Supersoft SUSY models and the 750 GeV diphoton excess, beyond effective operators

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Supersoft SUSY Models and the 750 GeV Diphoton Excess, Beyond Effective Operators

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We propose that the sbino, the scalar partner of a Dirac bino can explain the 750 GeV diphoton excess observed by the ATLAS and CMS collaborations. We first argue for the existence of couplings between sbino to pairs of Standard Model (SM) gauge bosons using effective operator analysis. We then analyze the minimal completion of the effective operator model in which the sbino couples to pairs of gauge bosons through loops of heavy sfermions, with the sfermion-Bino coupling originating from scalar potential D-terms. We find that the sbino model may be fit the 750 GeV excess by considering gluon fusion processes with decay to diphotons.

INTRODUCTION

Both the CMS and ATLAS collaborations have reported an excess in the diphoton resonance channel in the first stages of the LHC's 13 TeV run. This excess seems to correspond to a new boson with mass of approximately 750 GeV. ATLAS reports a diphoton resonance with mass 747 GeV at 3.6σ local significance while CMS reports a diphoton resonance of mass 760 GeV and a local significance of 2.6σ [1, 2]. If the excess persists, it would be a smoking gun for a new sector beyond the SM. Many beyond the SM (BSM) scenarios might accommodate such a resonance including models with exotic axion-like states, models with strong couplings, extra dimension, heavy Higgses and more [3]-[23]. The production process of the new state may be variable, the diphoton resonance may be produced in association with other states, or alone [1]. Thus, production may be through gluon or quark fusion to a single new resonance, vector boson fusion, or production in association with other states.

The simplest assumption for a BSM particle candidate which decays to two photons is a scalar field that couples to SM gauge bosons through a dimension 5 operator. This would indicate the existence of some heavy "messenger" particles with SM charges that couple both to SM gauge bosons and to the singlet field responsible for the possible excess. This mechanism is, in principle, exactly the same as the SM Higgs coupling to photon and gluon pairs. One guess, then, for the identity of the possible 750 GeV state is simply a heavy Higgs as would appear in a Type II two Higgs doublet model like the Minimal Supersymmetric Standard Model (MSSM). This possibility would be quite exciting as supersymmetry (SUSY) is the leading candidate for BSM physics. However, it has been pointed out that a heavy Higgs in the minimal MSSM scenario fails to reproduce the observed rate of the excess. The MSSM would have to be extended by adding multiple sets of vector like chiral superfields to enhance the signal [5]. There are, however, alternate SUSY scenarios which would fit the excess.

We propose that a well studied supersymmetric scenario contains all of the necessary pieces to fit the excess, that of an R symmetric MSSM. In these scenarios gauginos are Dirac particles, rather than Majorana [24, 25]. The Dirac gaugino gets its mass by "marrying" a chiral SM adjoint field. The superpartners of these new fermion fields are complex scalar particles in the adjoint representation of their respective gauge symmetry. Thus, there exists scalars and pseudoscalars which are a color octet, a SU(2) triplet, and SM singlet fields. The bino superpartner offers a scalar and pseudoscalar SM singlet candidate, and in this work we explore the possibility that the 750 GeV resonance is the real scalar part of the SM singlet superfield whose fermionic component marries the bino. In keeping with R symmetric parlance we can refer to this as the sbino.

The sbino fields may couple to SM gauge bosons in a variety of ways. First we may simply consider a set of general effective operators which couple scalar fields to SM field strength tensors. These operators are consistent with all symmetries of the theory, and extremely similar to operators which produce the Dirac gaugino masses themselves. We may complete these operators through loops in which the scalar fields couple to a heavy fermion or scalars which are charged under the SM gauge groups. However, these heavy fields need not be added to the model to explain the excess. In the case of fermion these may simply be the messenger fields already necessary to create Dirac gaugino masses. Even simpler, and the case we will study in this work, the messenger fields may be the superpartners of the fermions themselves which have Kahler potential couplings to the new chiral superfields. This means that Dirac gaugino models already contain the necessary fields, operators, and couplings to produce the diboson coupling needed to explain the LHC excess. We will explore a simplified version of a Dirac gaugino model calculating the loop level couplings of the sbino to pairs of gluons and photons. We calculate the gluon fusion production cross section and calculate relative decay rates into gluons, photons, and light Higgs fields of the sbino. We find that we can match observed resonant diphoton production rate at 13 TeV with a 750 GeV sbino, while obeying constraints from alternate decay channels, Higgs sector mixing and vacuum stability .

This paper is organized as follows, in Section II we review the formalism of models with Dirac gauginos and introduce couplings of the sbino to pairs of dibosons as an effective operator. In section III we discuss the UV generation of the effective operator through Kahler potential couplings between the sbino and the SM sparticles. In section IV we compute tree level decay widths for the sbino and discuss current collider constraints from alternate decay channels of the 750 GeV ressonance. In section V we compute the sbino production cross section through gluon fusion and decay rate to photons. In section VI we discuss constraints on the parameter space of Dirac-gaugino models from the Higgs potential and vacuum stability. In section VII we conclude.

OPERATORS IN DIRAC GAUGINOS MODELS

We consider a class of SUSY models in which gaugino mass terms are Dirac as opposed to Majorana [24, 25]. In such models, the gauginos get mass by "marrying" chiral fields which are adjoints under SM gauge groups. The Dirac mass is generated by the superpotential operator

$$W = \int d^2\theta \frac{W^{'}_{\alpha} W^{\alpha} A}{\Lambda} \supset \frac{D'}{\Lambda} \lambda \psi_A \tag{1}$$

where W is the standard model gauge field strength tensor, A is the chiral adjoint field, and W' is the field strength tensor of a hidden $U(1)$ gauge group. The hidden sector U(1) is broken at a high scale and gets a nonzero D-term vev. After the symmetry breaking this operator, known as the supersoft operator, contains a Dirac mass for the gaugino with mass $m_D \equiv D/\Lambda$.

