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# Strong Signatures of Right-Handed Compositeness

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**Abstract**

Right-handed light quarks could be significantly composite, yet compatible with experimental searches at the LHC and precision tests on Standard Model couplings. In these scenarios, that are motivated by flavor physics, one expects large cross sections for the production of new resonances coupled to light quarks. We study experimental strong signatures of right-handed compositeness at the LHC, and constrain the parameter space of these models with recent results by ATLAS and CMS. We show that the LHC sensitivity could be significantly improved if dedicated searches were performed, in particular in multi-jet signals.

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# 1 Introduction

Modern realizations of composite Higgs models rely on the hypothesis of partial compositeness, each SM state has a heavy partner with equal quantum numbers under the SM symmetries, see [1, 2] and references therein. Until recently most studies focused on the so called "anarchic scenario" where the SM light quarks are mostly elementary and the top largely composite [3]. This hypothesis hides strong coupling effects from flavor and electroweak observables but also eliminates the typical collider signatures of compositeness.

In references [4–7] it was shown that a different philosophy is possible within the partial compositeness paradigm, where one chirality of SM light quarks has large compositeness. These scenarios are in fact strongly motivated by flavor physics. Assuming universal couplings for either left-handed or right-handed fermions allows to realize the hypothesis of Minimal Flavor Violation (MFV) [9] in strongly coupled theories, solving the flavor problem of composite Higgs models [8]. Here the compositeness of the up quark cannot be small, it being determined by the one of the top. Generalisations allowing to split the third generation can also be considered [10].

In this note we will focus on the phenomenologically attractive scenario of composite right-handed quarks that is weakly constrained by precision electroweak tests allowing a large degree of compositeness, see [11] for a recent discussion. We will study in detail the collider phenomenology extending and updating the results in [5]. The experimental signatures are dramatically different from the ones of the widely studied anarchic models [12]. There the fact that the proton constituents are elementary makes it difficult to produce the new states at the LHC. If right-handed up and down quarks are composite instead, the couplings to the strong sector will be large. This implies larger production cross sections for the heavy states that can be tested with present LHC data.

The typical collider signatures of our scenario are jet final states. In particular we derive a strong bound on gluon resonances from the latest dijet searches at LHC. The phenomenology of heavy fermions depends on the chirality of the associated SM particles. Partners of left-handed quarks can be singly produced through electroweak interactions with large cross sections already at the 8 TeV LHC. This places a stringent and rather model independent bound that can be extracted from an ATLAS search [13]. Partners of right-handed quarks are instead more difficult to produce and lead to final states with up to six jets and no missing energy. We find that present multi-jet LHC searches, tailored for supersymmetric scenarios, are mostly insensitive to this signature even in the R-parity violation case. Bounds could be here significantly improved with dedicated searches and we suggest some possibilities that could be explored by the experimental collaborations.

The paper is organized as follows: In section 2 we review the model and discuss the relevant features of right-handed compositeness. We emphasize in particular the importance of chromo-magnetic interactions. In section 3 we discuss the phenomenology of the color octet. The relevant experimental searches will be discussed and limits on the octet mass extracted. In sections 4 and 5 the collider signatures of heavy quark partners will be discussed. Available searches will be analyzed and dedicated search strategies will be proposed in section 6. We conclude in section 7. In appendix A the model

used in our simulations is presented and in appendix B the $p_T$ distribution in single production of heavy quark partners is discussed.

## 2 Composite Light Quarks

Within the framework of partial compositeness SM fields mix with states of the composite sector of equal quantum numbers under the SM symmetries, see [5] for a detailed discussion. All the new states are classified according to representations of the composite sector global symmetry. We will make the minimal assumption that this contains $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X$. The SM Yukawa couplings are schematically given by

$$y_{SM} = \sin\phi_L \cdot Y \cdot \sin\phi_R, \tag{2.1}$$

where $\sin\phi_{L,R}$ are the mixings matrices of left and right chiralities of the SM quarks with the composite states. The coupling $Y$, in general a matrix, has a typical strength that characterizes the composite sector. For simplicity we will often assume this to be equal to the coupling of spin-1 resonances $g_\rho$ but it should be kept in mind that these are in principle independent parameters.

The standard assumption, naturally realized in Randall-Sundrum scenarios, is that the degree of compositeness is controlled by the mass of the SM states. Within this logic the light generations are practically elementary and couple only through mixing of the SM gauge fields. This property makes the new states experimentally well hidden both from direct and indirect searches. It was pointed out however that at least the right-handed chiralities of the light generations could be composite [5,6,14]. In this case the effects of compositeness are more visible at LHC because the proton constituents are strongly coupled to the composite states. Despite the large degree of compositeness, corrections to precisions observables measured at LEP are small and can be compatible with experimental bounds[1]. This perhaps counterintuitive possibility is in fact quite naturally realized if the right-handed quarks couple to singlets of the custodial symmetry. Moreover this possibility is automatic in scenarios that realize the MFV hypothesis [5] because a flavor symmetry relates the compositeness of the up quark to the one of the top that is necessarily large.

