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The fate of the Littlest Higgs with T-parity under 13 TeV LHC data

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Little Higgs models - which can most easily be thought of as a variant of composite Higgs models - explain a light Higgs boson at 125 GeV as an pseudo-Nambu-Goldstone boson of a spontaneously broken global symmetry. The mechanism of collective symmetry breaking shifts the UV scale of these models to the 10 TeV scale and higher. T-parity is introduced as a discrete symmetry to remove tree-level constraints on the electroweak precision data. Still after run 1 of LHC, electroweak precision observables gave stronger constraints than Higgs data and direct searches. We present a full recast of all available 13 TeV searches from LHC run 2 to show that now direct searches supersede electroweak precision observables. The latest exclusion limits on the LHT model will be presented, as well as an outlook on the full high-luminosity phase of LHC.

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1. Introduction

The Little Higgs mechanism whose most minimal implementation, the Littlest Higgs model [1], gives a solution to the hierarchy problem: the Higgs is light because it is a pseudo-Nambu-Golstone boson of some new global symmetry spontaneously broken at scale $f \sim$ TeV. In order to evade severe constraints from new strongly interacting sectors at the TeV scale, a collective symmetry breaking mechanism introduces a quadratically cut-off sensitive Higgs mass term only at the two-loop level and pushes an underlying strong sector to the tens of TeV scale. Despite this, electroweak precision observables (EWPO, cf. e.g. [2] still give tight constraints on Little Higgs models, particularly from the oblique corrections to the vacuum energies of the weak gauge bosons, such that the symmetry breaking scale f is limited to be larger than at least 3 TeV at 95 % confidence level. In order to allow for much lower scales, a discrete symmetry – TeV or T parity [3] – has been introduced. This symmetry relaxes the bound on f by an order of magnitude, and forces new particles to be pair-produced, and then undergo cascade decays. The lightest T-odd particle (LTP), the heavy photon partner A_H, is potentially stable. We investigate the corresponding model, the Littlest Higgs model with T-parity (LHT) and study the limits from the 8 and 13 TeV runs of the LHC from direct searches of the new heavy vector bosons, heavy quark and lepton partners predicted in this model. This study is based on [4] as well as on earlier work published in [5, 6]. Both due to tight constraints from searches for Dark Matter as well as the possibility for T-breaking UV completions, we also consider T-parity breaking.

The model is based on an $SU(5)/SO(5)$ coset space, where the EW gauge group has been doubled to $[SU(2)\times U(1)]^2 \to SU(2)_L \times U(1)_Y$ in order to implement collective symmetry breaking. T-parity renders the mixing angle 45 degrees. The implementation of T parity in the fermion sector necessitates the postulation of vector-like T-odd lepton and quark partners for all generations as well as T-even and -odd top partners ($T^\pm$). Besides the symmetry breaking scale f, the model depends on the ratio of the two Yukawa couplings in the top sector, $R := \lambda_1/\lambda_2$, and the Yukawa couplings of the heavy quark partners, κ_q and heavy lepton partners, κ_ℓ. Furthermore, the model predicts deviations of order v^2/f^2 of the SM charged and neutral current as well as Higgs couplings from their SM values. This leads to bounds from EWPO and Higgs measurements that together constrain $f \gtrsim 694$ GeV at 95% CL [6]. In the section we will discuss the limits from direct searches.

2. Recasting of direct searches and indirect constraints

For the direct searches from Run 1 (8 TeV) and Run 2 (13 TeV) we use the following notations for the heavy quark partners: $q_H = \{d_H, u_H, s_H, c_H, b_H, t_H\}$, the heavy lepton partners: $\ell_H = \{e_H, \mu_H, \tau_H, \nu_{eH}, \nu_{\mu H}, \nu_{\tau H}\}$, the heavy vectors $V_H = \{W_H, Z_H, A_H\}$ as well as the heavy T-even and -odd top partners, $T^\pm$. To compare with LHC Run 1 and Run 2 data, we studied six different categories of processes: 1. $pp \to q_H q_H, q_H \bar{q}_H, \bar{q}_H \bar{q}_H$, 2. $pp \to q_H V_H$, 3. $pp \to \ell_H \bar{\ell}_H$, 4. $pp \to V_H V_H$, 5. $pp \to T^+\bar{T}^+, T^-\bar{T}^-$, 6. $pp \to T_+\bar{q}, \bar{T}_+ q, T_+ W^\pm, \bar{T}_+ W^\pm$. This is pair production of heavy quarks (1), heavy leptons (3), heavy vectors (4), and heavy top partners (5) as well as quark-vector (2) and top partner (6) associated production. We studied a matrix of $2\times 2\times 3$ different scenarios: first three main scenarios, a so-called fermion-universality scenario with $\kappa_q = \kappa_\ell = 1.0$,

a light ℓ_H scenario with $\kappa_\ell = 0.2$ and a heavy q_H scenario with $\kappa_q = 3.0$. Each of these scenarios was combined with either light top partners $T^\pm$, i.e. $R = 1.0$, or heavy top partners inaccessible to the LHC, $R = 0.2$. Furthermore, each of these scenarios was studied for the T-parity conserving and violating cases. For the first, the LHC signals are the "classical" SUSY signals of squark-gluino production or electroweakino/slepton production, for the case of T-parity violation the A_H decays mainly via $A_H \to VV$ to SM gauge bosons, which add extra jets and leptons to the final

