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The Higgs Top Interface

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After some recollection of the implications that top quark and Higgs boson properties determination have had on each other, we discuss recent and future expected progress in the study of the top-Higgs sector. In particular we discuss some results concerning new physics states interacting with the top-Higgs sector, the impact of measuring top-Higgs interactions accurately to determine the Higgs boson self interaction, the CP nature of the Higgs boson and possible detection of flavor violating interaction at levels comparable with the prediction of viable new physics models.

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1 Introduction

Top quarks and Higgs boson interact in the Standard Model via Yukawa interactions; this is, literally speaking, the top-Higgs interface. Its nature is still largely unknown, though current experiments have started to probe it and future ones promise to do so with a finer level of detail.

Basic issues about this interaction have to do in part with fingerprinting the objects that participate to it, and in part with the understanding of the origin of this interaction *per se*. Remarkably, at the top-Higgs interface it is possible to probe the nature of the Higgs boson in a new way, independent of the many tests performed so far in Higgs boson studies carried out at the LHC. Properties of the Higgs boson such as its CP-nature may be probed in new ways. The gauge charge of the fields that gives rise the physical Higgs boson can be probed as well. Furthermore it is possible to explore the nature of the top quark, which may be the first quark to show signs of compositeness, that is to say to not be a point-like field, and its size can be established through the magnifying glass of the Higgs boson probe.

In addition, the UV origin of the top-Higgs Yukawa interaction needs to be established in order to claim some satisfactory degree of understanding of the Standard Model as a whole. A key question on the nature of the top-Higgs Yukawa interaction has to do with it being a marginal coupling, or having a steeper RG-flow at higher energy scales. For what we know this interaction may originate from a contact interaction involving more than one scalar, possibly related to the dynamics of flavor, or even be a low energy artifact from a more complete theory in which the Yukawa is a relevant interaction only at the long length-scales we currently probe in our still too-low energy experiments.

In addition to this "physical" connection, the Higgs boson and the top quark have an intertwined history, due to the strong theoretical relation that arises in the Standard Model between these two particles. For instance, the effect of the mass of one particle in radiative corrections to the mass of the other made possible to predict, in the pure Standard Model, where the Higgs boson mass would be within about 10% accuracy. Similarly, today, with the Higgs boson mass measured at few parts per one thousand, the top quark mass can be extracted from the rest of the parameters of the Standard Model to an accuracy that competes with the that of best direct measurements of today. The pretty consistent picture that emerges from this test of the Standard Model prediction is already putting bounds on generic new physics entering in radiative corrections and therefore affecting indirectly some measured quantities.

On top of this probe of generic new physics, the top-Higgs interface motivated deep questions on the validity of the Standard Model as ultimate theory of Nature, valid up to the shortest length-scale. On a very concrete ground the Higgs-top interaction may modify the Higgs boson potential to such a large extent that the potential may develop

new minima at field values much larger than the ones at which it has condensed in the Standard Model, implying a drastic change for our picture of fundamental interaction and possibly changing the history of the Universe, both in its early phase, where these large field values may be easily attained, or in the future, when our ground-state, if meta-stable, may tunnel to the true energy minimum of the theory, erasing the Universe as we know it.

On a possibly more philosophical level the Higgs-top interaction has raised questions about the possible sensitivity of weak interactions to details of the UV theory valid at the shortest-distances. The structure of the Standard Model seems to open the door to a possible hyper-sensitivity to microscopic changes in the short-distance degrees of freedom. Such a sensitivity would defy the common sense of decoupling of length-scales that lies at the foundation of the effective field theory paradigm on which we rely to apply quantum field theories to the natural world. The exploration of the top-Higgs interface, and of the extensions of the Standard Model that it has motivated, is a key tool to understand if decoupling of length-scales applies for weak interactions at the shortest distances we explore in high-energy physics.

2 Recent and future highlights

The discovery of the Higgs boson has provided already a number of tests of the structure of the Standard Model and constraints of its possible extensions. Precise measurements of the mass as well as the rates in each decay channel of the Higgs boson provide stringent bounds on new physics, or, looking from a different angle to these measurements, can provide hints on where to find new physics if it is out there.

