CP sensitive observables of a hypothetical heavy spin-0 particle with \(\gamma\gamma\)–interactions dominant.

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Abstract

We study observables sensitive to tensor structure of interactions of a hypothetical heavy spin-0 particle. It is assumed that the interactions of this particle are primary with photons; interactions with vector bosons \(gg\), \(WW\), \(ZZ\), and quarks \(t\bar{t}\) are suppressed. The above assumptions favor the production of this hypothetical particle through the vector boson fusion mechanism structurally dominated by \(\gamma\gamma\) and \(\gamma Z\) interactions. This particle will be produced in association with two light quarks. It is shown that the difference in azimuthal angle between the tagging jets provides an observable sensitive to the CP properties of this hypothetical particle.

Keywords: BSM, Heavy particle, Tensor structure, Extended Higgs sector, photon, jets, VBF, CP

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1. Introduction

After the discovery of the Higgs boson by the ATLAS and CMS collaborations at the LHC [1, 2], the particle content of Standard Model (SM) is complete. Searches for physics beyond the Standard Model (BSM) are currently on-going. Several anomalies observed in semi-leptonic decays of B mesons [3–5] could be better understood with the existence of a heavy resonance decaying predominantly to photons [6]. Many BSM theories predict the existence of heavy neutral resonances, which could be produced in pp collisions. Several flavors of Two Higgs doublet (2HDM), composite Higgs, singlet Higgs and other models can accommodate such particles primarily being detected through their decays into photon pairs. Such a resonance could have its couplings to $t\bar{t}$ and $ZZ$ significantly suppressed compared to $\gamma\gamma$. The couplings to a $W^+W^-$ pair may be further suppressed or absent. In the proposed models, the new particle may have CP-even, CP-odd or CP-mixed parity. These properties lead to important consequences related to the possible production mechanism of such a hypothetical resonance. The investigation of production mechanism may thus help to reveal the exact nature of such a particle.

In this paper we present a study of the properties of a new heavy neutral particle which could be discovered in high energy pp collisions. We concentrate on the class of models where the di-photon decays of such a particle will be the first decay mode to be observed experimentally. We further assume that this new hypothetical particle has spin 0. In case of observation of a heavy di-photon resonance, its spin-0 nature can be quickly investigated by studying the distribution of its production angle $\cos \theta^*$, as suggested in [7]. In this paper we concentrate on the spin-0 scenario, investigating CP-even, CP-odd and CP-mixed assumptions of parity by studying jet distributions from the production vertex of this resonance. Based on this model, we outline the experimental observables to be investigated to understand its exact nature.

This article is organized as follows. Section 2 provides a brief review of most relevant physics models capable of accommodating such a resonance. In
Section 3 the corresponding modifications to the Vector Boson Fusion (VBF) production mechanism are discussed. In Section 4 the characteristic jet distributions of such production are presented. The prospects for study is the exact nature of such a particle using these distributions are presented in Section 5.

2. Physics models

Production in pp collisions of a heavy neutral spin-0 resonance (we designate it as $S_0$) primarily detectable through its decay into pairs of photons corresponds to a relatively large class of theoretical models. Such resonances are predicted in certain flavors of two Higgs doublet (2HDM), composite Higgs models [8–15] and scalar singlet models where $S_0$ couples to new vector-like quarks via a Yukawa coupling (see [16] and references therein). The common property of the listed models is the presence of such a neutral spin-0 resonance with mass much larger than the SM Higgs boson mass. The production cross section of such a resonance would lie in the broad range of $30 - 6000$ fb, depending on the model and the resonance mass [17].

![Feynman diagram of photon fusion](image)

Figure 1: Photon fusion feynman diagram. The $S_0$ particle can then decay through $\gamma\gamma$ and $Z\gamma$ channels.

