

Probing top-philic sgluons with LHC Run I data

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Abstract

Many theories beyond the Standard Model predict the existence of colored scalar states, known as sgluons, lying in the adjoint representation of the QCD gauge group. In scenarios where they are top-philic, sgluons are expected to be copiously pair-produced at the LHC via strong interactions with decays into pairs of top quarks or gluons. Consequently, sgluons can be sought in multijet and multitop events at the LHC. We revisit two LHC Run I analyses in which events featuring either the same-sign dileptonic decay of a four-top-quark system or its single leptonic decay are probed. Adopting a simplified model approach, we show how this reinterpretation allows us to extract simultaneous bounds on the sgluon mass and couplings.

Keywords: Hadron collider phenomenology, sgluon, top quark

1. Introduction

Despite its success in describing all experimental high-energy physics data, the Standard Model (SM) of particle physics leaves many important and conceptual issues unanswered. As a consequence, many theoretical frameworks extending it have been developed over the last decades, and new phenomena have been searched for experimentally. Weak scale supersymmetry, and in particular its minimal realization known as the Minimal Supersymmetric Standard Model (MSSM) [1, 2], is one of the most studied of those beyond the SM setups. It is however more and more constrained by data, and especially by the recent results of the LHC experiments [3, 4]. There are nevertheless large varieties of alternative non-minimal supersymmetric models that deserve to be investigated and whose signatures may be different from the expectations of the minimal choice.

Along these lines, we focus on $N=1/N=2$ hybrid [5, 6] and R -symmetric [7–9] supersymmetric theories that both predict extra scalar partners to the SM gauge bosons. These additional degrees of freedom lie in the adjoint representation of the gauge group and are indeed not present in the MSSM. Among the new particles, the colored states

commonly dubbed sgluons have received special attention as they are expected to be copiously produced at hadron colliders [10–18]. Those fields however appear not only in supersymmetry but also in vector-like confining theories [19] and extra-dimensional models [20]. Motivated by typical sgluon signatures that are similar in all these models, we adopt a simplified model approach describing the dynamics of a scalar field lying in the octet representation of $SU(3)_c$ and interacting with the SM [17, 21]. This subsequently allows both for a model-independent approach and a simplification of the non-minimal supersymmetric parameter spaces that in general contain hundreds of free parameters.

This simplified approach has been used experimentally in order to search for hints of sgluons in LHC collision data at center-of-mass energies of 7 TeV and 8 TeV. As a consequence of null results, limits on the sgluon mass, m_S , have been extracted after probing the production of a sgluon pair that decays into either a four top-quark system yielding a same-sign dilepton final state [22], or a four-jet final state [23]. In the former case, m_S is bound to be larger than 800 GeV when we assume that the sgluon always decays into a top-antitop system. In the latter case, limits turn out to be weaker ($m_S \gtrsim 300$ GeV) and are obtained after assuming that the sgluon always decays into a dijet state. Additionally, stronger constraints could be derived in the context of single sgluon production, the sgluon mass being pushed in this case above the multi-TeV scale [24, 25]. These bounds are however

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very model-dependent and could be evaded as soon as the sgluon is allowed to couple to the top quark, as in realistic ultraviolet-complete setups such as those mentioned. We therefore consider a framework where sgluons can couple to both quarks and gluons, and then revisit constraints on sgluon simplified models by reinterpreting recent LHC analyses of all data recorded at a collision center-of-mass energy of 8 TeV. More precisely, we consider two CMS studies of four-top-quark topologies, a first one focusing on same-sign dilepton events [26] and a second one on single lepton events [27]. We hence derive, for the first time, limits on the sgluon mass and coupling strengths to the SM particles simultaneously.

The rest of this paper is organized as follows. In Section 2, we briefly describe our simplified theoretical framework for sgluon phenomenology at the LHC, and present the sgluon mass dependence of both the total sgluon-pair production rate and the sgluon branching ratios. The reinterpretation of the LHC analyses of Refs. [26, 27] is detailed in Section 3, and our conclusions are presented in Section 4.

