto \frac{1}{k_{1t}^2 k_{2t}^2} \left( (\vec{k}_{1t} \cdot \vec{k}_{2t})(M^2 + Q_1^2 + Q_2^2) + 2Q_1^2 Q_2^2 \right)^2 \frac{F^2(Q_1^2, Q_2^2)}{4X^2}, \quad (3)$$

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.

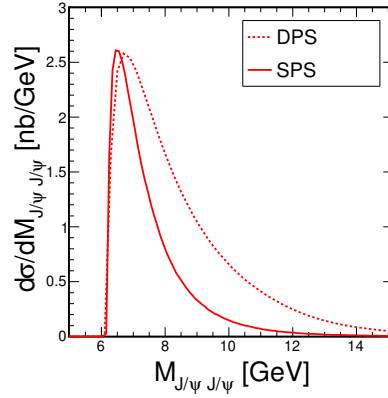
The mechanisms of the background productions are shown in Fig.3.

### 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.



**Figure 4:** Distribution of  $p_{t,Ac}$  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.

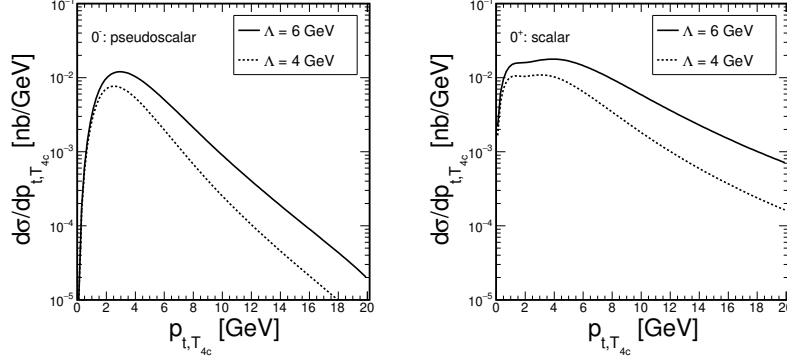


**Figure 5:** Distribution in invariant mass of the  $J/\psi J/\psi$  system for SPS (solid line) and DPS (dashed line). In this calculation  $\sqrt{s} = 13\text{ TeV}$  and we assumed that both  $J/\psi$  mesons have rapidity in the (2,4.5) interval.

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.



**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).

#### 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

This study was partially supported by the Polish National Science Center grant UMO-2018/31/B/ST2/03537 and by the Center for Innovation and Transfer of Natural Sciences and Engineering Knowledge in Rzeszów.

#### References

- [1] R. Aaij et al. (LHCb collaboration), ‘‘Observation of structure in the  $J/\psi$ -pair mass spectrum’’, *Sci. Bull.* **2020**, 65 [arXiv:2006.16957 [hep-ex]].

- [2] V.R. Debastiani and F.S. Navarra, “A non-relativistic model for the  $[cc][\bar{c}\bar{c}]$  tetraquark”, *Chin. Phys.* **C43**, 013105 (2019).
- [3] M.A. Bedolla, J. Ferretti, C.D. Roberts and E. Santopinto, “Spectrum of fully-heavy tetraquarks from a diquark+antidiquark perspective”, *Eur. Phys. J. C* **80**, no.11, 1004 (2020) [arXiv:1911.00960 [hep-ph]].
- [4] H.X. Chen, W. Chen, X. Liu and S.-L. Zhu, “Strong decays of fully-charm tetraquarks into di-charmonia”, *Sci. Bull.* **65**, 1994-2000 (2020) [arXiv:2006.16027 [hep-ph]].
- [5] Q.-F. Lu, D.-Y. Chen and Y.B. Dong, “Masses of fully heavy tetraquark  $QQ\bar{Q}\bar{Q}$  in an extended relativized quark model”, Q. F. Lü, D. Y. Chen and Y. B. Dong, *Eur. Phys. J. C* **80** (2020) no.9, 871 [arXiv:2006.14445 [hep-ph]].
- [6] M. Łuszczak, R. Maciuła and A. Szczurek, “Production of two  $c\bar{c}$  pairs in double-parton scattering”, *Phys. Rev.* **D85** (2012) 094034.
- [7] W. Schäfer and A. Szczurek, “Production of two  $c\bar{c}$  pairs in gluon-gluon scattering in high energy proton-proton scattering”, *Phys. Rev.* **D85** (2012) 094029.
- [8] R. Maciuła and A. Szczurek, “Production of  $c\bar{c}c\bar{c}$  in double-parton scattering within  $k_T$ -factorization approach: meson-meson correlations”, *Phys. Rev.* **D87** (2013) 074039.
- [9] A. van Hameren, R. Maciula and A. Szczurek, "Single-parton scattering versus double-parton scattering in the production of two  $c\bar{c}$  pairs and charmed meson correlations at the LHC", *Phys. Rev.* **D89** (2014) 094019.
- [10] A. van Hameren, R. Maciuła and A. Szczurek, “Production of two charm quark-antiquark pairs in single-parton scattering within the  $k_T$ -factorization approach”, *Phys. Lett.* **B748** (2015) 7737.
- [11] R. Aaij et al. (LHCb collaboration)  
“Observation of  $J/\psi$  pair production in  $pp$  collisions at  $\sqrt{s} = 7$  TeV”, *Phys. Lett.* **B707**, 52 (2012)
- [12] V. Khachatryan et al.(CMS collaboration)  
“Measurement of prompt  $J/\psi$  pair production in  $pp$  collisions at  $\sqrt{s} = 7$  TeV”, *JHEP* **1409**, 094 (2014).
- [13] “M. Aaboud et al.(ATLAS collaboration),  
“Measurement of the prompt  $J/\psi$  pair production cross section in  $pp$  collisions at  $\sqrt{s} = 8$  TeV with the ATLAS detector”, *Eur. Phys.J.* **C77**, 76 (2017); arXiv:1612.02950 [hep-ex].
- [14] S. P. Baranov, A. M. Snigirev, N. P. Zotov, A. Szczurek and W. Schäfer, “Interparticle correlations in the production of  $J/\psi$  pairs in proton-proton collisions”, *Phys. Rev. D* **87** (2013) no.3, 034035 doi:10.1103/PhysRevD.87.034035 [arXiv:1210.1806 [hep-ph]].
- [15] I. Babiarz, R. Pasechnik, W. Schäfer and A. Szczurek, “Hadroproduction of  $\eta_c(1S, 2S)$  in the  $k_T$ -factorization approach”, *JHEP* **2002** (2020) 037.

- [16] I. Babiarez, R. Pasechnik, W. Schäfer and A. Szczurek, “Hadroproduction of scalar  $P$ -wave quarkonia in the light-front  $k_T$ -factorization approach”, JHEP **06** (2020) 101.
- [17] R. Maciula, W. Schäfer and A. Szczurek, “On the mechanism of  $T_{4c}(6900)$  tetraquark production”, Phys. Lett. **B812** (2021) 136010.