Light Dirac right-handed sneutrino dark matter

Ki-Young Choi

Asia Pacific Center for Theoretical Physics,
Pohang, Gyeongbuk 790-784, Republic of Korea and
Department of Physics, POSTECH, Pohang,
Gyeongbuk 790-784, Republic of Korea

Osamu Seto

Department of Life Science and Technology,
Hokkai-Gakuen University, Sapporo 062-8605, Japan

Abstract

We show that mostly right-handed Dirac sneutrino is a viable supersymmetric light dark matter candidate. While the Dirac sneutrino scattering with nuclei is dominantly through the $Z$ boson exchange and is stringently constrained by the invisible decay width of $Z$ boson, it is possible to realize a large enough cross section with nucleon to account for possible signals observed at direct dark matter searches such as CDMS II-Si or CoGeNT. Even if the XENON100 limit is taken into account, a small part of signal region for CDMS II-Si events remains outside the excluded region by XENON100.

PACS numbers:
I. INTRODUCTION

Light weakly interacting massive particles (WIMPs) with the mass around 10 GeV have received a lot of attentions motivated by the results in some direct dark matter (DM) detection experiments. DAMA/LIBRA has claimed detection of the annual modulation signal by WIMPs [1]. CoGeNT has found an irreducible excess [2] and annual modulation [3]. CRESST has observed more events than expected backgrounds can account for [4, 5]. CDMS II collaboration has just announced [6] that their silicon detectors have detected three events and its possible signal region overlaps with the possible CoGeNT signal region analyzed by Kelso et al [7]. However, these observations are challenged to the null results obtained by other experimental collaborations, CDMS II [8, 9], XENON10 [10], XENON100 [11, 12] and SIMPLE [13]. Recently, Frandsen et al [14] have pointed out that the XENON10 exclusion limit in Ref. [10] might be overconstraining. It has been stressed that the signal region due to low energy signals in CDMS II-Si extends outside the XENON exclusion limit [15].

The Fermi-LAT collaboration has derived stringent constraints on s-wave annihilation cross section of WIMPs, by analyzing gamma ray flux from dwarf satellite galaxies [16]. Particularly, in the light mass region below $O(10)$ GeV, the annihilation cross section times relative velocity $\langle \sigma v \rangle$ of $O(10^{-26})$cm$^3$/s, which corresponds to the right thermal relic abundance $\Omega h^2 \approx 0.1$, has been excluded.

Light WIMPs have been investigated for the dark matter interpretation of those positive data. In fact, very light neutralino in the Minimal Supersymmetric Standard Model (MSSM) [17, 18] and the Next-to-MSSM (NMSSM) [19, 20] or very light right-handed (RH) sneutrino in the NMSSM [21, 22] had been regarded as such candidates. However, those candidates hardly avoid the above Fermi-LAT constraint [1].

In this paper, we show that mostly right-handed Dirac sneutrino is a viable supersymmetric light DM candidate and have a large enough cross section with nucleon to account for possible signals observed at direct DM searches. Dirac sneutrino scatters off with nuclei dominantly via the $Z$ boson exchange process through the suppressed coupling and mostly with not protons but neutrons. Although this $Z$ boson mediated scattering does not relax the tension among direct DM search experiments and its availability is limited by the invis-

---

1 If we give up the standard thermal relic, we may consider a WIMP with the small enough annihilation cross section to satisfy the Fermi-LAT bound [24] or nonvanishing dark matter asymmetry [25].
ible decay width of the $Z$ boson, a part of signal region for CDMS II-Si events \cite{6} remains outside the excluded region by XENON100 \cite{12}. We examine the cosmic dark matter abundance as well as the constraints from indirect dark matter searches for a viable model of Dirac sneutrino dark matter.

The paper is organized as follows. In Sec. II we estimate the DM-nucleon scattering cross section through the $Z$ boson exchange process and show the experimental bounds or signal regions for this case. We impose the bound from the $Z$ boson invisible decay width too. In Sec. III after brief description of a model, we examine other cosmological, astrophysical and phenomenological constraints. We then summarize our results in Sec. IV.

