

# Mechanisms of fully heavy tetraquark production in proton-proton collisions

A. Szczurek<sup>1,2</sup>, R. Maciula and W. Schäfer

<sup>1</sup> The Henryk Niewodniczański Institute of Nuclear Physics  
Polish Academy of Sciences    <sup>2</sup>University of Rzeszów

Low-x, Diffraction 2022, Corigliano, September 25-30 2022

# Contents

- ▶ Introduction
- ▶ LHCb discovery of  $T_{4c}(6900)$
- ▶ Mechanisms of the tetraquark production
- ▶ Mechanisms of  $J/\psi J/\psi$  background
- ▶ Results for  $T_{4c}(6900)$  production at LHCb
- ▶ Results for  $J/\psi J/\psi$  background
- ▶ Results for  $T_{4c}(6900)$  production at FCC
- ▶  $T_{2c2b}$  tetraquark production for LHCb
- ▶ Conclusions and outlook

# Introduction

- ▶ Standard mesons are of the  $q\bar{q}$  type (Zweig-Gell-Mann)
- ▶ Quarkonia are of the  $Q\bar{Q}$  type.
- ▶ Jaffe proposed existence of  $q\bar{q}q\bar{q}$  (tetraquarks) and discussed it in the context of MIT bag model.
- ▶ Some people considered  $X(3870)$  discovered by the Belle collaboration as  $q\bar{q}c\bar{c}$  tetraquark.
- ▶ Fully heavy tetraquarks were discussed in the literature in different theoretical approaches.
- ▶ LHCb announced a new state  $T_{4c}(6900)$  which decays into  $J/\psi J/\psi$  channel.
- ▶ **Hypothesis:** we observe a quantal state of  $c\bar{c}c\bar{c}$  system.

# Introduction

- ▶ Ground state  $c\bar{c}c\bar{c}$  is at  $M \sim 5.8$  GeV, decays e.g.  $T_{4c} \rightarrow \mu^+\mu^-\mu^+\mu^-$ .
- ▶ The observed state is most probably **excited state** of the  $c\bar{c}c\bar{c}$  system. **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 strictly unknown.
- ▶ **New Era has just opened** and the topic will be studied at the **LHC run 3** and **HL-LHC**.  
Could be also studied at the **FCC**.  
I shall argue that FCC may be much better.

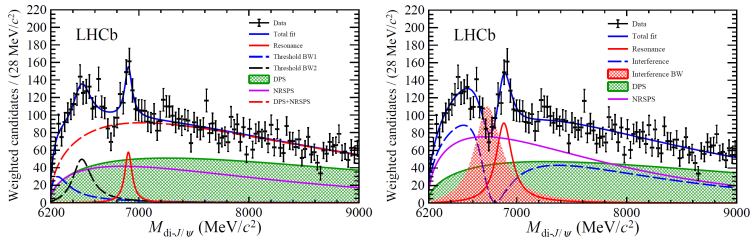
# Introduction

- ▶ Theoretical studies concentrated (almost totally) on **spectroscopy**.
- ▶ The tetraquark is then diquark-antidiquark system  $(cc)(\bar{c}\bar{c})$ .  
But could be also genuine  $c\bar{c}c\bar{c}$  system (such 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**.

# Introduction

- ▶ Our recent work concentrated on the **mechanism of tetraquark production**.
- ▶ I will try to address the issue why the fully heavy tetraquarks were not observed before LHC and could be produced at the LHC and even more efficiently at the FCC.
- ▶ This presentation will be partially based on:  
**R. Maciula, W. Schäfer and A. Szczurek**,  
“On the mechanism of  $T_{4c}(6900)$  tetraquark production”,  
Phys. Lett. **B812** (2021) 136010.

# LHCb result



Combined result from  $\sqrt{s} = 7, 8, 13$  TeV.

No cross section given by the LHCb collaboration.

The spectrum could be explained by a fit within coupled-channel approach, e.g.

(Dong, Baru, Guo, Hanhart, Nefediev, Phys.Rev.Lett.126, 132001 (2021)).

But physics depends on many more ( $y, p_t$ ) kinematical variables.

