PHYSICAL REVIEW D **90,** 055011 (2014)

Testing SUSY models for the muon $g-2$ anomaly via chargino-neutralino pair production at the LHC

Siba Prasad Das,[1] Monoranjan Guchait,[2] and D. P. Roy[3]

[1]*Institute of Physics, Sachivalaya Marg, Bhubaneswar 751 005, Orissa, India*
[2]*Department of High Energy Physics, Tata Institute of Fundamental Research,*
1, Homi Bhabha Road, Mumbai 400 005, India
[3]*Homi Bhabha's Centre for Science Education, Tata Institute of Fundamental Research,*
V. N. Purav Marg, Mumbai 400088, India

(Received 22 July 2014; published 10 September 2014)

Nonuniversal gaugino mass models can naturally account for the dark matter relic density via the bulk annihilation process with relatively light bino LSP and right sleptons in the mass range of ~100 GeV, while accommodating the observed Higgs boson mass of ~125 GeV with TeV scale squark/gluino masses. A class of these models can also account for the observed muon g-2 anomaly via SUSY loops with wino and left sleptons in the mass range of 400–700 GeV. These models can be tested at LHC via electroweak production of charged and neutral wino pair, leading to robust trilepton and same sign dilepton signals. We investigate these signals along with the standard model background for both 8 and 13 TeV LHC runs.

DOI: 10.1103/PhysRevD.90.055011 PACS numbers: 12.60.Jv, 12.60.-i, 14.80.Ly, 95.35.+d

I. INTRODUCTION

A large part of the supersymmetry (SUSY) phenomenology over the past years has been based on the minimal supergravity or the so-called constrained minimal supersymmetric standard model (CMSSM), which assumes universal gaugino and scalar masses $m_{1/2}$ and m_0 at the grand unified theory (GUT) scale [1–3]. In this case the lightest superparticle (LSP), i.e., the dark matter, is dominantly a bino over most of the model parameter space. Since the bino does not carry any gauge charge, its main annihilation process is via sfermion exchange into a pair of fermions. And the cosmologically compatible dark matter relic density requires rather small bino and sfermion masses ~100 GeV. This is the so-called bulk annihilation region. Unfortunately, the LEP limit on the light Higgs boson mass, $m_h > 114$ GeV practically rules out the bulk annihilation region of the CMSSM as it requires TeV scale squark/gluino masses [4]. This is further reinforced now with the reported discovery of Higgs boson at LHC by the ATLAS and CMS experiments [5,6] at

$$m_h \simeq 125\ \text{GeV}. \tag{1}$$

It was shown in [7] that the natural explanation of the cosmologically compatible dark matter relic density in the bulk annihilation region can be reconciled with the Higgs boson mass limit from LEP in a class of simple and well motivated MSSM with nonuniversal gaugino masses (NUGM) based on SU(5) GUT [8,9]. In these models one can have relatively small bino and right slepton masses in the range of ~100 GeV to account for the former along with TeV scale squark/gluino masses to account for the latter. Moreover, these models can raise the Higgs boson mass to the observed range of ~125 GeV with the help of a TeV scale trilinear coupling term A_0 [10]. More recently it was shown in [11] that some of these models have relatively modest wino and left slepton masses in the range of 400–700 GeV, so that they can also account for the reported muon g-2 anomaly [12,13] via wino-left slepton loops [14–18].

In this work we investigate the prospect of probing the above mentioned mass range of 400–700 GeV for wino and left sleptons in these models at the 8 TeV and the forthcoming 13 TeV runs of the LHC. Section II gives a brief description of the nonuniversal gaugino mass models based on SU(5) GUT. Section III discusses the weak scale SUSY spectra and muon g-2 prediction for two such models, where the wino and left slepton lie in the mass range of 400–700 GeV. In particular we shall list them for a few benchmark points of these models for computing the LHC signal. Section IV describes the electroweak production of charged and neutral wino pair, leading to distinctive trilepton and same sign dilepton signals at the LHC. It also discusses the selection cuts used in this analysis to extract these signals from the main standard model background. Section V discusses the results of our analysis of these two channels for both the 8 TeV and the forthcoming 13 TeV runs of LHC. We conclude with a summary in Sec. VI.

II. NONUNIVERSAL GAUGINO MASS MODEL IN SU(5) GUT

The gauge kinetic function responsible for the gaugino masses in the GUT scale Lagrangian originates from the vacuum expectation values of the F-term of a chiral superfield Ω responsible for SUSY breaking,

$$\frac{\langle \mathrm{F}_\Omega \rangle}{\mathrm{M}_{\mathrm{planck}}} \lambda_\mathrm{i} \lambda_\mathrm{j}, \tag{2}$$

where $\lambda_{1,2,3}$ are the U(1), SU(2), and SU(3) gaugino fields—bino, wino, and gluino respectively. Since gauginos belong to the adjoint representation of the GUT group, Ω and F_Ω can belong to any of the irreducible representations occurring in their symmetric product, i.e.,

$$(24 \times 24)_{\mathrm{sym}} = 1 + 24 + 75 + 200 \tag{3}$$

for the simplest GUT group SU(5). Thus for a given representation of the SUSY breaking superfield, the GUT scale gaugino masses are given in terms of one mass parameter as [8,9]

$$\mathrm{M}^{\mathrm{G}}_{1,2,3} = \mathrm{C}^{\mathrm{n}}_{1,2,3} \mathrm{m}^{\mathrm{n}}_{1/2}, \tag{4}$$

where

$$C^1_{1,2,3} = (1, 1, 1), \qquad C^{24}_{1,2,3} = (-1, -3, 2),$$
$$C^{75}_{1,2,3} = (-5, 3, 1), \qquad C^{200}_{1,2,3} = (10, 2, 1). \tag{5}$$

The CMSSM assumes Ω to be a singlet, leading to universal gaugino masses at the GUT scale. On the other hand, any of the nonsinglet representations of Ω would imply non-universal gaugino masses at the GUT scale via Eqs. (4) and (5). These nonuniversal gaugino masses are known to be consistent with the universality of gauge couplings at the GUT scale [8,9,19] with $\alpha_G \simeq \frac{1}{25}$. The phenomenology of nonuniversal gauginos arising from each of these nonsinglet Ω have been widely studied [20–22].

