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Update on 750 GeV diphotons from closed string states

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ABSTRACT

Motivated by the recent update on LHC searches for narrow and broad resonances decaying into diphotons we reconsider the possibility that the observed peak in the invariant mass spectrum at $M_{\gamma\gamma} = 750$ GeV originates from a closed string (possibly axionic) excitation φ (associated with low mass scale string theory) that has a coupling with gauge kinetic terms. We reevaluate the production of φ by photon fusion to accommodate recent developments on additional contributions to relativistic light–light scattering. We also study the production of φ via gluon fusion. We show that for both a narrow and a broad resonance these two initial topologies can accommodate the excess of events, spanning a wide range of string mass scales $7 \lesssim M_s/\text{TeV} \lesssim 30$ that are consistent with the experimental lower bound: $M_s > 7$ TeV, at 95% CL. We demonstrate that for the two production processes the LHC13 data is compatible with the lack of a diphoton excess in LHC8 data within $\sim 1\sigma$. We also show that if the resonance production is dominated by gluon fusion the null results on dijet searches at LHC8 further constrain the coupling strengths of φ, but without altering the range of possible string mass scales.

Recently, the ATLAS [1] and CMS [2] Collaborations reported excesses of events over expectations from standard model (SM) processes in the diphoton mass distribution around 750 GeV, using (respectively) 3.2 fb^{-1} and 2.6 fb^{-1} of data recorded at a center-of-mass energy $\sqrt{s} = 13$ TeV. This could be interpreted as decays of a new massive particle φ. For a narrow width approximation hypothesis, the ATLAS Collaboration gives a local significance of 3.6σ and a global significance of 2.0σ when accounting for the look-elsewhere-effect in the mass range $M_\varphi/$ GeV $\in$ [200–2000]. Signal-plus-background fits were also implemented assuming a large decay width for the signal component. The most significant deviation from the background-only hypothesis is reported for $M_\varphi \sim 750$ GeV and a total width $\Gamma_{\text{total}} \approx 45$ GeV. The local and global significances evaluated for the large width fit are about 0.3 higher than that for the fit using the narrow width approximation, corresponding to 3.9σ and 2.3σ, respectively. The CMS data yields a local significance of 2.6σ and a global significance smaller than 1.2σ. Fitting the LHC13 data with a resonance yields a cross section times branching ratio of

$$\sigma_{\text{LHC13}}(pp \to \varphi + \text{anything}) \times \mathcal{B}(\varphi \to \gamma\gamma) \approx \begin{cases} (10 \pm 3)\ \text{fb} & \text{ATLAS} \\ (6 \pm 3)\ \text{fb} & \text{CMS} \end{cases}, \tag{1}$$

at 1σ [3]. On the other hand, no diphoton resonances were seen in the data at $\sqrt{s} = 8$ TeV, although both ATLAS [4] and CMS [5] data show a mild upward fluctuation at invariant mass of 750 GeV. The lack of an excess at $\sqrt{s} = 8$ TeV allows a quite precise limit to be placed on the corresponding cross section at $\sqrt{s} = 13$ TeV. The most stringent limit comes from the CMS search $\sigma_{\text{LHC8}}(pp \to \varphi + \text{anything}) \times \mathcal{B}(\varphi \to \gamma\gamma) < 2.00$ fb at 95% CL [5]. This implies that if the diphoton cross section grows by less than about a factor of 3 or 3.5 the LHC8 data are incompatible with the LHC13 data at 95% CL.