Contrary to anarchic scenarios, composite light quarks have striking experimental signatures that could be seen at LHC. Among the new states we will consider the lightest partners of the up and down quarks. For the right-handed quarks we assume that these are singlets of $SU(2)_L \times SU(2)_R$ while left-handed quarks will be associated to bi-doublets. For the up sector we have,

$$L_U = (\mathbf{2},\mathbf{2})_{\frac{2}{3}} = \begin{pmatrix} U & U_{\frac{5}{3}} \\ D & U_{\frac{2}{3}} \end{pmatrix}, \qquad \tilde{U} = (\mathbf{1},\mathbf{1})_{\frac{2}{3}}. \tag{2.2}$$

The full model can be found in the appendix. Of the composite spin one states only the gluon partner,

[1] Modified Higgs couplings could also be obtained. See reference [15] for the discussion of Higgs precision phenomenology in models with composite right- handed quarks and reference [16] for related work.

Figure 1: *Above couplings of the color octet to SM quarks and their heavy partners. Below couplings to electroweak gauge bosons.*

a massive color octet vector, will be included. We assume that the color octet couples as a gauge field with strength $g_\rho$. Electroweak resonances will not be studied here but we expect the rough features to be similar. The mixing with SM quarks generates the trilinear couplings of the heavy gluon of figure 1 with strengths

$$\begin{aligned} X_R^{qq} &= g_s \left(\sin^2\phi_{Rq}\cot\theta - \cos^2\phi_{Rq}\tan\theta\right) \\ X_R^{qQ} &= g_s \frac{\sin\phi_{Rq}\cos\phi_{Rq}}{\sin\theta\cos\theta} \\ X_R^{QQ} &= g_s \left(\cos^2\phi_{Rq}\cot\theta - \sin^2\phi_{Rq}\tan\theta\right). \end{aligned} \tag{2.3}$$

where $\tan\theta = g_s/g_\rho$. We denote by $q$ ($Q$) a light (heavy) quark. Analogous formulas hold for the left-handed chiralities. We will be interested in the situation where the right-handed up and down quarks are significantly composite. Strictly in MFV models $\sin\phi_{Ru} = \sin\phi_{Rt} > \lambda_t/g_\rho$ but this can be relaxed in more general constructions based on $SU(2)$ flavor symmetries [10]. The SM right-handed quarks can couple to gluon resonances with a trilinear coupling $qq\rho$ as large as $g_\rho \sin^2\phi_{Rq}$. Moreover the partners of right-handed quarks can be produced and decay through the heavy-light vertex in figure 1. On the other hand the vertex with left-handed partners is negligible because the compositeness of left-handed light quarks is extremely small.

For electroweak interactions the situation is exactly reverted, see figure 1. In the limit of zero quark masses in the up sector the relevant vertices are

$$\begin{aligned} Y_{uD} = Y_{uU_{\frac{5}{3}}} &= \frac{g}{\sqrt{2}}\frac{Y_U\, v}{\sqrt{2}m_Q}\sin\phi_{Ru} \\ Y_{uU} = -Y_{uU_{\frac{2}{3}}} &= \frac{g}{2\cos\theta_W}\frac{Y_U\, v}{\sqrt{2}m_Q}\sin\phi_{Ru} \end{aligned} \tag{2.4}$$

where $v = 246$ GeV and $Y_U$ is the up sector fermionic coupling, see appendix A. These interactions allow to singly produce the partners of left-handed quarks. Higgs interactions are also generated but

we will not study them here, for more information see [17].

The last important ingredient in our analysis will be the chromomagnetic operator

$$\mathcal{L}_{\rm chromo}^{\rm SM} = \kappa \frac{g_s}{m_Q} \bar{U}_L \sigma_{\mu\nu} T^a u_R G^a_{\mu\nu} + \text{h.c.} \tag{2.5}$$

This dimension five operator is relevant in our analysis because it controls the decay of the right-handed partners in the region $m_\rho > m_Q$ where the decay into $Q \to \rho\, q$ is kinematically forbidden. It is generated by loops of the strong sector fields with a size (see appendix A)

$$\kappa \sim \frac{g_\rho^2}{16\pi^2} \frac{m_Q^2}{m_\rho^2} \sin\phi_{uR}. \tag{2.6}$$

Let us briefly comment on the scenario where left-handed quarks are strongly composite. Here precision electroweak tests, in particular modified coupling to the $Z$, strongly disfavours large compositeness. One finds [5],

$$\sin\phi_{Lq} \lesssim \frac{\lambda_t}{2\, g_\rho} \left(\frac{m_\rho}{3\,\text{TeV}}\right). \tag{2.7}$$

Repeating the analysis above implies that cross sections not larger than in the anarchic scenario will be obtained, at least for the scales and couplings that we expect in composite models that address the hierarchy problem. In fact due to the opposite sign of the two contributions in eq. (2.3) the couplings may even turn out to be smaller. In what follows we will only consider the scenario with composite right-handed quarks.

