Interpretations of the LHC 750 GeV Diphoton Signal

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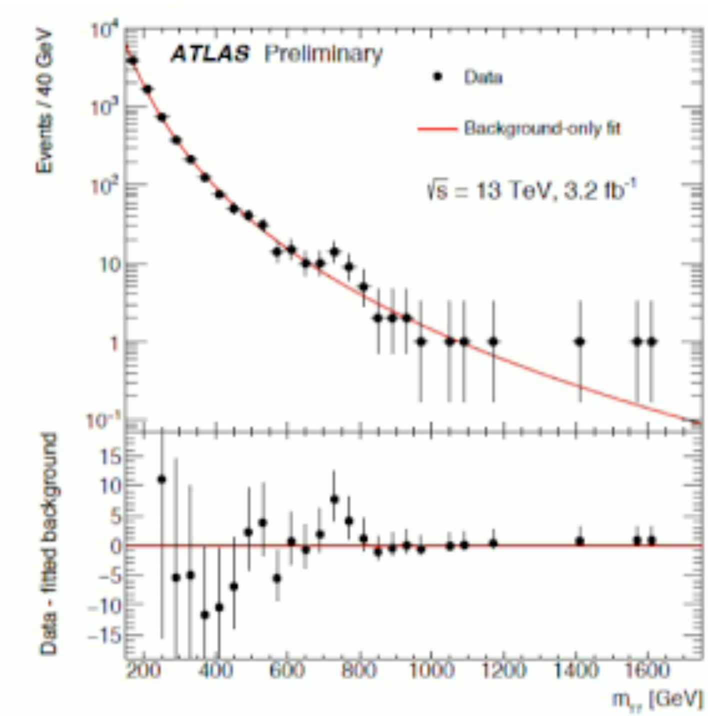
General Remarks

- You have heard from the previous presentation, the properties of the singal
- The search is inclusive, and all the information we have is the presence of a resonance at 750 GeV, with a production cross section times branching ratio into photons of about 5 to 10 fb.
- The first thing you do in these cases is to check what was the situation at the 8 TeV run, where ATLAS saw no signal



$$\sigma(pp \to S \to \gamma\gamma)_{\rm ATLAS} = 10 \pm 2.8 \text{ fb}$$

$$\sigma(pp \to S \to \gamma\gamma)_{\rm CMS} = 6.5 \pm 3.5 \text{ fb}$$

Limits extracted from 8 TeV, assuming gluon fusion producion by rescaling gluon gluon parton luminosities

$$\sigma(pp \to S \to \gamma\gamma)_{\rm ATLAS} < 11.8 \text{ fb}$$

So, there is marginal consistency between the run I and run II data

Two Higgs Doublet Models

- Second thing you do, is to check the simplest case, namely the addition of a new doublet

- In two Higgs doublet models, there are new CP-even H and CP-odd Higgs A, that can be produced and decay into photons

- The production cross sections are sizable, at 13 TeV and depend on the difference of the square of the ratio of the top coupling to the SM coupling

$$\sigma(gg \to H) = \kappa_t^2 \ 600 \text{ fb}$$
$$\sigma(gg \to A) = \kappa_t^2 \ 850 \text{ fb}$$

- But since these Higgs bosons can decay into top quarks and/or gauge bosons at tree level, the branching ratio is three orders of magnitude too small

$$BR(H \to \gamma\gamma) \simeq 4 \ 10^{-6}$$
$$BR(A \to \gamma\gamma) \simeq 5 \ 10^{-6}$$

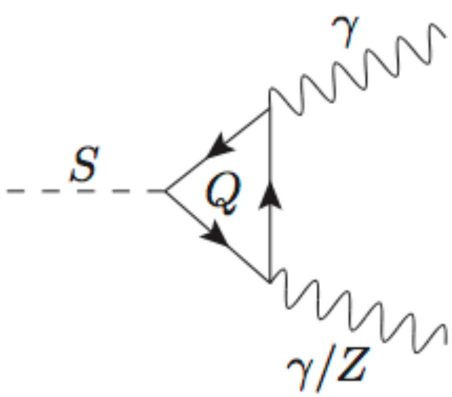
- In the above I assume a prominent decay of the Higgs bosons to top quarks, and then the Branching ratio depends weakly on κ_t

- One can now try to raise the value of κ_t, but perturbativity can only allow you to increase the cross section up to about 0.1 fb. Unless you add extra matter, this idea is dead !

