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ABSTRACT

We show that low-mass-scale string compactifications, with a generic D-brane configuration that realizes the standard model by open strings, can explain the relatively broad peak in the diphoton invariant mass spectrum at 750 GeV recently reported by the ATLAS and CMS Collaborations. Under reasonable assumptions, we demonstrate that the excess could originate from a closed string (possibly axionic) excitation φ that has a coupling with gauge kinetic terms. We estimate the φ production rate from photon–photon fusion in elastic pp scattering, using the effective photon and narrow width approximations. For string scales above today's lower limit $M_s \approx 7$ TeV, we can accommodate the diphoton rate observed at Run II while maintaining consistency with Run I data.

Very recently, ATLAS [1] and CMS [2] announced preliminary results on inclusive diphoton searches using (respectively) 3.2 fb^{-1} and 2.6 fb^{-1} of data recorded at a center-of-mass energy $\sqrt{s} = 13$ TeV. The two experiments observed an excess of events over expectations from standard model (SM) processes in the invariant mass spectrum at ≈ 750 GeV. This could be interpreted as decays of new massive particle φ. For a narrow width approximation hypothesis, ATLAS 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 width for the signal component. The most significant deviation from the background-only hypothesis is reported for a mass of about 750 GeV and a width $\Gamma_{\text{total}} \approx 45$ GeV. The local and global significances evaluated for the large width fit are roughly 0.3 higher than those for the narrow width approximation fit, corresponding to 3.9σ and 2.3σ, respectively. CMS reports a local significance of 2.6σ and a global significance smaller than 1.2σ. The observed number of events corresponds to a production rate of $\sigma(pp \to \varphi + \text{anything}) \times \mathcal{B}(\varphi \to \gamma\gamma) \approx 3\text{–}6$ fb. The data at $\sqrt{s} = 13$ TeV prefer a cross section which is roughly 16 times larger than the one at $\sqrt{s} = 8$ TeV [3,4]. A wide-eyed fit to the $pp \to \gamma\gamma$ rates demonstrates that the data at $\sqrt{s} = 8$ TeV are incompatible with those at $\sqrt{s} = 13$ TeV at 95% CL if the cross section grows less than about a factor of 3.5 [5]. Note that the background from SM processes, which is dominated by $q\bar{q} \to \gamma\gamma$, increases by a smaller factor: $\sigma(pp \to \gamma\gamma) \approx 6$ fb at $\sqrt{s} = 8$ TeV and $\sigma(pp \to \gamma\gamma) \approx 14$ fb at $\sqrt{s} = 13$ TeV, after imposing $M_{\gamma\gamma} > 750$ GeV and standard cuts. Even though the excess is not statistical significant yet, it is interesting to entertain the possibility that it corresponds to a real signal of new physics.

A plethora of models have been proposed to explain the data including some string inspired scenarios [6,7]. Actually in [6] the new massive particle φ corresponds to a state on a 'hidden' sector brane in F-theory that couples to the SM gauge bosons via (open

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Table 1
Chiral spectrum of SM fields in the 4 stack D-brane model. We have added the right handed neutrino stretching between the lepton brane and the right brane.

Fields	Sector	Representation	Q_B	Q_L	Q_{I_R}	Q_Y
U_R	$3 \leftrightharpoons 1^*$	$(3,1)$	1	0	1	$\frac{2}{3}$
D_R	$3 \leftrightharpoons 1$	$(3,1)$	1	0	-1	$-\frac{1}{3}$
L_L	$4 \leftrightharpoons 2$	$(1,2)$	0	1	0	$-\frac{1}{2}$
E_R	$4 \leftrightharpoons 1$	$(1,1)$	0	1	-1	-1
Q_L	$3 \leftrightharpoons 2$	$(3,2)$	1	0	0	$\frac{1}{6}$
N_R	$4 \leftrightharpoons 1^*$	$(1,1)$	0	1	1	0
H	$2 \leftrightharpoons 1$	$(1,2)$	0	0	1	$\frac{1}{2}$

string) messengers between the visible and hidden sector branes; on the other hand, in [7] φ corresponds to an exotic open string state on the visible sector branes. One feature of most of this kind of open string explanations is that the necessary coupling φF^2 is a priori forbidden by the $U(1)$ charge conservation in the open string D-brane sector, unless the $U(1)$ is spontaneously broken by the expectation value of φ that has Yukawa couplings to the messengers. (F is the photon field strength.)

