Reaching for Squarks and Gauginos at a 100 TeV p-p Collider

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We analyse the prospect of extending the reach for squarks and gauginos via associated production at a \(\sqrt{s} = 100\) TeV proton-proton collider, given \(3\) ab\(^{-1}\) integrated luminosity. Depending on the gluino mass, the discovery reach for squarks in associated production with a gluino can be up to 37 TeV for compressed spectra (small gluino-LSP mass splitting), and up to 32 TeV for non-compressed spectra. The discovery reach for Winos can be up to between 3.5 and 6 TeV depending on squark masses and Wino decay kinematics. Binos of up to 1.7 TeV could similarly be discovered. Squark-gaugino associated production could prove to be the discovery mode for supersymmetry at a 100 TeV collider in a large region of parameter space.

I. INTRODUCTION

Observational evidence for low energy Supersymmetry (SUSY) remains elusive. Current LHC data constrains strongly-interacting superpartner masses to lie near or above a TeV, disfavoring electroweak-scale SUSY in a wide variety of models. It is therefore becoming increasingly well motivated to consider the possibility that the superpartner masses lie above \(\sim 1\) TeV, perhaps evading the kinematic reach of LHC-14. This has prompted numerous studies of the SUSY discovery potential of future hadron colliders, which have demonstrated that a \(\sqrt{s} = 100\) TeV collider can extend the kinematic reach for superpartners into the multi-TeV range \([1-11]\).

Previous studies of SUSY at future hadron colliders have focused primarily on pair production, either of colored superpartners \([1, 2, 4]\) or of electroweakinos \([3, 6-10]\). In this paper, we instead examine the reach of a \(\sqrt{s} = 100\) TeV collider for associated production of a heavy squark along with a lighter gaugino. This production channel is particularly noteworthy if the squark masses are \(\mathcal{O}(10)'s\) of TeV, such that squark pair production is kinematically inaccessible at \(\sqrt{s} = 100\) TeV. Spectra where squarks are hierarchically heavier than the gluino/electroweakino are predicted in many SUSY breaking models such as anomaly mediation \([12, 13]\) or more general “mini-split”-type scenarios \([14-16]\). Moreover, multi-TeV squark masses can naturally accommodate the stop masses required to achieve a 125 GeV Higgs boson within the MSSM.

In this paper, we demonstrate that associated squark-gaugino production at a \(\sqrt{s} = 100\) TeV proton collider provides a probe of \(\gtrsim 10\) TeV squark masses which is complementary to pair production. Our main results are summarized in Figures 1-5, which show the reach of a \(\sqrt{s} = 100\) TeV p-p collider with \(3\) ab\(^{-1}\) integrated luminosity for squark-gauginos associated production in various spectra \(^1\).

Squark-gluino production can discover squark masses up to 32 TeV for \(\lesssim 4\) TeV gluino masses in spectra with a large gluino-neutralino LSP mass splitting (Fig 1). For spectra with a small gluino-neutralino LSP mass splitting, squark masses up to 37 TeV can similarly be discovered (Fig. 2). Notably, our analysis finds that the gluino-neutralino DM coannihilation region \([18, 19]\) can be excluded for squark masses \(\lesssim 28\) TeV. For squark-Wino (Bino) LSP production, Wino (Bino) masses up to \(4\) (1.7) TeV can be discovered for squark masses \(\lesssim 7\) (5) TeV (Figs. 3-4). We find a similar reach for squark-Wino NLSP production (Fig 5), even without utilizing objects resulting from NLSP \(\rightarrow\) LSP decay. Our results indicate that squark-gauginos production represents a SUSY discovery mode at a \(\sqrt{s} = 100\) TeV p-p collider in a wide variety of models with heavy first- and second-generation squarks.

The remainder of this paper is organized as follows. Section II discusses our general methodology

\(^1\) Note that a recent study in \([17]\) calls for an integrated luminosity of between 10 and 20 ab\(^{-1}\) at a future 100 TeV p-p collider. We present here results for \(3\) ab\(^{-1}\) as a conservative estimate, and so as to be directly comparable with the current literature.
and simulation strategies. Section III presents in
detail our analysis of squark-gluino associated
production, while Section IV presents our analysis of
squark-Wino/Bino associated production. We sum-
marize our results in Section V.

