750 GeV diphotons from a D3-brane

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Abstract

Motivated by the recently reported diphoton excess at 750 GeV observed by both CMS and ATLAS, we study string-based particle physics models which can accommodate this signal. Quite remarkably, although Grand Unified Theories in F-theory tend to impose tight restrictions on candidate extra sectors, the case of a probe D3-brane near an E-type Yukawa point naturally leads to a class of strongly coupled models capable of accommodating the observed signature. In these models, the visible sector is realized by intersecting 7-branes, and the 750 GeV resonance is a scalar modulus associated with motion of the D3-brane in the direction transverse to the Standard Model 7-branes. Integrating out heavy 3–7 string messenger states leads to dimension five operators for gluon fusion production and diphoton decays. Due to the unified structure of interactions, these models also predict that there should be additional decay channels to ZZ and $Z\gamma$. We also comment on models with distorted unification, where both the production mechanism and decay channels can differ.

1. Introduction

Recently, the LHC experiments CMS and ATLAS have both announced tentative evidence for a diphoton excess with a resonant mass near 750 GeV [1,2]. This signal is seen in the early

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data of the 13 TeV run, and appears to be compatible with the absence of a large signal in the earlier 7 and 8 TeV runs. Recall that the observed diphoton signal depends on the production cross section $\sigma_{pp \to s}$ for the resonance "s," as well as $B_{s \to \gamma\gamma} = \Gamma_{s \to \gamma\gamma} / \Gamma_{s \to \text{any}}$ its branching fraction to diphotons:

$$\sigma_{pp \to s} \times B_{s \to \gamma\gamma} \sim 5 \text{ fb.} \tag{1.1}$$

In the case of the ATLAS experiment, there is also an even more preliminary indication that this resonance may have a substantial width.

While the observed signal is on the order of three sigma (if one naively combines CMS and ATLAS), this is still far from meeting the threshold for discovery. Even so, it has already inspired a number of theoretical analyses (see e.g. [3–48]). One of the lessons which can already be drawn from these early phenomenological studies is that in general (but not always), models with some strongly coupled extra sector appear to fare better in generating a sufficiently large signal with a broader decay width. From this perspective, it is natural to ask whether there are UV motivated constructions of new physics which can accommodate the diphoton excess.

In this note we point out that string-based constructions from F-theory Grand Unified Theories (F-theory GUTs) naturally suggest particular strongly coupled extra sectors which can easily accommodate the diphoton excess. We stress that this is non-trivial, since the underlying exceptional gauge symmetries necessary for stringy unification tightly constrain both the structure of the visible sector matter content, as well as possible extra sectors. Indeed, experience from earlier constructions such as reference [49] shows that intersecting 7-branes can realize the visible sector, but little else. Rather, extra probe D3-branes must typically be included to get novel phenomenology from an extra sector [50]. The resulting physics is quite rich, and leads to several novel features. First, these models are strongly coupled, but nevertheless, preserve supersymmetric gauge coupling unification [51]. Additionally, depending on the mass scales available, they can lead to rather striking phenomenological signatures. One of our aims will be to show how this class of models can naturally interpolate between several of the simplified models presented which have been used to explain the diphoton excess.

2. Extra sector from a D3-brane

In more detail, we consider models of particle physics which embed in a supersymmetric Grand Unified Theory in F-theory known as an "F-theory GUT" [52,53]. For a review of the relevant particle physics constructions, see for example [54]. Though order TeV scale supersymmetry is not essential for most of our discussion, it is well motivated. It will also make details of the model more calculable, so we shall assume approximate supersymmetry in the extra sector as a convenient computational tool.

In these models, the visible sector is realized on a stack of intersecting 7-branes (i.e. spacetime filling branes which fill four extra dimensions). The extra sector is given by a D3-brane (i.e. a spacetime filling brane which is pointlike in the extra dimensions) probing the Standard Model (SM) stack. The same mechanism which generates subleading Yukawa couplings for the SM also generates a potential for D3-branes with a local minimum near the Yukawa point of the SM stack [50]. See Fig. 1 for a depiction.

