750 GeV Diphoton Excess from the Goldstino Superpartner

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We interpret the diphoton excess recently reported by the ATLAS and CMS Collaborations as a new resonance arising from the sgoldstino scalar, which is the superpartner of the Goldstone mode of spontaneous supersymmetry breaking, the goldstino. The sgoldstino is produced at the LHC via gluon fusion and decays to photons, with interaction strengths proportional to the corresponding gaugino masses over the supersymmetry breaking scale. Fitting the excess, while evading bounds from searches in the dijet, $Z\gamma$, ZZ, and WW final states, selects the supersymmetry breaking scale to be a few TeV and particular ranges for the gaugino masses. The two real scalars, corresponding to the CP-even and CP-odd parts of the complex sgoldstino, both have narrow widths, but their masses can be split of the order of 10–30 GeV by electroweak mixing corrections, which could account for the preference of a wider resonance width in the current low-statistics data. In the parameter space under consideration, tree level F-term contributions to the Higgs mass arise, in addition to the standard D-term contribution proportional to the Z-boson mass, which can significantly enhance the tree level Higgs mass.

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Introduction.—The ATLAS and CMS Collaborations recently presented the first results based on $\sqrt{s} = 13$ TeV LHC Run II data, where both experiments showed a slight excess around 750 GeV in the diphoton invariant mass spectrum [1–3]. The local significance of the ATLAS and CMS excesses based on 3.2 and 2.6 fb^{-1} of data, respectively, are 3.9σ and 2.6σ. Several interpretations of this excess in terms of new physics have already appeared [4–13].

In this Letter, we interpret the diphoton excess in terms of supersymmetry (SUSY). If SUSY is realized in nature, since the standard model (SM) particles are not mass degenerate with their superpartners, SUSY must be in a broken phase at low energies. A general consequence of the spontaneous breaking of SUSY is the existence of a Goldstone fermion, the goldstino. The superpartner of the goldstino is a complex scalar, the sgoldstino. In contrast to the goldstino, the sgoldstino is not protected by the Goldstone shift symmetry, and it generically acquires a mass, though the precise value depends on the details of how SUSY is broken; see, for instance, Ref. [14]. In terms of R parity, the goldstino is odd and the sgoldstino is even, implying that the sgoldstino can be produced as a resonance without violating R parity. In this we work, we interpret the diphoton excess as arising from a 750 GeV sgoldstino scalar.

Concerning the couplings between the sgoldstino and the SM particles, since it is the superpartner of the goldstino, these couplings are suppressed by the scale of SUSY breaking $\sqrt{f}$. Therefore, in order to have a viable interpretation of the excess, $\sqrt{f}$ should be low, of the order of a few TeV. Moreover, these couplings are proportional to the corresponding soft SUSY breaking masses, implying that particular relations and ranges for some of the superpartner masses are selected. Searches for the sgoldstino have been performed at the LEP [15] and at the Tevatron [16], which have placed bounds on $\sqrt{f}$. The ATLAS Collaboration has placed the currently most stringent lower bound on $\sqrt{f}$ at around 1 TeV; the precise value depends on the superpartner spectrum [17,18].

It has been previously stressed that the sgoldstino couples most strongly to SM gauge bosons and that one of the most promising signatures is in terms of a diphoton resonance [19–21]. See, also, Refs. [21–32] for different discussions concerning the sgoldstino. The fact that the sgoldstino is produced at the LHC via gluon fusion implies compatibility with the $\sqrt{s} = 8$ TeV LHC Run I data, in which no significant diphoton excess was found and where a 95% confidence level (C.L.) upper limit on the diphoton signal rate at around 1.5 fb was placed [33,34], since the gain in cross section from 8 to 13 TeV is about a factor of 4.7, in comparison to the $u\bar{u}/d\bar{d}$ gain of about a factor of 2.5/2.3 [4].

In the following section, we take into account the constraints from resonance searches in the dijet, diboson, and $Z\gamma$ final states and determine the values of the SUSY breaking scale and gaugino masses relevant to explain the diphoton excess. We then discuss the possibility of accounting for a broad width by splitting the charge-parity-(CP)-even and CP-odd part of the complex sgoldstino scalar. Also, the implications of the sgoldstino interpretation on the Higgs sector are discussed, such as the new tree level F-term contributions to the Higgs mass that it gives rise to.