In the listed models, $S_0$ couples relatively strongly to top quarks and photons. The dominant decay mode of $S_0$ is thus usually $t\bar{t}$, followed by the $\gamma\gamma$
mode. The third largest decay branching ratio is considered to be to \( Z\gamma \). The decay branching ratio to \( ZZ \) pairs in models with an extended Higgs sector can be \( 5 - 1000 \) times smaller than the one corresponding to the \( \gamma\gamma \) decay \[18, 19\]. In the simplest formulation, decays to \( W^+W^- \) can be further suppressed or absent. Observation of the \( pp \to S \to t\bar{t} \) process appears to be difficult due to the large QCD background and to the complexity of \( t\bar{t} \) final state reconstruction. The most probable channel in which to observe such resonance in hadron collider experiments is thus \( pp \to S_0 \to \gamma\gamma \). The \( pp \to S_0 \to Z\gamma \) decay observations should follow shortly after.

For some ranges of parameters of the models discussed above \( t\bar{t} \) coupling can be also suppressed with respect to \( \gamma\gamma \) coupling or even to be absent. The latter case can correspond to minimal singlet models with colorless vector-like fermions. The following study will be based on a minimal model with suppressed \( t\bar{t} \) coupling. Given the potent coupling to photons, the dominant \( S_0 \) production mode on hadron colliders in this model should be the photon-induced VBF production mechanism (see e.g. \[16, 20–24\] and references therein) with small contributions from \( Z\gamma \). The kinematic properties of this photon-dominated VBF production mechanism are studied under the following physics model assumptions:

- \( S_0 \) is a neutral s-channel resonance with mass about 1000 GeV and spin 0. Pure CP-even, CP-odd and CP-mixed parity assumptions are considered.
- The effective coupling of \( S_0 \) to \( \gamma\gamma \) is large compared to \( Z\gamma \) and \( ZZ \). The effective coupling to \( t\bar{t} \) and \( W^+W^- \) is very small or absent. The \( S_0 \) VBF production is dominated by di-photon interactions with some contributions from \( Z\gamma \) mechanisms. This process will be referred to as “photon fusion” hereafter.

3. Photon fusion production

Following the assumptions presented in the Section 2 the Effective Field Theory (EFT) approach to describe the interactions of a spin-0 particle \( S_0 \) with
vector bosons can be employed. It is assumed that the masses of BSM particles which might contribute to loop-induced couplings of $S_0$ to SM particles are large compared to the $S_0$ mass. The corresponding interaction Lagrangian can be built by using a subset of $\gamma$ and $Z$-related dimension-5 operators. The resulting effective Lagrangian involves the following operators:

$$\mathcal{L}_0^V = \left\{-\frac{1}{4} \left[ \kappa_{S\gamma\gamma} A_{\mu\nu} A^{\mu\nu} + \kappa_{P\gamma\gamma} A_{\mu\nu} \tilde{A}^{\mu\nu} \right] \right.$$
$$- \frac{1}{2} \left[ \kappa_{SZ\gamma} Z_{\mu\nu} A^{\mu\nu} + \kappa_{PZ\gamma} Z_{\mu\nu} \tilde{A}^{\mu\nu} \right] \right.$$
$$- \frac{1}{\Lambda} \kappa_{S\partial \gamma} Z_{\nu} \partial_{\mu} A^{\mu\nu} \right\} S_0, \quad (1)$$

where $\Lambda$ is the energy scale of new physics and the field strength tensors are defined as follows:

$$V_{\mu\nu} = \partial_{\mu} V_{\nu} - \partial_{\nu} V_{\mu} \quad (V = A, Z).$$

The dual tensor $\tilde{V}_{\mu\nu}$ is defined as:

$$\tilde{V}_{\mu\nu} = \frac{1}{2} \epsilon_{\mu\nu\rho\sigma} V^{\rho\sigma}.$$

The indices $S$ and $P$ represent respectively the CP-even and CP-odd states of $S_0$. The coupling constants $\kappa_{S\gamma\gamma}, \kappa_{SZ\gamma}, \kappa_{S\partial \gamma}, \kappa_{P\gamma\gamma}, \kappa_{PZ\gamma}$ govern the strength of respective interactions with pairs of vector bosons. CP-violation is induced when both CP-odd and CP-even contributions are present simultaneously.

