Consistency and Interpretation of the LHC (Di-)Di-Jet Excesses

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ATLAS observed a limit for the cross section of di-jets resonances, which is weaker than expected for a mass slightly below ≈1 TeV. In addition, CMS reported hints for the (non-resonant) pair production of di-jet resonances $X$ via a particle $Y$ at a very similar mass range with a local (global) significance of $3.6 \sigma$ ($2.5 \sigma$) at $m_X \approx 950$ GeV. In this article we show that using the preferred range for $m_X$ from the ATLAS analysis, one can reinterpret the CMS analysis of di-jets in terms of a resonant search with $Y \rightarrow XX$, with a significantly reduced look-elsewhere effect, finding an excess for $m_Y \approx 3.6$ TeV with a significance of $4.0 \sigma$ ($3.2 \sigma$) locally (globally). We present two possible UV completions capable of explaining the (di-)di-jet excesses, one containing two scalar di-quarks, the other one involving heavy gluons based on an $SU(3)_c\times SU(3)_2\times SU(3)_3$ gauge symmetry, spontaneously broken to $SU(3)$ color. In the latter case, non-perturbative couplings are required, pointing towards a composite or extra-dimensional framework. In fact, using 5D-AdS space-time, one obtains the correct mass ratio for $m_X/m_Y$, assuming the $X$ is the lowest lying resonance, and predicts a third (di-)di-jet resonance with a mass around $\approx 2.2$ TeV.

I. INTRODUCTION

Since the discovery of the Higgs boson in 2012 [1, 2] the main focus of the LHC has been on the discovery of new particles and new interactions beyond the ones included in the Standard Model (SM) of particle physics. While intriguing indirect signs emerged (see e.g. Refs. [3–5] for recent reviews of lepton flavour universality violation), no new resonance has been discovered yet. However, recently the number of hints for new physics (NP) in direct LHC searches increased. In particular, ATLAS [6] observed a weaker limit than expected in resonant di-jet searches$\dagger$ in a mass region slightly below 1 TeV, while CMS [7] found hints for the (non-resonant) pair production of di-jet resonances with a mass of $\approx 950$ GeV (see Appendix) with a local (global) significance of $3.6 \sigma$ ($2.5 \sigma$) when integrating over the di-di-jet mass.

While the ATLAS analysis by itself does not constitute a significant hint for beyond the SM physics once the look-elsewhere effect (LEE) is taken into account, the compatibility of the suggested di-jet mass with the one of the (non-resonant) CMS di-di-jet analysis is very good. This agreement suggests that both excesses might be due to the same new particle $X$, once directly (resonantly) produced in proton-proton collisions ($pp \rightarrow X \rightarrow jj$), once pair produced via a new state $Y$ ($pp \rightarrow Y^{(*)} \rightarrow XX \rightarrow (jj)(jj)$). While the CMS collaboration in their analysis interprets the di-di-jet excess as the non-resonant production of $XX$ (with $m_X \approx 950$ GeV) via a heavy new particle $Y$, with $m_Y \approx 8$ TeV, resulting in a local (global) significance of $3.9 \sigma$ ($1.6\sigma$) [8], it is also possible that the two $X$ particles are resonantly produced from the decay of an on-shell $Y$ particle. In fact, the CMS results suggest $3$ TeV $\lesssim m_Y \lesssim 4$ TeV (see Appendix) for such a resonant scenario, once $m_X$ is assumed to be within the preferred range of the ATLAS di-jet analysis.

In order to evaluate this option more quantitatively, a (at least simplified) model is necessary such that the experimental resolution and acceptance can be simulated. We will do this in Sec. [11] using a simplified model with new vector bosons in order to derive the significance resulting from the CMS analysis for such a scenario with an on-shell $Y$ resonance decaying to two $X$ particles, as illustrated in Fig [11]. Next, we will examine possible UV completions that can provide a common explanation of the (di-)di-jet excesses. As we will discuss in Sec. [11] two scalar di-quarks or new massive gluons seem to be the most plausible candidates. Concerning the latter, we will consider a specific example based on an $SU(3)_c\times SU(3)_2\times SU(3)_3$ gauge group, broken down to $SU(3)$ color via two bi-triplets. We then conclude and

$\dagger$ The analogous CMS di-jet search does not display an excess in the same region. However, the sensitivity is significantly lower, such that the signal suggested by the ATLAS analysis is not excluded.
present an outlook in Sec. IV.