2.1 Probes from the Higgs boson mass and inclusive rates

Extensions of the Standard Model that prevent TeV-scale physics to depend strongly on the dynamics of far higher energy scales usually have the property of being able to compute the Higgs mass as a function of few parameters of the theory. These parameters include those of the Standard Model and few extra ones, which also affect other measurable quantities. An example is the case of the MSSM in which the Higgs boson mass can be computed once the properties (masses and mixings) of the scalar top and bottom partners are known. As shown in Ref. [1], the values of the Higgs boson mass considered in the time between the validation of the SM at LEP and the discovery of the Higgs boson were significantly smaller than what observed. Plots from Ref. [1] indeed fall one GeV shorter than the measured value, but can be easily extrapolated (or one can look at post-discovery references such as Ref. [2]). In these plots one can see how the measured value of the Higgs boson mass, 125 GeV, cannot be accommodated in the MSSM unless the scalar top quarks are above

1 TeV, no matter what other MSSM parameters we pick. In view of this observation it appears not surprising at all that we did not find any sign of new states so far at the LHC. The mass range hinted by the value of the Higgs boson mass for where to find new scalar top quarks is just now being probed, with first exclusions of scalar top and bottom quarks masses extending above 1 TeV. It is remarkable that, at least under the assumption of a Higgs-top interface à la MSSM, the mere knowledge of the Higgs boson mass has preempted direct searches for scalar top quarks. Equally interesting is the fact that for the Higgs mass to match the observed one the mixing in the scalar top sector has to be picked in a somewhat special value. This defines some kind of "sweet spot" for the MSSM after the discovery of the Higgs boson and the measurement of its mass that has the lightest possible physical scalar top quark masses $m_{\tilde{t}_1} \sim m_{\tilde{t}_2} \simeq 1.5$ TeV and the mixing angle being large, $X_t/m_{\tilde{t}} \simeq \pm\sqrt{6}$ in the notation of Refs. [1, 2] and references therein. It is remarkable that this choice of large mixing is also approximatively the choice that makes any virtual effect of scalar tops almost disappear from the production cross-section of the Higgs boson in gluon fusion process at the LHC. Indeed computing the combined effect on gluon-Higgs and photon-Higgs boson couplings one can see that in the MSSM for $m_h \simeq 125$ GeV the total rate $gg \to h \to \gamma\gamma$ varies at most by around 5% with respect to the SM value [2]. This level of deviation from the SM in the Higgs couplings measurements is in the domain of LHC sensitivity [4] and is therefore a valuable observable to test the Higgs boson, the top quark and the potential existence of a larger sector of states that interact primarily with them. Future collider facilities under discussion in these days have all a rich Higgs boson program and promise to have an even finer control on the property of the Higgs boson, which may reveal, or put strong constraints on, new physics in the top-Higgs sector.

2.2 Direct access to the top quark Yukawa coupling and implications

Direct observations of the $pp \to t\bar{t}h$ reaction has given a direct measurement of the top quark Yukawa at the LHC. This opens up a new way of exploring new physics. In fact with this measurement it is possible to put the computation of Higgs main production $gg \to h$ on a firmer ground. The gluon-Higgs boson coupling depends linearly on the top Yukawa couplings. This implies that a direct knowledge of the latter allows to measure all independent combinations of couplings of the SM in the Higgs-top sector - hence giving a chance to constrain contributions to the $gg \to h$ process from physics beyond the Standard Model. A similar disentanglement of effects takes place in the photon-Higgs boson coupling. Putting these effects together allows to constrain generic new physics particles affecting the Higgs boson loop level couplings. In Ref. [3] these bounds have been computed, devoting also some attention to the cases in which they can be avoided by judicious choices of other parameters, such as the mixing

between pairs of BSM states contributing to the Higgs boson loop couplings. As we have seen for the case of the MSSM, dismissing choices of parameters as "ad-hoc hence uninteresting", may be too quick a judgement as they may be motivated by other considerations and convenient also to explain other aspects of the Higgs boson physics. However, if one takes the route to ignore these peculiar regions of parameter space, it is possible to draw conclusions and exclude the existence of new particles in the Higgs-top sector. These bounds rely crucially on the knowledge of the top quark Yukawa, hence they demand the best possible accuracy in the measurement of the tth cross-section at the LHC and motivate further efforts in future collides to pin down the Yukawa coupling of the top quark as precisely as possible. By the end of the HL-LHC we expect that these bounds may be sensitive to scalar stops lighter than 500 GeV, independently of how it decays, for a top quark Yukawa measured within around 10%, fully in the reach of HL-LHC [4].