II. GENERAL METHODOLOGY

In this section we briefly discuss the general
methodology of the analyses presented below. Event
topologies arising from heavy squark - light gaugino
associated production are characterized by a hard
leading jet and significant $E_T$. These objects result
primarily from the squark decay products, as the as-
gociated gaugino is produced at relatively low trans-
verse momentum. The dominant SM background
for such events is in the $t\bar{t}$+ jets and vector boson +
jets channels [1], which fall off rapidly with increas-
ing leading jet $p_T$, $E_T$, and $E_T/\sqrt{H_T}$ ($H_T$ is defined
as the scalar sum of the jet transverse energies).

In the following analyses, we consider the reach
of a $\sqrt{s} = 100$ TeV proton-proton collider given 3
ab$^{-1}$ integrated luminosity. The minimum produc-
tion cross section yielding $\geq 10$ events is roughly
$\sim 10^{-2}$ fb, corresponding to $m_{\tilde{q}} + m_{\tilde{g}} \sim 35$ TeV
($m_{\tilde{q}} + m_\chi^0 \sim 15$ TeV) for squark-gluino (squark-
Wino) associated production. For such masses, good
background discrimination is achieved with hard
leading jet $p_T$ cuts for squark-gluino production, and
with $E_T/\sqrt{H_T}$ cuts for squark-Wino/Bino pro-
duction. Our strategy is as follows: for each analy-
thesis we impose a set of baseline cuts catered to a set
of spectra. We then scan over leading jet $p_T$ and
$E_T$ cuts (squark-gluino) or $E_T/\sqrt{H_T}$ cuts (squark-
Wino/Bino) to maximize significance $\sigma$, defined by

$$\sigma \equiv \frac{S}{\sqrt{B + \lambda S^2 + \gamma S^4}}.$$  \hspace{1cm} (1)

$S$ ($B$) is the number of signal (background) events
passing cuts, and $\gamma$ ($\lambda$) parameterize systematic un-
certainties associated with signal (background) nor-
alization. Details of the event generation and col-
er simulation are given in Appendix A. Like most
future collider studies, our simulated $\sigma$ values are subject to $O(1)$ uncertainties associated with e.g.
the performance of a detector which is yet to be de-
signed. However, this translates to a comparatively
mild uncertainty for the predicted reach, due to the
rapid falling of production cross sections with in-
creasing mass.

Simplified Models

In the analyses presented below, we consider the
following SUSY simplified models:

| Model               | Particle Content                                      | Fig. |
|---------------------|------------------------------------------------------|------|
| Squark-Gluino       | $q\tilde{g}, \tilde{q}^0 \chi_1^0 = B$             |  1   |
| Non-compressed      | $M_1 = 100$ GeV                                       |      |
| Compressed          | $m_{\tilde{q}} - m_{\chi_1^0} = 15$ GeV             |  2   |
| Squark-Wino LSP     | $q\tilde{\chi}_1^0 = W$                             |  3   |
| Squark-Bino LSP     | $q\tilde{\chi}_1^0 = B$                             |  4   |
| Squark-Wino NLSP    | $q\chi_0^0 = W, \chi_1^0 = B/H$                     |  5   |
| Split               | $M_1/\mu = 100$ GeV                                  |      |
| Non-split           | $m_{\tilde{W}} - m_{\chi_0^0} = 200$ GeV            |      |

TABLE I. Simplified models considered in this paper.

which encompass a wide array of potential event
topologies arising from squark-gaugin production.
We take degenerate first and second generation
squark masses, and decouple all sparticles not listed
in Table I. For the squark-gluino non-compressed
model, our results are not sensitive to the choice
of $M_1 = 100$ GeV as the LSP is effectively mass-
less for $m_{\chi_0^0} \ll m_{\tilde{g}}$. The squark-gluino compressed
model is motivated by the gluino-neutralino anni-
hilation region $[18, 19]$. We choose $m_{\tilde{g}} - m_{\chi_0^0} = 15$
GeV as a fiducial value, though the leading jet $p_T$-
based analysis presented below is robust as long as
$m_{\tilde{g}} - m_{\chi_0^0} \ll m_{\tilde{g}}$. For the Wino NLSP models, we
choose two spectra with differing LSP masses to il-
lustrate the effects of increasing the NLSP-LSP mass
splitting. In the “non-split” case, we have chosen an
NLSP-LSP mass splitting of 200 GeV so that the
NLSP decays to the LSP + on-shell SM bosons.

