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Wh plus missing-E-T signature from gaugino pair production at the LHC

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In SUSY models with heavy squarks and gaugino mass unification, the gaugino pair production reaction 
\[ pp \rightarrow W^+ Z_0 \] dominates gluino pair production for \( m_{\tilde{g}} \gtrsim 1 \text{ TeV} \) at LHC with \( \sqrt{s} = 14 \text{ TeV} \) (LHC14). For this mass range, the two-body decays \( W_1 \rightarrow WZ_1 \) and \( Z_2 \rightarrow hZ_1 \) are expected to dominate the chargino and neutralino branching fractions. By searching for \( \ell\ell + E_T \) events from \( W^+ Z_0 \) production, we show that LHC14 with 100 fb\(^{-1}\) of integrated luminosity becomes sensitive to chargino masses in the range \( m_{\tilde{\chi}} \sim 450-550 \text{ GeV} \) corresponding to \( m_{\tilde{g}} \sim 1.5-2 \text{ TeV} \) in models with gaugino mass unification. For 100 fb\(^{-1}\), LHC14 is sensitive to the \( W^+ h \) channel for \( m_{\tilde{\chi}} \sim 300-800 \text{ GeV} \), corresponding to \( m_{\tilde{g}} \sim 1-2.8 \text{ TeV} \), which is comparable to the reach for gluino pair production followed by cascade decays. The \( W^+ + E_T \) search channel opens up a new complementary avenue for SUSY searches at LHC, and serves to point to SUSY as the origin of any new physics discovered via multijet and multilepton + \( E_T \) channels.

To estimate the SUSY reach of any collider, first the SUSY particle masses and mixings must be calculated for a given model. Then, the various sparticle pair production reactions must be generated according to their relative probabilities (cross sections), and unstable particles allowed to decay using the calculated decay widths and branching fractions. Incorporation of initial and final state QCD radiation, hadronization of partons, further decays of unstable particles and a modeling of the underlying collider event will then allow for a hopefully realistic determination of what sparticle pair production events look like at the LHC.

The reach of LHC14 for 10 fb\(^{-1}\) was first evaluated in Ref. [5] for events with multijets + \( E_T \), and later in Ref. [7] for events containing various isolated leptons plus jets + \( E_T \) topologies. Updated projections for 100 fb\(^{-1}\) were plotted in Ref. [8], where it was found that the LHC14 reach can extend to \( m_{\tilde{\chi}} \sim 3 \text{ TeV} \) for \( m_{\tilde{\chi}} \sim m_{\tilde{\chi}} \), while the reach is to \( m_{\tilde{\chi}} \sim 1700 \text{ GeV} \) for \( m_{\tilde{\chi}} \gg m_{\tilde{\chi}} \). The LHC7 reach was shown in Ref. [9] for integrated luminosities up to 2 fb\(^{-1}\) and later 30 fb\(^{-1}\), while the reach for LHC14 (and LHC10) was calculated in Ref. [10] for integrated luminosities up to 1000–3000 fb\(^{-1}\).\(^{1}\) In all these studies, work was performed in the \( R \)-parity conserving mSUGRA model with the lightest

\(^{1}\)In Ref. [10], the 100 fb\(^{-1}\) reach of LHC14 was found to extend to \( m_{\tilde{\chi}} \sim 2.1 \text{ TeV} \) for \( m_{\tilde{\chi}} \sim 3 \text{ TeV} \), for \( \tan\beta = 45 \). In this region, squarks have not completely decoupled in the focus point region, so the reach is somewhat higher than expected for the squark decoupling regime (\( m_{\tilde{g}} \gtrsim 5 \text{ TeV} \) at LHC14).
neutralino $\tilde{\chi}_1$ as lightest SUSY particle (LSP). A stable neutralino LSP provides a distinctive $E_T$ signature at LHC, and may be associated with a dark matter WIMP.