This SUSY breaking can be embedded in the framework of gauge mediation [26]. One may add to the theory a set of heavy messenger particles that are charged under the SM and the new U(1) gauge group. These messengers couple the SUSY breaking sector to the gauginos and SM adjoint fields, thus communicating the SUSY breaking to the visible sector.

The new chiral multiplets, A, contain real and imaginary scalar degrees of freedom. One might assume that the real and imaginary fields have large mass of order m_D. However, the masses of the real and imaginary parts of the multiplets may be quite split. These masses depend greatly on the details of the messenger sector of the model [27–29]. Since most models have large negative mass contributions for one combination of the fields, it is quite natural to assume that one of the adjoints is much lighter than the other, and may be thus accessible to colliders in the TeV range.

Consistent with all symmetries of the theory, we may also write a set of operators extremely similar to those that yield the Dirac gaugino masses in Eq. 1. These operators couple the scalar adjoint fields to the square of SM field strength tensors. We will denote the new chiral fields as follows; O denotes the SU(3) adjoint, T the SU(2) adjoint, and S the SM singlet. We then have a complete set of gauge invariant operators

$$W = \int d^2\theta \frac{W_{Y\alpha} W_Y^{\alpha} S}{\Lambda_1} + \frac{W_{2\alpha} W_2^{\alpha} T}{\Lambda_2} + \frac{W_{3\alpha} W_3^{\alpha} O}{\Lambda_3} \tag{2}$$

where W_Y is the hypercharge field strength, W_i is the appropriate SU(2) or SU(3) field strength tensor, and Λ_i is the appropriate cut-off scale which may be different for each operator. Integrating over the fermionic coordinates these operators become terms in the Lagrangian,

$$\mathcal{L} \supset \frac{1}{\Lambda_1} S_r B^{\mu\nu} B_{\mu\nu} + \frac{1}{\Lambda_2} T_r W^{\mu\nu} W_{\mu\nu} + \frac{1}{\Lambda_3} O_r G^{\mu\nu} G_{\mu\nu} \tag{3}$$

These operators couple the real part (as indicated by the subscript) of the scalar states to the square of the SM field strength tensors. Similarly, we may expect to generate operators which couple the imaginary part of the scalar states to the SM field strength tensor and its dual.

$$\mathcal{L} = \frac{1}{\Lambda_1} S_i B^{\mu\nu} \tilde{B}_{\mu\nu} + \frac{1}{\Lambda_2} T_i W^{\mu\nu} \tilde{W}_{\mu\nu} + \frac{1}{\Lambda_3} O_i G^{\mu\nu} \tilde{G}_{\mu\nu} \tag{4}$$

The full set of such operators were discussed in reference [30]. Interestingly, we may also write in the Lagrangian a gauge invariant term which couples pairs of gluons to the SU(2) adjoint, with Higgs fields inserted to ensure gauge invariance. This operator provides another interesting prospect for scalar states accessible by gluon fusion.

UV COMPLETIONS

We expect that the operators coupling the SM field strength tensors to the chiral adjoints may be completed by considering integrating out loops of heavy "messengers". One possibility is simply to consider loops of the heavy messengers which generate the Dirac gaugino masses themselves. These fields carry SM quantum numbers, the simplest messenger sector are those in which the messengers are fundamentals and antifundamentals under SU(5), see for example [28, 29]. Though messengers may couple to the chiral adjoint through large Yukawa like couplings, we expect that the messenger mass scale is very large, thereby suppressing the operator. Another possibility is to consider loops containing the scalar superpartners of the fermions.

Dirac gaugino models have a unique Kahler potential coupling between the new chiral states and the standard model sfermions generated by integrating out SM D terms. The scalar potential involving the singlet scalar contains the terms

$$V \sim m_D(S+S^*)D_Y + qg_Y D_Y \tilde{f}\tilde{f}^\dagger + \frac{1}{2}D_Y D_Y \tag{5}$$

where $\tilde{f}$ are the SM sfermions, q are the hypercharges of each sfermion, and D_Y is the U(1) hypercharge D-term. Once the SM D-term is integrated out, one finds a trilinear coupling between the real component of the scalar and each pair of sfermions with non-zero hypercharge,

$$V \sim qg_Y m_D(S+S^*)\tilde{f}\tilde{f}^\dagger. \tag{6}$$

There is also a coupling to the Higgs fields which we further discuss below. We see that the real part of the scalar field will couple to pairs of SM gauge bosons through loops of sfermions. The couplings will be proportional to the hypercharge of each field and the square of the Dirac mass. The relevant diagrams can be seen in Fig. 1. It should be noted that couplings from superpotential terms induce additional loop contributions to the decay of the singlet. For example, in the $\not{R}$SSM [31] or the MRSSM [32] one would expect additional diagrams with charged Higgsinos running in the loops. However, in what follows we have chosen not to fully specify the Higgs potential and we expect that these additional contributions will not qualitatively change our results as the charged Higgsinos are expected to be heavy.

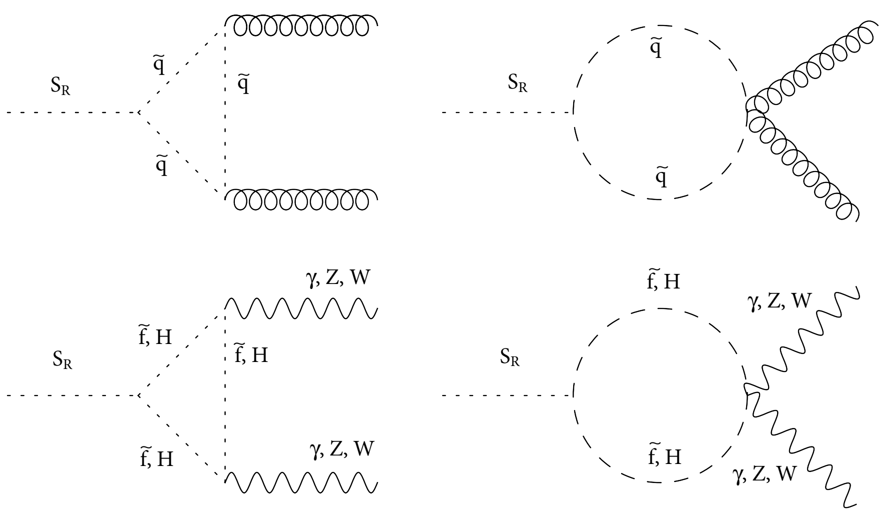

FIG. 1: One loop diagrams contributing to singlet coupling to pairs of gluons and electroweak gauge bosons.

