Interpreting the 750 GeV Di-photon Resonance using photon-jets in Hidden-Valley-like models

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Abstract

Motivated by the di-photon resonance recently reported by the ATLAS and CMS collaborations at $\sqrt{s} = 13$ TeV, we interpret the resonance as a scalar boson $X(750)$ in hidden-valley-like models. The scalar boson $X$ can mix with the standard model Higgs boson and thus can be produced via gluon fusion. It then decays into a pair of very light hidden particles $Y$ of $O(1\text{ GeV})$, each of which in turn decays to a pair of collimated $\pi^0$'s, and these two $\pi^0$'s decay into photons which then form photon-jets. A photon-jet ($\gamma$-jet) is a special feature that consists of a cluster of collinear photons from the decay of a fast moving light particle ($O(1\text{ GeV})$). Because these photons inside the photon-jet are so collimated that it cannot be distinguished from a single photon, and so in the final state of the decay of $X(750)$ a pair of photon-jets look like a pair of single photons, which the experimentalists observed and formed the 750 GeV di-photon resonance. Prospects for the LHC Run-2 about other new and testable features are also discussed.
I. INTRODUCTION

The Run-2 of the LHC has caught the eyes of everyone with a potential particle at around 750 GeV. Both the ATLAS [1] and CMS [2] collaborations have reported a ”bump” in the di-photon invariant mass distribution around 750 GeV. The ATLAS Collaboration with a luminosity of 3.2 fb$^{-1}$ showed a resonance structure at $M_X \approx 750$ GeV with a local significance of $\sim 3.64\sigma$ but corresponding to 1.88$\sigma$ when the look-elsewhere-effect is taken into account [1]. The CMS Collaboration also reported a similar though smaller excess with a luminosity of 2.6 fb$^{-1}$ at $M_X \approx 760$ GeV with a local significance of 2.6$\sigma$ but a global significance less than 1.2$\sigma$ [2]. Also, in the analysis of ATLAS a total width of $\Gamma/M \approx 6\% \sim 45$ GeV is preferred [1]. Such a large width might indicate something new beyond the Standard Model. Let us summarize the data here:

ATLAS : $M_X = 750$ GeV, $\sigma_{\text{fit}}(pp \rightarrow X \rightarrow \gamma\gamma) \approx 10 \pm 3$ fb (95% CL), $\Gamma_X \approx 45$ GeV

CMS : $M_X = 760$ GeV, $\sigma_{\text{fit}}(pp \rightarrow X \rightarrow \gamma\gamma) \approx 9 \pm 7$ fb (95% CL).

(1)

The uncertainties shown are 1.96$\sigma$ corresponding to 95% CL. Note that we estimate the best-fit cross section from the 95%CL upper limits given in the experimental paper, by subtracting the “expected” limit from the “observed” limit at $M_X = 750$ (760) GeV for ATLAS (CMS).

Before further exploring, let us summarize the information that is available so far to figure out some characteristics of new resonance. First, because the bump was observed in the di-photon channel, it forbade the direct decay of an on-shell spin $-1$ particle into di-photons by the Landau-Yang theorem [3][4]. [1] The spin of this new particle turns out to be either spin $-1$ or spin $\geq 2$. Second, because the production cross section is rather large $\mathcal{O}(10 \text{ fb})$, and the parton luminosity of gluons increases faster than that of quarks [5], the production mode is more likely the gluon fusion rather than quark-antiquark annihilation. Finally, because the total width of the new resonance is rather large ($\Gamma/M \approx 6\%$), it implies that the new particle couples rather strongly to its decay products or decays into objects that are hard to be observed. Given the severe exclusion bounds in search of new resonances decaying into vector-boson pairs, di-leptons, dijets, and $t\bar{t}$ pairs [6, 7], the new particle at

\footnote{1} It is nevertheless possible for a spin-1 particle to decay into two photon-jets via cascade decays, such that the spin-1 resonance for the 750 GeV resonance is not entirely excluded.
750 GeV may strongly couple to its decay particles, which are hard to be observe or excluded and also the decays into SM particles must be suppressed.

Although the hint is very preliminary, it has stimulated a lot of phenomenological activities, bringing in a number of models for interpretation. The first category is the Higgs section extensions, including adding singlet Higgs fields [8–10], two-Higgs-doublet models and the MSSM [11], but in general it fails to explain the large production cross section of $pp \rightarrow H \rightarrow \gamma \gamma$ in the conventional settings, unless additional particles are added, for example, vector-like fermions [8–11]. Another category is the composite models [12] that naturally contain heavy fermions, through which the production and the diphoton decay of the scalar boson can be enhanced. Other possibilities are also entertained, such as axion [13], sgoldstini [14], radion [15]. More general discussion can be found in Refs. [16]. The generic feature of the suggested interpretations is to enhance the production cross section of $pp \rightarrow H \rightarrow \gamma \gamma$, where $H$ is the 750 GeV scalar or pseudoscalar boson, by additional particles running in the $H\gamma\gamma$ decay vertex and/or $Hgg$ production vertex. Another generic feature though not realized in the CMS data is the relatively broad width of the particle, which motivates the idea that this particle is a window to the dark sector or dark matter [9, 10].

