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Discovery of supersymmetry with degenerate mass spectrum

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The discovery of supersymmetric (SUSY) particles at the Large Hadron Collider (LHC) has been studied for models where the squarks and gluinos are much heavier than the lightest supersymmetric particle. In this paper, we investigate SUSY discovery in models with a degenerate mass spectrum up to \( m_{\text{LSP}} \approx 0.7 m_{\tilde{q}} \). Such a mass spectrum is predicted in a certain parameter region of the mixed modulus anomaly mediation model. We find that the effective transverse mass of the signal for the degenerate parameters shows a distribution similar to that of the background. Experimental sensitivity to the SUSY particles at the LHC therefore depends on the uncertainty of the background in this class of model. We also find that the SUSY signal shows an interesting correlation between \( M_{\text{eff}} \) and \( \not{E}_T \) which may be used to better determine the signal region and enhance the S/N ratio even if the sparticle masses are rather degenerate. This correlation is universal for models with new heavy colored particles decaying into visible particles and a stable neutral dark matter.

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I. INTRODUCTION: TRANSVERSE PHYSICS AND ITS NONTRANSVERSE LIMIT

The minimal supersymmetric standard model (MSSM) is one of the most promising candidates for physics beyond the standard model (SM), which may solve the hierarchy problem in the Higgs sector [1]. The model predicts a set of superpartners (sparticles) whose charges are exactly the same as those of their SM partners but whose spins are different by one half.

Direct searches for these sparticles will be performed at the Large Hadron Collider (LHC) at CERN, which is a \( pp \) collider with 14 TeV center of mass energy. The LHC is scheduled to start its operation in 2007, followed by physics runs in 2008. If \( R \) parity is conserved, all sparticles are assigned to have an odd \( R \) parity. The lightest supersymmetric particle (LSP) is then stable, and a candidate for dark matter. Sparticles are produced in pairs, and each sparticle decay should produce at least one LSP. Supersymmetric (SUSY) events therefore have a distinctive missing transverse momentum signature.

If supersymmetry is an exact symmetry, the mass of a particle and its superpartner are the same. Since this has not been observed, SUSY must be spontaneously broken. In most models of spontaneous SUSY breaking, the SUSY breaking must occur in a “hidden sector” and is mediated to our sector by mediation fields. This mechanism is already severely constrained. For example, the masses of the first and second generation sfermions with the same charge must either be the same or very large so that they do not cause dangerous flavor-changing neutral-current interactions. This suggests that as yet unknown symmetry/dynamics in the mediation mechanism may exist. The origin of the supersymmetry breaking and mediation mechanism may be understood indirectly by measuring the masses of the SUSY particles. Therefore, both the discovery and the mass determination of the SUSY particles have been studied intensively in recent years [2–5].

If SUSY is broken at some high energy scale and the boundary conditions are universal at this scale, strongly interacting SUSY particles are heavier than electroweakly interacting (EWI) SUSY particles. For example, gaugino masses follow the relation

\[
M_1 : M_2 : M_3 \sim 0.4 : 0.8 : 2.4
\]

in the minimal supergravity model, so the gluino is 6 times heavier than the binolike particles. At the LHC, strongly interacting SUSY particles will be copiously produced in \( pp \) collisions and will subsequently decay into lighter EWI SUSY particles.

The gluino and squark decays give final states with high transverse momentum (\( p_T \)) jets. The transverse momentum is of the order of the gluino and squark masses. As the LSP is significantly lighter than the gluino, the LSP from the gluino decay also has a high \( p_T \), giving rise to a large missing transverse momentum in SUSY events. In addition, decays of the EWI sparticles may produce high \( p_T \) leptons. Events from SM processes are on average not associated with such high \( p_T \) particles.

Motivated by these observations, the following cuts are often applied to SUSY events to reduce the SM background [2,3]:

(i) events are required to have at least one jet with \( p_T > 100 \) GeV and three jets with \( p_T > 50 \) GeV within \( |\eta| < 3 \);

(ii) the effective mass of the event must satisfy \( M_{\text{eff}} > 400 \) GeV, where the effective mass is defined using the transverse missing energy (\( \not{E}_T \)) and the transverse momenta of four leading jets as

\[
M_{\text{eff}} \equiv \sum_{i=1}^{4} p_{Ti} + \not{E}_T.
\]
If the event has hard isolated leptons, the effective mass may be defined as follows:

$$M_{\text{eff}} = \sum_{i=1,4} p_{Ti} + \sum_{\text{leptons}} p_{Ti} + \mathcal{E}_T,$$  \hspace{1cm} (3)

where the sum of the lepton $p_T$ can be taken over the leptons with $p_T > 20$ GeV and $|\eta| < 2.5$ GeV;

(iii) the missing transverse energy must satisfy the relation

$$\mathcal{E}_T > \max(0.2M_{\text{eff}}, 100 \text{ GeV});$$  \hspace{1cm} (4)

(iv) The transverse sphericity $S_T$ must be greater than 0.2, where $S_T$ is defined as $2\lambda_2/(\lambda_1 + \lambda_2)$, with $\lambda_1$ and $\lambda_2$ being the eigenvalues of the $2 \times 2$ sphericity tensor $S_{ij} = \sum_k p_i^{(k)} p_j^{(k)}$, where $p_i^{(k)}$ is the transverse momentum vector of the $k$th calorimeter cell.

To reduce the background further, one or more hard, isolated leptons may be required.

These cuts are good enough to reduce the SM backgrounds from $t\bar{t} + n$ jets and $W(Z) + n$ jets productions down to a manageable level, although the production cross sections of the SM processes may be $O(10^4)$ higher than the signal cross sections. While the total SUSY production cross section reduces very quickly as sparticle masses increase beyond 1 TeV, the signal distribution peaks at higher $M_{\text{eff}}$ where backgrounds can be ignored. Previous studies show that the squark and gluino with masses around 2.5 TeV can be found at the LHC in the minimal supergravity (MSUGRA) model.

In MSUGRA, the SM background after the cuts can safely be neglected. The distribution of the accepted events can then be used to determine the mass scale of the SUSY particles. For example, the peak of the $M_{\text{eff}}$ distribution is sensitive to the squark and gluino masses. For events with same flavor opposite sign dileptons, the invariant mass distributions, $m_{jj}$, $m_{ej}$, $m_{jjll}$, and $m_{ejll}$, can be used to reconstruct the SUSY particle masses $m_{\tilde{q}}$, $m_{\tilde{g}}$, $m_{\tilde{u}}$, and $m_{\tilde{d}}$.

It was pointed out recently that a string inspired model based on flux compactification (KKLT models) [6] predicts a mass relation different to that of MSUGRA [7–9]. This SUSY breaking model, the so-called mixed modulus anomaly mediation (MMAM) model, has a volume modulus $T$ and a compensator field of minimum supergravity model $C$ as a messenger of the SUSY breaking. The SUSY mass spectrum depends on the ratio of the two SUSY breaking parameters $F_T$ and $F_C$. It is interesting that the unification scale of the soft SUSY parameters can be much lower than the grand unified theory (GUT) scale in this model. They may even unify at the weak scale for a special choice of the model parameters, so the mass spectrum can be significantly more degenerate than that of MSUGRA.