2. A simplified model for top-philic sgluon phenomenology

In our study of sgluon production and decay at the LHC, we rely on a minimal extension of the Standard Model allowing for a general description of sgluon dynamics. To this aim, we construct a simplified model in which we supplement the Standard Model by a single real color-octet scalar field S^a , the superscript a indicating an adjoint color index. The kinetic and mass terms associated with this field are given by the Lagrangian

$$\mathcal{L} = \frac{1}{2} D_\mu S^a D^\mu S_a - \frac{1}{2} m_S^2 S^a S_a, \quad (1)$$

which includes the gauge interactions of a sgluon pair to gluons through the QCD-covariant derivative,

$$D_\mu S^a = \partial_\mu S^a + g_s f_{bc}^a G_\mu^b S^c. \quad (2)$$

In our conventions, g_s denotes the strong coupling constant, f_{bc}^a the structure constants of the $SU(3)_c$ gauge group and G_μ^a represents the gluon field.

Furthermore, in order to allow the sgluon for singly coupling to the Standard Model degrees of freedom, we introduce the effective Lagrangian

$$\mathcal{L}_{\text{eff}} = \bar{t} T_a (a_t^L P_L + a_t^R P_R) t S^a + \frac{a_g}{\Lambda} d_a^{bc} S^a F_{\mu\nu, b} F^{\mu\nu, c} + \text{h.c.} \quad (3)$$

Its first term consists of dimension-four interactions of the sgluon with a pair of top-antitop quarks whose left-handed and right-handed coupling strengths are denoted by a_t^L and a_t^R , respectively. The second term of \mathcal{L}_{eff} models single sgluon interactions to gluons through a dimension-five operator, the dimensionless coupling strength a_g being suppressed by the theory cutoff energy scale Λ . In

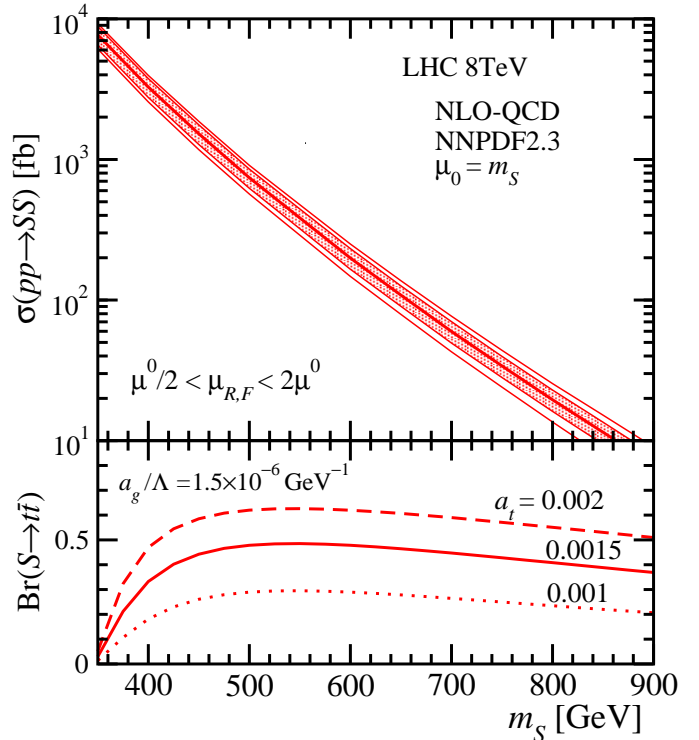


Figure 1: Total cross section for sgluon pair production at the LHC, for a center-of-mass energy of 8 TeV, given as a function of the sgluon mass. The lower panel shows the sgluon decay branching ratio into a top-antitop pair for different coupling strengths a_t .

our notations, the T_a matrices stand for the generators of $SU(3)_c$ in the fundamental representation, while d_a^{bc} are the symmetric structure constants of the group and $P_{L/R}$ denote the chirality projection operators. Although sgluons can in principle also couple in a flavor-changing-neutral way to different quark species, we only retain their flavor-conserving interactions with top quarks. While not general, this choice is motivated by minimally flavor-violating R -symmetric supersymmetric models where single sgluon interactions are loop-induced by squarks and gluino in a way such that only interactions involving a pair of gluons or top quarks are non-negligible [10].