# General idea

After many years of investigation there is no agreement on production mechanism even for quarkonia, pure  $Q\bar{Q}$  states. For  $C = +1$  quarkonia rather color singlet mechanism dominates. How big is color octet contribution is not quite clear at present.

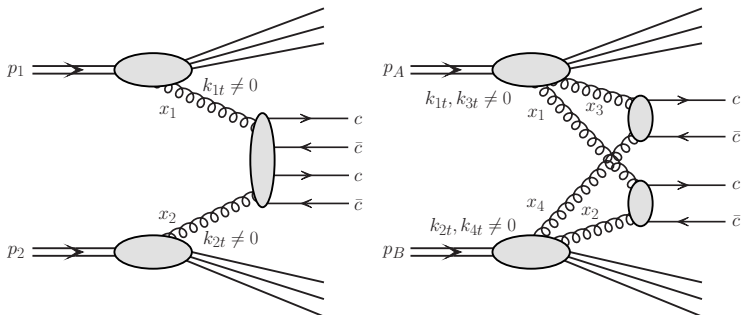
The production mechanism of the  $c\bar{c}c\bar{c}$  must be much more complicated. One has to produce four (heavy) (anti)quarks in a narrow window of mass and close to each other in ordinary space.

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

- (a)  $c\bar{c}c\bar{c}$  are produced in color singlet state,
- (b)  $c\bar{c}c\bar{c}$  are produced in 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 color singlet state relevant for the tetraquark hadron.



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



**Rysunek:** Two dominant reaction mechanisms of production of  $c\bar{c}c\bar{c}$  nonresonant continuum. The left diagram represents the SPS mechanism and the left diagram the DPS mechanism.

Luszczak, Maciula, Hameren, Schäfer, Szczurek

# A sketch of the formalism, $c\bar{c}c\bar{c}$ SPS

In the present study both the SPS and the DPS contributions are calculated in the framework of  $k_T$ -factorization. According to this approach the SPS cross section for  $pp \rightarrow c\bar{c}c\bar{c} X$  reaction can be written as

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

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

The uPDF depends on:

- (a) longitudinal momentum fraction  $x$ ,
- (b) transverse momentum squared  $k_t^2$  of the partons entering the hard process,
- (c) (factorization) scale of the hard process  $\mu^2$ .

# A sketch of the formalism, $c\bar{c}c\bar{c}$ SPS

The elementary cross section can be written as:

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

where  $E_l$  and  $p_l$  are energies and momenta of final state charm quarks.

The matrix element takes into account that both gluons entering the hard process are

**off-shell** with the virtualities:

$$k_1^2 = -k_{1t}^2 \text{ and } k_2^2 = -k_{2t}^2.$$

In numerical calculations we limit ourselves to the dominant **gluon-gluon fusion channel** of the  $2 \rightarrow 4$  type parton-level mechanism.

We checked numerically that the  **$q\bar{q}$ -annihilation** can be safely neglected in the kinematical region under consideration.

## A sketch of the formalism, $c\bar{c}c\bar{c}$ DPS

Within the **factorized ansatz**, the dPDFs are taken as:

$$D_{1,2}(x_1, x_2, \mu) = f_1(x_1, \mu) f_2(x_2, \mu) \theta(1 - x_1 - x_2), \quad (3)$$

where  $D_{1,2}(x_1, x_2, \mu)$  is the dPDF and  $f_i(x_i, \mu)$  are the standard single PDFs for the two partons in the same proton.

The factor  $\theta(1 - x_1 - x_2)$  ensures that the sum of the two parton momenta does not exceed 1.

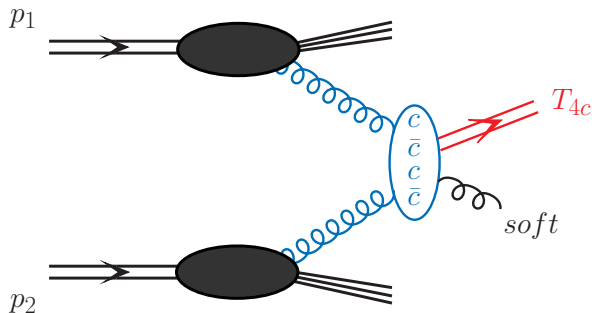
The differential cross section for  $pp \rightarrow c\bar{c}c\bar{c} X$  reaction within the DPS mechanism can be expressed as follows:

$$\frac{d\sigma^{DPS}(pp \rightarrow c\bar{c}c\bar{c} X)}{d\xi_1 d\xi_2} = \frac{m}{\sigma_{\text{eff}}} \cdot \frac{d\sigma^{SPS}(pp \rightarrow c\bar{c} X)}{d\xi_1} \frac{d\sigma^{SPS}(pp \rightarrow c\bar{c} X)}{d\xi_2}, \quad (4)$$

where  $\xi_1$  and  $\xi_2$  stand for generic phase space kinematical variables for the first and second scattering, respectively.

The combinatorial factor  $m$  is equal 0.5 for the  $c\bar{c}c\bar{c}$  case. Here,  $d\sigma^{SPS}(pp \rightarrow c\bar{c} X)$  is cross sections for the **off-shell initial state partons**.

# A sketch of the formalism for $T_{4c}$ production



Rysunek: Mechanisms of  $T_{4c}$  production in our **coalescence model**.

**soft gluon emission for initial color octet**  
as in color evaporation model.

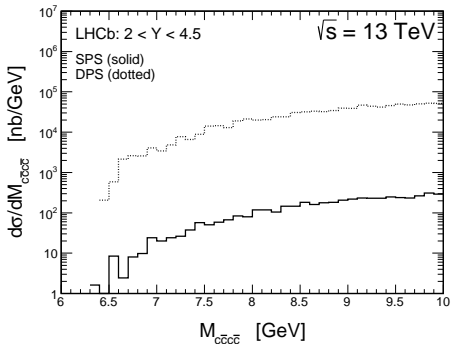
# A sketch of the formalism for $T_{4c}$ production

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

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

where  $F_{T_{4c}}$  is the probability of the  $c\bar{c}c\bar{c} \rightarrow T_{4c}$  transition which is unknown and could be fitted to a future experimental data,  $M_{T_{4c}} = 6.9$  GeV is the mass of  $T_{4c}$  tetraquark and  $M_{4c}$  is the invariant mass of the  $c\bar{c}c\bar{c}$ -system. In the numerical calculations we take  $\Delta M = 100$  MeV.

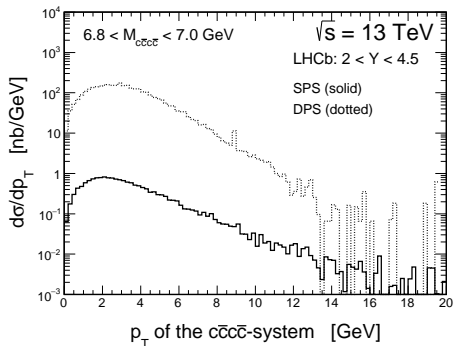
# Results



**Rysunek:** Distribution of invariant mass of four  $c - \bar{c}$  system. Here  $\sqrt{s} = 13 \text{ TeV}$  and 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.

The maximum of the cross section is reached above 6.9 GeV.

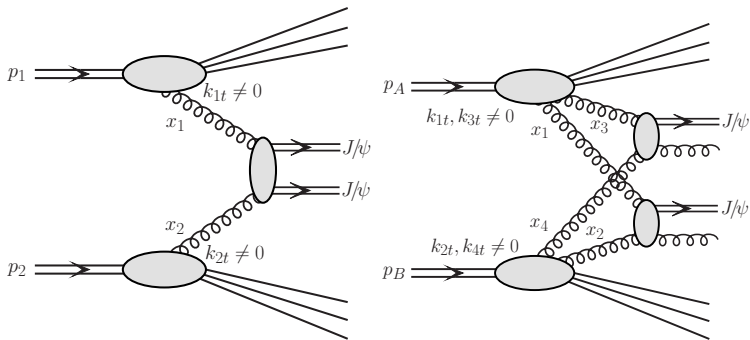
# Results



**Rysunek:** 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  $\sqrt{s} = 13$  TeV and each  $c/\bar{c}$  rapidity is contained in the rapidity interval (2,4.5). The solid line is for SPS and the dashed line for DPS contributions.



