LHC signatures of a Z' mediator between dark matter and the SU(3) sector

Otilia Ducu,[a,b] **Lucien Heurtier**[c] **and Julien Maurer**[a]

[a]*IFIN-HH,*
Str. Reactorului 30, Bucharest-Magurele RO-077125, Romania

[b]*University of Bucharest, Faculty of Physics,*
Str. Atomistilor 30, Bucharest-Magurele RO-077125, Romania

[c]*Centre de Physique Théorique, École polytechnique, CNRS,*
Université Paris-Saclay, F-91128 Palaiseau, France

E-mail: oducu@cern.ch, lucien.heurtier@cpht.polytechnique.fr,
jmaurer@cern.ch

ABSTRACT: In this paper, we study the experimental signatures of a gluophilic Z' at the LHC, in particular through the analysis of three jets or four tops events. The Z' couples to gluons through dimension six operators and the parameter space is constrained with experimental searches released at 7 and 8 TeV by CMS along these two different channels. Existing constraints coming from the study of dark matter where the Z' represents a possible mediator between the latter and the Standard Model are also included for comparison. Prospects at $\sqrt{s} = 13\,\text{TeV}$ allow us to evaluate for which values of the parameter space a gluophilic Z' could be discovered during the next run of the LHC. In particular, we show that the analysis of the three jets invariant mass could provide a clear signal ($> 5\sigma$) for masses of the Z' above 300 GeV. Four tops events bring in addition further discovery potential for heavy Z' (above ~ 2 TeV). A combination of both signals in four top channels and three jets analyses during the next run of the LHC could thus provide a clear signal of the presence of a heavy gluophilic Z'.

Contents

1 Introduction

One of the most simple extension of the Standard Model (SM) is to provide the latter an additional U(1) abelian symmetry [1, 2]. The associated gauge boson — usually denoted by Z' in the literature — has been given a particular attention in the last decades in particular as a potential candidate for mediating interaction between the dark sector and our visible world [3–25]. Within this approach, the Standard Model fermions can be considered to be charged or not under the additional — so called U(1)$_X$ in this paper — gauge group. In the case of charged fermions, a particular care must be devoted to anomaly cancellation and flavour changing constraints. The $B-L$ models are among the most popular example, and satisfy these requirements by considering a very heavy Z'. On the other hand, string inspired models propose an anomaly cancellation a la Green-Schwarz [26–41] where a very light U(1)$_X$ mediator is generated with the use of axionic couplings and generalized Chern-Simons terms, or via Stueckelberg realization of the Z' boson [8, 42–44]. Another option is to consider neutral Standard Model fermions under the new gauge group U(1)$_X$ [11].

By adding heavy degrees of freedom, charged under both SM and U(1)$_X$ symmetries, one can generate effective operators of dimension six and compute an effective interaction Lagrangian between a Z' boson and the SM gauge bosons. Such scenarios have already been studied in the context of Dark Matter (DM) model building [11, 48–50]. In such framework, dimension six operators are suppressed by a factor M^2 (M being the mass of heavy fermions integrated out) and the dark matter sector, charged under U(1)$_X$, couples with the weak or coloured sector of the Standard Model. An interaction with the weak SM sector was shown to have possible astrophysical signatures [48, 49], while a coupling to the coloured SM sector was constrained [11] using mono-jets events at the LHC [52], as well as indirect detection constraints arising from astrophysical measurements. Such couplings had been studied, together with couplings to the top quarks in [53] but only in the context
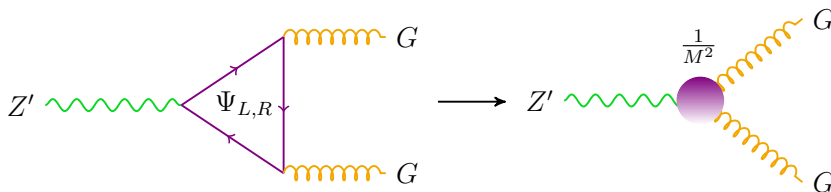
Figure 1. Z' coupling to colored sector of the Standard Model. The heavy mediators are suppressed when integrating over all considered heavy states [11].

of di-jets production without exhibiting clear signature in this case. We will however see that the coupling to gluons only can show clear evidences at the LHC in the future years.

In this paper we focus on the case aforementioned where Standard Model fermions are neutral under $U(1)_X$ and where the Z' boson interacts with the Standard Model gluons through effective operators of dimension six (and possibly to a dark matter sector). Interactions between the Z' mediator and the SM gluons will be detailed in section 2. The presence of such a feeble coupling has interesting features in the quark physics which may be discoverable during the Run-2 ($\sqrt{s} = 13\,\text{TeV}$) of the LHC. Therefore, this study aims to show what sensitivity can be reached for the theoretical model developed in [11] given the latest LHC Run-1 ($\sqrt{s} = 7$ or $8\,\text{TeV}$) experimental results. For completeness, the dark matter constraints and prospect studies for the LHC Run-2 are also included. In section 3 we discuss the possible experimental signatures. We notably identify two interesting and complementary channels that are analyzed in more details in sections 4 and 5, where we use the existing experimental constraints to investigate what would be the maximal coupling allowed for the Z' interaction with the SM gluons. Finally, in section 6 we present our conclusions concerning the potential of discovery of the model in the next years.