When sparticle masses are degenerate at the weak scale, we expect a reduced probability to have high $p_T$ jets, and smaller $M_{\text{eff}}$ and $\mathcal{E}_T$ for given squark and gluino masses. This means that the standard SUSY cuts also reduce the signal events, and SUSY discovery is more affected by the SM background. While there are some studies on the collider phenomenology of the MMAM model [10,11], there has been no emphasis on the parameter region with significant mass degeneracy, $m_{\tilde{q},\tilde{g}} > 0.5 m_{\tilde{q},\tilde{g}}$.

Quantitative understanding of the SM background distributions may be required in this case. Recently, several groups have emphasized the importance of including the matrix element corrections [12–14] in the parton shower estimate of the background. They report significant changes of the background distributions in the signal region with large $M_{\text{eff}}$ and high $p_T$ jets. In addition, there exists an uncertainty in the scale of QCD coupling due to the nonexistence of NLO calculations for many of the relevant processes. When the overlap between the signal and background distributions is large, as is expected for a degenerate SUSY spectrum, the uncertainty of the background must be taken seriously, and we also need to reconsider the cuts used to reduce the background.

The purpose of this paper is to illustrate the phenomenology of degenerate supersymmetry. We take the MMAM model as an example. By changing the ratio $F_C/F_T$, the mass spectrum changes smoothly from a MSUGRA-like one to an anomaly-mediation-like one. In between, there are regions where the squark, slepton, and gaugino masses are significantly degenerate compared with those expected in MSUGRA. The model therefore provides a one dimensional parametrization from the “transverse signature” to its nontransverse limit. The investigation of our analysis may easily be extended to other SUSY/non-SUSY scenarios with an $\mathcal{E}_T$ signature, such as the universal extra dimension [15] model or little Higgs model with $T$ parity [16].

This paper is organized as follows. In Sec. II we describe the MMAM model and its mass spectrum with an emphasis on the region of parameter space where sparticle masses are degenerate. In Sec. III, we describe our Monte Carlo simulations. In Sec. IV, we study how SUSY event distributions depend on the sparticle mass degeneracy and compare it to previously published background distributions. We find that the signal $M_{\text{eff}}$ distribution is quite similar to that of the background if $m_{\tilde{q},\tilde{g}} > 0.5 m_{\tilde{q},\tilde{g}}$. However, we find that $\mathcal{E}_T$ peaks at a certain large value for fixed $M_{\text{eff}}$ for the signal distribution, which might provide a handle to discriminate the signal from the background. This is a universal feature for models with heavy colored particles that finally decay into a stable neutral particle. Section V is devoted to discussions and conclusions.

II. THE MMAM MODEL

A. Boundary conditions at the GUT scale

In this section, we briefly describe the MMAM model following the notation in [7]. In this model, all shape
modulus and dilaton will be fixed by nonzero flux on a
Calabi-Yau manifold in the Type IIB string theory. The low
energy \( N = 1 \) Lagrangian of this model is given by an
unfixed volume modulus \( T \), a compensator field \( C \), and
gauge and matter fields \( W^a \) and \( Q_i \), as

\[
S_{N=1} = \int d^4x \sqrt{|g|} e^{-\pi \Phi} \left[ d^4 \theta C C^\ast \left(-3 \exp(-K_{\text{eff}}/3)\right) + \left[ d^4 \theta (f_a W^{a\alpha} W^\alpha_a + C^3 W_{\text{eff}}) + \text{H.c.} \right] \right]. \tag{5}
\]

Here \( K_{\text{eff}} = -3 \ln (T + T^\ast) + Z_i (T + T^\ast) Q_i^\ast Q_i \), \( g_{\mu \nu} \) is
the 4D metric in the superconformal frame. \( T = T_0 + F_T \theta^2 \) and \( C = C_0 + F_C \theta^2 \) are the volume modulus
and the chiral compensator superfield of \( N = 1 \) SUGRA,
respectively. \( W_{\text{eff}} = W_0(T) + \frac{1}{5} \lambda_{ijk} Q_i Q_j Q_k \) is the super-
potential for \( T \) and matter \( Q_i \). The \( T \) dependent functions
\( Z_i \) and \( f_i \) may be expressed as

\[
Z_i = \frac{1}{(T + T^\ast)^{n_i}}, \quad f_a = T^{n_a}, \tag{6}
\]

where \( n_i \) are the modular weights and \( n_i = 0(1) \) for matter
fields located on D7 (D3) branes, and \( n_i = 1/2 \) for matter
fields living at brane intersections [7].

In the KKLT model, \( W_0 = w_0 - A \exp^{-\alpha T} \), where the
last term of \( W_0 \) expresses nonperturbative effect (such as the
gaugino condensation on a D7 brane) which fixes the
volume modulus \( T \), and \( w_0 \) is the contribution of the flux.
In addition to the \( N = 1 \) supersymmetric action, there is
a nonsupersymmetric potential from anti-D3 branes. The
term is expressed by a spurion operator depending on \( T \)
and \( C \), and the minimum of the potential will be obtained by
solving the total potential. The nonsupersymmetric potential
lifts the minimum of the potential from an AdS vacuum to a
(nearly Minkowski) de Sitter vacuum.

The resulting theory is parametrized by \( \langle F_C/C_b \rangle \sim m_{3/2} \)
and \( \langle F_T/(T + T^\ast) \rangle \). The SUSY breaking terms are
gained by expanding the action by \( \langle F_T \rangle \) and \( \langle F_C \rangle \). Here
we define the soft terms as

\[
L_{\text{soft}} = -\frac{1}{2} M_a \lambda^a \lambda^a - m_i^2 |\tilde{Q}_i|^2 - A_{ijk} \tilde{Y}_{ij} \tilde{Q}_i \tilde{Q}_j \tilde{Q}_k + \text{H.c.}, \tag{7}
\]

where \( y_{ijk} \) is a canonically normalized Yukawa coupling

\[
y_{ijk} = \frac{\lambda_{ijk}}{\sqrt{e^{-\kappa_a Z_a Z_a Z_a}}} \tag{8}
\]

The soft masses are explicitly written as functions of \( m_{3/2} \)
and \( R \equiv m_{3/2} (T + T^\ast)/F_T \) as follows:

\[
M_a = \left( \frac{1}{R} + b_a \frac{g_{\text{GUT}}}{16 \pi^2} \right) m_{3/2},
\]

\[
m_i^2 = \frac{m_i}{R^2} + \frac{1}{R} \frac{\partial \gamma_i}{\partial \ln R} - \frac{1}{4} \frac{\partial \gamma_i}{\partial \ln \mu} m_{3/2}^2,
\]

\[
A_{ijk} = \left( \frac{1}{R} (m_i + m_j + m_k) - \frac{1}{2} (\gamma_i + \gamma_j + \gamma_k) \right) m_{3/2}, \tag{9}
\]

where \( m_i = 1 - n_i \) and

\[
\gamma_r = \frac{1}{8 \pi} \left( 2 \sum_a C_{r a} g_{a a}^2 - d_r y^2 \right) \tag{10}
\]

with \( C_{r 1} = \sum_a T_{a r}^2 (r) \), namely, for matter in the fundamental
representation \( C_{r 1} = 4/3 \), \( C_{r 2} = 3/4 \), \( C_{r 3} = Y^2 \). We only
include the effect of the top Yukawa coupling \( y \); therefore,
\( d_{Q_3} = 1 \), \( d_T = 2 \), \( d_{H^2} = 3 \), and \( d_i = 0 \) otherwise.