II. (DI-)DI-JETS

As outlined in the introduction, the preferred value for the di-jet invariant mass of ATLAS and CMS analyses strongly suggest that both signals are due to the same particle $X$, i.e. that $pp \rightarrow X \rightarrow jj$ and $pp \rightarrow Y \rightarrow XX \rightarrow (jj)(jj)$ account for the di-jet and the di-di-jet excess, respectively (see Fig. 1). In this section we consider this setup within a simplified model with a vector boson $Y$ decaying into two vector bosons $X$. We will assume that the vectors have a $Y - X - X$ coupling, depending on the momenta in the same way as the SM $Z - W - W$ coupling, with $m_Y > m_X$ and $\text{Br}[Y \rightarrow XX] = 100\%$. In addition to this triple gauge boson interaction, only $X$ and $Y$ couplings to SM quarks, which we assume to be flavour universal, are relevant.

First of all, we fix $900 \text{ GeV} \lesssim m_X \lesssim 1050 \text{ GeV}$ from the invariant mass preferred by the di-jet analysis of ATLAS which is based on $29.3 \text{ fb}^{-1}$ integrated luminosity at 13 TeV. Note that we do not include the significance of the ATLAS measurement in our fit but rather use it to confine ourselves to this range, which reduces the LEE with respect to the di-jet invariant mass. We then employ $m_X \approx 950 \text{ GeV}$, which corresponds to the best value obtained in the non-resonant analysis by CMS. As such, we move on to the di-di-jet mass $m_Y$ for which the CMS search for pairs of jets was performed with $139 \text{ fb}^{-1}$ integrated luminosity at 13 TeV center of mass energy. In this analysis, CMS selected four high transverse momentum jets, including both the cases of resonant $pp \rightarrow Y \rightarrow XX \rightarrow 4j$ and non-resonant $pp \rightarrow XX \rightarrow (jj)(jj)$ production. The observable

$$\alpha = \frac{m_1 + m_2}{2 \cdot m_{4j}},$$

is defined, where $m_1$ and $m_2$ are the di-jet invariant masses and $m_{4j}$ is the invariant mass of the four-jet system. The search is then performed in bins of $\alpha$, and in the non-resonant case an excess at $m_Y \approx 8.5 \text{ TeV}$ with a local (global) significance of $3.9 \sigma$ ($1.6 \sigma$) is reported. However, also a resonant-like excess in the four-jet invariant mass spectrum around 3-4 TeV, i.e. for $\alpha = 0.27, 0.29, 0.31$ with $m_X \approx 950 \text{ GeV}$, is visible. The cross-section of this four-jet excess can naively be estimated to be of the order of $O(1\text{fb})$.

The dominant background for di-jet resonance searches in proton-proton collisions is QCD production of multi-jets. For both ATLAS and CMS, Monte-Carlo simulations of this background are used for signal optimization and to provide an approximate comparisons with the observed data. The generation of multi-jets background is realized by simulating the leading order QCD $2 \rightarrow 2$ processes of jet production, including extra jets from QCD initial and final state radiation in the parton shower level. In order to avoid the miss-modeling of the multi-jets background, which is closely connected to the detector identification and isolation requirements, the final normalisation and shape of this background is estimated from data by ATLAS and CMS using a data-driven method, described and detailed in Refs. [12] [13].