2 The gluophilic Z' model

As mentioned in the introduction, a new $U(1)_X$ gauge group is added to the SM under which SM fermions are considered to be neutral [11]. Effective operators of dimension six between the Z' and the SM gluons are then assumed to be generated at the loop level by integration of heavy fermions — namely $\Psi_{L,R}$ of mass M — charged both under $U(1)_X$ and $SU(3)_c$ gauge symmetries. Such loops produce at low energies effective interactions between the Z' bosons and the SM gluons as depicted in figure 1. The heavy fermions $\Psi_{L,R}$ get mass through a spontaneous symmetry breaking mechanism of the $U(1)_X$ symmetry with the use of a heavy Higgs boson field (Φ). A gauge invariant Lagrangian describing such a theory can be written by realizing the gauge symmetry non linearly, a la Stueckleberg, as shown in what follows.

The heavy Higgs field can be written a la Stueckelberg

$$\Phi = \frac{V + \phi}{\sqrt{2}} e^{i\frac{a_X}{V}} \;\; \rightarrow \;\; \frac{V}{\sqrt{2}} e^{i\frac{a_X}{V}} \;, \tag{2.1}$$

if the Higgs boson mass is assumed to be much heavier than the Z' boson. Only the axionic component of the initial field thus remains in the low energy theory. The Z' and the axion

field transform non-linearly under $\mathrm{U}(1)_X$ as follows

$$\delta Z'_\mu = \partial_\mu \alpha \quad , \quad \delta \theta_X = \frac{g_X}{2} \alpha \quad \text{where} \quad \theta_X = \frac{a_X}{V} \,. \tag{2.2}$$

Moreover, in order to write down a gauge invariant interaction lagrangian, the covariant derivatives of the axion θ_X and SM gluon fields are introduced

$$\begin{aligned}
D_\mu \theta_X &\equiv \partial_\mu \theta_X - \frac{g_X}{2} Z'_\mu \,, \\
\mathcal{D}_\mu G^a_{\alpha\beta} &\equiv \partial_\mu G^a_{\alpha\beta} + g f^{abc} G^b_\mu G^c_{\alpha\beta} \,,
\end{aligned} \tag{2.3}$$

where g_X denotes the $\mathrm{U}(1)_X$ gauge coupling and g stands for strong coupling constant. The $\mathrm{U}(1)_X$ invariant Lagrangian under Equation (2.2) can finally be written as follows

$$\begin{aligned}
\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \frac{1}{M^2} \Big[& d_g \partial^\mu D_\mu \theta_X \mathcal{T}r(G\tilde{G}) + d'_g \partial^\mu D^\nu \theta_X \mathrm{Tr}(G_{\mu\rho}\tilde{G}^\rho_\nu) \\
& + e'_g D^\mu \theta_X \mathrm{Tr}(G_{\nu\rho}\mathcal{D}_\mu \tilde{G}^{\rho\nu}) + e_g D_\mu \theta_X \mathrm{Tr}(G_{\alpha\nu}\mathcal{D}^\nu \tilde{G}^{\mu\alpha}) \Big]
\end{aligned} \tag{2.4}$$

where $\mathcal{L}_{SM}$ is the Lagrangian describing the Standard Model interactions, and the dual field-strength $\tilde{G}^{\mu\nu} \equiv \frac{\epsilon^{\mu\nu\rho\sigma}}{2} G_{\rho\sigma}$ is introduced to protect the CP parity of the previous operators. An explicit computation of fermionic loops has been released in [11] where it has been shown that, interestingly, only the operators proportional to d_g and e_g are actually present in the theory and related as follows

$$e_g = -2d_g \,. \tag{2.5}$$

Thus, only these two interaction terms will be considered in this study, the only free parameters remaining in the model being d_g/M^2 and the coupling constant g_X. Finally, for the $Z'gg$ interaction the interaction terms presented in Equation (2.4) can be written explicitly

$$\begin{aligned}
\mathcal{L} &\supset \frac{d_g}{M^2} \Big[\partial^\mu D_\mu \theta_X \mathcal{T}r(G\tilde{G}) - 2M^2 D_\mu \theta_X \mathrm{Tr}(G_{\alpha\nu}\mathcal{D}^\nu \tilde{G}^{\mu\alpha}) \Big] \\
&\supset \frac{d_g}{M^2} \Big[g_X \partial^m Z'_m \epsilon^{\mu\nu\rho\sigma} \partial_\mu G^A_\nu \partial_\rho G^A_\sigma - g_X Z'_\mu \epsilon^{\mu\nu\rho\sigma} \partial_{[\nu} G^A_{m]} \partial^m \partial_\rho G^A_\sigma \Big]
\end{aligned} \tag{2.6}$$