For simplicity we consider the resonance to be a spin $-0$ particle and produced by gluon fusion. To make this spin $-0$ particle strongly couple to its decay products (which are hard to be observed) and suppress its decays into $WW, ZZ, \ell^+\ell^-, t\bar{t}$ and dijet pair but still can accommodate the experimental results, we advocate a special scenario: *Could the final state be photon-jets instead of a pair of single photons?*

A photon-jet ($\gamma$-jet) [17] is a special feature that consists of a cluster of collinear photons from the decay of a fast moving light particle ($O(1\text{ GeV})$). Because these photons inside the photon-jet are so collimated that they cannot be distinguished from a single photon, so a photon-jet looks like a photon experimentally unless specific procedures to unlock the substructure inside the photon-jet. We propose a *Hidden-Valley-like simplified model* [18], in which the spin $-0$ particle $X(750)$ decays to a pair of very light ($O(1\text{ GeV})$) particles $Y$ (which strongly couples to $X$). Each $Y$ in turn decays to a pair of collimated neutral pions $\pi^0$, and these two $\pi^0$ decay to photons. Therefore, each fast moving $Y$ gives rise to a photon-jet, and in the final state of the decay of $X(750)$ consists of a pair of photon-jets, which the experimentalists observed and formed the 750 GeV di-photon resonance.
The organization is as follow. We describe a Hidden-Valley-like simplified model in the next section, and in Sec. III the existing constraints for $X(750)$. Then we fit the di-photon resonance in the model in Sec. IV. Finally, we provide some discussion and outlook in Sec. V.

II. HIDDEN-VALLEY-LIKE SIMPLIFIED MODEL

Here we employ a Hidden Valley-like model \cite{18} in which the SM Higgs field $\Phi$ can mix with two real scalar fields $\chi_1$ and $\chi_2$. These additional scalar fields are neutral under the SM gauge group $G_{SM}$ and do not have any SM interactions. The simplified Lagrangian for this model is given by\cite{2}

$$\mathcal{L} = \frac{1}{2} \partial_\mu \chi_1 \partial^\mu \chi_1 + \frac{1}{2} \partial_\mu \chi_2 \partial^\mu \chi_2 + \frac{1}{2} \mu_1^2 \chi_1^2 + \frac{1}{2} \mu_2^2 \chi_2^2 + \mu_3^2 \chi_1 \chi_2 + (\lambda_1 \chi_1 + \lambda_2 \chi_2)[M(\Phi^\dagger \Phi) + N(\lambda_1 \chi_1 + \lambda_2 \chi_2)^2] + \mathcal{L}_{SM},$$

where the Higgs sector in the $\mathcal{L}_{SM}$ is

$$\mathcal{L}_{SM} \supset (D_\mu \Phi)^\dagger (D^\mu \Phi) + \mu^2 (\Phi^\dagger \Phi) - \lambda (\Phi^\dagger \Phi)^2.$$ \hspace{1cm} (3)

In the Lagrangian, all $\mu_i$, $M$ and $N$ are of mass dimension 1 while $\lambda$s are of mass dimension 0. After the electroweak symmetry breaking (EWSB), the SM Higgs doublet field $\Phi$ is expanded around its vacuum-expectation value:

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \langle \phi \rangle \end{pmatrix},$$ \hspace{1cm} (4)

where $\langle \phi \rangle \approx 246$ GeV. It is easy to see that the Higgs boson $\phi$ will mix with these two new scalar bosons $\chi_1$ and $\chi_2$ to form mass eigenstates denoted by $h$, $X$ and $Y$, respectively.

\footnote{Since we propose a simplified model, we do not take into account the details of the vevs for these singlet fields, their vevs will be related to the parameters $M, N$ in our simplified model.}
mass terms for the Higgs boson and these two new scalar bosons are

\[ \mathcal{L}_m = -\frac{1}{2} (\phi \chi_1 \chi_2) \begin{pmatrix} 2\lambda(\phi)^2 & -\lambda_1 M(\phi) & -\lambda_2 M(\phi) \\ -\lambda_1 M(\phi) & -\mu_1^2 & -\mu_2^2 \\ -\lambda_2 M(\phi) & -\mu_3^2 & -\mu_2^2 \end{pmatrix} \begin{pmatrix} \phi \\ \chi_1 \\ \chi_2 \end{pmatrix}, \quad (5) \]

We can rotate \((\phi \chi_1 \chi_2) \rightarrow (h X Y)\) through these angles \(\theta_1, \theta_2\) and \(\theta_3\)

\[
\begin{pmatrix} h \\ X \\ Y \end{pmatrix} = \begin{pmatrix} \cos \theta_1 & \sin \theta_1 & 0 \\ -\sin \theta_1 & \cos \theta_1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos \theta_2 & 0 & \sin \theta_2 \\ 0 & 1 & 0 \\ -\sin \theta_2 & 0 & \cos \theta_2 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_3 & \sin \theta_3 \\ 0 & -\sin \theta_3 & \cos \theta_3 \end{pmatrix} \begin{pmatrix} \phi \\ \chi_1 \\ \chi_2 \end{pmatrix}, \quad (6)\]

