Explaining the LHC 750 GeV Diphoton Excess via Photon Fusion

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Based on:

750 GeV Composite Axion as the LHC Diphoton Resonance
N. D. Barrie, A. Kobakhidze, M. Talia and L. Wu,
Phys. Lett. B **755** (2016) 343, arXiv:1602.00475.

Heavy Leptonium as the Origin of the 750 GeV Diphoton Excess
N. D. Barrie, A. Kobakhidze, S. Liang, M. Talia and L. Wu,
arXiv:1604.02803.

Outline

A signal!

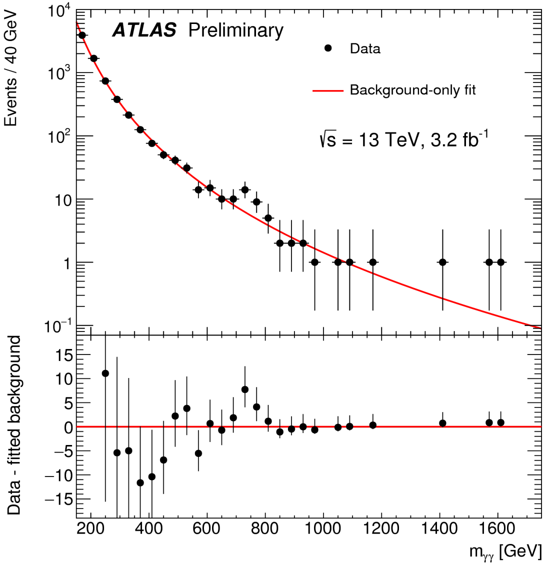
- The ATLAS and CMS Collaborations reported excesses of two-photon events in 13 TeV proton-proton collisions, respectively, at 3.9σ (2.3σ global) and 2.6σ (1.2σ global) local significance.

- The number of observed events requires the following cross sections for the process $pp \to R \to \gamma\gamma$:

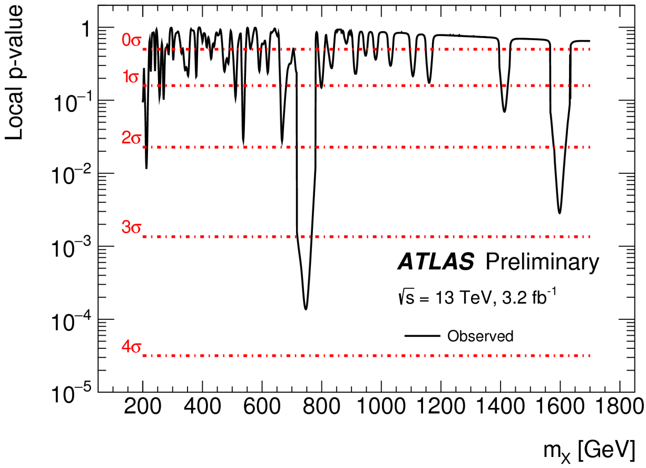
$$\begin{aligned}
\sigma^{\rm ATLAS}(pp \to R \to \gamma\gamma) &\approx (10 \pm 3)\ \mathrm{fb} \\
\sigma^{\rm CMS}(pp \to R \to \gamma\gamma) &\approx (6 \pm 3)\ \mathrm{fb}
\end{aligned}$$

- Initial reports have been confirmed at the recent Moriond conference, with a slightly increased significance.

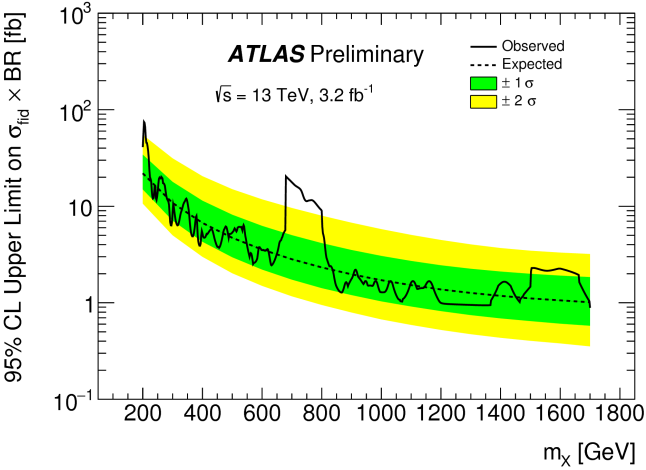
750 GeV Diphoton Excess: ATLAS



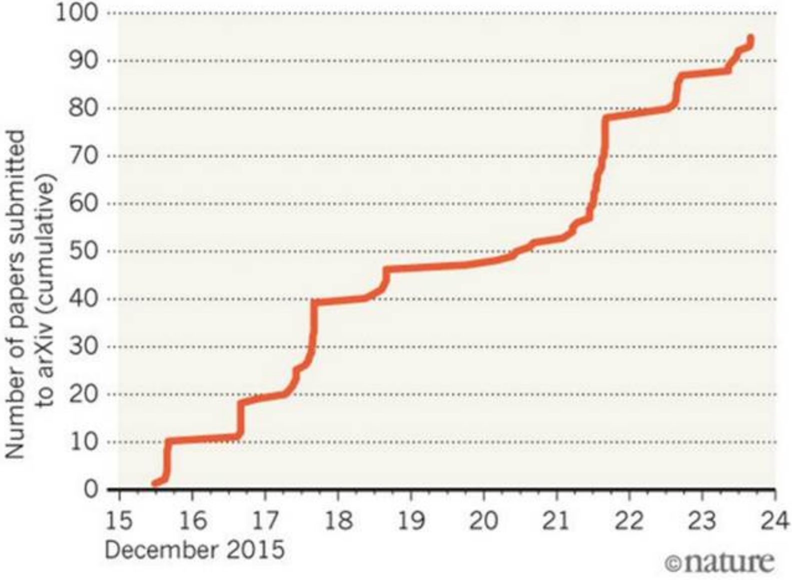
750 GeV Diphoton Excess: ATLAS



750 GeV Diphoton Excess: ATLAS



Real or a statistical fluctuation?



