

## Natural Gauge Mediation with a Bino Next-to-Lightest Supersymmetric Particle at the LHC

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Natural models of supersymmetry with a gravitino lightest supersymmetric particle provide distinctive signatures at the LHC. For a neutralino next-to-lightest supersymmetric particle, sparticles can decay to two high energy photons plus missing energy. We use the ATLAS diphoton search with  $4.8 \text{ fb}^{-1}$  of data to place limits in both the top-squark–gluino and neutralino-chargino mass planes for this scenario. If the neutralino is heavier than 50 GeV, the lightest top squark must be heavier than 580 GeV, the gluino must be heavier than 1100 GeV, and charginos must be heavier than approximately 300–470 GeV. This provides the first nontrivial constraints in natural gauge mediation models with a neutralino next-to-lightest supersymmetric particle decaying to photons and implies a fine-tuning of at least a few percent in such models.

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*Introduction.*—Supersymmetry remains the most favorable solution to the hierarchy problem. Not only does it elegantly cancel the quadratic divergences of an elementary Higgs boson, but it also achieves a precise gauge coupling unification without the need for large threshold effects. The Large Hadron Collider (LHC) has begun to systematically exclude a sizeable portion of the parameter space in the supersymmetric standard model. In particular, the limits on squark and gluino masses suggest that minimal versions of the supersymmetric standard model have become increasingly tuned, putting into question the original motivation for weak scale supersymmetry.

However, tuning in the Higgs sector of the supersymmetric standard model depends mainly on the  $\mu$  term and on sparticles with large couplings to the Higgs boson, namely, the third generation sfermions, gluinos, and electroweak gauginos. If the supersymmetry breaking mechanism is actually flavor dependent, third generation sfermions can be much lighter than the first two generations. The scenario has recently been coined “natural supersymmetry” [1–8] and, together with the fact that the top-squark production cross section is much smaller than that of the up- and down-squarks at the LHC, it allows the stringent limits on squark and gluino masses to be alleviated.

A distinguishing feature of such models is whether or not the gravitino is the lightest supersymmetric particle (LSP). Most analyses in the literature have focussed on the case of a heavy gravitino, but, when the gravitino is the LSP, sparticles decay via the next-to-lightest supersymmetric particle (NLSP) and provide distinctive collider signals [9]. In fact, there is a broad class of models based on new gauge forces and extra dimensions (or locality) where

supersymmetry breaking is transmitted to the first two generation sfermions in a flavor blind fashion, with third generation sfermions receiving suppressed contributions via gauge interactions [10–23]. Some of these models can simultaneously explain the fermion mass hierarchy [12,15] and even incorporate unification [21] but, as of yet, are not strongly constrained by collider searches. This motivates considering the phenomenology of natural supersymmetric models with a gravitino LSP, typical of models where supersymmetry breaking is mediated to the third generation sfermions by gauge interactions. These scenarios are collectively referred to as natural gauge mediation (NGM).

We will study a particularly interesting subset of NGM models that contains a light bino, although our analysis also applies to other mediation mechanisms that yield a similar spectrum. Natural supersymmetry is usually constrained at the LHC by searches for jets plus missing energy from a neutralino LSP, but, in NGM with a light bino, the neutralino can decay to a photon and a gravitino. The signal becomes two high energy photons plus missing energy, greatly reducing the standard model background, and was previously studied in Ref. [12]. In this Letter, we recast the  $4.8 \text{ fb}^{-1}$  ATLAS diphoton search to find bounds on NGM models with a neutralino NLSP. We investigate both electroweak and colored sparticle production, producing robust and otherwise model independent bounds in the top squark–gluino and neutralino-chargino mass planes, respectively. These limits provide the first nontrivial constraints on this class of models and allow us to quantify the degree of fine-tuning required to avoid the bounds.

*Natural gauge mediation.*—The NGM spectrum is determined by minimizing the amount of fine-tuning in the

Higgs sector, retaining the features of gauge mediated supersymmetry breaking where possible. In particular, we assume a light bino. While this is not necessary from a naturalness point of view, a small value for  $M_1$  is common in models with gauge mediated supersymmetry breaking.

