Collider Signature of T-quarks

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Little Higgs models with T Parity contain new vector-like fermions, the T-odd quarks or "T-quarks", which can be produced at hadron colliders with a QCD-strength cross section. Events with two acoplanar jets and large missing transverse energy provide a simple signature of T-quark production. We show that searches for this signature with the Tevatron Run II data can probe a significant part of the Little Higgs model parameter space not accessible to previous experiments, exploring T-quark masses up to about 400 GeV. This reach covers parts of the parameter space where the lightest T-odd particle can account for the observed dark matter relic abundance. We also comment on the prospects for this search at the Large Hadron Collider (LHC).

Introduction — Little Higgs (LH) models [1] (for reviews, see [2,3]) provide an interesting scenario for physics at the TeV scale, alternative to other popular scenarios such as supersymmetry or extra dimensions. The LH models contain a Higgs boson of mass m_h up to several hundred GeV, as well as additional gauge bosons, fermions, and scalar particles with masses in the 100 GeV – 5 TeV range. These models describe the physics up to a "cutoff scale" of order 10 TeV, beyond which they need to be embedded in a more fundamental theory. The hierarchy between the Higgs mass and the cutoff scale is due to the fact that the Higgs is a pseudo-Nambu-Goldstone boson, corresponding to a global symmetry spontaneously broken at a scale $f \sim 1$ TeV. Explicit breaking of the global symmetry by gauge and Yukawa couplings induces a non-trivial Higgs potential via quantum effects, triggering electroweak symmetry breaking (EWSB). However, the one-loop quadratically divergent contribution to the Higgs mass vanishes due to the special "collective" nature of the explicit global symmetry breaking, and thus the Higgs mass can be achieved with minimal fine-tuning.

Early implementations of the Little Higgs mechanism suffered from severe constraints from precision electroweak fits [4]. These constraints are elegantly avoided by the introduction of T Parity [5], a discrete $\mathcal{Z}_2$ symmetry which is constructed in such a way that all the Standard Model (SM) states are even, while most new TeV-scale states of the LH model are odd. This construction forbids all tree-level corrections to precision electroweak observables from the new states. Many LH models can be extended to incorporate T Parity. In this letter, we focus on one of the simplest examples, the Littlest Higgs model with T Parity (LHT) [6]. Precision electroweak constraints on this model have been analyzed at the one-loop level [7], and it was shown to provide consistent fits for values of f as low as 500 GeV, avoiding fine tuning. The model also provides an attractive dark matter candidate [8,9], the lightest T-odd particle (LTP).

Consistent implementation of T Parity in the LHT model requires the introduction of a T-odd vector-like fermion partner for each left-handed T-even SM fermion, yielding six new Dirac T-odd quarks ("T-quarks"), $\tilde{Q}_i^a = (\tilde{U}_i^a, \tilde{D}_i^a)$, and six new Dirac T-odd leptons ("T-leptons"), $\tilde{L}_i = (\tilde{E}_i, \tilde{N}_i)$, where $i = 1 \ldots 3$ is the generation index and a is the color index. The masses of these states lie in the 100 GeV – few TeV range. The main goal of this letter is to analyze the collider phenomenology of the T-quarks.

Model — The LHT model has been discussed in detail elsewhere [3,6–8]; here, it suffices to summarize the features important for our analysis. The LHT is based on a weakly gauged non-linear sigma model (nlsm). The global symmetry breaking pattern is $SU(5) \rightarrow SO(5)$, resulting in 14 Nambu-Goldstone bosons. The symmetry breaking scale, f (the pion decay constant of the nlsm), is a free parameter; in the absence of fine tuning, $f \sim 1$ TeV. The nlsm is valid up to the cutoff scale $\Lambda \sim 4\pi f \sim 10$ TeV. The physics above the cutoff scale will not be discussed here since it is outside of the reach of the Tevatron and the LHC. The gauge symmetry group is $[SU(2) \times U(1)]^2$, broken at the scale f down to the diagonal subgroup, $SU(2)_L \times U(1)_Y$, which is identified with the SM electroweak gauge symmetry. Four Nambu-Goldstone bosons are absorbed in this breaking; the remaining 10 form the SM Higgs doublet, H, and a new $SU(2)_L$ scalar triplet, Φ.

