Multiphoton signal in supersymmetry comprising nonpointing photon(s) at the LHC

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(Received 6 October 2010; revised manuscript received 6 March 2011; published 12 April 2011)

We study a distinct supersymmetric signal of multiphotons in association with jets and missing transverse energy. At least one of these photons has the origin in displaced vertex, and thus it is delayed and nonpointing. We consider a supersymmetric scenario in which the gravitino is the lightest supersymmetric particle (LSP) (with a mass ~1 keV) and the lightest neutralino is the next-to-lightest supersymmetric particle (NLSP). The NLSP decays dominantly into a photon and a gravitino within the detector with a decay length ranging from $c\tau_{\tilde{\chi}} \sim 50$–100 cm. In addition, we assume that the second-lightest neutralino and the lightest neutralino are nearly degenerate and this leads to a prompt radiative decay of the next-to-lightest neutralino into a photon and a lightest neutralino with a large branching ratio. Such degenerate neutralinos can be realized in various representations of the $SU(5)$, $SO(10)$ and $E(6)$ GUT group. The nonpointing photons can be reconstructed at the electromagnetic calorimeter of the ATLAS detector, which have been designed with good timing and directional resolution. We find that with a center-of-mass energy $E_{\rm cm} = 14$ TeV at an integrated luminosity of 100 fb^{-1} one may see evidence of hundreds of triphoton events at the LHC, in addition to several thousands diphoton events. We also predict the event rates even at the early phase of LHC run.

DOI: 10.1103/PhysRevD.83.075009 PACS numbers: 12.60.Jv, 11.30.Pb, 14.80.Ly, 14.80.Nb

I. INTRODUCTION

In this era of the Large Hadron Collider (LHC), the TeV scale physics is expected to be probed. The supersymmetric standard model is one of the most interesting and attractive candidate for physics beyond the standard model (SM). It offers a possibility of gauge coupling unification and a dark matter candidate, and also solves the gauge hierarchy problem. Once supersymmetry (SUSY) is realized as a local symmetry [1], it predicts the existence of the gravitino $\tilde{G}$ as the spin-$3/2$ superpartner of the graviton. Supersymmetry breaking leads to a nonzero mass of the gravitino through the super-Higgs mechanism, in which the gravitino "eats up" the spin-$1/2$ goldstino associated with spontaneously broken local supersymmetry [2–5]. The mass $m_{\tilde{G}}$ of the gravitino is governed by the scale of SUSY breaking and can range from as low as eV scale to as high as 100 TeV scale [6–13]. In this work, we choose a phenomenological supersymmetric scenario in which gravitino is the lightest supersymmetric particle (LSP) with a mass $m_{\tilde{G}} \sim 1$ keV and look at the collider signatures of such a scenario at the LHC. Such light gravitinos also have implications in cosmology. First of all, one should note that the dark matter relic density is presently known to be $\Omega_{DM}h^2 \simeq 0.11$ [14]. In addition, constraints on structure formation require that the bulk of the dark matter should be cold or warm [15]. For a gravitino with a mass $m_{\tilde{G}} \sim 1$ keV, nonstandard cosmology and a nonstandard gravitino production mechanism are required to satisfy small-scale-structure constraints and to avoid overclosure [16]. One might also need some other dark matter particle. An example of a nonstandard early-Universe physics is to consider a low-reheating temperature [17,18]. In Ref. [18], a low-reheat scenario has been proposed in which a gravitino of mass $m_{\tilde{G}} = 1$–15 keV can have the right abundance to be the warm dark matter.

The interactions of the gravitino are suppressed by the reduced Planck Scale $M_P = 2.4 \times 10^{18}$ GeV and a light gravitino interacts more strongly than a heavy gravitino. Light gravitinos are primarily produced at colliders in the decays of the NLSP. In our scenario, the lightest neutralino ($\tilde{\chi}_1^0$), which is predominantly a bino, is the NLSP and it decays dominantly into a photon and a gravitino. These photons are delayed and nonpointing as they are not pointing to the interaction vertex where the NLSP is produced. Along with this, we also look into the radiative decay of the second-lightest neutralino ($\tilde{\chi}_2^0$) i.e., $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\gamma$, where the emitted photons are prompt. Thus, our main goal in this paper is to study the spectacular multiphoton events at the LHC where there is a mixture of prompt photons and nonpointing photons in the final states. In order to have a large branching ratio of the decay $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\gamma$, we choose a framework where the $U(1)$ and $SU(2)$ gaugino soft SUSY breaking mass parameters M_1 and M_2, respectively, are very close and result in nearly mass degenerate $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$.

In a minimal supergravity (mSUGRA) like framework the gaugino masses are unified at the high scale (unification scale). When they run down to electroweak symmetry

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breaking scale (EWSB) the gaugino mass ratio gets modified through renormalization group effects . At the EWSB, scale the approximate ratio of the gaugino masses are given as M_1:M_2:$M_3 \simeq$ 1:2:6, where M_3 is the $SU(3)$ gaugino soft SUSY breaking mass parameter and M_1, M_2 have been defined in the previous paragraph. So, it is very clear from the above ratios that in an mSUGRA scenario it is almost impossible to have nearly degenerate neutralinos at the EWSB scale. But if the gauginos masses are nonuniversal at the high scale with $M_1 > M_2$, then the renormalization group effects compensate for M_2 and one can have nearly degenerate gauginos at the EWSB scale. In this paper, we point out a few grand unified gauge symmetry breaking patterns where this feature can be grabbed.