and the two associated vertex functions for processes involving $Z'(p_{Z'})G(p_1)G(p_2)$, symmetrized with respect to the two gluon functions, are simply

$$\Gamma_1^{\mu\nu\sigma} = -i(-1)^{n_{\mathrm{out}}} p_{Z'}^\mu (p_1)_m (p_2)_r \epsilon^{m\nu r\sigma} \tag{2.7}$$

$$\begin{aligned}
\Gamma_2^{\mu\nu\sigma} = +\frac{i(-1)^{n_{\mathrm{out}}}}{2} \Big[& (p_1)_m (p_2)^\nu (p_2)_r \epsilon^{\mu m r\sigma} \\
& + (p_2)_m (p_1)^\sigma (p_1)_r \epsilon^{\mu m r\nu} - (p_1 \cdot p_2)(p_2 - p_1)_r \epsilon^{\mu\nu r\sigma} \Big]
\end{aligned} \tag{2.8}$$

where n_{out} is the number of outgoing particles in the process considered. The gauge coupling g_X can generically take values of order $\mathcal{O}(0.1-1)$. For simplicity, g_X will be fixed in what follows to unity in order to incorporate it into the definition of the free coupling of the model, d_g/M^2.
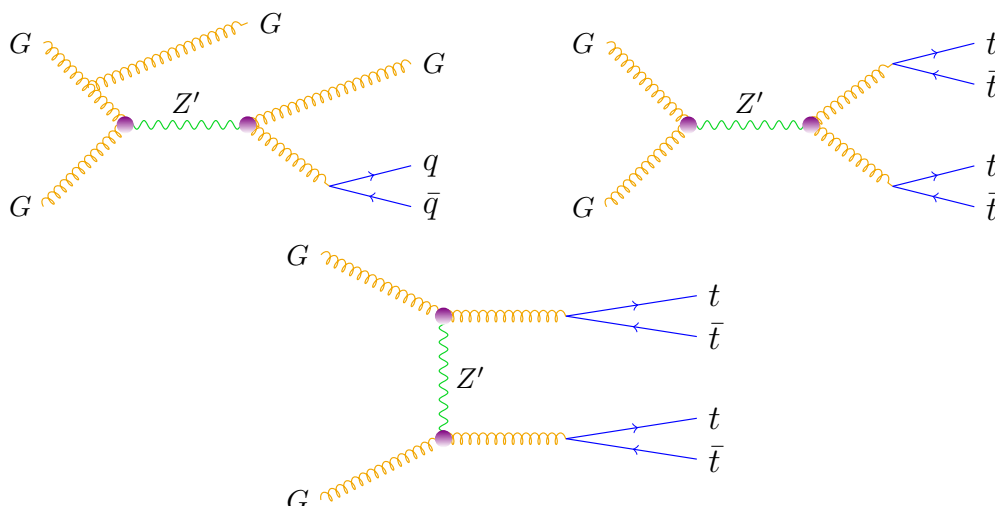
Figure 2. Example of Feynman diagrams for the processes involving a Z' boson discussed here.

	Z' 300 GeV	Z' 500 GeV	Z' 800 GeV	Z' 1.5 TeV	Z' 3 TeV
$Z' \to q\bar{q}g$	2.0 MeV	25 MeV	0.25 GeV	5.3 GeV	0.16 TeV
$Z' \to t\bar{t}g$	–	0.27 MeV	19 MeV	0.82 GeV	30 GeV
$Z' \to t\bar{t}t\bar{t}$	–	–	33 eV	0.79 MeV	0.13 GeV

Table 1. Decay widths of several Z' decay channels, for various Z' masses and an effective coupling $d_g/M^2 = 10^{-6}$. The branching ratio in the multijets channel $Z' \to q\bar{q}g$ always dominates almost exclusively.

Note that we will work in what follows in the unitary gauge, where the axionic field θ_X can be set to zero.[1]

As far as constraints coming from dark matter are concerned, we will see in the next sections that the study of [11] provides stringent constraints on the coupling d_g/M^2 for low masses of the Z' using an analysis of the monojets + missing E_T at the LHC (8 TeV). Such constraints will be only mentioned in the following study as a possible restriction of the results, since the presence of a gluophilic Z' does not necessarily implies the presence of a dark sector — nor constitutes the exclusive possibility of interaction of DM with the SM.

3 Phenomenology at hadron colliders

Thanks to its coupling to the colored sector, the Z' boson phenomenology at hadron colliders for these gluophilic models is pretty rich and in some aspects distinct from other BSM physics scenarios. Z' bosons may be produced directly in proton-proton collisions, or enhance the Standard Model cross-sections of rare processes through offshell contributions.