To compute each contribution to the diphoton diagram, we must add up all fields which have hypercharge. These fields include three generation of squarks and sleptons, Q_L, $\overline{u}_R$, $\overline{d}_R$ and L_L, $\overline{e}_R$ plus the Higgs doublets, H_u and H_d. However, only the three generations of squarks contribute to the digluon channel. Thus we expect to complete our operators by calculating loops of the roughly TeV scale scalar "messengers". We may control the ratio of the digluon channel to that of the of electroweak gauge boson channel by varying the mass scale of the squarks with respect to the sleptons. Making the squarks much heavier than the sleptons will reduce the digluon coupling while maintaining or enhancing the coupling to pairs of electroweak gauge bosons. In the limit of mass degenerate left and right handed states, the coupling of the singlet to dibosons will vanish due to a diagramatic cancelation. This is equivalent to the cancelation which occurs in the coupling of the sgluon (color octet adjoint) to pairs of gluons as noted in reference [33, 34]. Thus, the strength of the effective operators coupling the sbino to gauge bosons may be dialed by changing the mass differences between left and right handed states. We also note that by varying the masses of left handed to right handed particles in general, we may control the ratio of the coupling of S to the U(1) and SU(2) gauge bosons. In this way we may set the scales of our operators in Eq. 2.

In general models of Dirac gauginos have quite a flexible spectrum. In the simplest models, the mass ratio of the gauginos and sparticles differ by the square root of a loop factor. However the mass splittings between gauginos and scalars can in principle be arbitrary. In many completions of Dirac gaugino models, the physics which sets the scalar adjoint masses may also effect the SUSY spectrum; gauginos may have some mix of Dirac and Majorana masses, models may have extra R symmetric gauge mediated contributions, for example see [24, 27]. In addition, SUSY models with Dirac gauginos are generally less constrained by LHC searches than other SUSY scenarios [35]. The sparticle spectrum and decay chains are quite different in Supersoft scenarios than in other SUSY models, and mass constraints on squarks and sleptons can be weaked considerably.

TREE LEVEL SINGLET DECAYS AND COLLIDER BOUNDS

From arguments above, we also note that the singlet state S couples to the Higgs fields. In particular we the real part of the singlet couples to both H_u and H_d through the hypercharge D-term.

$$V = \frac{1}{2} g_Y m_D S_R (h_u {h_u}^\dagger - h_d {h_d}^\dagger) \tag{7}$$

We thus expect that the singlet will have tree level decays into the light Higgs boson. For TeV scale values of m_D, the tree level width may only be suppressed at low values of tan β. The trilinear coupling is proportional to $g_Y m_D \sim$ TeV, and the width is by

$$\Gamma_h = \frac{(g_Y m_D)^2}{16\pi m_S} (\cos^2\alpha - \sin^2\alpha)^2 \sqrt{1 - 4m_h^2/m_S^2}. \tag{8}$$

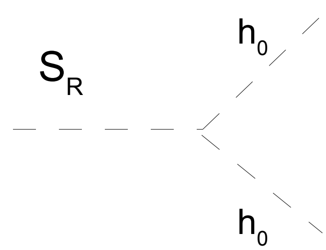

FIG. 2: SM singlet coupling to pairs of the lightest Higgs.

where m_S is the mass of the singlet, m_D is the Dirac bino mass and α is the Higgs mixing angle. The tree level singlet decay to pairs of the heavy Higgses, will of course be suppressed if the mass of the heavy states is more than half of the singlet mass. The 750 GeV resonance may be consistent with a narrow width, or an intermediate size width of order 10's of GeV. However, as we discuss below we expect that resonances with a larger width dominated by dihiggs decays to be incompatible with current collider constraints. Smaller resonance widths into light Higgses may be fit with judicious choices of parameters, for example a sbino Dirac mass of 1.5 TeV and tan$\beta \sim 1.1$ yields a tree level width of 66 MeV.

Other tree level decays may follow from additional Higgs sector operators. The physics of various Higgs sector operators in Dirac gaugino models has been studied, for example in references [28, 31, 32, 36–38]. Some examples of models with additional operators are Dirac gaugino models that include the μ-less MSSM [31] in which the scalar is given a tree level coupling to H_u and H_d and the MRSSM [32] which introduces two additional doublets, the R-Higgses. These models introduce tree level coupling of the singlet to Higgsino (or R-Higgsino) pairs. If the Higgsinos are light enough, this opens another avenue for a decay of the singlet which would provide a sizable width into invisible or highly mass degenerate states.

We will now briefly discuss collider limits on a scalar resonance from decay channels other than diphotons. Many models predict a large enhancement of the dihiggs production rate through decay of a heavy resonance. Current limits on dihiggs resonant production for a state of mass 750 GeV are tightest in the 4b channel [39–41]. ATLAS has placed limits on the total production cross section times branching fraction in this channel at 42 fb at 8 TeV. An extrapolation, then, for the limit on total rate into this channel at 13 TeV is approximately 200 fb [7]. If the singlet has a total production cross section large enough to explain the diphoton excess, its partial decay width to dihiggses, will be limited by this constraint.