The scale dependence of \( \gamma_i \) is expressed as

\[
\frac{d \gamma_i}{d \mu} = \frac{b_i C_i}{32 \pi^2} g_i^4 - d_i \frac{y^2}{32 \pi^2} \left( \frac{D}{2} y^2 - \sum_a C_{a i} g_a^2 \right), \tag{11}
\]

where

\[
\frac{dy_i}{d \ln \mu} = \frac{b_i}{8 \pi^2} g_i^3. \tag{12}
\]

Here, \( D = \sum_r d_r = 6 \), \( C_3 = \sum_r C_{r 3} = 8 \), \( C_2 = \frac{3}{2} \), \( C' = \frac{13}{18} \),
and \( b' = 11 \), \( b_1 = 33/5 \), \( b_2 = 1 \), \( b_3 = -3 \).

Finally,

\[
\frac{d \gamma_i}{d \ln T} = (m_i + m_j + m_k) \frac{d_r}{8 \pi^2} y^2 - \sum_a C_{r a} g_a^2. \tag{14}
\]

### B. Mass spectrum in the MMAM model

In Eq. (9), the highest term in \( 1/R \) is the contribution of
the modulus \( T \), while the terms independent of \( 1/R \) are due
to pure anomaly mediation. In [7], it is pointed out that the
mass spectrum in the MMAM model shows a special feature if \( \alpha \sim 1 \), where

\[
\alpha = \frac{R}{\ln (M_{\text{pl}}/m_{3/2})}. \tag{15}
\]

This can be seen by investigating the low energy mass
parameters as functions of \( \alpha \). For example, when \( l_a = 1 \),
gaugino masses at the scale \( \mu \) may be expressed as

\[1\text{Sign convention for the } A \text{ parameter is such that the off}-
\text{diagonal element of } \eta \text{ mass matrix is } -m_{\tau} (A_{\tau} + \mu \tan \beta).

115011-3
The Higgs soft mass parameters get a large positive correction from the gaugino masses. The top/stop loop correction is largely compensated by the gaugino corrections at the weak scale. As a result, $M_1 \sim \mu$ for $R \sim 37$. For larger values of $R$, $\mu$ becomes smaller than $M_1, M_2$ and the mass splitting among SUSY particles increases again.

In our study, we are interested in the model point where the mass splitting among the SUSY particles is the smallest. This can be achieved by increasing the $\mu$ parameter. The $\mu$ parameter would be largest when the GUT scale value of the Higgs soft SUSY breaking mass is the smallest, namely, $n_{H_u} = n_{H_d} = 1$. In that case, sfermion masses at the GUT scale must be large to avoid a $\tilde{t}_L$ or $\tilde{t}_R$ LSP when $\mu \sim M_1, n_{\text{matter}} = 0$. We call this choice of $n_i$ "model B." Some of the MSSM parameters for model B are also shown in Table II. The mass spectra of models A and B for $M_3(GUT) = 450$ GeV and $\tan \beta = 10$ are compared in Table III. The mass difference between the squark (gluino) and LSP is at a minimum when $M_1 \sim \mu$ at $R = R_c$. $R_c \sim 40$ for model A and 55 for model B, where $m_{\tilde{q}}/m_{\tilde{q}} = 0.55$

Note that ISAJET runs two loop RGE for all soft parameters, while the boundary conditions are calculated by the formula using one loop RGE.

### Table I. The relation between $\alpha$, $R$, and $m_{3/2}/R$ (TeV) for $M_3(GUT) = 450$ GeV.

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>$m_{3/2}/R$ (TeV)</th>
<th>$R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.26 \times 10^{-2}$</td>
<td>0.45</td>
<td>0.1</td>
</tr>
<tr>
<td>0.30</td>
<td>0.50</td>
<td>10</td>
</tr>
<tr>
<td>0.61</td>
<td>0.56</td>
<td>20</td>
</tr>
<tr>
<td>0.92</td>
<td>0.63</td>
<td>30</td>
</tr>
<tr>
<td>1.25</td>
<td>0.73</td>
<td>40</td>
</tr>
<tr>
<td>1.58</td>
<td>0.86</td>
<td>50</td>
</tr>
<tr>
<td>1.92</td>
<td>1.06</td>
<td>60</td>
</tr>
</tbody>
</table>

$M_n(\mu) = \frac{m_{3/2}}{R} \left[ 1 - \frac{1}{4\pi^2} b_n s_n^2(\mu) \ln \left( \frac{M_{\text{GUT}}}{(M_1/m_{3/2})^{2/3}} \right) \right]$

(16)

at the one loop level. When $\alpha \sim 2$, the log term in the equation becomes 0 at $M_{\text{SUSY}}$ and the gaugino masses unify at the weak scale, rather than at the GUT scale.

The mass spectrum in the matter sector depends on $n_i$. If the Yukawa couplings $y_{ijk}$ are nonvanishing only for the combination $Q_i Q_j Q_k$ satisfying $n_i + n_j + n_k = 2$, or if the effect of the Yukawa couplings in the renormalization group equation (RGE) can be ignored, the scalar masses and trilinear couplings also unify at the same scale as the gaugino mass unification. This relation is satisfied for the choice $n_{H_u} = 1$ and $n_{\text{matter}} = 1/2$; we call this choice of the boundary condition “model A.”

In Table I, we show the relation between $R$ and $\alpha$ at a fixed gluino mass parameter at a GUT scale of 450 GeV. This corresponds to $M_3(M_{\text{SUSY}}) = \alpha_s(M_{\text{SUSY}}) / \alpha_s(GUT) \times M_3(GUT) = 1.1$ TeV. The unification of gaugino/sfermion masses occurs at $R \sim 60$.

In the following discussion, we calculate the low energy mass spectrum using ISAJET [17] version 7.72 which solves the boundary condition given in Sec. II.A. The sparticle mass spectra for model A are listed in Table II for $M_3(GUT) = 450$ GeV. As $\alpha$ increases, gaugino masses and slepton and squark masses get closer, and the model shows a mass pattern different to that of MSUGRA. The numerical values roughly agree with those in [7].

