Measuring Higgs Couplings from LHC Data

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Following recent ATLAS and CMS publications we interpret the results of their Higgs searches in terms of standard model operators. For a Higgs boson mass of 125 GeV we determine several Higgs couplings from published 2011 data and extrapolate the results towards different scenarios of LHC running. Even though our analysis is limited by low statistics we already derive meaningful constraints on modified Higgs sectors.

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If a scalar Higgs boson [1] exists, it should soon be discovered by ATLAS [2] and CMS [3]. This would finally complete the standard model (SM) of elementary particles at the electroweak scale. Going well beyond an observation of spontaneous symmetry breaking it would establish the fundamental concept of field theories in general and non-Abelian gauge theories in particular.

A minimal Higgs sector with only one physical state predicts all properties of the Higgs boson, except for its mass: all couplings to other particles are proportional to their masses [4–6]. Modifications of any kind typically alter this structure and modify the relative coupling strengths to different fermions and gauge bosons.

One particularly appealing aspect of Higgs physics at the LHC is that it is sensitive to new physics orthogonally to direct searches [7]. First, the dimension-five operators (D5) coupling the Higgs boson to gluons and to photons determine the main Higgs production channel and one of the most promising decay channels [4–6]. New particles coupling to the Higgs boson will contribute to these operators [8]. As an example, chiral fermions do not even decouple, so their contributions to Higgs production strongly constrain the model parameters.

Second, new physics can couple to the standard model through a renormalizable dimension-four operator: a Higgs portal [9]. Typical LHC effects of such a portal include universally reduced Higgs couplings and Higgs decays to invisible particles. Similarly, strongly interacting models in general alter the Higgs couplings reflecting the structure of the underlying theory. Both of these peculiarities of the Higgs sector illustrate the high priority of a general Higgs coupling analysis [10–15].

SFITTER *Higgs analyses.*—The setup for our analysis follows Refs. [10,16]. Any Higgs coupling to SM particles is parametrized as

$$g_{xxH} \equiv g_x = (1 + \Delta_x) g_x^{\mathrm{SM}}. \qquad (1)$$

Independent variations of Δ_γ and Δ_g can be included. Using ratios modified by $(1 + \Delta_{x/y})$ can eventually be useful to cancel theoretical or systematic uncertainties.

The operator form of all couplings is given by the standard model, i.e., the Higgs boson is a parity-even scalar. An observation in the $\gamma\gamma$ channel suggests that we do not have to consider spin-one interpretations [17]. Alternative gauge-invariant forms for example of the WWH coupling ($W_{\mu\nu} W^{\mu\nu} H$) will eventually be testable in weak boson fusion (WBF) [18].

In the absence of a measurement of the Higgs width, which enters any rate prediction, we assume [19]

$$\Gamma_{\mathrm{tot}} = \sum_{\mathrm{obs}} \Gamma_x(g_x) + \text{2nd generation} < 2\ \mathrm{GeV}. \qquad (2)$$

Beyond this upper limit, corresponding for example to $\Delta_b = 28$, width effects would be visible. The LHC will have no sensitivity to the ccH coupling, which contributes to the total width at the level of several percent [4]; we take this into account by linking second-generation Yukawa couplings to their third-generation counter parts, e.g., $g_c = m_c/m_t \times g_t^{\mathrm{SM}}(1 + \Delta_t)$ with an appropriate scale choice in the running masses.

Together with the 2011 results [2,3] we assume: (a) 2011: (5 fb^{-1}, 7 TeV); (b) 2012$_{\mathrm{low}}$: (7.5 fb^{-1}, 8 TeV) ⊗ (5 fb^{-1}, 7 TeV); (c) 2012$_{\mathrm{high}}$: (17.5 fb^{-1}, 8 TeV) ⊗ (5 fb^{-1}, 7 TeV); (d) 2014: (30 fb^{-1}, 14 TeV); (e) HL-LHC: (3000 fb^{-1}, 14 TeV).

We rely on fully correlated experimental and theoretical uncertainties [20–22]. This includes a Poisson shape for counting rates and the centrally flat RFIT scheme for theory uncertainties [23]. For the 7 TeV (and 8 TeV) run we use background rates, efficiencies, and experimental uncertainties as published by ATLAS and CMS [2,3]. For 14 TeV our input is described in Refs. [10,11].

