The impossibility of heavy neutrino dark matter in the Littlest Higgs Model with T-parity: constraints from direct search

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Abstract

We consider the Littlest Higgs Model with T-parity (LHT), in the parameter region where a heavy neutrino is the lightest T-odd particle (LTP). Having emphasized that this corresponds to a sizable region in the parameter space of the theory, we show that both the Cryogenic Dark Matter Search (CDMS) and Xenon10 experiments disallow the entire region where the masses of the new particles in LHT can lie within several TeV. Therefore, any observation of the signals of a heavy neutrino LTP is likely to seriously reopen the issue of cold dark matter in the universe.

Introduction: In the last few years the existence of a dark matter (DM) candidate, comprising about 23% of the energy density of the Universe, has been firmly established by cosmological observations, of which the WMAP \cite{1} results are most recent and notable. Studies on the large scale distribution of galaxies as well as the anisotropy of the cosmic microwave background radiation (CMBR) disfavor hot dark matter as the primary DM component. However, the exact nature of cold dark matter (CDM) is largely unknown, and a vigorous experimental effort is devoted to the explication of its nature. If CDM is of particle physics origin, then one is forced to postulate a new elementary weakly interacting massive particle (WIMP), which must be stable.

Such particles occur naturally in several extensions of the standard model (SM). A typical CDM candidate can be a Dirac or a Majorana fermion, a vector boson or a scalar. Its mass may range anywhere from a few GeV to a few TeV. Rather interesting implications are thus suggested for collider experiments and in direct searches via elastic scattering on target nuclei. Its footprints are also expected in astrophysical observations such as gamma ray bursts from galactic centers. Artifacts of dark matter annihilation in the galactic halo or the center of the sun are also objects of recent investigation.

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The new physics theories which can accommodate a CDM candidate must also provide an explanation of its stability (though of course, one may assume something ad hoc, such as heavy stable fourth generation neutrinos [2]). This is done in a large class of models through a $Z_2$ symmetry against which the candidate particle is odd, with no other $Z_2$-odd particle below it in the spectrum. This happens in supersymmetric (SUSY) models [3], theories with universal extra dimensions (UED) [4, 5] as well as little Higgs models with T-parity. We focus on the last of these scenarios in this note.

Little Higgs theories [6, 7] form a class of models where the Higgs mass is stabilized via a new physics $f (\sim 1 \text{ TeV})$ at which the breakdown of a global symmetry gives rise to the standard model Higgs boson and host of other scalar as Goldstone bosons. The Higgs mass is generated by the Coleman-Weinberg mechanism. However, $f \lesssim \text{ TeV}$ is not found to be easily compatible with precision electroweak constraints, and some additional postulates are necessary.

Tree-level violation of precision constraints is avoidable through a discrete symmetry called T-parity is, for example, the Littlest Higgs Model [LHT] [8, 9]. All the particles in such a spectrum can be classified as T-even/odd, and the lightest T-odd particle (LTP) turns out to be a CDM candidate. Over a large part of the parameter space of this model, the LTP is a spin-1 particle (the heavy photon or $A_H$) whose implications as a CDM have been studied extensively [10, 11, 12]. However, a spin-1/2 neutral Dirac fermion (the heavy neutrino or $\nu_H$) becomes lighter than the heavy photon over a certain region which is otherwise viable phenomenologically. Thus the $\nu_H$ becomes the LTP in this region. Since this region in the parameter space is phenomenologically distinct from that with a heavy photon LTP, it is important to make a clear statement on whether this region is allowed by the extant results on direct dark matter searches. Here we probe this territory of the LHT model, and study the possibilities of this heavy neutrino LTP in direct detection experiments [13, 14, 15].