Mini Review of the 750 GeV Signal

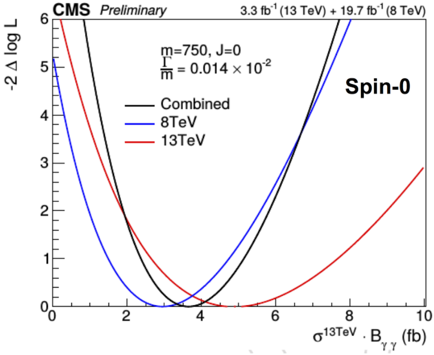
Properties known so far:

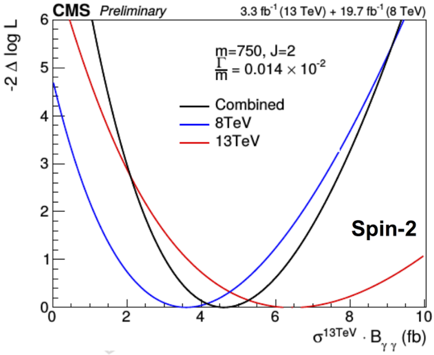
- Combining ATLAS/CMS data and including 8 TeV data:

$$\sigma(pp \to R \to \gamma\gamma) \approx (4.6 \pm 1.2)\ \mathrm{fb}$$

- Spin 0 or 2 resonance, from the Landau-Yang Theorem.
- Parity: The photon angular distributions are same for a scalar and pseudo-scalar. Other channels needed to determine the parity.
- Colour and electrically neutral.
- Enhanced branching ratio to photons.
- $pp \to \gamma\gamma + X$ allows other accompanying final states.
- ATLAS prefers a large width resonance.

Spin 0 vs Spin 2 analysis

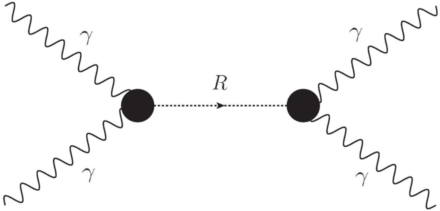


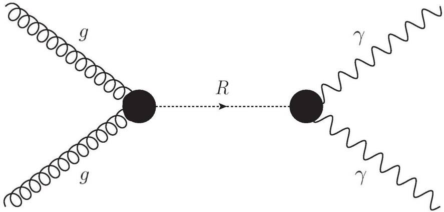


Could it be an RS graviton? With more particles in the TeV range to come!

Gluon-gluon and Photon-Photon fusion

- Photon pdfs lead to tension between run 1 and run 2 data, due to the scaling required. (scales less than gg)
- Recent work suggests that the tension with photon fusion data is not an issue due to the uncertainty in the photon pdfs.





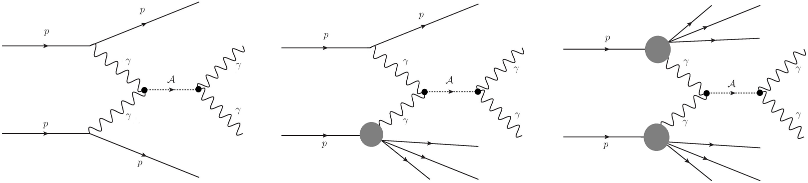
- Could also be a heavy particle cascade.

Types of Models Suggested

- Strong dynamics: composite Higgs, composite axion ...
- SUSY models: E6, RPV MSSM ...
- Multi-Higgs models: 2HDM, Higgs portal-like ...
- See-saw type models: Radiative neutrino seesaw, top/bottom seesaw, Higgs seesaw ...
- Extra dimension models: Randall-Sundrum model ...
- Effective Field Theory.

Photon fusion processes

Possible production mechanisms via photon fusion:



- inelastic : semi-elastic : elastic = 63:33:4
- $\gamma\gamma$, γZ and ZZ
- Many different photon pdfs, leading to some uncertainty in predictions

Model Descriptions

Model 1: Composite Axion

- A vector-like quark $\mathcal{Q}$ in a higher colour representation,
- The new quark forms a 750 GeV composite axion analogous to the pion for the light quarks,
- Produced via photon fusion, and decays to two photons.

Model 2: Leptonium Bound State

- A new heavy high charged lepton is introduced,
- Forms a bound state with a mass of 750 GeV,
- Produced by photon fusion.

Composite Axion

Introducing high-colour quarks

- Add a vector-like quark $\mathcal{Q}$ in some representation $\mathcal{R}$ of the $SU(3)$ colour gauge symmetry group.
- $\mathcal{Q}$ carries hypercharge $y_{\mathcal{Q}}$ and is a weak isospin singlet.
- A separate $U(1)_V \times U(1)_A$ global symmetry of strong interactions associated with $\mathcal{Q}$ quark number conservation and chiral phase rotation of $\mathcal{Q}$, respectively.
- The $U(1)_A$ symmetry is, broken explicitly by $m_{\mathcal{Q}}$, and by the QCD and hypercharge anomalies.
- Will have it's own $\bar{\mathcal{Q}}\mathcal{Q}$ condensate, and separate breaking scale, which can be related to the SM case.