At the quantum level, explicit breaking of the $SU(5)$ global symmetry by gauge and Yukawa couplings induces a potential for H and triggers EWSB, $SU(2)_L \times U(1)_Y \rightarrow U(1)_{\text{em}}$. The action of T Parity in the gauge sector interchanges the two sets of $SU(2) \times U(1)$ gauge fields. The T-even combinations of the gauge bosons correspond to the SM W, Z and γ, whereas the T-odd combinations, denoted by $\tilde{W}^a (a = \pm, 3)$ and $\tilde{B}$, acquire masses at the scale f:

$$M(\tilde{W}^a) \approx gf, \quad M(\tilde{B}) \approx \frac{g'f}{\sqrt{5}} \approx 0.16f, \qquad (1)$$

where g and g' are the SM $SU(2)_L$ and $U(1)_Y$ gauge couplings, and corrections of order v^2/f^2 due to the EWSB have been neglected. Note that the T-odd $U(1)$ gauge boson, $\tilde{B}$, or so called "heavy photon" is quite light com-

pared to f. In large parts of the parameter space, the $\tilde{B}$ is the LTP, and is stable. Since the $\tilde{B}$ is weakly interacting, its stability poses no cosmological difficulties, and in fact it can act as WIMP dark matter [8,9]. In the analysis of this letter we will assume that the heavy photon is the LTP. The scale f is bounded from below by precision electroweak data [7] and the corresponding bound on the LTP mass is $M(\tilde{B}) > 80$ GeV.

The masses of the T-quarks and T-leptons are given by

$$M_{ij}(\tilde{Q}) = \kappa_{ij}^Q f, \quad M_{ij}(\tilde{L}) = \kappa_{ij}^L f, \qquad (2)$$

where the couplings κ are free parameters. In this letter, we will focus on the T-quarks of the first two generations, and assume that they have a common mass, $\tilde{M}$. This degeneracy eliminates any potential loop-level flavor-changing effects via the GIM mechanism [10]. Experimental bounds on the flavor-conserving four-fermion operators such as $eeuu$ and $eedd$ imply the bound [7]

$$\tilde{M} < 4.8 \text{ TeV} \left(\frac{f}{\text{TeV}} \right)^2 . \qquad (3)$$

T-quark contributions to precision electroweak observables have been computed in [7], and do not impose any new bound on $\tilde{M}$. To avoid charged/colored LTP, we require $\tilde{M} > M(\tilde{B})$.

The LHT model contains additional states in the top sector, required to cancel the one-loop quadratic divergence in the Higgs mass from top loops. The collider phenomenology of these states [8,21], however, does not play a role in this analysis.

Before proceeding, it is useful to compare and contrast the spectrum of the LHT model with the more familiar case of the minimal supersymmetric standard model (MSSM). In both models, SM states acquire parity-odd partners with the same gauge quantum numbers. For example, the $\tilde{W}^a$ and $\tilde{B}$ bosons of the LHT model are the analogues of the wino and bino of the MSSM; the T-quarks and T-leptons are the counterparts of squarks and sleptons. The two important differences are: (1) the LHT partners have the same spin as the SM states; and (2) in the LHT, partners only exist for a subset of the SM: for example, the right-handed SM fermions and the gluon do not acquire T-odd partners.

Collider Signatures — At a hadron collider, the T-quarks can be pair-produced via QCD processes:

$$q\bar{q} \to \tilde{Q}_i \bar{\tilde{Q}}_i, \quad gg \to \tilde{Q}_i \bar{\tilde{Q}}_i. \qquad (4)$$