In the minimal supersymmetric model, there are three main sources of fine-tuning [24]: the  $\mu$  term

$$\Delta_\mu = \frac{2\mu^2}{m_h^2}, \quad (1)$$

one and two loop Higgs mass corrections from gauginos (with soft mass parameters  $M_2$  and  $M_3$ )

$$\Delta_2 = \frac{3\alpha_2 |M_2|^2}{2\pi m_h^2} \log\left(\frac{\Lambda}{\text{TeV}}\right), \quad (2)$$

$$\Delta_3 = \frac{2y_t^2 \alpha_3 |M_3|^2}{\pi^3 m_h^2} \frac{\tan^2 \beta}{1 + \tan^2 \beta} \log^2\left(\frac{\Lambda}{\text{TeV}}\right), \quad (3)$$

and the one loop correction from the top Yukawa coupling ( $y_t$ )

$$\Delta_t = \frac{3y_t^2 (m_{\tilde{Q}_3}^2 + m_{\tilde{u}_3}^2 + |A_t|^2)}{4\pi^2 m_h^2} \frac{\tan^2 \beta}{1 + \tan^2 \beta} \log\left(\frac{\Lambda}{\text{TeV}}\right), \quad (4)$$

where  $m_{\tilde{Q}_3}$ ,  $m_{\tilde{u}_3}$  are the third generation soft mass parameters and  $\Lambda$  represents the scale at which supersymmetry breaking is mediated. For simplicity, we assume the decoupling limit such that  $m_h$  denotes the physical Higgs boson mass and the mass scales in the logarithms have been replaced by the TeV scale. We will also neglect  $A$  terms (i.e.,  $A_t$ ), which are generally predicted to be small for gauge mediated supersymmetry breaking. Even if they are not (as occurs in some models [11,25–27]), our conclusions are not affected, as all bounds apply to the lightest, physical top squark mass.

Requiring that the fine-tuning is no worse than ten percent (i.e.,  $\Delta \lesssim 10$ ) and assuming that  $\Lambda$  is not much bigger than 10–100 TeV leads to the following constraints on the soft mass parameters:

$$m_{\tilde{Q}_3}, m_{\tilde{u}_3} \lesssim 500\text{--}700 \text{ GeV} \quad M_3 \lesssim 1100\text{--}2200 \text{ GeV}, \quad (5)$$

$$\mu \lesssim 300 \text{ GeV} \quad M_2 \lesssim 1500\text{--}2000 \text{ GeV}. \quad (6)$$

All sfermions other than the top squarks and the left-handed sbottom can be decoupled since they do not significantly affect the fine-tuning in the Higgs sector. (Sleptons only have a small effect on LHC phenomenology; hence, our results also apply to models where they are not decoupled. The exception is when the NLSP is a slepton, typically a stau, which is common if the entire third generation is kept light. Generalizing stau searches [28–30] to include light top squarks is therefore a well motivated extension to this work.) Hence, a common scale will be assumed for the remaining soft mass parameters

$$m_{\tilde{Q}_{1,2}}, m_{\tilde{u}_{1,2}}, m_{\tilde{d}_{1,2,3}}, m_{\tilde{L}_{1,2,3}}, m_{\tilde{e}_{1,2,3}}, m_{\tilde{\nu}_{1,2,3}} \equiv \tilde{M}, \quad (7)$$

where  $\tilde{M} > \text{few TeV}$ . This leaves the minimal sfermion spectrum required for naturalness.

