Physics Letters B 783 (2018) 51–58

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

New physics scale from Higgs observables with effective dimension-6 operators

Sudip Jana [a,b,*], S. Nandi [a,c]

[a] Department of Physics and Oklahoma Center for High Energy Physics, Oklahoma State University, Stillwater, OK 74078-3072, USA
[b] Theory Department, Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510, USA
[c] Department of Physics, Rice University, Houston, TX 77034, USA

A R T I C L E   I N F O

Article history:
Received 4 October 2017
Received in revised form 15 June 2018
Accepted 15 June 2018
Available online 21 June 2018
Editor: M. Cvetič

Keywords:
Higgs
LHC
Dimension-6

A B S T R A C T

No matter what the scale of new physics is, deviations from the Standard Model (SM) for the Higgs observables will indicate the existence of such a scale. We consider effective six dimensional operators, and their effects on the Higgs productions and decays to estimate this new scale. We analyze and identify the parameter space consistent with known properties of the Higgs boson using recent Run II results from ATLAS and CMS experiments corresponding to ~ 37 fb^{-1} of data. We then calculate the $\bar{t}th$ productions, as well as double Higgs production at the LHC using the effective couplings, and show that these can be much different than those predicted by the Standard Model, for a wide region of allowed parameter space. These predictions can be tested in the current or the future runs of the LHC. We find that the data are consistent with the existence of a new physics scale as low as 500 GeV for a significant region of parameter space of this six dimensional couplings with these new physics effects at the LHC. We also find that for some region of the parameter space, di-Higgs production can be much larger than that predicted by the Standard Model, giving rise to the prospect of its observation even in the current run II of the LHC.

1. Introduction

There have been several major discoveries in the past few decades culminating with the observation of the Higgs boson in 2012 [1,2]. This is a tremendous success of the SM. However, as most of us agree, SM can not be the whole story. The Higgs production in various modes and its decays into various final states so far agrees with the SM. But uncertainties with the SM predictions still remain in some of the observables of these measurements. This encourages us to venture into the possibility of a new physics scale that might be estimated from the uncertainty in these measurements. Also, using this approach, we might be able to make predictions which can be tested at the LHC. With this aim in mind, we consider the effect of a selected set of dimension six operators relevant for the Higgs Physics, in addition to the contribution from the SM. The dimension six operators related to the Higgs physics can be introduced both in the strong sector, as well as in the electroweak sector. Such operators will make extra contributions for the Higgs productions, as well as for its various decay modes. In the most general case, for the effective dimension six operators, there are many operators, and involve large number of parameters. In order to reduce the number of parameters, we only consider a selected set of such operators in the gauge sector (both strong and electroweak (EW)), as well as in the Yukawa sector. In particular, we include only those operators which are responsible for larger effects, and do not affect the constraints from the EW precision tests in a significant way.

The effective field theory provides a model independent framework for interpreting precision measurements connecting to specific UV models systematically [3]. Constraints on these operators have been derived from electroweak (EW) precision measurements [4–6], Higgs sector measurements [7–10] and from the triple gauge couplings [11,12]. Using EW data, global fits incorporating various searches have been performed in [13]. Subsequently fits have been performed including Higgs sector constraints [14–17]. In this context, di-Higgs production also has been studied here [18–21]. When the Standard Model is considered as an effective low-energy theory, higher dimensional interaction terms appear in the Lagrangian. Dimension-six terms have been enumerated [22,23] and there are $15 + 19 + 25 = 59$ independent operators (barring flavor

* Corresponding author.
E-mail addresses: sudip.jana@okstate.edu (S. Jana), s.nandi@okstate.edu, sn35@rice.edu (S. Nandi).

https://doi.org/10.1016/j.physletb.2018.06.038

structure and Hermitian conjugations). However, many of these operators affect processes that are well measured, e.g. flavor physics or electroweak precision observables set strong constraints on subsets of those operators. Some of them are also not relevant for the Higgs physics observables, which is the main emphasis of this work. Here, we focus on the effective operators that focus on the Higgs physics, and nothing else. This is in the spirit of reference [24]. At the LHC, SM Higgs boson (h) can be produced[1] significantly via gluon gluon fusion (ggF), vector boson fusion (VBF), associated production with W and Z bosons (Vh) or in association with $t\bar{t}$ ($t\bar{t}h$). Due to insertion of the dimension-6 terms, SM Higgs production as well as decay branching ratios can be largely affected in these production modes. (1) In the single Higgs production, the most important is the coupling of the gluon pairs to the Higgs boson. Here we have the contribution from the SM dimension-4 operators contributing via the top quark loop. There may exist effective dimension 6 operator (contact interaction) emerging from new physics contributing to this production. (2) The Yukawa coupling of the top quark to the Higgs boson is most important in single Higgs production. Here also, there may exist dimension-6 operator (in addition to the dimension 4 present in the SM) emerging again from the new physics. This will also affect the $t\bar{t}h$ production, as well as the double Higgs productions, which are of great importance in the upcoming LHC runs. (3) In the production of the Higgs boson in association with W or Z, the important contribution of dimension-6 operator will be the hZZ or hWW couplings, which will further effect the decays of the Higgs to WW^* and ZZ^*. Thus, in addition to the contribution from the usual SM, the contribution of the effective dimension six operators will be important here. (4) The dominant decay mode of the Higgs boson is to $b\bar{b}$, the branching ratio being $\simeq 60\%$. Thus the dimension-6 contribution to the Yukawa coupling of the Higgs to the bottom pairs will also be very important to look for a new physics scale in the Higgs observables. (5) We have also included dimension-6 operator in the Higgs potential. This has the largest effect on our results on the di-Higgs productions, since it changes the effective triple Higgs coupling in a major way. Using the above five criteria, we narrow down our analysis to include five new parameters and these are $g^{(6)}$, $y_t^{(6)}$, $y_b^{(6)}$, $y_g^{(6)}$, $\lambda^{(6)}$ and the new physics scale, M. We have done the analysis also including dimension-6 tau Yukawa term $y_\tau^{(6)}$. As the branching ratio of the Higgs in the $\tau\tau$ mode is $\simeq 6\%$, it does not significantly affect the major Higgs observables and hence, the phenomenology we are concentrating. We ignore its contribution for rest of our analysis. A complete list of all effective dimension-6 operators can be found in [22,23].

