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Sgluons in the same-sign lepton searches

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ABSTRACT: This work presents the interpretation of the ATLAS search of same-sign lepton production in association with b -jets in the context of the 4-top quark signal from sgluon decays. It is shown that using just 3.2/fb data sample from Run 2 collected in 2015 the exclusion limit is already competitive with the Run 1 limit. This data makes it possible to exclude sgluons with masses up to 0.95 TeV. Prospects for the total Run 2 integrated luminosity of 100/fb are briefly discussed.

KEYWORDS: Supersymmetry Phenomenology, QCD Phenomenology

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1 Introduction

With the Large Hadron Collider (LHC) delivering data at an unprecedented energy of 13 TeV, much work has been devoted to their interpretation in the context of BSM physics. For the time being, the main focus is on the Minimal Supersymmetric Standard Model (MSSM), or the so-called exotics. This of course leaves a lot of interesting models out. From the viewpoint of supersymmetry, this is a serious limitation. Recent years have brought considerable attention to the extended SUSY models, from simple extensions such as the NMSSM to models with an extended QCD sector such as various models with Dirac gluinos. Studies have proved that in many cases MSSM bounds are not applicable to these models [1]. On the other hand, 13 TeV data might already be more constraining than the 7 and 8 TeV ones, even though the collected integrated luminosity is smaller. This raises an important question about the validity of such models in light of new data.

Especially interesting are the multi top-quark processes which, while characterized by a high mass scale, enjoy big boosts in cross sections when going from 7 or 8 to 13 TeV. The 4-top quark final state was already searched for by ATLAS [2–5] and CMS [6–8] at Run 2. In the MSSM, this kind of final state may appear as decay products of 3rd generation stops produced as decay products of intermediate gluinos. In general SUSY models, the resonance structure might be quite different, though. For example, one might expect a two-body decay of a new color resonance directly to a $t\bar{t}$ pair. This is a general feature of models containing color octet (EW-singlet) scalars, commonly known as sgluons. Their LHC phenomenology was previously investigated in the context of R -symmetric/ $\mathcal{N} = 2$ /Dirac gaugino SUSY models, hyper-pions in vector-like confinement gauge theories and universal extra dimensions [9–21].

The Minimal R -Symmetric Supersymmetric Standard Model (MRSSM) [22] is a particularly well motivated BSM model [23–29]. Recent analyses [24, 25] have shown at full one- and leading two-loop levels that the 125 GeV Higgs boson can be consistently obtained in agreement with precision EW observables and flavor constraints. Moreover, interesting scenarios which provide a viable candidate for dark matter have been identified [26].

Within the framework of the MRSSM [22], sgluons are expected to decay, depending on their mass, mainly into gluons or top quarks. These kinds of signatures, in both channels, were searched for by the experimental collaborations in 7 and 8 TeV data. ATLAS excludes at 95% CL pair produced, complex sgluons decaying (with branching ratio 1) to gluon pairs in mass range from 100 to 287 GeV [30]. For $t\bar{t}$ decay mode, sgluons are excluded at 95% CL up to 1.06 TeV [31]. It should be noted, however, that these exclusions are based on a simplified model with a complex sgluon from ref. [32] while in the MRSSM the cross section is roughly 2 times smaller.¹ At the time of writing there are no 13 TeV analyses directly addressing sgluon pair production. Therefore, all the mentioned exclusions come from Run 1. This makes any projections for the target Run 2 integrated luminosity very difficult. To fill this gap, this work recasts ATLAS limits from search of SUSY in the 4-top quark final state in ref. [2] to sgluon pair production.

The paper is structured as follows. The next section describes and motivates the effective sgluon model used in this work. Section 3 presents NLO cross sections for the sgluon pair production. In section 4, the setup for the Monte Carlo simulation is described. Section 5 describes the parametrization of the detector response and the encoded ATLAS analysis. The reproduced analysis is validated on the associated production of top quark pair and a gauge boson in the Standard Model (SM) and on the production of gluinos in the MSSM, comparing predicted numbers of events with ones given in the ATLAS work. The analysis is then applied to the signal events. This work finishes with the derivation of the limit on the sgluon mass and prospects for this limit for the predicted $\gtrsim 100 \text{ fb}^{-1}$ data sample of Run 2.