In the gaugino sector, we first assume that the standard one loop relationship

$$\frac{3}{5} \frac{M_1}{\alpha_1} = \frac{M_2}{\alpha_2} = \frac{M_3}{\alpha_3}, \quad (8)$$

i.e., gaugino unification, continues to hold. Combined with the existing gluino mass bound from naturalness, this implies that

$$M_1 = \frac{5}{3} \frac{\alpha_1(M_Z)}{\alpha_3(M_Z)} M_3 \lesssim 160\text{--}320 \text{ GeV}, \quad (9)$$

which will be important in determining the identity of the NLSP. In the Higgs sector, we fix  $m_h = 125$  GeV. A number of examples with an NGM spectrum [15,17,18,20,21] already contain a mechanism to raise the Higgs-boson mass. However, it should be stressed that we only consider the fine-tuning of a minimal supersymmetric model with a  $\mu$  term, and that any mechanism which raises the Higgs mass may change the amount of tuning.

Little parameter space remains for top-squark or sbottom NLSPs. Searches for direct top squark production [31–35] exclude top squark masses between 220 and 500 GeV and between 110 and 165 GeV. In addition, left-handed top squark or sbottom NLSPs below 350 GeV and a right-handed top squark NLSP below about 200 GeV were excluded in Ref. [8] (although a top squark NLSP close to the top mass is not yet excluded). Since Eq. (8) implies that  $M_1 < M_2 < M_3$ , there are two further possibilities. The first is a Higgsino-rich chargino, requiring  $|\mu| < |M_1| \lesssim 160\text{--}320$  GeV. This scenario turns out to be somewhat nongeneric [36], so we do not focus on it here (although chargino NLSPs outside of an NGM context have been investigated in Ref. [37]). By far, the most common NLSP is a bino or Higgsino-rich neutralino, also lighter than about 160–320 GeV. NGM models with a Higgsino-rich neutralino NLSP decaying to  $Z$  bosons were analyzed in Ref. [38], so we focus on bino-rich neutralinos, which decay to photons and gravitinos. A typical spectrum is given in Fig. 1.

Relaxing the constraint imposed by Eq. (8), the spectrum may remain similar or may be quite different. For example, it is well known that many explicit models only generate gaugino masses at two loops. This further suppresses  $M_1$ , so the NLSP is still a bino-rich neutralino. On the other hand, one can easily construct more involved models where the gaugino mass hierarchy implied by Eq. (8) is completely disrupted, whereupon alternative NLSPs become possible. To constrain such models, one would need to repeat the relevant analysis in Ref. [9], but with a light third generation. Generically, one would expect to find stronger bounds on gluino and NLSP masses but

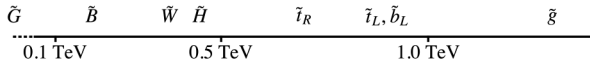


FIG. 1. A typical spectrum for natural gauge mediation.

weaker bounds for the top squark mass relative to those found for degenerate squarks.

In order to constrain the NGM framework, we take a purely phenomenological approach using simplified models. This enables robust bounds to be placed on physical masses independently of model details. Since fine-tuning requirements force all NGM models to contain light Higgsinos, light top squarks, and light gluinos, one expects both colored and electroweak sparticle production. We consider separate simplified models for each process. In practice, both processes contribute in any NGM model; hence, our bounds are always conservative.

For colored production, we decouple all sparticles other than the gluino, the right-handed top squark, and the bino. Hence, sparticle creation proceeds through gluino or top squark pair production. Including other light sparticles would strengthen our final bounds. The bino must be light enough such that the NLSP is mostly bino (so that it decays to photons), but otherwise its mass has only a weak kinematic effect on the signal strength. This can be seen in Refs. [39,40], and we have verified that the situation is the same here. We thus fix the bino mass at 100 GeV in this scenario. For electroweak production, we decouple all colored sparticles and keep only the Higgsinos and the bino in the electroweak sector. Sparticle creation now proceeds through electroweak gaugino pair production. Naturalness does not forbid heavy winos, and including them among the light states again leads to stronger bounds.

*Exclusion limits.*—Neutralino NLSPs decaying to photons lead to a very distinctive signature: two high energy photons and missing transverse momentum from the gravitinos. This channel has a low background and is the subject of recent updates from the ATLAS [39] and CMS [40] experiments. Only the ATLAS diphoton search is considered here, on the basis that CMS and ATLAS have a similar reach. We also considered the earlier 1 fb<sup>-1</sup> ATLAS search [41], which has softer kinematic

requirements, but found that it offered no additional constraints on NGM.

