LHC: Standard and Hidden Scalar Bosons

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Using recent ATLAS and CMS publications on Higgs boson searches we interpret these results in terms of coupling strengths of a Higgs boson possibly existing at a mass of 125 GeV. Extrapolations to different stages of future LHC running are presented as well. We also consider how hidden scalar bosons are affected by these searches.

1 Introduction

The scalar Higgs boson [1] is the last missing particle predicted by the Standard Model (SM). If it exists in nature, evidence of it should soon appear in the measurements of the two LHC experiments ATLAS [2] and CMS [3]. This would then complete our understanding of electro-weak symmetry breaking.

Interactions with the massive gauge bosons W and Z are generated automatically by the kinetic term of the Higgs field, while those with fermions have to be added explicitly via Yukawa-type terms. The mass terms of all massive particles originate from these, when the Higgs field is replaced by its vacuum expectation value (vev). This implies in turn that the coupling of the Higgs boson to all other particles can be predicted by the measured masses and the vev.

The only unknown parameter in the SM is the mass of the Higgs boson. Searches by LEP [4], the Tevatron experiments D0 and CDF [5], and in particular ATLAS [2] and CMS [3] have excluded large parts of the parameter space, leaving for a SM-like Higgs boson only a small region around 125 GeV.

Due to the predicted proportionality of the couplings to the masses of the particles, in measuring the Higgs couplings one is sensitive to effects from new physics [6]. The main Higgs production channel, gluon-fusion, as well as a very sensitive decay mode, namely into photons, are both loop-induced [7]. New particles occurring in beyond the Standard Model theories could modify these couplings, which are described by dimension-five operators (D5) [8]. Another possibility to modify Higgs couplings by renormalizable dimension-four operators is a Higgs portal [9,10,11]. This would results in Higgs couplings which are reduced by a global factor, and possibly also invisible decays into a hidden sector. Furthermore, a second Higgs boson will be present, which can be searched for. These features demonstrate the importance of studying the Higgs couplings [12,13,14,15,16,17,18].

2 Calculational Setup

As underlying model we assume the Standard Model with a generalised Higgs sector, i.e. the couplings of the Higgs to other particles are free and can take arbitrary values. We only consider those couplings accessible during the early running of the LHC, namely to the gauge bosons W

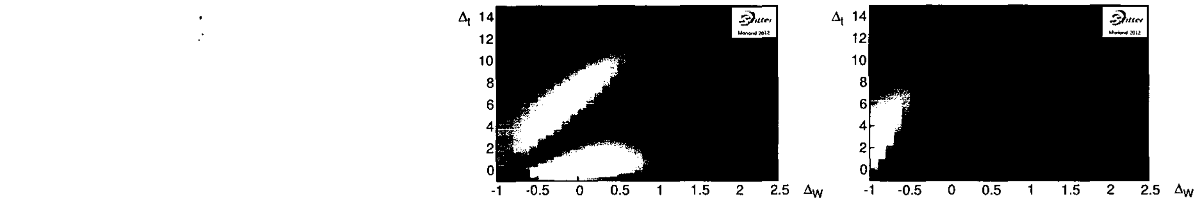

Figure 1: Δ_W vs. Δ_t for the measurements with expected SM rates *(left)* as well as the actual ones *(right)* for an assumed Higgs mass of 125 GeV. Two distinct solutions are observed, one with SM-like couplings and one with large Δ_t. For the actual data the two solutions overlap.

and Z and the third-generation fermions. The deviations of the couplings are parametrised as following:

$$g_{xxH} \equiv g_x = g_x^{\rm SM}(1+\Delta_x) \quad x \in \{W, Z, t, b, \tau\} \ . \tag{1}$$

Changes to the loop-induced couplings to photons and gluons are induced by corresponding changes in the tree-level couplings $\Delta_x^{\rm SM}$. For the LHC running at 14 TeV we also allow for additional contributions from dimension-five operators Δ_x, leading to

$$g_x = g_x^{\rm SM}(1+\Delta_x^{\rm SM}+\Delta_x) \quad x \in \{g, \gamma\} \ . \tag{2}$$