Other modes that will be associated with a particle decaying to diphotons include ZZ, WW, and $Z\gamma$. That is, if the singlet decays into two photons, it will also decay into other pairs of electroweak gauge bosons with fixed ratios as dictated by gauge invariance. The coefficients for the effective operators coupling the singlet to diboson pairs is derived directly from the effective superpotential terms in Eq. 2 and, after accounting for $SU(2) \times U(1)$ breaking, are given by

$$\begin{aligned} g_{\gamma\gamma} &= \frac{c_w^2}{\Lambda_1} + \frac{s_w^2}{\Lambda_2} \\ g_{Z\gamma} &= c_w s_w (\frac{1}{\Lambda_2} - \frac{1}{\Lambda_1}) \\ g_{ZZ} &= \frac{s_w^2}{\Lambda_1} + \frac{c_w^2}{\Lambda_2} \\ g_{WW} &= \frac{1}{\Lambda_2} \end{aligned} \tag{9}$$

where Λ is the effective operator cut-off scale. For our scenario we expect the ZZ and γZ resonant signals at a smaller rate of production than diphotons. However these signals will become observable in the coming data sets if the diphoton resonance persists.

Finally, the singlet scalar field can mix with the Higgs. This can greatly enhance the singlet decay rate to ZZ and WW if the mixing parameter is large enough. Scaling up limits from searches for ZZ resonances at 8 TeV, the limits at 13 TeV are 89 fb and 40 fb with the production modes of gluon fusion and vector boson fusion respectively. Scaling up limits from searches for WW resonances give limits on the allowed 13 TeV production rate of 174 fb and 70 fb from gluon fusion and vector boson fusion production modes respectively. The ZZ and WW constraints will limit the allowable Higgs-Singlet mixing. In this work we will aim for a Higgs-Singlet mixing of 1 percent or less. In the gluon fusion production mode, resonant dijet limits from the 8 TeV run will also be important, though due to the much higher background the limits are much more relaxed. The limits on the allowed dijet production at 13 TeV is $\sim 10^4$ fb after scaling up the 8 TeV results [7].

PRODUCTION AND LOOP LEVEL DECAYS

fractions. The total size of the excess is in the 5-10 fb range. We would thus want total production cross-section times branching fraction in the for that for total production cross section $pp \to V + O \to V + \gamma\gamma$ and $pp \to jj + O \to jj + \gamma\gamma$, we would like production cross sections in the 500 fb range.

We now discuss loop level couplings of the singlet field to pairs of electroweak gauge bosons. As stated above the loop level coupling of the singlet to gluons is mediated by squark loops. The value of the effective coupling of the singlet S to pairs of gluons is given by

$$\frac{g_Y g_s^2}{16\pi^2} \frac{m_D}{m_S^2} N_c (\Sigma q_{Q_L} C(0,0,m_s^2, m_{Q_L}, m_{Q_L}, m_{Q_L}) + \Sigma q_{Q_R} C(0,0,m_s^2, m_{Q_R}, m_{Q_R}, m_{Q_R})) \tag{10}$$

Here C is the dimensionless Passerino-Veltman form factor, m_{Q_L} and m_{Q_R} are the masses of the left and right handed species of squarks, and the sums are taken over each species of left or right handed squark. The hypercharge of each species is given by q_{Q_i} and we see that within each generation of squarks there will be cancelations due to sign differences in hypercharge. If all squarks are to contribute to the loop we must sum over 3 generations of up and down type left and right handed squarks.

The value of the effective coupling of the singlet S to the U(1) gauge boson is given by

$$\frac{g_Y^3}{16\pi^2} \frac{m_D}{m_S^2} (\Sigma N_c q_L^3 C(0,0,m_s^2, m_L, m_L, m_L) + \Sigma N_c q_R^3 C(0,0,m_s^2, m_R, m_R, m_R)) \tag{11}$$

where the sums are taken over every state with hypercharge, not just over squarks. Here q_i denotes the hypercharge of the field in the loop. Many more particles contribute to this coupling than to the effective coupling of the singlet to gluons. In principle the value of these two effective couplings depends on the hypercharges and masses of the light states that contribute to the loop. We may choose various masses for the left and right handed, and up and down type squarks and sleptons, and a complete spectrum will be given by the parameters of the high energy theory. Here however we may simplify the theory by considering some particles to be arbitrarily high in mass. There are several options for this 'simplified model' of Supersoft SUSY. One choice might be to consider all squarks except the lightest, presumably the right handed stop, to be very massive.

For the sake of simplicity we will consider a slightly different simplified model. We will send the soft masses of all of the left handed states very high, effectively decoupling them from the theory. This will serve as an existence proof that we may find points in parameter space which fit the excess. We will assume that the only sfermions to have small soft masses will be the right-handed squarks and right-handed sleptons. We will also set the masses of all 3 generations of up and down right handed squarks to be equal. We will will consider that masses of all three generations of sleptons are equal. In this way the couplings of the singlet and SU(3) and U(1) gauge boson are of comparable order.

With the singlet coupling to gluons above we may now calculate gluon fusion production rates for the singlet. In order to calculate the production cross section of the process $gg \to S$ in proton-proton collisions, we have implemented a our model into Feynrules [42] inputting right handed up type squarks with D-term coupling to the sbino singlet field. This model was renormalized using the the NLOCT [43] package and imported into Madgraph5@NLO [44] to calculate cross sections. The singlet mass was set to 750 GeV and cross sections were calculated. We have scaled our results by a k-factor of 2 for both 8 and 13 TeV production, as is consistent, for example, with loop induced heavy Higgs production at similar masses [45]. Below, in Fig. 3, we show contour plots of the total gluon fusion in the process $pp \to S$ in the $m_{\tilde{q}}$ vs. m_D plane at 13 and 8 TeV.

