Strongly interacting gauge mediation at the LHC

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ABSTRACT: Strongly interacting gauge mediation (SIGM) of supersymmetry breaking is very attractive, since it naturally predicts a light gravitino of mass $\lesssim \mathcal{O}(10)\,\mathrm{eV}$, which causes no cosmological problem. We discuss various signatures of the SIGM in the early stage (a low integrated luminosity period) of the LHC experiments. We show, in particular, a possible way to discriminate it from the conventional gauge mediation by counting the number of high P_T leptons.

Contents

1. Introduction

Strongly interacting gauge mediation (SIGM) of supersymmetry (SUSY) breaking [1, 2] is very attractive, since it naturally predicts a light gravitino of mass $\lesssim \mathcal{O}(10)\,\mathrm{eV}$ and such a light gravitino is free from all cosmological problems [3–6]. The SIGM predicts most likely a relatively light gluino compared with the conventional gauge mediation [7] and hence it may have more chance to be tested at the LHC.[1] Therefore, an early SUSY discovery at the LHC with multiple jets and missing transverse momentum P_{T} may already indicate the SIGM.

Furthermore, the next-to-lightest SUSY particle (NLSP) is the bino-like neutralino except for a very special case, which dominantly decays into the gravitino emitting a high energy photon. Hence, the SUSY events of multiple jets plus missing P_{T} are accompanied with two high P_{T} photons. Therefore, the early discovery of events with multiple jets + missing P_{T} + two photons provides us with a crucial test of the SIGM.

In this letter, we discuss further tests of the SIGM at the LHC. For definiteness, we adopt an SIGM model to calculate the spectrum of SUSY particles. We find that the gluino becomes lighter than the wino in a large region of parameter space. We find that, as a consequence, the production of high P_{T} leptons is surprisingly suppressed at the LHC, contrary to the folklore of the generic SUSY phenomenology.

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[1] Note that the gluino pair production cross section is a steeply falling function of the gluino mass [8]. In the conventional gauge mediation the gluino mass is comparable to the squark mass, while the squark mass should be larger than approximately 1 TeV in order to satisfy the mass bound on the lightest Higgs particle ($m_{h^0} > 114.4\,\mathrm{GeV}$ [9]). (The mass of SM-like Higgs receives a radiative correction from quark-squark loop diagrams.) On the other hand, in the SIGM, squarks are predicted much heavier than the gluino and hence the gluino mass can be in the range below 1 TeV, satisfying the Higgs mass bound.

	$\mathrm{SU(5)_{GUT}} \supset \mathrm{SM}$	$\mathrm{SU(5)_{hid}}$
Q	**1**	$\mathbf{5^*} + \mathbf{10}$
$P_d + P_\ell$	**5**	$\mathbf{5^*}$
$\bar{P}_d + \bar{P}_\ell$	$\mathbf{5^*}$	**5**

Table 1: The matter content of the SUSY breaking and messenger sectors.

2. A strongly interacting gauge mediation model

The present model is an extension of the SUSY-breaking $\mathrm{SU(5)_{hid}}$ model [10] which has quark multiplets Q transforming as $\mathbf{5^*} + \mathbf{10}$ under the gauge group $\mathrm{SU(5)_{hid}}$. We introduce two pairs of massive messengers $P_d + \bar{P}_d$ and $P_\ell + \bar{P}_\ell$ which form $\mathbf{5} + \mathbf{5^*}$ of the standard-model (SM) $\mathrm{SU(5)_{GUT}}$. A crucial assumption of the present SIGM model is that they also belong to $\mathbf{5} + \mathbf{5^*}$ of the strongly interacting $\mathrm{SU(5)_{hid}}$ [2] and hence the messengers take part in the strong interactions in the hidden sector (see table 1).[2]

We assume that the gauge coupling of the $\mathrm{SU(5)_{hid}}$ is strong at the messenger mass scale, since otherwise we may have a split SUSY spectrum with very heavy scalars [2]. Unfortunately, we can not provide a precise prediction of the masses of SUSY particles since the messenger particles are in the strong interactions when they decouple and the integration of the messengers is uncalculable. Therefore, we adopt in this letter the naive dimensional analysis (NDA) [11] to estimate the masses of SUSY particles.