Associated axial symmetry $U_A(1)$

- Analogously to the Standard Model Quarks we have an axial anomaly
- The divergence of the axial current density $J_A^\mu = \bar{\mathcal{Q}}\gamma^\mu\gamma^5\mathcal{Q}$:

$$\partial_\mu J_A^\mu = 2im_{\mathcal{Q}}\bar{\mathcal{Q}}\gamma^5\mathcal{Q} + \frac{\mathrm{T}(\mathcal{R})\alpha_3}{4\pi}\epsilon^{\mu\nu\alpha\beta}G^a_{\mu\nu}G^a_{\alpha\beta} + \frac{\mathrm{d}(\mathcal{R})y^2_{\mathcal{Q}}\alpha_1}{4\pi}\epsilon^{\mu\nu\alpha\beta}B_{\mu\nu}B_{\alpha\beta}$$

  - $\mathrm{d}(\mathcal{R}) =$ Dimension of the representation,
  - $\mathrm{C}_2(\mathcal{R}) =$ Eigenvalue of the quadratic Casimir operator,
  - $\mathrm{T}(\mathcal{R}) =$ Dynkin index for the SU(3) representation $\mathcal{R}$,

$$\mathrm{T}(\mathcal{R}) = \frac{1}{8}\mathrm{C}_2(\mathcal{R})\mathrm{d}(\mathcal{R})$$

Combining the two axial anomaly components

- Recall a separate axial symmetry for the light SM quarks is anomalous

$$\partial_\mu j_A^\mu = 2im_u\bar{u}\gamma^5 u + 2im_d\bar{d}\gamma^5 d + \frac{\alpha_3}{4\pi}\epsilon^{\mu\nu\alpha\beta}G^a_{\mu\nu}G^a_{\alpha\beta} + \frac{3(y_u^2+y_d^2)\alpha_1}{8\pi}\epsilon^{\mu\nu\alpha\beta}B_{\mu\nu}B_{\alpha\beta}\ ,$$

  where $j_A^\mu = \bar{u}\gamma^\mu\gamma^5 u + \bar{d}\gamma^\mu\gamma^5 d$.

- The colour anomaly actually eliminates one of these axial symmetries and through the QCD instantons solves the η mass problem.
- Colour anomaly-free result:

$$\tilde{J}_A^\mu = J_A^\mu - \mathrm{T}(\mathcal{R}) j_A^\mu\ .$$

- The corresponding charge is:

$$Q_5 = \int d^3x\ \tilde{J}_A^0\ .$$

High-colour quark condensate

- Just like in the case of light quarks, the conventional colour forces bind $\mathcal{Q}$ quarks into colourless hadrons.
- Composite meson condenses,

$$\langle 0|\bar{\mathcal{Q}}\mathcal{Q}|0\rangle = -cF_{\mathcal{A}}^{3} \ ,$$

breaking the axial symmetry, generated by Q_5.

- This breaking is accompanied by a composite pseudoscalar, $\mathcal{A} \sim \bar{\mathcal{Q}}\gamma^5\mathcal{Q}$, the pseudo-Goldstone boson of the spontaneously broken approximate axial symmetry.

Chiral symmetry breaking scale

- This chiral symmetry breaking scale can be related to the SM one: $C_2(3)\alpha_3(\Lambda_q) = C_2(R)\alpha_3(\Lambda_{\mathcal{Q}})$ and $F_{\mathcal{A}}/f_\pi \approx \Lambda_{\mathcal{Q}}/\Lambda_q$
- High-colour representation $\Rightarrow$ the scale of axial symmetry breaking in $\mathcal{Q}$-sector is naturally hierarchically larger, $F_{\mathcal{A}} \gg f_\pi \approx 130$ MeV.
- We assume that $m_{\mathcal{Q}} \gg m_{u,d}$, therefore $\mathcal{Q}$-sector can be safely considered as being decoupled from the q-sector. Approximately:

$$\mathcal{F}_{\mathcal{A}} \approx f_\pi \exp\left[\frac{2\pi}{7\alpha_3(\Lambda_{QCD})}\left(\frac{3}{4}\mathrm{C}_2(\mathcal{R}) - 1\right)\right] ,$$

  where $\Lambda_{\mathrm{QCD}} \sim 1$ GeV.
- $\mathcal{F}_{\mathcal{A}}$ is very sensitive to α_3 at low energies.

High colour representation properties

- α_3 at low energies contains significant uncertainties.

– charmonium fine stricture splitting is $\alpha_3(1 \text{ GeV}) \approx 0.38 \pm 0.05$,

– hadronic decays of taus give $\alpha_3(1.7 \text{ GeV}) \approx 0.331 \pm 0.013$.

- In our estimations we allow $\alpha_3(\Lambda_{QCD}) = 0.3 - 0.5$.

