A Boost Test of Anomalous Diphoton Resonance at the LHC

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The recently observed diphoton resonance around 750 GeV at the LHC Run-II could be interpreted as a weak singlet scalar. The scalar might also decay into a pair of Z-boson and photon. The Z-boson is highly boosted and appears as a fat jet in the detector. We use the jet substructure method to explore the possibility of discovering the singlet scalar in the process of pp → S → Zγ in the future LHC experiment.

**Introduction:** Recently, an anomalous resonance around 750 GeV is observed in the diphoton channel at the level of 3.9σ by the ATLAS collaboration and 2.6σ by the CMS collaboration at the LHC Run-II [1, 2]. The observation stimulates great interests in the field [3–37]. It is attractive to interpret the diphoton resonance as a weak singlet scalar (S) which democratically couples to gauge bosons in the Standard Model (SM) through a set of effective operators. There are only three such operators that couple the scalar S to pairs of vector bosons at the dimension five [38, 39]:

\[ \mathcal{L}_{\text{eff}} = \kappa_g \frac{S G_{\mu\nu}^a G^{\mu\nu}}{M_S^2} + \kappa_W \frac{S W_i^{\mu\nu} W^{i\mu\nu}}{M_S^2} + \kappa_B \frac{S B_{\mu\nu} B^{\mu\nu}}{M_S^2}, \]  

where \( G_{\mu\nu}^a, W_i^{\mu\nu} \) and \( B_{\mu\nu} \) denote the field strength tensor of the \( SU(3)_C \), \( SU(2)_W \) and \( U(1)_Y \) gauge group, respectively. Note that the coefficients \( \kappa_g,\kappa_W,\kappa_B \) are expected to be around \( \mathcal{O}(M_S/\Lambda) \) with \( \Lambda \) being new physics scale beyond the capability of current LHC. Our study can be extended to the weak singlet pesudo-scalar whose couplings to gauge bosons arise from a Wess-Zumino-Witten anomaly term [40]. After symmetry breaking the SM gauge bosons are interwoven such that the S scalar will also decay into pairs of WW, ZZ, and Zγ. Observing a resonance in the invariant mass spectrum of WW, ZZ and Zγ pairs would consolidate the diphoton anomaly. The hadronic modes of the W and Z boson decay are preferred as they exhibit large branching ratios. On the other hand, the W or Z boson from the S decay is highly boosted such that the two partons from W and Z decays tend to be collimated and appear in the detector as one fat jet, named as a V-jet where \( V = W/Z \). In this Letter we utilize the so-called jet substructure method to probe the signature of boosted V-jets from the S decay in the process of pp → S → Zγ to crosscheck the diphoton excess.

**Scalar production and decay:** We adapt narrow width approximation (NWA) to parameterize the process of \( pp \rightarrow S \rightarrow XY \) as following

\[ \sigma(pp \rightarrow S \rightarrow XY) = \sigma(pp \rightarrow S) \times \frac{\Gamma(S \rightarrow XY)}{\Gamma_S}, \]  

where \( X \) and \( Y \) denote the SM gauge bosons while \( \Gamma_S \) the total width of the S scalar. The scalar can decay into five modes induced by the three effective operators. The partial widths of the S decay are listed as follows:

\[ \Gamma(S \rightarrow gg) = \frac{M_S}{\pi} 2 \kappa_g^2, \]
\[ \Gamma(S \rightarrow \gamma\gamma) = \frac{M_S}{4\pi} (\kappa_W s_W^2 + \kappa_B c_B^2)^2, \]
\[ \Gamma(S \rightarrow Z\gamma) = \frac{M_S}{2\pi} (\kappa_W - \kappa_B)^2 (1 - r_Z)^3 c_W s_W^2, \]
\[ \Gamma(S \rightarrow WW) \approx \frac{M_S}{2\pi} (1 - 6 r_W) \kappa_W^2, \]
\[ \Gamma(S \rightarrow ZZ) \approx \frac{M_S}{4\pi} (\kappa_W c_W + \kappa_B s_W^2)^2 (1 - 6 r_Z), \]

where \( r_Y = m_Y^2/M_S^2 \). For a 750 GeV scalar, \( r_Y \sim 0.01 \) can be ignored in the above partial widths. We compare the branching ratio \( \Gamma(S \rightarrow XY) \) to \( \Gamma(S \rightarrow \gamma\gamma) \) in the following four special cases:

i) \( \kappa_B = 0, \)

\[ R_{WW} = \frac{\Gamma(S \rightarrow WW)}{\Gamma(S \rightarrow \gamma\gamma)} \sim 40, \]
\[ R_{ZZ} = \frac{\Gamma(S \rightarrow ZZ)}{\Gamma(S \rightarrow \gamma\gamma)} \sim 12, \]
\[ R_{Z\gamma} = \frac{\Gamma(S \rightarrow Z\gamma)}{\Gamma(S \rightarrow \gamma\gamma)} \sim 7; \]  

(3)

ii) \( \kappa_W = 0, \)

\[ R_{WW} = 0, \quad R_{ZZ} \sim 0.09, \quad R_{Z\gamma} \sim 0.6; \]  

