

CP-sensitive observables of a hypothetical heavy spin-0 particle with the dominant $\gamma\gamma$ and $Z\gamma$ -interaction.

N Belyaev¹, R Konoplich^{2,4} and K Prokofiev³

¹ National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Kashirskoe highway 31, Moscow, 115409, Russia

² Department of Physics, New York University, 4 Washington Place, New York, NY 10003, USA

³ Department of Physics and Institute for Advanced Study, the Hong Kong University of Science and Technology

E-mail: NLBelyayev@mephi.ru, RK60@nyu.edu, Kirill.Prokofiev@cern.ch

Abstract. We study observables sensitive to tensor structure of interactions of a hypothetical heavy spin-0 boson. It is assumed that interactions of this particle are dominated by interactions with photons. The interactions with other vector bosons and quarks are supposed to be suppressed. The above assumptions favor the production of this hypothetical particle through the vector boson fusion mechanism structurally dominated by the photon and Z-interactions. This particle will be produced in association with two light quarks. It is shown that the azimuthal angle difference between the tagging jets provides an observable to probe the tensor structure of the interaction vertices of such hypothetical particle.

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 flavours 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.

⁴ Also at Physics Department, Manhattan College, 4513 Manhattan College Parkway, Riverdale, New York, NY 10471, USA



2. Physics model

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 flavours of two Higgs doublet (2HDM), composite Higgs models [7–10] and scalar singlet models, where S_0 couples to new vector-like quarks via a Yukawa coupling (see [11] and references therein).

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 $Z\gamma$. In the simplest formulation, decays to W^+W^- can be further suppressed or absent. Observation of the $pp \rightarrow S \rightarrow t\bar{t}$ 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 $pp \rightarrow S_0 \rightarrow \gamma\gamma$. The $pp \rightarrow S_0 \rightarrow Z\gamma$ decay observations should follow shortly after.

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. [11–13] 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 γ and Z -related dimension-5 operators. The resulting effective Lagrangian involves the following operators:

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

where $V_{\mu\nu}$ and $\tilde{V}_{\mu\nu}$ are the field strength tensors and the dual tensors, respectively.

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 [14–17]. 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.

By using the helicity amplitude technique [18,19] and following the approach developed in [17] helicity amplitudes for $S_0 VV$ 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: $0 \rightarrow 00, 0 \rightarrow ++, 0 \rightarrow --$.

In the VBF process absolute values of vector boson invariant masses are small in comparison with the mass of S_0 : $\sqrt{|q_i^2|} \ll m_{S_0}$. 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 [17].

In the case of CP-even and CP-odd S_0 particles the azimuthal angle distribution can be presented in the form:

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

where the coefficients A and B could be obtained by combining helicity amplitudes for vector boson currents [17] with the helicity amplitudes for $S_0 VV$ interactions.

It can be shown that the $k_{S_0\partial\gamma}$ 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 [20]. The Higgs Characterisation model [21], implemented in MadGraph5, was used to study shapes of distributions in order to probe the possible effects of BSM physics. Parameters used in Monte Carlo production with the MadGraph5 generator were set up as follows: Mass of the resonance $m_{S_0} = 1000$ GeV; Jet transverse momentum $p_T^{\text{jet}} > 30$ GeV; Jet pseudorapidity $|\eta| < 4.0$.

To estimate the effect of the presence of various contributions to the Lagrangian of equation (1) on the kinematics of the final state jets, the following final 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^{lead} , p_T^{sublead} ;
- The pseudorapidities of the leading jet and subleading jet and the difference between jet pseudorapidities, respectively: η_{lead} , η_{sublead} , $|\eta| = |\eta_1 - \eta_2|$;
- The azimuthal angle difference between jets:
 $\Delta\Phi = \phi_1 - \phi_2$;
- The Zeppenfeld variable: $|\eta_{S_0} - \frac{\eta_1 + \eta_2}{2}|$.

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 figure 1 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 $k_{S\partial\gamma}$.

Note that a comparison of gluon fusion and photon fusion heavy resonance production mechanisms on the basis of p_T and η distributions was performed in [13].

