The 750 GeV diphoton excess from singlets in E_6SSM

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Outline

- Introduction
- A new variant of the E_6SSM
- 750 GeV diphoton excess
- Conclusions

Based on:

S. F. King, R. Nevzorov, JHEP **1603** (2016) 139 [arXiv:1601.07242 [hep-ph]];

P. Athron, D. Harries, R. Nevzorov, A. G. Williams, Phys. Lett. B **760** (2016) 19 [arXiv:1512.07040 [hep-ph]];

R. Nevzorov, Phys. Rev. D **87** (2013) 015029 [arXiv:1205.5967 [hep-ph]];

P. Athron, S. F. King, D. J. Miller, S. Moretti, R. Nevzorov, Phys. Rev. D **80** (2009) 035009 [arXiv:0904.2169 [hep-ph]];

S. F. King, S. Moretti, R. Nevzorov, Phys. Rev. D **73** (2006) 035009 [hep-ph/0510419].

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

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

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

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

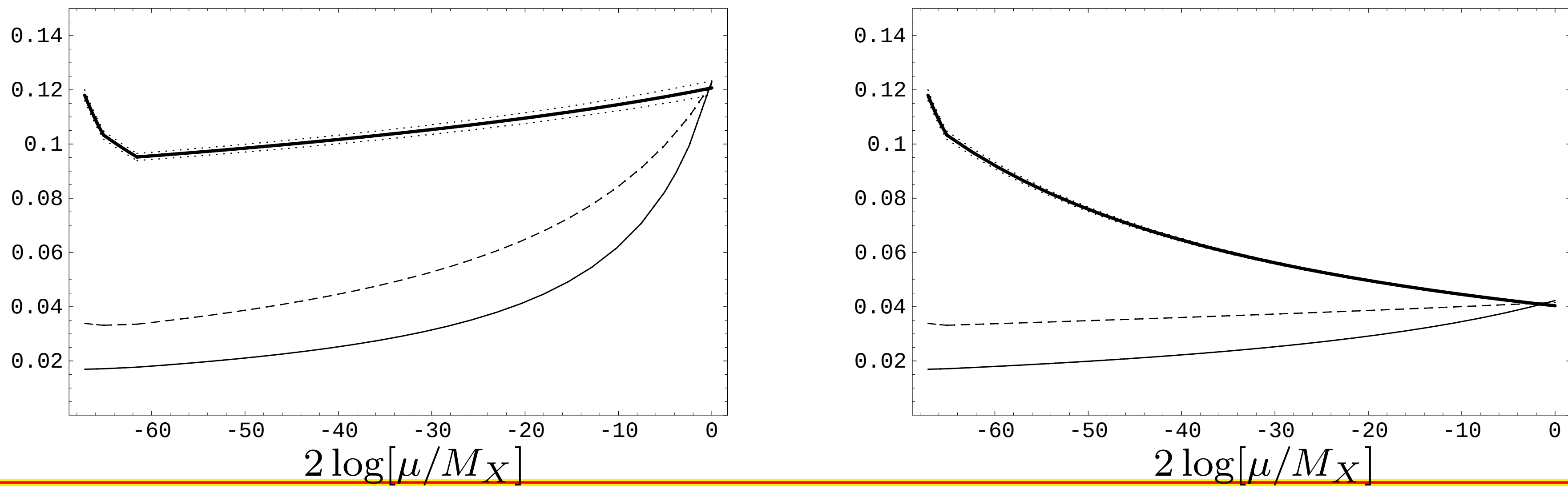
- The μ problem in these models is solved in a similar way to the NMSSM.
- The exceptional SUSY model (E_6SSM) is based on the SM gauge group together with an extra $U(1)_N$ gauge symmetry that corresponds to $\theta = \arctan\sqrt{15}$ [S.F.King, S.Moretti, RN, Phys. Rev. D 73 (2006) 035009; Phys. Lett. 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

$$3\times 27 + L' + \overline{L}' = \Big[Q_i,\, u^c_i,\, d^c_i,\, L_i,\, e^c_i\Big] + (D_i,\, \overline{D}_i) +$$
$$+ (H^u_i,\, H^d_i) + S_i + N^c_i + L' + \overline{L}' \,.$$