2 Description of the model

In the framework of a simplified model, inspired by the MRSSM scenario in which all the superpartners but the CP -odd sgluon are heavy, the SM is extended by a real color-octet (EW-singlet) scalar O . It couples exclusively to gluons and top quarks as given by the Lagrangian

$$\mathcal{L} = \mathcal{L}^{\text{SM}} + \frac{1}{2} D_\mu O^a D^\mu O^a - \frac{1}{2} m_O^2 O^2 - i c \bar{t} \gamma^5 T^a t O^a, \quad (2.1)$$

where D_μ is the $SU(3)_C$ covariant derivative and sum over the color index a is understood. This Lagrangian is motivated by the MRSSM, in which a complex sgluon field is split into CP -even and -odd components through a D -term SUSY breaking contribution [25].² The masses of the components are then $m_{O_S}^2 = m_O^2 + 4(M_O^D)^2$ for the scalar and $m_{O_A}^2 = m_O^2$ for the pseudoscalar, where m_O and M_O^D are sgluon and Dirac gluino soft masses. Since

¹The ATLAS analysis also does not specify the form of the sgluon-top quark coupling.

²We neglect possible (anti-)holomorphic soft-breaking sgluons mass terms.

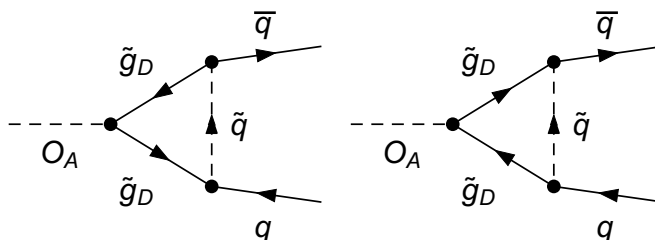


Figure 1. Lowest-order diagrams generating (effective) coupling of the pseudoscalar sgluon O_A to quarks.

physical gluino mass, which at the tree-level is exclusively controlled by the M_O^D , must be $\gtrsim 1$ TeV, this implies that either the pseudoscalar sgluon is very light and the scalar one is in a TeV range or, if pseudoscalar’s mass is around 1 TeV, the scalar one will be in the multi-TeV range. The focus here is on the latter scenario, which extends the SM with a pseudoscalar sgluon which for simplicity’s sake is denoted simply by O (without the A subscript).

Since in the MRSSM sgluon carries an R-charge 0, once produced it can decay to SM particles. The lowest-order coupling to quarks is loop-induced as shown in figure 1. Coupling to gluons vanishes for pseudoscalar sgluons, while coupling to quarks is proportional to a quark mass due to chirality. Pseudoscalar sgluons with mass $m_{O_A} \gtrsim 2m_t$ and smaller than other color-charged SUSY particles will therefore decay almost exclusively to top quarks with the coupling in the form written in eq. (2.1). Single sgluon production through (loop-induced) coupling to partons can be neglected, since it occurs mainly through coupling of gluons to the CP -even sgluon, which is significantly heavier than the CP -odd one and whose production is additionally suppressed by a small value of loop-induced coupling.

It should be noted, though, that the effective model described by the Lagrangian from eq. (2.1) is quite generic and can come from a multitude of complete, high-scale theories. However, different models would then be characterized by a different chiral structure of the coupling c .

3 NLO QCD corrections to sgluon pair production

For the Lagrangian of eq. (2.1) sgluons are produced at the LO through the Feynman diagrams in figure 2. The corresponding partonic cross sections are:³

$$\hat{\sigma}_{q\bar{q}}^B = \frac{2\pi\alpha_s^2}{9\hat{s}}\beta^3, \tag{3.1}$$

$$\hat{\sigma}_{gg}^B = \frac{3\pi\alpha_s^2}{32\hat{s}}(27\beta - 17\beta^3 + 6(-3 + 2\beta^2 + \beta^4)\text{arctanh}\beta), \tag{3.2}$$

³With an additional factor of 1/2 compared to cross sections for a complex sgluon pair production considered in ref. [9].

