Little Higgs phenomenology

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Abstract. Recently a new class of models has emerged that addresses the naturalness problem of a light Higgs boson. In these "little Higgs" models, the Standard Model Higgs boson is a pseudo-Nambu-Goldstone boson of an approximate global symmetry. The Higgs boson acquires mass radiatively only through "collective breaking" of the global symmetry, so that more than one interaction is required to give the Higgs a mass. This protects the Higgs mass from receiving quadratically divergent radiative corrections at one-loop. These models contain new vector bosons, fermions and scalars at the TeV scale that cancel the quadratic divergences in the Higgs mass due to the Standard Model gauge, top quark, and Higgs boson loops. In this talk I review the phenomenology of the little Higgs models, focusing on collider signatures and electroweak precision constraints.

1 Introduction

The Standard Model (SM) of strong and electroweak interactions has passed stringent tests up to the highest energies accessible today. The precision electroweak data [1] point to the existence of a light Higgs boson in the SM, with mass $m_H \lesssim 200$ GeV. The SM with such a light Higgs boson can be viewed as an effective theory valid up to a much higher energy scale Λ, which could be as high as the Planck scale. In particular, the precision electroweak data exclude dimension-six operators arising from strongly coupled new physics below a scale Λ of order 10 TeV [2]; any new physics appearing below this scale must be weakly coupled. However, without protection by a symmetry, the Higgs mass is quadratically sensitive to the cutoff scale Λ via quantum corrections, rendering the theory with $m_H \ll \Lambda$ rather unnatural. For example, for $\Lambda = 10$ TeV, the "bare" Higgs mass-squared parameter must be tuned against the quadratically divergent radiative corrections at the 1% level. This gap between the electroweak scale m_H and the cutoff Λ is called the "little hierarchy".

Little Higgs models [3,4,5,6,7,8,9,10] revive an old idea to keep the Higgs boson naturally light: they make the Higgs particle a pseudo-Nambu-Goldstone boson [11] of a broken global symmetry. The new ingredient of little Higgs models is that at least two interactions are needed to explicitly break all of the global symmetry that protects the Higgs mass. This forbids quadratic divergences in the Higgs mass at one-loop; the Higgs mass is then smaller than the cutoff scale Λ by *two* loop factors, making the cutoff scale $\Lambda \sim 10$ TeV natural and solving the little hierarchy problem.

From the bottom-up point of view, the most important quadratic divergences in the Higgs mass due to top quark, gauge boson, and Higgs boson loops are canceled by loops of new weakly-coupled fermions, gauge bosons, and scalars with masses around a TeV. In contrast to supersymmetry, the cancellations in little Higgs models occur between loops of particles with the *same* statistics. Electroweak symmetry breaking is triggered by a Coleman-Weinberg [12] potential generated by integrating out the heavy degrees of freedom.

The constraints on little Higgs models from electroweak precision data have been examined in detail in [13, 14,15,16]. The constraints come from Z pole data from LEP and SLD, low-energy neutrino-nucleon scattering, atomic parity violation, and the W boson mass measurement from LEP-II and the Tevatron. These measurements probe contributions from the exchange of virtual heavy gauge bosons between fermion pairs, the modification of Z-pole observables due to mixing of the Z with the heavy gauge bosons, and the shift in the mass ratio of the W and Z. The lower bounds on the masses of the new heavy gauge bosons are generally in the 1.5–2 TeV range [15,16]. The electroweak precision measurements tend to favor parameter regions in which the new heavy gauge bosons are approximately decoupled from the SM fermions, thereby suppressing four-fermi interactions. The electroweak precision measurements do not directly constrain the mass of the top-partner. However, the mass of the top-partner is related to the heavy gauge boson masses by the structure of the model. For naturalness, the top-partner should be as light as possible. The lower bounds on the top-partner mass are generally in the 1–2 TeV range.

