Same-sign Higgsino production at the CERN LHC: How not to hunt for natural supersymmetry

Patrick Stengel and Xerxes Tata

Phys. Rev. D **92**, 115024 — Published 30 December 2015

DOI: 10.1103/PhysRevD.92.115024

UH-511-1246-15

Same-sign Higgsino Production at the CERN LHC: How Not to Hunt for Natural Supersymmetry

Patrick Stengel[1*] and Xerxes Tata[1†]

[1]*Dept. of Physics and Astronomy, University of Hawaii, Honolulu, HI 96822, USA*

Abstract

We examine the prospects for detecting light charged higgsinos that are expected to be a necessary feature of natural SUSY models via $pp \to \widetilde{W}_1^{\pm}\widetilde{W}_1^{\pm}jj + X$ processes arising dominantly from $W^{\pm}W^{\pm}$ fusion at LHC13. The signal will be a pair of same-sign leptons (e or μ) in events with two relatively forward, hemispherically-separated jets with a large rapidity gap. We find that even though the higgsinos have a full-strength $SU(2)$ gauge couplings to W-bosons, the LHC13 cross section for the production of same sign higgsino pairs is smaller than 0.02 fb over most of the interesting range of natural SUSY parameters, even before leptonic branching fractions of the chargino are included. This cross section is strongly suppressed because the two neutral Majorana higgsinos can be combined into a single Dirac neutralino if the bino and the winos are much heavier than the higgsinos, as is the case in natural SUSY models: in this limit, higgsino couplings to W-bosons exhibit an emergent (approximate) $U(1)_{\rm ino}$ global symmetry that suppresses same sign higgsino production by vector boson fusion. We conclude that this channel is not a viable way to search for natural SUSY even at the high luminosity upgrade of the Large Hadron Collider.

*Email: pstengel@hawaii.edu

†Email: tata@phys.hawaii.edu

Despite the absence of any signals from direct production of superpartners in experiments at LHC8 [1, 2], weak scale supersymmetry (SUSY) remains the most promising extension of the Standard Model (SM). That interest in space-time supersymmetry continues more than four decades after its discovery [3] is largely driven by the fact that softly-broken SUSY stabilizes [4] the Higgs sector of the SM from run-away radiative corrections that arise [5] when the SM is embedded into a framework with a hierarchically different mass scale such as Grand Unification. While it is clear that supersymmetry elegantly resolves the big hierarchy problem if superpartners are at the weak scale, several authors [6] have expressed concern that LHC8 bounds on top squarks may be already indicative of fine-tuning at the percent level unless the SUSY spectrum happens to be compressed so that signals from t-squarks would have evaded experimental searches [7]. It has, however, been pointed out [8, 9, 10, 11] that these authors have implicitly ignored the possibility that various SUSY parameters might be correlated, and that it may be possible to find models with relatively modest fine-tuning, but with top squarks in the TeV range, well beyond the reach of LHC experiments. We note instead that a small value of the superpotential μ parameter (assuming that it arises from a different origin than the SUSY breaking parameters) which directly enters the Higgs potential, and through it in the well-known expression for M_Z^2 (see, *e.g.* Eq. (4) of the second paper of Ref. [11]), provides a necessary condition for low fine-tuning; see also Ref.[12]. We thus advocate light higgsinos in the 100-300 GeV range as the most robust feature of natural SUSY models without a proliferation of new particles beyond the MSSM.[1]

Electroweak higgsino pair production via $pp \to \widetilde{Z}_i\widetilde{Z}_j$, $\widetilde{W}_1^+\widetilde{W}_1^-$ and $\widetilde{W}_1^\pm\widetilde{Z}_i + X$ processes has a cross section of several hundred to over a thousand fb at LHC13 for higgsinos in the natural SUSY mass range of 100-300 GeV [15]. However, since electroweak gaugino mass parameters can easily be in the TeV range without endangering naturalness, the mass gaps $m_{\widetilde{W}_1} - m_{\widetilde{Z}_1}$ and $m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1}$ are typically just 10-30 GeV for electroweak fine-tuning no worse than 3% [16]. As a result, the visible energy and $E_T^{\rm miss}$ in these higgsino production reactions is small, and higgsino production is obscured by SM backgrounds.[2] This led several groups to examine the possibility of detecting the higgsino signal via higgsino pair production in association with a high p_T jet or photon from QCD/QED radiation. Careful studies have shown that while the signal occurs with an observable rate after hard cuts on $E_T^{\rm miss}$ and the hard jet/photon, the signal to background ratio is at the 1-2% level [18]. It seems difficult to imagine that the systematic error on the QCD backgrounds will be smaller than this level, strongly indicating that the signal will be difficult to detect in the absence of characteristic kinematic features in these events. In Ref.[19], it has been suggested that higgsino production with a radiated Z boson decaying to a lepton pair provides a better reach. Taking the results of this study at face value, there is no observable signal for an integrated luminosity of 300 fb^{-1} at LHC13, and a 5σ signal for higgsino masses up to 125-130 GeV for an integrated luminosity of 3000 fb^{-1}.