The LTP of the LHT model: In the Littlest Higgs model, a global $SU(5)$ spontaneously breaks down to $SO(5)$ at a scale $\Lambda = 4\pi f$, with $f \simeq 1 \text{ TeV}$. An $[SU(2) \otimes U(1)]^2$ gauge symmetry is imposed. This gauge group breaks simultaneously into the diagonal subgroup $SU(2)_L \otimes U(1)_Y$, which is identified as the SM gauge group. One thus has four heavy gauge bosons $W^\pm_H$, $Z_H$ and $A_H$ with masses $\sim f$, in addition to the SM gauge fields. The SM Higgs doublet $H$ is part of an assortment of pseudo-Goldstone bosons, together with a heavy $SU(2)$ triplet scalar $\Phi$, resulting from the spontaneous breaking of the global symmetry. The augmented symmetry controls quadratically divergent contributions to the Higgs mass. Finally, the Coleman-Weinberg mechanism leads to a radiatively generated Higgs mass which naturally remains within a TeV. The input used for making relatively low values of $f$ consistent with all precision electroweak observables is a discrete symmetry called T-parity, which maps the two pairs of gauge groups $SU(2)_i \otimes U(1)_i, i = 1, 2$ into each other, forcing the corresponding gauge couplings to be equal. All SM particles are even under T-parity, while the four additional massive gauge bosons and the Higgs triplet are T-odd. In order to render the fermionic sector consistent with T-parity and gauge invariant at the same time, one has to introduce additional heavy vector-like fermions for each family. Particular linear combinations of the fermions transforming under each of the two $SU(2)$’s yield the SM quarks and leptons, while the orthogonal combinations give us T-odd heavy fermions $\{u_H, d_H\}$ and $\{l_H, \nu_H\}$ for $i = 1, 2, 3$, which are vector-like doublets under the SM $SU(2)$. The requirement of cancellation of quadratic divergence in the Higgs mass further prompts one to postulate two extra heavy fermionic partners for the top quark, one of which is T-even and the other T-odd (see [8] for details). The multiplicative conservation of T-parity prevents the lightest T-odd state from further decays, thus making it the LTP and the CDM candidate.

The masses of the heavy gauge bosons are dictated by the scale $f$ which can be as low as 500 GeV
Figure 1: The region of the parameter space of the LHT model in the $\kappa_l - f$ plane (colored region) corresponding to $\nu_H$ as the LTP. The black band is strictly allowed by the WMAP observation ($\Omega_{\text{DM}} h^2 = 0.105^{+0.007}_{-0.013}$). In the pink (dark grey) region, there is a shortfall in the contribution to the relic density, while the blue (light grey) region corresponds to excessive relic density. The region corresponding to $m_l_H < 100 \text{ TeV}$, disallowed by the LEP experiment, has been excluded from the colored patches. As will be seen from the text, the entire colored region is disallowed from direct search for dark matter.

while the masses of the heavy leptons (quarks) are additionally determined by a parameter $\kappa_l$ ($\kappa_q$), where $\kappa \leq 4.8$ (for $f \sim 1 \text{ TeV}$) \[16\]. In particular, the masses of the heavy photon, the heavy neutrino and the heavy charged lepton are given by

$$m_{A_H} = \frac{fg}{\sqrt{5}} \left(1 - \frac{5v^2}{8f^2}\right), \quad m_{Z_H} = fg \left(1 - \frac{v^2}{8f^2}\right),$$

$$m_{\nu_H} = \sqrt{2}\kappa_l f \left(1 - \frac{v^2}{8f^2}\right), \quad m_l_H = \sqrt{2}\kappa_l f.$$  \hspace{1cm} (1)

This clearly indicates that small values of $\kappa_l$ will lead to $m_{\nu_H} < m_{A_H}$ making $\nu_H$ the LTP; otherwise $A_H$ plays that role. The colored region of Figure 1 shows the region on the $\kappa_l - f$ plane corresponding to $\nu_H$ LTP. The constraints from the production of $l_H$-pairs at the Large Electron Positron (LEP) experiment has been taken into account in marking the allowed region. Note that for every $f$ there exists one maximum and one minimum value of $\kappa_l$. The maximum $\kappa_l$ is determined from the requirement $m_{\nu_H} < m_{A_H}$. For large $f$, this translates into $\kappa_l < fg' / \sqrt{10}$ (neglecting corrections $\sim v^2 / f^2$ in Eq. \[1\]), and the upper limit therefore becomes almost independent of $f$. The lower limit on $\kappa_l$ is set by the fact that $m_{\nu_H} > m_Z / 2$ so that the $Z$ does not decay into a pair of $\nu_H$. Thus for large $f$, under the same approximations as before, the minimum $\kappa_l$ is almost independent of $f$. For smaller values of $f$ however, as the factor $f \left(1 - v^2 / 8f^2\right)$ becomes smaller, the minimum of $\kappa_l$ rapidly grows to larger values to maintain $m_{\nu_H} > m_Z / 2$. Note that the heavy electron $e_H$ becomes almost degenerate with $\nu_H$ for large values of $f$. In Figure 1 we have also ensured that the mass of $l_H$ is more than that of $\nu_H$ by $\sim 0.51 \text{ MeV}$, so that $e_H$ does not become stable on the cosmological scale.

