Quirky explanations for the diphoton excess

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We propose two simple quirk models to explain the recently reported 750 GeV diphoton excesses at ATLAS and CMS. It is already well known that a real singlet scalar \( \phi \) with Yukawa couplings \( \phi XX \) to vectorlike fermions \( X \) with mass \( m_X > m_\phi/2 \) can easily explain the observed signal, provided \( X \) carries both SM color and electric charge. We instead consider first the possibility that the pair production of a fermion, charged under both SM gauge groups and a confining \( SU(3)_c \) gauge group, is responsible. If pair produced it forms a quirk bound state, which promptly annihilates into gluons, photons, \( v \)-gluons and possibly SM fermions. This is an extremely minimal model to explain the excess, but is already in some tension with existing displaced searches, as well as dilepton and dijet resonance bounds. We therefore propose a hybrid quirk-scalar model, in which the fermion of the simple \( \phi XX \) toy model is charged under the additional \( SU(3)_c \) confining gauge group. Constraints on the new heavy fermion \( X \) are then significantly relaxed. The main additional signals of this model are possible dilepton, dijet and diphoton resonances at \( \sim 2 \text{ TeV} \) or more from quirk annihilation, and the production of \( v \)-glueballs through quirk annihilation and \( \phi \) decay. The glueballs can give rise to spectacular signatures, including displaced vertices and events with leptons, photons and \( Z \)-bosons. If the quirk-scalar model is responsible for the 750 GeV excess it should be discovered in one of these channels with 20 or 300 fb\(^{-1} \) of LHC Run 2 data.

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I. INTRODUCTION

Recently, both of the major LHC collaborations announced excesses in events containing two photons, near a diphoton invariant mass of around 750 GeV. The ATLAS search [1] used 3.2 fb\(^{-1} \) of data at \( \sqrt{s} = 13 \text{ TeV} \) and reports a local (global) excess significance of 3.9\( \sigma \) (2.3\( \sigma \)). The CMS search [2] used 2.6 fb\(^{-1} \) and reports a local excess significance of 2.6\( \sigma \).

This excess has already generated considerable interest in the theory community [3–20].\(^ \dagger \) If a Beyond Standard Model (BSM) process is responsible, compatibility with LHC Run 1 searches favors gluon or heavy quark initiated production. The best-fit width is around 45 GeV but a very narrow resonance is also compatible with the data. Events in the signal bins do not appear kinematically very different from the sidebands, somewhat disfavoring explanations that involve the production of additional missing transverse energy, leptons, etc. This motivates interpreting the signal in the context of a minimal benchmark model, where a Standard Model (SM) singlet scalar \( \phi \) with mass around 750 GeV is produced through gluon-fusion and decays to two photons \( gg \rightarrow \phi \rightarrow \gamma \gamma \). Taking acceptance into account, the approximate cross section corresponding to the excess [4] is \( \sigma(pp \rightarrow \phi \rightarrow \gamma \gamma) \approx (6 \pm 3) \text{ fb} \) at CMS and \( (10 \pm 3) \text{ fb} \) at ATLAS with \( \sqrt{s} = 13 \text{ TeV} \).

This excess is intriguing for several reasons. A SM-neutral scalar couples to gluons (photons) via a dimension-5 effective operator, which can be generated by loops of colored (electrically charged) particles with sizable couplings to the scalar. In order for the diphoton decay to be observable, the scalar cannot have any large tree-level couplings to other SM particles. This excludes gluon fusion via a SM top loop as the production mechanism, since otherwise \( \phi \rightarrow t\bar{t} \) would completely dominate. The diphoton excess, if its BSM origin is confirmed, might therefore imply the existence of additional matter states with color and electric charge.

