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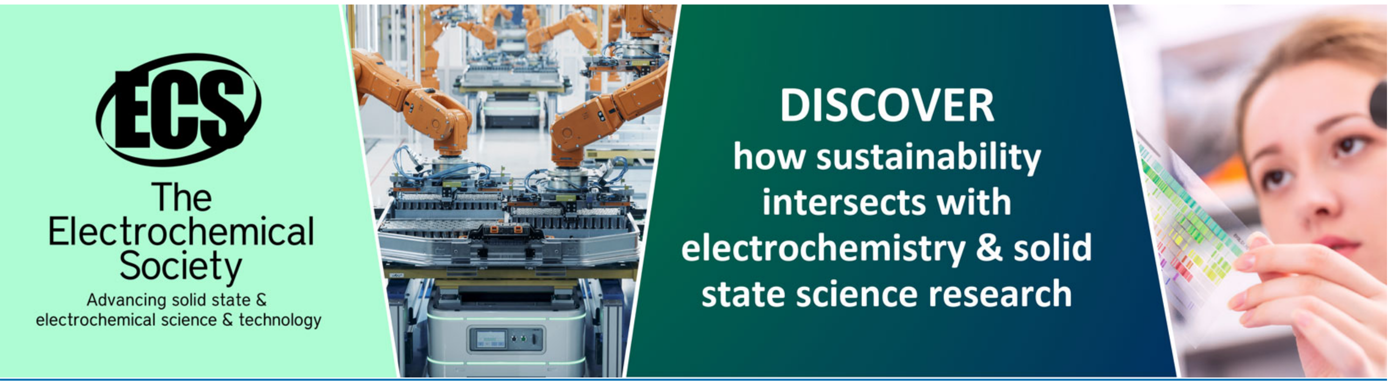

Tetraquark Production in Hadronic Collisions

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Abstract.
We develop a formalism to study the tetraquark production in hadronic collisions. We focus on double parton scattering and formulate a version of the color evaporation model for the production of the T_{4c} tetraquark, a state composed by the $c\bar{c}c\bar{c}$ quarks. We find that the production cross section grows rapidly with the collision energy $\sqrt{s}$ and the T_{4c} might be observable at LHC energies.

1. Introduction

Over the last years the existence of exotic hadrons has been firmly established [1] and now the next step is to determine their structure. The most popular proposed configurations are meson molecule and tetraquark. So far almost all the experimental information about these states comes from their production in B decays. The production of exotic particles in proton proton collisions is one of the most promising testing ground for our ideas about the structure of the new states. It has been shown [1] that it is extremely difficult to produce molecules in p p collisions. In the molecular approach the estimated cross section for $X(3872)$ production is two orders of magnitude smaller than the measured one. The present challenge for theorists is to show that these data can be explained by the tetraquark model. In this contribution we give a first step in this direction, considering the production of the T_{4c}, a state composed by charm quark pairs: $c\bar{c}c\bar{c}$. This state was first discussed some time ago [2] and has triggered some attention in more recent works [3, 4]. This state is supposed to be a genuine tetraquark, since it is much more difficult to produce meson molecules with the $c\bar{c}c\bar{c}$ quark content.

We shall consider the events with two independent parton-parton scatterings with the production of the two $c\bar{c}$ pairs. This is a particular case of double parton scattering (DPS) [5]. In [6] we have shown that DPS charm production is already comparable to single parton scattering (SPS) production at LHC energies. We shall generalize the color evaporation model (CEM) [7] of charmonium production to T_{4c} production in DPS events. In order to obtain analytical estimates, in this contribution we shall use some simple expressions for the gluon distributions and for the gluon - gluon cross section. A more detailed analysis will be presented in [8].