To perform the NDA we assume, for simplicity, that the SUSY is broken mostly by a composite state Φ_S which may be a bound state of the quarks Q ($\mathbf{5^*} + \mathbf{10}$).[3] The Φ_S is assumed to have both non-vanishing A and F terms to represent both the R symmetry and SUSY breakings, which are known to occur by the strong dynamics [10].[4]

The integration of the strongly interacting $\mathrm{SU(5)_{hid}}$ sector induces a low-energy effective Kähler potential. The relevant term for the scalar masses in the SUSY standard model (SSM) is given by

$$K \simeq \frac{-1}{16\pi^2} g_{\mathrm{SM}}^4 \phi_{\mathrm{SM}}^\dagger \phi_{\mathrm{SM}} \frac{1}{16\pi^2} \frac{(g\Phi_S^\dagger)(g\Phi_S)}{M_{d/\ell}^2}, \tag{2.1}$$

where ϕ_{SM} denote the SM superfields, g_{SM} are the SM gauge couplings, and g is a constant of $\mathcal{O}(4\pi)$ representing the strong dynamics [11]. $M_{d/\ell}$ are the effective masses of hadrons $\Phi_{d/\ell}$ which consist of at least one messenger quark $P_{d/\ell}$ and SUSY-breaking quarks Q. Here, contributions of higher dimensional terms are ignored, for simplicity. Eq. (2.1) results in

$$m_\varphi^2 \simeq \left(\frac{\alpha_{\mathrm{SM}}}{4\pi}\right)^2 \frac{|g\langle F_S\rangle|^2}{M_{d/\ell}^2}. \tag{2.2}$$

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[2]We assume that the SM gauge symmetry is not broken by the strong dynamics.

[3]The Φ_S may also contain covariant derivatives.

[4]The R symmetry breaking results in an R-axion [12], but it is marginally consistent with the constraints (cf. ref. [13]).

On the other hand, the Kähler potential relevant for the gaugino masses in the SSM is given by

$$K \simeq g_{\rm SM}^2 {\rm Tr}[W_{\rm SM} W_{\rm SM}] \frac{1}{16\pi^2} \frac{(g\Phi_S^\dagger)(g\Phi_S)(g\Phi_S^\dagger)(gD^2\Phi_S)}{M_{d/\ell}^6} + {\rm h.c.}, \qquad (2.3)$$

which leads to

$$m_\lambda \simeq \frac{\alpha_{\rm SM}}{4\pi} \frac{|g\langle F_S\rangle|^2 g\langle\Phi_S^\dagger\rangle g\langle F_S\rangle}{M_{d/\ell}^6}. \qquad (2.4)$$

Notice that the gaugino masses arise not at $\mathcal{O}(F_S)$ but at $\mathcal{O}(F_S^3)$, since there is no direct coupling between the SUSY breaking fields and the messenger fields [2, 14].

As for the masses of the messengers P_d and P_ℓ we consider $m_d = m_\ell$ at the GUT scale.[5] It is very important for our analysis that the SSM gauge interactions increase the value of m_d more than m_ℓ at low energies. We find, by solving one-loop renormalization group (RG) equations for the messenger masses, $m_d \simeq 2.5 \times m_\ell$ at the mass of the messenger P_d.[6] Below the threshold of the messenger P_d, only the messenger P_ℓ receives the mass renormalization from the strong $\mathrm{SU(5)_{hid}}$ interactions and hence the disparity in the messenger masses becomes milder. Furthermore, the hadrons $\Phi_{d/\ell}$ contain the dynamical quarks Q besides the messenger quark $P_{d/\ell}$ and hence their mass ratio M_d/M_ℓ is smaller than the mass ratio of messenger quarks m_d/m_ℓ. Since the mass ratio is uncalculable due to the strong dynamics, we simply introduce one parameter $\kappa_1 = M_d/M_\ell$ and consider a region of $1 \lesssim \kappa_1 \lesssim 2$.