This setup corresponds to the scenarios of class II introduced in Ref. [17], in which the sgluon is top-philic and only allowed to decay into a top-antitop pair or into two gluon-induced jets. We define our reference benchmark scenario by

$$a_t^L = a_t^R = a_t = 1.5 \times 10^{-3}, \quad a_g = 1.5 \times 10^{-3}, \quad \Lambda = 1 \text{ TeV}, \quad (4)$$

and impose the sgluon mass m_S to lie in the [350, 900] GeV window. For the phenomenological investigations performed in this work, we additionally study deviations from this reference scenario by varying the a_t and a_g parameters in the ranges $[0.5, 5] \times 10^{-3}$ and $[1.35, 1.65] \times 10^{-3}$, respectively. As shown in Ref. [10], those numerical values can be obtained in ultraviolet-complete supersymmetric mod-

els featuring colored superpartner masses of about 1 or 2 TeV.

The scenarios under consideration exhibit an enhancement of the production rate, at the LHC, of events containing four top quarks. This is illustrated on Figure 1 for proton-proton collisions at a center-of-mass energy of 8 TeV. First, we present, on the upper panel of the figure, the m_S -dependence of the sgluon-pair total production cross section evaluated at the next-to-leading order (NLO) accuracy in QCD [16, 18]. Second, we show, in the lower panel of the figure, the m_S -dependence of the sgluon branching ratios into a top-antitop system for several values of a_t . In order to calculate the sgluon-pair total cross section at NLO in QCD, we have followed the procedure described in Ref. [18]. More specifically, we have employed the FEYNRULES package [28] and its NLOCT module [29] to generate a UFO library [30] suitable to be used within the MADGRAPH5_aMC@NLO framework [31]. The central curve on Figure 1 is then obtained by fixing the renormalization and factorization scales to m_S and using the NNPDF 2.3 set of parton distributions [32], while the uncertainty band has been derived by varying the two unphysical scales by a factor of two up and down with respect to m_S (the inner range) and by using all parton density replicas provided by the NNPDF Collaboration (the outer range).

3. Constraining top-philic sgluons from LHC Run I data

As sketched on Figure 1, the production of a pair of top-philic sgluons, whose dynamics are described by the model presented in Section 2, leads to an enhancement of LHC events containing either two top-antitop systems, or two dijet systems, or one of each. Since in our class of realistic scenarios, the sgluon couples to both top quarks and gluons, the existing limits on its mass [22, 24, 25] do not directly apply and must be carefully reinterpreted. The most stringent and model-independent constraints have been derived in the context of an ATLAS analysis of partial LHC Run I data [22]. Sgluons are in this case searched for in same-sign dilepton events arising from the decay of a four-top ($t\bar{t}t\bar{t}$) system, since such a final state has the advantage to allow for a good experimental precision due to very low SM background. Instead of recasting this ATLAS analysis, we focus in Section 3.1 on its CMS counterpart [26] which benefits from the entire collision dataset at a center-of-mass energy of 8 TeV. Additionally, we choose to also explore the $t\bar{t}t\bar{t}$ topology via its single lepton plus jets decay channel. Although this mode exhibits considerable but well-understood background, it allows us to exploit a larger signal branching fraction. We reinterpret in Section 3.2 the SM $t\bar{t}t\bar{t}$ single lepton plus jets analysis of CMS [27] that also covers all 8 TeV data. Our results, that consist of the first attempt to reinterpret LHC analyses of the full 8 TeV dataset in the aim of constraining realistic sgluon models, are presented in Section 3.3.