Correspondingly, modifications of coupling ratios are defined as $\frac{g_x}{g_y} = \frac{g_x^{\rm SM}}{g_y^{\rm SM}}(1+\Delta_{x/y})$. A single parameter modifying all Higgs couplings by the same factor is denoted by Δ_H. The discrete quantum numbers are those of the SM Higgs, i.e. we consider only a CP-even scalar particle. As the Higgs width is too small to be measurable at the LHC, we assume

$$\Gamma_{\rm tot} = \sum_{\rm obs} \Gamma_x(g_x) + \text{generation universality} < 2 \text{ GeV} \ , \tag{3}$$

the upper limit, corresponding to $\Delta_b \simeq 28$, given by the experimental resolution where width effects would become visible. The assumption about generation universality is important, as the Higgs has for example a significant branching ratio into charm quarks, which will not be measurable at the LHC. Hence, we assume that these couplings are modified in the same way as its third-generation counterparts, c.g. $g_c = \frac{m_c}{m_t} g_t^{\rm SM}(1+\Delta_t)$ with appropriate scale choices for the running quark masses.

For correct results a proper treatment of all errors is important. The statistical uncertainties of rate measurements are of Poisson type. For systematic uncertainties we implement the full correlation matrix between different measurements. Theory uncertainties are centrally flat following the RFit scheme [19]. SFitter [20] provides a fully exclusive log-likelihood map, which is projected into lower dimensions using profile likelihood. Parameter distributions are obtained with cooling Markov chains and the best-fitting points are derived from those after an additional MINUIT step. The 68% CL errors on couplings we infer from 5000 toy measurements.

3 Visible-Higgs results

First, we present results based on the published 2011 measurements. Besides the actual data we also show expectations for the SM hypothesis, where we have injected a SM-strength signal on top of the expected backgrounds. In Fig. 1 we show the profile log-likelihood plot for Δ_W vs. Δ_t. For the SM expectation on the left-hand side we observe two distinct solutions. One corresponds to the SM one centred around $\Delta = 0$. The second one, with $\Delta\chi^2 = 0.86$, has an enlarged top Yukawa coupling. This results in a sign flip of the photon coupling, which is not

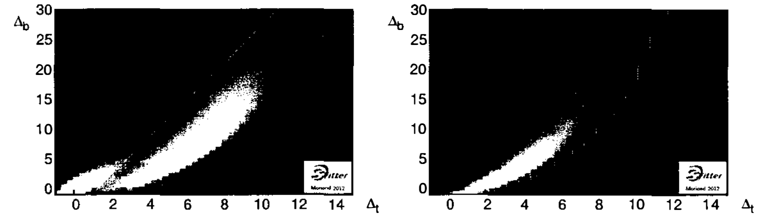

Figure 2: Δ_t vs. Δ_b for the measurements with expected SM rates *(left)* as well as the actual ones *(right)* for an assumed Higgs mass of 125 GeV. The dotted green line in the left plot separates the SM-like solution and the large-coupling solution. For the actual data no such split is possible. Figures taken from Ref. [18].

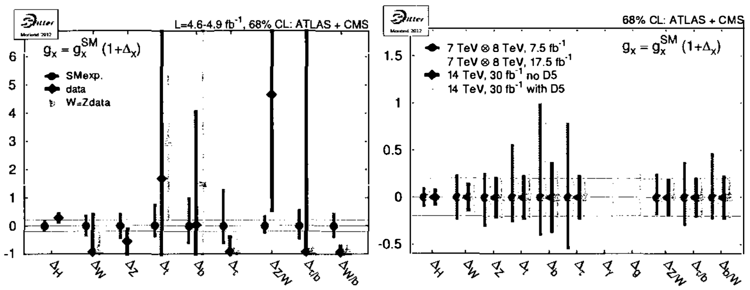

Figure 3: *Left:* Results with 2011 measurements for data and SM expectation, the latter limited to the SM-like solution. For the data we also present results with $\Delta_W = \Delta_Z$. *Right:* Extrapolations for the SM hypothesis assuming different scenarios of LHC running. Both cases assume $m_H = 125$ GeV. The band indicates a variation of $\pm 20\%$. Figures taken from Ref. [18].