Light gravitino and its collider signatures have been studied extensively in various context [16,19–44] and mostly in connection with gauge-mediated supersymmetry breaking [8–10]. Signatures involving photons are characteristics of scenarios with neutralino-NLSP. In most of the cases studied so far, the lightest neutralino is predominantly a bino and the second-lightest neutralino is dominated by its wino component with a large mass splitting between them. However, as emphasized earlier, we will consider a scenario where the lightest and the second-lightest neutralino are approximately degenerate in mass. This will lead to multiphoton signatures at the LHC for a 1 keV gravitino, where in the final states we can have combinations of prompt and delayed photons. This is a spectacular signal free from standard model backgrounds and has not been studied earlier. The signature of two nonpointing photons is very much distinct and clean with a large event rate at the LHC. We discuss the di- and triphoton signals at 14 TeV center-of-mass energy with 100 fb^{-1} integrated luminosity.

It is worth mentioning at this point that the possibility of having nonpointing photons can also be present in models with a flat extra dimension [45]. In addition, we note that the triphoton signatures of Randall-Sundrum model have been studied recently in Ref. [46].

We discuss the p_T distributions of multiphotons for different suggested benchmark points (BP). We use the decay kinematics of the neutralino with a sufficiently long lifetime. Schematic diagram of a neutralino decaying into a gravitino and a photon in the ATLAS detector is shown [35] in Fig. 1. If the decay length of the $\tilde{\chi}_1^0$ is comparable to the size of the ATLAS inner-detector [35,47], high-p_T photons could enter the calorimeter at angles (η_γ) deviating significantly from the nominal angle from the interaction point to the calorimeter cell (η_1).

The plan of the paper is as follows. We discuss the gravitino production from $\tilde{\chi}_1^0$ decay in Sec. II. In Sec. III, we discuss how nearly degenerate gaugino masses enhance the branching ratio of the radiative decay of the next-to-lightest neutralino and suggest the possible high-scale scenarios from where this degeneracy condition can be achieved. We suggest four benchmark points for our numerical analysis, and these are discussed in Sec. IV. In Sec. V, we start with our goal for collider simulation and discuss the multiphotons + jets associated with missing transverse energy as a potential signal at the LHC. Section VI contains the results of our numerical analysis, and the conclusion is provided in Sec. VII.

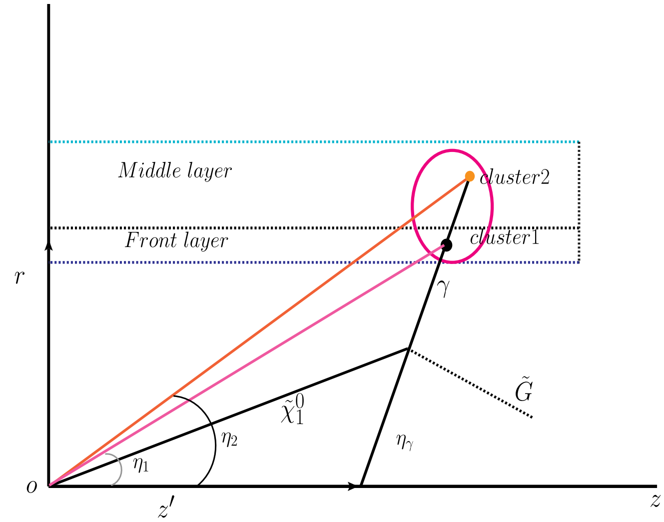

FIG. 1 (color online). Decay kinematics of the NLSP (the lightest neutralino) in the ATLAS detector [35,47].

II. GRAVITINO PRODUCTION FROM NEUTRALINO DECAY

As discussed earlier, the gravitino gets a mass by the super-Higgs mechanism. The mass of the gravitino is related to the fundamental supersymmetry-breaking scale $\sqrt{F}$, as

$$m_{\tilde{G}} = \frac{F}{\sqrt{3}M_P} \simeq 240\ \text{eV}\left[\frac{\sqrt{F}}{10^3\ \text{TeV}}\right]^2. \tag{1}$$

The weak-scale gravitino has a very feeble interaction and thus it is usually hard to find its signatures in collider experiments. However, once SUSY is broken spontaneously, the extremely weak gravitino interactions are enhanced at energy scales much larger than the gravitino mass $m_{\tilde{G}}$. This is because in the high energy limit the gravitino has the same interaction as the goldstino and the couplings of the goldstino are proportional to $1/F$ [48,49]. Hence, the decays of heavier sparticles to gravitinos are faster for light gravitinos. The partial decay widths of $\tilde{\chi}_1^0$ to $\tilde{G}$ are given as [22,32,50]

$$\Gamma(\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}) = \frac{k_{1\gamma}}{48\pi}\frac{m_{\tilde{\chi}_1^0}^5}{M_P^2 m_{\tilde{G}}^2}; \tag{2}$$

$$\Gamma(\tilde{\chi}_1^0 \to Z\tilde{G}) = \frac{2k_{1Z_T} + k_{1Z_L}}{96\pi} \frac{m_{\tilde{\chi}_1^0}^5}{M_P^2 m_{\tilde{G}}^2} \left[1 - \frac{m_Z^2}{m_{\tilde{\chi}_1^0}^2}\right]^4; \quad (3)$$

$$\Gamma(\tilde{\chi}_1^0 \to \phi\tilde{G}) = \frac{k_{1\phi}}{96\pi} \frac{m_{\tilde{\chi}_1^0}^5}{M_P^2 m_{\tilde{G}}^2} \left[1 - \frac{m_\phi^2}{m_{\tilde{\chi}_1^0}^2}\right]^4 \quad (4)$$

where

$$\begin{aligned} k_{1\gamma} &= |N_{11}\cos\theta_w + N_{12}\sin\theta_w|^2, \\ k_{1Z_T} &= |N_{11}\sin\theta_w + N_{12}\cos\theta_w|^2, \\ k_{1Z_L} &= |N_{13}\cos\theta_\beta - N_{14}\sin\theta_\beta|^2, \\ k_{1h^0} &= |N_{13}\sin\alpha - N_{14}\cos\alpha|^2, \\ k_{1H^0} &= |N_{13}\cos\alpha + N_{14}\sin\alpha|^2, \\ k_{1A^0} &= |N_{13}\sin\beta + N_{14}\cos\beta|^2. \end{aligned} \quad (5)$$

