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SCALAR GLUONS AT THE LHC*

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We investigate phenomenology of scalar gluons (sgluons), as appear in *e.g.* a hybrid $N=1/N=2$ or R-symmetric supersymmetric extension of the Standard Model. Prospects for their discovery at the 7 TeV LHC are discussed.

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1. Introduction

Scalar gluons (sgluons) are scalar particles in the adjoint representation of the SU(3) color group. They have been proposed in many different contexts: neutrino mass generation, grand unification, minimal or extended supersymmetry, dark matter *etc.* [1]. Colored particles couple directly to gluons and therefore should be copiously produced at the LHC. In particular, the production of sgluons (color-octet scalars) is enhanced by a large color charge and such states could be discovered in the early phase of the LHC.

Pair production of sgluons in pp collisions is determined by the strong coupling constant and their mass. An exciting possibility is a resonant s-channel single sgluon production. However, such a production process (and other possible production channels) and sgluon decay modes are model dependent. Therefore, to discuss their experimental signature a specific model has to be adopted. Here, as already advocated in the talk by Kalinowski at this conference [2], we will consider a hybrid $N=1/N=2$ [3] or R-symmetric [4] supersymmetric extension of the Standard Model. In both models the strongly interacting sector is isomorphic in which the color-octet scalars (σ^a, a is the color index) are introduced as scalar components of the chiral supermultiplet $\hat{\Sigma}^a = \{\sigma^a, \tilde{g}'^a\}$ needed to build a Dirac gluino. With

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the vanishing gluino Majorana masses the fermionic partner, $\tilde{g}'^a$, can be combined with the standard gluino $\tilde{g}^a$ to form a Dirac fermion $\tilde{g}^a_D$. In this paper, we briefly comment on the status of current searches for such states and discuss the LHC discovery potential at the CM energy of 7 TeV for relatively light sgluons $\lesssim 600$ GeV. In this mass range the decay channels to supersymmetric particles should be closed and the dominant are loop-induced two-body gg and $t\bar{t}$ decay modes.

2. Status of current searches

The scalars σ^a can be produced in pairs via their gauge interactions with gluons, $\sigma\sigma^* g$ and $\sigma\sigma^* gg$. At the LHC they are produced in tree-level $q\bar{q}$ and gg processes [3],

$$\sigma[q\bar{q} \to \sigma\sigma^*] = \frac{4\pi\alpha_s^2}{9s}\,\beta_\sigma^3\,, \tag{1}$$

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

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 $L_\sigma = \beta_\sigma^{-1}\log(1+\beta_\sigma)/(1-\beta_\sigma)$. A large color charge of sgluons implies that they should be more copiously produced than squarks of the same mass. Therefore, they have been searched for with the first data collected at the LHC in the mass range $M_\sigma = 100$–200 GeV [5]. The search strategy depends on the expected experimental signature. Since the sgluons are R_p even (in the hybrid model, or have vanishing R-charge in the R-symmetric version) they can decay to standard model particles without missing transverse momentum. Being scalar particles, their couplings to fermions are suppressed by the fermion mass with the dominant decay mode $\sigma \to gg$ below the top threshold. Therefore, they should signal themselves as resonances in the multijet final states. The main challenge for such a search is the enormous QCD multijet background, which exceeds the signal by orders of magnitude. The crucial point in devising the search strategy is the scalar nature of sgluons and that the two jets from the sgluon decay (due to the boost) tend to have $\Delta R \sim 1$ [6]. Therefore, the event selection calls for at least four jets with $p_{\rm T} > 0.55 M_\sigma$, with four highest $p_{\rm T}$ jets paired (ij) and (kl) by minimizing $|\Delta R_{ij} - 1| + |\Delta R_{kl} - 1|$, rejecting all events that have jet pairing greater than 1.6, requiring jet pairs to have equal invariant masses within 7.5% and a cut on the sgluon production angle in the four-jet rest frame $|\cos\theta^*| < 0.5$. The left panel of Fig. 1 shows the results of ATLAS based on 34 pb^{-1} data collected in 2010 [5]. The mass region 100–185 GeV is excluded at 95% C.L. with a small mass window of 5 GeV around 140 GeV.