With these above assumptions, we first identify the parameter space consistent with the Higgs observables and then we find two important results. (1) The $t\bar{t}h$ coupling can be much larger or smaller than that predicted by the SM, and thus giving rise to significantly different rate of $t\bar{t}h$ productions. (2) Double Higgs productions can be much larger than that predicted by the SM.

Very recently, the CMS collaboration has reported a search for the production of a Standard Model (SM) Higgs boson in association with a top quark pair ($t\bar{t}h$) at the LHC Run-2 and a best fit $t\bar{t}h$ yield of 1.5 ± 0.5 times the SM prediction with an observed significance of 3.3σ [25], whereas ATLAS reported limit is 1.8 ± 0.7 [26] on $t\bar{t}h$ production. ATLAS and CMS reported signal strength values are consistent with the SM. However, the central values of the signal strength $\mu_{t\bar{t}h}$ is significantly different from one. There are several literatures [27] attempting to explain the issue for the enhanced $t\bar{t}h$ production. As we shall see, in our framework, the signal strength $\mu_{t\bar{t}h}$ can be as large as 2.4 and also as low as 0.5. There are still large uncertainties in the $t\bar{t}h$ measurements. If any significant deviation (enhancement or suppression) arises in $t\bar{t}h$ production rate at the LHC, this is the best model independent approach to explain the scenario. On the other hand, ATLAS and CMS collaborations have reported the new results on di-Higgs boson searches [28–32] looking at the different final states ($bb\gamma\gamma, b\bar{b}\tau^+\tau^-, b\bar{b}b\bar{b}$ and $b\bar{b}W^+W^-$), using 36 fb^{-1} data from Run II of LHC at 13 TeV. No signal has been observed and the stringent limit of 646 fb on the di-Higgs production cross section is reported [28–32]. In SM, hh production cross-section is about 33.45 fb. After considering effective dimension six couplings, according to our analysis, the di-Higgs production can be as large as about ~ 636 fb, which is 19 times of the SM predicted cross-section for some region of the six dimensional parameter space. If nature does realize this parameter space, di-Higgs production may be observable even at the current run 2 of the LHC as more data are accumulated.

The paper is organized as follows: In Sec. 2, we discuss the formalism and analyze the dimension-6 operators. Thereafter in Sec. 3, we perform the numerical simulations for collider signatures. Finally we conclude.

2. Formalism

Our gauge symmetry is the same as the SM. We are introducing a selected set of additional dimension six operators which can affect the Higgs observables in a major way. These operators are all invariant under the SM gauge symmetry.

- **EW Yukawa sector:**

$$\mathcal{L}^{(6)}_{Yuk} \supset \frac{y_t^{(6)}}{M^2}(\bar{t}_L, \bar{b}_L)t_R\tilde{H}(H^\dagger H) + \frac{y_b^{(6)}}{M^2}(\bar{t}_L, \bar{b}_L)b_R H(H^\dagger H) + \frac{y_\tau^{(6)}}{M^2}(\bar{\nu}_\tau, \bar{\tau}_L)\tau_R H(H^\dagger H) + h.c. \tag{1}$$

We have included the dimension-6 terms for third generation fermions only. For simplicity, we have included only the flavor diagonal dimension six Yukawa couplings. Similarly, we can extend it for first and second generation fermions also. But, since we are interested in new physics affecting Higgs rates in a major way, we ignore the negligible effects originating from dimension-6 Yukawa terms for first and second generation fermions. We will also ignore the dimension six operator for the τ lepton. The Higgs branching ratio to τ pair is very small 6%, and its inclusion does not affect the phenomenology we are concentrating.

- **Strong sector:**

$$\mathcal{L}^{(6)}_{Strong} \supset \frac{g^{(6)}}{M^2}G^{\mu\nu a}G_{\mu\nu a}(H^\dagger H) \tag{2}$$

This operator will contribute to the Higgs production, as well as its decay to two gluons. $g^{(6)}$ is an unknown parameter, and M is the new physics scale. This operator (the contact term) will significantly contribute, in addition to the SM contribution via the top quark loop, in single Higgs production via gluon gluon fusion process.

- **EW gauge sector:**

$$\mathcal{L}^{(6)}_{EW gauge} \supset \frac{y_g^{(6)}}{M^2}(D^\mu H)^\dagger(D_\mu H)(H^\dagger H) \tag{3}$$

[1] At the 13 TeV LHC, SM Higgs production cross-section via different production modes are summarized as: $\sigma_{ggF} = 43.92$ pb, $\sigma_{VBF} = 3.748$ pb, $\sigma_{Wh} = 1.38$ pb, $\sigma_{Zh} = 0.869$ pb, $\sigma_{t\bar{t}h} = 508.5$ fb.