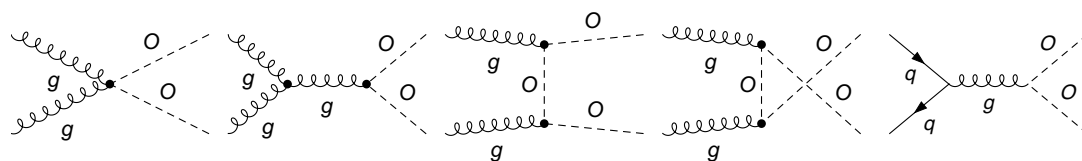


Figure 2. Feynman diagrams for the sgluon pair production at the LO.

where $\hat{s} \equiv (p_q + p_{\bar{q}})^2$ or $(p_g + p_{g'})^2$ and β is the sgluon’s velocity in the center of mass system of colliding partons.

The first calculation of higher-order corrections to the sgluon pair production was done in ref. [32] for a simplified model with a complex sgluon. Since ref. [21], a general procedure for obtaining NLO-capable UFO [33] models for MadGraph5_aMC@NLO [34] using conjunction of FeynRules [35], NLOCT [36], FeynArts [37] and FormCalc [38] became available. In ref. [21] this procedure was applied to, among others, obtaining an NLO model for a real sgluon field. Since the original model used in ref. [21], available under [39], does not work for the complex coupling ic as in eq. (2.1), a new model (this time in 5-flavor scheme) was generated and used for this analysis.⁴

Table 1 lists values of cross sections obtained with this model for 5 selected sgluon masses: 1, 1.25, 1.5, 1.75 and 2 TeV, for 13 and 14 TeV LHC. Numbers were obtained using the MMTH2014 baseline (5-flavor) NLO fit (MMTH2014n1o68c1) [40] interfaced through LHAPDF6 [41]. The K -factors listed in the table are defined as $K \equiv \sigma_{\text{NLO}}/\sigma_{\text{LO}}$ and refer to the LO calculation with MMTH2014 baseline LO fit with $\alpha_s(m_Z) = 0.135$ and up to 5 active flavors (MMTH2014l1o68c1). For the sgluon with mass of 1 TeV, one expects more than 100 events already with the 3.2 fb^{-1} data sample collected in 2015. Figure 3 shows the plot of the cross section as a function of the sgluon mass together with uncertainty bands for the K -factor coming from the PDFs (middle subplot) and the variation of renormalization/factorization scales by a factor of 2 (bottom subplot). The central values of renormalization and factorization scales are set equal to the sgluon’s mass while $m_t = 173 \text{ GeV}$.

Results of an automated MadGraph5_aMC@NLO calculation at the NLO were cross-checked with an independent computation based on FeynArts, FormCalc and the two-cut phase space slicing method [42]. Details of this computation are given in ref. [43].

4 Monte Carlo simulation setup

We now proceed to the description of methods used in the simulation of signal and background processes. Due to technical reasons, samples for signal and background were generated using two different methods outlined in the next two subsections. Both for signal and background simulation, the following values of SM gauge-boson masses were

⁴The NLO UFO model used for this analysis can be found in supplementary materials of the arXiv version of this work.