The produced T-quarks decay promptly. Due to conserved T Parity, their decay products necessarily contain the LTP $\tilde{B}$, leading to a missing energy signature in the detector. In particular, the decay channel
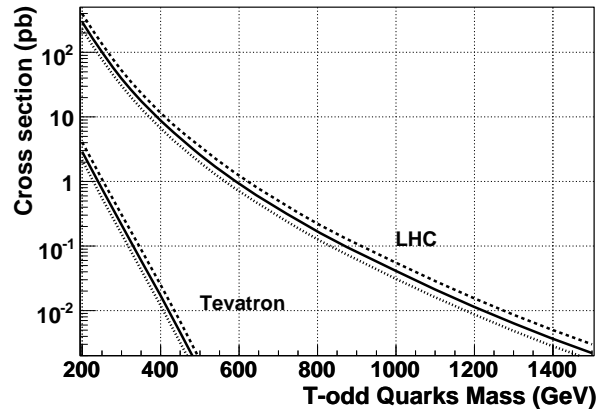
$$\tilde{Q}_i \to q_i \tilde{B} \qquad (5)$$

FIG. 1. Cross section of T-quark pair production (per flavor) at the Tevatron Run II and at the LHC. Solid, dashed and dotted lines correspond to $\mu = \tilde{M}, \tilde{M}/2$ and $2\tilde{M}$, respectively.

is open throughout the parameter space for $q_i = u, d, s, c$, with the exception of very narrow bands where the T-quarks and the LTP are nearly-degenerate. Events with both T-quarks decaying in this channel result in a $2j + \not{E}_T$ signature with acoplanar jets both at the Tevatron and the LHC. Within the T-quark mass range accessible at the Tevatron, the branching ratio in the channel (5) is very nearly 100%. For heavier T-quarks, competing channels such as $q\tilde{W}$ may open up, which could be relevant for LHC studies.

To analyze the experimental reach in terms of the model parameters, we have implemented the relevant sector of the LHT model in the `MadGraph` [11] parton-level event generator and simulated the reaction (4), (5). The total T-quark production cross sections (per T-quark flavor) at the Tevatron Run II and the LHC are shown in Fig. 1. The CTEQ6L1 PDF set [12] was used, and renormalization and factorization scales, μ, were varied between $\tilde{M}/2$ and $2\tilde{M}$ to obtain an estimate of the associated uncertainty. The rather large uncertainty (typically about 30%) is primarily due to the use of the leading-order matrix element, and could be improved by a next-to-leading order calculation of the process (4) in the LHT model. Based on the studies of squark production processes with similar kinematics, we expect that the NLO cross section is enhanced by $K \sim 1.3$ compared to the LO estimate. However, we do not rescale our leading order result, and so we expect our estimate is conservative.

The counterpart of the process (4), (5) in the MSSM is the production of squark pairs followed by the decay $\tilde{q} \to q\tilde{\chi}_1^0$. The production cross section of T-quark pairs is larger than that of squarks with the same mass due to the spin sum of the final state. However, if the T-quark and squark masses, as well as the LTP and LSP masses are equal, we find that the properties of the final-state jets (e.g. transverse energy and rapidity distributions) are essentially identical. Therefore, with the appropriate

overall rescaling, pair production and decay of T-quarks can be perfectly simulated using PYTHIA 6.323 [13] as an MSSM event generator which goes beyond the parton level. For this analysis, we generate a set of Monte Carlo events equivalent to the pair production of first and second generation T-quarks, assuming 100% branching fraction for the decay channel (5).

The DØ experiment developed two analyses searching for events in the acoplanar dijet topology using 310 pb^{-1} of data recorded during the Tevatron Run II, which can be reinterpreted as T-quark searches. The first one ("analysis A") is the search for squark pair production described in [14]. This analysis is efficient for large mass differences between the T-quarks and the LTP. The second analysis ("analysis B") is the search for scalar leptoquarks decaying into a quark and a neutrino [15], which is more efficient for low mass differences between T-quarks and the LTP. Those two event selections were applied to the Monte Carlo samples described above to extract signal efficiencies. As those Monte Carlo samples do not have any detector simulation, the signal efficiencies obtained in this way are overestimated. To take that effect into account, the signal efficiencies obtained at the generator level were compared to those reported in [14,15]. A conservative scale factor of 0.75 was applied on all T-quark signal efficiencies.

