Impact of a Higgs Boson at a Mass of 126 GeV on the Standard Model with Three and Four Fermion Generations

Otto Eberhardt,[1,*] Geoffrey Herbert,[2,†] Heiko Lacker,[2,‡] Alexander Lenz,[3,§] Andreas Menzel,[2,∥] Ulrich Nierste,[1,¶] and Martin Wiebusch[1,**]

[1]*Institut für Theoretische Teilchenphysik, Karlsruhe Institute of Technology, D-76128 Karlsruhe, Germany*
[2]*Humboldt-Universität zu Berlin, Institut für Physik, Newtonstr. 15, D-12489 Berlin, Germany*
[3]*CERN-Theory Divison, PH-TH, Case C01600, CH-1211 Geneva 23, Switzerland, and IPPP, Department of Physics, University of Durham, Durham DH1 3LE, United Kingdom*
(Received 13 September 2012; published 11 December 2012)

We perform a comprehensive statistical analysis of the standard model (SM) with three and four generations using the latest Higgs search results from LHC and Tevatron, the electroweak precision observables measured at LEP and SLD, and the latest determinations of M_W, m_t, and α_s. For the three-generation case we analyze the tensions in the electroweak fit by removing individual observables from the fit and comparing their predicted values with the measured ones. In particular, we discuss the impact of the Higgs search results on the deviations of the electroweak precision observables from their best-fit values. Our indirect prediction of the top mass is $m_t = 175.7^{+3.0}_{-2.2}$ GeV at 68.3% C.L., which is in good agreement with the direct measurement. We also plot the preferred area in the M_W-m_t plane. The best-fit Higgs boson mass is 126.0 GeV. For the case of the SM with a perturbative sequential fourth fermion generation (SM4) we discuss the deviations of the Higgs signal strengths from their best-fit values. The $H \to \gamma\gamma$ signal strength now disagrees with its best-fit SM4 value at more than 4σ. We perform a likelihood-ratio test to compare the SM and SM4 and show that the SM4 is excluded at 5.3σ. Without the Tevatron data on $H \to b\bar{b}$ the significance drops to 4.8σ.

DOI: 10.1103/PhysRevLett.109.241802 PACS numbers: 14.80.Bn, 12.15.Lk

Introduction.—Electroweak precision observables (EWPOs) played an important role in the prediction of the mass of the top quark prior to its discovery [1,2]. Later, with improving Tevatron data on the mass m_t of the top quark, EWPOs were used to constrain the mass m_H of the Higgs boson, albeit with little precision since EWPOs only depend logarithmically on this quantity [3]. Recently, ATLAS and CMS have discovered a convincing candidate for the Higgs boson with a mass of around 126 GeV [4,5]. With the information on m_H available, EWPOs enter a new era as they directly test the standard model (SM) without involving otherwise undetermined fundamental parameters. In this Letter, we present a combined fit of the EWPOs and Higgs signal strengths in the decays to $\gamma\gamma$, WW, ZZ, $b\bar{b}$, and $\tau\tau$ studied at the LHC and the $p\bar{p} \to H \to b\bar{b}$ signal strength determined at the Tevatron [6].

The SM is minimal in several respects; e.g., the fermions belong to the smallest possible representations of the gauge groups and electroweak symmetry breaking is achieved with a single Higgs doublet. However, the fermion field content is nonminimal and organized in at least three families. There has been a tremendous interest in the phenomenology of a fourth fermion generation, with more than 500 papers in the last decade. The SM with a sequential fourth generation, SM4, had survived global analyses of EWPOs and flavor observables [7–13], but was put under serious pressure from the first LHC data on Higgs searches [14–18]. In this Letter, we show that the perturbative SM4 is the first popular model of new physics which is ruled out by the LHC at the 5σ level. This strong statement is possible because of the nondecoupling property of the SM4, as loops with fourth-generation fermions do not vanish with increasing masses. For the same reason it is difficult to compute the statistical significance at which the SM4 is ruled out: the nondecoupling property implies that the SM4 and SM are non-nested; i.e., the SM is not obtained from the SM4 by fixing the additional parameters. This complicates the statistical procedure which compares the performance of the two models at describing the data. We have solved this problem with the help of a new method for toy Monte Carlo simulations, as implemented in the *my*Fitter package [19]. A first application of *my*Fitter to the SM4 with the data available before the announcement of the Higgs discovery right before the ICHEP 2012 conference has been presented in Ref. [18].

