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The energy dependence of the tetraquark production cross section

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We develop a model to estimate the production cross section of heavy tetraquarks as a function of the center of mass energy. The model employs two formalisms, namely the Double Parton Scattering (DPS) processes and the Color Evaporation Model (CEM). In a previous work we used our model to estimate the production cross section of the X(3872) and of the T_{4c} in proton-proton collisions at the LHC. Now we employ it to estimate the production cross section of the T_{4b}, a tetraquark composed by two $b\bar{b}$ pairs, and of the T_{2bc}, a tetraquark composed by a $b\bar{b}$ and a $c\bar{c}$, at the energies of the LHC.

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1. Introduction

The existence of exotic hadrons has been firmly established (see, e.g., [1] and references therein for a review) and the next step is to determine their structure. One of the most popular models used to describe them is the tetraquark, where two quark-antiquark pairs are confined in a compact region of space. However, it is not known a way to calculate the tetraquark production cross section. In Refs. [2] and [3] we give a step in this direction. We proposed a model to calculate the tetraquark production cross section as a function of the center of mass energy in proton-proton collisions. In [2] we used approximate analytical expressions for the gluonic distributions ($g(x) = 1/x^{1+\lambda}$, with $\lambda \geq 0$) and for the $gg \to c\bar{c}$ elementary cross section ($\sigma_{g_1 g_2 \to c\bar{c}} = \alpha_s / x_1 x_2 s$) and predicted a much faster growth with the energy for the production of the T_{4c} when compared with the production of open charm. Here T_{4c} stands for a tetraquark composed by two $c\bar{c}$ pairs. In summary, we obtained: $\sigma_{4D} \propto s^{2\lambda} (\ln s)^2$ and $\sigma_{T_{4c}} \propto s^{1+2\lambda} (\ln s)$. In Ref. [3] we used our model with more reliable gluonic pdf's and with the correct LO pQCD expression for the gluon-gluon elementary cross section and made predictions for the production cross section of the X(3872) and of the T_{4c} in proton-proton collisions at the energies of the LHC. For $\sqrt{s} = 14$ TeV we obtained: $\sigma_X \approx 45$ nb and $\sigma_{T_{4c}} \approx 7$ nb. In this work we use this model to calculate the production cross section of the T_{4b} and of the T_{2bc}. The first is a tetraquark composed by two $b\bar{b}$ pairs while the second is a tetraquark composed by a $b\bar{b}$ and a $c\bar{c}$.

2. A model for the production of tetraquarks

Our model for the tetraquark production is described in two steps. The first step is the production of two quark-antiquark pairs with invariant mass M_{12} and M_{34} in the double parton scattering (DPS) process. This is the process where two gluons from the hadron target scatter independently with two gluons from the hadron projectile, producing a quark-antiquark pair each. The second step is the coalescence of the clusters M_{12} and M_{34} in a compact four quark state of mass M, and its subsequent transition to the final tetraquark state M_T. This process is described by employing the main ideas of the color evaporation model (CEM), which successfully describes the production of charmonium. In this approach the clusters M_{12} and M_{34} are kinematically bound into the compact four quark state M, which in turn exchanges gluons with the hadronic color field to become color neutral and to acquire the correct final state tetraquark mass M_T. The gluons exchanged in this process carry energy Δ that goes from almost zero up to the Λ_{QCD} scale.

Our expression for the tetraquark production cross section was derived in Ref. [3], and is given by:

$$\begin{aligned}
\sigma_T = \frac{F_T}{\sigma_{eff}} & \left[\frac{1}{s} \int dy_{12} \int dM_{12}^2 \;\; g(\bar{x}_1, \mu^2)\, g(\bar{x}_2, \mu^2)\, \sigma_{g_1 g_2 \to c\bar{c}} \right] \\
\times & \left[\frac{1}{s} \int dy_{34} \int dM_{34}^2 \;\; g(\bar{x}_3, \mu^2)\, g(\bar{x}_4, \mu^2)\, \sigma_{g_3 g_4 \to b\bar{b}} \right] \\
\times & \;\; \Theta(1 - \bar{x}_1 - \bar{x}_3)\; \Theta(1 - \bar{x}_2 - \bar{x}_4) \\
\times & \;\; \Theta(M_{12}^2 - 4m_c^2)\; \Theta(M_{34}^2 - 4m_b^2)\, \delta(y_{34} - y_{12})
\end{aligned} \tag{2.1}$$

where $\sigma_{eff} \simeq 15$ mb for proton-proton collisions is the effective cross section that appears in the DPS pocket formula, which is the starting formula for our model. Here y_{12} (y_{34}) is the rapidity of the cluster with invariant mass M_{12} (M_{34}). Following the scheme of the CEM we introduced the parameter F_T which represents the probability for the four-quark system to evolve to a particular tetraquark T state. F_T is considered as energy-momentum and process independent, and after being determined by equalling above formula to the tetraquark production cross section at a given energy the model can be used to predict, with no additional free parameter, the tetraquark production cross section to any other value of the energy. All other terms of Eq. (2.1) are explicitly written in Ref. [3]. As in [3] we use the Martin-Roberts-Stirling-Thorne (MRST) gluon distribution [4] for $g(\bar{x},\mu^2)$ and $\Delta \approx \Lambda_{QCD} \approx 200$ GeV as the maximum energy carried by the gluons exchanged in the transition $M \to M_T$.