# $pp \rightarrow J/\psi J/\psi$ background

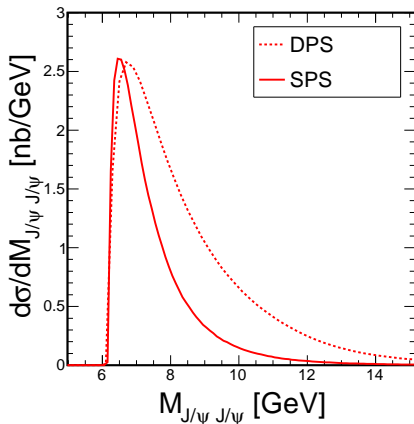


**Rysunek:** Two dominant reaction mechanisms of production of  $J/\psi J/\psi$  nonresonant continuum. The left diagram represent the SPS mechanism (box type) and the right diagram the DPS mechanism.

We studied such a channel in the past.

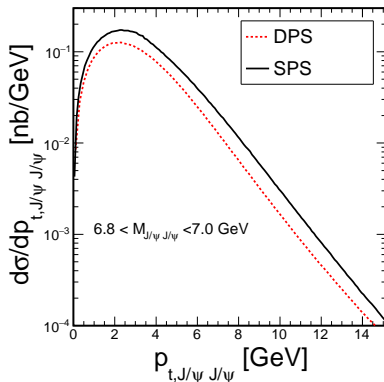
At the LHCb kinematics both contributions are similar.

## $J/\psi J/\psi$ background



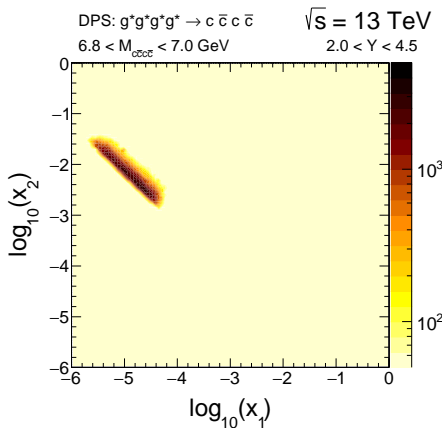
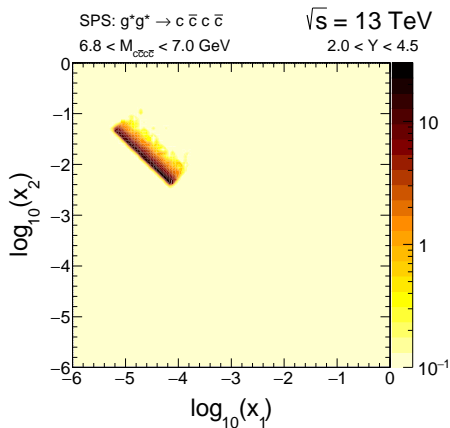
**Rysunek:** Distribution in invariant mass of the  $J/\psi J/\psi$  system for SPS (solid line) and DPS (dashed line). In this calculation  $\sqrt{s} = 13$  TeV and we assumed that both  $J/\psi$  mesons have rapidity in the (2,4.5) interval.

# Background in the tetraquark mass window



**Rysunek:** Distribution in transverse momentum of the  $J/\psi$  pairs within the invariant mass window ( $M_R - 0.1\text{GeV}, M_R + 0.1\text{GeV}$ ) for SPS (solid line) and DPS (dashed line) contributions. Here  $\sqrt{s} = 13$  TeV. The red lines represent the signal from the naive coalescence approach multiplied by different prefactor for the SPS (solid line) and DPS (dashed line)  $c\bar{c}c\bar{c}$  contributions.

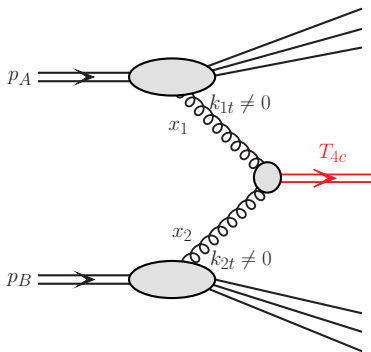
# Longitudinal momentum fractions



Rysunek: For SPS (left) and DPS (right).

rather small  $x$  enter the calculation

$g^* g^* \rightarrow T_{4c}(6900)$  resonance production,  
examples of the spin-parity assignment