Method and inputs.—We combine electroweak precision data with Higgs signal strengths provided by ATLAS, CMS, and Tevatron. (To study the impact of the excess in $H \to b\bar{b}$ events reported by CDF we also show results with the CDF input excluded.) Our fit parameters in the SM are the Z mass M_Z, the top quark mass m_t, the strong coupling α_s, the hadronic contribution $\Delta\alpha^{(5)}_{\rm had}$ to the fine structure constant at the scale M_Z in the five-flavor scheme and the Higgs boson mass m_H. In the SM4 the additional parameters are the fourth-generation quark masses $m_{t'}$ and $m_{b'}$ and the fourth-generation lepton masses m_{ℓ_4} and m_{ν_4}. The combination of Higgs signal strengths and EWPOs disfavors mixing between the fourth and the first three generations [18], so that we can safely neglect it. Direct searches at the Tevatron and the LHC put lower bounds

TABLE I. Experimental inputs for Higgs signal strengths. Except for $H \to \gamma\gamma$, CMS only provides signal strengths at 125.5 GeV. ATLAS has not published a 2012 update on $H \to \tau\tau$ and $H \to b\bar{b}$, so we take the 2011 data.

Process	Reference(s) (m_H free)	Reference(s) (m_H fixed)	Combination at 126 GeV
$pp \to H \to \gamma\gamma$	[4,12]	[4,21]	$1.583^{+0.337}_{-0.345}$
$pp \to H \to WW^*$	[4]	[4,5]	$0.905^{+0.323}_{-0.294}$
$pp \to H \to ZZ^*$	[4]	[4,5]	$0.861^{+0.391}_{-0.285}$
$p\bar{p} \to HV \to Vb\bar{b}$	[6]	[6]	$2.127^{+0.806}_{-0.763}$
$pp \to HV \to Vb\bar{b}$		[4,5]	$0.478^{+0.783}_{-0.680}$
$pp \to H \to \tau\tau$	[22]	[22,5]	$0.100^{+0.714}_{-0.699}$

on the masses of the fourth-generation quarks. For example, the current highest limit on $m_{b'}$ is $m_{b'} > 611$ GeV [20]. However, these limits rely on specific assumptions about the mass splitting and the decay patterns of the heavy quarks. We therefore use a conservative limit of $m_{t'}, m_{b'} > 400$ GeV in our fits. For the lepton masses we require $m_{\ell 4} > 100$ GeV and $m_{\nu 4} > M_Z/2$. As the upper limit for all fourth-generation fermion masses we choose 800 GeV. Our inputs for the Higgs signal strengths are summarized in Table I. For a given Higgs production and decay mode $X \to H \to Y$, the signal strength $\hat{\mu}(X \to H \to Y)$ is defined as the observed production cross section times branching ratio divided by the SM prediction. The asymmetric errors are accounted for by using an asymmetric Gaussian likelihood function. For the SM fit and the Higgs mass scans we treat m_H as a free parameter and interpolate the data from signal strength plots versus Higgs mass, as provided by the ATLAS, CMS, CDF, and D0 Collaborations. When comparing the SM and the SM4 we keep the Higgs mass fixed in our fit and use the combined signal strengths given in Table I as inputs.

On the theory side, the SM4 signal strengths are computed by appropriately scaling the SM branching fractions and production cross sections separately for each production mechanism. (Further details can be found in Ref. [16].) In this sense, our treatment of the Higgs signal strengths is a special case of effective coupling analyses such as Refs. [23–27]. Unfortunately, these analyses are insufficient to rule out the SM4: An effective coupling analysis which "contains" the SM4 would have to treat the Higgs couplings to $\gamma\gamma$, WW, ZZ, gg, $b\bar{b}$, $\tau\tau$, and $\nu_4\bar{\nu}_4$ as independent parameters and provide full information about the χ^2 function on this seven-dimensional parameter space. Even then one could not compute the p-value of the likelihood ratio test comparing the SM and the SM4, since this requires a numerical simulation with toy measurements.