2. A simple model for T_{4c} production

In the CEM formalism one gluon from the hadron target scatters with one gluon from the hadron projectile forming a charmonium state, which can absorb (emit) additional gluons from (to) the hadronic color field to become color neutral. This is the usual (SPS) $c\bar{c}$ production. Now we are going to generalize the CEM to the case where two gluons from the hadron target scatter independently with two gluons from the hadron projectile as depicted in Fig. 1, where we show DPS production of T_{4c}. In the figure two gluons collide and form a $c\bar{c}$ state with mass M_{12}, while other two gluons collide and form a second $c\bar{c}$ state with mass M_{34}. The two objects bind to each other forming the T_{4c}. Additional gluon exchanges with the environment are not shown in the figure.

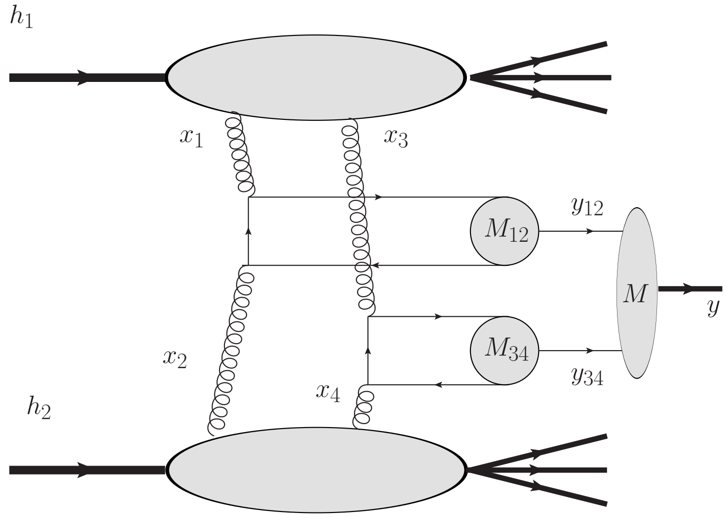

Figure 1. The gluons with odd (even) label come from the upper (lower) hadron, and carry momentum fraction x_i. The "gluon 1" scatters with "gluon 2", making the state M_{12}. Analogous processes occur with gluons 3 and 4. Finally M_{12} and M_{34} merge and form the T_{4c} with mass M.

Working with the usual CEM one-dimensional kinematics, the rapidities of the objects M_{12} and M_{34} are respectively:

$$y_{12} = \frac{1}{2}\ln\frac{x_1}{x_2} \quad \text{and} \quad y_{34} = \frac{1}{2}\ln\frac{x_3}{x_4} \tag{1}$$

and their invariant masses are

$$M_{12} = \sqrt{x_1\, x_2\, s} \quad \text{and} \quad M_{34} = \sqrt{x_3\, x_4\, s} \tag{2}$$

The invariant mass of the $c\bar{c}c\bar{c}$ system is then given by:

$$M^2 = M_{12}^2 + M_{34}^2 + 2M_{12}\, M_{34}\, \cosh(y_{12} - y_{34}) \tag{3}$$

2.1. Open charm production

Apart from a constant, the DPS cross section for the production of four charm quarks which hadronize independently (forming four heavy-light charm mesons) is given by:

$$\sigma_{4D} = \int_0^1 dx_1 \int_0^1 dx_2 \int_0^1 dx_3 \int_0^1 dx_4 \quad g(x_1,\mu^2) g(x_2,\mu^2) \sigma_{g_1 g_2 \to c\bar{c}} \quad g(x_3,\mu^2) g(x_4,\mu^2) \sigma_{g_3 g_4 \to c\bar{c}}$$

$$\times\, \Theta(1 - x_1 - x_3)\, \Theta(1 - x_2 - x_4)\Theta(M_{12}^2 - 4m_c^2)\, \Theta(M_{34}^2 - 4m_c^2) \tag{4}$$

where $g(x, \mu^2)$ is the gluon distribution in the proton at the gluon fractional momentum x and at the factorization scale μ^2 and $\sigma_{g_1 g_2 \to c\bar{c}}$ is the $gg \to c\bar{c}$ elementary cross-section. The step functions Θ enforce momentum conservation in the projectile and in the target. The step functions $\Theta(M_{ij}^2 - 4m_c^2)$ guarantee that the invariant masses of the gluon pairs 12 and 34 are large enough to produce two charm quark pairs. Note that Eq. (4) needs a multiplicative constant with dimension of σ^{-1} in order to give the correct dimension for the cross section. In fact, in the DPS formalism this constant is usually chosen to be the inverse of an effective cross section $(1/\sigma_{eff})$.