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[1]The implication of such choice has been discussed in the appendix of [11] in the case of anomalous low energy models, but has no implication on our model since the set of heavy fermions introduced to generate low energy effective operators is assumed to be anomaly free.

	Z' 300 GeV	Z' 500 GeV	Z' 800 GeV	Z' 1.6 TeV	Z' 3 TeV
$\sqrt{s} = 7\,\text{TeV}$	58 pb	16 pb	3.6 pb	0.14 pb	0.56 fb
$\sqrt{s} = 13\,\text{TeV}$	0.67 μb	0.22 μb	69 pb	7.8 pb	0.38 pb

Table 2. Cross-sections of $pp \to Z'j$ associate production for different Z' masses, with an effective coupling $d_g/M^2 = 10^{-6}$.

The leading order process $gg \to Z'$ is suppressed due to the Landau-Yang theorem and the typically narrow Z' width (cf table 1); therefore direct production may occur through the loop-induced process $q\bar{q} \to Z'$, or in association with a parton from initial state radiation (ISR), $qg \to qZ'$ and $gg \to gZ'$, since the latter theorem restricts at least one of the gluons producing the intermediate Z' to be off-shell in order to make any resonance visible. In this study we focused on the associate Z' + ISR jet production, the related cross-section being easier to evaluate than loop-induced processes.

The decay of a tree level Z' boson into two gluons is forbidden for the same reason as the $gg \to Z'$ process is. Possible decay channels thus involve final states with at least three quarks or gluons (e.g. $Z' \to q\bar{q}g$), including the experimentally interesting particular case of top quarks, and possibly radiated electroweak or Higgs bosons. For a more quantitative understanding we determined the Z' decay widths in various channels,[2] a few of which are summarized in table 1. For that we relied on the FeynRules 2.3 package [54] to establish the Feynman rules corresponding to the effective Lagrangian (2.4), allowing the computation of leading order matrix elements and cross-sections by the MadGraph 5.2.2.3 Monte Carlo generator [55]. One can observe that the channel $Z' \to q\bar{q}g$ is largely dominant, the branching ratios of channels involving top quarks or W bosons being typically below 1% apart for large Z' masses. While the latter provide resonant final states involving top quarks or electroweak bosons which are very clean experimental signatures, we focused on the (light flavored) multijets signature, which is very competitive thanks to its branching ratio close to unity.

We also studied non-resonant Z'-mediated contributions to rare SM processes, which may provide a nice complementarity to the direct production, in particular to probe very large Z' masses. One interesting such example is the four-tops production $pp \to t\bar{t}t\bar{t}$, which can be significantly enhanced by these new contributions.

4 Sensitivity in the multijets channel

We focus in this section on the experimental signature corresponding to the associate production of a Z' boson and an ISR parton, with a Z' assumed to decay into $q\bar{q}g$ with a 100% branching ratio. Various searches by the ATLAS and CMS collaborations look for the resonant production of heavy particles decaying into multijets final states [56–59]. However most of them are irrelevant here since they analyze either dijet production, or assume pair-production of the heavy particles (e.g. $pp \to \tilde{g}\tilde{g}$ with a gluino RPV decay). More useful

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[2]Note that no loop processes have been included here. Ideally, a full QCD computation including virtual corrections would be required for a better precision on the results.
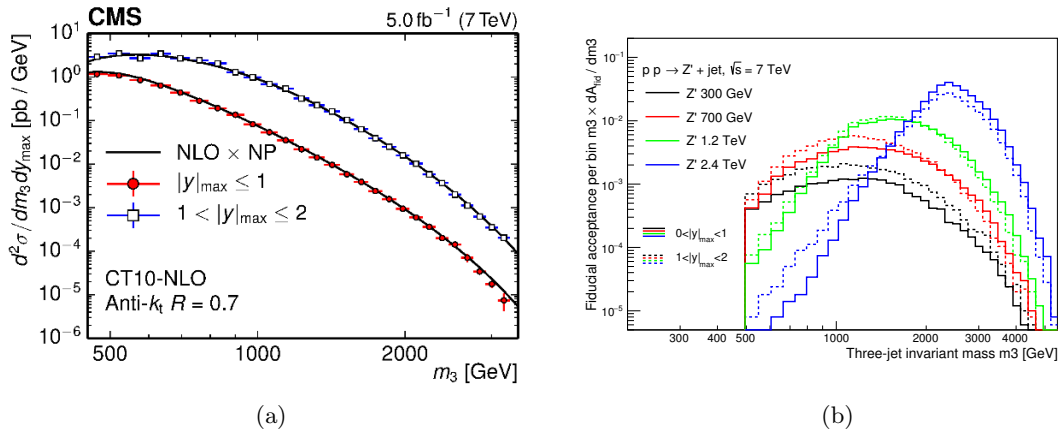
Figure 3. Three-jet invariant mass spectrum measured by CMS [60] (left), and for $pp \to Z'j \to q\bar{q}gj'$ signal models with different Z' masses (right).

are the measurements of the differential cross-section of QCD three-jets production at $\sqrt{s} = 7\,\text{TeV}$, as a function of the three-jet invariant mass [60, 61]. We evaluated the sensitivity of the measurement by CMS [60] to a potential Z' signal, and reinterpreted the measured cross-section into upper limits on the Z' effective coupling to gluons d_g/M^2.

