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Trinification can explain the di-photon and di-boson LHC anomalies

Giulio Maria Pelaggi,[a] **Alessandro Strumia**[a,b] **and Elena Vigiani**[a]

[a] *Dipartimento di Fisica dell'Università di Pisa and INFN, Largo B. Pontecorvo 3, Pisa, Italy*

[b] *CERN, Theory Division, 1211 Geneve 23, Switzerland*

E-mail: g.pelaggi@for.unipi.it, Alessandro.Strumia@cern.ch, elenavigiani@gmail.com

Abstract: LHC data show a diphoton excess at 750 GeV and a less significant diboson excess around 1.9 TeV. We propose trinification as a common source of both anomalies. The 1.9 TeV excess can be produced by the lightest extra vector: a $W_R^\pm$ with a gauge coupling $g_R \approx 0.44$ that does not decay into leptons. Furthermore, trinification predicts extra scalars. One of them can reproduce the $\gamma\gamma$ excess while satisfying constraints from all other channels, given the specific set of extra fermions predicted by trinification.

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Contents

1 Introduction

After the discovery of the Standard Model Higgs boson [1, 2] at the Large Hadron Collider, data indicate the presence of other excesses that can be interpreted as resonant production of new bosons. The two most notable anomalies found in present LHC data are:

1. An excess of di-boson events peaked around 1.9 TeV, found in run 1 data [3–6]. This has been explained in terms of resonant production of extra vectors, such as Z' or W_R that decay into ZZ or WZ, respectively [7–21]. Run 2 data do not confirm this excess, but (as we will see) do not significantly contradict it.

2. An excess of di-gamma events peaked around 750 GeV, mostly seen at run 2 [4–6]. This has been explained in terms of resonant production of an extra scalar S [22–42]. In order to achieve the needed $S \to \gamma\gamma$ decay width, extra vector-like fermions or scalars coupled to S with a relatively large coupling must be introduced [22–42].

Assuming that these excesses are not statistical fluctuations, we try to go beyond phenomenological considerations and explore which kind of bigger picture they can suggest.

The structure needed to explain both anomalies is present in models that extend the SM gauge group around the weak scale, thereby implying extra vectors, predicting a larger set of anomaly-free chiral fermions and needing extra Higgs scalars and Yukawa couplings. Among this class of models, trinification is the $\mathrm{SU}(3)_L \otimes \mathrm{SU}(3)_R \otimes \mathrm{SU}(3)_c$ subgroup of E_6 that explains the observed quantised hypercharges, that can be broken to the Standard Model at a scale V just above the weak scale, that allows a totally asymptotically free extension of the SM [43–47], which is suggested by non conventional ideas about naturalness of the Higgs mass [48]. Trinification contains left-right models and 3-3-1 models as subgroups [49–53]. Focusing on trinification:

JHEP03(2016)025

Field	spin	generations	$\mathrm{SU}(3)_L$	$\mathrm{SU}(3)_R$	$\mathrm{SU}(3)_c$
$\mathcal{Q}_R = \begin{pmatrix} U & D_1 & D_2 \end{pmatrix}^T$	1/2	3	1	3	$\bar{3}$
$\mathcal{Q}_L = \begin{pmatrix} Q & \bar{D}' \end{pmatrix}$	1/2	3	$\bar{3}$	1	3
$\mathcal{L} = \begin{pmatrix} \bar{L}' & L_2 & L_1 \\ E & N_2 & N_1 \end{pmatrix}$	1/2	3	3	$\bar{3}$	1
$\mathcal{H} = \begin{pmatrix} H_u^* & H_d & H_L \\ S^+ & S_1 & S_2 \end{pmatrix}$	0	3	3	$\bar{3}$	1

Table 1. Field content of minimal weak-scale trinification. Q is the SM left-handed quark doublet, U is the SM right-handed up quark, E is the SM right-handed lepton. The D_1 and D_2 quarks mix making D (right-handed down quarks) and D' (that gets a mass with $\bar{D}'$) the L_1 and L_2 lepton doublets mix making L (left-handed lepton doublet) and L' (that gets a mass with $\bar{L}'$). N_1 and N_2 are singlets.

- It predicts extra $W_R^\pm$ vectors with mass $\sim g_R V$ with properties compatible with the di-boson anomaly: no decays into leptons, appropriate value of its g_R gauge coupling.
- It predicts 27 chiral fermions per generation: the SM fermions, plus extra vector-like D' and L' fermions (and singlets), which receive masses $M' \sim y'V$. Large Yukawa couplings y' to fermions are needed in order to make M' above present bounds, if V is not much above the weak scale.
- It predicts a larger set of Higgs scalars, which contain various singlets and doublets (with neutral components). One of them can be identified with the Higgs doublet at 125 GeV, and another with the scalar S at 750 GeV.

In section 2 we briefly summarise the main ingredients of trinification models needed to interpret the LHC anomalies. In section 3 we discuss how trinification can reproduce the di-boson anomaly. In section 4 we discuss how trinification can reproduce the di-gamma anomaly. Conclusions are given in section 5.

2 Trinification

The minimal model of weak-scale trinification is obtained including 3 families of chiral-free fermions under the gauge group $G_{333} = \mathrm{SU}(3)_L \otimes \mathrm{SU}(3)_R \otimes \mathrm{SU}(3)_c$ and 3 families of Higgses, as summarised in table 1. The three trinification gauge coupling constants (g_2, g_R, g_3) allow to reproduce those of the SM (g_2, g_Y, g_3) as

$$g_R = \frac{2g_2 g_Y}{\sqrt{3g_2^2 - g_Y^2}} \approx 0.444. \tag{2.1}$$

The SM Yukawa couplings are obtained from the G_{333}-invariant interactions

$$-\mathscr{L}_Y = y_{Qn}^{ij}\, \mathcal{Q}_{Li}\mathcal{Q}_{Rj}\mathcal{H}_n + \frac{y_{Ln}^{ij}}{2}\mathcal{L}_i\mathcal{L}_j\mathcal{H}_n + \text{h.c.} \tag{2.2}$$

JHEP03(2016)025

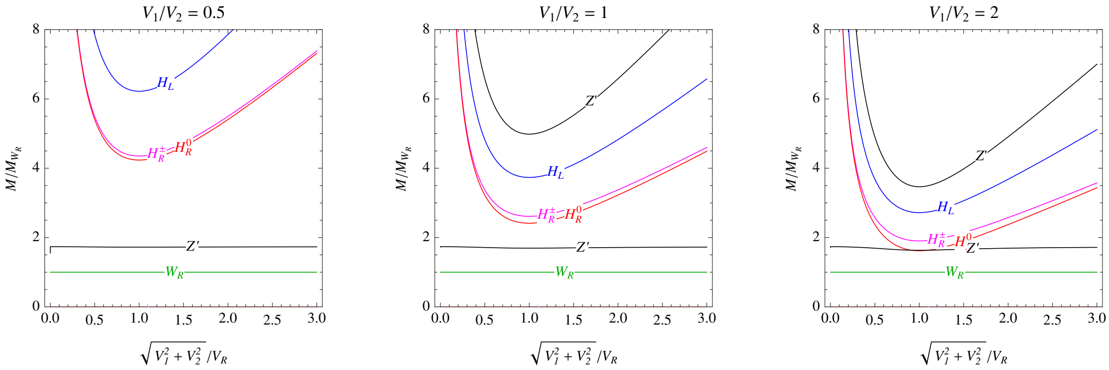

Figure 1. Trinification heavy vector masses normalised to the W_R mass. The next-to-lightest vector is a Z' with mass $\approx 1.7\, M_{W_R}$. For concreteness, we used a basis where $V_{R1} = 0$.

The most generic vacuum expectation values that give the desired pattern of symmetry breaking are

$$\langle \mathcal{H}_n \rangle = \begin{pmatrix} v_{un} & 0 & 0 \\ 0 & v_{dn} & v_{Ln} \\ 0 & V_{Rn} & V_n \end{pmatrix} . \tag{2.3}$$

Defining $V^2 \equiv \sum_n (V_n^2 + V_{Rn}^2)$ and the dimension-less ratios

$$\alpha \equiv \sum_n V_{Rn}^2 / V^2, \qquad \beta \equiv \sum_n V_n V_{Rn} / V^2 , \tag{2.4}$$

in the relevant limit $v \ll V$ one obtains the following extra massive vectors:[1]

- A left-handed weak doublet with mass $M_{H_L} = g_2 V/\sqrt{2}$, that contains two neutral components and two charged components.
- Two Z', Z'' vectors with masses:

$$M^2_{Z',Z''} = \frac{V^2}{3}\left[(g_2^2 + g_R^2) \pm \sqrt{(g_2^2+g_R^2)^2 + 3g_R^2(4g_2^2+g_R^2)(\alpha^2 - \alpha + \beta^2)}\right]. \tag{2.5}$$

- A $\mathrm{SU}(2)_R$ vector doublet A_{2R} splitted into two neutral components with mass $M_{H_R^0} = g_R V/\sqrt{2}$ and into 2 charged components with mass

$$M^2_{H_R^\pm} = \frac{g_R^2 V^2}{4}\left[1 + \sqrt{(1-2\alpha)^2 + 4\beta^2}\right]. \tag{2.6}$$

[1] Notice that trinification includes both left-right models (the group $\mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \otimes \mathrm{U}(1)_{B-L} \otimes \mathrm{SU}(3)_c$ is obtained in the limit $\alpha, \beta \ll 1$ [54]) and 3-3-1 models [49–53] (the group $\mathrm{SU}(3)_L \otimes \mathrm{SU}(3)_c \otimes \mathrm{U}(1)_X$ is obtained from trinification if $\mathrm{SU}(3)_R$ is broken to its U(1) component that commutes with $\mathrm{SU}(2)_R$. This can be achieved adding an extra Higgs scalar in the adjoint). 3-3-1 models have the same minimal set of chiral fermions as trinification, but do not have the W_R vector that can fit the di-boson anomaly. Minimal versions of left-right models have extra uncolored scalars but do not have extra fermions. In order to reproduce the di-gamma anomaly via gluon fusion, one can add extra quarks [55] and leptons [56], or rely on supersymmetric partners [54], or on extra components of unified multiplets which might remain light as in Alternative Left-Right Models [57].

- A $\mathrm{SU}(2)_R$ triplet A_{3R} that splits into a neutral Z' and into 2 charged right-handed $W_R^\pm$ vectors with mass

$$M^2_{W_R^\pm} = \frac{g_R^2 V^2}{4}\left[1 - \sqrt{(1-2\alpha)^2 + 4\beta^2}\right]. \tag{2.7}$$

We see that W_R is the lightest extra vector. The $W_R^\pm$ and $H_R^\pm$ mass eigenstates arise as

$$\begin{pmatrix} W_R^\pm \\ H_R^\pm \end{pmatrix} = \begin{pmatrix} \cos\theta_R & -\sin\theta_R \\ \sin\theta_R & \cos\theta_R \end{pmatrix} \begin{pmatrix} A_{R3}^\pm \\ A_{R2}^\pm \end{pmatrix} \tag{2.8}$$

in terms of the G_{333} interaction eigenstates $A_{R3}^\pm$ and $A_{R2}^\pm$. The mixing angle vanishes if $\beta \ll 1$:

$$\tan 2\theta_R = \frac{2\beta}{1-2\alpha}. \tag{2.9}$$

Concerning fermions, trinification adds to the chiral fermions under the SM group (Q, D, U, L and E in the usual notation), an extra vector-like $D' \oplus \bar{D}'$ and $L' \oplus \bar{L}'$ as well as some singlets N, N'. In presence of three Higgs multiplets $\mathcal{H}$, the theory has enough Yukawa couplings that the extra states can be naturally heavy, $M_{D',L'} \sim y_{Q,L} V$ thanks to large enough Yukawa couplings $y_{Q,L}$ [43–46]. The light and heavy fermion mass eigenstates can be parametrised as

$$\begin{pmatrix} D \\ D' \end{pmatrix} = \begin{pmatrix} \cos\theta_D & \sin\theta_D \\ -\sin\theta_D & \cos\theta_D \end{pmatrix} \begin{pmatrix} D_1 \\ D_2 \end{pmatrix}, \qquad \begin{pmatrix} L \\ L' \end{pmatrix} = \begin{pmatrix} \cos\theta_L & \sin\theta_L \\ -\sin\theta_L & \cos\theta_L \end{pmatrix} \begin{pmatrix} L_1 \\ L_2 \end{pmatrix} \tag{2.10}$$

where θ_D and θ_L are (for each generation) mixing angles, that can be of order one, computable in terms of Yukawa couplings and vevs. Then, the W_R coupling to quark mass eigenstates is

$$\frac{1}{\sqrt{2}} (\tilde{g}_R \bar{d}_R + \tilde{g}'_R \bar{d}'_R) \not{W}_R^+ u_R + \text{h.c.} \quad \tilde{g}_R = g_R \cos(\theta_D + \theta_R), \quad \tilde{g}'_R = g_R \sin(\theta_D + \theta_R)\,, \tag{2.11}$$

where the lightest mass eigenstate has been renamed d_R as usual in the SM and d'_R represents the heavy mass eigenstate. An important feature predicted by trinification is that the W_R does not couple to two light leptons. Rather, W_R couples the SM doublet of left-handed leptons L to the heavy doublet of anti-leptons $\bar{L}'$ with coupling $g_R \sin(\theta_R - \theta_L)$, and right-handed leptons E to heavy neutrinos N_1, N_2 with coupling $g_R \sin\theta_R$, $g_R \cos\theta_R$ respectively, in the limit of negligible mixing angle between neutral fermions N_1/N_2. Furthermore, W_R couples to pairs of heavy leptons.

3 The di-boson excess at 1.9 TeV

LHC data show an excess of di-boson events around 1.9 TeV [3]. Trinification can explain this excess as $pp \to W_R^\pm \to W^\pm Z$, and predicts an equal rate for $pp \to W_R^\pm \to W^\pm h$, some amount of $pp \to W_R^\pm \to jj$ but no $pp \to W_R^\pm \to \ell^\pm \nu$, as discussed below. No excess is observed in di-leptons, while jj data show some excess. The measured rates are summarised in table 2. Figure 2 shows the Feynman diagrams that describe such processes.

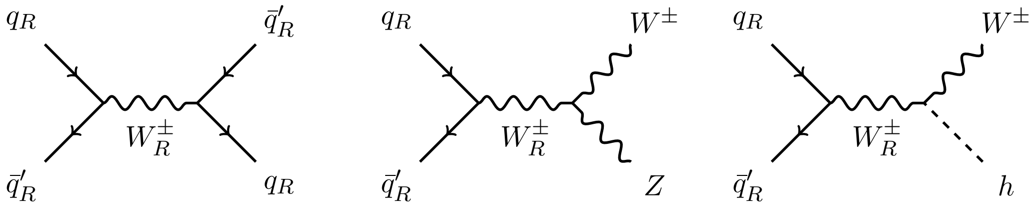

Figure 2. Resonant production of a $W_R^\pm$ that decays into jj, WZ and Wh.

process	mass	σ at $\sqrt{s} = 8\,\text{TeV}$		σ at $\sqrt{s} = 13\,\text{TeV}$	
$pp \to S \to \gamma\gamma$	750 GeV	0.5 ± 0.5 fb	[4–6, 58, 59]	8 ± 2 fb	[4–6]
$pp \to W_R^\pm \to W^\pm Z$	1.9 TeV	5.3 ± 2.0 fb	[3]	1 ± 13 fb	[4–6, 60, 61]
$pp \to W_R^\pm \to W^\pm h$	1.9 TeV	3.2 ± 3.7 fb	[62–64]	37 ± 32 fb	[65]
$pp \to W_R^\pm \to jj$	1.9 TeV	73 ± 39 fb	[66–68]	53 ± 230 fb	[69, 70]

Table 2. Observed cross sections for the anomalous digamma and diboson excesses at LHC that we try to interpret in terms of trinification.

3.1 Trinification predictions

The cross section for producing a on-shell $W_R^\pm$ in narrow-width approximation is

$$\sigma(pp \to W_R^\pm) = K\, \frac{\pi \tilde{g}_R^2}{6s}\, C_\pm(s), \tag{3.1}$$

where the dimensionless partonic coefficients are

$$C_+(s) = \sum_{u,d} |V_{ud}|^2 \int dy\, f_u\left(\frac{M_{W_R}}{\sqrt{s}} e^y\right) f_{\bar{d}}\left(\frac{M_{W_R}}{\sqrt{s}} e^{-y}\right), \tag{3.2}$$

$$C_-(s) = \sum_{u,d} |V_{ud}|^2 \int dy\, f_{\bar{u}}\left(\frac{M_{W_R}}{\sqrt{s}} e^y\right) f_d\left(\frac{M_{W_R}}{\sqrt{s}} e^{-y}\right), \tag{3.3}$$

to be integrated in the rapidity range $|y| < \ln \sqrt{s}/M_{W_R}$, summing over all up-type and down-type quarks. The factor $K = 1 + 8\pi\alpha_3(M_{W_R}^2)/9 \approx 1.23$ accounts for leading-order QCD corrections, with the partonic function distributions f_q renormalised at $Q = M_{W_R}$. The numerical values of the $C_\pm$ coefficients are given in table 3 using the MSTW2008NLO partonic distribution functions [71].

The cross sections into given final states X are

$$\sigma(pp \to W_R^\pm \to X) = \sigma(pp \to W_R^\pm) \times \text{BR}(W_R^\pm \to X). \tag{3.4}$$

We then need the decay widths and the branching ratios. Simple results hold into two extreme limits, described below.

JHEP03(2016)025

	$\sqrt{s}=8\,\text{TeV}$	$\sqrt{s}=13\,\text{TeV}$
$\sigma(pp\to W_R^\pm)$	$0.75\,\text{pb}\,\times\,\tilde g_R^2/\rho^{6.4}$	$5.3\,\text{pb}\,\times\,\tilde g_R^2/\rho^{4.8}$
$C_+(s)$	$0.14/\rho^{6.4}$	$2.6/\rho^{4.7}$
$C_-(s)$	$0.047/\rho^{6.5}$	$0.92/\rho^{5.1}$

Table 3. Cross section $\sigma(pp\to W_R^\pm)$ and partonic factors $C_\pm$, as function of the W_R mass, assumed to be close to 1.9 TeV. We defined $\rho = M_{W_R}/1.9\,\text{TeV}$.

JHEP03(2016)025

1. All fermions and scalars are much lighter than M_{W_R}, so that the W_R decay width into full G_{333} multiplets is simply given by

$$\Gamma(W_R^\pm\to Q_R\bar Q_R)=\Gamma(W_R^\pm\to L\bar L)=2\Gamma(W_R^\pm\to\mathcal{H}^*\mathcal{H})=\frac{g_R^2}{16\pi}M_{W_R} \tag{3.5}$$

independently of the mixing angle θ_R that defines W_R. Taking into account that there are 3 generations of fermions and scalars, the total width is $\Gamma_{W_R}/M_{W_R}=15g_R^2/32\pi\approx 0.029$.

2. W_R can only decay into the SM fermions and into the Higgs doublet, while all other states are so heavy that decays into them are kinematically forbidden. Interestingly, W_R cannot decay into leptons. The decay width into a light quark generation is

$$\Gamma(W_R^+\to u\bar d)=\frac{\tilde g_R^2|V_{ud}|^2}{16\pi}\,M_{W_R}\,. \tag{3.6}$$

The W_R decay width into the components of the SM Higgs doublet $H=(\chi^\pm,(h+i\eta)/\sqrt{2})$ (where, after $\text{SU}(2)_L$ breaking, $\chi^\pm$ and η become the longitudinal components of $W^\pm$ and Z, respectively) is

$$\Gamma(W_R^\pm\to W^\pm Z)=\Gamma(W_R^\pm\to W^\pm h)=\frac{g_R^2}{192\pi}\,M_{W_R}\cos^2\theta_H\ , \tag{3.7}$$

where θ_H is a mixing angle that defines which components of $\mathcal{H}$ contain the light SM Higgs doublet H, given by $\cos\theta_H\equiv r_{ud}\cos\theta_R - r_{uL}\sin\theta_R$ with[2]

$$r_{ud}=\frac{2\sum_n v_{un}v_{dn}}{\sum_n(v_{un}^2+v_{dn}^2+v_{Ln}^2)}\,,\qquad r_{uL}=\frac{2\sum_n v_{un}v_{Ln}}{\sum_n(v_{un}^2+v_{dn}^2+v_{Ln}^2)}. \tag{3.10}$$

In this limit, the total decay width is $\Gamma_{W_R}/M_{W_R}=g_R^2(18\cos^2(\theta_D+\theta_R)+\cos^2\theta_H)/96\pi$.

[2]The decay width into SM vector bosons can also be computed taking into account that the small SM vacuum expectation values v mixes W_R with the SM W by a small angle

$$\theta_{LR}\simeq\frac{g_R}{g_2}\frac{M_W^2}{M_{W_R}^2}\cos\theta_H\,, \tag{3.8}$$

and that

$$\Gamma(W_R^\pm\to W^\pm Z)=\Gamma(W_R^\pm\to W^\pm h)=\frac{g_2^2\theta_{LR}^2}{192\pi}\frac{M_{W_R}^5}{M_W^4}=\frac{g_R^2}{192\pi}M_{W_R}\cos^2\theta_H. \tag{3.9}$$

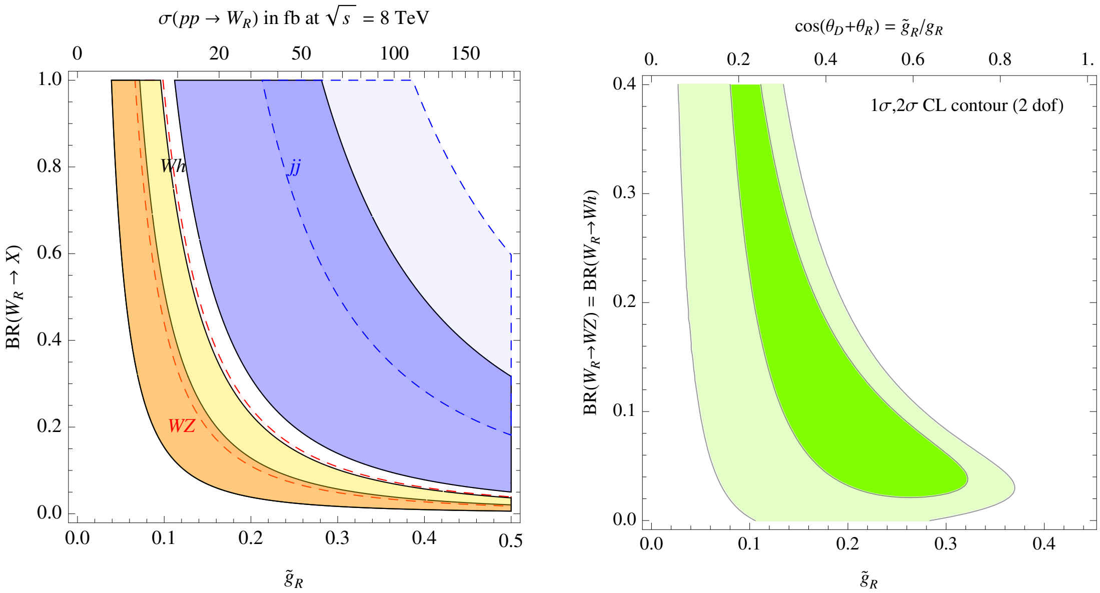

Figure 3. Global fit of run 1 and run 2 data. *Left*: $\pm 1\sigma$ experimental bands for the W_R Branching Ratios into jj (blue), WZ (red), Wh (yellow) as function of the coupling $\tilde{g}_R$ that controls the predicted W_R production cross section. We also show the bands obtained using 8 TeV data (dashed contours with lighter colors), and the cross section at 8 TeV (upper axis). *Right*: global fit (green region) assuming only W_R decays into jj, WZ, Wh.

One loop QCD corrections enhance the decay widths into quarks by $K_D = 1 + \alpha_3(M_{W_R})/\pi \approx 1.03$.

If all the mixing factors are of order unity, in case 2 one expects $\mathrm{BR}(W_R^\pm \to W^\pm Z) = \mathrm{BR}(W_R^\pm \to W^\pm h) \sim 1/38$. However this branching ratio can be much larger if $\cos^2\theta_H \gg \cos^2(\theta_D + \theta_R)$. In case 1 one has $\mathrm{BR}(W_R^\pm \to W^\pm Z) = \mathrm{BR}(W_R^\pm \to W^\pm h) \leq 1/90$.

3.2 Comparison with data

We are now ready to compare the trinification predictions with di-boson data.

The first issue that we address is the compatibility of run 1 data at $\sqrt{s} = 8$ TeV (that showed an excess around 1.9 TeV) with run 2 data at $\sqrt{s} = 13$ TeV, that show no excess so far. In view of the reduced luminosity so far accumulated at run 2, and of the larger backgrounds, run 2 data, as summarised in table 2, have much larger uncertainties. In our model the W_R production cross section grows by a factor ≈ 7 when going from $\sqrt{s} = 8$ to 13 TeV.

Taking into account all these factors, the incompatibility between the two data-sets is only mild, at the 1σ level, and the run 1 data still play the main role. This is shown in the left panel of figure 3, where we extract the W_R branching ratios into the various channels as function of the W_R production cross section, plotted at 8 TeV on the upper horizontal axis, and parametrised in terms of the coupling $\tilde{g}_R$ on the lower axis.

We next proceed in performing a global fit, assuming that W_R only decays into jj, WZ and Wh (case 2 in the discussion above) and using the theoretical prediction $\mathrm{BR}(W_R \to WZ) = \mathrm{BR}(W_R \to Wh)$. The result is shown in the right panel of figure 3. We see that data

JHEP03(2016)025

prefer $\tilde{g}_R \sim 0.25$. While in a generic context this is a free parameter, trinification predicts $\tilde{g}_R = g_R \cos(\theta_D + \theta_R)$, where $g_R = 0.444$ and the mixing factor depends on the details of the model. This means that trinification is non-trivially compatible with data, that favour a substantial amount of mixing among right-handed down quarks, $\cos(\theta_D + \theta_R) \sim 0.5$. The best fit has $\chi^2_{\rm best} = \chi^2_{\rm SM} - 2.7^2$, which can be interpreted as a 2.7σ hint, up to look-elsewhere reductions. Similar results are obtained for a slightly lighter or heavier W_R.

Allowing W_R to decay into extra light states (up to the opposite extremum of case 1 in the discussion above) reduces the W_R branching ratios into jj, WZ, Wh, such that a higher production cross section becomes needed to fit the data. Trinification allows to raise the production cross section up to $\tilde{g}_R = g_R$. At the same time, the extra decay channels give rise to extra more complicated signals.

In order to keep the discussion simple, let us divide particles into three main categories: q (generic quarks), ℓ (generic leptons), H (Higgses: h, W, Z), all approximatively massless. Then q' denotes the extra heavy quarks, ℓ' the extra heavy leptons, and H' denotes the extra heavy scalars (not eaten by the W, Z), with generic masses M'. The possible W_R decay modes are

$$W_R \to \begin{cases} qq, HH & \text{always} \\ qq', \ell\ell', HH' & \text{if } M' \lesssim M_{W_R} \\ q'q', \ell'\ell', H'H' & \text{if } M' \lesssim M_{W_R}/2 \end{cases} \tag{3.11}$$

The extra primed particles, if produced, can decay through gauge interactions as

$$q' \to qW_R^*, \qquad \ell' \to \ell W_R^*, \qquad H' \to HW_R^* \tag{3.12}$$

(where the virtual W_R^* can, in many cases, only materialise into qq or HH light particles) and through Yukawa interactions as

$$q' \to qH, \qquad \ell' \to \ell H, \qquad H' \to qq, \ell\ell. \tag{3.13}$$

If $W_R \to \ell\ell'$ is kinematically allowed, one obtains final states with two leptons accompanied by a jj or WZ or Wh pair or by a single W, Z, h. If ℓ' is a heavy neutrino, Majorana masses can give rise to same-sign di-leptons, accompanied by the same extra particles listed above. In particular, for appropriate values of its parameters, trinification can also reproduce the $eejj$ excess [72], as already discussed in [7–21] in the context of dedicated models. Needless to say, all decay widths can be computed in terms of unknown masses and of the mixing angles introduced above.

4 The di-photon excess at 750 GeV

The di-photon excess at 750 GeV [4–6] has been tentatively interpreted as a new scalar S with mass $M \approx 750$ GeV that is produced as $gg \to S$ and decays as $S \to \gamma\gamma$ through loops of extra fermions and/or scalars coupled to S by sizeable couplings [22–42]. ATLAS data [4–6] possibly indicate a large width $\Gamma_S/M \approx 0.06$, which would make this interpretation more difficult. In any case, the apparently large width can be faked by a multiplet of quasi-degenerate narrow resonances [22].

Trinification has built-in all the ingredients needed to provide such interpretation: extra scalars S as singlets and/or doublets in the Higgs $\mathcal{H}$ multiplets; extra fermions D' and L' that extend the SM chiral fermion content and receive masses only as yV; Yukawa couplings y that must be sizeable enough in order to push the extra fermions above the experimental bounds.

4.1 Trinification predictions

In order to compute the relevant decay widths of S into $\gamma\gamma$ and gg, we parameterise its linear Lagrangian couplings to generic fermions $\mathcal{Q}_f$ with Dirac mass M_f, to generic scalars $\tilde{\mathcal{Q}}_s$ with mass M_s and to generic vectors V with mass M_V as

$$S\bar{\mathcal{Q}}(y_f + y_{5f}\gamma_5)\mathcal{Q} - SA_s|\tilde{\mathcal{Q}}_s|^2 + g_V M_V S|V_\mu|^2. \tag{4.1}$$

The coupling g_V is normalised such that it coincides with the SM coupling g_2, if S is replaced by the SM Higgs h and V_μ by the SM $W^\pm_\mu$. Then S acquires the following decay widths at one-loop level [22]:

$$\begin{aligned}\frac{\Gamma(S\to\gamma\gamma)}{M} &= \frac{\alpha^2}{256\pi^3}\Bigg(\bigg|\sum_f \frac{y_{5f}M}{M_f}Q_f^2 F_{5f}\bigg|^2 + \\ &\quad + \bigg|\sum_f \frac{y_f M}{M_f}Q_f^2 F_f + \sum_s \frac{A_s M}{2M_s^2}Q_s^2 F_s - \sum_V \frac{g_V M}{2M_V}Q_V^2 F_V\bigg|^2\Bigg), \end{aligned}\tag{4.2a}$$

$$\frac{\Gamma(S\to gg)}{M} = \frac{\alpha_3^2}{32\pi^3}\Bigg(\bigg|\sum_f C_f \frac{y_{5f}M}{M_f}F_{5f}\bigg|^2 + \bigg|\sum_f C_f \frac{y_f M}{M_f}F_f\bigg|^2\Bigg), \tag{4.2b}$$

where multiplicities are implicitly included in sums. The color factors are $C_1 = 0$ for color singlets and $C_3 = 1/2$ for color triplets, and we have taken into account that trinification predicts no other coloured particles. The loop functions are [22]

$$\begin{aligned} F_s &= x[-1 + xf(x)] &&\stackrel{x\to\infty}{=} 1/3 \text{ with } x = 4M_s^2/M^2,\\ F_f &= 2x[1 + (1-x)f(x)] &&\stackrel{x\to\infty}{=} 4/3 \text{ with } x = 4M_f^2/M^2,\\ F_{5f} &= 2xf(x) &&\stackrel{x\to\infty}{=} 2 \quad \text{ with } x = 4M_f^2/M^2,\\ F_V &= 2 + 3x + 3x(2-x)f(x) &&\stackrel{x\to\infty}{=} 7 \quad \text{ with } x = 4M_V^2/M^2, \end{aligned}\tag{4.3}$$

where $f(x) = \arctan^2(1/\sqrt{x-1})$. The S decay width into gluons can be estimated as

$$\frac{\Gamma(S\to gg)}{M} \approx 0.6\ 10^{-4}\left(y_{5D}^2 + \frac{4}{9}y_D^2\right)\left(\frac{1\text{ TeV}}{M_{D'}}\frac{N_{D'}}{3}\right)^2 \tag{4.4a}$$

having assumed, for simplicity, $N_{D'} \le 3$ degenerate copies of D' with mass $M_{D'} \gg M/2$. This shows that the $\Gamma(S\to gg)/M \gtrsim 10^{-5}$ needed to fit the di-gamma anomaly [22] is easily achieved; furthermore trinification implies that some components of the $\mathcal{H}$ scalars have sizeable couplings to SM quarks, allowing for extra production channels of S. The S decay width into photons can be estimated as

$$\frac{\Gamma(S\to\gamma\gamma)}{M} \approx 10^{-6}\left[6.7\left(y_{5E}\frac{N_{L'}}{3}\right)^2 + \left(1.05 y_E \frac{N_{L'}}{3} + 1.15\frac{A_s}{M_s}\frac{N_s}{9}\right)^2\right] \tag{4.4b}$$

having assumed, for simplicity, $N_{L'} \leq 3$ copies of leptons degenerate at $M_{L'} \gtrsim M/2$, plus $N_s \leq 9$ copies of scalars with charge $Q_s = \pm 1$ degenerate at the same mass and with the same cubic A_s. We neglected the small contribution from heavy down-quarks and from vectors.

4.2 Comparison with data

In order to achieve the $\Gamma(S \to \gamma\gamma)/M \gtrsim 10^{-6}$ needed to reproduce the $\gamma\gamma$ anomaly [22] one either needs Yukawa couplings of order unity or larger, or the presence of multiple charged states, or a large A_s/M.

In a context where the theory can be extrapolated up to infinite energy [47, 48], some scalar quartic couplings can be predicted in terms of squared gauge couplings, times model-dependent order one factors. This implies that scalars typically have masses comparable to vectors, which must be heavier than about 2 TeV.[3] One can assume that one of the various scalar doublets contained in $\mathcal{H}_{1,2,3}$ is accidentally lighter and can be identified with the 125 GeV Higgs boson, and that one singlet (or doublet) is accidentally light and can be identified with the 750 GeV resonance. In such a case, the accidental cancellation that makes its mass M smaller than V does not generically suppress, at the same time, its cubic couplings A_s, such that A_s/M can be large (phenomenologically limited by vacuum decay constraints) enhancing $S \to \gamma\gamma$. The mixing of S with the physical Higgs h must be small enough. The two neutral components of a doublet generically receive a small mass splitting $\sim v^2/M \approx 10$ GeV and can mimic the large width favoured by ATLAS data [22]. The two components of all electroweak singlets in $\mathcal{H}$ generically receive mass splittings of order V.

If the $S \to \gamma\gamma$ process is dominated by a loop of either lepton doublets or scalar doublets (which have the same quantum numbers) one predicts the following extra electroweak decays:

$$\frac{\Gamma(S \to Z\gamma)}{\Gamma(S \to \gamma\gamma)} \approx 0.9 < 2, \qquad \frac{\Gamma(S \to ZZ)}{\Gamma(S \to \gamma\gamma)} \approx 3.5 < 6, \qquad \frac{\Gamma(S \to WW)}{\Gamma(S \to \gamma\gamma)} \approx 10 < 20. \tag{4.5}$$

These predictions satisfy the experimental bounds collected in [22] and quoted after the $<$ symbols and correspond, in the language of effective operators of [22], to equal coefficients $\Lambda_B = \Lambda_W$, or $\tilde{\Lambda}_B = \tilde{\Lambda}_W$. The extra loop contribution from charged scalar singlets or from right-handed down quarks can reduce the ratios in eq.(4.5).

5 Conclusions

Models based on the trinification gauge group $G_{333} = \mathrm{SU}(3)_L \otimes \mathrm{SU}(3)_R \otimes \mathrm{SU}(3)_c$ explain the quantisation of electric charge [43–46]. Weak scale trinification models provide natural

[3] An exception arises if the breaking of G_{333} proceeds through the Coleman-Weinberg mechanism. Then the scalar singlet that corresponds to a dilatation of all vacuum expectation values V remains lighter than the other ones by a loop factor. If this dilaton is the S state, one obtains more neat predictions, given that vectors and fermions acquire mass only from its vev $\langle S \rangle = V$, such that $M_V = g_V V/2$, $M_f = y_f V$, $y_{5f} = 0$. However, in such a case, $\Gamma(S \to \gamma\gamma)$ is somehow too small, given that such dilaton cannot have a large cubic A_s, and that $V \gtrsim$ few TeV.

JHEP03(2016)025

extensions of the Standard Model that can hold up to infinite energy, with all gauge and Yukawa and quartic couplings flowing to asymptotic freedom [47].

We have shown that these same models, without any extra ingredient, can simultaneously explain the $\gamma\gamma$ anomaly at 750 GeV (section 4) and the diboson anomaly at 1.9 TeV (section 3). Run 2 LHC data do not confirm the latter anomaly found in run 1 data, but do not significantly disfavour it (figure 3a).

The lightest extra vector of trinification is a $W_R^\pm$ with a gauge coupling $g_R \approx 0.444$ compatible with the cross section needed to fit the 1.9 TeV anomaly (figure 3b). Furthermore, the group structure of trinification implies that it does not decay to SM leptons, in agreement with data.

At the same time, trinification predicts a set of extra fermions (chiral under G_{333} but not under the SM) and of scalars which can be numerous and light enough to mediate the $gg \to S \to \gamma\gamma$ loops without giving, at the same time, excessive $gg \to S \to \gamma Z, ZZ, W^+W^-$. This interplay between the 2 anomalies implies extra W_R decay channels which give rise to the extra signals discussed in section 3.

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JHEP03(2016)025

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JHEP03(2016)025