II. DIRAC SNEUTRINO DARK MATTER DIRECT DETECTION

A. Invisible $Z$ boson decay

We are going to consider light Dirac sneutrino DM scattering with nuclei through $Z$ boson exchange process in the direct detection experiments. Since the property of $Z$ boson is well understood, the possibility of light sneutrino has been stringently constrained from the invisible decay width of $Z$ boson. First of all, here, we briefly summarize the bound.

The $Z$ boson invisible decay is $(20.00 \pm 0.06)\%$ for the total decay width of the $Z$ boson decay $\Gamma_Z = 2.4952 \pm 0.0023$ GeV \cite{26}. That gives constraint on the neutrino number which couples to $Z$ boson given by \cite{26}

$$N_\nu = 2.984 \pm 0.008, \quad \text{(PDG).}$$  \hfill (1)

The LEP bound on the extra invisible decay width is given as \cite{27}

$$\Delta \Gamma_{\text{inv}}^Z < 2.0 \text{ MeV} \quad \text{(95\% CL).}$$  \hfill (2)

If there is a light sneutrino which couples to $Z$ boson, the $Z$ boson can decay into light sneutrino. The spin averaged amplitude is

$$|M|^2 = \frac{|C_{\text{eff}}|^2 g^2 M_Z^2}{12 \cos^2 \theta_W} \left(1 - \frac{4 M_N^2}{M_Z^2}\right).$$  \hfill (3)

Here, $C_{\text{eff}}$ parametrizes the suppression in the (sneutrino)-(sneutrino)-(Z boson) coupling as shown in Fig. \ref{fig:fig1}. For pure left-handed sneutrinos, $C_{\text{eff}} = 1$. The decay width of $Z$ boson
The effective vertex between sneutrino and the $Z$ boson is given by

$$\Gamma_{Z \rightarrow \tilde{N}\tilde{N}^*} = \frac{|C_{\text{eff}}|^2 \frac{g^2 M_Z}{192 \pi \cos^2 \theta_W} \left(1 - 4 \frac{M_{\tilde{N}}^2}{M_Z^2}\right)^{3/2}}{M_{\tilde{N}}},$$

and we impose the upper bound (2) on this. Those bound corresponds to

$$C_{\text{eff}} \lesssim 0.15,$$

for a few GeV dark matter. The contour plot of invisible decay width is also shown in Fig. 3.

### B. Direct Detection

Dirac sneutrino DM can have elastic scattering with nuclei in the direct detection experiments. The mostly relevant process is due to the $Z$ boson exchange as in the left diagram in the Fig. 2. The $Z$ boson exchange cross section with nuclei $A_{\tilde{N}}$ is given by
\[ \sigma_{\chi N}^Z = |C_{\text{eff}}|^2 \frac{G_F^2}{2\pi} \frac{m_N^2}{(M_{\text{DM}} + m_N)^2} \left[ A_N + 2(2\sin^2 \theta_W - 1)Z_N \right]^2 \]

\[ \simeq (A_N - Z_N)^2 \left( \frac{\mu_X^2}{\mu^2} \right) \sigma_{\chi n}^Z, \]

where \( M_{\text{DM}} \) and \( m_N \) denote dark matter mass and nucleus mass respectively, \( A_N \) and \( Z_N \) are the mass number and proton number of the nucleus, and \( G_F \) is the Fermi constant \[28\]. Here \( \mu_X \) is the reduced mass defined by

\[ \mu_X = \frac{M_{\text{DM}}m_X}{(M_{\text{DM}} + m_X)}, \]

and \( m_n \) stands for the neutron mass. In the expression (7), \( \sigma_{\chi n}^Z \) denotes the DM scattering cross section with a neutron, we have used the fact that the \( Z \) boson dominantly couples with a neutron compared to a proton as \( (1 - 4\sin^2 \theta_W) \simeq 0.076 \) and hence neglected the contribution from the scattering with a proton.

