The 750 GeV diphoton excess from singlets in $E_6$ SSM

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Based on:

Introduction

- An excess of diphoton events at an invariant mass around 750 GeV recently reported by both ATLAS and CMS maybe the first hint of physics beyond the SM.

- It is worth to consider its interpretations within supersymmetric (SUSY) models.

- In SUSY extensions of the SM
  - lightest SUSY particle (LSP) is dark matter candidate;
  - electroweak (EW) scale is stabilized;
  - gauge coupling unification can be achieved that allows to embed the SM gauge group into GUTs based on $SU(5)$, $SO(10)$ or $E_6$ and incorporate SUSY models into superstring theories.

- It is especially interesting to study the interpretations of the observed excess within well motivated $E_6$ inspired SUSY extensions of the SM.
At high energies the gauge symmetry in the $E_6$ models may be broken to

$$E_6 \rightarrow SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)',$$

$$U(1)' = U(1)_\chi \cos \theta + U(1)_\psi \sin \theta,$$

where $E_6 \rightarrow SO(10) \times U(1)_\psi$, $SO(10) \rightarrow SU(5) \times U(1)_\chi$.

The $\mu$ problem in these models is solved in a similar way to the NMSSM.

The exceptional SUSY model ($E_6$SSM) is based on the SM gauge group together with an extra $U(1)_N$ gauge symmetry that corresponds to $\theta = \arctan \sqrt{15}$ [S.F.King, S.Moretti, RN, Phys. Rev. D 73 (2006) 035009; Phys. Lett. B 634 (2006) 278].

Only in this $E_6$ inspired SUSY model right–handed neutrinos have zero charge and may be superheavy.
To ensure anomaly cancellation and gauge coupling unification the matter content of the $E_6$ SSM involves

$$3 \times 27 + L' + \bar{L}' = \left[ Q_i, u_i^c, d_i^c, L_i, e_i^c \right] + (D_i, \bar{D}_i) +$$

$$+(H_i^u, H_i^d) + S_i + N_i^c + L' + \bar{L}'. $$

$D_i$ and $\bar{D}_i$ can be either diquarks or leptoquarks.

$H_i^d$ and $H_i^u$ are either Higgs or inert Higgs fields.

Two–loop RG flow of $\alpha_i(\mu)$ in the $E_6$ SSM and MSSM.
In the E$_6$SSM lepton asymmetry can be dynamically generated via the decay of $N_1^c$ and then gets converted into baryon asymmetry due to sphaleron interactions.

New exotic particles predicted by the E$_6$SSM contribute to the generation of lepton asymmetry.

In the E$_6$SSM the substantial lepton CP asymmetries can be induced even for $M_1 \sim 10^6$ GeV that may allow to avoid gravitino problem [S.King,R.Luo,D.Miller,RN, JHEP 12 (2008) 042].

Diagrams that contribute to the generation of lepton asymmetry
A new variant of the $E_6$ SSM

- New particles predicted by the $E_6$ SSM may be produced at the LHC and future colliders.
- At the same time exotic states give rise to new Yukawa interactions that lead to non-diagonal flavour transitions and rapid proton decay.
- Over last ten years several variants of the $E_6$ SSM have been studied.
- In the simplest variant an approximate $\mathbb{Z}_2^H$ symmetry, under which all superfields except $H_d \equiv H_3^d$, $H_u \equiv H_3^u$ and $S \equiv S_3$ are odd, was used to suppress flavour changing processes [S.F.King, S.Moretti, RN, Phys. Rev. D 73 (2006) 035009; Phys. Lett. B 634 (2006) 278.].
- However this simplest variant of the $E_6$ SSM does not allow for the consistent interpretation of the 750 GeV diphoton excess observed at the LHC.
We now propose a variant of the E\textsubscript{6}SSM in which we allow all singlets S\textsubscript{i} as well as H\textsubscript{d} and H\textsubscript{u} to be even under the Z\textsubscript{2}\textsuperscript{H} while all other supermultiplets are odd.

In order to avoid rapid proton decay we also impose an exact Z\textsubscript{2} symmetry which results in the baryon number conservation.

There are two different ways to impose an appropriate Z\textsubscript{2} symmetry that imply

– exotic quarks are diquarks, i.e. B\textsubscript{D},\overline{D} = \mp 2/3;
– exotic quarks are leptoquarks, i.e. B\textsubscript{D},\overline{D} = \pm 1/3, L\textsubscript{D},\overline{D} = \pm 1.

The Z\textsubscript{2}\textsuperscript{H} symmetry allows to reduce the structure of the Yukawa interactions in the superpotential to

\[ W_{E_6SSM} \simeq \lambda_{ji} H^d_j H^u_j S_i + \kappa_{ji} \bar{D}_j D_j S_i + W_{MSSM}(\mu = 0). \]
The superfield $S_3$ is assumed to acquire a large VEV ($\langle S_3 \rangle = s/\sqrt{2}$) giving rise to the effective $\mu$ term, masses of exotic quarks and inert Higgsino states.