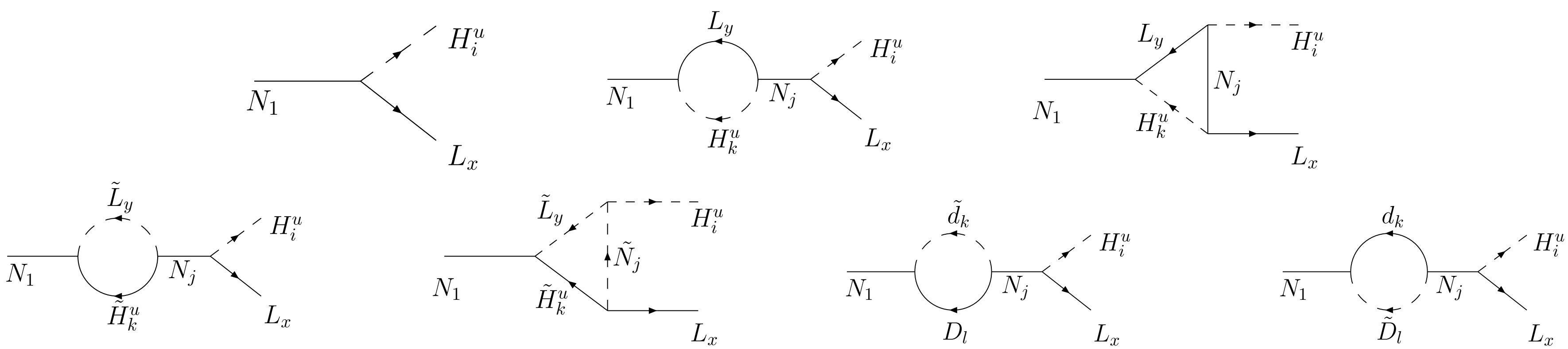
  - D_i and $\overline{D}_i$ can be either diquarks or leptoquarks.
  - H^d_i and H^u_i are either Higgs or inert Higgs fields.

Two–loop RG flow of $\alpha_i(\mu)$ in the E$_6$SSM and MSSM



- In the E_6SSM 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_6SSM contribute to the generation of lepton asymmetry.
- In the E_6SSM the substantial lepton CP asymmetries can be induced even for $M_1 \simeq 10^6$ 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_6SSM

- New particles predicted by the E_6SSM 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_6SSM have been studied.
- In the simplest variant an approximate 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_6SSM 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_6SSM in which we allow all singlets S_i as well as H_d and H_u to be even under the Z_2^H while all other supermultiplets are odd.
- In order to avoid rapid proton decay we also impose an exact Z_2 symmetry which results in the baryon number conservation.
- There are two different ways to impose an appropriate Z_2 symmetry that imply
  – exotic quarks are diquarks, i.e. $B_{D,\overline{D}} = \mp 2/3$;
  – exotic quarks are leptoquarks, i.e. $B_{D,\overline{D}} = \pm 1/3,\ L_{D,\overline{D}} = \pm 1$.
- The Z_2^H symmetry allows to reduce the structure of the Yukawa interactions in the superpotential to

$$W_{E_6SSM} \simeq \lambda_{ji} H_j^d H_j^u S_i + \kappa_{ji} \bar{D}_j D_j S_i + W_{MSSM}(\mu = 0)\,.$$

- The superfield S_3 is assumed to acquire a large VEV ($\langle S_3 \rangle = s/\sqrt{2}$) giving rise to the effective μ 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 diphoton 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_α 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_α develop rather small VEVs.
- The couplings κ_{i3}, $\lambda_{\alpha 3}$ and λ_{33} should be also rather small to ensure that exotic fermions ($\mu_{D_i} = \kappa_{i3}\langle S_3 \rangle$, $\mu_{H_\alpha} = \lambda_{\alpha 3}\langle S_3 \rangle$) are light and $\mu_{eff} = \lambda_{33}\langle S_3 \rangle \lesssim 1$ TeV.
- If κ_{i3}, $\lambda_{3\alpha}$, $\lambda_{\alpha 3}$ and λ_{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

$$W_{eff} \simeq \lambda_{\alpha 1} S_1 (H^d_\alpha H^u_\alpha) + \kappa_{i1} S_1 (D_i \bar{D}_i) + \lambda_{\alpha 2} S_2 (H^d_\alpha H^u_\alpha)$$
$$+\kappa_{i2} \hat{S}_2 (\hat{D}_i \hat{\bar{D}}_i) + \mu_{H_\alpha} (H^d_\alpha H^u_\alpha) + \mu_{D_i} (D_i \bar{D}_i) + W_{MSSM}(\mu \neq 0)\,.$$

- This superpotential does not contain any mass terms that involve S_α.