In models with gaugino mass unification (i.e. the soft SUSY breaking gaugino masses $M_1, M_2,$ and $M_3$ unify to a common value $m_{1/2}$ at energy scale $Q = M_{\text{GUT}}$), the weak scale gaugino masses are expected to be (aside from 2-loop RG effects) in the ratio $M_1:M_2:M_3 \sim 1:2:7$. Then, in models where the superpotential Higgs mass $\mu \gg M_{1/2}$, one expects a gluino of mass $m_{\tilde{g}} \sim M_3$, a winolike chargino and 2nd lightest neutralino with mass $m_{\tilde{\chi}_1} \sim M_2$ and a binolike lightest neutralino with mass $m_{\tilde{\chi}_1} \sim M_1$. If, in addition, one assumes heavy squarks (as are favored by the decoupling solution to the SUSY flavor and $CP$ problems, the cosmological gravitino problem and proton decay), then for low values of $m_{\tilde{g}} \lesssim 1$ TeV gluino pair production is expected to be the dominant SUSY cross section at LHC. However, as $m_{\tilde{g}}$ increases, one samples parton distribution functions (PDFs) at higher values of fractional momentum $x_F$ and the gluino pair cross section drops sharply. Meanwhile, pair production of the much lighter winolike and binolike states samples PDFs at much lower $x_F$ and will suffer only a mild kinematic suppression. At some point, as $m_{\tilde{g}}$ increases, production of $\tilde{W}^+ \tilde{W}^-$ and $\tilde{W}^+ \tilde{Z}_2$ will become dominant over $\tilde{g} \tilde{g}$ production.

To illustrate, we plot in Fig. 1 the next-to-leading-order (NLO) cross sections for $pp \rightarrow \tilde{g} \tilde{g}$, $\tilde{W}^+ \tilde{W}^-$ and $\tilde{W}^+ \tilde{Z}_2$, versus $m_{\tilde{g}}$, in a SUSY model with gaugino mass unification, but with $m_{\tilde{g}} = m_{\tilde{\chi}_1} = 15$ TeV, $\tan\beta = 10$, and $\mu \approx m_{\tilde{g}}$. The dark curves are for LHC14, while light curves are for LHC7. In this case, we see that at LHC7, $\tilde{W}^+ \tilde{Z}_2$ production (dashed curves) has already become dominant for $m_{\tilde{g}} \gtrsim 500$ GeV, while for LHC14, $\tilde{W}^+ \tilde{Z}_2$ becomes dominant for $m_{\tilde{g}} \gtrsim 1$ TeV. As $m_{\tilde{g}}$ increases, $\tilde{g} \tilde{g}$ production falls quickly, and gluino pair production becomes completely dominant. This suggests that in the case of very heavy squark masses, one may want to sample the dominant cross sections, which turn out to be gaugino pair production rather than gluino pair production.

Now let us restrict our analysis to LHC14, for which integrated luminosities in the 100–1000 fb$^{-1}$ range are expected. Assuming models with gaugino mass unification so that $2M_1 \approx M_2$ and $\mu > M_2$, the two-body decay $\tilde{W}_1 \rightarrow W\tilde{\chi}_1$ with $m_{\tilde{\chi}_1} \sim 1/2 m_{\tilde{W}_1}$ is expected to dominate the $\tilde{W}_1$ branching fraction for $m_{\tilde{W}_1} > 2M_{\tilde{W}_1}$, which corresponds to $m_{\tilde{g}} \gtrsim 560$ GeV. Likewise, the two-body decay $\tilde{Z}_2 \rightarrow Z\tilde{\chi}_1$ turns on for $m_{\tilde{z}} \gtrsim 2m_{\tilde{t}} \sim 230–280$ GeV, corresponding to $m_{\tilde{g}} \gtrsim 800–900$ GeV. The decay $\tilde{Z}_2 \rightarrow \tilde{\chi}_1 Z$ also will occur, but usually with branching fraction $\lesssim 5\%$, compared to $\text{BF}(\tilde{Z}_2 \rightarrow \tilde{\chi}_1 h) \approx 95\%$, for the models under consideration (since $\tilde{Z}_2 \tilde{Z}_2 Z$ coupling only involves small higgsino components of both neutralinos, whereas the $\tilde{Z}_1 \tilde{Z}_2 h$ coupling occurs via the higgsino component of just one of the two neutralinos). Thus, we are led to scrutinize a single production reaction followed by simple two-body decays: $pp \rightarrow \tilde{W}^+_1 \tilde{Z}_2 \rightarrow (W\tilde{\chi}_1) + (h\tilde{\chi}_1)$, as shown in Fig. 2. Because of potentially enormous SM backgrounds to the final state, this event topology has never been studied previously; indeed the decay $\tilde{Z}_2 \rightarrow \tilde{\chi}_1 h$ has been termed the “spoiler mode” in the literature. Here, we evaluate this signal reaction compared to SM backgrounds arising from $t\bar{t}$, $Wb\bar{b}$, $WZ$, $Wh$ and $Zb\bar{b}$ production.