observable, however. The large top coupling enhances the rate of all gluon-fusion channels. This is then counter-balanced by increasing Δ_b, which through its large contribution to the total width reduces all branching ratios, as can be seen on the left of Fig. 2. The secondary solution requires a large bottom coupling, which is clearly correlated with the top one. Both couplings are adjusted in such a way that the total rate in the $\gamma\gamma$ channel stays unchanged. This will then lead to a mismatch in the processes with other production modes. These channels are not yet sensitive enough to introduce a large penalty in the log-likelihood, though. Both solutions can be separated by a cut in the Δ_t-Δ_b-plane as indicated by the dashed green line in Fig. 2. The best-fit point of the secondary solution is located at $\Delta_{t(b)} = 5.2(3.7)$.

On the right-hand side of Figs. 1 and 2, the log-likelihood maps are shown for the actual measurements. As the $H \to WW$ channels force g_W to very small values, the photon coupling is always dominated by the top loop. To obtain the correct event rate in the $\gamma\gamma$ channel, this has to be large. Therefore, the distributions resemble those of the secondary SM case. A separation of the two possibilities cannot be performed any longer.

In Fig. 3 we show the best-fit point as symbol together with its corresponding 68% CL error bar for different assumptions on signal input and LHC running. The left-hand side is based on the 2011 data. SM expectations, limited to the primary solution, are plotted in red with dots. The typical size of errors corresponds to a factor 2 variation on g_x, with ratios slightly improving the results. Blue diamonds represent the actual measurements. The best-fit point for g_W is close to zero. Due to the large-coupling preference, the errors on top and bottom quark couplings are greatly enhanced. For the data we also present results where Δ_W and Δ_Z have been set equal, inspired by the approximate custodial symmetry observed in electroweak precision tests.

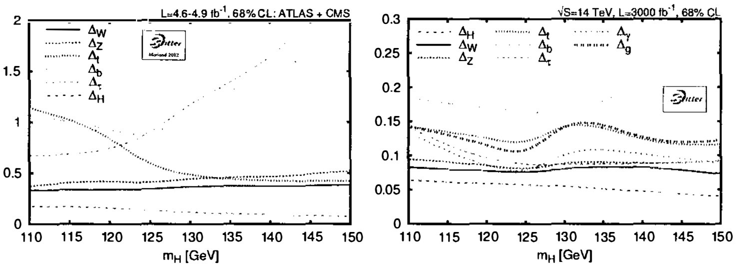

Figure 4: Dependence of the expected coupling errors on the Higgs mass for an assumed SM signal with 2011 luminosity *(left)* and for the HL-LHC with 14 TeV and 3000 fb^{-1} *(right)*.

As effects from new particles might cancel deviations [17], we cannot use these directly. We see that the fit is stabilised. The best-fit point for the common coupling still prefers a rather small value, but the distribution now shows a fairly wide log-likelihood plateau stretching from $\Delta_{W=Z} = -1 \ldots 0$. On the right-hand-side of Fig. 3 we present extrapolations for future LHC running. The SM hypothesis is taken as input, as future data will statistically dominate the combination with the 2011 results. For the 8 TeV runs we use a blind extrapolation of the 2011 measurements, adjusted for the increased energy and the higher integrated luminosity. The 14 TeV results follow Refs. [12,13]. We observe an increase in the precision of all couplings, as expected from the higher statistics available. Measuring the top Yukawa coupling precisely requires to look at the $t\bar{t}H$ production channel. The most likely possibility for such a measurement is combining it with decays into bottom quarks, possibly using subjet techniques [21]. This channel then also allows us to disentangle changes in g_t from new particles contributing to the effective couplings g_g and g_γ. The latter can be determined at the 30% and 20% level, respectively, for 14 TeV running with a luminosity of 30 fb^{-1}.