Here N_{ij} are the neutralino mixing matrices, θ_w is the weak mixing angle, α is the Higgs ($\Phi = h^0, H^0, A^0$) mixing angle and $\tan\beta$ is the ratio of the vacuum expectation values of the two Higgs doublets H_1 and H_2 in the supersymmetric standard model. From the above expressions, it is clear that for a binolike NLSP, $N_{11}\cos\theta_w$ is much larger than $N_{12}\sin\theta_w$. The decay modes into the photon dominates over Z and ϕ channels as the latter two have phase-space suppressions. Assuming that the decay widths in Z and ϕ channels are negligible, the decay length of the lightest neutralino is given by

$$c\tau_{\tilde{\chi}} = \frac{1}{k_{1\gamma}} \left(\frac{100 \text{ GeV}}{m_{\tilde{\chi}_1^0}}\right)^5 \left(\frac{\sqrt{F}}{100 \text{ TeV}}\right)^4 \times 10^{-2} \text{ cm}. \quad (6)$$

For a pure binolike lightest neutralino with a mass $m_{\tilde{\chi}_1^0} = 200$ GeV and $m_{\tilde{G}} = 1$ keV, we get a decay length $c\tau_{\tilde{\chi}} \approx 70$ cm.

III. RADIATIVE DECAY OF NEUTRALINO: $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\gamma$

The radiative decay of the second-lightest neutralino emanates at the one-loop level and decay width is given as [51]

$$\Gamma(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\gamma) = \frac{g_{\tilde{\chi}_2^0\tilde{\chi}_1^0\gamma}^2}{8\pi} \frac{(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\chi}_1^0}^2)^3}{m_{\tilde{\chi}_2^0}^5}, \quad (7)$$

where $g_{\tilde{\chi}_2^0\tilde{\chi}_1^0\gamma} \propto eg^2/16\pi^2$ is an effective coupling. This radiative decay is enhanced [51,52] by a kinematic factor when $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ are nearly degenerate as in this regime of parameter space three-body decays are suppressed by a factor ϵ^5, where $\epsilon = (1 - m_{\tilde{\chi}_1^0}/m_{\tilde{\chi}_2^0})$. It is noted in [52–54] that the decay branching ratio of $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\gamma$ is much larger for large $\tan\beta$ and $\mu > M_1, M_2$ with $2|\mu| \sim M_1\tan\beta$. In the general minimal supersymmetric standard model scenario, the radiative decay branching ratio can reach nearly 100% [54] for $|M_1|, M_2 \lesssim 1000$ GeV, with $|M_1|, M_2 < |\mu|$ and $|M_1| \sim M_2$. We have calculated the branching ratio of the radiative decay of the second-lightest neutralino using SDECAY [55].

A. Radiative decay with nonuniversal gaugino masses

In [54], the enhancement conditions in the radiative decay branching fractions are justified for the mSUGRA models with nonuniversal gaugino masses. The part of the N=1 supergravity Lagrangian (the part that contains only the real part of the left-chiral superfields Φ_i) containing the kinetic energy and the mass terms for the gauginos and the gauge bosons can be written as

$$\begin{aligned} e^{-1}\mathcal{L} &= -\frac{1}{4}\text{Re}f_{\alpha\beta}(\phi)(-1/2\bar{\lambda}^\alpha \not{D}\lambda^\beta) - \frac{1}{4}\text{Re}f_{\alpha\beta}(\phi)F_{\mu\nu}^\alpha F^{\beta\mu\nu} \\ &\quad + \frac{1}{4}e^{-G/2}G^i((G^{-1})_i^j)[\partial f_{\alpha\beta}^*(\phi^*)/\partial\phi^{*j}]\lambda^\alpha\lambda^\beta + \text{H.c.}, \end{aligned} \quad (8)$$

where $G^i = \partial G/\partial\phi_i$ and $(G^{-1})_j^i$ is the inverse matrix of $G_i^j \equiv \partial G/\partial\phi^{*i}\partial\phi_j$, λ^α is the gaugino field, ϕ is the scalar component of the chiral superfield Φ, and $F_{\mu\nu}^\alpha$ is the unified gauge kinetic term. The F-component of the symmetry breaking scalar field Φ generates gaugino masses with a consistent SUSY breaking with nonzero vacuum expectation value of the chosen $\tilde{F}$, where

$$\tilde{F}^j = \frac{1}{2}e^{-G/2}[G^i((G^{-1})_i^j)]. \quad (9)$$

The Φ^j's can be a set of grand unified theory (GUT) singlet supermultiplets Φ^S, which are part of the hidden sector, or a set of nonsinglet ones Φ^N, fields associated with the spontaneous breakdown of the GUT group to $SU(3) \otimes SU(2) \otimes U(1)$. The nontrivial gauge kinetic function $f_{\alpha\beta}(\Phi^j)$ can be expanded in terms of the nonsinglet components of the chiral superfields in the following way:

$$f_{\alpha\beta}(\Phi^j) = f_0(\Phi^S)\delta_{\alpha\beta} + \sum_N \xi_N(\Phi^s)\frac{\Phi_{\alpha\beta}^N}{M_P} + \mathcal{O}\left(\frac{\Phi^N}{M_P}\right)^2, \quad (10)$$

where f_0 and ξ^N are functions of chiral singlet superfields, essentially determining the strength of the interaction and M_P is the reduced Planck mass $= M_{\text{Pl}}/\sqrt{8\pi}$. The contribution to the gauge kinetic function from Φ^N has to come through symmetric products of the adjoint representation of the associated GUT group, since $f_{\alpha\beta}$ has such a transformation property for the sake of gauge invariance. The nonuniversal gaugino masses are calculated for $SU(5)$, $SO(10)$ and $E(6)$ grand unified gauge groups in [56]. The results for the ratios of gaugino masses are given in Table I. We have tabulated here only the cases where M_1 and M_2 are nearly degenerate at the EWSB scale with $M_1 < M_2$. This fits in our scenario.