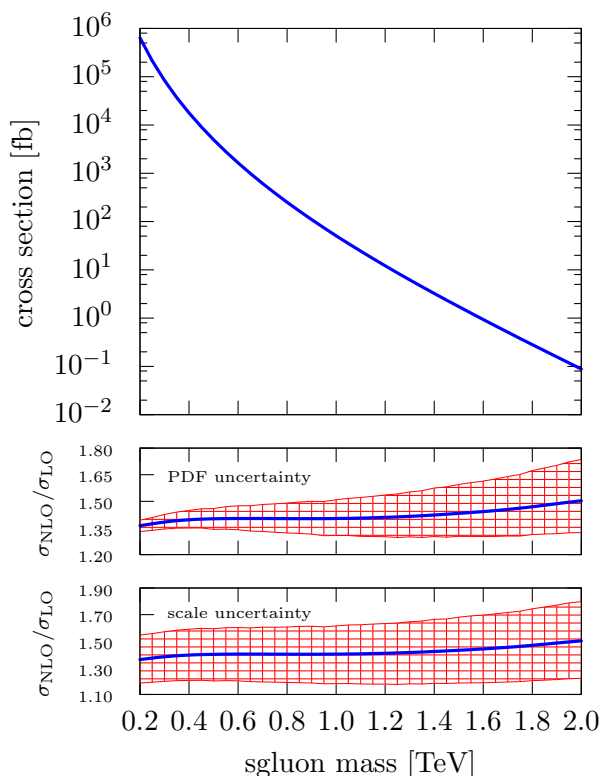


Figure 3. NLO cross section for the sgluon pair production as a function of their mass. Middle subfigure shows the K -factor (blue line) together with the uncertainty band coming from the PDFs. The lower one does the same for the uncertainty coming from the scale variation.

sgluon mass [TeV]	cross section at 13 TeV [fb]	K	cross section at 14 TeV [fb]	K
1	$50.8^{+15.3\%+7.7\%}_{-15.7\%-6.7\%}$	1.40	$71.4^{+14.1\%+7.2\%}_{-15\%-6.3\%}$	1.37
1.25	$8.66^{+16.3\%+9.5\%}_{-16.5\%-7.9\%}$	1.38	$12.9^{+14.9\%+8.8\%}_{-15.7\%-7.4\%}$	1.41
1.5	$1.73^{+17.3\%+11.3\%}_{-17.2\%-9.1\%}$	1.40	$2.75^{+15.8\%+10.5\%}_{-16.3\%-8.5\%}$	1.39
1.75	$0.380^{+18.4\%+13.3\%}_{-17.9\%-10.5\%}$	1.46	$0.648^{+16.7\%+12.3\%}_{-17\%-9.7\%}$	1.41
2	$0.0883^{+19.7\%+15.5\%}_{-18.8\%-11.9\%}$	1.47	$0.164^{+17.8\%+14.2\%}_{-16.5\%-11\%}$	1.45

Table 1. Cross sections for the sgluon pair production for 13 and 14 TeV LHC as a function of the sgluon mass (see main text for more details). First error comes from the scale variation, second is the PDF uncertainty (evaluated over PDF eigenvectors using Hessian method). Relative statistical errors are below 10^{-3} and are not shown here. Columns K give global K -factors.

used: $m_W = 80.385 \text{ GeV}$, $m_Z = 91.1876 \text{ GeV}$. Top quark mass was set to 173.21 GeV while other quarks were assumed massless in the hard matrix elements. The CKM matrix was set to identity. All samples were generated using MMTH2014n1o68c1 PDFs interfaced through LHAPDF6.

4.1 Signal

Signal events were generated using MadGraph5_aMC@NLO *v2.4.2* and an NLO-capable UFO model. For the analysis sgluon masses in the range $0.9 - 1.5 \text{ TeV}$ were considered. Renormalization and factorization scales were set equal to the sgluon mass. Sgluons were decayed into $t\bar{t}$ pairs (and further) using MadSpin [44], generating all configurations that give two same-sign muons. All spin correlations were preserved (at the LO). Total branching ratio into these channels is given by $\text{BR}^2(W \rightarrow \mu\nu)(2 - \text{BR}^2(W \rightarrow \mu\nu))$ where $\text{BR}(W \rightarrow \mu\nu) \approx 11\%$. Partonic events were matched to parton shower using MC@NLO [45] prescription and Pythia8 [46] *v219*. Pythia8 settings needed for consistent showering of MC@NLO events are described in appendix A. Since there are no genuine NLO underlying event tunes in Pythia8, the default LO tune was used.

