PROCEEDINGS OF SCIENCE

Looking for the solution to the Hierarchy Problem in Top Quark Physics

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The top quark plays an important role in the well-known Hierarchy Problem because it gives the leading quantum correction to the Higgs mass term. Traditional models address the issue by introducing TeV-scale top partners. However, the absence of these new particles urges for an alternative solution. In this talk, I will present a new scenario where the top Yukawa coupling is modified to tackle the Hierarchy Problem. In this scenario, the top Yukawa coupling is strongly suppressed at high scales due to new interactions and degrees of freedom which will have direct impacts on top quark physics. The relevant measurements, including $t\bar{t}h$, $t\bar{t}$, and $t\bar{t}t\bar{t}$ final states, are discussed.

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1. Introduction

The hierarchy problem is one of the most mysterious problems in the Standard Model (SM) of particle physics. The problem becomes more severe due to the absence of any new particles after the discovery of a light Higgs boson at the 125 GeV. The Higgs boson's mass term receives quadratically divergent corrections from all the particles it interacts with. Among them, the contribution of the top quark is given by

$$\Delta m_H^2|_{\rm top} \sim -i\, 2N_c\, y_t^2 \int \frac{d^4k}{(2\pi)^4} \frac{k^2+m_t^2}{(k^2-m_t^2)^2} = -\frac{3}{8\pi^2} y_t^2 \left[\Lambda_{\rm NP}^2 - 3\, m_t^2 \ln\left(\frac{\Lambda_{\rm NP}^2}{m_t^2}\right) + \cdots \right], \quad (1)$$

where $\Lambda_{\rm NP}$ is the scale of new physics corresponding to the top quark. The Naturalness principle suggests that $\Lambda_{\rm NP}$ to be 500 GeV for the observed Higgs potential, which is expected to be the lightest new physics and is within the reach of the LHC.

In traditional symmetry-based models, top partners as the new physics are introduced to solve the hierarchy problem. The new contribution $\Delta m_H^2|_{\text{top partner}}$ from the top partner loop cancels the quadratically divergent term $\Lambda_{\rm NP}^2$, which is guaranteed by some new symmetry, such as supersymmetry. However, the symmetry can not be exact and thus the Higgs mass term is still generated due to the difference between the top quark mass and the top partner mass as

$$\Delta m_H^2|_{\rm top} + \Delta m_H^2|_{\text{top partner}} \sim -\frac{3}{8\pi^2} y_t^2 M_T^2 \ln\left(\frac{\Lambda_{\rm NP}^2}{M_T^2}\right), \quad (2)$$

where M_T is the mass of the top partner. From the Naturalness principle, the top partners' mass M_T needs to be $\sim$ 500 GeV to get the observed Higgs potential.

However, after years of searches by the LHC, the bounds on the mass of colored top partners have reached around 1500 GeV for both scalar top partners [1, 2] and fermionic top partners [3–5]. The absence of top partners starts challenging the naturalness of these traditional models due to the increasing fine-tuning. To reduce fine-tuning, one alternative is to introduce colorless top partners. Since they are hard to be produced, the bound on their mass is weaker than the common colored top partners. It is even better if the top partner is a SM singlet like in Twin Higgs models [6], which is known as Neutral Naturalness. However, this alternative is still based on the idea of symmetry and the cancellation between $\Delta m_H^2|_{\rm top}$ and $\Delta m_H^2|_{\text{top partner}}$. In our works [7, 8], we explore another direction that does not require top partners. The idea is to have the top Yukawa coupling with a strong scale-dependence $y_t = y_t(k^2)$ which can make the top quark loop contribution converge. For example, taking

$$y_t(k^2) = y_t\left(\frac{\Lambda_t^2}{-k^2+\Lambda_t^2}\right) \quad (3)$$

where Λ_t is the mass scale of new degrees of freedom responsible for the nontrivial behavior of top Yukawa coupling. The correction is then given by

$$\Delta m_H^2|_{\rm top} \sim -i\, 2N_c \int \frac{d^4k}{(2\pi)^4}\, y_t^2(k^2) \frac{k^2+m_t^2}{(k^2-m_t^2)^2} \sim -\frac{3}{8\pi^2} y_t^2 \Lambda_t^2\,, \quad (4)$$

which is under control by the new scale Λ_t.

2. Zoom in the Top Yukawa vertex

To achieve this behavior, the top Yukawa coupling must originate from a more complicated diagram, which implies new physics in the top Yukawa vertex at high scales. There are several possibilities shown in Fig. 1. Each case (from left to right) is described as follows.