In order to evaluate this possibility of a resonant production of $X(950)$ more quantitatively, we use our simplified model to simulate $pp \rightarrow Y \rightarrow XX \rightarrow (jj)(jj)$ events using MadGraph5_aMC@NLO 2.6.7 with leading order (LO) accuracy in QCD. The parton showering and hadronization are simulated with PYTHIA 8.2 [15] using the NNPDF2.3 LO parton distribution function set [16]. The events were processed with Delphes 3 [17], which provides an approximate fast simulation of CMS detector. Jets were reconstructed using the anti-$k_t$ algorithm [18] with the radius parameter $R = 0.4$, as implemented in FastJet 3.2.2 [19]. Jets with $p_T > 80 \text{ GeV}$

\(^2\) In the next section we will consider models that could provide a common explanation of the (di)-di-jet excesses. There we will also consider a model with scalars. We did not explicitly simulate this setup, however the differences compared to the case with gauge bosons is expected to be small as the decay kinematics are very similar.

\(^3\) See e.g. Refs. [9] [11] for theory accounts of (di)-di-jet searches.
and $|\eta| < 2.5$ are considered. Reconstructed jets overlapping with photons, electrons or muons in a cone of size $R = 0.4$ are then removed. The four jets with the highest $p_T$ are considered as the leading jets. Then the most probably di-jet pairs combination are created by minimizing the $\eta - \phi$ space separations of the jets in each events:

$$\Delta R = |(\Delta R_1 - 0.8)| + |(\Delta R_2 - 0.8)|,$$

where $\Delta R_1$ and $\Delta R_2$ are the $\eta - \phi$ space separations between the two jets within the respective systems. The offset of 0.8 is chosen to avoid the pairings from hard jets produced by QCD processes. While the pseudo-rapidity separation $\Delta \eta_{jj}$ between each two jets of each di-jet system is required to be below 1.1, to remove contribution of backgrounds from QCD t-channel. In the end, we require the $\Delta R_{i;j}=1,2$ to be less than 2, in order to remove contribution from hard jets produced by QCD processes. When the pseudo-rapidity separation $\Delta \eta_{jj}$ between the two jets within the respective systems. The offset of 0.8 is chosen to avoid the pairings with overlapped jets. In addition, we require the $\Delta R_{i;j}=1,2$ to be below 1.1, to remove contribution of backgrounds from QCD t-channel. In the end, we require the asymmetry in the di-jet mass between the di-jet systems to be small ($m_1/m_2 < 0.1$) which essentially select the di-jets of equal mass taking into account the energy resolution. This, in turn, is the property of a pair of equal mass resonances, which is unlike to QCD jets that constitute the SM background.

The most significant signal in the CMS analysis is found in the bins with the central values $\alpha = 0.27$ and $\alpha = 0.29$. We therefore evaluated the acceptance and the resolution by simulating the process $pp \to Y \to XX \to (jj)(jj)$. The results for $m_V = 3.5 \text{ TeV}$ and $m_X = 1 \text{ TeV}$ is shown in left panel of Fig. 2. Because the number of NP events in the two bins is correlated, as given by the acceptance, we can write the $p$-value$^5$ of the weighted average of the two dominant bins as

$$p = 2 \times [1 - \Phi \left( \frac{\sum_{i=1}^2 w_i S_i}{\sqrt{\sum_{i=1}^2 w_i^2}} \right)],$$

where $S_i$ is the significance for the $i^{th}$ bin (given in standard deviations) and the weight $w_i$ is equal to the acceptance of each bin, where $\Phi(x) = \int_{-\infty}^{+\infty} \frac{1}{\sqrt{2\pi}} e^{-x^2/2} dx$ denotes the standard normal cumulative distribution function. From the right panel of Fig. 2 we can see that the best agreement with data is found for $m_V \approx 3.6 \text{ TeV}$, with a total cross-section for $pp \to Y \to XX \to jjjj$ of $\approx 5 \text{ fb}$. The corresponding local (global) significance is $4 \sigma$ ($3.2 \sigma$). Note that the global significance of our resonant excess is higher than the non-resonant effect of CMS mainly due to the smaller LEE as we fixed the range of the di-jet mass a priori with the help of the ATLAS data. The LEE effect evaluated here includes the range $m_Y$ used in the search.

