Shedding some light on the diphoton excess

Adrián Carmona

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Disclaimer

- The di-photon excess has triggered an incredible activity on the hep-ph comunity
- Do not expect a comprehensive summary from this talk!
- I will only try to illustrate some of the interesting questions introduced by the excess
- Apologies for the missing citations
- Even if current rumors are confirmed, we can still learn things for the future

What we know now

See M. Quittnat and F. Malek talks last Saturday!

- ATLAS reported a local significance of 3.9σ (3.8σ) for the spin-0 (spin-2) analysis, with a 2.1σ global significance arXiv:1606.03833
- CMS found a $2.8 - 2.9\sigma$ excess in the 13 TeV data that increased to 3.4σ after adding the 8 TeV one (1.6σ global) arXiv:1606.04093
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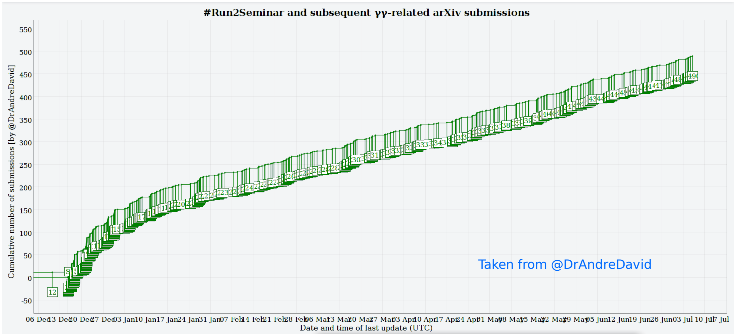

Open Questions

From the phenomenological point of view we still have a lot of open questions

- Resonance or not?
- Which production mechanism?
- Spin-0 or Spin-2?
- Singlet or Doublet?
- CP-even and/or CP-odd?
- Broad or narrow?

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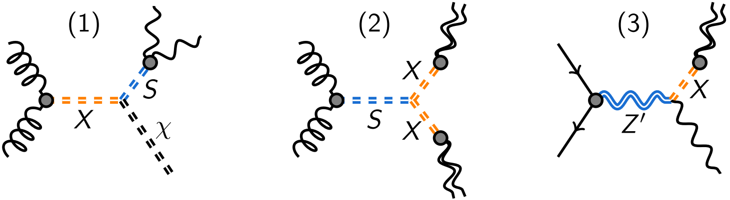
On the theory side, the main question is ... who order that?

More complicated kinematics



1. If χ is stable or decay to invisible stuff, the three-body decay can mimic a large width if $M_X \approx M_S + M_\chi$ 1512.04928, 1512.06113, 1512.08378, 1605.08772 ...

2. We can also pair produce X, which then decays to two collimed photons if $M_S \gg M_X$ 1512.04928, 1512.06083, 1512.06671, 1602.00949, 1605.01898, ...

3. We can also circunvent the Landau-Yang theorem if $M_{Z'} \gg M_X$ 1512.06833

An additional scalar singlet

At the dimension 5 level 1604.06446, 1604.07365, ...

$$\mathcal{L} \supset -(y_d^S)^{ij}\frac{S}{\Lambda}\bar{Q}_L^i H d_R^j - (y_u^S)^{ij}\frac{S}{\Lambda}\bar{Q}_L^i \tilde{H} u_R^j + \text{h.c.}$$
$$- \frac{S}{\Lambda}\frac{1}{16\pi^2}[g'^2 c_B^S B_{\mu\nu}B^{\mu\nu} + g^2 c_W^S W_{\mu\nu}^I W^{I\mu\nu} + g_S^2 c_G^S G_{\mu\nu}^a G^{a\mu\nu}]$$
$$- \frac{S}{\Lambda}\frac{1}{16\pi^2}[g'^2 \tilde{c}_B^S B_{\mu\nu}\tilde{B}^{\mu\nu} + g^2 \tilde{c}_W^S W_{\mu\nu}^I \tilde{W}^{I\mu\nu} + g_S^2 \tilde{c}_G^S G_{\mu\nu}^a \tilde{G}^{a\mu\nu}]$$
$$- \frac{S}{\Lambda}\left[c_{\lambda S} S^4 + c_{HS}|H|^2 S^2 + c_{\lambda H}|H|^4\right] + V_{\text{ren}}(H, S)$$