In Figure 2, we present the expected mass limits at the 95% C.L. in the $(\tilde{M}, M(\tilde{B}))$ plane. We have used the number of expected background events and the systematic uncertainties reported in [14,15], as well as the leading order T-quark pair production cross sections from Figure 1. In addition, the limits are computed using the modified frequentist CL_s method [16]. Also shown in Figure 2 are the regions excluded by the precision electroweak data, which place a lower bound on the scale f of about 500 GeV (see Ref. [7] for details) corresponding to $M(\tilde{B}) \gtrsim 80$ GeV, and by the LEP squark searches [17]. Note that the LEP reach for squarks is limited by kinematics, so that the reach for T-quarks is nearly identical in spite of different production cross sections. With only 310 pb^{-1}, Tevatron Run II data can place relevant bounds on the T-quark and LTP masses, probing a region of the parameter space not accessible to previous experiments. Taking into account the factorization scale uncertainty, the expected lower bound on the T-quark mass is approximately 325 GeV if $\tilde{M} - M(\tilde{B}) \gtrsim 245$ GeV (where analysis A is applicable) and 265 GeV if $\tilde{M} - M(\tilde{B}) \gtrsim 140$ GeV (where analysis B is used). There is no strict bound for smaller values of the T-quark-LTP mass difference, since in this case the produced jets are too soft to be detected. The reach can be extended further with additional integrated luminosity. An extrapolation to 8 fb^{-1}/experiment shows that T-quark masses up to 400 GeV will be probed (see Fig. 2).

A search for the $2j + \not{E}_T$ signature at the LHC is expected to have significantly better reach in $\tilde{M}$ due to the higher T-quark production cross sections, see Fig. 1. We

estimate that the T-quark masses up to about 850 GeV could be probed at the 3σ level with a few fb^{-1} of integrated luminosity. To obtain this estimate, we computed the number of signal and background events at the parton level, imposing the cuts $\not{E}_T \geq 200$ GeV, $p_{T\,jet} \geq 200$ GeV. We assumed that with these cuts the background is dominated by the irreducible component, Zjj with the Z decaying invisibly. This background can be calibrated using the events with the Z decaying leptonically; we assumed that the accuracy of this calibration is 10%. Note, however, that instrumental backgrounds, such as pure QCD multi-jet events with apparent $\not{E}_T$ due to jet mismeasurement, will likely play an important role in limiting the reach. A careful analysis of this issue, including a full detector simulation, is required to obtain a more robust estimate of the reach. Note also that our analysis assumed $\mathrm{Br}(\tilde{Q} \to q\tilde{B}) = 100\%$, and is not directly applicable if $M(\tilde{W}) < \tilde{M}$. (For a recent discussion of the potential signatures of T-quarks in leptonic final states at the LHC, see [18,19].)
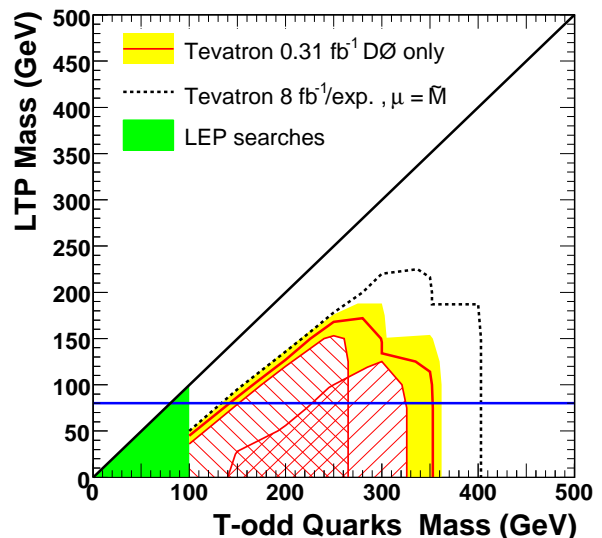

FIG. 2. Present and projected reach of the Tevatron Run II search for T-quarks in the $(\tilde{M}, M(\tilde{B}))$ plane. The thick red line shows the expected excluded region at the 95% C.L. for a luminosity of 310 pb^{-1}, and $\mu = \tilde{M}$. The yellow band shows the effect of varying the renormalization and factorization scale between $\mu = 2\tilde{M}$ and $\mu = \tilde{M}/2$. The hatched regions show the expected excluded regions by analysis A and B separately, for $\mu = 2\tilde{M}$. The dotted black line shows the projection to an integrated luminosity of 8 fb^{-1} per experiment at the Tevatron for $\mu = \tilde{M}$. The thick blue line corresponds to the indirect lower limit on the $\tilde{B}$ mass from precision electroweak data.