Thus within the colored region enclosed by the curve in Figure 1 the possible CDM candidate from the LHT model is the heavy Dirac neutrino $\nu_H$ and not $A_H$ (the latter corresponds to the white region in Figure 1). While the viability of $A_H$ from direct dark matter search and the associated

\[1\]In principle, $\kappa_l$ can be a $3 \times 3$ matrix carrying flavor indices, i.e. $m_{ij}^{l_H,q_H} \sim \kappa_{ij}^{l_H,q_H} f$. We have simplified our analysis by assuming $\kappa_{ij}^{l_H} = \kappa_i \delta^{ij}$. 

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Figure 2: Leading order Feynman graph for effective $\nu_H$-quark scattering through the exchange of the SM $Z$-boson.

The phenomena of have been studied in detail \[11, 12, 20\], we extend this study to a $\nu_H$ CDM. Though the observations pertaining to theories such as UED are broadly valid here, our emphasis is on the part of the LHT parameter space constrained in this manner. The colored region in Figure 1 is further constrained from relic density bounds. The region marked in green corresponds to relic density below 0.092, and thus leads to underclosure (in which case it cannot account for all dark matter but can still be a viable candidate). The region marked in red corresponds to relic density above 0.112, being thus by and large disallowed by the WMAP results due to overclosure. The blue-colored band, corresponding to relic density between 0.112 and 0.092, is the WMAP-allowed region where the $\nu_H$ is the lone CDM candidate. The relic density calculation for all the cases has been done using the package micrOMEGAs 2.2.

It should be noted here that, if one has to exactly fit the WMAP data with $\nu_H$ dark matter, then one requires a minimum value of $f$ on the order of 3 TeV. This, however, leads to such values of the $W_H$, $Z_H$ masses, which tend to shift the Higgs mass to well above a TeV, thus requiring some fine-tuning, and introducing a 'little hierarchy'. From this angle, a $\nu_H$ LTP is somewhat disallowed theoretically, especially if one uses it to account for all dark matter.

**Signature of $\nu_H$ dark matter:** Typically, the direct detection of a WIMP involves elastic scattering of the WIMP with a nucleus in a detector. The nucleus recoils with some energy whose distribution is a function of the masses of the WIMP and the nucleus, Thus the WIMP-nucleon (average) cross-section calculated in a specific model is the starting point, and a region in the parameter space is ruled out if the prediction exceeds the upper limit obtained from the absence of recoil events satisfying the appropriate cuts.

The Cryogenic Dark Matter Search (CDMS) experiment \[13\], for example, is designed to detect atomic nuclei in germanium (Ge) and silicon (Si) crystals that have been scattered by the incident WIMPs, while XENON10 \[14, 15\] uses liquid Xenon (Xe) as a sensitive detector medium. Generically the WIMP-nucleus interactions can be split into spin-independent (scalar) and spin-dependent parts. The scalar interactions add coherently in the nucleus, so that the heavier the nuclei the better is the sensitivity. Spin-dependent interaction, on the other hand, relies mainly on one unpaired nucleon, and thus dominates over scalar interactions for light nuclei. On the whole, the cross-section for the WIMP-nucleus interaction is typically low, so that large detectors are required.

To arrive at the WIMP-nucleus cross-section, one has to start with interactions at the quark level. For the case in study the leading contribution is shown in Figure 2 where the $\bar{\nu}_H \nu_H Z$ interaction is
given by

\[ \mathcal{L} = \frac{g}{2 \cos \theta_W} \bar{\nu}_H \gamma_\mu \nu_H Z^\mu \]  

(2)

The coupling of \( \nu_H \) with \( W, Z \) is vector-like \[21\]. Using this the WIMP-quark matrix element can be computed, and then it has to be converted into effective couplings of the WIMP to protons and neutrons \[22\ [23\], namely \( \lambda_p \) and \( \lambda_n \). This is an effective vector-vector four-fermion interaction, for which the spin-independent cross-section dominates. The effective couplings \( \lambda_p \) and \( \lambda_n \) are given as

\[ \lambda_p = 2 \lambda_u + \lambda_d = \frac{e^2}{4 \sin^2 \theta_W M_W^2} \left[ \frac{1}{2} (1 - 4 \sin^2 \theta_W) \right], \quad \lambda_n = 2 \lambda_d + \lambda_u = -\frac{e^2}{4 \sin^2 \theta_W M_W^2} \left[ \frac{1}{2} \right], \]  

