

SEARCHING FOR OCTET SCALARS IN THE $t\bar{t}$ CHANNEL AT THE EARLY STAGE OF THE LHC*

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We investigate phenomenology of color octet scalars that appear in *e.g.* the supersymmetric $N = 1/N = 2$ hybrid model. Prospects for their discovery at the 7 TeV LHC in the $t\bar{t}$ decay channel are discussed.

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1. Introduction

The Standard Model (SM) of elementary interactions is with no doubt an extremely successful theory. Until now, there have been no significant experimental deviations from its predictions. There are, however, theoretical arguments that the SM should rather be treated as a low-energy effective theory, not the final one. There are also experimental observations which the SM cannot address, like matter–antimatter asymmetry, dark matter *etc.* Thus, it is commonly expected, that there should be a new physics above the scale of roughly 1 TeV that would solve these issues. Many extensions of the SM were proposed, the most popular one being supersymmetry with its minimal realization MSSM. Although quite different, many propositions have a common feature, namely, they predict new color-charged particles. This is an exciting feature from the point of view of the already working LHC, which is a hadron collider. Such colored particles couple directly to gluons and therefore should be copiously produced at the LHC in gluon–gluon and/or quark–quark interactions. In particular, if there are color octet scalars (sgluons), which are the topic of this work, their production is enhanced by a large color charge and could be discovered in the early phase of the LHC experiment.

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Color octet states appear in many different contexts: neutrino mass generation, grand unification, $N = 2$ and/or R-symmetric extensions of the MSSM, dark matter *etc.*, and their phenomenological consequences have been analyzed in a number of papers [1, 2, 3, 4, 5, 6, 7, 8, 9]. Pair production of such scalars in pp collisions is (almost) model independent. However, their decay modes as well as possible additional production channels are model dependent. Therefore, to discuss their experimental signature a specific model has to be adopted. Here we will consider a well motivated extension of the MSSM, in which gluinos (and other gauginos) are Dirac fermions [10, 11]. Such scenarios can be based on supersymmetric $N = 1/N = 2$ hybrid models [8, 9].

The transition from Majorana to Dirac particle requires additional fermionic degrees of freedom, which together with their scalar partners are members of the chiral super-multiplet in the adjoint representation of the corresponding gauge group. In the next chapter we briefly recall the main features of the color sector of this model. Since we are interested in the LHC discovery potential at CMS energy of 7 TeV, we assume that the sgluons are relatively light. In this case their decay channels to supersymmetric particles are closed and one of the dominant decay modes is into top quark–antiquark pairs.

2. The color sector of the model

In the supersymmetric $N = 1/N = 2$ hybrid model the sgluons, σ , are scalar components of the chiral supermultiplet $\{\sigma^a, \tilde{g}'^a\}$ in the adjoint representation of the color gauge group (a is the color index). Assuming the proper structure of the mass matrix the fermionic component, $\tilde{g}'$, can be combined with the standard gluino $\tilde{g}$ to form a Dirac fermion $\tilde{g}_D$. The simplest way to achieve it is to assume that the new states and gauge fields are parts of $N = 2$ hyper-multiplets [12, 13, 14]. The chirality problem is avoided assuming the mirror fermions to be heavy [9]. Thus, in such a hybrid model, only the gauge part is expanded to $N = 2$.

At the LHC the scalars σ can be produced in pairs via their gauge interactions with gluons, $\sigma\sigma^*g$ and $\sigma\sigma^*gg$. Since σ states are R-parity even they can also be singly produced at the LHC, although only via loop-induced vertices $\sigma g\bar{q}$ and $\sigma q\bar{q}$. Such effective couplings originate from two sources:

- (i) tree level sgluon coupling to Dirac gluino pair via the Yukawa-type gauge interaction

$$\mathcal{L}_{\tilde{g}_D\tilde{g}_D\sigma} = -\sqrt{2}i g_s f^{abc} \bar{\tilde{g}}_{DL}^a \tilde{g}_{DR}^b \sigma^c + \text{h.c.}, \quad (1)$$

where f^{abc} are the $SU(3)_C$ structure constants and,

(ii) the σ coupling to squark–antisquark pair

$$\mathcal{L}_{\sigma\tilde{q}\tilde{q}} = -g_s M_3^D \sigma^a \frac{\lambda_{ij}^a}{\sqrt{2}} \sum_q (\tilde{q}_{Li}^* \tilde{q}_{Lj} - \tilde{q}_{Ri}^* \tilde{q}_{Rj}) + \text{h.c.}, \quad (2)$$

generated by the Dirac gluino mass M_3^D via the super-QCD D term [10].

