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Test of the Littlest Higgs model through the correlation among W boson, top quark and Higgs masses

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Motivated by the recent precision measurements of the W boson mass and top quark mass, we test the Littlest Higgs model by confronting the prediction of M_W with the current and prospective measurements of M_W and M_t as well as through the correlation among M_W, M_t and Higgs mass. We argue that the current values and accuracy of M_W and M_t measurements tend to favor the Littlest Higgs model over the standard model, although the most recent electroweak data may appear to be consistent with the standard model prediction. In this analysis, the upper bound on the global $SU(5)$ symmetry breaking scale turned out to be 26.3 TeV. We also discuss how the masses of the heavy gauge boson $M_{B'}$ in the Littlest Higgs model can be predicted from the constraints on the model parameters.

1. Introduction

There have been a great deal of works on the precision test of the Standard Model (SM) because of the incredibly precise data obtained at the LEP and the new measurements of M_W and M_t at the Fermilab Tevatron [1,2] as well as the recent theoretical progress in the higher order radiative corrections [3]. With such a dedicated effort for a long time to test the SM, it has been confirmed that the SM is the right model to describe the electroweak phenomena at the current experimental energy scale. What remains elusive is the origin of the electroweak symmetry breaking for which a Higgs boson is responsible in the SM. It has been known for some time that radiative corrections in the SM exhibit a small but important dependence on the Higgs boson mass, M_h. As a result, the value of M_h can, in principle, be predicted by comparing a variety of precision electroweak measurements with one another. The recent global fits to all precision electroweak data (see Erler and Langacker [4]) lead to $M_h = 113^{+56}_{-40}$ (1σ confidence level (CL)) and $M_h < 241$ GeV (95% CL). Those constraints are very consistent with bounds from direct searches for the Higgs boson at LEPII via $e^+ + e^- \longrightarrow Zh$, $M_h > 114.4$ GeV [5]. Together, they seem to suggest the range, 114 GeV $< M_h <$ 241 GeV, and imply very good consistency between the SM and experiment. However, in the context of the SM valid all the way up to the Planck scale, M_h diverges due to a quadratic divergence at one loop level unless it is unnaturally fine-tuned. Thus, we need a new physics beyond the SM to stabilize M_h, which is a so-called hierarchy problem that has motivated the construction of the LHC. Candidates for this physics include supersymmetry and technicolor models relying on strong dynamics to achieve electroweak symmetry breaking.

Inspired by *dimensional deconstruction* [6], an intriguing alternative possibility that the Higgs boson is a pseudo Goldstone boson [7,8] has been revived by Arkani-Hamed et al. They showed that the gauge and Yukawa interactions of the Higgs boson can be incorporated in such a way that a quadratically divergent one-loop contribution to M_h is canceled. The cancelation of this contribution occurs as a consequence of the special collective pattern in which the gauge and Yukawa couplings break the global symmetries. Since the remaining radiative corrections to M_h are much smaller, no fine tuning is required to keep the Higgs boson sufficiently light if the strong coupling scale is of order 10 TeV. Such a light Higgs boson was called "little Higgs". The models with little Higgs are described by nonlinear sigma models and trigger electroweak symmetry breaking by the collective symmetry breaking mechanism. Many such models with different "theory space" have been constructed [8,9], and electroweak precision constraints on various little Higgs models have been investigated by performing global fits to the precision data [10–12]. It is worthwhile to notice that the little Higgs models generally have three significant scales: an electroweak scale $v \sim \frac{g^2 f}{4\pi} \sim 200$ GeV, a new physics scale $g \cdot f \sim 1$ TeV and a cut-off scale of the non-linear sigma model $\Lambda \sim 4\pi f \sim 10$ TeV, where f is the scale of the global symmetry breaking. Therefore, we expect that the little Higgs models have rich and distinguishable TeV scale phenomena unlike other

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models, which provides strong motivation to probe them at the LHC.

Very recently, Fermilab CDF collaboration has reported the most precise single measurement of the W boson mass to date from Run II of the Tevatron [1],

$$M_W = 80.413 \pm 0.048 \text{ GeV}, \tag{1}$$

and updated the world average [13] to

$$M_W = 80.398 \pm 0.025 \text{ GeV}. \tag{2}$$

In addition, the world average result of M_t from the Tevatron experiments CDF and D0 has been given [2] by

$$M_t = 172.6 \pm 1.4 \text{ GeV}. \tag{3}$$

The mass of the top quark is now known with a relative precision of 0.8%, limited by the systematic uncertainties, and can be reasonably expected that with the full Run-II data set the top-quark mass will be known to much better than 0.8% in the foreseeable future. With the current level of experimental uncertainties as well as prospective sensitivities on M_W and M_t, we are approaching to the level to test the validity of new physics beyond the SM by a direct comparison with data or to strongly constrain new physics models.

The correlation among M_t, M_W and M_h is an important prediction of the SM, and thus deviations from it should be accounted for by the effects of new physics. In the minimal supersymmetric Standard Model (MSSM) case, the allowed ranges for M_W and M_t were checked by considering various parameter spaces of the MSSM [14]. They showed that the previous experimental results for M_W and M_t tend to favor the MSSM over the SM. Motivated by this fact, in this Letter, we confront the Littlest Higgs model (LHM) [8] with more precision measurements of M_W and M_t than before by computing the prediction of M_W in the LHM. We examine whether the current precision measurements of M_W and M_t tend to favor the LHM over the SM or not. From the careful numerical analysis, we obtain some constraints on the model parameters such as the global $SU(5)$ symmetry breaking scale and the mixing angles between heavy gauge bosons. By using the constraints on the model parameters, we show how the mass of heavy gauge boson B'_μ can be predicted, which could be probed at the LHC.