Usually the bound or signal of the direct detection experiments is given to the WIMP-Nucleon scattering cross section assuming isospin conserving case. This is true for the conventional WIMP such as neutralino where Higgs bosons exchange processes are dominant. For \( Z \) boson mediated case, the DM interacts dominantly with neutron, thus the bound should be modified according to this. Using Eq. (7), the corresponding WIMP-neutron cross section, \( \sigma_n^{(Z)} \), for \( Z \) boson mediated case is related to the isospin conserving (IC) WIMP-Nucleon scattering cross section, \( \sigma_n^{(IC)} \), by

\[ \sigma_n^{(Z)} = \sigma_n^{(IC)} \left( \frac{A}{A - Z} \right)^2. \]

For Xenon \( A \approx 130, Z = 54 \), for Si in CDMS II \( A = 28, Z = 14 \). Those factors give enhancement on the cross section by a factor 4 and 3 respectively.

In Fig. 3 we show the contour of the \( Z \) boson extra invisible decay width and the WIMP-neutron scattering cross section in the plane of \( C_{\text{eff}} \) and the dark matter mass \( M_{\text{DM}} \). The contours of the predicted scattering cross section with a neutron (blue) are given in the unit of \( 10^{-40}\)cm\(^2\) and those of the extra \( Z \) boson invisible decay width (red). The red region is disallowed by LEP bound on the \( Z \) boson extra invisible decay given in Eq. (2).

In Fig. 4 we show the WIMP-neutron scattering cross section versus dark matter mass. We show the constraint from XENON100 \[12\], and the signals measured by CDMS II-Si \[6\] and CoGeNT \[7\] with the contour of the \( Z \) boson extra invisible decay width. According
FIG. 3: The contours of the predicted scattering cross section with a neutron (blue) in $10^{-40}\text{cm}^2$ and those of the extra $Z$ boson invisible decay width (red) as a function of sneutrino mass and $C_{\text{eff}}$. The red region is disallowed by LEP bound, $\Delta\Gamma_{\text{inv}}^{Z} < 2.0 \text{MeV}$ [27].

to Ref. [14], we do not include the XENON10 limit in this paper to keep our discussion conservative. We find that still barely compatible region exist around dark matter mass around 6 GeV and the WIMP-Nucleon cross section $\sigma^{(Z)}_{n} \simeq 10^{-40}\text{cm}^2$.

III. OTHER CONSTRAINTS

Discussion and the conclusion in the previous section are model independent and applicable for any scalar DM scattering with nucleon dominantly through $Z$ boson exchange, by introducing the coefficient $C_{\text{eff}}$. In this section, we discuss other DM phenomenology and other experimental constraints. To do those, we need to specify particle model for Dirac sneutrino dark matter.

One model has been constructed with non-conventional supersymmetry breaking mediation [29]. Light sneutrino DM has been studied in Ref. [30, 31] and unfortunately has turned out to be hardly compatible with the large hadron collider (LHC) data, mainly due to the SM-like Higgs boson invisible decay width [31].

There is another available model proposed by us [32] in the context of neutrinophilic
Higgs doublet model [33–36]. Therefore in the rest of this section, as an example, we discuss other DM phenomenology based on this model.

A. Brief description of the model in Ref. [32]

The neutrinophilic Higgs model is based on the concept that the smallness of neutrino mass might not come from a small Yukawa coupling but a small vacuum expectation value (VEV) of the neutrinophilic Higgs field $H_\nu$. As a result, neutrino Yukawa couplings can be as large as of the order of unity for a small enough VEV of $H_\nu$. Other aspects, for instance collider phenomenology [37–39], astrophysical and cosmological consequences [32, 40–42], vacuum structure [43] and variant models [44–46], also have been studied.

The supersymmetric neutrinophilic Higgs model has a pair of neutrinophilic Higgs doublets $H_\nu$ and $H_{\nu'}$ in addition to up- and down-type two Higgs doublets $H_u$ and $H_d$ in the MSSM [40]. A discrete $Z_2$ parity is also introduced to discriminate $H_u(H_d)$ from $H_\nu(H_{\nu'})$, and the corresponding charges are assigned in Table I. Under this discrete symmetry, the
The superpotential is given by
\[ W = y_u Q \cdot H_u U_R + y_d Q \cdot H_d D_R + y_l L \cdot H_d E_R + y_{\nu} L \cdot H_\nu N + \mu H_u \cdot H_d + \mu' H_{\nu'} \cdot H_{\nu'} + \rho H_u \cdot H_{\nu'} + \rho' H_{\nu} \cdot H_d, \]
(10)
where we omit generation indices and dot represents $SU(2)$ antisymmetric product. The $Z_2$ parity plays a crucial role of suppressing tree-level flavor changing neutral currents (FCNCs) and is assumed to be softly broken by tiny parameters of $\rho$ and $\rho'(\ll \mu, \mu')$. Here, we do not introduce lepton number violating Majorana mass for RH neutrino $N$ to realize Dirac (s)neutrino.