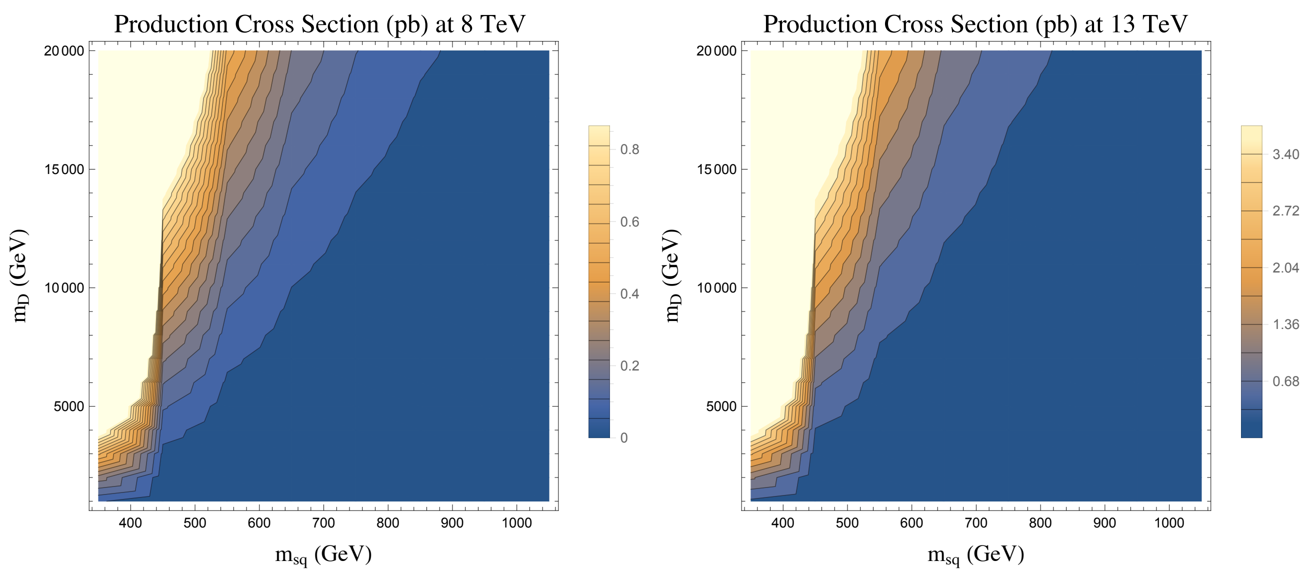

FIG. 3: $gg \to S$ rate in pb for squark mass vs Dirac mass plane in p-p collisions at 8 TeV and 13 TeV.

Again, the total production cross section will depend on how many light squarks are allowed to run in the loop, and what their masses and hypercharges are. The total production rate via gluon fusion increases with the square of m_D. The cross section also increases dramatically as the squarks are made lighter.

We may also compute the partial decay width, Γ_{gg}, of the singlet state into digluon pairs. This depends on the chosen value of m_D as well as the value of the squark masses. In Fig. 4 below we show a contour plot of the this width in the $m_D - m_{\tilde{q}}$ plane.

The ratio of the S width to photons and to gluons depends on the loop form factors, but also on the admixture of fields contributing to the photon loop vs the gluon loop. In our simple model with only right handed squarks and sleptons contributing to loops, we can express the ratio of partial widths of the singlet into photons over partial width into gluons as

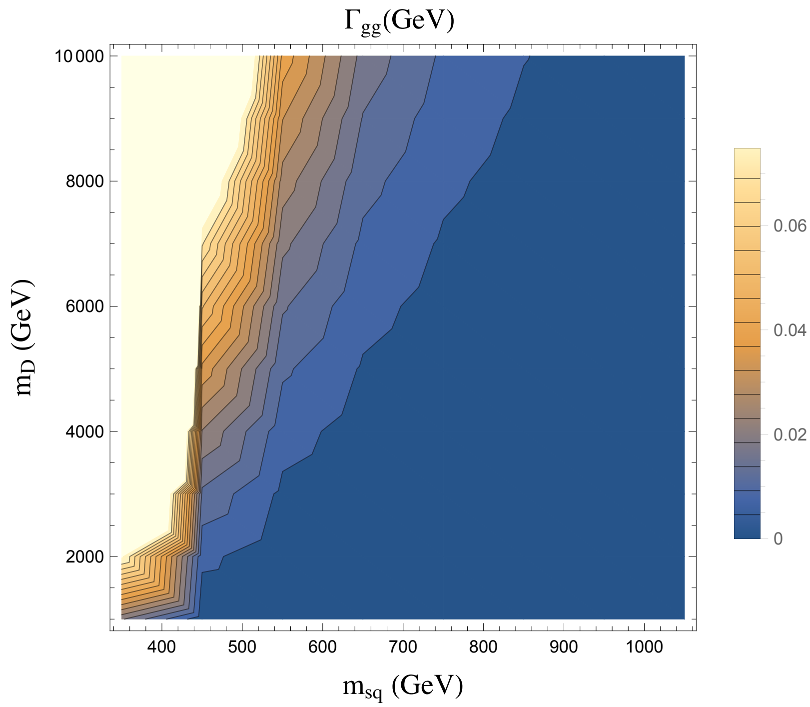

FIG. 4: Partial width (GeV) of S to gluon gluon in m_D-m_s plane.

$$\Gamma_{\gamma\gamma}/\Gamma_{gg} = \frac{c_w^4 g_Y^4}{N_c^2 g_3^4}\left(\frac{\Sigma q_{l_R}^3 C(0,0,m_s^2,m_{e_R},m_{e_R},m_{e_R}) + \Sigma N_c q_{Q_R}^3 C(0,0,m_s^2,m_{Q_R},m_{Q_R},m_{Q_R})}{\Sigma q_{Q_R} C(0,0,m_s^2,m_{Q_R},m_{Q_R},m_{Q_R})}\right)^2. \quad (12)$$

The form factors are quite sensitive to the ratio of the squark and slepton masses and the ratio is independent of the Dirac mass. We see that we may vary the ratio of partial widths to gluons and photons by varying the squark and slepton masses. In particular, in the regime that the squarks are heavier than the sleptons, we find that the partial width to photons may be made appreciable. Below we have created a contour plot of the ratio of decay widths of the singlet to gluons and photons over the squark, slepton mass plane Fig. 5.

