Implications of the Little Higgs Dark Matter and T-odd fermions

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Abstract: We study the phenomenology of dark matter in the Littlest Higgs model with T-parity after the discovery of Higgs boson. We analyze the relic abundance of dark matter, focusing on the effects of coannihilaitons with T-odd fermions. After determining the parameter space that predicts the correct relic abundance measured by WMAP and Planck collaborations, we evaluate the elastic scattering cross section between dark matter and nucleon. In comparison with experimental results, we find that the lower mass of dark matter is constrained mildly by LUX 2013 while the future XENON experiment has potential to explore most of the parameter space for both T-odd lepton and T-odd quark coannihilation scenarios. We also study the collider signatures of T-odd fermion pair production at the LHC. Even though the production cross sections are large, it turns out very challenging to search for these T-odd fermions directly at the collider because the visible charged leptons or jets are very soft. Furthermore, we show that, with an extra hard jet radiated out from the initial state, the T-odd quark pair production can contribute significantly to mono-jet plus missing energy search at the LHC.

Contents

1 Introduction

Recently, a new scalar with mass of about 125 GeV has been discovered at the Large Hadron Collider (LHC) [1, 2], it is still unclear at this moment whether or not this new particle is the Higgs boson in the Standard Model (SM). Due to the large radiative corrections in Higgs boson mass parameter in the SM, a very precise cancelation must take place in order to have the Higgs boson mass in the electroweak scale if the SM is valid up to Planck scale. This so-called naturalness problem serves a driving force for theorists to propose many solutions, the leading new physics beyond the SM is supersymmetry. Another elegant idea is Little Higgs mechanism, in which the light Higgs boson is realized as a pseudo-Goldston boson. With collective symmetry breaking mechanism [3] (also see [4, 5] for review), the global symmetry breaking scale f can be at $\mathcal{O}(1\,\text{TeV})$ without a fine tuning. The one-loop quadratic divergences induced by the SM particles are exactly cancelled by new fermions, gauge bosons and scalars. An economical model is Littlest Higgs model [6]. However, in order to satisfy the electroweak precision measurements, the scale f is required to be greater than 4 TeV [7–9] and a fine tuning to the light Higgs boson mass is reintroduced. One of the solutions is to embed a discrete symmetry, called T-parity, into the model [10–12] so that no mixing between new particles which are assigned with T-parity odd and the SM particles which are T-parity even. The corrections to electroweak observables are therefore all loop-induced. As a result, the scale f can be as low as about 500 GeV [13] and the LHC has great potential to examine the model. The phenomenology of the Littlest Higgs model with T-parity has been studied in the literature [14–32]. Moreover, the T-parity also ensures the stability of the lightest T-odd particle (LTP) that is naturally can be the candidate of dark matter if it is charge-neutral and colorless. There are two possible candidates of dark matter in Littlest Higgs model with T-parity: T-odd partner of the hypercharge gauge boson A_H [14, 33, 34] and the T-odd partner of neutrino ν_H.

The current dark matter relic abundance in our universe has been measured by WMAP [35] and recently by Planck [36] with the combined value

$$\Omega_{DM}h^2 = 0.1199 \pm 0.0027. \tag{1.1}$$

We found that it is possible to explain the measurement of dark matter relic abundance with ν_H dark matter. However, the direct search experiment excludes such a possibility. The reason is that the coupling strength of ν_H to Z-boson is similar to that of Z-boson to SM fermions, therefore, the cross section of elastic scattering between ν_H and nucleus is about $4 \sim 5$ order of magnitude larger than the current experimental search bound. This situation has been also noticed in the case of KK-neutrino dark matter in Universal Extra-dimensional model [37]. Hence, we will focus on A_H dark matter in our study. To predict the relic abundance of dark matter, we should calculate the dark matter annihilation cross section. The pair annihilation of two A_H dark matter is mainly through the Higgs boson in the s-channel to SM particle final states. With a $125\,\text{GeV}$ Higgs boson, the annihilation cross section of a pair of A_H is too small to fit the measurement of dark matter relic density (eq. (1.1)) unless the mass of A_H is very close to half of the Higgs boson mass in order to have resonance enhancement. Such restriction can be lifted when various coannihilation channels are included [38].In this paper, we take coannihilation processes into account and explore the effects in direct search experiments and implications of LHC phenomenology.

The rest of paper is organized as follows. We begin in section 2 with a brief introduction of the Littlest Higgs model with T-parity. In section 3, we study the coannihilation with light T-odd fermions, separately for T-odd leptons and for T-odd quarks. We first determine the parameter space that can fit the current measurement of dark matter relic abundance, and then calculate the dark matter elastic scattering with nucleus. The LHC study is present in section 4. We calculate the production cross section of T-odd fermion. We point out that the T-odd fermion production contribute significantly to the mono-jet with missing energy search for dark matter at the LHC. Our conclusion appears in section 5.

2 Littlest Higgs model with T-parity

The Littlest Higgs model is a SU(5)/SO(5) nonlinear sigma model where Higgs boson is a pseudo Nambu-Goldstone boson. The global symmetry SU(5) is broken down to SO(5) by a 5×5 symmetric tensor Σ_0 at the scale f, where

$$
\Sigma_0 = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \end{bmatrix}. \tag{2.1}
$$

A subgroup of $SU(5)$, $[SU(2) \times U(1)]_1 \times [SU(2) \times U(1)]_2$, is gauged, and is broken down to the diagonal $SU(2) \times U(1)$ that is identified as SM $SU(2)_L \times U(1)_Y$. A discrete symmetry, T-parity, that governs the transformation of fields between $[SU(2) \times U(1)]_1$ and $[SU(2) \times U(1)]_2$ is introduced. Two different linear combinations of fields under the gauged $[SU(2) \times U(1)]_1$ and $[SU(2) \times U(1)]_2$ define the SM particles and extra heavy particles. For gauge bosons sector, the heavy gauge bosons take the form $W_{H\mu}^a = (W_{1\mu}^a - W_{2\mu}^a)/\sqrt{2}$ and $A_{H\mu} = (B_{1\mu} - B_{2\mu})/\sqrt{2}$ and are odd under T-parity transformation, where $W_{1,2\mu}^a$ and $B_{1,2\mu}$ are gauge boson fields of $SU(2)_{1,2}$ and $U(1)_{1,2}$, respectively, and $a = 1, 2, 3$. For fermion

sector, the T-odd fermion is assigned as $\psi_H = (\psi_1 + \psi_2)/\sqrt{2}$, while the SM fermion is $\psi_{SM} = (\psi_1 - \psi_2)/\sqrt{2}$ that is even under T-parity transformation, where $\psi_{1,2}$ are doublet under $SU(2)_{1,2}$. As a result, there is no mixing between heavy T-odd particles and SM particles and the all the tree-level contributions to electroweak precision tests are forbidden. The stringent constraints on scale f can be relaxed and the model is then testable at the LHC.