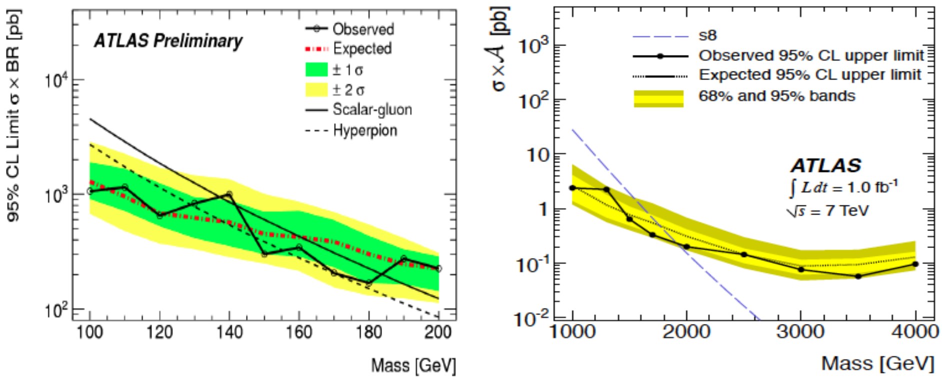

Fig. 1. The 95% C.L. upper limits on the cross-sections $\times$ branching ratio for σ-pair (left panel) and on the cross-section $\times$ acceptance for the single resonant production of the state $s8$ (right panel).

The color-octet scalars can also be singly produced at the LHC. The Atlas Collaboration has searched for resonances in the di-jet mass distribution using 1 fb^{-1} of data in the mass range above 717 GeV [7]. The right panel of Fig. 1 shows the limits derived on the cross-section times acceptance (that includes all reconstruction steps and analysis cuts). The mass range below 1.92 TeV is excluded. However, the state labeled as $s8$ is a color-octet scalar of Ref. [8], which is assumed to couple strongly to the gluon pair

$$i\Gamma^{abc}_{\mu\nu} = -2ig_{\mathrm{s}}d^{abc}M_{s8}\left(g^{\mu\nu} - \frac{2k_1^\nu k_2^\mu}{M_{s8}^2}\right) , \qquad (3)$$

where g_{s} is the strong coupling constant, d^{abc} is a symmetric invariant of color SU(3) and the gluon momenta, colors and Lorentz indices are as follows $g(k_1, b, \mu)$, $g(k_2, c, \nu)$.

In our scenario the σ state does not couple directly to quarks or gluons; such couplings are generated only at the loop level and are strongly suppressed in comparison to the model in Eq. (3). As a result, the limit of 1.92 TeV does not apply to the σ states.

3. Prospects for discovering $\sigma\sigma$ states in $t\bar{t}t\bar{t}$ channel

The relevant part of the Lagrangian for the σ fields has the form

$$\begin{aligned}\mathcal{L} \;=\; & (D^\mu\sigma^a)^\dagger (D_\mu\sigma^a) - m_\sigma^2 |\sigma|^2 - \sqrt{2}i\, g_{\mathrm{s}}\, f^{abc}\, \overline{\tilde{g}^a_{\mathrm{DL}}}\, \tilde{g}^b_{\mathrm{DR}}\, \sigma^c \\ & -\tfrac{1}{\sqrt{2}}\, g_{\mathrm{s}} M_{\mathrm{D}} \sigma^a \textstyle\sum_q \left(\tilde{q}^*_{\mathrm{L}}\lambda^a\tilde{q}_{\mathrm{L}} - \tilde{q}^*_{\mathrm{R}}\lambda^a\tilde{q}_{\mathrm{R}}\right) \\ & -\tfrac{1}{\sqrt{2}}\, g_{\mathrm{s}} \textstyle\sum_q \left(\overline{q_{\mathrm{L}}}\lambda^a\tilde{g}^a_{\mathrm{DR}}\; \tilde{q}_{\mathrm{L}} + \overline{q_{\mathrm{R}}}\lambda^{aT}\tilde{g}^{aC}_{\mathrm{DL}}\; \tilde{q}_{\mathrm{R}}\right) + \mathrm{h.c.}\,, \qquad (4)\end{aligned}$$

where λ^a are the Gell-Mann $\mathrm{SU}(3)_C$ matrices, the parameter M_{D} is the Dirac gluino mass, $\tilde{g}_{\mathrm{DL}} = \frac{1}{2}(1-\gamma^5)\tilde{g}_{\mathrm{D}}$ and $\tilde{g}_{\mathrm{D}}^{cT}$ is the charge–conjugate Dirac gluino. The term proportional to M_{D} is generated by the Dirac gluino mass which gives rise to a supersymmetry breaking trilinear scalar interaction between σ and the MSSM squarks; note that L and R squarks contribute with opposite signs.