\[
= \begin{pmatrix} C_{\theta_1}C_{\theta_2} & (S_{\theta_1}C_{\theta_2} - C_{\theta_1}S_{\theta_2}S_{\theta_3}) & (S_{\theta_1}S_{\theta_2} + C_{\theta_1}S_{\theta_2}C_{\theta_3}) \\ -S_{\theta_1}C_{\theta_2} & (C_{\theta_1}C_{\theta_2} + S_{\theta_1}S_{\theta_2}S_{\theta_3}) & (C_{\theta_1}S_{\theta_2} - S_{\theta_1}S_{\theta_2}C_{\theta_3}) \\ -S_{\theta_2} & -C_{\theta_2}S_{\theta_3} & C_{\theta_2}C_{\theta_3} \end{pmatrix} \begin{pmatrix} \phi \\ \chi_1 \\ \chi_2 \end{pmatrix}, \quad (7)\]

where \(\theta_{1,2,3}\) is the mixing angle between \(\phi\) and \(\chi_1\), between \(\phi\) and \(\chi_2\), and between \(\chi_1\) and \(\chi_2\), respectively. \(C_{\theta_i}\) stands for \(\cos \theta_i\) and \(S_{\theta_i}\) stands for \(\sin \theta_i\). If we assume \(\theta_1, \theta_2\) are rather small compared with \(\theta_3\), then the masses for the Higgs boson \(h\) and two scalar bosons \(X, Y\), and the interaction governing \(X \rightarrow hh, X \rightarrow YY\) are given by, in terms of the parameters in Eq. [2]:

\[
m_h^2 \simeq 2\lambda(\phi)^2 - (\mu_1^2 \sin^2 \theta_1 + \mu_2^2 \sin^2 \theta_2) - M(\phi)(\lambda_1 \sin 2\theta_1 + \lambda_2 \sin 2\theta_2) = (125 \text{ GeV})^2
\]

\[
m_X^2 \simeq -\mu_1^2 \cos^2 \theta_3 - \mu_2^2 \sin^2 \theta_3 - \mu_3^2 \sin 2\theta_3 + 2\lambda(\phi)^2 \sin^2 \theta_1 + \lambda_1 M(\phi) \sin 2\theta_1
\]

\[
m_Y^2 \simeq -\mu_1^2 \sin^2 \theta_3 - \mu_2^2 \cos^2 \theta_3 + \mu_3^2 \sin 2\theta_3 + 2\lambda(\phi)^2 \sin^2 \theta_2 + \lambda_2 M(\phi) \sin 2\theta_2
\]

\[
\mathcal{L}_{Xhh} \simeq \frac{1}{2} [2\lambda(\phi) \cos^2 \theta_1 \sin \theta_1 + 6N\lambda_1^3 \cos \theta_1 \sin^2 \theta_1 + \lambda_1 M(\cos^3 \theta_1 - 2 \cos \theta_1 \sin^2 \theta_1)] Xhh \equiv \frac{\mu_{Xhh}}{2} Xhh
\]

\[
\mathcal{L}_{XYY} \simeq \frac{6N}{2} [\lambda_1^2 \cos^2 \theta_3 \sin \theta_3 + \lambda_3^2 \cos \theta_3 \sin^2 \theta_3 + \lambda_1 \lambda_2^2 (\cos^3 \theta_3 - 2 \cos \theta_3 \sin^2 \theta_3) + \lambda_2 \lambda_1^2 (\sin^3 \theta_3 - 2 \cos^2 \theta_3 \sin \theta_3)] YYY \equiv \frac{\mu_{HY}}{2} YYY,
\]
In order to interpret the 750 GeV di-photon resonance, we set \( m_X = 750 \) GeV. The 750 GeV scalar boson \( X \) can decay into SM particles via the mixing with the SM Higgs boson. Thus, the partial decay widths for \( X \to W^+W^- \), \( X \to ZZ \) and \( X \to t\bar{t} \) are given by \([19]\)

\[
\Gamma(X \to W^+W^-) = \sin^2 \theta_1 \frac{g^2 m_X^3}{64 \pi m_W^2} \left[ 1 - \frac{4m_W^2}{m_X^2} \right] \left( 1 - \frac{4m_W^2}{m_X^2} + \frac{12m_W^4}{m_X^4} \right), \tag{10}
\]

\[
\Gamma(X \to ZZ) = \sin^2 \theta_1 \frac{g^2 m_X^3}{128 \pi m_Z^2} \left[ 1 - \frac{4m_Z^2}{m_X^2} \right] \left( 1 - \frac{4m_Z^2}{m_X^2} + \frac{12m_Z^4}{m_X^4} \right), \tag{11}
\]

\[
\Gamma(X \to t\bar{t}) = \sin^2 \theta_1 \frac{N_c g^2 m_t^2}{32 \pi m_W^2} \left[ 1 - \frac{4m_t^2}{m_X^2} \right]^{3/2} (1 + \Delta_{QCD}), \tag{12}
\]

where \( \Delta_{QCD} \) are higher order QCD corrections \([20]\). Other than the decays into SM particles via the mixing with the Higgs boson, \( X(750) \) can have more decay channels \( X \to YY \) and \( X \to hh \). The partial decay width for \( X \to YY \) is given by

\[
\Gamma(X \to YY) = \frac{\mu_{HS}^2}{32 \pi m_X} \times \sqrt{1 - 4 \left( \frac{m_Y}{m_X} \right)^2} . \tag{13}
\]

and that for \( X \to hh \) is given by

\[
\Gamma(X \to hh) = \frac{\mu_{Xhh}^2}{32 \pi m_X} \times \sqrt{1 - 4 \left( \frac{m_h}{m_X} \right)^2} . \tag{14}
\]

We show the branching ratios of the scalar boson \( X(750) \) with \( \Gamma_X = 45 \) GeV for the four most dominant modes \( YY, W^+W^-, ZZ, \) and \( t\bar{t} \) in Fig. 1 where we have neglected the branching ratios of \( B(X \to hh, hY) \) (we will come back to this point in the next section).