Another important point is that the powers of $M_{d/\ell}$ are different between gauginos and scalars. Assuming that $g\langle\Phi_S\rangle = \Lambda$ and $g\langle F_S\rangle = \Lambda^2$, we obtain

$$m_\varphi^2 \simeq \left(\frac{\alpha_{\rm SM}}{4\pi}\right)^2 \frac{\Lambda^4}{M_{d/\ell}^2}, \qquad m_\lambda \simeq \frac{\alpha_{\rm SM}}{4\pi} \frac{\Lambda^7}{M_{d/\ell}^6}. \qquad (2.5)$$

Here, Λ denotes the hadron mass scale. We introduce one more parameter $\kappa_2 = M_d/\Lambda$, which is of order unity and satisfies $\kappa_2 \gtrsim 1$. Note that $F_S = \Lambda^2/g \simeq \Lambda^2/4\pi$ yields a relatively small gravitino mass compared with the case of $F_S \simeq \Lambda^2$ (i.e., $g \simeq 1$).

3. Spectrum of the SUSY particles

The low energy spectrum of the SSM particles can be obtained by using eq. (2.5) at the messenger mass scale and then RG-evolving their masses from the messenger mass scale down to the weak scale. As discussed in the previous section, we introduce two parameters $\kappa_1 = M_d/M_\ell$ and $\kappa_2 = M_d/\Lambda$ to represent the uncertainties arising from the strong dynamics. We investigate the regions

$$1 \leq \kappa_1 \leq 2 \qquad \text{and} \qquad \kappa_2 \geq 1. \qquad (3.1)$$

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[5]$m_{d/\ell}$ are the masses of constituent messenger quarks $P_{d/\ell}$, while $M_{d/\ell}$ are the masses of composite hadrons $\Phi_{d/\ell}$.

[6]Here, we assume $m_d = \mathcal{O}(100)\,{\rm TeV}$ to realize $m_{3/2} = \mathcal{O}(1)\,{\rm eV}$ and $m_{\rm gaugino} = \mathcal{O}(100)\,{\rm GeV}$ as we shall see later.

The explicit mass formulae at the messenger mass scale are

$$m_{\tilde{g}} = \frac{\alpha_3}{4\pi}\frac{\Lambda}{\kappa_2^6}, \quad m_{\widetilde{W}} = \frac{\alpha_2}{4\pi}\frac{\Lambda}{\kappa_2^6}\kappa_1^6, \quad m_{\widetilde{B}} = \frac{\alpha_1}{4\pi}\frac{\Lambda}{\kappa_2^6}\left[\frac{1}{3} + \frac{1}{2}\kappa_1^6\right] \tag{3.2}$$

for the gauginos and

$$m_\varphi^2 = \frac{\Lambda^2}{\kappa_2^2}\left\{C_{\mathrm{SU(3)}_C}^\varphi\left(\frac{\alpha_3}{4\pi}\right)^2 + C_{\mathrm{SU(2)}_L}^\varphi\left(\frac{\alpha_2}{4\pi}\right)^2\kappa_1^2 + C_{\mathrm{U(1)}_Y}^\varphi\left(\frac{\alpha_1}{4\pi}\right)^2\left[\frac{1}{3} + \frac{1}{2}\kappa_1^2\right]\right\} \tag{3.3}$$

for the scalar particles, where $\alpha_i = g_i^2/4\pi$ are the SM gauge couplings and $C_{\mathrm{SU(3)}_C}^\varphi$, $C_{\mathrm{SU(2)}_L}^\varphi$ and $C_{\mathrm{U(1)}_Y}^\varphi$ are the quadratic Casimir invariants of the corresponding gauge groups for the field φ.[7] We should mention as a reminder that there exist $\mathcal{O}(1)$ uncertainties in these formulae.