There are various points in the overall parameter space that give a total diphoton rate in the 5-10 fb range at the 13 TeV run of LHC. However, we may describe the general requirements for viable points the parameter space. Allowed points generally require m_D to be in the multi TeV range, with squarks masses in the 400-1000 GeV range. These values maximize the overall production cross section. By keeping the sleptons near the onshell threshold mass, the partial decay rate to photons is maximized. The simplest possible region in parameter space is one in which the tree-level diHiggs decay is suppressed by choosing low tanβ, with the Singlet decay dominated by gluons and photons. As the tree-level decay width to light Higgses is made larger, it begins to dominate the Singlet branching fraction. Therefore, maintaining a high enough partial width to photons requires that the overall production rate by scaled up-which begins to impinge on the dihiggs resonance limits. The viable region of parameter space in the minimal model, will therefore be one in which the overall Singlet decay width is small, with limited allowed tree-level decays to diHiggses.

An example point has values $(m_D, m_{\tilde{q}}, m_{\tilde{e}})$ of $(3.5\text{ TeV}, 420\text{ GeV}, 375\text{ GeV})$ with a diphoton rate $\sigma_{\gamma\gamma}$ of 5.7 fb. Here we have chosen to suppress the partial width into Higgses, by working at tanβ of 1. The total decay width of the singlet is purely to gauge bosons. At this point in parameter space the partial width to gluons, Γ_{gg}, is 31.6 MeV. The branching fraction into photons at this point is roughly 0.95%. There is a very small mixing between the S and the light Higgs at this point-as we show in the following section. The rate for diboson channels is thus σ_{WW} and σ_{ZZ} are 4.7 fb and 2.3 fb. At this point in parameter space, the total production cross section for the scalar is 603 fb at 13 TeV, which is within bounds for dijet production. This point relies on quite light squarks in order to pump up the gluon fusion production rate. These, however, are very mass degenerate with the NLSP which we have, in this case, chosen to be a right handed stau in a gauge mediated scenario. In our scenario, and Dirac gaugino scenarios in

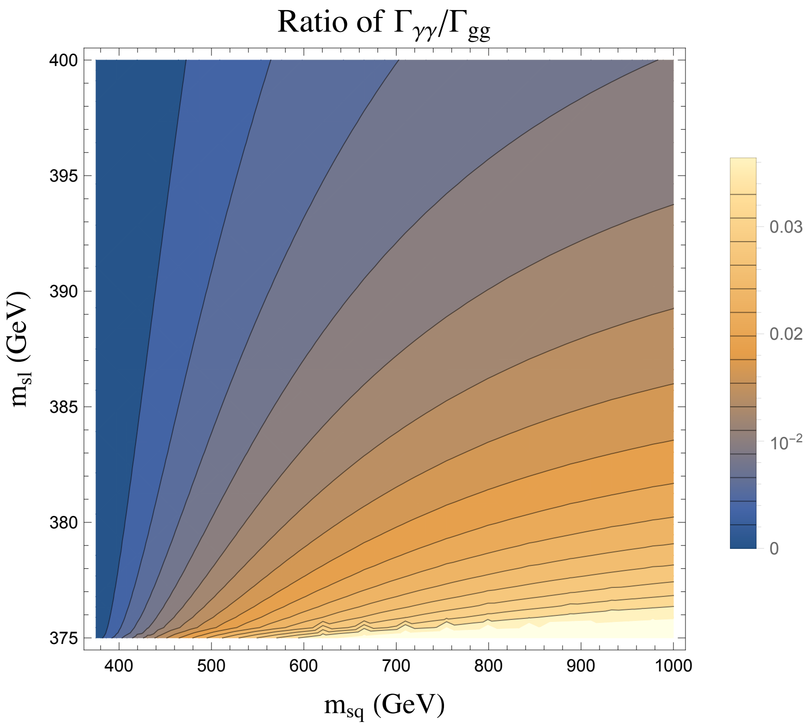

FIG. 5: Ratio of diphoton to digluon partial widths in the squark mass vs. slepton mass plane.

general, the Gauginos have large Dirac masses and are heavier than the sfermions. The squarks decay chain is thus highly nonstandard, the squark decays through an offshell gaugino to a stau which then decays to tau and gravitino. Collider bounds on stops and light flavor squarks in compressed MSSM scenarios still allow for squark masses down to 400 GeV[46][47]. It is therefore quite probable that this non-standard decay scenario is unconstrained.

An alternate point might be one where the Singlet has a more appreciable partial width into light Higgses, however, this will require a large Dirac mass as discussed above. For example, with parameters $(m_D, m_{\tilde{q}}, m_{\tilde{e}})$ of value $(15\text{ TeV}, 750\text{ GeV}, 375\text{ GeV})$ we may have a partial width into Higgses of 40 MeV, and a Higgs-Singlet mixing of 1 percent. This produces a diphoton rate of 4.8 fb. The total production cross section of the singlet is 361 fb with a digluon rate of 106 fb. The total rate in the dihiggs channel is 168 fb, nearly saturating the bound. Due to Higgs mixing the production rates in the WW and ZZ channels are 54 and 26 fb respectively.

Our points in parameter space are in accordance with 8 TeV constraints in alternate singlet channels, and follow from the most minimal model involving Dirac gauginos. This serves as an existence proof that Dirac gaugino models may fit the 750 GeV excess. However, in the next section we will explore the behavior of the scalar potential for these models where we will see additional caveats placed on the parameter space. We will find that points like our first one above are in accordance with vacuum stability, while points like the second-with large Dirac mass- are meta-stable.