A simple toy model can be constructed by adding the 750 GeV singlet scalar \( \phi \) and a new vectorlike fermion \( X \) to the SM. \( X \) is an \( SU(3)_c \) fundamental, carries electric charge \( Q_X \), and is heavier than about 380 GeV to avoid tree-level decays of \( \phi \). The simple interaction Lagrangian

\[
\mathcal{L}_{\text{int}} = y_X \phi \tilde{X} X, \tag{1}
\]

where \( \phi \) does not couple directly to any SM fields, can then give rise to the observed diphoton signal for \( m_X \sim \text{ TeV} \), \( y_X \sim 1 \) and \( Q_X \sim 1 \). Several varieties of this model have already been explored [3–12], even before 13 TeV LHC data was available [39].

\[\text{References [21–38] on this subject have recently appeared.}\]
The existence of new colored and electrically charged matter states around 1 TeV has many important consequences, which must be considered in the context of the diphoton excess. If X lives long enough to escape the detector it has to be heavier than about ∼1.1 TeV [40]. A stable TeV-scale colored fermion would have serious implications for cosmology, and making it unstable adds considerable complication for the model, which would still be subject to direct search constraints.

In this paper, we examine two very simple models to explain the diphoton excess. In both cases, we add a vectorlike fermion X and a new confining gauge group SU(3)c to the Standard Model. X is a fundamental under both SU(3)c and SU(3)c and carries hypercharge

\[ Q_X. \]

Assuming no lighter states with SU(3)c charge, this new gauge group confines in the IR and realizes a pure-glue hidden valley [41–44], with v-glueballs making up the low-energy hidden hadron spectrum [45]. (We assume the confinement scale is significantly below \( m_X \).) When X is pair produced via its SM color charge it forms a quirky bound state [46–48], since the v-gluon string connecting them cannot break by exciting light quark pairs out of the vacuum. For SU(3)c, confinement scale \( \Lambda_c \gtrsim \Lambda_{QCD} \), the bound state promptly deexcites via emission of soft quanta like gluons and photons, which randomize its orbital angular momentum. Since s-wave annihilation is very strongly preferred, this suppresses annihilation until the quirk has deexcited to near its lowest lying states, which is a distribution of quirkonium bound states in analogy to SM quarkonia.

The relevant quirkonium annihilation widths can be adapted from [50,57]. Before annihilation, the bound state can be either in a spin singlet or triplet state. The decay width of the triplet is only ∼3% of the singlet. Therefore, if soft emissions randomize the quirk between the singlet and triplet state while it deexcites and annihilates, the singlet decay branching fractions will dominantly determine the final states. If, on the other hand, the singlet and triplet states are democratically populated after soft emission ceases, but well before annihilation occurs, then both singlet and triplet decay branching fractions determine the final state in comparable proportion. The large uncertainties in understanding this strongly coupled bound state make it difficult to make a definitive determination of which possibility is realized. We will discuss both cases.

Assume first that the spin singlet state \( ^1S_0 \) dominates annihilation. The branching functions are very insensitive to mass. For SU(3)c coupling \( \alpha_c \sim \alpha_s \) (evaluated at \( \mu = 2m_X \)), \( m_X \sim \text{TeV} \), and \( Q_X \lesssim 2 \), they are

\[ \frac{d\sigma}{dx}(\gamma \gamma \rightarrow X X) \sim 0.01. \]

FIG. 1. \( \bar{X}X \) pair production cross section at the 8 and 13 TeV LHC. Computed at leading order in MADGRAPH [56].
where $g'$ are v-gluons. The $\alpha_s/\alpha_t$ ratio can be expressed in terms of the lightest glueball mass $m_0 \approx 7\Lambda_\chi$, assuming pure gauge renormalization group (RG) evolution between $m_0$ and $2m_\chi$. As shown in Fig. 2, this favors ratios in the range $0.7$–$2.5$. Note that there is no gluon-mediated $\bar{X}X \to \bar{q}q$ decay, since the quirks form a color singlet state.

The diphoton final state could generate the diphoton excess observed at ATLAS and CMS, as discussed below. The gluon final state results in a dijet resonance. The potentially most exciting additional signal of quirk production is their annihilation into v-gluons, which hadronize into jets of glueballs. A similar signature has been recently discussed in the context of neutral naturalness [58]. Details of hadronization in a pure $SU(3)$ gauge theory are currently unknown, which makes detailed study of this signal challenging. However, the glueballs produced in quirk annihilation may give rise to displaced vertices, lepton pairs, resonant and nonresonant photons, and dijets. We study some possible aspects of glueball phenomenology below. Even without detailed knowledge of hadronization, several important predictions can be made.

