Possible 750 GeV diphoton signal via light pseudoscalars

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with C. Hugonie, arXiv:1602.03344,

see also F. Domingo et al., arXiv:1602.07691

Data ($\lesssim$ Moriond 2016):

- ATLAS at 13 TeV, 710 GeV $< M_{\gamma\gamma} <$ 790 GeV (two bins):
  21 events vs. 11.3 expected; local excess 3.9 σ (2.0 σ incl. LLE);
  compatible with 8 TeV at the 1.2 σ level (assuming ggF)

- CMS at 13 TeV, 750 GeV $< M_{\gamma\gamma} <$ 770 GeV (one bin):
  11 events vs. 5.4 expected; local excess 2.8 σ ($\sim$ 1 σ incl. LLE);
  combined with 8 TeV: local excess 3.4 σ (1.6 σ incl. LLE)

- Signal cross sections of $\sim 3 - 8$ fb would explain the excesses

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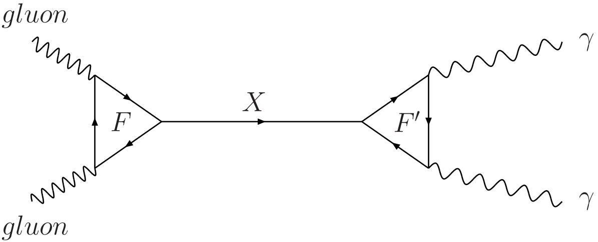
"Standard" interpretation:



- X: Scalar or pseudoscalar (possibly composite) with $M_X \sim 750$ GeV
- Coupling to gluons through loops of coloured fermions F
- Coupling to photons through loops of charged fermions F' ($\sim F$?)
- Possibly a large width ($\gtrsim$ a few GeV) in order to explain the ATLAS data

Challenges:

- Need large (loop induced) production cross section
  $\rightarrow$ need large ($\sim$ non-perturbative) XFF Yukawa coupling

- Need large (loop induced) width into $\gamma\gamma$
  $\rightarrow$ need large ($\sim$ non-perturbative) $XF'F'$ Yukawa coupling

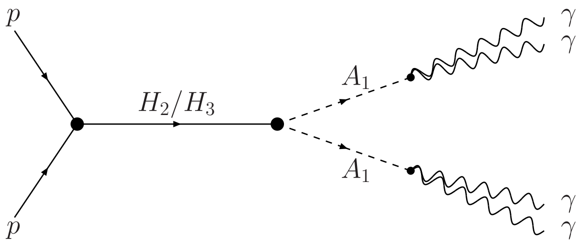
- Tree level decays of X must be (practically) forbidden, otherwise the loop induced decay into $\gamma\gamma$ would have a too small branching fraction
  $\rightarrow$ X must not couple to Standard Model fermions (or Higgs), the new fermions F (F') must be heavier than $M_X/2 \sim 375$ GeV

- A large width into $\gamma\gamma$ is tough to get...

- $\gtrsim 200$ BSM scenarios of this type... (more than events)

Alternative scenario with light pseudoscalars A_1:

(S. Knapen et al., P. Agrawal et al., J. Chang et al., ...)



Viable if $M_{A_1} \lesssim 800$ MeV; then the photons from A_1 decays are sufficiently collimated such that they appear (mostly) as a single photon in the electromagnetic calorimeters (see below)

Constraints on resonance(s) $H_{(i)}$ at $\approx$ 750 GeV:

- Sufficient production cross section in *ggF* or ass. prod. with *b*-quarks
- Large branching fraction into $A_1 A_1$

Constraints on a light pseudoscalar A_1 below $\approx$ 800 MeV:

- Not ruled out by low energy experiments
- Large branching fraction into $\gamma\gamma$
- Decay length $\lesssim 1$ m, preferably shorter

A concrete scenario: the NMSSM

featuring 3 scalars $H_{1,2,3}$ and two pseudoscalars $A_{1,2}$

With H_1 = SM-Higgs at 125 GeV:
Two candidates for scalar(s) H_2/H_3 at ≈ 750 GeV:

— the "MSSM-like" scalar H with potentially large production cross section via bbH if $\tan\beta \gtrsim 10$

— the singlet-like scalar H_S with potentially large branching fraction into singlet-like $A_1 A_1$ (A_2 is the MSSM-like pseudoscalar with $M_{A_2} \sim M_H$)

$\longrightarrow$ Best solution: both scalars have masses of ≈ 750 GeV,
H and H_S mix strongly and form H_2/H_3;
two nearby narrow states can imitate a large width as seen by ATLAS

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A light pseudoscalar A_1 can be a (pseudo-) Goldstone boson of an R-symmetry
($\leftrightarrow$ small trilinear couplings A_λ, A_κ in the scalar potential);

Impossible in the MSSM where the μ-term breaks R-symmetry;
in the NMSSM, μ is replaced by the vev of a singlet field S
$\longrightarrow$ a (weakly broken) R-symmetry is possible

But: Broken by radiative corrections $\sim A_{top}$, gaugino masses
$\longrightarrow$ Tuning is still required for $M_{A_1} \lesssim 800$ MeV

Possible A_1 masses satisfying the above constraints:

(1) $M_{A_1} \sim M_{\pi^0} \sim 135$ MeV (Domingo et al., arXiv:1602.07691):

— A_1 mixes with π^0, hence A_1 decays with a similar width (short decay length) into $\gamma\gamma$; calculable using PCAC

Heavier A_1: 135 MeV $< M_{A_1} < 2m_\mu$:

— Susy loops generate flavour changing couplings of the extra (MSSM-like) Higgs bosons, hence also for A_1 (through mixing with the MSSM-like A_2)