The top quark Yukawa is one of the several couplings of the Standard Model that affects double Higgs boson production. The dependence of the rate on the top quark Yukawa and relevant effective couplings of an effective theory for the SM up to dimension-6 operators is reported in Refs. [5, 6]. The joint study of double Higgs production, top-Higgs boson associated production $t\bar{t}h$, and single Higgs boson production rates allows to constrain simultaneously three effective couplings and in particular those that result in modified Higgs boson self-interaction. The impact of the error on the effective coupling entering the $t\bar{t}h$ process has been studied in Ref. [5], where it is shown that Higgs self-coupling constraints can improve by a factor around 2 thanks to the improvements on the top-Higgs interactions coming from direct observation of the $t\bar{t}h$ process.

The nature of the top-Higgs coupling is also a very sensitive probe of CP properties of the Higgs boson. While these are tested already in other processes such as Higgs boson decays to vector bosons, it should be stressed that in concrete models the effects of CP-mixing may be enhanced in fermionic interactions and in particular there might be effects that depend on the flavor of the fermion. A concrete example of this type of scenario is the model for baryogenesis discussed in Ref. [7]. Future HL-LHC sensitivity to CP-odd components of the Higgs boson is discussed in Ref. [8], which shows how kinematical variables of the $t\bar{t}h$ final state can be exploited to attain bounds on mixing angles larger than $\cos\alpha \simeq 0.5$, which are interesting for the generation of the baryon number of the Universe in models such as that discussed in Ref. [7].

2.3 New processes with top quarks and Higgs bosons

It is worth recalling new processes that may involve the top quark and an extended Higgs sector, such as those predicted by non-minimal models of composite Higgs scenarios. One interesting example is the possible decay of the top quark in light flavor quarks, e.g. a charm quark, and new Higgs bosons, $t \to \phi c$. This process

has been studied in Ref. [9] which finds that HL-LHC can be sensitive to branching fractions of order 10^{-4}. Remarkably this level of branching ratio is compatible with the expectation in concrete models, thereby offering a chance to test flavor violation in top quark decay, which instead turns out to be very challenging for h, Z, and γ final states of top decays.

Also non-standard final states such as $pp \to th + X$ offer interesting possibilities to study more closely the top-Higgs interface. For instance the thW and thq rates are sensitive to interference effects among SM amplitudes that entails some sensitivity to the sign of the top quark Yukawa coupling relative to the Higgs-Vector bosons couplings [10, 11, 12] and has lead to conclusive exclusion of the hypothesis $y_t = -y_{t,SM}$[14, 13].

3 Conclusions

The top quark and the Higgs boson are two pillars of the Standard Model and have only been studied so far at a very coarse level. These studies are nonetheless already yielding interesting conclusions on the validity of the SM and posing constraints on the existence of new physics. In some scenarios these results, e.g. the mass measurement and the rate measurements of the Higgs boson, especially when combined, suggest that new physics may be sitting at the TeV scale though has properties that make it appear elusive in Higgs physics, but not necessarily so in direct searches.

Other examples of important lessons that will be made sharper by sharpening our knowledge of the top-Higgs coupling have been presented and include the possible constraints on Higgs self-interactions, the CP nature of the Higgs boson, possible links between the top-Higgs sector and flavor violation.

From this vast range of possible BSM scenarios to which the top-Higgs sector is sensitive, it seems natural to argue that, whatever the nature of the new physics, any improvement on the knowledge of Higgs and top properties will teach us a lot on the SM and its possible extensions. Indeed in many respects the top-Higgs sector is the cornerstone of the SM, but its study is only at the beginning and we need to get a more fine picture of these two particles and their interactions. Therefore it appears very well motivated to pursue a strong program towards the realization of future colliders that can study the top quark and the Higgs boson producing and detecting them in copious number.

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