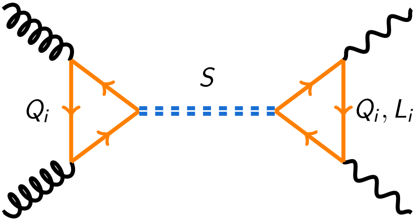
Compatibility with 8 TeV data

Channel	$u\bar{u}$	$d\bar{d}$	$s\bar{s}$	$c\bar{c}$	$b\bar{b}$	$\gamma\gamma$	gg
$\sigma_{13\,\text{TeV}}/\sigma_{8\,\text{TeV}}$	2.5	2.7	4.3	5.1	5.4	(4) 2	4.7

1512.04933, 1512.05751, 1512.05753, 1601.00638, ...

A vanilla model

One of the simplest explanations for the di-photon anomaly would be



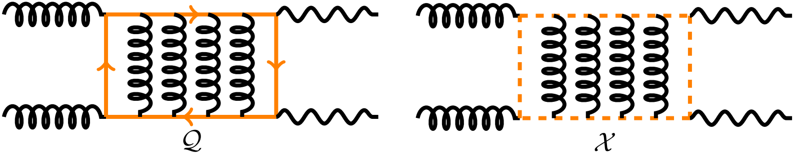
- In the narrow-width case, $\sigma_{\gamma\gamma}$ can be reproduced with $N_f \sim \mathcal{O}(1)$, $y_{SQQ} \sim y_{SLL} \sim 1$ and $m_{Q,L} \sim \mathcal{O}(1)$ TeV, e.g. [1512.07616]

  $2 \times (\mathbf{3}, \mathbf{1})_{2/3} \oplus 2 \times (\mathbf{1}, \mathbf{1})_1$ with $M_{Q,L} \sim (750, 1500)$ GeV and $y_{SFF} = 1$

- $\Gamma / M \sim 0.06$ requires large values of N_f and/or Q_f and/or y_{SFF}
  - VLFs enter $\beta_{g'}$ with $N_f Q_f^2$, bringing the Landau pole to lower energies
  - y_{SFF} and λ_S renormalize to larger values at high energy

'Known' strong dynamics

S could be a QCD bound state of heavy quarks $\mathcal{Q}\bar{\mathcal{Q}}$ or scalars $\mathcal{X}\bar{\mathcal{X}}$, with masses $M_{\mathcal{Q}} \approx M_{\mathcal{X}} \approx 1/2 M_S$ 1512.06670, 1602.08100, 1602.08819



One compelling candidate is a scalar $\mathcal{X} \sim (\mathbf{3}, \mathbf{1})_{-4/3}$, which gives $\sigma(gg \to \mathcal{X}\mathcal{X}^* \to \gamma\gamma) \sim 3 - 6\,\text{fb}$ [1602.08819]

$$\mathcal{L}_{\text{int}} = -\frac{c_{ij}}{2}\epsilon_{\alpha\beta\gamma}\mathcal{X}^{*\alpha}\bar{u}^{\beta}_{Ri}u^{\gamma C}_{Rj} + \text{h.c.}$$

and dijets $\mathcal{X} \to \bar{u}\bar{c}$, $\bar{t}\bar{u}$, $\bar{t}\bar{c}$

New strong dynamics

S could be also a bound state $\mathcal{Q}\mathcal{Q}$ of an additional $SU(N_{HC})$ 1512.07733, 1603.07719 1603.08802, ...

- Then, we can assume that $\Lambda_{HC} \lesssim M_{\mathcal{Q}}$ (vs $\Lambda_{QCD} \ll M_{\mathcal{Q}}$)
- Now, the value of the wave-function that controls the decay rate is set by $\alpha_{HC} > \alpha_S$, leading to larger xsecs
- However, now we also expect color-octet scalars almost degenerate in mass, leading to gg or $g\gamma$!

