HAL open science

Update on 750 GeV diphotons from closed string states

Luis A. Anchordoqui, Ignatios Antoniadis, Haim Goldberg, Xing Huang, Dieter Lüst, Tomasz R. Taylor

To cite this version:

Luis A. Anchordoqui, Ignatios Antoniadis, Haim Goldberg, Xing Huang, Dieter Lüst, et al.. Update on 750 GeV diphotons from closed string states. Physics Letters B, 2016, 759, pp.223-228. 10.1016/j.physletb.2016.05.063 . hal-01426038

HAL Id: hal-01426038

https://hal.sorbonne-universite.fr/hal-01426038v1

Submitted on 4 Jan 2017

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Distributed under a Creative Commons Attribution 4.0 International License

Physics Letters B 759 (2016) 223–228

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Update on 750 GeV diphotons from closed string states

Luis A. Anchordoqui [a,b,c,*], Ignatios Antoniadis [d,e], Haim Goldberg [f], Xing Huang [g], Dieter Lüst [h,i], Tomasz R. Taylor [f]

[a] Department of Physics and Astronomy, Lehman College, City University of New York, NY 10468, USA
[b] Department of Physics, Graduate Center, City University of New York, NY 10016, USA
[c] Department of Astrophysics, American Museum of Natural History, NY 10024, USA
[d] LPTHE, UMR CNRS 7589, Sorbonne Universités, UPMC Paris 6, 75005 Paris, France
[e] Albert Einstein Center, Institute for Theoretical Physics, Bern University, Sidlerstrasse 5, CH-3012 Bern, Switzerland
[f] Department of Physics, Northeastern University, Boston, MA 02115, USA
[g] Department of Physics, National Taiwan Normal University, Taipei, 116, Taiwan
[h] Max-Planck-Institut für Physik, Werner-Heisenberg-Institut, 80805 München, Germany
[i] Arnold Sommerfeld Center for Theoretical Physics Ludwig-Maximilians-Universität München, 80333 München, Germany

ARTICLE INFO

Article history:
Received 10 April 2016
Accepted 20 May 2016
Available online 25 May 2016
Editor: M. Cvetič

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.

© 2016 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/). Funded by SCOAP[3].

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 $M_\varphi/\text{ GeV} \in [200\text{–}2000]$. 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.

* Corresponding author.
E-mail address: laa410@nyu.edu (L.A. Anchordoqui).

http://dx.doi.org/10.1016/j.physletb.2016.05.063
0370-2693/© 2016 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/). Funded by SCOAP[3].

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].

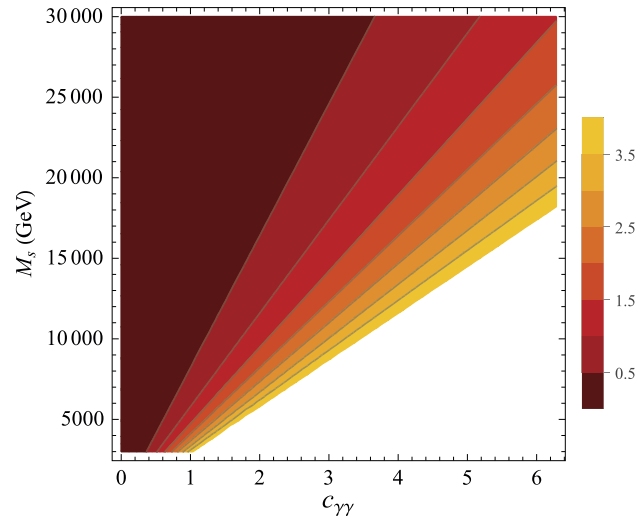

Fig. 1. Contours of constant partial width $\Gamma_{\gamma\gamma}$. The color encoded scales are in GeV. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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

