SIBi
SISTEMA INTEGRADO DE BIBLIOTECAS
UNIVERSIDADE DE SÃO PAULO

Universidade de São Paulo

Biblioteca Digital da Produção Intelectual - BDPI

Outros departamentos - IF/Outros

Artigos e Materiais de Revistas Científicas - IF/Outros

2012

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

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

Howard Baer,[1] Vernon Barger,[2] Andre Lessa,[3] Warintorn Sreethawong,[1] and Xerxes Tata[4]

[1]*Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, 73019, USA*
[2]*Department of Physics, University of Wisconsin, Madison, Wisconsin 53706, USA*
[3]*Instituto de Física, Universidade de São Paulo, São Paulo - SP, Brazil*
[4]*Department of Physics and Astronomy, University of Hawaii, Honolulu, Hawaii 96822, USA*

In SUSY models with heavy squarks and gaugino mass unification, the gaugino pair production reaction $pp \rightarrow \tilde{W}_1^\pm \tilde{Z}_2$ dominates gluino pair production for $m_{\tilde{g}} \gtrsim 1$ TeV at LHC with $\sqrt{s} = 14$ TeV (LHC14). For this mass range, the two-body decays $\tilde{W}_1 \rightarrow W \tilde{Z}_1$ and $\tilde{Z}_2 \rightarrow h \tilde{Z}_1$ are expected to dominate the chargino and neutralino branching fractions. By searching for $\ell b \tilde{b} + \not{E}_T$ events from $\tilde{W}_1^\pm \tilde{Z}_2$ production, we show that LHC14 with 100 fb^{-1} of integrated luminosity becomes sensitive to chargino masses in the range $m_{\tilde{W}_1} \sim$ 450–550 GeV corresponding to $m_{\tilde{g}} \sim 1.5$–2 TeV in models with gaugino mass unification. For 10^3 fb^{-1}, LHC14 is sensitive to the *Wh* channel for $m_{\tilde{W}_1} \sim 300$–800 GeV, corresponding to $m_{\tilde{g}} \sim 1$–2.8 TeV, which is comparable to the reach for gluino pair production followed by cascade decays. The $Wh + \not{E}_T$ 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 $+ \not{E}_T$ channels.

One of the major goals of the CERN LHC is to discover or rule out as best as possible particle physics theories based on weak scale supersymmetry [1] (SUSY). Recent SUSY searches by ATLAS [2] and CMS [3] using pp collisions at $\sqrt{s} = 7$ TeV (LHC7) have been performed in the context of the minimal supergravity (mSUGRA or CMSSM) model [4]. In this model, all scalar particles receive a common mass m_0 and all gauginos acquire a common mass $m_{1/2}$ at the grand-unified scale $M_{\rm GUT} \sim 2 \times 10^{16}$ GeV. Assuming the MSSM as the low energy effective theory, the various soft SUSY breaking parameters are then evolved via renormalization group equations to the weak scale, whereupon the various sparticle masses and mixings can be calculated.

Based on nonobservation of signal events at rates expected beyond standard model backgrounds in ~ 1 fb^{-1} of data, ATLAS and CMS have been able to plot excluded regions in the $m_0 vs. m_{1/2}$ plane of the mSUGRA model. These exclusion limits correspond to $m_{\tilde{g}} \gtrsim 1$ TeV in the case where $m_{\tilde{g}} \sim m_{\tilde{q}}$, and $m_{\tilde{g}} \gtrsim 600$ GeV in the case where $m_{\tilde{q}} \gg m_{\tilde{g}}$ (the case with $m_{\tilde{q}} \ll m_{\tilde{g}}$ does not occur in the mSUGRA model).

At the present time, ATLAS and CMS have each accumulated more than 5 fb^{-1} of data, and analyses of this data set are anxiously awaited by the particle physics community. Further running in 2012 is expected to net 10–30 fb^{-1} of integrated luminosity at $\sqrt{s} = 7$ TeV. It is expected that LHC will be shut down during the years 2013–2014 for upgrading, and running will resume in 2015 at a center-of-mass energy close to the LHC design value, $\sqrt{s} \sim 14$ TeV (LHC14).

In evaluating the reach of LHC for SUSY particles, searches tend to focus on gluino pair production ($\tilde{g}\tilde{g}$), squark pair production ($\tilde{q}\tilde{q}$) and gluino-squark production ($\tilde{g}\tilde{q}$), since strongly interacting sparticles are expected to be produced at the larger rates than chargino/neutralino or

slepton pair production [5]. Since the gluinos and squarks are typically amongst the most massive members of the entire SUSY particle spectrum, they are expected to *cascade decay* [6] via lengthy chains into final states containing numerous jets, isolated leptons and missing transverse energy $\not{E}_T$.