New strong dynamics

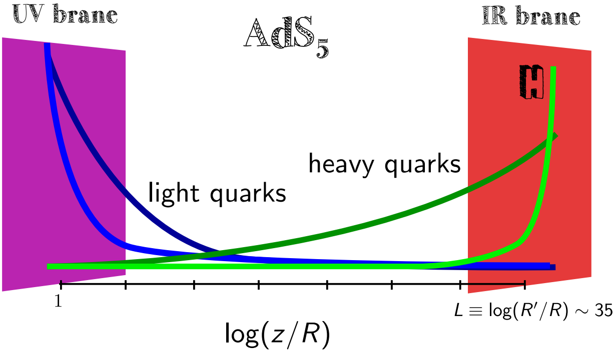
We could also have $m_{\mathcal{Q}} < \Lambda_{HC}$ and identify S with a pNGB arising from the spontaneous breaking of some global symmetry of the strong sector, something like pions in QCD. They can decay via anomalies

$$\mathcal{L}_{\text{eff}} = \frac{S}{\Lambda}\frac{1}{16\pi^2}[g'^2\tilde{c}_B^S B_{\mu\nu}\tilde{B}^{\mu\nu} + g^2\tilde{c}_W^S W_{\mu\nu}^I \tilde{W}^{I\mu\nu} + g_S^2\tilde{c}_G^S G_{\mu\nu}^a \tilde{G}^{a\mu\nu}]$$

- Usual CHMs with extra singlets do not feature a $SU(3)_C$ anomaly, but for sizable values of $\tilde{c}_\gamma^S$ production via $t\bar{t}$ loops is allowed 1512.05330
- UV completions of partial compositeness embed $SU(3)_C$ in larger groups 1311.6562, 1312.5330, 1404.7137, 1506.00623, 1512.0450, 1512.0724, ...
- It is also possible to consider e.g. $SO(5) \times U(1)_\eta / SO(4)$, ... 1605.09647

Extra dimensions

Extra dimensional models can be thought as 'duals' to the strongly coupled ones



Possible candidates to explain the anomaly

- Radion 1512.05618, 1512.05771, 1512.06106, ...
- Graviton 1512.06376, 1603.06980, 1603.08250, 1603.08913, 1603.09550, ...
- Additional scalars 1603.05978, 1603.07303, ...

The radion/dilaton

- The radion can be identified as the pNGB of the spontaneous symmetry breaking of conformal invariance by the IR brane
- The general form of the coupling is expected to be

$$\frac{r}{f}\partial_\mu J^\mu = \frac{r}{f}\partial_\mu \left(x^\nu T_{\mu\nu}\right) = \frac{r}{f} T^\mu_\mu$$

- The couplings will be proportional to non-scale invariant terms, they will look kind of Higgs-ish!

In the original RS model, $\mathcal{L}_{\rm int} = \frac{\phi_0}{\Lambda_\phi} T^\mu_\mu$, with $\Lambda_\phi = \sqrt{6} M_{\rm Pl} e^{-kL}$ and

$$\begin{aligned} T^\mu_\mu \quad = \quad & -(1-6\xi)\left[\partial_\mu h_0 \partial^\mu h_0 + m_V^2 V_{a\ \mu} V^{a\ \mu}\left(1+\frac{h_0}{v_0}\right)^2 - m_i \bar{\psi}_i \psi_i \left(1+\frac{h_0}{v_0}\right) - \lambda(v_0+h_0)^4\right] \\ & -(1-3\xi) m_{h_0}^2 (v_0+h_0)^2 + b_3 \frac{\alpha_s}{8\pi} \mathrm{Tr}[G_{\mu\nu} G^{\mu\nu}] + (b_2+b_Y)\frac{\alpha}{8\pi} F_{\mu\nu} F^{\mu\nu}, \end{aligned}$$

Allowing gauge fields to propagate into the bulk could help but,

$$m_1^G = \frac{2.45}{\sqrt{6}} \frac{k}{M_{\rm Pl}} \Lambda_\phi$$

The KK graviton

The situation with the KK graviton is very similar, in the original RS

$$\mathcal{L}_{\text{int}} = \frac{\sqrt{6}}{\Lambda_\phi} T^{\mu\nu} h_{\mu\nu}$$