[1]Very recently models with additional chiral superfields in the adjoint representation [13], or with additional superfields needed to complete representations of a large global symmetry group so that the Higgs is a pseudo-Goldstone boson [14], where the higgsino mass is independent of the μ parameter that enters the Higgs boson sector have been constructed. In these relatively complex scenarios, higgsinos may be heavy consistent with low electroweak fine-tuning.

[2]It is possible that bino and wino mass parameters have a magnitude comparable to $|\mu|$. In this fortuitous case the resulting substantial mixing between the gauginos and higgsinos typically splits the various states and leads to the possibility of several observable signals at the LHC [17].

Following earlier work in Ref.[20], Han *et al.* [21] suggested that it may be possible to reduce SM backgrounds by requiring soft dileptons in higgsino pair production in association with a hard monojet. A subsequent detailed study [22] showed that by requiring low invariant mass, opposite sign, same flavour dileptons in hard mono-jet events, it is possible to extract the higgsino signal above SM backgrounds at LHC14 for $|\mu| < 170$ (200) GeV, assuming an integrated luminosity of 300 (1000) fb^{-1}. Though this covers the range of μ most favoured by naturalness considerations, the strategy does not lead to observability over the entire range of μ allowed by 3% electroweak fine-tuning. While signals from the production of higgsinos will be readily detectable at an electron-positron collider with $\sqrt{s} > 2m_{\rm higgsino}$ and availability of electron beam polarization [16], it is clear that alternative strategies to search for these at the LHC are worthy of examination.

The ATLAS [23] and CMS [24] collaborations have recently reported observation of same-sign (SS) W-pair production via $W^\pm W^\pm$ scattering at LHC8. This, together with the fact that charged higgsinos of natural SUSY must have masses not hierarchically larger than M_W, motivated us to examine SS charged higgsino pair production via $pp \to \widetilde{W}_1^\pm \widetilde{W}_1^\pm jj + X$ at LHC13 in this paper. The signal is a pair of same-sign dileptons (from the leptonic decays of the charginos) together with forward hemispherically separated jets with a large rapidity separation and $E_T^{\rm miss}$. Unlike the leptons from W decay which would typically have $p_T \sim M_W/2$, the leptons from $\widetilde{W}_1$ decays are expected to be soft because $m_{\widetilde{W}_1} - m_{\widetilde{Z}_1}$ is expected to be just 10-25 GeV in natural SUSY models. It would then be of interest to examine if it is possible to search for a signal in events triggered by high E_T forward jets with a large rapidity separation, with a pair of soft, acollinear dileptons and modest $E_T^{\rm miss}$.

SS chargino pair production occurs via the SUSY analogues of the Feynman diagrams that lead to inclusive $W^\pm W^\pm jj$ production at the LHC. Representative examples are illustrated in Fig. 1. Fig. 1a shows the classic vector boson fusion (VBF) diagram for SS chargino production. Fig. 1b shows the s-channel W^* diagram. This is expected to be suppressed once we require the hard, hemispherically separated jets (see below) characteristic of VBF events. Fig. 1c shows a mixed QCD-electroweak diagram which is strongly suppressed in natural SUSY because squarks and gluinos are expected to be heavy. Finally, Fig. 1d illustrates a purely electroweak diagram that is also suppressed if squarks are heavy.

Superpartner production via VBF processes was first examined almost a decade ago in Ref.[25]. It has more recently received attention in Ref.[20], and most extensively in a series of papers by the Texas A and M group [26]. Since $\widetilde{W}_1^\pm \widetilde{W}_1^\mp$ and $\widetilde{Z}_i \widetilde{Z}_j$ production in association with high transverse momentum jets also occurs via conventional quark-antiquark initiated processes, we confine our examination to production of just same-sign chargino pairs in this paper.

Since our focus is the SS higgsino signal in natural SUSY, for definiteness, we adopt the Radiative Natural SUSY (RNS) model line developed in Ref.[15] for our calculations.[3] The RNS framework zeroes in on the portion of parameter space of the non-universal Higgs mass model with two additional parameters (NUHM2 model) beyond those of the well-studied

[3] Assuming that the electroweak gauginos are not fortuitously light, we expect that the same sign higgsino production cross section is largely determined by the magnitude of μ, and largely independent of the details of the model.

