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Cornering sgluons with four-top-quark events

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The existence of colour-octet scalar states, often dubbed sgluons, is predicted in many extensions of the Standard Model of particle physics, such as supersymmetric realisations featuring Dirac gauginos. Such states have a large pair-production rate at hadron colliders and mainly decay into pairs of jets and top quarks. Consequently, they represent a primary target for experimental searches for new resonances in the multijet and multitop channels at the Large Hadron Collider. Adopting a phenomenologically-motivated simplified model, we reinterpret the results of a recent experimental search for the four-top-quark Standard Model signal, from which we constrain the sgluon mass to be larger than about 1.06 TeV. We additionally consider how modifications of the existing four-top-quark studies could enhance our ability to unravel the presence of scalar octets in data.

I. INTRODUCTION

Since its discovery as the heaviest particle of the Standard Model of particle physics, the top quark is considered as an attractive probe for new physics, in particular at the Large Hadron Collider (LHC). In many theories extending the Standard Model, top-quark production at the LHC is indeed expected to be enhanced by contributions originating from the decay of new states into one or more top quarks. Moreover, as the corresponding Standard Model background is usually well understood, top-quark studies consist of particularly clean targets for new physics searches, especially when leptonic top decays are in order.

Whilst most studies have so far solely focused on single-top and top-quark pair production, the increased integrated luminosity and centre-of-mass energy of the LHC Run 2 reinforce the potential role of new physics probes exhibiting a higher top-quark multiplicity. Among all interesting processes, there has been a growing experimental push in measuring the four-top production cross section at the LHC. The most recent experimental measurement undertaken by the CMS collaboration [1],

$$\sigma_{4t}^{\text{exp}} = 16.9_{-11.4}^{+13.8} \text{ fb}, \quad (1.1)$$

has been found to agree with the Standard Model expectation [2],

$$\sigma_{4t}^{\text{SM}} = 11.97_{-2.51}^{+2.15} \text{ fb}, \quad (1.2)$$

where the latter results include next-to-leading order (NLO) corrections both in QCD and in the electroweak theory, and where the error only accounts for scale uncertainties. The theoretical and (still statistically-limited)

experimental precision available today nevertheless open bright prospects for advancing our knowledge on new physics from four-top probes, as the room for a significant beyond the Standard Model contribution starts to be more and more reduced.

Many new physics theories feature heavy coloured resonances that essentially decay into a pair of top quarks, so that their pair production could hence yield an enhancement of the four-top production cross section. Conversely, the current measurement of the latter and its confrontation to theoretical predictions in varied new physics setups could lead to constraints on the corresponding models. For instance, models with composite top quarks have historically offered one of the theoretical motivations for LHC searches in this channel [3–6] and led to early recasting results [7]. In this work, we focus instead on scenarios featuring the presence of light scalar or pseudoscalar states lying in the adjoint representation of the QCD gauge group. Such states are commonly dubbed sgluons and for instance arise in non-minimal supersymmetric models [8–18], vector-like confining theories [19] and extra-dimensional frameworks [20]. Among those models, the supersymmetric case is especially interesting as it predicts the existence of a *complex* colour-octet scalar which is split into *two* non-degenerate real components after supersymmetry-breaking. When its couplings preserve CP these become a real scalar and a real pseudoscalar. The pseudoscalar state is generally expected to be lighter, as unrelated to the heavy gluino field, contrary to its scalar sibling, and it solely decays into a pair of quarks where the top-antitop channel dominates. In contrast, the scalar resonance is generally heavier and decays both into quarks and gluons. Investigating sgluon production and decay, both in the scalar and pseudoscalar cases, is therefore crucial for assessing the viability of this class of supersymmetric extensions. In this context, four-top production can be considered as one of the most relevant smoking guns as it could receive contributions from the lightest new physics particles.

Pioneering studies have been dedicated to the phe-

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nomenology of both complex [21–23] and real [16, 24–26] sgluons. More recently, the results of the LHC Run 1 have been confronted to the predictions of a simplified real sgluon model [25], using state-of-the-art Monte Carlo simulations matching fixed-order calculations at the next-to-leading order in QCD with parton showers [26] and relying on several LHC four-top studies [27]. The advantage of such an approach is that bounds can easily be reinterpreted in different, possibly ultraviolet-complete, theoretical frameworks [17, 28–30]. On the other hand, early four-top LHC Run 2 results from the ATLAS collaboration [31] have also been reinterpreted, this time to constrain a pseudoscalar sgluon model [32].

Driven by the recent experimental progress on the path to a potential four-top signal observation [1], we investigate in this letter how the analysis of 35.9 fb^{-1} of LHC proton-proton collisions at a centre-of-mass energy of 13 TeV could constrain light pseudoscalar sgluons, such as those predicted in supersymmetric models featuring Dirac gauginos. To this aim, we have implemented the above-mentioned CMS four-top study in the MADANALYSIS 5 framework [33, 34] and made it publicly available through the MADANALYSIS 5 Public Analysis Database [35] and INSPIRE [36]. While this offers a possibility to test any given new physics model against the results of this particular search, we focus on the pseudoscalar sgluon case and use state-of-the-art Monte Carlo simulations [26] to constrain the associated four-top signal. We moreover present some of the most interesting features that could allow for the distinction of Standard Model and sgluon-induced four-top production.

The rest of this letter is organised as follows. We briefly review the simplified sgluon model that we adopt in Sec. II and connect it to one of its possible ultraviolet origins. We next detail in Sec. III our reimplementations of the considered four-top CMS analysis and reinterpret its results in the context of our sgluon simplified model. Sec. IV is then dedicated to the presentation of various handles on sgluon-induced four-top production that could be enhanced the LHC sensitivity to these states in the future. We finally summarise our findings in Sec. V.

II. SIMPLIFIED MODEL OF SGLUONS

Our phenomenological analysis relies on a simplified sgluon model in which the Standard Model is supplemented by a scalar colour-octet field O of mass m_O , singlet under the electroweak gauge group and traditionally dubbed sgluon. After electroweak symmetry breaking, the Lagrangian describing its dynamics is given by [25]

$$\begin{aligned} \mathcal{L} = & \frac{1}{2} D_\mu O^a D^\mu O^a - \frac{1}{2} m_O^2 O^a O^a \\ & + g_8 d_{abc} O^a G_{\mu\nu}^b G^{\mu\nu c} + \tilde{g}_8 d_{abc} O^a G_{\mu\nu}^b \tilde{G}^{\mu\nu c} \\ & + \left\{ \bar{q} \left[\mathbf{y}_8^L P_L + \mathbf{y}_8^R P_R \right] O^a T^a q + \text{h.c.} \right\}, \end{aligned} \quad (2.1)$$

where fundamental colour and flavour indices are understood for clarity, T^a and d_{abc} respectively stand for the fundamental representation matrices and symmetric structure constants of $SU(3)$, $P_{L,R}$ are the usual chirality projectors, and $G_{\mu\nu}^a$ ($\tilde{G}_{\mu\nu}^a$) is the gluon field strength (dual field strength). This Lagrangian includes standard gauge-invariant kinetic and mass terms for a real field lying in the adjoint representation of the QCD gauge group, as well as the effective interactions of a single sgluon with the Standard Model quarks and gluons. The respective interaction strengths of the latter are embedded within the $\mathbf{y}_8^{\text{L,R}}$ matrix parameters in generation space and the (dimensionful) g_8 parameter.

Since the octets are real fields, the couplings must satisfy $\mathbf{y}_8^{\text{L}} = \mathbf{y}_8^{\text{R}\dagger}$. Furthermore, we assume in the following that CP is conserved in the new physics sector, so that we can distinguish a scalar from a pseudoscalar sgluon. For a pseudoscalar sgluon g_8 vanishes and the \mathbf{y}_8 matrices are pure imaginary; whereas in the scalar case, the fermion couplings are real and \tilde{g}_8 vanishes.

As a precise example stemming from a top-down perspective, one can link our simplified model of Eq. (2.1) to a class of supersymmetric realisations featuring Dirac gauginos. The spectrum of such models typically contains a complex scalar octet field \mathbf{O} whose scalar (O_R) and pseudoscalar (O_I) component obtain different masses after supersymmetry breaking. Introducing the supersymmetry-breaking scalar-octet mass m_O and bilinear coupling B_O , as well as the Dirac gluino mass m_D , the mass terms of the O_R and O_I components read [16]

$$\begin{aligned} \mathcal{L}_O = & -m_O^2 |\mathbf{O}|^2 - \frac{1}{2} (B_O \mathbf{O}^2 + \text{h.c.}) - (m_D \mathbf{O} + \text{h.c.})^2 \\ \stackrel{CP}{=} & -\frac{1}{2} (m_O^2 + B_O + 4m_D) O_R^2 - \frac{1}{2} (m_O^2 - B_O) O_I^2. \end{aligned} \quad (2.2)$$

As the pseudoscalar mass is not related to the gluino mass, it can easily lie in the sub-TeV mass range while respecting the severe gluino LHC bounds [17]; moreover, that it should be lighter than the stops and other SUSY particles is a *prediction* of the ‘‘Goldstone gaugino’’ scenario [37, 38]. Finally, in Dirac gaugino models

$$\tilde{g}_8 = 0 \quad (2.3)$$

to one loop order [16], while the $\mathbf{y}_8^{\text{L,R}}$ couplings are generated at one loop and are proportional to the masses of the respective quarks. This last property is generic and stems from the fact that the quark-quark-sgluon interactions of Eq. (2.1) are not $SU(2)$ -invariant and that any new flavour-violating effects cannot be significantly larger than in the Standard Model. Realistic sgluon benchmark configurations could hence feature, motivated by this top-down approach, a relatively heavy scalar sgluon coupling both to gluons and quarks and a relatively light pseudoscalar sgluon coupling almost entirely to top quarks with a small coupling to bottom quarks.

A generic prediction of Dirac gaugino models is then that the pseudoscalar sgluons should decay almost exclusively to tops. If pseudoscalar sgluons are indeed light,

Object reconstruction				
p_T (GeV)	Electrons > 20	Muons > 20	Jets > 40	b -tagged jets > 25
η	< 2.5	< 2.4	< 2.4	< 2.4
Isolation: All jets used for imposing lepton isolation are discarded [39].				
Baseline selection				
Jets	$H_T > 300$ GeV, $p_T^{\text{miss}} > 50$ GeV, at least two jets and two b -tagged jets.			
Leptons	Pair of same-sign isolated leptons, with the leading one satisfying $p_T > 25$ GeV.			
Vetoos	Third loosely-isolated electron (muon) with $p_T > 5$ (7) GeV forming an opposite-sign same-flavour lepton pair with an invariant mass $m_{\text{OS}} < 12$ GeV or $m_{\text{OS}} \in [76, 106]$ GeV.			

TABLE I. Summary of the object reconstruction and baseline selection procedure of the CMS four-top analysis of Ref. [1].

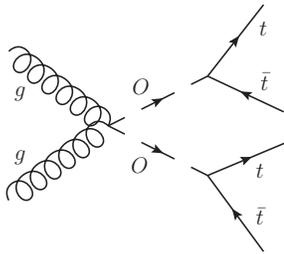


FIG. 1. Representative Feynman diagram illustrating sgluon pair production and decay into a four-top system.

they are expected to be copiously produced at hadronic colliders, the four-top signal arising then from their decay into a top-antitop pair with an almost 100% branching ratio (see Fig. 1). In this work, we compare predictions for this sgluon-induced four-top signal with the recent measurement achieved by the CMS collaboration in the multileptonic channel [1], and suggest that a more dedicated search strategy is necessary to potentially improve the limits in the upcoming years. To this aim, we have implemented a common scalar and pseudoscalar sgluon simplified model in FEYNRULES [40], which we jointly use with NLOCT [41] and FEYNARTS [42] to generate a UFO module [43] allowing for NLO calculations in QCD within the MADGRAPH5_aMC@NLO framework [44].

The simulation of the sgluon signal is achieved by generating hard scattering events where NLO matrix elements in QCD are convoluted with the NLO set of NNPDF3.0 parton densities [45]. After including sgluon decays into a top-antitop system as performed by MADSPIN [46] and MADWIDTH [47], the fixed-order results are matched with parton showers, the latter being described by PYTHIA 8 [48] that also takes care of the simulation of the hadronisation effects. We finally model the response of the CMS detector with DELPHES 3 [49], that internally relies on FASTJET [50] for object reconstruction, and we mimic the CMS four-top selection strategy by reimplementing the analysis of Ref. [1] in the MADANALYSIS 5 [33–35] framework.

III. PSEUDOSCALAR SGLUON BOUNDS FROM FOUR-TOP PRODUCTION

In the scenarios under consideration, pseudoscalar sgluons almost exclusively couple to top quarks, so that all existing sgluon bounds are automatically evaded. The latter are indeed derived from resonance searches in top-antitop [51, 52] or dijet [53–55] final states, from the shape of the $t\bar{t}$ differential cross section [56–59] or from dijet pair production [60, 61], which all require a non-vanishing sgluon coupling either to light quarks or to gluons or to both. The only potential constraints hence arise from searches for new physics in the four-top final state. For this reason, we have implemented the most recent Standard Model CMS four-top analysis [1] in the MADANALYSIS 5 framework, and we have used our reimplementations to revisit the CMS results in the context of our pseudoscalar sgluon model. Our C++ code is additionally publicly available from INSPIRE [36] through its digital object identifier (DOI) [10.7484/INSPIREHEP.DATA.BBBC.6732](https://doi.org/10.7484/INSPIREHEP.DATA.BBBC.6732).

The main object reconstruction features and baseline selection criteria of the considered search are summarised in Table I. Jets are reconstructed by means of the anti- k_T algorithm [62] with a radius parameter $R = 0.4$, and only those jets with a transverse momentum p_T and pseudorapidity η satisfying the criteria indicated in the top panel of the table are retained, a slighter selection being imposed on b -tagged jets. Furthermore, electron and muon candidates are required to be central and rather hard (see again the top panel of the table), and the various reconstructed objects are imposed to be isolated as described in Ref. [39]. The baseline selection first includes constraints on the hadronic activity H_T , defined as the scalar sum of the p_T of all reconstructed jets, and on the missing transverse energy p_T^{miss} . It next requests the presence of at least two jets, two b -tagged jets and one pair of same-sign leptons. Moreover, events exhibiting a third lepton forming an opposite-sign same-flavour pair compatible with a low-mass hadronic resonance or a Z -boson are vetoed (see the lower panel of the table).

As is customary in this type of analysis, the selection strategy then relies on eight non-overlapping signal regions whose definition asks for different requirements on

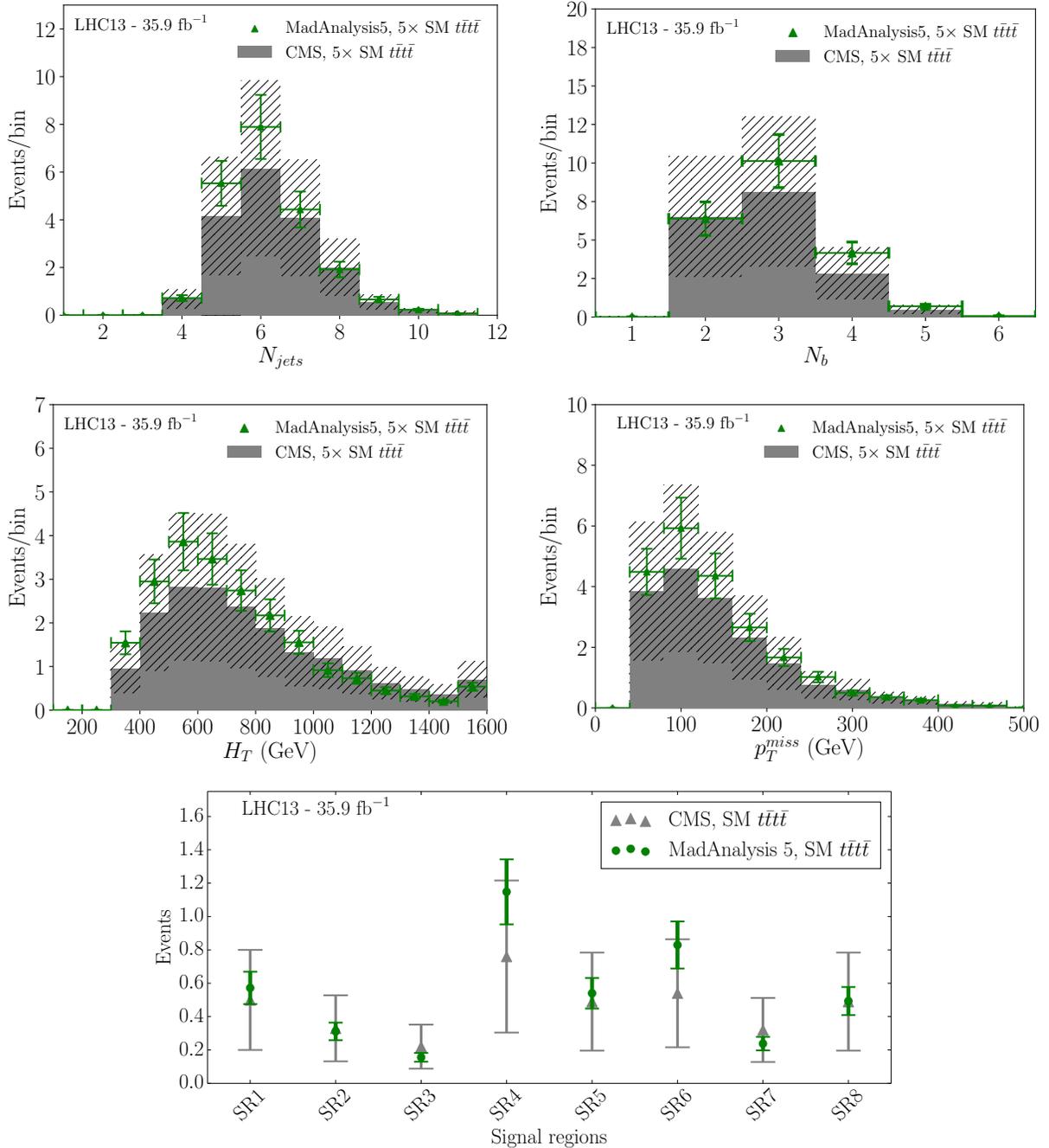


FIG. 2. Validation figures of our reimplementation, in the MADANALYSIS 5 framework, of the CMS four-top analysis of Ref. [1]. We compare MADANALYSIS 5 predictions (green) with the CMS official results (dark grey) for the jet multiplicity (upper-left panel), b -jet multiplicity (upper-right panel), H_T (central-left panel) and p_T^{miss} (central-right panel) spectra, as well as for the event counts populating each signal region (lower panel). The MADANALYSIS 5 predictions include statistical uncertainties (green error bars) whilst the CMS numbers include both systematical and statistical errors (black dashed bands and light grey error bars in the lower panel).

the lepton and jet multiplicities. A first set of three signal regions SR1, SR2 and SR3 focuses on events featuring a same-sign dilepton, 2 b -tagged jets and respectively 6, 7 and at least 8 jets. The SR4 and SR5 regions are dedicated to events with a same-sign dilepton, 3 b -jets and

5–6 or at least 7 jets respectively, whilst the SR6 region allows instead for at least 4 b -jets and at least 5 jets. Finally, two extra regions concern events with at least 3 leptons, and either 2 b -jets and at least 5 jets (SR7) or at least 3 b -jets and at least 4 jets (SR8).

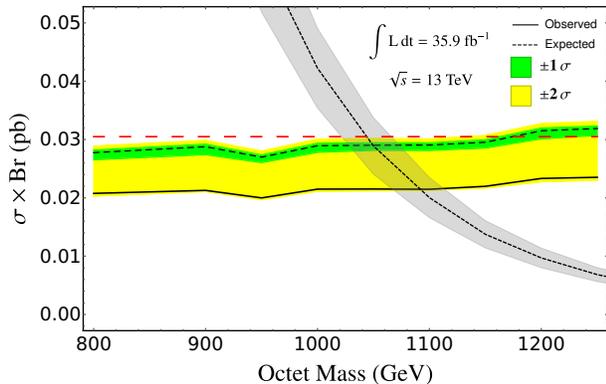


FIG. 3. Expected (dashed) and observed (solid) pseudoscalar sgluon pair-production cross section excluded at the 95% confidence level when making use of the results associated with the SR6 region of the four-top CMS analysis of Ref. [1]. Theoretical predictions for the signal rate are indicated by the grey band.

In order to validate our reimplementation, we consider Standard Model four-top production. We compare MAD-ANALYSIS 5 predictions for various differential distributions and for the number of events populating each of the eight signal regions of the considered analysis with official CMS simulated results. Although a deeper comparison would have been desirable, for instance by analysing cutflows for each signal region on a cut-by-cut basis, the necessary validation material has not been made publicly available by the CMS collaboration. We thus generate a Standard Model four-top signal using our simulation chain and show, after imposing the baseline selection, the jet multiplicity (upper-left panel), b -jet multiplicity (upper-right panel), H_T (left central panel) and p_T^{miss} (right central panel) spectra in Fig. 2. On each subfigure, we compare our predictions (green) with the CMS official simulation results (dark grey), including statistical uncertainties for what concerns our predictions (green error bars) and both the statistical and systematical uncertainties for the CMS results (light grey band). In the lower panel of the figure, we present the number of events expected to populate each of the eight signal regions after imposing the entire selection, again comparing the results returned by our simulation chain (green) with the official CMS expectation (grey). A very good agreement can be observed, so that we consider our reimplementation as validated.

Bounds on our pseudoscalar sgluon model are extracted from the generation of the corresponding signal for different choices of the sgluon mass m_O . For each signal region of the considered CMS four-top analysis, we evaluate by means of our simulation chain the number of signal events n_s surviving the selection, and then confront it to the observed number of events n_{data} after accounting for the Standard Model expectation $\hat{n}_b \pm \Delta\hat{n}_b$. In practice, we generate 10^5 Monte Carlo toy experiments

in which we take the number of background events n_b from a Gaussian distribution with mean \hat{n}_b and a width $\Delta\hat{n}_b$. The p -values associated with the background-only (p_b) and signal-plus-background (p_{s+b}) hypotheses are extracted from the Poisson distributions of parameters n_b and $n_b + n_s$ knowing that n_{data} events have been observed. By keeping the signal total production cross section free, we derive the value for which the new physics signal is excluded at the 95% confidence level, *i.e.* the smallest cross section for which

$$1 - \frac{p_{s+b}}{p_b} > 0.95 . \quad (3.1)$$

The SR6 region is typically the one most populated by the signal, its selection focusing on one pair of same-sign leptons, at least 4 b -jets and at least 5 hard jets. In Fig. 3, we present the dependence of the cross section excluded at the 95% level on the sgluon mass, using the results from this region only for which

$$\hat{n}_b \pm \Delta\hat{n}_b = 1.2 \pm 0.4 \quad \text{and} \quad n_{\text{data}} = 0 , \quad (3.2)$$

assuming an integrated luminosity of 35.9 fb^{-1} . The expected results (when one considers $n_{\text{data}} = n_b$) are shown by a dashed line, and we include the cross section values spanned by 1σ (green) and 2σ (yellow) variations found by repeating the process 10^4 times, now taking the “data” events from a gaussian distribution of mean \hat{n}_b and width $\Delta\hat{n}_b$. The solid line corresponds to the limit from the observed results, which exclude the signal most severely due to the downward fluctuation exhibited in Eq. (3.2) (as no event was observed instead of an expectation of 1.2 ± 0.4). Conclusive statements are achieved by superimposing those results to theoretical predictions for the signal rate extracted from our model. NLO predictions and the associated theoretical uncertainties are shown by a grey band, which indicates that pseudoscalar sgluons of mass equal to 1.06 TeV are conservatively excluded at the 95% confidence level. We have hence found a slight gain in exclusion after comparing our results with what could be expected from the new physics contributions allowed by the CMS four-top total cross section measurement, the corresponding upper limit being represented by the red dashed line on the figure.

IV. DEDICATED SEARCH STRATEGY

The CMS analysis under consideration targets the observation of a Standard Model four-top signal [1]. However, the signal selection strategy is not adapted to a new-physics-induced four-top signal, as the final-state kinematics could be largely different. For example, we find that the octets are produced almost at rest in the centre-of-mass frame, and the angular distribution of the top decays is therefore flat, in contrast to the SM four-top processes. Consequently, better bounds could be in principle derived from data. In Fig. 4, we impose the baseline event selection and present the H_T (upper panel) and