Finally, in Fig. 4 we present the Higgs mass dependence of the errors for the SM hypothesis. On the left, the results for 2011 luminosity show that a 125 GeV Higgs would be a very lucky spot. The rise in the top Yukawa error for smaller masses happens because it is largely dominated from gluon-fusion production with decay into WW. This channel quickly looses sensitivity as the final-state leptons become too soft. For larger masses the branching ratios into τ and bottom quarks drop and decrease the corresponding rates. On the right, we show the same plot for a high-luminosity LHC, assuming 3000 fb^{-1} of luminosity collected at 14 TeV. Such a large extrapolation should be taken with the appropriate grain of salt. We observe a significant improvement for all couplings, but a naive statistics-induced scaling does not hold any longer. The precision on the single-parameter modifier Δ_H for example is predominantly limited by the theory error on the Higgs production channels.

4 Higgs Portal

In new-physics models, where the Higgs doublet mixes with a hidden sector, Higgs decay into the hidden sector and therefore into invisible particles can become possible. We parametrise these via a Higgs portal [9,10,11], where the hidden sector is a singlet under the SM gauge groups. Then, the only possible connection to SM particles is via a term $\Phi_s^\dagger \Phi_s \Phi_h^\dagger \Phi_h$, which connects the standard Higgs field Φ_s and the hidden one Φ_h. After electro-weak symmetry breaking, both fields obtain a vev. Both Higgs bosons mix and need to be rotated into mass eigenstates by a rotation matrix with angle χ. Then all cross sections and partial widths get changed by a factor $\cos^2\chi$ for H_1 and $\sin^2\chi$ for H_2. Additionally, decays into the hidden sector are possible.

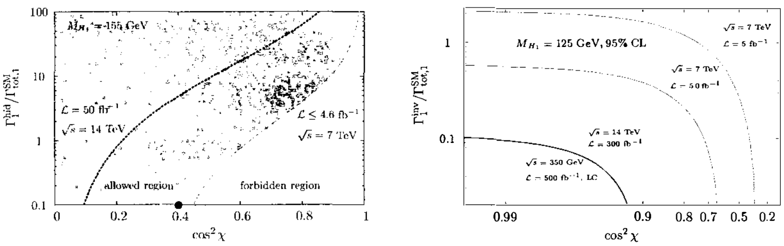

Figure 5: *Left:* Bound on the mixing and hidden decay width of H_1 for $M_{H_1} = 155$ GeV; $\mathcal{R} = 0.4$. Small squares denote points compatible with unitarity and precision measurements. The dot indicates the limit of the exclusion curve at $\mathcal{R}$ for $\Gamma_1^{\rm hid} \to 0$. *Right:* Projections of the obtainable precision at 95% CL for different scenarios of LHC running as well as a future linear collider assuming the SM. Figures taken from Refs. [10,11].

Its partial widths depend on the structure of the hidden sector, and for lack of any knowledge about it are free parameters. Furthermore, decays $H_2 \to H_1 H_1$ might be kinematically allowed.

On the left-hand side of Fig. 5, we show the allowed range in the $\cos^2\chi$-$\Gamma_1^{\rm hid}/\Gamma_{\rm tot,1}^{\rm SM}$-plane for a hypothetical H_1 boson with 155 GeV mass, illustrated using the observed exclusion limit $\mathcal{R} = 0.4$ at this mass point. The squares, which fill almost the entire grey area, denote points compatible with unitarity and precision measurements. Hence, there is still a large area of the portal parameter space available, which can accommodate the current experimental results.

Looking into the future, a direct measurement of the invisible branching ratio might become available at the LHC [22], and will be possible at a future linear collider [23]. Now looking at a 125 GeV Higgs and assuming it is SM-like, we can ask how compatible are the experimental observations with the SM. The remaining area is plotted in Fig. 5 on the right. Besides different LHC scenarios we also show 95% CL expectations for the linear collider, which will leave only a very small region of the portal parameter space.

5 Conclusions

Published results by ATLAS and CMS allow us to determine Higgs couplings under the assumption that a 125 GeV Higgs boson exists. The results are compatible with the Standard Model expectation, but the error bars are enlarged, as a secondary large-coupling solution is preferred by the data. Furthermore, extrapolations for future LHC running were presented. At a HL-LHC the precision for a global coupling-strength modifier will be limited by the theory error on the Higgs production modes.

We also investigated how a Higgs portal model can partly evade the experimental bounds due to invisible decays. Future data, in particular from a linear collider, will strongly narrow the portal parameter space.

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