Herein we put forward an alternative solution from string theory, namely that φ corresponds to a closed string state. Namely we consider extensions of the SM based on D-brane string compactifications with large extra dimensions [8]. The basic unit of gauge invariance for D-brane constructions is a $U(1)$ field, so that a stack of N identical D-branes eventually generates a $U(N)$ theory with the associated $U(N)$ gauge group; for $N = 2$, the gauge group can be $Sp(1) \cong SU(2)$ rather than $U(2)$ [9,10]. In the presence of many D-brane types, the gauge group becomes a product form $\prod U(N_i)$, where N_i reflects the number of D-branes in each stack. In the perturbative regime, gauge interactions emerge as excitations of open strings ending on D-branes, with gauge bosons due to strings attached to stacks of D-branes and chiral matter due to strings stretching between intersecting D-branes.

Our explanation of the peak in the diphoton invariant mass spectrum is independent of the structure of the D-brane model. Nevertheless, to motivate the discussion we adopt a minimal model containing 4 stacks of D-branes. The basic setting of the gauge theory is given by $U(3)_C \times Sp(1)_L \times U(1)_L \times U(1)_{I_R}$ [11–13]. In the bosonic sector the open strings terminating on the QCD stack contain, in addition to the $SU(3)_C$ octet of gluons g_μ^a, an extra $U(1)$ boson C_μ, most simply the manifestation of a gauged baryon number. The $Sp(1)_L$ stack is a terminus for the electroweak gauge bosons W_μ^a. The $U(1)_Y$ boson Y_μ that gauges the usual electroweak hypercharge symmetry is a linear combination of C_μ, and the $U(1)$ bosons B_μ and X_μ terminating on the separate $U(1)_L$ and $U(1)_{I_R}$ branes. The general properties of the chiral spectrum are summarized in Table 1.

One can check by inspection that the hypercharge,

$$Q_Y = \frac{1}{2} Q_{I_R} + \frac{1}{6} Q_B - \frac{1}{2} Q_L \,, \tag{1}$$

is anomaly free. However, the Q_B (gauged baryon number) is not anomaly free and we expect this anomaly to be canceled via a Green–Schwarz mechanism involving the exchange of twisted Ramond–Ramond (RR) closed string states [14–18]. There is an explicit mass term in the Lagrangian for the new gauge field $-\frac{1}{2} M'^2 Y'_\mu Y'^\mu$ whose scale comes from the compactification scheme. The scalar that gets eaten up to give the longitudinal polarization of the Y' is a closed string field and there is no extra Higgs particle [19]. In addition to the intermediate RR field, which is absorbed by the Y' in the anomaly cancellation, there is a closed string mode φ which couples to the anomaly free combination of the hypercharge (1). It can be either a scalar field from the Neveu–Schwarz sector that is complexified with the RR state absorbed by Y', or another RR pseudo-scalar (axion) coupled to $F\tilde{F}$.

In this Letter we propose that the observed diphoton excess originates from the closed string excitation φ. 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 *decoupled* from F^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 $U(1)_L$ and $U(1)_{I_R}$ stack of D-branes, however is not or only weakly attached to the wrapped cycle of $Sp(1)_L$ or the color $SU(3)$ stack of D-branes. In this way, we can avoid unwanted dijet signals[1]. Furthermore, since the string mass scale is now known to be larger than $M_s \approx 7$ TeV [20], 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 [21]. With this in mind, we parametrize the coupling of φ to the photon by the following vertex

$$\frac{c_{\gamma\gamma}}{v} \varphi F^2 \,, \tag{2}$$

where $v \sim M_s$. To remain in the perturbative range, we also require $c_{\gamma\gamma}$ to be reasonably small. The partial decay width of φ to diphotons then follows as