It was assumed in [7] that SUSY is broken by a combination of a singlet and a non-singlet superfields belonging to the $1 + 24$, $1 + 75$ or $1 + 200$ representations of SU(5). Then the GUT scale gaugino masses are given in terms of two mass parameters,

$$\mathrm{M}^{\mathrm{G}}_{1,2,3} = \mathrm{C}^1_{1,2,3} \mathrm{m}^1_{1/2} + \mathrm{C}^{\ell}_{1,2,3} \mathrm{m}^{\ell}_{1/2}, \quad \ell = 24, 75, 200. \tag{6}$$

which are determined by the two independent VEVs of the F terms of the singlet and the nonsinglet superfields. The corresponding weak scale superparticle and Higgs boson masses are fixed in terms of these two gaugino mass parameters and the universal scalar mass parameter m_0 along with the trilinear coupling A_0 via the RGE. In these models one could access the bulk annihilation region of dark matter relic density, while keeping the Higgs boson mass above the LEP limit of 114 GeV [7] and raise it further to the LHC value of ∼125 GeV with the help of a TeV scale A_0 parameter [10]. To understand this result, one can equivalently consider the two independent gaugino mass parameter of Eq. (6) in any of these three models to be M^G_1 and M^G_3. The corresponding weak scale gaugino masses are given to a good approximation by the one loop RGE,

$$\mathrm{M}_{1,2,3} = \frac{\alpha_{1,2,3}}{\alpha_\mathrm{G}} \mathrm{M}^{\mathrm{G}}_{1,2,3} \simeq \frac{25}{60, 30, 9} \mathrm{M}^{\mathrm{G}}_{1,2,3}. \tag{7}$$

Thus one can choose a relatively small $M^G_1 \sim 200$ GeV along with a small $m_0 \sim 100$ GeV to ensure a small weak scale bino mass $M_1 \sim 80$ GeV along with right slepton masses ∼100 GeV. Then the annihilation of the bino LSP pair via right slepton exchange

$$\chi\chi \xrightarrow{\tilde{\ell}_R} \bar{\ell}\ell \tag{8}$$

gives the desired dark matter relic density. The other mass parameter M^G_3 can then be raised to an appropriate level to give TeV scale squark/gluino masses as required by the Higgs boson mass of ∼125 GeV and the negative squark/gluino search results from LHC.

The issue of naturalness for these nonuniversal gaugino mass models has been discussed in [7,23] via the fine-tuning parameters, Δ^Ω and Δ^{EW}, required for achieving the right dark matter relic density and radiative EW symmetry breaking. It was found that $\Delta^\Omega \sim 1$ over the bulk annihilation region of these models, which means there is no fine-tuning required in achieving the right dark matter relic density. In contrast the allowed dark matter compatible regions of the CMSSM or the nonuniversal scalar mass models had 1–2 orders of magnitude higher values of this fine-tuning measure. Of course, one has to pay the usual fine-tuning price for radiative symmetry breaking, $\Delta^{\mathrm{EW}} \sim 10^2$, in the dark matter compatible regions of all these MSSM. However, a quantitative evaluation of this fine-tuning parameter in [23] showed that the bulk annihilation region of the nonuniversal gaugino mass models had one of the lowest Δ^{EW} of them all. Thus the low value of Δ^Ω is achieved here without any additional cost to the Δ^{EW}.

Note that with given M^G_1 and M^G_3 inputs, each of the above three models makes a definitive prediction for M^G_2. It follows from Eqs. (5) and (6) that the $(1 + 200)$ model predicts the smallest M^G_2 and hence the smallest weak scale wino and left slepton masses among all the three models. Hence it offers the best chance to account for a significant SUSY contribution to the muon g-2 anomaly, as discussed in [11]. As further discussed in [11], one can extend the analysis to a general nonuniversal gaugino mass model with three independent gaugino mass parameters, M^G_1, M^G_2, and M^G_3. This can be realized in a scenario of SUSY breaking by three superfields, belonging to different representations of the GUT group, e.g., a $(1 + 75 + 200)$ model. The three gaugino mass parameters are linearly related to the VEVs of the F terms of these three superfields. In this case one can have very modest wino and left slepton masses ∼400 GeV, so as to give a SUSY contribution to the muon g-2 anomaly very close to its experimental central value. In the next section we shall focus on some benchmark points from these two models, which can account for the muon g-2 anomaly within 2σ level.

III. THE WEAK SCALE SUSY SPECTRA AND MUON g-2 CONTRIBUTIONS IN THE $(1+200)$ MODEL AND THE GENERAL NONUNIVERSAL GAUGINO MASS MODEL

We have used the two-loop RGE code in SuSpect [24] to generate the weak scale SUSY and Higgs spectra. One should note that the $\overline{\text{MS}}$ renormalization scheme used in the SuSpect RGE code is known to predict a lower Higgs boson mass than the on-shell renormalization scheme used in FeynHiggs [25] by 2–3 GeV [26–30]. Therefore a predicted Higgs boson mass $\gtrsim 122$ GeV in the following tables is compatible with the reported mass of ~ 125 GeV [5,6].