TABLE I. Ratios of gaugino masses for F-terms in representations of $SU(5)$, $SO(10)$ and $E(6)$ leading to nearly degenerate gauginos at low scale.

Representations	M_1:M_2:M_3 (at $M_{\rm GUT}$)	M_1:M_2:M_3 (at M_Z)
$\mathbf{75} \subset SU(5)$	-5:3:1	-5:6:1
$\mathbf{210}$, $\mathbf{770} \subset SO(10)$		
$\mathbf{2430} \subset E(6)$	$-\frac{9}{5}$:1:1	-1.8:2:6
	$\frac{5}{2}$: $-\frac{3}{2}$:1	2.5: $-$ 3:6

IV. BENCHMARK POINTS

In this section, we present four benchmark points (see Table II) we have worked with to demonstrate that the nearly degenerate M_1 and M_2 at the EWSB scale can lead to significant branching ratio of the radiative decay of the second-lightest neutralino. In addition to this, we have also shown that if one has $M_1 < M_2$ and the gravitino in the bottom of the spectrum, then the lightest neutralino has a sizeable branching fraction to decay into a photon and gravitino. This leads to multiphoton signatures in collider experiments. The spectrum has been generated using the SUSPECT VERSION 2.41 [57] with all the input parameters specified at the electroweak scale. The gravitino mass is taken to be $\sim$1 keV which is necessary for the fact that the lightest neutralino decays within the detector with a decay length $c\tau_{\tilde{\chi}_1^0} \sim 50$–100 cm. The radiative

TABLE II. Proposed benchmark points (BP) for the study of radiative decay of 0 2 and the NLSP $\tilde{\chi}_1^0$. We have set $A_0 = -1000$ GeV for the third generation squarks and sleptons and it is zero for the rest. Masses of the particles are given in GeV.

	BP-1	BP-2	BP-3	BP-4
$\tan\beta$	40	15	10	15
μ	1500	1500	1500	2500
$m_{\tilde{e}_L}$, $m_{\tilde{\mu}_L}$	601	601	502	701
$m_{\tilde{e}_R}$, $m_{\tilde{\mu}_R}$	601	601	502	701
$m_{\tilde{\nu}_{e_L}}$, $m_{\tilde{\nu}_{\mu_L}}$	597	596	496	697
$m_{\tilde{\nu}_{\tau_L}}$	597	596	496	697
$m_{\tilde{\tau}_1}$	591	567	473	652
$m_{\tilde{\tau}_2}$	611	634	529	747
$m_{\tilde{\chi}_1^0}$	200	199	206	206
$m_{\tilde{\chi}_2^0}$	236	237	236	239
$m_{\tilde{\chi}_1^\pm}$	236	237	236	240
$m_{\tilde{g}}$	413	414	688	739
$m_{\tilde{d}_L}$	613	614	521	728
$m_{\tilde{d}_R}$	611	612	518	727
$m_{\tilde{u}_L}$	609	609	515	724
$m_{\tilde{u}_R}$	610	610	516	725
$m_{\tilde{b}_1}$	599	573	486	680
$m_{\tilde{b}_2}$	626	651	551	771
$m_{\tilde{t}_1}$	366	421	215	422
$m_{\tilde{t}_2}$	735	708	627	434
m_{h^0}	110	118	115	119

TABLE III. Branching fractions for the decays $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\gamma$ and $\tilde{\chi}_1^0 \to \gamma\tilde{G}$ for different benchmark points.

	BP-1	BP-2	BP-3	BP-4
$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\gamma$	0.30	0.11	0.26	0.10
$\tilde{\chi}_1^0 \to \gamma\tilde{G}$	0.89	0.89	0.87	0.88

decay of the $\tilde{\chi}_2^0$ and decay of $\tilde{\chi}_1^0$ have been calculated using SDECAY VERSION 1.3B [55]. The benchmark points we have worked with are consistent with all the low energy constraints like muon $(g-2)_\mu$, $b \to s\gamma$ and the LEP limit on the lightest Higgs boson mass and other charged particles masses [58,59].

Throughout all of our benchmark points, we have kept the value of $m_{\tilde{\chi}_2^0}$ and $m_{\tilde{\chi}_1^0}$ nearly the same with different choices of μ, $\tan\beta$, squarks, gluino and slepton masses. The high value of μ is important for enhancement of the radiative decay branching fraction of $\tilde{\chi}_2^0$ into a $\tilde{\chi}_1^0\gamma$ pair. We have worked with $m_{\tilde{g}}$ starting from as low as 413 GeV to 740 GeV. We set $A_t = A_\tau = A_b = A_0 = -1000$ GeV. The large value of $|A_0|$ is required for obtaining a large radiative decay branching ratio of $\tilde{\chi}_2^0$. For $A_0 = 0$, the three-body-decay modes of $\tilde{\chi}_2^0$ are dominant and the radiative decay is very much suppressed in our case. We have also noted that the radiative decay branching fraction depends less significantly on the sign of A_0. It is a little less for the positive value of A_0 than the negative one, keeping $|A_0|$ same. In Table III, we tabulate the decay branching fraction of the $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ for our choice of input parameters. From this table, one can see the effect of μ, $\tan\beta$, squark, and slepton masses on the radiative decay of $\tilde{\chi}_2^0$. However, the decay branching fraction of the lightest neutralino is determined once the mass of the gravitino, the lightest neutralino, and the neutralino mixing parameters are fixed, and does not depend at all on the choices of squarks, gluino, and sleptons masses.

