

Implications of the axino LSP on the naturalness

Gabriela Barenboim,^{1,*} Eung Jin Chun,^{2,3,†} Sunghoon Jung,^{2,‡} and Wan Il Park^{1,2,§}

¹*Departament de Física Teòrica and IFIC,*

Universitat de València-CSIC, E-46100, Burjassot, Spain.

²*Korea Institute for Advanced Study, Seoul 130-722, Korea*

³*Kavli Institute for Theoretical Physics,*

University of California, Santa Barbara, CA 93106, USA

Both the naturalness of the electroweak symmetry breaking and the resolution of the strong CP problem may require a small Higgsino mass μ generated by a realization of the DFSZ axion model. Assuming the axino is the lightest supersymmetric particle, we study its implications on μ and the axion scale. Copiously produced light Higgsinos (effectively only neutral NLSP pairs) eventually decay to axinos leaving prompt multi-leptons or displaced vertices which are being looked for at the LHC. The Higgsino-axino phenomenology is illustrated by comparing with a standard case without lightest axinos as well as with a more general case with additional light gauginos in the spectrum, and current limits on μ and the axion scale are derived.

arXiv:1407.1218v1 [hep-ph] 4 Jul 2014

*Electronic address: Gabriela.Barenboim@uv.es

†Electronic address: ejchun@kias.re.kr

‡Electronic address: nejsh21@gmail.com

§Electronic address: wipark@kias.re.kr

Contents

I. Introduction	2
II. Current limits on (N)LSP Higgsinos without axinos	4
III. Higgsino NLSP and axino LSP	7
IV. Higgsino NNLSP, Bino NLSP and axino LSP	12
V. Conclusion	15
A. Ino decays	15
B. Bound estimation	16
References	16

I. INTRODUCTION

The strong CP problem is elegantly resolved by introducing a Peccei-Quinn (PQ) symmetry [1] and its spontaneous breaking resulting in a dynamical field called the axion [2]. In this mechanism, the CP-violating QCD θ term is determined by a vacuum expectation value of the axion which dynamically cancels out the non-zero QCD θ -term. The PQ symmetry can be realized either by introducing heavy quarks (KSVZ) [3] or by extending the Higgs sector (DFSZ) [4] and its breaking scale v_{PQ} is related with the axion coupling constant as $f_a \equiv \sqrt{2}v_{PQ}/N_{DW}$ with N_{DW} being the domain wall number counting the QCD anomaly¹. The conventionally allowed window of the axion coupling constant is $10^9 \lesssim f_a/\text{GeV} \lesssim 10^{12}$ (For a review, see [5]). The upper bound comes from the axion cold dark matter contribution which is cosmological model dependent. A recent simulation of axionic topological defect contributions provides a stringent upper bound $f_a/\text{GeV} \lesssim \text{a few} \times 10^{10}$ if PQ-symmetry were broken after inflation [6]. The window can be widened if PQ-symmetry were broken before or during inflation in certain class of PQ symmetry breaking models avoiding too large axionic isocurvature perturbations [7]. The existence of such a high scale causes quadratic divergences to the Higgs boson mass and thus requires a huge fine-tuning to keep stable two scales, the electroweak scale and the PQ scale (or a generic UV scale).

Supersymmetry (SUSY) would be the best-known framework to avoid such a hierarchy problem. However, the electroweak symmetry breaking in SUSY suffers from a certain degree

¹ The standard DFSZ model has $N_{DW} = 6$, but a certain variations can allow $N_{DW} = 1$ to avoid the domain wall problem

of fine-tuning to maintain a desirable potential minimization condition:

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2 \beta}{\tan^2 \beta - 1} - \mu^2 \quad (1)$$

where $m_{H_{u,d}}$ are the soft masses of the two Higgs doublets, $\tan \beta \equiv v_u/v_d$ is the ratio of their vacuum expectation values, and μ is the Higgs bilinear parameter in the superpotential. As LHC finds no hint of SUSY, it pushes up the soft mass scale above TeV range, the minimization condition (1) requires a fine cancellation among different terms. Barring too huge cancellation, one may arrange $m_{H_{u,d}}$ and μ not too larger than m_Z . This has been advocated as “natural SUSY” [8] implying stops/sbottoms at sub-TeV and light Higgsinos with

$$\mu \lesssim 200 \text{ GeV}. \quad (2)$$

Such a spectrum can also be obtained radiatively with multi-TeV soft masses at a UV scale [9].

An electroweak μ may be related to the PQ symmetry in the manner of DFSZ [10], which introduces a non-renormalizable superpotential in the Higgs sector:

$$W = \lambda_\mu \frac{P^2}{M_P} H_u H_d \quad (3)$$

where P and thus $H_u H_d$ carries a non-trivial PQ charge and M_P is the reduced Planck mass. Upon the PQ symmetry breaking $v_{PQ} \sim \langle P \rangle$, a μ term is generated by $\mu = \lambda_\mu \langle P \rangle^2 / M_P$. Once PQ-symmetry is broken, there appear the axion a , its scalar partner, the saxion s , and the fermion super-partner, the axino \tilde{a} . Forming an axion superfield $A = (s + ia, \tilde{a})$, one can schematically write down the effective μ -term superpotential;

$$W = \mu H_u H_d + c_H \frac{\mu}{v_{PQ}} A H_u H_d \quad (4)$$

where c_H is a parameter depending on the PQ symmetry breaking sector; we use $c_H = 2$ in this paper. In the context of the natural SUSY having a small μ parameter, a neutral Higgsino tends to be the lightest supersymmetric particle (LSP) and thus is a dark matter candidate assuming R-parity. In this case, a heavy axino decay to the LSP can change the standard thermal Higgsino dark matter density resulting in different mixtures of the axion and Higgsino dark matter components depending on the PQ scale [11].

In this paper, we investigate implications of the axino LSP in the framework of “the natural SUSY DFSZ model”. Naively speaking, the axino mass is expected to be of order

of the soft SUSY breaking scale, but it is in general model dependent [12, 13]. As a dark matter, the abundance of axino depends on the history of the universe involving either the condensation of saxion or the reheating temperature of the primordial inflation. Axinos can be produced abundantly either by saxion decay [14, 15] or by interactions with thermal particles [16–19]². To avoid axino over-production, we assume the axino is very light or the reheat temperature is low enough to suppress the thermal production in this paper.

Since Higgsinos are predicted to be light in the natural SUSY scenario, they can be copiously produced at the LHC and decay to axino plus the Higgs boson h or Z boson through the coupling in Eq. (4). This leads to interesting signatures of multi-leptons/jets and missing transverse energy(MET) which can be prompt or displaced depending on the PQ scale. Notice that the standard Higgsino LSP scenario is hard to probe as heavier Higgsino decays produce unobservably soft leptons or pions due to a small mass gap between a heavier Higgsino and the Higgsino LSP. Currently, the ATLAS and CMS collaborations look for prompt multi-lepton plus MET and displaced di-jet/lepton signatures. Applying the current search results to the Higgsino-axino system, we obtain various limits on the μ parameter as well as the PQ scale. We assume that sleptons, squarks and gluinos are heavy, but see Refs. [21] for earlier collider studies in the presence of light sleptons.

In Sec. II, we first translate the current multi-lepton +MET search results to the Higgsino-bino system where the Higgsino and bino are taken to be the next-to-LSP (NLSP) and the LSP, respectively, and thus the NLSP decay to the LSP plus h or Z can lead to prompt multi-lepton signatures. In Sec. III, we turn into a case of the Higgsino NLSP and the axino LSP which can lead to displaced vertices from the NLSP decay. Then, we extend our analysis to the case of the Higgsino NNLSP and the bino NLSP with the axino LSP in Sec. IV. Finally, we conclude in Sec. V.

II. CURRENT LIMITS ON (N)LSP HIGGSINOS WITHOUT AXINOS

Before considering the axino LSP, let us first deduce and summarize the current exclusion bounds in the case of (1) the standard Higgsino-like NLSP and Bino-like LSP as well as in the case of (2) Higgsino-like LSP. The results will be later compared with those with axino LSPs.

Consider first the case (1) with Higgsino NLSP and Bino LSP. Being relatively light, a sizable number of charged and neutral Higgsinos, χ_1^\pm and $\chi_{2,3}^0$, can be produced electroweakly and decay to the LSP χ_1^0 through $\chi_1^\pm \rightarrow \chi_1^0 W^\pm$ and $\chi_{2,3}^0 \rightarrow \chi_1^0 + h, Z$. The neutral Higgsino

² For the axino dark matter property in the KSVZ model, see Ref. [20].