Repr.	$C_2(\mathcal{R})$	$T(\mathcal{R})$	$\mathcal{F}_{\mathcal{A}}$, GeV
$d(\mathcal{R})=6$	10/3	5/2	$2.0 - 12.0$
$d(\mathcal{R})=8$	3	3	$1.3 - 6.0$
$d(\mathcal{R})=10$	6	15/2	$75 - 4590.0$
$d(\mathcal{R})=15$	28/3	35/2	$(0.007 - 8.13) \cdot 10^6$

Composite axion mass and couplings

- The mass of the axion can be computed using the standard current algebra technique. In the decoupling limit, Dashen's formula gives:

$$m_{\mathcal{A}}^2 = -\frac{1}{\mathcal{F}_{\mathcal{A}}^2}\langle 0|\left[Q_5, \partial_\mu \tilde{J}_A^\mu\right]|0\rangle \approx -\frac{4}{\mathcal{F}_{\mathcal{A}}^2}\frac{m_{\mathcal{Q}}}{\mathrm{T}^2(\mathcal{R})}\langle 0|\bar{\mathcal{Q}}\mathcal{Q}|0\rangle$$
$$\approx 4cm_{\mathcal{Q}}\mathcal{F}_{\mathcal{A}} \ ,$$

- The mass of the heavy axion, $m_{\mathcal{A}} \approx 750$ GeV, is defined (up to a constant c) by the $\mathcal{Q}$ quark mass and the axion decay constant.

- The heavy axion coupling to the hypercharge can be read off from the hypercharge anomaly of the current density.

$$\mathcal{L}_{\mathcal{A}BB} = C_{\mathcal{A}}\epsilon^{\mu\nu\alpha\beta}\mathcal{A}B_{\mu\nu}B_{\alpha\beta} \ , \quad \text{where} \quad C_{\mathcal{A}} = \mathrm{d}(\mathcal{R})\frac{y_{\mathcal{Q}}^2\alpha_1}{4\pi\mathcal{F}_{\mathcal{A}}}$$

- Enhancement factor $\mathrm{d}(\mathcal{R})$ due to the high-colour representation of $\mathcal{Q}$.

Composite axion couplings and decays

- Can extract $\mathcal{A}\gamma\gamma$, $\mathcal{A}\gamma Z$ and $\mathcal{A}ZZ$ couplings, respectively:

$$C_{\gamma\gamma} = C_{\mathcal{A}} \cos^2\theta_W \ , \quad C_{\gamma Z} = -2\tan\theta_W C_{\gamma\gamma} \ , C_{ZZ} = \tan^2\theta_W C_{\gamma\gamma} \ ,$$

  where $\tan\theta_W \approx 0.55$.

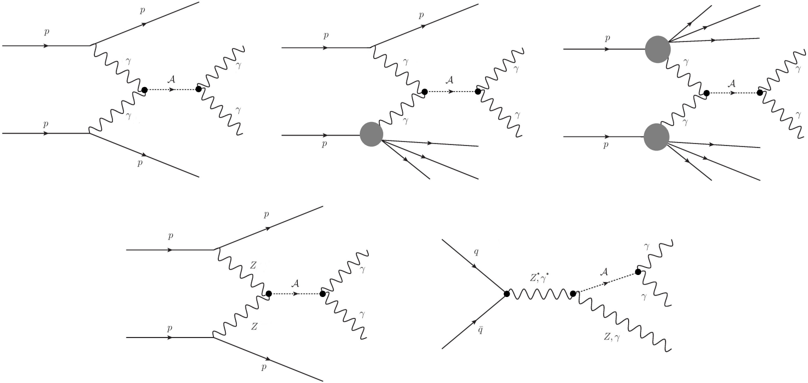
- The composite axion in principle decays to ordinary quarks and leptons through weak processes, and light mesons as well as to exotic bound states of ordinary quarks and the high-colour quark.

- Keep Γ_{tot} as a free parameter, subject to the constraint $\Gamma_{tot} \leq 45$ GeV, where

$$\Gamma_{tot} = \Gamma_{\gamma\gamma} + \Gamma_{Z\gamma} + \Gamma_{ZZ} + \Delta\Gamma.$$

Production of the 750 GeV composite Axion

Production of the 750 GeV composite Axion



Three production subprocesses: photon fusion production ($\gamma\gamma \to \mathcal{A}$), Z VBF production ($qq \to \mathcal{A}qq$) and AP ($q\bar{q} \to \mathcal{A}\gamma/Z$).

Numerical Calculations

- The contribution to the photon-fusion is dominated by the inelastic scattering, followed by the semi-elastic then elastic processes. Each of these processes is included.
- The Lagrangian described by

$$\mathcal{L}_{\mathcal{A}BB} = C_{\mathcal{A}} \epsilon^{\mu\nu\alpha\beta} \mathcal{A} B_{\mu\nu} B_{\alpha\beta} \ ,$$

  is implemented by using `FeynRules`.
- The cross sections of these production processes are calculated with `Madgraph 5` at $\sqrt{s} = 13$ TeV with `NN23LO1` PDFs.
- The coupling $C_{\mathcal{A}}$ is taken to be a free parameter which is scanned over.

Other possible decay channels

- Dependence of the leading order production cross sections of the heavy axion on the effective coupling $C_{\mathcal{A}}$.
- The production rate of the photon fusion is about $\mathcal{O}(10)$ times larger than that of the Z vector boson fusion.
- Hierarchy between the couplings $C_{\gamma\gamma}$, $C_{\gamma Z}$ and C_{ZZ},
- AP of $\mathcal{A}\gamma$ has a larger cross section than $\mathcal{A}Z$, can reach 1.3 fb for $C_{\mathcal{A}} = 2.5 \times 10^{-4}$.
- Sizable number of three photon events at the future LHC searches.
- The rare decay $Z \to \gamma\gamma\gamma$ can also be induced, but Br less than 10^{-12}, which is hardly observable at future colliders such as FCC-ee ($\sim 10^{12}$ events of Z) or CEPC ($\sim 10^{10}$ events of Z).