Before looking at the numerical results, we note some general features of the mass spectrum which can be read from the above formulae. The parameter κ_2 dictates the hierarchy between the gaugino masses and the scalar masses. As the value of κ_2 increases, the scalars become heavier than the gauginos. The parameter κ_1 determines the relative mass relations between $\mathrm{SU(3)}_C$ charged particles ($\tilde{g}$ and $\tilde{q}$) and the $\mathrm{SU(3)}_C$ neutral particles ($\tilde{\ell}$, $\tilde{\chi}$ and $H_{u,d}$). As the value of κ_1 increases, $\mathrm{SU(3)}_C$ neutral particles become heavier. In the limit $\kappa_1, \kappa_2 \to 1$, we recover the GUT relation for the gaugino masses and $m_{\mathrm{scalar}} \sim m_{\mathrm{gaugino}}$ as in the conventional gauge mediation model. Λ provides the overall scale for the soft SUSY breaking masses.

As remarked earlier, the gravitino is very light in our model. Its mass is given by

$$m_{3/2} = \frac{\langle F_S\rangle}{\sqrt{3}M_P} \simeq \frac{\Lambda^2}{4\pi\sqrt{3}M_P}, \tag{3.4}$$

where $M_P = 2.44 \times 10^{18}\,\mathrm{GeV}$ is the reduced Planck mass. We see that $m_{3/2} < 10\,\mathrm{eV}$ corresponds to $\Lambda \lesssim 730\,\mathrm{TeV}$.

An important issue is the occurrence of the electroweak (EW) symmetry breaking.[8] In our model, the Higgs scalars can be relatively heavy and accordingly, we must check whether the squared Higgs masses become so small at the weak scale that the EW symmetry breaking occurs. In fact, as the value of κ_1 increases, the soft SUSY breaking Higgs masses squared $m_{H_{u,d}}^2$ become larger and there is an upper bound on κ_1 (for each value of κ_2) above which no EW symmetry breaking occurs.

Now we present the numerical results. We calculate the SUSY-particle masses by using the one-loop RG equations for the SSM parameters. In figures 1 and 2, we show the gluino mass ($m_{\tilde{g}}$), the first two lightest neutralino masses ($m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}$) and the lighter stau mass ($m_{\tilde{\tau}_1}$) as functions of κ_1. Two examples for $(\kappa_2, \Lambda) = (1.35, 280\,\mathrm{TeV})$ and $(1.8, 900\,\mathrm{TeV})$ are shown in figures 1 and 2, respectively. Here, $\tan\beta = 10$ in both cases. The upper bound of κ_1 in each figure corresponds to the point where $\mu = 0$ above which EW symmetry breaking does not occur.

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[7]In our normalization of hypercharge, $\alpha_1 = \frac{5}{3}\frac{g'^2}{4\pi}$ with $g'\cos\theta_W = e$ and $C_{\mathrm{U(1)}_Y}^\varphi = \frac{3}{5}\left(Q_{\mathrm{em}}^\varphi - T_{\mathrm{SU(2)}}^{\varphi,3}\right)^2$.

[8]We do not discuss the origin of the μ- and B-terms (the μ-problem) in the present model and take the $\tan\beta$ as a free parameter.
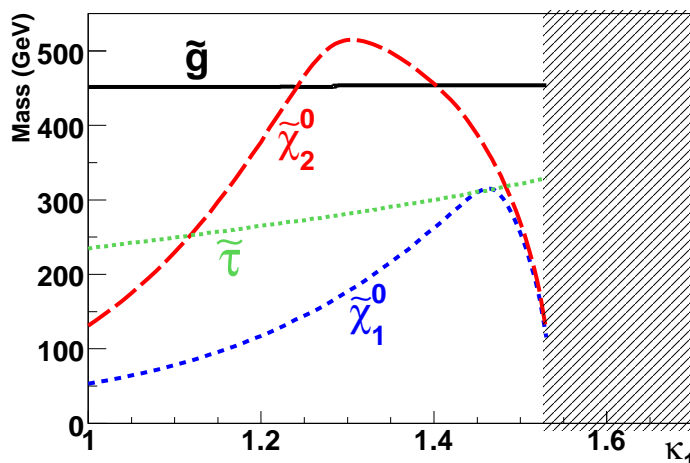
Figure 1: Mass spectrum for $\Lambda = 280\,\mathrm{TeV}$ and $\kappa_2 = 1.35$. Here, scalar quark masses are approximately $1.5\,\mathrm{TeV}$. In the shaded region, EW breaking dose not occur.

The general features of the mass spectrum discussed above can be seen in those examples. The NLSP is the lightest neutralino in most of the parameter region.[9] The GUT relation among the gaugino masses, which holds in the conventional gauge mediation models, is violated for $\kappa_1 > 1$. In particular, for $\kappa_1 \gtrsim 1.2$, $m_{\widetilde{W}}$ becomes larger than $m_{\tilde{g}}$. Note also that the gluino becomes the NLSP for $\kappa_1 \gtrsim 1.6$ in figure 2. The scalars are heavier compared with in the conventional gauge mediation for $\kappa_2 > 1$. The stau is the lightest among the scalar particles, whose mass is also shown in figures 1 and 2.

4. Test for $m_{\widetilde{W}} > m_{\tilde{g}}$ at the LHC

If the SIGM is the case and the neutralino is the NLSP, its experimental signatures are high P_{T} photons, high P_{T} multiple jets and large missing P_{T}. However, the conventional minimal gauge mediated SUSY breaking (mGMSB) models with ultralight gravitino LSP and neutralino NLSP will also have similar signatures. Here, we discuss possible ways to discriminate between those two models.

We have seen that the SIGM predicts heavier scalar particles and violation of GUT relation for the gaugino masses. Therefore, we can straightforwardly discriminate the SIGM models from the mGMSB ones by measuring the SUSY particles' masses. However, it may require a large integrated luminosity. In the following, we propose another way to discriminate the SIGM at an earlier stage of the LHC experiments.

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[9]The lightest neutralino is bino-like and the second lightest neutralino is wino-like in a large region of the parameter space where κ_1 is not near the upper bound value. As κ_1 approaches the upper bound, μ becomes much smaller than $m_{\tilde{B}}$ and $m_{\widetilde{W}}$, and the higgsino components dominate in the first two lightest neutralino, whose masses approach zero when κ_1 is near the upper bound.
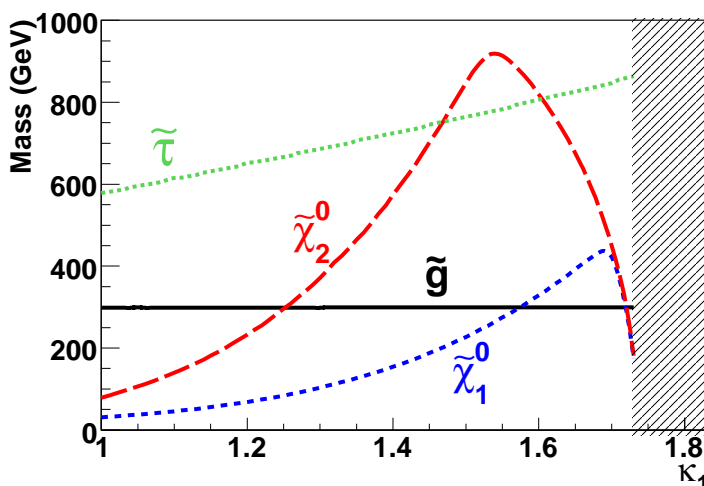
Figure 2: Mass spectrum for $\Lambda = 900\,\text{TeV}$ and $\kappa_2 = 1.8$. Here, scalar quark masses are approximately $3.5\,\text{TeV}$. In the shaded region, EW breaking dose not occur.

At the LHC, if the SIGM is the case, SUSY particles are mainly produced through:

$$pp \rightarrow \tilde{g} + \tilde{g} + X. \tag{4.1}$$

In the case that $m_{\widetilde{W}} > m_{\widetilde{g}}$, the gluinos dominantly decay into $\tilde{B} + q + \bar{q}$, $\tilde{B} + g$ and $\tilde{B} + t + \bar{t}$ if not kinematically forbidden. Then, the produced binos $\tilde{B}$ dominantly decay into $\gamma + \tilde{G}_{3/2}$, and $Z^0 + \tilde{G}_{3/2}$ if not kinematically forbidden ($\tilde{G}_{3/2}$ denotes the gravitino). Thus if $m_{\widetilde{W}} > m_{\widetilde{g}}$ is the case, there are no high P_{T} leptons except for ones which come from Z^0's and t's decays.

On the other hand, in the case of mGMSB, many lepton production channels exist since the wino (and sleptons) are lighter than the gluino. Therefore, we can distinguish between mGMSB and SIGM by counting the number of high P_{T} leptons. We consider two examples, by taking an SIGM ($m_{3/2} = 10\,\text{eV}$, $\kappa_1 = 1.35$, $\kappa_2 = 1.5$, $\tan\beta = 10$) and an mGMSB ($F/M_{\text{mess}} = 80\,\text{TeV}$, $M_{\text{mess}} = 160\,\text{TeV}$, $N_5 = 1$, $\tan\beta = 10$). The mass spectrums are shown in figures 3 and 4.[10] These spectrums are calculated by ISAJET7.72 [15]. To simulate LHC signatures for these models, we use programs Herwig 6.5 [16] and AcerDET-1.0 [17].

We take the events cuts as follows:

- ≥ 4 jets with $P_{\text{T}} > 50\,\text{GeV}$ and $P_{\text{T},1,2} > 100\,\text{GeV}$.

- ≥ 2 photons with $P_{\text{T}} > 10\,\text{GeV}$ and $P_{\text{T},1} > 20\,\text{GeV}$.

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[10]This mGMSB example has a light gluino, but it does not satisfy the Higgs mass bound. (See the discussion in section 1.) We take this model point just as a demonstration, for a comparison to the SIGM.
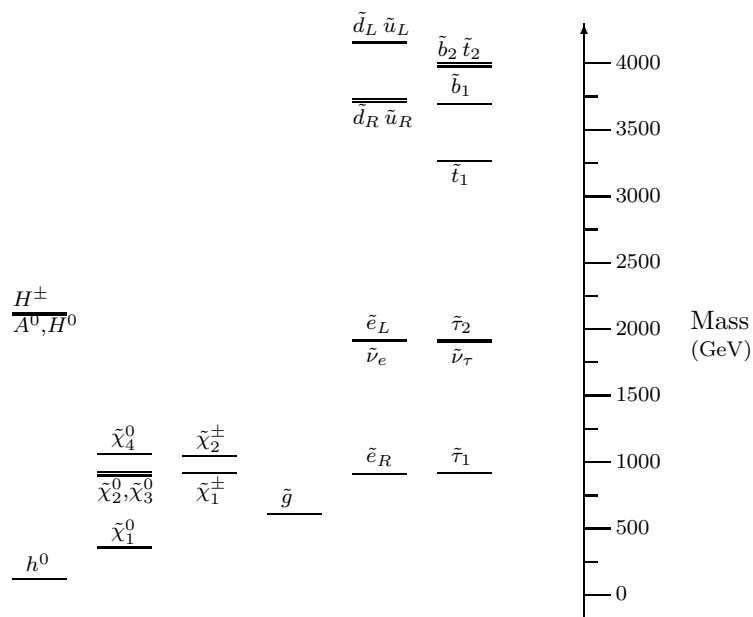
Figure 3: SIGM mass spectrum for $m_{3/2} = 10\,\text{eV}$, $\kappa_1 = 1.35$, $\kappa_2 = 1.5$ and $\tan\beta = 10$.
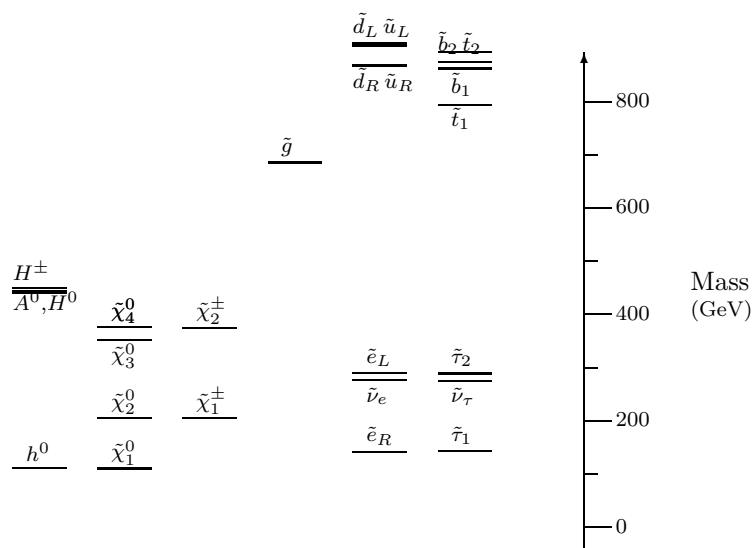

