Higgs boson signal at complete tree level in the SM extension by dimension-six operators

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Abstract

Deviations from the standard Higgs sector generated by some new (non-standard) physics at an energy scale $\Lambda$ could be described by an effective $SU(3)_c \times SU(2)_L \times U(1)$ invariant non-renormalizable Lagrangian terms of dimension six. The set of dimension-six operators involving the Higgs field is chosen in such a way that the form of gauge bosons kinetic terms remains untouched, preserving all high-precision electroweak constraints. A systematic study of effects in various Higgs boson production channels ($\gamma\gamma$, $ZZ$, $WW$, $b\bar{b}$, $\tau\bar{\tau}$) caused by effective operators is carried out beyond the production $\times$ decay approximation (or infinitely small width approximation). Statistical methods are used to establish consistency of the standard Higgs sector with the available LHC data. A global fit in the two-parametric anomalous coupling space indicating to possible deviations from the standard Higgs-fermion and Higgs-gauge boson couplings is performed, using post-Moriond 2012 data and more precise LC 2013 data. We find that the standard Higgs sector is consistent with the current CMS and ATLAS experimental results both in the infinitely small width approximation and the calculation with complete gauge invariant sets of diagrams. However, visible difference of the exclusion contours is found for some combinations of production and decay channels, although minor for the global fits for all possible channels. Updates of the signal strength and the signal strength error reported at LC 2013 result in a significant improvements of the allowed regions in the anomalous coupling space, which are recalculated also at complete tree level.
1 Introduction

Discovery of a Higgs-like signal at the LHC [1] provides a possibility to accomplish the Standard Model (SM) scheme, which is however considered as an effective theory at the energy scale $v = 246 \text{ GeV}$ rather than a self-contained field theory model. Physical observables up to energies of the order of 'new physics' scale $\Lambda$ are described by an effective Lagrangian which can be written as an expansion in the inverse powers of $\Lambda$. It is assumed usually that electroweak symmetry breaking scale $v$ is disconnected with the scale of new physics $\Lambda$, so the effective Lagrangian terms are invariant with respect to the gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$. Effective operators, first introduced in connection with a hypothetical baryon number violation and the four-fermion contact interactions [2], then were used [3] to consider flavor-changing neutral currents, extended technicolor, composite models and other BSM extensions. In the following we are using results of a systematic study [4], where sector-by-sector extensions of the SM by dimension 5 and dimension 6 effective operators can be found. Improved classification of anomalous terms, where some redundant dimension-six operators were excluded, can be found in [5]. An equivalent basis, which isolates in a more convenient manner the operators essential for the decays $H \rightarrow \gamma\gamma$, $\gamma Z$ has been elaborated in [6] including higher order corrections. Insofar as the effective Lagrangian terms include classical fields, equations of motion can be used for simplifications in both the scalar-fermion and scalar-gauge boson sectors, with result for the following set of dimension 6 operators

- **scalar-gauge boson sector**

  \[
  O_{\Phi G} = \frac{1}{2} (\Phi^\dagger \Phi - \frac{v^2}{2}) G_{\mu\nu}^a \tilde{G}^{a\mu\nu} \\
  O_{\Phi B} = \frac{1}{2} (\Phi^\dagger \Phi - \frac{v^2}{2}) B_{\mu\nu} B^{\mu\nu} \\
  O_{\Phi W} = \frac{1}{2} (\Phi^\dagger \Phi - \frac{v^2}{2}) W_{\mu\nu}^i W_i^{\mu\nu} \\
  O_{\Phi}^{(1)} = (\Phi^\dagger \Phi - \frac{v^2}{2}) D_\mu \Phi^\dagger D^\mu \Phi
  \]

- **scalar-fermion sector**

  \[
  O_{t\Phi} = (\Phi^\dagger \Phi - \frac{v^2}{2})(\bar{Q}_L \Phi^c t_R) \\
  O_{b\Phi} = (\Phi^\dagger \Phi - \frac{v^2}{2})(\bar{Q}_L \Phi b_R) \\
  O_{\tau\Phi} = (\Phi^\dagger \Phi - \frac{v^2}{2})(\bar{L}_L \Phi \tau_R)
  \]

where dual tensor $\tilde{F}_{\mu\nu} = \epsilon_{\mu\nu\gamma\delta} F^{\gamma\delta}$. Deviations from the SM are defined by the effective Lagrangian

\[
L^{(6)}_{\text{eff}} = \frac{1}{\Lambda^2} \sum_{k=V,F} C_k \Phi O_{k\Phi}
\]

where the anomalous couplings $C$ modify the SM Higgs boson couplings to the vector bosons and to the fermions.