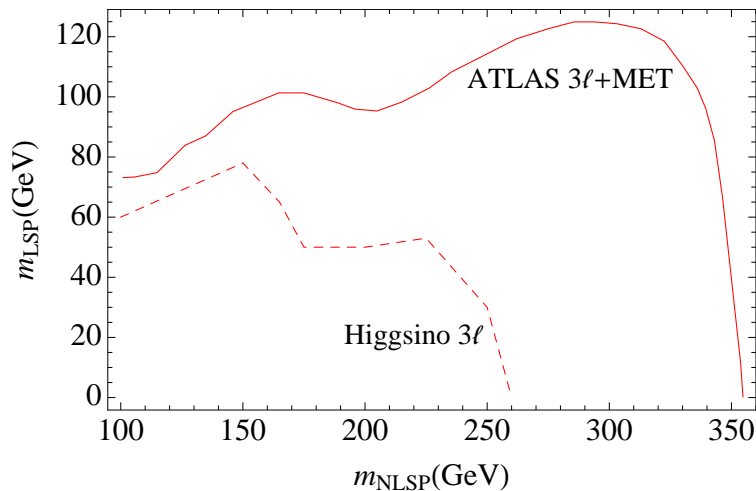


FIG. 1: Current exclusion limits on the standard case with Higgsino NLSP and Bino LSP. The official bound on the Wino NLSP (Bino LSP and 100% branching ratios to W and Z bosons) from the 3ℓ +MET search (20.3/fb) is shown as the solid line for reference [27]. Assuming the Higgsino NLSP with the Bino LSP, we re-interpret the 3ℓ +MET search (dashed). The relevant BR is taken into account with $\mu > 0$, and the 3ℓ search is not sensitive to the sign of μ as depicted in Fig. 2. We assume $M_2 = 2$ TeV and $t_\beta = 3$. More on Sec. II.

decays to the Z boson are relevant to the multi-lepton searches³, and its branching ratio (BR) is a function of t_β and the sign of μ . In Fig. 1, we show current bounds on the Higgsino NLSP overlapping the officially reported bound on the Wino NLSPs from the 3ℓ +MET search [27] for reference. The associate production of charged and neutral Higgsinos is the largest and is constrained from the 3ℓ +MET search: $\chi_1^\pm \chi_2^0 \rightarrow \chi_1^0 \chi_1^0 W Z \rightarrow \chi_1^0 \chi_1^0 + 3\ell \nu$. Here, the dependence on the underlying model parameters such as t_β and the sign of μ is weak as demonstrated in the left panel of Fig. 2 – the relevant BR of Higgsino pairs is in general close to a half [24]. So we use a positive μ to draw the bound in Fig. 1. The bound on Higgsinos is weaker than the official bound on Winos due to two modifications: i) The total production cross-section of Higgsino pair $\chi_2^0 \chi_1^\pm + \chi_3^0 \chi_1^\pm$ is smaller than that of Wino pairs $\chi_2^0 \chi_1^\pm$ (by about a factor 2 for $\mathcal{O}(100)$ GeV NLSPs), and ii) the BR for $\chi_{2,3}^0 \rightarrow \chi_1^0 + Z$ is smaller than 1. The actual bound on Winos will also be weaker than the officially reported one according to a smaller BR. On the other hand, other multi-lepton searches contributed mainly from other pair productions of Higgsinos currently lead to weaker or null bounds; for example, the associate production of two neutral Higgsinos is only weakly constrained from the 4ℓ +MET search [28] via $\chi_2^0 \chi_3^0 \rightarrow \chi_1^0 \chi_1^0 Z Z \rightarrow \chi_1^0 \chi_1^0 4\ell$. In all, the NLSP Higgsino mass

³ Contributions from intermediate Higgs bosons are generally small because of the small leptonic BR via $h \rightarrow WW^*, ZZ^*$ although Higgs decay products can certainly be useful when Higgsinos are heavy [22–25]; see also [26]. Considering light Higgsinos, we ignore Higgs contributions in this work.

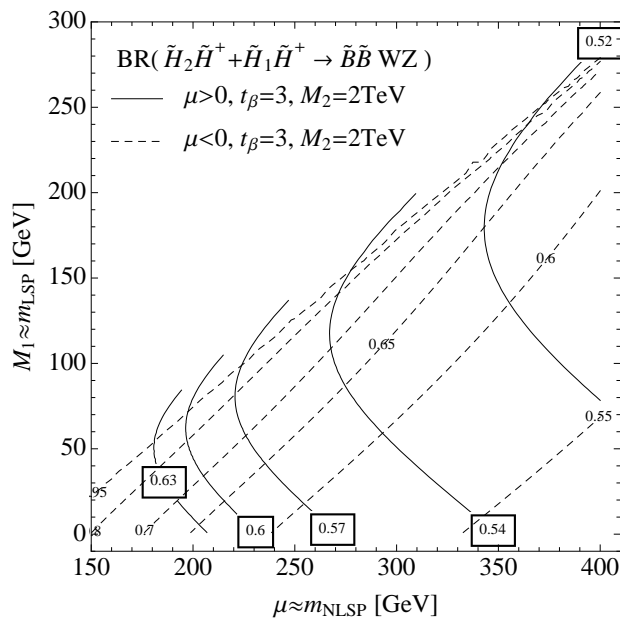


FIG. 2: The branching ratios of NLSP Higgsino pairs to LSP Binos that are relevant to the $3\ell+\text{MET}$ search. Both $\mu > 0$ (solid) or $\mu < 0$ (dashed) are shown. The relevant BR shown does not vary much in most of the parameter space with both signs of μ [24]. This result is used in Fig. 1.

exclusion currently reaches up to about 250 GeV while the LHC sensitivity drops quickly as the mass-gap between the NLSP and LSP becomes smaller.

There exist other experimental results on $3\ell+\text{MET}$ [28] and $4\ell+\text{MET}$ [29]. But they are not essentially different from the ones used above. The $2\ell+2j$ [28, 30] and the same-sign dilepton [28] searches do not give a much stronger bound for such a light μ . The $2\ell+0j+0Z$ search for the WW is also potentially useful [23, 30]. In any case, our interpretation of a few standard searches in Fig. 1 (and similar figures throughout in this paper) is a reasonable and useful estimation of current Higgsino exclusion limits. See Appendix B for more details on how we obtain the bounds.

The Higgsino can also be the LSP (the case (2) above). If other gauginos are far away in mass, all three Higgsino states – one charged and two neutral – are nearly degenerate. Even though light Higgsinos are abundantly produced, visible decay products of decays between them are generally too soft to be observable at collider and two LSPs are produced in back-to-back directions giving a small MET. It is why the search of nearly degenerate spectrum is difficult. The squeezed spectrum is typically searched by triggering hard initial state radiations (ISR) which subsequently boost the visible and invisible decay products. No dedicated LHC search is reported yet, but several theoretical studies of LHC prospects have been carried out in Refs. [31]. It is expected that only up to ~ 150 GeV of Higgsino LSPs will be excluded at LHC14 with $\mathcal{O}(100)$ /fb of data (and essentially no bound at current LHC8 is possible). Decays between Higgsinos are rather prompt [32], so the disappearing track