The resulting dark matter relic density and the muon anomalous magnetic moment (g-2) were computed using the microOMEGAs code [31–33]. In view of the high precision of the dark matter relic density data [34] we have considered solutions lying within 3σ of its central value as in [11], i.e.,

$$0.102 < \Omega h^2 < 0.123. \tag{9}$$

On the other hand the measured value [12] of the muon anomalous magnetic moment excess has a relatively large uncertainty,

$$\Delta a_\mu = (28.7 \pm 8.0) \times 10^{-10}, \tag{10}$$

where

$$a_\mu = \frac{(g-2)_\mu}{2}. \tag{11}$$

Therefore we have considered SUSY solutions to a_μ [11] lying within 2σ of the central value, i.e.,

$$\delta a_\mu = \Delta a_\mu - a_\mu^{\mathrm{SUSY}} < 2\sigma \tag{12}$$

so that a_μ^{SUSY} is at least of the same order as the central value of the experimental excess of Eq. (10).

Explicit formulas for a_μ^{SUSY}, arising from wino-left slepton and bino-right slepton loops, can be found e.g., in [14,15]. It increases linearly with $\tan\beta$ at constant SUSY masses. However, one has to choose a higher m_0 at larger $\tan\beta$ to maintain the $\tilde{\tau}_1$ mass in the desired range for the dark matter relic density of Eq. (9). The resulting increase in slepton masses compensate the linear rise of a_μ^{SUSY} with $\tan\beta$. This results in a broad peak of a_μ^{SUSY} at $\tan\beta \simeq 15$, which remains nearly constant over the moderate $\tan\beta (= 10–20)$ regions [11]. Therefore we have chosen the following benchmark points at $\tan\beta = 15$.

Table I lists three benchmark points from [11], of which the BP1 and BP2 belong to the $(1+200)$ model and BP3 to the general nonuniversal gaugino mass model. The corresponding weak scale SUSY and Higgs spectra are listed in Table II. We have checked that the rather low $\tilde{\tau}_1$ masses are still above the direct and indirect LEP limits [4]. The M_3^G inputs for the BP1 and BP2 were chosen rather high to ensure that the resulting squark/gluino masses are well above the 8 TeV LHC search limits [35]. This results in a fairly high values of M_2^G, so that the corresponding wino $(\chi_1^\pm, \chi_2^0)$ masses are $\gtrsim 600$ GeV. The resulting δa_μ is in the range of $1.6–1.9\sigma$. For BP3, all the three gaugino mass inputs are independent. Thus we have chosen a large enough M_3^G to correspond to squark/gluino masses even beyond the reach of 13 TeV LHC along with a modest M_2^G to correspond to wino $(\chi_1^\pm, \chi_2^0)$mass ≈ 460 GeV. The

TABLE I. Benchmark points of SUSY parameter space taken from Ref. [11] to simulate signal process(all masses are in GeV and A parameters are in TeV). The corresponding SUSY contributions to muon anomalous magnetic moment are shown along with their differences from the measured central value of Eq. (10).

Parameters	m_0	$\tan\beta$	$A_{t0} = A_{b0}$	M_1^G	M_2^G	M_3^G	a_μ^{SUSY}	δa_μ
BP1	103	15	−2.4	200	734.3	800	1.59×10^{-9}	1.61σ
BP2	103	15	−2.4	200	822.2	900	1.37×10^{-9}	1.89σ
BP3	138	15	−2.4	200	575	1200	2.67×10^{-9}	0.26σ

TABLE II. Masses of SUSY particles(in GeV) calculated using SuSpect v2.41 [24] for the three benchmark points given in Table I.

Point	$\tilde{g}$	$\tilde{q}_L$	$\tilde{q}_R$	$\tilde{t}_{1,2}$	$\tilde{b}_1$	$\tilde{\ell}_{L,R}$	$\tilde{\tau}_{1,2}$	χ_1^0	χ_2^0	χ_1^+	χ_2^+	h
BP1	1764	1600	1540	820,1531	1311	479,133	94,480	80	593	593	1494	124
BP2	1967	1778	1711	1012,1524	1490	531,132	90,532	80	666	666	1584	124
BP3	2578	2252	2235	1596,1994	1967	380,159	96,396	78	461	461	1871	123

resulting $a_\mu^{\rm SUSY}$ is within 0.26σ of the experimental value. However, we shall see below that this benchmark point can be easily tested with the available 8 TeV data.

We note from Table II that the left slepton ($\tilde{l}_L$), representing left selectron and smuon is always ≈20% lighter than the charged and neutral wino ($\chi_1^\pm, \chi_2^0$). It is a robust feature of these nonuniversal gaugino mass models, following from a small and universal m_0—the smallness being required by the bulk annihilation region of dark matter relic density. It ensures that the produced $\chi_1^\pm, \chi_2^0$ pair dominantly decay via the left sleptons, resulting in viable trilepton and same sign dilepton signals with two hard leptons. The latter signal is unaffected even if the left sleptons mass becomes very close to the wino mass. These multilepton signals will become unviable only if the left slepton becomes heavier than the wino, which will require a large m_0. This means one has to sacrifice either the bulk annihilation region of dark matter relic density or the common scalar mass for the left and right sleptons. With these two reasonable constraints, the muon g-2 satisfying SUSY models predict trilepton and even more robust same sign dilepton signals at LHC. Note that for simplicity we have assumed the same low m_0 value of the slepton sector for the squark sector as well. However, this assumption has no impact on our result. Assuming a large m_0 for the squark sector instead will only increase the squark masses, which has no effect however on the electroweak SUSY signal of our interest. LHC searches for other muon g-2 satisfying SUSY models have been discussed in [36–38].