If both the spin singlet and triplet $^3S_1$ democratically determine the branching fraction, the situation is quite different. The triplet state can mix with the SM $\gamma/Z$ and decay to SM fermions $f \bar{f}$. For $m_\chi \sim 1\text{TeV}$, the branching fractions are very well described by

$$\sum_i \text{Br}^{i}(^3S_1 \to f \bar{f}) \approx \frac{Q_X^2}{Q_X^2 + 0.05(1 + (\alpha_s/\alpha_t)^3)}$$

$$\text{Br}^{(3)S_1 \to ggg} \approx \frac{0.05(\alpha_s/\alpha_t)^3}{Q_X^2}$$

$$\text{Br}^{(3)S_1 \to g'g'g'} \approx \frac{0.05(\alpha_s/\alpha_t)^3}{Q_X^2 + 0.05(1 + (\alpha_s/\alpha_t)^3)}.$$  \hfill (4)

(Here we have omitted for simplicity the strongly subdominant $Zh, Zg^0g^0$, and $\gamma g^0g^0$ decay modes.) The branching fraction to SM fermions is $\sim50\%$ for $Q_X \sim 1/3$ and $\alpha_s/\alpha_t \sim 1$ and quickly becomes dominant as $Q_X$ is increased. As determined by hypercharges, $27\%$ of the produced SM fermions are $e^+e^-$ or $\mu^+\mu^-$. Therefore, dilepton resonance searches could strongly constrain light quirks if a significant fraction annihilates in the triplet state.

Given the uncertainties, the total width of the quirk annihilation signature cannot be exactly determined. However, for $m_\chi \sim 1\text{TeV}$ and $\alpha_s \sim \alpha_t$, the individual quirkonion states have $\sim\text{MeV}$ widths or below, with $\sim\text{GeV}$ splittings between the states [48,53]. Annihilation from these states would therefore lead to at most few-GeV-scale resonance widths, but this could be broadened if annihilation proceeds while the quirks are still somewhat excited.

**III. GLEEBALL PHENOMENOLOGY**

A pure $SU(3)_c$ confining gauge theory has $\sim12$ stable glueball states [45]. The lightest state is the singlet $0^{++}$ with a mass of $m_0 \approx 7\Lambda_\chi$, while the heaviest state has a mass of $\approx 2.8m_0$. The $X$ acts as a bifundamental messenger, being charged under both SM gauge groups and $SU(3)_c$. Loops of $X$ allow the glueballs to decay to SM gauge bosons and in some cases fermion pairs via dimension-8 operators, with decay rates that have been computed by [54,55] in terms of hadronic matrix elements that can be extracted from lattice calculations. [Note that $X$ carries no $SU(2)_L$ charge.] The glueball lifetime can be very long and is subject to significant uncertainties due to several uncomputed hadronic matrix elements. Furthermore, there are potentially many orders of magnitude of lifetime difference between the different glueball states. Finally, the details of hadronization of v-gluons are unknown. While it is possible to parameterize our ignorance in this regard [58], here we merely point out that a significant fraction of the produced glueballs is expected to be in the lightest $0^{++}$ state [59], and that the lifetime of this state is relatively well known.

Figure 3 shows the range of possible glueball lifetimes as a function of $m_0$, the mass of the lightest $0^{++}$ state, for $m_\chi = 370 \text{GeV}$ (black), $1 \text{TeV}$ (blue) and $2 \text{TeV}$ (orange). The green shaded region indicates decay that is prompt on collider scales, $\tau \approx 10 \mu\text{m}$. The red shaded region indicates lifetimes longer than $0.1 \text{s}$, which is problematic for BBN. The vertical gray band indicates $m_0 = 375 \text{GeV}$, above which a $750 \text{GeV}$ scalar cannot decay to v-gluons.