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 sparticles 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 $+\not{E}_T$, and later in Ref. [7] for events containing various isolated leptons plus jets $+\not{E}_T$ topologies. Updated projections for 100 fb^{-1} were plotted in Ref. [8], where it was found that the LHC14 reach can extend to $m_{\tilde{g}} \sim 3$ TeV for $m_{\tilde{q}} \sim m_{\tilde{g}}$, while the reach is to $m_{\tilde{g}} \sim 1700$ GeV for $m_{\tilde{q}} \gg m_{\tilde{g}}$. 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 $m_{\tilde{g}} \sim 2.1$ TeV for $m_0 \sim 3$ 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 ($m_{\tilde{q}} \gtrsim 5$ TeV at LHC14).

neutralino $\tilde{Z}_1$ as lightest SUSY particle (LSP).[2] 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 $m_{\tilde{W}_1,\tilde{Z}_2} \sim M_2$ and a binolike lightest neutralino with mass $m_{\tilde{Z}_1} \sim M_1$. 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 $\tilde{W}_1^+ \tilde{W}_1^-$ and $\tilde{W}_1^\pm \tilde{Z}_2$ will become dominant over $\tilde{g}\tilde{g}$ production.

To illustrate, we plot in Fig. 1 the next-to-leading-order in QCD (NLO) cross sections in *pb* (from Prospino [15]) for $pp \to \tilde{g}\tilde{g}$, $\tilde{W}_1^+ \tilde{W}_1^-$ and $\tilde{W}_1^\pm \tilde{Z}_2$, versus $m_{\tilde{g}}$, in a SUSY model with gaugino mass unification, but with $m_{\tilde{q}} = m_{\tilde{\ell}} = 15$ TeV, $\tan\beta = 10$, and $\mu \simeq m_{\tilde{g}}$. The dark curves are for LHC14, while light curves are for LHC7. In this case, we see that at LHC7, $\tilde{W}_1^\pm \tilde{Z}_2$ production (dashed curves) has already become dominant for $m_{\tilde{g}} \gtrsim 500$ GeV, while for LHC14, $\tilde{W}_1^\pm \tilde{Z}_2$ becomes dominant for $m_{\tilde{g}} \gtrsim 1$ TeV. As $m_{\tilde{g}}$ increases, $\tilde{g}\tilde{g}$ production falls quickly, and gaugino 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 $2M_1 \simeq M_2$ and $\mu > M_2$, the two-body decay $\tilde{W}_1 \to W\tilde{Z}_1$ with $m_{\tilde{Z}_1} \sim \frac{1}{2} m_{\tilde{W}_1}$ is expected to dominate the $\tilde{W}_1$ branching fraction for $m_{\tilde{W}_1} > 2M_W$, which corresponds to $m_{\tilde{g}} \gtrsim 560$ GeV. Likewise, the two-body decay $\tilde{Z}_2 \to \tilde{Z}_1 h$ turns on for $m_{\tilde{Z}_2} \gtrsim 2m_h \sim 230$–280 GeV, corresponding to $m_{\tilde{g}} \gtrsim 800$–900 GeV. The decay $\tilde{Z}_2 \to \tilde{Z}_1 Z$ also will occur, but usually with branching fraction $\sim 5\%$, compared

FIG. 1 (color online). Total NLO cross sections for $\tilde{g}\tilde{g}$, $\tilde{W}_1^\pm \tilde{Z}_2$ and $\tilde{W}_1^+ \tilde{W}_1^-$ production at LHC7 (light) and LHC14 (dark), versus $m_{\tilde{g}}$, with $m_{\tilde{q}} = 15$ TeV.

to BF$(\tilde{Z}_2 \to \tilde{Z}_1 h) \sim 95\%$, for the models under consideration (since $\tilde{Z}_1 \tilde{Z}_2 Z$ 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: $pp \to \tilde{W}_1^\pm \tilde{Z}_2 \to (W\tilde{Z}_1) + (h\tilde{Z}_1) \to (\ell\nu_\ell \tilde{Z}_1) + (b\bar{b} + \tilde{Z}_1)$, 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 $\tilde{Z}_2 \to \tilde{Z}_1 h$ 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/CMSSM model using the Isasugra [16] spectrum calculator with $m_0 = 5$ TeV, $A_0 = -1.8m_0$, $\tan\beta = 10$, $\mu > 0$, and with $m_t = 173.3$ GeV. We vary $m_{\tilde{W}_1,\tilde{Z}_2}$ by varying $m_{1/2}$. We feed the resulting IsaWIG file into the HERWIG event generator [17], which maintains

FIG. 2. Feynman diagram for $q'\bar{q} \to \tilde{W}_1^\pm \tilde{Z}_2 \to (W^\pm \tilde{Z}_1) + (h\tilde{Z}_1)$.

