The Chances to Produce and Detect the $\text{bb}\bar{u}\bar{d}$ Tetraquark at LHC

D. Janc\textsuperscript{1}\textdagger M. Rosina\textsuperscript{1,2} D. Treleani\textsuperscript{3} and A. Del Fabbro\textsuperscript{3}

\textsuperscript{1}J. Stefan Institute, 1000 Ljubljana, Slovenia
\textsuperscript{2}Faculty of Mathematics and Physics, University of Ljubljana, 1000 Ljubljana, Slovenia
\textsuperscript{3}Universita di Trieste; Dipartimento di Fisica Teorica, Strada Costiera 11, Miramare-Grignano, and INFN, Sezione di Trieste, I-34014 Trieste, Italy.

Abstract. In the LHC collider a significant rate of events with double parton scattering is expected. This will be the leading mechanism for production of two $\text{bb}$ pairs. We estimate the probability of binding two $b$ quarks into a diquark and the probability of dressing this diquark into a $\text{bb}\bar{u}\bar{d}$ ($I\!P = 0^+$) tetraquark. Calculations shows that that this bound state of two $B$ mesons is stable against the strong interaction and has a life time of the order of ps. We estimate that the production rate at luminosity $\mathcal{L} = 0.1$ events per second will be about 6 tetraquarks per hour or more.

1 Introduction

In the new large hadron collider at CERN on can expect a sizable rate of events where two heavy $b$ quarks and two heavy $\bar{b}$ antiquarks are simultaneously produced. This makes it possible that two heavy quarks or antiquarks combine to create a double heavy hadron after they dress with light quarks.

There are two mechanisms for creation of two heavy quark-antiquark pairs. The first is by a single parton scattering where initially only one heavy quark-antiquark pair is produced and the second pair is then created by the fragmentation of one of initial quarks. The second mechanism is a double parton scattering. Calculations show that the double scattering although power suppressed gives at the center of the mass energy of 14 TeV a four times larger cross section for the production of two $b$-quark pairs. For the creation of a heavy diquark one requires that the two quarks are close together in momentum space. Since in the fragmentation the two $b$ quarks tend to fly in opposite

\textdagger E-mail address: damijan.janc@ijs.si
directions this also confirms that the dominant mechanism would be two parton scattering. The creation of the double heavy hadron is then a two step process. First two heavy quarks which are close together in momentum space bind into a diquark. We can estimate that the probability for this is proportional to the overlap of the wave functions of the quarks which are considered to be free with the wave function of the diquark. The second step is then dressing of this diquark with the light quark into a doubly heavy baryon or dressing with the two light quarks into a heavy dimeson.

2 Phenomenological estimate

Let me first give a very simple phenomenological estimate why a BB dimeson should exist with a binding energy of about 100 MeV and why a similar DD dimeson is unstable against strong interaction [2]. In this estimation we consider the heavy dimeson to be a bound state of two heavy b-quarks combined in a diquark with the spin 1 and two light antiquarks with the quantum numbers spin 0, isospin 0. The starting point is that the light antiquarks around the heavy diquark behave as in \( \Lambda_b \). This would be exactly true in the limit where the mass of the b quark goes to infinity and the heavy diquark is point-like. This correspond to assumption that we can neglect the size of the heavy diquark in dimeson. The second assumption is that the interaction between heavy b quarks in a colour antitriplet state is half as strong as the interaction between heavy quark and antiquark in heavy meson. With this assumption we can estimate the binding energy of heavy dimeson. Since the spectroscopy of heavy mesons is quite well described with nonrelativistic potential models we see that the binding energy for a system with half as strong interaction \( V_{QQ} \) is half the binding energy for a system with original interaction \( V_{Q\bar{Q}} \) and twice lighter particles (\( m_Q \rightarrow m_Q/2 \)).

\[
\left[ \frac{p^2}{m_Q} + V_{QQ} \right] \psi = \frac{1}{2} \left[ \frac{p^2}{m_{Q/2}} + V_{Q\bar{Q}} \right] \psi = \frac{1}{2} E(m_Q/2) \psi
\]

We obtain \( E(m_Q/2) \) by plotting the binding energy of heavy mesons as a function of the reduced mass of the system [2]. We do that for different choices of constituent quark masses, to estimate the uncertainty due to quark masses. The plot is very smooth and we estimate the binding energy of the heavy bb diquark \( E(m_b/2)/2 \) to be \(-390 \pm 15 \text{ MeV}\). If we combine this with the masses of heavy mesons and \( \Lambda_b \) baryon we can obtain the phenomenological estimate for binding energy of the heavy dimeson \( \Delta T_{bb} \)

\[
\Delta T_{bb} = m_{\Lambda_b} + \left[ m_T - E(m_b) + E(m_b/2) \right]/2 - m_B - m_{B*} = -130 \pm 15 \text{ MeV}
\]

while the heavy dimeson with the two c quarks is unbound. This agrees well with some previous four body calculations [3] [4] in the constituent quark model.
3 b-quark pair production