- In the simplest scenario the fermion components of S_α can be lighter than 0.1 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 $\lambda_{\alpha 2} = \kappa_{i2} = 0$ the Yukawa couplings $\lambda_{\alpha 1} = \kappa_{i1} \lesssim 0.6$.

750 GeV diphoton excess

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

$$\mathcal{L}_{eff} = \sum_\alpha (c_{1\alpha} N_\alpha B_{\mu\nu} B^{\mu\nu} + c_{2\alpha} N_\alpha W^a_{\mu\nu} W^{a\mu\nu} + c_{3\alpha} N_\alpha G^\sigma_{\mu\nu} G^{\sigma\mu\nu} + \tilde{c}_{1\alpha} A_\alpha B_{\mu\nu} \widetilde{B}^{\mu\nu} + \tilde{c}_{2\alpha} A_\alpha W^a_{\mu\nu} \widetilde{W}^{a\mu\nu} + \tilde{c}_{3\alpha} A_\alpha G^\sigma_{\mu\nu} \widetilde{G}^{\sigma\mu\nu}) \,.$$

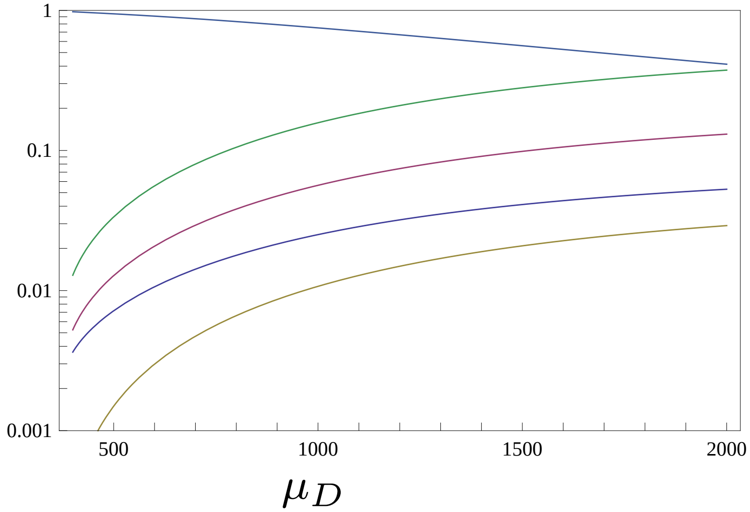
- The effective Lagrangian that describes the interactions of these fields with the electromagnetic one is given by

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

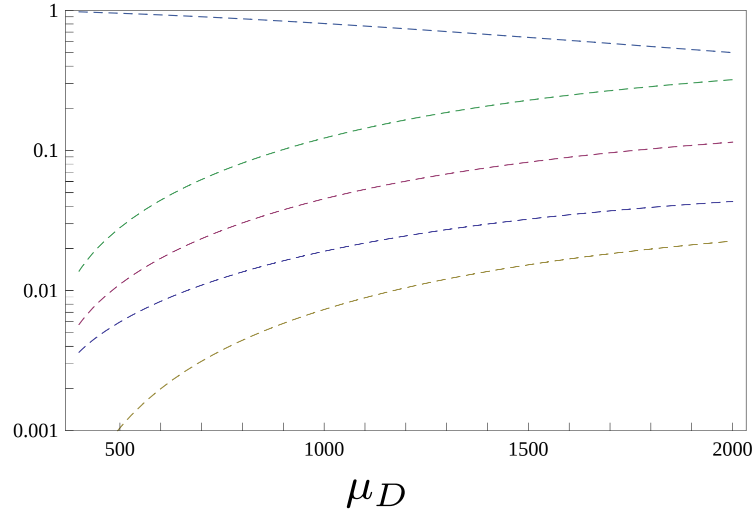
$$c^\gamma_\alpha = c_{1\alpha} \cos^2\theta_W + c_{2\alpha} \sin^2\theta_W \,, \qquad \tilde{c}^\gamma_\alpha = \tilde{c}_{1\alpha} \cos^2\theta_W + \tilde{c}_{2\alpha} \sin^2\theta_W \,.$$

- At the LHC the exotic states N_α and A_α are mainly produced through gluon fusion.