In the case of the gluon-fusion ($ggH$) process in the SM, the distribution of the azimuthal angle difference $\Delta \Phi = \Phi_2 - \Phi_1$ between the two tagging jets demonstrates a non-trivial structure sensitive to CP-properties of the Higgs boson [25–28]. In the case of the electroweak SM VBF process the distribution in $\Delta \Phi$ is relatively flat and thus is only barely sensitive to CP. This is the result of the interference between $++$ and $--$ helicity states of vector bosons in gluon fusion Higgs boson production and the dominance of the 00 helicity state in the weak VBF case. Below we demonstrate that in models with suppressed $S_0ZZ$ and $S_0WW$ modes vector boson fusion processes could also reveal non-trivial azimuthal angle correlations.
The tensor structure of $S_0VV$ vertices corresponding to the Lagrangian in Eq. 1 is given in Table 1. For comparison, the SM $HZZ$ amplitude is also shown.

Using the helicity amplitude technique [29, 30] and following the approach developed in [28] helicity amplitudes for $S_0VV$ vertices can be calculated. For a spin zero particle $S_0$ as a result of conservation of angular momentum only three amplitudes contribute to the VBF process: $0 \rightarrow 00, 0 \rightarrow ++, 0 \rightarrow --$.

These amplitudes are presented in Table 2.

In the VBF process absolute values of vector boson invariant masses are small in comparison with the mass of $S_0$: $\sqrt{|q_i^2|} << M_{S_0}$. In this limit the 00-amplitude is dominant for the so-called contact term $k_K\partial\gamma$ and for the SM term. We cannot expect a non-trivial behavior of the azimuthal angle distribution for these cases. However in this limit the dominant amplitudes for $S_0\gamma\gamma$ and $S_0Z\gamma$ vertices are the ++ and -- amplitudes and their interference could lead to non-trivial azimuthal angle distributions in agreement with [28].

| Interaction | CP  | Tensor structure |
|-------------|-----|------------------|
| $S_0\gamma\gamma, S_0Z\gamma$ | even | $g_{\mu\nu}(q_1q_2) - q_1^\mu q_2^\nu$ |
| $S_0\gamma\gamma, S_0Z\gamma$ | odd | $\epsilon_{\mu\nu\alpha\beta}q_{1\alpha}q_{2\beta}$ |
| $S_0\partial\gamma$          | even | $g_{\mu\nu}q_1^\nu - q_1^\mu q_2^\nu$ |
| $HZZ SM$                  | even | $M_Z^2g_{\mu\nu}$ |

Table 1: Tensor structure of vertices for $S_0$ interactions with vector bosons. $q_1$ and $q_2$ are photon and vector boson four vectors, respectively.

| Helicities | 00   | ++   | --   |
|------------|------|------|------|
| $S_0\gamma\gamma, S_0Z\gamma$, even | $(q_1^2q_2^2)^{1/2}$ | $-\frac{1}{2}M^2$ | $-\frac{1}{2}M^2$ |
| $S_0\gamma\gamma, S_0Z\gamma$, odd | 0 | $-\frac{i}{2}(M^2 - 4q_1^2q_2^2)^{1/2}$ | $\frac{i}{2}(M^2 - 4q_1^2q_2^2)^{1/2}$ |
| $S_0\partial\gamma$, even | $q_1^2 - M_Z^2$ | $\frac{M^2}{2(q_1^2q_2^2)^{1/2}}$ | $\frac{M_Z}{2}$ |
| $HZZ SM$, even | $-M_Z^2$ | $-M_Z^2$ |