The subtraction of $v^2/2$ leaves out undesirable mixing in the gauge field kinetic terms. Such operator basis was considered in [7]. Reduced set of five

\[\text{(1)}\]

\[\text{(2)}\]

\[\text{(3)}\]

\[\text{(4)}\]
operators for anomalous Higgs couplings to gauge bosons only was analysed in [8], where additional operators containing covariant derivatives of the scalar doublet, $O_W = D_\mu \Phi \Phi^\dagger D_\nu W^{\mu\nu}$ and $O_B = D_\mu \Phi \Phi^\dagger B^{\mu\nu}$, modifying the triple gauge-boson couplings, were either accepted or rejected in the two independent scenarios. The operator $O_{BW} = \Phi^\dagger \tau^a \Phi B_{\mu\nu} W^{\mu\nu}$, contributing to the $W^3 - B$ mixing of $SU(2)$ eigenstates at the tree level is strongly constrained by the electroweak data. Mixing terms with derivatives of vector fields would imminently shift gauge boson masses which are severely constrained by the electroweak precision data. The operator $(\Phi^+ \Phi)^3$ (denoted also by $O_\Phi^{(3)}$) which shifts the minimum of the Higgs potential and the Higgs boson mass is not introduced in our analysis.

In the general case when all possible dimension six contributions are accounted for, the effective Higgs-boson and Higgs-fermion couplings are related to the coefficients $C_\Phi$ in front of the operators $O_{\Phi G}, \ldots O_{\pm \Phi}$ in a rather untrivial way, since a number of different coefficients $C_\Phi$ mix while contributing to a single effective Higgs-boson or Higgs-fermion coupling. For the sake of distinctness we restrict the general multidimensional anomalous coupling space to the two-dimensional space, where the Higgs-boson and the Higgs-fermion couplings are rescaled by independent parameters $c_V$ and $c_F$. Such reduction is meaningful also to avoid modifications of the Lorentz structure for a vertex. Nonzero anomalous couplings $C_\Phi$ and $C_{BW}$, for instance, lead to modifications of the tensor structure for $HW^+W^-$ and $HZZ$ vertices (see Section 2 and Table 2, more details can be found in [9]). As a result, the phase space distributions could be substantially modified in [10] in comparison with the SM, making questionable the experimental interpretation of the signal reconstruction which is based specifically on the SM. Linear rescaling of the Higgs-boson and the Higgs-fermion couplings ($c_V, c_F$) (sometimes denoted by $k_v$ and $k_f$) is a common feature of a majority of existing analyses (see more comprehensive list [11]) which refer to different theoretical backgrounds. Particular parametrization of the Higgs couplings of the form $k_f = \sqrt{2} (m_f / M)^{1+\epsilon}$, $k_v = 2 (m_V^{2(1+\epsilon)} / M^{1+2\epsilon})$ (specific to the genuine Englert-Brout-Higgs spontaneous symmetry breaking mechanism; the limiting case of the SM is $\epsilon = 0$, $M = v$) has been analysed in [12]. One can distinguish a group of approaches where the fundamental scalar field is not a component of $SU(2)$ doublet [13, 14]. Anomalous operators of dimension five form the corresponding effective operator basis in the framework of a nonlinear realization of the $SU(2)_L \times U(1)$ symmetry by means of an effective chiral Lagrangian. In such models the Goldstone bosons $\pi^a$ are introduced in the form of a field $\Sigma(x) = \epsilon (i\tau^a \pi_a / v)$, which transforms linearly under the group $SU(2)_L \times SU(2)_R$. Parameter $v$ is not a vacuum expectation value associated with a minimum of some potential, the Higgs field is an additional scalar singlet under the gauge group transformations. An effective Lagrangian in the form of expansion in the powers of $h/v$ can be found in [12]-[15]. The effective

\footnote{Analysis of the complete set of operators is in progress and will be presented separately.}
parameters $a, b, \ldots$ in front of various powers of $h/v$ in the expansion define the values of $H$ couplings to gauge bosons, fermions and $H$ self-interaction. The leading operators appearing in the expansion in the inverse powers of the cutoff scale $\Lambda$ have the dimension five \cite{14}.

