Explaining the LHC 750 GeV Diphoton Excess via Photon Fusion

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May 26, 2016

Based on:

750 GeV Composite Axion as the LHC Diphoton Resonance
N. D. Barrie, A. Kobakhidze, M. Talia and L. Wu,

Heavy Leptonium as the Origin of the 750 GeV Diphoton Excess
N. D. Barrie, A. Kobakhidze, S. Liang, M. Talia and L. Wu,
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The ATLAS and CMS Collaborations reported excesses of two-photon events in 13 TeV proton-proton collisions, respectively, at $3.9\sigma$ ($2.3\sigma$ global) and $2.6\sigma$ ($1.2\sigma$ global) local significance.

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

\[
\begin{align*}
\sigma^{\text{ATLAS}}(pp \rightarrow R \rightarrow \gamma\gamma) & \approx (10 \pm 3) \text{ fb} \\
\sigma^{\text{CMS}}(pp \rightarrow R \rightarrow \gamma\gamma) & \approx (6 \pm 3) \text{ fb}
\end{align*}
\]

Initial reports have been confirmed at the recent Moriond conference, with a slightly increased significance.
750 GeV Diphoton Excess: ATLAS

\[ \sqrt{s} = 13 \text{ TeV}, 3.2 \text{ fb}^{-1} \]
750 GeV Diphoton Excess: ATLAS

![Graph showing the diphoton excess with local p-values and masses in GeV. The graph indicates an excess at around 750 GeV with a p-value of 4σ.]
750 GeV Diphoton Excess: ATLAS

\[ \sqrt{s} = 13 \text{ TeV, } 3.2 \text{ fb}^{-1} \]

ATLAS Preliminary

95\% CL Upper Limit on \( \sigma_{\text{fid}} \times \text{BR} \) [fb]

\[ \begin{array}{c}
\text{Observed} \\
\text{Expected} \\
\pm 1 \sigma \\
\pm 2 \sigma
\end{array} \]

\[ m_\chi \text{ [GeV]} \]
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:
  \[ \sigma(pp \rightarrow R \rightarrow \gamma\gamma) \approx (4.6 \pm 1.2) \text{ fb} \]

- 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.

- \( pp \rightarrow \gamma\gamma + X \) 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
- $\gamma\gamma$, $\gamma Z$ and $ZZ$
- Many different photon pdfs, leading to some uncertainty in predictions
Model Descriptions

Model 1: Composite Axion
- A vector-like quark $Q$ 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 $Q$ in some representation $R$ of the $SU(3)$ colour gauge symmetry group.

- $Q$ carries hypercharge $y_Q$ and is a weak isospin singlet.

- A separate $U(1)_V \times U(1)_A$ global symmetry of strong interactions associated with $Q$ quark number conservation and chiral phase rotation of $Q$, respectively.

- The $U(1)_A$ symmetry is, broken explicitly by $m_Q$, and by the QCD and hypercharge anomalies.

- Will have it’s own $\bar{Q}Q$ 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 $J^\mu_A = \bar{Q} \gamma^\mu \gamma^5 Q$:

$$\partial_\mu J^\mu_A = 2 i m_Q \bar{Q} \gamma^5 Q + \frac{T(\mathcal{R}) \alpha_3}{4\pi} \epsilon^{\mu\nu\alpha\beta} G^a_{\mu\nu} G^a_{\alpha\beta} + \frac{d(\mathcal{R}) y_\alpha^2 \alpha_1}{4\pi} \epsilon^{\mu\nu\alpha\beta} B_{\mu\nu} B_{\alpha\beta}$$

- $d(\mathcal{R})$ = Dimension of the representation,
- $C_2(\mathcal{R})$ = Eigenvalue of the quadratic Casimir operator,
- $T(\mathcal{R})$ = Dynkin index for the SU(3) representation $\mathcal{R}$,

$$T(\mathcal{R}) = \frac{1}{8} C_2(\mathcal{R}) d(\mathcal{R})$$
Combining the two axial anomaly components

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

\[ \partial_{\mu} j_{A}^{\mu} = 2im_{u}\bar{u}\gamma^{5}u + 2im_{d}\bar{d}\gamma^{5}d + \frac{\alpha_{3}}{4\pi}\varepsilon_{\mu\nu\alpha\beta}G_{\mu\nu}^{a}G_{\alpha\beta}^{a} \]

\[ + \frac{3(y_{u}^{2} + y_{d}^{2})\alpha_{1}}{8\pi}\varepsilon_{\mu\nu\alpha\beta}B_{\mu\nu}B_{\alpha\beta} \]

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 \( \eta \) mass problem.