Although we combine results from the 7 and 8 TeV LHC runs, we compute the signal strengths using 7 TeV SM cross sections only. This is justified because the signal strengths only depend on the ratios of Higgs production cross sections for different production mechanisms and not on their absolute size. The ratios are constant to a good approximation when going from 7 to 8 TeV [28]. Note, however, that we treat the $H \to b\bar{b}$ signal strengths from the Tevatron and LHC detectors as two different observables because the ratio

TABLE II. Experimental inputs and fit results for the electroweak precision observables in the SM calculated using ZFitter [42–44]. The inputs are listed in the second column. The first error is statistical while the second (if present) is systematic. We also use the correlations from Ref. [51]. The input for α_s is the value determined from the τ lifetime. In the fourth column, we show the results of a global fit using all available inputs. Here, the errors are 68.3% C.L. intervals. The fifth column contains the prediction for each observable, obtained by removing the direct input for that observable and rerunning the fit. The corresponding difference of the minimal χ^2 values is shown in column six. The quantities in the last five rows were used as fit parameters.

Quantity	Input	Reference	Best-fit value	Prediction	$\Delta\chi^2$
$\sigma^0_{\rm had}$[nb]	41.541 ± 0.037	[52]	$41.4766^{+0.0075}_{-0.0141}$	$41.468^{+0.014}_{-0.012}$	2.83
$A^{0,l}_{\rm FB}$	0.0171 ± 0.0010	[51]	$0.016182^{+0.000073}_{-0.000079}$	$0.016180^{+0.000072}_{-0.000081}$	0.90
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	[51]	$0.07357^{+0.00018}_{-0.00020}$	$0.07357^{+0.00018}_{-0.00019}$	0.27
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	[51]	$0.10297^{+0.00023}_{-0.00025}$	$0.10303^{+0.00023}_{-0.00024}$	4.74
A_l	0.1499 ± 0.0018	[13,51]	$0.14689^{+0.00033}_{-0.00036}$	$0.14679^{+0.00033}_{-0.00045}$	2.89
A_c	0.670 ± 0.027	[51]	$0.66781^{+0.00014}_{-0.00016}$	$0.66781^{+0.00014}_{-0.00016}$	0.02
A_b	0.923 ± 0.020	[51]	0.934643 ± 0.000025	0.934643 ± 0.000025	0.19
R^0_l	20.767 ± 0.025	[51]	$20.7420^{+0.0176}_{-0.0088}$	$20.7365^{+0.0147}_{-0.0042}$	0.84
R^0_c	0.1721 ± 0.0030	[51]	$0.172249^{+0.000053}_{-0.000031}$	$0.172249^{+0.000053}_{-0.000030}$	0.01
R^0_b	0.21629 ± 0.00066	[51]	$0.215804^{+0.000040}_{-0.000020}$	$0.215803^{+0.000040}_{-0.000020}$	0.27
$\sin^2\theta^{\rm eff}_l$	$0.2324 \pm 0.0012 \pm 0.000047$	[13,51]	$0.231539^{+0.000045}_{-0.000041}$	$0.231538^{+0.000044}_{-0.000042}$	0.46
$M_W[GeV]$	$80.385 \pm 0.015 \pm 0.004$	[13,53]	$80.3694^{+0.0049}_{-0.0072}$	$80.3682^{+0.0051}_{-0.0135}$	0.66
Γ_W[GeV]	2.085 ± 0.042	[54]	$2.09145^{+0.00113}_{-0.00086}$	$2.09146^{+0.00113}_{-0.00087}$	0.02
Γ_Z[GeV]	2.4952 ± 0.0023	[51]	$2.49561^{+0.00143}_{-0.00080}$	$2.49532^{+0.00164}_{-0.00060}$	0.12
M_Z[GeV]	91.1876 ± 0.0021	[52]	$91.1878^{+0.0020}_{-0.0021}$	$91.192^{+0.014}_{-0.010}$	0.17
m_t[GeV]	$173.18 \pm 0.56 \pm 0.75$	[55]	$174.04^{+0.54}_{-1.14}$	$175.7^{+3.0}_{-2.2}$	0.61
$\alpha_s(M_Z)\vert_\tau$	$0.1202 \pm 0.0006 \pm 0.0021$	[56]	$0.1189^{+0.0026}_{-0.0013}$	0.1189 ± 0.0027	0.00
$\Delta\alpha^{(5)}_{\rm had}(M_Z)$	0.02757 ± 0.00010	[57]	0.027558 ± 0.000097	$0.02735^{+0.00042}_{-0.00047}$	0.26
m_H[GeV]	signal strengths	see Table I	$126.00^{+0.36}_{-0.67}$	108^{+25}_{-33}	6.26