\[
L_{\text{eff}}^{(5)} = -\frac{c_{g}g_{s}^{2}}{2\Lambda} hG_{\mu\nu}^{A}G_{\mu\nu} + \frac{c_{W}g_{s}^{2}}{2\Lambda} hW_{\mu}^{a}W_{\mu}^{a} + \frac{c_{B}g_{s}^{2}}{2\Lambda} hB_{\mu\nu}B_{\mu\nu}
\]

and are enhanced by the factor $\Lambda/v$ in comparison with the effective dim-6 operators. In the minimal composite pseudo-Goldstone boson scenario the Higgs-boson and the Higgs-fermion anomalous couplings are identically rescaled, but it is not the case for a nonminimal compositeness, when some higher-order chiral symmetry is broken down to the symmetry of the standard Higgs sector. A scenario where light composite Higgs boson, emerging from a strongly interacting sector as a pseudo-Goldstone boson, causes electroweak symmetry breaking has been analysed in details \cite{12}-\cite{17} in connection with LHC data. The Higgs-fermion effective terms lead to a number of observable consequences for vector boson scattering and enhanced double Higgs boson production \cite{15, 16}.

Recent updates of CMS and ATLAS results in $\gamma\gamma$ and $ZZ, WW$ channels \cite{18} for the standard model Higgs boson allow to improve previous considerations, analyzing consistency of an experimental data to expectations for the SM Higgs boson production. Note that these analyses are based on a phenomenological parametrisation \cite{19} specific to production $\times$ decay approximation, when the Higgs boson width is infinitely small, the Breit-Wigner propagator is replaced by delta function so the signal cross section for the channel $ii \rightarrow H \rightarrow ff$ is $\sigma_{ii}(ii \rightarrow H) \propto \Gamma_{ff}/\Gamma_{tot}$. While “dressing” cross-sections $\sigma_{ii}$ and decay widths $\Gamma_{ff}$ by the scale factors $k_{f,i}$, factorizable deviations from the SM are introduced. For example, in the channel $gg \rightarrow H \rightarrow \gamma\gamma$ anomalous factor has a simple form $k_{g}^{2}k_{\gamma}^{2}/k_{H}^{2}$. The factors $k_{g}$ and $k_{\gamma}$ are independent parameters, i.e. vector boson and fermion loops are not resolved.

In the following we are going to analyse the LHC results in the framework of the SM extension by the dimension six operators and clear up the consistency of data and the consequences of the SM for Higgs-fermion and Higgs-gauge boson couplings. The paper is organized as follows. In section 2 convenient normalization of effective vertices in the dimension-six operator basis is defined. Section 3 contains statistical analysis of Higgs production data. Results of our computations are summarized in section 4.

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\footnote{ATLAS and CMS results reported in the beginning of 2013 (Recontres de Moriond, \cite{20}) were substantially improved in May 2013 (European LC Workshop). ATLAS results in the $\gamma\gamma$ channel: significance $7.4\sigma$, $\mu = 1.65^{+0.34-0.30}$ (2.3\sigma above the expected for SM), $m_{H} = 126.8^{+0.2}_{-0.7}$ GeV; in the $ZZ$ channel: significance $6.6\sigma$, $\mu = 1.70^{+0.5-0.4}$, $m_{H} = 124.3^{+0.6-0.5}$ GeV; CMS results in the $\gamma\gamma$ channel: significance $7\sigma$, $\mu = 1.55^{+0.5}$ consistent with $m_{H} \sim 125$ GeV; in the $ZZ$ channel: significance $6.6\sigma$, $\mu = 0.91^{+0.30-0.24}$, $m_{H} = 125.8^{+0.5}_{-0.2}$ GeV. Improvements in May 2013 can be found in section 4.}
### Table 1: Effective triple vertices in the Buchmueller-Wyler operator basis. Anomalous couplings $C$ (Wilson coefficients) are multiplicative factors in front of $O$.

#### 2 Normalization of effective vertices

A set of $P$-conserving operators, Eqs. (1), (2), leads to the set of Feynman rules listed in Table 1.