(4)

iii) \( \kappa_W = \kappa_B, \)

\[ R_{WW} = 2R_{ZZ} \sim 2, \quad R_{Z\gamma} = 0; \]  

(5)

iv) \( \kappa_W = -\kappa_B, \)

\[ R_{WW} \sim 6.9, \quad R_{ZZ} \sim 1, \quad R_{Z\gamma} \sim 4.9. \]

(6)

Large \( R_{WW}, R_{ZZ} \) and \( R_{Z\gamma} \) are needed for a discovery of the S scalar in the processes of pp → S → WW/ZZ/Zγ at the LHC. However, the parameter spaces of \( \kappa_g,\kappa_W,\kappa_B \) are constrained severely by the LHC Run-I data, e.g.
\( \sigma(WW) \leq 40 \text{ fb} \) \cite{41}, \( \sigma(ZZ) \leq 12 \text{ fb} \) \cite{42} and \( \sigma(Z\gamma) \leq 4 \text{ fb} \) \cite{43}. After fixing \( \sigma(pp \rightarrow S \rightarrow \gamma\gamma) = 10 \text{ fb} \) to explain the diphoton anomaly \cite{1, 2}, one can convert the cross section bounds into constraints on the ratio \( R_{XY} \) as \cite{44}

\[
R_{WW} \leq 19, \quad R_{ZZ} \leq 6, \quad R_{Z\gamma} \leq 2.
\]  

(7)

Obviously, the two cases of \( \kappa_B = 0 \) and \( \kappa_W = -\kappa_B \) have a tension with the current experimental data. It is worth mentioning that the \( R_{XY} \) limits are no longer valid if the diphoton excess turns out to be a statistical fluctuation. If the diphoton excess is indeed confirmed in the future experiments, then those two simple cases are excluded. In the following \( R_{XY} \) should be treated as the cross section \( \sigma(pp \rightarrow S \rightarrow XY) = R_{XY} \times 10 \text{ fb} \).

Collider simulation: We now turn to collider simulation. The hadronic decay of \( WW \) and \( ZZ \) from 750 GeV \( S \) decay are overwhelmed by the QCD backgrounds and difficult to be triggered at the LHC. The hard photon in the \( Z\gamma \) mode offers a good trigger of the signal events. We thus focus on the \( Z(\rightarrow jj)\gamma \) mode hereafter.

For illustration we choose \( \kappa_g = \kappa_W = -\kappa_B = 0.01 \) as our benchmark parameters, which yield the reference cross section and the total width of the \( S \) scalar as follows:

\[
\sigma_0(Z\gamma) = 42.07 \text{ fb}, \quad \Gamma_S^0 = 0.07 \text{ GeV}.
\]  

(8)

Taking advantage of the NWA, the cross section of \( pp \rightarrow S \rightarrow Z\gamma \) for other parameters can be obtained from

\[
\sigma(pp \rightarrow S \rightarrow Z\gamma) = \sigma_0(Z\gamma) \left( \frac{\kappa_g}{0.01} \right)^2 \left( \frac{\kappa_W - \kappa_B}{0.02} \right)^2 \frac{\Gamma_S^0}{\Gamma_S^0}.
\]  

(9)

Even though our study is based on the NWA, the results are valid for a large-width scalar, e.g. \( \Gamma_S = 0.06M_S \sim 45 \text{ GeV} \).

The \( Z \) boson in the scattering of \( pp \rightarrow S \rightarrow Z\gamma \) tends to be highly boosted. The distance of two partons from the \( Z \)-boson decay can be estimated approximately as

\[
\Delta R \sim 2M_Z/p_T \sim 4M_Z/M_S \sim 0.4 - 0.5,
\]  

(10)

where \( \Delta R_{ij} = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2} \) with \( \eta_i \) and \( \phi_i \) denoting the rapidity and azimuthal angle of parton \( i \). Given such a small angular separation, the hadronic decay products from the \( Z \)-boson would form a fat jet with a substructure in the detector. That yields a special collider signature of one fat \( Z \)-jet and one hard photon. In order to mimic the signal events, the SM background should consist of \( W \) or \( Z \) boson and a hard photon. We consider SM backgrounds as follows: i) the associated production of a \( W \) boson and a photon (denoted by \( W+\gamma \)); ii) the associated production of a \( Z \) boson and a photon (\( Z+\gamma \)); iii) the associated production of a photon and multiple jets (denoted by \( \gamma+\text{jets} \)). The other backgrounds such as \( W+\text{jets} \), \( Z+\text{jets} \) and \( tt \) are highly suppressed by demanding a hard photon in the final state.