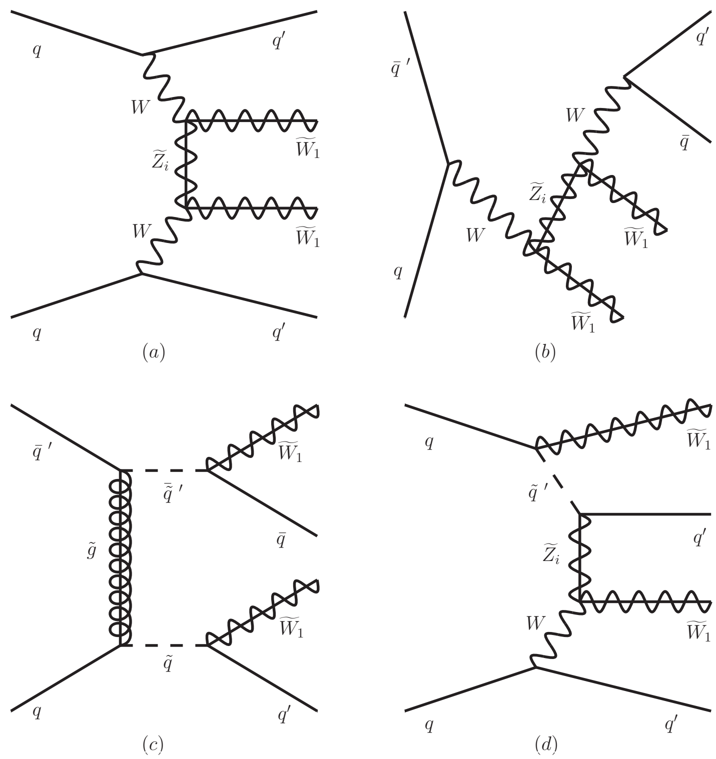

Figure 1: Representative Feynman diagrams for the underlying parton processes that contribute to the production of same-sign charginos in pp collisions at LHC13. As explained in the text, we that contributions from the processes b-d to be strongly suppressed.

mSUGRA/CMSSM framework [27]. The NUHM2 model which is defined by the parameter set,

$$m_0, m_{1/2}, A_0, \tan\beta, \mu, m_A,$$

allows for spectra with modest electroweak fine-tuning[4] ($\Delta_{\rm EW}^{-1} \geq 3\%$), consistent with the observed Higgs mass [9], if parameters are appropriately correlated. Specifically, we first fix,

$$m_0 = 5\ \text{TeV}, A_0 = -1.6 m_0, \tan\beta = 15, \mu = 150\ \text{GeV}, m_A = 1\ \text{TeV}, \tag{1}$$

and examine the signal versus $m_{1/2}$ which we allow to vary up to 2 TeV.[5] The higgsino masses, $m_{\widetilde{W}_1}$ and $m_{\widetilde{Z}_{1,2}}$, are essentially fixed by $|\mu|$ (as long as $m_{1/2}$ is chosen large enough so that the weak scale gaugino parameters $M_{1,2} \gg |\mu|$). Given heavy sfermions expected in natural SUSY, our results are insensitive to the specific values of m_0, $\tan\beta$ and m_A.

We use the subroutines in ISAJET v7.83 [28] to compute the sparticle spectrum (illustrated in Fig. 2 of Ref.[15]) and mixing parameters. We then use Madgraph5.2.2.1 [29] to evaluate the squared matrix element for the $2 \to 4$ parton subprocess, and feed the result into Pythia

[4]As explained at length in Ref.[11], we regard low $\Delta_{\rm EW}$ as a necessary (but not sufficient) condition for low fine-tuning in any SUSY model.

[5]For this model line, the electroweak fine-tuning parameter $\Delta_{\rm EW} < 30$ (80) if $m_{1/2} < 1.2$ (2.0) TeV.

v6.426 [30] where we convolute the partonic cross section with CTEQ6L1 distribution functions [31], implement the p_T-ordered shower using the k_T clustering scheme to form jets, and obtain the cross section at LHC13. We use PGS4 [32] for a toy simulation of the detector in the LHC configuration, and define jets to be hadronic clusters with $E_T(j) > 30$ GeV within $|\eta_j| < 5$.

The solid (black) curve in Fig. 2 shows the result of our computation of $\sigma(pp \to \widetilde{W}_1^\pm \widetilde{W}_1^\pm jj + X)$ versus $m_{1/2}$ for the natural SUSY model-line in (1). In this figure we have required:

- At least two jets with $E_T(j) > 30$ GeV, and
- the rapidity separation between the two highest E_T jets, $\Delta\eta(j_1, j_2) > 4.2$.

We have checked that requiring the jets to be in opposite hemispheres so that $\eta(j_1) \cdot \eta(j_2) < 0$ does not affect the result. The range with $m_{1/2} \lesssim 475$ GeV is, of course, excluded by the lower bound $m_{\tilde{g}} > 1.3$ TeV [1, 2]. For small values of $m_{1/2}$, the chargino is a mixed gaugino-higgsino state, but becomes almost a pure higgsino with a mass $m_{\widetilde{W}_1} \simeq \mu = 150$ GeV once $m_{1/2}$ exceeds 500-600 GeV. The surprising feature is that the cross section drops off to below 0.02 fb for $m_{1/2} \geq 500$ GeV and continues to fall with increasing $m_{1/2}$ *even though the chargino mass, remains fixed close to* μ *across most of the range of* $m_{1/2}$ *where* $\widetilde{W}_1$ *is dominantly higgsino-like.* For comparison, we also show by the dashed (red) line the cross section for the same model line but with $\mu = 1$ TeV for which the lighter chargino is mostly wino-like. This cross section also drops off with increasing $m_{1/2}$ but this fall-off is clearly because the wino mass increases with $m_{1/2}$ according to $M_2 \simeq 0.8 m_{1/2}$.