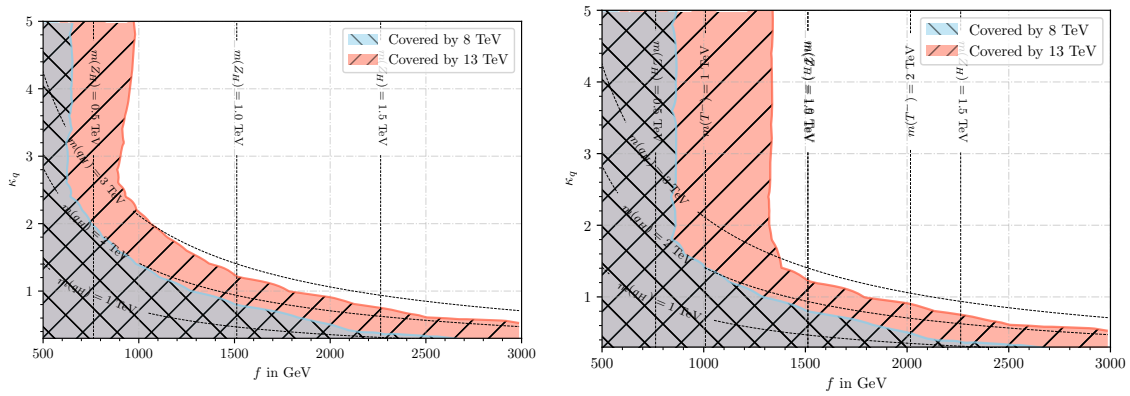

Figure 1: Limits of 8 and 13 TeV data (grey and brown, respectively) for the LHT scenario with fermion universality, T-parity conservation and light/heavy T-even/T-odd top partners (left/right panel, respectively). For more details cf. [4]

state selection, but in most cases leaves enough missing energy by a sufficient number of neutrinos. We used `MG5_aMC@NLO` [8] and `WHIZARD` [9] for the event generation, `PYTHIA8` [10] for parton showering and hadronization and `Delphes` [11] for detector simulation. The recasting of the SUSY searches from ATLAS and CMS has been done with `CheckMate` [7]. For more details on the used analyses cf. [4]. For brevity we show only the fermion universality scenario in

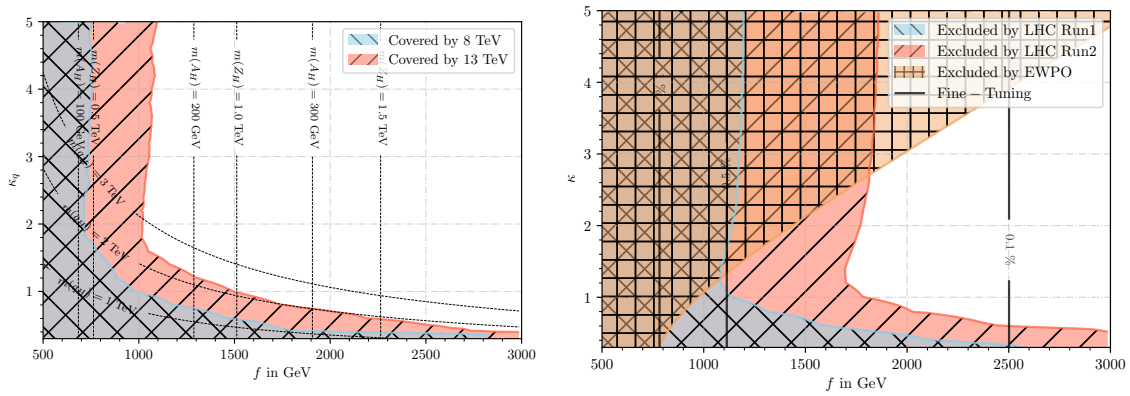

Figure 2: Combination of exclusion for the light ℓ and light T scenario with T-parity conversation for LHC Run 1 and Run 2 direct searches, respectively, as well as from 4-fermion operators. The latter are not as model-independent as the direct searches, and complementary in exclusion regions compared to the direct searches.

Fig. 1 with heavy (left) and light top partners (right). The most effective analysis is for two jets and missing transverse energy (MET) searching for $pp \to q_H q_H \to jjA_H A_H + X$. For high values of f,

the bounds follow isocontours of $M(q_H) \sim f \times \kappa_q$. For low f, the exclusion is independent of q_H and comes from $V_H V_H$ pair production, cf. Fig 1 left. If light top partners, $T^{\pm}$, are accessible, this improves the low f, κ_q-independent bounds (Fig. 1 right).

Considering T parity violation does not grossly change the picture, as can be seen in the left panel of Fig. 2. Considering all different cases, the Run 1 limits on the scale f have been increased from ca. 700 GeV to 1300 GeV. Taking into account the full energy of 14 TeV and 3,000 fb^{-1} of integrated luminosity, these bounds will increase to 1.5-1.8 TeV (95% CL) bound on the scale f.

Besides the direct searches, there are also bounds from four-fermion operators when integrating out the heavy vectors and heavy fermions. These are proportional to $\kappa^2_{q/\ell}$. Dijet and dilepton searches lead to stringent bounds for large values of κ (right panel of Fig. 2). However, these bounds depend on the details of the UV completion and are not as reliable as those from direct searches (e.g. small coefficients and cancellations between operators).

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