STABILITY AND ELECTROWEAK CONSTRAINTS

We now briefly examine the compatibility of our minimal scenario with Higgs sector constraints and briefly discuss vacuum stability. Dirac gaugino models allow for various Higgs sector operators in addition to new trilinear couplings involving the SM adjoints. In order to specify a scalar potential we must choose a set of Higgs operators. Here we choose to complete our Higgs sector in the framework of the μ-less MSSM, where the μ term is enhanced by a tree-level coupling between the Higgs and adjoint fields. This framework has several advantages, additional quartic couplings appear in the Higgs potential, and loop effects involving the adjoint fields substantially raise the tree-level Higgs mass. The viability of the Higgs sector of such models was studied in [37]and [28]. We note we require a heavy Higgsino in this scenario. In the superpotential, we will also include a supersymmetric masses for our adjoints as well as usual Yukawa couplings for sleptons. The additional superpotential terms involving the Singlet are thus, $W = \lambda_S H_u S H_d + M_S S^2$. The soft terms in the potential, arising once SUSY is broken, include soft masses and b terms for the Higgs fields, a soft mass and b term for the S field as well as a linear term for the S field. In addition, we include quartic terms for the S field and sleptons.

$$\begin{aligned} V_{soft} &= m_u^2|h_u|^2 + m_d^2|h_d|^2 + m_S^2|S|^2 + m_e^2|\tilde{e}_R|^2 + m_l^2|\tilde{l}|^2 + \left(bh_uh_d + b_S S^2 + h.c\right) + t_S S \\ V_q &= \lambda_{SS}(SS^*)^2 + \lambda_l(\tilde{l}\tilde{l}^* + \tilde{e}_R\tilde{e}_R^*)^2 \end{aligned} \tag{13}$$

D terms also give a contribution to the scalar potential, $V_D = \frac{1}{2}\Sigma D_i^2$. For example, the $U(1)$ D-term is

$$D_Y = g'(\frac{1}{2}|h_u|^2 - \frac{1}{2}|h_d|^2 - \frac{1}{2}|\tilde{l}|^2 + |\tilde{e}_R|^2) + m_D(S + S^*) \tag{14}$$

We may now analyze the potential. With parameters picked below we may enforce the conditions to find the Higgs breaking minimum.

$\tan(\beta)$	1
λ_S	0.4
λ_{SS}	0.7
λ_l	1.2
m_{D_S}	3.5 TeV
M_S	−120 GeV
b	5×10^9 GeV^2
b_S	-5×10^4 GeV^2
t_S	1.21×10^8 GeV^3

The above parameters produce a real scalar sbino of the correct mass to fit the excess, while maintaining a small mixing parameter between the Higgs and Singlet fields of 1.7×10^{-3}. We have set the slepton soft masses such that the mass eigenstates of right and left handed slepton masses are 376 GeV and 5040 GeV respectively. This point has parameters consistent with our first point in the previous section which predicted the correct diphoton excess. However, we must check for the existence of alternate vacua.

In particular we may look in the direction in which the Higgs vev is zero where the potential is given by

$$\begin{aligned} V &= \frac{1}{8}(g^2 + g'^2)(\tilde{l}\tilde{l}^*)^2 + \frac{1}{2}(g'^2)(\tilde{e}_R\tilde{e}_R^*)^2 - \frac{1}{2}(g'^2 - 2y_e^2)(\tilde{e}_R\tilde{e}_R^*)(\tilde{l}\tilde{l}^*) + \lambda_l(|\tilde{l}|^2 + |\tilde{e}_R|^2)^2 + \lambda_{SS}(SS^*)^2 \\ &- \frac{g'm_D}{2}|\tilde{l}|^2(S + S^*) + g'm_D|\tilde{e}_R|^2(S + S^*) \\ &+ m_e^2|\tilde{e}_R|^2 + m_l^2|\tilde{l}|^2 + (m_S^2 + 4M_S^2)|S|^2 + m_D^2(S + S^*)^2 + \frac{1}{2}(b_S S^2 + h.c.) \\ &+ (t_S S + h.c.). \end{aligned} \tag{15}$$

In analyzing the potential, we find an extremum with right and left handed slepton vevs equal to zero and S at non-zero vev. The Higgs vacuum has a lower energy than this extremum. However, for certain values of parameters, we find additional minima in which either the left or right handed slepton has large vevs. These charge breaking minima may have lower energy than the Higgs vacuum, rendering the Higgs vacuum meta-stable. The meta-stability arises from the large D term coupling between the singlet and the sleptons. The effect of such trilinear terms on vacuum stability is well known, for example see [48].

We see from the minimization conditions we may, for example, set the vev of the left handed slepton, $\tilde{l}$ to zero. Then the vev of field $\tilde{e}_R$ is given by

$$\frac{\partial V}{\partial \tilde{e}_R} = \tilde{e}_R(m_e^2 + g'^2\tilde{e}_R^2 + 2\sqrt{2}m_D S + 2\lambda_l\tilde{e}_R^2) = 0. \tag{16}$$

This is a cubic equation with one zero root. The third term in parentheses follows from the large trilinear coupling between the singlet and the sleptons, proportional to m_D. We find for certain values of parameters the remaining roots are imaginary, thus there is a single real solution for the vev of $\tilde{e}_R$ corresponding to the extremum described above. There is a critical point for the remaining roots when the value of $\tilde{e}_R^2$ passes through zero. Then for other values of parameters, in particular large m_D compared to the slepton soft mass, there are three real solutions for the slepton vev corresponding to a minimum or saddle point at zero, and symmetric charge breaking vacua at large slepton vev. The necessary condition for avoidance of additional charge breaking vevs is

$$-2\sqrt{2}t_S - \left(2b_S + 4m_D^2 + 2m_S^2 + 8M_S^2\right)\frac{m_e^2}{2\sqrt{2}g'm_D} - 2\lambda_{SS}\frac{m_e^6}{16\sqrt{2}g'^3m_D^3} \leq 0. \tag{17}$$

For large Dirac mass and insufficient slepton soft mass, charge breaking vacua will develop. A similar condition holds if one considers the left handed slepton direction. In general this feature of the minimal model limits the size of m_D. Our point given above has no charge breaking vacua. In Figure 6 we show a contour plot of the potential value in the S vs $\tilde{e}_R$ plane given our parameters. We find a single U(1) preserving extremum with higher energy than our Higgs potential. However points with much larger values of Dirac mass will have only metastable Higgs breaking vacua. As the Dirac mass is made larger with all other parameters fixed, charge breaking vacua develop and move out to large values of $\tilde{e}_R$ and S vevs along the enlogated 'horns' seen in Figure 6.