The CMS measurement selects events with at least three jets ($p_T > 100\,\text{GeV}$, $|y| < 3.0$) and provides the observed cross-section as function of the invariant mass m_{jjj} of the three leading p_T jets in the range $445 < m_{jjj} < 3270\,\text{GeV}$, in two bins of rapidity $|y|_{\text{max}} < 1$ and $1 \le |y|_{\text{max}} < 2$, where $|y|_{\text{max}}$ corresponds to the largest rapidity among the three considered jets. To evaluate the Z' signal acceptance for this selection and construct the corresponding three-jet mass spectrum, we generated Monte-Carlo samples of signal events for different Z' masses (and a decay width fixed to[3] $1\,\text{GeV}$) at leading order using MadGraph with the CTEQ6L1 set of parton distribution functions [62], and interfaced to Pythia 6.4.28 [63] for parton showering, hadronization and modeling of the underlying event. Jets were then reconstructed from visible particles (no detector simulation involved), with their momentum randomly smeared by 10% to mimic the finite detector resolution. Apart from this emulation of the jet energy resolution, the detector reconstruction and data acquisition inefficiencies were neglected — a reasonable assumption as they are at the percent level [60, 64]. The signal production cross-sections were evaluated altogether, a few typical values are gathered in table 2. The fiducial acceptance corresponding to the aforementioned event selection was found to increase from 5 to 50% for Z' masses in the $300-3000\,\text{GeV}$ range. The low acceptance at small masses originates from the rather hard jet p_T cut used in the selection.

A quick look at the invariant mass spectrum for the signal, shown on figure 3(b) already provides some useful insight. While one would a priori expect that the presence of a resonant peak[4] at the Z' mass on top of an exponentially decreasing QCD background

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[3]Note that for such values of the decay width — as computed in table 1 — the influence of the latter on the simulation turns out to be neglectable.

[4]The Z' narrow width and the good jet energy resolution in ATLAS or CMS would allow such a feature.
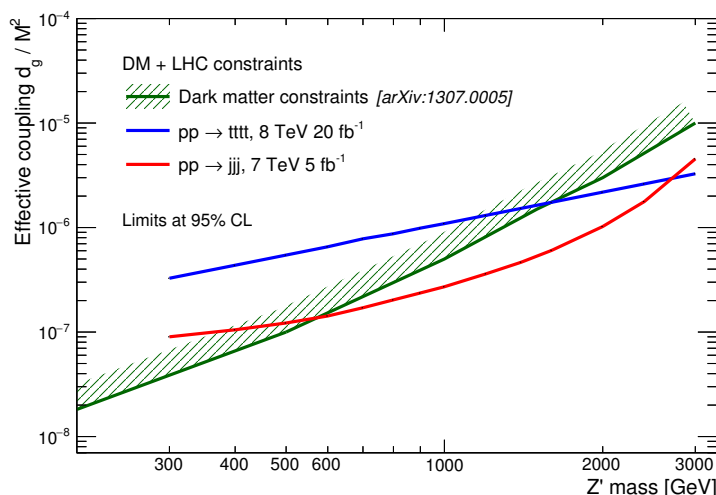
Figure 4. Current LHC sensitivity to the Z'-gluon coupling in the three-jets and four-tops channels, together with dark matter-related constaints from [11].

would provide the best evidence, the presence of the ISR parton complicates the situation. Indeed, it tends to be very energetic and be selected as one of the jets entering the invariant mass computation. As a result the signal invariant mass spectrum is not a sharp peak, but considerably smeared, even more so for light Z'. This is in fact a rather nice feature, as it allows some signal to populate bins at large invariant mass (above the resonance mass) where the QCD background is much lower. On the other hand, it would make the interpretation of a hypothetical observed excess less straightforward. One can see that the jets tend to be more central in signal events than in QCD events, therefore the measurement in the bin $|y|_{\max} \leq 1$ can be expected to provide most of the sensitivity.