Explaining the diphoton excess.—In this section, we interpret the complex sgoldstino scalar $x = (\phi + ia)/\sqrt{2}$, where ϕ and a are the CP-even and CP-odd real scalars, as being responsible for the recently reported diphoton excess. The production cross section and all the relevant partial decay widths of the sgoldstino can be found in Ref. [32]. Because of the experimental limit on the gluino mass and the color factor, the dominant sgoldstino partial decay width is into gluons, $\Gamma(\phi \to gg) = (m_3^2 m_\phi^3)/(4\pi f^2)$, where m_3 is the gluino mass, $\sqrt{f}$ is the scale of SUSY breaking, and m_ϕ is the mass of ϕ. Thus, the sgoldstino scalars ϕ and a are produced at the LHC via gluon fusion, with the production cross section being proportional to $\Gamma(\phi \to gg)$. The partial width into photons is instead given in terms of a linear combination of the bino and wino masses, $\Gamma(\phi \to \gamma\gamma) = (m_1 c_W^2 + m_2 s_W^2)^2 m_\phi^3/(32\pi f^2)$, where s_W and c_W are the sine and cosine of the weak mixing angle. The partial decay widths of a are obtained by simply replacing $\phi \to a$. The Feynman diagram for the gluon fusion produced sgoldstinos decaying to two photons is shown in Fig. 1.

Run I searches for resonances in the $Z\gamma$ [35], ZZ [36], and WW [37,38] final states place 95% C.L. upper limits on the signal rate at around 11, 12, and 40 fb, respectively. These constraints translate into bounds on the sgoldstino couplings to gauge bosons, which are given by ratios of different linear combinations of gaugino masses over f. In Table I, we give the constraints in terms of the sgoldstino parameter space. In the last line of the table, we have translated the range preferred by the diphoton excess obtained by requiring $6\,\text{fb} < \sigma \times \text{BR}_{\gamma\gamma} < 10\,\text{fb}$ at 13 TeV [4], into a range of the relevant combination of bino and wino masses.

The interplay between the different constraints on m_1 and m_2 and the observed excess in diphotons in the plane $(m_1/f, m_2/f)$ is shown in Fig. 2. From the figure, we see that the constraints from the ZZ and WW searches in Run I on the region preferred by the diphoton excess are comparable. However, the constraint from the $Z\gamma$ searches is weaker and is not visible in the figure since it lies in the

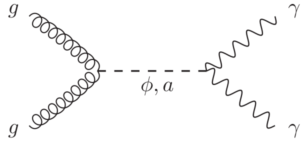

FIG. 1. Gluon fusion production of the sgoldstino scalars ϕ and a, which subsequently decay to two photons.

TABLE I. Constraints on the relevant gaugino mass combinations from searches in dijet and diboson final states.

Analysis	Constraint in units of f/TeV
jj [39]	$m_3 \lesssim 0.11$
$Z\gamma$ [35]	$m_2 - m_1 \lesssim 5.7 \times 10^{-2}$
ZZ [36]	$m_1 s_W^2 + m_2 c_W^2 \lesssim 3.5 \times 10^{-2}$
WW [37,38]	$m_2 \lesssim 4.5 \times 10^{-2}$
$\gamma\gamma$ [1–3]	$1.1 \times 10^{-2} \lesssim m_1 c_W^2 + m_2 s_W^2 \lesssim 1.4 \times 10^{-2}$

region $m_2/f > 5.7 \times 10^{-2}$/TeV. Hence, if the diphoton excess can be attributed to the sgoldstino, additional 750 GeV excesses are most likely to appear at Run II, first in the ZZ and WW channels and then in the $Z\gamma$ one.