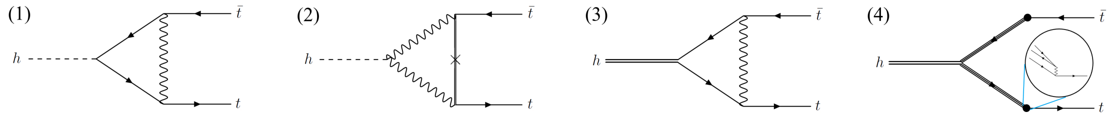

Figure 1: Four possible UV completions for the nontrivial behavior of the top Yukawa coupling.

The first diagram (1) corresponds to **"large y_t running"**, where an additional top-philic interaction is introduced. It can lead to a large running and reduce the top Yukawa coupling at high scales. Already in the SM, there is a negative contribution to the y_t running by QCD. However, it is not large enough and a stronger interaction is required to bring down the top Yukawa coupling at the desired scale. The wavy propagator can be various top-philic bosons, such as Z' [9] or coloron [10], with strong enough couplings in order to reduce the top Yukawa coupling.

In diagram (2), called **"radiative y_t generation"**, the top Yukawa coupling is forbidden at the tree level but is generated at one loop. In this scenario, the Higgs boson and the top quarks are only connected through new top-philic bosons (wavy line) and vector-like fermions (double line). The top Yukawa coupling thus only arises after integrating out these new degrees of freedom, which also means, above the mass scale of these mediators, the top Yukawa coupling will decrease as desired. The interactions among these new particles should also be strong enough to reproduce the observed value of the top Yukawa coupling.

The first two scenarios can be realized with an elementary Higgs boson, see [7] for more details. The last two scenarios **"y_t from four-fermion interactions"**, on the other hand, are based on the composite Higgs models with the top Yukawa coupling generated from either bilinear (3) or linear (4) operators. The bilinear case is studied in [8], where the top Yukawa coupling directly arises from a four-fermion vertex. The idea can be traced back to Extended Technicolor (ETC) [11, 12]. The modern version is introduced with a light composite Nambu-Goldstone Higgs and is usually called Extended Hypercolor (EHC) [13, 14]. Differently from the first two scenarios, which require new strong interactions due to their one-loop nature, the last two scenarios introduce new weakly-coupled extended-hypercolor gauge bosons accompanying the existing strongly coupled composite Higgs sector.

3. Phenomenology

To test new physics, the first thing that comes into mind is always to search for new resonances. However, it is not ideal in our scenarios because the idea is to modify the top Yukawa coupling at high scales. As discussed in the last section, the new degrees of freedom are quite diverse according to the different UV completions. Furthermore, in each scenario, there are also different difficulties. For the first two, the modification happens at the one-loop level, which means the quantum number of the new states is not uniquely determined. Besides, the requirement of strong couplings implies resonances with broad widths, which make them hard to search. For the composite Higgs scenarios, the quantum number is also diverse, depending on the hypercolor group and how it is extended. Therefore, direct searches are hard to perform due to the requirements of the UV theory and the presence of strong couplings. However, the direct test of the idea can be realized in measurements of top quark physics.

3.1 Running top Yukawa coupling and $t\bar{t}h$ differential cross section

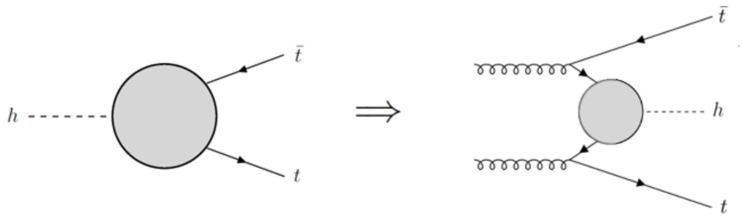

Figure 2: The $y_t = y_t(k^2)$ can be tested through $t\bar{t}h$ differential cross section.

The direct probe of the top Yukawa coupling at high scales can be realized in the measurement of $t\bar{t}h$ final state as shown in Fig. 2. The nontrivial behavior of the top Yukawa coupling at high scales will reveal itself in differential momentum distributions of $t\bar{t}h$ production [15, 16]. However, due to three heavy final states, the $t\bar{t}h$ cross section is quite small. The current measurement has not yet achieved the desired sensitivity. However, with more data during the HL-LHC era, it could push the constraint on Λ_t to the relevant scale $\sim$ 1 TeV.