Here we restrict our consideration to the case when exotic quarks and inert Higgsinos are much lighter compared to $s > 8$ TeV, but are heavier than 375 GeV.

Scalar components of $S_{1,2}$ can be identified with the resonances which give rise to the 750 GeV di-photon excess.

ATLAS and CMS measurements indicate that the branching ratios of the decays of such resonances into SM fermions have to be sufficiently small.

This implies that the mixing between $S_\alpha$ and $H_u^0$ as well as $H_d^0$ should be strongly suppressed.
The appropriate suppression of this mixing can be achieved when $\lambda_{3\alpha} \to 0$ \((\lambda_{3\alpha} S_\alpha(H_d H_u))\) which also guarantees that $S_\alpha$ develop rather small VEVs.

The couplings $\kappa_{i3}$, $\lambda_{\alpha3}$ and $\lambda_{33}$ should be also rather small to ensure that exotic fermions $(\mu_{D_i} = \kappa_{i3} \langle S_3 \rangle$, $\mu_{H_\alpha} = \lambda_{\alpha3} \langle S_3 \rangle)$ are light and $\mu_{\text{eff}} = \lambda_{33} \langle S_3 \rangle \lesssim 1\,\text{TeV}$.

If $\kappa_{i3}$, $\lambda_{3\alpha}$, $\lambda_{\alpha3}$ and $\lambda_{33}$ are set to be small at the scale $M_X$ then they remain small at any scale below $M_X$.

The low energy effective superpotential of the modified $E_6$ SSM below the scale $\langle S_3 \rangle$ can be written as

$$W_{\text{eff}} \simeq \lambda_{\alpha1} S_1(H_\alpha^d H_\alpha^u) + \kappa_{i1} S_1(D_i \bar{D}_i) + \lambda_{\alpha2} S_2(H_\alpha^d H_\alpha^u) + \kappa_{i2} \hat{S}_2(\hat{D}_i \bar{\hat{D}}_i) + \mu_{H_\alpha} (H_\alpha^d H_\alpha^u) + \mu_{D_i} (D_i \bar{D}_i) + W_{\text{MSSM}}(\mu \neq 0).$$

This superpotential does not contain any mass terms that involve $S_\alpha$. 
In the simplest scenario the fermion components of $S_\alpha$ can be lighter than $0.1\,\text{eV}$ forming hot dark matter in the Universe.

Such fermion states have negligible couplings to all SM particles and therefore would not have been observed at earlier collider experiments.

If $Z'$ boson is sufficiently heavy the presence of such light fermion states does not affect Big Bang Nucleosynthesis [J.P.Hall, S.F.King, JHEP 1106 (2011) 006].

The requirement of validity of perturbation theory up to the GUT scale $M_X$ restricts the interval of variations of the Yukawa couplings at low-energies.

In the case when $\lambda_{\alpha2} = \kappa_{i2} = 0$ the Yukawa couplings $\lambda_{\alpha1} = \kappa_{i1} \lesssim 0.6$. 

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Integrating out heavy states one obtains the effective Lagrangian which describes the interactions of $N_\alpha$ and $A_\alpha$ ($S_\alpha = (N_\alpha + iA_\alpha)/\sqrt{2}$) with the SM gauge bosons

$$\mathcal{L}_{\text{eff}} = \sum_\alpha (c_{1\alpha} N_\alpha B_{\mu\nu} B^{\mu\nu} + c_{2\alpha} N_\alpha W^a_{\mu\nu} W^{a\mu\nu} + c_{3\alpha} N_\alpha G^\sigma_{\mu\nu} G^{\sigma\mu\nu}$$

$$+ \tilde{c}_{1\alpha} A_\alpha B_{\mu\nu} \tilde{B}^{\mu\nu} + \tilde{c}_{2\alpha} A_\alpha W^a_{\mu\nu} \tilde{W}^{a\mu\nu} + \tilde{c}_{3\alpha} A_\alpha G^\sigma_{\mu\nu} \tilde{G}^{\sigma\mu\nu}) \).$$

The effective Lagrangian that describes the interactions of these fields with the electromagnetic one is given by

$$\mathcal{L}_{\gamma\gamma\text{eff}} = \sum_\alpha (c^\gamma_\alpha N_\alpha F_{\mu\nu} F^{\mu\nu} + \tilde{c}^\gamma_\alpha A_\alpha F_{\mu\nu} \tilde{F}^{\mu\nu}) ,$$

$$c^\gamma_\alpha = c_{1\alpha} \cos^2 \theta_W + c_{2\alpha} \sin^2 \theta_W , \quad \tilde{c}^\gamma_\alpha = \tilde{c}_{1\alpha} \cos^2 \theta_W + \tilde{c}_{2\alpha} \sin^2 \theta_W .$$