In F-theory, grand unification requires unbroken exceptional gauge symmetries at subspaces of the internal dimensions, which in turn demands that the string coupling is order one. So, the extra sector on the D3-brane is always strongly coupled. If the D3-brane is at a generic
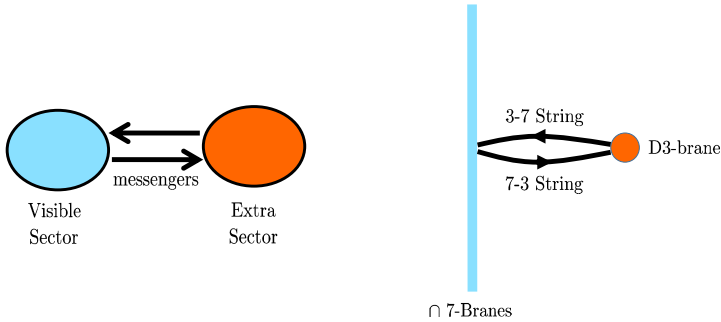
Fig. 1. Depiction of how strongly coupled extra sectors arise in F-theory GUTs. The Standard Model comes from intersecting 7-branes, and a probe D3-brane provides an extra sector. The two communicate with each other via 3–7 strings, i.e. "messenger states".

point of the SM stack, then we get a $U(1)$ gauge theory, and messengers transforming as a supersymmetric vectorlike generation in the $\mathbf{5} \oplus \overline{\mathbf{5}}$ of an $SU(5)$ GUT.

If the D3-brane localizes at the special points of unbroken exceptional symmetry (as expected from the mechanism used to generate flavor physics in the model), additional light states enter the spectrum, and we instead get a strongly coupled conformal field theory [51,55]. This is given by an $\mathcal{N} = 1$ deformation of an $\mathcal{N} = 2$ superconformal field theory (SCFT) with E_8 flavor symmetry known as the "Minahan–Nemeschansky theory" [56,57]. The Standard Model gauge group arises from weakly gauging an $SU(3) \times SU(2) \times U(1)$ subgroup of E_8. There can also be order one couplings between the Higgs sector and the third (i.e. heaviest) generation of SM states.

For the purposes of explaining the diphoton excess, our interest in this class of models is the generic feature that they are strongly coupled (i.e. $g_{\text{extra}}^2/4\pi \sim O(1)$), and that there are states which are charged under both the SM gauge group, and the extra sector $U(1)_{\text{extra}}$ of the D3-brane which we refer to as 3–7 strings or "messenger states."[1] To emphasize that these strings couple to the SM gauge groups, we shall sometimes write 3–7$_{\text{vis}}$.

An additional important feature is that although they are strongly coupled, some still preserve supersymmetric gauge coupling unification at the percent level [51]. This is perhaps not too surprising when the messengers are very heavy, i.e. 10^{13} GeV, since the overall magnitude of the threshold correction is suppressed by a moderate sized logarithm. In the case where the messengers are far lighter, i.e. 1 TeV, this log-running is more pronounced, but remarkably enough there are *still* a few models where precision unification is still respected at the percent level. As a benchmark model of this type, we shall often focus on the case of the "$Dih_4^{(2)}$ monodromy model" of reference [51].[2] For this model, the effects of the heavy messenger states contribute a threshold correction on the order of 2.2 supersymmetric vector-like generations in the $\mathbf{5} \oplus \overline{\mathbf{5}}$ of $SU(5)_{GUT}$.

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[1] In string theory, these messengers actually arise from multi-prong strongly coupled bound states of fundamental strings and D1-branes. Nevertheless, we shall find it helpful to use this concise characterization.

[2] The name of the model has to do with the details of how the visible sector is constructed, i.e. it is the Galois group of the spectral equation for a matrix valued position dependent complex scalar which controls the profile of intersecting 7-branes. Other choices such as the S_3 and $Dih_4^{(1)}$ monodromy models lead to order ten percent threshold corrections when running from the TeV to GUT scale, which is still tolerable considering there could be additional thresholds at both the TeV and GUT scale.

This extra sector includes various mass scales which can lead to phenomenologically relevant effects. Of particular significance is the complex scalar S which controls the position of the D3-brane in the direction transverse to the 7-brane. Activating a non-zero vev $f \equiv \sqrt{2} \langle S \rangle \neq 0$, all of these 3–7 states pick up a mass of rough order $4\pi f$, so depending on the overall value of this vev, these states could be near the TeV scale, or far higher, i.e. near the GUT scale [51], with the details depending on the structure of the potential for the D3-brane. There is a general expectation that if supersymmetry breaking occurs in the visible sector in the 1–10 TeV range (as would be expected in a model of approximate low energy supersymmetry), then the mass scale $4\pi f$ will also be on the order of the TeV scale. On general grounds, we also expect the colored states to be somewhat heavier than their color-neutral counterparts, simply due to SM loop corrections.