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

We studied  $g^* g^* \rightarrow Q\bar{Q}$  for **pseudoscalar** and **scalar** quarkonia  
(**Babiarz, Pasechnik, Schäfer, Szczurek**)

## $g^* g^* \rightarrow T_{4c}(6900)$ mechanism

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

$$d\sigma_{g^* g^* \rightarrow 0^-} \propto \frac{1}{k_{1t}^2 k_{2t}^2} (\vec{k}_{1t} \times \vec{k}_{2t})^2 F^2(Q_1^2, Q_2^2)$$
$$d\sigma_{g^* g^* \rightarrow 0^+} \propto \frac{1}{k_{1t}^2 k_{2t}^2} \left( (\vec{k}_{1t} \cdot \vec{k}_{2t})(M^2 + Q_1^2 + Q_2^2) + 2Q_1^2 Q_2^2 \right)^2 \frac{F^2(Q_1^2, Q_2^2)}{4X^2}, (6)$$

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 **Babiarz et al.** we expect the LL contribution to be smaller.

In our calculation for the tetraquark production we also use the **KMR UGDFs**.

## $g^* g^* \rightarrow T_{4c}(6900)$ mechanism

The  $g_{ggT_{4c}}$  coupling constants are in both cases roughly adjusted to get the signal-to-background ratio of the order of 1.

In our calculation here we use the **nonfactorizable** monopole form factor:

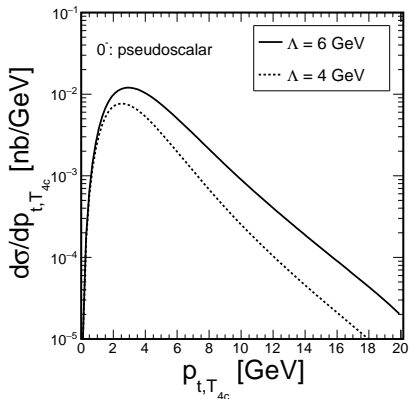
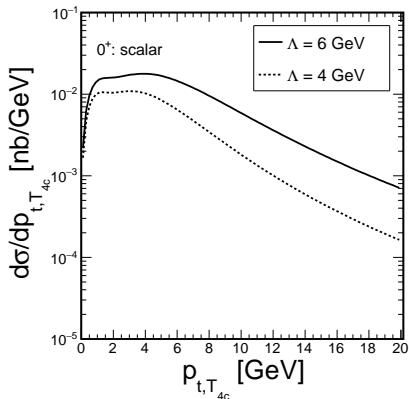
$$F(Q_1^2, Q_2^2) = \frac{\Lambda^2}{\Lambda^2 + Q_1^2 + Q_2^2}, \quad (7)$$

where  $Q_1^2$  and  $Q_2^2$  are gluon virtualities.

$\Lambda$  is a free parameter.

In future such a form factor should be calculated.

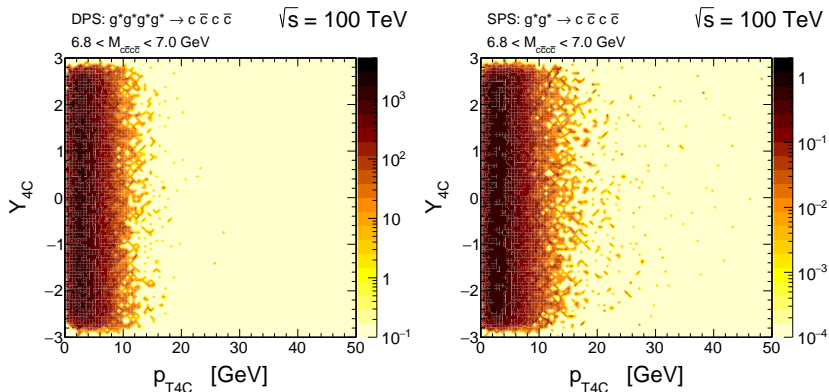
$g^* g^* \rightarrow T_{4c}(6900)$  mechanism