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More recently, we proposed a model [6] to explain the data in which the resonance production mechanism is calculable in string based dynamics, with large extra dimensions [7]. In our proposal the observed diphoton excess originates from a closed string excitation φ living on the compact space of generic intersecting D-brane models that realize the SM chiral matter contents and gauge symmetry [8,9]. There are two properties of the scalar φ that are necessary for explaining the 750 GeV signal. It should be a special closed string state with dilaton-like or axion-like coupling to F^2 (respectively to $F\tilde{F}$) of the electromagnetic field, but *may be decoupled* from G^2 of color $SU(3)$. The couplings of closed string states to gauge fields do indeed distinguish between different D-brane stacks, depending on the localization properties of D-branes with respect to φ in the compact dimensions. More specifically, it is quite natural to assume that φ is a closed string mode that is associated to the wrapped cycles of the (lepton) $U(1)_L$ and (right isospin) $U(1)_{I_R}$ stack of D-branes, however it is not or only weakly attached to the wrapped cycle of (left) $Sp(1)_L$ or the color $SU(3)$ stack of D-branes. In this way, we may avoid unwanted dijet signals. Actually, within a selection of string based explanations of the resonance [10–19] our proposal is uniquely exemplified by the *possible suppression* of dijet topologies in the final state.[1] By choice, as we already advertised in [6], we may also allow a coupling φ to G^2. This is possible by modifying the localization properties of D-branes with respect to φ in the internal space.

Very recently, the ATLAS and CMS Collaborations updated their diphoton resonance searches [26–28]. The ATLAS Collaboration reported two separate analyses performed with 3.2 fb^{-1} of data at 13 TeV, targeting spin-0 and spin-2 resonances. For spin-0, the largest deviation from the background-only hypothesis is reported for $M_\varphi \sim 750$ GeV and $\Gamma_{\rm total} \approx 45$ GeV. While the local significance somewhat increases to 3.9σ the global significance remains at the 2σ level. For the spin-2 resonance, both the local and global significances are somewhat smaller: 3.6σ and 1.8σ, respectively. The new CMS analysis is based on 3.3 fb^{-1} collected at $\sqrt{s} = 13$ TeV. The additional data was recorded in 2015 while the CMS magnet was not operated. The largest excess is observed for $M_\varphi = 760$ GeV and $\Gamma_{\rm total} \approx 11$ GeV and has a local significance of 2.8σ for spin-0 and 2.9σ spin-2 hypothesis. After taking into account the effect of searching for several signal hypotheses, the significance of the excess is reduced to $< 1\sigma$. The CMS Collaboration also reported a combined search on data collected at $\sqrt{s} = 13$ TeV and $\sqrt{s} = 8$ TeV. For the combined analysis, the largest excess is observed at $M_\varphi = 750$ GeV and $\Gamma_{\rm total} = 0.1$ GeV. The local significance is $\approx 3.4\sigma$ and the global significance 1.6σ.

In this short note we extend our previous discussion in three directions. The first is a calculation to accommodate recent developments on additional contributions to relativistic light–light scattering [29–31]. The second is the explicit calculation for production via gluon fusion disclosed in [6]. The third is a scan of the parameter space to entertain the possibility of a narrow width favored by the recent CMS analysis that combines data from LHC8 and LHC13. Before proceeding we note that the ATLAS excess is quite broad and probably with a large uncertainty. The CMS excess, however, is smaller and has no clear preference for a large width. This seems to indicate that the ATLAS excess could be a real signal combined with a large fluctuation, making the excess appear larger and wider than the underlying physical signal. Throughout we assume the resonance needs to have a signal [32]

$$\sigma_{\rm LHC13}(pp \to \varphi + \text{anything}) \times \mathcal{B}(\varphi \to \gamma\gamma) \approx 3\text{–}6 \text{ fb}\,. \tag{2}$$

[1] A related stringy explanation in which φ can be produced through photon fusion has been put forward in [20]. Alternative axion and dilaton models have been discussed in [21–25].