III. SQUARK-GLUINO ASSOCIATED
PRODUCTION

In this section we discuss squark-gluino associated
production. As this process only involves $\alpha_s$, it can be
important at a $\sqrt{s} = 100$ TeV p-p collider even
if $m_{\tilde{q}} + m_{\tilde{g}} \gtrsim 35$ TeV. If a heavy squark of order
tens of TeV is produced in association with a gluino
of mass $\lesssim 10$ TeV, the leading jet from the squark
decay will be very hard, $p_T \sim m_{\tilde{q}}/2$. Furthermore
the neutralino resulting from the decay chain $q\tilde{q} \rightarrow 3q\chi_0^0$ will be very boosted, resulting in large
$E_T$. These kinematic features result in a striking
collider signature with very low SM background.
We explore the reach in squark-gluino production at a $\sqrt{s} = 100$ TeV p-p collider for the two types of squark-gluino spectra listed in Table I. For simplicity we assume the LSP is a Bino, and all other neutralinos/charginos are decoupled. Relaxing this assumption allows squark decays to intermediate neutralinos/charginos, resulting in additional final state objects which can be used for background discrimination.

For both non-compressed and compressed spectra, we impose the following baseline cuts:

$$H_T > 10 \text{ TeV}, \quad \frac{E_T}{\sqrt{H_T}} > 20 \text{ GeV}^{1/2}$$

while for the non-compressed spectra we impose the additional cut:

$$8 \text{ jets with } p_T > 50 \text{ (150) GeV}$$

The softer cut is optimized for heavier squarks and lighter gluinos, while the harder cut is optimized for lighter squarks and heavier gluinos. Upon imposing these baseline cuts, we then scan over leading jet $p_T$ and $E_T$ cuts in order to maximize significance $\sigma$ as defined in (1). We have verified that the optimal cuts render any “background” from gluino pair production subdominant to the SM background.

The results of this analysis are depicted in Figs. 1 and 2, which show the reach of a $\sqrt{s} = 100$ TeV proton collider with 3 ab$^{-1}$ of integrated luminosity for spectra with $m_{\tilde{g}} - m_{\tilde{\chi}_1^0} = 15$ GeV. The different lines follow the conventions of Fig. 1. We assume 20% systematic uncertainty in the background.

As is evident from Figs. 1 and 2, a $\sqrt{s} = 100$ TeV collider with 3 ab$^{-1}$ integrated luminosity can begin probing much of the “mini-split” parameter space for sufficiently low gluino masses. Final states in the compressed spectra yield more $E_T$ compared to the non-compressed spectra, resulting in the greater reach depicted in Figure 2. Notably, with 3 ab$^{-1}$ integrated luminosity the entire neutralino-gluino coannihilation region (whose upper endpoint lies at $m_{\tilde{g}} \approx m_{\tilde{\chi}_1^0} \approx 8$ TeV [19]) can be excluded if the squark masses are $\lesssim 28$ TeV.

It is worthwhile to compare Figs. 1 and 2 to projected reaches for gluino pair production. Our results for non-compressed spectra have some overlap with [1]$^2$, which considered both pair production and associated production in similar spectra with squark

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$^2$ A search optimizing over $H_T$ cuts as opposed to leading jet $p_T$ cuts was done in [1]. For the spectra in Fig. 1, the $H_T$
masses $\lesssim 24$ TeV. The results of [1] indicate that gluino pair production will likely be the discovery channel for colored superpartners for the spectra in Fig. 1 provided $m_{\tilde{g}} \lesssim 14$ TeV. On the other hand, if the gluino and the LSP are nearly degenerate, searches for gluino pair production rapidly lose sensitivity [1]. Thus if the gluino and the LSP are nearly degenerate as in the gluino-neutralino coannihilation scenario, squark-gluino associated production would be a potential discovery channel for colored superpartners.