The "Littlest Higgs" model [5] is a minimal model of this type. It consists of a nonlinear sigma model with a global SU(5) symmetry which is broken down to SO(5) by a vacuum condensate $f \sim \Lambda/4\pi \sim$ TeV. The gauged subgroup $[\text{SU}(2)\times\text{U}(1)]^2$ is broken at the same time to its diagonal subgroup SU(2)×U(1), identified as the SM elec-
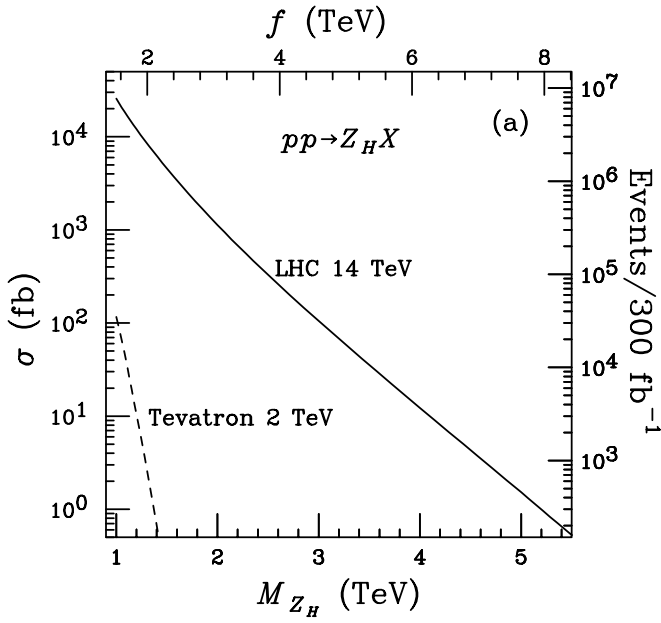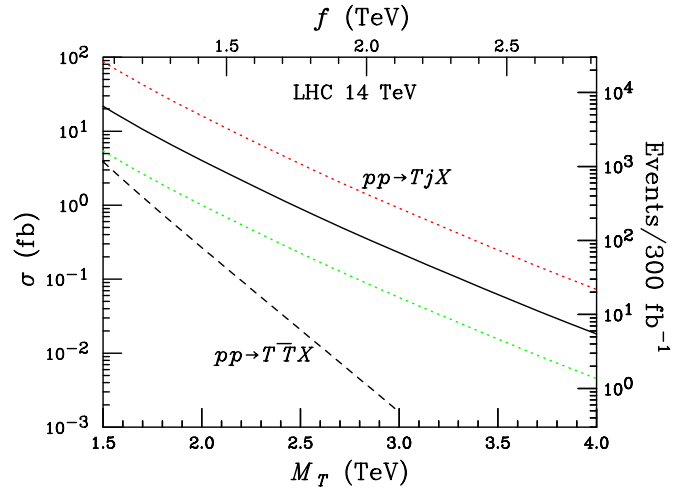
Fig. 1. Cross section for Z_H production in Drell-Yan at the LHC and Tevatron, for $\cot\theta = 1$. From [17]

Fig. 2. Cross sections for T production at the LHC. The single T cross section is shown for $\lambda_1/\lambda_2 = 1$ (*solid*) and $\lambda_1/\lambda_2 = 2$ (*upper dotted*) and $1/2$ (*lower dotted*). The QCD pair production cross section is shown for comparison (*dashed*). From [17].

troweak gauge group. The breaking of the global symmetry leads to 14 Goldstone bosons, four of which are eaten by the broken gauge generators, leading to four massive vector bosons: an SU(2) triplet Z_H, $W_H^\pm$, and a U(1) boson A_H. The ten remaining uneaten Goldstone bosons transform under the SM gauge group as a doublet h (which becomes the SM Higgs doublet) and a triplet ϕ (which gets a mass of order f). A vector-like pair of colored Weyl fermions is also needed to cancel the divergence from the top quark loop, leading to a new heavy vector-like quark with charge $+2/3$. In this talk I review the phenomenology of the Littlest Higgs model, following [17,18].

2 Collider phenomenology

The heavy SU(2) gauge bosons Z_H and W_H can be produced via Drell-Yan at the LHC (and at the Tevatron, if they are light enough). The cross section is proportional to $\cot^2\theta$ because the Z_H and W_H couplings to fermion pairs are proportional to $\cot\theta \equiv g_2/g_1$ (see [17]). In Fig. 1 we show the cross section for Z_H production at the Tevatron and LHC for $\cot\theta = 1$. In the region of small $\cot\theta \simeq 0.2$ favored [13,14,15,16] by the precision electroweak data, the cross section must be scaled down by $\cot^2\theta \simeq 0.04$. Even with this suppression factor, a cross section of 40 fb is expected at the LHC for $M_{Z_H} \simeq 2$ TeV, leading to 4,000 events in 100 fb^{-1} of data. The production and decay of Z_H and W_H at the LHC has also been studied in [19].