V. COLLIDER SIMULATION

The $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ are produced in cascade decays of squarks and gluinos accompanied by hard jets. In an R-parity conserving scenario, the gravitino is produced at the end of each cascade, which goes undetected at the collider detector, leading to a large amount of missing transverse energy ($\not{E}_T$) (see, Fig. 2). Thus, one can have multiphoton signals in association with hard jets and $\not{E}_T$. The collider simulation has been performed with a center-of-mass energy $E_{\rm cm} = 14$ TeV, at an integrated luminosity of 100 fb^{-1} using the event generator PYTHIA 6.4.16 [60]. We have used the parton distribution function CTEQ5L [61] with the factorization (μ_F) and renormalization (μ_R) scale set at $\mu_R = \mu_F =$ average mass of the final state particles produced in the initial hard scattering. The effects of initial (ISR) and final state radiation (FSR) have also been taken into account. Below, we mention the numerical values of

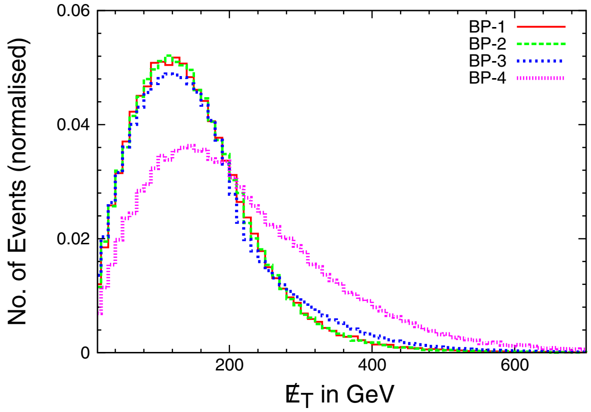

FIG. 2 (color online). Missing Energy distribution for different benchmark points with $E_{\rm cm} = 14$ TeV.

various parameters used in our calculation [58] $M_Z = 91.187$ GeV, $M_W = 80.398$ GeV, $M_t = 172.3$ GeV $\alpha_{\rm em}^{-1}(M_Z) = 127.9$, $\alpha_s(M_Z) = 0.118$, where M_Z, M_W, and M_t are the masses of the Z-boson, W-boson, and top quark, respectively. $\alpha_{\rm em}(M_Z)$ and $\alpha_s(M_Z)$ are the electromagnetic coupling constant and strong coupling constant at the scale of M_Z.

A. Event selection criteria

We have considered the following final states to demonstrate the event rates in multiphoton channels:

(i) $2\gamma + \not{E}_T +$ jets
(ii) $3\gamma + \not{E}_T +$ jets

where at least one of these photons has the origin in displaced vertex due to the fact that the decay length of the lightest neutralino is $\mathcal{O}$(50–100 cm). The photon out of a $\tilde{\chi}_2^0$ decay is soft (see Fig. 3-top) while the p_T of the photon coming from a $\tilde{\chi}_1^0$ are normally hard (see Fig. 3-bottom) as the mass difference between $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ is $\mathcal{O}$(30 GeV).

The following requirements have been implemented to select isolated photons:

- We have identified photons with p_T more than 30 GeV and $|\eta| \leq 2.5$.
- A minimum ΔR separation between two photons has been demanded in terms of $\Delta R > 0.2$, where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.
- A lepton-photon and jet-photon isolation of $\Delta R_{l\gamma} > 0.4$ and $\Delta R_{j\gamma} > 0.6$, respectively, have been imposed.
- The sum of hadronic E_T deposit in a cone of $\Delta R = 0.2$ around the photon is required to be $\Sigma|E_T| < 10$ GeV.
- To reduce the diphoton background from $\pi^0 \to 2\gamma$, we have also required a photon-photon invariant mass cut $m_\pi - 20$ GeV $< M_{\gamma\gamma} < m_\pi + 20$ GeV.

The photons have been ordered according to their hardness (see Figs. 4 and 5) and a minimum p_T cut has been imposed on each of them depending on the various final states:

(i) *diphoton*: $p_{T_{\gamma_1}} > 50$ GeV, $p_{T_{\gamma_2}} > 40$ GeV
(ii) *triphoton*: $p_{T_{\gamma_1}} > 50$ GeV, $p_{T_{\gamma_2}} > 40$ GeV, $p_{T_{\gamma_3}} > 30$ GeV

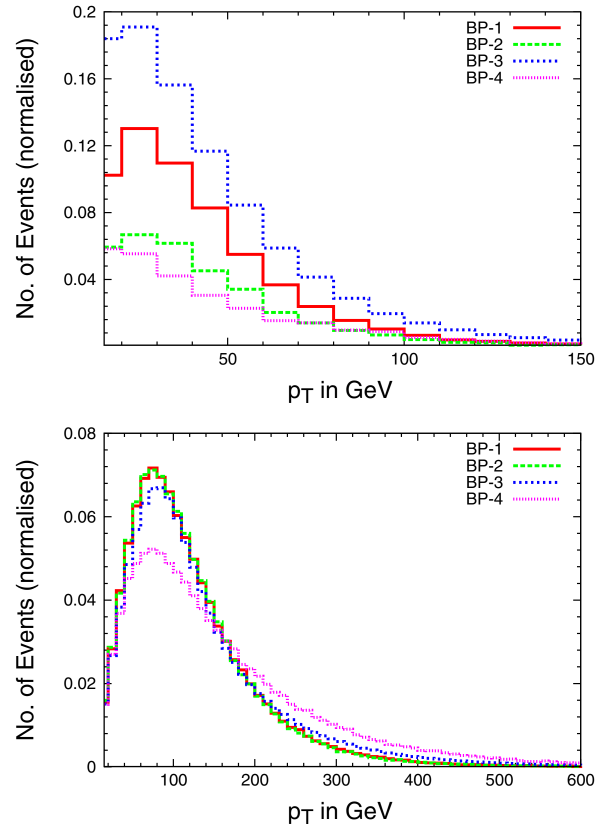

FIG. 3 (color online). p_T distributions of the prompt photon (top) and nonpointing photon (bottom) with $E_{\rm cm} = 14$ TeV for all benchmark points.

