Physics Letters B 759 (2016) 159–165

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

The 750 GeV diphoton excess as a first light on supersymmetry breaking

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ARTICLE INFO

Article history:
Received 15 February 2016
Received in revised form 27 April 2016
Accepted 21 May 2016
Available online 25 May 2016
Editor: G.F. Giudice

ABSTRACT

One of the most exciting explanations advanced for the recent diphoton excess found by ATLAS and CMS is in terms of sgoldstino decays: a signal of low-energy supersymmetry-breaking scenarios. The sgoldstino, a scalar, couples directly to gluons and photons, with strength related to gaugino masses, that can be of the right magnitude to explain the excess. However, fitting the suggested resonance width, $\Gamma \simeq 45$ GeV, is not so easy. In this paper we explore efficient possibilities to enhance the sgoldstino width, via the decay into two Higgses, two Higgsinos and through mixing between the sgoldstino and the Higgs boson. In addition, we present an alternative and more efficient mechanism to generate a mass splitting between the scalar and pseudoscalar components of the sgoldstino, which has been suggested as an interesting alternative explanation to the apparent width of the resonance.

1. Introduction

The ATLAS and CMS Collaborations have recently reported an excess in diphoton searches at $\sqrt{s} = 13$ TeV for a ~ 750 GeV diphoton invariant mass [1–3]. The local significance is 3.9σ (ATLAS) and 2.6σ (CMS), although it gets smaller once the look-elsewhere effect is taken into account. However, the fact than both experiments see the signal in the same place has created in the community the expectation that it could be the long expected signal of new physics.

Once the accumulated statistics at ATLAS and CMS grow large enough, we will see finally whether or not this excess is an statistical fluctuation. In the meantime, it is tempting to try and interpret the data as a signal of new physics as the flood of papers studying different BSM scenarios that could accommodate the excess testify. Those most relevant to our discussion are [4–10]. In our opinion, probably the most exciting theoretical possibility to accommodate this resonance is the one pursued by the authors of [5,6,8], who have contemplated scenarios with a scale of SUSY breaking not far from the TeV scale (low-scale SUSY breaking) [11–14]. Potentially, these models contain the main ingredient to fit the signal: an scalar field ϕ (the sgoldstino) coupled to gluons and photons in a direct way, so that an effective production via gluon fusion and the subsequent decay into photons are possible. Beside reproducing the observed cross section, any good explanation of the data should account for the apparent sizeable width of the resonance, $\Gamma_\phi/M_\phi \simeq 0.06$, although the data are not yet conclusive and the significance of such a large width is not too large. For this reason, in the following, scenarios that are able to explain at least a significant fraction of that apparent large width are considered favorably. The authors of ref. [6] discussed a simple explanation for the apparent width: a mass splitting (as advocated in [4]) between the scalar and pseudoscalar degrees of freedom of the sgoldstino.

In this paper we review the explanation of the diphoton signal (sect. 3) based on this type of scenarios (sect. 2), exploring mechanisms for a broad Γ_ϕ, potentially consistent with the data. We present other mechanisms for the mentioned sgoldstino mass splitting, which are more efficient than those considered up to now (sect. 4). In our analysis we discuss some subtleties not previously considered that can constrain and affect substantially the results. We also discuss the possibility that sgoldstinos decay efficiently into Higgses (sect. 5), as the partial width into that channel is naively parametrically enhanced with respect to other channels; into Higgs decay channels through sgoldstino-Higgs mixing (sect. 6); and into Higgsinos (sect. 7), as there is more freedom to enhance this width without clashing with previous LHC searches.

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http://dx.doi.org/10.1016/j.physletb.2016.05.070
0370-2693/

2. The low-scale SUSY-breaking scenario

The low-scale SUSY-breaking (LSSB) scenario [11–14] is a framework in which the scale of SUSY breaking, $\sqrt{F}$, and its mediation, M, are not far from the TeV scale. The main differences with respect to more conventional supersymmetric models, where the latter scales are large, are the following: i) the low-energy effective theory includes the chiral superfield, Φ, responsible for SUSY breaking, in particular its fermionic (goldstino) and scalar (sgoldstino) degrees of freedom; ii) besides the ordinary SUSY-soft breaking terms, the effective theory contains additional hard-breaking operators, e.g. quartic Higgs couplings. The latter make the Higgs sector resemble a two-Higgs doublet model with an additional (complex) singlet. LSSB models present a much milder electroweak fine-tuning than usual MSSMs [12,13] and a rich phenomenology [11–14]. As discussed in refs. [5,6,8], the LSSB scenario can nicely explain the diphoton excess at 750 GeV observed at the LHC.