**Rysunek:** 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).



# Results for FCC with the tetraquark mass window

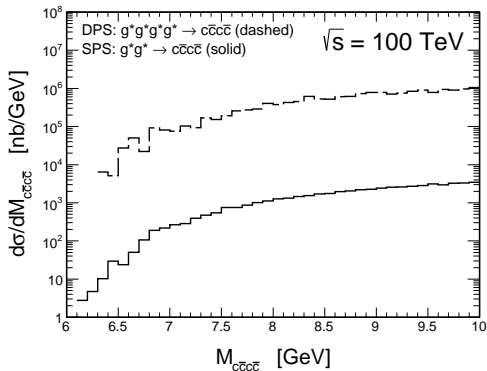


Rysunek: Two-dimensional distribution in the tetraquark mass window.

Quite regular behaviour

For illustration we shall fix the rapidity interval as for ATLAS

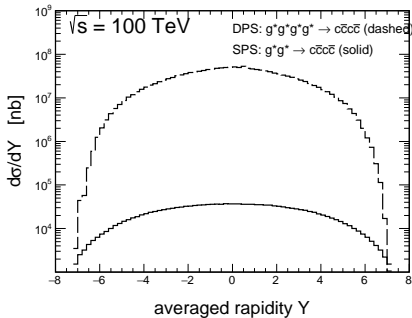
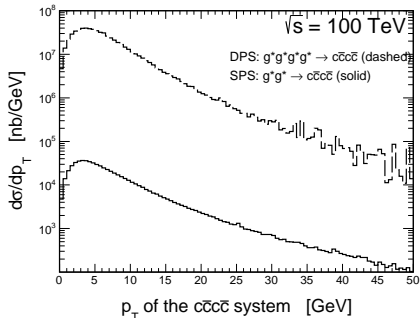
# $c\bar{c}c\bar{c}$ production at FCC



Rysunek: Invariant mass distribution of the  $c\bar{c}c\bar{c}$  system at  $\sqrt{s} = 100 \text{ TeV}$ .

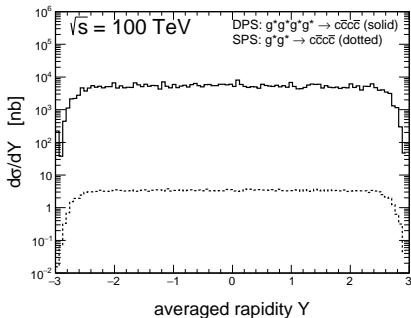
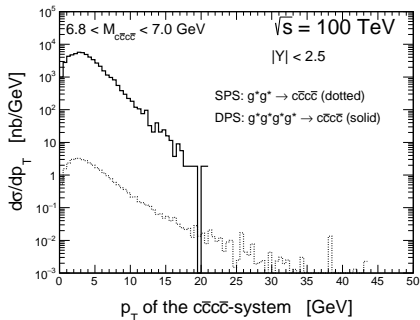
The cross section for DPS  $c\bar{c}c\bar{c}$  production is even larger than for SPS  $c\bar{c}c\bar{c}$  production compared to  $\sqrt{s} = 13 \text{ TeV}$ .

# $c\bar{c}c\bar{c}$ production at FCC



Rysunek: Other distributions for the  $c\bar{c}c\bar{c}$  system for  $\sqrt{s} = 100$  TeV without the tetraquark mass window.

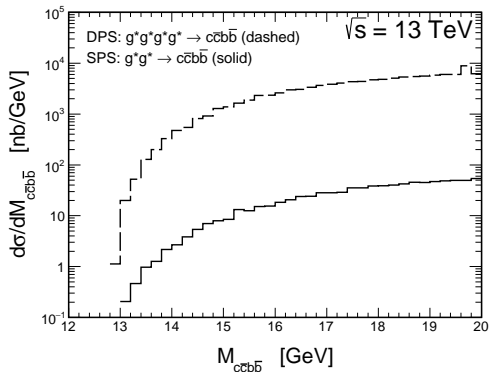
# $T_{4c}$ production at FCC



Rysunek: Distributions for the  $c\bar{c}c\bar{c}$  system for  $\sqrt{s} = 100$  TeV with the tetraquark mass window.