There are also SM neutral states from both $3-7_{\text{flav}}$ and 3–3 strings. Here, a 7_{flav}-brane is one which acts as an approximate flavor symmetry for the F-theory GUT model, which is supported on a 7_{vis}-brane. Indeed, the intersection between a 7_{flav}-brane and a 7_{vis}-brane leads to localized matter of the Standard Model (i.e. the quarks and leptons). Now, when the $U(1)_{\text{extra}}$ gauge symmetry is unbroken, a seesaw mechanism tends to makes some of the $3-7_{\text{flav}}$ and 3–3 strings much lighter than the $3-7_{\text{vis}}$ states [58]. In addition to this scalar vev, there are also electric and magnetically charged states of $U(1)_{\text{extra}}$. Supersymmetry breaking usually causes this $U(1)$ to be broken, and so depending on the details of this process, the extra photon could either be light (i.e. below 750 GeV / 2 so that it is a candidate decay mode), or could be quite heavy (i.e. above the TeV scale).

Finally, there is also the mass of S itself. As already mentioned, we expect that at least near the GUT scale, we can approximate the dynamics of the D3-brane by an $\mathcal{N} = 1$ SCFT with a Coulomb branch scalar $\widetilde{S}$. Non-perturbative instanton corrections can generate a superpotential for this modulus, which has the leading order behavior:

$$W(\widetilde{S}) = m\widetilde{S}^2 + \ldots \tag{2.1}$$

Even though this superpotential deformation is quadratic in $\widetilde{S}$, it is actually an irrelevant deformation of the SCFT. The reason is that $\widetilde{S}$ will typically have dimension Δ greater than $3/2$. Indeed, for the benchmark $Dih_4^{(2)}$ model mentioned above, we have $\Delta \sim 2$. Working in terms of a canonically normalized field $S = (M_{\text{GUT}})^{\Delta-1} \times \widetilde{S}$, we find that the effective mass of the excitation is of order:

$$m_S \sim M_{\text{GUT}} \cdot \left(\frac{M_{\text{IR}}}{M_{\text{GUT}}} \right)^{\Delta-1}, \tag{2.2}$$

i.e. we run down to the scale of conformal symmetry breaking and calculate the size of the perturbation in the infrared. So, for $\Delta \sim 2$, a value of $M_{\text{IR}} \sim 1$ TeV produces a TeV scale mass for S. Depending on how supersymmetry is broken in the extra sector, the two real degrees of freedom in S can have different masses.

Summarizing, we see that in this class of models, there are generically a few different characteristic mass scales, which we summarize as $M_{3-7_{\text{vis}}}$, $M_{3-7_{\text{flav}}}$, M_{3-3}, $M_{U(1)}$, M_S. Depending on how we adjust these parameters, we can expect various types of phenomenological scenarios. For illustrative purposes, we shall consider first the case where we have the most analytic control, i.e. where the various mass scales are all heavier than that of S. In other limits, we still generate a diphoton excess though we have less quantitative control over the model.

2.1. Minimal D3-brane models

To give an example, consider the special case where we can approximate the effects of the 3–7 strings as much heavier, i.e. $M_{3-7} \gg M_S$. In this case, we can treat these charged states as giving a threshold correction, and we integrate them out of the low energy theory. Since the mass of the threshold is controlled by $\langle S \rangle$, we can also read off the dimension five operator which couples S to the SM gauge fields. In the holomorphic approximation of references [59,60], i.e. when the effects of wave function renormalization are small (as is indeed the case for us) we get:

$$L \supset \sum_G \text{Re} \int d^2\theta \, \frac{\delta b_G}{32\pi^2} \log S \text{Tr} \mathcal{W}_G^\alpha \mathcal{W}_\alpha^G, \tag{2.3}$$

where here all gauge algebra generators are embedded in the standard way in $SU(5)_{GUT}$, and the sum runs over the three simple gauge factors of the SM. The overall size of δb_G depends on the specific D3-brane probe theory, but in our benchmark $Dih_4^{(2)}$ model, $\delta b_G \sim 2.2$. In our normalization, this amounts to roughly 2.2 supersymmetric vector-like generations in the $\mathbf{5} \oplus \mathbf{\bar{5}}$ of $SU(5)_{GUT}$. There are also subleading order 1% differences between the threshold corrections.