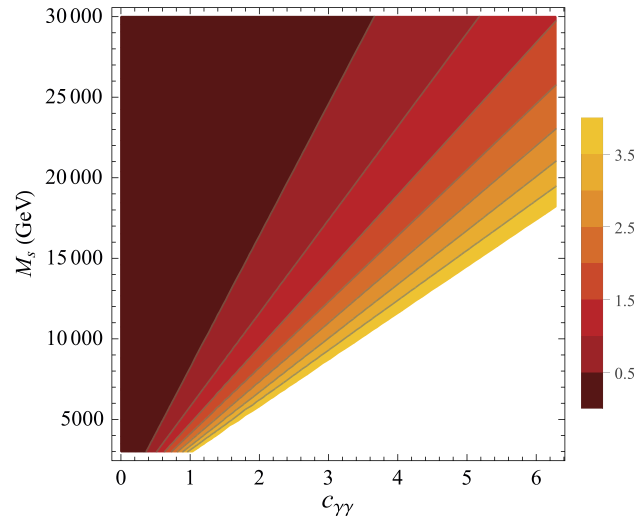

Fig. 1. Contours of constant partial width $\Gamma_{\gamma\gamma}$. The color encoded scales are in GeV. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Since the string mass scale is now known to be larger than $M_s \approx 7$ TeV [33], the mass $M_\varphi \approx 750$ GeV must be suppressed with respect to the string scale by some anomalous loop corrections. Because φ is a twisted closed string localized at an orbifold singularity, its coupling to $\gamma\gamma$ should be suppressed by M_s^{-1}, provided the bulk is large [34]. With this in mind, we parametrize the coupling of φ to the photon by the following vertex

$$\frac{c_{\gamma\gamma}}{M_s}\,\varphi\, F^2\,. \tag{3}$$

To remain in the perturbative range, we also require $c_{\gamma\gamma} \lesssim 2\pi$. The partial decay width of φ to diphotons then follows as

$$\Gamma_{\gamma\gamma} = \frac{c_{\gamma\gamma}^2}{4\pi}\,\frac{M_\varphi^3}{M_s^2}\,. \tag{4}$$

In Fig. 1 we exhibit a scan of the parameter space $(c_{\gamma\gamma}, M_s)$ for constant values of $\Gamma_{\gamma\gamma}$ as obtained from (4).

Let us first assume the diphoton signal is produced via photon–photon fusion with φ as the resonance state. Following [30], herein we include the elastic–elastic processes (already considered in [6]) as well as elastic–inelastic and inelastic–inelastic contributions. The elastic production is suppressed with respect to inelastic by about an order of magnitude. However, elastic photoproduction events result in forward and backward protons which can be detected by forward detectors installed by ATLAS [35] and CMS [36]. Therefore, the detection of two unbroken protons in the final state, with M_{pp} paired to $M_{\gamma\gamma}$, may be a promising way to reduce the background in the future [29,31].

The total photo-production cross section at LHC13 is [30]

$$\sigma_{\rm LHC13}(\gamma\gamma \to \varphi \to \gamma\gamma) = 4.1 \text{ pb} \left(\frac{\Gamma_{\rm total}}{45 \text{ GeV}}\right) \mathcal{B}^2(\varphi \to \gamma\gamma)\,, \tag{5}$$

where

$$\mathcal{B}(\varphi \to \gamma\gamma) = \frac{2.3 \times 10^6 c_{\gamma\gamma}^2}{\pi} \left(\frac{M_s}{\text{GeV}}\right)^{-2} \left(\frac{\Gamma_{\rm total}}{45 \text{ GeV}}\right)^{-1}. \tag{6}$$

Substituting (6) into (5), and demanding (5) reproduces the diphoton signal (2) we obtain an equation connecting $c_{\gamma\gamma}$ with M_s for given $\Gamma_{\rm total}$. In Fig. 2 we show the best fit contours for $\sigma_{\rm LHC13} \sim 5$ fb and total widths $\Gamma_{\rm total} = 45, 10, 1, 0.1$ GeV. We assume that

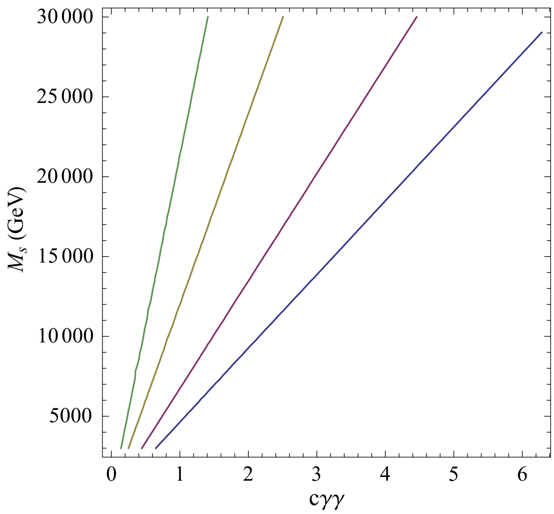

Fig. 2. Best fit contours of diphoton cross section $\sigma_{\rm LHC13} \sim 5$ fb produced via photon fusion $\gamma\gamma \to \varphi \to \gamma\gamma$. The four lines (blue, red, yellow, green) are for $\Gamma_{\rm total} = 45, 10, 1.0, 0.1$ GeV, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