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$^4$ The distance $\Delta R$ between two jets in the $\eta - \phi$ space is defined as $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$.

$^5$ See e.g. Ref. [20] for the statistical combination of the results from two or more measurements.
the mass eigenstates, $g$, seven possibilities for such charge assignments (with the corresponding generators $T^a$) SU(3) gauge group. In fact, we find the suggested cross sections are too large to originate the (di-)di-jet excesses. Furthermore, the sizable couplings $g_2$ and $g_3$ can be traced back to the smallness of the $g_{2g}$ and $g_{3g}$ couplings to SM quarks which requires small mixing among the colored gauge bosons. Nonetheless, as the decay width to SM fermions is small and the right masses and couplings can be obtained, this suggests that the gauge group $SU(3)_1 \times SU(3)_2 \times SU(3)_3$, broken to $SU(3)_c$, via the described breaking, can in fact explain the (di-)di-jet excesses. Furthermore, the sizable couplings $g_2$ and $g_3$ point towards an extra-dimensional or composite realization of this setup.  

B. Scalar Di-Quarks

Alternatively to the vector-boson model proposed above, one could try to find a perturbative explanation of the (di-)di-jet excesses using scalar bosons. Because the suggested cross sections are too large to originate from a scalar produced via gluon fusion (with perturbative couplings) [41], relevant couplings to valence quarks

$$L_M = \frac{1}{2} \begin{pmatrix} G_1^{\mu a} & G_2^{\mu a} & G_3^{\mu a} \\ G_1^{\mu a} & G_2^{\mu a} & G_3^{\mu a} \\ G_1^{\mu a} & G_2^{\mu a} & G_3^{\mu a} \end{pmatrix} \begin{pmatrix} v_1^2 g_1^2 & v_1^2 g_2^2 & v_1^2 g_3^2 \\ v_1^2 g_1^2 & \frac{v_1^2 g_2^2 + v_2^2 g_3^2}{v_1^2 g_3^2} & 0 \\ v_1^2 g_1^2 & v_2^2 g_2^2 & v_2^2 g_3^2 \end{pmatrix} \begin{pmatrix} G_1^{\mu a} \\ G_2^{\mu a} \\ G_3^{\mu a} \end{pmatrix},$$  

where each block corresponds to $a = 1, ..., 8$ gauge bosons with the corresponding generators $T^a$ and equal masses.

We can now diagonalize this mass matrix to obtain the mass eigenstates, $g_1^{\mu a}$, $g_2^{\mu a}$, and $g_3^{\mu a}$, and identify the state with the zero eigenvalue $g_3^{\mu a}$ with the SM gluons and the corresponding coupling with the strong coupling constant $g_s$. The mass of $g_2^{\mu a}$ ($g_3^{\mu a}$) should correspond to $X$ ($Y$) resonance, i.e. $950$ GeV ($3.6$ TeV). We can furthermore determine the couplings of $g_2^{\mu a}$ and $g_3^{\mu a}$ by demanding that the correct signal strengths are obtained. Since ATLAS finds a preferred value of $g_3 \approx 0.07$ (in their conventions where quarks couple only to the axial-vector current) for the $X$ resonance, and in our model we have 8 $g_3^{\mu a}$ fields which couples each vectorially and flavour universal to quarks, we find that the production cross section is 4 times larger (for equal couplings) resulting in $g' \approx 0.035$, where $g'$ ($g''$) is the (effective) coupling of $g_2^{\mu a}$ ($g_3^{\mu a}$) to SM quarks. The preferred value for the di-jet cross section obtained in the last section is $\approx 5$ fb. From this we find $g'' \approx 0.07/\sqrt{\text{Br}(g_3^{\mu a} \rightarrow g_{2g}^{\mu a} g_{1g}^{\mu a})}$, by using the total production cross section for a sequential SM $Z'$ of this mass (20 fb [38]) and taking into account the $Z'$ branching ratio and the PDF scaling, using the PDF of Ref. [49] implemented in ManeParse [40], in order to rescale the cross section to the one of our model.