$$-6.8 \text{ GeV} < M_{c\bar{c}c\bar{c}} < 7.0 \text{ GeV}$$

# $c\bar{c}b\bar{b}$ production at the LHC

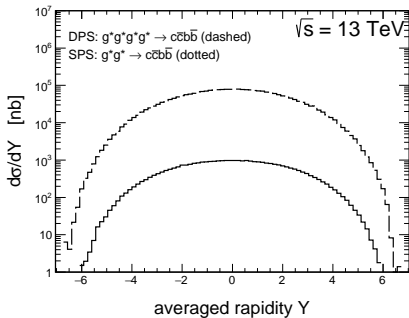
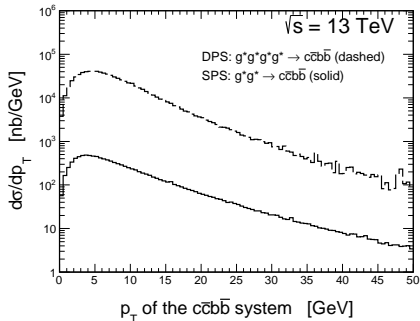


Rysunek: Invariant mass distribution of the  $c\bar{c}b\bar{b}$  system.

Much smaller cross section than for  $c\bar{c}c\bar{c}$  production.

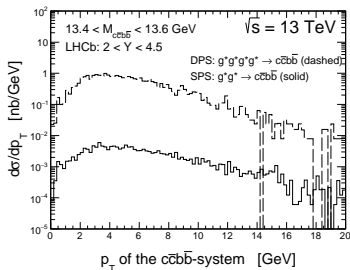
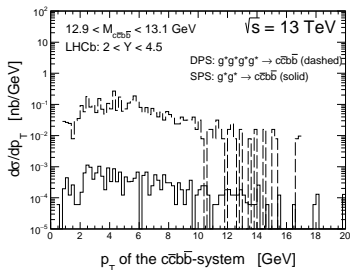
Maximum of the cross section is far from the threshold !

# $c\bar{c}b\bar{b}$ production at the LHC



**Rysunek:** Other distributions for the  $c\bar{c}b\bar{b}$  system. No cuts on the tetraquark mass.

# Charm-bottom tetraquark - two mass windows



**Rysunek:** Transverse momentum distribution of the "potential tetraquark" for **two invariant mass windows**. Here  $-2.5 < Y < 2.5$  was imposed.

**We do not know the actual mass of the  $T_{2c2b}$  tetraquark**  
Almost the same result for  $(c\bar{c})(b\bar{b})$  and  $(cc)(\bar{b}\bar{b})$  or  $(\bar{c}\bar{c})(bb)$ .

# Conclusions

- ▶ Possible SPS and DPS mechanisms of  $T_{4c}$  production have been discussed.
- ▶ The mechanisms of the SPS and DPS  $J/\psi J/\psi$  background have been discussed.
- ▶ The DPS mechanism of  $c\bar{c}c\bar{c}$  production is larger than the SPS mechanism of  $c\bar{c}c\bar{c}$  production.
- ▶ The results for LHC and FCC have been shown.
- ▶ Similar analysis for the  $T_{2c2b}$  tetraquark production have been considered for the LHC.  
The cross section seems **two orders** of magnitude smaller than that for the  $T_{4c}$  tetraquark.
- ▶ **Strong dependence of the cross section on the  $T_{2c2b}$  mass window !**



# Outlook

- ▶ Quite probable that at high energies the coalescence mechanism dominates.
- ▶ At high energies where  $c\bar{c}c\bar{c}$  is abundantly produced such a mechanism seems very probable.
- ▶ Our coalescence mechanism leads to very small cross section close to  $c\bar{c}c\bar{c}$  ( $J/\psi J/\psi$ ) threshold.  
It can mean that the cross section for production of *g.s.* tetraquark may be very small.
- ▶ In addition, the branching ratio into charged leptons may be small.
- ▶  $D\bar{D}$  may be difficult channel –  
multihadron state and huge background.  
Compare the  $D\bar{D}$  background to  $J/\psi J/\psi$  background.
- ▶ Try to measure  $J/\psi \Upsilon$ . So far such a channel was not measured.
- ▶ Calculation with  $gg \rightarrow T(c\bar{c}c\bar{c})$  with realistic tetraquark wave function is needed. This is rather difficult.