Since the dominant decay mode of the sgoldstino is into gluons, important limits are placed by resonance searches in the dijet final states [39]. The 95% C.L. upper limit of 2.5 pb on the dijet signal rate can be translated into the bound reported in the first line of Table I, which can be rewritten in the form

$$\frac{\sqrt{f}}{3.9\ \text{TeV}} \gtrsim \sqrt{\frac{m_3}{1.7\ \text{TeV}}}, \tag{1}$$

where the constraint has been normalized to the current lower limit on the gluino mass from Run II searches at around 1.7 TeV [1,40]. For this minimum m_3 value, we obtain an absolute minimum value of $\sqrt{f}$ of 3.9 TeV. Since

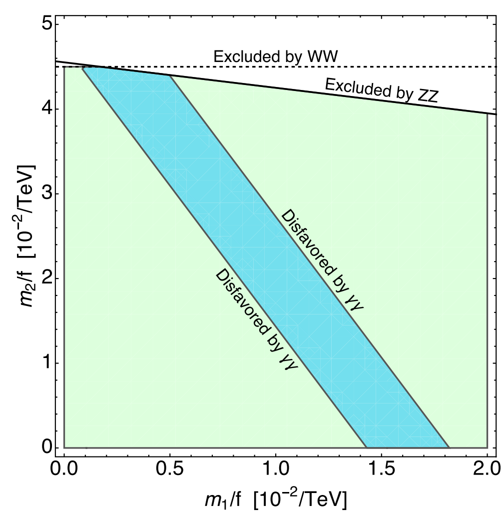

FIG. 2. The green region is allowed by the Run I searches in the $Z\gamma$, ZZ, and WW final states, while the blue region is preferred by the Run II diphoton excess. The different edges of the allowed region correspond to the exclusion limits from ZZ (excluded above the solid line) and WW (excluded above the dashed line) searches, while the $Z\gamma$ constraint lies outside of the upper edge of the plot.

the maximum sgoldstino total decay width is obtained by saturating the dijet constraint (1), we conclude that the total sgoldstino width does not exceed about 0.4 GeV. Therefore, the fact that the largest significance for the diphoton excess in the current data [1–3] is obtained for a resonance width of around 45 GeV cannot be explained by the narrow widths of the sgoldstino scalars if they are mass degenerate at around 750 GeV. In the following section, we investigate alternative explanations to account for a broader width.

We will from hereon focus on the case where the SUSY breaking scale $\sqrt{f}$ is as low as possible, i.e., when the dijet constraint (1) is saturated. This is motivated by the fact that, as we will discuss in the following section, new F-term contributions to the tree level Higgs mass are maximized for low values of $\sqrt{f}$. This also maximizes the mass splitting between ϕ and a that we propose below as an explanation of the broad resonance width preferred by the data. Moreover, low values of $\sqrt{f}$ correspond to low values of m_3, which is the most interesting case from the point of view of fine-tuning and gluino searches.

In Fig. 3, we show in the (m_3, m_1) plane the regions that are allowed by all Run I constraints and where the diphoton excess can be explained by the sgoldstino. The two blue regions correspond to two representative values of the wino mass, $m_2 = 0.7$ and $m_2 = 1.4$ TeV. Constraints from dijets are satisfied by construction since we require the bound in Eq. (1) to be saturated throughout the plane. The left edges of these regions are again due to the constraints placed by the Run I ZZ and WW searches [36–38], while the width of the regions is determined by the diphoton signal rate preferred by the Run II excess. Of course, different values of m_2 are possible and would give rise to regions that are shifted towards the left or right for smaller or larger values of m_2, respectively.

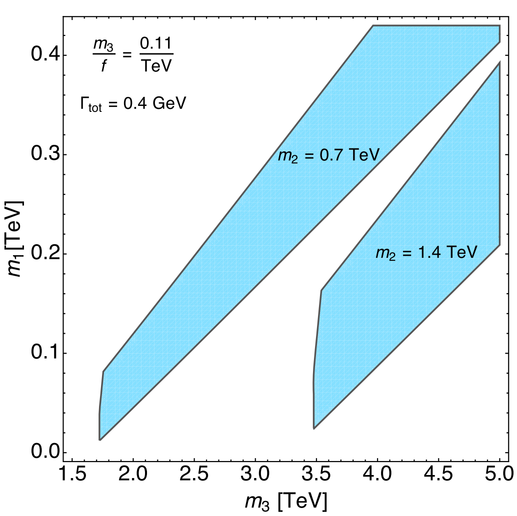

FIG. 3. The two blue regions in the (m_3, m_1) plane corresponding to two different values of m_2 show the viable parameter space that can fit the diphoton excess without being excluded by any other search channel.

