

Pseudo-Axions in Little Higgs Models

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In Little Higgs models, the Higgs mass is stabilized at the one-loop level by the mechanism of collective symmetry breaking. Typically, the basic ingredient of these models is a large(r) global symmetry group spontaneously broken at a scale of several TeV. The (light) Higgs appears as a Goldstone boson corresponding to a non-diagonal broken generator of this global symmetry. There could also be physical pseudoscalar particles present which belong to diagonal generators, having the properties of axions with masses in the range from several GeV up to the electroweak scale. We investigate the interesting phenomenology of these pseudo-axions at the linear collider as well as the photon collider.

I. LITTLE HIGGS MODELS

A motivation for physics beyond the Standard Model (SM) in the electroweak (EW) sector lies in the vast difference between the Planck (or unification) and the EW scale (hierarchy problem), that requires some stabilization of light scalar masses (fine tuning problem). In contrast to the supersymmetric solution to that problem where the quadratic sensitivity of the scalar masses to the cut-off is cancelled above the SUSY breaking scale between partners of opposite statistics, models have been constructed that contain a spontaneously broken global symmetry with the Higgs being light because it is one of the Goldstone bosons appearing in this breaking. In the simplest variant this construction fails because the scale for new strong interactions is too close to the electroweak scale, leaving traces in the low-energy effective action which would have shown up at LEP and Tevatron. There are two ways to evade these complications, either to use non-simple global groups (deconstruction models) or to entangle the global with the local symmetry breaking to forbid one-loop contributions to the Higgs mass parameters [1]. This shifts the scale where new strong dynamics naturally appears by one order of magnitude upwards. If the Higgs is among the Goldstone bosons of a broken global symmetry group, one always has a reduction of the rank of the global group. The Higgs thereby corresponds to a broken non-diagonal generator like the kaon in chiral symmetry breaking.

II. PSEUDOSCALARS IN DIFFERENT MODELS

In most Little Higgs models there is a diagonal generator in the global symmetry breaking which corresponds to an (anomalous) unbroken global $U(1)$ subgroup. The boson that parameterizes this subgroup is analogous to the $\eta^{(\prime)}$ in chiral symmetry breaking, i.e. it couples like a pseudoscalar to fermions. Hence, its properties resemble those of an axion-like particle, so we call it the *pseudo-axion* of Little Higgs models [4]. In order to lift the bounds (mainly from astrophysics) on axions, we have to assume that the $U(1)$ symmetry is explicitly broken and the relation between the mass of the axion and its (loop-induced) coupling to photons is shifted. This is plausible, since the Yukawa interactions of the non-linear extended Higgs-axion multiplet representation break the anomalous $U(1)$ anyway.

In some cases, these additional (pseudo-)scalar degrees of freedom have been absorbed as longitudinal modes of heavy neutral vector bosons (Z'), which are quite easy to detect either at LHC or at ILC. We consider the case where the additional group remains ungauged (and can therefore be anomalous), so that the pseudoscalar is part of the physical spectrum.

Particles analogous to the Little Higgs pseudo-axion exist in other models of EWSB like technicolor, topcolor and the NMSSM (for an overview and a list of references, cf. [6]). We focus on the influence of this particle on the EW observables and on the phenomenology of the heavy quark states present in Little Higgs models.

Generically, the η is an EW singlet which parameterizes the anomalous $U(1)$ subgroup as $\xi = \exp[i\eta/F]$, where F is the vacuum expectation value of the global symmetry breaking, assumed to be of the order of $1 - 5$ TeV. If it were an exact Goldstone boson, there would be no potential for the η , so it would be exactly massless. This is ruled out by the non-existence of long-range forces. As already mentioned the fermion couplings (Yukawa interactions) break the global symmetry explicitly, generating a potential and a mass for the η , so that the astrophysical axion bounds are evaded. In order not to reintroduce a hierarchy problem, power-counting demands a mass $m_\eta \lesssim v \sim 250$ GeV. All couplings of the η to SM particles appear only via EWSB and mixing effects and are therefore v/F suppressed. The dominant decays of the η are to the heaviest SM fermions (tops, bottoms, and taus), as well as to gluons and photons via the triangle anomaly. In a model with a heavy $SU(2)$ singlet T quark, the chiral structure of the η couplings is [3, 4],

$$\begin{array}{|l|l|} \hline \bar{T}TH & O(\frac{v}{F}) \\ \bar{T}tH & O(1)\mathcal{P}_L + O(\frac{v}{F})\mathcal{P}_R \\ \bar{t}tH & O(1) \\ \hline \end{array} \quad \begin{array}{|l|l|} \hline \bar{T}T\eta & O(1)\gamma_5 \\ \bar{T}t\eta & O(1)\mathcal{P}_R + O(\frac{v}{F})\mathcal{P}_L \\ \bar{t}t\eta & O(\frac{v}{F})\gamma_5 \\ \hline \end{array}$$

where $\mathcal{P}_{L(R)}$ are the left-(right-)handed projectors, respectively.