As already mentioned in the Introduction, the following analysis will be focused on the Higgs-fermion and the Higgs-gauge boson anomalous couplings $C_{t\Phi}$, $C_{b\Phi}$, $C_{\tau\Phi}$ and $C_{\phi(1)}$, $C_{\Phi G}$, which conserve the SM Lorentz structure of vertices. It is convenient to use a parametrisation which gives explicitly the SM one-loop contributions for the Higgs decays at some point of the anomalous couplings parameter space. If the effective Lagrangians for $H \rightarrow \gamma\gamma$ and $H \rightarrow gg$ are

$$L^{\text{eff}}_{\gamma\gamma H} = \frac{\lambda_{\gamma\gamma H}}{4} F_{\mu\nu} F^{\mu\nu} H, \quad L^{\text{eff}}_{gg H} = \frac{\lambda_{gg H}}{4} C_{\mu\nu} G^{\mu\nu} H$$

then the effective vertices

$$\Gamma^{\mu\nu}(p_1, p_2)_{\gamma/g} = -\lambda_{\gamma\gamma H/9gH}(g^{\mu\nu} p_1 p_2 - p_1^\nu p_2^\mu)$$
where $\lambda_{\gamma\gamma H/9gH}$ are defined by the one-loop integrals. The dominant fermionic contribution of the top-quark loop leads to well-known effective Lagrangians (see details in the survey [21]) ($\sqrt{G_F} \sqrt{2} = 1/v$)

$$L_{\gamma\gamma H}^{\text{eff}} = \frac{2\alpha}{9\pi v} F_{\mu\nu} F^{\mu\nu} H, \quad L_{9gH}^{\text{eff}} = -\frac{\alpha_s}{12\pi v} G^{a\mu\nu} G_{a\mu\nu} H$$

(6)

for the case of rather small $m_H^2/4m_{\text{top}}^2$ which is valid satisfactory for $m_H = 126$ GeV. So for the top one-loop induced couplings

$$\lambda_{\gamma\gamma H}^t = \frac{8\alpha}{9\pi v}, \quad \lambda_{9gH}^t = -\frac{\alpha_s}{3\pi v}$$

(7)

The contribution of $W$ is known for a long time [22]

$$\lambda_{\gamma\gamma H}^W = -\frac{7\alpha}{2\pi v}$$

(8)

and the one-loop induced decay widths are [21]

$$\Gamma(H \to \gamma\gamma) = \frac{\alpha^2 G_F m_H^3}{128\pi^3 \sqrt{2}} \left[ 3 \left( \frac{2}{3} \right)^2 \frac{4}{3} - 7 \right] = \left( \frac{47}{9} \right) \frac{\alpha^2 G_F m_H^3}{128\pi^3 \sqrt{2}}$$

(9)

$$\Gamma(H \to gg) = \frac{1}{36} \frac{\alpha^2 G_F m_H^3}{\pi \sqrt{2}}.$$ 

(10)

It is convenient to introduce the effective parameters

$$c_F = 1 + C_{\Phi} \frac{v^2}{\Lambda^2}$$
$$c_V = 1 + \frac{v^2}{2\Lambda^2} \cdot C_{\Phi}^{(1)}$$
$$c_G = c_F + \frac{6\pi}{\alpha_s} \cdot C_{\Phi G} \cdot \frac{v^2}{\Lambda^2}$$
$$c_{\gamma} = \frac{63c_F - 16c_V}{47} + \frac{9\pi}{4\alpha} \cdot (c_w^2 \cdot C_{\Phi B} + s_w^2 \cdot C_{\Phi W}) \cdot \frac{v^2}{\Lambda^2}$$
$$c_Z = (s_w^2 \cdot C_{\Phi B} + c_w^2 \cdot C_{\Phi W}) \cdot \frac{v^2}{\Lambda^2}$$
$$c_W = C_{\Phi W} \cdot \frac{v^2}{\Lambda^2}$$

such that at the leading order the SM limit with the one-loop induced $H \to \gamma\gamma$ and $h \to gg$ channels is clearly seen. A compact set of Feynman rules for the triple vertices to be used in the following analyses is presented in Table 2.