### 2.1 Simulations

In this paper we will study the phenomenology of the gluon resonance, partners of left-handed quarks $(\mathbf{2},\mathbf{2})_{\mathbf{2/3}}$ and partners of right-handed quarks, $\mathbf{1}_{\mathbf{2/3}}$ and $\mathbf{1}_{\mathbf{-1/3}}$. We focus on the first generation partners whose mass is however equal to the one of the top partners under the MFV hypothesis. The searches are very sensitive to the spectrum of the new states. We will mostly work under the assumption that the fermionic scale $m_Q$ is smaller than $m_\rho$. This hypothesis appears to be necessary for the theory to be natural, given that spin one particles lighter than 2 TeV are disfavoured. On the other hand new vectorial fermions are the most relevant from the naturalness point of view, have weaker direct bounds.

In our simulations we generate event samples with MadGraph5 [18], using a model[2] generated with Feynrules 1.6 [19]. The parton level events are passed to Pythia 6.4 [20] to simulate the effects of parton showering, and then to Delphes 2.0 [21] or ATLFAST [22] for a fast detector simulation. We use the default CMS and ATLAS parameters for Delphes depending on what experimental analysis we are comparing with, and reconstruct jets with the anti-$k_T$ algorithm [23] using 0.5 and 0.7 for the jet cone radius respectively. These simulated events are then analyzed using the experimental analyses, providing a method to interpret the relevant experimental searches in terms of our model.

[2]The FeynRules implementation of the right-handed partial compositeness model is available upon request by the authors.

## 3 Color Octet

Among possible spin-1 resonances we will focus on the gluon partner, a color octet with mass $m_\rho$. The experimental searches of dijets and $t\bar{t}$ by CMS and ATLAS imply important bounds on the parameter space of our scenario that we derive in this section. Constraints on spin one resonances from flavor physics are not necessarily negligible, even if MFV is realized, as certain operators (in particular $(\bar{q}_L y_u y_u^\dagger q_L)^2$) are generated at tree level [10]. Nevertheless, these bounds are more model dependent (for example they could be avoided in extensions of MFV) and we will not include them here (see however [11]).

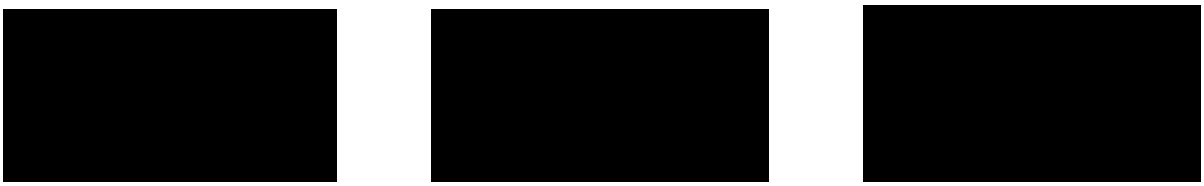

Figure 2: *The heavy color octet is dominantly produced from a quark anti-quark pair and then decays into any kinematically accessible combination of light and heavy quarks.*

### 3.1 Octet Phenomenology

The color octet can be produced through the Drell-Yan process $q\bar{q} \to \rho$ of figure 2. Through the coupling with light quarks (2.3), it can be copiously produced at LHC if $\sin\phi_{Ru}$ is sufficiently large. No gluon fusion is possible due to gauge invariance.

The decay of the $\rho$ will play an important role in the phenomenology. The decay into SM right-handed quarks is equal for all generations while only the one into $t_L$ is relevant for left-handed quarks. If the heavy fermions are lighter than the color octet the decay into a single heavy and one SM fermion or two heavy fermions (for $2m_Q < m_\rho$) will be possible. Since the couplings to the composite states are large this can affect strongly the phenomenology.

The decay modes are displayed in figure 2. Analytic formulas for the partial widths read

$$\begin{aligned}
\Gamma(\rho \to q\bar{q}) &= \frac{\alpha_s}{12} m_\rho \left[ \left(X_L^{qq}\right)^2 + \left(X_R^{qq}\right)^2 \right] \\
\Gamma(\rho \to q\bar{Q},\, Q\bar{q}) &= \frac{\alpha_s}{12} m_\rho \left(1 - \frac{m_Q^2}{m_\rho^2}\right) \left(1 - \frac{m_Q^2}{2m_\rho^2} - \frac{m_Q^4}{2m_\rho^4}\right) \left[ \left(X_L^{qQ}\right)^2 + \left(X_R^{qQ}\right)^2 \right] \\
\Gamma(\rho \to Q\bar{Q}) &= \frac{\alpha_s}{12} m_\rho \sqrt{1 - \frac{4m_Q^2}{m_\rho^2}} \left[ \left(1 - \frac{m_Q^2}{m_\rho^2}\right) \left[ \left(X_L^{QQ}\right)^2 + \left(X_R^{QQ}\right)^2 \right] + 6\frac{m_Q^2}{m_\rho^2} X_L^{QQ} X_R^{QQ} \right] .
\end{aligned} \tag{3.1}$$

in the limit $m_q \ll m_Q$. $X_{L/R}$'s are the couplings as defined in equation (2.3). As shown in figure 3 the width of the color octet changes drastically when the decay modes to one or two heavy fermions open up. In the last case the resonance is very broad.