$\rightarrow$ dangerous rare decays $K^\pm \to \pi^\pm e^+ e^-$ (less constraining: $B^\pm \to K^\pm e^+ e^-$) unless the soft Susy breaking terms are chosen such that contributions to flavour changing couplings cancel, which is possible (see arXiv:1602.07691)

— A_1 decays dominantly into e^+e^- with a decay length $\gtrsim 40$ m $\longrightarrow$ useless

(2) $M_{A_1} \lesssim 2m_\mu \sim 211$ MeV (U.E., C. Hugonie, arXiv:1602.03344):

— The muon loop induced BR into $\gamma\gamma$ is enhanced up to $\sim 75\%$ if M_{A_1} is just below the threshold (see A. Bharucha et al., arXiv:1603.04464)

— The decay length is reduced to 2–5 m, but the production cross section can be large enough such that enough $A_1 \to \gamma\gamma$ decays take place before the EM calorimeter

— Soft Susy breaking terms have to be chosen such that flavour changing couplings are cancelled

$M_{A_1} \gtrsim 500$ MeV: Constraints from rare K decays disappear

(3) $M_{A_1} \sim 510$ MeV (U.E., C. Hugonie, arXiv:1602.03344):

— At the parton level, the dominant decays of A_1 are into $s\bar{s}$ and gluons

— But: one is still in the nonperturbative regime of QCD
Best guess: $s\bar{s}$ and $F\widetilde{F}_{(QCD)}$ act as interpolating fields;
these are part of the η wave function in Fock space ($M_\eta \sim 548$ MeV),
hence A_1 decays like the η meson:
$BR(\eta \to \gamma\gamma) \sim 39\%$, $BR(\eta \to 3\pi^0) \sim 33\%$, $BR(\eta \to \pi^+\pi^-\pi^0) \sim 23\%$

→ $BR(A_1 \to \gamma\gamma) \sim 39\%$, $BR(A_1 \to 3\pi^0 \to 6\gamma) \sim 33\%$
with a decay length below 1 mm (?to be confirmed?)

— Dominant constraint: Now from searches for $\Upsilon(1S) \to \gamma\,\eta$ decays by CLEO
where no events were seen
(but 2 events for $M_{\pi^+\pi^-\pi^0} \sim 510$ MeV in the $\eta \to \pi^+\pi^-\pi^0$ search channel)
→ constraints on the coupling $A_1 b\bar{b}$;
if too large, CLEO would have observed $\Upsilon(1S) \to \gamma\, A_1 \to 3\pi^0$ decays

— These constrain the $BR(H_{2,3} \to A_1 A_1)$, still:
a signal cross section up to 6.7 fb is possible[1]

[1] Modulo acceptance of multiphotons as a single photon, see below

(4) $M_{A_1} \sim M_\eta \sim 550$ MeV (U.E., C. Hugonie, arXiv:1602.03344):

— A_1 mixes strongly with the η meson, its corresponding branching fractions are no longer educated guesses (calculable using PCAC)

— But: Constraints from CLEO from unseen $\Upsilon(1S) \to \gamma\, A_1$ decays are somewhat stronger, still:

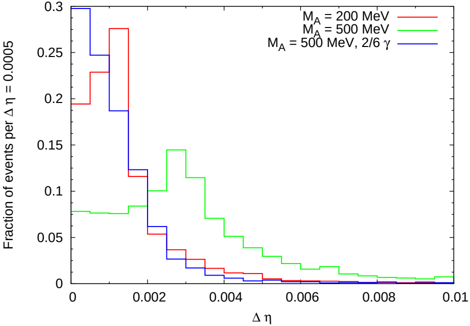
a signal cross section up to 3.4 fb is possible[2]

These - and a recent MSSM scenario with $M_{\text{stop}} \sim 375$ GeV by A. Djouadi and A. Pilaftis - are the only known scenarios for the 750 GeV diphoton excess without extra "ad hoc" fermions, but based on known Susy extension of the SM

[2]Modulo acceptance of multiphotons as a single photon, see below

If the excess of events persists, these scenarios can be distinguished (or ruled out) experimentally:

- The fineness of first layer of cells of the EM calorimeter along η (rapidity, the angle along the beam axis) ranges from 0.003 to 0.006 (ATLAS); the spread of in $\Delta\eta$ of multiphotons depends on M_{A_1}:
  (2/6 γ denote the two leading among 6 photons from $3\pi^0$)



$\rightarrow$This plot helps to estimate the acceptances for multiphotons to fake a single photon: $\sim 80\%$ for $M_A \sim 200$ MeV or 2/6 γ, $\sim 30\%$ for $M_A \sim 200$ MeV

- If $M_{A_1} \sim 211$ MeV: The A_1 decay length is macroscopic, and A_1 may decay inside the EM calorimeters
(before the EM calorimeters, the $A_1 \to \gamma\gamma$ vertex is invisible)

- The photons can convert in the material before the EM calorimeter leading to electrons which are visible, but usually added to the photon signal in the EM (20% for rapidity $\eta \sim 0$ to 45% for $\eta \sim 1.6$)
$\to$ photon-jets lead to more converted photons than a single photon
$\to$ one can potentially distinguish single photons from collinear diphotons or, in the case $A_1 \to 3\pi^0 \to 6\gamma$, from collinear 6 photons (B. Dasgupta et al., arXiv:1602.04692) iff the A_1 decays occur inside the material

- If the signal originates from two nearby states H_2/H_3, their masses can potentially be separated (depending on the actual H_2/H_3 mass splitting)

$\to$With more data, the different scenarios can be distinguished!

Exciting times may lie ahead of us!