Decay widths

- If the heavy axion only couples with $\gamma\gamma$, $Z\gamma$ and ZZ, the production cross sections and the decay widths of the heavy axion will be linearly correlated,
- Tension between the predicted total width and the value $\Gamma \sim 45$ GeV, favoured by ATLAS.
- The heavy axion usually can have other decay modes.
- The corresponding decay partial width $\Delta\Gamma$ depends on the specific representation of the extra quarks, their masses and couplings.
- Treat $\Delta\Gamma$ as a free parameter in our model.

Branching ratio to two photons

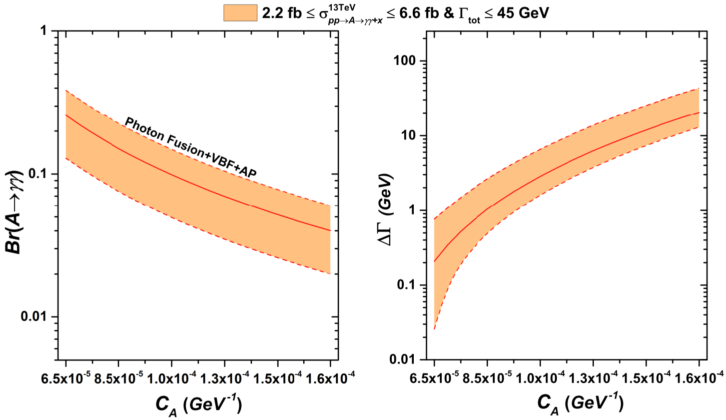
- The branching ratio of $\mathcal{A} \to \gamma\gamma$ can be computed by,

$$Br(\mathcal{A} \to \gamma\gamma) = \frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma} + \Gamma_{Z\gamma} + \Gamma_{ZZ} + \Delta\Gamma}$$

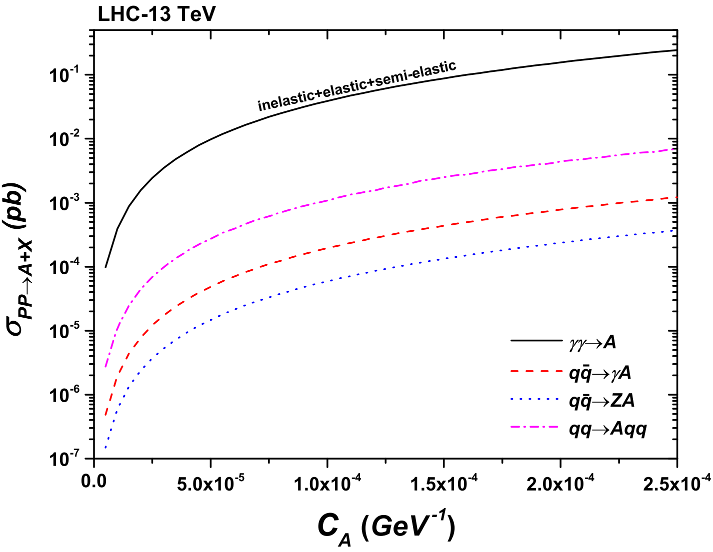
where in the limit $m_{\mathcal{A}} \gg m_Z$,

$$\Gamma_{\gamma\gamma} = \frac{C_{\gamma\gamma}^2 m_{\mathcal{A}}^3}{4\pi}, \quad \Gamma_{Z\gamma} = \frac{C_{Z\gamma}^2 m_{\mathcal{A}}^3}{8\pi}, \quad \Gamma_{ZZ} = \frac{C_{ZZ}^2 m_{\mathcal{A}}^3}{4\pi}.$$

- $\Delta\Gamma \geq 0 \Rightarrow$ upper limit on the $Br(\mathcal{A} \to \gamma\gamma) \simeq 61\%$, providing a lower limit on $C_{\mathcal{A}}$.
- We require the total width $\Gamma_{tot} \leqslant 45$ GeV in our following calculations.



Contour plots of the branching ratio of $\mathcal{A} \to \gamma\gamma$ and the exotic decay width $\Delta\Gamma$ versus the effective coupling $C_{\mathcal{A}}$ within 2σ.



Dependence of the leading order production cross sections of the heavy axion on the effective coupling $C_{\mathcal{A}}$ at 13 TeV LHC.

Numerical Results

- We perform a fit of the branching ratio of $\mathcal{A} \to \gamma\gamma$, the exotic decay width $\Delta\Gamma$ and the effective coupling $C_{\mathcal{A}}$ to the observed number of excess events within 2σ range under the total width bound $\Gamma_{tot} \leqslant 45$ GeV.
- As the coupling $C_{\mathcal{A}}$ becomes large, the branching ratio $Br(\mathcal{A} \to \gamma\gamma)$ should be smaller to suppress the cross section of $pp \to \mathcal{A} + X$.
- Total width bound produces an upper limit $C_{\mathcal{A}} < 1.65 \times 10^{-4}$ GeV^{-1}
- Lower limit provided by the upper limit of the branching ratio, $C_{\mathcal{A}} > 6.5 \times 10^{-5}$ GeV^{-1}.
- A small value of $C_{\mathcal{A}}$ easier to satisfy the current experimental constraints and achieve the diphoton enhancement by a large branching ratio of $\mathcal{A} \to \gamma\gamma$.

Allowed coupling range and interpretation

- Required cross section: $1.6 \times 10^{-4}\ \text{GeV}^{-1} \gtrsim C_{\mathcal{A}} \gtrsim 6.5 \times 10^{-5}\ \text{GeV}^{-1}$
- Determine the high colour representations $\mathcal{R}$ of $\mathcal{Q}$ most compatible.