In order to take into account the NLO corrections, the normalization of $ggH$

\footnote{In the numerical computations well-known formulae including $m^2_H/4m_{\text{top}}^2$ terms were used.}
Table 2: Triple vertices in the Buchmueller-Wyler operator basis. The SM limit with the one-loop induced vertices $H \to \gamma\gamma$ and $h \to gg$ is achieved at $c_V = c_F = c_G = c_\gamma = 1$, $c_Z = c_W = C_{\Phi B} = C_{\Phi W} = 0$.

and $\gamma\gamma H$ vertices was changed using the output of HDECAY code [23], where higher-order QCD and leading electroweak corrections from different sources have been incorporated. For example, the effective coupling constants $\lambda_{\gamma\gamma H}$ and $\lambda_{\gamma\gamma Z}$ can be found using partial widths

$$\lambda_{\gamma\gamma H} = 8 \frac{\pi}{m_H^3} \Gamma_{tot} Br(H \to \gamma\gamma), \quad \lambda_{\gamma\gamma Z} = 8 \left( \frac{\pi m_H^3}{2 (m_H^2 - m_Z^2)^3} \right) \Gamma_{tot} Br(H \to \gamma Z)$$

Such normalization reproduces the SM limit at $c_i = 1$, $i = F, V, G, \gamma$, $c_Z = c_W = 0$. The one-loop vertices are "resolved" at the leading order. For example, destructive interference between the top and $W$ loops, see Eqs.(7) and (8), leads to an enhancement in the $\gamma\gamma$ channel at negative $c_F$, where an extensive region compatible with the data appears (see Section 4). However, NLO corrections from anomalous dim-6 terms inside the loops are not accounted for.

### 3 Signal strength and exclusion contours in the space of anomalous parameters

The method of exclusion contours reconstruction in the relevant anomalous parameter space which we are using is similar to the method developed in [17, 24]. Available experimental data provides the signal strength

$$\mu_i = \frac{\left[ \sum_j \sigma_{j \to h} Br(h \to i) \right]_{obs}}{\left[ \sum_j \sigma_{j \to h} Br(h \to i) \right]_{SM}}$$

(12)
where $i$ is the number of Higgs boson decay channel and $j$ is the number of Higgs production process for a given final state. Best fit value of a signal strength can be expressed using the observed number of signal events $N_{\text{obs}}$, the number of background events $N_{\text{backgr}}$, and the number of signal events calculated in the SM $N_{\text{signal}}^{SM}$

$$\hat{\mu}_i = \frac{N_{\text{obs},i} - N_{\text{backgr},i}}{N_{\text{signal}}^{SM},i}$$

(13)

The global $\chi^2$ is defined as

$$\chi^2(\mu_i) = \sum_{i} \frac{(\mu_i - \hat{\mu}_i)^2}{\sigma_i^2}$$

(14)

for the number of production channels $N_{\text{ch}}$. Theoretical predictions for $\sigma_{j\rightarrow h}$ and related errors can be found on the LHC Higgs Cross Sections WG webpage [25]. Minimization of $\chi^2 \rightarrow \chi^2_{\text{min}}$ gives us the 1$\sigma$, 2$\sigma$ and 3$\sigma$ regions $\chi^2 = \chi^2_{\text{min}} + \Delta \chi^2$ where $\Delta \chi^2$ is defined by cumulative distribution function. Assuming that the signal strengths of various channels have Gaussian distributions with the probability density functions having the expected values $\hat{\mu}_i$ and the dispersions (1$\sigma$ deviations) $\sigma_i$, normalized to one, combined probability density function (pdf) for a number of production channels can be found by multiplication of pdf’s for individual channels. Combined probability density function is also Gaussian characterized by $\mu_c$ and $\sigma_c$

$$\frac{1}{\sigma_c^2} = \sum_{i} \frac{1}{\sigma_i^2}, \quad \hat{\mu}_c = \sum_{i} \frac{\hat{\mu}_i}{\sigma_i^2}$$

(15)

which allows to determine, for example, 95% CL exclusion upper $\mu_U$ and lower $\mu_L$ limits on the signal strength parameter integrating the combined pdf from $\hat{\mu}$ to $\mu_U$ and from $\mu_L$ to $\hat{\mu}$, respectively, then equating result to 0.95/2. Possible negative values of the lower limit for the signal strength at a small luminosities allow to determine only $\mu_U$ by integrating probability density function from 0 to $\mu_U$ and equating to 0.95.