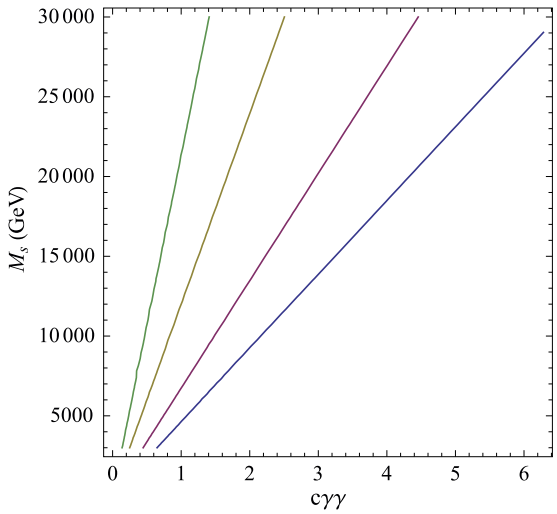

Fig. 2. Best fit contours of diphoton cross section $\sigma_{\rm LHC13} \sim 5$ fb produced via photon fusion $\gamma\gamma \to \varphi \to \gamma\gamma$. The four lines (blue, red, yellow, green) are for $\Gamma_{\rm total} = 45, 10, 1.0, 0.1$ GeV, respectively. (For interpretation of the references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

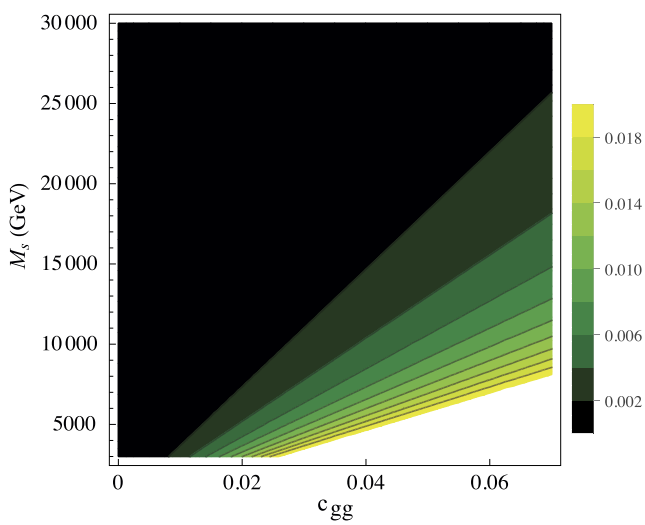

Fig. 3. Contours of constant partial width Γ_{gg}. The color encoded scales are in GeV. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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 functions. The luminosity ratio is [30]