We generate both the signal and the background processes at the parton level using MadEvent \cite{45} at the 14 TeV LHC and pass events to Pythia \cite{46} for showering and hadronization. The Delphes package \cite{47} is used to simulate detector smearing effects in accord to a fairly standard Gaussian-type detector resolution given by \( \delta E/E = A/\sqrt{E/\text{GeV}} + B \), where \( A \) is a sampling term and \( B \) is a constant term. For leptons we take \( A = 5\% \) and \( B = 0.55\% \), and for jets we take \( A = 100\% \) and \( B = 5\% \). We also impose the lepton veto if the lepton has transverse momentum \( (p_T) \) greater than 20 GeV, rapidity \( |\eta| \leq 2.5 \) and its overlap with jets \( \Delta R_{j\ell} \geq 0.4 \).

In the signal event, the photon arises from the heavy scalar decay and thus exhibits a hard peak in the transverse momentum distribution. As sharing the energy with the associated \( Z \)-boson, the \( p_T \) distribution of the photon peaks around \( \sim m_S/2 \approx 375 \text{ GeV} \); see Fig. 1(a). In the analysis we require tagging a hard photon in the final state which satisfies

\[
p_T^\gamma \geq 250 \text{ GeV}, \quad |\eta| \leq 1.4.
\]  

(11)

A 2-pronged boosted \( Z \)-jet is tagged using the so-called “mass-drop” technique with asymmetry cut introduced in Ref. [48]. The \( Z \)-jet reconstruction is performed using Cambridge/Aachen algorithm with Fastjet \cite{49}. The distance parameter of 1.2 is used to cluster a fat jet that is initiated by the boosted \( Z \)-boson. We further require the invariant mass of the reconstructed \( Z \)-jet \((M_J) \) within mass window \cite{50}:

\[
|M_J - m_Z| \leq 13 \text{ GeV}
\]  

(12)

where \( m_Z = 91.2 \text{ GeV} \). Furthermore, the invariant mass of the reconstructed \( Z \)-jet and the photon is required to lie within the mass window

\[
\Delta M_{J\gamma} \equiv |M_{J\gamma} - M_S| \leq 25 \text{ GeV}.
\]  

(13)
TABLE I: The numbers of the signal ( $\kappa_g = \kappa_W = -\kappa_B = 0.01$ ) and background events after kinematic cuts at the 14 TeV LHC with an integrated luminosity of 1 fb$^{-1}$.

| Cut Condition          | Signal $\gamma + \text{jets}$ | $Z\gamma$ | $W + \gamma$ |
|------------------------|-------------------------------|------------|---------------|
| No cut                 | 42.07                         | 454200     | 2255.5        | 4690          |
| $p_T^Z$, cut and $Z$-jet tagging | 1.15                          | 179.46     | 6.15          | 3.63          |
| $M_{J\gamma}$, cut     | 0.72                          | 10.85      | 0.43          | 0.27          |

Fig. 2: The discovery potential of the process of $pp \to S \to Z\gamma$ at the 14 TeV LHC with the integrated luminosity of 300 fb$^{-1}$ (a) and 3000 fb$^{-1}$ (b). The black curves label the 5$\sigma$ discovery potential while the red curves represent the 2$\sigma$ exclusion. The gray (yellow, green) region denotes the parameter space of $R_{Z\gamma} < 1$ ($1 < R_{Z\gamma} < 2$, $2 < R_{Z\gamma} < 7$), respectively.

Figure 1(b) plots the invariant mass distribution of the reconstructed $Z$-jet and $\gamma$. The numbers of events of the signal for our benchmark parameter and the backgrounds after all the above cuts are shown in the fourth row of Table I with an integrated luminosity ($\mathcal{L}$) of 1 fb$^{-1}$. Cross sections of other parameters can be derived from Eq. 9 and those numbers given in Table I. The cut efficiency of the signal event is not sensitive to the values of $\kappa_{g,W,B}$ or the narrow width of the $S$ scalar. After all the cuts the major background is from the productions of $\gamma$-jets.

As the numbers of the signal and background events are large, we estimate the needed cross section of the signal to claim a 5$\sigma$ discovery from

$$\sigma_{Z\gamma} = \frac{5 \times \sqrt{\sigma_B}}{\epsilon_{\text{cut}} \times \sqrt{\mathcal{L}}},$$

where $\epsilon_{\text{cut}} \sim 0.02$ denotes the cut efficiency of the signal. Figure 2(a) displays the discovery potential of the 750 GeV scalar in the process of $pp \to S \to Z\gamma$ at the 14 TeV LHC with an integrated luminosity of 300 fb$^{-1}$. The gray (yellow, green) region represents $R_{Z\gamma} \leq 1$ ($1 < R_{Z\gamma} < 2$, $2 < R_{Z\gamma} < 7$), respectively. A large ratio $R_{Z\gamma} = 4.93$ is needed to reach a discovery at the level of 5$\sigma$; see the black curve. If no excess were observed, then one can exclude the parameter spaces of $R_{Z\gamma} > 1.97$ at the 2$\sigma$ level; see the red curve. The high luminosity phase of the LHC ($\mathcal{L} = 3000$ fb$^{-1}$) could probe the parameter spaces of $R_{Z\gamma} \geq 1.56$ at the 5$\sigma$ level and exclude the parameter spaces of $R_{Z\gamma} \geq 0.62$ at the 2$\sigma$ level; see Fig. 2(b).

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