This marginally work since it predicts $\mathcal{B}(h_{\mu\nu} \to \gamma\gamma) \sim \mathcal{B}(h_{\mu\nu} \to \ell^+\ell^-)$
On the other hand, if we allow gauge bosons to propagate into the bulk

- We will weight differently the different pieces of $T^{\mu\nu}$ depending on the localization of the fields
- EWPT and direct seraches require will either $k/M_{\text{Pl}} > 1$ or changing M_{Pl} by some intermediate scale
- In principle, the ratio $m_h^1/m_g^1 \sim 1.5$. Lifting m_g^1 requires large BKT that may turn the radion into a ghost!

One way out is to think of the WED as the dual of vector-like confinement, which allows lighter gauge resonances 1603.08913

An additional singlet

Adding an additional singlet to RS setups should also work fine since

- for custodial models there is a large multiplicity of vector-like fermions running in the loop
- the couplings to this scalar are not 'protected' by any shift symmetry like in CHMs

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The main problem is that it will generate a non-negligible Higgs portal

$$\mathcal{L} \supset -\lambda_1 m_S S|H|^2 - \lambda_2 S^2|H|^2$$

One possible solution is to

- Make this scalar 'odd' under the orbifold $\mathbb{Z}_2$ symmetry 1603.05978
- Localize S in a new additional brane 1603.07303

The sgoldstino

1512.05330, 1512.05333, 1512.05723, 1512.07895, 1603.05682, ...

In any supersymmetric theory, we can parametrize the spontaneous SUSY breaking by

$$-\frac{M_a}{2\mathcal{F}}\int d^2\theta\, X W_a^\alpha W_\alpha^a = \frac{M_a}{2}\lambda_a\lambda_a + \frac{M_a}{2\sqrt{2}\mathcal{F}}(\sigma W_a^{\mu\nu}W_{\mu\nu}^a - \eta W_a^{\mu\nu}\tilde{W}_{\mu\nu}^a) + \dots$$

where

$$X = \frac{\sigma + i\eta}{\sqrt{2}} + \sqrt{2}\theta\psi + \theta^2 F_X, \quad \langle F_X \rangle = \mathcal{F}$$

Explaining the anomaly requires [1603.05682]

$$\sqrt{\mathcal{F}} \lesssim 5\,\text{TeV}\left(\frac{M_\gamma}{200\,\text{GeV}}\right)^{1/2}\left(\frac{6\,\text{fb}}{\sigma_{\gamma\gamma}}\right)^{1/4}$$

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Requiring therefore a low scale os SUSY breaking

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The presence of the sgoldstino in the low energy spectrum is UV dependent. Since $\sqrt{\mathcal{F}} \sim$ TeV, we can think in gauge mediation

$$\mathcal{L} = \int d\theta^2 \lambda_i X \Phi_i \bar{\Phi}_i + \text{h.c.}, \qquad \langle X \rangle = M + \mathcal{F}\theta^2$$

After integrating out the mediators, we get at the loop level

$$\mathcal{L}_{\text{eff}} = \frac{\alpha_a}{8\pi M} N_a \int d^2\theta \, X W_a^{\alpha} W_{\alpha}^a, \quad N_a = \sum_i N_{a,i}$$

Again, explaining the anomaly would require [1603.05682]

$$\lambda_m N_\gamma \gtrsim 14 \frac{M_m}{\text{TeV}} \left(\frac{\sigma_{\gamma\gamma}}{6\,\text{fb}} \right)^{1/2}$$

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Bounds on the gluino mass makes things worse!

Apologies!

- It is difficult to make a comprehensive talk in 25 minutes!

- A lot of interesting topics not covered:

  - Scalar doublet
  - Flavor issues
  - Collider phenomenology
  - Measuring CP
  - ...

Conclusions

- Regarding NP, a 750 GeV di-photon 'resonance' would not have been the first thing to come to our minds before december
- It is not straightforward to accommodate it in frameworks solving the hierarchy problem
- If the signal persists, it may help us to take new paths to understand nature (it may give us more questions than answers)
- In any case, we experienced an impressive collective effort to parametrize, understand and accommodate such signal

Thanks!