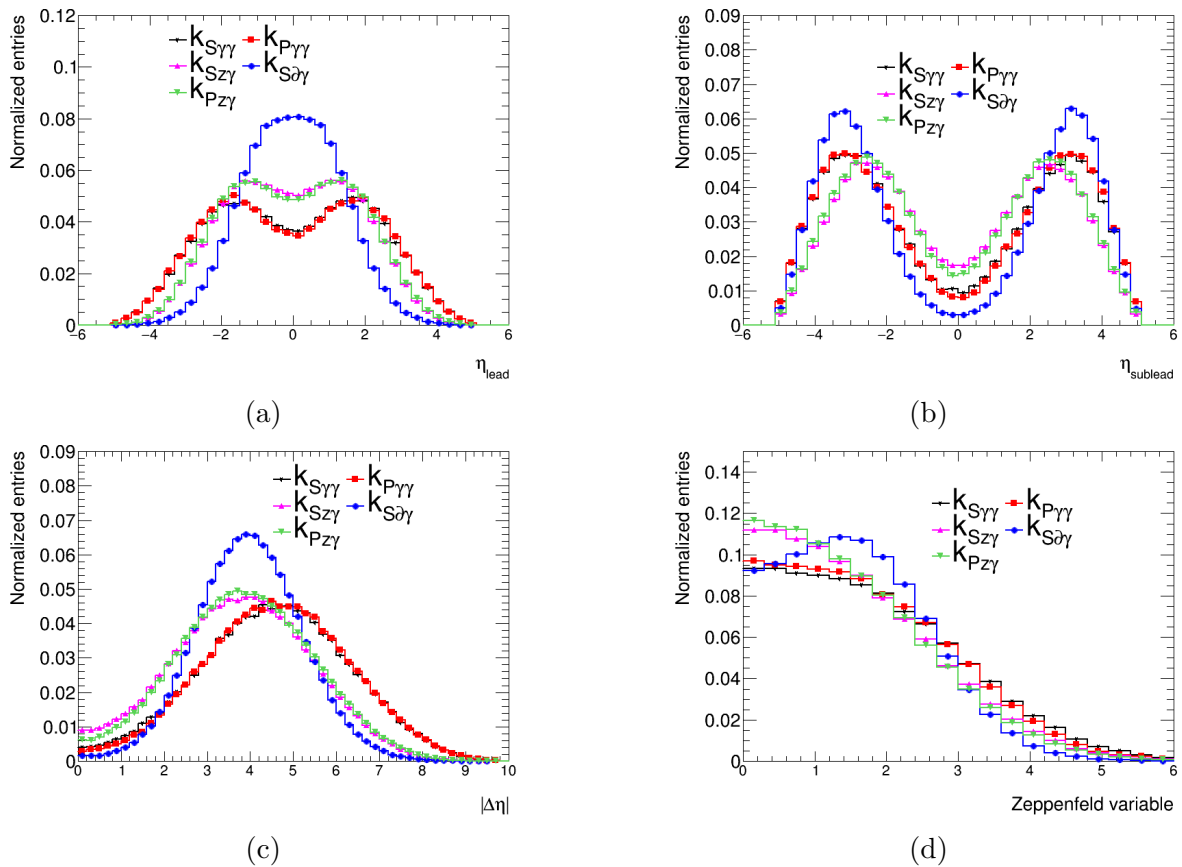


Figure 1. Distributions of pseudorapidities of tagging jets under various assumptions about the structure of the S_0 production mechanism.