As can be seen in Table II, the higgsino mass parameter $\mu$ decreases as $\alpha$ increases. The $\mu$ parameter is determined by solving the minimization condition of the Higgs effective potential. In the minimal supergravity model ($R = 0$ limit), the square of the Higgs soft scalar mass receives a large negative correction from the stop/top loop. The $\mu$ parameter is chosen to compensate the negative value to get correct electroweak symmetry breaking. Therefore, $\mu$ can be as large as the stop mass in the minimal supergravity model. When $\alpha$ is large, $M_1, M_2 \gg M_3$ at the GUT scale.

### Table II. Example of ISAJET solutions of the low energy particle mass spectrum for models A and B, for different values of $R$. Here we fix the low energy gluino mass roughly constant by choosing $M_3(GUT) = 450$ GeV and $\tan \beta = 10$. All mass parameters are given in GeV.

<table>
<thead>
<tr>
<th>model A</th>
<th>$R$</th>
<th>$M_3$</th>
<th>$M_1$</th>
<th>$M_2$</th>
<th>$\mu$</th>
<th>$m_{\tilde{g}}$</th>
<th>$m_{\tilde{q}}$</th>
<th>$m_{3/2}/R$</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1055</td>
<td>184</td>
<td>350</td>
<td>700</td>
<td>957</td>
<td>435</td>
<td>354</td>
<td>450</td>
<td>0.26 $\times 10^{-2}$</td>
</tr>
<tr>
<td>30</td>
<td>1045</td>
<td>436</td>
<td>536</td>
<td>607</td>
<td>913</td>
<td>531</td>
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</tr>
<tr>
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<td>1038</td>
<td>573</td>
<td>653</td>
<td>545</td>
<td>879</td>
<td>578</td>
<td>541</td>
<td>729</td>
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</tr>
<tr>
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<td>1034</td>
<td>657</td>
<td>717</td>
<td>499</td>
<td>852</td>
<td>604</td>
<td>576</td>
<td>790</td>
<td>1.41</td>
</tr>
<tr>
<td>55</td>
<td>1020</td>
<td>882</td>
<td>892</td>
<td>339</td>
<td>765</td>
<td>671</td>
<td>675</td>
<td>951</td>
<td>1.74</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>model B</th>
<th>$R$</th>
<th>$M_3$</th>
<th>$M_1$</th>
<th>$M_2$</th>
<th>$\mu$</th>
<th>$m_{\tilde{g}}$</th>
<th>$m_{\tilde{q}}$</th>
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<td>897</td>
<td>892</td>
<td>744</td>
<td>990</td>
<td>945</td>
<td>953</td>
</tr>
</tbody>
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### Table III. The squark, gluino, and the lightest neutralino masses in models A and B. $M_3(GUT) = 450$ GeV and $\tan \beta = 10$.

<table>
<thead>
<tr>
<th>set A</th>
<th>$R$</th>
<th>$m_{\tilde{u}_L}$</th>
<th>$(m_{\tilde{g}})$</th>
<th>$m_{\tilde{q}}$</th>
<th>$2p_{CM}$</th>
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<tbody>
<tr>
<td>0</td>
<td>1055</td>
<td>182</td>
<td>961</td>
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<td>354</td>
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<tr>
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<td>924</td>
<td>435</td>
<td>354</td>
</tr>
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<td>326</td>
<td>793</td>
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<td>354</td>
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<tr>
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<td>726</td>
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<td>700</td>
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</tbody>
</table>

Note: ISAJET runs two loop RGE for all soft parameters, while the boundary conditions are calculated by the formula using one loop RGE.
and 0.70, respectively. Model set B has a more degenerate mass spectrum at $R = R_1$, because the $\mu$ parameter is larger for the same gaugino masses.

In the following sections, we discuss the discovery potential of degenerate SUSY particles at the LHC. A phenomenologically important parameter at a hadron collider is the typical mass scale of the event. This can be expressed by the energy of the jet from a $q \rightarrow \tilde{q} \tilde{l}$ decay in the $\tilde{q}$ rest frame, which is given by

$$2p_{CM} = \frac{m_{\tilde{q}}^2 - m_{\tilde{l}}^2}{m_{\tilde{q}}}.$$  

(17)

Because sparticles are pair produced, $2p_{CM}$ shows the typical size of the effective transverse mass $M_{\text{eff}}$ of the SUSY production process. We list the value of $2p_{CM}$ for the model points in Table III. $M_{\text{eff}} \approx 2p_{CM}$ can be reduced by a factor of 2/3 to 1/2 for $m_{\tilde{l}} > 0.5m_{\tilde{q}}$. In the following sections, we find that the discovery of SUSY particles will be nontrivial in this region.

It is worth noting that gauginos and higgsinos are highly mixed when $p_{CM}$ is close to the minimum value. A relatively large nucleon-LSP scattering cross section and small dark matter density are expected, possibly consistent with cosmological constraints. The mass density is much above 1 for $R < 20$ because the LSP is gauginolike and the sleptons are heavy. When $\mu \sim M_1$, the mass density is as small as current observation $\Omega h^2 \sim 0.1$ [18]. We found $\Omega h^2 = 0.27(0.031)$ at $R = 30(40)$ for model A, $\Omega h^2 = 0.423(0.037)$ at $R = 40(50)$ for model B, both for $M_3(GUT) = 450$ GeV and $\tan\beta = 10$, with $\chi p$ cross section between $10^{-7}$ pb and $10^{-9}$ pb.

The branching ratios of the gluino and squarks into leptons are other important quantities for collider phenomenology. The leptons tend to be produced from the neutralino or chargino decays arising from squark decays. For model A, the decay channels $\tilde{q} \rightarrow \tilde{l}(\tilde{W}, \tilde{B})$ are open unless $R > 50$. In particular, if the decay channel $\tilde{q} \rightarrow \tilde{l}(l = e, \mu) \rightarrow \tilde{\chi}^0_1 l$ is open, a large branching ratio into the golden mode $\tilde{q} \rightarrow \tilde{\chi}^0_1 ll$ is expected. For example, $\text{Br}(\tilde{\chi}^+ \rightarrow \tau\nu) \sim 80\%$ and $\text{Br}(\tilde{\chi}^0_2 \rightarrow \mu^+ \mu^-) \sim 14\%$ for model A with $M_{\tilde{l}}(GUT) = 450$ GeV, $\tan\beta = 10$, and $R = 37$. For model A, $M_2 > M_1$ if $R > 20$, so the decay channel is open in the degenerate region. For model B, slepton masses are large so the decay into sleptons is always forbidden.

**III. MONTE CARLO SIMULATION AND RECONSTRUCTION**

Here we describe the event simulation method used in the next section. As explained earlier, the SUSY mass spectrum is calculated by ISAJET [17] which is interfaced to the HERWIG [19] event generator using ISAWIG [20]. HERWIG generates hard SUSY processes, takes care of initial and final state radiation, and fragments partons into hadrons.