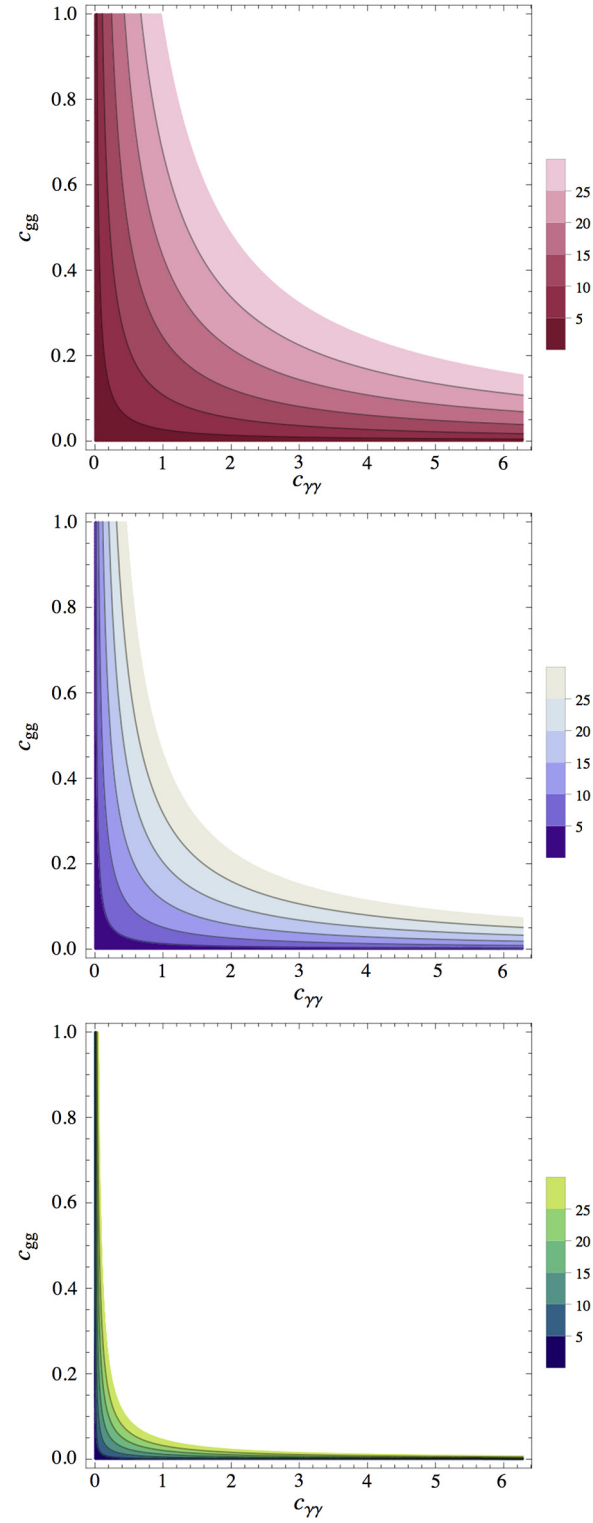

Fig. 4. Contours of constant string scale M_s for best fit of diphoton cross section ($\sigma_{\rm LHC13} = 5$ fb) produced via gluon fusion ($M_\varphi \simeq 750$ GeV, $\sqrt{s} = 13$ TeV). The color encoded scales are in TeV. The different panels correspond to $\Gamma_{\rm total} = 45, 10, 0.1$ GeV,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

