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Impact of single-top measurement to Littlest Higgs model with T-parity

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ABSTRACT

We show that a precise measurement of the single-top production cross section at the Tevatron and the LHC can strongly constrain the model parameters of the Littlest Higgs model with T-parity. A reduction in the single-top production rate from the Standard Model prediction implies new physics phenomena generated by the heavy T-parity partners of the top quark. We show that the degree of polarization of the top quark produced from the decay of its heavy T-odd partner (T_-) can be utilized to determine the new physics energy scale, and the mass of T_- can be measured from the missing transverse momentum distribution in the $T_-\bar{T}_-$ event.

In spite of the great success of the Standard Model (SM) of particle physics, there is no explanation on the mass of the SM Higgs boson to be at the weak scale. One extension of the SM, as a low energy effective theory below the cutoff scale Λ, is the class of Little Higgs (LH) models [1] in which the electroweak symmetry is collectively broken and a weak scale Higgs boson mass is radiatively generated. At one loop order, the large Λ^2 correction to the Higgs boson mass term induced by the top quark (t) is cancelled by its fermionic partner, and those induced by the electroweak gauge bosons are cancelled by their bosonic partners. Constraints from low energy precision data, especially the ρ-parameter measurement, require the symmetry breaking scale of the LH models has to be so high that the predicted phenomenology has little relevance to the current high energy collider physics program [2]. To relax the constraints from low energy data, a discrete symmetry called T-parity was introduced in the Little Higgs models, to warrant the ρ-parameter to be one at tree-level, known as the Little Higgs models with T-parity [3–7]. Consequently, the cutoff scale of the model, $\Lambda = 4\pi f$, can be as low as 10 TeV and the masses of new heavy resonances, at the scale of f, can be of sub-TeV [3]. This type of models is particularly interesting because it also provides a dark matter candidate which is the lightest T-odd particle (LTP) A_H, the heavy bosonic T-parity partner of photon [8]. Here, we shall focus on the "Littlest" Higgs model with T-parity (LHT), which is based on an $SU(5)/SO(5)$ nonlinear sigma model whose low energy Lagrangian is described in detail in Ref. [7]. The new particle mass scale f of the model is bounded from below by low energy precision data to be about 500 GeV [4]. In this Letter, we will concentrate on the phenomenology associated with the T-even top partner (T_+), T-odd top partner (T_-) and T-odd partners of the electroweak gauge bosons [7].

After the electroweak symmetry breaking, the masses of the T-parity partners of the photon (A_H), Z-boson (Z_H) and W-boson (W_H) are generated as $M_{A_H} = \frac{g'f}{\sqrt{5}}(1 - \frac{5v^2}{8f^2} + \cdots)$ and $M_{Z_H} \simeq M_{W_H} = gf(1 - \frac{v^2}{8f^2} + \cdots)$. Here, v characterizes the weak scale ($\simeq 246$ GeV), and at tree level the SM-like W and Z gauge boson masses can be expressed as $M_W = \frac{g}{2}v$ and $M_Z = \frac{\sqrt{g^2+g'^2}}{2}v$, respectively. Because of the smallness of the $U(1)_Y$ gauge coupling constant g', the T-parity partner of the photon A_H tends to be the lightest T-odd particle in the LHT. We note that the mass of W_H is determined by f, for the $SU(2)_L$ gauge coupling constant g and the vacuum expectation value v have been fixed by the measured values of W and Z boson masses. Hence, if M_{W_H} can be directly measured from collider data, then the cutoff scale of the LHT can be determined. Another way to determine the scale f is to study the T-parity partners of the top quark which is to be shown below.