Exclusion limits on Z' signal. As the CMS measurement showed good consistency between the observed data ($\sqrt{s} = 7\,\mathrm{TeV}$, $L = 5.0\,\mathrm{fb}^{-1}$) and the Standard Model QCD predictions at NLO + non-perturbative corrections (figure 3(a)), we reinterpreted these observations in terms of upper limits on the Z' free coupling to gluons d_g/M^2, as a function of the Z' mass, using the signal three-jet invariant mass spectra determined as described in the previous paragraph. For that we relied on the public 2.0 version of the HistFitter software[5] [65], which allows the computation of exclusion limits at 95% confidence level in the CL_s formalism with a test statistic built from a one-sided profile likelihood ratio. The limits were determined by a simultaneous maximum-likelihood estimation (MLE) fit of the observed invariant mass distributions in the two $|y|_{\max}$ bins with the signal and background components, with a free signal strength. We observed that the contribution from the bin $1 < |y|_{\max} < 2$ is indeed minor, improving the upper limit on the signal cross-section by only 10%. The uncertainty on the background prediction included in the likelihood is detailed later on, and amounts to 20% in the most sensitive bins. Finally, the tool was setup to use asymptotic formulas for the distribution of the test statistic, as explained in [65].

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[5]This software is largely used by the ATLAS collaboration, notably for all SUSY searches results.

The upper limits thus determined are shown on figure 4 together with the existing dark matter-related constraints established in [11], which set limits on the parameter d_g/M^2 based on searches for events with monojets + missing E_T at LHC as well as astrophysical constraints coming from indirect detection and relic density. As a matter of fact, both approaches reach sensitivity to free Z'-gluons couplings of the same order of magnitude, the reinterpretation of the CMS measurement proposed here performing a bit better at high Z' mass (above 1 TeV) while the dark matter search dominates at lower masses.

Projections for the next LHC run at $\sqrt{s} = 13$ TeV. The next phase of data-taking at the LHC (2015-2018) will provide a new dataset with increased luminosity (up to $100\,\mathrm{fb}^{-1}$) and a center-of-mass energy raised to 13 TeV, which will particularly improve the sensitivity to heavy Z'. We evaluated the discovery potential that could be achieved during this exploitation phase. To predict the QCD background yields in these new conditions, we generated Monte-Carlo samples of $pp \to jjj$ events with the same generator configuration as described previously. We also generated similar samples at $\sqrt{s} = 7$ TeV for validation purpose: we compared the differential cross-sections we obtained to the ones measured by CMS [60]. Our simple prediction is consistent with the reference (within 10%) at low invariant mass, but overshoots the reference by a factor up to 3 at large invariant mass. We didn't correct our prediction to take into account this observation, which means that the results we present should be conservative as the level of background is clearly overestimated.[6] Reducing the background by a factor 3 would only improve the limits on the effective coupling by about 30%, with essentially no impact on the qualitative conclusions set from these first projections.

We also extended the invariant mass range probed, the upper bound increasing from 3270 to 5540 GeV: we chose the latter so that the expected QCD background yield in the last bin for ($\sqrt{s} = 13$ TeV, $\mathrm{L} = 5\,\mathrm{fb}^{-1}$) is $\mathcal{O}(10)$ events, i.e. similar to the 7 TeV case. This extension is quite helpful as the sensitivity to the Z' signal comes mostly from the high end of the invariant mass spectrum. We used in the new range a variable-width binning ($\frac{\Delta m}{m} = 6\%$), identical to the one used for the CMS measurement (figure 3(a)), which was chosen as to minimize the impact of the finite jet energy resolution on the measurement.

We used a very similar setup to the one aforementioned to perform the hypothesis tests gauging the significance of a potential signal, only switching to a two-sided test statistic instead. The uncertainty on the background prediction is strongly inspired by the CMS results (cf figure 1 and 3 in [60]), in which the theoretical uncertainties are comprised between 10 and 20%, to which should be added the experimental uncertainties dominated by sources related to the jet energy scale (JES, 5 to 30%). We decided to assign a flat uncertainty of 20%, counting on a future reduction of JES uncertainty for high p_T jets solely based on increased statistics for performance measurements. The correlation of uncertainties between the different invariant mass bins is not straightforward though: if one assumes a fully correlated uncertainty, it might lead to an overly optimistic significance as the associate nuisance parameter can be strongly constrained in the MLE fit due to the

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[6]This only applies to the 13 TeV projections, which rely on the LO prediction, but not the reinterpretation of the 7 TeV results which use the more accurate prediction from [60].

	SM (NLO)	Z' 300 GeV	Z' 500 GeV	Z' 800 GeV	Z' 1.6 TeV	Z' 3 TeV
$\sqrt{s} = 8$ TeV	~ 1.3 fb	2.8 pb	0.36 pb	55 fb	5.9 fb	0.28 fb
$\sqrt{s} = 13$ TeV	9.2 fb [55]	0.57 μb	74 pb	11 pb	1.2 pb	57 fb

Table 3. Production cross-sections of the four-tops process $pp \to t\bar{t}t\bar{t}$ in Standard Model (left-most column) and via Z' mediation (not including the SM contribution) with an effective coupling $d_g/M^2 = 10^{-6}$.

bins at low invariant mass that have large statistics and are signal-free — an instance of so-called "profiling" which is undesired here. On the other hand, fully uncorrelated uncertainties may also lead to a too optimistic significance, as the signal generally spans several bins. We therefore adopted a conservative compromise, assuming full correlation but reducing the size of the uncertainty in the bins with low signal yields. Specifically, the uncertainty in each bin was set to $20\% \times (S_i/B_i)/\max(S_j/B_j)$, where S_i and B_i are the respective signal and background yield in a particular bin i. Consequently, different uncertainty profiles are used for different Z' masses.