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

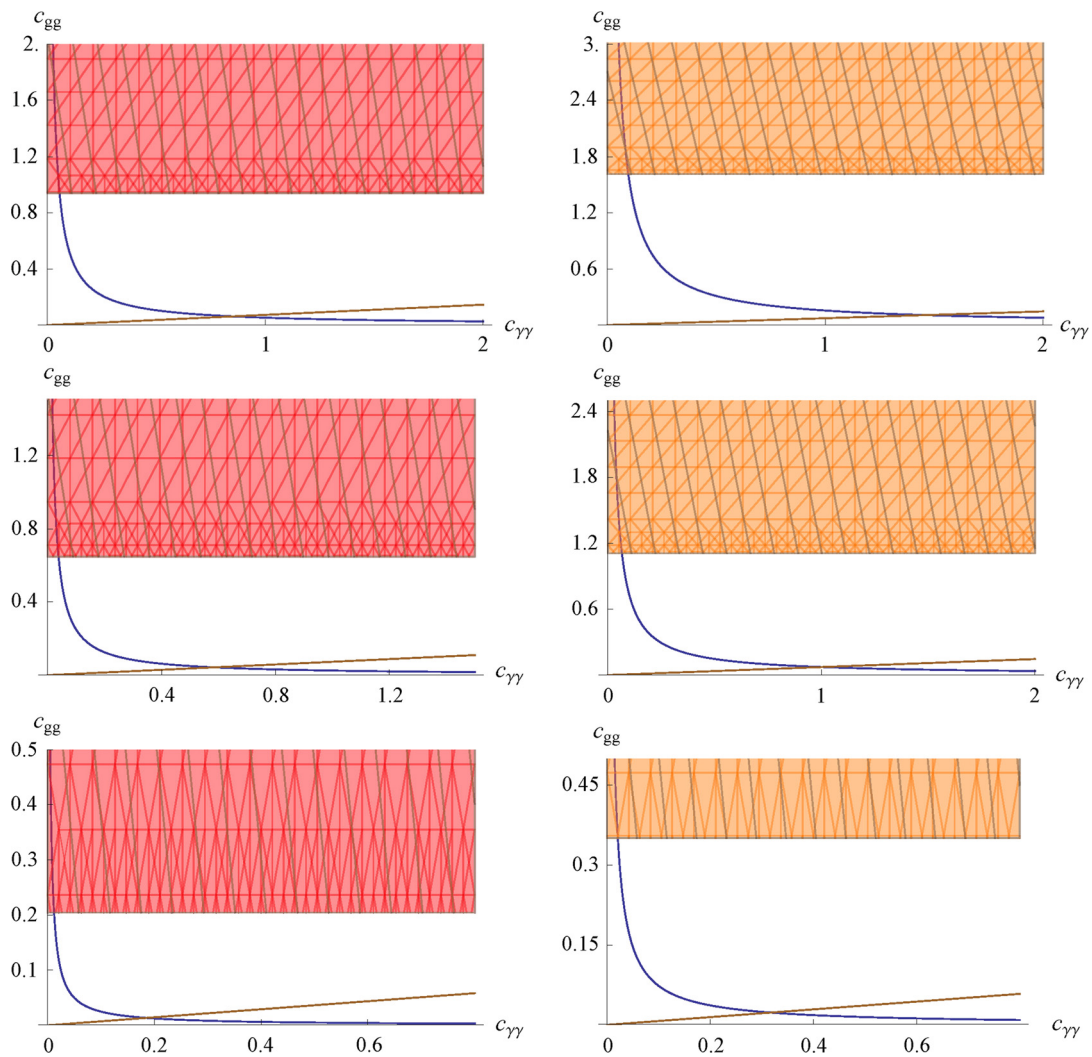

Fig. 5. Allowed parameter space on the c_{gg} vs $c_{\gamma\gamma}$ plane for $M_s = 7$ TeV (left) and $M_s = 12$ TeV. The blue curves indicate the best fit of diphoton cross section ($\sigma_{\rm LHC13} = 5$ fb) for $M_s = 7$ TeV (left) and $M_s = 12$ TeV (right). The (red and orange) shaded regions 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 $\Gamma_{\rm total}$. 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, $\sigma_{\rm LHC8}(pp \to jj) < 2.5$ pb at 95%CL [44]. The cross section for dijet production is

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

Imposing the dijet constraint, $\sigma_{\rm LHC8}(pp \to jj) < 2.5$ 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.

Acknowledgements

L.A.A. is supported by U.S. National Science Foundation (NSF) CAREER Award PHY1053663 and by the National Aeronautics and Space Administration (NASA) Grant No. NNX13AH52G; he thanks the Center for Cosmology and Particle Physics at New York University for its hospitality. H.G. and T.R.T. are supported by NSF Grant No. PHY-1314774. X.H. is supported by the MOST Grant 103-2811-M-003-024. D.L. is partially supported by the ERC Advanced Grant Strings and Gravity (Grant No. 32004) and by the DFG cluster of excellence "Origin and Structure of the Universe." Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