3.1. Dilepton analysis

The first topology chosen to be investigated in this work consists of a same-sign dilepton signature, for which CMS has analyzed the entire recorded dataset of collisions at a center-of-mass energy of $\sqrt{s} = 8$ TeV [26]. This CMS analysis consists of a collection of counting experiments searching for new physics from events containing two isolated same-sign charged leptons (ee , $e\mu$, $\mu\mu$) and jets. Results are presented in multiple search regions which are determined by requirements on the number of selected jets (N_{jets}) with transverse momentum $p_T > 40$ GeV and pseudorapidity satisfying $|\eta| < 2.4$, as well as on the number of jets identified as originating from the fragmentation of a b -quark ($N_{b\text{-jets}}$), the scalar sum of the p_T of the selected jets (H_T) and the missing transverse energy (\cancel{E}_T). Without a knowledge of the correlations between the uncertainties on the background expectations in the search regions, the reinterpretation of a combination of search regions is not possible. Therefore we utilise the results from the search region 28 (SR28) only. This search region is chosen as its requirements can be fully emulated using the selection efficiency parameterizations included in the publication and closely correspond to the four-top-quark signature. This region is defined by requirements of $N_{\text{jets}} \geq 4$, $N_{b\text{-jets}} \geq 2$, $H_T > 400$ GeV and $\cancel{E}_T > 120$ GeV, imposed together with the demand of two same-sign leptons with $p_T > 20$ GeV and $|\eta| < 2.4$. Events containing an opposite-sign same-flavor lepton pair with an invariant mass $M_{\ell\ell}$ satisfying either $M_{\ell\ell} < 12$ GeV or 76 GeV $< M_{\ell\ell} < 106$ GeV are also vetoed. This was implemented in the original analysis in Ref. [26] to suppress background events arising from the decay of a low-mass bound state or multiboson production.

The analysis of Ref. [26] contains very useful information allowing for reinterpretation studies, following closely the recommendations of Refs. [33, 34]. In particular it includes parameterizations of the selection efficiencies which allows the signal acceptance to be estimated from generator-level information without the need for full detector simulation. Using these parameterizations we define an event-by-event weight

$$w_{\text{event}} = \varepsilon_{H_T} \times \varepsilon_{\cancel{E}_T} \times \varepsilon_{\geq 2b\text{-tags}} \times \varepsilon_{\geq 1SS2L}, \quad (5)$$

that uses the individual efficiencies for the hadronic activity H_T (ε_{H_T}), the missing energy \cancel{E}_T ($\varepsilon_{\cancel{E}_T}$), the selection of at least two b -jets ($\varepsilon_{\geq 2b\text{-tags}}$) and at least one same-sign lepton pair ($\varepsilon_{\geq 1SS2L}$), this last efficiency being obtained after considering all possible permutations among the event leptons. In addition, a mistagging rate of a jet originating from a light quark or a gluon as a b -jet of 1% is incorporated in the calculation of $\varepsilon_{\geq 2b\text{-tags}}$.

Using the MADGRAPH5_aMC@NLO generator [31], we simulate the production, at the LHC with $\sqrt{s} = 8$ TeV, of a sgluon pair that decays into a $t\bar{t}t\bar{t}$ final state. Our event sample is generated inclusively in the top decays, and we subsequently match the hard-scattering events to the

PYTHIA 6 parton showering and hadronization [35]. Jets are reconstructed by using the anti- k_T algorithm with a radius parameter set to $R = 0.5$ [36] as included in the FASTJET package [37], while the event selection and reweighting procedure are implemented within the MADANALYSIS 5 framework [38, 39]. A signal acceptance of 0.60% has been calculated for SM $t\bar{t}\bar{t}$ events using the efficiency modeling of Eq. (5). This can be compared with the acceptance of 0.49% obtained by CMS for the same process [26]. These two efficiencies agree within the 30% uncertainty quoted on the efficiency model.

Scanning over the parameter space introduced in Section 2, we compute signal event yields for different (m_S, a_t) values by using the relevant NLO cross section (see Figure 1), a luminosity of 19.6 fb^{-1} and the signal acceptance derived with the efficiency model. The obtained results are then compared to the 2 (2.21) events observed (expected) by CMS in the SR28 region. Considering a 30% uncertainty on the signal yield (see above), we use the asymptotic CL_S method [40] as implemented in the ROOSTAT package [41] to calculate a 95% CL observed (expected) upper limit on the number of signal events N in SR28. We have computed upper limits of 4.68 (4.89), therefore we exclude the region of the (m_S, a_t) plane where N is predicted to be larger than 4.68 events.