To cancel the one-loop quadratic divergence indued by SM top quark in Higgs boson mass correction, another set of singlet U_1 and U_2 is introduced in such a way that a new T-even particle $T_+ = (U_1 - U_2)/\sqrt{2}$ exactly cancels the contribution of SM top quark loop. And the other combination $T_- = (U_1 + U_2)/\sqrt{2}$ is odd under T-parity. The masses of these new gauge bosons and fermions, including the corrections after SM electroweak symmetry is broken, are

$$M_{A_H} = \frac{g'f}{\sqrt{5}}\left[1 - \frac{5v^2}{8f^2}\right], \qquad\qquad M_{W_H} = gf\left[1 - \frac{v^2}{f^2}\right], \qquad (2.2)$$

$$M_{d_H} = \sqrt{2}\kappa_q f, \qquad\qquad M_{u_H} = \sqrt{2}\kappa_q f\left[1 - \frac{v^2}{8f^2}\right],$$

$$M_{\ell_H} = \sqrt{2}\kappa_\ell f, \qquad\qquad M_{\nu_H} = \sqrt{2}\kappa_\ell f\left[1 - \frac{v^2}{8f^2}\right],$$

$$M_{T_+} = \sqrt{\lambda_1^2 + \lambda_2^2}\,f\left[1 - \frac{\lambda_1^2\lambda_2^2}{2(\lambda_1^2 + \lambda_2^2)^2}\frac{v^2}{f^2}\right], \qquad M_{T_-} = \lambda_2 f,$$

where g and g' are respectively the gauge couplings for SM $SU(2)_L$ and $U(1)_Y$, κ_q, κ_ℓ, λ_1 and λ_2,[1] are free parameters in the Lagrangian that generates masses for heavy fermions. Here, u_H (d_H) denote the T-odd partners of the SM up-(down-)type quarks, ν_H are T-odd partners of the neutrinos and ℓ_H are T-odd partners of the charged leptons. Note that the masses of heavy gauge bosons depend on f only, and T-odd fermions rely on an additional parameter κ_q or κ_ℓ. For simplicity, we assume the universal κ_ℓ (κ_q) for T-odd partners of three generations of leptons (quarks) of SM unless otherwise specified. We can see that, when κ_q is smaller than 0.11, the up-type T-odd quarks become the lightest T-odd particle and are stable, which conflicts with results of dark matter searches. For $\kappa_\ell \lesssim 0.11$, T-odd ν_H can be the dark matter candidate. However, such a possibility is excluded by the direct searches as we mentioned previously. Therefore, in the following studies, we take both κ_q and κ_ℓ to be larger than 0.11. We should refer readers who are interested in details of the Littlest Higgs model with T-parity to ref. [10–12].

3 Relic abundance and direct detection

In this section, we study the dark matter A_H in Littlest Higgs Model with T-parity (LHT) in comparison with current dark matter experiments. We will first calculate the relic abundance and then the direct detections. All the calculations shown here are performed with MicrOMEGAs3.1 package [39].

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[1]λ_1 and λ_2 can be related by the mass of top quark.
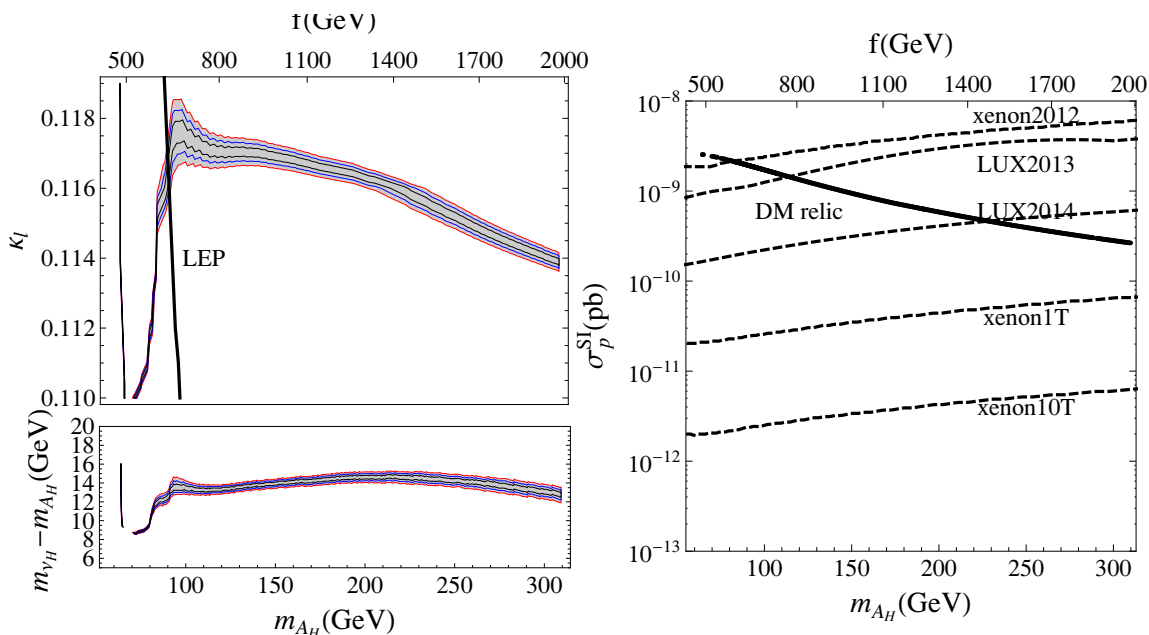
Figure 1. Left: The parameter space of (κ_ℓ, m_{A_H}) and also $(m_{\nu_H} - m_{A_H}, m_{A_H})$ that predicts dark matter relic abundance that is consistent with observation eq. (1.1) within $1\sigma, 3\sigma, 5\sigma$, shown respectively in black, blue and red lines. The thick black line shows lower limit of f from searches of heavy charged particles at LEP II. Right: The one-nucleon-normalized spin-independent elastic cross-section of heavy photon A_H scattering off the nucleon together with the current experimental limits of XENON100 (2012) [49], LUX(2013) [46]. The projective limits of LUX(2014), XENON 1T [50], and XENON10T [51, 52] are also shown.