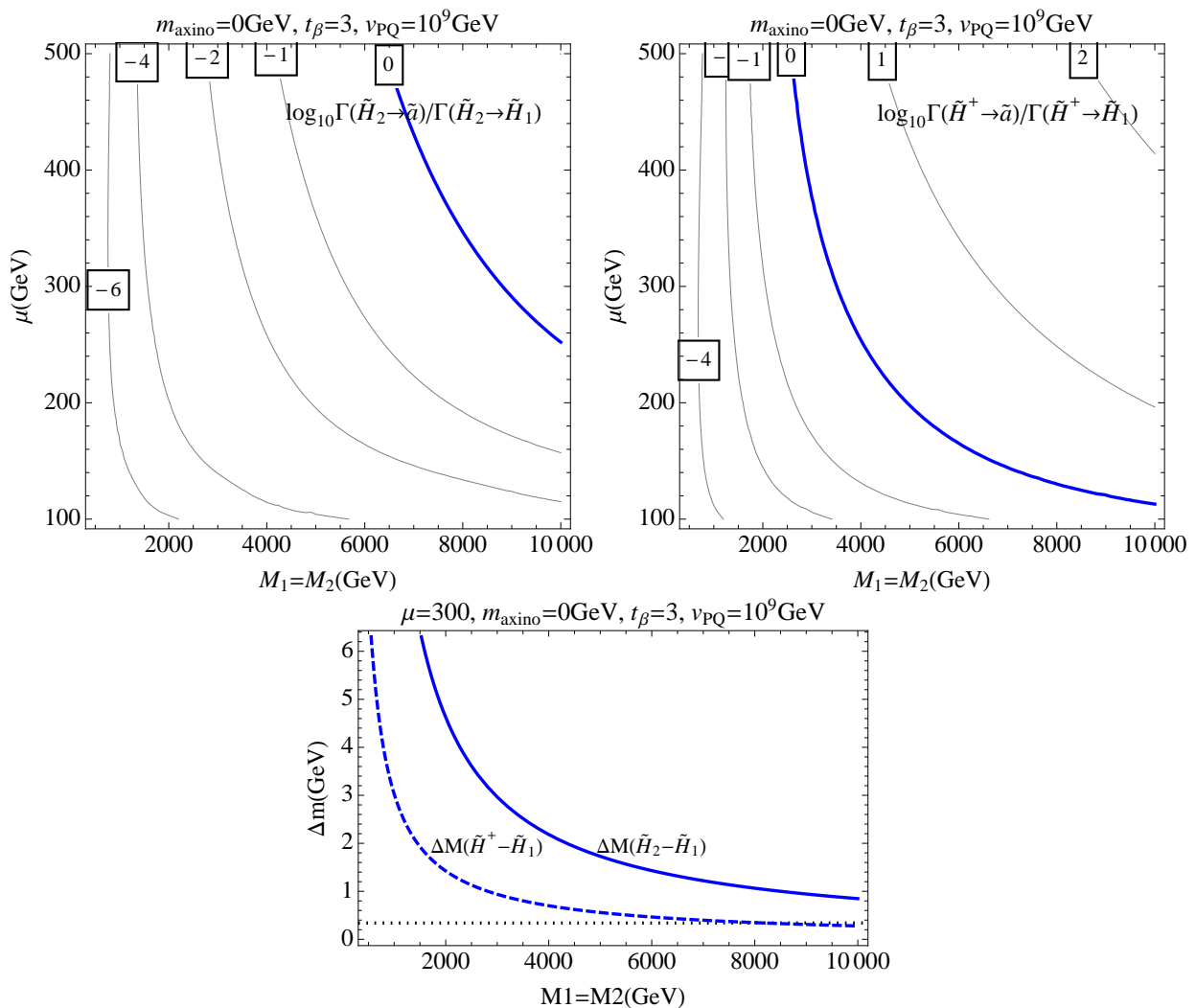


FIG. 3: The decays of heavier Higgsinos (neutral one in the left panel, and charged one in the right panel) to the lightest Higgsino vs. to the axino LSP are compared in the upper panels. Massless axinos and $v_{PQ} = 10^9$ GeV are assumed here. In the lower panel, we show tree-level mass splittings between Higgsino states. The loop-induced mass splitting of the Higgsinos, $\Delta m \sim 355$ MeV [32], is marked as a horizontal dotted line.

searches [33] that are sensitive to the degenerate Wino LSPs are not so useful for Higgsino LSPs; see Appendix A.

III. HIGGSINO NLSP AND AXINO LSP

In this section, we consider the situation of light (NLSP) Higgsinos and heavy gauginos with the axino LSP. In the decoupling limit of gauginos, there occurs an interesting and rich situation for the decays of heavier Higgsinos. Since the axino LSP is weakly interacting, Higgsinos can dominantly decay either to the lightest Higgsino or to the axino LSP, depending

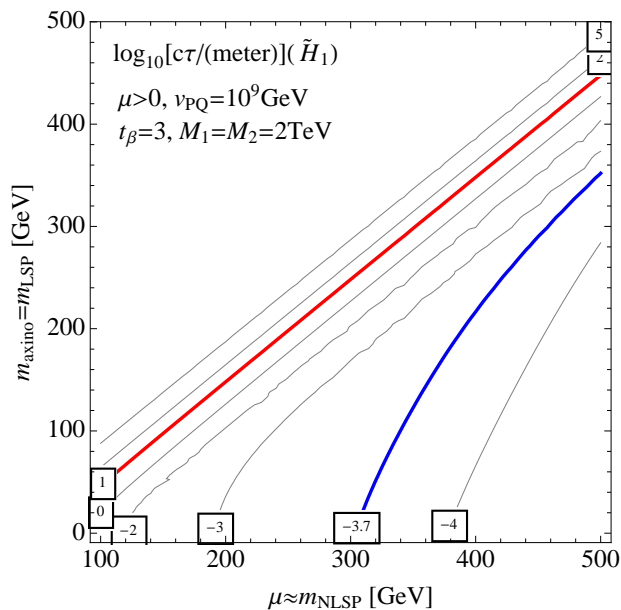


FIG. 4: The proper decay length of the lightest Higgsino NLSP, \tilde{H}_1^0 , in the presence of the axino LSP. $v_{PQ} = 10^9 \text{ GeV}$ here, and the lifetime scales with v_{PQ}^2 . We mark $c\tau \sim 200\mu\text{m}$ with a blue line as a convenient reference for the displaced decay, and we mark $c\tau = 10\text{m}$ with a red line for decaying outside detector. The rapid increase of the lifetime below $m_{\text{NLSP}} - m_{\text{LSP}} \lesssim 90\text{ GeV}$ is due to the closing of any two-body decay modes.

on the gaugino masses and the PQ symmetry breaking scale, v_{PQ} . In Fig. 3, we show relative decay widths of the heavier Higgsinos for massless axinos and $v_{PQ} = 10^9 \text{ GeV}$. Heavier axinos (for a fixed μ) and a higher v_{PQ} scale only make the decays to the axino smaller. For $M_1 = M_2 \lesssim$ a few TeV, both charged and neutral Higgsinos decay dominantly to the lightest Higgsinos even with massless axinos and $v_{PQ} = 10^9 \text{ GeV}$. For larger $M_1 = M_2$, the mass splitting between Higgsino states are too small to have quick enough decays between them. In this paper, we simply assume $M_1 = M_2 = 2\text{ TeV}$ for which all heavier Higgsinos decay to the lightest Higgsinos.

Whether or not the decays of the Higgsino NLSP to the axino LSP can leave observable displaced vertices depends on the values of μ , v_{PQ} and the mass gap between the NLSP and LSP. The proper decay length of the Higgsino NLSP, \tilde{H}_1^0 , is shown in Fig. 4. The distinction between the prompt and displaced decays (also whether decaying inside or outside detector) is not determined solely by the $c\tau$ but also by kinematics of decay products and the probabilistic distributions of decay lengths. But by conveniently referring to the contours of $c\tau = 200\mu\text{m}$ (blue) and 10m (red) – standard tight leptons are required to satisfy $d_0 \gtrsim 200\mu\text{m}$ at LHC [34] and the size of ATLAS detector, for example, is $\sim 10\text{m}$ [34] –, we find that the decay is most likely be inside detector (and to be displaced) at collider for the favored region of parameter space with a smaller μ and $v_{PQ} \gtrsim 10^9 \text{ GeV}$ (unless the mass-gap between

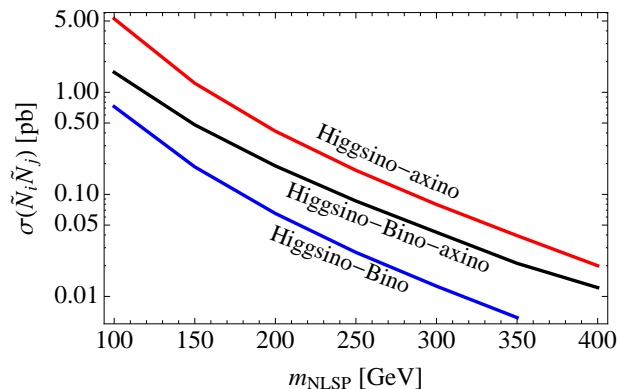


FIG. 5: The production rates of the NLSP neutralino pair effectively relevant to collider physics. For the standard Higgsino-Bino case in Sec. II, $\sigma(\tilde{H}_1^0\tilde{H}_2^0)$ is shown as blue. For the Higgsino-axino case in Sec. III, $\sigma(\tilde{H}_1^0\tilde{H}_1^0)$ is shown as red. For the Higgsino-Bino-axino case in Sec. IV, it is the $\sigma(\tilde{B}\tilde{B})$ shown as black; $\mu = M_1 + 50\text{GeV}$ is assumed. All prompt pair productions of inos effectively leading to the aforementioned production are added; see text for more discussions.

Higgsino NLSPs and axino LSPs is very small). See Ref. [35] for earlier studies of displaced decays of singlinos in a most related context, Refs. [36, 37] for displaced decays of standard neutralinos and Refs. [38, 39] for lightest Higgsino phenomenology with gravitino LSPs.

Based on the Higgsino decay patterns discussed above, we have a simple scenario where any Higgsino pair productions would essentially be the same as the $\tilde{H}_1^0\tilde{H}_1^0$ pair production and relevant collider signals come only from $\tilde{H}_1^0 \rightarrow \tilde{a} + h/Z$. It is useful to summarize several differences between the current situation and the standard Higgsino NLSP and Bino LSP case discussed in Sec. II:

1. The $\tilde{H}_1^0\tilde{H}_1^0$ production is sizable. Any pair productions of Higgsinos essentially lead to the $\tilde{H}_1^0\tilde{H}_1^0$ and resulting total production rate (adding all) is about 8 times larger than that of the usual $\tilde{H}_1^0\tilde{H}_2^0$ pair production as shown in Fig. 5. Note that pair productions of neutral Winos or Binos are highly suppressed. The enhanced neutralino pair production can also be resulted in the case with the weakly interacting gravitino LSP [38].
2. The $\tilde{H}_1^0\tilde{H}_1^0$ can now contribute to the stringent $3\ell+\text{MET}$ ($2\ell+\text{MET}$ as well) searches only by accidentally losing one or more leptons. Thus, such multi-lepton searches are weakened. Among standard multi-lepton searches, the $4\ell+\text{MET}$ search is most relevant through $\tilde{H}_1^0\tilde{H}_1^0 \rightarrow \tilde{a}\tilde{a}ZZ \rightarrow \tilde{a}\tilde{a}4\ell$.
3. Higgsino phenomenology depends only on the decay pattern of \tilde{H}_1^0 . Decays of a single neutral Higgsino, \tilde{H}_1^0 , depends sensitively on t_β and the sign of μ (as can be seen, e.g. in Fig. 8). On the other hand, in the standard case without axino LSPs, decays

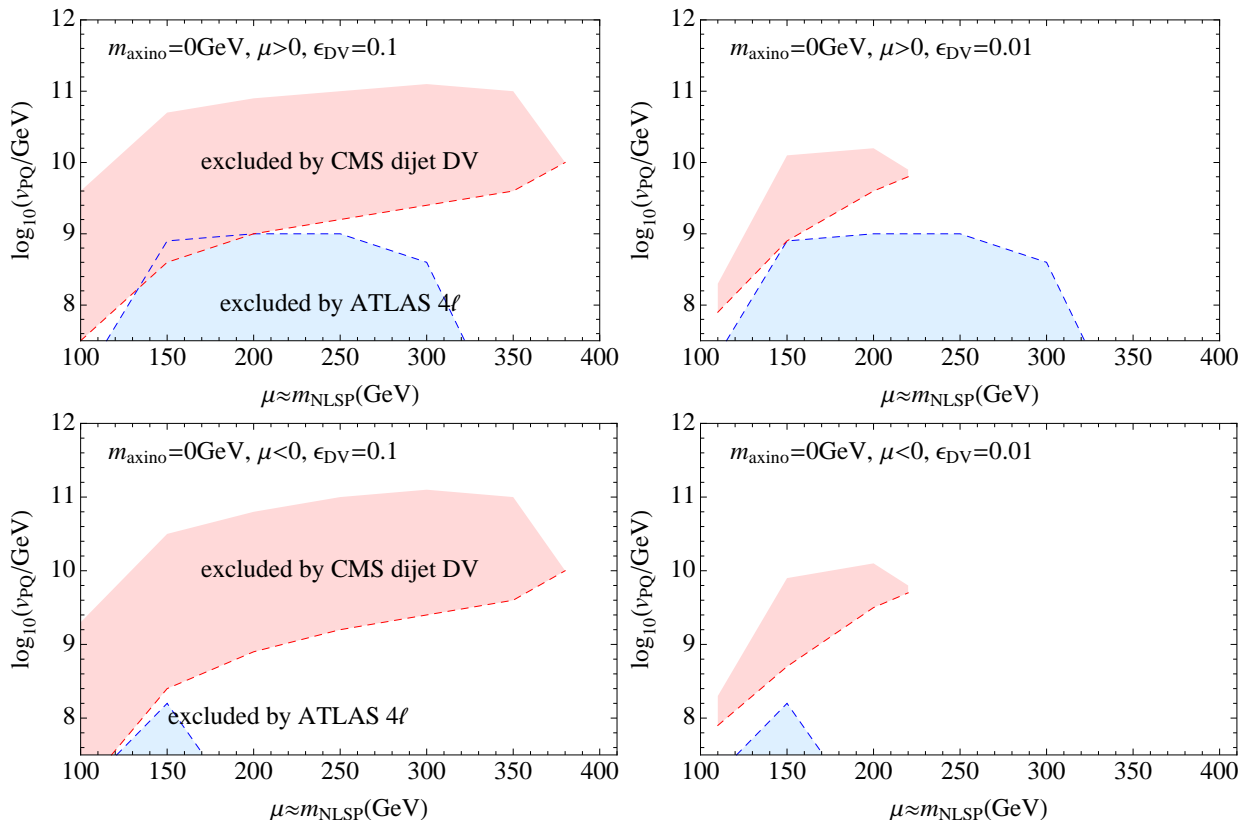


FIG. 6: The excluded parameter space of the case with the Higgsino-NLSP and axino-LSP discussed in Sec. III for $\mu > 0$ (upper) and < 0 (lower). The $4\ell + \text{MET}$ search (blue) [28] and the CMS dijet DV search (red) [40] are most relevant. We assume two extreme values of the DV reconstruction efficiencies: $\epsilon_{DV} = 0.1$ (left) and 0.01 (right). $m_{\text{axino}} = 0 \text{ GeV}$ is used, but see Fig. 7 for results on other values of m_{axino} . $M_1 = M_2 = 2 \text{ TeV}$ and $t_\beta = 3$. More on Sec. III.

of all Higgsino states are indistinguishable at collider and are equally important, and summing all indistinguishable decays make some standard Higgsino phenomenology less sensitive to those parameters [24]; see one example in Fig. 2.

4. As discussed, the decay of \tilde{H}_1^0 is likely displaced. The displaced decay further weakens the standard multi-lepton SUSY searches. However, dedicated displaced vertex (DV) searches are now relevant.

In Fig. 6, we analyze the exclusion bounds on the $\mu - v_{PQ}$ parameter space with $m_{\text{axino}} = 0 \text{ GeV}$. Both the $4\ell + \text{MET}$ search [28] (constraining too much prompt decays) and the CMS dijet DV search [40] (constraining a certain range of displaced decay) are relevant. Fig. 7 shows results in the more general parameter space. For high enough v_{PQ} scales, no bound exists; either the Higgsino decays still dominantly inside detector but its DV is not searched efficiently or the Higgsino dominantly decays outside detector and its phenomenology is essentially the same as that of the Higgsino-LSP case whose current null bounds are discussed

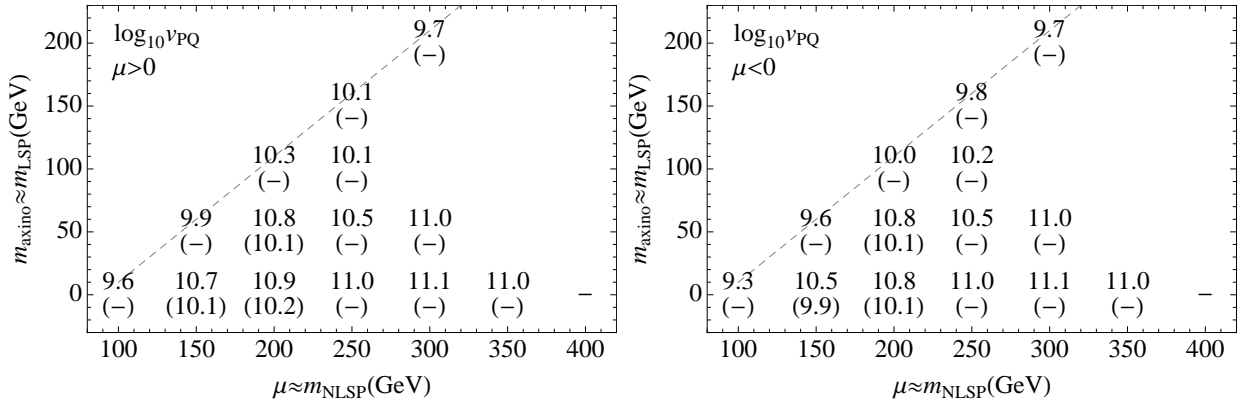


FIG. 7: The highest excluded value of $\log_{10} v_{PQ}$ for the given parameter space of Higgsino NLSP with axino LSP; for example, see Fig. 6 that the value would be ~ 11.0 for the 250-0 case with $\mu < 0$. Although there can be a smaller v_{PQ} not excluded, we conveniently choose this highest excluded value to show in these plots. CMS dijet DV and $4\ell + \text{MET}$ are used. Numbers without (with) parentheses are results with $\epsilon_{DV} = 0.1 (0.01)$. The “-” implies no existing bounds. The parameter space without anything written is not simulated by ourselves. The light-gray-dashed diagonal lines imply $m_{\text{NLSP}} - m_{\text{LSP}} = 90 \text{ GeV}$ below which the decays to the off-shell Z boson begins to be phase-space suppressed and $v_{PQ} \gtrsim 10^8 \text{ GeV}$ is already high enough to make all Higgsinos decay far outer region or outside the detector – thus, no collider bounds in general.

in Sec. II. The bound from the DV search is sensitive to the DV reconstruction efficiency, ϵ_{DV} , which is an experimental factor capturing how much fraction of DVs are really reconstructed. For the low extreme value of $\epsilon_{DV} = 0.01$ (see Ref. [40] that $\epsilon_{DV} = 0.01 - 0.1$ is a reasonable range to consider), the bound almost disappears. The bound from the $4\ell + \text{MET}$ search is stronger for $\mu > 0$ than $\mu < 0$ because the relevant BR is larger as depicted in the right panel of Fig. 8.

It is useful to understand why the $3\ell + \text{MET}$ search is now significantly weaker than the $4\ell + \text{MET}$ search here as opposed to the results of Sec. II. The main reason why the $4\ell + \text{MET}$ search is now sensitive to this model while it is not sensitive to the standard Higgsino-Bino case in Sec. II is the enhanced neutral Higgsino pair production in this model as discussed in regard of Fig. 5. Another minor reason is that the relevant BR (right panel of Fig. 8) can be somewhat larger than a half while it is typically not in the standard case (left panel of Fig. 8)⁴. On the other hand, compared to the dominant $\tilde{H}^\pm \tilde{H}_1^0$ production in the Higgsino-Bino case leading to the $3\ell + \text{MET}$ signal, the $\tilde{H}_1^0 \tilde{H}_1^0$ here is not much larger, thus a small selection efficiency to the $3\ell + \text{MET}$ here (needing to accidentally lose one lepton) has a big impact to decrease the exclusion reach of the $3\ell + \text{MET}$ in this model.

⁴ The difference is that the same Higgsino, \tilde{H}_1^0 , is pair produced here. The decays of \tilde{H}_1^0 and \tilde{H}_2^0 are typically opposite [24].

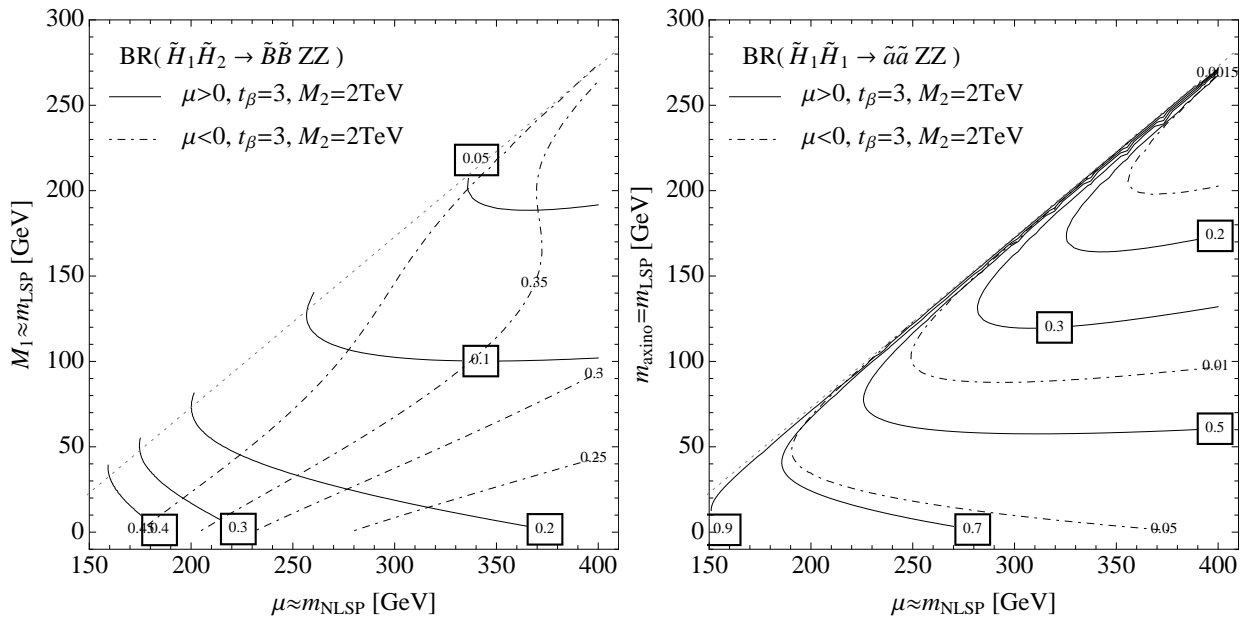


FIG. 8: The BR of the NLSP Higgsino pairs to the ZZ channel relevant to the 4ℓ +MET search. (Left): The Higgsino-Bino case in Sec. II. (Right): The Higgsino-axino case in Sec. III. Both $\mu > 0$ (solid) and $\mu < 0$ (dashed) are shown. The dotted diagonal lines are at $m_{\text{NLSP}} - m_{\text{LSP}} \simeq m_h$ above which the decays to the (on- or off-shell) Z boson is almost 100%. The BR can be larger than a half in the right panel with $\mu > 0$. These results are used in obtaining the 4ℓ +MET bounds.

The CMS dilepton DV search [41] can also give a relevant bound, but this search looks for a similar range of decay length $\sim 30 - 60\text{cm}$; so we conservatively use the dijet DV results to obtain bounds. Other dedicated DV searches [42] are less relevant and less stringent.

In all, by having the axino LSP, some ranges of μ and v_{PQ} can be probed at the LHC since the currently allowed range of v_{PQ} falls in the right range to allow NLSP Higgsinos to decay inside detector either promptly or with DVs. On the other hand, a higher $v_{PQ} \gtrsim 10^{10} - 10^{11}\text{GeV}$ with $\mu \sim 100\text{-}400\text{GeV}$ can avoid all the current LHC searches. When the mass gap between the Higgsino and the axino is smaller than about m_Z , the Higgsino generally decays far outer region or outside the detector and no current collider searches constrain the model.

IV. HIGGSINO NNLSP, BINO NLSP AND AXINO LSP

Having another gauginos in the light spectrum is another interesting possibility. In this section, we consider the case with the Higgsino NNLSP, Bino NLSP and axino LSP. As direct Bino pair production is very small, the collider phenomenology relies on all possible pair productions of NNLSP Higgsinos and NLSP Bininos. We assume that $|\mu| = M_1 + 50\text{GeV}$ so that these productions are big enough for collider analysis. Similarly to the case of the

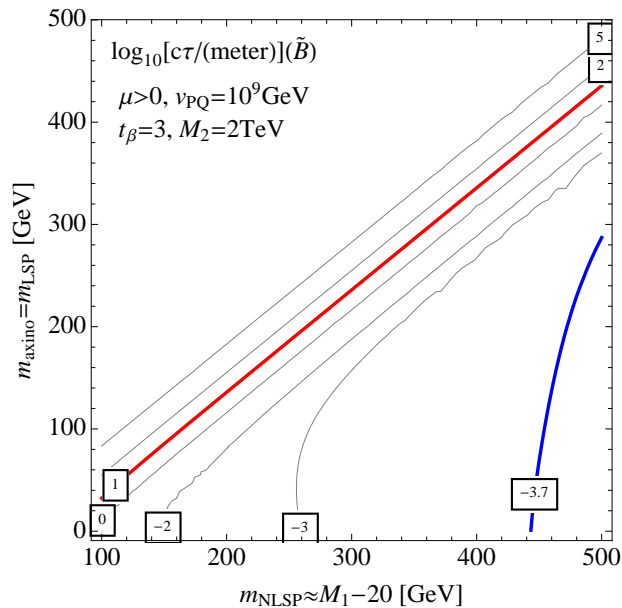


FIG. 9: The proper decay length of the Bino NLSP in the presence of the axino LSP. Figure details are as in Fig. 4. The Higgsino NNLSP is assumed to be nearby with $\mu = M_1 + 50 > 0$. For a positive μ assumed here, the mass eigenvalue of the Bino NLSP is related as $m_{\text{NLSP}} \simeq M_1 - 20\text{GeV}$. More on Sec. IV.

Higgsino NLSP with axino LSP discussed in Sec. III, the produced Higgsinos dominantly and promptly decay to the Bino NLSP. It is more obviously true here because the decays between Higgsinos and Binos are not small-gap-suppressed. Then, again the model is essentially the same as abundant Bino pair productions.

Binos can also decay to the axino LSP with substantial lifetime. In Fig. 9, we show the proper decay length of Bino NLSPs. In the majority of relevant parameter space, Binos likely decay inside detector either promptly or with DVs. Compared to the Higgsino NLSP's decay in Fig. 4, Binos have a somewhat longer lifetime because Binos couple to axinos via Higgsino mixtures in the DFSZ model. Numerically, it turns out that the Bino typically has a 3–5 times longer lifetime (with the same other parameters) which implies that about 2 times lower v_{PQ} scale is needed for a similar lifetime. If Higgsinos are much heavier, the Bino decays are much slower with about 10–20 times longer lifetime due to a smaller Bino-Higgsino mixing.

It is useful to note several differences between this scenario and the Higgsino-axino case in Sec. III. (i) For the given NLSP mass, the effective total production of NLSP pairs is smaller here as shown in Fig. 5 because the model here relies on the (associate) productions of heavier Higgsinos. (ii) Decays of NNLSP Higgsinos to NLSP Binos can produce observable particles as we assume about 50GeV mass-gap. We will explain later how we treat these visible particles in our analysis. (iii) Now the decay pattern of the Bino NLSP is relevant to

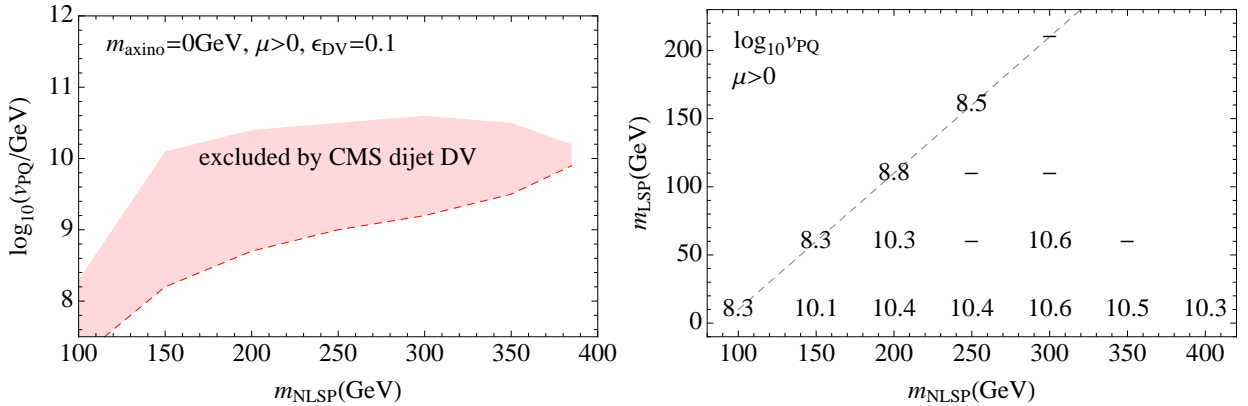


FIG. 10: The highest excluded value of $\log_{10} v_{PQ}$ for the given parameter space of the Higgsino NNLSP, Bino NLSP and axino LSP discussed in Sec. IV with $\mu > 0$. Figure details are as in Fig. 6 and 7. No bound is derived from multi-lepton searches in this case. For $\mu < 0$, a similar bound is obtained from the DV search. $\epsilon_{DV} = 0.1$ here, and no DV bound exists for $\epsilon_{DV} = 0.01$.

collider searches instead of that of the Higgsino.

In Fig. 10, we analyze the exclusion bounds. Again, both the 4ℓ +MET search (constraining too much prompt decays) and the CMS dijet DV search (constraining a certain range of displaced decay) are relevant. For high enough v_{PQ} scales, no bound exists; either the Bino decays still dominantly inside detector but its DV is not searched efficiently or the Bino dominantly decays outside detector. When the Bino decays outside detector, the visible decay products of NNLSP Higgsinos can be important in collider searches – the collider physics will then be essentially the same as that of the Higgsino NLSP and Bino LSP considered in Sec. II as if axinos were absent. However, the mass-gap between the Higgsino and Bino is only 50GeV in this work, and by referring to Fig. 1 showing the current bounds on the Higgsino-Bino model, we find that the visible decay products of Higgsino NNLSP with such small-gap is weakly constrained. We conservatively assume that we can ignore all (soft) leptons from Higgsino decays in our multi-lepton analysis, but we will include all and only leptons from Bino decays to axinos in our analysis (when Binons decay promptly inside detector) – the more accurate analysis will not give a much stronger bound anyway.

The Fig. 10, compared with Fig. 6 and 7, shows that the bound on this model is somewhat weaker than that of the Higgsino-axino case in Sec. III. For $\epsilon_{DV} = 0.01$, no bounds from the DV search is derived. For $\mu < 0$, no bounds from the multi-lepton search is derived. These weaker bounds are mainly because the effective total production of Bino pairs is smaller for the given Bino mass as discussed above and as shown in Fig. 5.

But again, in all, by having the axino LSP as well as light gauginos, some ranges of μ and v_{PQ} can be probed at the LHC since the currently allowed range of v_{PQ} falls in the right range to allow NLSP Binons to decay inside detector either promptly or with DVs. On the

other hand, a higher $v_{PQ} \gtrsim 10^{10} - 10^{11} \text{ GeV}$ with $\mu \sim 100\text{-}400 \text{ GeV}$ can avoid all the current LHC searches. If the NNLSP Higgsino is much heavier, the model has a looser connection with the naturalness; in any case, no any sizable production modes are available then and the search will rely on heavier particle productions.

V. CONCLUSION

The electroweak-scale axino and Higgsino are perhaps predicted altogether by a naturalness philosophy of particle physics. The implications and the consistency of having both light axinos and Higgsinos are studied in the context of a few benchmark models of supersymmetry. Interestingly, for the typical range of the PQ scale, $10^9 \text{ GeV} \lesssim v_{PQ} \lesssim 10^{12} \text{ GeV}$, the electroweak-scale NLSP can still decay to the axino LSP inside detector both promptly and by leaving a DV. The $4\ell + \text{MET}$ signature from the prompt decay of the NLSP is enhanced among standard SUSY searches as all heavier neutralinos and charginos decay promptly first to NLSP neutralinos so that NLSP neutralino pair productions which are relevant to the collider physics are effectively enhanced. The displaced decay of the NLSP is constrained by dedicated DV searches for a certain range of v_{PQ} typically of $10^9 \lesssim v_{PQ} \lesssim 10^{11} \text{ GeV}$ depending on the mass spectrum – searches for a wider range of decay lengths maybe possible [36, 43]. A higher PQ scale of $v_{PQ} \gtrsim 10^{10} - 10^{11} \text{ GeV}$ with the electroweak-scale μ or the mass spectrum with small mass-gap between the NLSP and LSP is generally safe from all current collider searches. We hope that we provided a basic collider physics of the natural supersymmetry with the axino LSP and light Higgsino which can also be complementary to the widely studied axino sector cosmology.

Acknowledgement. S.J. thanks Kiwoon Choi and Hyung Do Kim for useful conversations. S.J. thanks KIAS Center for Advanced Computation for providing computing resources. G.B. acknowledges support from MEC Grant FPA2011-23596, the GV Grant PROMETEOII/2013/017 and EU FP7 ITN INVISIBLES (Marie Curie Actions, PITN-GA-2011-289442). E.J.C. was supported in part by the National Science Foundation under Grant No. NSF PHY11-25915. S.J. is supported in part by National Research Foundation (NRF) of Korea under grant 2013R1A1A2058449.

Appendix A: Ino decays

All the relevant two- and three-body decay widths of inos are calculated and collected in Ref. [24] (see also Refs. [16, 35, 44] for earlier results). In this appendix, we further

summarize how we calculate the two-body decays to pions which is relevant when the mass gap is very small $\lesssim \mathcal{O}(1)\text{GeV}$.

The two-body decay $\chi_1^+ \rightarrow \chi_1^0 \pi^+$ is calculated as [32, 45]

$$\Gamma(\chi^+ \rightarrow \chi^0 \pi^+) = \Gamma(\pi^+) \cdot \frac{16 \delta m^3}{m_\pi m_\mu^2} \left(1 - \frac{m_\pi^2}{\delta m^2}\right)^{1/2} \left(1 - \frac{m_\mu^2}{m_\pi^2}\right)^{-2}, \quad (\text{A1})$$

where the total decay width of a charged pion is $c\tau = 7.80\text{m}$ or $\tau = 26.03\text{ns}$ or $\Gamma(\pi^+) = 2.53 \times 10^{-17}\text{GeV}$ [46]. The mass splitting between the chargino and the neutralino is denoted by δm . We use $m_\pi = 139.6\text{MeV}$, $m_\mu = 105.7\text{MeV}$ [46]. For $\delta m = 164.4(355)\text{MeV}$ which is the one-loop asymptotic Wino(Higgsino) mass splitting [32, 45], the proper decay length is $c\tau = 5.9(0.34)\text{cm}$ (equivalently, $\tau = 0.20(0.011)\text{ns}$). The current disappearing track search [33] is sensitive to $\tau \gtrsim 0.1\text{ns}$, thus is currently not so sensitive to the nearly degenerate Higgsinos.