Since the scalar boson \( Y \) also mixes with the SM Higgs boson, it can decay into SM particles via the mixing. Thus, for the \( \mathcal{O}(1) \) GeV scalar boson \( Y \), the dominant decay modes are \( Y \to \ell^+\ell^- (\ell = e, \mu) \) and \( Y \to \pi\pi \) given by \([19]\)

\[
\Gamma(Y \to \ell^+\ell^-) = \sin^2 \theta_2 \frac{m_Y^2 m_{\ell^+}\ell^-}{8\pi\langle\phi\rangle^2} \left( 1 - \frac{4m_{\ell^+}\ell^-}{m_Y^2} \right)^{3/2} , \tag{15}
\]

\[
\Gamma(Y \to \pi\pi) = \sin^2 \theta_2 \frac{m_Y^4}{216\pi\langle\phi\rangle^2} \left( 1 - \frac{4m_{\pi^+}\pi^-}{m_Y^2} \right)^{1/2} \left( 1 + \frac{11m_{\pi^+}\pi^-}{2m_Y^2} \right)^2 , \tag{16}
\]

\[
\Gamma_Y = \frac{1}{\tau_Y} = \sum_{\ell=e,\mu} \Gamma(Y \to \ell^+\ell^-) + \sum_{\pi=\pi^+,\pi^0} \Gamma(Y \to \pi\pi) , \tag{17}
\]

Here \( \pi\pi \) includes \( \pi^+\pi^- \), \( \pi^0\pi^0 \) and \( \Gamma(Y \to \pi^+\pi^-) = 2\Gamma(Y \to \pi^0\pi^0) \). Since the tree-level
estimation of $\Gamma(Y \rightarrow \pi\pi)$ is not correct when $m_Y$ is not far from the pion threshold, where
strong final-state interaction becomes important \cite{21,22}, so we follow Ref.\cite{21,22} for numerical estimates of $\Gamma(Y \rightarrow \pi\pi)$. For a 1 GeV scalar boson $Y$, the branching ratio into $\pi\pi$ is almost 100% and for $\mu^+\mu^-$ is just about 0.4\% \cite{22}. The lifetime of $Y$ is equal to the inverse of the total width of $Y$. The total width is calculated by summing all the partial widths given in Eqs. \cite{15} and \cite{16}. For a 1 GeV scalar boson $Y$ with $\sin\theta_2 = 1.6 \times 10^{-2}$, we have $\Gamma_Y \approx 4.25 \times 10^{-10}$ GeV and so $\tau_Y = \frac{1}{\Gamma_Y} \approx 1.55 \times 10^{-15}$ (s).

The production cross section of $X(750)$ via gluon fusion is simply given by the gluon fusion cross section of a would-be 750 SM Higgs boson multiplied by the factor $\sin^2 \theta_1$ as

$$\sigma(pp \rightarrow gg \rightarrow X(750)) = \sin^2 \theta_1 \times \sigma_{SM}(pp \rightarrow gg \rightarrow H_{SM}) .$$  (18)
III. CONSTRAINTS

A. Constraints on X

The scalar boson $X(750)$ mixes with the SM Higgs boson, and so it will affect the Higgs boson data collected at the Run-1. Indeed, the $X(750)$ interacts with the SM particles via the mixing with the SM Higgs boson with the angle $\theta_1$. In this setup, being similar to the Higgs-portal models, a previous global fit to all the Higgs-boson data was performed \[23\]. The mixing angle $\theta_1$ is constrained to be, at 95% CL \[23\].

$$\cos \theta_1 > 0.86,$$

which implies $|\sin \theta_1| < 0.51$ or $\sin^2 \theta_1 < 0.26$. In the following, we shall use a moderate value for $|\sin \theta_1| = 0.3$ unless stated otherwise.

There are also other direct searches for new resonances decaying into $W^+W^-$, $ZZ$, $t\bar{t}$, $hh$, and dijets with the 8 TeV data by both the ATLAS and CMS collaborations.