Let us now turn to the expected couplings of S with the SM gauge fields. The same methods developed in references [59–61] (for earlier work see [62]) to explore possible enhancements of couplings to the Higgs sector are readily adapted.[3] Expanding out in terms of:

$$S = \frac{1}{\sqrt{2}}(f + s + ia), \tag{2.4}$$

we get the interaction terms[4]:

$$L \supset \sum_G -\frac{1}{2g_G^2} \text{Tr} F_G^{\mu\nu} F_{\mu\nu}^G + \frac{\delta b_G}{32\pi^2} \left(\frac{s}{f} \right) \text{Tr} F_G^{\mu\nu} F_{\mu\nu}^G + \frac{\delta b_G}{32\pi^2} \left(\frac{a}{f} \right) \text{Tr} F_G^{\mu\nu} \widetilde{F}_{\mu\nu}^G. \tag{2.5}$$

By inspection, we see that there are couplings to all of the SM gauge fields for both the real and imaginary parts of S. In particular, we expect there to be production and decay channels with strength set by the overall size of the threshold correction. Some examples important for current and upcoming experiment are:

- $pp \to s/a \to \gamma\gamma$
- $pp \to s/a \to gg$
- $pp \to s/a \to ZZ$
- $pp \to s/a \to WW$
- $pp \to s/a \to Z\gamma$

where the decay rates will be primarily set by the ratios of the gauge couplings – at least for a multiplet structure with approximate gauge coupling unification. As alluded to above, based on the structure of the model, we see that there can even be two nearly degenerate resonances (with s CP-even and a CP-odd), though this can of course be split by supersymmetry breaking effects.

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[3] We note that in general, the size of the cutoff means that there may also be interesting corrections to Higgs sector couplings. It would be interesting to explore these signatures further in future work.

[4] We note that including an arbitrary scale μ in the logarithm of line (2.3) i.e. $\log(S/\mu)$ does not change the resulting couplings.

When s is the lightest mode of S, the phenomenology is actually quite close to the "hidden glueball model" and when a is the lightest mode of S, we instead get the "hidden pion model" of reference [4]. The primary features common to both our models is a strongly coupled extra sector with multiplets compatible with gauge coupling unification. Additionally, in the D3-brane context, we can expect some additional decay channels to light SM neutral states such as 3–3 states and 3–7$_{\mathrm{flav}}$ states. These masses are in turn dependent on the breaking scale for the extra $U(1)$. Depending on whether the extra $U(1)$ is light enough, there can also be additional decay channels to SM neutral extra sector states. This can lead to a significant enhancement in the width of S but also a decrease in the branching fraction $B_{s \to \gamma\gamma}$.

Working in the computationally most tractable regime where we decouple these additional extra states, there are no decays to hidden sector states and we can simply match the parameters of our model to that of reference [4]. Doing so, we get that the production cross section times the branching fraction to diphotons is roughly:

$$\sigma_{pp \to s} B_{s \to \gamma\gamma} \sim 1.3 \text{ fb} \times (\delta b_{\mathrm{GUT}})^2 \times \left(\frac{1 \text{ TeV}}{4\pi f} \right)^2. \tag{2.6}$$

In the benchmark "$Dih_4^{(2)}$ model" $\delta b_G \sim 2.2$, so to match to an observed excess of order 5 fb, we need to set $4\pi f \sim 1.1$ TeV, which is not altogether surprising considering that the mass of the resonance is 750 GeV. Even so, we expect the threshold approximation adopted here to be valid due to the fact that the leading order wave function renormalization effects have already been taken into account in the quantity δb_{GUT}. For other probe D3-brane theories with a larger threshold correction (i.e. $\delta b_G \sim 3$), the value of $4\pi f$ is somewhat higher, though there is then a bit more tension with precision unification considerations.[5] In any case, this would indeed suggest that exciting the 3–7 string states may be within reach in the near term.

Another general comment is that even when we work in this decoupled limit, the overall decay rate to gluons is going to be bigger than in the case of a weakly coupled messenger model. Roughly speaking, it is as if the messengers had "non-perturbative Yukawas" to the field S. Fitting to the examples of weakly coupled messengers presented in reference [8], we see that the overall width in this regime is on the order of 10–100 MeV. This is compatible with overall $pp \to s/a \to jj$ limits, see e.g. [11]. For earlier discussion of constraints from production via gluon fusion and decay to diphotons, see e.g. [63].