Appendix B: Bound estimation

We list methods and numerical results that we used to obtain various exclusion bounds in this paper. For the $3\ell+\text{MET}$ result, we use the reported upper limits on the number of events in various $\text{SR0}\tau\text{a}$ bins of Ref. [27]. The $\text{SR0}\tau\text{a-bin16}$ is usually strongest for heavy NLSPs. For the $4\ell+\text{MET}$ result, we interpret the result in the bin of $20\text{SSF} + 0\tau_h$ with $\text{MET} > 100\text{GeV}$ of Ref. [28] to the upper limit of number of events $N \lesssim 2.0$ at $1.96\sigma \simeq 95\%\text{CL}$. Interestingly, a very similar analysis has been carried out by ATLAS in Ref. [29], but their weaker cut on $\text{MET} > 75\text{GeV}$ leads to a much weaker bound. Thus, the optimization of the $4\ell+\text{MET}$ cuts in each parameter space as roughly done for the $3\ell+\text{MET}$ above will be useful. For the dijet DV result in Ref. [40], we conservatively use the result for $L_{xy} < 20\text{cm}$ (combined with 2 observed events) to obtain the upper limit on the new physics contribution $N \lesssim 3.1$ at $1.96\sigma \simeq 95\%\text{CL}$. For all results, we generate `MadGraph` [47] events with up to one additional parton and showered them by interfacing with `pythia` [48] using the MLM [49] matching. We use `FastJet` [50] for particle reconstruction.

-
- [1] R. D. Peccei and H. R. Quinn, *Phys. Rev. Lett.* **38** (1977) 1440.
 - [2] S. Weinberg, *Phys. Rev. Lett.* **40** (1978) 223; F. Wilczek, *Phys. Rev. Lett.* **40** (1978) 279.
 - [3] J. E. Kim, *Phys. Rev. Lett.* **43** (1979) 103; M. A. Shifman, A. Vainshtein and V. I. Zakharov, *Nucl. Phys.* **B166** (1980) 493.
 - [4] M. Dine, W. Fischler and M. Srednicki, *Phys. Lett.* **B104** (1981) 199; A. P. Zhitnitskii, *Sov. J. Phys.* **31** (1980) 260.

- [5] J. E. Kim and G. Carosi, “Axions and the Strong CP Problem,” *Rev. Mod. Phys.* **82** (2010) 557 [arXiv:0807.3125 [hep-ph]].
- [6] T. Hiramatsu, M. Kawasaki, K. i. Saikawa and T. Sekiguchi, “Production of dark matter axions from collapse of string-wall systems,” *Phys. Rev. D* **85**, 105020 (2012) [Erratum-ibid. *D* **86**, 089902 (2012)] [arXiv:1202.5851 [hep-ph]].
- [7] T. Higaki, K. S. Jeong and F. Takahashi, “Solving the Tension between High-Scale Inflation and Axion Isocurvature Perturbations,” arXiv:1403.4186 [hep-ph]; K. Choi, K. S. Jeong and M. -S. Seo, “String theoretic QCD axions in the light of PLANCK and BICEP2,” arXiv:1404.3880 [hep-th]; E. J. Chun, “Axion Dark Matter with High-Scale Inflation,” arXiv:1404.4284 [hep-ph].
- [8] R. Kitano and Y. Nomura, “Supersymmetry, naturalness, and signatures at the LHC,” *Phys. Rev. D* **73** (2006) 095004 [hep-ph/0602096]; C. Brust, A. Katz, S. Lawrence and R. Sundrum, “SUSY, the Third Generation and the LHC,” *JHEP* **1203** (2012) 103 [arXiv:1110.6670 [hep-ph]]. M. Papucci, J. T. Ruderman and A. Weiler, “Natural SUSY Endures,” *JHEP* **1209** (2012) 035 [arXiv:1110.6926 [hep-ph]].
- [9] H. Baer, V. Barger, P. Huang, A. Mustafayev and X. Tata, “Radiative natural SUSY with a 125 GeV Higgs boson,” *Phys. Rev. Lett.* **109** (2012) 161802 [arXiv:1207.3343 [hep-ph]].
- [10] J. E. Kim and H. P. Nilles, “The mu Problem and the Strong CP Problem,” *Phys. Lett. B* **138** (1984) 150; E. J. Chun, J. E. Kim and H. P. Nilles, “A Natural solution of the mu problem with a composite axion in the hidden sector,” *Nucl. Phys. B* **370** (1992) 105.
- [11] K. J. Bae, H. Baer and E. J. Chun, “Mainly axion cold dark matter from natural supersymmetry,” *Phys. Rev. D* **89** (2014) 031701 [arXiv:1309.0519 [hep-ph]]. K. J. Bae, H. Baer and E. J. Chun, “Mixed axion/neutralino dark matter in the SUSY DFSZ axion model,” *JCAP* **1312** (2013) 028 [arXiv:1309.5365 [hep-ph]].
- [12] T. Goto and M. Yamaguchi, “Is axino dark matter possible in supergravity?,” *Phys. Lett. B* **276**, 103 (1992);
- [13] E. J. Chun, J. E. Kim and H. P. Nilles, “Axino mass,” *Phys. Lett. B* **287** (1992) 123 [hep-ph/9205229]. E. J. Chun and A. Lukas, “Axino mass in supergravity models,” *Phys. Lett. B* **357** (1995) 43 [hep-ph/9503233];
- [14] E. J. Chun, D. Comelli and D. H. Lyth, “The Abundance of relativistic axions in a flaton model of Peccei-Quinn symmetry,” *Phys. Rev. D* **62** (2000) 095013 [hep-ph/0008133]; E. J. Chun, H. B. Kim and D. H. Lyth, “Cosmological constraints on a Peccei-Quinn flatino as the lightest supersymmetric particle,” *Phys. Rev. D* **62** (2000) 125001 [hep-ph/0008139].
- [15] S. Kim, W. -I. Park and E. D. Stewart, “Thermal inflation, baryogenesis and axions,” *JHEP* **0901**, 015 (2009) [arXiv:0807.3607 [hep-ph]].
- [16] E. J. Chun, “Dark matter in the Kim-Nilles mechanism,” *Phys. Rev. D* **84** (2011) 043509 [arXiv:1104.2219 [hep-ph]]. K. J. Bae, E. J. Chun and S. H. Im, “Cosmology of the DFSZ axino,” *JCAP* **1203** (2012) 013 [arXiv:1111.5962 [hep-ph]].
- [17] K. J. Bae, K. Choi and S. H. Im, “Effective Interactions of Axion Supermultiplet and Thermal Production of Axino Dark Matter,” *JHEP* **1108** (2011) 065 [arXiv:1106.2452 [hep-ph]].
- [18] K. J. Bae, H. Baer, A. Lessa and H. Serce, “Coupled Boltzmann computation of mixed axion neutralino dark matter in the SUSY DFSZ axion model,” arXiv:1406.4138 [hep-ph].
- [19] W. -I. Park, “PQ-symmetry for a small Dirac neutrino mass, dark radiation and cosmic neutrinos,” *JCAP* **1406**, 049 (2014) [arXiv:1402.6523 [hep-ph]].