IV. SIGNAL AND BACKGROUND

As discussed in the previous section the NUGM models provide a framework which can accommodate the bulk annihilation region of the right DM relic density as well as the required muon g-2. It implies that the wino masses are in the range of 400–700 GeV, which implies pair production of $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ at the LHC with a sizable cross section. Once this pair is produced in proton-proton collision, their cascade decays lead to the final state containing hard leptons along with lightest neutralinos($\tilde{\chi}_1^0$), which is assumed to be the lightest SUSY particle (LSP). The presence of LSPs in the final state results in an imbalance in the measured transverse momentum ($\not{p}_T$) due to its very weak interaction with the detector. Hence the decay channel,

$$\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \to (\ell^\pm \nu \tilde{\chi}_1^0)(\ell^+ \ell^- \tilde{\chi}_1^0) \tag{13}$$

with $\ell = {\rm e}, \mu$, leads to a trilepton signal having same flavor opposite sign (SFOS) leptons or a same sign dilepton (SSDL) signal, each with a reasonable amount of $\not{p}_T$. It is to be noticed that this signal is hadronically quiet which can be exploited to get rid of standard model (SM) backgrounds. The dominant SM background is due to the WZ production with the leptonic decays of W and Z boson providing identical final states like the signal events. In addition, the pair production of top quarks with the semileptonic decays, $t \to bW \to b\ell\nu$, and semileptonic decay of one of the b-quark leads to three lepton final states. Besides these two dominant SM backgrounds, there are other sources of backgrounds, e.g., from WW, WZ, and $W\gamma/Z\gamma$ production, where the decay hadronic jets from W/Z can fake as leptons. However, these backgrounds are expected to be very small. In the present analysis, we consider only the SM backgrounds due to the top pair and WZ production. It is to be noted that in comparison with the SM backgrounds the leptons and $\not{p}_T$ in the signal are expected to be harder, since they originate from comparatively more massive particles like $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$. We have exploited all these signal characteristics to isolate signal events from large background samples.

The signal and background events are simulated using PYTHIA6 [39]. In cross section calculation we use CTEQ6L1 [40] for parton distribution function setting both factorization and renormalization scales to $\hat{s}$—the center of mass energy in the partonic frame. In our simulation we adopt the following strategy to select events:

(i) Lepton selection: As already mentioned, the signal events are expected to contain two hard leptons due to the large mass gap between the left slepton and the LSP. So we apply hard cuts on the first two leptons and a soft cut on the third lepton. Here leptons are arranged in decreasing order of p_T. For three lepton case with SFOS,

$$p_T^{\ell_{1,2,3}} \geq 80, 50, 10\ {\rm GeV}; \qquad |\eta^{\ell_{1,2,3}}| \leq 2.5 \tag{14}$$

and for same sign dilepton events (SSDL),

$$p_T^{\ell_{1,2}} \geq 50, 50\ {\rm GeV}; \qquad |\eta^{\ell_{1,2}}| \leq 2.5. \tag{15}$$

The isolation of lepton is ensured by the total accompanying transverse energy cut $E_T^{\rm ac} \leq 20\%$ of the p_T of the corresponding lepton, where $E_T^{\rm ac}$ is the scalar sum of transverse energies of jets within a cone of size $\Delta R(l, j) \leq 0.2$ between jet and lepton. These selections of cuts are very useful in suppressing the background events, which will be discussed later.

(ii) Jet selection: Jets are reconstructed using FastJet [41] with jet size parameter R = 0.5 and anti k_T algorithm [42]. Jets are selected with following thresholds,

$$p_T^j \geq 30\ {\rm GeV}; \qquad |\eta^j| \leq 3.0. \tag{16}$$

As mentioned before, signal events are hadronically quiet at the parton level, where as $t\bar{t}$ background events have reasonable hadronic activities. Hence,

TABLE III. Event summary for trilepton final state with same flavor opposite sign (SFOS) corresponding to signal and SM backgrounds at 8 TeV energy along with production cross section in LO (third column). The last two columns show the normalized cross-section [$\sigma \times$ acceptance efficiency$(\varepsilon_{\mathrm{ac}})$] without and with jet veto (JV). The $t\bar{t}$ is simulated for three $\hat{p}_T$ bins.

								$\sigma\varepsilon_{\mathrm{ac}}$(fb)	
Proc	NoE	σ(fb)	3ℓ	$\not{p}_T \geq 150$	$m_{ll} \neq M_Z \pm 20$	$m_T(\ell_3, \not{p}_T) \geq 150$	Jet Veto(JV)	No JV	JV
BP1	50 K	1.8	9354	7393	6728	5811	3407	0.20	0.12
BP2	50 K	0.88	9591	7909	7318	6409	3707	0.11	0.06
BP3	50 K	11.3	7254	4996	4263	3543	2180	0.80	0.49
$t\bar{t}$: 0–200	2 M	88400	689	15	13	1	0	0.04	0.00
$t\bar{t}$: 200–500	0.2 M	9710	238	22	18	7	0	0.33	0.00
$t\bar{t}$: 500–up	10^5	130	288	128	119	44	0	0.05	0.0
$W^{\pm}Z$	0.45 M	13000	525	32	10	10	6	0.28	0.17

vetoing out events having at least one jet drastically reduce the $t\bar{t}$ background by enormous amount, which can be observed from Tables III–VI below.

(iii) In case of SFOS, we require opposite sign and same flavor dilepton invariant mass should not lie within the range 70–110 GeV, i.e., if $70 < m_{ll} < 110$, events are rejected. This cut is applied with a goal to suppress background from WZ, where this dilepton invariant mass is expected to have a peak around M_Z.

(iv) The transverse missing momentum ($\not{p}_T$) is calculated adding the momentum of visible particles vectorially and then reverse its sign, and it is required to be $\not{p}_T > 150$ GeV.