  - $d(\mathcal{R}) = \mathbf{6}$ and $\mathbf{8}$: ruled out by the predicted mass of the quark which violates $m_Q < \mathcal{F}_{\mathcal{A}}$.
  - $d(\mathcal{R}) = \mathbf{10}$: $1.1 \times 10^{-5} y_Q^2\ \text{GeV}^{-1} \gtrsim C_{\mathcal{A}} \gtrsim 1.6 \times 10^{-6} y_Q^2\ \text{GeV}^{-1}$, (upper limit is due to the requirement of $m_Q < \mathcal{F}_{\mathcal{A}}$).
  - $d(\mathcal{R}) = \mathbf{15}$: $1.7 \times 10^{-6} y_Q^2\ \text{GeV}^{-1} \gtrsim C_{\mathcal{A}} \gtrsim 1.5 \times 10^{-10} y_Q^2\ \text{GeV}^{-1}$.

- Each of these scenarios has a maximum effective coupling of approximately $\sim 10^{-6} y_Q^2$,
- Consistency with observation favours narrow width resonances for hypercharges of $y_Q^2 \sim \mathcal{O}(10)$.

Model 1: Summary

- Heavy composite axion resulting from condensation of hypothetical quarks in a high-colour representation of conventional QCD.
- The axion mass and its coupling to two photons can be computed using the colour charge, y_Q and m_Q.
- Predominantly produced via photon fusion, followed by Z vector boson fusion and AP.
- Allowed couplings 1.6×10^{-4} GeV$^{-1} \gtrsim C_{\mathcal{A}} \gtrsim 6.5 \times 10^{-5}$ GeV^{-1}.
- Possible in $d(\mathcal{R}) = \mathbf{10}$ and $\mathbf{15}$ cases, requires a narrow width resonance and $y_Q^2 \sim \mathcal{O}(10)$.
- AP of $q\bar{q} \to \mathcal{A}\gamma$ can produce a sizeable number of three photon events at future LHC.
- The rare decay $Z \to \gamma\gamma\gamma$ is too small to be probed in the near future.

Leptonium Bound State

Model 2: Leptonium Bound State

- Economical extension of the Standard Model
- A vector-like, weak isospin singlet lepton ℓ with mass m_ℓ and hypercharge (equal to the electric charge) Y_ℓ.
- Typically stable, and forms an unstable heavy spin-0 para-leptonium state $\psi_\ell \sim \bar{\ell}\ell$, we identify with the LHC 750 GeV resonance.
- Only one extra parameter to fit the diphoton data is Y_ℓ, as m_ℓ can be expressed through the leptonium bound state mass and Y_ℓ.
- We allow deviation from the minimal model by treating the total decay width of the leptonium as a free parameter.

Exotic Leptons

- Heavy stable multi-charged particles, are being extensively searched for at the LHC
- Limits have been put on m_ℓ assuming the perturbative Drell-Yan production mechanism.
- These limits are valid if the heavy lepton is considered to be stable.
- Constrain the parameter Y_ℓ to fit the diphoton data.
- In addition, we predict a spin-1 ortho-leptonium bound state, whose mass is dependent on the allowed Y_ℓ.

Leptonium binding energy

- The leptonium bound state (in the non-relativistic approximation) is described by the Schrödinger equation

$$\left(-\frac{\nabla^2}{m_\ell} + V(r)\right)\psi = E\psi \ ,$$

with the binding Coulomb potential

$$V(r) = -\frac{Y_\ell^2\alpha}{r} \ ,$$

where $\alpha \approx 1/128$ is the fine structure constant evaluated at m_Z.

- Leptonium Bohr radius: $r_\ell = \frac{2}{m_\ell}\frac{1}{Y_\ell^2\alpha}$, is larger than the Compton wavelength of the Z-boson, $r_\ell \gtrsim 1/m_Z$,

Leptonium binding energy

- In this approximation, the ground state $(n = 1,\ l = 0)$ energy is given by:

$$E = -\frac{1}{4} m_\ell \left(Y_\ell^2 \alpha \right)^2 \ ,$$

- We also include the leading $\left[\sim \mathcal{O}\left(Y^8 \alpha^4 \right) \right]$ relativistic Breit correction to the binding energy:

$$\delta E_{\mathrm{Breit}} = -\frac{1}{2m_\ell} \left(E^2 - 2E \langle V \rangle + \left\langle V^2 \right\rangle \right) = -\frac{5}{16} m_\ell \left(Y_\ell^2 \alpha \right)^4 \ .$$

- The leptonium mass is then given by:

$$m_{\psi_\ell} = 2m_\ell + E + \delta E_{\mathrm{Breit}}$$

Exotic lepton mass and otho-leptonium

- Assuming $m_{\psi_\ell} = 750$ GeV and expressing m_ℓ through Y_ℓ,

$$m_\ell = m_{\psi_\ell} \left(2 - \frac{1}{4} \left(Y_\ell^2 \alpha \right)^2 - \frac{5}{16} \left(Y_\ell^2 \alpha \right)^4 \right)^{-1} ,$$

  tthe hypercharge Y_ℓ as the single unknown parameter of the model.

- The model predicts a spin-1 ortho-leptonium bound state as well, heavier than the spin-0 para-leptonium state:

$$m_{\psi_\ell}^{ortho} = m_{\psi_\ell} \frac{\left(2 - \frac{1}{16} \left(Y_\ell^2 \alpha \right)^2 - \frac{5}{196} \left(Y_\ell^2 \alpha \right)^4 \right)}{\left(2 - \frac{1}{4} \left(Y_\ell^2 \alpha \right)^2 - \frac{5}{16} \left(Y_\ell^2 \alpha \right)^4 \right)} ,$$

  and is produced via Drell-Yan processes at LHC.