If the SM is fully adequate, the values of $\mu_i$ are as close to one as allowed by experimental errors. In the framework of the SM extension by dim-6 effective operators the values of $\mu_i$ obviously may depart from one for individual channels, so it is convenient to normalize the signal strengths (13) to the expectation values in the given SM extension $N_{\text{signal},i,cF,cV,cW,...}^{SM}$ rather than the SM expectation $N_{\text{signal},i}^{SM}$, which does not depend on the anomalous parameters $c_F, c_V, c_W, ...$. In this case the combined signal strength with expectation 1 can be introduced again if the exclusion bounds $\hat{\mu}_i \pm \sigma_i$ are renormalized by a factor $N_{\text{signal},i}^{SM}/N_{\text{signal},i,cF,cV,cW,...}$. While the experimental signal strength error is provided by ATLAS and CMS collaborations, the theoretical signal strength error is evaluated using numbers on the web page of LHC Higgs Cross Sections WG [25].
In the following fits we are using the signal strength calculated at $m_H = 125$ GeV. At the first stage a two-dimensional fit $\chi^2(c_V, c_F)$ has been performed, the anomalous couplings $C_{\Phi B}$ and $C_{\Phi W}$ (see Section 2) are taken to be zero, so for the SM case $(c_V, c_F) = (1, 1)$, $c_\gamma = 1$ and $c_Z = c_W = 0$. Calculation of the $\Delta \chi^2$ for the best fit defines a given number $\times$ CL contours corresponding to the departure of the SM point $(1, 1)$ from the best fit point in the $(c_V, c_F)$ parameter plane. Following [17] the contours in all figures correspond to 65%, 90% and 99% best fit CL regions with $\Delta \chi^2$ less than 2.10, 4.61 and 9.21, respectively.

**4 Beyond the infinitely small width approximation**

Calculations of complete gauge invariant sets of diagrams, although complicated and CPU time consuming, are more precise than production $\times$ decay approximation. They take into account

- untrivial interference between signal diagrams. For example, the four-lepton final states $l^+l^-l'^+l'^-$ and/or $\nu\nu l^+l^-$ are produced through $H \rightarrow Z^*Z^*$, $H \rightarrow W^*W^*$ and $\gamma\gamma$ intermediate states (see Figures 1 and 2) with untrivial interferences, not accounted for in the production $\times$ decay approximation.

- untrivial interference between the signal and the irreducible background diagrams. Although very small for narrow width resonances of the order of a few MeV, in the meaningful regions of the anomalous coupling space the anomalous Higgs boson width differs by around one order of magnitude from the SM total width. Numerical results for complete tree level sets are in some cases sensitive to Breit-Wigner propagators, especially when strong gauge cancellations between diagrams take place for a given Higgs production channel

- lepton and jet distributions, calculated at complete tree level, are based on correct kinematics, oftenly not available for the production $\times$ decay approximation. Correct distributions are important in real experimental environment, when detector acceptances must be accounted for.

Some theoretical issues and numerical examples in this connection were analysed for LEP2 physics [26].

A number of exclusion contours were reconstructed using the statistical approach described in Section 3. The following Higgs production processes have been calculated

- for the $\gamma\gamma$ event signature: gluon fusion $gg \rightarrow \gamma\gamma$, vector boson fusion (VBF) $qg \rightarrow qg\gamma\gamma$, associated production with vector bosons $qq \rightarrow W\gamma\gamma$, $qq \rightarrow Z\gamma\gamma$ and the top-antitop quark pair $qq \rightarrow t\bar{t}\gamma\gamma$. Contributions
to the Higgs boson production rate involving Higgs couplings to $c$ and $b$ quarks, such as diagrams with intermediate Higgs in the processes $c\bar{c} \to \gamma\gamma$ and $b\bar{b} \to \gamma\gamma$ and diagrams with the Higgs radiation from $c$ and $b$ quark lines in the associated production with $W, Z$ and $t\bar{t}$ (for example, $s\bar{c} \to W^+\gamma\gamma$, $s\bar{c} \to W^-\gamma\gamma$, 6 diagrams) give very small yield and for this reason are omitted. Only gauge-invariant subset of 8 diagrams with Higgs boson radiation from the top line $gg \to W^+W^-$, omitting 18 diagrams with different topologies. Being marginally small in the SM, such amplitudes could give substantial contributions in the anomalous coupling space. We checked explicitly the absence of anomalous enhancements. 20 partonic subprocesses $q\#q\# \to q\#q\#\gamma\gamma$ were accounted for in the VBF channel, including interference terms between the diagrams. The notation $q\#$ is used to account for all possible combinations of $u, d, c, s$ quarks and anti-quarks.