As shown in Ref. [7], the mass of top quark is generated from top-Yukawa interaction Lagrangian which depends on two parameters of the LHT. In this work they are chosen to be f and the mixing angle α which describes the amount of mixing among the fermionic degrees of freedom needed to cancel the quadratic divergence of Higgs boson mass term at the one loop level. The mass of top quark (m_t) has been measured to a good accuracy [9]. Given m_t and v, we can trade the two parameters f and α by the masses of the top quark T-parity partners T_+ and T_-. Up to the $O(v^2/f^2)$ corrections, they can be expressed, respectively, as

$$M_{T_+} = \frac{m_t f}{v c_\alpha s_\alpha}, \qquad M_{T_-} = \frac{m_t f}{v s_\alpha}, \tag{1}$$

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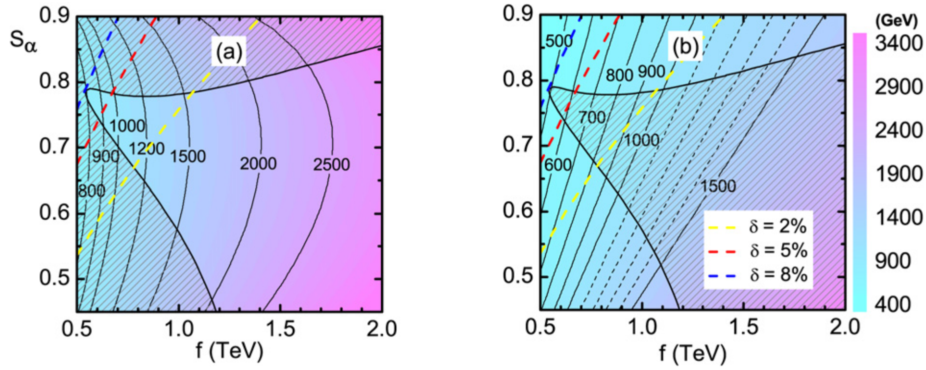

Fig. 1. Contours of M_{T_+} (a) and M_{T_-} (b) (in the unit of GeV) in the plane of s_α and f. See detailed explanation in the text. (For interpretation of the references to color in this figure, the reader is referred to the web version of this Letter.)

where s_α denotes $\sin\alpha$ and is bounded from above to be less than 0.96 by the unitarity requirement for considering the $J = 1$ partial wave amplitudes in the coupled system of $(t\bar{t}, T_+\bar{T}_+, b\bar{b}, WW, Zh)$ states [7]. Moreover, $\sin\alpha$ cannot be exactly equal to zero because the "collective" symmetry breaking mechanism of the LHT only works for a non-zero s_α, and M_{T_+} cannot be larger than the cutoff scale Λ of the low energy effective theory. If we take the "naturalness" argument seriously for the Higgs mass corrections, then s_α has to be larger than about 0.1 for f to be around 1 TeV [7]. In Fig. 1, we show the contours of M_{T_+} (left panel) and M_- (right panel) in the plane of s_α and f. The shadowed (grey) region of this two-dimensional parameter space is excluded by the electroweak precision test (EWPT), with V_{tb} set to be 1, at the 95% confidence level [4].

Due to the mixing between t and T_+, the couplings of $W^+_\mu \bar{t}b$ and $W^+\bar{T}_+b$ are expressed, respectively, as

$$V_{tb}\left(i\frac{g}{\sqrt{2}}c_L\gamma_\mu P_L\right) \quad \text{and} \quad V_{tb}\left(i\frac{g}{\sqrt{2}}s_L\gamma_\mu P_L\right), \tag{2}$$

where V_{tb} is the value of the (t,b) element of the Cabibbo–Kobayashi–Maskawa (CKM) matrix, $c_L = \sqrt{1-s_L^2}$ with $s_L = s_\alpha^2\frac{v}{f} + \cdots$, and $P_L = \frac{1-\gamma_5}{2}$ and $P_R = \frac{1+\gamma_5}{2}$ are the left-handed and right-handed projection operators, respectively. In the above expression, the product of $V_{tb}c_L$, which is denoted as V_{tb}^{eff}, should be identified with the CKM matrix element determined from the low energy processes up to the one-loop order. In the SM, the value of V_{tb} element is constrained by the unitarity of CKM matrix, which requires its value to be very close to 1 (about 0.999 [10]). For simplicity, we will take $V_{tb} = 1$ in our numerical analysis. When the parameter s_α varies, the effective coupling strength of $W^+\bar{t}b$, hence the single-top production rate at the Fermilab Tevatron and the CERN Large Hadron Collider (LHC), also varies. As $s_\alpha \to 0$, it is approaching the SM $W^+\bar{t}b$ coupling strength. Furthermore, since $|s_\alpha|$ is bounded by 1, c_α has to be larger than $\sqrt{1-(v/f)^2}$ in the LHT; with $f = 500$ GeV, $c_\alpha > 0.88$. Hence, V_{tb}^{eff} is consistent with the Tevatron measurement on the decay branching ratio of $t \to bW^+$ in the $t\bar{t}$ events [10]. It is also consistent with the most recent measurement of single-top event rate at the Tevatron: $|V_{tb}| = 1.0^{-0.12}_{+0.0}$ [11].