Three signal regions were defined in the ATLAS diphoton analysis. Of these, the first two are the most constraining for colored production and the third is the most constraining for electroweak production. At least two isolated photons with  $p_T > 50$  GeV are required, for which the energy in a cone of  $\Delta R = 0.2$  surrounding the photon's deposition in the calorimeter must be less than 5 GeV. Table I summarizes the further selection cuts for each signal region, the results of the ATLAS search, and the ATLAS derived limits on the number of events attributable to new physics. These results may be used to constrain the NGM parameter space if we evaluate the signal expectation for candidate NGM models.

We use SUSY-HIT 1.3 [42] to produce mass and decay spectra for a given set of model parameters, PYTHIA 6.24.26 [43], to generate 10 000 Monte Carlo events for each point, and a custom version of DELPHES 1.9 [44] (with photon isolation added) to provide a fast ATLAS detector simulation. The total supersymmetric production cross section is calculated at next-to-leading order using PROSPINO 2.1 [45]. A cone-based overlap removal procedure is used to avoid double counting particles that are reconstructed as more than one object (e.g., an electron and a jet).

To approximate the ATLAS limit setting procedure, we follow the approach used in Ref. [46]. We use the published ATLAS limit in the  $m_{\tilde{\chi}_1^0} - m_{\tilde{g}}$  plane to calibrate systematic error parameters in a simplified model of the ATLAS likelihood function, and then use this likelihood function to generate limits in the NGM parameter space. We have confirmed that our procedure reproduces the ATLAS 95% confidence level exclusion contours and, where modest discrepancies are encountered, we tune our parameters to ensure that our results are more conservative. See Fig. 2 for details.

In our exploration of the NGM parameter space, we fix  $\tan\beta = 2$ ,  $\tilde{M} = 2.5$  TeV, and  $c\tau_{\tilde{\chi}_1^0} < 0.1$  mm (to ensure prompt neutralino decays) throughout. For colored production, we fix  $m_{\tilde{Q}_3}$ ,  $\mu$ , and  $M_2$  at the high scale  $\tilde{M}$ ,  $M_1 = 100$  GeV, then scan over  $m_{\tilde{u}_3}$  (approximately equal to  $m_{\tilde{t}_1}$

TABLE I. Selection cuts for the three ATLAS diphoton search signal regions.  $\Delta\phi(\gamma, p_T^{\text{miss}})_{\text{min}}$  is the smallest of the azimuthal separations between the missing momentum  $p_T^{\text{miss}}$  and the momenta of the two leading photons in the event. The total visible transverse energy  $H_T$  is the scalar sum of the transverse momenta of the jets, leptons, and two leading photons in the event.

Region	R1	R2	R3
Photons ( $E_T > 50$ GeV)	$\geq 2$	$\geq 2$	$\geq 2$
$E_T^{\text{miss}}$ (GeV)	$>200$	$>100$	$>125$
$\Delta\phi(\gamma, p_T^{\text{miss}})_{\text{min}}$	$>0.5$		$>0.5$
$H_T$ (GeV)	$>600$	$>1100$	
Expected background	$0.10 \pm 0.03 \pm 0.07$	$0.36 \pm 0.05 \pm 0.27$	$2.11 \pm 0.37 \pm 0.77$
Observed events	0	0	2
95% C. L. upper limit	3.1	3.1	4.9