To estimate event distributions to be measured by the LHC detectors, we smear particle energies, identify isolated leptons, and reconstruct jets. We independently developed a fast detector simulation program,\(^3\) which takes the following steps:

1. **Finding isolated leptons.**—If a lepton ($e$ or $\mu$) with $E_T > 10$ GeV and $|\eta| < 2.5$ is found in an event record, we take a cone with a size $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.2$ around the lepton. If the sum of $E_T$ of the particles in the cone (except the lepton at the center of the cone) is less than 10 GeV, we regard it as an isolated lepton candidate. After the jet reconstruction described below, isolated lepton candidates with min$(\Delta R(lj)) > 0.4$ are accepted as isolated leptons.

2. **Reconstruction of jets.**—We adopt a simple jet finding algorithm PYCELL, a subroutine in PYTHIA [22], with minor modifications in its treatment of leptons and energy smearing:

   a. We remove isolated lepton candidates for the jet reconstruction.

   b. Particle energies are measured by the electromagnetic and hadronic calorimeters. We assume that the number of calorimeter cells in the $\eta$ direction is 50 within $|\eta| < 3$ and 50 in the $\phi$ direction. The transverse energy deposit $E_T$ in a cell is summed for electrons, photons, and hadrons as

   $$E_T(\text{EM}) = \sum_{\text{electrons}} E_T + \sum_{\text{photons}} E_T,$$

   $$E_T(\text{had}) = \sum_{\text{hadrons}} E_T,$$

   which correspond to the hits in the electromagnetic and hadronic calorimeter cells, respectively.

   c. The transverse energy deposit in each cell is smeared by Gaussian energy resolutions $\sigma_{E_T}(\text{EM}) = 0.1/\sqrt{E_T(\text{EM})}$ [GeV] and $\sigma_{E_T}(\text{had}) = 0.5/\sqrt{E_T(\text{had})}$ [GeV]. After the energy smearing, we regard the sum of smeared $E_T(\text{EM})$ and $E_T(\text{had})$ as the measured energy deposit in the cell.

   d. We take the highest $E_T$ cell as the initiator and sum the energy deposits in the cells within $\Delta R < 0.4$. We accept the cluster as a jet if $\sum_{\text{cluster}} E_T > 10$ GeV. We repeat this procedure after removing the cells which have been used already for the jet reconstruction.

\(^3\)Recently, a fine event simulator PGS (pretty good simulation) [21] is also available.
The reconstruction process (1 and 2) is similar to the fast simulation codes used by the ATLAS and CMS groups. Note that we do not smear the energy of isolated leptons and assume they are identified correctly, because the energy resolution and particle identification of leptons are excellent in both the LHC detectors. We smear photon and nonisolated electron energies with better resolution than that for hadrons; however, for simplicity we do not assume a fine grained electromagnetic calorimeter in our simulation.

Our simulation does not take care of other detector effects, such as misidentification of leptons and hadrons, nonuniformity of detector responses (cracks), and non-Gaussian smearing in the energy measurements. The simulation, however, reproduces the signal distributions of past simulation studies reasonably well.

To check the validity of our simulation, we compare our simulation results with published distributions of SUSY signals using the ATLASTFAST simulator [23]. Figure 1 shows simulation results with published distributions of SUSY event samples reasonably well. In this subsection, we study the signal distributions of past simulation studies. In Fig. 1 we show the distribution for the plot, corresponding to \( \int L dt = 1.8 \text{ fb}^{-1} \). The edge and the end point appear at their expected positions. The distribution has a sharper edge compared with that in [5], because we do not smear lepton energies in our simulation. We find that 445 events remain after the cuts and the background subtraction. In the report [5] roughly \( 2.5 \times 10^4 \) events remain after the cuts for \( \int L dt = 100 \text{ fb}^{-1} \). The acceptance of the two simulations therefore agree within 1\( \sigma \).

**IV. DISCOVERY OF THE DEGENERATE SUSY MODEL**

A. Mass degeneracy and signal distributions

In this subsection, we study the \( M_{\text{eff}} \) distributions at the SUSY model points with a degenerate mass spectrum discussed in the previous section.

We first show the \( p_T \) distribution of the first jet in the left panel of Fig. 2. Here we take the model B, \( M_3(\text{GUT}) = 450 \text{ GeV} \), \( \tan \beta = 10 \) and vary the degeneracy of the mass spectrum by changing \( R \) from 0 to 55. As \( R \) increases, the sparticle mass differences get smaller, resulting in a softer \( p_T \) distribution. The positions of the peaks are positively correlated with \( p_{CM} \) which ranges from 504 GeV to 265 GeV when we change \( R \) from 0 to 55. The acceptance for SUSY events would depend on \( R \). For example, the fraction of events with \( p_T < 160 \text{ GeV} \) is only 16% for \( R = 0 \) but is 35% for \( R = 55 \). This means that roughly one third of the events are rejected by the requirement on the first jet \( p_T \) cut \( p_T > 150 \text{ GeV} \) for the latter point.

The \( M_{\text{eff}} \) distribution shows a similar behavior. In Fig. 2 (right), we show the \( M_{\text{eff}} \) distributions for model B, with \( M_3(\text{GUT}) = 450 \text{ GeV} \) (solid histograms) and \( M_3(\text{GUT}) = 650 \text{ GeV} \) (dashed histograms), respectively. We apply the cuts listed in Sec. I and additionally require one hard isolated lepton with \( p_T > 20 \text{ GeV} \) and \( |\eta| < 2.5 \). In the figure, we compare the distributions with \( R = 0.1 \) (MSUGRA-like) and \( R = 30 \) to 55 (degenerate). It should be noted that, while the mass spectra are considerably different, the power law of each distribution beyond the

![FIG. 1. The dilepton invariant mass distribution](image-url)
peak is roughly the same. These high $M_{\text{eff}}$ events originate from collisions with $\sqrt{s} \gg m_{\tilde{g}}, m_{\tilde{g}}$. The power law of the distributions is then described by the luminosity function. The peak position of the $M_{\text{eff}}$ distribution has a direct correlation with the produced sparticle mass. In Ref. [25] the correlation between $M_{\text{eff}}^\text{peak}$ and the effective SUSY mass scale $M_{\text{SUSY}}^\text{eff}$ defined as

$$M_{\text{SUSY}}^\text{eff} = \left( M_{\text{SUSY}} - \frac{M_{\chi}^2}{M_{\text{SUSY}}} \right)$$

is found, where $M_{\chi}$ is the LSP mass and $M_{\text{SUSY}} = (\sum \sigma_{\ell} m_\ell)/(\sum \sigma_{\ell})$. The peak position of the $M_{\text{eff}}$ distribution is a linear function of $M_{\text{SUSY}}^\text{eff}$ for MSUGRA and gauge mediation models. We find that a similar relation holds for the signal distribution, but we do not provide the fit results here, because the existence of the standard model background is very important for the models discussed in this paper, as will be discussed in the following subsections.