- The searches for a scalar resonance decaying to $ZZ$ and $WW$ with the full data set exist for both ATLAS \[24, 25\] and CMS \[26\]. Combining all relevant decay modes of $Z$ and $W$, the 95% CL upper limit on the production cross sections are

$$\sigma(pp \to S)_{8\text{TeV}} \times B(S \to ZZ) < 22 \text{ fb}(\text{ATLAS}), \quad 27 \text{ fb}(\text{CMS})$$

$$\sigma(pp \to S)_{8\text{TeV}} \times B(S \to W^+W^-) < 38 \text{ fb}(\text{ATLAS}), \quad 220 \text{ fb}(\text{CMS}).$$

(20)

(21)

For $\sin \theta_1 = 0.3$, with $\sigma_{\text{SM}}(pp \to gg \to H_{\text{SM}}) \approx 157 \text{ fb}$ at $\sqrt{s} = 8 \text{ TeV}$ and the branching ratio of $X(750)$ into $WW$, $ZZ$, and $t\bar{t}$ can be found in Table I

$$\sigma(pp \to X)_{8\text{TeV}} \times B(X \to ZZ) = 2.0 \text{ fb}$$

$$\sigma(pp \to X)_{8\text{TeV}} \times B(X \to W^+W^-) = 4.1 \text{ fb}$$

(22)

(23)

- The searches for a scalar resonance decaying to a pair of top quarks for both ATLAS
and CMS impose a 95% CL upper limit of

\[
\sigma(pp \to S)_{8\text{TeV}} \times B(S \to t\bar{t}) < 0.7 \text{ pb}_{\text{(ATLAS)}}, \quad 0.6 \text{ pb}_{\text{(CMS)}},
\]  \tag{24}

For \( \sin \theta_1 = 0.3 \), \( \sigma(pp \to X)_{8\text{TeV}} \times B(X \to t\bar{t}) = 0.38 \text{ fb.} \)

- The searches for a scalar resonance decaying to a Higgs boson pair for both ATLAS and CMS impose a 95% CL upper limit of

\[
\sigma(pp \to S)_{8\text{TeV}} \times B(S \to hh) < 35 \text{ fb}_{\text{(ATLAS)}}, \quad 52 \text{ fb}_{\text{(CMS)}},
\]  \tag{25}

By imposing this constraint, we have

\[
|\mu_{Xhh}| \lesssim 435 \text{ GeV}.
\]  \tag{26}

Because \( |\mu_{Xhh}| \) is a free parameter in our model and not relevant to explain the diphoton resonance, let us assume \( Br(X \to hh) \ll O(1\%) \) (i.e. \( |\mu_{Xhh}| \lesssim 190 GeV \)) and ignore its effect below.

Since the leading term in \( L_{Xhh} \) in Eq. (8) and \( L_{XYY} \) in Eq. (9) are not suppressed by any of the mixing angles \( \sin \theta_i \) (\( i = 1, 2, 3 \)) while the leading term for \( L_{XYh} \) derived from the Lagrangian contains at least one factor of \( \sin \theta_i \), and therefore the \( XYh \) coupling will be suppressed relative to \( Xhh \) and \( XYY \). In the computation of branching ratios of \( X \), we shall also ignore \( X \to hY \), as we have assumed \( B(X \to hh) \ll O(1\%) \).

- The searches for a scalar resonance decaying to dijet also appear for both ATLAS and CMS. Here since we produce \( X(750) \) by gluon fusion, we also consider the 95% CL upper limit on the production of a RS graviton decaying to \( gg \) from CMS:

\[
\sigma(pp \to S)_{8\text{TeV}} \times B(S \to gg) \times \alpha < 1.8 \text{ pb}.
\]  \tag{27}

where \( \alpha \) is the acceptance. For \( \sin \theta_1 = 0.3 \) and conservatively setting \( \alpha = 1 \), \( \sigma(pp \to \)
\[ X_{3\text{TeV}} \times B(X \rightarrow gg) = 1.76 \times 10^{-3} \text{fb}. \]

B. Constraints on \( Y \)

So far, we have discussed the constraints related to the heavy resonance of 750 GeV. The very light boson \( Y \), which has mass of order 1 GeV, is also subject to a number of constraints as follows.

- The boson \( Y \) mixes with the SM Higgs boson via the mixing angle \( \theta_2 \), which is very similar to the mixing between \( X \) and the SM Higgs. Thus, the constraint on \( \theta_2 \) from the Higgs boson data is the same as \( \theta_1 \):

\[
\cos \theta_2 > 0.86 \quad \text{the same as Eq. (19)}.
\]

Since \( h \) also decays into \( YY \) via the mixing angle \( \theta_2 \), the size of \( \theta_2 \) is then carefully chosen to be consistent with the Higgs boson data in the same way as \( \theta_1 \).

- Another set of constraints on \( \sin \theta_2 \) arise from \( B \) and \( K \) meson decays \[33\] For \( 360 \text{ MeV} < m_Y < 4.8 \text{ GeV} \), the strongest constraint comes from \( B \rightarrow K\mu^+\mu^- \) decay limit, which constrains \( \sin^2 \theta_2 \times B(Y \rightarrow \mu^+\mu^-) < 10^{-6} \), which implies \( \sin^2 \theta_2 \times 0.4\% < 10^{-6} \) for \( m_Y = 1 \text{ GeV} \). Therefore, \( \sin \theta_2 < 1.6 \times 10^{-2} \).