4.2 Background validation

Background samples were generated using Sherpa *v.2.2* [47], with virtual matrix elements provided by OpenLoops *v1.3.1* [48] and evaluated using CutTools [49, 50] or COLLIER [51–54]. $t\bar{t}\mu\nu_\mu$ events (i.e. including $\mu^- \bar{\nu}_\mu$ and $\mu^+ \nu_\mu$ combinations) were generated with up to 1 additional jet at the NLO order and 3 jets at the LO, while for $t\bar{t}\mu^+\mu^-$ up to 1 and 2 jets, respectively, were generated. Different multiplicities were merged/matched to parton shower using the MEPS@NLO technique [55, 56]. In the case of $t\bar{t}\mu^+\mu^-$, a generation cut on an invariant mass of the muon pair $m_{\mu^+\mu^-} > 20 \text{ GeV}$ was applied. Top quarks were then decayed in all ways that ensure two same-sign muons with spin correlations preserved at the LO as in the case of MadSpin. The inclusive cross sections for those samples (including appropriate top-quarks decays) are 7.77 and 5.43 fb , respectively. These predictions agree within (still very large) experimental uncertainties with the LHC measurements [57, 58].

The setup of Sherpa mostly follows standard settings, and only the most important ones are mentioned here. Samples were generated with `EXCLUSIVE_CLUSTER_MODE = 1` setting (meaning that only QCD splittings are considered when reconstructing parton shower history) to ensure that $t\bar{t}\mu\nu_\mu/t\bar{t}\mu^+\mu^-$ is always identified as the core process. Since ATLAS analysis uses jets with $p_T > 20 \text{ GeV}$, the merging cut was set to 15 GeV . Also, a default scale definition for the core process was used.

5 Recasting current ATLAS 13 TeV analysis

The ATLAS analysis of ref. [2] targeted topologies with 2 same-sign leptons or 3 leptons, looking at 4 different signal regions. In case of the production of sgluon pair which then decays to top-quark pairs, the interesting signal region is SR3b defined in table 1 of [2]. To match experimental data as closely as possible, the detector response was parametrized using Delphes [59] *v3.3.2*.

The following list gives a summary of `Delphes` detector card settings⁵ and applied cuts:

- 1 Muons are identified with the efficiency of 95% if they have $p_T > 10$ GeV and $|\eta| < 1.5$ and 85% if $1.5 < |\eta| < 2.7$. Candidate muons are required to have $p_T > 20$ GeV and $|\eta| < 2.5$. Candidate muons must also be isolated, i.e. have the scalar sum of the p_T of tracks within a variable-size cone around the lepton, excluding its own track, less than 6% of the muon p_T . The isolation cone size is taken to be the smaller of $10 \text{ GeV}/p_T$ and 0.3 (where p_T denotes the muon's transverse momentum).⁶ The analysis requires (at least) two same-sign muons fulfilling above criteria.
- 2 At least 3 b -tagged jets reconstructed using anti-kt algorithm [60] from `FastJet` [61, 62] with $p_T > 20$ GeV and $|\eta| < 2.5$ are required. Jets are b -tagged if they are within $\Delta R_{jb} < 0.3$ of a b -quark which had $p_T^b > 5$ GeV and $|\eta_b| < 2.5$ with an efficiency

$$b\text{-tagging efficient} = \frac{24 \tanh(0.003 \cdot p_T)}{1 + 0.086 \cdot p_T}. \quad (5.1)$$

The probabilities of misidentifying c and light quarks as b ones are given by

$$c\text{-mistag rate} = \frac{0.2 \tanh(0.02 \cdot p_T)}{1 + 0.0034 \cdot p_T}, \quad (5.2)$$

$$\text{light quark mistag rate} = 0.002 + 7.3 \cdot 10^{-6} p_T, \quad (5.3)$$

respectively. The efficiency formulas are based on [63]. Jet energy scale (JES) correction is applied according to the following formula⁷

$$E_j \rightarrow \sqrt{1 + (3 - 0.2|\eta|)^2/p_T} \cdot E_j \quad (5.4)$$

- 3 $E_T^{\text{miss}} > 125$ GeV

- 4 Effective mass m_{eff} of the event, defined as a scalar sum of p_T of signal leptons, b -jets and missing E_T , must satisfy $m_{\text{eff}} > 650$ GeV.