Since the strength of the $W^+_\mu \bar{t}b$ coupling in the LHT is always smaller than that in the SM, the single-top production rate at the Tevatron and the LHC will also be smaller than that predicted by the SM. Hence, the measurement of the single-top production cross section provides a crucial test to the LHT. The deviations of the cross sections of the single-top production from the SM predictions ($\delta \equiv \Delta\sigma/\sigma_{\text{SM}}$) can be expressed in terms of s_α and f as

$$\delta = \frac{\sigma_{\text{SM}} - \sigma_{\text{LHT}}}{\sigma_{\text{SM}}} = s_\alpha^4\frac{v^2}{f^2} + \mathcal{O}\left(\left(\frac{v}{f}\right)^4\right). \tag{3}$$

Table 1
Mass limits (in unit of GeV) of T_+ and T_- quarks for various δ values. Here the brackets denote the range of δ, M_{T_+} and M_{T_-}, respectively

$\delta(\%)$	$[5, 8]$	$[2, 5]$	< 2
M_{T_+}	$[800, 1000]$	$[870, 1600]$	> 1100
M_{T_-}	$[500, 620]$	$[580, 950]$	> 830

For illustration, we show in Fig. 1 the constraints on the parameter s_α and f for $\delta = 2\%$ (yellow dashed-line), 5% (red dashed-line) and 8% (blue dashed-line), respectively. In the same figure we also show the contours of M_{T_+} (left panel) and M_{T_-} (right panel). The pattern of the contour lines can be easily understood from Eq. (1). We note that the allowed parameter space is strongly constrained when δ is small. For example, when $\delta \lesssim 2\%$, $f \geqslant 780$ GeV and $0.67 < s_\alpha < 0.78$; when $\delta \lesssim 5\%$, $f \geqslant 600$ GeV and $0.74 < s_\alpha < 0.85$; and when $\delta \lesssim 8\%$, $f \geqslant 550$ GeV. The above constraints can be translated into non-trivial limits of M_{T_+} and M_{T_-}, which are summarized in Table 1.

At hadron colliders, single-top events can be produced via three processes: s-channel ($u\bar{d} \to t\bar{b}$), t-channel ($ub \to dt$) and tW associated channel ($gb \to tW^-$); each process generates distinct event distributions and can be measured separately. In the LHT, the deviations of the single-top production rates of these three processes from the SM predictions have to be identical at the tree level, i.e. $\delta(s) = \delta(t) = \delta(tW)$. This is an important test of the LHT. In contrast, the above relation does not hold for LH models without T-parity [12].

As noted above, the value of s_α cannot be zero in order for the LH mechanism to take place. Therefore, a heavy T_+ can be produced singly in hadron collisions via weak charged current ($W^+\bar{T}_+b$) interaction, similar to the SM single-t production, and is referred as single-T_+ production in this work. In Fig. 2 we present the inclusive cross sections of single T_+ production at the LHC in the plane of s_α and f. (Its production rate is too small to be observed at the Tevatron for f greater than 500 GeV.) In the same figure, we also show the constraints from the single-t production rate measurement on the parameters s_α and f for $\delta = 2\%$ (yellow dashed-line), 5% (red dashed-line) and 8% (blue dashed-line), respectively. Again, the gray region is excluded by EWPT. We note that the large single-T_+ cross sections ($\gtrsim 50$ fb) occur in the regime of $f < 750$ GeV and $s_\alpha \sim 0.75$, where the single-top production rates are reduced as compared to the SM rates by about 3–8%. Should no deviation be found in the single-t production, e.g. $\delta \leqslant 2\%$ (below the yellow dashed curve), it will be very difficult to directly observe the single-T_+ signal at the LHC due to its small cross section ($\lesssim 13$ fb). Therefore, the correlation of the single top production to the single-T_+ production rates can be used to test the LHT.