---

[2]For LHC reach in GMSB, see Ref. [11]; for reach in AMSB, see Ref. [12] and for reach in inoMSB, see Ref. [13]; for reach in mSUGRA with hadronic RPV neutralino decays, see [14].
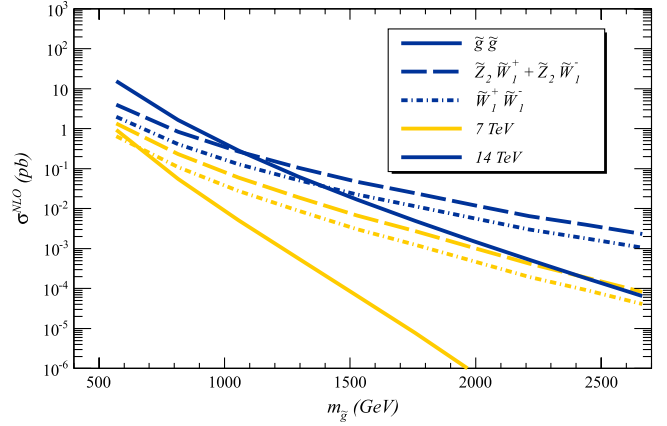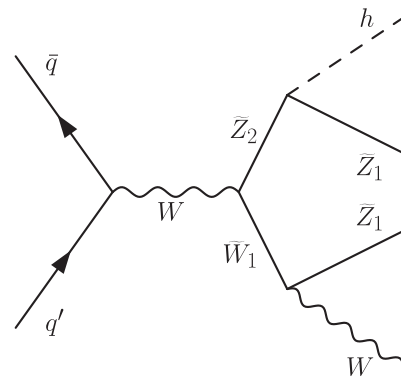
SUSY particle spin correlations via preprogrammed spin density matrices [18]. We normalize the signal cross section to the Prospino NLO result. We also generate Wh, WZ and $t\bar{t}$ backgrounds using Herwig, and $Wb\bar{b}$, $Zb\bar{b}$ as well as the single top[3] backgrounds using an AlpGEN [20]/Herwig 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 ℓ ($\ell = e$ or μ) 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 ≥ 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 $m_{\tilde{g}} = 1800$ GeV) and backgrounds, including E_T, $M_{\text{eff}} = \sum_{\text{jets}} E_T(\text{jets}) + \not{E}_T$, $\Delta\phi(b\bar{b})$ and the transverse mass $m_T(\ell, \not{E}_T)$. In this case, the light Higgs mass is found to be $m_h \simeq 125$ GeV. The SUSY signal is expected to have a much harder $\not{E}_T$ and M_{eff} distribution than background, due to the large masses of the $\tilde{W}_1$ and $\tilde{Z}_2$ particles, and the presence of two $\tilde{Z}_1$ in the final state. In addition, since the $\tilde{Z}_2$ is produced typically with $p_T(\tilde{Z}_2) \sim m_{\tilde{Z}_2}$, it is expected that the h from $\tilde{Z}_2$ decay will be at high p_T, and give rise to more nearly collimated di-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 $m_T \lesssim M_W$ 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) $\not{E}_T > 220$ GeV,
  (ii) $M_{\text{eff}} > 350$ GeV,
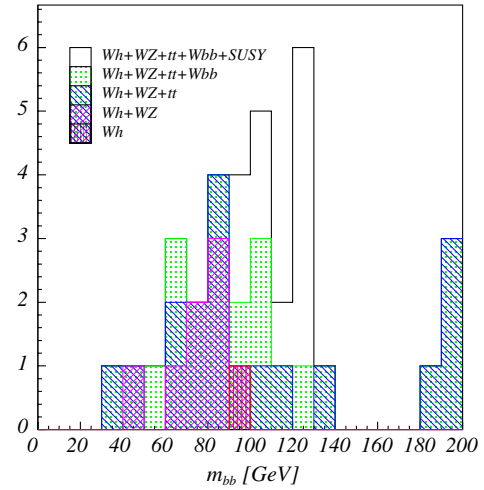 (iii) $\Delta\phi(b, \bar{b}) < \pi/2$ and
  (iv) $m_T(\ell, \not{E}_T) > 125$ GeV.

FIG. 3 (color online). Number of events expected in 100 fb^{-1} of LHC14 data versus $m(b\bar{b})$ for various summed SM backgrounds (shaded) and SUSY signal, with $m_{\tilde{W}_1} = 620$ GeV and $m_h = 125$ GeV.

In Fig. 3, we plot the di-b-jet invariant mass distribution after the above set of cuts I and II. The various shaded histograms show the Wh, $Wh + WZ$, $Wh + WZ + t\bar{t}$, and $Wh + WZ + t\bar{t} + Wb\bar{b}$ backgrounds (single top and $Zb\bar{b}$ events are eliminated after cut II). The unshaded histogram shows the sum of all backgrounds plus the SUSY signal for $m_{\tilde{W}_1} = 620$ GeV. From the plot, one can see the $h \to b\bar{b}$ peak standing out beyond background, indicating a clear signal from $\tilde{W}_1^{\pm} \tilde{Z}_2 \to Wh\tilde{Z}_1\tilde{Z}_1$ production.[4] Both the h and Z peaks are located somewhat below their naively expected positions due to jet energy loss via radiation outside the $\Delta R = 0.4$ cone, due to neutrino emission in the b-decays and due to calorimeter mismeasurements.

To calculate a reach for LHC14 with 100 fb^{-1}, we implement an invariant mass cut (*cut III*):

  (i) 110 GeV $< m(b\bar{b}) < 130$ GeV,

to gain a final signal sample along with background. A tabulation of signal and BG rates after cuts I, II and III is shown in Table I. We note here that the WZ, Wh, and $t\bar{t}$ backgrounds should be very well-known due to their independent studies, and are potentially subtractable.

The statistical significance of the signal, evaluated using Poisson statistics, for 100 fb^{-1} (solid) and 1000 fb^{-1} (dashes) of LHC14 data with several different $m(b\bar{b})$ bin sizes is shown in Fig. 4. Here, our signal only comes from

---

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

[4]Since the stabilization of the electroweak scale prefers sub-TeV scale third generation squarks, $bb\ell + \not{E}_T$ 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 $m_{\tilde{W}_1} = 620$ GeV and from various background processes, after cuts I, II, and III.

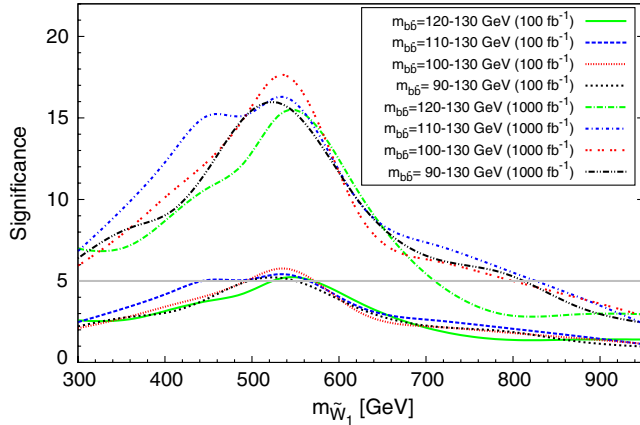| cuts	# of events in 100 fb^{-1}						
	SUSY	$t\bar{t}$	$Wb\bar{b}$	WZ	Wh	Zbb	total BGs
cuts I	30	612 001	12 130	709	664	669	626 173
cuts II	10	12	7	7	1	0	27
cuts III	6	1	1	0	0	0	2

FIG. 4 (color online). Significance of signal in 100 fb^{-1} and 1000 fb^{-1} of LHC14 data versus $m_{\tilde{W}_1}$ 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 $A_0 = -1.8m_0$.

the $\tilde{W}_1^{\pm}\tilde{Z}_2$ 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 $m_{\tilde{W}_1} \sim 450$–550 GeV. However, the 1000 fb^{-1} LHC14 reach extends across the entire mass range $m_{\tilde{W}_1} \sim$ 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 $\tilde{W}_1^{\pm}\tilde{Z}_2$ 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).[5] 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 $\tilde{W}_1^{\pm}\tilde{Z}_2 \to Wh + \not{E}_T$ 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 $2 \to 2$ 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 $m_{\tilde{g}} \gtrsim 1$ TeV is $pp \to \tilde{W}_1^{\pm}\tilde{Z}_2 \to Wh\tilde{Z}_1\tilde{Z}_1$ 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 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.

[5]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 $Wb\bar{b}$ 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 $Wb\bar{b}$ 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}.

[1] For reviews of SUSY, see H. Baer and X. Tata, *Weak Scale Supersymmetry: From Superfields to Scattering Events* (Cambridge University Press, Cambridge, England, 2006).