Our analysis starts with a full log-likelihood map of the parameter space. Lower-dimensional distributions we

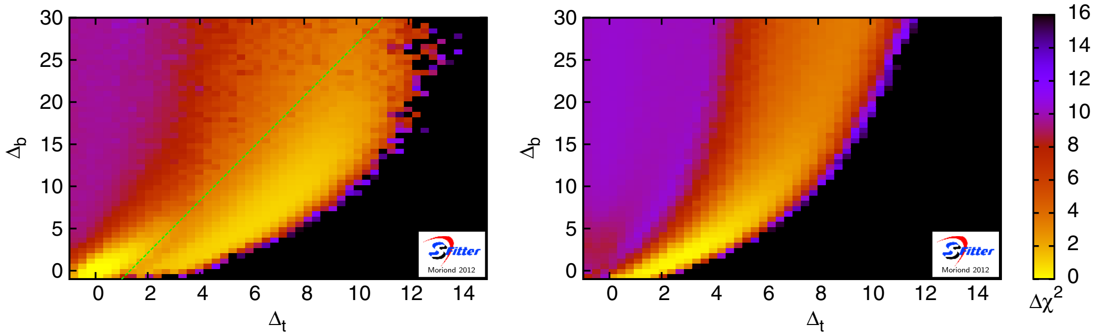

FIG. 1 (color online). Δ_t vs Δ_b for the expected SM measurements (left) and the actual measurements (right), assuming $m_H = 125$ GeV. The diagonal line separates the SM and the large-coupling solutions. For the actual data both solutions overlap.

project using a profile likelihood. The best-fitting parameter points we identify using MINUIT. Finally, we obtain 68% confidence levels from 5000 toy measurements.

2011 fit to standard model.—In a first attempt, we use 2011 data to determine all couplings to heavy standard model particles. The effective Higgs couplings to gluons and photons are limited to SM loops.

To study general features of the Higgs parameter space with the help of a global log-likelihood map, we first assume a set of measurements with the SM expectation as central values, but with the uncertainties of the 2011 data set. For ATLAS and CMS, our 2011 data set includes all $\gamma\gamma$, ZZ, WW, $\tau\tau$, and $b\bar{b}$ channels, separated by the number of recoil jets, if available [2,3]. In the $\gamma\gamma$ channel of CMS we separate the 2-jet mode [24,25]; as in the published results the remaining categories are combined. A separation of the eight inclusive channels into soft and hard $p_{T,H}$ might eventually be beneficial; however, in 2011 weak boson fusion and VH associated production only contributed 10% to 20% to the rate, not giving measurable numbers of events [14].

In the left panel of Fig. 1, we see that two scenarios fit the expected standard model measurements: the SM-like solution only allows for moderate values $\Delta_{b,t} \lesssim 3$. An alternative large-coupling solution appears for a correlated increase of Δ_t and Δ_b towards large values, with a best fit in the $\Delta_{t,b} = 4$–5 range. It reflects a cancellation between the effective ggH coupling (Δ_t) and the total width. To reach this large-coupling regime from the SM-like solution the $H \to \gamma\gamma$ rate has to stay stable, which requires Δ_W to increase with Δ_t. However, the $H \to WW$ measurements do not allow for such a correlation. So when for increasing Δ_b there is a point where Δ_W switches back to the SM regime, Δ_t adjusts the large effective $\gamma\gamma H$ coupling, defining a secondary starting point at $\Delta_t \sim 3$ with a changed sign of g_γ.

For the expected SM central values we can separate the two solutions, as indicated in Fig. 1. In the absence of any $t\bar{t}H$ rate measurement, i.e., for the 7 and 8 TeV runs, we limit our extraction to the SM regime. This restriction is theoretically justified because top Yukawa couplings of $5 \times m_t = 875$ GeV require a UV completion already at the scale of this Yukawa coupling. Nevertheless, we have checked that enforcing the large-coupling regime instead does not pose any technical problems.

In the right panel of Fig. 1, we see that for the actual measurements the two solutions are not separable. This is due to a best-fit value around $g_W \sim 0$, so the effective $\gamma\gamma H$ coupling is always dominated by the top loop.

In Fig. 2, we show the error bars on the best fit values from the 2011 run. Red dots correspond to the expected measurements, fixing $\Delta_x = 0$ but including the correct uncertainties. Typical error bars for many couplings range around $\Delta_x = -0.5\ldots1$, corresponding to a variation of g_x by a factor of two. Forming ratios slightly improves the results. Blue diamonds show the 2011 measurements. As mentioned before, the best fit resides around $\Delta_W = -1$. Because we cannot ignore the large-coupling solution, Δ_b and Δ_t now cover a significant correlated enhancement, inflating the error bars. The best fit at $\Delta_\tau \sim -1$ reflects inconclusive results.

