The energy dependence of the tetraquark production cross section

Institute of Physics

University of Sao Paulo

F. Carvalho, E.R. Cazaroto*, V.P. Gonçalves, F.S. Navarra

*e-mail: cazaroto@if.usp.br

We develop a very first model to describe the energy dependence of the tetraquark production cross section in proton-proton collisions. The model implements a mixture of two different formalisms. It employs the Double Parton Scattering (DPS) formalism to describe the production of two quark pairs (a $q_1\bar{q}_1$ plus a $q_2\bar{q}_2$) and uses the Color Evaporation Model (CEM) to describe the coalescence of the two quark pairs in a compact tetraquark state. After using the experimental value of the X(3872) production cross section measured by the CMS collaboration we fixed the parameters of our model at 7 TeV and make predictions for 14 TeV. We also make predictions for the production cross section of the T_{4c} (a tetraquark composed by 2 $c\bar{c}$ pairs) for the energies of the LHC.

Introduction

The existence of exotic hadrons has been firmly established [1,2]. However, their structure is still unknown. The two configurations most discussed in the literature are the meson molecule and the tetraquark. One difficult of the meson molecule approach is that it is not able to describe properly the measured value of the production cross sections [1,3,4]. In the particular case of the X(3872) production in proton-proton collisions the value obtained using the molecule formalism is 2 orders of magnitude smaller than the measured one. The present challenge for theorists is to show that these data can be described using the tetraquark model. To the best of our knowledge a estimative of the exotic hadrons production cross sections using the tetraquark approach was not done yet in the literature. In this work we give a first step in this direction developing a model to calculate the production cross section of tetraquarks as a function of the center of mass energy of the collision. We then estimate the production cross sections of the X(3872) and of the T_{4c} (a tetraquark compose by 2 $c\bar{c}$ pairs) at the energies of the LHC.

The Model

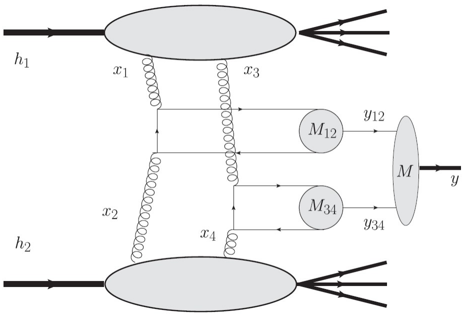
Our model employs two different formalisms. We use the Double Parton Scattering (DPS) to describe the production of 2 quark pairs ($q_1\bar{q}_1$ and $q_2\bar{q}_2$) and the Color Evaporation Model (CEM) to describe the coalescence of the two pairs in a compact tetraquark.

The Double Parton Scattering (DPS)

The production of 2 quark pairs, e.g. a $c\bar{c}c\bar{c}$, can take place as an ${\alpha_s}^2$ correction to the standard Single Parton Scattering (SPS) process, where one gluon from the proton target scatters with one gluon from the proton projectile, i.e., the process: $gg \rightarrow c\bar{c}c\bar{c}$. Nonetheless, due the rapid increase of the gluonic distributions with the center of mass energy of the proton-proton collision, the occurrence of multiple parton scatterings cannot be disregarded. In other words, at high energies there is a high probability that two independent $gg \rightarrow c\bar{c}$ processes take place in the same p-p collision, and this is another possibility of producing two $c\bar{c}$ pairs. This is called Double Parton Scattering (two gluons from the target scatter independently with two gluons from the projectile). In fact, it has been shown that in p-p collisions at the LHC the contribution of the DPS channel to the charm production cross section is of the same order of magnitude as the SPS contribution [5,6]. For our purposes, here we consider the production of two $c\bar{c}$ pairs as well as the production of a $c\bar{c}$ and a $q\bar{q}$ in DPS processes, with q a light quark.

The Color Evaporation Model (CEM)

After producing the 2 quark pairs we need a mechanism to bind them together in a compact tetraquark. To do this we use the same ideas of the Color Evaporation Model formalism for the production of charmonium. In the CEM the $c\bar{c}$ pair is kinematically bound, i.e., the pair sticks together because its invariant mass is not large enough to produce anything else. The pair can exchange additional gluons with the hadronic color field to become color neutral. We use the CEM ideas to study the production of the T_{4c} and of the $X(3872)$ in DPS events. Our scheme is depicted in the figure below.



When the clusters 12 and 34 contain a $c\bar{c}$ pair each one, the final state will be the T_{4c}. If we change the $c\bar{c}$ by a light $q\bar{q}$ pair in the cluster 34 the final state will be a X(3872).

T_{4c}: The all-charm tetraquark

The T_{4c} state was first discussed in 1975 by Iwasaky [7], and then many other discussions were done in the 1980's and early 1990's concerning its existence. More recently Lloyd and Vary found that deeply bound ($\approx$ 100 MeV) states may exist with masses close to 6 GeV [8]. In [9], using the hyper-spherical harmonic formalism, the authors found that the T_{4c} may exists with quantum numbers 0^{+-}, 2^{+-} and 2^{++} and masses 6.50, 6.65 and 6.22 GeV. And in 2012 the authors of [10] studied this problem with the Bethe-Salpeter approach and found that a T_{4c} state can exists with $J^{PC} = 0^{++}$ and $M_{T4c} = 5.3 \pm 0.5$ GeV.

