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 phenomenology of both complex [16–18] and real [11, 19–21] sgluons. More recently, the results of the LHC Run 1 have been confronted to the predictions of a simpli-
fied real sgluon model [20], using state-of-the-art Monte Carlo simulations matching fixed-order calculations at the next-to-leading order in QCD with parton showers [21] and relying on several LHC four-top studies [22]. The advantage of such an approach is that bounds can easily be reinterpreted in different, possibly ultraviolet-complete, theoretical frameworks [12, 23–25]. On the other hand, early four-top LHC Run 2 results from the ATLAS collaboration [26] have also been reinterpreted, this time to constrain a pseudoscalar sgluon model [27].

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 [28, 29] and made it publicly available through the MADANALYSIS 5 Public Analysis Database [30] and INSPIRE [31]. 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 to constrain a pseudoscalar sgluon model [27]. However, if CP is conserved, for a pseudoscalar sgluon the y8L,R matrices are purely imaginary; whereas in the scalar case, the fermion couplings are real and y8L,R 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 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 [11]

\[
\mathcal{L}_O = -m_O^2 |O|^2 - \frac{1}{2} (B_O O^2 + \text{h.c.}) - (m_D O + \text{h.c.})^2
\]

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 [12]; moreover, that it should be lighter than the stops and other supersymmetric particles is a prediction of the “Goldstone gaugino” scenario [32, 33]. Finally, in Dirac gaugino models

\[
y_8 = 0
\]

to one loop order [11], while the y8L,R couplings are generated at one loop and are proportional to the masses of the respective quarks. 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, 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

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. The Lagrangian describing its dynamics is given by [20]

\[
\mathcal{L} = \frac{1}{2} D^a \mu O^a D^\mu O^a - \frac{1}{2} m_O^2 O^a O^a + g_8 d_{abc} O^a G^8_{\mu \nu} G^{abc}_{\mu \nu} + \tilde{g}_8 d_{abc} O^a \tilde{G}^8_{\mu \nu} \tilde{G}^{abc}_{\mu \nu} + \left\{ \bar{q} \gamma^\nu y_8^L P_L + \bar{q} y_8^R P_R \right\} O^a T^c q + \text{h.c.}
\]

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^8_{\mu \nu}, (\tilde{G}^8_{\mu \nu}) is the gluon field strength (dual field strength) tensor. 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 y8L,R matrices in generation space and the (dimensionful) g_8 and \tilde{g}_8 parameters. Since the octets are real fields, the couplings must satisfy y8L,R = y8R,L.
muons

jets

a Third loosely-isolated electron (muon) with

Pair of same-sign isolated leptons, with the leading one satisfying

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.

| Object reconstruction | Electrons | Muons | Jets | \( b \)-tagged jets |
|-----------------------|-----------|-------|------|-------------------|
| \( p_T \) (GeV) | \( > 20 \) | \( > 20 \) | \( > 40 \) | \( > 25 \) |
| \( |\eta| \) | \( < 2.5 \) | \( < 2.4 \) | \( < 2.4 \) | \( < 2.4 \) |

**Baseline selection**

| Jets | Leptons | Vetoes |
|------|--------|--------|
| \( H_T > 300 \) GeV, \( p_T^{\text{miss}} > 50 \) GeV, at least two jets and two \( b \)-tagged jets. | Pair of same-sign isolated leptons, with the leading one satisfying \( p_T > 25 \) GeV. | 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.

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 [35], which we jointly use with NLQCD [36] and FeynArts [37] to generate a UFO module [38] allowing for NLO calculations in QCD within the MadGraph5_aMC@NLO framework [39].

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 [40]. After including sgluon decays into a top-antitop system as performed by MadSpin [41] and MadWidth [42], the fixed-order results are matched with parton showers, the latter being described by PYTHIA 8 [43] that also takes care of the simulation of the hadronisation effects. We finally model the response of the CMS detector with Delphes 3 [44], that internally relies on FastJet [45] for object reconstruction, and we mimic the CMS four-top selection strategy by reimplementing the analysis of Ref. [1] in the MadAnalysis 5 [28–30] 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 [46, 47] or dijet [48–50] final states, from the shape of the \( tt \) differential cross section [51–54] or from dijet pair production [55, 56], 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 reimplementation to revisit the CMS results in the context of our pseudoscalar sgluon model. Our C++ code is additionally publicly available through its digital object identifier (DOI) 10.7484/IN-SPIREHEP.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 [57] with a radius parameter \( R = 0.4 \), and only those jets with a transverse momentum \( p_T \) and pseudorapidity \( \eta \) 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. [34]. 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 \( p_T^{\text{miss}} \). 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 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).

In order to validate our reimplementation, we consider Standard Model four-top production. We compare MADAnalysis 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 $p_T^{\text{min}}$ (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 (dashed 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 $n_{\text{data}}$ 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 $n_{\text{data}}$ 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

$$1 - \frac{p_{s+b}}{p_b} > 0.95 .$$  

(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 measurement only.

The 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, and the red dashed line represents the bound that would be extracted using the four-top total cross section measurement only.

In Fig. 3, we present the dependence of the cross section only for which $n_b \pm \Delta \hat{n}_b = 1.2 \pm 0.4$ and $n_{\text{data}} = 0$.

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 1$\sigma$ (green) and 2$\sigma$ (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 $\pm$ 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 smaller than or 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 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 Standard Model four-top production. Consequently, better bounds could be in principle derived from data. In Fig. 4, we impose the baseline event selection and present the $H_T$ (left panel) and jet multiplicity (right panel) distributions for the background (dark grey with the statistical and systematical uncertainties being encompassed in the hashed band) and two representative signal scenarios that differ by the
value of the sgluon mass being fixed to \(m_O = 1 \text{ TeV}\) (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 \(H_T \gtrsim 800 \text{ GeV}\). 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 5\(\sigma\) 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 MADANALYSIS 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 been 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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[1] CMS Collaboration, A. M. Sirunyan et al., “Search for standard model production of four top quarks with same-sign and multilepton final states in proton-proton collisions at $\sqrt{s} = 13$ TeV,” arXiv:1710.10614 [hep-ex].

[2] R. Frederix, D. Pagani, and M. Zaro, “Large NLO corrections in $W^+W^-$ and $t\bar{t}t\bar{t}$ hadroproduction from supposedly subleading EW contributions,” JHEP 02 (2018) 031, arXiv:1710.02116 [hep-ph].

[3] A. Salam and J. StratdRose, “Supersymmetry and Fermion Number Conservation,” Nucl.Phys. B87 (1975) 85.

[4] P. Fayet, “Supergauge Invariant Extension of the Higgs Mechanism and a Model for the electron and Its Neutrino,” Nucl.Phys. B90 (1975) 104–124.

[5] P. Fayet, “Fermi-Bose Hypersymmetry,” Nucl.Phys. B113 (1976) 135.

[6] L. Alvarez-Gaume and S. Hassan, “Introduction to S duality in N=2 supersymmetric gauge theories: A Pedagogical review of the work of Seiberg and Witten,” Fortsch.Phys. 49 (1997) 159–236, arXiv:hep-th/9701069 [hep-th].

[7] P. J. Fox, A. E. Nelson, and N. Weiner, “Dirac gaugino masses and supersoft supersymmetry breaking,” JHEP 08 (2002) 035, arXiv:hep-ph/0206096 [hep-ph].

[8] G. D. Kribs, E. Poppitz, and N. Weiner, “Flavor in supersymmetry with an extended R-symmetry,” Phys.Rev. D75 (2002) 055010, arXiv:0712.2039 [hep-ph].

[9] K. Benakli and M. D. Goodsell, “Dirac Gauginos in General Gauge Mediation,” Nucl. Phys. B816 (2009) 185–203, arXiv:0811.4409 [hep-ph].

[10] K. Benakli, M. Goodsell, F. Staub, and W. Porod, “Constrained minimal Dirac gaugino supersymmetric standard model,” Phys. Rev. D90 no. 4, (2014) 045017, arXiv:1403.5122 [hep-ph].

[11] M. D. Goodsell and P. Tziveloglou, “Dirac Gauginos in Low Scale Supersymmetry Breaking,” Nucl. Phys. B889 (2014) 650–675, arXiv:1407.5076 [hep-ph].

[12] K. Benakli, L. Darmé, M. D. Goodsell, and J. Harz, “The Di-Photon Excess in a Perturbative SUSY Model,” Nucl. Phys. B911 (2016) 127–162, arXiv:1605.05313 [hep-ph].

[13] K. Benakli, M. D. Goodsell, and S. L. Williamson, “Higgs alignment from extended supersymmetry,” arXiv:1801.08849 [hep-ph].

[14] C. Kilic, T. Okui, and R. Sundrum, “Vectorlike Confinement at the LHC,” JHEP 1002 (2010) 018, arXiv:0906.0577 [hep-ph].

[15] G. Burdman, B. A. Dobrescu, and E. Ponton, “Resonances from two universal extra dimensions,” Phys.Rev. D74 (2006) 075008, arXiv:hep-ph/0601186 [hep-ph].

[16] T. Plehn and T. M. P. Tait, “Seeking Sgluons,” J. Phys. G36 (2009) 075001, arXiv:0810.3919 [hep-ph].

[17] S. Y. Choi, M. Drees, J. Kalinowski, J. M. Kim, E. Popenda, and P. M. Zerwas, “Color-Octet Scalars of N=2 Supersymmetry at the LHC,” Phys. Lett. B672 (2009) 246–252, arXiv:0812.3586 [hep-ph].

[18] D. Goncalves-Netto, D. Lopez-Val, K. Mawatari, T. Plehn, and I. Wigmore, “Sgluon Pair Production to Next-to-Leading Order,” Phys.Rev. D85 (2012) 114024, arXiv:1203.6358 [hep-ph].

[19] S. Schumann, A. Renaud, and D. Zerwas, “Hadreronically decaying color-adjoint scalars at the LHC,” JHEP 1109 (2011) 074, arXiv:1108.2957 [hep-ph].

[20] S. Calvet, B. Fuks, P. Gris, and L. Valery, “Searching for sgluons in multijet events at a center-of-mass energy of 8 TeV,” JHEP 1304 (2013) 043, arXiv:1212.3360 [hep-ph].

[21] C. Degrange, B. Fuks, V. Hirschi, J. Proudom, and H.-S. Shao, “Automated next-to-leading order predictions for new physics at the LHC: the case of colored scalar pair production,” Phys. Rev. D91 no. 9, (2015) 094005, arXiv:1412.5589 [hep-ph].

[22] L. Beck, F. Blekman, D. Dobur, B. Fuks, J. Keaveney, and K. Mawatari, “Probing top-philic sgluons with LHC Run I data,” Phys. Lett. B746 (2015) 48–52, arXiv:1501.07580 [hep-ph].

[23] G. Valencia, “Colour Octet Extension of 2HDM,” Int. J. Mod. Phys. A31 no. 20n21, (2016) 1630033, arXiv:1606.02810 [hep-ph].

[24] D. Buarque Franzosi, F. Fabбри, and S. Schumann, “Constraining scalar resonances with top-quark pair production at the LHC,” arXiv:1711.00102 [hep-ph].

[25] A. Hayreter and G. Valencia, “LHC constraints on color octet scalars,” Phys. Rev. D96 no. 3, (2017) 035004, arXiv:1703.04164 [hep-ph].

[26] ATLAS Collaboration, M. Aaboud et al., “Search for squarks and gluinos in final states with jets and missing transverse momentum using 36 fb$^{-1}$ of $\sqrt{s}=$13 TeV $pp$ collision data with the ATLAS detector,” arXiv:1712.02332 [hep-ex].

[27] W. Kotlarski, “Squinos in the same-sign lepton searches,” JHEP 02 (2017) 027, arXiv:1608.00915 [hep-ph].

[28] E. Conte, B. Fuks, and G. Serret, “MadAnalysis 5, A User-Friendly Framework for Collider Phenomenology,” Comput.Phys.Commun. 184 (2013) 222–256, arXiv:1206.1599 [hep-ph].

[29] E. Conte, B. Dumont, B. Fuks, and C. Wyman, “Designing and recasting LHC analyses with MadAnalysis 5,” Eur. Phys. J. C74 no. 10, (2014) 3103, arXiv:1405.3982 [hep-ph].

[30] B. Dumont, B. Fuks, S. Kraml, S. Bein, G. Chalons, E. Conte, S. Kulkarni, D. Sengupta, and C. Wyman, “Toward a public analysis database for LHC new physics searches using MADANALYSIS 5,” Eur. Phys. J. C75 no. 2, (2015) 56, arXiv:1407.3278 [hep-ph].

[31] L. Darmé and B. Fuks, “MadAnalysis5 implementation of the four-top analysis of CMS with 35.9 fb-1 of data (CMS-TOP-17-009),” 10.7484/INSPIREHEP.DA.TA.BBC.6732.

[32] D. S. M. Alves, J. Galloway, M. McCullough, and N. Weiner, “Goldstone Gauginos,” Phys. Rev. Lett. 115 no. 16, (2015) 161801, arXiv:1502.03819 [hep-ph].

[33] D. S. M. Alves, J. Galloway, M. McCullough, and N. Weiner, “Models of Goldstone Gauginos,” Phys. Rev. D93 no. 7, (2016) 075021, arXiv:1506.05685 [hep-ph].

[34] CMS Collaboration, V. Khachatryan et al., “Search for new physics in same-sign dilepton events in
proton–proton collisions at \( \sqrt{s} = 13 \) TeV,” *Eur. Phys. J.* C**76** no. 8, (2016) 439, arXiv:1605.03171 [hep-ex].

[35] A. Alloul, N. D. Christensen, C. Degrande, C. Duhr, and B. Fuks, “FeynRules 2.0 - A complete toolbox for tree-level phenomenology,” *Comput. Phys. Commun.* **185** (2014) 2250–2300, arXiv:1310.1921 [hep-ph].

[36] C. Degrande, “Automatic evaluation of UV and R2 terms for beyond the Standard Model Lagrangians: a proof-of-principle,” *Comput. Phys. Commun.* **197** (2015) 239–262, arXiv:1406.3030 [hep-ph].

[37] T. Hahn, “Generating Feynman diagrams and amplitudes with FeynArts 3,” *Comput. Phys. Commun.* **140** (2001) 418–431, arXiv:hep-ph/0012260 [hep-ph].

[38] C. Degrande, C. Duhr, B. Fuks, D. Grellscheid, O. Mattelaer, and T. Reiter, “UFO - The Universal FeynRules Output,” *Comput. Phys. Commun.* **183** (2012) 1201–1214, arXiv:1108.2040 [hep-ph].

[39] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. S. Shao, T. Stelzer, P. Torrielli, and M. Zaro, “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations,” *JHEP* **07** (2014) 079, arXiv:1405.0301 [hep-ph].

[40] NNPDF Collaboration, R. D. Ball et al., “Parton distributions for the LHC Run II,” *JHEP* **04** (2015) 040, arXiv:1410.8849 [hep-ph].

[41] P. Artuso, R. Frederix, O. Mattelaer, and R. Rietkerk, “Automatic spin-entangled decays of heavy resonances in Monte Carlo simulations,” *JHEP* **03** (2013) 015, arXiv:1212.3460 [hep-ph].

[42] J. Alwall, C. Duhr, B. Fuks, O. Mattelaer, D. G. Öztürk, and C.-H. Shen, “Computing decay rates for new physics theories with FeynRules and MadGraph 5 amC@NLO,” *Comput. Phys. Commun.* **197** (2015) 312–323, arXiv:1402.1178 [hep-ph].