IV. SQUARK-WINO AND SQUARK-BINO ASSOCIATED PRODUCTION

In this section we discuss squark-Wino and squark-Bino associated production. These channels are particularly important if squark-gluino associated production is inaccessible due to a sufficiently heavy gluino mass. The event topology is qualitatively similar to squark-gluino production, as the squark will decay to a boosted jet and boosted Wino/Bino while the associated Wino/Bino is produced at relatively low $p_T$. However as noted in Section II, associated squark-Wino/Bino production probes significantly lighter squark masses than squark-gluino production. Consequently, multi-TeV leading jet $p_T$ and $E_T$ cuts are not as effective for background discrimination in squark-Wino/Bino production. Instead, we find that hard $E_T/\sqrt{H_T}$ cuts are quite effective at reducing the $t\bar{t}+\text{jets}$ and vector boson + jets background without rejecting too many signal events.

In order to determine the projected reach for squark-Wino/Bino production at a $\sqrt{s} = 100$ TeV pp collider with 3 ab$^{-1}$ integrated luminosity, we impose the following baseline cuts:

$$p_T(j_1) > 2 \text{ TeV}, \ E_T > 3 \text{ TeV}, \ \Delta\phi(j, E_T) > 0.5$$

where the $\Delta\phi$ cut is imposed only on the two leading jets. We then scan over $E_T/\sqrt{H_T}$ cuts for each spectrum to maximize $\sigma$ as defined in (1).

Our focus is on spectra listed in Table I where at most one of the gaugino/Higgsino mass parameters $M_1, M_2, \mu$ are $\lesssim 1$ TeV, such that the gauge eigenstates are approximately aligned with the mass eigenstates in the neutralino/chargino sectors. We omit the “compressed” region $m_{\tilde{g}} - m_{\tilde{\chi}} < 1$ TeV, as in this region the event topology of associated squark-Wino/Bino production is similar to squark pair production, only with a substantially smaller cross section. Assuming a systematic uncertainty of 10% for the signal normalization, the results of the above analysis for the various spectra in Table I are depicted in Figures 3-5.

Figure 3 shows the reach for squark-Wino production with a pure Wino LSP; the solid, short-dashed, long-dashed lines correspond to background uncertainties of 1%, 2% and 3%. In Figure 4 we show the reach for squark-Bino production with a pure Bino LSP. The solid, short-dashed, long-dashed lines correspond to background systematic uncertainties of 0.5%, 1% and 1.5%. Compared to squark-Wino production, the reach for squark-Bino associated production is quite sensitive to background uncertainties. This is because the 5$\sigma$ contours for squark-Bino production correspond to significantly lower masses due to the smaller production cross-section, resulting in lower optimal $E_T/\sqrt{H_T}$ cuts and thus larger backgrounds.

In Figure 5 we show the reach of the $E_T/\sqrt{H_T}$...
FIG. 4. Experimental reach for squark-Bino LSP associated production at a 100 TeV proton collider with 3 ab$^{-1}$ integrated luminosity. The solid, long dashed and short dashed lines are for and 0.5, 1, 1.5% systematic uncertainty for the background respectively. Blue lines indicate 5σ discovery reach and red lines indicate 95% exclusion limits. We do not consider the region ($m_{\tilde{q}} - m_{\tilde{\chi}} < 1$ TeV) for reasons given in the text. We assume 10% systematic uncertainty in the signal.

FIG. 5. Experimental reach for squark-Wino associated production at a 100 TeV proton collider with 3 ab$^{-1}$ integrated luminosity. Solid lines indicate 5σ discovery reach, and dotted lines indicate 95% exclusion limits. Blue curves correspond to a Wino LSP, while the green (red) curves correspond to a Wino NLSP with $M_{NLSP} - M_{LSP} = 200$ GeV ($M_{LSP} \sim 100$ GeV). The results are applicable for both Bino- and Higgsino-like LSP. We do not consider the grey shaded region ($m_{\tilde{q}} - m_{\tilde{\chi}} < 1$ TeV) for reasons given in the text. We assume 1% systematic uncertainty in the background and 10% in the signal.