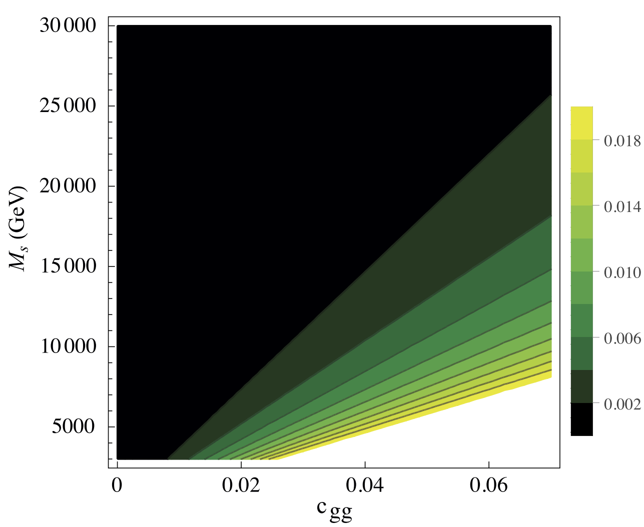

Fig. 3. Contours of constant partial width Γ_{gg}. The color encoded scales are in GeV. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

for a broad resonance the missing fraction of the decay width arises from the coupling of φ to some fermion bulk fields. These hidden fermions could make a contribution to the dark matter content of the universe [37–39]. We conclude that for both the narrow and the broad resonance hypotheses there is an allowed region of the parameter space which is consistent with the experimental lower bound of $M_s \simeq 7$ TeV [33] and reproduces the LHC13 signal. For the broad resonance hypothesis, $7 \lesssim M_s/\text{TeV} \lesssim 30$.

The total photo-production cross section at LHC8 is [30]

$$\sigma_{\rm LHC8}(\gamma\gamma \to \varphi \to \gamma\gamma) = 1.4 \text{ pb} \left(\frac{\Gamma_{\rm total}}{45 \text{ GeV}}\right) \mathcal{B}^2(\varphi \to \gamma\gamma)\,, \quad (7)$$

showing consistency with the 95% CL upper limit [5]. Actually, the ratio of the LHC13/LHC8 partonic luminosity is largely dominated by systematic uncertainties driven by the parton distribution func-