Broad width from split scalars.—In this section, we discuss the possibility of the sgoldstino to account for the broad width around 45 GeV for which ATLAS obtains the highest significance. We start by discussing why some possibilities, such as additional sgoldstino decays to top quarks or invisible decays, do not work for the sgoldstino. We then discuss a more promising alternative corresponding to splitting the masses of ϕ and a. This latter alternative is viable because of the current low statistics in the diphoton channel, which is not yet sensitive enough to discriminate between one broad peak and two narrow peaks.

Concerning the explanation in terms of a large partial decay width into top quarks, this is not an option for the sgoldstino for the following reason. The sgoldstino coupling to top quarks arises from the superpotential operator corresponding to the soft A term, $(A/f)XQH_uU^c$, which gives rise to the following interactions,

$$\mathcal{L}_{t\bar{t}} = \frac{m_t A_t}{\sqrt{2}f}(-\phi t\bar{t} - iat\gamma^5\bar{t}). \tag{2}$$

We see that the coupling is suppressed by the ratio $(m_t A_t)/f$, implying that this decay cannot compete with the decay into gluons and, therefore, cannot be responsible for a large sgoldstino width. Another option could be to enhance the sgoldstino total width by maximising the invisible width into goldstinos. However, this has the form $\Gamma(\phi \to \tilde{G}\tilde{G}) = m_\phi^5/(32\pi f^2)$, which is always very suppressed for the values of $\sqrt{f}$ under consideration.

Let us now consider the possibility of splitting the masses of ϕ and a, with the purpose of generating two narrow peaks that are close by and thereby mimicking a single broad peak. The sgoldstino masses receive contributions from the following SUSY operators,

$$\int d^4\theta \frac{m_x^2}{4f^2}(X^\dagger X)^2 + \left\{\int d^2\theta\left(\mu - \frac{B_\mu}{f}X\right)H_u H_d + \text{H.c.}\right\} \tag{3}$$

with $X = x + \sqrt{2}\theta\tilde{G} + \theta^2 F_X$, where, in addition to the sgoldstino $x = (\phi + ia)/\sqrt{2}$, $\tilde{G}$ is the goldstino, and F_X is the auxiliary field that acquires a vacuum expectation value $\langle F_X \rangle = f$. The μ and B_μ parameters are the standard ones appearing in the minimal supersymmetric standard model (MSSM) Higgs sector. The first operator in Eq. (3) provides the dominant, equal mass contribution m_x to ϕ and a. However, small electroweak corrections arise from the remaining operators, which split the tree level masses of ϕ and a according to

$$m_a^2 - m_\phi^2 = \frac{2v^2\mu^2 B_\mu}{m_x^2 f^2}(2\mu^2 \sin 2\beta - B_\mu), \tag{4}$$

where $v = 246$ GeV. We refer the reader to Ref. [28] for a treatment of all the relevant operators and the electroweak symmetry breaking conditions. The fact that the μ and B_μ

parameters are not relevant for the diphoton excess allows for some freedom in terms of this splitting. We provide some numerical examples in the following section, where we also take into account the Higgs mass and Higgs couplings.

Higgs mass and couplings.—For low values of $\sqrt{f}$, the mass of the lightest Higgs scalar h receives additional tree level contributions, which arise upon integrating out the auxiliary field F_X in Eq. (3), thereby generating additional quartic Higgs couplings in the F-term scalar potential [28,41]. In the parameter space under consideration, the tree level Higgs mass is

$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{v^2}{2f^2}\left[(2\mu^2 - B_\mu \sin 2\beta)^2 - \frac{4\mu^6}{m_x^2}\sin^2 2\beta\right]. \tag{5}$$

The first term is the standard MSSM D-term contribution. The last term arises from Higgs-sgoldstino mixing. The remaining terms arise as a consequence of treating F_X dynamically and display a destructive interference between the terms $2\mu^2$ and $B_\mu \sin 2\beta$. Note that the contribution involving B_μ is analogous to the extra tree level contribution to the Higgs mass achieved in the next-to-minimal supersymmetric standard model, where the role of the dimensionless coupling λ is here played by the ratio B_μ/f.