Singlets

- Since the problem is associated with the decay into SM gauge bosons and fermions, one should consider singlets, since they don't couple to these particles at tree level.
- CP-even singlet particles, however, will generically mix with the SM Higgs, unless a condition of somewhat precise Higgs alignment is fulfilled.
- On the other hand, CP-odd singlets do not mix with the SM Higgs and therefore are the most natural candidates for this
- But, wait a second ! How are they effective couplings to gluons and photons goind to be produced ?
- The obvious trick is to add new new vector-like fermions to the theory.

$$\mathcal{L} = -M\bar{\Psi}\Psi - g_f \bar{\Psi} i\gamma_5 \Psi A_S$$



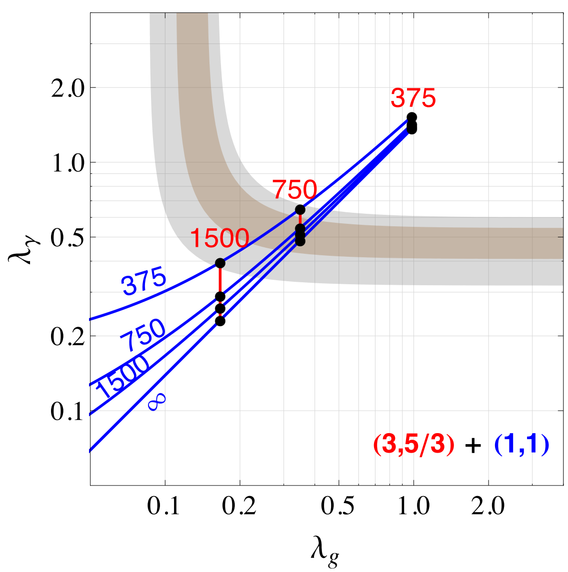
- Depending on their quantum numbers, they will induce decays into different gauge bosons !
- The rate is suppressed by the fermion masses, so a delicate balance must be achieved between couplings and masses.

Gauge Invariance

- From the point of view of gauge invariance, the coupling of singlets to gauge bosons will be obtained via loop processes and is given by

$$\mathcal{L} \supset \lambda_g \frac{\alpha_s}{12\pi v_W} S G^a_{\mu\nu} G^a_{\mu\nu} + \lambda_B \frac{\alpha}{\pi c_W^2 v_W} S B_{\mu\nu} B^{\mu\nu} + \lambda_W \frac{\alpha}{\pi s_W^2 v_W} S W^a_{\mu\nu} W^{a\mu\nu},$$

- The coefficients are proportional to the coupling of the singlet to fermions, to the square of their charges and to the ratio of the Higgs vev to the fermion masses. To maximize the effect, one could avoid weak eigenstates and leave decays into gluons, Z and photons.



Altmannshofer, Galloway, Gori Kagan, Martin, Zupan'15

Optimized case of a charge 5/3 vector like quark and a charge one vector like lepton.

The coupling of fermions to the singlet has been fixed to one

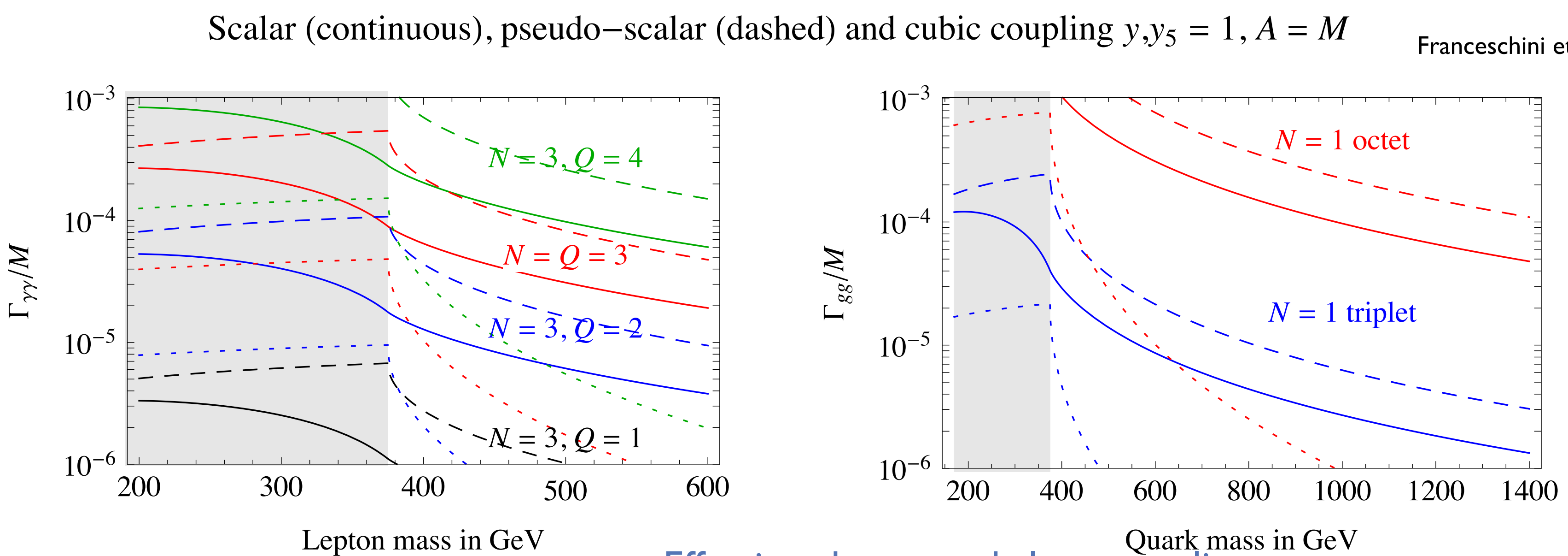
Masses of the order of the TeV scale leads to the right interpretation