Leptonium production cross section

- The parton level cross section for photoproduction of the bound state ψ_ℓ can be written in terms of the $\Gamma_{\psi_\ell \to \gamma\gamma}$, since both the production and decay processes share the same matrix elements:

$$\hat{\sigma}_{\gamma\gamma\to\psi_\ell}(\hat{s}) = 8\pi^2 \frac{\Gamma_{\psi_\ell\to\gamma\gamma}}{m_{\psi_\ell}} \delta(\hat{s} - m_{\psi_\ell}^2)$$

- The decay width $\Gamma_{\psi_\ell\to\gamma\gamma}$ in turn is given in terms of the annihilation cross section of a free lepton-antilepton pair into two photons and the wave function for the leptonium bound state evaluated at the origin:

$$\Gamma_{\psi_\ell\to\gamma\gamma} = \frac{16\pi\alpha^2 Y_\ell^4 \left|\psi(0)\right|^2}{m_{\psi_\ell}^2} ,$$

$$\left|\psi(0)\right|^2 = \frac{1}{4\pi} \left|R(0)\right|^2$$

with the radial part evaluated as:

$$\left|R(0)\right|^2 = \frac{\left(Y_\ell^2 \alpha m_\ell\right)^3}{2}$$

Leptonium production cross section

- At leading order, we can then calculate the two photon production and decay cross section by convolution with the parton distribution function (PDF) for the photon in the proton, $f_\gamma(x)$:

$$\sigma_{\gamma\gamma\to\psi_\ell\to\gamma\gamma} = \frac{8\pi^2}{s m_{\psi_\ell}} \frac{\Gamma^2_{\psi_\ell\to\gamma\gamma}}{\Gamma_{\psi_\ell}} \int \delta(x_1 x_2 - m^2_{\psi_\ell}/s) f_\gamma(x_1) f_\gamma(x_2) dx_1 dx_2$$

  where $\sqrt{s} = 13$ TeV and $m_{\psi_\ell} = 750$ GeV. Γ_{ψ_ℓ} denotes the leptonium total width.

- In the minimal scenario, $\Gamma_{\psi_\ell} = \Gamma_{\psi_\ell\to\gamma\gamma} + \Gamma_{\psi_\ell\to\gamma Z} + \Gamma_{\psi_\ell\to ZZ} = \Gamma_{\psi_\ell\to\gamma\gamma}/0.6$.
- However, we keep the total leptonium width as a free parameter.
- e.g. leptonium decays into a pair of dark matter particles χ.

- The Lagrangian describing interactions of vector-like leptons ℓ with χ can have, e.g., the form:

$$\mathcal{L}_{\ell\chi} = \kappa \left(\bar{\ell}\ell\right)(\bar{\chi}\chi) \ ,$$

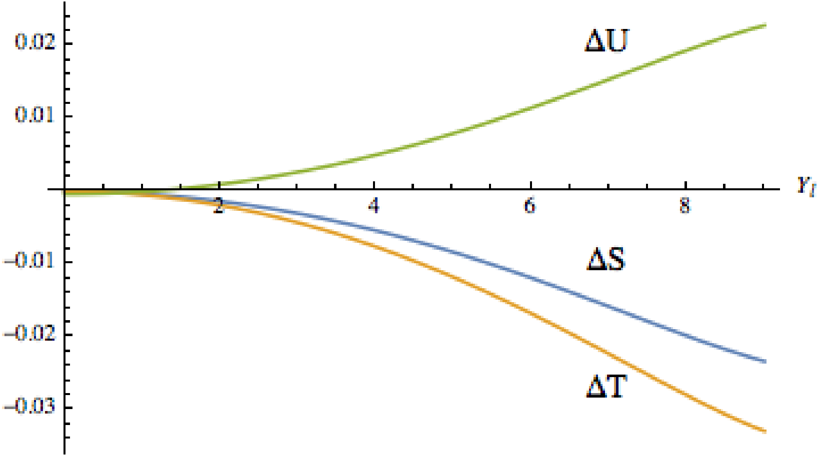
where (assuming χ is a fermion) κ is a parameter of mass dimension -2.

- No significant constraints on the parameter κ from the LHC mono-X plus missing energy searches, since the relevant processes induced via interactions are necessarily radiative.

- One may have quite a large partial decay width (and hence total width Γ_{ψ_ℓ}) $\Gamma_{\psi_\ell \to \chi\chi} \sim (Y_\ell^2 \alpha)^4 \kappa^2 m_\ell^5$.

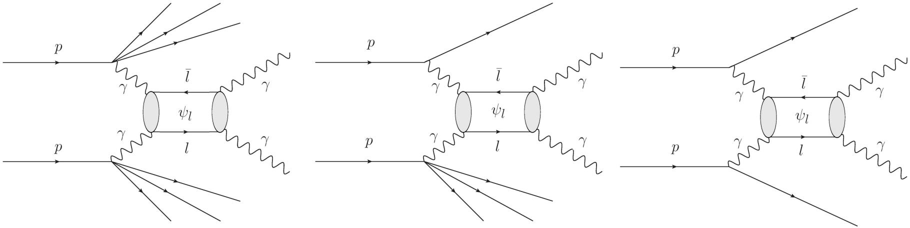
- In numerical analysis we restrict the total width $\Gamma_{\psi_\ell} \leq 45$ GeV, the upper bound favoured by ATLAS.