We now turn to the relation between $E_T$ and $M_{\text{eff}}$ for degenerate points. In Fig. 3 we show the distributions for model B with $M_3(GUT) = 650$ GeV, $\tan\beta = 10$, and $R = 0.1, 40, 50$, respectively. The $x$- and $y$-axes correspond to $M_{\text{eff}}$ and $E_T$. We see that the $E_T$ takes a significant fraction of $M_{\text{eff}}$ for all model points if $M_{\text{eff}}$ is sufficiently high.

This distribution can be understood as follows. Suppose we have events with two uncorrelated jets with energy $E_{\text{jet}} = p_{CM}$. In the SUSY production process at the LHC, the dominant part of the cross section is squark/gluino pair productions near the threshold. If they decay directly into two jets and two LSPs, the event kinematics are indeed of this type up to the boost to the beam direction.

We now calculate the missing energy $E_{\text{miss}}$ and effective energy $M(\text{eff})$ of the 2 jet events. The momentum of the two jets and the missing momentum can be expressed as follows:

$$p_1 = (p_{CM}, 0, 0, p_{CM}),$$

$$p_2 = (p_{CM}, p_{CM} \sin\theta, 0, p_{CM} \cos\theta),$$

$$p_{\text{miss}} = (E_{\text{miss}}, -p_{CM} \sin\theta, 0, -p_{CM}(1 + \cos\theta)),$$

where we take the frame so that the direction of the $p_1$ momentum is along the $z$ axis and events are in the $x$-$z$ plane. Then the missing energy $E_{\text{miss}}$ and effective mass $M(\text{eff})$ are

$$E_{\text{miss}} = p_{CM} \sqrt{2 + 2 \cos\theta},$$

$$M(\text{eff}) = 2 p_{CM} + E_{\text{miss}},$$

where $M(\text{eff})$ ranges from $2p_{CM}$ to $4p_{CM}$.

The relation between $E_T$ and $M_{\text{eff}}$ is somewhat similar to that of $E_{\text{miss}}$ and $M(\text{eff})$ as can be seen in Fig. 3. For each plot $E_T$ tends to be small when $M_{\text{eff}} \sim 2p_{CM}$, where $2p_{CM} = 1.36, 0.95, 0.7$ TeV for $R = 0.1, 40, 50$, respectively. It increases linearly as a function of $M_{\text{eff}}$ up to $M_{\text{eff}} \sim 3p_{CM}$, and the number of events reduces quickly beyond $M_{\text{eff}} > 4p_{CM}$. For a fixed $M_{\text{eff}}$ between $2p_{CM}$ and $4p_{CM}$, the $E_T$ distribution peaks well above 0. Indeed, this relation should be true for any new particles which are pair produced at LHC and both decay into a visible and an invisible particle.

The dominant background comes from $W(Z) + n$ jets or $t\bar{t} + n$ jets. The $E_T/M_{\text{eff}}$ of such processes should be smaller than that of the signal. In these processes, neutrinos from $W$, $Z$, and $b$ decays provide the dominant part of $E_T$, which accounts for only a small fraction of the total energy of the event. In addition to being a background event, the $W(Z)$ or $t$ must be highly boosted, so the original kinematical relation between $E_T$ and $M_{\text{eff}}$ would be smeared away. The canonical cut to reduce the SM background is $E_T > 0.2 M_{\text{eff}}$. The background distribution in the $M_{\text{eff}}$ and $E_T$ plane is significantly different from the signal distribu-

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4Reference [25] also finds that the linear relation does not hold in general SUSY model. These are corresponding to the points where the dominant contribution to the total SUSY production cross section comes from lighter sparticles such as chargino, neutralino, and sleptons, which do not contribute to the 4 jet + missing $E_T$ signals.
This channel has been studied in [2,4,25] with an emphasis on the model-independent reconstruction of the SUSY scale, as discussed in the previous subsection.

In Fig. 4, the signal distributions for model A, with $M_S$(GUT) = 450 GeV and 650 GeV, are plotted for $R \sim 0$ and $R \sim 37$. The signal distributions (solid and dashed histograms) are parallel to the background distribution (thick histogram) beyond the peak of the $M_{\text{eff}}$ distribution. The difference appears only in the overall normalizations. As already discussed, this is because the signal distribution is determined mainly by the luminosity function once $M_{\text{eff}} \gg 2M_{\text{SUSY}}$.

The background shown in the plots has a large uncertainty. The estimation has been made by the lowest order Monte Carlo generator ISAJET. The distribution is subject to the scale uncertainty which is typically $O(30\%)$. We also require at least 4 high $p_T$ jets, while the number of final state partons involved in the tree level diagram is much less than 4 for $W$ and $Z$ production. The number of additional jets is estimated by the parton shower approximation. The parton shower approximation provides a good description of jets collinear to the leading jets. Recently, several groups have emphasized the importance of matrix element (ME) corrections to the SM background processes. The matrix elements of the diagrams involving $W, Z, t + n$ partons are calculated by generators devoted to multijet processes [12,14,26]. Experimental groups are also working to take the ME corrections into account: for example, in the ATLAS group [13], the backgrounds from $t\bar{t}, W, Z$ are calculated up to $n = (3,6,6)$, respectively, using ALPGEN [14]. After the inclusion of the ME corrections, the SM background is increased by a factor of $2 - 4$ for $M_{\text{eff}} > 2$ TeV. Even in the highest bin in Fig. 4, the expected background is above 1. This enhancement of the background is caused by the increased high $p_T$ jets in SM events. The improved ME background estimation is still preliminary and at the level of the leading order and is subject to the scale uncertainty of the QCD coupling.

We find that the signal rate is of the same order as the background rate for the degenerate parameters with $m_{\tilde{g}}>0.5m_{\tilde{g}}$. If the uncertainty of the overall normalization of the background is 100%, no bound would be obtained from the no-lepton channel by considering only the $M_{\text{eff}}$ distribution. However, as we noted previously, the structure of the signal distribution may be visible over the background distribution in the $M_{\text{eff}}$ and $E_T$ plane.

C. One lepton channel

A significant fraction of SUSY events gives rise to isolated leptons ($p_T > 20$ GeV and $|\eta| < 2.5$). We show the $M_{\text{eff}}$ distribution of events with one lepton for model A in Fig. 5. We do not show the background distributions, because they are not given in previous literature. In an ATLAS study [13], the distribution of the SM background is given with ME corrections, which is roughly $1/20$ of the
The histograms in Fig. 5 show the signal distributions for $M_3$ (GUT) $= 450$ GeV with $R = 0.1$ (MSUGRA) and $R = 37$ (degenerate) in the left panel, and for $M_3$ (GUT) $= 650$ GeV with $R = 0.1$ (MSUGRA) and $R = 38$ (degenerate) in the right panel, respectively. All plots are normalized for $\int dt L = 10$ fb$^{-1}$.

where we take $M_3$ (GUT) $= 450$ GeV (left) and 650 GeV (right), $R = 55$ and 50 (dashed histograms), respectively. The overall normalization of the signal above $M_{\text{eff}} > 1.6$ TeV is 10 times lower for $M_3$ (GUT) $= 650$ GeV (Fig. 6, right panel) than that of the most degenerate point of model A (Fig. 5, left panel). We conclude that the one lepton signal is not accessible at the most degenerate points in Fig. 6 ($m_{\tilde{\chi}_1^0} \sim 0.7 m_{\tilde{q}}$) by looking at the $M_{\text{eff}}$ distribution alone, assuming the SM background in the one lepton channel given in [13], and a factor $2 \sim 3$ theoretical un-
certainty, even though the SUSY scale is relatively small $m_{\tilde{g}} = 1.48 \text{ TeV}$. The mass reach at the LHC will be revisited again in Sec. IV E.