Figure 4: mGMSB mass spectrum $F/M_{\text{mess}} = 80\,\text{TeV}$, $M_{\text{mess}} = 160\,\text{TeV}$, $N_5 = 1$ and $\tan\beta = 10$.

- $M_{\text{eff}} > 500\,\text{GeV}$, where

$$M_{\text{eff}} = \sum_{\text{jets}}^{4} P_{\text{T}j} + P_{\text{T,miss}}. \qquad (4.2)$$

- $P_{\text{T,miss}} > 0.2 M_{\text{eff}}$.

Under these cuts, we see that the standard model backgrounds are almost negligible.

The number distributions for high P_{T} leptons (with $P_{\text{T}} > 20\,\text{GeV}$) are shown in figure 5. In figure 5, we can see there are very few leptons produced at the LHC in the SIGM.
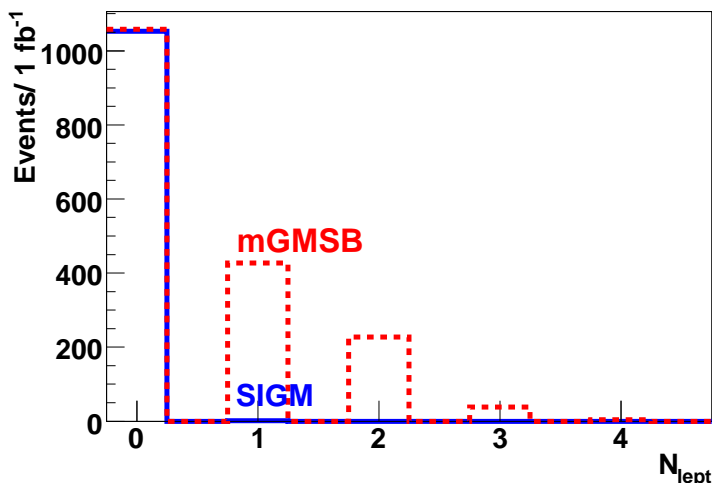
Figure 5: The lepton number distributions for mGMSB and SIGM.

The photon cuts reduce the lepton production from $\tilde{B}$'s decay, and the decay $\tilde{g} \to \tilde{B} + t + \bar{t}$ is kinematically forbidden in the SIGM example.

In general, larger κ_1 results in the smaller production rate for high P_T leptons. To see the relation of κ_1 to the lepton production rate, we define R as

$$R \equiv \frac{\text{\# of events after the cuts with at least one lepton } (P_T > 20 \text{ GeV})}{\text{\# of all events after the cuts}}. \qquad (4.3)$$

For the conventional mGMSB with the parameters given above, we obtain $R = 0.40$. In figures 6 and 7 we show the κ_1 dependence of R and $(m_{\tilde{g}}, m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0})$ in the SIGM ($m_{3/2} = 10 \,\text{eV}$, $\kappa_2 = 1.5$ and $\tan\beta = 10$), respectively. To compute R, 20000 SUSY events are generated for each value of κ_1.

Figure 6 clearly shows that there are less lepton production for larger κ_1. It is also confirmed that in the case $m_{\tilde{W}} \gtrsim m_{\tilde{g}}$ almost no leptons are produced. Thus, we may distinguish between mGMSB and SIGM by counting the number of high P_T leptons.