Independently varying Δ_W and Δ_Z will typically lead to a conflict with electroweak precision data. Because the

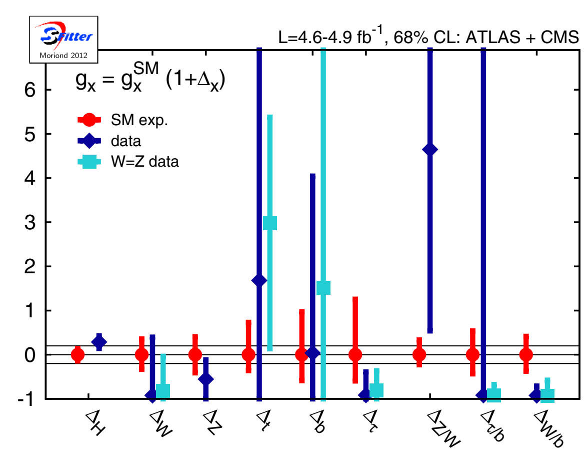

FIG. 2 (color online). Results with 2011 data, for the SM signal expectation and for the data ($m_H = 125$ GeV). For the latter we also show $\Delta_W = \Delta_Z$. The band indicates a $\pm20\%$ variation.

measurements do not include searches for new particles which might compensate for such an offset [15], we cannot include these measurements in our fit. However, we can constrain our fit to $\Delta_W = \Delta_Z$. In Fig. 2, we see that this condition stabilizes the fit, and we get a wide log-likelihood plateau at $\Delta_{W,Z} = -1\ldots0$. However, the large-coupling solution still overlaps with the SM regime.

After confirming that 2011 data have sensitivity to the individual Higgs couplings we can simplify our hypothesis to arrive at tighter constraints. The simplest hypothesis is a universal shift of all Higgs couplings

$$\Delta_x \equiv \Delta_H \quad \text{for all } x. \qquad (3)$$

This form factor could reflect mixing in a Higgs portal or the strongly interacting nature of a composite Higgs boson. The first entry in Fig. 2 shows that the best fit of Δ_H to the 2011 data is at $\Delta_H = 0.28 \pm 0.14$, consistent with zero. Its expected and observed error bars agree. This corresponds to the current local significance of the Higgs hypothesis if we keep in mind that $\sigma \times \text{BR}$ scales like $(1+\Delta_H)^2$. The slightly high value from data is an effect of the overlapping large-coupling solution.

Standard model projections.—In 2012, Higgs analyses will make major progress. Including a significant amount of 8 TeV data will increase the constraining power of WBF processes. Any (close to) 14 TeV run should finally probe the top Yukawa coupling directly, so we can include Δ_γ and Δ_g as independent model parameters.

The 2011 fit shows that the expected and the observed error bars on the Higgs couplings are similar, but that the observed central values lead to problems with a nonseparable large-coupling solution. Because the 2011 data will statistically not dominate the 2012 analysis, we use expected measurements on the standard model values for all projections.

For the 8 TeV results we use the same Higgs channels as have been reported for the 2011 run at 7 TeV, with scaled-up rates and uncertainties. The analysis for 14 TeV collider energy follows Refs. [10,11]. An additional observation of the $t\bar{t}H$, $H \to b\bar{b}$ channel [26,27] could significantly bolster our results.

Fig. 3 shows the measurements we can expect from the near future. Comparing the 2012 expectations with the 2011 results shown in Fig. 2, we see that $\Delta_{W,Z}$ [28] and Δ_τ [29] benefit from enhanced WBF production channels. The couplings to heavy quarks can only really be probed once we include the full set of 14 TeV channels with $t\bar{t}H$ production and $H \to b\bar{b}$ decay channels [26,27]. The direct measurement of all SM Higgs couplings then allows us to not only probe the structure of the Higgs sector but also search for new physics effects in the effective couplings g_g and g_γ. Error bars in the 20% range for both of these higher-dimensional operators can strongly constrain any new particles which either rely on the Higgs mechanism for their mass generation or couple to scalars like the Higgs boson.

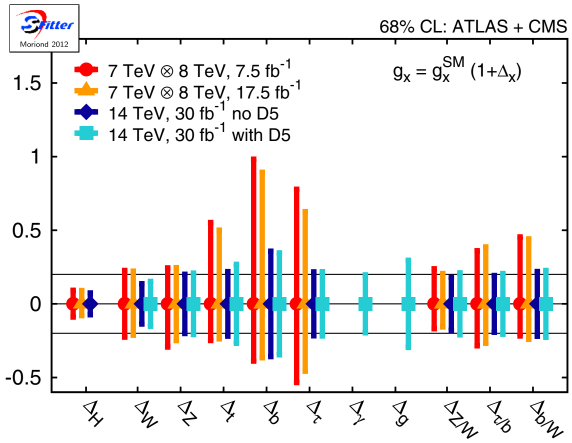

FIG. 3 (color online). Projections for an assumed SM signal at $m_H = 125$ GeV. The band indicates a $\pm20\%$ variation.