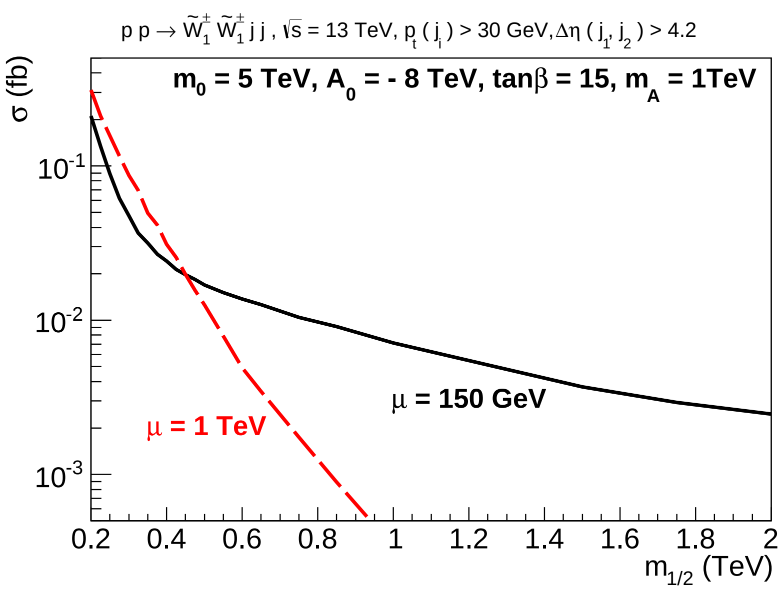

Figure 2: The cross section for SS chargino production via $pp \to \widetilde{W}_1^\pm \widetilde{W}_1^\pm jj + X$ at a centre-of-mass energy $\sqrt{s} = 13$ TeV versus $m_{1/2}$ for the RNS model line (1) of the text (solid, black curve) and for the same model-line but with $\mu = 1$ TeV (dashed, red curve).

To illustrate the dependence of the SS chargino production cross section in natural SUSY on the chargino mass, we show $\sigma(pp \to \widetilde{W}_1^{\pm}\widetilde{W}_1^{\pm}jj + X)$ versus μ in Fig. 3 for the same model-line but with $m_{1/2} = 1$ TeV (uppermost solid curve). The lighter chargino is dominantly a higgsino along this curve. Also shown are the component cross sections for $\widetilde{W}_1^{+}\widetilde{W}_1^{+}jj$ events and $\widetilde{W}_1^{-}\widetilde{W}_1^{-}jj$ events at the LHC. The production of positive chargino pairs exceeds that of negative chargino pairs because there are more up type than down type quarks in a proton. We also see that the total same sign chargino production cross section lies below 0.01 fb over essentially the entire range of the plot. The dashed lines in the figure illustrate the cross sections for the same reaction, but in a model without gaugino mass unification where the lighter chargino is essentially a pure wino. We show this cross section versus the wino mass parameter M_2, with $M_1 = M_2 - 20$ GeV and $\mu = 1$ TeV, with values of other *weak scale parameters* the same as those for the solid curves. We see that the cross section for SS higgsino pair production is about

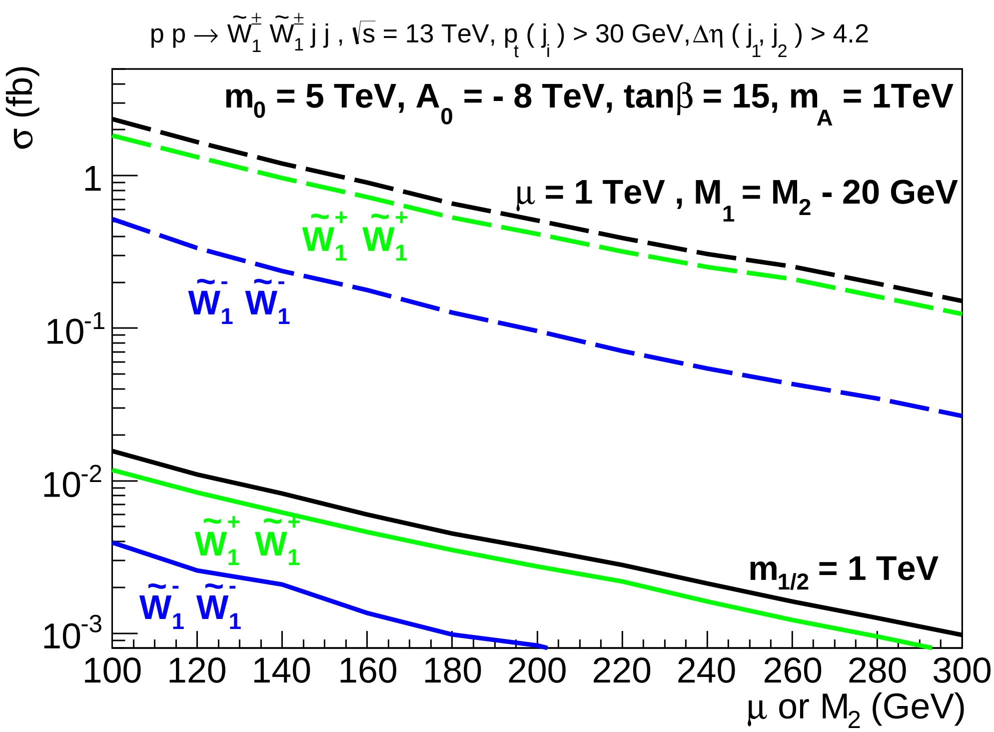

Figure 3: The cross section for SS chargino production via $pp \to \widetilde{W}_1^{\pm}\widetilde{W}_1^{\pm}jj + X$ at a centre-of-mass energy $\sqrt{s} = 13$ TeV versus μ for the RNS model line (1) of the text with $m_{1/2} = 1$ TeV (solid curves), and versus M_2 with $M_1 = M_2 - 20$ GeV and $\mu = 1$ TeV (dashed curves), with other weak scale parameters at the same values used for the solid curves. The uppermost of each set of curves shows the total SS chargino cross section, while the other two curves in each set denote the component cross sections. Plotted this way, the scale on the horizontal axis is, to a good approximation, the mass of the lighter chargino for both sets of curves in the figure.

two orders of magnitude smaller than that for SS wino pair production for the same mass of the particle.[6] Indeed the latter occurs at an observable rate even after factoring in the branching fraction of 0.22 for the leptonic decay of each chargino, for an integrated luminosity of 300 (3000) fb^{-1} expected to be accumulated at LHC Run 2 (the high luminosity upgrade of the LHC). In contrast, the cross section for SS higgsino production appears to be below the level of observability at LHC13:[7] the projected event rate is < 1 SS dilepton jj event/ab^{-1} of integrated luminosity even before acceptance, trigger and analysis cuts on $E_T(j)$ and jet invariant masses that are necessary to extract the signal [20, 26]. Clearly the disparity between the cross sections for higgsino-like and wino-like charginos cannot be explained by the difference in the magnitudes of the $\tilde{h}^0\tilde{h}^\pm W^\mp$ and $\widetilde{W}^0\widetilde{W}^\pm W^\mp$ couplings. A resolution of this disparity forms the subject of the remainder of this paper.

Toward this end, we show in Fig. 4 the VBF cross section for the underlying sub-process $W^+W^+ \to \widetilde{W}_1^+\widetilde{W}_1^+$ versus $m_{1/2}$ for the same model-line as for the solid, black curve in Fig. 2, taking $\sqrt{s} = 1$ TeV. In the MSSM, this process occurs via the exchange of the four neutralinos in the t- and u-channels. It is easy to see that the Majorana nature of the neutralinos is essential to obtain a non-vanishing amplitude. Indeed SS chargino production from VBF has been stressed as a definitive test of Majorana nature of neutralinos [25]. As before, we see that the cross section rapidly decreases with increasing $m_{1/2}$, even though the produced chargino mass is close to 150 GeV across the entire plot. The figure makes it obvious that the cross section for same sign higgsino pair production is being *dynamically suppressed*.

To better understand this suppression, we examine the interactions of the chargino-neutralino system with W bosons in the limit of large gaugino masses, the situation we expect in natural SUSY. In this limit, the winos and binos essentially decouple, leaving the charged (Dirac) higgsino,

$$\widetilde{W}_1 \equiv (-i\gamma_5)^{\theta_\mu+1}\left(P_L\psi_{h_d^-} - P_R\psi_{h_u^+}\right),$$

and the two Majorana neutralinos,

$$(-i\gamma_5)^{\theta_\mu}\frac{(\psi_{h_u^0}+\psi_{h_d^0})}{\sqrt{2}} \text{ and } (-i\gamma_5)^{\theta_\mu+1}\frac{(\psi_{h_u^0}-\psi_{h_d^0})}{\sqrt{2}},$$

each with mass $|\mu|$ in the spectrum. Here, $\psi_{h_u^0}$ and $\psi_{h_d^0}$ are the Majorana higgsino fields in the notation of Ref.[35], $\theta_\mu = 0$, if $\mu > 0$ and $\theta_\mu = 1$ if $\mu < 0$. One can then combine the two

[6] Same sign higgsino production with a (nearly) pure higgsino LSP has not been examined in the literature. We have, however, checked that our results for same sign chargino production are compatible with results in Ref.[20] (where the cases with a mixed bino-wino and mixed bino-higgsino LSP are examined) but not with those in Ref.[25]. We also obtain a same sign chargino cross section that is a factor of about 20 smaller than the uppermost curve in Fig. 2 of the second paper of Ref. [26]. We have contacted these authors who have since confirmed that they agree with our result. We thank B. Dutta, T. Ghosh, A. Gurrola, T. Kamon and especially T. Plehn and S. Wu for extensive communications and discussion concerning the discrepancy.

