1. A new resonance at 750 GeV?
2. First interpretations: singlet or doublet?
3. Implications for the resonance and additional matter
4. Summary

Based on (but representative of the >200 papers on the subject):
A. Angelescu, G. Moreau, AD: 2HDMs/MSSM+VLFs, arXiv:1512.04921
A. Bharucha, A. Goudelis, AD: threshold enhancement, 1603.04464
1. A new resonance at 750 GeV?

ATLAS di-photon results:
3.9σ local excess at 13 TeV
(and now about 2σ from 8 TeV).

CMS di-photon results:
3.4σ local excess at 8+13TeV
(improvement since December).

Following Alessandro Strumia:
the biggest discovery since decades?
the mother of statistical fluctuations?

Moriond-QCD, 19/03/2016
1. A new resonance at 750 GeV?

**Experimentalists:**
Too early to claim anything... it is only three poor sigmas!

**And?**

**Poor theorists:**
Waiting for new physics for 30 years, and recently started to get desperate... and something interesting appears.

and if you insist a little bit:

**So do your job and collect data (and leave the theorists enjoy!)**

We do our job and interpret data!
Even more: look at far implications!
1. A new resonance at 750 GeV?

Tsunami of theory papers trying to interpret the 750 GeV diphotons:
10 papers the very first day,
100 at the end of the year,
about 250 papers as of today..

Nature article/Dorigo/Jester blogs:

Florilège of explanations:
– cascading heavy quarks,
– collimated 2x2 photons,
– new gauge bosons $Z'+X$
– sgoldstinos and other SUSY,
– quirks, hidden valleys?
– statistical fluctuation...

But most papers are talking about a new heavy resonance:
– Dark matter mediators
– Technipions/Goldstones, ..
– Axions, radions/dilatons,..
– Gravitons or any spin 2...
– Higgs bosons...

and other possibilities...

I try a quick/basic interpretation
(adding a little to Alessandro...)
2. First interpretations: singlet or doublet

So was is this diphoton resonance?

- Landau–Yang theorem: spin 0 or 2
- more likely spin–0 (own prejudice?)
- does it come from initial gg or $q\bar{q}$?
- to cope with 8 TeV data better be gg

Couples to gg via heavy particles like a Higgs: baptize it $\Phi \equiv H$ or $A$.

- $\Phi$ production cross section large:
  $\Rightarrow \sigma(gg \rightarrow \Phi \rightarrow \gamma\gamma) = 6 \pm 2$ fb
- $\Phi$ width? conflicting statements:
  ATLAS prefers large, CMS narrow.

The $\Phi\gamma\gamma$ (and $\Phi gg$) couplings induced by heavy “fermion” loops:

For large enough loop contributions, we need (maybe even simultaneously):

- large Yukawas (perturbativity?),
- big electric charge (dileptons, more?),
- $m_F \approx \frac{1}{2} M_{\Phi}$ (and more enhanced?),
- many copies (so not really minimal)...
2. First interpretations: singlet or doublet

Narrow width (as in CMS?): $\Phi$ couples only via loops, also to WW, ZZ, $Z\gamma$

In addition, one has $m_F \gtrsim \frac{1}{2} M_\Phi$ so that there are no decays $\Phi \rightarrow f\bar{f}, \bar{F}F$

Effective Lagrangian approach with the field strengths and their duals:

$$\mathcal{L}^{S/P}_{\text{eff}} = \frac{e^2}{4v} c_{\Phi\gamma\gamma} \Phi F_{\mu\nu} F^{\mu\nu} / \tilde{F}^{\mu\nu} + \frac{g_s^2}{4v} c_{\Phi gg} \Phi G_{\mu\nu} G^{\mu\nu} / \tilde{G}^{\mu\nu}$$

$$\text{BR}(\Phi \rightarrow \gamma\gamma) = \frac{\Gamma(\Phi \rightarrow \gamma\gamma)}{\Gamma(\Phi \rightarrow \gamma\gamma) + \Gamma(\Phi \rightarrow gg)} \approx \frac{\Gamma(\Phi \rightarrow \gamma\gamma)}{\Gamma(\Phi \rightarrow gg)} \approx \frac{c_{\Phi\gamma\gamma}^2}{c_{\Phi gg}^2} \frac{\alpha}{8\alpha_s} \approx 10^{-2}$$

Only vector-like fermion loops,

discuss several possibilities:

**model 1**: an $e_Q = \frac{2}{3} T_{R,L}$ singlet.

**model 2**: $e_Q = \frac{2}{3}, -\frac{1}{3} (U, D)_{R,L}$.


LHC $\Phi$ crosssection reproduced for perturbative cplgs $\lambda^2 / 4\pi < \frac{1}{2}$

and not too large VLF masses...
2. First interpretations: singlet or doublet

Large width scenario (as in ATLAS?): \( \Phi \) couples directly to heavy particles:

- the couplings to W/Z bosons: all eaten by the SM-like 125 GeV \( h \) state,
- only fermion couplings allowed: either tops, bottoms, or new ones...