The relic density of dark matter today is determined by its annihilation processes in the non-relativistic limit. In LHT, a pair of A_H mainly annihilate through a Higgs boson as the mediator in s-channel to a pair of b quarks, W/Z bosons, Higgs bosons or top quarks, depending on the mass of A_H [14, 33, 34]. When A_H is lighter than W-boson, it annihilates to b quarks, however, when W-boson channel is open, a pair of W-boson final state is always dominant. With Higgs boson mass $m_H = 125$ GeV, A_H has to be heavier than $m_H/2 = 62.5$ GeV so that the decay of Higgs boson into a pair of A_H is kinematically forbidden. Otherwise, if the channel $H \to A_H A_H$ is opened, it always dominates the Higgs boson decay branching ratios and conflicts with the current limit of invisible decay branching ratio of Higgs boson [40–45]. In our study, we vary f between ~ 480 GeV and ~ 2 TeV which corresponds to 62.7 GeV $\lesssim \mathrm{m_{A_H}} \lesssim 312.4$ GeV.

In the case that A_H is much lighter than other new heavy particles, in order to have right pair annihilation cross section to fit the current dark matter relic abundance measurement, cf. eq. (1.1), the mass of A_H is required to be just slightly heavier than half of Higgs boson mass $m_{A_H} \gtrsim m_H/2 = 62.5$ GeV. However, the A_H-nucleon elastic scattering cross section is about 10^{-9} pb that is in tension with current result form LUX [46] and

will be certainly examined by projected LUX 2014 data. When A_H becomes heavier, A_H pair annihilation cross section drops quickly and the corresponding relic abundance will be too large to agree with the observation. One possible solution to enlarge the dark matter annihilation cross section is to include coannihilation effects with T-odd fermions [47]. For coannihilation to take place, T-odd fermions should be as light as dark matter A_H. We will demonstrate the coannihilation of T-odd leptons and T-odd quarks separately.

When T-odd leptons participate in coannihilation processes, one more parameter κ_ℓ needs to be considered in addition to f. We show in left panel of figure 1 the parameter space of κ_ℓ and f that predicts the right dark matter relic abundance together with a mass difference between T-odd lepton ν_H and dark matter A_H for demonstration. The black, blue and red curves denote that the relic abundance is consistent with observation within 1σ, 3σ, and 5σ level. We also see that, when coannihilation occurs, the number density of T-odd lepton is about $e^{-\frac{\Delta m}{T}} \sim 35\%$ of that of dark matter A_H when $m_{A_H} = 300\,\mathrm{GeV}$. Here, we take the freeze-out temperature $T \sim m_{A_H}/20$. The value of κ_ℓ is bounded from below by 0.11 below which the A_H is no longer the LTP and can not serve as the dark matter candidate. In calculations, we set all of the T-odd quarks to be much heavier than A_H and are irrelevant in annihilation cross section. The nearly vertical narrow band in the left part of the plot corresponds to the case that m_{A_H} is just slightly heavier than $m_H/2$ where the resonance effect is significant. However, due to narrow width of Higgs boson, when A_H becomes heavier, A_H pair annihilation cross section drops quickly and significant contributions of coannihilation processes involving light T-odd leptons are needed to enlarge the total annihilation cross section of dark matter. When A_H is heavier than W-boson, pair annihilation cross section becomes larger since $A_H A_H \to W^+ W^-$ is opened. Therefore, the contribution from T-odd lepton coannihilation becomes less important than the previous case. As a result, we see that κ_ℓ goes higher, meaning the mass gap between the T-odd lepton and A_H is larger so that the coannihilation becomes less efficient. Furthermore, the nearly vertical black line situated at $m_{A_H} \simeq 92$ GeV (or $f \sim 650$ GeV) is the lower mass limit of T-odd lepton set by the heavy charged lepton searches at LEP, below which the T-odd pair production is too large and contradicts the null result.[2]

In the right panel of figure 1 we show the spin-independence scattering cross-section of heavy photon A_H with nucleon using the parameter space of (κ_ℓ, f) which is compatible to the correct relic. The scattering process is dominated by Higgs t-channel mediated while the contributions from heavy T-odd quarks is small due to the small couplings of A_H to T-odd quarks and the heaviness of T-odd quarks [33]. We also show the experimental limits of XENON in 2012 [49], LUX 2013 [46], LUX expected in 2014, projective XENON 1T [50], and projective XENON 10T [51, 52] for comparison. As we see that the predicted SI cross-section monotonically decreases from $\sim 2 \times 10^{-9}$ pb for $m_{A_H} \gtrsim m_H/2$ down to 2×10^{-10} pb for $m_{A_H} \simeq 310$ GeV. It is clear that the LUX 2013 result disfavors the region where A_H is lighter than ~ 120 GeV which is stronger than the LEP bound shown in left panel. In the near future, for example, projective LUX 2014 can explore the mass of

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[2]The LHT limit is obtained by scaling the results from LEP2 SUSY Working Group on combined LEP Selectron/ Smuon/ Stau Results, 183 - 208 GeV with ALEPH, DELPHI, L3, OPAL Experiments [48].
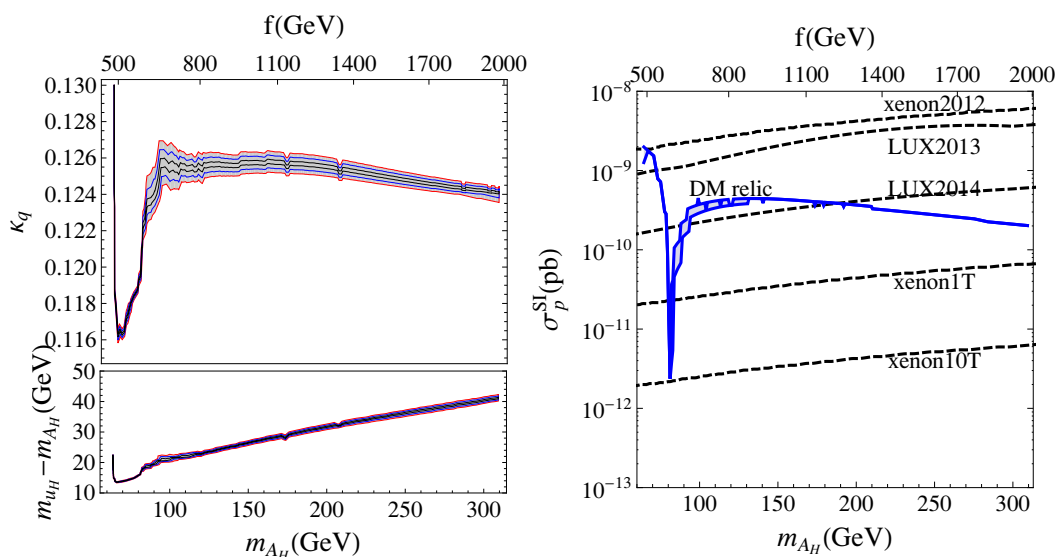
Figure 2. Left: The parameter space of (κ_q, m_{A_H}) and also $(m_{u_H} - m_{A_H}, m_{A_H})$ that predicts dark matter relic abundance that is consistent with observation eq. (1.1) within $1\sigma, 3\sigma, 5\sigma$, shown respectively in black, blue and red lines. Right: The one-nucleon-normalized spin-independent elastic cross-section of heavy photon A_H scattering off the nucleon together with the current experimental limits of XENON100 (2012) [49], LUX(2013) [46]. The projective limits of LUX(2014), XENON 1T [50], and XENON10T [51, 52] are also shown.