Table 2 shows the cross sections (in fb) for signal and selected background processes passing this sequence of cuts (cuts are stacked, i.e. a cut in the n -th column also implies that cuts in $n - 1$ first columns were applied). Table 3 then compares final numbers of events, i.e. after multiplying last column of table 2 by 3.2 fb^{-1} of integrated luminosity and a factor of 4, to account for all possible leptonic channels taken into account in the ATLAS analysis, with the column SRb3 of table 5 of ref. [2]. The analysis was also validated on the signal process considered in the ATLAS work, i.e. gluino pair production with $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_0$ decay through off-shell stops. The gluino sample was generated at the LO with up to 1 additional jet, merged using CKKW-L prescription [64] with merging scale, defined as Lund p_T , set to 300 GeV. Table 4 shows the predicted number of signal events after the considered sequence of cuts

⁵The complete ATLAS detector card used in this analysis can be found in supplementary materials made available together with the `arXiv` version of this work.

⁶`Delphes` Isolation module was modified to allow for a variable isolation cone size.

⁷JES is applied *before* the requirement of $p_T > 20$ GeV.

	SS muon pair	# b-jets ≥ 3	$E_T^{\text{miss}} > 125$ GeV	$m_{\text{eff}} > 650$ GeV
$t\bar{t}\mu\nu$	3.1876	0.0899	0.0241	0.0117 ± 0.0006
$t\bar{t}\mu^+\mu^-$	2.850	0.102	0.0146	0.008 ± 0.001
$m_O = 0.90$ TeV	1.352	0.707	0.452	0.424 ± 0.002
$m_O = 1.00$ TeV	0.6410	0.3324	0.2264	0.2172 ± 0.0007
$m_O = 1.25$ TeV	0.1144	0.0569	0.0433	0.0426 ± 0.0001
$m_O = 1.50$ TeV	0.02365	0.01109	0.00903	0.00897 ± 0.00003

Table 2. Cut-flow analysis summary (numbers in fb). For brevity’s sake, only errors for the final results are given. Errors are statistical only.

	this analysis	ATLAS
$t\bar{t}\mu\nu$	0.149 ± 0.007	0.10 ± 0.05
$t\bar{t}\mu^+\mu^-$	0.12 ± 0.02	0.14 ± 0.06
$m_O = 0.90$ TeV	5.42 ± 0.02	
$m_O = 1.00$ TeV	2.781 ± 0.009	
$m_O = 1.25$ TeV	0.546 ± 0.002	
$m_O = 1.50$ TeV	0.1148 ± 0.0003	

Table 3. Final result of analysis (last column of table 2) after multiplying by 3.2 fb^{-1} of integrated luminosity and roughly a factor of 4, to account for all possible leptonic channels taken into account in the ATLAS analysis [2], compared to column SRb3 of table 5 of that analysis.

for 3.2 fb^{-1} of integrated luminosity in comparison to the ATLAS result [65]. Contrary to the case of SM background, all possible decays of top quarks were generated. We checked on this example, that selection efficiencies calculated taking into account both electrons and muons and efficiencies calculated using only muons are roughly the same. Although electron identification criteria are tighter than the muon ones,⁸ the difference is within the accuracy of the simplified detector parametrization. This justifies the approach used in the case of sgluon signal and SM backgrounds, where only muonic decays were simulated.

The fact that the simplified analysis based on *Delphes* predicts roughly the same number of events for background coming from $t\bar{t}\mu\nu_\mu/t\bar{t}\mu^+\mu^-$ and gluino pair production signal as the ATLAS one is a check of its implementation.

As can be seen in table 5 of ref. [2], a significant contribution to the SM background comes from processes which cannot be reliably simulated by tools like *Delphes*, i.e. fake/non-prompt leptons and charge flips. This implies that the cuts used in the definition of SR3b could not be changed (adapting them to the kinematics of the sgluon pair production) as it would change the size of those contributions. Therefore, to check the separating power of cuts used by ATLAS on the sgluon signal, we looked at the effective

⁸The selection efficiencies for both electrons and muons are taken to be the same in the *Delphes* card. Electron must fulfill tighter isolation criteria, though, with the isolation cone size taken to be the smaller of $10 \text{ GeV}/p_T$ and 0.2 (not 0.3 as in the case of muons). Also, candidates within the transition region between the barrel and endcap electromagnetic calorimeters, $1.37 < |\eta| < 1.52$, and with $|\eta| > 2$ are removed.

	this analysis	ATLAS
≥ 2 SS leptons ($p_T > 20$ GeV)	11.56 ± 0.09	9.28 ± 0.18
≥ 3 b -jets ($p_T \geq 20$ GeV)	5.50 ± 0.06	4.26 ± 0.12
$E_T^{\text{miss}} > 125$ GeV	4.34 ± 0.06	3.31 ± 0.11
$m_{\text{eff}} > 650$ GeV	2.86 ± 0.05	3.20 ± 0.10

Table 4. The validation of our analysis on the gluino pair production studied by ATLAS. Total number of signal events in this analysis was normalized to 275 as given by ATLAS.