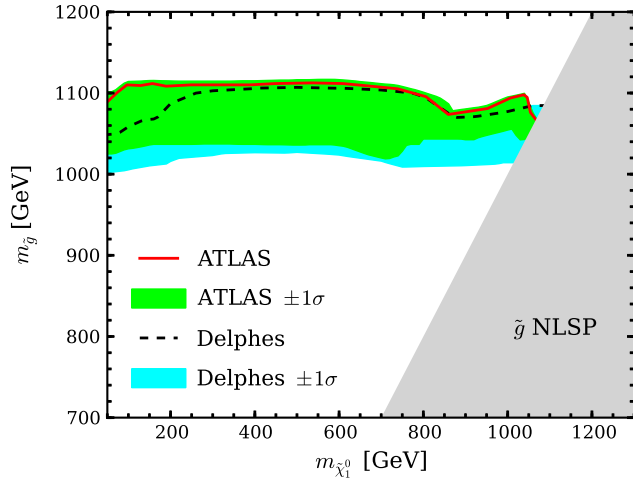


FIG. 2 (color online). Comparison between the Delphes and ATLAS 95% exclusion limits in the  $m_{\tilde{\chi}_1^0} \approx m_{\tilde{g}}$  plane. The Delphes limit is obtained by taking the union of the Delphes limits for each signal region, with the limits tuned to match the ATLAS results.

when  $m_{\tilde{u}_3} > m_t$ ) and  $M_3$  (i.e., the gluino mass  $m_{\tilde{g}}$ ). For electroweak production, we instead fix  $m_{\tilde{Q}_3}$ ,  $m_{\tilde{u}_3}$ ,  $M_2$ , and  $M_3$  at the high scale  $\tilde{M}$ , then scan over  $M_1$  (approximately equal to  $m_{\tilde{\chi}_1^0}$  when  $M_1 < \mu$ ) and  $\mu$  (approximately equal to  $m_{\tilde{\chi}_1^\pm}$  when  $M_1 < \mu$ ).

The resulting limits are shown in Fig. 3. For colored production, the gluino mass limit approaches  $\approx 1100$  GeV for heavy top squarks, in agreement with the published limits from ATLAS and CMS [39,40] (note that varying the bino mass does not significantly change the limits, as can be seen from Fig. 2). Consequently, one must accept a fine-tuning of at least 10–40% due to two loop Higgs mass corrections from gluinos. Top squark masses less than

$\approx 580$  GeV are excluded (the effect of including weak production as well would raise this limit further), corresponding to a fine-tuning of at least 8–17% due to one loop Higgs mass corrections from the top Yukawa coupling. These limits do not degrade at low top squark mass, as photons from neutralino decays typically remain hard enough to pass all cuts for  $m_{\tilde{\chi}_1^0} = 100$  GeV

Limits on weak production reveal that a significant slice of the  $m_{\tilde{\chi}_1^0} - m_{\tilde{\chi}_1^\pm}$  plane is also excluded. The limit does not extend to neutralino masses below 50 GeV, as too few events in these models pass the missing energy requirement of the ATLAS search. Nor does it extend to  $m_{\tilde{\chi}_1^0} \approx m_{\tilde{\chi}_1^\pm}$ , where the branching ratio of neutralinos to photons drops off. One could in principle have models with  $m_{\tilde{\chi}_1^0} < 50$  GeV and a small value of  $\mu$  (and hence low fine-tuning), although, if one insists on gaugino unification, this is difficult to achieve due to limits on the gluino mass from colored production. If  $m_{\tilde{\chi}_1^0} > 50$  GeV, one must have  $m_{\tilde{\chi}_1^\pm} \geq 300$ –470 GeV and a fine-tuning of at least 4–9% from the  $\mu$  term.

Combining both limits, one can search for the most natural NGM model (with a neutralino NLSP) not yet excluded by the LHC. If gaugino unification is assumed, both charginos, from the Higgsino and the wino, are light. Constraints from electroweak production are therefore severe. Choosing

$$m_{\tilde{g}} \gtrsim 2200 \text{ GeV}, \quad \mu \gtrsim 1000 \text{ GeV} \quad (10)$$

avoids both limits and yields a fine-tuning of at least 1% from the  $\mu$  term. The fine-tuning from the top Yukawa coupling is subdominant. The constraints are relaxed if gaugino unification is not assumed such that the wino is allowed to be heavy and the bino light. Then,