The finite detector resolution for the nonpointing photons has been taken into account and this is presented in Table IV [62].

In addition, we use the following set of cuts:

Cut-I:

$$\text{Number of jet} \geq 4$$
$$p_T \text{ of leading jet} \geq 100 \text{ GeV}$$
$$\not{E}_T \geq \max(100, 0.2M_{\rm eff})$$

where $M_{\rm eff} = \sum|\vec{p}_T| + \not{E}_T$ and the sum runs over all jets in the final state, to suppress the SM backgrounds.

In [47,63], the SM backgrounds at $\sqrt{s} = 14$ TeV and integrated luminosity of 1 fb^{-1} have been predicted using the same set of cuts.

Since $\tilde{\chi}_1^0$ is long-lived and the decay length is comparable to the ATLAS inner detector, photons with large transverse momentum could enter the calorimeter at angles deviating significantly from the nominal pointing angle (see Fig. 1). We assume a decay length distribution of the

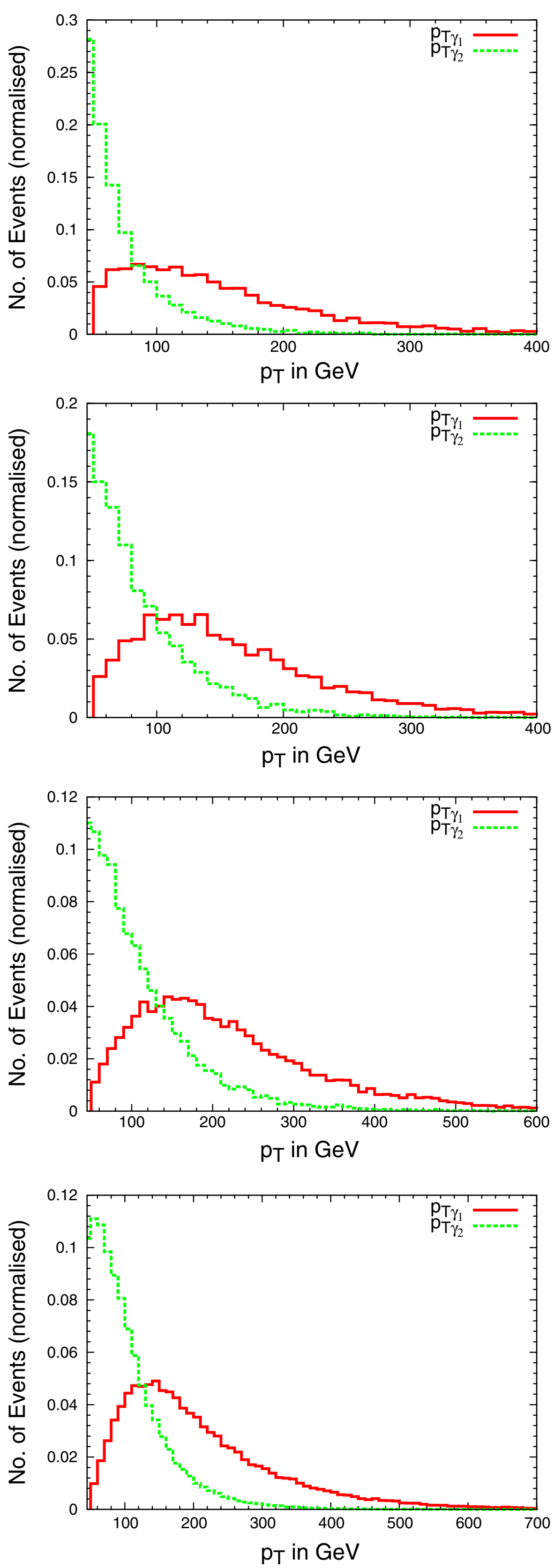

FIG. 4 (color online). p_T distributions of diphotons for (from top to bottom) BP-1, BP-2, BP-3, and BP-4 with $E_{\rm cm} = 14$ TeV.