D. Two lepton channel

In model A, there is a significant fraction of two lepton events in the $\mu \sim M_1$ region because $\tilde{t}$ is lighter than the Wino-like neutralino. We show the $m_{\tilde{t}}$ and $m_{\tilde{\mu}}$ distributions for model A, with $M_1(\text{GUT}) = 450 \text{ GeV}$ and $R = 37$ in Fig. 7. Here we require that one of the two isolated leptons has $p_T > 20 \text{ GeV}$ and the other has $p_T > 10 \text{ GeV}$. We also apply the standard cuts described in Sec. I. The masses of the sparticles relevant to the most prominent end points are $m_{\tilde{g}} = 901 \text{ GeV}$, $m_{\tilde{d}_R} = 869 \text{ GeV}$, $m_{\tilde{g}_R} = 554 \text{ GeV}$, $m_{\tilde{\chi}_1^0} = 499 \text{ GeV}$, and $m_{\tilde{\mu}_R} = 524 \text{ GeV}$. The predicted $m_{\tilde{t}_L}$ edge and $m_{\tilde{\tau}}$ end point for the decay chain $\tilde{q}_R \rightarrow \tilde{\chi}_2^0 \rightarrow \tilde{l}_R \rightarrow \tilde{\chi}_1^0$ are $m_{\tilde{\tau}} = 54.9 \text{ GeV}$ and $m_{\tilde{t}_L} = 308 \text{ GeV}$, respectively, consistent with Fig. 7. The edges and end points of other cascade decays are also visible in the plots.

To select jets from $\tilde{q}$ decays, of the two highest $p_T$ jets, we take the one which gives the smaller $m_{\tilde{\mu}}$. If the mass difference between $m_{\tilde{g}}$ and $m_{\tilde{\mu}}$ is smaller, we may have a reduced probability to find the correct jet arising from the $\tilde{q}$ decay. However, we do not observe such an effect in the $m_{\tilde{\mu}}$ distribution.

The number of accepted events $N_i$ (where $i$ denotes the number of isolated leptons with $p_T > 20 \text{ GeV}$ and $|\eta| < 2.5$) for this point is $N_0 = 11229$, $N_1 = 5167$, $N_2 = 2645$ for $5 \times 10^4$ generated events (corresponding to $\sim 20 \text{ fb}^{-1}$). The number of two lepton events below the most prominent edge is 2933 after the background subtraction. Because the $m_{\tilde{t}}$ distribution of the one lepton channel is not very prominent over the background, SUSY particles may be discovered in the two lepton channel for this point.

Note that for the most degenerate SUSY spectrum we have $M_1 \sim M_2 \sim \mu$, so all neutralinos are highly mixed. In such a situation, the dominant source of $\tilde{\chi}_2^0$ is $\tilde{q}_R$, because $\tilde{q}_L$ has significant decay branching ratios into charginos. It is worth pointing out that the relative weight of the decays $\tilde{q}_L(R) \rightarrow \tilde{\chi}_2^0 \rightarrow \tilde{l}_L(R)$ may be studied by looking into the charge asymmetry in the $m_{\tilde{\mu}}$ distribution, $A = (m_{\tilde{\mu}_L} - m_{\tilde{\mu}_R})/(m_{\tilde{\mu}_L} + m_{\tilde{\mu}_R})$ [27,28]. The charge asymmetry comes from the polarization of the $\tilde{\chi}_2^0$ from $\tilde{q}$ decay. However, as discussed in [29], this effect tends to be sup-

FIG. 6. The $M_{\ell\ell}$ distributions for one lepton signal events for model B, $M_1(\text{GUT}) = 450 \text{ GeV}$ (left panel), $M_3(\text{GUT}) = 650 \text{ GeV}$ (right panel), and $\tan \beta = 10$. The solid histograms are for $R = 0.1$ (MSUGRA-like). The dashed histograms are for $R = 55$ and 50, corresponding to degenerate mass spectra with $m_{\tilde{g}} \sim 0.7m_{\tilde{q}}$. All plots are normalized for $\int L dt = 10 \text{ fb}^{-1}$.

FIG. 7. The $m_{\tilde{t}_L}$ and $m_{\tilde{\mu}}$ distribution of signal for a degenerate SUSY point. $5 \times 10^4$ SUSY events are generated for model A, $M_3(\text{GUT}) = 450 \text{ GeV}$, $\tan \beta = 10$, and $R = 37$ ($m_{\tilde{\mu}_R} < m_{\tilde{\mu}_L}$).
pressed if sparticle masses are degenerate, and the $\tilde{\chi}_2^0$ is nonrelativistic in the $\tilde{q}$ rest frame.

For model B, the decays of $\tilde{\chi}_0^0$ into sleptons are closed for any value of $R$. For $M_3(\text{GUT}) = 450$ GeV and $R = 40$, we have $N_0 = 13433$, $N_1 = 4412$, $N_2 = 642$ for $5 \times 10^4$ generated events. While $N_0$ and $N_1$ are about the same as those of model A, $N_2$ is reduced by a factor of 4. In addition, no significant number of events with opposite sign same flavor leptons are seen after the subtraction of $e^{\pm} \mu^{\mp}$ events.

### E. Discovery potential in the one lepton channel

In MSUGRA, the signal $M_{\text{eff}}$ distribution is clearly harder than that of the background. In particular, when the background is negligible, one can see the increase of the signal towards its peak. If the total $M_{\text{eff}}$ distribution shows a bump or a clear change in the power behavior, one may claim discovery of SUSY particles without precise understanding of the background distribution.

On the other hand, when the SUSY mass spectrum is degenerate, the peak of the signal distribution shifts to a lower position where the background may be $\sim 10$ times higher. The signal distribution shows a similar power law behavior to that of the background for $M_{\text{eff}} > M_{\text{peak}}$, as can be seen in Fig. 4. The bump structure may not be detected and a precise understanding of the background would be required. Searching for edges in the $m_{\ell\ell}$ distribution from the decay $\tilde{\chi}_0^0 \rightarrow l \rightarrow \chi_1^0$ may become more important; however, as we have discussed already, the signal rate is highly model-parameter dependent. We do not consider the possibility of improving the $S/N$ ratio by selecting a signal region in $M_{\text{eff}}$ vs $E_T$ plane in this subsection.