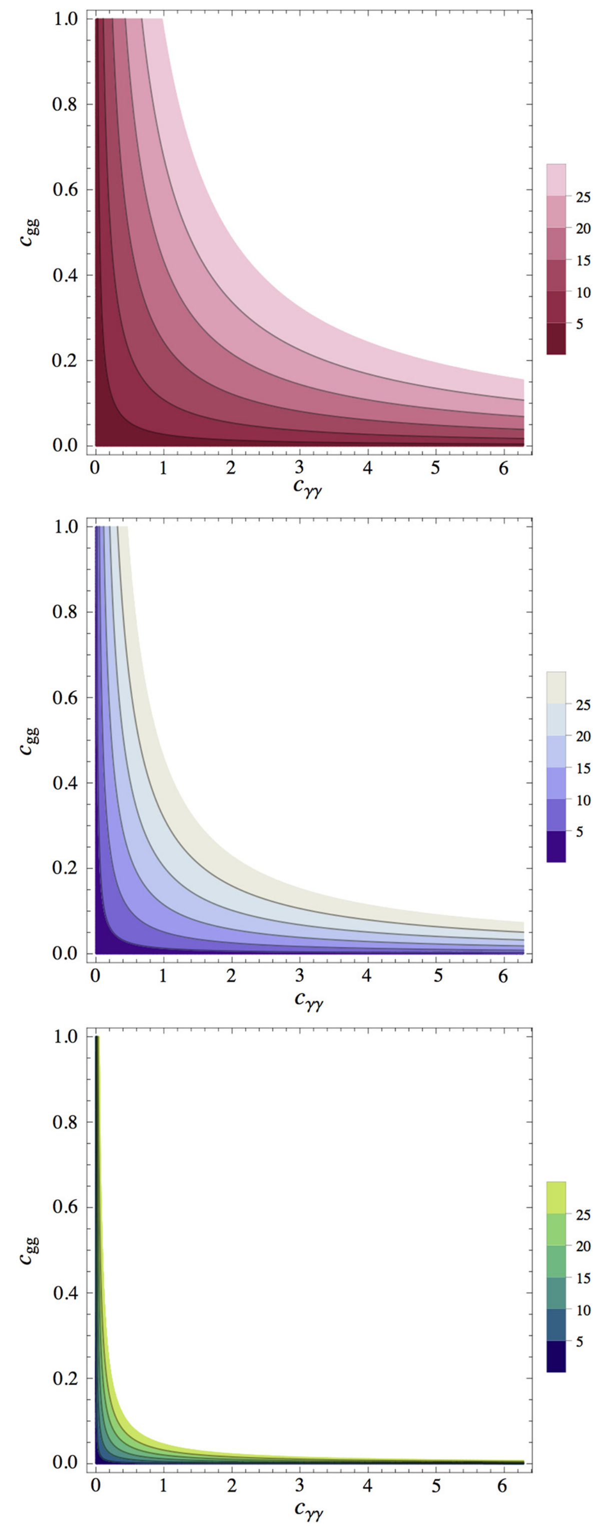

Fig. 4. Contours of constant string scale M_s for best fit of diphoton cross section ($\sigma_{\rm LHC13} = 5$ fb) produced via gluon fusion ($M_\varphi \simeq 750$ GeV, $\sqrt{s} = 13$ TeV). The color encoded scales are in TeV. The different panels correspond to $\Gamma_{\rm total} = 45, 10, 0.1$ GeV, downwards. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

tions. The luminosity ratio is [30]

$$\frac{\mathcal{L}_{\gamma\gamma}(\sqrt{s} = 13 \text{ TeV})}{\mathcal{L}_{\gamma\gamma}(\sqrt{s} = 8 \text{ TeV})} = 3^{+0.1}_{-0.2},\ 2.65 \pm 0.15,\ 2.1 \pm 0.4, \quad (8)$$