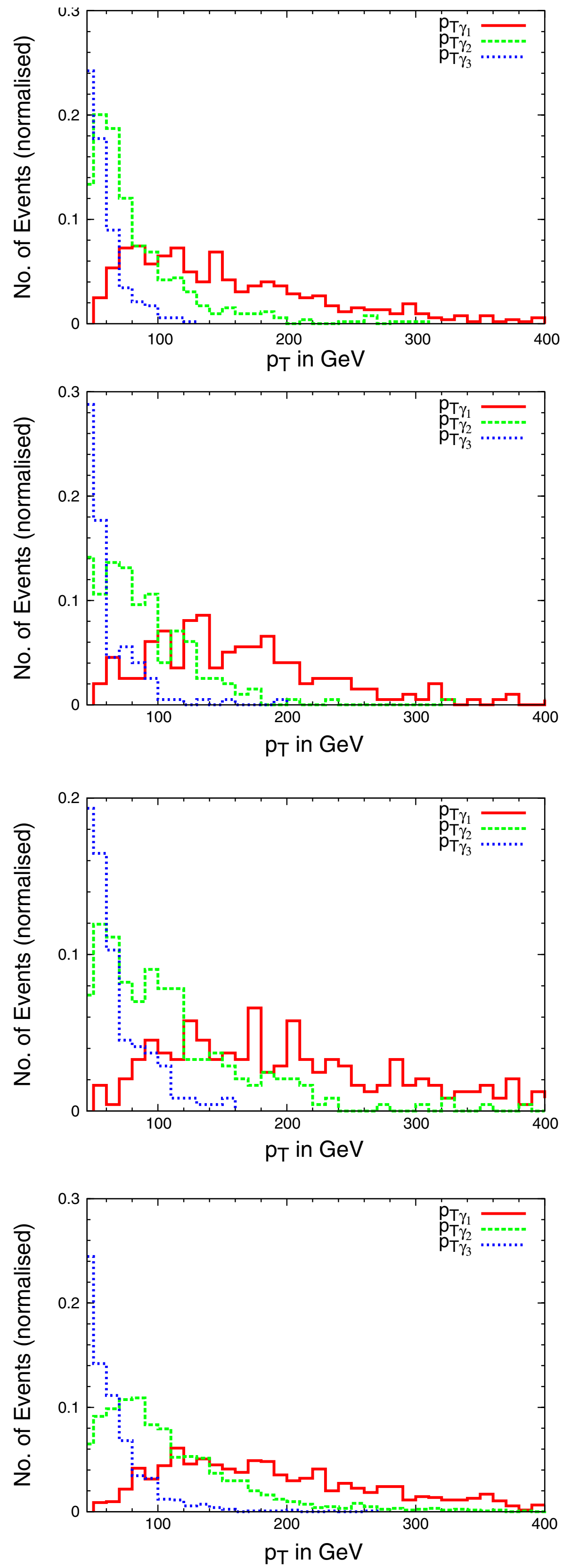

FIG. 5 (color online). p_T distributions of triphotons for (from top to bottom) BP-1, BP-2, BP-3, and BP-4 with $E_{\rm cm} = 14$ TeV.

TABLE IV. Resolution applied to the reconstructed nonpointing photons observables.

Observable	Resolution
Energy	$\frac{\delta E}{E} = \frac{10\%}{\sqrt{E}} \oplus \frac{245\ \text{MeV}}{E} \oplus 0.7\%$
Rapidity	$\sigma_\eta = \frac{0.004}{\sqrt{E\ (\text{GeV})}}$
Azimuthal angle	$\sigma_\phi = \frac{5\ \text{mrad}}{\sqrt{E(\text{GeV})}}$

lightest neutralino with average decay length $L = c\tau\beta\gamma$. The probability that $\tilde{\chi}_1^0$ decays after travelling a distance λ is given as $P(\lambda) = 1 - \exp(-\lambda/L)$. The decay length distribution can be obtained as $\lambda = -L\ln(1 - P(\lambda))$, where $P(\lambda)$ is a random number between 0 and 1 generated event by event. The photon arrival position in the barrel electromagnetic calorimeter has been randomly generated using a random number generator assuming cylindrical geometry. The finite detector resolution mentioned in Table IV has been applied to the direction (η_2) measured with respect to the interaction vertex. The true pseudorapidity (η_γ) of the nonpointing photons have been obtained using the information of nonvanishing Z-coordinate of the neutralino decay vertex.

Then we define (see Fig. 1):

(i) η_2 as the "detector" pseudorapidity of photon

(ii) η_γ as "true" pseudorapidity of photon

We select the event when at least one of the photons satisfy the following cut:

Cut-II: $\Delta\eta > 0.01$, where, $\Delta\eta = \eta_2 - \eta_\gamma$.

to ensure that at least one of the photons in the multiphoton final state is nonpointing in nature. This suppresses the SM backgrounds and other fake backgrounds severely.

We have also incorporated the probability of jet-faking as photon, which is taken to be 0.1% [47,64] and an identification efficiency of 60% has been used for the nonpointing photons following [47,65]. We have not taken into account the rapidity dependence of the identification efficiency and used a uniform efficiency for a conservative approach.

VI. RESULTS

In this section, we present the numerical results of our simulation. In Table V, we tabulate the number of events in the multiphoton channels after applying various cuts (Cut-I + Cut-II) to suppress the SM backgrounds. Though the cuts mentioned in this table are motivated to suppress the SM backgrounds, we have nevertheless pointed out the contribution of the fake backgrounds comprising ISR and/or FSR photon, jet-faking photon, π^0's yielding photon pairs only in this table after imposing those cuts.

The following estimator for the signal significance is used:

$$\text{Sig} = \sqrt{2[(S + B)\ln[1 + S/B] - S]}, \qquad (11)$$

where S and B are the signal and fake background events, respectively [66].

The different benchmark points we have selected correspond to similar $m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\chi}_2^0}$ with different values of μ, tanβ, slepton, and squark masses as given in Table II. The radiative decay branching fraction of $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\gamma$ (see Table III) depends on the choice of squarks and slepton masses as well as on the values of tanβ and μ, which in turn affects the event rates in various multiphoton channels. In BP-1, the gluino is lighter than the squarks. In this case, $\tilde{\chi}_2^0$ is produced via radiative and three-body decay of gluino, which together has a branching fraction of more than 50%. The left-handed squarks decay into a $\tilde{\chi}_2^0 q$-pair either directly (with a branching fraction ~8%) or via gluino decay. The right-handed squarks mainly decay into a gluino, and a quark pair and the gluino further can decay into a $\tilde{\chi}_2^0 g$ or $\tilde{\chi}_2^0 q\bar{q}$-pair. The situation is similar in BP-2 with the only difference is that it has smaller radiative decay branching fraction (11%) of decaying into a $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\gamma$-pair due to small tan$\beta = 10$. In BP-3, the squarks are lighter than the gluino. In this case, the gluino directly decays into a $q\tilde{q}$-pair. Therefore, the production cross section of $\tilde{\chi}_2^0$ in SUSY cascade decreases as the dominant contribution in this case comes only from the decay of left-handed squarks with a branching fraction ranging from 30%–35%. The radiative decay branching fraction $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\gamma$ is slightly greater than BP-2, due to the fact that the squarks and slepton masses are smaller than that in BP-2 (see Table II), which contribute in the loop.