- **event signatures with four leptons** $gg \to \nu\bar{\nu}l^+l^-$ and $gg \to l^+l^-l^+l^-$ including interference terms between $H \to W^+W^-$ and $H \to ZZ$. Vector boson channels $H \to W^+W^-$ and $H \to ZZ$ usually mix. A complete set of six Higgs production diagrams in the channel $pp \to WW \to \nu\bar{\nu}\mu^+\mu^-$ ($WW$ production via gluon fusion) is shown in Fig.1 where not only diagram 2 accounted for in the production $\times$ decay approximation contributes, but also $H \to ZZ$ channel, diagram 1, as well as four $s$-channel amplitudes, diagrams 4-6, together with interference terms which are rather small in this case. In this channel the $WW^*ZZ^*$ interference term is negative (the value of the order of a few percent in comparison with $|WW^*|^2 + |ZZ^*|^2$), cancelling the yield of $|ZZ^*|^2$ term. Leptonic event signatures in $WW$ and $ZZ$ VBF processes were included in the $(2 \to 4) \times (1 \to 2)$ infinitely small width approximation which can be justified by their smaller significance in comparison with $\gamma\gamma$ VBF. One more example for the $ZZ \to \mu^+\mu^-\mu^+\mu^-$ channel is shown in Fig.2 where the "exchange" interference term $ZZ^*ZZ^*$ is positive with the magnitude approximately 20% of the $|ZZ^*|^2$ term. Diagrams with intermediate photons contribute insignificantly in the anomalous coupling space. As one could expect, the amplitudes with triple Higgs vertex (diagram 9) and $t$-channel gluon exchange (diagram 10) were found insignificant for the fit in the vicinity of the SM point.

- **event signatures with $b\bar{b}$ and $\tau^+\tau^-$.** For $H \to b\bar{b}$ the processes $q_1\bar{q}_2 \to Wb\bar{b}$ and $q\bar{q} \to Zb\bar{b}$ were calculated. Again diagrams with Higgs boson radiation from $c$ and $b$ quark lines were neglected. For $H \to \tau^+\tau^-$ channel we calculated $\tau^+\tau^-, \tau^+\tau^- VBF, \tau^+\tau^- t\bar{t}, \tau^+\tau^- W$ and $\tau^+\tau^- Z$ production.

For validation of our codes and numerical fitting procedures we reproduce the global fit of the first paper in [17], which was reconstructed in the $(a,c)$ plane on the basis of 2012 post-Moriond data in the infinitely small width approxi-
Table 3: The signal strength and the signal strength error following [28].

| channel                  | ATLAS    | CMS       |
|--------------------------|----------|-----------|
| $V H \to V b b$          | -0.4±1.0 | 1.15±0.62 |
| $H \to \tau^+\tau^-$    | 0.8±0.7  | 1.10±0.41 |
| $H \to W W^*$            | 1.0±0.3  | 0.68±0.20 |
| $H \to Z Z^*$            | 1.5±0.4  | 0.92±0.28 |
| $H \to \gamma\gamma$    | 1.6±0.3  | 0.77±0.27 |

Latest data from LC2013 [28] (Hamburg, May 2013) are represented in Table 3. Significant improvements of the precision have been achieved for $b\bar{b}$ and $\tau^+\tau^-$ channels. In the 2012 data the signal strength error both of ATLAS and CMS was about 2, with the three-four times decrease reported the beginning of 2013.

5A special regime of ‘table calculations’ (numerical operations with multidimensional tables) has been implemented in CompHEP version 4.5.
Improvements for the $WW$, $ZZ$ and inclusive $\gamma\gamma$ channels have been also quite substantial, reducing the signal strength error approximately by a factor of two. The $H \to W^+W^-$ signal strength reported by ATLAS was reduced to 1. CMS signal strength for the $\gamma\gamma$ channel was reported on the level of 0.77 in 2013, compared with 1.6 in the earlier data processing. ATLAS reduced it from 1.8 to 1.65. Some improvement for the VBF $\gamma\gamma$ channel was found. A new result for the signal strength 1.1 with the reduced error in the $\tau^+\tau^-$ channel by CMS improves the primary value of 0.7. The contours generated with post-Moriond 2012 and preliminary LC2013 data again for the three groups of channels (a),(b) and (c), see above, are shown in Fig.7. As a result, the area at negative $c$ disappeared almost completely while contours of the positive $(a,c)$ quadrant demonstrate the consistency of the SM hypothesis with the data on the level of 95%. These modifications are in a qualitative agreement with the global combination from [29] which is based on Moriond 2013 (La Thuile, March 2013) experimental data [30].