- Colour anomaly-free result:

\[ \tilde{j}_{A}^{\mu} = j_{A}^{\mu} - T(R)j_{A}^{\mu} \]

- The corresponding charge is:

\[ Q_{5} = \int d^{3}x \tilde{j}_{A}^{0} \]
High-colour quark condensate

• Just like in the case of light quarks, the conventional colour forces bind $Q$ quarks into colourless hadrons.

• Composite meson condenses,

$$\langle 0|\bar{Q}Q|0\rangle = -cF^3_A,$$

breaking the axial symmetry, generated by $Q_5$.

• This breaking is accompanied by a composite pseudoscalar, $A \sim \bar{Q}\gamma^5 Q$, 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:
  \[ C_2(3) \alpha_3(\Lambda_q) = C_2(R) \alpha_3(\Lambda_Q) \text{ and } F_A/f_\pi \approx \Lambda_Q/\Lambda_q \]

- High-colour representation \( \Rightarrow \) the scale of axial symmetry breaking in \( Q \)-sector is naturally hierarchically larger, \( F_A \gg f_\pi \approx 130 \text{ MeV.} \)

- We assume that \( m_Q \gg m_u, d \), therefore \( Q \)-sector can be safely considered as being decoupled from the \( q \)-sector. Approximately:
  \[ F_A \approx f_\pi \exp \left[ \frac{2\pi}{7\alpha_3(\Lambda_{QCD})} \left( \frac{3}{4} C_2(R) - 1 \right) \right] , \]
  where \( \Lambda_{QCD} \sim 1 \text{ GeV.} \)

- \( F_A \) is very sensitive to \( \alpha_3 \) at low energies.
High colour representation properties

- $\alpha_3$ at low energies contains significant uncertainties.
  - charmonium fine structure 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 $\alpha_3(\Lambda_{QCD}) = 0.3 - 0.5$.

<table>
<thead>
<tr>
<th>Repr.</th>
<th>$C_2(\mathcal{R})$</th>
<th>$T(\mathcal{R})$</th>
<th>$\mathcal{F}_A$, GeV</th>
</tr>
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<tbody>
<tr>
<td>$d(\mathcal{R})=6$</td>
<td>10/3</td>
<td>5/2</td>
<td>$2.0 - 12.0$</td>
</tr>
<tr>
<td>$d(\mathcal{R})=8$</td>
<td>3</td>
<td>3</td>
<td>$1.3 - 6.0$</td>
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<tr>
<td>$d(\mathcal{R})=10$</td>
<td>6</td>
<td>15/2</td>
<td>$75 - 4590.0$</td>
</tr>
<tr>
<td>$d(\mathcal{R})=15$</td>
<td>28/3</td>
<td>35/2</td>
<td>$(0.007 - 8.13) \cdot 10^6$</td>
</tr>
</tbody>
</table>
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:

\[ m_A^2 = - \frac{1}{F_A^2} \langle 0 | \left[ Q_5, \partial_\mu \tilde{J}_A^\mu \right] | 0 \rangle \approx - \frac{4}{F_A^2 \langle T_2(R) \rangle} m_Q \langle 0 | \bar{Q}Q | 0 \rangle \approx 4cm_Q F_A, \]

- The mass of the heavy axion, \( m_A \approx 750 \text{ GeV} \), is defined (up to a constant \( c \)) by the \( Q \) 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.

\[ \mathcal{L}_{ABB} = C_A \epsilon^{\mu\nu\alpha\beta} A B_{\mu\nu} B_{\alpha\beta}, \text{ where } C_A = d(R) \frac{y_Q^2 \alpha_1}{4\pi F_A} \]

- Enhancement factor \( d(R) \) due to the high-colour representation of \( Q \).
Composite axion couplings and decays

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

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

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 $\Gamma_{tot}$ 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

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

\[ \mathcal{L}_{A\beta} = C_A \epsilon^{\mu\nu\alpha\beta} A_{\mu\nu} B_{\alpha\beta}, \]

is implemented by using FeynRules.