In our calculations, we generate sparticle mass spectra in the mSUGRA/CMSM model using the Isasugra [16] spectrum calculator with $m_0 = 5$ TeV, $A_0 = -1.8m_0$, $\tan\beta = 10$, $\mu > 0$, and with $m_{\tilde{t}} = 173.3$ GeV. We vary $m_{\tilde{t}}, m_{\tilde{g}}$ by varying $m_{1/2}$. We feed the resulting Isasugra file into the HERWIG event generator [17], which maintains...
SUSY particle spin correlations via preprogrammed spin density matrices [18]. We normalize the signal cross section to the Prospino NLO result. We also generate WH, WZ and t\bar{t} backgrounds using Herwig, and Wbb, Zbb as well as the single top\(^3\) backgrounds using an AlpGEN [20]/Herwig interface. For t\bar{t} production, we use a k-factor of 2 with no k-factors for the other backgrounds. For each signal and background process, we generate a statistical sample corresponding to 100 fb\(^{-1}\) of data at LHC14.

We implement the AcerDET fast detector simulation program [21], using default ATLAS detector parameters including a cone-type jet finding algorithm with \(\Delta R(\text{jet}) = 0.4\) and \(E_T(\text{jet}) > 10\) GeV. A jet is tagged as a \(b\)-jet if it contains a \(b\)-quark with \(|\eta_b| < 2.5\), \(p_T(b) > 5\) GeV and the \(b\) is located within \(\Delta R < 0.2\) around the reconstructed jet axis. We also impose a \(b\)-jet reconstruction efficiency of 60\%, plus a \(b\)-jet mistag probability on QCD jets as in Ref. [22]. We then require the following preselection cuts (cuts I):

(i) exactly one isolated lepton \(\ell\) (\(\ell = e\) or \(\mu\)) with \(p_T(\ell) > 10\) GeV and \(|\eta(\ell)| < 2.5\).

(ii) two \(b\)-jets with \(p_T(b_{\text{jet}}) > 50\) GeV and \(|\eta(b_{\text{jet}})| < 2\) (events with \(\geq 3\) \(b\)-jets are rejected), and

(iii) number of non-\(b\)-jets with \(p_T(j) > 50\) GeV equals zero \((n(j) = 0)\).

Next, we examine a variety of distributions for a \(m_{\tilde{W}_1} = 620\) GeV signal (corresponding to \(m_{1/2} = 700\) GeV with \(m_\chi = 1800\) GeV) and backgrounds, including \(E_T, M_{\text{eff}} = \sum_{j}\eta, E_T, \Delta \phi(b\bar{b})\) and the transverse mass \(m_T(\ell, E_T)\). In this case, the light Higgs mass is found to be \(m_h \approx 125\) GeV. The SUSY signal is expected to have a much harder \(E_T\) and \(M_{\text{eff}}\) distribution than background, due to the large masses of the \(W\) and \(Z\) particles, and the presence of two \(Z\) in the final state. In addition, since the \(Z\) is produced typically with \(p_T(Z) \sim m_Z\), it is expected that the \(b\) from \(Z\) decay will be at high \(p_T\), and give rise to more nearly collimated \(b\)-jet cluster than background. Also, the \(m_T\) cut is expected to be very effective at cutting the bulk of the background processes, since we generally expect a Jacobian peak structure with \(m_T \leq m_W\) in the background, while the signal yields a continuum. We find we can gain a large background rejection while retaining much of the signal by requiring (cuts II):

(i) \(E_T > 220\) GeV,

(ii) \(M_{\text{eff}} > 350\) GeV,

(iii) \(\Delta \phi(b, \bar{b}) < \pi/2\) and

(iv) \(m_T(\ell, E_T) > 125\) GeV.

\(^3\)Since our signal requires two high \(E_T\) \(b\) jets we have focussed on single top production from the \(gq' \rightarrow tb\) (or \(t\bar{b}\)) process with \(s\)-channel \(W\) exchange, and neglected contributions from \(gq \rightarrow tbq'\) and the \(gb \rightarrow tW\) processes [19].

\(^4\)Since the stabilization of the electroweak scale prefers sub-TeV scale third generation squarks, \(bb\ell + E_T\) events could potentially also arise from top squark pair production although in this case the \(m_{bb}\) distribution would not peak at \(m_h\).
TABLE I. Number of events expected in 100 fb$^{-1}$ of data at LHC14 from SUSY signal with $m_{\tilde{W}} = 620$ GeV and from various background processes, after cuts I, II, and III.