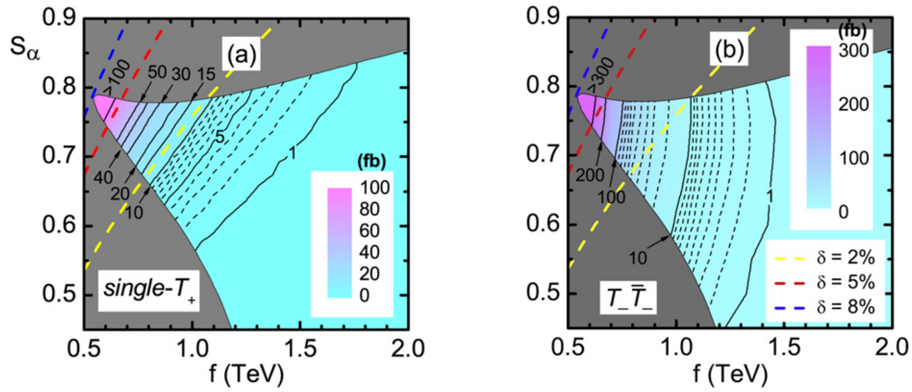

Fig. 2. Contours plots of the inclusive cross section (in unit of fb) in the plane of s_α and f: (a) for the single T_+ process given in Eq. (7) and (b) for the $T_-\bar{T}_-$ pair process given in Eq. (8). The W-boson decay branching ratio is *not* included here. (See detailed explanation in the text.) (For interpretation of the references to color in this figure, the reader is referred to the web version of this Letter.)

It is worthwhile mentioning that, other new physics processes, e.g. $qb \to q'T_+$ followed by $T_+ \to tZ(\to \nu\nu)$, might also induce the same collider signature as the SM single top production process. They will inevitably affect the precision measurement of the single top production cross section. However, we expect those New Physics (NP) processes to be suppressed by making use of the kinematics differences between the SM single top production and those new physics processes. Needless to say, in order to fully understand how well one can measure the single top production rate, one needs to perform a realistic collider simulation, including all the background (both the SM and NP) processes, the detector effects, b-jet tagging efficiency, as well as the theoretical uncertainties, etc. However, it is beyond the scope of this work and will be presented elsewhere.

While T_+ is mainly produced via single-T_+ process, the T-odd heavy quark T_- is predominantly produced in pairs via strong QCD interaction because of the requirement of T-parity symmetry. Since the coupling of gluon to $\bar{T}_-T_-$ pair is fixed by the QCD gauge interaction, the $T_-\bar{T}_-$ pair production rate is determined by the mass of T_-, and its dependence on the parameters s_α and f is shown in Fig. 2. Again, we see that a precise measurement of the single-t production cross section can provide a stringent test on the LHT. A reduction in the single-top production rate by more than 5% would imply the $\bar{T}_-T_-$ pair production rate at the LHC to be larger than about 200 fb and f to be less than about 700 GeV. We also note that the $\bar{T}_-T_-$ cross section is more sensitive to f than s_α, as compared to the single-T_+ cross section.

The T_- quark preferentially decays into t plus A_H, so the collider signature of the $T_-\bar{T}_-$ pair event is

$$q\bar{q}(gg) \to T_-\bar{T}_- \to A_H A_H t\bar{t}, \tag{4}$$

where the two A_H's produce the missing transverse energy signature. For the $t\bar{t}$ plus missing transverse energy signature, the intrinsic SM background is generated from the process $q\bar{q}(gg) \to t\bar{t}Z$, where Z decays into a pair of neutrinos, whose cross section is about 60 fb at the LHC. To observe the $T_-\bar{T}_-$ signal, one has to suppress this large background. Usually, this is done by making kinematic selections to enhance the signal-to-background ratio, such as the study done in Ref. [6] which concluded that a large background rate remained even after imposing a set of kinematic cuts. Here, we propose a new method to largely suppress the SM background rate by measuring the degree of polarization of the top quark (or top anti-quark) in the final state.