We have examined in this paper the kinematic reach for squark-gaugino associated production at a 100 TeV proton collider. In models where a collider probe of pure Wino LSP pair production. Extrapolating the disappearing tracks background from the 8 TeV ATLAS study [22], the projected reach is 2-3 TeV for pure Winos [3]. However, the data-driven disappearing-track background at 100 TeV is difficult to estimate, making this projected reach less reliable than the reach in the VBF channel or the reach depicted in Figure 3. Finally, pair production of Wino NLSPs has been considered in [6, 7]. Assuming no systematic uncertainties, for a Higgsino LSP the projected discovery reach is 2.3 TeV, while for a Bino LSP the reach is 1-3 TeV depending on the NLSP $\rightarrow$ Z LSP branching ratio. Comparing these reaches to Figures 3-5, we see that squark-Wino/Bino associated production can provide a SUSY discovery mode provided the squark is not too much heavier than the Wino/Bino.

V. SUMMARY

We have examined in this paper the kinematic reach for squark-gaugino associated production at a 100 TeV proton proton collider. In models where
squark pair production is kinematically inaccessible at a 100 TeV collider, squark-gaugino associated production may be the discovery mode for SUSY in a large portion of parameter space.

We have considered the various simplified models listed in Table I. For squark-gluino production with $O$(TeV) gluinos, the discovery reach for first-generation squarks can be up to 37 TeV for compressed spectra (small gluino-LSP mass splitting), and up to 32 TeV for non-compressed spectra, subject to systematic uncertainties. For squark-Wino LSP production, we have shown that the discovery reach for the Wino is almost 4 TeV for squarks of $\sim$ 7 TeV, subject to systematic uncertainties. For squark-Wino NLSP production we have analysed two scenarios: one where the NLSP-LSP mass difference is 200 GeV, and one where the LSP mass is $\sim$ 100 GeV. In the first scenario, the Wino discovery reach is about 3.5 TeV for squarks of $\sim$ 7 TeV. In the second scenario, the Wino reach extends up to 6 TeV. Our results in the Wino-NLSP scenario are insensitive to the nature of the LSP. For $\lesssim$ 9 TeV squark masses, squark-Wino associated production marks a significant increase in the Wino reach compared to pair production channels. We also consider squark-Bino associated production, and find that the kinematic reach for the Bino is up to 1.7 TeV for squarks of mass $\sim$ 5 TeV, subject to systematic uncertainties.

The results presented here raise the exciting prospect of directly probing a region of parameter space that so far has been the exclusive domain of indirect searches through low-energy FCNC observables. The squark-gaugino associated production channels studied here, coupled with studies of supersymmetry at 100 TeV colliders already undertaken [1–11], provide a strong physics case for the construction of such a collider.

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Appendix A: Event generation

Signal events were generated using MADGRAPH5 [23], with showering and hadronization implemented via PYTHIA6.4 [24]. We do not perform MLM for the signal events. We have validated this approximation by performing MLM with 2 additional jets for a number of benchmark spectra. We use the simulated Snowmass backgrounds [25], processed with Delphes3.1.2 [26] supplemented by the Snowmass detector card [27] for a $\sqrt{s} = 100$ TeV hadron collider. Production cross sections for squark-gluino associated production are computed at NLO using PROSPINO2 [28]. For squark-Wino/Bino production we use the LO result computed by MADGRAPH5. Event analysis is performed with MadAnalysis5 [29]. We expect our kinematic cuts to effectively remove any contamination from QCD backgrounds and pileup effects, so we neglect both of these in our analysis. Note that for squark-gluino associated production in the $m_\tilde{q} \gg m_\tilde{g}$ region, the dijet background may not be negligible for non-compressed spectra. For these spectra, jet substructure techniques can help distinguish signal events from the QCD background [30].