In order to gain some insight on the problem and to determine the energy ($\sqrt{s}$) dependence of the cross section (4) we shall use simple expressions for the gluon distributions $g(x)$ and gluon cross sections $\sigma_{gg \to c\bar{c}}$, which are given by:

$$g(x) \;=\; \frac{1}{x^{1+\lambda}} \tag{5}$$

$$\sigma_{g_1 g_2 \to c\bar{c}} \;=\; \frac{\alpha_s}{x_1 x_2 s} \tag{6}$$

with $\lambda \geq 0$. With these simple expressions and in the high energy limit, $s \gg 4m_c^2$, the cross section (4) can be integrated giving:

$$\sigma_{4D} = C\,\alpha_s^2\,\frac{1}{(1+\lambda)^2}\,\frac{1}{(4m_c^2)^{2+2\lambda}}\;s^{2\lambda}\;\left\{\left[\ln\left(\frac{s}{4m_c^2}\right)\right]^2 - \frac{2}{1+\lambda}\ln\left(\frac{s}{4m_c^2}\right)\right\} \tag{7}$$

where the constant C represents $1/\sigma_{eff}$ and also normalization corrections due to the use of the approximate expressions (5) and (6). The expression above contains two constants, which are adjusted fitting (7) to the theoretical prediction for $c\bar{c}c\bar{c}$ production in DPS events calculated in [6]. A good fit of the $c\bar{c}c\bar{c}$ production cross section is obtained with $\lambda = 0.45$ and $C\,\alpha_s^2 = 5 \times 10^{-3}$ GeV^{-2}.

2.2. *Tetraquark production*

Having fixed the parameters and knowing that (7) reproduces the data on double open charm production we now proceed to calculate the cross section for T_{4c} production. All known charm tetraquarks have small binding energies, i.e., they lie right below the threshold of two open charm mesons. We shall assume that the T_{4c} mass (M_T) is smaller than the lightest two charm meson threshold, $2M_{\eta_c}$, i.e., $M_T \leq 2M_{\eta_c}$. Looking at (3) one can check that the condition $M^2 = M_T^2 \leq 4M_{\eta_c}^2$ implies that $y_{12} \simeq y_{34}$ even in the extreme case where $M_{12} \simeq M_{34} \simeq 2m_c$ and $m_c \simeq 1$ GeV, and hence the total system $M_{12} + M_{34}$ has the largest internal kinetic energy. We shall thus assume that the two objects (12 and 34) have the same rapidity, $y_{12} = y_{34}$, which implies that:

$$\frac{x_2}{x_1} = \frac{x_4}{x_3} \tag{8}$$

To simplify the calculation we also require that the two objects have equal masses, i.e., $M_{12} = M_{34}$. This condition is not really very restrictive. Assuming that $m_c \simeq 1$ GeV and $M_{\eta_c} \simeq 3$ GeV the T_{4c} mass must be in the range $4 \leq M_T (= M_{12} + M_{34}) \leq 6$ GeV. The maximal difference between M_{12} and M_{34} will happen when, for example, $M_{12} = 2$ GeV and $M_{34} = 4$ GeV. In other words, in the worst case one mass is twice the other. Since we will always work with $m_c > 1$ GeV, assuming $M_{12} = M_{34}$ will not be a bad approximation. This implies that $M_{12}^2 = M_{34}^2 = x_1 x_2 s = x_3 x_4 s$ and hence:

$$x_1 x_2 = x_3 x_4 \ . \tag{9}$$

Combining (9) with (8) we find that $x_3 = x_1$ and $x_4 = x_2$. With these new conditions we go back to Eq. (4). With the help of (3) we multiply (4) by the unity, written as:

$$\int_{16m_c^2}^{4M_{\eta_c}^2} dM^2 \ \delta(M^2 - [M_{12}^2 + M_{34}^2 + 2M_{12}M_{34}\cosh(y_{12} - y_{34})]) = 1 \tag{10}$$