(3)

where \( \lambda_{u,d} = \frac{e^2}{4 \sin^2 \theta_W M_W^2} (T_{3u,d}^u - 2 Q_{u,d} \sin^2 \theta_W) \) are the strengths of WIMP-quark interactions. Starting from the input Lagrangian shown in Eq. \( (2) \), the WIMP-nucleon cross-section can be computed following a procedure similar to that in \[22\]. This yields

\[ \sigma_{0}^{SI} = \frac{4 \mu_{\nu_H}^2}{\pi} \left[ \lambda_p Z + \lambda_n (A - Z) \right], \]  

(4)

where \( \mu_{\nu_H} = M_{\nu_H} M_Z / (M_{\nu_H} + M_Z) \) is WIMP-nucleon reduced mass, \( Z \) is the number of protons and \( (A - Z) \) is the number of neutrons in the detector nucleus. Note that \( \sigma_{0}^{SI} \) is the cross-section for the WIMP scattering at rest from a point-like nucleus being known as the ‘standard’ cross-section at zero momentum transfer. To obtain the cross-section precisely, one has to convolute \( \sigma_{0}^{SI} \) with the nuclear form factor \( F(Q) \) where \( Q \) is the energy transferred from the WIMP to the nucleus, and then integrate over \( Q \). However, for an order of magnitude estimation of the WIMP-nucleus cross-section, estimation of \( \sigma_{0}^{SI} \) alone is sufficient\[3\]. This is because the energy exchange between the WIMP and the nucleus is on the order of a few hundreds of KeV. Given such small recoil energy compared to nucleon masses, the inclusion of the nuclear form-factor is not expected to yield cross-sections drastically different from \( \sigma_{0}^{SI} \). Finally, the scattering cross-section per nucleon is,

\[ \sigma_{\text{nuc}}^{SI} = \frac{\sigma_{0}^{SI} m_{\text{nuc}}^2}{\mu_{\nu_H}^2 A^2}. \]  

(5)

The scattering cross-section per nucleon estimated from Eq. \( (5) \) is plotted in Figure \[8\] as a function of the WIMP mass. Since \( \sigma_{\text{nuc}}^{SI} \) is independent of the WIMP mass, the plot is a straight line parallel to the \( x \)-axis with an estimated value \( \sigma_{\text{nuc}}^{SI} \sim 2.34 \times 10^{-39} \text{cm}^2 \) for Ge and \( 2.55 \times 10^{-39} \text{cm}^2 \) for Xe respectively. Figure \[8\] also shows the existing experimental limits on the cross-section from CDMS \[13\] and Xenon10 \[14\] are drawn by the red and the green lines respectively. Note that the experimental plots have been linearly extrapolated to a WIMP-mass \( \sim 1.6 \text{ TeV} \), a value which corresponds to \( f = 10 \text{ TeV} \) (and \( \kappa = 0.1 \)). For larger values of \( f \), the little hierarchy problem crops up in the LHT-model, and it becomes phenomenologically uninteresting. Figure \[8\] clearly shows that the theoretical estimation of \( \sigma_{\text{nuc}}^{SI} \) is way beyond the limits obtained from the experiments. Thus a \( \nu_H \) LTP, in the entire colored region in Figure 1, is ruled out, at least up to \( f = 10 \text{ TeV} \). An even further extrapolation does not leave any room for a \( \nu_H \) CDM, unless one goes way above the 10 TeV mark in \( f \), something that cannot be motivated from the stabilization of the electroweak scale.

Is this study, focusing on the \( f - \kappa_l \) plane, unduly restricted? The answer is no, for the following reasons. First of all, the LTP can be one of three particles, namely, \( Z_H, A_H \) and \( \nu_H \). As is obvious

\[ ^{\ddagger}\text{Our calculation has been cross-checked against results using the package micrOMEGAs 2.2 [23 [24].} \]
from Eq. (11), one always has $m_{Z_H} > m_{A_H}$. This leaves us with two possibilities only, of which one, namely an $A_H$ LTP, has been studied extensively. We take up the remaining one here, and establish its impossibility. We emphasize that our demonstration is not affected on varying the rest of the parameters of the model. Over the region with a $\nu_H$ LTP, $\kappa_q$ must be such as to make the heavy quark more massive than the heavy leptons, but there is no further dependence on its value in the cross-section pertinent to dark matter detection. In a similar vein, any departure from $\chi_{ij}^{(q)} = \delta_{ij}$, on which limits are imposed from various flavor-changing processes [19], does not affect our conclusions. Non-diagonality as well as non-universality in $\kappa_l$ is even more restricted from the limits on lepton flavor violating phenomena [19]. Moreover, such non-universality does not prevent a $\nu_H$ from being the LTP, in which case our Figure 1 will contain that particular $\kappa_l$ to which its mass is related. A heavy neutrino LTP is completely disallowed in such a situation as well.