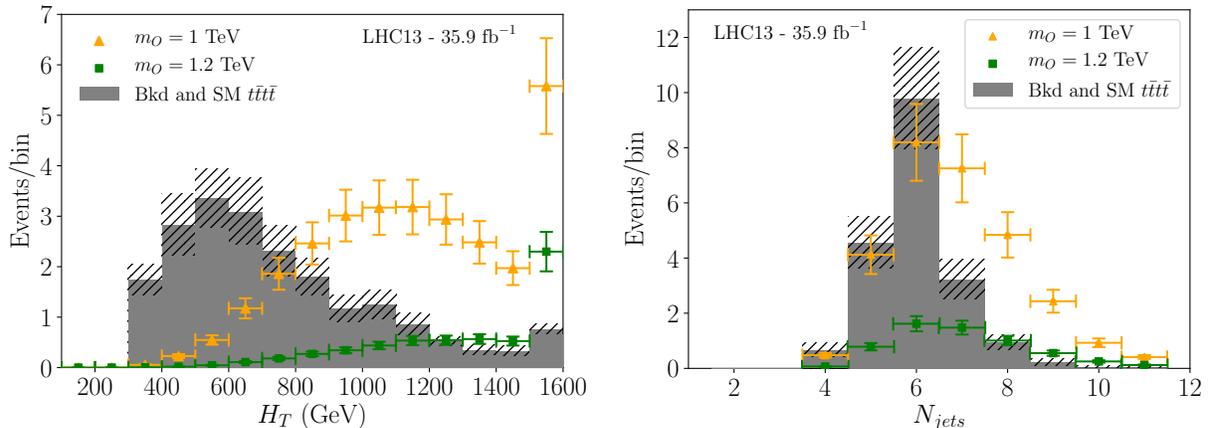


FIG. 4. Distributions in the H_T variable (left panel) and in the jet multiplicity (right panel) after applying the baseline selection of the CMS four-top analysis of Ref. [1]. We present the Standard Model distributions as provided by the CMS collaboration (dark grey with black dashed error bands) and our predictions for the signal in the case of a sgluon mass of 1 TeV (orange) and 1.2 TeV (green).

jet multiplicity (lower panel) distributions for the background (dark grey with the statistical and systematical uncertainties being encompassed in the light grey band) and two representative signal scenarios that differ by the value of the sgluon mass being fixed to $m_O = 1$ TeV (orange) and 1.2 TeV (green). In both cases, we observe a more important hadronic activity attached to the signal, which stems from the pair-production and decay of a colour-octet state lying in the TeV mass range. The signal H_T distribution indeed presents a peak close to the sgluon mass and it tends to feature a larger jet multiplicity. The H_T variable could hence provide an excellent discriminant between Standard Model and sgluon-induced four-top production after imposing a selection cut like $H_T \gtrsim 800$ GeV. Similarly, relying on probes targeting the tail of the jet multiplicity spectrum could offer extra handles on the signal, provided that a sufficient integrated luminosity is available as the statistics steeply falls with both the sgluon mass and the number of jets.

V. SUMMARY

In this work, we have investigated how current LHC new physics results constrain the existence of pseudoscalar fields lying in the adjoint representation of the QCD gauge group and almost exclusively coupling to top quarks. These fields naturally arise in many extensions of the Standard Model, and in particular in supersymmetric realisations featuring Dirac gauginos. By virtue of their vanishing coupling to light quarks and gluons in these scenarios, pseudoscalar sgluons cannot be probed via standard resonance searches in the dijet, top-antitop or dijet pair modes, and one must rely instead on four-top production. Recently, the CMS collaboration has performed the first measurement of the Standard Model

four-top production cross section. Whilst the error bars are still large and the path to a 5σ observation is still long, such a result can already be used to constrain new physics in general and pseudoscalar sgluons in particular.

We have implemented this CMS search in the MAD-ANALYSIS 5 framework and made it publicly available for LHC result reinterpretation studies. We have then recast these results in the context of a pseudoscalar sgluon simplified model. We have shown that LHC Run 2 results already constrain these sgluons to lie in the TeV mass regime, the corresponding bound on the sgluon pair-production cross section being slightly stronger than what could have obtained by using the naive cross-section limit from the four-top production rate measurement. We have moreover shown that we could benefit from the design of a search dedicated to a sgluon-induced four-top signal. Specific features in the hadronic activity associated with a sgluon signal indeed offer a strong potential in terms of discovery prospects.

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