3.2 Running top mass and $t\bar{t}$ differential cross section

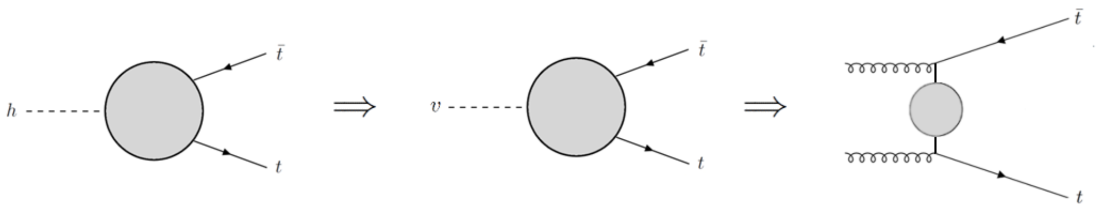

Figure 3: The $m_t = m_t(k^2)$ can be tested through $t\bar{t}$ differential cross section.

Besides probing the top Yukawa coupling at high scales directly, we can also measure the top quark mass at high scales instead, where the Higgs boson is replaced with its VEV. Without a Higgs, the measurement can then be done from $t\bar{t}$ final states, which has a much larger total cross section. Such measurement has already been done by the CMS collaboration using the 2016 Run 2 data with an integrated luminosity of 35.9 fb^{-1} [17]. The result was interpreted in the study [18]. We can get a constraint as $\Lambda_t > 700$ GeV at 95% C.L., which is already challenging the Naturalness principle. The relevant parameter spaces will soon be tested in LHC Run 3 and HL-LHC, but a more precise differential $t\bar{t}$ cross-section calculation at orders beyond NNLO in QCD is also required to distinguish the signals.

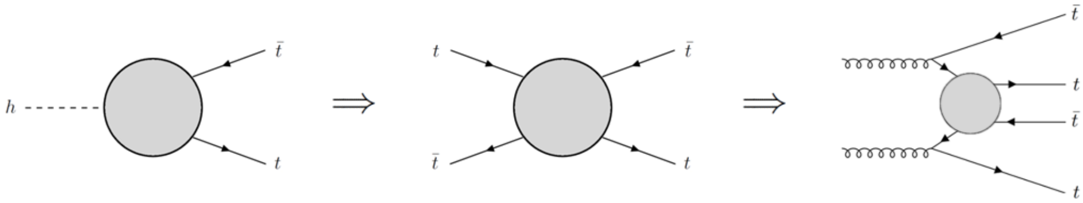

Figure 4: New top-philic interactions can be tested through $t\bar{t}t\bar{t}$ cross section.

3.3 Top-philic interactions and $t\bar{t}t\bar{t}$ cross section

Modifications on the top Yukawa coupling running require some new top-philic interactions, which will also introduce additional contributions to the four-top cross section. Various four-top operators can be generated in different scenarios. To determine the Lorentz structure of the operators and their coefficients, UV completion is again required. However, coefficients $\sim C/\Lambda_t^2$ by dimensional analysis are expected, which can introduce a sizable contribution to the cross section. It turns out that the four-top cross section might be the most promising channels to look for. In the SM, the prediction with next-to-leading logarithmic (NLL') accuracy is calculated [19], giving a value $13.4^{+1.0}_{-1.8}$ fb with uncertainty stemming from scale variation and PDF error. From the experimental side, both ATLAS and CMS announced the observation [20, 21] last year using the LHC Run-2 data with cross sections $22.5^{+6.6}_{-5.6}$ fb and $17.7^{+4.0}_{-1.8}$ fb respectively. The measurements start approaching the relevant parameter space [22] and the current excess could be the first hint of new physics.

4. Conclusion

The top quark plays the most important role in the hierarchy problem. To cancel the top-loop correction, top partners were introduced in traditional models. In this talk, we discuss an alternative where the top-loop contribution is reduced by modifying the running of the top Yukawa coupling. The new degrees of freedom expected to appear at the Naturalness scale $\Lambda_t \sim 500$ GeV will be some new top-philic particles instead of top partners. Direct tests of the idea can be realized in top quark physics, including measurements of $t\bar{t}h$ differential cross section (for the top Yukawa coupling at high scales), $t\bar{t}$ differential cross section (for the top mass at high scales), and $t\bar{t}t\bar{t}$ cross section (for new top-philic interactions). We show that the current LHC data is reaching the relevant parameter space. The solution to the Hierarchy Problem might still be hidden in Top Quark physics but will be revealed in the coming years!

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