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Theory News Higgs

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I review new developments in Higgs physics, with a focus on Yukawa couplings in and beyond the standard model. In particular, I discuss different methods of measuring the light Yukawas, new sources of CP violation in the Higgs sector, and lepton flavor violation.

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1. Introduction

The Higgs boson plays a central role in the standard model (SM): On the one hand, the Higgs mechanism spontaneously breaks the electroweak gauge symmetry, providing mass terms for the W and Z bosons and unitarizing gauge boson scattering amplitudes at energies beyond the electroweak scale. On the other hand, it sets the scale for the fermion masses via the Yukawa interactions.

With the measurement of the Higgs mass, all SM parameters are fixed; in particular, all Higgs couplings are determined. This opens a window to new physics (NP) via the precision measurement of these couplings. For instance, the SM Yukawa couplings are real and diagonal; any deviation would be a clear sign of NP.

While the Higgs couplings to heavy particles seem to agree reasonably well with SM predictions [1], we know much less experimentally about the couplings to the light fermions. A simple understanding of how we can change the Yukawa couplings can be obtained by parameterizing NP contributions in terms of higher-dimensional operators. The terms $y_t(\bar{Q}_L t_R H^c) + \text{h.c.}$, for instance, lead to the top-quark mass $m_t = \frac{y_t v}{\sqrt{2}}$ and the corresponding top-Higgs Yukawa coupling $\frac{y_t}{\sqrt{2}}$. Consider now the contribution of a dimension-six effective operator of the form $\frac{H^\dagger H}{\Lambda^2}(\bar{Q}_L t_R H^c) + \text{h.c.}$ to the SM Lagrangian. (You could think of the scale Λ as the mass of a heavy vector-like fermion that has been integrated out.) This operator will lead to additional contributions to the top-quark mass $\delta m_t \propto \frac{(v/\sqrt{2})^3}{\Lambda^2}$ and Yukawa coupling $\delta y_t \propto 3\frac{(v/\sqrt{2})^2}{\Lambda^2}$. The relative factor of 3 between the two new contributions breaks the strict alignment of mass terms and Yukawa couplings in the SM. This will lead to off-diagonal and, potentially, imaginary contributions to the Yukawa couplings after rotating to the mass eigenstates, signalling the presence of flavor-changing neutral currents (FCNC) and CP violation.

2. Size of Yukawa Couplings

I will first discuss the prospects of measuring the Yukawa couplings, in particular, to the light fermions. Are there NP models that can lead to substantial deviations in the Yukawa couplings? One model that can enhance the light Yukawas by factors of order ten was given by Giudice and Lebedev [2]. While the simplest version of this model is already excluded by the measurement of the partial decay width of the Higgs into bottom quarks, a modified version employing a Two-Higgs-doublet model is still viable [3] (see also [4]). For the opposite scenario with vanishing light Yukawa couplings see, e.g., [5].

Measuring the Yukawa couplings to light fermions with processes involving off-shell Higgs bosons is extremely difficult, as the neutral Higgs current always competes with the much larger neutral currents induced by gluon, photon, or Z-boson exchange. One possibility to circumvent these difficulties is to study the decay of on-shell Higgs bosons into a photon and a vector meson (ϕ, J/Ψ, Υ) [6, 7, 8, 9]. The interference of the diagrams where the Higgs directly couples to the light quark currents and those where the Higgs decays into a photon and an off-shell photon or Z, converting into the vector meson, leads to sensitivity to the corresponding Yukawa couplings (s, c, b). The branching ratios turn out to be very small. They are of the order of 10^{-6} for $h \to \phi\gamma$ and $h \to J/\Psi\gamma$, and, maybe somewhat surprisingly, of the order of 10^{-9} for $h \to \Upsilon\gamma$. In the latter case the two amplitudes accidentally cancel almost completely, leading to an increased sensitivity for deviations in the bottom Yukawa. Unfortunately, the small branching ratios make these processes very difficult to observe at the LHC.

There are several ways to constrain the charm Yukawa coupling [10]. Apart from exclusive Higgs decays discussed above, information can be obtained from the measurement of the total Higgs decay width via the invariant mass distribution in the $h \to 4\ell$ and $h \to \gamma\gamma$ channels, yielding $|\kappa_c| \lesssim 120 - 150$. Furthermore, heavy-flavor tagging currently gives a bound of the order of $|\kappa_c| \lesssim 230$, while future improvement in charm tagging can tighten thayt constraint [11]. Finally, combining all Higgs data in a global fit leads to the currently strongest constraint $|\kappa_c| \lesssim 6.2$ [10].

What do we know about the electron Yukawa? In fact, the best current bound on the absolute value obtains from direct searches for $h \to e^+e^-$ at the LHC [12], leading to $|\kappa_e| < 611$ [13] (we use the notation $\kappa_f \equiv y_f/y_f^{\rm SM}$ for the Yukawa coupling of any fermion f in terms of its SM value). This bound is expected to go down to $|\kappa_e| \lesssim 150$ at the 14 TeV LHC with 3000/fb of data, and to roughly $|\kappa_e| \lesssim 75$ at a future 100 TeV collider with the same amount of data. A future e^+e^- collider, collecting 100/fb on the Higgs resonance, would be sensitive to $|\kappa_e| \sim 15$ [13][1].

It is interesting to compare these bounds to limits obtained from indirect probes. The anomalous magnetic moment of the electron $(g-2)_e$ is, via Barr-Zee-type diagrams, proportional to the electron Yukawa coupling. Usually $(g-2)_e$ is used to define the fine-structure constant α; however, given an independent determination of α, the MDM is a sensitive probe of NP [14]. Using the measurements of α [15] and $(g-2)_e$ [16] yields a bound $|\kappa_e| \lesssim 3000$ [13]. This is weaker than the current LHC bound; however, it depends linearly on the electron Yukawa and the sensitivity is expected to increase by a factor of ten in the next few years [14].