III. THE μ MODEL

In [4], we investigate several different realizations of the Little Higgs mechanism: the Littlest Higgs, the simple-group model and the μ model [1, 2]. In all of these models the η particle has the gross properties mentioned above. Let us concentrate here on the μ model, where the embedding of the $U(1)$ and the quantum numbers of the particles are manifest, and the predictability is much better than in the other models. The model is a “moose”-like model, where a μ term like in the MSSM breaks the global symmetry explicitly and triggers EWSB. The EW gauge group is enlarged to $SU(3)_L \times U(1)_Y$ while the global symmetry breaking is $U(3) \rightarrow U(2)$. There are two non-linear sigma model fields, $\Phi_1 = \exp[iF_2/F_1\Theta](0, 0, F_1)$ and $\Phi_2 = \exp[-iF_1/F_2\Theta](0, 0, F_2)$, with Θ being the matrix

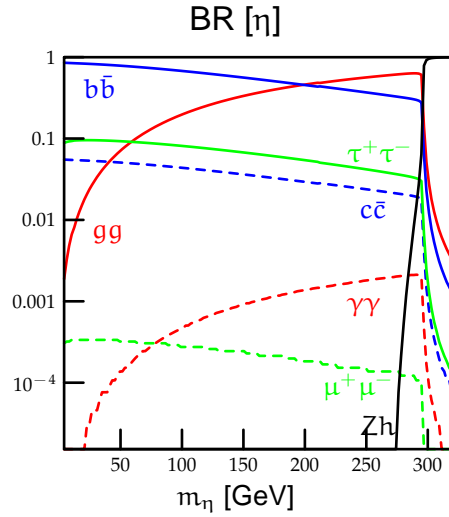
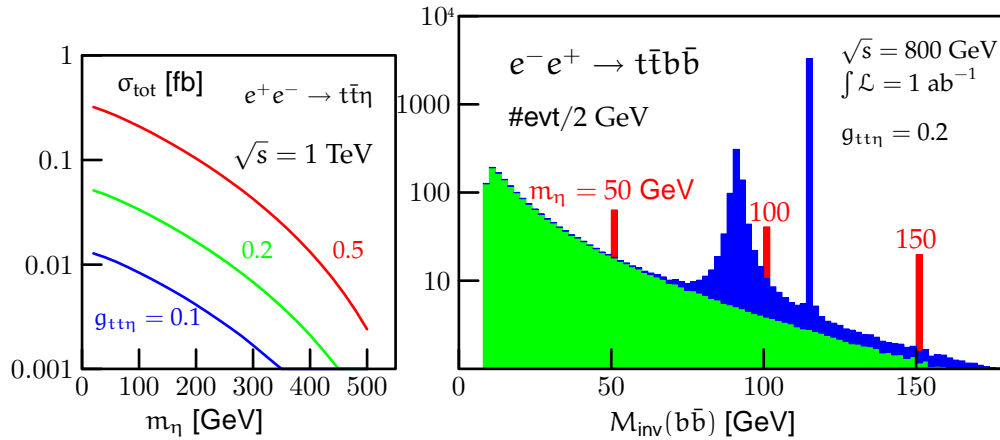
$$\Theta = \frac{1}{\sqrt{F_1^2 + F_2^2}} \begin{pmatrix} \eta & 0 & h^* \\ 0 & \eta & \\ h^T & & \eta \end{pmatrix}.$$

Introducing the parameter $\kappa \equiv F_1/F_2 + F_2/F_1 \geq 2$ the scalar potential can be written as

$$-V = -(\delta m^2 + \mu^2 \kappa)(h^\dagger h) - \mu^2 \kappa \frac{\eta^2}{2} + \left(\frac{\mu^2 \kappa^2}{12 F_1 F_2} - \delta \lambda\right)(h^\dagger h)^2 + \dots,$$

where δm^2 and $\delta \lambda$ are the one-loop contributions from the Coleman-Weinberg potential. The mass of the pseudo-axion is then given by $m_\eta = \sqrt{\kappa} \mu \geq \sqrt{2} \mu$, while the η and the Higgs masses are connected by the relation $m_H^2 = -2(\delta m^2 + m_\eta^2)$. From this one can read off that $\mu \sim v$ in order to avoid fine-tuning. But μ anyhow is restricted to lie within several GeV and nearly 400 GeV, where the upper bound comes from the EWSB constraint, the lower bound is due to the LEP Higgs exclusion limit. The Higgs mass varies between 140 and 800 GeV, depending on the ratio of the two VEVs, F_1/F_2 . This ratio plays a role similar to $\tan \beta$ in the MSSM. m_η varies between several GeV and roughly 400 GeV, rising linearly with μ .