The structure of Eq. (2) implies, however, that L- and R-squark contributions come with opposite signs, so they cancel each other for mass degenerate squarks. Moreover, the chirality structure implies that the induced effective quark–antiquark coupling is suppressed by the quark mass. Thus the single resonant σ production in pp collisions can be generated only in gluon–gluon fusion. For the same reason decays to top quarks, if kinematically open, will dominate in the $q\bar{q}$ channel.

3. Sgluon decays

At the tree level the σ particle can decay only to a pair of Dirac gluinos or a pair of squarks, giving the following expressions for the decay widths

$$\Gamma(\sigma \rightarrow \tilde{g}_D \tilde{g}_D) = \frac{3\alpha_s M_\sigma}{4} \beta_{\tilde{g}} (1 + \beta_{\tilde{g}}^2), \quad (3)$$

$$\Gamma(\sigma \rightarrow \tilde{q}_a \tilde{q}_a^*) = \frac{\alpha_s |M_3^D|^2}{4M_\sigma} \beta_{\tilde{q}_a}, \quad (4)$$

where β_i is the rest-frame velocity of the i decay product. However, for relatively light sgluons these decay channels might be closed. In such case, the sgluons will predominantly decay into gluon or quark–antiquark pairs via loop-induced couplings (see Fig. 1 for relevant LO diagrams). For no

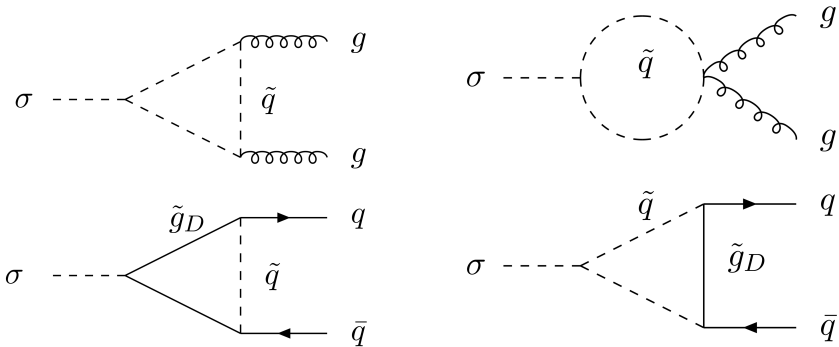


Fig. 1. Leading order diagrams generating $\sigma q\bar{q}$ and σgg effective couplings.

L/R squark mixing the decay widths take the form

$$\Gamma(\sigma \rightarrow gg) = \frac{5\alpha_s^3}{384\pi^2} \frac{|M_3^D|^2}{M_\sigma} \left| \sum_q [\tau_{\tilde{q}_L} f(\tau_{\tilde{q}_L}) - \tau_{\tilde{q}_R} f(\tau_{\tilde{q}_R})] \right|^2, \quad (5)$$

$$\Gamma(\sigma \rightarrow q\bar{q}) = \frac{9\alpha_s^3}{128\pi^2} \frac{|M_3^D|^2 m_q^2}{M_\sigma} \beta_q [(M_\sigma^2 - 4m_q^2) |\mathcal{I}_S|^2 + M_\sigma^2 |\mathcal{I}_P|^2], \quad (6)$$