Table IV shows the number of signal events in intervals of $M_{\text{eff}}$ for $5 \times 10^4$ generated events (upper row) and number of events for $10 \text{ fb}^{-1}$ (lower row) for both models A and B. We take a moderate value of $M_3(\text{GUT}) = 650$ GeV for the table, which corresponds to $m_{\tilde{g}}, m_{\tilde{q}} \sim 1.4$ TeV.

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<td>175</td>
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<td>9.5</td>
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In the MSUGRA limit (R \sim 0), the background rate is negligible in the signal region. The number of events in $M_{\text{eff}} > 2.4$ TeV is greater than 10 for $R < 20$, where the number of background events would be around 1 according to [13]. However, the signal rate is reduced by more than a factor of 4 for $R > 30$ compared to that at $R \sim 0$. Another important question is if we have a flat power spectrum in a certain $M_{\text{eff}}$ region. The number of background events reduce steeply with increasing $M_{\text{eff}}$ in Fig. 4, while we have a nearly flat signal distribution between 1.2–2.4 TeV for SUSY-like ($R \sim 0$) points. The ratio between the signal in the bins $N(1.6 \text{ TeV} < M_{\text{eff}} < 2.0 \text{ TeV})$ and $N(2.0 \text{ TeV} < M_{\text{eff}} < 2.4 \text{ TeV}) \sim 3:1$ for $R = 30, 40$ for model A and for $R = 30, 40, 50$ for model B; therefore, the power law for the signal is similar to that of the background in Fig. 4. We can describe the discovery potential in terms of the mass degeneracy rather than $R$. In the Table IV, $2p_{\text{CM}}$ ranges from 1.4 \sim 0.7 \text{ TeV}. Once $2p_{\text{CM}}$ is below 1 \text{ TeV}, 35% of $M_{\tilde{q}}$, the separation between signal and background is not good in the $M_{\tilde{q}}$ distribution. A good understanding of the background distributions and detector effects is required to exclude the model.

A factor 2 decrease of the signal is found for model A between $R = 50$ and $R = 55$. In this model, the squark mass decreases as $R$ increases. While the production cross section increases as $\bar{q}$ gets lighter, the masses of the heavier neutralino and chargino increase. They are heavier than $\tilde{q}$ at $R = 55$, so that they would not be produced at all in $\tilde{q}$ decay. The lighter neutralinos and charginos are still lighter than $\tilde{q}$ but their mass is very close to $m_{\tilde{q}}$ so that only soft leptons are produced in the decay. The two lepton signal is also suppressed for this model point. This is an example where the rate of signal events with a lepton is model dependent.

The tendency of the signal reduction is the same for the higher mass spectrum. The luminosity needed to discover the SUSY signal is larger at the degenerate SUSY points. For example, the production cross section is 43.6 fb for model A with $M_{\tilde{q}} = 850$ GeV and $R = 0$, and 15.1 events/10 fb$^{-1}$ are expected in the region $2.4 \text{ TeV} < M_{\text{eff}} < 4 \text{ TeV}$, which may be enough to claim the discovery for $\int L dt = 30 \text{ fb}^{-1}$. On the other hand, for $R = 37$ only 3.8 events/10 fb$^{-1}$ are expected, and it is not possible to discover the signal in the low luminosity run of the LHC for this point.

**V. DISCUSSION AND CONCLUSION**

In this paper, we study the discovery potential of minimal supersymmetric models with a degenerate mass spectrum at the LHC. Such parameter regions have not been studied systematically in the past. The SUSY discovery potential at the LHC has been studied mainly in models where the gluino and squarks are significantly heavier than the LSP, i.e. in the MSUGRA model, gauge mediation model, and so on.

We do not study a general MSSM model here, but take mixed modulus anomaly mediation (MMAM) models, which are parametrized by $R \propto F_C/F_T$, $\tan \beta$, and $M_3$(GUT). The parameter $R$ is the ratio of the $F$ terms of the volume modulus $T$ in the KKLT model and the compensator field $C$ in $N = 1$ MSUGRA. This parameter $R$ gives us a one parameter description from a SUSY-like mass spectrum (where $M_3 \gg M_1$), to a (moderately) degenerate mass spectrum. The models we have studied include the MSSM points with $m_{\tilde{G}}/M_{\tilde{q} \tilde{g}} \sim 0.7$.

When the partice mass spectrum is degenerate, the energy of particles from squark and gluino decays are small relative to the mass scale of their parents. This is reflected in the distributions of the highest jet $p_T$, $E_T$, and $M_{\text{eff}}$. They tend to peak at smaller values than the MSUGRA prediction for the same gluino and squark masses. Since the background from the SM processes increases rapidly for such a low $p_T$ and low $M_{\text{eff}}$ region, the signal competes with a large background. Indeed, the signal and background $M_{\text{eff}}$ distributions are quite similar for the degenerate mass spectrum with $m_{\tilde{G}} > 0.5 m_{\tilde{q}}$. We find that the S/N ratio can be far below 1 for our most degenerate parameter points with $m_{\tilde{G}} \sim m_{\tilde{q}}$. We find that the signal distribution for a degenerate SUSY mass spectrum shows a distinctive pattern in the $M_{\text{eff}}$ and $E_T$ plane: unlike the background distribution, the signal $E_T$ distribution peaks at some nonzero value for fixed $M_{\text{eff}}$. This may help to determine an appropriate signal region to better discriminate the signal from the background.

The discovery potential at the degenerate points depends on our knowledge of the background distribution. The main background sources are multijet final states involving $W, Z$, and $t$. Recently, there have been significant improvements in the lowest order estimation of the backgrounds; matrix element corrections of the backgrounds are now included. Theoretical uncertainties come from the matching between the parton shower approximation and the matrix corrections, and higher order QCD corrections (scale uncertainty).

Experimental backgrounds are partly estimated by the experimental data themselves. For example, the overall normalization of the dominant $t\bar{t}$ background can be determined by looking at events with low $E_T$, where contamination from SUSY events is small. However the background estimate in the signal region requires extrapolation using Monte Carlo, and there is a nontrivial contamination in the calibration region in the case of a degenerate SUSY mass spectrum. We look at the $E_T$ distribution and find that the number of events with $E_T < 200 \text{ GeV}$ is increased by a factor of 2 for our most degenerate point (the model B with $R = 55, M_3$(GUT) = 450 GeV) with respect to the MSUGRA limit ($R = 0.1$).

Current studies find that the discovery of supersymmetric particles in MSUGRA models would not be a
problem up to \( \sim 2 \) TeV region. However, as we have discussed in this paper, this is not the case even for moderately degenerate SUSY parameters in the mixed modulus anomaly mediation model. We stress the importance of including the SM background and its uncertainty to study SUSY discovery and parameter measurement for a degenerate or general MSSM mass spectrum, although they tend to have been ignored in recent studies [11,30].

ACKNOWLEDGMENTS

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