- The \( \theta_2 \) is also constrained by more specific searches of the Higgs boson decays, such as \( h \rightarrow aa \rightarrow (\gamma\gamma)(\gamma\gamma) \). The closest one that we can find is by the ATLAS Collaboration \[34\]. In the paper, one of the searches is \( h \rightarrow aa \rightarrow (\gamma\gamma)(\gamma\gamma), \) but only for \( 10 \text{ GeV} < m_a < 62 \text{ GeV} \). In this case, the photon pair in each decay of the boson \( a \) is widely separated and can be detected. It is very different from our case of \( Y \) being around 1 GeV such that the photon pair is really collimated.

- There was another search by ATLAS \[35\] in

\[
h(125) \rightarrow aa \rightarrow (\gamma\gamma)(\gamma\gamma),
\]

for \( m_a = 100, 200, 400 \text{ MeV} \). In this case, the photon pair from each boson \( a \) is very collimated and could not be distinguished from a single photon. ATLAS then used
$h \to \gamma \gamma$ to constrain this rare decay and set a limit:

$$B(h \to aa) \times B^2(a \to \gamma \gamma) < 0.01.$$  

However, the range of the boson $Y$ that we are using in this work is $O(1\text{ GeV})$ such that most of the range is not covered by this current limit. Thus, it is important to set up specific high-angular-resolution search for the case of $m_Y \sim O(1\text{ GeV}).$

For the mass range of $Y$ from 0.5 GeV to 1 GeV, the major decay mode is $\pi \pi$, which is larger than 90%, and the sub-leading decay mode is $\mu^+\mu^-$, which is less than 10%. We choose $m_Y = 1\text{ GeV}$ as our benchmark point because it can give $B(Y \to \pi \pi) \sim 100\%$ and $B(Y \to \mu^+\mu^-) \sim 0.4\%$. On the other hand, there is no reliable calculation for the hadronic branching ratios for $m_Y$ between 1 GeV to 2.5 GeV. Finally, for $m_Y > 2.5\text{ GeV}$ the decay mode of $\pi \pi$ becomes negligible. Therefore, we focus on the mass of $Y$ to be $O(1\text{ GeV}).$

In summary, for $m_Y \sim O(1\text{ GeV})$ the angle $\theta_2$ is constrained to be $\sin \theta_2 < 1.6 \times 10^{-2}$. We shall then use $\sin \theta_2 = 1.6 \times 10^{-2}$ and $m_Y = 1\text{ GeV}$ for numerical results. With this choice of $\sin \theta_2$ the $h \to YY$ easily satisfies all the constraints.

IV. FITTING THE DI-PHOTON RESONANCE

To fit the di-photon resonance, we consider the following process

$$pp \to X \to YY \to (\pi^0\pi^0)(\pi^0\pi^0) \to (4\gamma)(4\gamma).$$  \hspace{1cm} (28)$$

The Feynman diagram for this process is shown in Fig. 2. Since each $\pi^0$ almost 100% decays to $\gamma \gamma$, the final state consists of a total 8 photons. Because these photons come from the decay of a fast moving light particle $Y$, they form a cluster of collinear photons (which we called photon-jet ($\gamma$-jet)) on each side. Because the photons inside each photon-jet are so collimated that they cannot be distinguished from a single photon, we use this feature to interpret the di-photon excess. Before discussing how the photon-jet can escape from the experimental isolation conditions, let us first fit the observed di-photon resonance width and production rate.
A. Fitting the width for $X(750)$

In order to fit the width of $X(750)$ to 45 GeV with the mixing angle $\sin \theta_1 = 0.3$, we need a very strong coupling for $X$ with a pair of $Y$'s

$$|\mu_{HS}| \gtrsim 1308 \text{ GeV}.$$  \hspace{1cm} (29)

We have pointed out in the Introduction that because the width relative to the mass of the resonance is rather large ($\Gamma/M \approx 6\%$), it implies that the new particle must couple strongly to its decay products. The branching ratios and partial widths for $X(750)$ into the four most dominant modes $YY$, $W^+W^-$, $ZZ$, and $t\bar{t}$ are shown in Table I. We also show in Fig. 3 the contour of $\sin \theta_1$ versus $|\mu_{HS}|$ where we fix $\Gamma_{X(750)} = 45$ GeV. The contour indicates that the weaker the mixing angle $\sin \theta_1$, the stronger coupling of $X \rightarrow YY$ required. The lower region of the contour corresponds the total width $\Gamma_{X(750)} < 45$ GeV.
FIG. 3. The contour of \( \sin \theta_1 \) versus \( |\mu_{HS}| \) for a fixed \( \Gamma_{X(750)} = 45 \text{ GeV} \) and \( m_Y = 1 \text{ GeV} \).

| \( YY \) | \( W^+W^- \) | \( ZZ \) | \( t\bar{t} \) |
|-------|--------|------|-----|
| BR    | 50.45% | 29.07% | 14.38% | 6.10% |
| \( \Gamma_i \) (GeV) | 22.70 | 13.08 | 6.47 | 2.75 |

TABLE I. The branching ratios and partial widths for \( X(750) \) into the four most dominant modes \( YY, W^+W^-, ZZ, \) and \( t\bar{t} \) with the mixing angle fixed at \( \sin \theta_1 = 0.3 \).