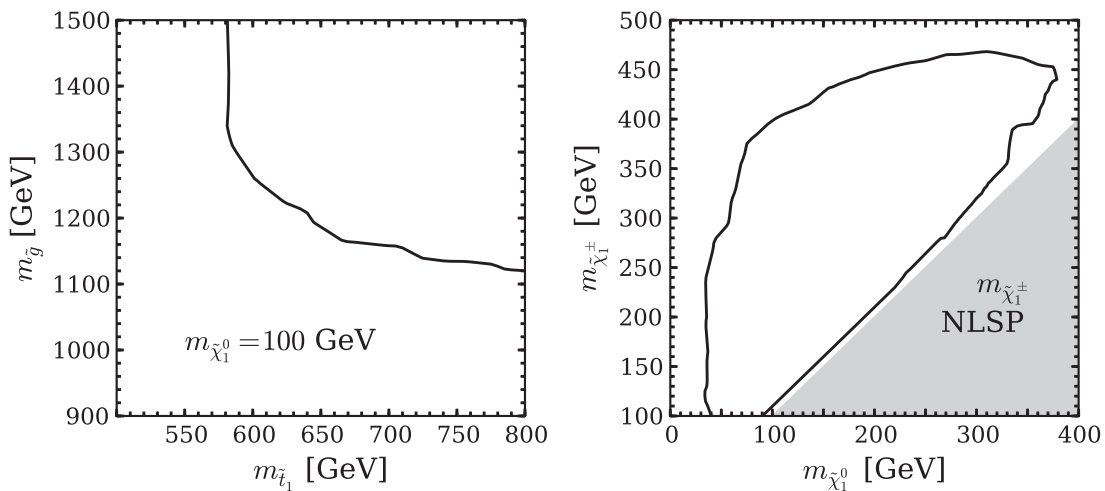


FIG. 3. The 95% confidence level exclusion contours. *Left*: Limits on colored production in the  $m_{\tilde{t}_1} - m_{\tilde{g}}$  plane (note that the limit does not degrade at low top-squark mass for  $m_{\tilde{\chi}_1^0} = 100$  GeV). *Right*: Limits on electroweak production in the  $m_{\tilde{\chi}_1^0} - m_{\tilde{\chi}_1^\pm}$  plane. Both production processes are active in any given model, so all limits are conservative.

$$\begin{aligned}
m_{\tilde{g}} &\gtrsim 1600 \text{ GeV}, & \mu &\gtrsim 400 \text{ GeV}, \\
m_{\tilde{Q}_3}, m_{\tilde{u}_3} &\gtrsim 800 \text{ GeV}
\end{aligned}
\tag{11}$$

avoids both limits with a fine-tuning of at least 5% from the  $\mu$  term and 5–9% from the top Yukawa coupling. As expected, the fine-tuning in a realistic spectrum is worse than that suggested by the simplified models alone.

Finally, we note that the current ATLAS search has not been optimized for direct top squark production. A more dedicated search using  $b$  tagging and reoptimized selections on  $E_T^{\text{miss}}$  and  $H_T$  could increase the reach, and we strongly encourage effort in this area.

*Conclusion.*—In summary, using a  $4.8 \text{ fb}^{-1}$  ATLAS diphoton search, we have placed mass limits on simplified models of natural gauge mediation with a neutralino NLSP for colored and electroweak sparticle production. Because both production mechanisms are active in actual realizations of natural gauge mediation, our bounds are conservative. Top squarks with a mass below  $\approx 580 \text{ GeV}$  are excluded, as are gluinos with a mass below  $\approx 1100 \text{ GeV}$ . Assuming the neutralino is heavier than  $50 \text{ GeV}$  means that charginos lighter than  $\approx 300\text{--}470 \text{ GeV}$  are ruled out. Otherwise, a neutralino lighter than  $\approx 50 \text{ GeV}$  may allow our bounds to be evaded. This places the first nontrivial constraints that test the naturalness of this class of models.

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