where $\tau_{\tilde{q}_{L,R}} = 4m_{\tilde{q}_{L,R}}^2/M_\sigma^2$ and $f(\tau)$ is the standard function from a squark circulating in the loop [15]. The effective scalar ($\mathcal{I}_S$) and pseudoscalar ($\mathcal{I}_P$) $\sigma q\bar{q}$ couplings are given in [9]. Because of the chirality, decays to quark–antiquark pair are governed by the quark mass, so the decays into top quark pair will dominate. Since both loop-induced decays $\sigma \rightarrow gg$ and $\sigma \rightarrow q\bar{q}$ are absent if L and R squarks are degenerate, squarks with substantial mass splitting (mostly top squarks) will contribute the most to the decay width. If $\tilde{q}_L$ and $\tilde{q}_R$ mix, chiral states should be replaced with mass-matrix eigenstates with overall suppressing factor of $\cos(2\theta_q)$ for a given flavor q , where θ_q parametrizes rotation that diagonalizes mass-matrix.

The hierarchy between the tree-level and loop-induced decay modes depends on the values of various soft breaking parameters. The tree-level two-body decays, given by Eqs. (3) and (4), dominate if they are kinematically allowed. When they are kinematically shut, even for small L–R squark mass splitting, the loop-induced sgluon decays into two gluons or a $t\bar{t}$ pair always dominate over tree-level off-shell three-body decays. This is illustrated in Fig. 2, where the branching ratios for σ decays are shown for a scenario with unified masses of five light squarks $m_{\tilde{q}_L} = 1$ TeV and $m_{\tilde{q}_R} = 0.95$ TeV. We assume the sixth generation to be somewhat lighter with a greater mass splitting, $m_{\tilde{t}_L} = 0.95$ TeV and $m_{\tilde{t}_R} = 0.8$ TeV, as suggested by the GUT models. We also assume no significant L/R mixing. The gluino is taken to be a pure Dirac state with mass $m_{\tilde{g}} = |M_3^D| = 0.5$ TeV. As seen in Fig. 2 below $M_\sigma \sim 0.8$ TeV the sgluons decay almost exclusively to gg and $t\bar{t}$.

4. Sgluons production at the LHC

Since sgluons have a large color charge, they might be more copiously produced than squarks at the LHC. They can be pair-produced in $q\bar{q}$ and gg partonic processes at the tree-level with cross-sections

$$\sigma(q\bar{q} \rightarrow \sigma\sigma^*) = \frac{4\pi\alpha_s^2}{9s} \beta_\sigma^3, \quad (7)$$

$$\sigma(gg \rightarrow \sigma\sigma^*) = \frac{15\pi\alpha_s^2\beta_\sigma}{8s} \left[1 + \frac{34}{5} \frac{M_\sigma^2}{s} - \frac{24}{5} \left(1 - \frac{M_\sigma^2}{s} \right) \frac{M_\sigma^2}{s} L_\sigma \right], \quad (8)$$

where $\sqrt{s}$ is the invariant parton–parton energy, M_σ and β_σ are the mass and center-of-mass velocity of the σ particle and $L_\sigma = \beta_\sigma^{-1} \log[(1 + \beta_\sigma)/(1 - \beta_\sigma)]$.

The dominant production process for a single σ is the gluon–gluon fusion via squark loops since the production via $q\bar{q}$ annihilation is negligible for light incoming quarks. The partonic cross-section in the LO is given by

$$\hat{\sigma}(gg \rightarrow \sigma) = \frac{\pi^2}{M_\sigma^3} \Gamma(\sigma \rightarrow gg), \quad (9)$$

where the partial width for $\sigma \rightarrow gg$ decay has been given in Eq. (5).

The expected cross-sections for double and single σ production at the LHC running at the CMS energy of 7 TeV are shown in Fig. 3 as a functions of the sgluon mass (for parameters defined in the previous section using CTEQ6L1 proton structure functions [16]).

For comparison, the cross-section for squark-pair production is also shown. Due to a large color charge of the sgluon the $\sigma\sigma^*$ cross-section exceeds the $\tilde{q}\tilde{q}^*$ one by a large factor. The resonance production dominates only for very heavy sgluons (but with a very small production rate).

