Testing Top Yukawa Form Factor

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Abstract: We propose to study the energy-scale dependence of the top Yukawa coupling, $y_t(Q^2)$ at HL-LHC, future hadron and lepton colliders. The scale Q^2 could be related to the off-shellness of the top/anti-top or Higgs connected to $Ht\bar{t}$ vertex. We first discuss possible parametrizations of $y_t(Q^2)$ motivated by stabilizing the electroweak scale against quantum corrections from the top sector. We then study the $t\bar{t}H(H^*)$ final states at HL-LHC and future 100 TeV hadron colliders, to directly probe the strucutre of $y_t(Q^2)$. In addition, we consider the precision measurement of the process $e^+e^- \to Z^* \to ZH$ at future lepton colliders, e.g. FCC-ee, in the hope to narrow down the form of possible $y_t(Q^2)$.

Contents

1 Background

The discovery of the Higgs boson at the CERN Large Hadron Collider (LHC) [1, 2] on the one hand, provides us a self-consistent theory, the Standard Model (SM), that is valid up to Planck scale. On the other hand, it confronts us with a profound puzzle: how can the Higgs be just that light given the huge corrections from quantum fluctuations of the fields it couples to. However, this puzzle, aka the hierarchy problem, is a common feature of elementary scalar fields, and thus has motivated generations of physicists to pursue its solutions. To date, there have been two main ideas on which that a plethora of theories are based, namely supersymmetry and composite Higgs. Almost all of those theories predict their lightest resonances $\lesssim \mathcal{O}(\text{TeV})$, based on which experimental searches have been implemented. However, the null results at LHC so far seem to indicate tensions in the known solutions or holes in the searching strategies, and motivate us to revisit this puzzle.

If Higgs is not an elementary particle, there could be other places where its non-SM-ness shows up. One example could be to assume some the Higgs couplings, such as the coupling to the top quark, are turned off in some way as the energy scale goes up. Testing this out-of-box idea would require measuring the Euclidean off-shell properties of the Higgs couplings and new search strategies would have to be developed. Another example could be that the new physics introduced to solve the hierarchy problem is $\gtrsim \mathcal{O}(10\text{TeV})$, therefore its signature may only be revealed in the Higgs coupling deviation from the SM prediction, especially in the top Yukawa, Thus, searches focusing Higgs coupling measurement is not only crucial, but also orthogonal to the searches based on the bump hunt.

2 Plan

We take off from the top Yukawa coupling, assuming some form of its scale-dependence $y_t(Q^2)$. Studies considering the running of top Yukawa in extra-dimensional models or a dipole-like form factor have been carried out, utilizing the off-shell Higgs production channel $gg \to H^* \to ZZ$ [3]. We propose to study the top associated Higgs production $pp \to t\bar{t}H(H^*)$ at HL-LHC and future hadron colliders, given its direct connection to the possible new physics related to top Yukawa coupling and its constructive interference (destructive interference in $gg \to H^* \to ZZ$) with background. More importantly at future hadron colliders, such as the FCC-hh, the phase space suppression due to the additional two

Obs	$\sigma(gg \to H)$	$\sigma(pp \to t\bar{t}H)$	$\mathrm{Br}(H \to \gamma\gamma)$
Precision(%)	8.6[12]	21[12]	18[12]

Table 1: Current constraints on relevant on-shell Higgs observables.

tops are negligible and the cross section for this channel (with off-shell Higgs production) would possibly be comparable to that from gluon fusion [4].

We go further to include the scale-dependent $y_t(Q^2)$ with Q^2 quantifying the off-shellness of top/anti-top. Precision measurment of the on-shell Higgs couplings, e.g. couplings in TAB. 1, could also put constraints on $y_t(Q^2)$ if the scale-dependence is on the off-shellness of top/anti-top. For example, if the top Yukawa coupling is turned off when the top/anti-top off-shellness is above 500 GeV, it would lead to modification of $\mathrm{Br}(H \to \gamma\gamma)$ by 3%[1]. Future hadron colliders with higher energies (e.g. FCC-hh [5–7]) or lepton colliders with cleaner environment (FCC-ee [8], CEPC [9], ILC [10]), would provide us unprecedented precisions on those couplings and would be perfect to probe the said Higgs couplings modification. One channel that deserve more attention for this purpose is $\sigma(e\bar{e} \to Z^* \to ZH)$. In the SM, the radiative correction to this channel from a triangle loop mediated by a top quark could be 10% of the Born value [11], which is actually sizable. It would be valuable to study the constraint on $y_t(Q^2)$ from the precision of $\sigma(e\bar{e} \to Z^* \to ZH)$. The direct measurement with $pp \to t\bar{t}H(H^*)$ channel at hadron colliders would also provide complementary information and combining with the precision measurement will further constrain the form of scale-dependent top Yukawa coupling.

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