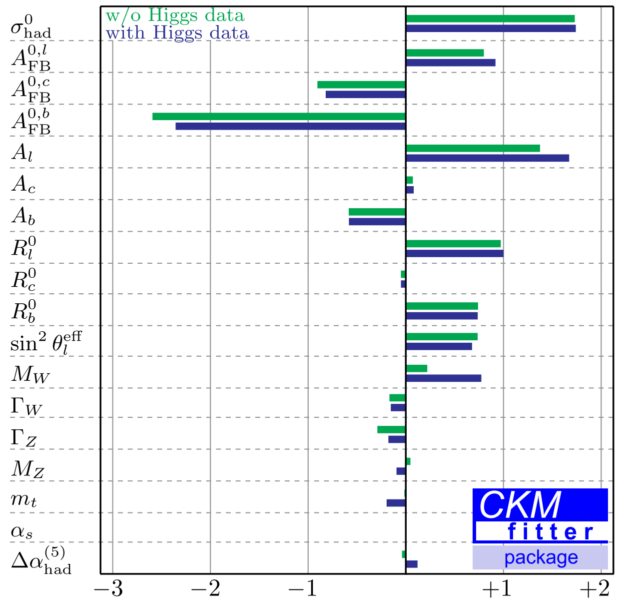

FIG. 1 (color online). Deviations of the EWPOs in the standard model. The observables were calculated with ZFitter [42–44]. For an observable $\mathcal{O}$ with experimental value $\mathcal{O}_{\rm exp}$, experimental error $\Delta\mathcal{O}_{\rm exp}$, and best-fit prediction $\mathcal{O}_{\rm fit}$, we define the deviation as $(\mathcal{O}_{\rm exp} - \mathcal{O}_{\rm fit})/\Delta\mathcal{O}_{\rm exp}$.

of W and Z associated production cross sections is different at the Tevatron and at the LHC.

Heavy fourth-generation fermions imply large Yukawa couplings which eventually make the theory nonperturbative. The 1978 paper [29] estimated a breakdown of perturbation theory at $m_{b'} \geq 500$–600 GeV from considerations of tree-level partial wave unitarity [30]. However, this bound merely implies that for $m_{b'} \approx 500$ GeV, loop corrections become important. In our fits we compute the Higgs width and branching ratios with HDECAY v. 4.45 [31], which implements the higher-order corrections of Refs. [32–35] (see also Ref. [36]).

The global fits with a variable Higgs mass were done with the CKMfitter software [37]. The EWPOs in the SM4 were calculated as in Ref. [38], using FeynArts, FormCalc, and LoopTools [39–41] to compute the SM4 corrections to the EWPOs. The EWPOs in the SM were calculated with the ZFitter software [42–44]. The SM Higgs production cross sections were taken from Ref. [45] (LHC) and Refs. [46,47] (Tevatron). For the computation of the p-values we use the *my*Fitter package [19] which in turn uses the DVEGAS code [48–50] for numerical Monte Carlo integration.

SM fit results.—The EWPO inputs as well as the SM fit results can be found in Table II. The experimental error on the Higgs mass is determined in a fit to all available signal strengths (see the second column of Table I). A large $\Delta\chi^2$ value in the last column indicates that the observable is in strong disagreement with the other observables. The most prominent "outlier" is therefore $A^b_{\rm FB}$, followed by $\sigma^0_{\rm had}$ and A_l. The leptonic left-right asymmetry A_l is the main cause for the disagreement between the predicted and measured value of m_H: removing the A_l input leads to a predicted Higgs mass

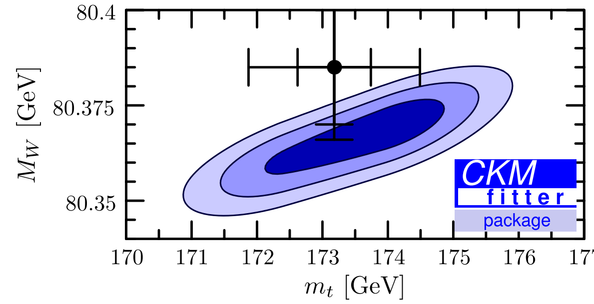

FIG. 2 (color online). The 68.3%, 95.5%, and 99.7% C.L. regions in the m_t-M_W plane using Higgs signal strengths and EWPOs. Also shown are the experimental values of m_t and M_W and their errors. The inner error bars are the statistical errors.

of 124 GeV. Note, however, that the updated inputs for m_t and M_W move the predicted Higgs mass up to 108 GeV.