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**FIG. 2.** Ratio of $\alpha_s/\alpha_t$ evaluated at $\mu = 2m_\chi$ as a function of glueball mass $m_0 \approx 7\Lambda_\chi$, derived using the pure $SU(3)_c$ gauge renormalization group equation (RGE), and assuming $m_0 < m_\chi$.
The solid lines indicate the reasonably well-known lifetime of the $0^{++}$ glueball, which should be commonly produced in $v$-hadronization. The other glueball lifetimes are contained between the dashed and dotted lines. In cases where the hadronic matrix elements have not been computed on the lattice we employ the estimates of [55] varied within a factor of $1/3$–$3$. The dashed lines indicate the lifetime of the longest-lived $2^{++}$ or $2^{-+}$ state with lower estimates for the unknown hadronic matrix elements. The dotted lines indicate the lifetime of the shortest-lived $1^{--}$ state with upper estimates for the unknown hadronic matrix elements. (The resonance feature at $m_0 \approx 40$ GeV occurs when $m_{1^{--}} \approx 2.2 m_0 \approx m_2$.) Most of the glueballs decay radiatively to other glueballs via emission of photons, or directly to SM gauge bosons. Decays to gluons dominate, with $10^{-2}$ branching fractions to $\gamma\gamma$, $\gamma Z$ and $ZZ$ (when kinematically accessible). An interesting exception is the $1^{--}$ state, which can mix with the SM Z-boson and have significant branching fraction into SM fermion pairs, including leptons.

This basic discussion of glueball phenomenology allows us to evaluate the feasibility of our quirky toy models for the diphoton excess.

**IV. PURE QUIRK MODEL**

The pure quirk model, as outlined above, is defined by merely adding $X$ and $SU(3)_c$ to the SM. In order to produce the diphoton excess, the mass of $X$ has to be about 370 GeV, which we assume here. At that mass, the 13 TeV (8 TeV) LHC production cross section is about 26 pb (5 pb) at lowest order, which is sufficient for this discussion. Coincidentally, this leads to about the same number of $\bar{X}X$ pairs produced at 13 TeV with 3.2 fb$^{-1}$ as at 8 TeV with 20 fb$^{-1}$, which simplifies our discussion.

We first assume that the quirk annihilates in the spin singlet state. In that case, Fig. 4 shows the number of $\gamma\gamma$, $Z\gamma$ and $ZZ$ events produced through quirk pair production and annihilation at the 13 TeV LHC with 3.2 fb$^{-1}$. The ATLAS excess favors $\sim 20$–40 events, which is easily accommodated for $Q_X \sim 1/3$–$1/2$. However, this model produces a similar number of diphoton events at Run 1, placing it in tension with those searches.

In this range of $Q_X$, quirks produce only a few $ZZ$ events, which is safe from Run 1 constraints like [60] but may be discovered in future searches. The number of $Z\gamma$ events is smaller but comparable to $\gamma\gamma$. This is well within 8 TeV limits [61], but is potentially detectable with more Run 2 data.

Apart from the large diphoton rate at Run 1, the most important constraints on this model with pure spin-singlet annihilation actually stem from the gluon and $v$-gluon final states of quirk annihilation.

Annihilation into gluons occurs some $O(1)$ fraction of the time, and can be constrained by dijet resonance searches. These searches are challenging due to the large event rates, but CMS performed an unrescaled dijet resonance search using data scouting techniques [62] at Run 1. At a dijet mass of 750 GeV, this search gives the constraint

$$\sigma(pp \rightarrow \bar{X}X) \cdot Br(\bar{X}X \rightarrow gg) \leq 1 \text{ pb}$$

Since the 8 TeV production cross section is about 5 pb, this already constrains $Br(\bar{X}X \rightarrow gg) \leq 0.2$, which implies $\alpha_e/\alpha_s \gtrsim 2$. Such a large ratio for $m_X = 370$ GeV can only

![FIG. 4. Number of $\gamma\gamma$ (red solid), $Z\gamma$ (blue dashed) and $ZZ$ (green dot-dashed) events produced at the 13 TeV LHC with 3.2 fb$^{-1}$ from $\bar{X}X$ pair production and quirk annihilation. Shown in the plane of $X$ electric charge $Q_X$ and the ratio $\alpha_e/\alpha_s$ evaluated at $\mu = 2m_X$, which can be mapped to the mass of the lightest glueball $m_0$, see Fig. 2.](image-url)
be achieved if the glueballs are almost as heavy as the X fermions themselves, see Fig. 2.