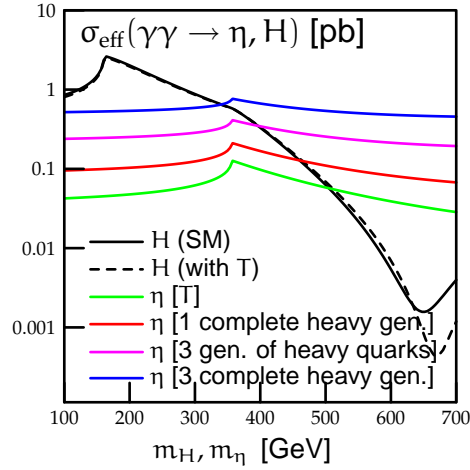
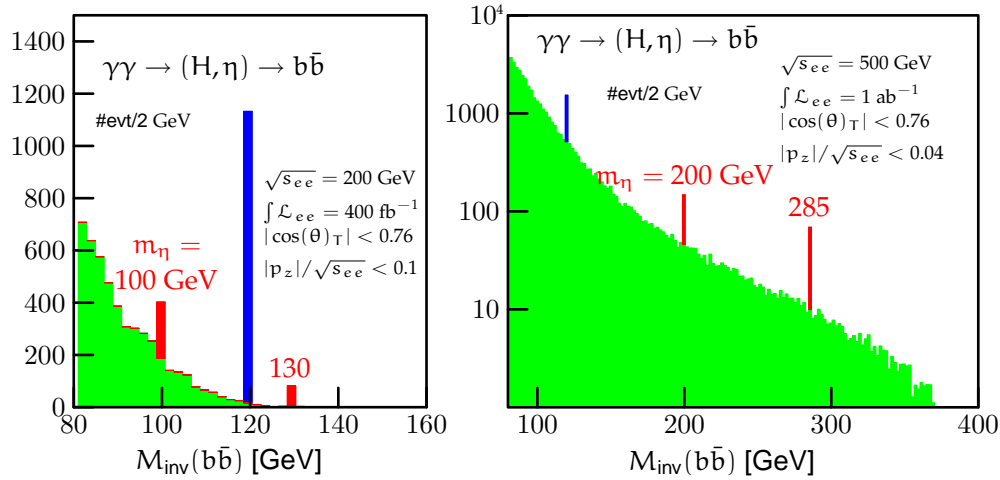
To simplify phenomenology, we assume that there is no mixing between the SM and heavy fermions for the first two generations, and that the heavy top mass takes its minimal value. Then the only free parameters are F_1 , F_2 and μ with the following bounds: $\sqrt{F_1^2 + F_2^2} \gtrsim 2$ TeV from EW precision observables and bounds on contact interactions, $F_1 \gtrsim v$, $F_2 > F_1$ from fermion mixing and the universality of fermion couplings. In ref. [2], a so called “golden


 FIG. 1: Branching ratios of the η in the μ model.

 FIG. 2: Associated production of the η at the ILC.

point” is defined for which all constraints are fulfilled: $F_1 = 0.5$ TeV, $F_2 = 2$ TeV, $M_T = 1$ TeV, $M_{D,S} = 0.7$ TeV, $M_{W'} = 0.95$ TeV, $M_{Z'} = 1.2$ TeV. D and S are the other heavy quarks (for more details see [2, 4]), and W', Z' are the additional heavy vector bosons. The pseudo-axion η resembles the pseudoscalar A in a two-Higgs doublet model (2HDM) for small $\tan\beta = F_1/F_2 < 1$. The branching ratios of the η for the golden point are given in fig. 1. Concerning the Higgs phenomenology, there are new decays $H \rightarrow Z\eta$, which can amount to 1 – 2% BR for a light η , while $H \rightarrow \eta\eta$ is negligible, but can reach 5 – 10% in the extended simple group model.