The deviations of the EWPOs from their best-fit predictions are shown in Fig. 1. This figure shows the fit with Higgs signal strength and EWPO inputs as well as the fit with EWPO inputs only. Note that, due to the logarithmic dependence of the EWPOs on the Higgs mass, the inclusion of the Higgs signal strengths is essentially equivalent to fixing the Higgs mass at 126 GeV. We see that the new Higgs data have a relatively small impact on the deviations of most EWPOs. The main difference is an increase in the deviation of M_W to 0.8σ. The 68.3%, 95.5%, and 99.7% C.L. regions in the m_t-M_W plane (using Higgs signal strengths and EWPOs) are shown in Fig. 2 [58].

SM4 fit results.—The impact of a fourth fermion generation on the Higgs signal strengths has been discussed extensively in the literature. The Higgs production cross section via gluon fusion is enhanced by a factor of 9 due to the additional heavy quarks in the loop [8,60]. In $H \to \gamma\gamma$ searches, this factor is overcompensated by a reduction of the branching ratios, which is due to an accidental cancellation between gauge boson and fermion loops at next-to-leading order [35].

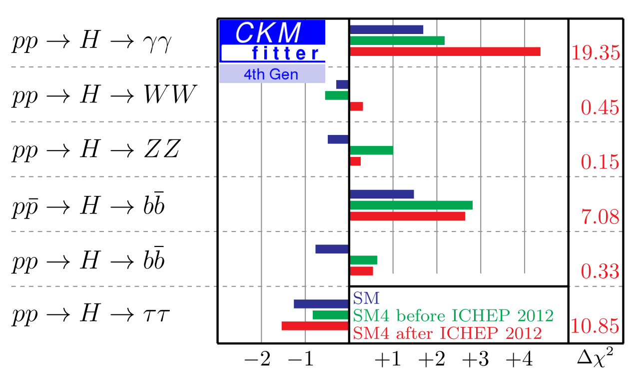

FIG. 3 (color online). Deviations (defined as in Fig. 1) of the Higgs signal strengths for the SM (blue) and for the SM4 (red) at a fixed Higgs mass of 126 GeV. For comparison, the results of the fit to pre-ICHEP2012 data from Ref. [18] are also shown in green. In the right column we show, for the SM4 fit to current data, the change in the minimum χ^2 value when the corresponding signal strength is removed from the fit.

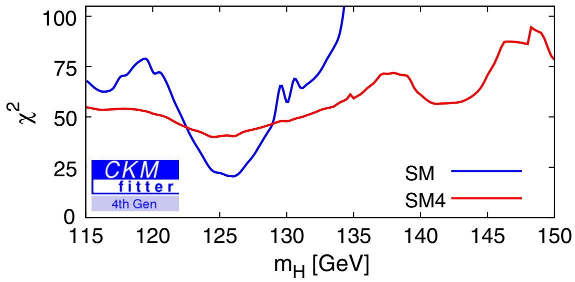

FIG. 4 (color online). Higgs mass scan for the SM (blue line) and the SM4 (red line) based on the input set in the second column of Table I.

Finally, all signal strengths can be suppressed by a common factor if the invisible $H \to \nu_4 \bar{\nu}_4$ decay is kinematically allowed [61–68].

The deviations of the Higgs signal strengths in the SM and the SM4 are shown in Fig. 3. We see that the deviation of the $H \to \gamma\gamma$ signal strength has increased dramatically with the new data and now exceeds 4 standard deviations. Furthermore, the SM4 cannot explain an excess in $H \to b\bar{b}$ searches because the Higgs production mechanisms for these searches are HW and HZ associated production, which are not enhanced by a factor of 9 like the gluon fusion production mode. Thus, the fit improves significantly if the Tevatron measurement of the $H \to b\bar{b}$ signal strength is removed.

Figure 4 shows the minimum χ^2 values in the SM and the SM4 as functions of the Higgs mass. The absolute minimum in the SM4 is at $m_H = 124.5$ GeV and the minimum χ^2 value is larger than the one in the SM by 20 units.