Decays into gluon an Z's also induced and depend on the masses of the two added states.

Width of Scalar and pseudoscalars coupled to fermions

$$S\bar{\mathcal{Q}}_f(y_f + i\,y_{5f}\gamma_5)\mathcal{Q}_f + SA_s\tilde{\mathcal{Q}}_s^*\tilde{\mathcal{Q}}_s$$

Franceschini et al'15



Effective photon and gluon coupling

$$g_{S\gamma\gamma} \simeq \frac{NQ^2\alpha\, y_f}{4\pi m_f}$$

$$g_{Sgg} \simeq \frac{y_f C(r)\alpha_s}{4\pi m_f}$$

For doublets a Higgs vev is necessary due to gauge invariance.
Since the coupling is dimensional, the width

$$\Gamma(S\to\gamma\gamma) \propto M_S^3 \frac{g^2_{S\gamma\gamma}}{16\pi}$$

Comments

- The introduction of a singlet and vector like fermions is a predominant theme in the many papers that have been written in the literature. It is one of the most obvious ones

- The addition is add-hoc, and can be done also in supersymmetry. For instance, Hall and Nomura, added to the MSSM a singlet coupled to vector like fermions. The singlet had not couplings to any of the MSSM fields and hence is just introduced to fix the data without andy particular motivation for being there

$$W_{\rm eff} = W_{\rm MSSM} + S \sum_i \lambda_i \, \Phi_i \bar{\Phi}_i + \frac{\mu_S}{2} S^2 + \mu_i \, \Phi_i \bar{\Phi}_i .$$

- Perhaps the only motivation for SUSY is the existence of a symmetry that solves the additional hierarchy problem associated with the second Higgs !

- This is different from an extension of the so-called NMSSM, since there is no coupling of S to the Higgs doublets !

- The branching ratio into gammas may be just extracted from the coefficient of the different operator, which follow from the quantum numbers of the particles in the loop. From there bounds on the masses of the particles in the loop may be obtained

Low, Lykken'15

Additional degrees of freedom in 2HDM

- As we saw, in 2HDM the rate is naturally too small. Can one add extra fermions to make it work ?
- Well, one can do it. But with some pain. One would have to go to regions of parameter were the top coupling is suppressed and the bottom is not too large. And for the fermions one should introduced couplings likes the one we introduced with P. Shwaller and A. Joglekar a few years ago to enhance the Higgs coupling to photons, namely