[7] This situation may be different at a 100 TeV pp collider (SppC) being envisioned for the distant future [33]. Assuming that the $\widetilde{W}_1^\pm\widetilde{W}_1^\pm jj$ cross section scales by the same factor as the corresponding neutralino cross section from VBF [34] between the LHC and the SppC, we may expect ~ 2 SS dilepton + jj events per ab^{-1} for a charged higgsino mass of 200 GeV and $m_{1/2} = 1$ TeV. For an integrated luminosity of 30 ab^{-1} [33], this corresponds to ~ 60 events before any acceptance, trigger and analysis cuts, or efficiency corrections. We make no representation about the observability of the SS chargino signal via the dilepton plus forward jet events. We note, however, that neutral higgsino production via VBF has been suggested as a promising search channel after hard cuts on the dijet invariant mass and $E_T^{\rm miss}$ [34].

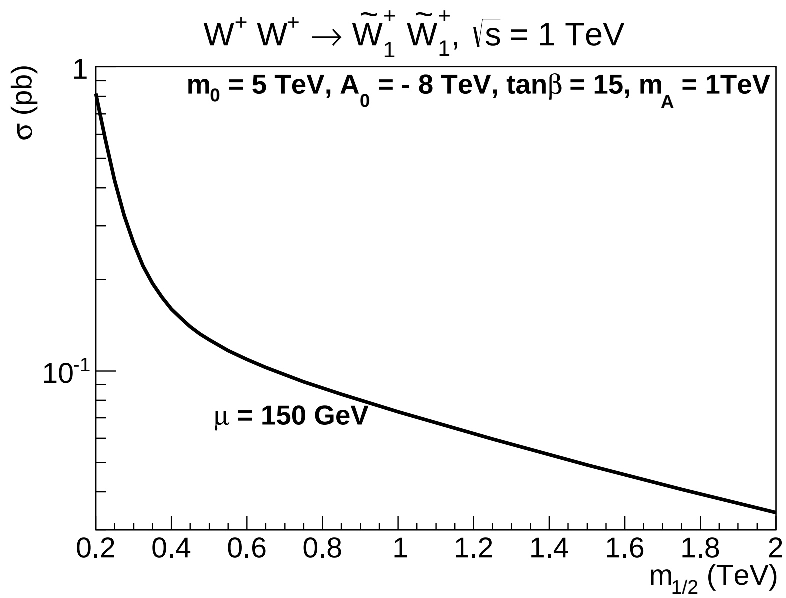

Figure 4: The cross section for the underlying VBF process $W^+W^+ \to \widetilde{W}_1^+\widetilde{W}_1^+$ versus $m_{1/2}$ for the RNS model line (1) of the text, assuming a centre-of-mass energy of 1 TeV. Notice that the chargino mass is close to $\mu = 150$ GeV over essentially the entire plot.

degenerate neutralinos into a single Dirac higgsino-neutralino

$$\widetilde{Z}_D \equiv (-i\gamma_5)^{\theta_\mu+1}\left(P_L\psi_{h_d^0} - P_R\psi_{h_u^0}\right)$$

with mass $|\mu|$. The masses of the charged and neutral Dirac higgsinos and their couplings to the W-boson can readily be worked out. In the limit that the gauginos are completely decoupled, we find,

$$\mathcal{L} = -|\mu|(\overline{\widetilde{W}_1}\widetilde{W}_1 + \overline{\widetilde{Z}_D}\widetilde{Z}_D) + \left[\frac{g}{\sqrt{2}}\overline{\widetilde{W}_1}\gamma^\mu\widetilde{Z}_D W_\mu + h.c.\right]. \tag{2}$$

We see that the Lagrangian in Eq. (2) respects a new global $U(1)_{\rm ino}$ symmetry, and so conserves ino-number, defined to be +1 for the Dirac particles $\widetilde{W}_1$ and $\widetilde{Z}_D$, -1 for the corresponding anti-particles, and 0 for sfermions and all SM particles. It is also clear that it is not possible to consistently define $U(1)_{\rm ino}$ transformations unless the two neutral higgsino states are exactly degenerate. Ino-number conservation then requires the cross section for the process $W^+W^+ \to \widetilde{W}_1^+\widetilde{W}_1^+$ must vanish in the limit $M_{1,2} \to \infty$, accounting for the fall-off of the cross section in Fig. 4. In the original language of two light, neutral Majorana neutralinos, it is straightforward to analytically see that the amplitude from the exchange of $\widetilde{Z}_1$ exactly cancels that from the exchange of $\widetilde{Z}_2$ in the limit $M_{1,2} \to \infty$ in both the t- and the u-channels: the magnitudes of the $\widetilde{Z}_i\widetilde{W}_1^\pm W^\mp$ $(i = 1, 2)$ couplings and masses are identical for each of these amplitudes, and the destructive interference arises because the two neutralinos necessarily have opposite signs of the eigenvalue of the neutralino mass matrix.

The couplings of the higgsinos to the fermion-sfermion system do not respect the $U(1)_{\rm ino}$ invariance and so violate ino number conservation. However, since first and second generation masses are only weakly constrained by naturalness considerations, we expect that the sfermion-mediated amplitudes in Fig. 1 will be strongly suppressed (recall that we took first/second generation squark masses to be 5 TeV in our illustrative examples) so that (approximate) ino-number conservation once again accounts for the strong suppression of the SS chargino production cross section for large values of electroweak gaugino mass parameters at LHC13. Although obvious, we note that ino-number conservation *does not* constrain $\widetilde{W}_1^+\widetilde{W}_1^-$, $\widetilde{W}_1\widetilde{Z}_i$ and $\widetilde{Z}_i\widetilde{Z}_j$ production since the final states can have zero ino-number.