[1] T. Cohen, T. Golling, M. Hance, A. Henrichs, K. Howe, J. Loyal, S. Padhi and J. G. Wacker, JHEP 1404 (2014) 117 [arXiv:1311.6480 [hep-ph]].
[2] S. Jung and J. D. Wells, Phys. Rev. D 89 (2014) 7, 075004 [arXiv:1312.1802 [hep-ph]].
[3] M. Low and L. T. Wang, JHEP 1408 (2014) 161 [arXiv:1404.0682 [hep-ph]].
[4] T. Cohen, R. T. D’Agnolo, M. Hance, H. K. Lou and J. G. Wacker, JHEP 1411 (2014) 021 [arXiv:1406.4512 [hep-ph]].
[5] S. A. R. Ellis, G. L. Kane and B. Zheng, arXiv:1408.1061 [hep-ph].
[6] B. S. Acharya, K. Bozek, C. Pongkitivanichkul and K. Sakurai, JHEP 1502 (2015) 181 [arXiv:1410.1532 [hep-ph]].
[7] S. Gori, S. Jung, L. T. Wang and J. D. Wells, JHEP 1412 (2014) 108 [arXiv:1410.6287 [hep-ph]].
[8] J. Bramante, P. J. Fox, A. Martin, B. Ostdiek, T. Plehn, T. Schell and M. Takeuchi, Phys. Rev. D 91 (2015) 5, 054015 [arXiv:1412.4789 [hep-ph]].
[9] G. G. di Cortona, JHEP 1505 (2015) 035 [arXiv:1412.5952 [hep-ph]].
[10] A. Berlin, T. Lin, M. Low and L. T. Wang, arXiv:1502.05044 [hep-ph].
[11] H. Beauchesne, K. Earl and T. Gregoire, arXiv:1503.03099 [hep-ph].
[12] L. Randall and R. Sundrum, Nucl. Phys. B 557 (1999) 79 [hep-th/9810155].
[13] G. F. Giudice, M. A. Luty, H. Murayama and R. Rattazzi, JHEP 9812 (1998) 027 [hep-ph/9810442].
[14] J. D. Wells, hep-ph/0306127.
[15] B. S. Acharya, K. Bobkov, G. L. Kane, P. Kumar and J. Shao, Phys. Rev. D 76 (2007) 126010 [hep-th/0701034].
[16] A. Arvanitaki, N. Craig, S. Dimopoulos and G. Villadoro, JHEP 1302 (2013) 126 [arXiv:1210.0555 [hep-ph]].
[17] I. Hinchliffe, A. Kotwal, M. L. Mangano, C. Quigg and L. T. Wang, arXiv:1504.06108 [hep-ph].
[18] S. Profumo and C. E. Yaguna, Phys. Rev. D 69 (2004) 115009 [hep-ph/0402208].
[19] J. Ellis, F. Luo and K. A. Olive, arXiv:1503.07142 [hep-ph].
[20] P. Fayet, Phys. Lett. B 78 (1978) 417.
[21] P. J. Fox, A. E. Nelson and N. Weiner, JHEP 0208, 035 (2002) [hep-ph/0206096].
[22] G. Aad et al. [ATLAS Collaboration], Phys. Rev. D 88 (2013) 11, 112006 [arXiv:1310.3675 [hep-ex]].
[23] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.-S. Shao and T. Stelzer et al., JHEP 1407 (2014) 079 [arXiv:1405.0301 [hep-ph]].
[24] T. Sjostrand, S. Mrenna and P. Z. Skands, JHEP 0605 (2006) 026 [hep-ph/0603175].
[25] A. Avetisyan, J. M. Campbell, T. Cohen, N. Dhingra, J. Hirscher, K. Howe, S. Malik and M. Narain et al., arXiv:1308.1636 [hep-ex].
[26] J. de Favereau et al. [DELPHES 3 Collaboration], JHEP 1402 (2014) 057 [arXiv:1307.6346 [hep-ex]].
[27] J. Anderson, A. Avetisyan, R. Brock, S. Chekanov, T. Cohen, N. Dhingra, J. Dolen and J. Hirschauer et al., arXiv:1309.1057 [hep-ex].
[28] W. Beenakker, R. Hopker and M. Spira, hep-ph/9611232.
[29] E. Conte, B. Fuks and G. Serret, Comput. Phys. Commun. 184 (2013) 222 [arXiv:1206.1599 [hep-ph]].
[30] J. Fan, D. Krohn, P. Mosteiro, A. M. Thalapillil and L. T. Wang, JHEP 1103, 077 (2011) [arXiv:1102.0302 [hep-ph]].
[31] C. Borschensky, M. Krämer, A. Kulesza, M. Mangano, S. Padhi, T. Plehn and X. Portell, Eur. Phys. J. C 74 (2014) 12, 3174 [arXiv:1407.5066 [hep-ph]].