To compute the statistical significance at which the SM4 is ruled out one has to perform a likelihood-ratio test. This task is complicated by the fact that the SM and the SM4 are not *nested*; i.e., the extra parameters in the SM4 cannot be fixed in such a way that all observables assume their SM values. As explained in Ref. [19], analytical formulas for p-values are not valid in this case and one has to rely on numerical simulations. In our analysis we used the improved simulation methods implemented in the *my*Fitter package. For performance reasons, we fixed the SM parameters M_Z, m_t, α_s, $\Delta\alpha_{\mathrm{had}}^{(5)}$, and m_H to their best-fit values in these simulations. This is a valid approximation since the SM4 fit is now dominated by the Higgs signal strengths and their dependence on the SM parameters is negligible. If all inputs are used, the p-value of the SM4 is 1.1×10^{-7} corresponding to an exclusion at 5.3 standard deviations. Without the Tevatron input for $H \to b\bar{b}$ the p-value of the SM4 is 1.9×10^{-6} and the number of standard deviations drops to 4.8. Note that these significances hold for a SM4 with a minimal Higgs sector and may be weakened if the Higgs sector of the SM4 is extended [69–74].

Conclusions.—We performed a combined fit of the parameters of the standard model with three and four generations, combining Higgs search results and electroweak precision data. In the SM electroweak fit, the prediction for the Higgs mass from EWPOs has moved closer to the value favored by direct Higgs searches due to new inputs for m_t and M_W. When the Higgs signal strength inputs are combined with the EWPOs the discrepancy between the measurement of M_W and its best-fit value increases but stays below 1σ. All other deviations are essentially unaffected by the new input.

In the SM4 the measured $H \to \gamma\gamma$ signal strength disagrees with the best-fit prediction by more than 4 standard deviations. Another source of tension is the excess in $H \to b\bar{b}$ searches at the Tevatron in combination with the deficit in $H \to \tau\tau$ events. The dominant Higgs production mechanism for $H \to \tau\tau$ searches (gluon fusion) is enhanced by a factor of 9 in the SM4 while the relevant production mechanism for $H \to b\bar{b}$ searches (HW and HZ associated production) is slightly reduced. The statistical significance at which the SM4 is excluded must be computed by numerical simulation methods like those implemented in *my*Fitter since analytical formulas for p-values do not hold in the case of non-nested models. Using a conservative lower limit of 400 GeV for the fourth-generation quark masses and fixing the SM parameters to their best-fit values we find that the SM4 with a minimal Higgs sector is ruled out at 5.3σ. If the results of $H \to b\bar{b}$ searches at Tevatron are excluded from the analyses, the SM4 is still ruled out at 4.8σ.

We thank Grégory Schott, Johann Kühn, and Jérôme Charles for fruitful discussions. We acknowledge support by DFG through Grants No. NI1105/2-1, No. LA2541/1-1, LE1246/9-1, and No. LE1246/10-1.

*otto.eberhardt@kit,edu
†geoffrey.herbert@physik.hu-berlin.de
‡lacker@physik.hu-berlin.de
§alenz@cern.ch
‖amenzel@physik.hu-berlin.de
¶ulrich.nierste@kit.edu
**martin.wiebusch@kit.edu

[1] F. Abe *et al.* (CDF Collaboration), Phys. Rev. Lett. **74**, 2626 (1995).
[2] S. Abachi *et al.* (D0 Collaboration), Phys. Rev. Lett. **74**, 2632 (1995).
[3] M. Veltman, Acta Phys. Pol. B **8**, 475 (1977).
[4] G. Aad *et al.* (ATLAS Collaboration), Phys. Lett. B **716**, 1 (2012); see also Supplemental Material at https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2012-27/.
[5] S. Chatrchyan *et al.* (CMS Collaboration), Phys. Lett. B **716**, 30 (2012).
[6] Tevatron New Physics Higgs Working Group, CDF Collaboration, and (D0 Collaboration), arXiv:1207.0449.
[7] P. H. Frampton, P. Hung, and M. Sher, Phys. Rep. **330**, 263 (2000).
[8] G. D. Kribs, T. Plehn, M. Spannowsky, and T. M. P. Tait, Phys. Rev. D **76**, 075016 (2007).
[9] B. Holdom, W. Hou, T. Hurth, M. Mangano, S. Sultansoy, and Gokhan Ünel, PMC Phys. A **3**, 4 (2009).
[10] M. S. Chanowitz, Phys. Rev. D **79**, 113008 (2009).
[11] J. Erler and P. Langacker, Phys. Rev. Lett. **105**, 031801 (2010).
[12] O. Eberhardt, A. Lenz, and J. Rohrwild, Phys. Rev. D **82**, 095006 (2010).