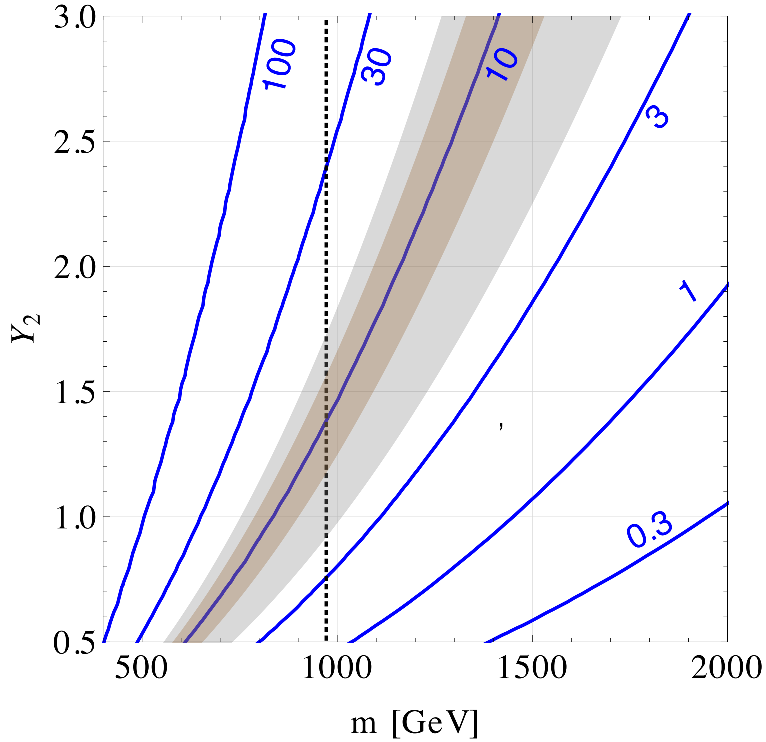
$$\mathcal{L} = -Y_1 H_1 \bar{Q}_L U_R - Y_2 H_2 \bar{Q}_R U_L + h.c.$$

- The advantage is that the effective operator is of the form

$$\frac{Y_1 Y_2 Q_1 Q_2 H_1 H_2}{m_f^2} F_{\mu\nu} F^{\mu\nu}$$

- This enhances the coupling of the Higgs that does not acquire expectation value, namely the non-standard Higgs bosons !
- So, one can take a type I Higgs model, where the top coupling is suppressed by tanbeta. The reduced coupling to the top still competes efficiently with the vector like quark effects and one needs high multiplicity of fermions..

In general, large values of tanβ,
large multiplicities and sizable charges and Yukawas needed



Altmannshofer, Gori, Kagan, Martiin, Zupan'15

Countors of cross sections, in fb, for 6 copies of vector like quarks of charge 5/3. $Y_1 = 0.4$

Theories tend to have Landau poles or instabilities in the potential. Better to enhance Y_2, related to the non-standard Higgs boson, in order to avoid large instabilities in standard Higgs potential.

MSSM

- Here we want to discuss the R-parity conserving MSSM. It is known that the Higgs sector in such a case is just a type II Higgs doublet sector

- So, for heavy superparticles, the constraints on the two Higgs doublet model will also apply to supersymmetry.

- One can imagine using sparticles to enhance either the loop induced production cross section or the branching ratio in to gammas. Moreover, sparticle can be heavier than half of the Higgs mass and then the Higgs will not decay into them.

- Two problems arise : The only sparticles that have large enough couplings are the third generation sfermions, and the loop induced processes are suppressed by the ratio of the Higgs vev to the square of the heavy sparticle masses.

- One can try to use large trilinear couplings to fulfill the role. Ideally, the effective operator must be of the form

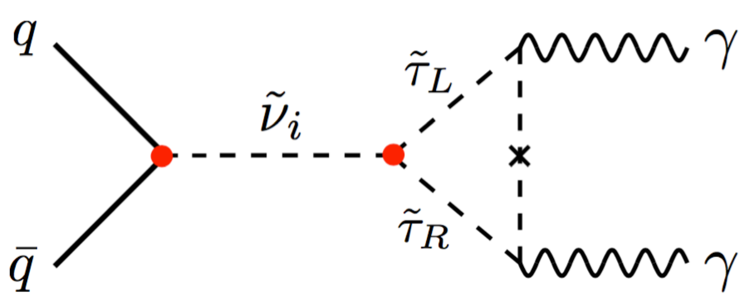
$$\mathcal{A}(H \to \gamma\gamma)_{\tilde{t}} / \mathcal{A}(H \to \gamma\gamma)_{\tilde{t}} \simeq \left(\frac{1}{2} \frac{m_t^2 \mu A_t}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2} \right)$$