Annihilation into v-gluons yields jets of v-glueballs, which can decay in the detector with measurable displacement. This allows us to estimate constraints using the CMS displaced dijet search at Run 1 [63]. In the $m_{q} \sim O(100 \text{ GeV})$ range favored by the dijet bounds, the $0^{++}$ glueballs decay promptly into gluons. Since they are presumably a sizable fraction of the produced glueballs, and given that the $XX$ state has an invariant mass of around 750 GeV, the resulting prompt jets should surpass the $H_T > 325 \text{ GeV}$ threshold of this search and lead to large signal acceptance when any other glueball decays in the tracker. In this range of $m_{q}$, the $2^{\pm}$ glueball state has lifetimes in the cm range, see Fig. 3. This means that events with $2^{\pm}$ glueballs should be detected by this analysis. For cm-scale lifetimes, the limit can be translated as roughly

$$\sigma(pp \rightarrow \bar{X}X) \cdot \text{Br}(\bar{X}X \rightarrow 2^{\pm}0^{++} + \cdots) \lesssim 10^{-3} \text{ pb} \quad (6)$$

at 8 TeV. That means that less than $\sim 0.1\%$ of $\bar{X}X$ pair production events can contain any glueballs which decay on cm scales like the $2^{\pm}$. While no details on v-gluon hadronization are known, this nevertheless appears to be a fairly stringent requirement.

When a fraction $R_{3/1}$ of quirks annihilate in the spin triplet state, the diphoton rate described above is correspondingly reduced. Even so, the pure quirk scenario could still describe the diphoton excess quite easily with slightly increased $Q_X$. The far more significant change is the dilepton resonance signature of quirk production. For $m_X = 370 \text{ GeV}$ and $Q_X = 1/2$, the triplet branching fraction to electron and muon pairs is about 20% (8%) for $\alpha_v/\alpha = 0.7$ (2).

The sensitivity of dilepton resonance searches at 750 GeV from LHC Run 1 searches [64,65] is around $10^{-3} \text{ pb}$. This translates to a bound on the fraction of quirks that annihilate in the triplet state,

$$R_{3/1} \lesssim 10^{-3}. \quad (7)$$

(The bound derived from the Run 2 searches with $\sim 3 \text{ fb}^{-1}$ [66,67] is nearly identical.) This seems like another very stringent requirement for the pure quirk model to satisfy.

Given the tension between the quirk-produced diphoton signal at 13 TeV and the lack of a large excess at 8 TeV, as well as the lack of signals in the CMS displaced dijet analysis and dilepton channels, we conclude that this model is at best marginally viable as an explanation for the diphoton excess. However, if direct quirk pair production is responsible, it should show up with 20 fb$^{-1}$ of LHC Run 2 data as a dijet or dilepton resonance peak, or a displaced signal.

V. QUIRK-SCALAR MODEL

We now modify the original toy model of Eq. (1) by charging the vectorlike fermion $X$ under the $SU(3)_c$ gauge group. The BSM particle content is therefore

$$
\begin{array}{c|c|c|c|c}
& SU(3)_c & SU(3)_c & SU(2)_L & U(1)_Y \\
\hline
X & 3 & 3 & 1 & Q_X \\
\hline
\phi & 1 & 1 & 1 & 0 \\
\end{array}
\quad (8)
$$

$\phi$ is taken to be a real singlet scalar. The minimal additional nonkinetic terms of the Lagrangian are

$$\mathcal{L} = \frac{1}{2} m_\phi^2 \phi^2 + m_X \bar{XX} + y_X \phi \bar{XX}. \quad (9)$$