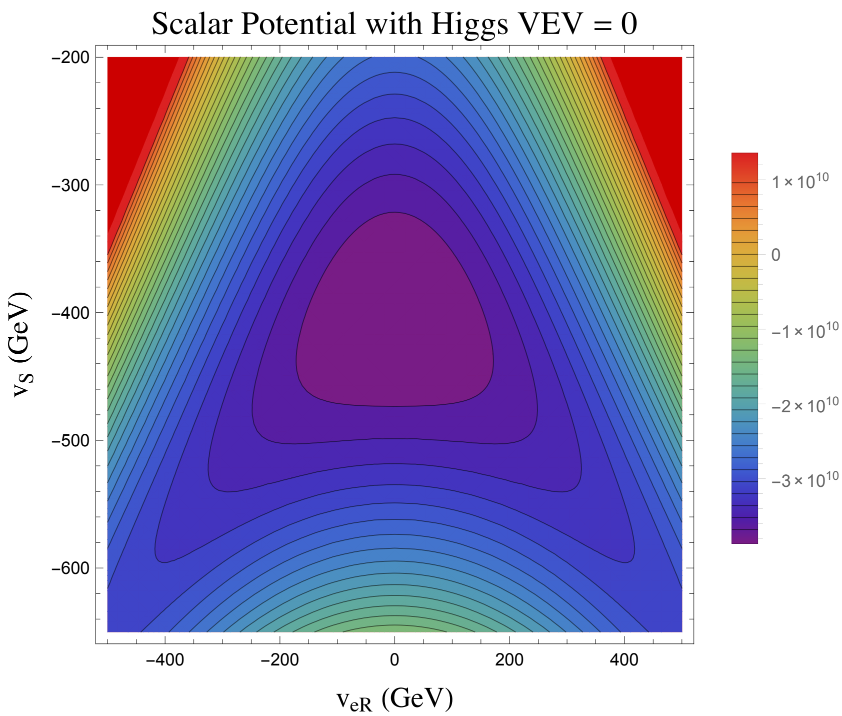

FIG. 6: Scalar potential as a function of slepton vev and S vev.

Our very minimal Dirac gaugino model may fit the diphoton excess while maintaining consistency with bounds from alternate decay channels. However, maintaining stability of the scalar potential requires points in parameter space with low values of the Dirac mass. The lifetime of the possible metastable vacua remains to be calculated, and it is topic for study whether the thin wall approximation is appropriate in these cases. Since the original appearance of this work, several extensions of the Dirac gaugino scenario have been proposed [49][50]. In particular [49] attempt to lower the singlet Dirac mass by including additional fields and trilinear couplings to enhance the loop coupling of the S field to gauge bosons while avoiding additional charge breaking vacua. Other extension of the Dirac gaugino scenario may yield less constrained parameter spaces for fitting the excess.

CONCLUSIONS

We have proposed that the LHC diphoton excess may be explained minimally in a model with Dirac gauginos. The signal follows from production and decay of the sbino, the real component of the scalar partner of the field which gives Dirac mass to the bino. This particle is a scalar SM singlet. In the most minimal case, the sbino couples to pairs of dibosons through loops of squarks and sleptons. The sbino may exhibit tree level decay width to pairs of Higgs bosons, and possibly also to Higgsinos.

As a simple viability proof we have calculated the production cross section and decays of the sbino in a very simple model in which we consider only the loop contributions of up type right handed squarks and right handed sleptons. We find the the sbino-gluon-gluon coupling, and hence the gluon fusion production cross section of the sbino, is highly sensitive to the squark masses running in the squark loop. We have produced production cross sections for the full one loop computation. The total branching fraction of the sbino into diphotons may be on the percent level. However, we may vary the maximize photon to gluon branching ratio by choosing slepton masses lighter than those for squarks.

We find that in general, we do not run aground of the 8 TeV dijet search. However, a constraining feature in our model is a large rate in the resonant dihiggs channel. We have shown this is within the bounds of LHC exclusion limits at 8 TeV if we limit ourselves to low tanβ. Further study of the Higgs sectors of the model would be fruitful and it is possible that with further studies of parameter space, more viable points will be found. For example, by opening up decays to light Higgsinos, which would appear to searches as very mass degenerate particles, the sbino branching fraction may be dumped into an invisible channel. This may allow a broadening of the total sbino decay width and thus partial width into light Higgses without impinging on additional collider constraints. This possibility would entail models with larger Dirac masses therefore, a study of the lifetime of the metastable vacuum would be necessary.

It is a topic of further study to determine how minimal Dirac gaugino scenarios might be extended. For example, the Dirac bino scenario mixed with other SUSY mediation scenarios, for example anomaly mediation as in [51]. Such models might lend themselves toward SUSY mass spectra and additional couplings that might further be able to increase the Singlet production rate or decay into diphotons.

As many have already pointed out, due to gauge invariance, if our state produced a diphoton signal, it must also be seen in the ZZ and $Z\gamma$ and possibly WW channels. These production rates are only a factor of a few less than the diphoton rate, and thus must be observed soon if the resonance is to stay. As a final note, we mention that Dirac gaugino models also contain an scalar SU(2) adjoint. Loops similar to those we discussed couple the neutral component of the SU(2) adjoint to gluons and photons. In the case of gluon coupling, the loops come with powers of Higgs insertions to preserve SU(2) quantum numbers. This state also couples to electroweak boson pairs through loops of sleptons and it may therefore be possible to explain the excess as a swino.

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