Table 2: Helicity amplitudes for $S_0VV$ interactions. $M^2 = M_{S_0}^2 - q_1^2 - q_2^2$
In the case of CP-even and CP-odd $S_0$ particles the azimuthal angle distribution can be presented in the form:

$$d\hat{\sigma} \sim A + B\cos(2\Delta\Phi),$$  \hspace{1cm} (2)

where the coefficients $A$ and $B$ are obtained by combining helicity amplitudes for vector boson currents \cite{28} with the amplitudes given in Table 2. In the limit $\sqrt{q_t^2} \ll M_{S_0}$ these coefficients are presented in Table 3, where $c_i = \cos \Theta_i$ and $s_i = \cos(\pi/2 - \Theta_i) = \sin \Theta_i$. Values $\Theta_i$ and $\pi/2 - \Theta_i$ are correspond to the angles between directions of quarks and vector bosons in $q_i$ Breit frames.

| Coefficients | $A$ | $B$ |
|--------------|-----|-----|
| $S_0\gamma\gamma$, $S_0Z\gamma$, even | $q_1^2q_2^2M_{S_0}^4(1 + c_1^2)(1 + c_2^2)c_1^{-2}c_2^{-2}$ | $q_1^2q_2^2M_{S_0}^4s_1^2s_2^2c_1^{-2}c_2^{-2}$ |
| $S_0\gamma\gamma$, $S_0Z\gamma$, odd | $q_1^2q_2^2M_{S_0}^4(1 + c_1^2)(1 + c_2^2)c_1^{-2}c_2^{-2}$ | $-q_1^2q_2^2M_{S_0}^4s_1^2s_2^2c_1^{-2}c_2^{-2}$ |
| $S_0\partial\gamma$, even | $q_1^4M_{S_0}^4s_1^2s_2^2c_1^{-2}c_2^{-2}$ | $\sim 0$ |
| $HZZ$ SM, even | $M_Z^4M_{S_0}^4s_1^2s_2^2c_1^{-2}c_2^{-2}$ | $\sim 0$ |

Table 3: Coefficients $A$ and $B$ of Eq.2

According to this table $k_{S_0\partial\gamma}$ and the SM cases are dominated by the $A$ coefficient in Eq. (2) resulting in a flat distribution over $\Delta \Phi$. For $S_0\gamma\gamma$ and $S_0Z\gamma$ interactions the coefficients $A$ and $B$ are comparable leading to non-trivial correlation in $\Delta \Phi$.

4. Jet distributions

To study the kinematic properties of the $S_0$ interactions with vector bosons, the corresponding Monte Carlo samples of 500k events each were produced in leading order using MadGraph5 generator \cite{31}. The Higgs Characterisation model \cite{32}, implemented in MadGraph5, was used to study shapes of distributions in order to probe the possible effects of BSM physics. The parameters used in Monte Carlo production are listed in Table 3.

To estimate the effect of the presence of various contributions to the Lagrangian of Eq. (1) on the kinematics of the final state jets, the following final
Table 4: Parameters used in Monte Carlo production with the MadGraph5 generator.

| Parameter                                      | Value       |
|------------------------------------------------|-------------|
| Mass of the resonance (GeV)                    | $m_{S_0} = 1000$ |
| Jet transverse momentum (GeV)                  | $p_T^{\text{jet}} > 30$ |
| Jet pseudorapidity                             | $|\eta| < 4.0$ |

state observables are defined:

- The invariant mass of the final state jets: $m_{jj}$;

- The transverse momenta of $S_0$, the leading jet and the subleading jet, respectively: $p_T^{S_0}$, $p_T^{\text{lead}}$, $p_T^{\text{sublead}}$;

- The pseudorapidities of the leading jet and subleading jet and the difference between jet pseudorapidities, respectively: $\eta_{\text{lead}}$, $\eta_{\text{sublead}}$, $|\eta| = |\eta_1 - \eta_2|$;

- The azimuthal angle difference between jets: $\Delta \Phi = \phi_1 - \phi_2$;

- The Zeppenfeld variable: $|\eta_{S_0} - \frac{\eta_1 + \eta_2}{2}|$.

Fig. 2 shows the distributions of final state jet observables for various assumptions about the structure of the $S_0$ production mechanism. In each case only one BSM operator is present at time; contributions from all other BSM operators are set to zero.