Formulas

We start with the DPS "pocket formula":

$$\sigma_{\text{DPS}} \propto \frac{\sigma^{12}_{\text{SPS}}\sigma^{34}_{\text{SPS}}}{\sigma_{\text{eff}}}$$

With $\sigma_{eff} \approx 15$ mb a constant determined from a fit to experimental data and σ_{SPS} the standard QCD parton model formula. In terms of the masses and of the rapidities of the clusters 12 and 34 (rather than the Bjorken variables x_1, x_2, x_3 and x_4 of the individual quarks) the above formula is expanded as:

$$\begin{aligned}\sigma_{\text{DPS}} = \frac{F_{T_{4c}}}{\sigma_{\text{eff}}}&\left[\frac{1}{s}\int dy_{12}\int dM^2_{12}g(\bar{x}_1,\mu^2)g(\bar{x}_2,\mu^2)\sigma_{g_1g_2\rightarrow c\bar{c}}\right]\\ &\times\left[\frac{1}{s}\int dy_{34}\int dM^2_{34}g(\bar{x}_3,\mu^2)g(\bar{x}_4,\mu^2)\sigma_{g_3g_4\rightarrow c\bar{c}}\right]\\ &\times\Theta(1-\bar{x}_1-\bar{x}_3)\Theta(1-\bar{x}_2-\bar{x}_4)\Theta(M^2_{12}-4m^2_c)\\ &\times\Theta(M^2_{34}-4m^2_c)\delta(y_{34}-y_{12})\end{aligned}$$

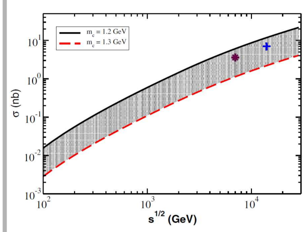
Where the θ functions were introduced to impose the momentum conservation and to guarantee that the gluon pairs have invariant masses high enough to produce the desired quark pairs. The g functions are the gluonic distributions of the protons and the delta function imposes that the two clusters are "flying together" (they are bound).

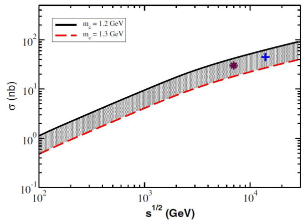
Results

Once the quark masses have been chosen, the only free parameter of the model is the normalization constant F_T. To determine it we just need a single experimental value of the tetraquark production cross section, and done it the model is able to predict other values for different energies. For the X(3872) we use the value measured by the CMS collaboration [11], $\sigma(\sqrt{s} = 7\text{ TeV}) \approx 30$ nb. On the other hand, nothing is known about the T_{4c}. For the time being we can only make a simple estimate. For this we use the experimental point of the X(3872) production cross section and multiply it by a penalty factor.

$$\sigma_{T_{4c}} = \frac{\sigma_{c\bar{c}c\bar{c}}}{\sigma_{c\bar{c}q\bar{q}}}\sigma_X \simeq \frac{\sigma_{c\bar{c}}\sigma_{c\bar{c}}}{\sigma_{c\bar{c}}\sigma_{q\bar{q}}}\sigma_X \simeq \frac{\sigma_{c\bar{c}}}{\sigma_{\text{inel}}} \simeq 0.12\sigma_X$$

Our results are:





Predictions are:

$$\sigma_{T_{4c}}(\sqrt{s} = 14\text{ TeV}) \simeq (7.0 \pm 4.8)\text{ nb} \qquad \sigma_X(\sqrt{s} = 14\text{ TeV}) \simeq 44.6 \pm 17.7\text{ nb}$$

References

[1] A. Esposito, A. L. Guerrieri, F. Piccinini, A. Pilloni, and A. D. Polosa, Int. J. Mod. Phys. A 30, 1530002 (2015).
[2] M. Nielsen and F. S. Navarra, Mod. Phys. Lett. A 29, 1430005 (2014); M. Nielsen, F. S. Navarra, and S. H. Lee, Phys. Rep. 497, 41 (2010); F. S. Navarra, M. Nielsen, and S. H. Lee, Phys. Lett. B 649, 166 (2007).
[3] C. Bignamini, B. Grinstein, F. Piccinini, A. D. Polosa, and C. Sabelli, Phys. Rev. Lett. 103, 162001 (2009).
[4] A. Esposito, A. L. Guerrieri, L. Maiani, F. Piccinini, A. Pilloni, A. D. Polosa, and V. Riquer, Phys. Rev. D 92, 034028 (2015).
[5] E. R. Cazaroto, V. P. Goncalves, and F. S. Navarra, Phys. Rev. D 88, 034005 (2013).
[6] M. Luszczak, R. Maciula, and A. Szczurek, Phys. Rev. D 85, 094034 (2012).
[7] Y. Iwasaki, Prog. Theor. Phys. 54, 492 (1975).
[8] R. J. Lloyd and J. P. Vary, Phys. Rev. D 70, 014009 (2004).
[9] N. Barnea, J. Vijande, and A. Valcarce, Phys. Rev. D 73, 054004 (2006).
[10] W. Heupel, G. Eichmann, and C. S. Fischer, Phys. Lett. B 718, 545 (2012).
[11] S. Chatrchyan et al. (CMS Collaboration), J. High Energy Phys. 04 (2013) 154.

This work was partially financed by the Brazilian funding agencies: