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From the 750 GeV diphoton resonance to multilepton excesses

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Weakly coupled models for the 750 GeV diphoton resonance often invoke new particles carrying both color and/or electric charges to mediate loop-induced couplings of the resonance to two gluons and two photons. The new colored particles may not be stable and could decay into final states containing standard model particles. We consider an electroweak doublet of vectorlike quarks (VLQs) carrying electric charges of $5/3$ and $2/3$, respectively, which mediate the loop-induced couplings of the 750 GeV resonance. If the VLQ has a mass at around 1 TeV, it naturally gives rise to the observed diphoton signal strength while all couplings remain perturbative up to a high scale. At the same time, if the charge-$5/3$ VLQ decays into final states containing top quark and W boson, it would contribute to the multilepton excesses observed in both run 1 and run 2 data. It is also possible to incorporate a dark matter candidate in the decay final states to explain the observed relic density.

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I. INTRODUCTION

After the discovery of the 125 GeV Higgs boson at run 1 of the Large Hadron Collider (LHC) [1,2], the standard model (SM) of particle physics is now complete. However, SM is far from being perfect, since there is much empirical evidence pointing to its failures, ranging from the compelling case for cold dark matter to the baryon asymmetry in the universe. The evidence strongly calls for existence of physics beyond the SM (BSM).

Not surprisingly, there are many measurements exhibiting excesses over SM expectations at the LHC run 1. While some, or perhaps all, of the excesses may be statistical fluctuations, it is difficult to over-emphasize the importance of pursuing the theoretical implications of the first signs of BSM physics, which if remains true, would be a discovery that is more profound and no less grand than that of the Higgs boson.

Among the run 1 excesses, there is one which seems to persist in the early run 2 results, showing up in searches for final states containing multilepton, b jets, and missing transverse momentum (MET). The multilepton searches are often further divided into a same-sign dilepton (2L) category, a three-lepton (3L) category, and a four-lepton (4L) category. As was pointed out in Refs. [3,4], the multilepton excesses were observed with varying degrees of significance in many run 1 analyses in both ATLAS and CMS collaborations, which include searches for ttH production [5,6], for scalar bottom quarks in supersymmetry [7,8], for SM production of ttW [9,10] and for heavy VLQs [11]. (The CMS run 1 search for VLQ's, which imposes very hard cuts on the kinematics, is the only exception which didn't see an excess [12].) At run 2, the multilepton excesses were seen by ATLAS in searches for scalar bottom quarks [13] and SM ttW production [14]. CMS, which collected 50% less "good" data than the ATLAS at run 2 so far, sees a deficit in the 2L channel and an excess in the 3L channel [15,16].

The left panel of Fig. 1 summarizes the best-fit signal strength $\mu = \sigma/\sigma_{\rm SM}$ in the ttH multilepton channel from the public run 1 and run 2 results, as well as a statistical combination of μ obtained from using the online script at Ref. [17], which is based on Ref. [18]. The resulting signal strength is $\mu = 2.4^{+0.8}_{-0.7}$ from combining both ATLAS and CMS run $1/2$ results.[1] In the right panel of Fig. 1 we display measurements of $\sigma(pp \to t\bar{t}W)$ from ATLAS, at both run 1 and 2, and CMS at run 1. The presence of excesses in the multilepton channel at both run 1 and run 2 is clear, although uncertainties in the measurements remain large. A number of works have theorized on the nature of these excesses [3,4,19,20].

Nevertheless, the most significant sign of BSM physics in run 2 undoubtedly comes from the observation of excessive events in the diphoton channel that are clustered at around an invariant mass of 750 GeV [21,22]. Moreover, kinematic distributions of events in the signal region seem consistent with those expected from SM background [23], indicating single production of a resonance, with no or very

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[1] We have added an offset of -0.3 in the combined central value to take into account correlated systematic uncertainties. This procedure reproduces the individual central values from ATLAS and CMS, respectively, with good precision.

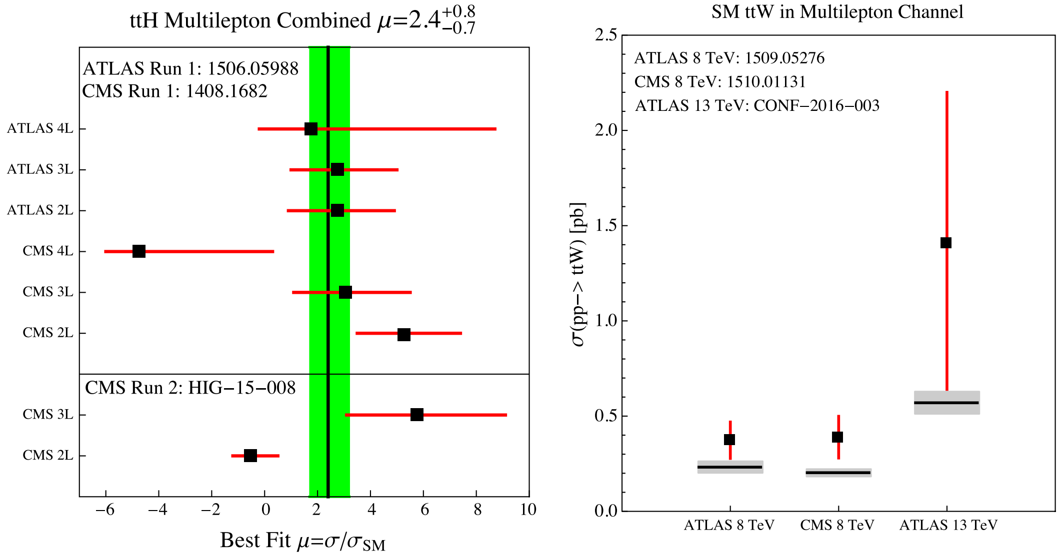

FIG. 1. Left: Best-fit signal strength $\mu = \sigma/\sigma_{\mathrm{SM}}$ in the ttH multilepton channel at both the 8 and 13 TeV LHC. Right: Measured $\sigma(pp \to ttW)$ in the multilepton channel at both the 8 and 13 TeV LHC. Shaded areas are the expected cross sections with theoretical uncertainties.

soft extra particles, decaying into diphoton final states. On the other hand, compatibility with the null result from ATLAS run 1 searches for a heavy resonance in the diphoton channel [24] prefers a production mechanism from the gluon initial states, due to the larger increase in the parton luminosity of the gluon.

If one further assumes the resonance is a spin-0 boson, then in weakly coupled theories the neutral scalar couplings to massless gauge bosons such as the photon and the gluon are induced only at one-loop level by particles carrying QCD color and/or electric charges (see, for example, Ref. [25].) The particles in the loop, however, cannot be the SM particles, for it would immediately imply tree-level decays of the resonance into the SM particles, which in turn would swamp the loop-induced decays into diphotons and reduce the signal strength far below the observed ones. Therefore, in these scenarios additional new particles, other than the 750 GeV scalar itself, must be present. These new particles should carry color and/or electric charges and be heavier than 375 GeV so as to turn off the tree-level decay channel of the 750 GeV resonance.[2] A popular possibility for the new particles mediating the loop-induced couplings is VLQ's carrying QCD color and electric charges [27–133].

There have been few discussions on the collider phenomenology of VLQs associated with the 750 GeV scalar [128–132], although VLQs have been proposed in other contexts, as partners of the third generation quarks in the SM [134,135], which could decay into third generation quarks and W, Z, or the Higgs bosons. In this work we aim to demonstrate that, if the VLQ is an electroweak doublet with hypercharge 7/6, and has a mass at around 1 TeV, it could simultaneously explain the signal strength of the 750 GeV diphoton resonance and contribute to the aforementioned multilepton excesses associated with b jets and MET. And the model could remain perturbative all the way up to a very high scale [132,133].

This work is organized as follows: in the next section, we demonstrate the connection between VLQs and the 750 GeV diphoton resonance, as well as the RG running of the relevant gauge and Yukawa couplings, which is followed by a Monte Carlo study on the contribution of the VLQs to the multilepton excesses at the LHC, using the ttH and ttW channels as examples. In the last section, we conclude.

II. VECTORLIKE QUARKS AND DIPHOTON EXCESS

Assuming that the 750 GeV scalar S is produced by the gluon fusion, the diphoton signal rate is given by

$$\begin{aligned}\sigma(pp \to S \to \gamma\gamma) &\simeq \frac{C_{gg}}{s \cdot m_S} \frac{\Gamma(S \to \gamma\gamma)\Gamma(S \to gg)}{\Gamma_{S;\mathrm{total}}} \\ &\simeq 6.4\ \mathrm{fb} \times \left(\frac{\Gamma(S \to \gamma\gamma)}{1\ \mathrm{MeV}}\right) \mathrm{Br}(S \to gg)\end{aligned} \tag{1}$$

where $m_S \simeq 750$ GeV is the scalar mass, $\sqrt{s} = 13$ TeV and $C_{gg} = (\pi^2/8) \int_0^1 dx_1 \int_0^1 dx_2\, \delta(x_1 x_2 - m_S^2/s) g(x_1) g(x_2)$ with $g(x)$ being the gluon parton distribution function. In

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[2] This argument holds in weakly coupled theories as we state in the text. For other possible models with strong interactions, see a recent review [26] and references therein.

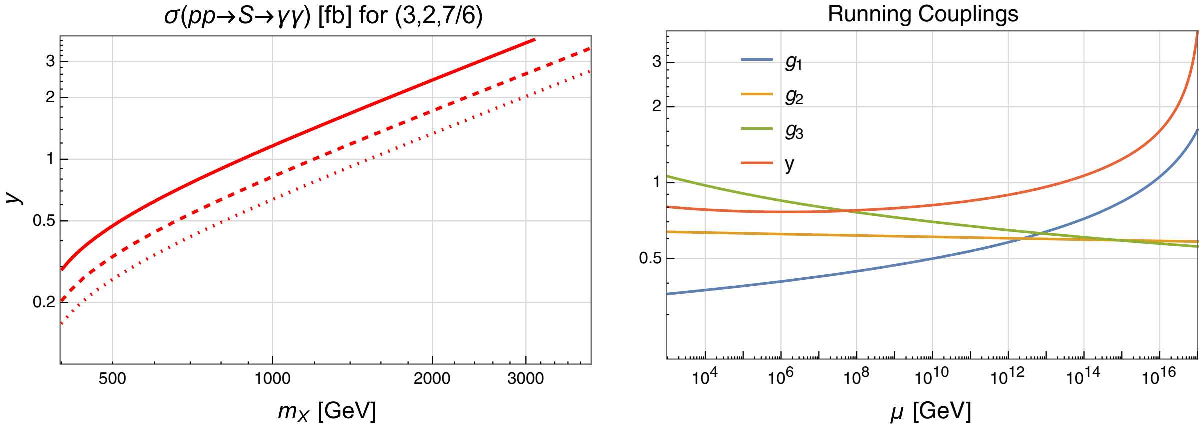

FIG. 2. Left: contours of $\sigma(pp \to S \to \gamma\gamma)$ in (m_X, y) plane. Solid, dashed and dotted lines respectively show contours for 10, 5, 3 fb. Right: the running of the SM gauge couplings and the Yukawa coupling y for a benchmark point $m_X = 950$ GeV and $y = 0.8$.

the second equation, we have used $C_{gg} \simeq 2.1 \times 10^3$ which is obtained from MSTW2008 NLO set [136] evaluated at the scale $\mu = m_S$. The reported signal strengths at run 2 are somewhere between 1 and 10 fb [21,22].

We assume that couplings of the scalar S to photons and gluons are induced by a VLQ X which transforms as $(\mathbf{3}, \mathbf{2}, 7/6)$ under $\mathrm{SU(3)_c} \times \mathrm{SU(2)_L} \times \mathrm{U(1)_Y}$ of the SM gauge group:

$$-\mathcal{L}_{\mathrm{int}} = yS\bar{X}i\gamma_5 X, \tag{2}$$

where S is assumed to be CP-odd.[3] Then, the partial decay width of S into the diphoton is given by

$$\begin{aligned}\Gamma(S \to \gamma\gamma) &= \frac{\alpha^2}{64\pi^3} m_S^3 \left[\frac{y}{m_X} \mathrm{Tr}(Q^2) f(m_S^2/4m_X^2)\right]^2 \\ &\simeq 1.4\ \mathrm{MeV} \times y^2 \left(\frac{1\ \mathrm{TeV}}{m_X}\right)^2 [f(m_S^2/4m_X^2)]^2\end{aligned} \tag{3}$$

where $\mathrm{Tr}(Q^2) = 3[(5/3)^2 + (2/3)^2] = 29/3$ and the loop function is given by $f(\tau) = \tau^{-1}\arcsin^2\sqrt{\tau}$ [137].

In Fig. 2, we show contours of $\sigma(pp \to S \to \gamma\gamma)$ in (m_X, y) plane. The observed diphoton signal rate can be obtained with $m_X \lesssim 1$ TeV and $y \lesssim \mathcal{O}(1)$. In the right panel of Fig. 2, the running of the SM gauge couplings and the Yukawa coupling y are shown for a benchmark point $m_X = 950$ GeV and $y = 0.8$, which leads to $\sigma(pp \to S \to \gamma\gamma) \simeq 5.4$ fb. As can be seen in the figure, the model remain perturbative up to about 10^{17} GeV.[4]

III. VECTORLIKE QUARKS AND MULTILEPTON EXCESS

The VLQ X, introduced in Sec. II to explain the diphoton excess, cannot be stable nor long-lived in order to avoid severe collider bound [138]. We will assume the lifetime of the VLQ is short enough to decay promptly inside the detector, when produced through QCD interactions at the LHC. Given the X carries SM quantum numbers, its decay product would include SM particles such as quarks and gauge bosons. In particular, if the charge-5/3 VLQ, $X_{5/3}$, decays into the top quark and the W boson, it could potentially contribute to the multilepton excesses observed at both run 1 and run 2 of the LHC.

We consider two simplified models in the spirit of minimality, one with a dark matter candidate and one without. Matter contents of both models are shown in Table. I. In the first model, Model S, the only new particles are the S and X which are introduced in Sec. II. We assume that the X field mainly couples to the third generation SM quark:

$$-\mathcal{L}_{\mathrm{int}}^{\mathrm{Model\,S}} = -\lambda(H \cdot \bar{X})t_R + \mathrm{H.c.} + yS\bar{X}i\gamma_5 X. \tag{4}$$

where t_R is the right-handed SM top quark and $(H \cdot \bar{X}) = H^+\bar{X}_{5/3} + H^0\bar{T}$ with (H^+, H^0) and $(X_{5/3}, T)$ being the

TABLE I. Matter contents of two simplified models. Model 3 contains a new parity under which the SM and S are even, while $X = (X_{5/3}, T)$, T' and ϕ are odd. ϕ is the lightest particle charged under the parity and could serve as a dark matter candidate ϕ.

Model S		Model 3		
S	$(\mathbf{1}, \mathbf{1})_0$	S	$(\mathbf{1}, \mathbf{1})_0$	+
X	$(\mathbf{3}, \mathbf{2})_{7/6}$	X	$(\mathbf{3}, \mathbf{2})_{7/6}$	−
		T'	$(\mathbf{3}, \mathbf{1})_{2/3}$	−
		ϕ	$(\mathbf{1}, \mathbf{1})_0$	−

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[3] In the case of the CP-even S, the diphoton signal rate is suppressed by a factor of about 4/9.

[4] If we add an additional VLQ T', which is introduced in model 3 discussed in the next section, the Landau pole of the $\mathrm{U(1)}_Y$ coupling becomes slightly lower, about 10^{16} GeV.

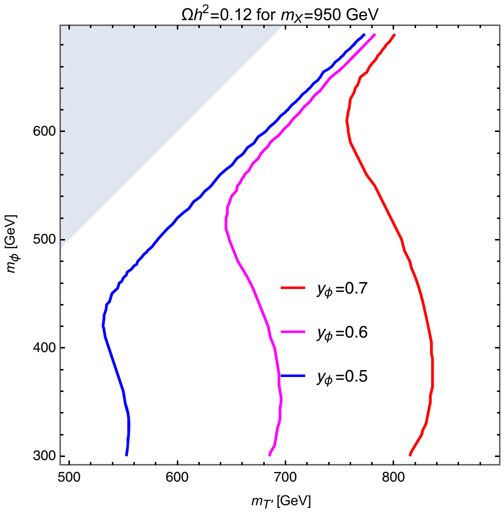

FIG. 3. Region of parameter space of Model 3 leading to the observed dark matter relic density.

component fields of the $\mathrm{SU}(2)_{\mathrm{L}}$ doublets. In this setup, the decay chain of the VLQ $X_{5/3}$ is given by

$$X_{5/3} \to W^+ t \to W^+ W^+ b. \tag{5}$$

Therefore, pair-produced $X_{5/3}$ can lead to signatures containing multilepton, b jets, and MET, where the MET comes from the neutrino in the W decay.

In the second model containing the dark matter, Model 3, we introduce a singlet scalar dark matter field ϕ together with an additional VLQ, T', and assign an odd parity to $X = (X_{5/3}, T)$, T', and ϕ under a Z_2 parity to ensure the stability of the dark matter. The interaction is then given by[5]

$$\begin{aligned} -\mathcal{L}_{\mathrm{int}}^{\mathrm{Model\ 3}} &= (H \cdot \bar{X})(\lambda + \lambda_5 \gamma^5) T' + y_\phi \phi \bar{T}' t_R + \mathrm{H.c.} \\ &\quad + y S \bar{X} i \gamma_5 X. \end{aligned} \tag{6}$$

In the following, we assume $\lambda_5 = 0$, for simplicity. In this model the decay of $X_{5/3}$ leads to

$$X_{5/3} \to W^+ T' \to W^+ t \phi \to W^+ W^+ b \phi, \tag{7}$$

which again leads to the multilepton signal, with the additional MET contribution from the DM candidate ϕ. Furthermore, T' decays as follows

$$T' \to t + \phi, \tag{8}$$

therefore pair-production of T' at the LHC could lead to the final state $t\bar{t}$ + MET. In the early universe, the dark matter ϕ could annihilate through the process $\phi\phi \to t\bar{t}$. In Fig. 3 we show the region of parameter space leading to the observed relic density of the dark matter in the $m_\phi - m_{T'}$ plane for some choices of y_ϕ.[6] For numerical calculation, we generate model files using `FeynRules 2.3` [139] and obtain the relic density of dark matter using `micrOMEGAs 4.1.7` [140]. In addition, in this simple model the only SM particle that directly couples to the dark matter particle ϕ is the top quark. Therefore the direct detection constraint does not apply.

TABLE II. Total signal strengths for the same-sign dilepton final state, normalized to the SM expectations, of our benchmark models in ttH channel at both 8 and 13 TeV and in ttW channel at 13 TeV. The mass spectrum is $m_X = 950$ GeV, $m_{T'} = 750$ GeV and $m_\phi = 380$ GeV.

	8 TeV μ_{ttH}	13 TeV μ_{ttH}	13 TeV μ_{ttW}
Model S	1.5	3.1	1.3
Model 3	1.4	2.9	1.3

There are collider searches for $X_{5/3} \to tW^+$ at the LHC. In this channel the latest result from CMS using the early run 2 data puts a lower bound $m_X \gtrsim 950$ GeV at the 95% confidence level (C.L.) [16], which would apply to the $X_{5/3}$ in Model S. In Model 3 $X_{5/3}$ decays into $tW^+\phi$ and the strong bound from CMS does not necessarily apply since the decay final state is different. On the other hand, the charge $2/3$ component of the doublet, T, decays mainly to $t + Z/h$, and does not contribute to the tW^+ search channel. The current constraint on T production via tZ and th channels is weaker than that of $X_{5/3}$ [141,142]. For the electroweak singlet T', no dedicated searches exist, although there exist searches for the scalar top quark (stop) in supersymmetry which also decays to $t\bar{t}$ + MET. These limits, however, are sensitive to a variety of kinematic variables including the mass of the particle carrying away the extra MET. In particular, constraints on direct stop productions in the $t\bar{t}$ + MET final states disappear when the LSP mass becomes larger than ~300 GeV [143–146]. Due to these considerations, we choose the following benchmark in our study:

$$\text{Model S}: \; m_X = 950\ \text{GeV}, \tag{9}$$

$$\begin{aligned} \text{Model 3}: \; m_X &= 950\ \text{GeV}, \qquad m_{T'} = 750\ \text{GeV}, \\ m_\phi &= 380\ \text{GeV}. \end{aligned} \tag{10}$$

The choice of m_X in Model S maximizes the contribution to the multilepton excess without contradicting the limits from searches for $X_{5/3}$ at the LHC.[7] If one considers $m_X > 950$ GeV, the signal strength for multilepton

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[5] The T' field can also have a coupling with S as $y' S \bar{T}' i \gamma_5 T'$, which slightly increases the diphoton rate.

[6] The λ term in Eq. (6) induces a mixing between T' and T after electroweak symmetry breaking. We choose a small mixing, $\lambda = 0.01$ in Fig. 3.

[7] We emphasize that the CMS bound on $X_{5/3}$ from Ref. [15] does not apply to our Model 3. However, we choose the same m_X in both models for simplicity.

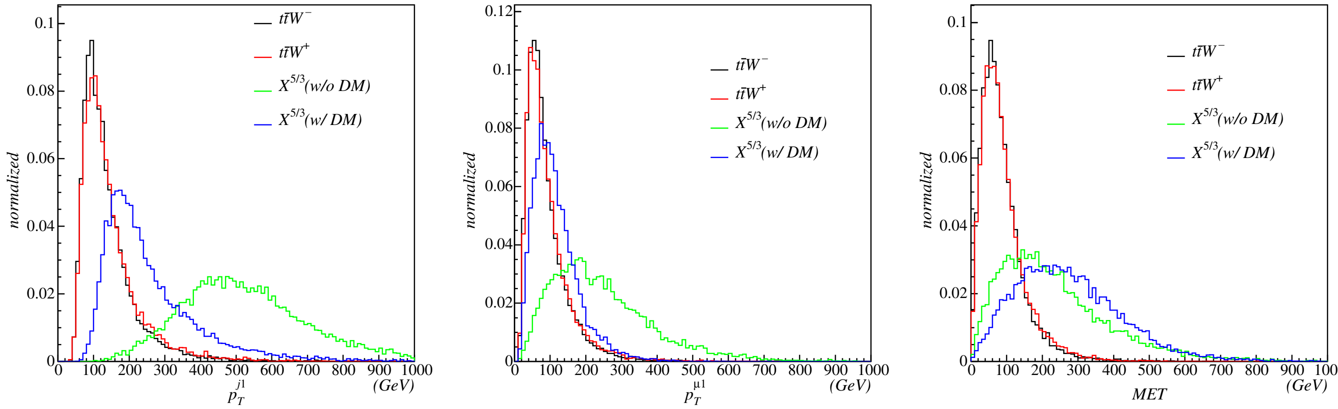

FIG. 4. From left to right: distributions of p_T of the leading jet, p_T of the leading muon, and MET for events from our Model S ($X_{5/3}$ without the dark matter), Model 3 ($X_{5/3}$ with the dark matter), and SM ttW.

becomes smaller than that in our benchmark scenarios due to smaller production cross section of $X_{5/3}$, while diphoton excess can be explained by larger coupling y as shown in left panel of Fig. 2. The value for m_ϕ is motivated not only by the stop constraints but also the need to turn off possible tree-level decay $S \to \phi\phi$,[8] so as not to overwhelm the loop-induced decays into diphotons. $m_{T'}$ is then chosen to allow for on-shell W bosons and top quarks in the decay product.

In Table II, we show the total signal strength for the same-sign dilepton final state, in unit of SM expectations, of our two benchmarks in the ttH and ttW channels at the LHC.[9] In the Monte Carlo simulation we generate signal events using `Madgraph` [147] + `Pythia` [148] + `Delphes` [149] and a tagging efficiency of b jet at 77%. In the ttH channel, the final state contains exactly two leptons with the same electric charge and at least four jets of which two are b jets. We implement the same cuts as in Refs. [4,6] at both 8 and 13 TeV: $p_T^\ell > 20$ GeV, $p_T^j > 25$ GeV, $\mathrm{L_D} > 30$ GeV, $S_T > 100$ GeV, where $S_T = p_T^{\ell_1} + p_T^{\ell_2} + E_\mathrm{T}^\mathrm{miss}$ is the scalar sum of transverse momentum of two charged leptons and the missing transverse momentum $E_\mathrm{T}^\mathrm{miss}$ and $\mathrm{L_D} = 0.6 \times E_\mathrm{T}^\mathrm{miss} + 0.4 \times H_\mathrm{T}^\mathrm{miss}$ with $H_\mathrm{T}^\mathrm{miss}$ being the negative vector p_T sum of selected jets and two same-sign leptons. In the ttW channel, based on the same-sign di-muon analysis in Sec. 5. 1 of Ref. [14], events containing two muons with the same electric charge and at least two b jets are selected. The kinematic cuts being applied are: $p_T^\mu > 25$ GeV, $p_T^b > 25$ GeV, $E_\mathrm{T}^\mathrm{miss} >$ 40 GeV and $H_T > 240$ GeV, where H_T denotes the scalar sum of p_T^μ and transverse momentum of jets. The total signal strength is then the sum of the SM expectation and the contribution from the $X_{5/3}$ VLQ,

$$\mu \equiv \frac{\sigma_\mathrm{SM} + \sigma_\mathrm{VLQ}}{\sigma_\mathrm{SM}} = 1 + \mu_\mathrm{VLQ}, \tag{11}$$

which is shown in Table II. For comparison, we note that the 95% C.L. upper limit in the ttH multilepton channel from CMS run 2 data is [15]

$$\mu_{ttH} < 3.3\ (2.6\ \text{expected}) \quad \text{at 95\% C.L.} \tag{12}$$

We see that both benchmarks give good fits to the multilepton excesses observed at both run 1 and run 2.

In the future, should the multilepton excess persist, it would be crucial to understand the nature of the excess. In this regard, we compare some kinematic distributions of events in the same-sign di-muon channel from our benchmark models with those from SM ttW in Fig. 4. In particular, we plot p_T of the leading jet and the leading muon, respectively, as well as the MET distribution. It is clear that events from our benchmarks in general have harder decay spectra than those from the SM.

Figure 4 also highlights the importance of conducting dedicated searches for VLQs whose decay product contains a dark matter candidate carrying away extra MET, as the kinematic distributions are quite different between the two benchmarks. Such searches have not been performed at the LHC to the best of our knowledge. Although the MET distribution for Model 3 is harder than Model S, p_T distributions of the leading jet and the leading muon are softer in Model 3. Therefore we expect the selection efficiency will be different between the two benchmarks.

IV. CONCLUSION

In this work, we studied the LHC phenomenology of the VLQ that is often invoked to mediate loop-induced couplings of the 750 GeV diphoton resonance. In particular, we considered an electroweak doublet VLQ with

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[8] Such a decay could arise from the interaction $S\phi\phi$, which is irrelevant for our study for $m_\phi \geq m_S/2$.

[9] The same-sign dilepton final state is the most sensitive channel for our model, and currently the other multilepton channels are less sensitive.

hypercharge $7/6$, giving rise to an exotic charge-$5/3$ VLQ and a toplike VLQ with charge-$2/3$. When the mass of the VLQ is at around 1 TeV, the desired diphoton signal strength can be obtained for a Yukawa coupling $y \lesssim \mathcal{O}(1)$. In this scenario, all gauge couplings as well as the VLQ Yukawa coupling remain perturbative up to a very high energy scale, of the order of 10^{17} GeV.

Decay phenomenology of the VLQ is quite distinct at the LHC, especially if they decay into the third generation fermions and the SM gauge bosons. For example, the charge-$5/3$ VLQ, $X_{5/3}$, could decay into a top quark and a W^+ boson. Alternatively, it is possible to include a stable neutral particle as the dark matter candidate with the correct relic density. Then the VLQ always decays into SM particles and the dark matter particle, which carries away additional MET in the collider detectors. Interestingly, we demonstrated that decays of $X_{5/3}$ could contribute to the mild excess in the multilepton, b jets, and MET channel that are observed at both run 1 and run 2 of the LHC.

We performed numerical studies on two benchmark models, one with the dark matter particle and one without, and compared their kinematic distributions with those from the SM ttW processes. Should the multilepton excess persists in the future, such comparisons will shed light on the nature of the excess. Furthermore, we showed that kinematic distributions between the two benchmarks are quite distinct, calling out the need for dedicated experimental efforts to search for a new decay topology of VLQs, into final states containing a dark matter candidate.

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