Finally, in Fig. 4 we show the dependence of some expected error bars on the Higgs mass. Again, we assume standard model measurements and quote errors for 2011 and for a very rough HL-LHC extrapolation. For the 2011 results we see that $m_H = 125$ GeV is indeed a particularly lucky spot. Taken with the appropriate grain of salt the HL-LHC projections show a very significant improvement, but the naive statistics-dominated scaling with luminosity does not apply any longer.

Exotic hypotheses.—Until now we have limited our fit to the extraction of SM-like couplings. Given their good agreement with 2011 data and the lack of hints for new physics at the LHC, this hypothesis is well motivated. Modest deviations from a standard model Higgs sector include either supersymmetric or more general type-II two-Higgs-doublet models, as well as form factors or mixing angles affecting the Higgs couplings in a more or less constrained manner.

More exotic Higgs hypotheses illustrate the statistical limitations of the 2011 measurements. Ignoring obvious problems with the UV completion of such models we interpret the 2011 measurements in terms of a fermiophobic and a gauge phobic Higgs model [30]; i.e., we assume that an observed 125 GeV resonance only couples to gauge bosons or to fermions. For each model we compute the best $\chi^2 = -2\log L$ value:

Hypothesis	χ^2_{2011}/dof
Independent Δ_Z	9.3/22
$\Delta_W = \Delta_Z$	12.3/23
$\Delta_W = \Delta_Z$ and $\Delta_b = \Delta_t = \Delta_\tau$	18.0/26
$\Delta_x \equiv \Delta_H$	18.6/26
Gaugephobic	13.2/25
Fermiophobic	16.0/25

The set of SM-like free couplings gives an excellent fit. The good performance for a Higgs boson only coupling to

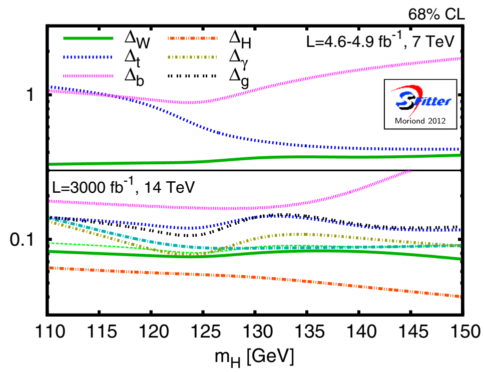

FIG. 4 (color online). Error bars for an assumed SM signal as a function of the Higgs mass for 2011 data (top) and the HL-LHC with 14 TeV and 3000 fb^{-1} (bottom).

fermions is based on effective Higgs couplings to gluons and photons all generated by heavy fermions. Only the $H \to ZZ$ channel implies a slight statistical price to pay.

The fermiophobic Higgs hypothesis is more of a challenge, because WBF and VH are the only production channels. All relevant branching ratios grow as g_b vanishes. In addition, g_γ increases without the destructive interference between the W and top loops. The best-fit point lies in the neighborhood of $\Delta_W \sim -0.8$ and $\Delta_Z \sim 0$. For example in the $H \to ZZ$ channel WBF and ZH production are roughly equal and get combined with a branching ratio around 75%. The observed WW channel still forces g_W to be small, so too few photon events are predicted for a perfect fit. We note, however, that 2011 data are too scarce to meaningfully distinguish between all these hypothesis.

Outlook.—In this comprehensive Higgs coupling analysis we show that the published ATLAS and CMS measurements are well explained by a standard model Higgs boson. The reason that the 2011 coupling measurements are weaker than the expected results is a secondary large-coupling solution which cannot be separated. A universal Higgs form factor Δ_H can be determined with a 15% precision and is in good agreement with unity [32].

In the future, major improvements of the Higgs coupling measurements will be an increased sensitivity to WBF production processes and the direct measurement of the heavy quark Yukawa couplings in $H \to b\bar{b}$ decays or $t\bar{t}H$ production. Unfortunately, the Higgs self-coupling is still an unsolved problem for $m_H \sim 125$ GeV [31].

The LHC projections presented in this Letter might well serve as part of the scientific case for a future Linear Collider Higgs factory.

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Note added.—After completion of this study ATLAS and CMS announced a Higgs discovery around 126 GeV. Qualitatively, the conclusions of this Letter are unchanged. An update of the results shown here will be available soon [32].

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[32] Frequent theory-only updates of some figures in this Letter can be found under http://www.thphys.uni-heidelberg.de/~plehn.