A_H up to about 230 GeV and XENON 1T can test all the model parameter space we are interested in.

For the scenario of coannihilation with T-odd quarks, we notice that if T-odd quarks are degenerate, the decay width of T-odd partner of top quark t_H is so narrow that it will leave a displaced vertex inside the detector, which contradicts with current data [53]. The reason is that the 2-body $t_H \to A_H t$ and 3-body $t_H \to A_H b W^+$ decay modes are kinematically forbidden since the mass difference between t_H and A_H is much smaller than top quark mass and W-boson mass. Therefore the only decay channel for t_H is $t_H \to A_H b f \bar{f}'$, where f and f' are SM light fermions. Numerically, the decay width of t_H is at the order of 10^{-14} GeV in the coannihiliation region. Hence, we focus on the situation that the T-odd partners of third generation quarks are much heavier than the first two generations and are irrelevant in coannihilation processes. Also, we set all of the T-odd leptons to be much heavier than dark matter A_H.

The left panel of figure 2 shows the parameter space of (κ_q, f) that agrees with the dark mater relic abundance together with a mass difference between T-odd quark u_H and dark matter A_H for demonstration. The region between black (blue, red) lines is consistent with measurement within $1(3, 5)\,\sigma$ level. Similar to the case of T-odd lepton coannihilation, as we explained previously, the sharp dropoff at $m_{A_H} \gtrsim 62.5$ GeV is due to the fact that the cross section of A_H pair annihilation is dropping very quickly when A_H is away the resonance of Higgs boson. Therefore, light T-odd quarks are needed to join the coannihilation to
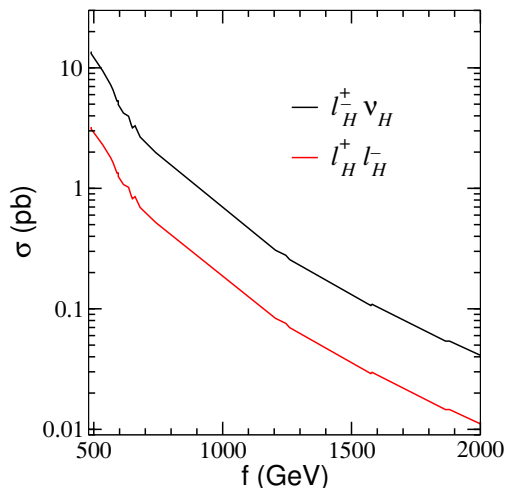
Figure 3. Total production cross section of T-odd lepton pairs at the 8 TeV LHC.

compensate. The rising is because the W-boson final state is opened in A_H pair annihilation and enlarges the annihilation cross section. Then, the mass gap between T-odd quarks and A_H should be larger to suppress the contributions of coannihilaiton processes. Similar to our estimate in the scenario of T-odd lepton coannihilation, the number density of T-odd quark is about 7% of that of dark matter A_H when $m_{A_H} = 300$ GeV.

Shown in the right plot of figure 2 is the predicted spin-independent cross-section of A_H scattering off nucleon, using the parameter space corresponding to the correct relic abundance of dark matter in the left panel of figure 2. In addition to the Higgs-boson-exchanged t-channel diagrams in A_H-nucleon scattering, as we mentioned in previous T-odd lepton coannihilation case, the diagrams which involve T-odd quarks also play an important role since the T-odd quarks now can be as light as about 100 GeV [33]. Therefore, the effects of T-odd quarks can be as significant as the one involving Higgs boson. The amplitudes between diagrams with T-odd quark exchanged interference destructively between s-channel and t-channel and may become negative in some portions of parameter space. The sharp drop-off structure at $m_{A_H} \sim 80$ GeV is due to the fact that the total amplitude of the T-odd quark diagrams is negative and destructs the amplitude of the Higgs boson diagram.

In comparison with the experimental limits, LUX 2013 excludes $m_{A_H} \lesssim 70$ GeV, and the expected LUX data in 2014 has the sensitivity up to $m_{A_H} \simeq 200$ GeV. In the future, the projective XENON 1T and XENON 10T can explore whole parameter except for the region where $m_{A_H} \simeq m_W$.

4 Implications at the LHC

In the co-annihilations region, The T-odd fermion f_H becomes the second lightest T-odd particle and decays 100% to a dark matter A_H and its SM partner fermion f, among which A_H contributes to missing transverse momentum (MET) in the collider signatures. For example, a T-odd electron e_H^- decays into A_H and an electron e^-. Since the T-odd
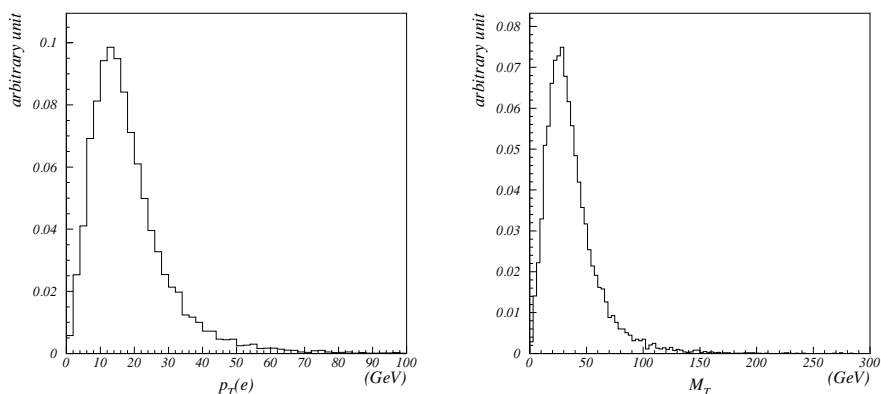
Figure 4. Left: Normalized distribution of transverse momentum of $\ell^{\pm}$ in $pp \to \ell_H^{\pm}(\to \ell^{\pm}A_H)\nu_H(\to \nu A_H)$ production at the LHC. Right: Normalized distribution of transverse mass in $pp \to \ell_H^{\pm}(\to \ell^{\pm}A_H)\nu_H(\to \nu A_H)$ production at the LHC.