Now, as we lower the value of $4\pi f$, the overall mass scale for the 3–7 strings will become lighter. When we do this, the threshold approximation adopted above will start to break down, and indeed, there can even be cascade decays from a heavy messenger state to S. The signature space for this class of models has recently appeared in reference [8], to which we refer the interested reader. We can also consider the case where we decrease the $U(1)_{\mathrm{extra}}$ breaking scale. When we do this, it is also expected that some of the SM neutral states of the extra sector will also become quite light [58], and we can expect qualitatively similar phenomenology to the case of a hidden valley scenario (see e.g. [64]) of the type considered in [8].

Finally, another important feature of this class of models is that because the states organize according to supersymmetric GUT multiplets, we should also expect a decay rate to $s \to ZZ \to 4\ell$ and $s \to Z\gamma \to 2\ell\gamma$ though presently, current limits do not impose much of a constraint. This

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[5] For example, in the S_3 7-brane monodromy model, $\delta b_G \sim 3$ and we get $4\pi f \sim 1.5$ TeV, while for the $Dih_4^{(1)}$ 7-brane monodromy model, $\delta b_G \sim 2.4$ and $4\pi f \sim 1.2$ TeV. In these cases, however, there is a somewhat bigger threshold correction to precision unification of order 9% to 12%, respectively.

appears to be a common feature of many of the earlier phenomenological models considered in [3–20].

2.2. Models with distorted unification

Though the models based on supersymmetric unification are more elegant (and also far easier to construct), it is also of interest to consider how far we can distort this structure to accommodate possible phenomenological signatures. Indeed, depending on whether the reported large width from ATLAS is confirmed, and if an eventual signal is seen in other channels, this would give a way to further narrow the list of options presented in this note.

First of all, there are effects coming from various threshold corrections, i.e. how we generate the various dimension five operators for production and decay. In most of the unified models, this appears to be dominated by gluon fusion production, but as pointed out for example in [31,37,39], this may make it difficult to accommodate the preliminary indication of a 45 GeV width state, a point we can confirm at least in the models we have studied. Though we lose analytic control over various aspects of the model, one could envision that in some extreme region of the mass scales of the D3-brane probe theory, there is a sufficient mass splitting in the various thresholds so that the low energy physics is dominated by the coupling to the $U(1)_Y$ gauge boson, in which case photon fusion may become the dominant production mechanism [31,37]. In such models, a strongly coupled extra sector is still quite helpful, a feature which is manifestly present in the D3-brane construction.

One can also contemplate more extreme distortions where one simply works with a stack of intersecting 7-branes with no apparent unification at high scales. For concreteness, suppose that we have at least three stacks of branes, as in the quiver model of reference [65]. Then, by moving the D3-brane close to the stacks where say $SU(3)$ and a $U(1)$ factor are localized, we can raise the suppression scale of the dimension five operator which couples S to $SU(2)$ gauge bosons. This would in turn suppress the decay modes $s \to ZZ$ and $s \to Z\gamma$ since now they must proceed through the $U(1)_Y$ gauge boson. Alternatively, we can move the D3-brane to regions where it only touches the $U(1)$ stack, which would provide a way to generate the signature primarily through photon fusion.

3. Conclusions

The recent hints of a 750 GeV diphoton excess at CMS and ATLAS is quite exciting. There are by now many proposed models which aim to accommodate this excess. Here, we have taken a different approach, asking whether considerations from strings can guide us to a particular class of motivated choices. In this note we have pointed out that in F-theory GUTs, there are some preferred classes of models. These models are based on introducing an additional probe D3-brane close to the stack of intersecting 7-branes used to engineer the Standard Model. Integrating out messenger states yields dimension five operators of precisely the kind needed to explain the diphoton excess. We have also seen that various distortions in unification can lead to some deviations from this simplest class of models, though the qualitative feature of a strongly coupled extra sector remains. We find it encouraging that rather than positing an "ad hoc" extra structure, the necessary ingredients to explain the diphoton excess are already a part of many F-theory GUT models.

Acknowledgements

We thank C. Kilic, D. Pappadopulo, J. Ruderman and N. Weiner for helpful discussions. JJH also thanks the theory groups at Columbia University, the ITS at the CUNY graduate center, and the CCPP at NYU for hospitality during the completion of this work. The work of JJH is supported by NSF CAREER grant PHY-1452037. JJH also acknowledges support from the Bahnson Fund at UNC Chapel Hill.

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