By solving the stationary conditions for Higgs fields, one find that tiny soft $Z_2$-breaking parameters $\rho, \rho'$ generate a large hierarchy of $v_{u,d}(\equiv \langle H_{u,d} \rangle) \gg v_{\nu,\nu'}(\equiv \langle H_{\nu,\nu'} \rangle)$ expressed as
\[ v_\nu = O\left( \frac{\rho}{\mu'} \right) v. \]
(11)
It is easy to see that neutrino Yukawa couplings $y_\nu$ can be large for small $v_\nu$ using the relation of the Dirac neutrino mass $m_\nu = y_\nu v_\nu$. For $v_\nu \sim 0.1$ eV, it gives $y_\nu \sim 1$. At the vacuum of $v_{\nu,\nu'} \ll v_{u,d}$, physical Higgs bosons originated from $H_{u,d}$ are almost decoupled from those from $H_{\nu,\nu'}$, except a tiny mixing of the order of $O(\rho/M_{SUSY}, \rho'/M_{SUSY})$ where $M_{SUSY}(\sim 1$ TeV) denotes the scale of soft SUSY breaking parameters. The former $H_{u,d}$ doublets almost constitute Higgs bosons in the MSSM - two CP-even Higgs bosons $h$ and $H$, one CP-odd Higgs boson $A$, and a charged Higgs boson $H^\pm$ - while the latter, $H_{\nu,\nu'}$, constitutes two CP-even Higgs bosons $H_{2,3}$, two CP-odd bosons $A_{2,3}$, and two charged Higgs bosons $H_{2,3}^\pm$. Thus, our model does not suffer from a large invisible decay width of SM-like Higgs boson $h$ even for a large $y_\nu$ and the light dark matter.

At the vacuum, the mixing between left- and right-handed sneutrino is estimated as
\[ \sin \theta_\nu = O\left( \frac{m_\nu}{M_{SUSY}} \right). \]
(12)
We find that the RH sneutrino $\tilde{N}$ has very suppressed interactions to the SM-like Higgs boson or $Z$ boson at tree level, since they are proportional to the mixing of LH and RH neutrinos $\sin\theta_\nu$ in Eq. (12). However, radiative corrections induce a sizable coupling between RH sneutrino and $Z$ boson. We have parametrized the effective interaction between the RH sneutrino DM and $Z$ boson by $C_{\text{eff}}$, then the vertex induced by scalar ($H_\nu$-like Higgs boson and $\tilde{\nu}_L$) loop $^2$ is given as

$$\text{Vertex} = \frac{g}{2\cos\theta_W} (k_1^\mu + k_2^\mu) C_{\text{eff}},$$

with

$$C_{\text{eff}} = \frac{(-i)(y_\nu A_\nu)^2}{12(4\pi)^2 M^2},$$

where $k_1^\mu$ and $k_2^\mu$ are the ingoing and outgoing momentum of RH sneutrino and for simplicity we take equal masses of particles in the loop $M = M_{H_\nu} = M_{\tilde{\nu}_L}$.

By comparing Fig. 4 and Eq. (7) with Eq. (14), we find that a parameter set

$$y_\nu A_\nu \simeq 14.4 \, M \quad \text{and} \quad M_{\text{DM}} \simeq 6 \, \text{GeV},$$

can explain CDMS II-Si result.