**Conclusion**: In summary, we probe the particular parameter region in the $\kappa_l - f$ plane of the Littlest Higgs model, which corresponds to the heavy neutrino $\nu_H$ as the lightest $T$-odd particle. We then estimate the spin-independent scattering cross-section for $\nu_H$ with the Germanium and Xenon nuclei, and compare them with the limits obtained from the CDMS and Xenon10 experiments. We find that the possibility of $\nu_H$ being the WIMP is ruled out up to very large values of $f (>> 10 \text{ TeV})$. Although it may not be straightforward to identify a $\nu_H$ LTP at a hadron collider, a careful analysis of (leptons + $E_T$) final states at, say, a linear electron-positron collider may supply crucial information on its identity. Our study serves to establish that direct dark matter searches forbid such a final state in the LHT scenario, unless $f$ is so large that the model itself becomes phenomenologically irrelevant.

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References

[1] E. Komatsu et al. [WMAP Collaboration], arXiv:0803.0547 [astro-ph].

[2] D. Fargion, M. Y. Khlopov, R. V. Konoplich and R. Mignani, JETP Lett. 68, 685 (1998) arXiv:astro-ph/9810048; K. Belotsky, D. Fargion, M. Khlopov and R. V. Konoplich, Phys. Atom. Nucl. 71, 147 (2008) arXiv:hep-ph/0411093.

[3] For reviews see, for example, H. E. Haber and G. L. Kane, Phys. Rept. 117, 75 (1985); M. Drees and S.P. Martin, hep-ph/9504324; M. Drees, arXiv:hep-ph/9611409; J.D. Lykken, TASI-96 lectures, hep-th/9612114; S. P. Martin, arXiv:hep-ph/9709356 and references therein; J.F. Gunion, hep-ph/9704349.

[4] T. Appelquist, H. C. Cheng and B. A. Dobrescu, Phys. Rev. D 64, 035002 (2001) arXiv:hep-ph/0012100.

[5] G. Servant and T. M. P. Tait, New J. Phys. 4, 99 (2002) arXiv:hep-ph/0209262; D. Majumdar, Phys. Rev. D 67, 095010 (2003) arXiv:hep-ph/0209277.

[6] N. Arkani-Hamed, A. G. Cohen and H. Georgi, Phys. Lett. B 513, 232 (2001) arXiv:hep-ph/0105239; N. Arkani-Hamed, A. G. Cohen, T. Gregoire and J. G. Wacker, JHEP 0208, 020 (2002) arXiv:hep-ph/0202089; N. Arkani-Hamed, A. G. Cohen, E. Katz and A. E. Nelson, JHEP 0207, 034 (2002) arXiv:hep-ph/0206021.

[7] M. Schmaltz and D. Tucker-Smith, Ann. Rev. Nucl. Part. Sci. 55, 229 (2005) arXiv:hep-ph/0502182; M. C. Chen, Mod. Phys. Lett. A 21, 621 (2006) arXiv:hep-ph/0601126; E. Accomando et al., hep-ph/0608079, Chapter 7; M. Perelstein, Prog. Part. Nucl. Phys. 58, 247 (2007) arXiv:hep-ph/0512128.

[8] H. C. Cheng and I. Low, JHEP 0309, 051 (2003) arXiv:hep-ph/0308199; JHEP 0408, 061 (2004) arXiv:hep-ph/0405243.

[9] C. Csaki et al., J. Terning, Phys. Rev. D 67, 115002 (2003) arXiv:hep-ph/0211124; J. L. Hewett, F. J. Petriello and T. G. Rizzo, JHEP 0310, 062 (2003) arXiv:hep-ph/0211121; C. Csaki et al., J. Terning, constraints,” Phys. Rev. D 68, 035009 (2003) arXiv:hep-ph/0303236; M. Perelstein, M. E. Peskin and A. Pierce, Phys. Rev. D 69, 075002 (2004) arXiv:hep-ph/0310039; M. C. Chen and S. Dawson, Phys. Rev. D 70, 015003 (2004) arXiv:hep-ph/0311032; W. Kilian and J. Reuter, Phys. Rev. D 70, 015004 (2004) arXiv:hep-ph/0311095; G. Marandella, C. Schappacher and A. Strumia, Phys. Rev. D 72, 035014 (2005) arXiv:hep-ph/0502096.