Figure 5 presents the discovery potential for integrated luminosities of 5 and 100 fb^{-1}, for two common levels of significance (3σ or 5σ) expressed in terms of Gaussian standard deviations. One can see that even with a luminosity not exceeding the one used for the CMS measurement at 7 TeV, it would already be possible to probe free couplings up to one order of magnitude smaller than those excluded by the current searches.

Other searches with jets. Measurements of the QCD trijet cross-section were already performed by experiments anterior to LHC, notably at Tevatron [66, 67]. We did not precisely evaluate the sensitivities reached by these searches, which were performed with lower center-of-mass energy and integrated luminosity. There is furthermore no enhancement of tree-level Z' + ISR jet production in proton-antiproton collisions over proton-proton collisions, leading order Feynman diagrams involving at least one gluon. Since it was shown in figure 5 that an increase of the center-of-mass energy is very beneficial to the sensitivity to Z' signal, it seems safe to assume that LHC results largely outmatch those from Tevatron experiments. The same conclusion also applies to next section as well, further reinforced by the fact that the final state is in that case very energetic (four top quarks being produced).

Finally, we'd like to mention existing searches [68, 69] for micro black holes or string balls, which select events with several jets and look at the H_T spectrum, the scalar sum of the jets p_T. While this signature is closely related to our scenario and could potentially be quite sensitive to Z' production, a quick estimate obtained from the measured H_T spectrum in [68] (figure 1) showed that these searches are less competitive than the results based on the three-jet invariant mass that we present here.

5 Sensitivity in the four-tops channel

Measurements of rare Standard Model processes can be powerful tools to search for new physics in an indirect way. In our case, the Z' boson, through its coupling to gluons, might play an indirect role in QCD physics and particularly in top quark physics. We estimated

the leading order Z'-mediated contributions to the cross-sections of a few SM processes involving top or bottom quarks, such as $pp \to t\bar{t}g$, $pp \to t\bar{t}b\bar{b}$, $pp \to b\bar{b}b\bar{b}$ or $pp \to t\bar{t}t\bar{t}$. It turns out that potential Z' contributions manifest themselves most visibly in the latter process, the associate production of four top quarks, thanks to the very small corresponding SM cross-section (about 1 fb at $\sqrt{s} = 8\,\text{TeV}$). This is illustrated in table 3, which provides cross-sections for a few Z' masses. The cross-sections were computed at leading order with MadGraph as described in the previous section. As it is especially relevant here, one should note that the cross-sections of the Z'-mediated contributions were seen not to depend on the Z' decay width, the resonant contributions being suppressed by the Landau-Yang theorem. Furthermore, we checked that interferences between Standard Model and Z'-mediated contributions are negligible (below 5%).

The peculiar signature of four top quarks appears in various BSM scenarios such as Supersymmetry or new heavy quark generations, and is looked for at the LHC [70–73]. To evaluate the current sensitivity of these searches to Z' bosons, we reinterpreted the results obtained in [71] in terms of upper limits on the Z' effective coupling to gluons, as was done in the previous section. In this publication by the CMS collaboration, events with four top quarks were looked for in the collision data produced by the LHC in 2012 ($\sqrt{s} = 8\,\text{TeV}$, $L = 20\,\text{fb}^{-1}$), using final states with one isolated lepton and jets. Minimal requirements were placed on the missing transverse momentum in the event ($E_T^{\text{miss}} > 30\,\text{GeV}$), the number of jets (at least 7 with $p_T > 30\,\text{GeV}$), and the scalar sum of selected jets and leptons transverse momentum ($H_T > 400\,\text{GeV}$), after what a boosted decision tree (BDT) was used to discriminate signal from background events, in four distinct categories (electron or muon, exactly 7 or ≥ 8 jets). The hypothetical signal yield was extracted through a combined fit of the final BDT discriminant distributions in the four categories.

The absence of excess over the expected background lead to the establishment of an upper limit on the cross-section of the $pp \to t\bar{t}t\bar{t}$ process of 32 fb, that is 24 times the signal strength of the Standard Model process. Assuming that kinematic distributions do not vary significantly between Standard Model and Z'-mediated contributions, this limit can be directly translated into a limit on the Z'-gluon coupling. This new constraint is represented in figure 4, together with the limits obtained from the three-jets final state and the dark matter-related constraints. One can notice that the four tops final state brings a useful complementarity to the other channels for very heavy Z' (above 3 TeV), since the upper limit on the effective coupling increases only linearly with the Z' mass, while the sensitivity in the three-jets channel vanishes quickly when the Z' mass approaches the collider center-of-mass energy.