Multi-charged lepton can contribute to the electroweak observables, so must consider the dependence of $\Delta S, \Delta T, \Delta U$ parameters on Y_ℓ



The predictions of the oblique parameters are consistent with the experimental measurements.

Photon fusion production

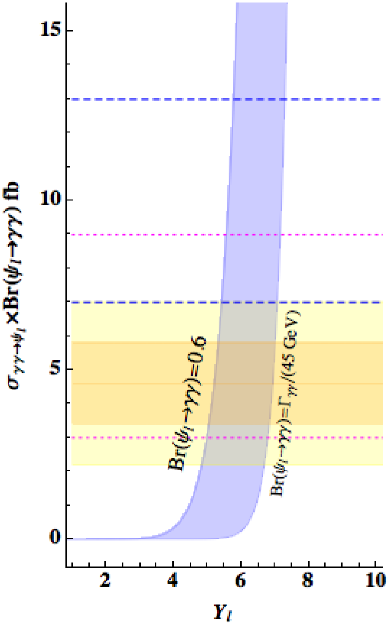


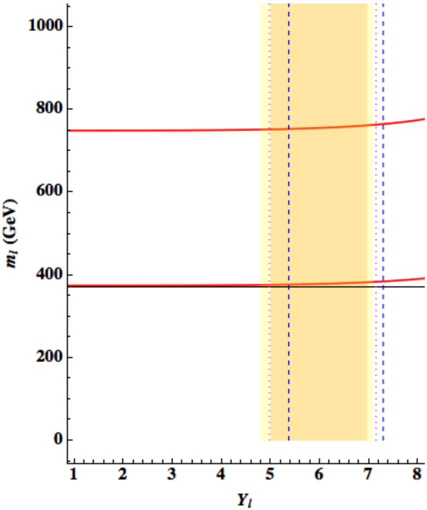
The processes contributing to the inclusive production cross section: inelastic, semi-elastic and elastic scattering photoproduction processes.

Numerical analysis

- Photoproduction is dominated by inelastic scattering, which is followed by the semi-elastic and elastic processes in the ratio 63:33:4.
- Using the `NNPDF2.3QED` PDF, we calculate the inelastic contribution to the total cross section and subsequently weight the semi-elastic and elastic contributions.

$$\sigma_{\gamma\gamma\to\psi_\ell\to\gamma\gamma} = \frac{8\pi^2}{s m_{\psi_\ell}} \frac{\Gamma^2_{\psi_\ell\to\gamma\gamma}}{\Gamma_{\psi_\ell}} \int \delta(x_1 x_2 - m^2_{\psi_\ell}/s) f_\gamma(x_1) f_\gamma(x_2) dx_1 dx_2$$


15
10
5
0
2
4
6
8
10
Y_l
$\sigma_{\gamma\gamma\to\psi_l}\times\text{Br}(\psi_l\to\gamma\gamma)$ fb
$\text{Br}(\psi_l\to\gamma\gamma)=0.6$
$\text{Br}(\psi_l\to\gamma\gamma)=\Gamma_{\gamma\gamma}/(45\text{ GeV})$


1000
800
600
400
200
0
1
2
3
4
5
6
7
8
Y_l
m_l (GeV)

Results of the numerical analysis

- Dependence of the cross section on Y_ℓ.
- Minimal scenario: only $\gamma\gamma$, $Z\gamma$ and ZZ decays are permitted, with the two photon channel being the dominant one, $Br(\psi_\ell \to \gamma\gamma) \approx 0.6$.
- For cross sections within the 2σ band that reproduce the LHC diphoton excess, $Y_\ell \approx 4.8 - 7.1$.
- Lepton masses m_ℓ as a function of Y_ℓ, $m_\ell \approx 372 - 384$ GeV

Discussion

- Caveat: large uncertainties in photon parton distribution functions (PDFs) of the proton.
- Recently, the constraints imposed by CMS measurements of W-pair production via photon fusion on photon PDFs,
  Predicted cross section of the 750 GeV scalar photoproduction at 13 TeV is reduced by a factor in the range $\sim$3 to 6.
- Uupdated photon PDF seems to further support the explanation for why the excess was not observed during the 8 TeV run.
- Require somewhat larger hypercharges, and hence heavier leptons, to explain the diphoton excess.

- Taking at face value Drell-Yan constraints, they further constrain the hypercharge in our range of charges model $Y_\ell \approx 4.8 - 7.1$.
- As mentioned above, in addition to the 750 GeV para-leptonium, one expects the existence of spin-1 ortho-leptonium. In light of the constraints on Y_ℓ, the mass of this state is predicted to be $\sim$ 752 to 764 GeV.

Model 2: Summary

- Heavy spin-0 leptonium bound state of exotic vector-like leptons with high hypercharge Y_ℓ.
- Leptonium predominantly produced in photon-fusion at the LHC and decays into two photons.
- For $Y_\ell \approx 4.8 - 7.1$ the cross section needed to explain the diphoton excess.
- In this range, $m_\ell \approx 372 - 384$ GeV
- The model also predicts a spin-1 bound state of mass $\sim$752 to 764 GeV.

Conclusion and Outlook

- Possible exciting signs of new physics
- Many models have been propsed to provide explanations for the source of the resonance.
- Some of the properties are known but need more information

– Possibly a heavy composite axion, from higher colour representation quarks.

– Or a heavy leptonium bound state.

Outlook

We need more data!

Thank You! :)