Above all, due to different squarks and gluino masses at different benchmark points the overall SUSY production cross section changes from one benchmark point to the other. This, combined with the different decay branching

TABLE V. Number of signal events (S) and fake backgrounds (B), after applying the set of cuts (Cut-I and Cut-II) at an integrated luminosity of 100 fb^{-1} and $E_{\text{cm}} = 14$ TeV for all our benchmark points.

FINAL STATE		BP-1			BP-2			BP-3			BP-4		
		S	B	Sig	S	B	Sig	S	B	Sig	S	B	Sig
$2\gamma + E_T +$ jets	Cut-I	3360	1173	74.4	3040	1203	67.9	1678	576	52.8	3977	543	105.8
	Cut-II	2119	5	143.9	1726	7	125.1	1102	4	101.1	2633	3	174.5
$3\gamma + E_T +$ jets	Cut-I	308	216	17.7	156	245	9.1	86	81	8.3	170	57	16.9
	Cut-II	194	2	37.5	67	3	17.5	51	2	15.6	107	1	28.2

fractions of $\tilde{q}_L \to \tilde{\chi}_2^0 q$ for various benchmark points, affects the production cross section of the second-lightest neutralino in cascade decay of squarks and gluino and shows up in the final event rates.

From Table V, one can find that in the diphoton channel one has a substantial rate at $E_{\rm cm} = 14$ TeV and an integrated luminosity of 100 $\rm fb^{-1}$. The dominant contribution to this channel comes from the two nonpointing photons out of a $\tilde{\chi}_1^0 \to \tilde{G}\gamma$ decay from the two cascades, and constitutes of more than 92% of the total diphoton cross section. The decay branching fraction of $\tilde{\chi}_1^0 \to \tilde{G}\gamma$ are more than 87% for all of our benchmark points. The next subdominant contribution to it comes from one nonpointing photon from $\tilde{\chi}_1^0$ decay and the other prompt photon from radiative decay of $\tilde{\chi}_2^0$. This constitutes ~7% of the total diphoton cross section. The rest comprises of two prompt photons when we have radiative decay of $\tilde{\chi}_2^0$ from both the cascade or a combination of prompt or nonpointing photon with the ISR and/or FSR photon, the fraction of which is rather small. In BP-1, the diphoton rate is larger than BP-2 with nearly identical spectrum. This attributes to the fact that the radiative decay branching fraction of $\tilde{\chi}_2^0$ at BP-2 is one-third of that in BP-1.

The number of events in the triphoton channel are relatively small since one of these photons comes from radiative decay of $\tilde{\chi}_2^0$. The overall triphoton event rates are small due to following two reasons: the smaller radiative decay branching fraction of the second-lightest neutralino and together with the fact that the photon out of a $\tilde{\chi}_2^0$ decay comes with relatively small p_T (see Fig. 5), because of small mass splitting between $m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\chi}_2^0}$. Hence, in a very small fraction of events they pass the requisite hardness cut.

VII. SUMMARY AND CONCLUSION

We have considered a supersymmetric scenario in which the gravitino (with a mass ~1 keV) is the LSP and the NLSP is the lightest neutralino. The second-lightest neutralino is nearly degenerate in mass with the lightest neutralino. A possible origin of such a degeneracy at the low-scale lies in the form of nonuniversal high-scale ($\sim 10^{16}$ GeV) inputs of the soft SUSY breaking gaugino mass parameters. We have pointed out that such nonuniversal high-scale inputs can be realized in various representations of the $SU(5)$, $SO(10)$, and $E(6)$ GUT group.

We have examined the decays of the NLSP and the second-lightest neutralino at the LHC. In such a scenario, the second-lightest neutralino has a substantial branching fraction of decaying into a photon and the lightest neutralino. The branching fraction depends on μ, $\tan\beta$, and other scalar masses in the theory. The lightest neutralino is predominantly a bino and it too decays into a photon and a gravitino with a large branching ratio. Thus, one naturally has spectacular multiphoton final states in a collider experiment, where light neutralinos are produced in abundance. The photons out of the NLSP decay are nonpointing and can be identified at the barrel Transition Radiation Tracker of the ATLAS inner-detector with an efficiency of 60%. Such nonpointing photons are free from any SM contamination.

We have studied the diphoton and triphoton final states in association with hard jets and missing transverse energy in the context of LHC both at $E_{\rm cm} = 14$ TeV and at an integrated luminosity of 100 $\rm fb^{-1}$.

Detection of such multiphoton final states comprising nonpointing photons at the LHC would have serious implications for early-Universe cosmology and supersymmetry model building. On one hand, one needs to have a suitable supersymmetry-breaking mediation mechanism, which allows for light gravitino with a mass ~1 keV and nearly mass degenerate $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$. On the other hand, this may give some hints toward a nonstandard cosmological scenario, leading to a keV gravitino which is a warm dark matter candidate with the right relic abundance.

ACKNOWLEDGMENTS

S. B. and J. C. would like to thank the Department of Theoretical Physics, Indian Association for the Cultivation of Science for the hospitality where a part of the work was done. S. B. also thanks KEK and the Institute of Physics and Mathematics of the Universe for their hospitality while part of this work was being carried out. This work was partially supported by funding available from the Department of Atomic Energy, Government of India for the Regional Centre for Accelerator-based Particle Physics, Harish-Chandra Research Institute, XIth Plan 'Neutrino physics.' Computational work for this study was partially carried out at the cluster computing facility of Harish-Chandra Research Institute (http://cluster.mri.ernet.in).

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