### B. Annihilation cross section

The dominant tree-level annihilation mode of $\tilde{N}$ in the early Universe is the annihilation into a lepton pair $\tilde{N}\tilde{N}^* \rightarrow f_1 f_2$ mediated by the heavy $H_\nu$-like Higgsinos as described in Fig. 5. The final states $f_1$ and $f_2$ are charged leptons for the $t$-channel $H_\nu$-like charged Higgsino ($\tilde{H}_\nu^\pm$) exchange, while those are neutrinos for the $t$-channel $\tilde{H}_\nu$-like neutral Higgsino ($\tilde{H}_\nu^0$) exchange. The thermal averaged annihilation cross section for this mode in the early Universe when using the partial wave expansion method is given by $^4$7

$$\langle \sigma v \rangle_{f\bar{f}} = \sum_f \left( \frac{y_\nu^4}{16\pi} \frac{m_f^2}{(M_{\tilde{N}}^2 + M_{H_\nu}^2)^2} + \frac{y_\nu^4}{8\pi} \frac{M_{\tilde{N}}^2}{(M_{\tilde{N}}^2 + M_{\tilde{H}_\nu}^2)^2} \frac{T}{M_{\tilde{N}}} + \ldots \right),$$

where we used $\langle v_{\text{rel}}^2 \rangle = 6T/M_{\text{DM}}$ with $v_{\text{rel}}$ being the relative velocity of annihilating dark matter particles, and $m_f$ is the mass of the fermion $f$ and $M_{\tilde{H}_\nu} \simeq \mu'$ denotes the mass of

$^2$ Fermion loop contribution is suppressed by helicity.
FIG. 5: Tree-level diagram for the annihilation of RH sneutrinos.

$\tilde{H}_\nu$-like Higgsino. For simplicity we have assumed that Yukawa couplings are universal for each flavor. Since the s-wave contribution of the first term in the right-hand side is helicity suppressed, the p-wave annihilation cross section of the second term is relevant for the dark matter relic density at freeze-out epoch.

In the neutrinophilic Higgs model, sneutrino has, in addition to the tree level processes, sizable annihilation cross section into two photons through one-loop diagram and it has been pointed out in Ref. [32]. The charged components of the $H_\nu$ scalar doublet and charged scalar fermions make the triangle or box loop-diagram and the two photons can be emitted from the internal charged particles. For the mass spectrum we are interested in now $M_{H_\nu}, M_\tilde{l} \gg M_{\tilde{N}}$, we obtain the annihilation cross section to two photons via one loop as

$$\langle \sigma v \rangle_{2\gamma} \simeq \frac{\alpha_{em}^2 y_\nu^4 (A_\nu^2 + \mu^2)^2}{8 \pi^3} \frac{4}{M_{\text{ch}}^4 M_{\tilde{N}}^2},$$

where we have used $M_{H_\nu} = M_{H'_\nu} = M_\tilde{l} \equiv M_{\text{ch}}$ for simplicity.

Therefore for the total annihilation cross section of RH sneutrino DM, we obtain

$$\langle \sigma v \rangle = \langle \sigma v \rangle_{ff} + \langle \sigma v \rangle_{2\gamma}. $$

Now if we consider to reproduce the latest CDMS II-Si data by taking a parameter set given as Eq. (15), we find that two-photon production via one-loop is dominant and thus

$$\langle \sigma v \rangle \simeq \langle \sigma v \rangle_{2\gamma} \simeq 10^{-3} \text{ GeV}^{-2},$$

for the given parameter in Eq. (15). This loop-induced annihilation does not only dominate the tree-level annihilation but also exceeds the standard value $\langle \sigma v \rangle \simeq 10^{-9} \text{ GeV}^{-2}$. Then, this DM appears not to have the correct thermal relic abundance if the relic density would be determined from its thermal freeze-out.
C. Dark matter relic abundance and indirect DM search constraints

As stated above, from Eq. (19), we see that the standard thermal relic density of $\tilde{N}$ with zero chemical potential leads to too few $\Omega h^2 \ll 0.1$. However, we know our Universe is baryon asymmetric. Hence, we expect that lepton asymmetry is also nonvanishing. In fact, the sphaleron process, which interchanges baryons and leptons, plays an important role in many baryogenesis mechanism and leaves the similar amount of baryon asymmetry and lepton asymmetry. A promising mechanism would be Affleck-Dine baryo(lepto)genesis \[^{48}\], because our model is supersymmetric. Since Dirac sneutrino carries lepton number and has a large annihilation cross section as Eq. (19), our sneutrino is one natural realization of the so-called asymmetric dark matter (ADM) \[^{49–55}\], only $\tilde{N}$ remains after annihilation with $\tilde{N}^*$. Thus, the relic abundance is actually determined by its asymmetry and the mass.