(v) Another important observable, the transverse mass is found to be very useful to eliminate SM backgrounds without costing signal events too much. The transverse mass is defined to be

$$m_T(\ell, \not{p}_T) = \sqrt{2 p_T^{\ell} \not{p}_T (1 - \cos\phi(p_T^{\ell}, \not{p}_T))}, \qquad (17)$$

where $\phi(p_T^{\ell}, \not{p}_T)$ is the azimuthal angle between lepton and missing transverse momentum. In SFOS case, after applying $m_{\ell\ell}$ cut, the remaining third lepton is used to construct $m_T(\ell_3, \not{p}_T)$. The m_T distribution for leptons coming from W decay either in top pair production or from WZ channel is expected to show a Jacobian peak around M_W; hence a cut on $m_T(\ell_3, \not{p}_T) > 150$ GeV effectively suppresses these backgrounds. The main suppression of the WZ background comes of course from the $m_{\ell\ell}$ cut.

(vi) For the SSDL case, transverse mass for each lepton, $m_T(\ell_1^{\pm}, \not{p}_T)$ and $m_T(\ell_2^{\pm}, \not{p}_T)$ are constructed and selection cuts are applied separately requiring these to be more than 100 GeV. These cuts are very useful in suppressing the $t\bar{t}$ and WZ backgrounds. In this case a transverse mass cut of the dilepton system with the $\not{p}_T$, $m_T(\ell_1 + \ell_2, \not{p}_T) > 125$ GeV, also helps to suppress these backgrounds further.

The signal and backgrounds are simulated for both LHC energies 8 TeV and as well as 13 TeV which is expected to be the Run 2 LHC energy in the next year. For illustration, the signal rates are estimated for the three representative choices of parameter space as shown in Table I, and the corresponding mass spectra as presented in Table II.

V. RESULTS AND DISCUSSIONS

We present the summary of events in Tables III–VI for both 8 and 13 TeV energies simulating both signal and SM backgrounds $t\bar{t}$ and WZ, adopting the strategy as described in the previous section. Table III presents the number of

TABLE IV. Same as Table III, but for same sign dilepton case (SSDL).

									$\sigma\varepsilon_{\mathrm{ac}}$(fb)	
Proc	NoE	σ(fb)	$n_{\ell} = 2$ SSDL	$\not{p}_T \geq 150$	$m_T(\ell_1, \not{p}_T) \geq 100$	$m_T(\ell_2, \not{p}_T) \geq 100$	$m_T(\ell_1 + \ell_2, \not{p}_T) \geq 125$	JetVeto(JV)	No JV	JV
BP1	50 K	1.8	9249	7180	6953	6082	5921	3338	0.21	0.12
BP2	50 K	0.88	9692	7876	7642	6753	6790	3678	0.12	0.06
BP3	50 K	11.3	6541	4260	4131	3548	3469	2031	0.78	0.45
$t\bar{t}$0–200	2 M	88400	148	3	1	0	0	0	0	0
$t\bar{t}$200–500	0.2 M	9710	75	10	5	0	0	0	0	0
$t\bar{t}$500–up	0.1 M	130	474	203	56	2	1	0	0.001	0
$W^{\pm}Z$	45 M	13000	568	14	12	3	1	1	0.003	0.003

TABLE V. Event summary for SFOS case, same as Table III but for 13 TeV energy.

								$\sigma\epsilon_{\rm ac}$(fb)	
Proc	NoE	σ(fb)	3ℓ	$\not{p}_T > 150$	$m_{ll} \neq m_Z \pm 20$	$m_T(\ell_3, \not{p}_T) > 150$	Jet Veto(JV)	No JV	JV
BP1	50 K	7.4	8880	7123	6459	5519	2883	0.81	0.43
BP2	50 K	4.2	9290	7753	7168	6228	3084	0.52	0.26
BP3	50 K	38	6941	4882	4196	3470	1885	2.64	1.42
$t\bar{t}$0–200	30 M	362000	10983	543	468	48	1	0.57	0.012
$t\bar{t}$200–500	4 M	40000	4286	615	549	175	6	1.75	.06
$t\bar{t}$500–inf	0.1 M	810	300	129	116	46	0	0.37	0
$W^\pm Z$	4 M	26000	4330	902	97	84	45	0.54	0.29

trilepton events for 8 TeV energy after each set of cuts as shown on top of each columns. The 2nd and 3rd columns show the number of events (NoE) simulated and leading order (LO) cross sections (in fb), respectively, for each process, where as the fourth column presents the number of events having 3 leptons in the final states passing cut, Eq. (14). Note that the $t\bar{t}$ events are simulated for three $\hat{p}_T$ bins to consider statistics appropriately in different phase space regions. Here $\hat{p}_T$ is the transverse momentum of top quark pair in partonic frame. Notice that selection cuts on $\not{p}_T$ and $m_T(\ell_3, \not{p}_T)$ are very effective to suppress background events, in particular $t\bar{t}$ events, where as dilepton invariant mass ($m_{\ell\ell}$) cut suppresses mainly WZ background, with little effect on signal events. Eventually the jet veto (JV) criteria, i.e., reject events if there exist jets in the final states, reduces the $t\bar{t}$ backgrounds drastically with a mild effect on signal events. As noted earlier, in signal events presence of jets are mainly due to initial state radiation; and hence the signal events are not expected to have many hard jets unlike the $t\bar{t}$ background. The last two columns display the final cross sections multiplying by acceptance efficiency for both cases, with and without jet veto. Clearly, jet veto completely brings down the top backgrounds to a negligible level, but residual WZ background remains.

In Table IV we show event summary for SSDL case at 8 TeV energy. In this case we apply the same set of selection cuts as discussed before, but in addition two more selection cuts $m_T(\ell_1, \not{p}_T)$ and $m_T(\ell_2, \not{p}_T)$ are used with a purpose to suppress mainly WZ background. It is motivated by the fact that in WZ channel two leptons always come from W and Z decays, and the one coming from W decay will not kinematically pass the $m_T > 100$ GeV cut. In contrast the signal events, where leptons originate from heavier $\chi_1^\pm$ and $\tilde{\chi}_2^0$ decays pass the $m_T > 100$ GeV cut for both the leptons. Finally, as indicated by the Table IV, the level of backgrounds cross sections turn out to be negligible. So the discovery limit in the SSDL channels is determined essentially by the signal size.

Similarly we simulate signal and background events for 13 TeV energy using same set of cuts for both SFOS and SSDL cases, which are presented in Tables V and VI, respectively. The pattern of suppression of background events with respect to signal events are more or less the same as observed before. However, the effect of jet veto kills signal events a little more than at 8 TeV due to the fact that hadronic activities from ISR/FSR are more at this higher energy.

Finally we summarize our results presenting signal and background cross sections along with the signal significance ($S/\sqrt{B}$) in Tables VI and VIII for SFOS and SSDL cases, respectively. The significance is estimated for integrated luminosity 20 fb^{-1} and 100 fb^{-1} corresponding to 8 and 13 TeV LHC energies. In calculating both signal

TABLE VI. Event summary for SSDL, same as Table IV but for 13 TeV energy.

									$\sigma\epsilon_{\rm ac}$(fb)	
Proc	Evt	σ(fb)	$n_\ell = 2$ SSDL	$\not{p}_T \geq$ 150	$m_T(\ell_1, \not{p}_T)$ ≥ 100	$m_T(\ell_2, \not{p}_T)$ ≥ 100	$m_T(\ell_1 + \ell_2, \not{p}_T)$ ≥ 125	JetVeto (JV)	No JV	JV
BP1	50 K	7.4	8803	6961	6721	5882	5710	2925	0.84	0.44
BP2	50 K	4.2	9663	7942	7691	6772	6582	3145	0.55	0.26
BP3	50 K	38	6420	4295	4131	3481	3383	1821	2.57	1.38
$t\bar{t}$0–200	30 M	362000	2566	165	30	2	1	0	0.01	0
$t\bar{t}$200–500	4 M	40000	1835	297	129	17	13	0	0.13	0
$t\bar{t}$500–up	0.1 M	810	546	255	74	9	5	0	0.04	0
$W^\pm Z$	4 M	26000	4607	157	104	2	2	1	0.013	.006

TABLE VII. Total background and signal cross sections (in fb) for trilepton final states after all selection cuts corresponding to each benchmark point. Note that these cross sections are obtained by multiplying the background and signal cross sections of Tables III and V by the appropriate K-factors as described in the text. The significance is computed for integrated luminosities 20 fb^{-1} and 100 fb^{-1} for 8 and 13 TeV energies, respectively.

Process	8 TeV No JV	8 TeV JV	13 TeV No JV	13 TeV JV
$t\bar{t}$	0.67	–	4.3	0.11
WZ	0.48	0.29	0.92	0.5
Total Bg	1.15	0.29	5.22	0.61
BP1	0.3	0.18	1.21	0.64
$\frac{S}{\sqrt{B}}$	1.25	1.5	5.3	8.2
BP2	0.165	0.09	0.78	0.39
$\frac{S}{\sqrt{B}}$	0.68	0.74	3.4	5
BP3	1.2	0.73	3.96	2.13
$\frac{S}{\sqrt{B}}$	5.0	6.	17.3	27

TABLE VIII. Same as Table VII, but for SSDL case. In this case we show the expected number of signal events for the integrated luminosities of 20 fb^{-1} and 100 fb^{-1} for 8 and 13 TeV, respectively. The corresponding $S/\sqrt{B} \geq 10$ for all cases.

Process	8 TeV No JV	8 TeV JV	13 TeV No JV	13 TeV JV
$t\bar{t}$	.002	0	0.28	0
WZ	0.005	0.005	0.022	0.01
Total Bg	0.007	.005	0.30	0.01
BP1	0.31	0.18	1.26	0.66
S	6	3.6	126	66.
BP2	0.18	0.09	0.82	0.39
S	3.6	1.8	82	39
BP3	1.17	0.67	3.85	2.07
S	23	13	385	207

and background cross sections, we have taken into account the next to leading order effect by multiplying the K-factors for each cases. For example, for $t\bar{t}$ and WZ processes, we multiply cross sections by 1.6 [43] and 1.7 [44], whereas for signal it is 1.5 [45]. Although these K-factors are derived for 14 TeV energy, they are not expected to be very different at 8 and 13 TeV.

Table VII shows the summary of the trilepton (SFOS) channel results. We see from this table that the BP3 corresponding to modest wino $(\chi_1^\pm, \chi_2^0)$ mass of $\approx$460 GeV can be probed at $5(6)\sigma$ level with 24(15) trilepton signal events without(with) jet veto from the available 20 fb^{-1} data at 8 TeV. Even without a dedicated search with the model, it may be reasonable to assume that trilepton signal of this size could not be missed in generic search of chargino-neutralino pair production events. On the other hand for BP1 and BP2, corresponding to wino mass $m_{\chi_1^\pm}$, $m_{\chi_2^0} \gtrsim 600$ GeV, one expects only a couple of trilepton signal events at a significance level $< 2\sigma$ with the available 20 fb^{-1} data at 8 TeV. But with the 100 fb^{-1} data at 13 TeV one can probe BP1(BP2) at a significance level of $\sim 8\sigma(5\sigma)$ with 60(40) trilepton signal events. This means that even with a 20 fb^{-1} data at 13 TeV a negative search result can rule out wino $(\chi_1^\pm, \chi_2^0)$ masses up to 600–700 GeV at $> 2\sigma$ level. This will essentially cover the nonuniversal gaugino mass models satisfying muon g-2 anomaly up to 2σ level.

The summary of the corresponding results for the SSDL channel is shown in Table VIII. In this case the possibility of observing signal events is more promising due to the presence of tiny backgrounds. Indeed the $S/\sqrt{B}$ ratio is ≥ 10 for all the cases studied here so that the discovery limit is essentially determined by the number of signal events. Therefore, we show this number here instead of the $S/\sqrt{B}$ ratio. We see from this table that the BP3, corresponding to modest wino mass of $\approx$460 GeV, can be probed with 23(13) SSDL signal events without(with) jet veto from the available 20 fb^{-1} data at 8 TeV. Again it is reasonable to assume that a signal of this size cannot be missed even in a generic search of chargino-neutralino pair production with this data. For BP1 and BP2, corresponding to wino mass $\gtrsim$600 GeV, one expects only 4–6 and 2–3 SSDL signal events, respectively. This falls short of a conservative discovery limit of at least 5–6 events. With the 100 fb^{-1} data at 13 TeV one can probe BP1(BP2) at a significance level of ≈ 26–$66\sigma(15$–$39\sigma)$ with 125-65(80-40) SSDL signal events. Thus even with a 20 fb^{-1} data at 13 TeV a negative search results can rule out wino $(\chi_1^\pm, \chi_2^0)$ masses up to 600–700 GeV at $> 5\sigma$ level. Thus one can unambiguously probe the muon g-2 anomaly satisfying nonuniversal gaugino mass models at the 13 TeV LHC using either the trilepton or SSDL channels. The SSDL channel has the advantage of a very small background. Besides the SSDL channel also has the advantage of being viable even when the left slepton mass comes very close the wino mass, as discussed earlier.

Recently the ATLAS collaboration have published the analysis of their 20 fb^{-1} data at 8 TeV for chargino pair production signal in the unlike sign dilepton channel [46]. For a 80 GeV LSP $(\tilde{\chi}_1^0)$, they show an expected exclusion region up to $m_{\chi_1^\pm} = 450$–550 GeV at the 95% C.L. ($\simeq 2\sigma$), which is similar to our BP3. There is a preliminary CMS result of search for electroweak chargino-neutralino pair production in the trilepton channel using their 20 fb^{-1} data at 8 TeV [47]. While most of their analysis focuses on a left slepton mass midway between the χ_1^0 and $\chi_2^0 (= \chi_1^\pm)$ masses, there is one figure (Fig. 15b in Ref. [47]) showing the 95% C.L. exclusion regions in χ_1^0 and χ_2^0 masses for left slepton mass close to the latter. The edge of their expected 95% C.L. ($\simeq 2\sigma$) exclusion region for $m_{\chi_1^0} = 80$ GeV touches $m_{\chi_2^0} = 600$ GeV which is close to our BP1. Thus their expected 2σ exclusion limit is stronger than our estimated 1.5σ exclusion for BP1 in Table VII. The main reason for this seems to be their use of b-jet veto instead of a general jet veto, so that they can suppress the $t\bar{t}$ background without sacrificing the SUSY signal. Their b-jet veto criteria have been tuned to their $t\bar{t}$ data. Having no access to this data, we had to rely on the general jet veto to suppress the $t\bar{t}$ background. We hope the CMS collaboration will do a dedicated analysis of their 8 TeV data for chargino-neutralino pair production in trilepton and SSDL channels in these nonuniversal gaugino mass models, where the electroweak super particle masses are fairly well constrained by the dark matter relic density and the muon g-2 anomaly.

VI. SUMMARY

Nonuniversal gaugino mass models can naturally account for the dark matter relic density via the bulk annihilation process with relatively light bino LSP and right sleptons in the mass rage of ∼100 GeV, while accommodating the observed Higgs boson mass of ∼125 GeV with TeV scale squark/gluino masses. Some of these models can also account for the observed muon g-2 anomaly via SUSY loops with wino and left sleptons in the mass range of 400–700 GeV. We have investigated the prospect of testing these models via electroweak production of charged and neutral wino pairs at the LHC. The left slepton masses in these models are predicted to lie typically ∼20% below the wino mass. Thus one expects robust trilepton and same sign dilepton signals of these models arising from the cascade decays of the charged and neutral wino pair via the left sleptons. In particular the SSDL signal holds even when the left slepton mass lies very close to the wino mass. It also has the advantage of a very small standard model background. Our simulation study shows that the available 8 TeV LHC data is adequate to probe the wino mass range of 400–500 GeV in both the trilepton and the SSDL channels. This mass range of wino covers the muon g-2 range within 0–1σ of its observed central value. Moreover the probe can be extended to the wino mass range of 600–700 GeV with the 13 TeV LHC data, which covers the muon g-2 range up to 2σ of its central value. Thus the nonuniversal gaugino mass models satisfying the observed dark matter relic density and the muon g-2 anomaly can be unambiguously tested via electroweak production of the charged and neutral wino pair at the forthcoming 13 TeV run of LHC.

ACKNOWLEDGMENTS

The work of D. P. R. was partly supported by the senior scientist fellowship of the Indian National Science Academy. The authors are also thankful to the organizers of the “13th Workshop on High Energy Physics Phenomenology (WHEPP 13)” held at Puri, Odisha, 12–21st December, 2013, where this project was started.

---

[1] G. L. Kane, *Prespectives in Supersymmetry* (World Scientific, Hackensack, USA, 1998).

[2] M. Drees, R. Godbole, and P. Roy, *Theory and Phenomenology of Sparticles* (World Scientific, Singapore, 2004).

[3] H. Baer and X. Tata, *Weak Scale Supersymmetry: From Superfields to Scattering Events* (Cambridge University Press, Cambridge, England, 2006).

[4] J. Beringer *et al.* (Particle Data Group), Phys. Rev. D **86**, 010001 (2012).

[5] G. Aad *et al.* (ATLAS Collaboration), Phys. Lett. B **716**, 1 (2012).