Best way to describe large width option: the (perturbative!) 2HDM/MSSM

\[
H_1 = \left( \begin{array}{c} H_0^1 \\ H_1^- \end{array} \right), \quad H_2 = \left( \begin{array}{c} H_0^2 \\ H_2^- \end{array} \right)
\]

\( \longrightarrow \) 5 physical states: \( h, H, A, H^\pm \)

General 2HDM: 6+1 free parameters: \( \tan \beta, \alpha, M_h, M_H, M_A, M_{H^\pm}, m_{12} \)

MSSM: two parameters at tree-level: \( \tan \beta, M_A \) but rad. cor. important:

- \( M_h \lesssim M_Z |\cos 2\beta| + r c \lesssim 130 \text{ GeV} \), \( M_H \approx M_A \approx M_{H^\pm} \lesssim M_{\text{EWSB}} \)
- \( h/H \) VV couplings suppressed by \( \sin/cos(\beta - \alpha) \); no AVV couplings.

Decoupling/alignement of MSSM/2HDM: \( \alpha = \beta - \frac{1}{2}\pi \Rightarrow h \) SM-like and \( H/A \) have only couplings to (3d generation) fermions and they are similar (decoupling limit of MSSM: also \( M_A \approx M_H \approx M_{H^\pm} \gg M_Z \) and \( h \) light)

one SM-like light \( h \) and two CP-odd like heavy \( H/A \) with cplg to \( t, b, \tau \) only

Here we will assume: \( \Rightarrow h \equiv H_{\text{SM}} , \Phi = H, A \)
2. First interpretations: singlet or doublet

H and A couplings to 3d generation fermions with $1 \lesssim \tan \beta = \frac{v_2}{v_1} \lesssim 60$

$g_{\Phi tt} = \frac{m_t}{v} \cot \beta$, $g_{\Phi bb} = \frac{m_b}{v} \tan \beta$, $g_{\Phi \tau \tau} = \frac{m_\tau}{v} \tan \beta$

- $\tan \beta \approx 60$: $\text{BR}(\Phi \rightarrow b\bar{b}) \approx 0.9$, $\text{BR}(\gamma\gamma) \approx 10^{-7}$, $\Gamma_{\Phi} \approx 30$ GeV
  but area $\tan \beta \gtrsim 20$ excluded by $gg/bb \rightarrow H/A \rightarrow \tau\tau$ searches.

- $\tan \beta \approx 3 - 10$: should allow for extra decays to get $\Gamma_{\Phi} \approx 30$ GeV:
  DM neutral lepton with $m_N \lesssim \frac{1}{2}M_\Phi$ and $y_N \approx 1$ makes it exactly.

- $\tan \beta \approx 1$: $\text{BR}(\Phi \rightarrow t\bar{t}) \approx 1$, $\text{BR}(\gamma\gamma) \approx 10^{-5}$, $\Gamma_{\Phi} \approx 30$ GeV:
  seems most reasonable possibility as both width and $\text{BR}(\gamma\gamma)$ largest.
2. First interpretations: singlet or doublet

Unfortunately 2HDM/MSSM\(^\ast\) with no new particle does not make it.

**Rates for** \(gg \to \Phi \to \gamma \gamma\):

\[
\begin{align*}
\sigma(H) &= 0.85 \text{ fb at 13 TeV} \\
\text{BR}(H \to \gamma \gamma) &\approx 6 \times 10^{-6} \\
\sigma(A) &= 1.70 \text{ fb at 13 TeV} \\
\text{BR}(A \to \gamma \gamma) &\approx 7 \times 10^{-6} \\
\sigma \times \text{BR}(H + A) &\approx 10^{-2} \text{ fb}
\end{align*}
\]

We are short by a factor 500...

**Include a bunch of VLFs:**

- 3 families of 2 VLL doublets
- 3 doubly charged leptons
- one family of VLQ and VLL (we set \(\tan \beta = 3\) to reduce \(\Gamma_\Phi\))

with usual Yukawa couplings optimal effect at \(m_F = \frac{1}{2} M_\Phi\) (but watch out for light Higgs!)

\(^\ast\)\(\chi^\pm\) threshold enhancement maybe?

Bharucha+Goudelis+AD:1603.1111.
3. Implications: singlet resonance at colliders

Reproduce Φ resonance in pp:
- same process \( gg \rightarrow Φ \rightarrow γγ \)
- grows with the gluon luminosity and extrapolation to high energy.

