Physics Letters B 700 (2011) 221–228

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Bottom pair production and search for heavy resonances

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ARTICLE INFO

Article history:
Received 13 March 2011
Received in revised form 20 April 2011
Accepted 4 May 2011
Available online 7 May 2011
Editor: G.F. Giudice

Keywords:
Axigluon
Coloron
Tevatron
LHC
$b\bar{b}$

ABSTRACT

The search for heavy resonances has for long been a part of the physics program at colliders. Traditionally, the dijet channel has been examined as part of this search. Here, $b\bar{b}$ production is examined as a possible search channel. The chiral color model (flavor universal as well as non-universal) and the flavor universal coloron model are chosen as templates of models that predict the existence of heavy colored gauge bosons. It is seen that, apart from the resonance, the interference of the Standard Model and new physics amplitudes could provide a useful signal. Of particular interest, is the case of the non-universal chiral color model, as this channel may allow the model to be confirmed or ruled out as the reason behind the forward–backward asymmetry in $t\bar{t}$ production.

1. Introduction

The Standard Model (SM) seeks to describe Nature as a realization of the gauge group $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$. While there exists substantial experimental evidence to suggest that this is indeed correct, at least up to the scale of a few hundred GeVs, the picture is far from complete. Several extensions of the SM have been suggested [1] and continue to be suggested in the attempt to redress the 'unsatisfactory' aspects of the model. One common feature among many of these models is the existence of massive particles that couple to a pair of SM fermions and are likely to appear as a resonance in the process $f\bar{f} \to f'\bar{f}'$. Experimental searches for such particles are most often carried out in the dijet channel or in the Drell–Yan process. However, as one wishes to study a fermion–anti-fermion final state, the $b\bar{b}$ channel is also an option that could be investigated. If the new particles under consideration have only strong interactions, then the Drell–Yan process would not be sensitive to their presence. As for the dijet process, while it may receive contributions from new strongly interacting particles, sensitivity would be limited by the fact that final states consisting of a quark–anti-quark pair not be distinguishable from those with qq, $\bar{q}\bar{q}$, qg, $\bar{q}g$ or gg. On the other hand, b-jets can be identified with reasonable accuracy using flavor-tagging techniques. Thus, $b\bar{b}$ production may prove to be useful as a search channel.

In this Letter, the reach of the $b\bar{b}$ channel in the search for some classes of new physics (NP) models, namely, the chiral color model (with and without flavor universality) and the flavor universal coloron model, is examined. This channel is of particular importance for the flavor non-universal chiral color model. The observation of forward–backward asymmetry in $t\bar{t}$ production (A^t_{FB}) caused a slew of models to be proposed as plausible explanations. In a majority of these, new couplings were introduced for the top quark while keeping bottom quark couplings unchanged. The nu-axigluon is an exception to this and a search in the $b\bar{b}$ channel can provide one way to distinguish this model amongst a host of others.

The next section contains a brief description of the models and the existing limits on their constituents. The details of the calculation are discussed in Sections 3 and 4.

2. Models

In the Standard Model, the gauge group $SU(2)_L \otimes U(1)_Y$ is broken to $U(1)_{em}$. This has prompted attempts to examine whether QCD may be the remnant of a broken symmetry too. The unifiable chiral color model and the flavor universal coloron model are two models which propose that $SU(3)_C$ is actually a relic of an $SU(3) \otimes SU(3)$ symmetry broken spontaneously at a high scale.

Chiral color models [2] assume the gauge group describing strong, weak and electromagnetic interactions to be $SU(3)_L \otimes SU(3)_R \otimes SU(2)_L \otimes U(1)_Y$. $SU(3)_{R-L}$ is sought to be broken spontaneously at a scale comparable to the scale of electroweak symmetry breaking. $SU(3)_{R+L}$ remains and is identified with $SU(3)_C$. Thus, in these models, there exists an octet of massive colored gauge bosons (axigluons) alongside an octet of massless ones (gluons). The axigluons (A) have an axial vector coupling to quarks

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0370-2693/$ – see front matter
doi:10.1016/j.physletb.2011.05.006

which has the *same* strength (g_s) as the gluon–quark coupling. These models also require the existence of additional fermions and colored scalars. In fact, in the most optimistic scenario [3], five generations of quarks and leptons, three Higgs doublets and additional electrically neutral as well as charged fermion multiplets in 'non-standard' representations are predicted. This gives rise to a model that, besides replicating many of the successes of the Standard Model, is rich in high scale physics and is unifiable at a scale much lower than that for the latter.

Initially the scale of chiral-color breaking was assumed to be the same as that of electroweak symmetry breaking and axigluons were expected to have mass ~ 250 GeV. Early experimental bounds obtained from measurements of Υ decays and hadronic cross-sections in e^+e^- collisions [4] ruled out $M_A < 50$ GeV. The region 50 GeV $< M_A <$ 120 GeV was ruled out by considering effects on hadronic decays of Z^0 and the possibility of associated production of axigluons [5]. Dijet production in hadronic colliders has been repeatedly surveyed for signals of a resonant axigluon [6]. A series of searches at the Tevatron in this channel [7] have now resulted in exclusion of $M_A < 1250$ GeV at 95% confidence [8]. The use of forward–backward asymmetry[1] as a signal for axigluons has also been studied [9] and possible limits from top production data have been considered in Refs. [10–12].