Since at LHC there will be a large parton luminosity we can hope that the production rate of double heavy dimers will be high enough to make detection possible. The dominant contribution to b-quark pairs production will be double parton scattering - the gluon fusion \( gg \rightarrow b\bar{b} \). To calculate this cross section one needs to make an assumption about the two body distribution function \( \Gamma(x_1, x_2, d) \):

\[
\Gamma(x_1, x_2, d) = G(x_1)G(x_2)F(d),
\]

where \( G(x) \) is the one-body parton function while the parton pair density is described by the normalized function \( F(d) \). The distance of the two partons belonging to the same proton is \( d \) and the \( x_1 \) and \( x_2 \) are their fractional momenta. Doing so, we neglect the correlations in momenta. Then the cross section \( \sigma_D \) for the double gluon fusion has a form

\[
\sigma_D(b\bar{b}b\bar{b}) = \frac{\sigma_s(b\bar{b})^2}{2\sigma_{ff}}, \quad \sigma_{ff}^{-1} = \int d^2bF(b)^2,
\]

where \( \sigma_s(b\bar{b}) \) is cross section for a fusion of two gluons into a b quark-antiquark pair. For \( \sigma_{ff} \) we take the value measured in the experimental study of double parton collision by CDF at Fermilab in the reaction \( p\bar{p} \rightarrow \gamma/\pi^0 + 3 \text{jets} + X \) \cite{5}. This experimental value is 14.5 mb. Doing this we assume that also some correlation between quarks in the same proton are taken into account which were neglected in \cite{1}. There is also same uncertainty about the single scattering cross section \( \sigma_s \) since the higher order corrections are large and they enter squared into the cross section for double scattering \cite{2}. For details see \cite{1}. The cross section calculated then from \cite{2}, taking into account that only the pseudorapidity region \( 1.8 < \eta < 4.9 \) will be covered by forward LHCb detector, is 85 nb. For two b quarks to combine into a diquark it is very important that they are close together in momentum space. Calculations gives that the cross section is approximately proportional to momentum volume \( d\sigma/d^3p \approx 0.4 \text{nb}/\text{GeV}^3 \) up to \( p \leq 2\text{GeV} \).

4 Formation of the diquark and dressing

We assume that the production of the two heavy b quarks in double parton scattering is uniform inside the protons. Furthermore we take an instantaneous approximation so that the amplitude \( M(p) \) for the formation of the diquark is simply given by the overlap \( M(p) = \langle \phi(p) | \psi \rangle \) of the wave function of the two b quarks \( \phi(p) \) with the wave function of the diquark \( \psi \). This wave function is calculated in constituent quark model used also in \cite{3} and \cite{4}. So the production cross section is given by

\[
\sigma = \int d^3p \frac{d\sigma}{d^3p} M^2(p) = 0.15 \text{nb}
\]

Dressing of a heavy diquark is governed by the quantum chromodynamics. But
since fragmentation of diquark into a hadron is impossible to calculate using perturbative QCD methods, we estimate the probability from experimental data obtained at Fermilab and at LEP experiment \[6\]. Their results show that the probability that the b quark will be dressed with u or d antiquark is \(0.38 \pm 0.02\), with s antiquark \(0.16 \pm 0.03\) and the probability for dressing with light quarks to form \(\Lambda_b\) is \(0.10 \pm 0.03\). In our estimation we compared the heavy dimeson with the \(\Lambda_b\) baryon where the role of diquark in the first case is played by the heavy b quark in the second. So we assume that the diquark will get dressed into a dimeson with the same probability as heavy quark is dressed into a lambda b baryon - that is \(0.10 \pm 0.03\). The cross section for the heavy dimeson production is thus \(\sigma = 0.015 \text{nb}\) which will give at the expected luminosity the production rate of 5-6 events per hour.

5 Decay and detection

We expect that the bb\(\bar{u}\)d tetraquark will be stable against strong and electromagnetic decay and will decay only weakly. The main channel would be the decay of one of the b quarks into c quark followed by the weak decay of the second b quark. But this channel will be difficult to distinguish from the channel of two unbound B mesons which will be the main background contribution. The more characteristic decay channel would be the formation of the \(\Upsilon\) and light meson through b \(\rightarrow\bar{b}\) oscillation inspired by B\(^0\) \(\rightarrow\bar{B}^0\) oscillations. But this oscillations are here negligible since the tetraquark is not degenerate with final state of two unbound mesons. We are still searching for new ideas for the detection of doubly b tetraquarks.

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