[43] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C. O. Rasmussen, and P. Z. Skands, “An Introduction to PYTHIA 8.2,” *Comput. Phys. Commun.* **191** (2015) 159–177, arXiv:1410.3012 [hep-ph].

[44] DELPHES 3 Collaboration, J. de Favereau, C. Delaere, P. Demin, A. Giammanco, V. Lemaître, A. Mertens, and M. Selvaggi, “DELPHES 3, A modular framework for fast simulation of a generic collider experiment,” *JHEP* **02** (2014) 057, arXiv:1307.6346 [hep-ex].

[45] M. Cacciari, G. P. Salam, and G. Soyez, “FastJet User Manual,” *Eur. Phys. J.* C**72** (2012) 1806, arXiv:1111.6097 [hep-ph].

[46] ATLAS Collaboration, M. Aaboud et al., “Search for heavy particles decaying into top-quark pairs using lepton-plus-jets events in proton–proton collisions at \( \sqrt{s} = 13 \) TeV with the ATLAS detector,” Submitted to: *Eur. Phys. J.* (2018), arXiv:1804.10823 [hep-ex].

[47] CMS Collaboration, A. M. Sirunyan et al., “Search for t\( \bar{t} \) resonances in highly boosted lepton+jets and fully hadronic final states in proton-proton collisions at \( \sqrt{s} = 13 \) TeV,” *JHEP* **07** (2017) 001, arXiv:1704.03366 [hep-ex].

[48] ATLAS Collaboration, M. Aaboud et al., “Search for new phenomena in dijet events using 37 fb\(^{-1}\) of pp collision data collected at \( \sqrt{s} = 13 \) TeV with the ATLAS detector,” *Phys. Rev.* D**96** no. 5, (2017) 052004, arXiv:1703.09127 [hep-ex].

[49] CMS Collaboration, “Search for new physics with dijet angular distributions in proton-proton collisions at \( \sqrt{s} = 13 \) TeV and constraints on dark matter and other models,” CMS-PAS-EXO-16-046.

[50] CMS Collaboration, “Searches for dijet resonances in pp collisions at \( \sqrt{s} = 13 \) TeV using data collected in 2016,” CMS-PAS-EXO-16-056.

[51] ATLAS Collaboration, M. Aaboud et al., “Measurements of top-quark pair differential cross-sections in the lepton+jets channel in pp collisions at \( \sqrt{s} = 13 \) TeV using the ATLAS detector,” arXiv:1801.02052 [hep-ex].

[52] ATLAS Collaboration, M. Aaboud et al., “Measurements of \( t\bar{t} \) differential cross-sections of highly boosted top quarks decaying to all-hadronic final states in pp collisions at \( \sqrt{s} = 13 \) TeV using the ATLAS detector,” arXiv:1801.02052 [hep-ex].

[53] CMS Collaboration, V. Khachatryan et al., “Measurement of differential cross sections for top quark pair production using the lepton+jets final state in proton-proton collisions at 13 TeV,” *Phys. Rev.* D**95** no. 9, (2017) 092001, arXiv:1610.04191 [hep-ex].

[54] CMS Collaboration, A. M. Sirunyan et al., “Measurement of normalized differential \( t\bar{t} \) cross sections in the dilepton channel from pp collisions at \( \sqrt{s} = 13 \) TeV,” *JHEP* **04** (2018) 060, arXiv:1708.07638 [hep-ex].

[55] ATLAS Collaboration, M. Aaboud et al., “A search for pair-produced resonances in four-jet final states at \( \sqrt{s} = 13 \) TeV with the ATLAS detector,” arXiv:1710.07171 [hep-ex].

[56] CMS Collaboration, “Search for low-mass pair-produced dijet resonances using jet substructure techniques in proton-proton collisions at a center-of-mass energy of \( \sqrt{s} = 13 \) TeV,” CMS-PAS-EXO-16-029.

[57] M. Cacciari, G. P. Salam, and G. Soyez, “The Anti-k(t) jet clustering algorithm,” *JHEP* **04** (2008) 063, arXiv:0802.1189 [hep-ph].