References

[1] ATLAS Collaboration, Search for resonances decaying to photon pairs in 3.2 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, ATLAS-CONF-2015-081.
[2] CMS Collaboration, Search for new physics in high mass diphoton events in proton–proton collisions, at 13 TeV, CMS-PAS-EXO-15-004.
[3] R. Franceschini, et al., arXiv:1512.04933 [hep-ph].
[4] G. Aad, et al., ATLAS Collaboration, Search for high-mass diphoton resonances in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, Phys. Rev. D 92 (2015) 032004, http://dx.doi.org/10.1103/PhysRevD.92.032004, arXiv:1504.05511 [hep-ex].
[5] V. Khachatryan, et al., CMS Collaboration, Search for diphoton resonances in the mass range from 150 to 850 GeV in pp collisions at $\sqrt{s} = 8$ TeV, Phys. Lett. B 750 (2015) 494, http://dx.doi.org/10.1016/j.physletb.2015.09.062, arXiv:1506.02301 [hep-ex].
[6] L.A. Anchordoqui, I. Antoniadis, H. Goldberg, X. Huang, D. Lüst, T.R. Taylor, 750 GeV diphotons from closed string states, Phys. Lett. B 755 (2016) 312, http://dx.doi.org/10.1016/j.physletb.2016.02.024, arXiv:1512.08502 [hep-ph].
[7] I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos, G.R. Dvali, New dimensions at a millimeter to a Fermi and superstrings at a TeV, Phys. Lett. B 436 (1998) 257, http://dx.doi.org/10.1016/S0370-2693(98)00860-0, arXiv:hep-ph/9804398.
[8] R. Blumenhagen, M. Cvetic, P. Langacker, G. Shiu, Toward realistic intersecting D-brane models, Annu. Rev. Nucl. Part. Sci. 55 (2005) 71, http://dx.doi.org/10.1146/annurev.nucl.55.090704.151541, arXiv:hep-th/0502005.
[9] R. Blumenhagen, B. Kors, D. Lüst, S. Stieberger, Four-dimensional string compactifications with D-branes, orientifolds and fluxes, Phys. Rep. 445 (2007) 1, http://dx.doi.org/10.1016/j.physrep.2007.04.003, arXiv:hep-th/0610327.
[10] J.J. Heckman, 750 GeV diphotons from a D3-brane, arXiv:1512.06773 [hep-ph].
[11] M. Cvetic, J. Halverson, P. Langacker, String consistency, heavy exotics, and the 750 GeV diphoton excess at the LHC, arXiv:1512.07622 [hep-ph].
[12] L.E. Ibanez, V. Martin-Lozano, A megaxion at 750 GeV as a first hint of low scale string theory, arXiv:1512.08777 [hep-ph].
[13] E. Palti, Vector-like exotics in F-theory and 750 GeV diphotons, arXiv:1601.00285 [hep-ph].
[14] A. Karozas, S.F. King, G.K. Leontaris, A.K. Meadowcroft, 750 GeV diphoton excess from E_6 in F-theory GUTs, arXiv:1601.00640 [hep-ph].
[15] A.E. Faraggi, J. Rizos, The 750 GeV diphoton LHC excess and extra Z's in heterotic-string derived models, arXiv:1601.03604 [hep-ph].
[16] P. Anastasopoulos, M. Bianchi, Revisiting light stringy states in view of the 750 GeV diphoton excess, arXiv:1601.07584 [hep-th].
[17] M. Cvetic, J. Halverson, P. Langacker, String consistency, heavy exotics, and the 750 GeV diphoton excess at the LHC, Addendum, arXiv:1602.06257 [hep-ph].
[18] T. Li, J.A. Maxin, V.E. Mayes, D.V. Nanopoulos, The 750 GeV diphoton excesses in a realistic D-brane model, arXiv:1602.09099 [hep-ph].
[19] G.K. Leontaris, Q. Shafi, Diphoton resonance in F-theory inspired flipped $SO(10)$, arXiv:1603.06962 [hep-ph].
[20] S. Abel, V.V. Khoze, Photo-production of a 750 GeV di-photon resonance mediated by Kaluza–Klein leptons in the loop, arXiv:1601.07167 [hep-ph].
[21] T. Higaki, K.S. Jeong, N. Kitajima, F. Takahashi, The QCD axion from aligned axions and diphoton excess, Phys. Lett. B 755 (2016) 13, http://dx.doi.org/10.1016/j.physletb.2016.01.055, arXiv:1512.05295 [hep-ph].
[22] E. Megias, O. Pujolas, M. Quiros, On dilatons and the LHC diphoton excess, arXiv:1512.06106 [hep-ph].
[23] I. Ben-Dayan, R. Brustein, Hypercharge axion and the diphoton 750 GeV resonance, arXiv:1601.07564 [hep-ph].
[24] N.D. Barrie, A. Kobakhidze, M. Talia, L. Wu, 750 GeV composite axion as the LHC diphoton resonance, Phys. Lett. B 755 (2016) 343, http://dx.doi.org/10.1016/j.physletb.2016.02.010, arXiv:1602.00475 [hep-ph].
[25] L. Aparicio, A. Azatov, E. Hardy, A. Romanino, Diphotons from diaxions, arXiv:1602.00949 [hep-ph].
[26] M. Delmastro, on behalf of the, ATLAS Collaboration, Diphoton searches in ATLAS, in: 51st Rencontres de Moriond (Electroweak session), 17 May 2016, La Thuile, Italy.
[27] P. Musella, on behalf of the CMS Collaboration, Search for high mass diphoton resonances at CMS, in: 51st Rencontres de Moriond (Electroweak session), 17 May 2016, La Thuile, Italy.
[28] CMS Collaboration, Search for new physics in high mass diphoton events in 3.3 fb^{-1} of proton–proton collisions at $\sqrt{s} = 13$ TeV and combined interpretation of searches at 8 TeV and 13 TeV, CMS-PAS-EXO-16-018.
[29] C. Csaki, J. Hubisz, S. Lombardo, J. Terning, Gluon vs. photon production of a 750 GeV diphoton resonance, arXiv:1601.00638 [hep-ph].
[30] L.A. Harland-Lang, V.A. Khoze, M.G. Ryskin, The production of a diphoton resonance via photon–photon fusion, arXiv:1601.07187 [hep-ph].
[31] A.D. Martin, M.G. Ryskin, Advantages of exclusive $\gamma\gamma$ production to probe high mass systems, J. Phys. G 43 (4) (2016) 04LT02, http://dx.doi.org/10.1088/0954-3899/43/4/04LT02, arXiv:1601.07774 [hep-ph].
[32] Y. Kats, M. Strassler, Resonances from QCD bound states and the 750 GeV diphoton excess, arXiv:1602.08819 [hep-ph].
[33] V. Khachatryan, et al., CMS Collaboration, Search for narrow resonances decaying to dijets in proton–proton collisions at $\sqrt{s} = 13$ TeV, arXiv:1512.01224 [hep-ex].
[34] I. Antoniadis, E. Kiritsis, J. Rizos, Anomalous $U(1)$'s in type 1 superstring vacua, Nucl. Phys. B 637 (2002) 92, http://dx.doi.org/10.1016/S0550-3213(02)00458-3, arXiv:hep-th/0204153.