The observable sensitive to CP properties of a heavy resonance produced via photon fusion is the azimuthal angle difference between the tagging jets. In figure 2 $\Delta\Phi$ and $\sin\left|\frac{\Delta\Phi}{2}\right|$ 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 $\sin\left|\frac{\Delta\Phi}{2}\right|$ appears, leading to a shift in the distribution of $\sin\left|\frac{\Delta\Phi}{2}\right|$ as shown in figure 2(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

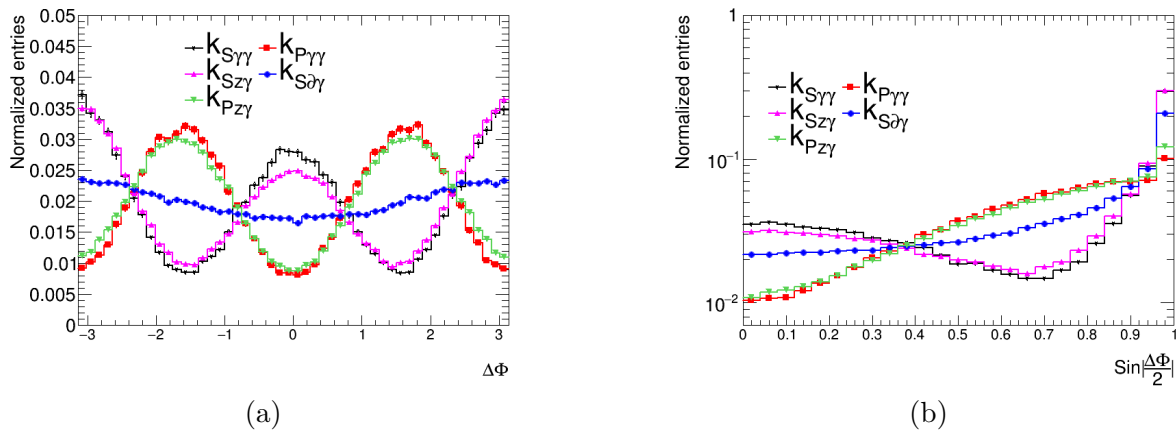


Figure 2. The azimuthal angle difference distributions between the tagging jets.

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.

6. Acknowledgements

The work of R. Konoplich is partially supported by the US National Science Foundation under Grant No.PHY-1402964. The work of K. Prokofiev is partially supported by a grant from the Research Grant Council of the Hong Kong Special Administrative Region, China (Project Nos. CUHK4/CRF/13G). The work of N. Belyaev was performed within the framework of the Center for Fundamental Research and Particle Physics supported by the MEPHI Academic Excellence Project (contract 02.a03.21.0005, 27.08.2013).

References

- [1] Aad G *et al.* 2012 *Phys. Lett. B* **716** 1–29
- [2] Chatrchyan S *et al.* 2012 *Phys. Lett. B* **716** 30–61
- [3] Lees J P *et al.* 2013 *Phys. Rev. D* **88** 072012
- [4] Huschle M *et al.* 2015 *Phys. Rev. D* **92** 072014
- [5] Aaij R *et al.* 2015 *Phys. Rev. Lett.* **115** 111803
- [6] Murphy C W 2016 *Phys. Lett. B* **757** 192–198
- [7] Lee T D 1973 *Phys. Rev. D* **8** 1226–1239
- [8] Donoghue J F and Li L F 1979 *Phys. Rev. D* **19** 945
- [9] Agashe K, Contino R and Pomarol A 2005 *Nucl. Phys. B* **719** 165–187
- [10] Eberhardt O, Nierste U and Wiebusch M 2013 *JHEP* **07** 118
- [11] Falkowski A, Slone O and Volansky T 2016 *JHEP* **02** 152
- [12] Franceschini R *et al.* 2016 *JHEP* **03** 144
- [13] Csa'ki C *et al.* 2016 *Phys. Rev. D* **93** 095020
- [14] Dolan M J *et al.* 2014 *Phys. Rev. D* **90** 073008
- [15] Plehn T, Rainwater D L and Zeppenfeld D 2002 *Phys. Rev. Lett.* **88** 051801
- [16] Hankele V *et al.* 2006 *Phys. Rev. D* **74** 095001
- [17] Hagiwara K, Li Q and Mawatari K 2009 *JHEP* **07** 101
- [18] Coradeschi F and Lodone P 2013 *Phys. Rev. D* **87** 074026
- [19] Badger S D, Glover E W and Khoze V V 2006 *JHEP* **01** 066
- [20] Alwall J *et al.* 2011 *JHEP* **06** 128
- [21] Artoisenet P *et al.* 2013 *JHEP* **11** 043