fermions are light, LHC can copiously produce them. First, we study the case of light T-odd leptons. As shown in figure 3 , we use CalcHEP [54] package with CTEQ6L [55] parton distribution functions (PDF) to calculate the total production cross sections of T-odd lepton pairs at 8 TeV LHC. The cross section of $\ell_H^{\pm}\nu_H$ can be as large as 13 pb when f is about 500 GeV, where $\ell = e$, or μ or τ. The collider signature of $\ell_H^{\pm}\nu_H$ is single charged lepton plus MET $\not{E}_T$, which is the same as generic W' search in leptonic decay modes. The current limit for W' in single charged lepton plus MET final state requires that the W' should be heavier than about 2.9 TeV when W' with SM couplings to SM fermions [56], which, in principle, can be used to interpret the constraints on T-odd lepton mass. However, since the mass gap between T-odd lepton $\ell_H^{\pm}$ and dark matter A_H is small, the charge lepton $\ell^{\pm}$ in the decay $\ell_H^{\pm} \to \ell^{\pm}A_H$ is soft. As shown in right plot of figure 4, the transverse momentum of $\ell^{\pm}$ peaks around 10 GeV. After imposing selection cuts in W' search [56], the signal of $pp \to \ell_H^{\pm}\nu_H \to \ell^{\pm}\nu A_H A_H$ is entirely cut off, especially the high transverse momentum cut on charged lepton $p_T^{\ell} > 40$ GeV and hard transverse mass cut $M_T = \sqrt{2p_T^{\ell} \cdot \not{E}_T \cdot (1 - \cos\Delta\phi_{\ell\nu})} > 1$ TeV. For $\ell_H^+\ell_H^-$ pair production at the LHC, the signal is $\ell^+\ell^- A_H A_H$ after T-odd leptons decay. Such dilepton plus MET signal has been searched at the LHC for slepton or chargino pair production in supersymmetry [57]. However, due to high transverse momentum cuts on charged leptons $p_T^{\ell_{1(2)}} > 35(20)$ GeV and high m_{T2} cut ($m_{T2} > 90$ GeV) [57], most of the signal of $\ell_H^+\ell_H^-$ do not pass the event selection. Therefore, the current searches for heavy colorless charged particles in single charge lepton plus MET or in dilepton plus MET have no sensitivity to light T-odd lepton pair production in coannihilation region. It is quite challenging to directly search for them because of the soft charged lepton in the final state.

We now turn to study the coannihilation region where T-odd quark is light. The main production mechanism of T-odd quarks is though QCD interaction. After summing over
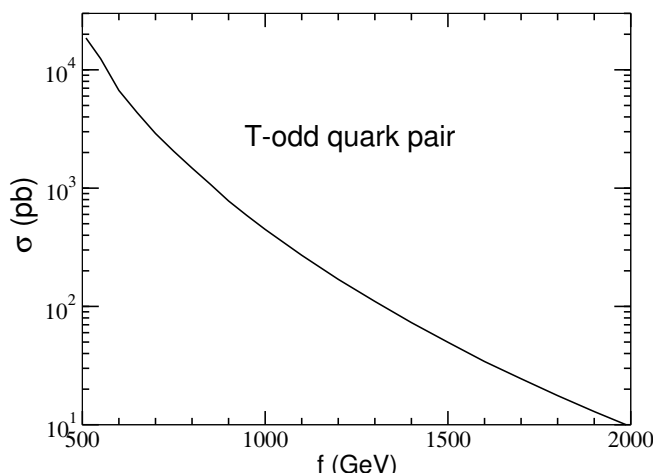
Figure 5. The production cross section of a pair of T-odd quarks $q_H\bar{q}_H$ at the LHC with $8\,\mathrm{TeV}$ center-of-mass energy. The cross section is the sum of the T-odd partners of the first two generation quarks.
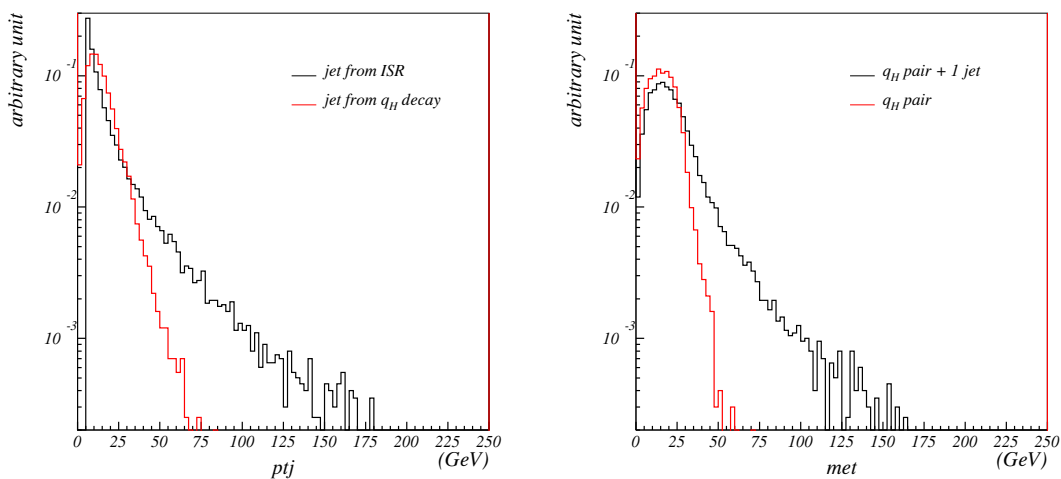

Figure 6. Left: Normalized distributions of transverse momentum of the jet from initial state radiation in $pp \to q_H\bar{q}_H j$ (black histogram) and the jet from T-odd quark decay in $pp \to q_H\bar{q}_H$ (red histogram); Right: Normalized distributions of missing transverse energy in $pp \to q_H\bar{q}_H j$ (black histogram) and in $pp \to q_H\bar{q}_H$ (red histogram).

first two generations, the total cross section of pair production of T-odd quarks $pp \to q_H\bar{q}_H$ at the LHC with $8\,\mathrm{TeV}$ center-of-mass energy is shown in figure 5. The cross section can be as large as about 2×10^4 pb when $f \simeq 500\,\mathrm{GeV}$ and decreases down to ~ 10 pb when f is $2\,\mathrm{TeV}$. The collider signature of T-odd quark pairs at the LHC is 2 jets plus MET, which can mimic the signal of squark or gluino pairs in supersymmetry. One may expect that the

current data of dijet plus MET will testify this parameter space of LHT. However, similar to the charged lepton in T-odd lepton production, the jet in T-odd quark production at the LHC is very soft and most of the signals won't pass the jet ($p_T^{leading} > 130$ GeV) and MET ($\not{E}_T > 160$ GeV) selection criteria in dijet plus MET search [58]. As a result, the current dijet plus MET search for new physics at the LHC has no constraint on light T-odd quark scenario in the region of coannihilation. Instead, we consider the situation that a hard jet radiated from the initial state $pp \to q_H \bar{q}_H j$. As we see in figure 6, the transverse momentum distribution of jet radiated from the initial state decreases slower than the one from the decay of T-odd quark. Furthermore, the MET also shifts to higher value when there exists an extra hard jet. Therefore, the process of a T-odd quark pair plus one jet can contribute to collider search for new physics, like dark matter, in mono-jet plus MET channel. The effects of initial state radiation in the search of T-odd quark that is nearly degenerate with A_H at the LHC has also been studied in [38]. We calculate the T-odd pair with an extra jet from initial state using Madgraph 4 [59] and compare with results of monojet plus missing transverse momentum final states at the LHC by ATLAS collaboration [60]. The event selection criteria in the analysis are summarized as follows:

- MET $\not{E}_T > 120$ GeV.