We can now attempt to solve this system of equations if one specifies under which $SU(3)_1$ gauge factors the SM quarks transform as a triplet. There are seven possibilities for such charge assignments ($SU(3)_1$, $SU(3)_2$, $SU(3)_3$, $SU(3)_1 \times SU(3)_2$, $SU(3)_1 \times SU(3)_3$, $SU(3)_1 \times SU(3)_3$ and $SU(3)_1 \times SU(2)_1 \times SU(3)_3$) among which only the option that the SM quarks are $SU(3)_1$ triplets, but uncharged under both other $SU(3)$ gauge factors, provides a solution. In fact, we find $g_1 \approx 1$, $g_2 \approx 10$, $g_3 \approx 15$ which is clearly in the non-perturbative regime. Therefore, these values should not be taken at face value, but rather only show that the system of equations has a solution. These large values for the couplings $g_2$ and $g_3$ can be traced back to the smallness of the $g_{2g}$ and $g_{3g}$ couplings to SM quarks which requires small mixing among the colored gauge bosons. Nonetheless, as the decay width to SM fermions is small and the right masses and couplings can be obtained, this suggests that the gauge group $SU(3)_1 \times SU(3)_2 \times SU(3)_3$, broken to $SU(3)_c$, via the described breaking, can in fact explain the (di-)di-jet excesses. Furthermore, the sizable couplings $g_2$ and $g_3$ point towards an extra-dimensional or composite realization of this setup.

![FIG. 2. Left: Acceptance obtained from our simulation of pp → Y → XX → 4j for m_X = 1 TeV and m_Y = 3.5 TeV. Right: p-value as a function of m_Y, obtained by combining the two leading bins in α, i.e. $α = 0.27$ and $α = 0.29$.](image-url)
are needed. Since SU(3)_c, singlet scalars can only interact with quarks in the same way as the SM Higgs boson, the couplings are naturally related to the respective Yukawa couplings, rendering them tiny for valence quarks, thus resulting in too small cross sections.

However, SU(3)_c, triplet or sextuplet (symmetric 3 × 3) scalars can couple to quarks of the same SU(2)_L representation such that their couplings are unrelated to EW symmetry breaking and therefore also unrelated to quark Yukawa couplings. Searches for such di-quarks via di-jet and di-di-jet signatures were proposed in Refs. 42–49.

The choice of quantum numbers for di-quarks is restricted to five possibilities

| Quantum Numbers | SU(3)_c | SU(2)_L | U(1)_X |
|-----------------|---------|---------|--------|
| \( \Phi_u \)    | 6       | 1       | -4/3   |
| \( \Phi_d \)    | 6       | 1       | 2/3    |
| \( \Phi_1 \)    | 3       | 1       | -1/3   |
| \( \Phi_2 \)    | 3       | 3       | -1/3   |
| \( \Phi_{ud} \) | 6       | 1       | 1      |

if we restrict ourselves to the cases which allow couplings to the respective Yukawa couplings with quarks in the same way as the SM Higgs boson, the 950 GeV one is possible. In this case, it has to be assumed that the couplings to quarks are universal, such that the CKM rotation between the interaction and the mass eigenbasis does not generate flavour changing couplings that would contribute to \( \Delta F = 2 \) processes.

IV. CONCLUSIONS AND OUTLOOK

In this article we pointed out that the ATLAS di-jet excess with a mass slightly below 1 TeV is perfectly consistent with the preferred di-jet mass of 950 GeV of the CMS di-di-jet analysis. We then used the suggested range for \( m_X \) from ATLAS to recast the CMS di-di-jet analysis in terms of a resonant search for \( Y \rightarrow XX \rightarrow (jj)(jj) \). This significantly reduces the LEE and results in a local (global) significance of 4.0 \( \sigma \) (3.2 \( \sigma \)) for a resonance \( Y \) with mass \( m_Y \approx 3.6 \) TeV.