We next implement the conditions (9) and (8) with delta functions and obtain:

$$\begin{aligned} \sigma_{T_{4c}} \quad = \quad & C \int_{16m_c^2}^{4M_{\eta_c}^2} dM^2 \int_0^1 dx_1 \int_0^1 dx_2 \int_0^1 dx_3 \int_0^1 dx_4 \ \frac{1}{x_1^{1+\lambda}} \frac{1}{x_2^{1+\lambda}} \frac{\alpha_s}{x_1 x_2 s} \ \frac{1}{x_3^{1+\lambda}} \frac{1}{x_4^{1+\lambda}} \frac{\alpha_s}{x_3 x_4 s} \\ & \times \Theta(1 - x_1 - x_3) \ \Theta(1 - x_2 - x_4) \ \Theta(x_1 x_2 s - 4m_c^2) \ \Theta(x_3 x_4 s - 4m_c^2) \\ & \times \delta(M^2 - [M_{12}^2 + M_{34}^2 + 2M_{12}M_{34}\cosh(y_{12} - y_{34})]) \ \delta(x_3 - x_1) \, \delta(x_4 - x_2) \end{aligned} \tag{11}$$

This equation can be readily integrated to give:

$$\begin{aligned} \sigma_{T_{4c}} = C \, \alpha_s^2 \, \frac{4^{3+2\lambda}}{3+2\lambda} \, s^{1+2\lambda} \Bigg[& \frac{(3+2\lambda)\,\ln(1/16m_c^2) \, - 1}{(3+2\lambda)\,(16m_c^2)^{3+2\lambda}} \; - \; \frac{(3+2\lambda)\,\ln(1/4M_{\eta_c}^2) \, - 1}{(3+2\lambda)\,(4M_{\eta_c}^2)^{3+2\lambda}} \\ & + \left(\frac{1}{(16m_c^2)^{3+2\lambda}} - \frac{1}{(4M_{\eta_c}^2)^{3+2\lambda}} \right) \ln(s) \Bigg] \end{aligned} \tag{12}$$

The constants C and λ are the same as before. The above cross section still has the double open charm cross section as a reference normalization. This derivation was made in the spirit of the CEM, emphasizing the kinematical aspects of hidden charm production and neglecting some microscopic aspects, especially those related to the quantum numbers of the produced particles.

It is instructive to compare the asymptotic limits of Eqs. (7) and (12). At very high energies we have:

$$\sigma_{4D} \propto s^{2\lambda} (lns)^2 \qquad \sigma_{T_{4c}} \propto s^{1+2\lambda} (lns) \tag{13}$$

From this comparison we may expect the tetraquark production cross section to grow much faster than the one for double open charm production.

In the usual CEM it is further assumed that the nonperturbative probability for the $Q\bar{Q}$ pair to evolve into a quarkonium state H is given by a constant F_H that is energy-momentum and process independent. Once F_H has been fixed by comparison with the measured total cross section for the production of the quarkonium H at one given energy, the CEM can predict, with no additional free parameters, the energy dependence of the production cross section and the momentum distribution of the produced quarkonium. Following the CEM strategy we shall multiply (12) by the constant factor F_T, which represents the nonperturbative probability that the four quark system $c\bar{c}c\bar{c}$ (with the right mass) evolves to the T_{4c}. Since we do not have experimental data to fix F_T, we will estimate it as follows. In Table I we collect the available data on cross sections of open charm, J/ψ, double open charm and double J/ψ production in high energy proton-proton collisions. From the table we can define the probability $P_{2\to 1}$ that the two quarks c and $\bar{c}$ get together to form a J/ψ. It is given in terms of the cross sections as:

$$P_{2\to 1} = \frac{\sigma_{J/\psi}}{\sigma_{c\bar{c}}} \simeq 10^{-3} \ . \tag{14}$$

Table 1. Total inclusive cross sections measured in proton-proton collisions at $\sqrt{s} = 7$ TeV.