3. CP Violation in the Higgs Sector

For successful baryogenesis new sources of CP violation are needed (see, e.g., [17]). They could be provided by complex Yukawa couplings; see [18] for a minimal setup. Can we test this scenario?

Modifying the top Yukawa will change Higgs production via gluon fusion and the $h \to \gamma\gamma$ decay, while changing the bottom Yukawa will change all Higgs branching ratios. LHC measurements currently still allow for order one deviations from SM predictions in the Higgs couplings to the third generation. However, electric dipole moments (EDMs) induced via Barr-Zee diagrams [19, 20] tend to yield much stronger constraints. For instance, the recent measurement of the electron EDM, $d_e/e < 8.7 \times 10^{-29}\,$cm [21] leads to $\mathrm{Im}\,\kappa_t \lesssim 0.01$ [22]. (See [23, 24] for a comprehensive discussion of theory uncertainties.) For the bottom and τ, EDMs lead to constraints comparable to those from LHC [22]. Information from differential decay distributions can, however, provide additional information on the CP phase at colliders [26, 25].

A complete analytic results for the two-loop electron-Yukawa contributions to the electron EDM has only been given recently [13] and leads to $\mathrm{Im}\,\kappa_e \lesssim 0.017$ (using the same measurement as above). A corresponding full result for the light-quark Yukawas has not yet been published; a preliminary calculation, however, yields $\mathrm{Im}\,\kappa_u \lesssim 0.08$ and $\mathrm{Im}\,\kappa_d \lesssim 0.02$ for the up- and down-

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[1] During this conference, it was pointed out to me that even SM sensitivity could be achieved at FCCee [Stephane Monteil, private communication].

quark Yukawa, respectively [28]. (Here, I used the most recent measurement of the neutron EDM from [29]).

4. Lepton Flavor Violation

Some excitement was caused recently by a hint for a non-zero branching ratio of the lepton-flavor violating decay $h \to \tau\mu$ [30]. Indeed, precision observables in the lepton sector (for instance, $(g-2)_\mu$, EDMs, $\tau \to 3\mu$, $\mu \to 3e$, $\tau \to \mu\gamma$, $\mu \to e\gamma$) allow for $\text{Br}(h \to \tau\mu) = \mathscr{O}(10\%)$ [27]. The most "directly related" precision observable is the rare decay $\tau \to \mu\pi\pi$ [31]. While the CMS result implies $\text{BR}(\tau \to \mu\pi^+\pi^-) < 1.6 \times 10^{-11}$, the current bounds are $\text{BR}(\tau \to \mu\pi^+\pi^-) \lesssim \text{few} \times 10^{-8}$ from Belle [32] and $\text{BR}(\tau \to \mu\pi^0\pi^0) < 1.4 \times 10^{-5}$ from Cleo [33]. Stronger constraints could are expected at Belle II.

The CMS measurement of $\text{Br}(h \to \tau\mu) = (0.84^{+0.39}_{-0.37})\%$[2] corresponds to an average flavor-changing $\mu\tau$ Yukawa of $\sqrt{|Y_{\tau\mu}|^2 + |Y_{\mu\tau}|^2} = (2.6 \pm 0.6) \times 10^{-3}$ [35]. In general, a (large) $h \to \tau\mu$ branching ratio will imply a large $\tau\mu$ dipole operator, as at least on of the particles in the loop has to be electrically charged. To be consistent with precision constraints, this then requires either fine tuning, or a second source of electroweak symmetry breaking [35]. A plethora of models has been proposed (e.g., 2HDM [36, 37, 38]; leptoquarks [39, 40]; new strong interactions [35]). Interestingly, it is not possible to explain a large $h \to \tau\mu$ branching ratio within the MSSM: all (necessarily fine-tuned) solutions consistent with precision bounds are ruled out by the existence of charge-breaking vacua [41].

5. New Ideas

At last, I would like to mention two new ideas how to constrain the light-quark Yukawa couplings.

The first is to constrain the product of electron and light-quark quark Yukawa via so-called "atomic clock transitions" [42]. The point-like and attractive Higgs force will induce small changes in the characteristic energy (frequency) differences in suitable atomic transitions. Since the Higgs contribution cannot be switched off, the measurement of transitions in several isotopes is required; measuring the "difference of differences" allow for the elimiation of hadronic uncertainties. In this way, an independent measurement of the light-fermion Yukawas could be possible, with a sensitivity comparable to that of the current LHC bounds or better [42].

The second idea is to constrain the light Yukawas by measuring the charge asymmetry in the process $hW^\pm \to (\ell^\pm)(\ell^\pm \nu jj)$ [43]. It encodes mainly the underlying pdf asymmetry. While the dominant SM contribution is the radiation of a higgs boson off a W boson (corresponding to a charge asymmetry of order 25%), for enhanced light Yukawas, the emission of a higgs from an initial light-quark line becomes comparable, leading to a sensitivity to these couplings. Additional contributions to the asymmetry between -30% and $+5\%$ can be expected [43].

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[2] Note that the significance of this measurement decreased after analysis of new data [34].

6. Summary

The Higgs couplings are completely determined in the SM; that is why we need to measure them! Any deviation (for instance, CP-violating or flavor-changing Yukawa couplings) would be a clear sign of NP. The measurement of the light-fermion Yukawa couplings, in particular, is a difficult experimental problem, and an interesting interplay between collider observables and precision probes exists. The discovery of the Higgs boson opened a new window to search for new physics in the Higgs sector, which quickly became an active and exciting new field of research.

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