An interesting feature of the T_- decay is that the top quark from T_- decay is predominately right-handedly polarized because

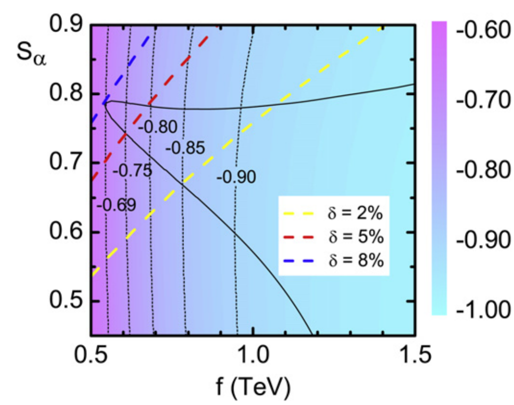

Fig. 3. Contour plot of $\mathcal{A}_{LR}$ in the $T_-\bar{T}_-$ pair production in the plane of s_α and f.

the left-handed component of the $A_H T_- t$ coupling is suppressed by a factor of $\frac{v}{f}s_\alpha$, for

$$g_{A_H T_- t} = \frac{2}{5} g' s_\alpha \gamma_\mu \left(s_\alpha \frac{v}{f} P_L + P_R \right). \tag{5}$$

Parity is clearly broken in this coupling. In order to quantify the parity violation effects, we define an asymmetry quantity $\mathcal{A}_{LR}$ as

$$\mathcal{A}_{LR} \equiv \frac{\sigma(t_L) - \sigma(t_R)}{\sigma(t_L) + \sigma(t_R)}, \tag{6}$$

where t_L and (t_R) denote the left-handedly and right-handedly polarized top quark, respectively. The Z boson preferentially couples to a left-handedly polarized top quark such that $\mathcal{A}_{LR}^{\rm SM}$ of the $t\bar{t}Z$ process is always larger than zero. (At the LHC, $\mathcal{A}_{LR}^{\rm SM} = 0.106$.) On the contrary, $\mathcal{A}_{LR}^{\rm LHT}$ of the signal process (4) is always smaller than zero. Therefore, the SM intrinsic background rate can be largely suppressed by demanding a negative value of $\mathcal{A}_{LR}$. In Fig. 3 we present the contour of $\mathcal{A}_{LR}^{\rm LHT}$ in the plane of s_α and f. We note that $\mathcal{A}_{LR}$ mainly depends on f and is not sensitive to s_α. This result leads to an important observation that the new particle mass scale parameter f can be determined by measuring the asymmetry $\mathcal{A}_{LR}$ in the production rates of left-handed and right-handed top quarks in the events with the $t\bar{t}$ plus missing transverse energy signature. For example, if $\mathcal{A}_{LR}$ takes the value around -0.69, then f is about 550 GeV. For a larger value of f, the asymmetry $\mathcal{A}_{LR}$ approaches to -1. After measuring f via $\mathcal{A}_{LR}$, one can uniquely determine s_α from the measurement of M_{T_-} or M_{T_+}. Should all these three observables $(\mathcal{A}_{LR}, M_{T_-}, M_{T_+})$ be measured, together with the single-top precision measurements, one can test the consistency of the LHT with data.