In summary, we have studied prospects for detecting the light higgsinos that are expected to be the most robust characteristic of at least the simplest models of natural SUSY at the LHC. We focussed our attention on the production of SS higgsinos produced via $pp \to \widetilde{W}_1^\pm\widetilde{W}_1^\pm jj + X$ which, we anticipated would be dominated by VBF processes because the W-boson couples to the higgsino system with the *full-strength* $SU(2)$-doublet coupling. In natural SUSY models, the signature would be a pair of same-sign, low p_T leptons in events with two forward high E_T jets with a large rapidity separation between them. We found that the cross section for the process is typically smaller than 0.02 fb at LHC13 (two orders of magnitude smaller than the corresponding cross section for SS wino production), even before leptonic branching fractions of the charginos, or acceptance, trigger and analysis cuts are folded in. We traced this suppression to an approximate $U(1)_{\rm ino}$ symmetry that emerges in natural SUSY models when $|\mu| \ll M_{1,2}$, or equivalently, to a (nearly) complete cancellation between amplitudes from $\widetilde{Z}_1$ and $\widetilde{Z}_2$ exchange (the amplitudes from other two neutralinos are suppressed because these are heavy). We conclude that while chargino and neutralino production via VBF processes may lead to observable signals at the LHC, it will not be possible to search for the light charged higgsinos of natural SUSY even at the high luminosity LHC via SS chargino production by VBF (unless electroweak gaugino mass parameters are also fortuitously small – in which case there will be signals in several other channels) because the signal is severely rate-limited.

Acknowledgments

We thank H. Baer and A. Mustafayev for helpful comments on the text. This work was supported in part by the US Department of Energy.

References

[1] G. Aad *et al.* [ATLAS Collaboration], *J. High Energy Phys.* **1409** (2014) 176 and *J. High Energy Phys.* **1504** (2015) 116; G. Aad *et al.* (ATLAS Collaboration) *J. High Energy Phys.* **1405** (2014) 071 and *Eur. Phys. J.* **C 75** (2015) 208.

[2] S. Chatrchyan *et al.* [CMS Collaboration], *J. High Energy Phys.* **1406** (2014) 055; V. Khachatryan *et al.* [CMS Collaboration] *J. High Energy Phys.* **1505** (2015) 078; V. Khachatryan *et al.* (CMS Collaboration) *Eur. Phys. J.* **C 74** (2014) 3036 and *Phys. Rev.* **D90** (2014) 092007;

[3] Y. Golfand and E. Likhtman, *JETP Lett.* **13** (1971) 323; D. Volkov and V. Akulov, *JETP Lett.* **16** (1972) 621; J. Wess and B. Zumino, *Nucl. Phys.* **B70** (1974) 39.

[4] E. Witten, *Nucl. Phys.* **B188** (1981) 513; S. Dimopoulos and H. Georgi, *Nucl. Phys.* **B193** (1981),150; N. Sakai, *Z. Phys.* **C11** (1981) 153; R. Kaul, *Phys. Lett.* **B109** (1982) 19.

[5] E. Gildener and S. Weinberg, *Phys. Rev.* **D13** (1976) 3333; E. Gildener, *Phys. Rev.* **D14** (1976) 1667; L. Susskind, *Phys. Rev.* **D20** (1979) 2619.

[6] For early discussions, see *e.g.* R. Kitano and Y. Nomura, *Phys. Lett.* **B631** (2005) 58 and *Phys. Rev.* **D73** (2006) 095004; For more recent studies in light of LHC results, see M. Papucci, J. T. Ruderman and A. Weiler, *J. High Energy Phys.* **1209** (2012) 035; A. Strumia, *J. High Energy Phys.* **1104** (2011) 073; J. Lykken and M. Spiropulu, *Sci. Am.* **310N5** (2014) 5, 36; N. Craig, arXiv:1309.0528 [hep-ph].

[7] CMS Collaboration, S. Chatrchyan *et. al. Eur. Phys. J.* **C 73** (2013) 2677 and V. Khachatryan *et al. J. High Energy Phys.* **1506** (2015) 116; ATLAS Collaboration, G. Aad *et al.* arXiv:1506.08616 [hep-ex].

[8] H. Baer, V. Barger, P. Huang, A. Mustafayev and X. Tata, *Phys. Rev. Lett.* **109** (2012) 161802.

[9] H. Baer, V. Barger, P. Huang, D. Mickelson, A. Mustafayev and X. Tata, *Phys. Rev.* **D87** (2013) 115028.

[10] H. Baer, V. Barger and D. Mickelson, *Phys. Rev.* **D88** (2013) 095013; H. Baer, V. Barger and M. Savoy, *Physica Scripta* **90** (2015) 6, 068003, arXiv:1502.04127.