For a nonvanishing sneutrino asymmetry of the similar amount of baryon asymmetry

$$Y_{\tilde{N}} \equiv \frac{n_{\tilde{N}} - n_{\tilde{N}^*}}{s} = \mathcal{O}(10^{-10}),$$

\(^{(20)}\)

and the mass of about $5 - 6$ GeV, the correct relic density for dark matter $\Omega_{\tilde{N}} h^2 \simeq 0.1$ is obtained.

Finally we note that our model is free from any indirect DM search constraint, in other words, DM can not produce any signal because of the ADM property, namely, the absence of anti-DM particles in our Universe.

IV. CONCLUSION

We have shown that mostly right-handed Dirac sneutrino is a viable supersymmetric light DM candidate and have a large enough cross section with nucleon to account for possible signals observed at direct DM searches. The $Z$ boson mediated scattering does not relax the tension among direct DM search experiments and is constrained by the invisible decay width of the $Z$ boson. Nevertheless, we have found that a part of signal region for CDMS II-Si events remains outside the excluded region by XENON100. As an example of specific particle models, we have shown that a Dirac right-handed sneutrino with neutrino-phobic Higgs doublet fields is a viable light dark matter candidate.
Acknowledgments

K.-Y.C. was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology Grant No. 2011-0011083. K.-Y.C. acknowledges the Max Planck Society (MPG), the Korea Ministry of Education, Science and Technology (MEST), Gyeongsangbuk-Do and Pohang City for the support of the Independent Junior Research Group at the Asia Pacific Center for Theoretical Physics (APCTP).