Future e+e- high E linear colliders can be turned into \( γγ \) colliders:
- 80% energy and same luminosity
- \( Φ \) production in \( γγ \)

Ideal for HE-LHC, FCC-hh, SPPC:
- 2 orders magnitude more at 100 TeV
- check other \( WW, ZZ, Zγ \) final states.

Ideal machine for diphoton state:
- measure precisely \( Φγγ \) coupling
- check resonance CP properties.
3. Implications: doublet resonance at colliders

Many more processes if $\Phi$ is in a 2HDM/hMSSM like scenario; in pp:

$$
\begin{align*}
\text{gg} &\rightarrow A \\
\text{pp} &\rightarrow t\bar{t}A/H \\
\text{gg} &\rightarrow AA \\
\text{gg} &\rightarrow HH \\
\text{q}\bar{q} &\rightarrow HA \\
\text{gg} &\rightarrow HA \\
\text{gg} &\rightarrow HZ \\
\text{gg} &\rightarrow HW \\
\text{q}\bar{q} &\rightarrow HZ \\
\end{align*}
$$
3. Implications: doublet resonance at colliders

Many more processes if $\Phi$ is in a 2HDM/hMSSM like scenario; in e$^+$$e^-$:

$$\sigma(e^+e^- \to \Phi + X) \ [fb]$$

$M_\Phi = 750$ GeV

$$\cos^2(\beta - \alpha) = 10^{-2}$$

$\sqrt{s}$ [TeV]
3. Implications: vector–like fermions

The vector–like fermions can be produced in pair or singly at colliders:

\[ V = Z, W \]

\[ q \rightarrow g^* \rightarrow Q, \bar{Q} \]

\[ e^+/\bar{q} \rightarrow V = \gamma, Z, W \rightarrow F \]

\[ e^-/q \rightarrow V = Z, W \rightarrow \bar{F} \]

\[ g \rightarrow q^* \rightarrow Q, \bar{Q} \]

\[ Q^* \rightarrow V \rightarrow Q \]

\[ g \rightarrow \bar{q} \rightarrow V \rightarrow q \]
3. Implications: vector–like fermions

First pair production of VLQs in pp and then single production via mixing:

\[ \sigma(\text{pp} \to \bar{Q}Q) \ [\text{pb}] \]
\[ \sqrt{s}=8,13,14,33,100 \ \text{TeV} \]
3. Implications: vector–like fermions

First pair production of VLQs in pp and then single production via mixing:

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<td>4</td>
<td>1.6 2.0 3.7 13.7</td>
<td>0.56 0.73 1.7 5.3</td>
</tr>
</tbody>
</table>

Table 1: Prospective model sensitivities to massive vector-like quarks (left) and leptons (right) [with the particle masses in TeV] in the indicated \( pp \) collider and scenario from extrapolations of the present LHC searches.
3. Implications: vector–like fermions

Pair production of VLLs in $e^+e^-$ and then single production via mixing:

\[
\begin{align*}
\left( I_3^F \right) F &= \left( \begin{array}{c} N \\nu_e \\bar{\nu}_e \end{array} \right) \\
\left( -\frac{1}{2} \right) L^+ &= \left( \begin{array}{c} \mu^+ \\
\tau^+ \end{array} \right) \\
\left( +\frac{1}{2} \right) L^- &= \left( \begin{array}{c} \mu^- \\
\tau^- \end{array} \right) \\
\left( 0 \right) L^- &= \left( \begin{array}{c} e^- \end{array} \right) \\
\left( +\frac{1}{2} \right) N &= \left( \begin{array}{c} \nu_e \end{array} \right)
\end{align*}
\]

\[
\sigma(e^+e^- \to \bar{L}L) \text{ [pb]} \\
m_L = 400 \text{ GeV}
\]

\[
\sigma(e^+e^- \to \bar{F}F) \text{ [pb]} \\
\sqrt{s} = 3 \text{ TeV}
\]

\[
\sigma(e^+e^- \to hL\bar{L}) \text{ [fb]} \\
M_h = 125 \text{ GeV} \\
m_L = 400 \text{ GeV}
\]

\[
\sigma(e^+e^- \to \bar{F}f) \text{ [pb]} \\
m_L = 400 \text{ GeV} \\
\zeta^2 = 10^{-2}
\]

3. Implications: Dark Matter

$\Phi$ resonance is ideal mediator for Dark Matter: case of lepton $N$ cosmological relic density $\Omega h^2$ obtained by annihilation $NN \rightarrow \Phi \rightarrow \text{SM}$.

Good prospects for direct/indirect detection in astrophysical experiments.
4. Summary

And? Too early to conclude... but life suddenly became bright...

It is really a new resonance? or simply another (big) mirage?

But again we should hear the experimentalists and their credo:

If true then the future is bright! a new continent is ahead and needs decades of exploration...

OK, OK, we wait for more data; in summer we will know more...

(in the meantime, let me “speculate” and have a glass of champagne?)