- Leading jet with transverse momentum $p_T > 120$ GeV and rapidity $|\eta| < 2.0$.

- At most two jets with transverse momentum $p_T > 30$ GeV and rapidity $|\eta| < 4.5$.

- If there are more than one jet, the azimuthal angle difference between second leading jet and MET $\Delta\phi(j^{2\mathrm{nd}}, \not{E}_T) > 0.5$.

- Lepton veto: no isolated electron (muon) with $p_T > 20$ GeV ($p_T > 7$ GeV) and rapidity $|\eta| < 2.47$ ($|\eta| < 2.5$).

Furthermore, four signal regions denoted as SR1, SR2, SR3, SR4 are defined with different cuts on $p_T > 120$ GeV, 220 GeV, 350 GeV, 500 GeV and $\not{E}_T > 120$ GeV, 220 GeV, 350 GeV, 500 GeV. We find that the SR1 give the most stringent constraint, and the result is shown in figure 7. The black curve is the cross section of $pp \to q_H \bar{q}_H j \to q\bar{q} A_H A_H j$ after imposing cuts in signal region of SR1. The grey shaded region represents the exclusion of mono-jet plus MET search. We can see that the f value below about 1.4 TeV is excluded, which corresponds to exclusion of $m_{A_H} \lesssim 215$ GeV.

5 Conclusion

In this paper, we study the phenomenology of dark matter in the Littlest Higgs Model with T-parity, focusing on the coannhilation scenario and its implications at the LHC. We find that, even though the T-odd partner of neutrino ν_H can be the lightest T-odd particle and satisfy the current measurement of dark matter relic abundance, it is ruled out by the direct dark matte search experiments because of its large cross section when scattering with nucleon. The T-odd heavy photon A_H is therefore the only suitable dark
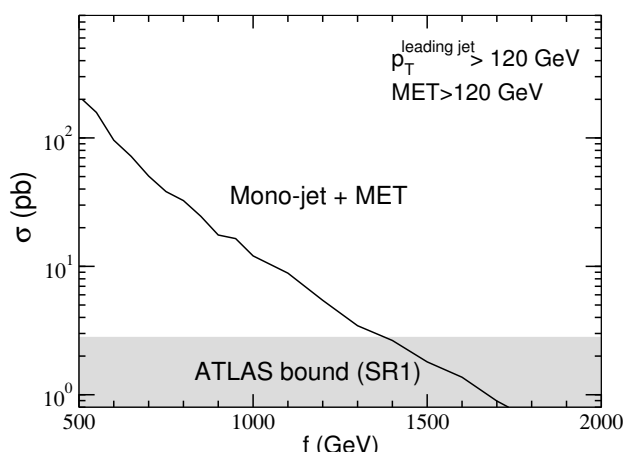
Figure 7. The predicted cross section of mono-jet plus MET events from process of $pp \rightarrow q_H \bar{q}_H j$ at the LHC, using the event selection criteria in signal region SR1. The grey shaded area is excluded by the ATLAS [60].

matter in the model. For pair annihilation cross section of A_H to explain the observed dark matter relic abundance with the Higgs boson being 125 GeV, the mass of A_H should be just slightly heavier than half of Higgs boson mass. However, the direct detection of dark matter of current data from LUX disfavors this case. When m_{A_H} becomes heavier, coannihilation contributions from T-odd fermions must be taken into account in order to fit the relic abundance measurement.

For the case of coannihilation with light T-odd leptons, the existing LEP limit for heavy charged lepton search excludes the region where $f \lesssim 650$ GeV, which corresponds to $m_{A_H} \lesssim 92$ GeV. The current dark matter direct search result from LUX 2013 requires $m_{A_H} \gtrsim 110$ GeV while the future projected sensitivity of XENON 1T has potential to examine the whole parameter space. Since the T-odd leptons are as light as dark matter, the production cross section of T-odd lepton pairs at the LHC can be as large as $O(10)$ pb. However, the charged lepton in the final sate is very soft since the mass difference between T-odd lepton and dark matter is small. Therefore the direct searches at the LHC is very challenging and the current searches for heavy charged particles have no constraints on these light T-odd leptons. For the scenario of T-odd quark coannihilation, we have to consider the situation that T-odd partner of top quark t_H is much heavier than the T-odd partners of the first two generations of SM quarks and is irrelevant in all the results we have shown here. Otherwise, t_H will be stable enough to generate displaced vertex signature at the LHC, which is inconsistent with data. When T-odd quarks are light, they contribute significantly to the A_H-nucleon elastic scattering cross section. The current dark matter direct search result from LUX 2013 imposes a constraint on $m_{A_H} \lesssim 70$ GeV while the projected result of LUX 2014 has the sensitivity for $m_{A_H} \lesssim 200$ GeV. The future XENON 1T has potential to testify the whole parameter space except for $m_{A_H} \sim 80$ GeV where a large destruction effect by T-odd quarks happens. Similar to the case of T-odd

leptons, even though the LHC can produce the light T-odd quarks copiously, with the total production cross section as large as 10^4 pb for $f \sim 500$ GeV, the final state jets from T-odd quark decay are very soft, and therefore, it very difficult to directly search for these light T-odd quarks at the LHC. However, the production of a T-odd quark pair plus one jet contributes significantly to mono-jet plus missing energy signature and the current data from ATLAS set a stringent constraint that disfavors $f \lesssim 1.4$ TeV, corresponding to $m_{A_H} \lesssim 215$ GeV.

In summary, A_H dark matter, the T-odd partner of photon, in Littlest Higgs Model with T-parity fits the measurement of dark matter relic abundance and can satisfy the direct search results well when coannihilaiton processes are considered. The current LHC mono-jet plus missing energy data sets a strong constraint on A_H mass in the T-odd quark coannihilation scenario. For T-odd lepton coannihilaiton case, the LHC has no constraint while the direct detection of dark matter can be sensitive. Combining the future data from dark matter direct search experiments and from LHC, we should be able to fully testify the whole interesting parameter of the model.