[11] A. Mustafayev and X. Tata, invited contribution in volume commemorating C.V. Raman's 125th birth anniversary, *Indian J. Phys.* **88** (2014) 991; X. Tata, arXiv:1506.07151 [hep-ph].

[12] K. Chan, U. Chattopadhyay and P. Nath, *Phys. Rev.* **D58** (1998) 096004.

[13] A. Nelson and T. Roy, *Phys. Rev. Lett.* **114** (2015) 201802; S. Martin, *Phys. Rev.* **D92** (2015) 035004.

[14] T. Cohen, J. Kearney and M. Luty, *Phys. Rev.* **D91** (2015) 075004.

[15] H. Baer, V. Barger, P. Huang, D. Mickelson, A. Mustafayev, W. Sreethawong and X. Tata *J. High Energy Phys.* **1312** (2013) 013 and *J. High Energy Phys.* **1506** (2015) 053 (Erratum).

[16] H. Baer, V. Barger, D. Mickelson, A. Mustafayev and X. Tata, *J. High Energy Phys.* **1406** (2014) 172.

[17] H. Baer, V. Barger, P. Huang, D. Mickelson, M. Padeffke-Kirkland and X. Tata, *Phys. Rev.* **D91** (2015) 075005.

[18] H. Baer, A. Mustafayev and X. Tata, *Phys. Rev.* **D89** (2014) 055007; C. Han, A. Kobakhidze, N. Liu, A. Saavedra, L. Wu and J. M. Yang, *J. High Energy Phys.* **1402** (2014) 049. P. Schwaller and J. Zurita, *J. High Energy Phys.* **1403** (2014) 060; D. Barducci, A. Belyaev, A. Bharucha, W. Porod and V. Sanz, *J. High Energy Phys.* **1507** (2015) 066 express a more optimistic viewpoint for detection of the monojet signal.

[19] A. Anandakrishnan, L. Carpenter and S. Raby, *Phys. Rev.* **D90** (2014) 055004.

[20] G Giudice, T. Han, K. Wang and L-T. Wang, *Phys. Rev.* **D81** (2010) 115011.

[21] Z. Han, G. Kribs, A. Martin and A. Menon, *Phys. Rev.* **D89** (2014) 075007.

[22] H. Baer, A. Mustafayev and X. Tata, *Phys. Rev.* **D90** (2014) 115007.

[23] G. Aad *et al.* (ATLAS Collaboration) *Phys. Rev. Lett.* **113** (2014) 141803.

[24] V. Khachatryan *et al.* (CMS Collaboration) *Phys. Rev. Lett.* **114** (2015) 051801.

[25] G. Cho, K. Hagiwara, J. Kanzaki, T. Plehn, D. Rainwater and T. Stelzer, *Phys. Rev.* **D73** (2006) 054002.

[26] A. Delannoy *et al. Phys. Rev. Lett.* **111** (2013) 061801; B. Dutta *et al. Phys. Rev.* **D87** (2013) 035029; B. Dutta *et al. Phys. Rev.* **D90** (2014) 095022; B. Dutta *et al. Phys. Rev.* **D91** (2015) 055025.

[27] D. Matalliotakis and H. P. Nilles, *Nucl. Phys.* **B435** (1995) 115; V. Berezinsky, A. Bottino, J. Ellis, A. Fornengo, G. Mignola and S. Scopel, *Astropart. Phys.* **5** (1996) 1; P. Nath and R. Arnowitt, *Phys. Rev.* **D56** (1997) 2820; J. Ellis, K. Olive and Y. Santoso, *Phys. Lett.* B539 (2002) 107; J. Ellis, T. Falk, K. Olive and Y. Santoso, *Nucl. Phys.* **B652** (2003) 259; H. Baer, A. Mustafayev, S. Profumo, A. Belyaev and X. Tata, *J. High Energy. Phys.* **0507** (2005) 065.

[28] ISAJET, H. Baer, F. Paige, S. Protopopescu and X. Tata, hep-ph/0312045.

[29] Madgraph 5, J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer and T. Stelzer, *J. High Energy Phys.* **1106** (2011) 128; J. Alwall *et al.*, *J. High Energy Phys.* **1407** (2014) 079.

[30] PYTHIA 6.4, T. Sjostrand, S. Mrenna and P. Skands, *J. High Energy Phys.* **0605** (2006) 026 [hep-ph/0603175].

[31] J. Pumplin, D. Stump, J. Huston, H. Lai, P. Nadolksy and W.-K. Tung, *J. High Energy Phys.* **0207** (2002) 012.

[32] PGS, J. Conway, http://www.physics.ucdavies.edu/ conway/research/software/pgs/pgs4-general.htm.

[33] M. Ahmad *et al.* (CEPC-SPPC Study Group) http://cepc.ihep.ac.cn/preCDR/volume.html

[34] A. Berlin, T. Lin, M. Low and L-T. Wang, *Phys. Rev.* **D91** (2015) 115002.

[35] H. Baer and X. Tata, *Weak Scale Supersymmetry* (Cambridge, 2006).