- The cross sections of these production processes are calculated with Madgraph 5 at \( \sqrt{s} = 13 \text{ TeV} \) with NN23L01 PDFs.

- The coupling \( C_A \) 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 $C_A$.

- 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 $A\gamma$ has a larger cross section than $AZ$, can reach 1.3 fb for $C_A = 2.5 \times 10^{-4}$.

- Sizable number of three photon events at the future LHC searches.

- The rare decay $Z \rightarrow \gamma\gamma\gamma$ 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.
The branching ratio of $A \rightarrow \gamma\gamma$ can be computed by,

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

where in the limit $m_A \gg m_Z$,

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

$\Delta\Gamma \geq 0 \Rightarrow$ upper limit on the $Br(A \rightarrow \gamma\gamma) \simeq 61\%$, providing a lower limit on $C_A$.

We require the total width $\Gamma_{tot} \leq 45$ GeV in our following calculations.
Contour plots of the branching ratio of $\mathcal{A} \rightarrow \gamma\gamma$ and the exotic decay width $\Delta \Gamma$ versus the effective coupling $C_A$ within $2\sigma$. 

$2.2 \text{ fb} \leq \sigma_{pp \rightarrow A \rightarrow \gamma\gamma + x}^{13\text{TeV}} \leq 6.6 \text{ fb} \ & \Gamma_{\text{tot}} \leq 45 \text{ GeV}$
Dependence of the leading order production cross sections of the heavy axion on the effective coupling $C_A$ at 13 TeV LHC.
Numerical Results

- We perform a fit of the branching ratio of $A \rightarrow \gamma\gamma$, the exotic decay width $\Delta \Gamma$ and the effective coupling $C_A$ to the observed number of excess events within $2\sigma$ range under the total width bound $\Gamma_{tot} \leq 45$ GeV.

- As the coupling $C_A$ becomes large, the branching ratio $Br(A \rightarrow \gamma\gamma)$ should be smaller to suppress the cross section of $pp \rightarrow A + X$.

- Total width bound produces an upper limit $C_A < 1.65 \times 10^{-4}$ GeV$^{-1}$

- Lower limit provided by the upper limit of the branching ratio, $C_A > 6.5 \times 10^{-5}$ GeV$^{-1}$.

- A small value of $C_A$ easier to satisfy the current experimental constraints and achieve the diphoton enhancement by a large branching ratio of $A \rightarrow \gamma\gamma$. 
Allowed coupling range and interpretation

- **Required cross section:** \(1.6 \times 10^{-4} \text{ GeV}^{-1} \gtrsim C_A \gtrsim 6.5 \times 10^{-5} \text{ GeV}^{-1}\)

- Determine the high colour representations \(R\) of \(Q\) most compatible.
  - \(d(R) = 6\) and \(8\): ruled out by the predicted mass of the quark which violates \(m_Q < \mathcal{F}_A\).
  - \(d(R) = 10\): \(1.1 \times 10^{-5} y_Q^2 \text{ GeV}^{-1} \gtrsim C_A \gtrsim 1.6 \times 10^{-6} y_Q^2 \text{ GeV}^{-1}\), (upper limit is due to the requirement of \(m_Q < \mathcal{F}_A\)).
  - \(d(R) = 15\): \(1.7 \times 10^{-6} y_Q^2 \text{ GeV}^{-1} \gtrsim C_A \gtrsim 1.5 \times 10^{-10} y_Q^2 \text{ GeV}^{-1}\).

- 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 $1.6 \times 10^{-4} \text{ GeV}^{-1} \gtrsim C_A \gtrsim 6.5 \times 10^{-5} \text{ GeV}^{-1}$.
- Possible in $d(\mathcal{R}) = 10$ and $15$ cases, requires a narrow width resonance and $y_Q^2 \sim \mathcal{O}(10)$.
- AP of $q\bar{q} \to A\gamma$ 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 $\ell$ with mass $m_\ell$ and hypercharge (equal to the electric charge) $Y_\ell$.

- 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 $Y_\ell$, as $m_\ell$ can be expressed through the leptonium bound state mass and $Y_\ell$.