5 Conclusions

The LHC data in various channels of Higgs boson production have been analysed in the framework of the Standard Model extension by the dimension-six
effective operators. In order to understand the consistency between the SM
consequences and the experimental data a number of global fits for the signal
strengths in various channels was performed and the exclusion regions in the
\((c_V, c_F)\) anomalous coupling plane were reconstructed using post-Moriond 2012
data and recent LC 2013 data. In agreement with \cite{17} two best fit regions were
found for positive and negative values of \(c_F\), demonstrating consistency of the
SM hypothesis with the post-Moriond 2012 data on the level of 82\%. In the
infinitely small width approximation (or \(\text{production} \times \text{decay approximation}\)) we
reproduced practically identically the results of \cite{17}, although different physics
frameworks (effective operator bases) for the rescaling of the Higgs-boson and
the Higgs-fermion couplings are used in the analyses. Evaluations beyond the
infinitely small width approximation demonstrate visible departures of the ex-
clusion contours for the combination of \(H \rightarrow W^+W^-, ZZ\) and \(\gamma\gamma\) channels,
however insignificant for the global fits. Improvements of the precision achieved
in 2013 \cite{28} excluded practically completely the region with negative values of
\(c_F\) showing consistency of the SM hypothesis with the 2013 data on the level of
95\%.

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Figure 2: Signal diagrams for the process $gg \rightarrow ZZ \rightarrow \mu^+ \mu^- \mu^+ \mu^-$
Figure 3: (a) - global $\chi^2$ fit in the $(c_V, c_F)$ plane calculated with Higgs boson width for all two-particle, WW$^*$ and ZZ$^*$ decay channels including VBF(diagrams with gluon fusion omitted) combined with $\gamma\gamma$ VBF, within the production×decay approximation, (b) - global $\chi^2$ fit in the $(a, c)$ plane from [17]
Figure 4: $\chi^2$ fits in the $(c_V, c_F)$ plane calculated within the production $\times$ decay approximation (a) - $b\bar{b}$ and $\tau^+\tau^-$ channels; (b) - $WW^*$ and $ZZ^*$ channels including VBF (diagrams with gluon fusion omitted) combined with $\gamma\gamma$ VBF, (c) - $\gamma\gamma$ channels including VBF; (d) - the same fits for $b\bar{b}$, $\tau^+\tau^-$, $WW^*$, $ZZ^*$ and $\gamma\gamma$ channels in the (a, c) plane from [17]. Note that different ranges for $c_F$ are used in upper and lower rows of plots.
Figure 5: (a),(b),(c) - $\chi^2$ fits (2012 data) in the $(c_V, c_F)$ plane calculated within the production × decay approximation; (d),(e),(f) - the same fits calculated with complete gauge invariant sets of diagrams. (a),(d) - $b\bar{b}$ and $\tau^+\tau^-$ channels; (b),(e) - $WW^*$ and $ZZ^*$ channels including VBF (diagrams with gluon fusion omitted) combined with $\gamma\gamma$ VBF, (c),(f) - $\gamma\gamma$ channels including VBF.
Figure 6: $\chi^2$ fits in the $(c_V, c_F)$ plane calculated for $WW^*$ and $ZZ^*$ channels, (a) - including VBF (ladder) diagrams with the fusion of gluons radiated from the quark lines, (b) - diagrams with intermediate gluons omitted. Identical signal strength and signal strength error were taken for the four-lepton final states produced either without forward jets or with forward jets tagging. $\gamma\gamma$ VBF diagrams are not accounted for.
Figure 7: (a),(b),(c) - $\chi^2$ fits in the $(c_V, c_F)$ plane calculated using post-Moriond 2012 data; (d),(e),(f) - the same fits calculated using LC 2013 data (see Table 3). (a),(d) - $b\bar{b}$ and $\tau^+\tau^-$ channels; (b),(e) - $WW^*$ and $ZZ^*$ channels (including VBF) combined with $\gamma\gamma$ VBF, (c),(f) - $\gamma\gamma$ channels including VBF.
Figure 8: Global $\chi^2$ fits in the $(c_V, c_F)$ plane. (a),(c) - calculated without VBF diagrams in the $\gamma\gamma$, $WW^*$ and $ZZ^*$ channels, (b),(d) - calculated with VBF diagrams in the $\gamma\gamma$, $WW^*$ and $ZZ^*$ channels; (a),(b) based on 2012 data, (c),(d) based on preliminary 2013 data (Table 3).