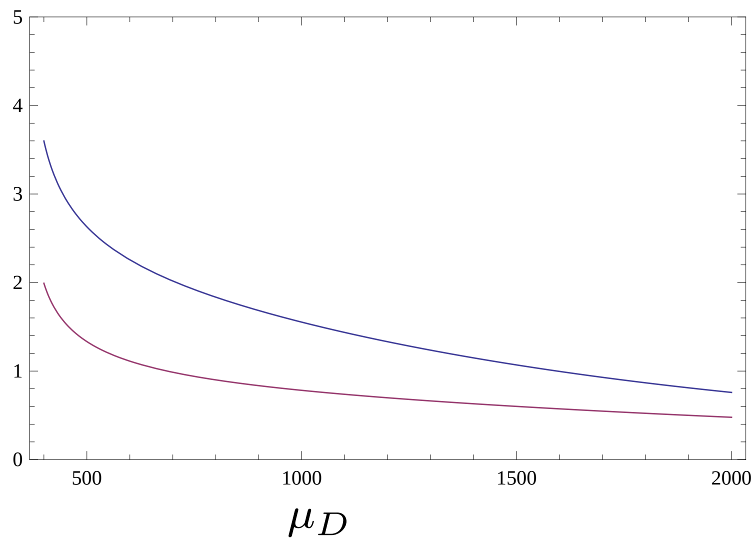
BR$(A_1 \to gg, WW, ZZ, \gamma\gamma, \gamma Z)$



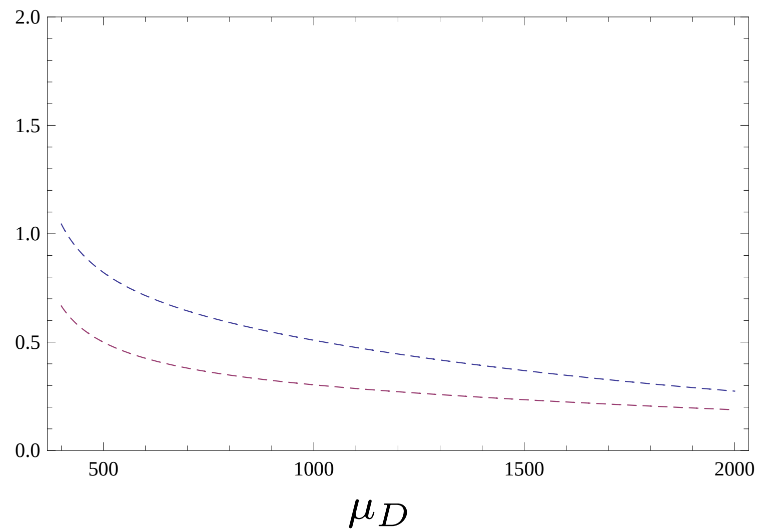
BR$(N_1 \to gg, WW, ZZ, \gamma\gamma, \gamma Z)$



$\sigma(pp \to A_1 \to \gamma\gamma)$[fb]



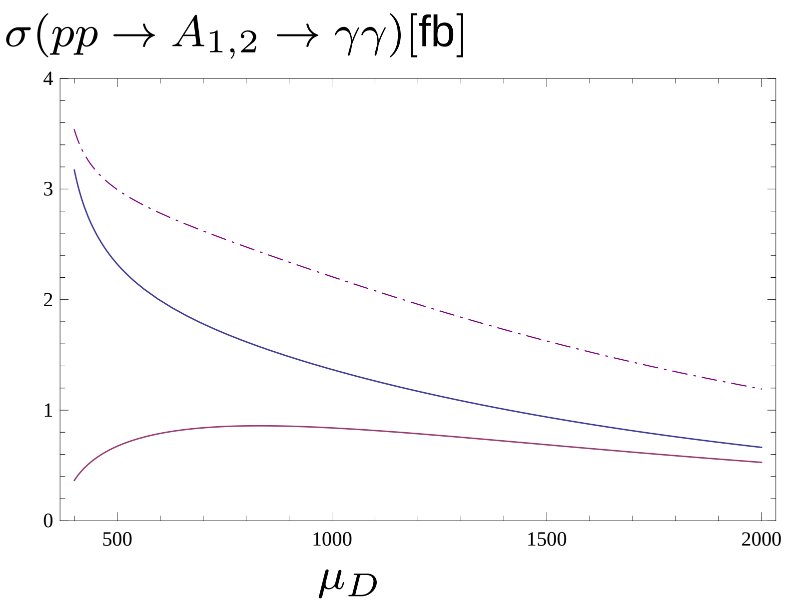
$\sigma(pp \to N_1 \to \gamma\gamma)$[fb]

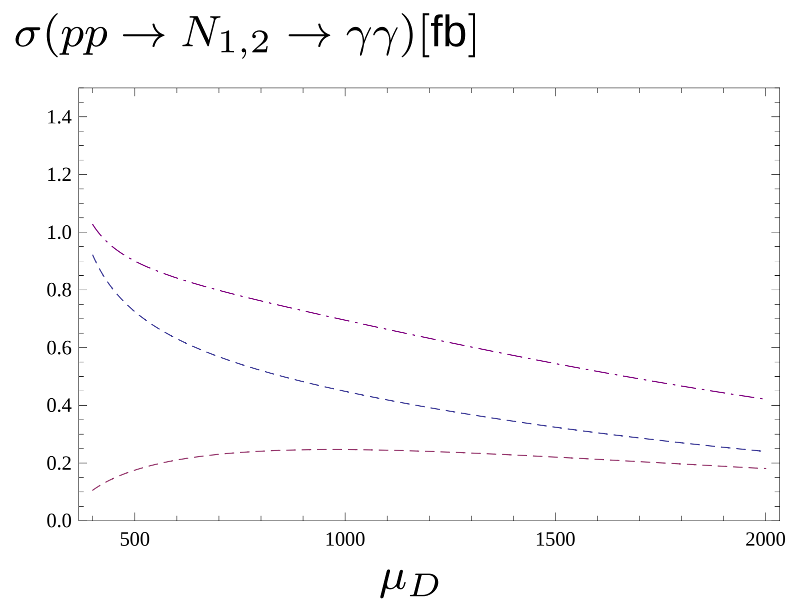


- Here we set $\mu_{D_i} = \mu_D$, $\mu_{H_\alpha} = \mu_H \simeq 400$ GeV and $\lambda_{\alpha 1} = \kappa_{i1} = 0.6$.
- The states A_1 and N_1 decay mainly into a pair of gluons.
- The branching ratios of $A_1(N_1) \to WW$ and $A_1(N_1) \to ZZ$ are the second and third largest ones.
- The branching 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 $\mu_D \simeq 400$ GeV.

- The presence of two nearly degenerate resonances may also explain why the analysis performed by the ATLAS collaboration leads to large width (~ 45 GeV).
- Unfortunately, the cross sections mentioned above decreases substantially with increasing μ_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 $\lambda_{\alpha 1} = \kappa_{i2} \lesssim 0.8$.
- Assuming maximal mixing between A_1 and A_2 as well as N_1 and N_2 we find that $\sigma(pp \to \gamma\gamma)$ can vary from 4.5 fb to 3 fb when $\mu_D = 400 - 1000$ GeV for $\mu_H \simeq 400$ 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 γZ are expected to be observable at the $13-14$ TeV LHC.





Conclusions

- Over last ten years several variants of the E_6SSM have been considered.
- Recently we studied the modification of the E_6SSM 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 γZ.

Backup slide

- Assuming that D and $\overline{D}$ couple most strongly with the third family quarks and leptons the exotic quarks decay into
  - $\overline{D} \to t + b + \chi_1^0$ if exotic quarks are diquarks;
  - $D \to t + \tau + \chi_1^0$ and $D \to \nu_\tau + b + \chi_1^0$ if exotic quarks are leptoquarks.
- Thus the presence of light exotic quarks should result in enhancement of the cross sections of
  - $pp \to t\bar{t}b\bar{b} + E_T^{miss} + X$ if exotic quarks are diquarks;
  - $pp \to t\bar{t}l\bar{l} + E_T^{miss} + X$ if new quark states are leptoquarks.