Final state	cross section (μb)	Reference
$c\bar{c}$	8.5×10^3	[9]
J/ψ	10.7	[10]
$c\bar{c}c\bar{c}$	3.5×10^3	[6]
$J/\psi\ J/\psi$	1.5×10^{-3}	[11]

Analogously we define $P_{4\to 2}$, which is the probability that four quarks, $c\bar{c}c\bar{c}$ form two J/ψ's. Using the numbers from Table I, we have:

$$P_{4\to 2} = \frac{\sigma_{J/\psi J/\psi}}{\sigma_{c\bar{c}c\bar{c}}} =\simeq 10^{-6} \ . \tag{15}$$

These relations suggest that each time that two charm quarks coalesce we pay a penalty of a factor 10^{-3}. This would explain the above observation, namely that $P_{4\to 2} \simeq (P_{2\to 1})^2$. We shall assume that when two charmoniumlike objects coalesce to form the T_{4c} the penalty factor is the same. Looking at Fig. 1 we see that T_{4c} is a two step process: first we have a $4 \to 2$ process and then a $2 \to 1$ coalescence. With this assumption we can estimate F_T as:

$$F_T = \frac{\sigma_{T_{4c}}}{\sigma_{c\bar{c}c\bar{c}}} = P_{4\to 2} \, . \, P_{2\to 1} = (P_{2\to 1})^3 = 10^{-9} \ . \tag{16}$$

Multiplying (12) by the F_T found above we obtain the final cross section for the production of T_{4c}, which is shown in Fig. 2 for two values of the charm mass. The main feature of the curves is the rapid rise with $\sqrt{s}$, which might render the T_{4c} easily observable already at 14 TeV. This same fast growing trend was observed in other estimates with DPS [5].

The next step would be to replace (5) by a parametrization of the gluon distribution obtained in the global analysis of the current experimental data and also replace (6) by the full charm production cross section. Finally it would be useful to study the decay channels of the T_{4c}, making more concrete predictions. We postpone this for a future work [8].

Acknowledgments

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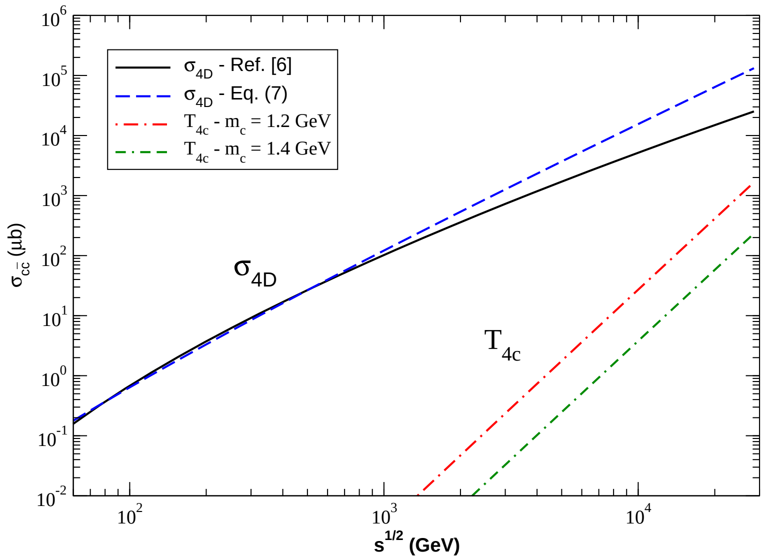

Figure 2. Cross sections as a function of the energy. Solid line: σ_{4D} calculated in [6]. Dashed line: σ_{4D} calculated with Eq. (7). Dot-dashed lines: $\sigma_{T_{4c}}$ calculated with two different masses for the charm quark.