Let us summarize the main ingredients of LSSB scenarios. Expanding in inverse powers of M, superpotential, W, Kähler potential, K, and the gauge kinetic function, f_{ab}, read [11]

$$
\begin{aligned}
W &= W_{\rm MSSM} + F\left(\Phi + \frac{\rho_\phi}{6M^2}\Phi^3 + \cdots\right) \\
&\quad + \left(\mu + \frac{\mu'}{M}\Phi + \cdots\right) H_u\cdot H_d \\
&\quad + \frac{1}{2M}\left(\ell + \frac{\ell'}{M}\Phi + \cdots\right)(H_u\cdot H_d)^2 \ + \ \cdots , \qquad (1)
\end{aligned}
$$

$$
\begin{aligned}
K &= |\Phi|^2\left(1 - \frac{\alpha_\phi}{4M^2}|\Phi|^2 + \cdots\right) + |H_u|^2\left[1 + \frac{\alpha_u}{M^2}|\Phi|^2 + \cdots\right] \\
&\quad + |H_d|^2\left[1 + \frac{\alpha_d}{M^2}|\Phi|^2 + \cdots\right] \\
&\quad + \left[H_u\cdot H_d\left(\frac{\alpha_{ud}}{2M^2}\bar{\Phi}^2 + \cdots\right) + \text{h.c.}\right] \ + \ \cdots , \qquad (2)
\end{aligned}
$$

$$
f_{ab} = \frac{\delta_{ab}}{g_a^2}\left[1 + c_a\frac{\Phi}{M} \ + \ \cdots\right] . \qquad (3)
$$

Here all the parameters are dimensionless, except the $\mu, \mu' \cdots$ parameters in the superpotential, which have dimensions of mass. Replacing Φ by its auxiliary field, F, one gets the soft breaking terms of the theory. In particular, from Eq. (3), one gets masses for gluinos, M_3, winos, M_2, and the bino, M_1, e.g. $M_1 = c_1 F/M$. Likewise, replacing Φ by its scalar component, a complex singlet field, that we also denote by Φ,

$$
\Phi = \frac{1}{\sqrt{2}}(\phi_S + i\phi_P) \qquad (4)
$$

(where ϕ_S is the scalar component and ϕ_P the pseudoscalar one), one obtains couplings of the ϕ's with the MSSM fields. In particular, the coupling to gluons and photons is directly related to gaugino masses as:

$$
\begin{aligned}
\mathcal{L} \supset\ & \frac{M_3}{2\sqrt{2}F}\,\mathrm{tr}\, G^a_{\mu\nu}(\phi_S G^{a\mu\nu} - \phi_P \tilde{G}^{a\mu\nu}) \\
& + \frac{M_{\tilde\gamma}}{2\sqrt{2}F}\,\mathrm{tr}\, F_{\mu\nu}(\phi_S F^{\mu\nu} - \phi_P\tilde{F}^{\mu\nu}) , \qquad (5)
\end{aligned}
$$

where $M_{\tilde\gamma}$ is the photino mass,

$$
M_{\tilde\gamma} = M_1\cos^2\theta_W + M_2\sin^2\theta_W . \qquad (6)
$$

Similarly, from Eqs. (1) and (2), the scalar potential $V = V_F + V_D$ for the two supersymmetric Higgs doublets plus the complex singlet field Φ, is[1]:

$$
\begin{aligned}
V &= F^2 + \alpha_\phi\tilde{m}^2|\Phi|^2 + \frac{1}{2}(\rho_\phi\tilde{m}^2\Phi^2 + \text{h.c.}) \\
&\quad + m^2_{H_u}|H_u|^2 + m^2_{H_d}|H_d|^2 + \left(m^2_{12}H_u\cdot H_d + \text{h.c.}\right) \\
&\quad + (m_{X_1}\Phi + m^*_{X_1}\Phi^*)|H_u|^2 + (m_{X_2}\Phi + m^*_{X_2}\Phi^*)|H_d|^2 \\
&\quad + \left[(m_{X_3}\Phi + m_{X_4}\Phi^*)H_u\cdot H_d + \text{h.c.}\right] \\
&\quad + \frac{1}{2}\lambda_1|H_u|^4 + \frac{1}{2}\lambda_2|H_d|^4 + \lambda_3|H_u|^2|H_d|^2 + \lambda_4|H_u\cdot H_d|^2 \\
&\quad + \left[\frac{1}{2}\lambda_5\,(H_u\cdot H_d)^2 + \lambda_6|H_u|^2H_u\cdot H_d + \lambda_7|H_d|^2H_u\cdot H_d + \text{h.c.}\right] \\
&\quad + \ldots \qquad (7)
\end{aligned}
$$