5. Discussion

The strongly interacting gauge mediation (SIGM) predicts gaugino masses without the GUT relation, in particular a relatively light gluino compared with a conventional gauge mediation. We have calculated the SUSY mass spectrum by taking some explicit examples, and shown that the SIGM with such a mass spectrum can be discriminated simply by counting the number of high P_T leptons.

If many events with two photons, multiple jets and missing energy are discovered at the LHC, it naturally points to gauge mediation models with a neutralino NLSP and the gravitino LSP. If the number of such events is large, which suggests the light gluino or squark, it may already indicate an unconventional gauge mediation mass spectrum even
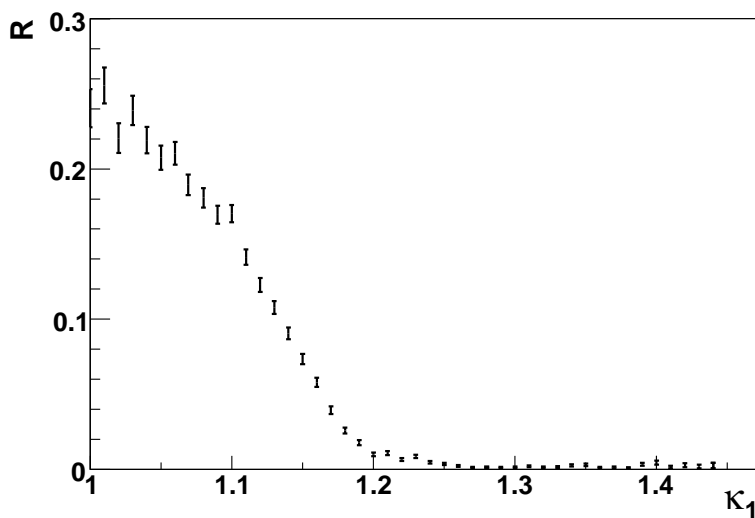
Figure 6: The relation of κ_1 to R. SIGM parameters are the same as in figure 3 except for κ_1. Error bars represent only the statistical errors.
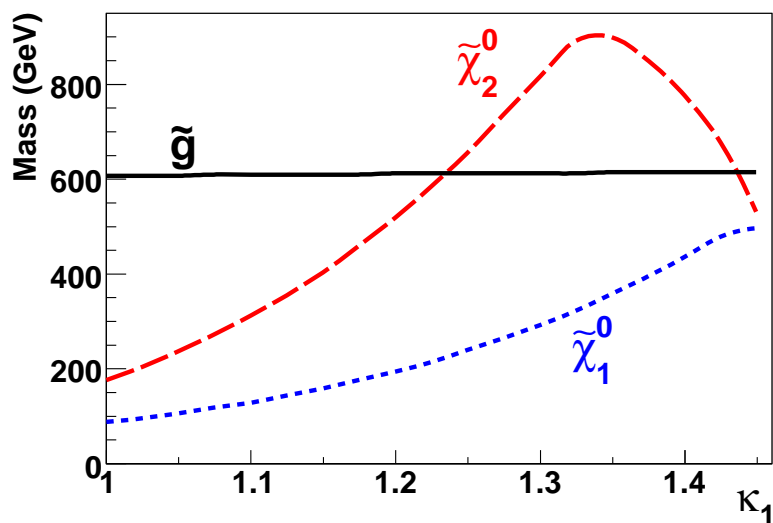

Figure 7: The relation of κ_1 to $m_{\tilde{g}}$ and $m_{\tilde{\chi}^0_{1,2}}$.

at an early stage of the LHC experiments.[11] We can then test a peculiar mass hierarchy among gauginos by simply counting the number of high P_{T} leptons, as investigated in this letter.

We have also found that the gluino can even be the NLSP for some parameter region.

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[11]Note that the gluino and squarks are heavy in the conventional GMSB models. See footnote 1.

In this case the main SUSY event signal will be two jets + missing energy. In such a case, it will be challenging to identify the LSP (gravitino) and the NLSP (gluino).

Acknowledgments

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