More recently, flavor non-universal versions of the original chiral color model have been proposed [13,14] as possible explanations of the forward–backward asymmetry observed in $t\bar{t}$ production at the Tevatron [15,16]. In particular, the model in Ref. [13] contains four quark generations and is based on the gauge group $SU(3)_A \otimes SU(3)_B \otimes SU(2)_L \otimes U(1)_Y$. The gluon and the flavor non-universal axigluon (A') are admixtures of the gauge bosons corresponding to $SU(3)_A$ and $SU(3)_B$ with $\theta_{A'}$ being the mixing angle. The coupling of the non-universal axigluon[2] consists of a vector and an axial–vector part. While the vector coupling is generation universal ($-g_s \cot 2\theta_{A'}$), the axial–vector coupling is not, with $g_A^q = -g_s \operatorname{cosec} 2\theta_{A'}$ for the first two generations and $g_A^t = +g_s \operatorname{cosec} 2\theta_{A'}$ for the other two. Demanding that the couplings be perturbative, restricts $10^\circ < \theta_{A'} < 45^\circ$.

Although, the Lorentz structure of the couplings is the similar to that in the original chiral color model, the non-universal nature of the couplings implies that the mass limits on the former from the dijet search, are not directly applicable. However, as the main motivation behind the proposition was to explain the observed A_{FB}^t, the parameter space can be constrained using measurements in the top sector, such as the $t\bar{t}$ cross-section, A_{FB}^t and the $m_{t\bar{t}}$ spectrum [13]. In particular, the apparent agreement of the invariant mass distribution (which is reported for $m_{t\bar{t}}$ up to 1400 GeV) with the SM, can be used immediately, albeit somewhat naively, to put a lower limit of 1400 GeV on $M_{A'}$.

In the flavor universal coloron model [17], the high scale color gauge group is $SU(3)_I \otimes SU(3)_{II}$. This is broken to $SU(3)_C$ at the TeV scale. Here again, there is an octet of massive colored gauge bosons (colorons) in addition to gluons. The original model [18] was aimed at constructing a dynamical mechanism for electroweak symmetry breaking involving a $\langle\bar{t}t\rangle$ condensate. In this model, the third generation quarks belonged to a different representation of $SU(3)_I \otimes SU(3)_{II}$ as compared to the other quark families. However, in the flavor universal version of the model, all quarks transform as $(1, 3)$ under the extended color gauge group. The couplings are proportional to ξ_1 and ξ_2 for $SU(3)_I$ and $SU(3)_{II}$ respectively with $\xi_1 \ll \xi_2$. The coupling of the coloron (C) to quarks is then proportional to $\gamma_\mu \cot\xi$, where, ξ is the mixing angle and $\cot\xi = \xi_2/\xi_1$. An additional scalar multiplet, transforming as $(3, \bar{3})$, effects the symmetry breaking. Initially, this model was proposed in order to explain excess seen in the inclusive jet cross-section in the high E_T region by the CDF experiment at the Tevatron [19]. With increase in statistics and improvement in both theoretical calculations and experimental techniques, the agreement between theory and experiment has improved considerably [20]. However, the model itself continues to be of interest as it can accommodate, within its framework, a theory with composite quarks [17]. Further, as in the case of the original top-color proposal [18,21], the flavor universal version too can provide a scheme for dynamical EWSB via formation of a $\langle\bar{t}t\rangle$ condensate [22].

The original proponents of the model [17], placed the limit $M_C/\cot\xi > 450$ GeV required to keep corrections to the electroweak ρ parameter within allowed limits [23]. In addition, demanding that the model remain in its Higgs phase at low energies, results in an upper limit ~ 4 on the value of $\cot\xi$ [24]. The phenomenology of colorons was studied in detail in Refs. [24,25] wherein dijet data from the Tevatron [26–28] was used to place a lower limit of 870 GeV and 1 TeV on M_C for $\cot\xi$ values of 1 and 2 respectively, and the lower limit on $M_C/\cot\xi$ was raised to 837 GeV. Sensitivity to this variety of new physics is also expected in the top sector and this has been explored in Refs. [11,29]. The latest measurement of dijet mass spectrum at the CDF experiment at the Tevatron, however, rules out the existence of flavor-universal colorons with mass below 1250 GeV [8].

2.1. Search efforts

As mentioned earlier, in the search for axigluons and colorons, the dijet channel has been studied extensively and has been the focus of most experimental searches. Rates have been calculated for on-shell production of axigluons/colorons followed by decay and this has been used for comparison with data. Some searches have also been carried out in the $t\bar{t}$ channel [12]. It is clear that a (nu-)axigluon/coloron resonance, if present, will also affect $b\bar{b}$ production rates. While both the CDF and D0 experiments have vast B-physics programs, they are mostly concerned with studying properties of B-mesons [30]. The potential of the $b\bar{b}$ channel in searches for heavy resonances remains largely untapped.

In the case of the models described above, qg and gg dijet final states are not sensitive to the new particles and create a background. On the other hand, t-channel processes such as $qq' \to qq'$, while getting contributions from new physics, tend to render difficult, the task of identification of a resonance structure in the dijet invariant mass spectrum. This is specially true when $M_{boson} \sim 1$ TeV and the resonance is a broad one to begin with.[3] On the other hand contribution to $b\bar{b}$ production from the t-channel is negligible. This, coupled with advancements in b-tagging algorithms may be exploited in strengthening the search for (nu-)axigluons and colorons as well as other new particles with similar interactions.

3. $b\bar{b}$ production

At a hadron collider, $b\bar{b}$ production gets contributions from the processes $q\bar{q} \to b\bar{b}$ and $gg \to b\bar{b}$. At the center-of-mass energies

[1] Axial–vector coupling of axigluons to quarks implies that interference between gluon-mediated and axigluon-mediated processes can give rise to a forward–backward asymmetry. This is discussed in detail later.

[2] This will henceforth be referred to as the nu-axigluon for purposes of disambiguation.

[3] Efficiency factors associated with the reconstruction of jets also lead to broadening of the resonance peak. However, for (nu-)axigluons and colorons in the mass range ~ 1 TeV, the natural width itself is large.