At the LHC the exotic states $N_\alpha$ and $A_\alpha$ are mainly produced through gluon fusion.
\[ \text{BR}(A_1 \rightarrow gg, WW, ZZ, \gamma\gamma, \gamma Z) \]

\[ \text{BR}(N_1 \rightarrow gg, WW, ZZ, \gamma\gamma, \gamma Z) \]

\[ \sigma(pp \rightarrow A_1 \rightarrow \gamma\gamma)[fb] \]

\[ \sigma(pp \rightarrow N_1 \rightarrow \gamma\gamma)[fb] \]
Here we set $\mu_{D_i} = \mu_D$, $\mu_{H_\alpha} = \mu_H \simeq 400\text{ GeV}$ and $\lambda_{\alpha 1} = \kappa_{i 1} = 0.6$.

The states $A_1$ and $N_1$ decay mainly into a pair of gluons.

The branching ratios of $A_1(N_1) \to WW$ and $A_1(N_1) \to ZZ$ are the second and third largest ones.

The branching ratio of $A_1(N_1) \to \gamma\gamma$ is considerably smaller but still larger than $A_1(N_1) \to \gamma Z$.

Although the branching ratios of $A_1(N_1) \to WW$ and $A_1(N_1) \to ZZ$ are large their detection might be problematic since $W$ and $Z$ decays mainly into quarks.

If we assume that $A_1$ and $N_1$ have masses around 750 GeV then $\sigma(pp \to A_1 \to \gamma\gamma) + \sigma(pp \to N_1 \to \gamma\gamma)$ can reach 4.5 fb for $\mu_D \simeq 400\text{ GeV}$.
The presence of two nearly degenerate resonances may also explain why the analysis performed by the ATLAS collaboration leads to large width (\(\sim 45 \text{ GeV}\)).

Unfortunately, the cross sections mentioned above decreases substantially with increasing \(\mu_D\).

The modest enhancement of the signal in the diphoton channel can be achieved when \(A_1, A_2, N_1\) and \(N_2\) have masses around 750 GeV.

In the case, when \(\lambda_{\alpha 2} = \kappa_{i1} = 0\), one obtains that \(\lambda_{\alpha 1} = \kappa_{i 2} \lesssim 0.8\).

Assuming maximal mixing between \(A_1\) and \(A_2\) as well as \(N_1\) and \(N_2\) we find that \(\sigma(pp \rightarrow \gamma\gamma)\) can vary from 4.5 fb to 3 fb when \(\mu_D = 400 - 1000 \text{ GeV}\) for \(\mu_H \sim 400 \text{ GeV}\).
Three families of exotic quarks with masses below 1 TeV and two families of inert Higgsinos around 400 GeV are not necessarily ruled out because of their non–standard decay patterns.

These exotic states as well as further decay modes of the 750 GeV resonance into $WW$, $ZZ$ and $\gamma Z$ are expected to be observable at the 13 – 14 TeV LHC.

\[
\sigma(pp \rightarrow A_{1,2} \rightarrow \gamma\gamma)[fb] \quad \quad \quad \sigma(pp \rightarrow N_{1,2} \rightarrow \gamma\gamma)[fb]
\]
Conclusions

Over last ten years several variants of the E\(_6\) SSM have been considered.

Recently we studied the modification of the E\(_6\) SSM that allows for reasonably good interpretation of the 750 GeV diphoton excess observed at the LHC.

This model implies that the observed excess is associated with the set of almost degenerate scalar and pseudoscalar states which can lead to the LHC diphoton production cross section of about 4.5 \(-\) 3 fb.

In this scenario exotic quarks have masses below 1 TeV while the masses of inert Higgsinos are close 400 GeV.

Further data from Run 2 should begin to resolve a set of almost degenerate exotic states around 750 GeV that decay into a pair of gluons, \(WW\), \(ZZ\), \(\gamma\gamma\) and \(\gamma Z\).
Assuming that $D$ and $\overline{D}$ couple most strongly with the third family quarks and leptons the exotic quarks decay into

- $\overline{D} \rightarrow t + b + \chi^0_1$ if exotic quarks are diquarks;
- $D \rightarrow t + \tau + \chi^0_1$ and $D \rightarrow \nu_\tau + b + \chi^0_1$ if exotic quarks are leptoquarks.

Thus the presence of light exotic quarks should result in enhancement of the cross sections of

- $pp \rightarrow t\overline{t}b\overline{b} + E_T^{miss} + X$ if exotic quarks are diquarks;
- $pp \rightarrow t\overline{t}l\overline{l} + E_T^{miss} + X$ if new quark states are leptoquarks.