An issue that is relevant to this discussion concerns the corrections to the Higgs couplings induced by sgoldstino-Higgs mixing. As can be seen in Ref. [30], the sgoldstino-Higgs mixing corrections to the Higgs coupling to gluons, photons, and $Z\gamma$ are all proportional to $v^2\mu^3 \sin 2\beta/(m_x^2 f^2)$. Moreover, the different corrections are proportional to the corresponding linear combination of gaugino masses, which can be found in Table I. The fact that the Higgs corrections depend cubically on μ severely constrains the possibility of using large values of μ to get a substantial mass splitting (4) and an enhanced tree level Higgs mass (5), even for large values of $\tan\beta$. We find that, by requiring not more than 10% modification to the Higgs couplings, we can neither achieve the mass splitting needed to explain the broad width nor get a significant Higgs mass enhancement at tree level.

Instead, the only viable possibility is to consider small values of $\tan\beta$ and large values of B_μ, thereby maximizing the contribution from the $B_\mu \sin 2\beta$ term in Eq. (5). In order to minimize the cancellation in Eq. (5), small values of μ are now required, implying that the Higgs coupling corrections, as well as the last term in Eq. (5), both of which arise from sgoldstino-Higgs mixing, are small. As a numerical example, for $B_\mu/f = 0.8$, $\mu = 400$ GeV, and $\tan\beta = 2$, one obtains a tree level Higgs mass around $m_h = 120$ GeV and a mass splitting between ϕ and a of about 15 GeV, while keeping the modifications to the Higgs couplings below 10%.

Conclusions.—Sharing the excitement of the theory community for the recent announcement of an excess of events in the diphoton spectrum at an invariant mass of about 750 GeV [1–3], we propose an interpretation in terms of the complex scalar superpartner of the goldstino, the sgoldstino. We study the parameter space where this interpretation is compatible with the excess, while evading all other constraints. The production cross section and branching ratios of the sgoldstino depend only on the gaugino masses and the SUSY breaking scale, and the strong limits from Run I resonance searches set strong constraints on them. Nevertheless, we find an allowed region of the parameter space pointing towards hierarchical gaugino masses $m_1 < m_2 < m_3$ and a low SUSY breaking scale in the few TeV range.

We also study the possibility to, within the sgoldstino interpretation, mimic the large width of around 45 GeV, as suggested by the data. Since the dominant sgoldstino decay width is into two gluons, the constraints from dijet searches in Run I set the maximum allowed width to less than a GeV. However, a natural splitting between the masses of the CP-even and CP-odd real sgoldstino scalars arises from electroweak mixing corrections, and can be in the range of 10–30 GeV. This would allow for an explanation of a broader peak, while at the same time provide a significant additional F-term tree level contribution to the tree level Higgs mass. Because of the small width of the two scalars and to the good experimental invariant mass resolution, we expect that the two peaks could be resolved by the experiments with a bit more data.

Let us stress that if the diphoton excess is due to the sgoldstino scalar, this would provide crucial information about the full supersymmetric model that lies beyond the SM, as if would select a range for the SUSY breaking scale that is lower than the typical range selected by the standard SUSY frameworks such as gauge mediation, gravity mediation, and anomaly mediation. Another interesting aspect of the sgoldstino interpretation is the fact that it predicts relations between seemingly disconnected experimental analyses, such as direct searches for gluinos, winos, Higgsinos, as well as Higgs measurements and searches for new resonances. And given the relations it predicts between different gauge boson channels, hints could appear in the ZZ, WW, dijet, and $Z\gamma$ channels already with the next few inverse femtobarns of data. We are looking forward to see whether this signal is actually due to new physics or yet another statistical fluctuation.

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Note added.—Recently, the ATLAS and CMS Collaborations updated their searches in Refs. [1–3]. At the 51st Rencontres de Moriond EW 2016 conference, they presented new results on the diphoton excess [42]. No new data were added by ATLAS, while CMS was able to add 0.6 fb^{-1} of data recorded with zero magnetic field. This allowed CMS to update their results to a total of 3.3 fb^{-1} of data at 13 TeV. The main result is a more careful reanalysis of the 8 TeV data and a combination with the 13 TeV results, which shows a better compatibility in the excess region. The final number for the significances is around 3.6σ (3.4σ) local for ATLAS (CMS), corresponding to roughly 2σ global significance for each experiment [1–3]. These new results do not affect the interpretation presented in the present Letter.

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