where the dots stand for higher order terms in Φ and nonrenormalizable terms suppressed by powers of M. The various mass parameters and quartic couplings in (7) are explicit combinations of the parameters in W and K (see ref. [11] for explicit formulae). As a summary, denoting by μ the typical scale of the supersymmetric mass parameters [$\mu, \mu', \cdots$ in Eq. (1)] and $\tilde{m} = F/M$, the mass terms in the potential have contributions of order μ^2, $\tilde{m}^2$, $\tilde{m}\mu$. We assume $\mu \lesssim \tilde{m}$, so that all these squared mass terms are expected to be $\lesssim \tilde{m}^2$. Analogously, trilinear terms, m_{X_i}, have contributions of order μ^2/M, $\tilde{m}^2/M$, $\tilde{m}\mu/M$. Finally, the Higgs quartic couplings have supersymmetric D-term and F-term contributions, where the latter include supersymmetry breaking contributions as well: $\lambda_i = \lambda_i^{(D)} + \lambda_i^{(F)}$. The $\lambda_i^{(D)}$ are as in the MSSM:

$$
\begin{aligned}
&\lambda_1^{(D)} = \lambda_2^{(D)} = \frac{1}{4}(g^2 + g'^2) , \quad \lambda_3^{(D)} = \frac{1}{4}(g^2 - g'^2) , \\
&\lambda_4^{(D)} = -\frac{1}{2}g^2 , \qquad (8)
\end{aligned}
$$

and $\lambda_5^{(D)} = \lambda_6^{(D)} = \lambda_7^{(D)} = 0$. Besides, typically $\lambda_i^{(F)} \sim \tilde{m}^2/M^2$, $\tilde{m}\mu/M^2$, μ^2/M^2, although some of these couplings can receive contributions at a lower order, $\lambda_5^{(F)} \sim \tilde{m}/M$, $\lambda_{i=6,7}^{(F)} \sim \mu/M$. Whether the effective theory expansion starts at order $\tilde{m}/M$ or $\tilde{m}^2/M^2$ is a model-dependent question. In what follows we will generically assume $\lambda_i^{(F)} \sim \tilde{m}^2/M^2$ but the reader should keep in mind this exception, which might be important in some cases. The effective quartic self-coupling of the light (SM-like) Higgs, $\lambda|H|^4$, reads

$$
\lambda = \lambda^{(D)} + \lambda^{(F)} + \delta_{\rm rad}\lambda , \qquad (9)
$$

where

$$
\begin{aligned}
\lambda &= \frac{1}{2}\left(\lambda_1 c_\beta^2 + \lambda_2 s_\beta^2\right) + \frac{1}{4}(\lambda_3 + \lambda_4 + \lambda_5)\sin^2 2\beta \\
&\quad + \left(\lambda_6 c_\beta^2 + \lambda_7 s_\beta^2\right)\sin 2\beta , \qquad (10)
\end{aligned}
$$

with $\tan\beta = \langle H_u\rangle/\langle H_d\rangle \equiv v_u/v_d$. This quartic coupling determines the Higgs mass as in the SM, i.e. $m_h^2 = 2\lambda v^2$, with $v^2 = v_u^2 + v_d^2 = (246\ \text{GeV})^2$. The sizes of the various contributions are

$$
\begin{aligned}
&2\lambda^{(D)}v^2 = m_Z^2\cos^2(2\beta) , \quad 2\lambda^{(F)}v^2 \sim \frac{\tilde{m}^2}{M^2}v^2 , \\
&2\delta_{\rm rad}\lambda v^2 \sim \frac{3}{2\pi^2}\frac{m_t^4}{v^2}\log\frac{m_{\tilde t}^2}{m_t^2} , \qquad (11)
\end{aligned}
$$

where $m_{\tilde t}$ is the stop mass scale.

[1] A linear term in Φ can always be removed by a field redefinition. For more details, see [11].