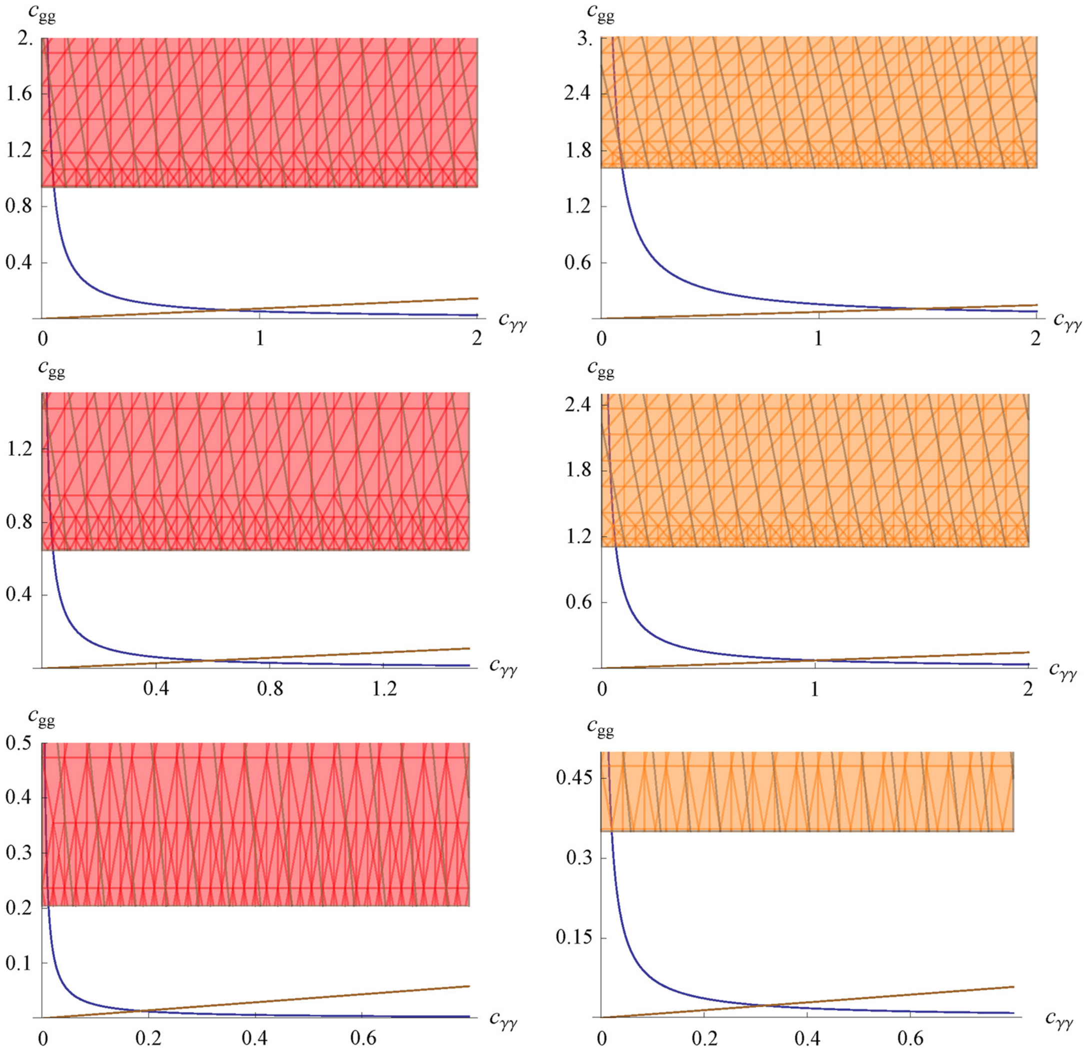

Fig. 5. Allowed parameter space on the c_{gg} vs $c_{\gamma\gamma}$ plane for $M_s = 7$ TeV (left) and $M_s = 12$ TeV. The blue curves indicate the best fit of diphoton cross section ($\sigma_{\rm LHC13} = 5$ fb) for $M_s = 7$ TeV (left) and $M_s = 12$ TeV (right). The (red and orange) shaded regions are excluded at 95% CL by null results on dijet searches. The slanted (brown) curve determines the transition between c_{gg} and $c_{\gamma\gamma}$ dominance at production. Gluon fusion dominates above this curve. Results for three possible total widths are exhibited in the vertical columns, $\Gamma_{\rm total} = 45, 10, 0.1$ GeV, downwards. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

for CT14QED [41], MRST2004 [42], and NNPDF2.3 [43]; respectively. We note that the predictions of NNPDF2.3 are only marginally compatible with LHC8 data [5].

The assumed coupling of φ to the hypercharge field strength yields additional decay channels in the visible sector, namely $\varphi \to \gamma Z$ and $\varphi \to ZZ$, with

$$\frac{\Gamma_{\gamma Z}}{\Gamma_{\gamma\gamma}} = 2\tan^2\theta_W \approx 0.6 \quad \text{and} \quad \frac{\Gamma_{ZZ}}{\Gamma_{\gamma\gamma}} = \tan^4\theta_W \approx 0.08\,. \tag{9}$$

This prediction is in agreement with the recent upper limit reported in by the ATLAS Collaboration from searches in the γZ channel [40].

We now turn to discuss the production via gluon fusion. We parametrize the coupling of φ to the gluon by the following vertex

$$\frac{c_{gg}}{M_s}\,\varphi\, G^2. \tag{10}$$

The partial decay width of φ to dijets is

$$\Gamma_{gg} = 8\,\frac{c_{gg}^2}{4\pi}\,\frac{M_\varphi^3}{M_s^2}\,. \tag{11}$$

In Fig. 3 we show a scan of the parameter space (c_{gg}, M_s) for constant values of Γ_{gg} as obtained from (11).