3. Predictions for T_{4b} and T_{2bc} production cross sections

The T_{4b} and the T_{2bc} are two hypothetical tetraquarks that have not yet been found experimentally, but at least in principle they may exist. Recently their possible quantum numbers were determined in Ref. [5] by using the diquark model. Unfortunately, the arbitrary number of gluons exchanged by the cluster M in the transition to the final state makes our model lose any control over the quantum numbers of the tetraquark produced, except for its mass. In the case of the T_{4b} the authors of [5] found three possible states, all of them with masses very close to $M_{T_{4b}} = 18.8$ GeV. For the T_{2bc} six different states were found, all with masses close to $M_{T_{2bc}} = 12.5$ GeV. We assume these values in our calculations. Since there is no experimental data on the production of these tetraquarks, for the time being the best we can do is to make a guess of reasonable values for their production cross sections at a given energy so as to determine the constant F_T, and then make predictions for higher energies. This is what we did to make estimations for the T_{4c} in Ref. [3]. The production cross section of the X(3872) was measured by the CMS collaboration [6] at 7 TeV, so we tried to guess a value for $\sigma_{T_{4c}}$ at this energy based on the value measured for σ_X. It happens that energetically speaking the T_{4c} is more difficult to be produced than the X(3872) because this last is composed by a $c\bar{c}$ and a light $q\bar{q}$. Based on this observation we took the experimental value of σ_X (≈ 30 nb) and multiplied by a penalty factor given by $\sigma_{c\bar{c}}\sigma_{c\bar{c}}/\sigma_{c\bar{c}}\sigma_{q\bar{q}} \simeq 0.12$, obtaining $\sigma_{T_{4c}} = 0.12 \times \sigma_X = 3.6$ nb. Following this same strategy let us guess values for $\sigma_{T_{4b}}$ and for $\sigma_{T_{2bc}}$ at 7 TeV based on the value determined for $\sigma_{T_{4c}}$ in Ref. [3]. We have:

$$\sigma_{T_{4b}} = \frac{\sigma_{b\bar{b}} \cdot \sigma_{b\bar{b}}}{\sigma_{c\bar{c}} \cdot \sigma_{c\bar{c}}}\, \sigma_{T_{4c}} \simeq 4.2 \times 10^{-3}\, nb \qquad ; \qquad \sigma_{T_{2bc}} = \frac{\sigma_{b\bar{b}} \cdot \sigma_{c\bar{c}}}{\sigma_{c\bar{c}} \cdot \sigma_{c\bar{c}}}\, \sigma_{T_{4c}} \simeq 0.12\, nb \tag{3.1}$$

where the experimental values $\sigma_{c\bar{c}} \simeq 8.5$ mb [7] and $\sigma_{b\bar{b}} \simeq 288\ \mu$b [8] at 7 TeV were used. Now we use the values determined in (3.1) to fix the constants $F_{T_{4b}}$ and $F_{T_{2bc}}$, respectively to the tetraquarks T_{4b} and T_{2bc}. Then we plot their production cross sections as functions of the energy in Fig. 1. On the left we have the curves for the T_{4b} and on the right we have the ones for the T_{2bc}. It is difficult to determine the uncertainty of this calculation. However we verified that our results are very sensitive to the masses chosen for the heavy quarks. So we varied the charm mass from 1.2 to 1.5 GeV and the bottom mass from 4.3 to 4.6 GeV and determined an error band based on these choices. In each plot the upper curve corresponds to the lightest masses for the heavy quarks, while the lower curve corresponds to the heavier masses. The points at 7 and 14 TeV were chosen so that the average value of the curves cross them.

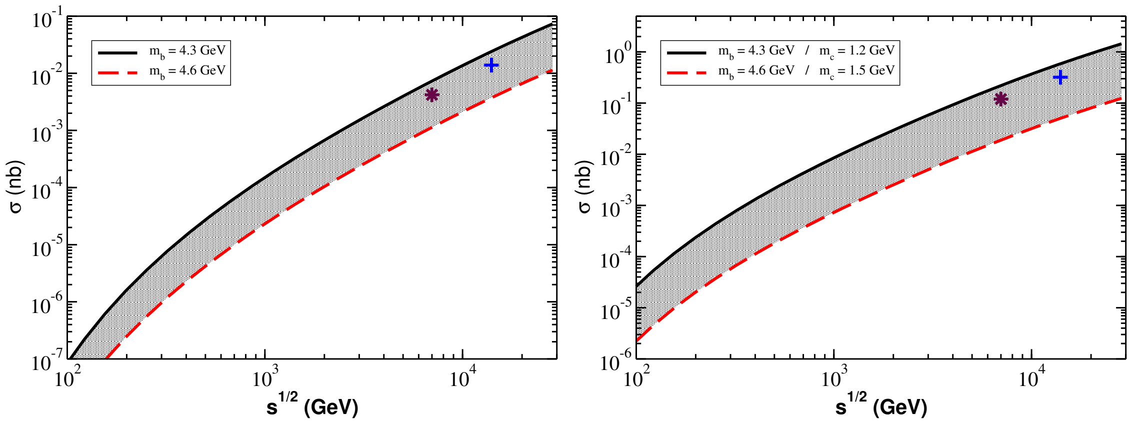

Figure 1: Prediction for the tetraquark production cross section as a function of the center of mass energy in proton-proton collisions. Left: prediction for the T_{4b}; and Right: prediction for the T_{2bc}. The asterisk is the point used to fix the constant F_T at $\sqrt{s} = 7$ TeV and the cross is the prediction of the model for $\sqrt{s} = 14$ TeV.

For 14 TeV our model predicts:

$$\sigma_{T_{4b}} \approx (13.9 \pm 10.1) \times 10^{-3} nb \qquad ; \qquad \sigma_{T_{2bc}} \approx (0.32 \pm 0.27) nb \tag{3.2}$$

The large band error shows the sensitiveness of the model to the choice of the heavy quark masses.

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