3.2. Single lepton analysis

The CMS $t\bar{t}\bar{t}$ single lepton analysis has been performed assuming the specific kinematics of the SM $t\bar{t}\bar{t}$ production, and it places, at the 95% CL an upper limit of 32 fb on the associated cross section [27]. For certain values of m_S and a_t , sgluon-induced contributions could enhance the $t\bar{t}\bar{t}$ total cross section to a value larger than 32 fb, so that constraints on the parameter space could be extracted from the $t\bar{t}\bar{t}$ single lepton analysis of CMS. However, in order to properly estimate which regions of the parameter space are disfavored by data, it is necessary to verify that the final state kinematics in the decay of a sgluon pair are similar to the SM case. To this aim, we employ a simplified matrix-element method.

Matrix-element methods are normally based upon two stages. First, the detector level kinematics of the events of interest are translated into parton-level kinematics via transfer functions which describe the effects of the fragmentation, hadronization and detector reconstruction. Second, the probabilities of predicting a specific parton-level event configuration when assuming one or more theoretical hypotheses are calculated on the basis of the associated matrix elements [42–44]. The simplified method used in this work relies on the fact that the event kinematics are entirely defined by the configuration of the four top quarks, so that one could compute the probabilities using this information only. The decays of the top quarks and subsequent fragmentation, hadronization and reconstruction of the final state objects are identical for the sgluon-induced and the SM contributions, so that these effects are not simulated in detail. Instead, the four-momenta of the

four top quarks are smeared by sampling a Gaussian distribution with a width corresponding to 20% of the original values. As the events are uniquely defined by single points in phase space, the CPU-intensive phase-space integration normally required by matrix-element methods is avoided. Moreover, our method is further simplified by evaluating the probabilities in the SM hypothesis only.

In order to probe how SM-like are $t\bar{t}\bar{t}$ events induced by the decay of a sgluon pair, we make use of the MADGRAPH5_aMC@NLO program to generate one sample of SM $t\bar{t}\bar{t}$ events and a collection of samples including sgluon contributions for different m_S values in the [350, 900] GeV range. We then estimate the probabilities in the SM hypothesis of the events in each sample, and compute a quantity known as the discrimination significance (D) [45] that is used to assess the similarity of the probability distributions for SM and sgluon events. It is defined as

$$D = \frac{|\bar{P}_{\text{SM}} - \bar{P}_{\text{Sgluon}}|}{\sqrt{(P_{\text{SM}}^{\text{RMS}})^2 + (P_{\text{Sgluon}}^{\text{RMS}})^2}}, \quad (6)$$

where \bar{P}_{SM} and \bar{P}_{Sgluon} are the means of the probability distributions for the SM and sgluon cases, respectively, and where $P_{\text{SM}}^{\text{RMS}}$ and $P_{\text{Sgluon}}^{\text{RMS}}$ are the root-mean-squares of these probability distributions. The numerator consists of the difference between the means of the two distributions in question, while the denominator is the effective resolution σ in measuring this difference. A D value of unity would hence correspond to means differing by 1σ .

We have found that in the case of the generated sgluon samples, the discrimination significance has a minimal value of $D \approx 0.1$ that is reached for $m_S = 400 \text{ GeV}$. The D quantity then rises approximately linearly to a value of $D \approx 0.5$ for $m_S = 900 \text{ GeV}$. Furthermore, the dependence of D on a_t is found to be negligible. Consequently, the $t\bar{t}\bar{t}$ kinematics for the SM and in the presence of top-philic sgluons lighter than about 1 TeV only mildly differ, so that the parameter space regions of our model in which the $t\bar{t}\bar{t}$ cross section is predicted larger than 32 fb are excluded.