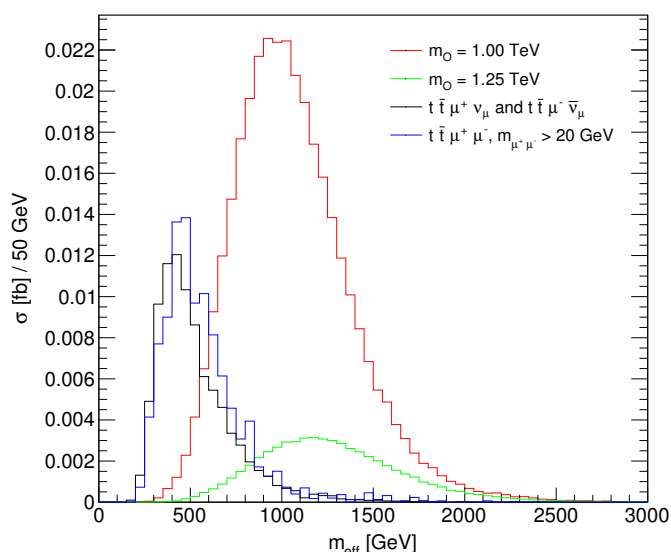


Figure 4. Effective mass spectrum after requiring 2 same-sign leptons and at least 3 b -tagged jets (see text for details) for the signal from 1 and 1.25 TeV sgluon pair and background from $t\bar{t}\mu^+\nu_\mu/t\bar{t}\mu^-\bar{\nu}_\mu$ and $t\bar{t}\mu^+\mu^-$.

mass spectrum after the same-sign muon pair requirement and the cut on the number of b -jets. This is shown in figure 4 for two sgluon masses: 1 and 1.25 TeV and backgrounds from $t\bar{t}\mu\nu_\mu$ and $t\bar{t}\mu^+\mu^-$. It is clear that the cut of $m_{\text{eff}} > 650$ GeV used in the ATLAS analysis does also a good job of separating background from the sgluon signal.

The 95% CL ATLAS upper limit on the number of signal (BSM) events in the SR3b is 3.8. The predicted numbers of signal events for selected sgluon masses are given in table 3. The ATLAS limit does corresponds to sgluons mass in the range $0.9 < m_O < 1$ TeV. To facilitate reading of its precise value, predicted numbers of signal events are plotted in figure 5 together with the interpolation between them. From this, sgluon masses < 0.95 TeV are excluded at 95% CL. This result is already on par with the 8 TeV ATLAS exclusion, which was 1.06 TeV for the case of a complex sgluon (i.e. with a cross section greater by a factor of 2).

The ATLAS experiment is supposed to gather 100 fb^{-1} of integrated luminosity by the end of Run 2, which is roughly 30 times more than what is currently available. Since

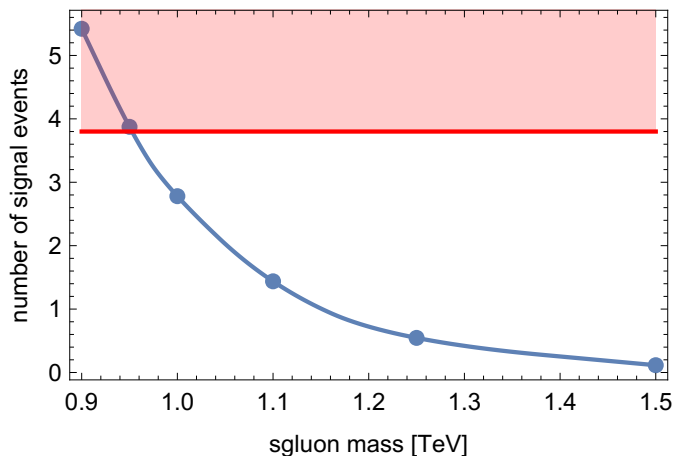


Figure 5. Predicted number of observed signal events as a function of the sgluon mass (blue points). Solid line shows interpolation between these points. Red region is excluded by ATLAS for SR3b at 95% CL. Interpreted in the context of sgluon production, it corresponds to a lower limit on the sgluon mass $m_O \lesssim 0.95$ TeV.