[2] See e.g. G. Aad *et al.* (ATLAS Collaboration), J. High Energy Phys. 11 (2011) 099; arXiv:1109.6572.

[3] See e.g. S. Chatrchyan *et al.* (CMS Collaboration), Phys. Rev. Lett. **107**, 221804 (2011).

[4] For a review, see e.g. P. Nath, arXiv:hep-ph/0307123.

[5] H. Baer, C. H. Chen, F. Paige, and X. Tata, Phys. Rev. D **52**, 2746 (1995).

[6] H. Baer, V. Barger, D. Karatas, and X. Tata, Phys. Rev. D **36**, 96 (1987); H. Baer, R. M. Barnett, M. Drees, J. F. Gunion, H. E. Haber, D. L. Karatas, and X. R. Tata, Int. J. Mod. Phys. A **2**, 1131 (1987); H. Baer, A. Bartl, D. Karatas, W. Majerotto, and X. Tata, Int. J. Mod. Phys. A **4**, 4111 (1989); H. Baer, X. Tata and J. Woodside, Phys. Rev. D **42**, 1568 (1990); for earlier work on sparticle decays to just gauginos, see H. Baer, J. Ellis, G. Gelmini, D. V. Nanopoulos, and X. Tata, Phys. Lett. B **161**, 175 (1985); G. Gamberini, Z. Phys. C **30**, 605 (1986); H. Baer and E. Berger, Phys. Rev. D **34**, 1361 (1986).

[7] H. Baer, C. H. Chen, F. Paige, and X. Tata, Phys. Rev. D **53**, 6241 (1996); H. Baer, C. H. Chen, M. Drees, F. Paige, and X. Tata, Phys. Rev. D **59**, 055014 (1999); B. Allanach, J. Hetherington, A. Parker, and B. Webber, J. High Energy Phys. 08 (2000) 017.

[8] H. Baer, C. Balázs, A. Belyaev, T. Krupovnickas, and X. Tata, J. High Energy Phys. 06 (2003) 054; S. Abdullin and F. Charles, Nucl. Phys. **B547**, 60 (1999); S. Abdullin *et al.* (CMS Collaboration), J. Phys. G **28**, 469 (2002).

[9] H. Baer, V. Barger, A. Lessa, and X. Tata, J. High Energy Phys. 06 (2010) 102.

[10] H. Baer, V. Barger, A. Lessa, and X. Tata, J. High Energy Phys. 09 (2009) 063.

[11] H. Baer, P. Mercadante, F. Paige, X. Tata, and Y. Wang, Phys. Lett. B **435**, 109 (1998); H. Baer, P. Mercadante, X. Tata, and Y. Wang, Phys. Rev. D **62**, 095007 (2000), .

[12] H. Baer, J. K. Mizukoshi, and X. Tata, Phys. Lett. B **488**, 367 (2000); A. J. Barr, C. G. Lester, A. Parker, B. Allanach, and P. Richardson, J. High Energy Phys. 03 (2003) 045.

[13] H. Baer, A. Belyaev, T. Krupovnickas, and X. Tata, Phys. Rev. D **65**, 075024 (2002).

[14] H. Baer, C. H. Chen, and X. Tata, Phys. Rev. D **55**, 1466 (1997).

[15] W. Beenakker, R. Hopker, and M. Spira, arXiv:hep-ph/9611232.

[16] H. Baer, C. H. Chen, R. Munroe, F. Paige, and X. Tata, Phys. Rev. D **51**, 1046 (1995); F. Paige, S. Protopopescu, H. Baer, and X. Tata, arXiv:hep-ph/0312045.

[17] G. Corcella *et al.* (HERWIG collaboration), J. High Energy Phys. 01 (2001) 010.

[18] P. Richardson, J. High Energy Phys. 11 (2001) 029.

[19] T. Stelzer, Z. Sullivan, and S. Willenbrock, Phys. Rev. D **56**, 5919 (1997); **58**, 094021 (1998)see also V. Barger, M. McCaskey, and G. Shaughnessy, Phys. Rev. D **81**, 034020 (2010).

[20] M. Mangano, M. Moretti, F. Piccinini, R. Pittau, and A. Polosa, J. High Energy Phys. 07 (2003) 001.

[21] E. Richter-Was, arXiv:hep-ph/0207355.

[22] R. Kadala, P. Mercadante, J. K. Mizukoshi, and X. Tata, Eur. Phys. J. C **56**, 511 (2008).

[23] F. Febres Cordero, L. Reina, and D. Wackeroth, Phys. Rev. D **80**, 034015 (2009).