- [20] For a review on the KSVZ axino, see, K. -Y. Choi, J. E. Kim and L. Roszkowski, “Review of axino dark matter,” J. Korean Phys. Soc. **63** (2013) 1685 [arXiv:1307.3330 [astro-ph.CO]].
- [21] A. Brandenburg, L. Covi, K. Hamaguchi, L. Roszkowski and F. D. Steffen, “Signatures of axinos and gravitinos at colliders,” Phys. Lett. B **617**, 99 (2005) [hep-ph/0501287]. K. Hamaguchi, M. M. Nojiri and A. de Roeck, “Prospects to study a long-lived charged next lightest supersymmetric particle at the LHC,” JHEP **0703**, 046 (2007) [hep-ph/0612060]. A. Freitas, F. D. Steffen, N. Tajuddin and D. Wyler, “Axinos in Cosmology and at Colliders,” JHEP **1106**, 036 (2011) [arXiv:1105.1113 [hep-ph]].
- [22] H. Baer, V. Barger, A. Lessa, W. Sreethawong and X. Tata, “Wh plus missing-ET signature from gaugino pair production at the LHC,” Phys. Rev. D **85**, 055022 (2012) [arXiv:1201.2949 [hep-ph]]. K. Howe and P. Saraswat, “Excess Higgs Production in Neutralino Decays,” JHEP **1210**, 065 (2012) [arXiv:1208.1542 [hep-ph]]. A. Arbey, M. Battaglia and F. Mahmoudi, “Higgs Production in Neutralino Decays in the MSSM - The LHC and a Future e+e- Collider,” arXiv:1212.6865 [hep-ph].
- [23] T. Han, S. Padhi and S. Su, “Electroweakinos in the Light of the Higgs Boson,” Phys. Rev. D **88**, 115010 (2013) [arXiv:1309.5966 [hep-ph]].
- [24] S. Jung, “Resolving the existence of Higgsinos in the LHC inverse problem,” JHEP **1406**, 111 (2014) [arXiv:1404.2691 [hep-ph]].
- [25] S. Gori, S. Jung, L. T.Wang and J. D.Wells, work in progress
- [26] D. Ghosh, M. Guchait and D. Sengupta, “Higgs Signal in Chargino-Neutralino Production at the LHC,” Eur. Phys. J. C **72**, 2141 (2012) [arXiv:1202.4937 [hep-ph]]. A. Bharucha, S. Heinemeyer and F. von der Pahlen, “Direct Chargino-Neutralino Production at the LHC: Interpreting the Exclusion Limits in the Complex MSSM,” Eur. Phys. J. C **73**, 2629 (2013) [arXiv:1307.4237]. F. Yu, “Anatomizing Exotic Production of the Higgs Boson,” arXiv:1404.2924 [hep-ph].
- [27] G. Aad *et al.* [ATLAS Collaboration], “Search for direct production of charginos and neutralinos in events with three leptons and missing transverse momentum in $\sqrt{s} = 8$ TeV pp collisions with the ATLAS detector,” arXiv:1402.7029 [hep-ex].
- [28] V. Khachatryan *et al.* [CMS Collaboration], “Searches for electroweak production of charginos, neutralinos, and sleptons decaying to leptons and W, Z, and Higgs bosons in pp collisions at 8 TeV,” arXiv:1405.7570 [hep-ex].
- [29] [ATLAS Collaboration], “Search for supersymmetry in events with four or more leptons in 21 fb⁻¹ of pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector,” ATLAS-CONF-2013-036.
- [30] G. Aad *et al.* [ATLAS Collaboration], “Search for direct production of charginos, neutralinos and sleptons in final states with two leptons and missing transverse momentum in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector,” JHEP **1405**, 071 (2014) [arXiv:1403.5294 [hep-ex]].
- [31] S. Gori, S. Jung and L. -T. Wang, “Cornering electroweakinos at the LHC,” JHEP **1310**, 191 (2013) [arXiv:1307.5952 [hep-ph]]. C. Han, A. Kobakhidze, N. Liu, A. Saavedra, L. Wu and J. M. Yang, “Probing Light Higgsinos in Natural SUSY from Monojet Signals at the LHC,” JHEP **1402**, 049 (2014) [arXiv:1310.4274 [hep-ph]]. P. Schwaller and J. Zurita, “Compressed electroweakino spectra at the LHC,” JHEP **1403**, 060 (2014) [arXiv:1312.7350 [hep-ph]]. Z. Han, G. D. Kribs, A. Martin and A. Menon, “Hunting quasidegenerate Higgsinos,” Phys. Rev. D **89**, 075007 (2014) [arXiv:1401.1235 [hep-ph]]. M. Low and L. -T. Wang, “Neutralino Dark Matter at 100 TeV,” arXiv:1404.0682 [hep-ph].

- [32] S. D. Thomas and J. D. Wells, “Phenomenology of Massive Vectorlike Doublet Leptons,” *Phys. Rev. Lett.* **81**, 34 (1998) [hep-ph/9804359].
- [33] The ATLAS collaboration, “Search for charginos nearly mass-degenerate with the lightest neutralino based on a disappearing-track signature in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector,” ATLAS-CONF-2013-069.
- [34] G. Aad *et al.* [ATLAS Collaboration], “Expected Performance of the ATLAS Experiment - Detector, Trigger and Physics,” arXiv:0901.0512 [hep-ex].
- [35] S. P. Martin, “Collider signals from slow decays in supersymmetric models with an intermediate scale solution to the mu problem,” *Phys. Rev. D* **62**, 095008 (2000) [hep-ph/0005116].
- [36] P. Meade, M. Reece and D. Shih, “Long-Lived Neutralino NLSPs,” *JHEP* **1010**, 067 (2010) [arXiv:1006.4575 [hep-ph]].
- [37] P. W. Graham, D. E. Kaplan, S. Rajendran and P. Saraswat, “Displaced Supersymmetry,” *JHEP* **1207**, 149 (2012) [arXiv:1204.6038 [hep-ph]]. S. Bobrovskiy, J. Hajer and S. Rydbeck, “Long-lived higgsinos as probes of gravitino dark matter at the LHC,” *JHEP* **1302**, 133 (2013) [arXiv:1211.5584 [hep-ph]].
- [38] P. Meade, M. Reece and D. Shih, “Prompt Decays of General Neutralino NLSPs at the Tevatron,” *JHEP* **1005**, 105 (2010) [arXiv:0911.4130 [hep-ph]].
- [39] K. T. Matchev and S. D. Thomas, “Higgs and Z boson signatures of supersymmetry,” *Phys. Rev. D* **62** (2000) 077702 [hep-ph/9908482]. H. Baer, P. G. Mercadante, X. Tata and Y. -l. Wang, “The Reach of Tevatron upgrades in gauge mediated supersymmetry breaking models,” *Phys. Rev. D* **60**, 055001 (1999) [hep-ph/9903333]. S. Dimopoulos, M. Dine, S. Raby and S. D. Thomas, “Experimental signatures of low-energy gauge mediated supersymmetry breaking,” *Phys. Rev. Lett.* **76**, 3494 (1996) [hep-ph/9601367]. S. Dimopoulos, M. Dine, S. Raby, S. D. Thomas and J. D. Wells, “Phenomenological implications of low-energy supersymmetry breaking,” *Nucl. Phys. Proc. Suppl.* **52A**, 38 (1997) [hep-ph/9607450]. H. Baer, P. G. Mercadante, X. Tata and Y. -l. Wang, “The Reach of the CERN large hadron collider for gauge mediated supersymmetry breaking models,” *Phys. Rev. D* **62**, 095007 (2000) [hep-ph/0004001]. J. T. Ruderman and D. Shih, “General Neutralino NLSPs at the Early LHC,” *JHEP* **1208**, 159 (2012) [arXiv:1103.6083 [hep-ph]].
- [40] CMS Collaboration [CMS Collaboration], “Search for long-lived neutral particles decaying to dijets,” CMS-PAS-EXO-12-038.
- [41] CMS Collaboration [CMS Collaboration], “Search for long-lived particles decaying to final states that include dileptons,” CMS-PAS-EXO-12-037.
- [42] V. M. Abazov *et al.* [D0 Collaboration], *Phys. Rev. Lett.* **103**, 071801 (2009) [arXiv:0906.1787 [hep-ex]]. T. Aaltonen *et al.* [CDF Collaboration], *Phys. Rev. D* **85**, 012007 (2012) [arXiv:1109.3136 [hep-ex]]. G. Aad *et al.* [ATLAS Collaboration], *Phys. Rev. Lett.* **108**, 251801 (2012) [arXiv:1203.1303 [hep-ex]]. G. Aad *et al.* [ATLAS Collaboration], *Phys. Lett. B* **721**, 32 (2013) [arXiv:1210.0435 [hep-ex]]. CMS Collaboration [CMS Collaboration], CMS-PAS-B2G-12-024.
- [43] G. Aad *et al.* [ATLAS Collaboration], “Triggers for displaced decays of long-lived neutral particles in the ATLAS detector,” *JINST* **8**, P07015 (2013) [arXiv:1305.2284 [hep-ex]].
- [44] J. F. Gunion and H. E. Haber, “Two-body Decays of Neutralinos and Charginos,” *Phys. Rev. D* **37**, 2515 (1988).
- [45] M. Ibe, S. Matsumoto and R. Sato, “Mass Splitting between Charged and Neutral Winos at

- Two-Loop Level,” *Phys. Lett. B* **721**, 252 (2013) [arXiv:1212.5989 [hep-ph]].
- [46] J. Beringer *et al.* [Particle Data Group Collaboration], “Review of Particle Physics (RPP),” *Phys. Rev. D* **86**, 010001 (2012).
- [47] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer and T. Stelzer, “MadGraph 5 : Going Beyond,” *JHEP* **1106**, 128 (2011) [arXiv:1106.0522 [hep-ph]].
- [48] T. Sjostrand, S. Mrenna and P. Z. Skands, “PYTHIA 6.4 Physics and Manual,” *JHEP* **0605**, 026 (2006) [hep-ph/0603175].
- [49] M. L. Mangano, M. Moretti, F. Piccinini and M. Treccani, “Matching matrix elements and shower evolution for top-quark production in hadronic collisions,” *JHEP* **0701**, 013 (2007) [hep-ph/0611129].
- [50] M. Cacciari, G. P. Salam and G. Soyez, “FastJet User Manual,” *Eur. Phys. J. C* **72**, 1896 (2012) [arXiv:1111.6097 [hep-ph]].