The organization of this Letter is as follows. In Section 2 we briefly review the LHM. In Section 3 we discuss how the formula for M_W can be derived from the effective theory of the LHM, and confront the prediction of M_W with the current and prospective measurements of M_W and M_t. We also show how an upper bound on the global symmetry breaking scale f can be obtained and how it is correlated with the Higgs mass. In Section 4 we investigate how the mixing parameters in the LHM can be constrained, and discuss how the mass of the heavy gauge boson B'_μ in the LHM can be predicted from the constraints on the model parameters. Finally we conclude our work.

2. Aspects of the littlest Higgs model

The LHM is one of the simplest and phenomenologically viable models, which realizes little Higgs idea. It initially has a global symmetry $SU(5)$ which is broken down to a global symmetry $SO(5)$ via a vacuum expectation value of order f, and a gauge group $[SU(2)\times U(1)]^2$ which is broken down to $SU(2)\times U(1)$, identified as the electroweak gauge symmetry. Thus the characteristic feature of the LHM is to predict the existence of the new gauge bosons with masses of order TeV. The vacuum expectation value (VEV) associated with the spontaneous global symmetry breaking of $SU(5)$ is proportional to the 5×5 symmetric matrix Σ_0 given by

$$\Sigma_0 = \begin{pmatrix} & & & 1 & \\ & & & & 1 \\ & & 1 & & \\ 1 & & & & \\ & 1 & & & \end{pmatrix}. \tag{4}$$

After the global symmetry breaking, 14 Goldstone bosons are generated. Among them four Goldstone bosons are eaten by the gauge bosons corresponding to broken gauge symmetry and remaining Goldstone bosons become the SM Higgs doublet and an additional complex triplet Higgs. The fluctuations of the uneaten Goldstone bosons in the broken direction can be described by $\Pi = \pi^a X^a$ with the broken generators of the $SU(5)$, X^a. Then the Goldstone bosons can be parameterized by a nonlinear sigma model field $\Sigma(x)$,

$$\Sigma(x) = e^{i\Pi/f}\Sigma_0 e^{i\Pi^T/f} = e^{2i\Pi/f}\Sigma_0, \tag{5}$$

where the explicit form of the field Π is given in [10].

The kinetic energy term of the nonlinear sigma field Σ is given by

$$\frac{f^2}{8}\,\mathrm{Tr}\, D_\mu\Sigma\cdot\left(D^\mu\Sigma\right)^\dagger, \tag{6}$$

where the covariant derivative of Σ is

$$D_\mu\Sigma = \partial_\mu\Sigma - i\Sigma_j\big[g_j W^a_{j\mu}\big(Q^a_j\Sigma + \Sigma Q^{aT}_j\big) + g'_j B_{j\mu}(Y_j\Sigma + \Sigma Y_j)\big], \tag{7}$$

with $j = 1, 2$. Here $W^a_{j\mu}$ and $B_{j\mu}$ stand for the $SU(2)$ and $U(1)$ gauge fields, respectively and g_j and g'_j denote the corresponding gauge coupling constants. The generators of the $SU(2)$ and $U(1)$ gauge symmetries are denoted by Q^a_i and Y_i, respectively, and their explicit forms are given by

$$Q^a_1 = \begin{pmatrix} \sigma^a/2 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \qquad Y_1 = \mathrm{diag}(-3,-3,2,2,2)/10, \tag{8}$$

$$Q^a_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\sigma^{a*}/2 \end{pmatrix}, \qquad Y_2 = \mathrm{diag}(-2,-2,-2,3,3)/10, \tag{9}$$

where σ^a are the Pauli spin matrices.

From Eqs. (6), (7), we see that the mixing terms between gauge bosons are given by

$$\mathcal{L}_{\Sigma,\mathrm{LO}} \sim \frac{f^2}{8}\,\mathrm{Tr}\big|\Sigma_{j=1,2}\big[g_j W^a_{j\mu}\big(Q^a_j\Sigma_0 + \Sigma_0 Q^{aT}_j\big) + g'_j B_{j\mu}(Y_j\Sigma_0 + \Sigma_0 Y_j)\big]\big|^2. \tag{10}$$

With the help of the following transformations

$$W^a_\mu = sW^a_{1\mu} + cW^a_{2\mu}, \qquad W^{a'}_\mu = -cW^a_{1\mu} + sW^a_{2\mu}, \tag{11}$$

$$B_\mu = s'B_{1\mu} + c'B_{2\mu}, \qquad B'_\mu = -c'B_{1\mu} + s'B_{2\mu}, \tag{12}$$

where $s = g_2/\bar g$, $c = g_1/\bar g$, $s' = g'_2/\bar g'$, $c' = g'_1/\bar g'$ with $\bar g = \sqrt{g_1^2 + g_2^2}$ and $\bar g' = \sqrt{g_1'^2 + g_2'^2}$, two massive states $W^{a'}_\mu$ and B'_μ are obtained whose masses are given by

$$M_{W^{a'}_\mu} = \frac{\bar g f}{2}, \quad M_{B'_\mu} = \frac{\bar g' f}{2\sqrt5}, \tag{13}$$

respectively, and two massless W^a_μ and B_μ bosons which are identified as the massless SM gauge bosons before the electroweak symmetry breaking. Hereafter we denote the SM gauge fields in the mass basis as W, Z and A. We also notice that the SM gauge couplings are $g = g_1 s = g_2 c$ and $g' = g'_1 s' = g'_2 c'$ for $SU(2)_L$ and $U(1)_Y$, respectively.