At tree level there are no σgg and $\sigma q\bar{q}$ couplings. Such effective couplings are generated by diagrams with squarks and gluinos in the loop; pure gluino loops do not contribute to the σgg coupling, due to the Bose symmetry of the gluons. Since the σ coupling to L and R squarks comes with opposite signs, squark loop contribution to the effective couplings vanishes for mass degenerate squarks[1]. Moreover, the effective $\sigma q\bar{q}$ is suppressed by the quark mass due to general chirality rules. Specifically, we find for the σgg effective vertex

$$\begin{aligned} i\Gamma^{abc}_{\mu\nu} &= \frac{ig_{\mathrm{s}}^3 M_{\mathrm{D}}}{8\sqrt{2}\pi^2}\, d^{abc}\left(g^{\mu\nu} - \frac{2p_1^{\nu}p_2^{\mu}}{M_\sigma^2}\right) \\ &\quad \times \sum_{h=\mathrm{L,R}} \sum_{\tilde{q}_h} (-1)^{\alpha_h} m^2_{\tilde{q}_h} C_0\left(M_\sigma^2, 0, 0, m^2_{\tilde{q}_h}, m^2_{\tilde{q}_h}, m^2_{\tilde{q}_h}\right) \end{aligned} \tag{5}$$

with $\alpha_{\mathrm{L}} = 0$, $\alpha_{\mathrm{R}} = 1$, C_0 is the standard Passarino–Veltman function. For the effective $\sigma q\bar{q}$ vertex we have

$$\begin{aligned} i\Gamma^{aij} &= \frac{ig_{\mathrm{s}}^3 M_{\mathrm{D}} m_q \lambda^a_{ij}}{96\sqrt{2}\pi^2} \int_0^1 dx \int_0^{1-x} \\ &\quad \times dy\, \left[9\left(1-x-y+\gamma^5\right)\left(C_{\mathrm{L}} - C_{\mathrm{R}}\right) + (x+y)\left(D_{\mathrm{L}} - D_{\mathrm{R}}\right)\right], \end{aligned} \tag{6}$$

where D_h, C_h for $h = \mathrm{L,R}$ read

$$\begin{aligned} C_h^{-1} &= (x+y)M_{\mathrm{D}}^2 + (1-x-y)m^2_{\tilde{q}_h} - xyM_\sigma^2 - (x+y)(1-x-y)m_q^2\,, \\ D_h^{-1} &= (x+y)m^2_{\tilde{q}_h} + (1-x-y)M_{\mathrm{D}}^2 - xyM_\sigma^2 - (x+y)(1-x-y)m_q^2\,. \end{aligned}$$

Because of the chirality suppressing factor m_q, the $q\bar{q} \to \sigma$ channel for the single resonant production in pp is irrelevant. They can be generated only in gluon–gluon fusion, $gg \to \sigma$, however with the rates strongly suppressed in comparison to the case of $s8$, *cf.* Eqs. (3), (5). The predicted value for the cross-section depends on the gluino and squark masses. Since both loop-induced couplings σgg and $\sigma q\bar{q}$ are absent if L and R squarks are degenerate, squarks with substantial mass splitting (mostly top squarks) will contribute to the decay widths.

[1] We neglect L–R squark mixing, as required by the R-symmetry.

The LHC data tell us that for the top squarks to be the lightest among squarks, the exclusion limits for $M_{\tilde{g}}$ and $m_{\tilde{t}}$ are rather modest. On the other hand, the first and second generation of squarks should be above ~ 1 TeV. Therefore, for our case study we adopt the following simplified scenario for the soft masses

$$\begin{aligned} M_{\mathrm{D}} &= 0.75\ \mathrm{TeV}\,, \qquad m_{\tilde{q}_{\mathrm{L}}} = 1.2\ \mathrm{TeV}\,, \\ m_{\tilde{q}_{\mathrm{R}}} &= 0.95 m_{\tilde{q}_{\mathrm{L}}}\,, \qquad m_{\tilde{t}_{\mathrm{L}}} = 0.9 m_{\tilde{t}_{\mathrm{L}}}\,, \qquad m_{\tilde{t}_{\mathrm{R}}} = 0.5 m_{\tilde{q}_{\mathrm{L}}}\,, \end{aligned} \tag{7}$$

where we assume a moderate splitting between first five L and R squarks, and a larger splitting between $\tilde{t}_{\mathrm{L}}$ and $\tilde{t}_{\mathrm{R}}$.