[13] M. Baak, M. Goebel, J. Haller, A. Hoecker, D. Kennedy, K. Mönig, M. Schott, and J. Stelzer, Eur. Phys. J. C **72**, 2003 (2012).
[14] A. Djouadi, and A. Lenz, Phys. Lett. B **715**, 310 (2012).
[15] E. Kuflik, Y. Nir, and T. Volansky, arXiv:1204.1975.
[16] O. Eberhardt, G. Herbert, H. Lacker, A. Lenz, A. Menzel, U. Nierste, and M. Wiebusch, Phys. Rev. D **86**, 013011 (2012).
[17] M. Buchkremer, J.-M. Gerard, and F. Maltoni, J. High Energy Phys. 06 (2012) 135.
[18] O. Eberhardt, A. Lenz, A. Menzel, U. Nierste, and M. Wiebusch, Phys. Rev. D **86**, 074014 (2012).
[19] M. Wiebusch, arXiv:1207.1446.
[20] S. Chatrchyan *et al.* (CMS Collaboration), J. High Energy Phys. 05 (2012) 123.
[21] CMS Physics Analysis Summary, Report No. CMS PAS HIG-12-015, http://cdsweb.cern.ch/record/1460419.
[22] G. Aad *et al.* (ATLAS Collaboration), Phys. Rev. D **86**, 032003 (2012).
[23] R. Lafaye, T. Plehn, M. Rauch, D. Zerwas, and M. Duhrssen, J. High Energy Phys. 08 (2009) 009.
[24] A. Azatov, R. Contino, D. Del Re, J. Galloway, M. Grassi, and Shahram Rahatlou, J. High Energy Phys. 06 (2012) 134.
[25] M. Klute, R. Lafaye, T. Plehn, M. Rauch, and D. Zerwas, Phys. Rev. Lett. **109**, 101801 (2012).
[26] D. Carmi, A. Falkowski, E. Kuflik, T. Volansky, and J. Zupan, arXiv:1207.1718.
[27] J. Espinosa, C. Grojean, M. Muhlleitner, and M. Trott, arXiv:1207.1717.
[28] For example, the ratio of the gluon fusion and the vector boson fusion production cross sections is 12.577 at 7 TeV and 12.258 at 8 TeV for $m_H = 126$ GeV.
[29] M.S. Chanowitz, M. Furman, and I. Hinchliffe, Nucl. Phys. **B153**, 402 (1979).
[30] B. W. Lee, C. Quigg, and H. B. Thacker, Phys. Rev. D **16**, 1519 (1977).
[31] A. Djouadi, J. Kalinowski, and M. Spira, Comput. Phys. Commun. **108**, 56 (1998), SM4 contributions implemented since version 4.45.
[32] A. Djouadi and P. Gambino, Phys. Rev. D **51**, 218 (1995); and **53**, 4111(E) (1996).
[33] A. Djouadi and P. Gambino, Phys. Rev. Lett. **73**, 2528 (1994).
[34] G. Passarino, C. Sturm, and S. Uccirati, Phys. Lett. B **706**, 195 (2011).
[35] A. Denner, S. Dittmaier, A. Mück, G. Passarino, M. Spira, C. Sturm, S. Uccirati, and M. M. Weber , Eur. Phys. J. C **72**, 1992 (2012).
[36] C. Anastasiou, R. Boughezal, and E. Furlan, J. High Energy Phys. 06 (2010) 101.
[37] A. Hocker, H. Lacker, S. Laplace, and F. Le Diberder, Eur. Phys. J. C **21**, 225 (2001).
[38] P. Gonzalez, J. Rohrwild, and M. Wiebusch, Eur. Phys. J. C **72**, 2007 (2011).
[39] T. Hahn and M. Perez-Victoria, Comput. Phys. Commun. **118**, 153 (1999).
[40] T. Hahn, Comput. Phys. Commun. **140**, 418 (2001).
[41] T. Hahn and M. Rauch, Nucl. Phys. B, Proc. Suppl. **157**, 236 (2006).
[42] D. Y. Bardin, M. S. Bilenky, T. Riemann, M. Sachwitz, and H. Vogt, Comput. Phys. Commun. **59**, 303 (1990).
[43] D. Y. Bardin, P. Christova, M. Jack, L. Kalinovskaya, A. Olchevski, S. Riemann, and T. Riemann, Comput. Phys. Commun. **133**, 229 (2001).