Projections for the next LHC run at $\sqrt{s} = 13\,\text{TeV}$. For this channel as well, we estimated the discovery potential that may be achieved during the LHC second phase of exploitation at $\sqrt{s} = 13\,\text{TeV}$. Heavy final states, such as those with four top quarks, will largely benefit from the increased center-of-mass energy. As can be seen in table 3, this is true not only for the Standard Model process (cross-section increased by a factor 7), but also for Z'-mediated contributions in much greater proportions (a factor 200 increase).

Taking the simplest but most approximate approach to extrapolate the current experimental results, we relied on the distributions of the BDT discriminant for the main
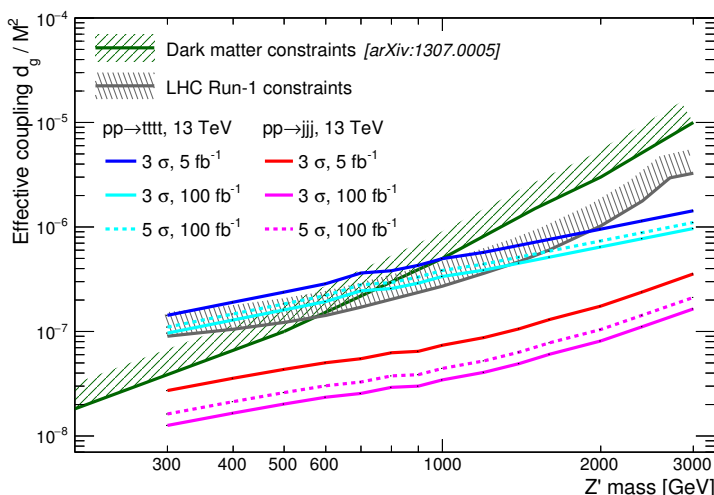
Figure 5. Discovery potential at LHC during the Run-2 phase, in terms of the Z'-gluon coupling, together with current constraints established here and in [11].

backgrounds ($t\bar{t}$+light jets, $t\bar{t} + c\bar{c}/b\bar{b}$) and Standard Model $t\bar{t}t\bar{t}$ contribution that are presented in the CMS publication (figure 3 in [71]). We reweighted these distributions by the ratios of the leading order cross-sections between $\sqrt{s} = 13$ and 8 TeV, which are respectively ~ 5.3 ($t\bar{t}$+ light jets), ~ 7 ($t\bar{t}+c\bar{c}/b\bar{b}$) and ~ 7.4 ($t\bar{t}t\bar{t}$). We then used these reweighted distributions to evaluate the signal significance at $\sqrt{s} = 13$ TeV through a combined fit of the signal strength in the four categories, the hypothesis test being performed again with the HistFitter software. We assigned global systematic uncertainties of 20% on the $t\bar{t}$+jets, and 50% on the $t\bar{t} + c\bar{c}/b\bar{b}$ background predictions, reflecting the total uncertainties mentioned in [71]. We first checked that this configuration allowed us to reproduce the CMS analysis result at 8 TeV: we indeed obtained an upper limit on the $pp \to t\bar{t}t\bar{t}$ cross-section only differing by 5% from the reference.

Figure 5 presents the estimated sensitivity at 13 TeV, again for integrated luminosities of 5 and 100 fb^{-1}. The sensitivity in terms of the effective coupling is improved by a factor 2-3 with respect to the sensitivity in this channel at 8 TeV, but does not allow to go beyond the upper limits already set by the 7 TeV experimental results in the three-jets channel apart at large Z' masses (above 2 TeV), a region the four-tops channel is the best tool to probe.

6 Conclusions

In this paper, we studied the effect of the presence of a gluophilic Z' on multi-tops event at the LHC, and in particular three jets and four tops events. The only coupling parameter of the model — the effective coupling involved in dimension six operators — has been constrained in detailed from experimental searches released at 7 and 8 TeV by CMS along these two different channels. The latter restrictions led us to evaluate for which values of the parameter space a gluophilic Z' could be discovered during the next run of the LHC. In particular, the analysis of the three jets invariant mass could provide a clear signal ($> 5\sigma$)

for masses of the Z' above 300 GeV. In addition, the four tops events analysis could furnish a potential of discovery for heavy Z' (above ~ 2 TeV). Existing constraints coming from the study of dark matter [11] where the studied Z' represents a possible mediator of the latter were furthermore added to the analysis, showing a tension with potential of discovery for low masses of the Z': masses lower than 300 GeV are disfavored to be detected from this perspective.

In conclusion, observed excesses in both four top and three jets production (for large trijet invariant masses) during the next run of the LHC could provide a clear signal of the presence of a gluophilic Z'.

Acknowledgments

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