3.3. Interpretation

We present in Figure 2 the regions of the top-philic sgluon parameter space that are excluded by the dilepton and single lepton analyses of Section 3.1 and Section 3.2. The results (solid lines) are represented in the (m_S, a_t) plane for a fixed value of $a_g/\Lambda = 1.5 \times 10^{-6} \text{ GeV}^{-1}$ (see Eq. (4)). We then vary a_g by 10% up and down, and show the induced variations on the constraints by dashed lines. For a sgluon mass of about 400–550 GeV, values of a_t down to about 0.6×10^{-3} are excluded. This is related to the signal cross section $\sigma(pp \rightarrow SS \rightarrow t\bar{t}\bar{t})$ which is maximal in this parameter space region. For smaller and larger values of m_S , the sensitivity worsens due to the decreasing sgluon branching ratio to a top-antitop system and the decreasing inclusive sgluon pair cross section, respectively.

The dilepton analysis turns out to be more constraining than the single lepton one, with constraints on m_S ranging

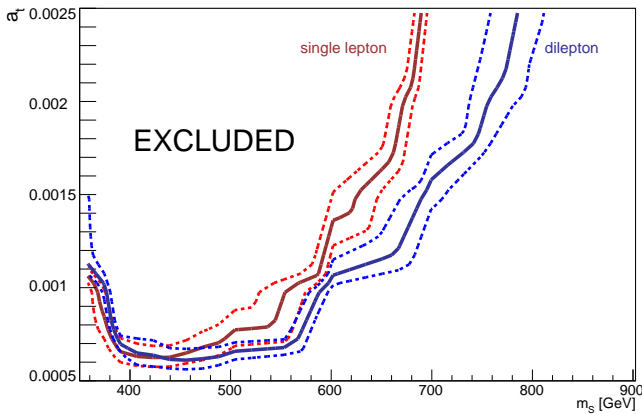


Figure 2: The excluded regions in (m_S, a_t) space derived from the single lepton analysis (red solid line) and dilepton analysis (blue solid line). In both cases, the dashed lines correspond to the exclusion regions obtained when a_g is varied by $\pm 10\%$.

up to about 750 GeV for $a_t \approx 2 \times 10^{-3}$. This analysis has in addition the advantage of being not sensitive to the signal kinematics, in contrast to the single lepton one. We however recall that for the parameter space regions that are reachable with LHC collisions at $\sqrt{s} = 8$ TeV, the kinematics differences between the SM and the sgluon cases cannot be pinned down. Nevertheless, the situation could be different for the LHC Run II expected to probe much larger sgluon masses, as the discrimination significance D rises with m_S (see Section 3.2).

4. Conclusion

Many new physics theories predict the existence of new colored scalar fields, named sgluons, lying in the octet representation of QCD. These fields are expected, at least in top-philic sgluon scenarios, to either decay to a pair of gluons or to a top-antitop system. In this work, we have adopted a simplified model approach describing the dynamics of such top-philic sgluons and probed the associated parameter space (spanned by one mass parameter m_S and two coupling strengths a_t and a_g/Λ) by extracting constraints from two recent analyses of $t\bar{t}t\bar{t}$ events by the CMS Collaboration in the entire LHC collision dataset at a center-of-mass energy of 8 TeV. We have found that sgluon masses ranging up to 750 GeV are excluded for sgluon couplings to the top quark of $a_t = 1.5 \times 10^{-3}$, a value typical of non-minimal supersymmetric scenarios with superpartner masses of about 1 TeV or 2 TeV. In the case of smaller top-sgluon couplings of $a_t = 0.75 \times 10^{-3}$ (the smallest value which the LHC Run I is sensitive to), the sgluon mass is imposed to satisfy $m_S \notin [400, 550]$ GeV. We have finally also observed that the picture does not drastically change with respect to 10% variations of the sgluon-gluon coupling strength whose reference value has been fixed to

$a_g/\Lambda = 1.5 \times 10^{-6}$ GeV $^{-1}$, a value again typical of supersymmetric setups with superpartners around the TeV scale.

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