The Z_H boson decays to fermion pairs with partial widths proportional to $\cot^2\theta$ and to boson pairs (ZH and W^+W^-) with partial widths proportional to $\cot^2 2\theta$. This feature can be used to distinguish the Littlest Higgs model from a "big Higgs" model with the same gauge group in which the Higgs doublet transforms under only one of the

SU(2) groups [19], in which case the ZH and W^+W^- partial widths would be proportional to $\cot^2\theta$. Neglecting final-state masses, the branching fraction into three flavors of charged leptons is equal to that into one flavor of quark ($\simeq 1/8$ for $\cot\theta \gtrsim 0.5$), due to the equal coupling of Z_H to all SU(2) fermion doublets. The branching ratio into ZH is equal to that into W^+W^-. The decay branching fractions of W_H follow a similar pattern.

The Littlest Higgs model also contains a heavy U(1) gauge boson, A_H, which is generally the lightest new particle in the model. Its couplings to fermions are more model dependent than those of Z_H and W_H, since they depend on the U(1) charges of the fermions (see [17] for details). Even the presence of A_H is somewhat model-dependent, since this particle can be eliminated by gauging only one U(1) group (hypercharge) without adding a significant amount of fine-tuning [15].

The heavy top-partner T can be pair-produced via QCD with model-independent couplings. The cross section for this production mode falls quickly with increasing M_T due to phase space suppression. The single T production mode, $W^+b \to T$, dominates for $M_T \gtrsim$ TeV (Fig. 2). The cross section for single T production depends on the ratio of couplings λ_1/λ_2 (see [17]), which relates M_T to the scale f. T decays into tH, tZ, and bW^+ with branching fractions $1/4$, $1/4$, and $1/2$, respectively. The top sector is quite similar in many of the other little Higgs models in the literature, so these general features of T production and decay should apply. Some models contain more than one top-partner [6,7,8,10,20] or contain partners for all three fermion generations [7,9]; in these cases the phenomenology will be modified.

The decay partial widths of the Higgs boson into gluon pairs or photon pairs are modified in the Littlest Higgs model by the new heavy particles running in the loop and by the shifts in the Higgs couplings to the SM W boson and top quark [18]. These modifications of the Higgs couplings

to gluon or photon pairs scale like $1/f^2$, and thus decouple at high f scales. The range of partial widths for given f values accessible by varying the other model parameters was computed in [18].

For $f \gtrsim 1$ TeV, the correction to $\Gamma(H \to gg)$ is unlikely to be observable because of the large SM QCD uncertainty [21]. The correction to $\Gamma(H \to \gamma\gamma)$ is more promising; it could be observed at a photon collider, where the $\gamma\gamma \to H \to b\bar{b}$ rate can be measured to about 2% [22] for $m_H \sim 115$–120 GeV. Combining this with BR($H \to b\bar{b}$) measured to about 1.5–2% at an e^+e^- collider [23] allows the extraction of $\Gamma(H \to \gamma\gamma)$ with a precision of about 3%. Such a measurement would be sensitive to $f < 2.7$ (1.8, 1.2) TeV at the 1σ (2σ, 5σ) level. For comparison, the electroweak precision constraints require $f \gtrsim 1$ TeV in the Littlest Higgs model [15].

3 Conclusions

The little Higgs idea provides a new way to address the little hierarchy problem of the Standard Model by making the Higgs a pseudo-Nambu-Goldstone boson of a spontaneously broken global symmetry. The global symmetry is explicitly broken by gauge and Yukawa interactions; however, no single interaction breaks all the symmetry protecting the Higgs mass. This prevents quadratically divergent radiative corrections to the Higgs mass from appearing at the one-loop level, and thus allows the cutoff scale to be pushed higher by one loop factor, to ~ 10 TeV. From the bottom-up point of view, the quadratically divergent radiative corrections to the Higgs mass due to top quark, gauge boson, and Higgs loops are canceled by new heavy quarks, gauge bosons, and scalars, respectively.

The details of the phenomenology depend on the specific model. Since quite a few little Higgs models have appeared over the past two years, finding generic features of the phenomenology is important. Very generically, there must be new gauge bosons, fermions and scalars to cancel the quadratic divergences in the Higgs mass.

There is some tension between the precision electroweak constraints pushing up the new particle masses and the requirement that the new particles be light to avoid fine tuning. However, by tuning the parameters of the models appropriately one can satisfy both constraints. This tuning of the parameters should be explained in the ultraviolet completion of the nonlinear sigma model. Our developing understanding of the effects of little Higgs models on the electroweak precision observables is now driving model building to incorporate features that loosen the constraints. Taking these constraints into account, the new particles should live in the 1–2 TeV mass range and should be accessible at the LHC.

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