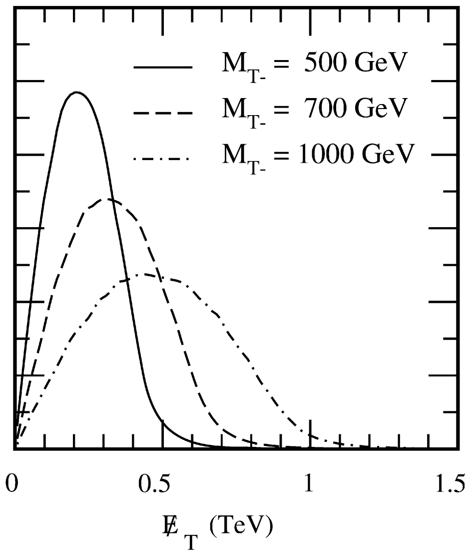

Fig. 4. Normalized distributions of $\not{E}_T$ with different choices of M_{T_-} for $s_\alpha = 1/\sqrt{2}$.

In the rest of the Letter, we discuss how to directly measure M_{T_+} and M_{T_-} to test the LHT. T_+ quark has four tree level decay channels which produce separately the W^+b, Ht, Zt and $A_H T_-$ final states. Their decay branching ratios generally depend on the model parameters f and s_α. In this study we focus on the $T_+ \to W^+b$ decay mode. The single-T_+ event could be detected via

$$qb \to q'T_+ \to q'bW^+, \tag{7}$$

where the W boson decays leptonically. For the single-T_+ production, the SM backgrounds mainly come from the single-top processes and the top quark pair production. The discovery potential of the LHC for the single-T_+ production has been studied in the literature [13]. If the single-t rate is found to be much smaller than the SM prediction, then the LHT would predict a sizable single-T_+ signal which is characterized by a much larger transverse mass (or scalar sum of transverse energy) as compare to that predicted for the SM single-t signal. The mass reconstruction of the T_+ quark is straightforward. It is similar to the mass reconstruction of the single-top event. One can first determine the longitudinal momentum of the neutrino from the W-boson mass constraint and then reconstruct the T_+ invariant mass $M_{T_+} = \sqrt{(p_b + p_\nu + p_{\ell^+})^2}$ [14].

One of the experimental signatures of the $T_-\bar{T}_-$ pair production at the LHC is

$$q\bar{q}(gg) \to T_-\bar{T}_- \to 2A_H + t(\to bW^+) + \bar{t}(\to \bar{b}W^-), \tag{8}$$

where W^+ decays leptonically and W^- decays hadronically. We have performed a Monte Carlo study and found a strong correlation between the location of the (broad) peak of the missing transverse energy (caused by the two LTP A_H bosons) distribution in the $T_-\bar{T}_-$ event and the mass of T_-. As shown in Fig. 4, the distribution of $\not{E}_T$ peaks about half of M_{T_-} for a wide range of f values. This special feature originates from the spin correlation in the $T_-\bar{T}_-$ production. In order to determine the T-odd fermion mass from the $\not{E}_T$ distribution, a more detailed analysis, which includes detection efficiency and smearing effect due to the imperfectness of the detector, should be carried out. That is however beyond the scope of this short Letter and will be deferred in a future work.

In summary, we have shown that the measurement of the single-top production cross section is important for testing the LHT. Depending on the amount of its deviation from the SM prediction, the masses of the heavy T-even (T_+) and T-odd (T_-) partners of the top quark would be highly constrained. Furthermore, the single-T_+ and the $T_-\bar{T}_-$ pair production rates are strongly correlated to the single-top production rate. Hence, their discovery potentials strongly depend on the result of the single-t production cross section measurement. We also proposed a new method to suppress the SM background for detecting the $T_-\bar{T}_-$ events by noting that the signal process tends to produce right-handed top quark from T_- decay while its SM background process ($t\bar{t}Z$) tends to produce left-handed top quark. The asymmetry in the production rates of right-handed versus left-handed top quarks in the events with $t\bar{t}$ plus $\not{E}_T$ signature can be utilized not only to largely suppress the SM intrinsic background, but also to provide a measurement of the f parameter itself. We also point out that because of the spin correlations in the $T_-\bar{T}_-$ production and decay processes, the $\not{E}_T$ distribution peaks around half of the mass of T_- which in turns provides a new method for measuring M_{T_-}. From the measured values of f and M_{T_-}, one can determine the remaining parameter s_α.

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