Acknowledgments

References

[1] ATLAS collaboration, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, *Phys. Lett.* **B 716** (2012) 1 [arXiv:1207.7214] [ɪɴSPIRE].

[2] CMS collaboration, *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, *Phys. Lett.* **B 716** (2012) 30 [arXiv:1207.7235] [ɪɴSPIRE].

[3] N. Arkani-Hamed, A.G. Cohen and H. Georgi, *Electroweak symmetry breaking from dimensional deconstruction*, *Phys. Lett.* **B 513** (2001) 232 [hep-ph/0105239] [ɪɴSPIRE].

[4] M. Schmaltz and D. Tucker-Smith, *Little Higgs review*, *Ann. Rev. Nucl. Part. Sci.* **55** (2005) 229 [hep-ph/0502182] [ɪɴSPIRE].

[5] M. Perelstein, *Little Higgs models and their phenomenology*, *Prog. Part. Nucl. Phys.* **58** (2007) 247 [hep-ph/0512128] [ɪɴSPIRE].

[6] N. Arkani-Hamed, A.G. Cohen, E. Katz and A.E. Nelson, *The Littlest Higgs*, *JHEP* **07** (2002) 034 [hep-ph/0206021] [ɪɴSPIRE].

[7] C. Csáki, J. Hubisz, G.D. Kribs, P. Meade and J. Terning, *Big corrections from a little Higgs*, *Phys. Rev.* **D 67** (2003) 115002 [hep-ph/0211124] [ɪɴSPIRE].

[8] J.L. Hewett, F.J. Petriello and T.G. Rizzo, *Constraining the littlest Higgs*, *JHEP* **10** (2003) 062 [hep-ph/0211218] [INSPIRE].

[9] M.-C. Chen and S. Dawson, *One loop radiative corrections to the rho parameter in the littlest Higgs model*, *Phys. Rev.* **D 70** (2004) 015003 [hep-ph/0311032] [INSPIRE].

[10] H.-C. Cheng and I. Low, *TeV symmetry and the little hierarchy problem*, *JHEP* **09** (2003) 051 [hep-ph/0308199] [INSPIRE].

[11] H.-C. Cheng and I. Low, *Little hierarchy, little Higgses and a little symmetry*, *JHEP* **08** (2004) 061 [hep-ph/0405243] [INSPIRE].

[12] I. Low, *T parity and the littlest Higgs*, *JHEP* **10** (2004) 067 [hep-ph/0409025] [INSPIRE].

[13] J. Hubisz, P. Meade, A. Noble and M. Perelstein, *Electroweak precision constraints on the littlest Higgs model with T parity*, *JHEP* **01** (2006) 135 [hep-ph/0506042] [INSPIRE].

[14] J. Hubisz and P. Meade, *Phenomenology of the littlest Higgs with T-parity*, *Phys. Rev.* **D 71** (2005) 035016 [hep-ph/0411264] [INSPIRE].

[15] J. Hubisz, S.J. Lee and G. Paz, *The Flavor of a little Higgs with T-parity*, *JHEP* **06** (2006) 041 [hep-ph/0512169] [INSPIRE].

[16] C.-R. Chen, K. Tobe and C.-P. Yuan, *Higgs boson production and decay in little Higgs models with T-parity*, *Phys. Lett.* **B 640** (2006) 263 [hep-ph/0602211] [INSPIRE].

[17] C.-S. Chen, K. Cheung and T.-C. Yuan, *Novel Collider Signature for Little Higgs Dark Matter Models*, *Phys. Lett.* **B 644** (2007) 158 [hep-ph/0605314] [INSPIRE].

[18] A. Freitas and D. Wyler, *Phenomenology of mirror fermions in the littlest Higgs model with T-parity*, *JHEP* **11** (2006) 061 [hep-ph/0609103] [INSPIRE].

[19] A. Belyaev, C.-R. Chen, K. Tobe and C.-P. Yuan, *Phenomenology of littlest Higgs model with T-parity: including effects of T-odd fermions*, *Phys. Rev.* **D 74** (2006) 115020 [hep-ph/0609179] [INSPIRE].

[20] L. Wang, W. Wang, J.M. Yang and H. Zhang, *Production of $ht\bar{t}$ and $ht\bar{T}$ in littlest Higgs model with T-parity*, *Phys. Rev.* **D 75** (2007) 074006 [hep-ph/0609200] [INSPIRE].

[21] M. Blanke et al., *Rare and CP-Violating K and B Decays in the Littlest Higgs Model with T-parity*, *JHEP* **01** (2007) 066 [hep-ph/0610298] [INSPIRE].

[22] S. Matsumoto, M.M. Nojiri and D. Nomura, *Hunting for the Top Partner in the Littlest Higgs Model with T-parity at the CERN LHC*, *Phys. Rev.* **D 75** (2007) 055006 [hep-ph/0612249] [INSPIRE].

[23] D. Choudhury and D.K. Ghosh, *LHC signals of T-odd heavy quarks in the Littlest Higgs model*, *JHEP* **08** (2007) 084 [hep-ph/0612299] [INSPIRE].

[24] L. Wang, W. Wang, J.M. Yang and H. Zhang, *Higgs-pair production in littlest Higgs model with T-parity*, *Phys. Rev.* **D 76** (2007) 017702 [arXiv:0705.3392] [INSPIRE].

[25] Q.-H. Cao and C.-R. Chen, *Signatures of extra gauge bosons in the littlest Higgs model with T-parity at future colliders*, *Phys. Rev.* **D 76** (2007) 075007 [arXiv:0707.0877] [INSPIRE].

[26] S. Matsumoto, T. Moroi and K. Tobe, *Testing the Littlest Higgs Model with T-parity at the Large Hadron Collider*, *Phys. Rev.* **D 78** (2008) 055018 [arXiv:0806.3837] [INSPIRE].

[27] G. Cacciapaglia, A. Deandrea, S.R. Choudhury and N. Gaur, *T-parity odd heavy leptons at LHC*, *Phys. Rev.* **D 81** (2010) 075005 [arXiv:0911.4632] [INSPIRE].

[28] D. Choudhury, D.K. Ghosh and S.K. Rai, *Dijet Signals of the Little Higgs Model with T-Parity*, *JHEP* **07** (2012) 013 [arXiv:1202.4213] [INSPIRE].

[29] K. Cheung, K.Y. Lee, S.Y. Shim, J. Song and N. Yoo, *Using the Higgs boson to probe the littlest Higgs model with T-parity through $Z_H W_H$ production at the LHC*, *Phys. Rev.* **D 87** (2013) 097701 [arXiv:1302.0594] [INSPIRE].