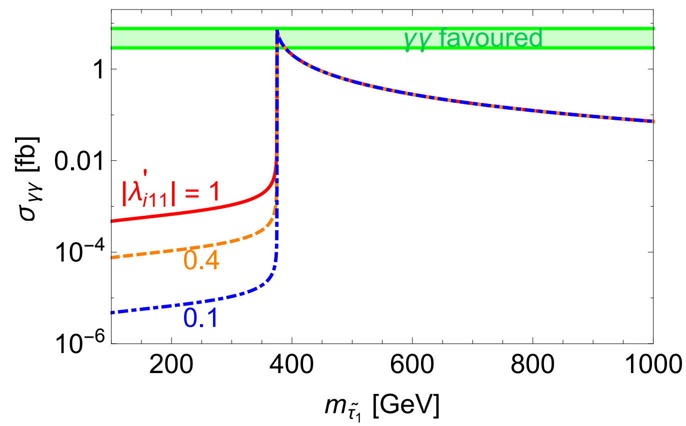
- It is impossible to push the parameters of the model to obtain the desired signal without inducing color breaking minima and/or large effects effects in the SM Higgs like particle

R-Parity Violation

- Here you can produce the resonance from quark annihilation and not gluon fusion and then the bounds are somewhat weakened
- The resonance would be a scalar neutrino, and it would decay into gammas via loops of charged and light staus. The dimensionful scalar coupling and the R-parity violating coupling must be adjusted

$$W_{\rm LV} \;=\; \lambda'_{i11} L_i Q_1 \bar{D}_1 \qquad\qquad \mathcal{L}^{\rm soft}_{\rm LV} \;=\; A_{i33}\tilde{\ell}_i \tilde{\ell}_3 \tilde{\tau}^+_R + ({\rm H.c.})$$





Allanach et al'15

- Here the dimensionful scalar coupling was set to be 14 times the stau mass, that is when the theory breaks unitarity, and yet can only be done in a very narrow region of parameters
- I think this explanation is really difficult to swallow and unlikely to be true.

Low Energy SUSY Breaking

Peterson, Torre'15; Casas, Espinosa'15

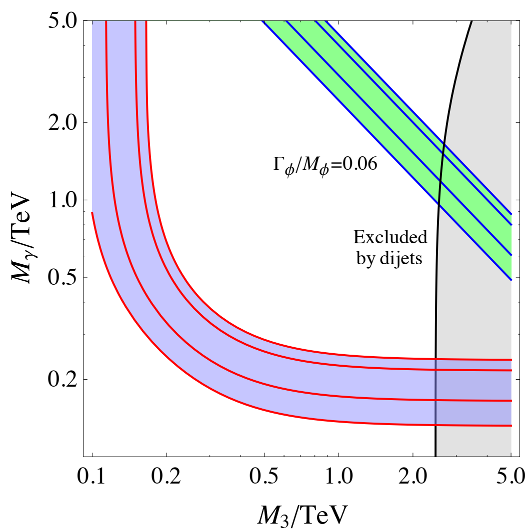
- A chiral field responsible for the gauge kinetic term, via a vev of its auxiliary component

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

$$\mathcal{L} \supset \frac{M_3}{2\sqrt{2}F}\ \mathrm{tr}\ G^a_{\mu\nu}(\phi_S G^{a\mu\nu} - i\phi_P \tilde{G}^{a\mu\nu})\ +\ \frac{M_{\tilde{\gamma}}}{2\sqrt{2}F}\ \mathrm{tr}\ F_{\mu\nu}(\phi_S F^{\mu\nu} - i\phi_P \tilde{F}^{\mu\nu})$$

- Couplings proportional to gaugino masses and inversely proportional to the square of the supersymmetry breaking scale

- Obviously, for this explanation to be true, the SUSY breaking scale must be of order of a few TeV ! (gravitino couplings will also relevant)



Here we fix the SUSY breaking scale to be as low as 4 TeV

Blue band is were the signal is reproduced
Green band gives a large width

An effective larger width may be obtained by splitting the scalar and psudoscalar components

I don't know of any realistic scenario realizing this possibility, but is something to consider.

Are there SUSY alternatives ?

- Again, so far in the literature the only alternative to these ones is NMSSM with vector like quarks and/or leptons
- Why are they there ? Maybe a remnant of E6 unification
- Remember that a 27 of E6 has a generation plus a 5 a 5bar and a singlet !
- This may work, but demands alignment of the singlets, namely small mixing with the doublets and/or large charges and multiplicities.
- But maybe we are looking at it wrongly, and the production is not via gluon fusion but from cascade decays
- The question is what comes with the scalars in this case
- In any case, no weakly interacting model presented so far is particularly well motivated, but maybe that is the way it should go....