The SM Higgs doublet cannot couple to the $SU(2)_L$ singlet $X$ via renormalizable operators. Loops of $X$ induce effective couplings between $\phi$ and gluons, photons and v-gluons. In the notation of [68],

$$\mathcal{L}_{\text{eff}} = \tilde{c}_g \frac{\alpha}{12\pi v} G_{\mu\nu} G^{\mu\nu} + \tilde{c}_\gamma \frac{\alpha_s}{\pi} A_{\mu\nu} A^{\mu\nu}$$

$$+ \tilde{c}_v \frac{\alpha_v}{12\pi v} \phi G_{\mu\nu} G^{\mu\nu} \quad (10)$$

where $G_{\mu\nu}, A_{\mu\nu}$ and $G_{\mu\nu}'$ are the gluon, photon, and v-gluon field strengths respectively. This effective field theory (EFT) description is valid as long as $m_\phi \ll m_X$. The coefficients can be obtained by a simple rescaling of SM results,

$$\tilde{c}_g = \tilde{c}_v = v \frac{y_X}{m_X} N_v, \quad \tilde{c}_\gamma = \frac{\tilde{c}_g}{2} Q_X^2. \quad (11)$$

where $N_v = 3$ is the additional $SU(3)_c$ color factor.

The production cross section and decay widths of $\phi$ can now be straightforwardly calculated using Eq. (10). At 13 TeV, the production cross section for $m_\phi = 750 \text{ GeV}$ in the EFT approximation is

$$\sigma_{13 \text{ TeV}} \approx (100 \text{ fb}) y_X^2 \left( \frac{1 \text{ TeV}}{m_X} \right)^2. \quad (12)$$

The decay widths to gluons, photons and v-gluons (ignoring hadronic effects, like mass of the glueballs) is approximately

$$\Gamma_{gg} \approx (13 \text{ MeV}) y_X^2 \left( \frac{1 \text{ TeV}}{m_X} \right)^2 \quad (13)$$

$$\Gamma_{\gamma\gamma} \approx (0.4 \text{ MeV}) y_X^2 \left( \frac{1 \text{ TeV}}{m_X} \right)^2 Q_X^4 \quad (14)$$

$$\Gamma_{g'g'} \approx \Gamma_{gg} \left( \frac{\alpha_v}{\alpha_s} \right)^2, \quad (15)$$
where we have included the color factor $N_c = 3$, and in the last line the couplings are evaluated at scale $\mu = m_\phi$. Note that decay to $v$-gluons will not be kinematically available if the glueball mass is heavier than about 380 GeV.

Figure 5 shows the number of diphoton events from $\phi$ decay in the $(m_X/y_X, Q_X)$ plane at the 13 TeV LHC with 3.2 fb$^{-1}$ of luminosity (blue contours). In the top plot we assume $\phi$ decay to $v$-glueballs is kinematically forbidden. In the bottom plot we allow $\phi \rightarrow g'g'$ with $\alpha_s/\alpha = 1$, which corresponds to $O(10–100$ GeV) glueballs, see Fig. 2. The ATLAS excess [1] favors $\sim$20–40 events, which can be achieved for $m_X/y_X \sim$ TeV and $Q_X \sim 1.5$.

The detailed prediction for the number of diphoton events is subject to hadronization uncertainties in $\phi$ decay to both gluons and $v$-gluons, but this schematic estimate shows that the quirk-scalar model can easily generate the excess of observed diphoton events. Note that the total decay width of $\phi$ in this model is always very small. Therefore, if a significant decay width for $\phi$ was confirmed it would disfavor this minimal setup.

A. Additional signals of the quirk-scalar model

In Fig. 5 we also show, now in the $(m_X, Q_X)$ plane for $\alpha_s/\alpha_s = 1$, the number of diphoton events with $m_{g'g'} \approx 2m_X$ expected in current Run 2 data from quirk pair production and annihilation (dotted red contours), assuming annihilation is dominated by the spin singlet quirk state. For $m_X \gtrsim$ TeV there is currently little appreciable photon signal from quirk annihilation, but this could be detectable with 300 fb$^{-1}$ or even 20 fb$^{-1}$ of data.

Current 13 TeV dijet resonance searches [69,70] are still compatible with $m_X > 1$ TeV but may be sensitive to quirk annihilation into SM gluons for $m_X \lesssim 1.5$ TeV with 300 fb$^{-1}$ of data, depending on $\alpha_s/\alpha_s$.