[30] W. Kilian and J. Reuter, *The Low-energy structure of little Higgs models*, *Phys. Rev.* **D 70** (2004) 015004 [hep-ph/0311095] [INSPIRE].

[31] J. Reuter and M. Tonini, *Can the 125 GeV Higgs be the Little Higgs?*, *JHEP* **02** (2013) 077 [arXiv:1212.5930] [INSPIRE].

[32] J. Reuter, M. Tonini and M. de Vries, *Littlest Higgs with T-parity: Status and Prospects*, *JHEP* **02** (2014) 053 [arXiv:1310.2918] [INSPIRE].

[33] A. Birkedal, A. Noble, M. Perelstein and A. Spray, *Little Higgs dark matter*, *Phys. Rev.* **D 74** (2006) 035002 [hep-ph/0603077] [INSPIRE].

[34] M. Asano, S. Matsumoto, N. Okada and Y. Okada, *Cosmic positron signature from dark matter in the littlest Higgs model with T-parity*, *Phys. Rev.* **D 75** (2007) 063506 [hep-ph/0602157] [INSPIRE].

[35] WMAP collaboration, G. Hinshaw et al., *Nine-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Cosmological Parameter Results*, *Astrophys. J. Suppl.* **208** (2013) 19 [arXiv:1212.5226] [INSPIRE].

[36] PLANCK collaboration, P.A.R. Ade et al., *Planck 2013 results. XVI. Cosmological parameters*, arXiv:1303.5076 [INSPIRE].

[37] G. Servant and T.M.P. Tait, *Elastic scattering and direct detection of Kaluza-Klein dark matter*, *New J. Phys.* **4** (2002) 99 [hep-ph/0209262] [INSPIRE].

[38] M. Perelstein and J. Shao, *T-Quarks at the Large Hadron Collider: 2010-12*, *Phys. Lett.* **B 704** (2011) 510 [arXiv:1103.3014] [INSPIRE].

[39] G. Bélanger, F. Boudjema, A. Pukhov and A. Semenov, *MicrOMEGAs₃: A program for calculating dark matter observables*, *Comput. Phys. Commun.* **185** (2014) 960 [arXiv:1305.0237] [INSPIRE].

[40] P.P. Giardino, K. Kannike, M. Raidal and A. Strumia, *Is the resonance at 125 GeV the Higgs boson?*, *Phys. Lett.* **B 718** (2012) 469 [arXiv:1207.1347] [INSPIRE].

[41] D. Carmi, A. Falkowski, E. Kuflik, T. Volansky and J. Zupan, *Higgs After the Discovery: A Status Report*, *JHEP* **10** (2012) 196 [arXiv:1207.1718] [INSPIRE].

[42] K. Cheung, J.S. Lee and P.-Y. Tseng, *Higgs Precision (Higgcision) Era begins*, *JHEP* **05** (2013) 134 [arXiv:1302.3794] [INSPIRE].

[43] P.P. Giardino, K. Kannike, I. Masina, M. Raidal and A. Strumia, *The universal Higgs fit*, *JHEP* **05** (2014) 046 [arXiv:1303.3570] [INSPIRE].

[44] A. Djouadi and G. Moreau, *The couplings of the Higgs boson and its CP properties from fits of the signal strengths and their ratios at the 7+8 TeV LHC*, arXiv:1303.6591 [INSPIRE].

[45] ATLAS collaboration, *Search for Invisible Decays of a Higgs Boson Produced in Association with a Z Boson in ATLAS*, arXiv:1402.3244 [INSPIRE].

[46] LUX collaboration, D.S. Akerib et al., *First results from the LUX dark matter experiment at the Sanford Underground Research Facility*, *Phys. Rev. Lett.* **112** (2014) 091303 [arXiv:1310.8214] [INSPIRE].

[47] L. Wang, J.M. Yang and J. Zhu, *Dark matter in the little Higgs model under current experimental constraints from the LHC, Planck and Xenon data*, *Phys. Rev.* **D 88** (2013) 075018 [arXiv:1307.7780] [INSPIRE].

[48] http://lepsusy.web.cern.ch/lepsusy/www/sleptons_summer04/slep_final.html.

[49] XENON100 collaboration, E. Aprile et al., *Dark Matter Results from 225 Live Days of XENON100 Data*, *Phys. Rev. Lett.* **109** (2012) 181301 [arXiv:1207.5988] [INSPIRE].

[50] XENON1T collaboration, E. Aprile, *The XENON1T Dark Matter Search Experiment*, arXiv:1206.6288 [INSPIRE].

[51] K. Arisaka for the XENON collaboration, *Xenon10T, G3 expected sensitivity*, SLAC Workshop Talk, SNOMASS on the Mississippi (2013), http://www.snowmass2013.org/tiki-index.php?page=XENON.

[52] DMtools, http://dmtools.brown.edu.

[53] CMS collaboration, *Searches for long-lived charged particles in pp collisions at $\sqrt{s}$=7 and 8 TeV*, *JHEP* **07** (2013) 122 [arXiv:1305.0491] [INSPIRE].

[54] A. Belyaev, N.D. Christensen and A. Pukhov, *CalcHEP 3.4 for collider physics within and beyond the Standard Model*, *Comput. Phys. Commun.* **184** (2013) 1729 [arXiv:1207.6082] [INSPIRE].

[55] J. Pumplin et al., *New generation of parton distributions with uncertainties from global QCD analysis*, *JHEP* **07** (2002) 012 [hep-ph/0201195] [INSPIRE].

[56] CMS collaboration, *Search for new physics in final states with a lepton and missing transverse energy in pp collisions at the LHC*, *Phys. Rev.* **D 87** (2013) 072005 [arXiv:1302.2812] [INSPIRE].

[57] ATLAS collaboration, *Search for direct-slepton and direct-chargino production in final states with two opposite-sign leptons, missing transverse momentum and no jets in 20 fb^{-1} of pp collisions at with the ATLAS detector*, ATLAS-CONF-2013-049 (2013).

[58] ATLAS collaboration, *Search for squarks and gluinos with the ATLAS detector in final states with jets and missing transverse momentum and 20.3fb^{-1} of $\sqrt{s}$ = 8 TeV proton-proton collision data*, ATLAS-CONF-2013-047 (2013).

[59] J. Alwall et al., *MadGraph/MadEvent v4: The New Web Generation*, *JHEP* **09** (2007) 028 [arXiv:0706.2334] [INSPIRE].

[60] ATLAS collaboration, *Search for New Phenomena in Monojet plus Missing Transverse Momentum Final States using 10fb-1 of pp Collisions at sqrts=8 TeV with the ATLAS detector at the LHC*, ATLAS-CONF-2012-147 (2012).