[44] A. B. Arbuzov, M. Awramik, M. Czakon, A. Freitas, M. W. Grünewald, K. Mönig, S. Riemann, and T. Riemann, Comput. Phys. Commun. **174**, 728 (2006).
[45] S. Dittmaier *et al.* (LHC Higgs Cross Section Working Group), arXiv:1101.0593, updated results at https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt7TeV.
[46] O. Brein, A. Djouadi, and R. Harlander, Phys. Lett. B **579**, 149 (2004).
[47] J. Baglio and A. Djouadi, J. High Energy Phys. 10 (2010) 064.
[48] Publicly available at http://dvegas.hepforge.org/.
[49] N. Kauer and D. Zeppenfeld, Phys. Rev. D **65**, 014021 (2001).
[50] N. Kauer, Phys. Rev. D **67**, 054013 (2003).
[51] ALEPH Collaboration, DELPHI Collaboration, L3 Collaboration, OPAL Collaboration, SLD Collaboration, LEP Electroweak Working Group, SLD Electroweak Group, and SLD Heavy Flavour Group, Phys. Rep. **427**, 257 (2006).
[52] J. Beringer *et al.* (Particle Data Group), Phys. Rev. D **86**, 010001 (2012).
[53] Tevatron Electroweak Working Group CDF Collaboration, D0 Collaboration, arXiv:1204.0042.
[54] Tevatron Electroweak Working Group, arXiv:1003.2826.
[55] T. Aaltonen *et al.* (CDF Collaboration, D0 Collaboration, arXiv:1207.1069.
[56] P. A. Baikov, K. G. Chetyrkin, and J. H. Kuhn, Phys. Rev. Lett. **101**, 012002 (2008).
[57] M. Davier, A. Hoecker, B. Malaescu, and Z. Zhang, Eur. Phys. J. C **71**, 1515 (2011).
[58] Taking into account recently published higher-order corrections for R_b^0 [59] changes the deviation of R_b^0 in Fig. 1 to $+1.2$. The effect on the best-fit parameters is marginal. For instance, the best-fit value of m_t changes to 174.01 GeV.
[59] A. Freitas and Y.-C. Huang, J. High Energy Phys. 08 (2012) 050.
[60] J. F. Gunion, D. W. McKay, and H. Pois, Phys. Rev. D **53**, 1616 (1996).
[61] V. A. Khoze, arXiv:hep-ph/0105069.
[62] K. Belotsky, D. Fargion, M. Khlopov, R. Konoplich, and K. Shibaev, Phys. Rev. D **68**, 054027 (2003).
[63] S. Bulanov, V. Novikov, L. Okun, A. N. Rozanov, and M. Vysotsky, Phys. At. Nucl. **66**, 2169 (2003).
[64] A. Rozanov and M. Vysotsky, Phys. Lett. B **700**, 313 (2011).
[65] W.-Y. Keung and P. Schwaller, J. High Energy Phys. 06 (2011) 054.
[66] S. Cetin, T. Cuhadar-Donszelmann, M. Sahin, S. Sultansoy, and G. Unel, Phys. Lett. B **710**, 328 (2012).
[67] C. Englert, J. Jaeckel, E. Re, and M. Spannowsky, Phys. Rev. D **85**, 035008 (2012).
[68] L. M. Carpenter, arXiv:1110.4895.
[69] S. Bar-Shalom, S. Nandi, and A. Soni, Phys. Rev. D **84**, 053009 (2011).
[70] X.-G. He and G. Valencia, Phys. Lett. B **707**, 381 (2012).
[71] S. Bar-Shalom, S. Nandi, and A. Soni, Phys. Lett. B **709**, 207 (2012).
[72] N. Chen and H.-J. He, J. High Energy Phys. 04 (2012) 062.
[73] L. Bellantoni, J. Erler, J. J. Heckman, and E. Ramirez-Homs, Phys. Rev. D **86**, 034022 (2012).
[74] S. Bar-Shalom, M. Geller, S. Nandi, and A. Soni, arXiv:1208.3195.