In the narrow width approximation the cross section for diphoton production via gluon fusion is given by [29]

$$\sigma_{\rm LHC13}(gg \to \varphi \to \gamma\gamma) = 5.8 \times 10^3\ {\rm pb}\, c_{gg}^2 \left(\frac{M_s}{\rm TeV}\right)^{-2} \mathcal{B}(\varphi \to \gamma\gamma) \tag{12}$$

and

$$\sigma_{\rm LHC8}(gg \to \varphi \to \gamma\gamma) = 1.2 \times 10^3\ {\rm pb}\, c_{gg}^2 \left(\frac{M_s}{\rm TeV}\right)^{-2} \mathcal{B}(\varphi \to \gamma\gamma)\,. \tag{13}$$

Substituting (2) and (6) into (12) we arrive at the targeting constraint equation connecting c_{gg}, $c_{\gamma\gamma}$, and M_s, for given $\Gamma_{\rm total}$. In Fig. 4 we show contours of constant string scale M_s for the best fit of the diphoton cross section ($\sigma_{\rm LHC13} = 5$ fb) produced via gluon fusion, with different values of the total decay width, $\Gamma_{\rm total} = 45, 10, 0.1$ GeV. By comparing the different panels of the figure we can see that the phase space critically shrinks with decreasing Γ_{total}. For φ production via gluon fusion, there is an additional constraint due to the null result on dijet searches above SM expectations. It is this that we now turn to study.

As of today the upper limit on dijet production at $M_{jj} = 750$ GeV is dominated by LHC8 data, $\sigma_{\text{LHC8}}(pp \to jj) < 2.5$ pb at 95%CL [44]. The cross section for dijet production is

$$\sigma_{\text{LHC8}}(gg \to \varphi \to gg) = 7.6 \times 10^3 \text{ pb } c_{gg}^4 \left(\frac{M_s}{\text{TeV}}\right)^{-4} \left(\frac{\Gamma_{\text{total}}}{45 \text{ GeV}}\right). \tag{14}$$

Imposing the dijet constraint, $\sigma_{\text{LHC8}}(pp \to jj) < 2.5$ pb, on (14) we obtain the excluded region of the $(c_{gg}, c_{\gamma\gamma})$ plane. The allowed region of the $(c_{gg}, c_{\gamma\gamma})$ parameter space, which explains the observed diphoton excess at LHC13 and is consistent with LHC8 data, is shown in Fig. 5 for illustrative values of the string scale, $M_s = 7$ TeV and 12 TeV. From (12) and (13) the LHC13/LHC8 luminosity ratio is found to be

$$\frac{\mathcal{L}_{gg}(\sqrt{s} = 13 \text{ TeV})}{\mathcal{L}_{gg}(\sqrt{s} = 8 \text{ TeV})} = 4.7. \tag{15}$$

Therefore, the production of φ by gluon fusion is consistent with the lack of a diphoton excess in LHC8 data. As we have seen, imposing the LHC8 dijet limit [44] further constrains the $(c_{gg}, c_{\gamma\gamma})$ parameter space. However, it remains the case that for $7 \lesssim M_s/\text{TeV} \lesssim 30$ there is always some allowed region of the $(c_{gg}, c_{\gamma\gamma})$ plane.

Summarizing, we embrace this joyous moment that appears to be the emergence of non-standard model physics in collider data, by investigating low-mass-scale string compactifications endowed with D-brane configurations that realize the SM by open strings. We have shown that generic D-brane constructs can explain the peak in the diphoton invariant mass spectrum at 750 GeV recently reported by the LHC experiments. Under reasonable assumptions, we have demonstrated that the excess could originate from a closed string (possibly axionic) excitation φ that has a coupling with gauge kinetic terms. We estimated the φ production rate from photon and gluon fusion. For string scales above todays lower limit $M_s \approx 7$ TeV, we can accommodate the diphoton rate observed at Run II while maintaining consistency with Run I data.

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