**B. Fitting the production rate for \( X(750) \)**

To fit the production rate, we consider the cross section for \( pp \to X \to YY \to (\pi^0\pi^0)(\pi^0\pi^0) \to (4\gamma)(4\gamma) \)

\[
\sigma \left( pp \to X \to YY \to (\pi^0\pi^0)(\pi^0\pi^0) \to (4\gamma)(4\gamma) \right)
= \sigma(pp \to X) \times B(X \to YY) \times [B(Y \to \pi^0\pi^0)]^2 \times [B(\pi^0 \to \gamma\gamma)]^4 \\
\approx [736 \text{ fb} \times (0.3)^2] \times [50.45\%] \times \left[ 100\% \times \frac{1}{3} \right]^2 \times [100\%]^4 \\
\approx 3.71 \text{ fb}
\]

(30)

where the gluon fusion production cross section at \( \sqrt{s} = 13 \text{ TeV} \) for a SM Higgs boson of mass \( M_H = 750 \text{ GeV} \) is \( \sigma(gg \to H_{SM}) \approx 0.736 \text{ pb} \). We also show the variation of production rate versus \( \sin \theta_1 = 0.1 - 0.5 \) in Fig. 4. We can see the maximum cross section
that we can obtain is about 4 fb and it occurs at around $\sin \theta_1 \approx 0.3$.

C. Discussion of the photon-jet scenario

Since the photon-jet can arise from a highly boosted object that decays into multiple photons, which merge into a photon-jet appearing like a single photon, which then hit the electromagnetic calorimeter (ECAL) at essentially the same place. In our Hidden-Valley-like simplified model, the $X(750)$ decays into a pair of $Y$. Each $Y$ decays into two neutral pions and each neutral pion further decays into 2 photons. Therefore, the final state consists of a back-to-back pair of photon-jets, each of which consists of 4 collimated photons. Due to very tiny angular separation among the photons in each photon-jet and the long lifetime, the $\gamma$-jet may be reconstructed as a single photon.

The ATLAS and CMS have different capabilities in both detecting photons and distinguishing them from other possible electromagnetic objects. Let us briefly summarize them here [38, 39]. The granularity of CMS ECAL is $0.0174 \times 0.0174$ in $\eta \times \phi$. The ATLAS electromagnetic calorimeter consists three longitudinal layers. The granularity for the first layer (a thickness between 3 and 5 radiation lengths) is $0.003 – 0.006$ in $\eta$ within the regions...
1.4 < |η| < 1.5 and |η| > 2.4, sufficient for the photons decaying from π^0. The second layer (thickness around 17 radiation lengths) granularity is 0.025 × 0.025 in η × φ. The third layer is for high energy shower correction.

Let us perform a simple estimate for the angular separation and the lifetime of Y in order to confirm this scenario. The angular separation in the decay products of Y is roughly ΔR ≈ 2m_Y/P_T_Y = 2GeV/375GeV = 0.0053. The lab-frame lifetime of Y is γτ_Y ≈ 2τ_Y/ΔR ≈ 5.85 × 10^{-13}(s), so the decay length could be γcτ_Y ≈ 0.18(mm), where γ and c are the boost factor and the speed of light, respectively [37]. As we know, if the decay length of a particle is less than 0.15 mm, then we can take it as a prompt decay. Even though the boson Y in our scenario is a rather long-lived particle, its decay length is very close to the prompt decay.

The high-granularity calorimeter of ATLAS is capable of resolving single photons from π^0's. However, they used an elliptical cone (Δη/0.025)^2 + (Δφ/0.05)^2 < 1 (corresponding roughly to a 3 × 5 cluster) to associate the photon candidate [3] which might take the highly boosted photon-jet as a single photon.

The LHC experiments in the Higgs measurements of the di-photon channel are able to distinguish photons of m_h/2 ∼ 65 GeV from π^0's of the same energy [40]. The angular separation between the two photons in the 65 GeV pion decay is roughly 0.004. The efficiency also depends strongly on the direction of the pions. Since X → YY → (π^0π^0)(π^0π^0), so that each π^0 has a maximum energy of 187.5 GeV, which corresponds to an angular separation between the pair of photons from π^0 of about 0.0015, which is about a factor of 3 smaller. When we go one step back in the decay chain, the angular separation between two neutral pions from each Y decay is about 2m_Y/P_T_Y ≈ 0.005. The overall picture is exactly what we showed in Fig.2. Each Y decays into 2π^0 with an angle 0.005, and each π^0 decays into 2 photons with an angle 0.0015. All 4 photons are contained in a cone of 0.005 forming a photon-jet. Certainly without a dedicated high-photon-resolution analysis, it is very difficult to distinguish a photon-jet from a single photon in this case. In the limited information given in the proceedings [1, 2], we cannot tell if the signal contains single photons or photon-jets. A more elaborate experimental analysis is needed to determine if it is possible.

---

3 For the photon selection efficiency, the ATLAS experiment selects the photon candidate with an elliptical cone, inside (Δη/0.025)^2 + (Δφ/0.05)^2 < 1 (corresponding roughly to a 3 × 5 cluster) the true photon with highest p_T is associated to the candidate [38]. They extrapolated the “final state” particle to their impact point in the second sampling of the electromagnetic calorimeter (EMS2). The reconstructed photon and the true particle association are depending on the difference between the position (η^{clus}, φ^{clus}) of the cluster barycentre and the coordinates (η^{extr}, φ^{extr}), Δη = η^{extr} - η^{clus} and Δφ = φ^{extr} - φ^{clus}.
Finally, our scenario is still valuable to make some predictions even without a detailed detector simulation. Let us discuss it in the following 3 points.