We then examined possible combined explanations of the (di-)di-jet excesses and proposed both a model with scalar di-quarks and a model with new heavy colored vector bosons based on an SU(3)_c × SU(3)_c × SU(3)_3 gauge symmetry spontaneously broken to SU(3)_c. While the scalar di-quark model has couplings that are at most the order one, the SU(3)_3 model requires large non-perturbative couplings, pointing towards an extra-dimensional or composite realization. Interestingly, interpreting this model in a Randall-Sundrum (RS) framework 51, the ratio of the masses of the gauge boson excitations are predicted to be

\[ m_n/m_1 = 4(n-1/4)/3, \]

where \( m_1 \) is the first gluon excitation with a non-vanishing mass. This means if the first resonance \( (n = 1) \) is at \( \approx 950 \) GeV, the second one \( (n = 2) \) should be at \( \approx 2.2 \) TeV while the third \( (n = 3) \) is at \( \approx 3.5 \) TeV. While the latter value fits nicely the (di-)di-jet data, this RS framework predicts the existence of another (di-)di-jet resonance with a mass around 2.2 TeV. Note that such a resonance, if it has similar couplings to quarks as the first one \( n = 1 \), is not excluded by current di-jet searches due to the PDF scaling w.r.t. the 950 GeV resonance. Furthermore, the CMS di-di-jet data even points towards a slight excess in this region of the di-jet invariant mass \( m_Y \) (see Appendix).

In light of the intriguing hints for NP in semi-leptonic B decays 53, 54, \( g - 2 \) of the muon 55, 57, the W mass 58, 59, the Cabibbo angle anomaly 60, 62, the 96 GeV 63, 151 GeV 64 and 680 GeV 65 excesses, the multi-lepton anomalies 66, 69, the di-Higgs 70 excess as well as the hint for non-resonant di-electrons 22, 71.
the (di-)di-jet excesses constitute one more very interesting sign of physics beyond the SM. While the other signals for NP are in general related electroweak processes within the SM, the (di-)di-jet signals points towards colored new particles. This broadens the range of interactions for which the anomalies suggest NP and has important consequences for collider searches and model building in the collaborative search for the next SM of particle physics.

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Appendix A: ATLAS and CMS Plots

Here we quote the main results of the ATLAS and CMS searches for (di)-di-jet searches for the convenience of the reader. The result of the di-jet resonance search of ATLAS is shown in the left plot of Fig. 3. The di-jet invariant mass $m_{XX}$ of the CMS di-di-jet analysis is given in the right plot of Fig. 3 while the relevant plots for the di-di-jet mass $m_{YY}$ are displayed in Fig. 4.
FIG. 3. Left: Di-jet search of ATLAS [9] showing the expected and observed limits on the axial coupling $g_\alpha$ of a $Z'$ boson to quarks. Right: Cross section times branching ratio times acceptance in units of pico barn as a function of the di-jet invariant mass obtained in the CMS di-di-jet analysis [8].

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FIG. 4. Observed and expected limit on cross section times branching ratio times acceptance in units of pico barn as a function of the di-di-jet invariant mass for different values of $\alpha = m_X/m_Y$. 

$Y \rightarrow XX \rightarrow (jj)(jj)$

$95\%$ CL limits

- Observed
- Diquark: $S \rightarrow \chi \chi \rightarrow (ug)(ug)$

$\chi_u = 0.4$, $\chi_x = 0.6$

$M(X) / M(Y) = 0.11$

$M(X) / M(Y) = 0.19$

$M(X) / M(Y) = 0.29$

$M(X) / M(Y) = 0.13$

$M(X) / M(Y) = 0.21$

$M(X) / M(Y) = 0.31$

$M(X) / M(Y) = 0.15$

$M(X) / M(Y) = 0.23$

$M(X) / M(Y) = 0.33$

$M(X) / M(Y) = 0.17$

$M(X) / M(Y) = 0.27$

$M(X) / M(Y) = 0.42$
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