[6] S. Chatrchyan *et al.* (CMS Collaboration), Phys. Lett. B **716**, 30 (2012).

[7] S. King, J. Roberts, and D. Roy, J. High Energy Phys. 10 (2007) 106.

[8] J. R. Ellis, K. Enqvist, D. V. Nanopoulos, and K. Tamvakis, Phys. Lett. **155B**, 381 (1985).

[9] M. Drees, Phys. Lett. **158B**, 409 (1985).

[10] S. Mohanty, S. Rao, and D. Roy, J. High Energy Phys. 11 (2012) 175.

[11] S. Mohanty, S. Rao, and D. Roy, J. High Energy Phys. 09 (2013) 027.

[12] G. Bennett *et al.* (Muon (g-2) Collaboration), Phys. Rev. D **80**, 052008 (2009).

[13] M. Davier, A. Hoecker, B. Malaescu, and Z. Zhang, Eur. Phys. J. C **71**, 1515 (2011).

[14] T. Moroi, Phys. Rev. D **53**, 6565 (1996).

[15] M. Endo, K. Hamaguchi, S. Iwamoto, and T. Yoshinaga, J. High Energy Phys. 01 (2014) 123.

[16] C. Gnendiger, D. Stckinger, and H. Stckinger-Kim, Phys. Rev. D **88**, 053005 (2013).

[17] H. Fargnoli, C. Gnendiger, S. Paehr, D. Stckinger, and H. Stckinger-Kim, Phys. Lett. B **726**, 717 (2013).

[18] H. Fargnoli, C. Gnendiger, S. Paehr, D. Stckinger, and H. Stckinger-Kim, J. High Energy Phys. 02 (2014) 070.

[19] U. Chattopadhyay and P. Nath, Phys. Rev. D **65**, 075009 (2002).

[20] G. Anderson, H. Baer, C.-h. Chen, and X. Tata, Phys. Rev. D **61**, 095005 (2000).

[21] K. Huitu, Y. Kawamura, T. Kobayashi, and K. Puolamaki, Phys. Rev. D **61**, 035001 (2000).

[22] U. Chattopadhyay and D. Roy, Phys. Rev. D **68**, 033010 (2003).

[23] S. King and J. Roberts, J. High Energy Phys. 09 (2006) 036.

[24] A. Djouadi, J.-L. Kneur, and G. Moultaka, Comput. Phys. Commun. **176**, 426 (2007).

[25] A. Arbey, M. Battaglia, A. Djouadi, and F. Mahmoudi, J. High Energy Phys. 09 (2012) 107.
[26] S. Heinemeyer, O. Stal, and G. Weiglein, Phys. Lett. B **710**, 201 (2012).
[27] B. Allanach, A. Djouadi, J. Kneur, W. Porod, and P. Slavich, J. High Energy Phys. 09 (2004) 044.
[28] G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich, and G. Weiglein, Eur. Phys. J. C **28**, 133 (2003).
[29] R. Harlander, P. Kant, L. Mihaila, and M. Steinhauser, Phys. Rev. Lett. **100**, 191602 (2008).
[30] S. P. Martin, Phys. Rev. D **75**, 055005 (2007).
[31] G. Belanger, F. Boudjema, P. Brun, A. Pukhov, S. Rosier-Lees, P. Salati, and A. Semenov, Comput. Phys. Commun. **182**, 842 (2011).
[32] G. Belanger, F. Boudjema, A. Pukhov, and A. Semenov, Comput. Phys. Commun. **174**, 577 (2006).
[33] G. Belanger, F. Boudjema, A. Pukhov, and A. Semenov, Comput. Phys. Commun. **149**, 103 (2002).
[34] E. Komatsu, J. Dunkley, M. R. Nolta, C. L. Bennett, B. Gold, G. Hinshaw, N. Jarosik, D. Larson, M. Limon, L. Page, D. N. Spergel, M. Halpern, R. S. Hill, A. Kogut, S. S. Meyer, G. S. Tucker, J. L. Weiland, E. Wollack, and E. L. Wright, Astrophys. J. Suppl. Ser. **180**, 330 (2009).
[35] S. Sekmen, arXiv:1405.4730.
[36] A. Fowlie, K. Kowalska, L. Roszkowski, E. M. Sessolo, and Y.-L. S. Tsai (BayesFITS Group Collaboration), Phys. Rev. D **88**, 055012 (2013).
[37] A. Freitas, J. Lykken, S. Kell, and S. Westhoff, J. High Energy Phys. 05 (2014) 145.
[38] M. Chakraborti, U. Chattopadhyay, A. Choudhury, A. Datta, and S. Poddar, J. High Energy Phys. 07 (2014) 019.
[39] T. Sjostrand, S. Mrenna, and P. Z. Skands, J. High Energy Phys. 05 (2006) 026.
[40] J. Pumplin, D. R. Stump, J. Huston, H.-L. Lai, P. M. Nadolsky, and W.-K. Tung, J. High Energy Phys. 07 (2002) 012.
[41] M. Cacciari, G. P. Salam, and G. Soyez, Eur. Phys. J. C **72**, 1896 (2012).
[42] M. Cacciari, G. P. Salam, and G. Soyez, J. High Energy Phys. 04 (2008) 063.
[43] N. Kidonakis, arXiv:1109.3231.
[44] J. M. Campbell, R. K. Ellis, and C. Williams, J. High Energy Phys. 07 (2011) 018.
[45] W. Beenakker, M. Klasen, M. Krämer, T. Plehn, M. Spira, and P. Zerwas, Phys. Rev. Lett. **83**, 3780 (1999).
[46] G. Aad *et al.* (ATLAS Collaboration), J. High Energy Phys. 05 (2014) 071.
[47] V. Khachatryan *et al.* (CMS Collaboration), arXiv:1405.7570.