- First, since the angular separation between the pair of photons from $\pi^0$ in our scenario is just about a factor of 3 smaller than that between the photon pair from the decay of a neutral pion of energy 65 GeV, it could be resolved for either ATLAS or CMS in the near future, similar to the case between the 65 GeV photon and a neutral pion of same energy. We have shown a clear physical picture in Fig.2.

- Second, it will be much more plausible to detect the photon-jet from the prompt decay of $Y$ rather than the non-prompt case. The decay length of $Y$ in our scenario is only 0.18 mm which is not far from the prompt decay. We suggest that both ATLAS and CMS can have a higher chance to distinguish the photon-jet from the single photon in our scenario than the other proposals, e.g. in Ref. [37], of longer decay lengths of very light particles with seriously non-prompt decays. These kind of seriously non-prompt decays will become virtually impossible to make any quantitative predictions without detailed detector simulations, but our scenario is almost free from the complication of the non-prompt decays.

- Third, if the experimental groups have fine enough resolution to distinguish the photon-jet from the single photon in our scenario, then they can also clearly observe a resonance around 1 GeV.

Based on these three points, our scenario can explain why the photon-jet is still indistinguishable from the single photon under the current experimental studies and the current constraints. However, it is still plausible to explore the difference between photon-jets and single photons in our scenario with $m_Y \approx 1$ GeV. Therefore, we strongly encourage our experimental colleagues to perform a more elaborate experimental analysis to confirm or rule out this kind of scenario.

V. DISCUSSION

We have studied the 750 GeV di-photon resonance by interpreting it as the production of the resonance $X(750)$ decaying into a pair of very light $(O(1\text{ GeV}))$ particles $Y$, each of
which in turn decays to 4 photons which form photon-jets. Since these photons inside the photon-jet are so collimated that they cannot be distinguished from a single photon. So far, we have found that this scenario can simultaneously accommodate the width and the production rate though moderately, and is consistent with the current constraints from the 8 TeV searches and the isolation of photon-jets from single photons.

We offer the following comments with regards to our scenario.

1. There are also two other processes with the production rate of order $O(15 \text{ fb})$ in our scenario:

$$pp \rightarrow X \rightarrow YY \rightarrow (\pi^0\pi^0)(\pi^+\pi^-)$$

(31)

and

$$pp \rightarrow X \rightarrow YY \rightarrow (\pi^+\pi^-)(\pi^+\pi^-).$$

(32)

The Feynman diagrams for these two processes are shown in Fig. 5 and Fig. 6, respectively. Since the two charged pions coming from $Y$ decay are very collimated, they will appear as a “microjet”, which looks like a $\tau$-jet experimentally, which is rather “thin” compared to the usual hadronic jet [41]. The pixel detector inside the LHC experiments has some chances of separating them [41, 42]. If the experiment cannot resolve these two charged pions, then the final state will consist of a “microjet” of two unresolved charged pions and a photon-jet for Eq. (31) and two “microjets” for Eq. (32).

2. Another interesting process but with a much smaller production rate of order $O(0.1 \text{ fb})$ in our scenario is

$$pp \rightarrow X \rightarrow YY \rightarrow (\pi^0\pi^0)(\mu^+\mu^-)$$

(33)

The Feynman diagram for this process is shown in Fig. 7. The collimated muon-pair seems more possible to be resolved than the photon-jet or microjet [43], because of the much-refined pixel detector in the central region together with the outer muon chamber. Thus, the final state will consist of a pair of collimated muons appearing as a muon-jet and a photon-jet. It is a rather clean signal to be identified.

3. Similar ideas using collimated photons to explain the di-photon resonance also appeared in Ref. [37, 40]. They also used a scalar boson of 750 GeV, but the differences
FIG. 5. The Feynman diagram for $pp \rightarrow X \rightarrow YY \rightarrow (\pi^0 \pi^0)(\pi^+ \pi^-)$.

FIG. 6. The Feynman diagram for $pp \rightarrow X \rightarrow YY \rightarrow (\pi^+ \pi^-)(\pi^+ \pi^-)$.

are as follows.

- In Ref. [40], they used a simplified model of Hidden Valley. However, they considered a very light scalar with a new charged vector-like fermion at the weak scale.
FIG. 7. The Feynman diagram for $pp \to X \to YY \to (\pi^0\pi^0)(\mu^+\mu^-) \to (4\gamma)(\mu^+\mu^-)$

to produce collimated pairs of photons. They also focus on the mass range of the very light scalar less than 1 GeV.

- In Ref.[37], they used two types of models. The first one is a very light CP-odd scalar axion (about 2 GeV) with a new heavy lepton to produce collimated pairs of photons. The second one is using “fake” photons by adding new dark photons.

Comparing to these two works, our scenario is somewhat more economical and offers different signatures. The new 750 GeV resonance is currently detected by a pair of photon-jets, yet the scenario allows other interesting signatures to distinguish them.
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