5. Experimental expectations at 7 TeV LHC

Observing the sgluon as an s -channel resonance would be very exciting. Unfortunately, at 7 TeV the production rates are far too small. Increasing the gluino mass could enhance the production, but it also increases the decay rate into gg channel in which the detection will not be easy. On the other hand, σ -pair production can be of the order of tens of femtobarns for

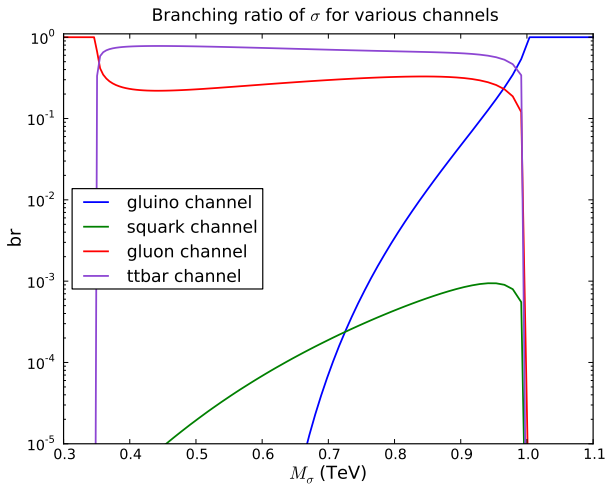


Fig. 2. Branching ratios for σ decays for $m_{\tilde{q}_L} = 2m_{\tilde{g}} = 1$ TeV, $m_{\tilde{q}_R} = m_{\tilde{t}_L} = 0.95$ TeV and $m_{\tilde{t}_R} = 0.8$ TeV.

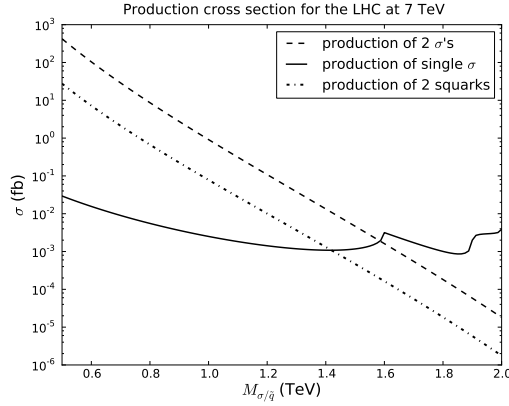


Fig. 3. Cross-sections for σ -pair and resonant σ production in pp collisions at the 7 TeV LHC (dashed and solid line), as well as for a pair of squarks assuming no left-right mixing (dash-dotted line). We use CTEQ6L1 structure functions [16].

$M_\sigma \leq 0.8$ TeV. Fig. 2 shows that such a relatively light sgluon decays almost exclusively into $t\bar{t}$ and gg pairs. The gluon channel suffers from a very large background but the $t\bar{t}$ decay mode would result in a spectacular signal of tens of events with four top-quark jets in the final state with no missing p_T . The angular distribution of top jets, their average p_T and total transverse energy are quite different from the SM $t\bar{t}jj$ and $t\bar{t}t\bar{t}$ background. The SUSY background, *e.g.* process $pp \rightarrow \tilde{g}_D \tilde{g}_D \rightarrow t\bar{t}t\bar{t}\chi_i^0\chi_j^0$, can be distinguished by their large missing p_T from escaping neutralinos. Detailed experimental simulations are under investigation.

6. Summary

Extended SUSY scenarios with Dirac-type gauginos predict scalars in the adjoint representation of the $SU(3)_C$ group. Their large color charge greatly enhances their production cross-section in hadron colliders, which is especially important in the context of the already working LHC. Observing loop-induced single σ production would be really spectacular. However, single sgluon production does not dominate over sgluon pair production in a range of sgluon's masses that are of interest at 7 TeV. It is more promising to look for a production of their pairs. Pair of light sgluons could give $t\bar{t}t\bar{t}$, $t\bar{t}gg$ and $gggg$ as final states, with structures quite different from the background processes. We encourage experimentalists to look for such final states at the LHC.

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