[35] ATLAS Collaboration, Letter of intent for the phase-I upgrade of the ATLAS experiment, Technical Report CERN-LHCC-2011-012, LHCC-I-020, CERN, Geneva, Nov. 2011.
[36] M. Albrow, et al., CMS Collaboration, TOTEM Collaboration, CMS-TOTEM precision proton spectrometer, Technical Report CERN-LHCC-2014-021, TOTEM-TDR-003, CMS-TDR-13, CERN, Geneva, Sep. 2014.
[37] K.R. Dienes, B. Thomas, Dynamical dark matter: I. Theoretical overview, Phys. Rev. D 85 (2012) 083523, http://dx.doi.org/10.1103/PhysRevD.85.083523, arXiv:1106.4546 [hep-ph].
[38] K.R. Dienes, B. Thomas, Dynamical dark matter: II. An explicit model, Phys. Rev. D 85 (2012) 083524, http://dx.doi.org/10.1103/PhysRevD.85.083524, arXiv:1107.0721 [hep-ph].
[39] D. Chialva, P.S.B. Dev, A. Mazumdar, Phys. Rev. D 87 (6) (2013) 063522, http://dx.doi.org/10.1103/PhysRevD.87.063522, arXiv:1211.0250 [hep-ph].
[40] ATLAS Collaboration, Search for heavy resonances decaying to a Z boson and a photon in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, ATLAS-CONF-2016-010.
[41] C. Schmidt, J. Pumplin, D. Stump, C.-P. Yuan, CT14QED PDFs from isolated photon production in deep inelastic scattering, arXiv:1509.02905 [hep-ph].
[42] A.D. Martin, R.G. Roberts, W.J. Stirling, R.S. Thorne, Parton distributions incorporating QED contributions, Eur. Phys. J. C 39 (2005) 155, http://dx.doi.org/10.1140/epjc/s2004-02088-7, arXiv:hep-ph/0411040.
[43] R.D. Ball, et al., NNPDF Collaboration, Parton distributions with QED corrections, Nucl. Phys. B 877 (2013) 290, http://dx.doi.org/10.1016/j.nuclphysb.2013.10.010, arXiv:1308.0598 [hep-ph].
[44] G. Aad, et al., ATLAS Collaboration, Search for new phenomena in the dijet mass distribution using pp collision data at $\sqrt{s} = 8$ TeV with the ATLAS detector, Phys. Rev. D 91 (2015) 052007, http://dx.doi.org/10.1103/PhysRevD.91.052007, arXiv:1407.1376 [hep-ex].