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

The diphoton signal is produced via photon–photon fusion with φ as the resonance state [22,23]. The simplest way to get a reliable estimate of $\sigma(pp \to \gamma\gamma)$ is provided by the equivalent photon approximation (originally due to Fermi [24] and later on developed by Weizsäcker [25] and Williams [26]). Under the narrow width approximation, the cross section is found to be

$$\sigma(pp \to pp\gamma\gamma) = \frac{8\pi^2}{M_\varphi} \frac{\Gamma_{\gamma\gamma}^2}{\Gamma_{\text{total}}} \int dx_1\, dx_2\, f_s^\gamma(x_1)\, f_s^\gamma(x_2)\, \delta(x_1 x_2 s - M_\varphi^2) \,, \tag{4}$$

where $f_s^\gamma(x_1)$ is the photon distribution function, which for small x takes the following approximate form

$$f_s^\gamma(x) dx = \frac{dx}{x} \frac{2\alpha}{\pi} \log\left[\frac{q_*}{m_p} \frac{1}{x}\right] , \tag{5}$$

where $\alpha \approx 1/129$, m_p is the proton mass, and q_* is the inverse of the minimum impact parameter for elastic scattering [27,28]. Following [23] we consider the range 130 MeV $< q_* <$ 170 MeV, which accommodates the LHC two photon Higgs production cross section. The total cross sections are

$$\sigma_{\sqrt{s}=13\ \text{TeV}} = 162\ \text{fb} \left(\frac{\Gamma_{\text{total}}}{45\ \text{GeV}}\right) \mathcal{B}^2(\varphi \to \gamma\gamma) \,, \tag{6}$$

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[1] We may note in passing that if an excess of dijet events is observed in future LHC data, this can be easily accommodated by coupling φ to F^2 of $SU(3)_C$ changing the localization properties of D-branes with respect to φ in the internal space.

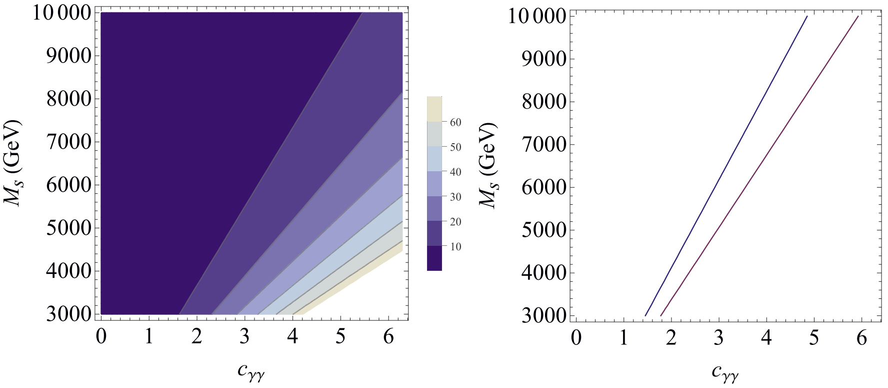

Fig. 1. Contours of constant partial width $\Gamma_{\gamma\gamma}$ (left) and best fit contours ($\sigma = 5$ fb) of cross section $pp \to pp\varphi \to pp\gamma\gamma$ (right), for $M_\varphi \simeq 750$ GeV, $\Gamma_{\rm total} = 45$ GeV and $\sqrt{s} = 13$ TeV. The color encoded scales are in GeV. The blue and red contours (on the right) correspond to $q_* = 170$ MeV and $q_* = 130$ MeV, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

for $q_* = 170$ MeV and

$$\sigma_{\sqrt{s}=13\ {\rm TeV}} = 73\ {\rm fb}\left(\frac{\Gamma_{\rm total}}{45\ {\rm GeV}}\right)\mathcal{B}^2(\varphi \to \gamma\gamma)\,, \tag{7}$$

for $q_* = 130$ MeV. With the observed total decay width of $\Gamma_{\rm total} = 45$ GeV, the branching fraction is given by

$$\mathcal{B}^2(\varphi \to \gamma\gamma) = \frac{2.3 \times 10^6 c^2_{\gamma\gamma}}{\pi\, v^2_{\rm GeV}}\,, \tag{8}$$

where $v_{\rm GeV} \equiv v/{\rm GeV}$. We perform a scan in the parameter space $(c_{\gamma\gamma}, v)$. As one can see in Fig. 1, for reasonably large $c_{\gamma\gamma}$, a string scale $M_s \sim v$ above the experimental lower bound of 7 TeV [20] can give $\sigma_{\sqrt{s}=13\ {\rm TeV}} \sim 5$ fb, *i.e.*, $\mathcal{B}(\varphi \to \gamma\gamma) \sim 0.17$ ($q_* = 170$ MeV) or $\mathcal{B}(\varphi \to \gamma\gamma) \sim 0.26$ ($q_* = 130$ MeV). These correspond to $\Gamma_{\gamma\gamma} = 8$ GeV and $\Gamma_{\gamma\gamma} = 12$ GeV, respectively. For a cross section $\sigma_{\sqrt{s}=13\ {\rm TeV}} \sim 6$ fb, $9\ {\rm GeV} \lesssim \Gamma_{\gamma\gamma} \lesssim 13$ GeV.