We can again use dilepton searches to place a constraint on $R_{3/1}$, the fraction of quirks that annihilates as the spin triplet state. Due to the higher quirk mass, the most important constraint is derived from the 13 TeV bounds [66,67]. For $\alpha_s/\alpha_s$ in the 0.7–2 range, the current Run 2 data has no sensitivity to quirk annihilation for $m_X \gtrsim 1.2$ TeV, even for $R_{3/2} = 1$ and $Q_X \sim O(1)$. With $\sim$300 fb$^{-1}$ of Run 2 data, dilepton resonance searches would only be sensitive to order unity $R_{3/1}$ for $m_X \lesssim 1.5$ TeV. Therefore, while a future dilepton signal is certainly possible in this quirk-scalar model, it is also easily possible to generate the 750 GeV diphoton excess without being excluded by dilepton bounds in the foreseeable future.

We now discuss the glueball signatures of the quirk-scalar model. Figure 3 makes clear that a wide range of glueball phenomenology is possible. Very conservatively, these glueballs are cosmologically safe for $m_0 \gtrsim 50$ GeV if $m_X \sim$ TeV (though these bounds may be somewhat relaxed depending on the relative abundances of glueballs in the early Universe for $T < \Lambda_s$). Importantly, this cosmological bound implies that the $0^{++}$ decay length cannot be significantly longer than about a km.

Glueballs can be produced both through quirk direct production, and in a large fraction of $\phi$ decays. If the quirk-scalar model explains the diphoton excess, then $O(100)$ $\phi$ production events have already occurred at Run 1 and
Run 2. 3 If a $\mathcal{O}(1)$ fraction of these $\phi$’s decays to v-glueballs, then the fraction of events in which these v-glueballs decay with measurable displacement in the detector cannot be larger than $\mathcal{O}(1\%−10\%)$ [63]. This could be easily accommodated by long decay lengths, in which case additional luminosity will eventually reveal these glueballs in displaced dijet searches. A wildcard in these predictions are the shorter-lived glueballs like $1^-$, which can yield dilepton final states. Their production fraction in v-hadronization is currently unknown, but their decay, displaced or prompt, could be another spectacular signature.

We also point out that the glueball lifetimes we have calculated could be reduced if $\phi$ were allowed to mix with the Higgs via the Higgs portal operator $\kappa |H|^2 \phi^2$, allowing additional mixing-suppressed operators for glueball decay [55]. However, the size of $\kappa$ is severely constrained to forbid large decays of $\phi$ to SM particles, so we do not consider this possibility here.

VI. CONCLUSIONS

In this paper, we make the general point that quirks, i.e. additional SM-charged fermions 4 interacting under their own confining gauge group, can be responsible for the diphoton excess reported by ATLAS [1] and CMS [2].

In the pure quirk model we examined, only the quirks are responsible; this is under tension from several other experimental constraints. In the quirk-scalar model, the quirks serve to “hide” the heavy SM-charged fermions required in the simple $\phi XX$ toy model for the diphoton excess. This ameliorates the cosmological problems on heavy stable colored fermions, and gives rise to a pure glue hidden valley with quirky phenomenology. The notable LHC signals of the quirk-scalar model are a narrow width for the scalar $\phi$ and quirky pair production of a $XX$ bound state which annihilates to v-gluons, SM gluons and photons, as well as possibly SM fermions. In addition to the 750 GeV diphoton resonance, this model may generate additional diphoton, dijet or dilepton resonances around $\gtrsim 2$ TeV from quirk annihilation, as well as v-glueball production from either $\phi$ decay or quirk annihilation. The v-glueballs can give rise to displaced vertices, lepton pairs, and photon pairs at the LHC Run 2, which can be picked up by a variety of searches. Overall, if the quirk-scalar toy model is responsible for the 750 GeV diphoton excess, we would expect it to show up in one of these additional channels with 20 or 300 fb$^{-1}$ of LHC Run 2 data.

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3For $m_X \gtrsim 1$ TeV (which is implied by the presumed lack of a $\gtrsim 2$ TeV diphoton resonance in the 13 TeV data, see Fig. 5), the cross section for $\phi$ production is greater than for $XX$ production as long as $\gamma_X \gtrsim 0.5$.

4Scalars are of course also a possibility.

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