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FIG. 4 (color online). Significance of signal in 100 fb$^{-1}$ and 1000 fb$^{-1}$ of LHC14 data versus $m_{\tilde{W}}$, for various $m(b\bar{b})$ bin sizes. The dashed gray horizontal line shows the $S/\sqrt{B} = 5$ significance level. We have checked that whenever the statistical significance exceeds 5σ the signal level exceeds 5 events. We take $m_0 = 5$ TeV and $\Lambda_0 = -1.8m_0$.

The $\tilde{W}_1^-\tilde{Z}_2$ production reaction. Other SUSY production processes would only add to these signal rates. We see that with 100 fb$^{-1}$ of data at LHC14, a 5σ signal emerges only for $m_{\tilde{W}} \sim 450–550$ GeV. However, the 1000 fb$^{-1}$ LHC14 reach extends across the entire mass range $m_{\tilde{W}} \sim 300–800$ GeV. These results require only that weak scale gaugino masses satisfy $M_1 \sim M_2/2$ and $\mu > M_2$, since we only consider $\tilde{W}_1^-\tilde{Z}_2$ production. If we assume the full gaugino mass unification with $M_3 \sim 3.5M_2$, then the 100 fb$^{-1}$ range of chargino masses that is accessible at better than the 5σ level in Fig. 4 corresponds to $m_\tilde{g} \sim 1.5–1.9$ TeV, while the 1000 fb$^{-1}$ range corresponds to $m_\tilde{g} \sim 1–2.8$ TeV (the range of $m_\tilde{g}$ depends on variations within the SUSY model parameter space). These values turn out to be comparable to values found in Ref. [8]. The maximal SUSY reach determined in Ref. [8,10] were found using very hard cuts, with very low backgrounds originating from QCD processes yielding very high jet multiplicity, for which theoretical uncertainties are quite large. In contrast, the reach derived from $\tilde{W}_1^-\tilde{Z}_2 \rightarrow Wh + \not{E}_T$ is determined using well-known QCD and electroweak background processes with lower jet multiplicities for which theoretical uncertainties should be much smaller. In addition, since our signal involves just a single $2 \rightarrow 2$ production process followed by simple 2-body decays, the process may allow for a $\tilde{Z}_2$ mass extraction for instance from the $p_T(h)$ distribution if a sizable event sample can be obtained.

Summary:

For LHC running at $\sqrt{s} = 14$ TeV, the dominant SUSY reaction for $m_\tilde{g} \geq 1$ TeV is $pp \rightarrow \tilde{W}_1^-\tilde{Z}_2 \rightarrow Wh\tilde{Z}_1\tilde{Z}_1$ in models with decoupled (heavy) scalars, gaugino mass unification and $|\mu| > M_1, M_2$. This reaction leads to a distinctive $\ell b\bar{b} + \not{E}_T$ final state which can be detected above background levels for chargino masses of 450–550 GeV, corresponding to $m_\tilde{g} \sim 1.5–1.9$ TeV, in models with gaugino mass unification, for an integrated luminosity of 100 fb$^{-1}$. For a 1000 fb$^{-1}$ data sample, LHC14 should probe chargino masses in the 300–800 GeV range corresponding to $m_\tilde{g} \sim 1–2.8$ TeV. This novel signal for supersymmetry from chargino-neutralino pair production not only serves to point toward SUSY as the origin of any new physics that may be discovered in the canonical multijet plus multilepton plus $\not{E}_T$ channel, but potentially also increases the projected SUSY reach of LHC in models where gluinos and first generation squarks are very heavy. The simplicity of production and decay modes begs for a $\tilde{Z}_2$ mass extraction if a sufficiently large data sample can be realized.

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The precise numerical ranges should be interpreted with care since neither statistical fluctuations nor some of the background K-factors have been included in this analysis and these could somewhat alter the background expectations. (For example, Ref. [23] quotes a K-factor of 1.4 for $Wbb$ production at LHC with $\sqrt{s} = 14$ TeV in the exclusive production process with two high $p_T$ $b$-jets and at scale $Q = M_w + 2m_b$. We would still expect our $Wbb$ background in Table I to be at the 1-2 event level.) Our qualitative expectation is that, for the mass ranges quoted here, there could be hints of a signal in this new channel with about 100 fb$^{-1}$ or a bit more, and a robust signal with a data sample of 1000 fb$^{-1}$. 