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

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

The precise branching fraction into γZ and ZZ is one of the hallmark predictions of our model. In general one would expect a coupling to hypercharge and a coupling to $SU(2)$ bosons with a parameter controlling their relative strength. This would appear in the emergent couplings to ZZ, $\gamma\gamma$, and γZ. This would be the generic situation even in other effective field theory models.

One may wonder whether the missing fraction of the decay width can be explained through the coupling of φ to gravitons. However, as we show in the Appendix, the KK tower of gravitons gives a negligible contribution to the total width. On the other hand, the missing fraction of the decay width could arise from the coupling of φ to other bulk fields, such as fermions, which has less number of derivatives. These hidden fermions could make a contribution to the dark matter content of the universe [29,30].

For collisions at $\sqrt{s} = 8$ TeV,

$$\sigma_{\sqrt{s}=8\ {\rm TeV}} = 31\ {\rm fb}\left(\frac{\Gamma_{\rm total}}{45\ {\rm GeV}}\right)\mathcal{B}^2(\varphi \to \gamma\gamma)\,, \tag{10}$$

when $q^* = 170$ MeV and

$$\sigma_{\sqrt{s}=8\ {\rm TeV}} = 6.5\ {\rm fb}\left(\frac{\Gamma_{\rm total}}{45\ {\rm GeV}}\right)\mathcal{B}^2(\varphi \to \gamma\gamma)\,, \tag{11}$$

when $q^* = 130$ MeV [23]. Although both agree with LHC8 data [3,4], we see that smaller values of q^* correspond to a much larger increase in going from 8 TeV to 13 TeV.

In closing, we comment on other anomalies observed by the LHC experiments. As noted elsewhere [13] the new Abelian gauge bosons of the D-brane structure (which suffer a mixed anomaly with the SM but are made self-consistent by the Green–Schwarz mechanism) can also accommodate the diboson [31,32] and dijet [33,34] excesses above SM backgrounds observed in the invariant mass region of ≈ 1.8–2.0 TeV by ATLAS and CMS in collisions at $\sqrt{s} = 8$ TeV. Under reasonable assumptions we have shown that $\sigma(pp \to Z') \times \mathcal{B}(Z' \to JJ) = 123$ fb and $\sigma(pp \to Z') \times \mathcal{B}(Z' \to W^+W^-/ZZ) = 7.7$ fb, in agreement with observations. The Z' production cross section grows by a factor ≈ 7 when going from $\sqrt{s} = 8$ to 13 TeV [35]. It is straightforward to see that the predicted production of dijet topologies is in good agreement with the small excess observed by ATLAS and CMS around 1.8 TeV [20,36], and that the diboson [37–39] and dilepton [40,41] final states are partially consistent with data.

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Appendix A

The φR^2 vertex is at least suppressed by $M_s/M_{\rm Pl}$ compared to φF^2, where R is the Ricci scalar and $M_{\rm Pl} \sim 10^{19}$ GeV is the Planck mass. In fact it should be $(M_\varphi/M_{\rm Pl})^2$ because there are two gravitons and four derivatives. To estimate the graviton emission we sum over KK modes with momentum less than M_φ (so that the decay is kinematically allowed). The number of modes is given by the volume of a 6-sphere of radius $(M_\varphi L)/(2\pi)$, where L is the scale of the extra dimension and is related to $M_{\rm Pl}$ by

$$L^n M_s^{n+2} \sim M_{\rm Pl}^2\,.$$

For $M_s \sim 10$ TeV and $n = 6$, this implies $L \sim 10$ GeV^{-1}. The graviton decay width can then be estimated as

$$\frac{\Gamma_{GG}}{\Gamma_{\gamma\gamma}} < \left(\frac{M_s}{M_{\rm Pl}}\right)^2 \frac{S_5}{n} \left(\frac{M_\varphi L}{2\pi}\right)^6 \sim 10^{-11}\,,$$

where S_5 is the area of unit 5-sphere. As we can see, this is basically negligible.

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