T-Quark Searches and Dark Matter — The relic density of the heavy photon LTP in the LHT model is sensitive to its mass, the Higgs boson mass, and also to

3

the mass of T-quarks and T-leptons, due to the possibility of coannihilation between these states and the LTP. Assuming that the LTP accounts for all of the dark matter, the precise measurement of the present dark matter abundance by the WMAP collaboration ($\Omega_{\rm dm}h^2 = 0.104^{+0.007}_{-0.010}$ [20]) imposes a tight constraint on these parameters [8,9]. In Fig. 3, the constraints obtained in Ref. [9] (for several values of the Higgs mass) are superimposed onto the Tevatron reach in the $(\tilde{M}, M(\tilde{B}))$ plane. Tevatron Run II experiments are already in the position to probe some of the parameter space relevant for cosmology. If a signal in the $2j + \not{E}_T$ channel is seen, the observed jet p_T distributions and the total cross section should allow an approximate determination of $\tilde{M}$ and $M(\tilde{B})$. The LHC will probe the parameter space further, and, together with the expected direct measurement of the Higgs boson mass, will provide a direct collider test of the LTP dark matter hypothesis.
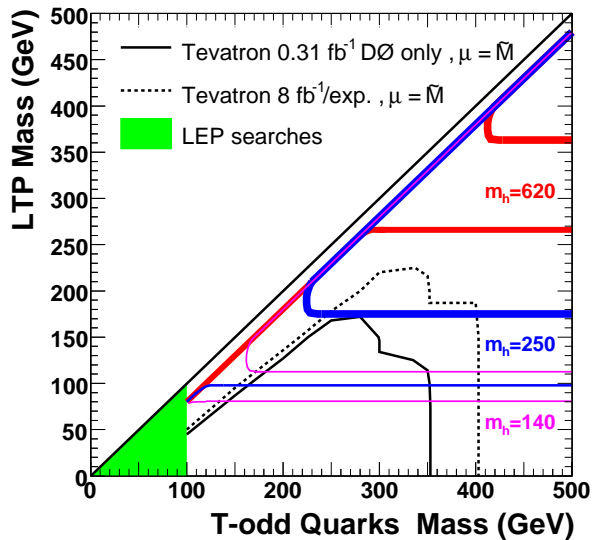

FIG. 3. Prospective reach of the T-quark search at the Tevatron Run II superimposed with the bands for which the LTP accounts for all of the observed dark matter for three representative values of the Higgs mass, 140, 250 and 620 GeV.

Discussion — The LHT signature discussed here is complementary to the previously studied signatures involving direct production of the T-odd gauge bosons and the triplet Higgs [8], as well as the T-even and T-odd partners of the top quark [8,21]. The process (4) provides a simple signature with relatively low backgrounds and a QCD-strength cross section, making it a very promising channel experimentally. On the other hand, note that while naturalness puts rather strong constraints on the masses of the new states in the gauge and top sectors, the T-odd quarks could be as heavy as 5 TeV without fine tuning. It is therefore important to pursue searches in all

possible channels to maximize the discovery potential.

It is clear that a $2j + $ MET signal will not be a conclusive signature of the LHT model. As noted above, the jet p_T, η and $\not{E}_T$ distributions are identical in the LHT model and the MSSM with matching spectra. While the production cross section for the T-quarks and squarks of the same mass is different, the ambiguity in the overall mass scale due to the presence of missing energy does not allow one to easily discriminate between the two cases based on the overall rate [22]. Unambiguous discrimination between the LHT and SUSY models will require a measurement of spin correlations in cascade decays [23], if such decays are available, or will have to wait until the experiments at the International Linear Collider (ILC).

Conclusions — Events with acoplanar jets and large missing transverse energy provide a promising experimental signature for T-quarks of the LHT model at hadron colliders. Our study indicates that the Tevatron Run II has an interesting reach in this channel, even using only the first 310 pb^{-1} of the collected data. A dedicated study by the CDF and DØ collaborations in the context of the LHT model will be of great interest.

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