IV. COLLIDER SIGNATURES

Here we discuss the capability of the ILC and the photon collider to detect such a pseudoscalar particle. Since the largest coupling to SM particles is the $\eta t\bar{t}$ coupling, the most promising channel is associated production with a $t\bar{t}$ pair and the subsequent decay of the pseudo-axion into a $b\bar{b}$ pair. Fig. 2 (left) shows the cross section for the associated production depending on the coupling ratio $g_{tt\eta}/g_{tth}$ and the mass of the η . The right plot shows the $b\bar{b}$ invariant mass spectrum at an 800 GeV ILC with high luminosity; the light area is the QCD background, while the dark area is the EW background, the Z and a 115 GeV Higgs, respectively. The sharp spikes at 50, 100 and 150 GeV are possible signals from the η resonance. So, except for the case that the η lies too close to the Z or Higgs


 FIG. 3: Effective $\gamma\gamma \rightarrow H, \eta$ cross sections.

 FIG. 4: η signal at the 200 and 500 GeV photon collider.

resonance, it is clearly visible at the ILC. While for higher η masses the cross section goes down, also the background fades away so that for higher masses the signal-to-background ratio should be even better.

In the μ model – in contrast to the Littlest Higgs model – there is a coupling $ZH\eta$, which is v/F suppressed, but enhanced by a $\tan\beta$ effect. Therefore it is possible to study the process $Z^* \rightarrow H\eta$ in analogy to A production in the 2HDM [5].

At a photon collider which is a precision machine dedicated to Higgs physics, scalar and pseudoscalar particles can be studied as s channel resonances coupled to two photons by their anomaly couplings. The signal/background ratio is similar to the linear collider, with the signal cross section going down with increasing pseudoscalar mass, while the background also vanishes for higher energies. Fig. 3 shows the effective production cross section for the pseudo-axion in Little Higgs models in comparison to the SM Higgs production cross section. For higher masses (over 300 GeV), the cross sections for the pseudoscalar reach the same order of magnitude as for the SM Higgs, and can be even larger since for the η there is no destructive interference with gauge boson loops. The cross section depends crucially on the number of particles running in the loop. From bottom to top, the curves correspond to one heavy top quark (as in the Littlest Higgs), one complete heavy generation, three generations of heavy quarks, and three complete heavy generations (as in the simple-group model), respectively. The spike in the cross section comes from the interference of the heavy particle loops with the top loop which is important since the η couples with order one to the SM top.

The collider phenomenology of the η at the golden point ($m_\eta = 310$ GeV) is almost identical to the MSSM

pseudoscalar higgs A , as investigated in [7]. For the coupling of the η to $b\bar{b}$ we took $0.45 \times g_{bbh}$. The partial width $\Gamma(\eta \rightarrow \gamma\gamma)$ rises with increasing m_η from 0.15 keV for $m_\eta = 100$ GeV to 3.6 keV for $m_\eta = 285$ GeV, where the last value has been chosen to be just below the threshold for $\eta \rightarrow Zh$ decay, and to stay in the area of a dominant $b\bar{b}$ final state. Fig. 4 shows the $b\bar{b}$ invariant mass spectra for a photon collider running at 200 and 500 GeV, respectively. The plots have been made using the programs in [8]. Standard cuts have been applied, and a b tagging efficiency of 80% has been taken into account. The signal of a 120 GeV SM Higgs has been shown for comparison. One can see that over a wide range of η masses a discovery at the photon collider is possible. To optimize the search, the energy of the linear collider can be tuned once a significant deviation from the SM spectrum has been seen [7]; for conservative reasons, this was not done here. For more details, see [4].

V. CONCLUSIONS

Little Higgs models are an elegant alternative to supersymmetry to solve (part of) the hierarchy problem and provide a consistent framework for EWSB. If there are (approximate) $U(1)_\eta$ symmetries in the model, this gives rise to new EW singlet pseudoscalars, called pseudo-axions of Little Higgs models. In some models, these particles are absorbed as longitudinal modes of heavy Z' states, which would generally be easy to detect at future colliders. If these particles are in the physical spectrum, they would be difficult to detect, but alter the phenomenology of the Higgs and the new heavy quark states present in this class of models. An explicit breaking of the $U(1)$ symmetry by Yukawa and gauge interactions circumvents the axion limits from astrophysics. At the LHC the pseudoscalar could be detected in gluon fusion as a signal in the diphoton spectrum, if it is heavy enough. For smaller η masses the linear and photon colliders would be well-suited to detect such a state, where the linear collider could specially cover the low η mass range, and would give a spectacular opportunity (in some of the models) via the $Z^* \rightarrow H\eta$ process. The photon collider could search for the pseudo-axion over a wide range of masses, enabling a measurement complementary to the linear collider and also to possibly give access to branching ratios of the η .

Acknowledgments

This research was supported in part by the National Science Foundation under Grant No. PHY99-07949, the U.S. Department of Energy under grant No. DE-FG02-91ER40685, and by the Helmholtz-Gemeinschaft under Grant No. VH-NG-005.

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