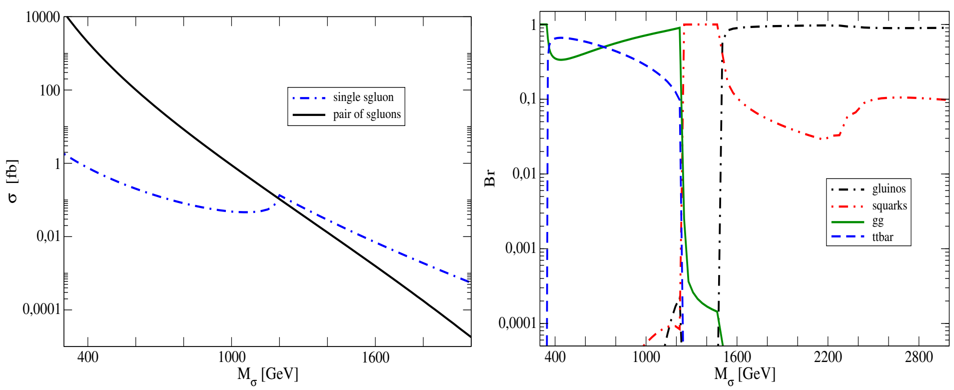

Fig. 2. Cross-sections for σ-pair and single resonant σ production (left panel), and the branching ratios into gg, $t\bar{t}$, gluino and squark channels (right panel) as functions of M_σ.

The cros-section[2] for a single σ production in pp collisions at 7 TeV is shown in Fig. 2 as a function of M_σ. The predicted values are of the order of 1 fb or less, with a cusp around 1.2 TeV due to the opening of $\tilde{t}_{\mathrm{R}}$ threshold. For comparison, the cross-section for the σ-pair production is also shown. It is amusing to notice that the resonant production wins over the pair production for masses above ~ 1.2 TeV. Observing the sgluon as an s-channel resonance would be very exciting. However, the expected rates in the high mass range are too low to be useful, while the low mass region is overwhelmed by huge SM background.

The experimental signature of the σ states depends on the decay modes. In Fig. 2 the expected branching ratios into the final states are shown as a function of M_σ for the scenario of Eq. (7). Before the stop channel opens (at 1.2 TeV), the sgluons decay almost exclusively into gg and $t\bar{t}$ pairs; below-threshold tree-level four-body and three-body decays via virtual squark(s),

[2] We use the CTEQ6L1 structure functions [9] for numerical analyses.

$\sigma \to q\bar{q}\tilde{\chi}\tilde{\chi}$, $\sigma \to \tilde{q}\bar{q}\tilde{\chi}$, and vitrual gluinos, $\sigma \to \tilde{g}q\bar{q}\tilde{\chi}$, have Br below 0.1%. Once the squark and gluino channels open, the two-body tree-level decays $\sigma \to \tilde{q}\tilde{q}^*$ and $\tilde{g}_{\rm D}\tilde{g}^c_{\rm D}$ dominate. Above all thresholds the gluino mode wins, since its partial width grows as M_σ while for squarks the partial width scales as $1/M_\sigma$.

All the σ decays give rise to striking signatures that should easily be detectable. However, for relatively light sgluons $\lesssim 800$ GeV, that can be accessed at the 7 TeV LHC, the decays into susy channels are closed and only the gg and $t\bar{t}$ modes can be used, which might allow the direct kinematic reconstruction of M_σ. Particularly interesting is the $t\bar{t}$ channel, which via the σ-pair production leads to $t\bar{t}t\bar{t}$ final state with no missing $p_{\rm T}$. Taking $M_\sigma = 600$ GeV as an example, for which ${\rm Br}(\sigma \to t\bar{t}) = 57\%$, we expect $\sigma(pp \to \sigma\sigma^* \to t\bar{t}t\bar{t}) = 33$ fb. The irreducible SM background is very small ~ 0.25 fb. However, the top quarks are not directly observable and one has to consider other background processes that contribute at the observable level. The reconstruction of four top quarks is a very difficult task which suffers from combinatorial background, final state objects overlap *etc.*

An interesting possibility is to look for same-sign dileptons from top decays as a means to suppress the SM background. Such a strategy has been considered recently in Ref. [10], in which the four top final states are due to heavy states as predicted in models of extra dimensions on the real projective plane. Although their model is different, the main effect for the enhancement of four top events comes from a pair production of heavy objects ((2,0) and (0,2) tiers with masses 600 GeV), each decaying into $t\bar{t}$. Benefiting from their careful treatment of the background processes we can estimate that in our scenario σ states could be observed in the $t\bar{t}t\bar{t}$ channel for masses up to 600 GeV for an integrated luminosity of 10 fb^{-1}.

It would be interesting to check if the opposite-sign dilepton channel could also be used. A measurement of spin–spin correlations between two leptons from semileptonic decays of a $t\bar{t}$ pair coming from the same sgluon would provide an experimental verification of the spin of the sgluon and could help distinguishing our scenario from other models.

4. Summary

The color-octet scalars, sgluons, can be copiously produced at the LHC since they carry large color charge. Their signatures at the LHC are distinctly different from the usual susy topologies. Pair production of sgluons with subsequent decays into $t\bar{t}$ giving rise to four top jets in the final state looks promising and deserves detailed simulations.

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