[10] A. Martin, arXiv:hep-ph/0602206; A. Birkedal, A. Noble, M. Perelstein and A. Spray, Phys. Rev. D 74, 035002 (2006) arXiv:hep-ph/0603077; M. Perelstein and A. Spray, Phys. Rev. D 75, 083519 (2007) arXiv:hep-ph/0610357; Y. Bai, Phys. Lett. B 666, 332 (2008) arXiv:0801.1662 [hep-ph]].

[11] D. Hooper and G. Zaharijas, Phys. Rev. D 75, 035010 (2007) arXiv:hep-ph/0612137.

[12] V. Barger, W. Y. Keung and G. Shaughnessy, arXiv:0806.1962 [hep-ph].
[13] D. Abrams et al. [CDMS Collaboration], Phys. Rev. D 66, 122003 (2002) [arXiv:astro-ph/0203500]; D. S. Akerib et al. [CDMS Collaboration], Phys. Rev. Lett. 93, 211301 (2004) [arXiv:astro-ph/0405033]; D. S. Akerib et al. [CDMS Collaboration], Phys. Rev. Lett. 96, 011302 (2006) [arXiv:astro-ph/0509259].

[14] E. Aprile [The XENON Collaboration], arXiv:astro-ph/0502279.

[15] J. Angle et al. [XENON Collaboration], Phys. Rev. Lett. 100, 021303 (2008) [arXiv:0706.0039 [astro-ph]].

[16] J. Hubisz, P. Meade, A. Noble and M. Perelstein, JHEP 0601, 135 (2006) arXiv:hep-ph/0506042.

[17] M. Asano, S. Matsumoto, N. Okada and Y. Okada, Phys. Rev. D 75, 063506 (2007) arXiv:hep-ph/0602157.

[18] R. S. Hundi, B. Mukhopadhyaya and A. Nyffeler, Phys. Lett. B 649, 280 (2007) arXiv:hep-ph/0611116.

[19] J. Hubisz, S. J. Lee and G. Paz, JHEP 0606, 041 (2006) arXiv:hep-ph/0512169; M. Blanke et al., JHEP 0612, 003 (2006) arXiv:hep-ph/0605214; JHEP 0701, 066 (2007) arXiv:hep-ph/0610298; S. R. Choudhury et al., Phys. Rev. D 75, 055011 (2007) arXiv:hep-ph/0612327; M. Blanke, A. J. Buras, B. Duling, A. Poschenrieder and C. Tarantino, JHEP 0705, 013 (2007) arXiv:hep-ph/0702136; M. Blanke, A. J. Buras, S. Reckziegel, C. Tarantino and S. Uhlig, Phys. Lett. B 657, 81 (2007) arXiv:hep-ph/0703254; JHEP 0706, 082 (2007). arXiv:0704.3329 [hep-ph].

[20] D. Choudhury and D. K. Ghosh, JHEP 0708, 084 (2007) arXiv:hep-ph/0612299; A. Datta, P. Dey, S. K. Gupta, B. Mukhopadhyaya and A. Nyffeler, Phys. Lett. B 659, 308 (2008) arXiv:0708.1912 [hep-ph]; L. Wang and J. M. Yang, Phys. Rev. D 77, 015020 (2008) arXiv:0710.5038 [hep-ph]; A. Belyaev et al., arXiv:0806.2838 [hep-ph]; S. Matsumoto, T. Moroi and K. Tobe, Phys. Rev. D 78, 055018 (2008) arXiv:0806.3837 [hep-ph]; M. Burns, K. Kong, K. T. Matchev and M. Park, JHEP 0810, 081 (2008) arXiv:0808.2472 [hep-ph].

[21] J. Hubisz and P. Meade, Phys. Rev. D 71, 035016 (2005) arXiv:hep-ph/0411264.

[22] G. Jungman, M. Kamionkowski and K. Griest, Phys. Rept. 267, 195 (1996) arXiv:hep-ph/9506380.

[23] G. Belanger, F. Boudjema, A. Pukhov and A. Semenov, arXiv:0803.2360 [hep-ph];

[24] G. Belanger, F. Boudjema, A. Pukhov and A. Semenov, Comput. Phys. Commun. 176, 367 (2007) arXiv:hep-ph/0607059.