[1] R. Bernabei et al. [DAMA and LIBRA Collaborations], Eur. Phys. J. C 67, 39 (2010).
[2] C. E. Aalseth et al. [CoGeNT Collaboration], Phys. Rev. Lett. 106, 131301 (2011).
[3] C. E. Aalseth et al. [CoGeNT Collaboration], Phys. Rev. Lett. 107, 141301 (2011).
[4] G. Angloher et al., Eur. Phys. J. C 72, 1971 (2012).
[5] A. Brown, S. Henry, H. Kraus and C. McCabe, Phys. Rev. D 85, 021301 (2012).
[6] R. Agnese et al. [CDMS Collaboration], [arXiv:1304.4279 [hep-ex]].
[7] C. Kelso, D. Hooper and M. R. Buckley, Phys. Rev. D 85, 043515 (2012).
[8] D. S. Akerib et al. [CDMS Collaboration], Phys. Rev. D 82, 122004 (2010).
[9] Z. Ahmed et al. [CDMS Collaboration], Phys. Rev. Lett. 106, 131302 (2011).
[10] J. Angle et al. [XENON10 Collaboration], Phys. Rev. Lett. 107, 051301 (2011).
[11] E. Aprile et al. [XENON100 Collaboration], Phys. Rev. Lett. 107, 131302 (2011).
[12] E. Aprile et al. [XENON100 Collaboration], Phys. Rev. Lett. 109, 181301 (2012).
[13] M. Felizardo et al., Phys. Rev. Lett. 108, 201302 (2012).
[14] M. T. Frandsen, F. Kahlhoefer, C. McCabe, S. Sarkar and K. Schmidt-Hoberg, [arXiv:1304.6066 [hep-ph]].
[15] E. Del Nobile, G. B. Gelmini, P. Gondolo and J. -H. Huh, [arXiv:1304.6183 [hep-ph]].
[16] M. Ackermann et al. [Fermi-LAT Collaboration], Phys. Rev. Lett. 107, 241302 (2011).
[17] D. Hooper and T. Plehn, Phys. Lett. B 562, 18 (2003).
[18] A. Bottino, N. Fornengo and S. Scopel, Phys. Rev. D 67, 063519 (2003).
[19] D. G. Cerdeno, C. Hugonie, D. E. Lopez-Fogliani, C. Munoz and A. M. Teixeira, JHEP 0412, 048 (2004).
[20] J. F. Gunion, D. Hooper and B. McElrath, Phys. Rev. D 73, 015011 (2006).
[21] D. G. Cerdeno, C. Munoz and O. Seto, Phys. Rev. D 79, 023510 (2009).
[22] D. G. Cerdeno, J. -H. Huh, M. Peiro and O. Seto, JCAP 1111, 027 (2011).
[23] K. -Y. Choi, E. J. Chun and C. S. Shin, arXiv:1211.5409 [hep-ph].
[24] R. Allahverdi, B. Dutta, R. N. Mohapatra and K. Sinha, arXiv:1305.0287 [hep-ph].
[25] N. Okada and O. Seto, arXiv:1304.6791 [hep-ph].
[26] J. Beringer et al. [Particle Data Group Collaboration], Phys. Rev. D 86, 010001 (2012).
[27] S. Schael et al. [ALEPH and DELPHI and L3 and OPAL and SLD and LEP Electroweak Working Group and SLD Electroweak Group and SLD Heavy Flavour Group Collaborations], Phys. Rept. 427 257 (2006).
[28] C. Arina and N. Fornengo, JHEP 0711 029 (2007).
[29] N. Arkani-Hamed, L. J. Hall, H. Murayama, D. Tucker-Smith and N. Weiner, Phys. Rev. D 64, 115011 (2001).
[30] G. Belanger, M. Kakizaki, E. K. Park, S. Kraml and A. Pukhov, JCAP 1011, 017 (2010).
[31] B. Dumont, G. Belanger, S. Fichet, S. Kraml and T. Schwetz, JCAP 1209, 013 (2012).
[32] K. -Y. Choi and O. Seto, Phys. Rev. D 86 043515 (2012) [Erratum-ibid. D 86 089904 (2012)].
[33] E. Ma, Phys. Rev. Lett. 86, 2502 (2001).
[34] F. Wang, W. Wang and J. M. Yang, Europhys. Lett. 76, 388 (2006).
[35] E. Ma, Phys. Rev. D 73, 077301 (2006).
[36] S. Gabriel and S. Nandi, Phys. Lett. B 655, 141 (2007).
[37] S. M. Davidson and H. E. Logan, Phys. Rev. D 80, 095008 (2009); Phys. Rev. D 82, 115031 (2010).
[38] H. E. Logan and D. MacLennan, Phys. Rev. D 81, 075016 (2010).
[39] N. Haba and K. Tsumura, JHEP 1106, 068 (2011).
[40] N. Haba and O. Seto, Prog. Theor. Phys. 125, 1155 (2011); Phys. Rev. D 84, 103524 (2011).
[41] N. Haba, O. Seto and Y. Yamaguchi, arXiv:1305.2484 [hep-ph].
[42] M. Sher and C. Triola, Phys. Rev. D 83, 117702 (2011);
S. Zhou, Phys. Rev. D 84, 038701 (2011).
[43] N. Haba and T. Horita, Phys. Lett. B 705, 98 (2011);
T. Morozumi, H. Takata and K. Tamai, Phys. Rev. D 85, 055002 (2012).
[44] N. Haba and M. Hirotsu, Eur. Phys. J. C 69, 481 (2010).
[45] N. Haba, K. Kaneta and Y. Shimizu, Phys. Rev. D 86, 015019 (2012).
[46] Y. Morita, H. Nakano and T. Shimomura, arXiv:1212.4304 [hep-ph].
[47] M. Lindner, A. Merle and V. Niro, Phys. Rev. D 82, 123529 (2010).
[48] I. Affleck and M. Dine, Nucl. Phys. B 249, 361 (1985).
[49] S. M. Barr, R. S. Chivukula and E. Farhi, Phys. Lett. B 241, 387 (1990).
[50] S. M. Barr, Phys. Rev. D 44, 3062 (1991).
[51] D. B. Kaplan, Phys. Rev. Lett. 68, 741 (1992).
[52] S. D. Thomas, Phys. Lett. B 356, 256 (1995).
[53] D. Hooper, J. March-Russell and S. M. West, Phys. Lett. B 605, 228 (2005).
[54] R. Kitano and I. Low, Phys. Rev. D 71, 023510 (2005).
[55] D. E. Kaplan, M. A. Luty and K. M. Zurek, Phys. Rev. D 79, 115016 (2009).