- 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 $m_{\ell}$ assuming the perturbative Drell-Yan production mechanism.
- These limits are valid if the heavy lepton is considered to be stable.
- Constrain the parameter $Y_\ell$ to fit the diphoton data.
- In addition, we predict a spin-1 ortho-leptonium bound state, whose mass is dependent on the allowed $Y_\ell$. 
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, \( r_\ell \gtrsim 1/m_Z \),

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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 \(\sim \mathcal{O}(Y^8 \alpha^4)\) relativistic Breit correction to the binding energy:

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

- The leptonium mass is then given by:

\[
m_{\psi_\ell} = 2m_\ell + E + \delta E_{\text{Breit}}
\]
Exotic lepton mass and otho-leptonium

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

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

the hypercharge $Y_\ell$ as the single unknown parameter of the model.

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

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

and is produced via Drell-Yan processes at LHC.
Leptonium production cross section

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

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

- The decay width $\Gamma_{\psi_\ell \rightarrow \gamma \gamma}$ 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:

$$\Gamma_{\psi_\ell \rightarrow \gamma \gamma} = \frac{16\pi\alpha^2 Y^4_\ell |\psi(0)|^2}{m_{\psi_\ell}^2}$$

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

with the radial part evaluated as:

$$|R(0)|^2 = \left(\frac{Y^2_\ell \alpha m_\ell}{2}\right)^3$$
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, $f_{\gamma}(x)$:

$$\sigma_{\gamma \gamma \rightarrow \psi \rightarrow \gamma \gamma} = \frac{8\pi^2}{s m_{\psi}} \frac{\Gamma_{\psi \rightarrow \gamma \gamma}^2}{\Gamma_{\psi \rightarrow \psi}} \int \delta(x_1 x_2 - m_{\psi}^2/s) f_{\gamma}(x_1) f_{\gamma}(x_2) dx_1 dx_2$$

where $\sqrt{s} = 13$ TeV and $m_{\psi} = 750$ GeV. $\Gamma_{\psi \rightarrow \psi}$ denotes the leptonium total width.

- In the minimal scenario,
  $$\Gamma_{\psi \rightarrow \psi} = \Gamma_{\psi \rightarrow \gamma \gamma} + \Gamma_{\psi \rightarrow \gamma Z} + \Gamma_{\psi \rightarrow ZZ} = \Gamma_{\psi \rightarrow \gamma \gamma} / 0.6.$$  

- However, we keep the total leptonium width as a free parameter.

- E.g. leptonium decays into a pair of dark matter particles $\chi$. 
The Lagrangian describing interactions of vector-like leptons $\ell$ with $\chi$ can have, e.g., the form:

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

where (assuming $\chi$ is a fermion) $\kappa$ is a parameter of mass dimension $-2$.

No significant constraints on the parameter $\kappa$ 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 $\Gamma_{\psi_\ell}$) $\Gamma_{\psi_\ell \rightarrow \chi \chi} \sim (Y_\ell^2 \alpha)^4 \kappa^2 m_\ell^5$.

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 $Y_\ell$.

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.

\[
\sigma_{\gamma\gamma \rightarrow \psi \rightarrow \gamma\gamma} = \frac{8\pi^2}{sm_{\psi}} \frac{\Gamma_{\psi \rightarrow \gamma\gamma}^2}{\Gamma_{\psi \rightarrow \gamma\gamma}} \int \delta(x_1 x_2 - m_{\psi}^2 / s) f_\gamma(x_1) f_\gamma(x_2) dx_1 dx_2
\]
Results of the numerical analysis

- Dependence of the cross section on $Y_\ell$.

- Minimal scenario: only $\gamma\gamma$, $Z\gamma$ and $ZZ$ decays are permitted, with the two photon channel being the dominant one, $Br(\psi_\ell \rightarrow \gamma\gamma) \approx 0.6$.

- For cross sections within the $2\sigma$ band that reproduce the LHC diphoton excess, $Y_\ell \approx 4.8 - 7.1$.

- Lepton masses $m_\ell$ as a function of $Y_\ell$, $m_\ell \approx 372 - 384$ GeV
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.

Updated 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 \( Y_\ell \), 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 $Y_\ell$.

- 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 proposed 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.
We need more data!
Thank You! :)