These observables can provide some sensitivity to the presence of an operator corresponding to the coupling $k_{S\partial \gamma}$. The presence of operators corresponding to $k_{S\gamma\gamma}$ and $k_{P\gamma\gamma}$ results in nearly indistinguishable distributions for all $P_T$ observables. A similar situation arises for the case when only operators corresponding to $k_{SZ\gamma}$ and $k_{PZ\gamma}$ couplings are present.

In Fig. 3 pseudorapidity distributions of jets are presented. These distributions demonstrate the prominent feature of VBF processes: the suppression of central jets and the appearance of a central pseudorapidity gap. The only exception here is the leading jet distribution corresponding to the term $k_{S\partial \gamma}$.  

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Figure 2: Distributions of di-jet mass and the transverse momentum of tagging jets under various assumptions about the structure of the $S_0$ production mechanism.
Figure 3: Distributions of pseudorapidities of tagging jets under various assumptions about the structure of the $S_0$ production mechanism.
Note that a comparison of gluon fusion and photon fusion heavy resonance production mechanisms on the basis of $P_T$ and $\eta$ distributions was performed in [23].

![Figure 4: The azimuthal angle difference distributions between the tagging jets.](image)

(a) (b)

The observable sensitive to CP properties of a heavy resonance produced via photon fusion is the azimuthal angle difference between the tagging jets. In Fig. 4, $\Delta \Phi$ and $\sin |\Delta \Phi|$ distributions are presented for the CP-even, CP-odd and CP-mixed cases.

A clear separation in shapes of the observables is visible for cases with different CP-parity. The CP-mixing examples are produced by requiring the simultaneous presence of operators corresponding to the $k_{S\gamma\gamma}$ and $k_{P\gamma\gamma}$ terms. The terms corresponding to the $k_{S\gamma\gamma}$ and $k_{P\gamma\gamma}$ couplings contribute $2/3$ and $1/3$ of the total cross-section, respectively. In the mixed CP-case, an additional term proportional to $\sin |\Delta \Phi|$ appears in Eq. 2 leading to a shift in the distribution of $\sin |\Delta \Phi|$ as shown in Fig. 4(b). This is an important property of photon fusion that can be used to reveal the structure of $Z\gamma$ and $\gamma\gamma$ vertices in current and future collider experiments.
5. Conclusion

In this paper we study CP sensitive observables and the tensor structure of interactions of a hypothetical heavy spin-0 particle \( S_0 \). We assume that the effective coupling of \( S_0 \) to \( \gamma\gamma \) is large compared to \( t\bar{t}, ZZ \) and \( WW \). Particles with these properties appear in models with an extended Higgs sector.

We focus on photon fusion production of \( S_0 \) and study various jet distributions and correlations between tagging jets from the production vertex. In the SM, jets produced via VBF are weakly correlated resulting in a flat distribution in the azimuth angle difference \( \Delta\Phi \) between the jets and limited sensitivity to the CP properties of \( S_0 \). On the other hand, we demonstrate that in the case of photon fusion the higher dimension operators lead to non-trivial \( \Delta\Phi \) dependence and sensitivity to CP properties. This result is independent of decay processes because for a spin-0 s-channel resonance the production and decay vertices are decoupled.

Production jet distributions in photon fusion are also sensitive to a specific type of higher dimension operators. In particular, we show that the contact term proportional to \( k_S\partial\gamma \) in the Lagrangian of the model considered can be distinguished from other BSM terms by analyzing \( P_T, \eta \) and \( \Delta\Phi \) distributions.

In this paper we consider a model with a negligible \( S_0t\bar{t} \) interaction. This is not the case when the dominant \( S_0 \) production is gluon fusion. In analogy with the SM, \( \Delta\Phi \) distribution of jets produced in gluon fusion would have CP sensitivity. If gluon fusion and photon fusion production processes for \( S_0 \) could be effectively separated then the analysis of \( \Delta\Phi \) distributions for these two processes would reveal important information about the tensor structure of \( S_0 \) interactions.

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