statistical significance scales like a square-root of integrated luminosity, numbers in table 3 suggest that even without further exploiting event kinematics and adapting cuts, it should be possible to exclude (or discover) sgluons with masses up to $\lesssim 1.25$ TeV by the end of Run 2.

6 Conclusions

In this work current ATLAS exclusion limits coming from the search of 4-top quark final state in events with same-sign leptons were recast to the case of sgluon pair production. Although sgluons decay to a top-quark pair without the presence of the invisible LSP assumed in the ATLAS analysis, the cuts used prove to work well also in this case. Data sample of 3.2/fb allows to exclude sgluons with masses $\lesssim 0.95$ TeV, a result already on par with the 8 TeV exclusion. It should, therefore, be possible to push this limit up to 1.25 TeV by the end of Run 2 based just on the increased statistics. Naturally, with an increased statistics, experimental collaboration will be able to adapt the selection criteria to further exploit sgluon kinematics, pushing this exclusion even further. We therefore encourage experimentalist to look into this.

Acknowledgments

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A Pythia8 technical setup

By default, the final state shower algorithm in `Pythia8` is based on dipole-style recoils. As stated in `Pythia8` manual, for `MC@NLO`, where a full analytic knowledge of the shower radiation pattern is needed, one has to switch to global recoil approach which does not contain color coherence phenomena (and hence factorizes). A minimal set of settings needed to consistently shower `MC@NLO` events is then given by⁹

```
SpaceShower:pTmaxMatch = 1
SpaceShower:pTmaxFudge = 1.
SpaceShower:MEcorrections = off
TimeShower:pTmaxMatch = 1
TimeShower:pTmaxFudge = 1.
TimeShower:MEcorrections = off
TimeShower:globalRecoil = on
TimeShower:weightGluonToQuark = 1
```

Those settings cannot be modified. What can be chosen, though, is when to return from the global recoil mode to the dipole recoil. Since color coherence phenomena are very important (see for example [67]), it is advantageous to switch back to dipole recoils already after the first emission. This can be done in two ways, either by setting `TimeShower:globalRecoilMode = 1` or by setting it to 2. Option 2 applies global recoil only if the first branching in evolution is a timelike splitting of a parton in an event with Born-like kinematics (the so called \mathbb{S} -events in the `MC@NLO` language), while for option 1 this is done both for Born-like (\mathbb{S}) and real-emission events (\mathbb{H} -events). With option 2, the impact of global recoil should be minimal. For options 1 and 2, a maximal number of splittings in the timelike shower with global recoil strategy should be set to 1 through `TimeShower:nMaxGlobalBranch` flag. Also, to distinguish between \mathbb{S} and \mathbb{H} events, the number of color-charged particles for Born-like configurations must be given through `TimeShower:nPartonsInBorn` option. The `MC@NLO` matching is done at the level of the hard process. To that end, `Pythia8` removes decay chains generated by `MadSpin` by traversing the event tree and identifying intermediate particles with status code `ISTUP= \pm 2` [68] which have a single parent. `TimeShower:nPartonsInBorn` then counts the number of remaining color-charged particles. For the sgluon pair production one therefore sets:

```
TimeShower:globalRecoilMode = 2
TimeShower:nMaxGlobalBranch = 1
TimeShower:nPartonsInBorn = 2
TimeShower:limitPTmaxGlobal = on
```

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⁹See `Pythia8` manual at <http://home.thep.lu.se/~torbjorn/pythia82html/Welcome.html>, section *Link to Other Programs* \rightarrow *Matching and Merging* \rightarrow *aMC@NLO Matching*. See also the discussion in ref. [66].

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