The study of $q_L\tilde{q}_L$ production at LHC in the $l^\pm l'^\pm$ channel
and sensitivity to other models

Mihoko M. Nojiri* and Michihisa Takeuchi†

*† Theory Group, KEK,
and *the Graduate University for Advanced Studies (SOKENDAI)
1-1 Oho, Tsukuba, 305-0801, Japan
† Yukawa Institute for Theoretical Physics,
Kyoto University,
Kyoto 606-8502, Japan
(Dated: July 6, 2018)

Abstract

At the LHC, $q_L\tilde{q}_L$ production is one of the main SUSY production processes in the MSSM, which occurs due to the chirality flip caused by the Majorana gluino mass. This process is one of the sources of same sign two lepton (SS2$l$) events, however, gluino production also contributes to this channel. In this paper, we develop a method to identify gluino and squark production separately in the SS2$l$ channel, based on cuts on the kinematical configuration of the jets. We applied the method to the MSSM, a model with an extended gluino sector, and the Littlest Higgs model with T-parity (LHT), and found a distinctive difference between these models when considering the numbers of SS2$l$ events selected by the cuts.

*Electronic address: nojiri@post.kek.jp
†Electronic address: tmichii@post.kek.jp
I. INTRODUCTION

The Standard Model (SM) describes interactions among elementary particles very well. However astrophysical and cosmological observations such as WMAP have confirmed the existence of dark matter (DM) that cannot be explained in the SM [1]. The particle which DM consists of does not leave detectable signals in the detectors at high energy collider experiments, because it should be weakly interacting.

If new particles are produced at collider experiments and decay into visible particles and a DM particle, we can observe large missing transverse momentum ($E_T$) in the events. Many models which predict DM candidates have been proposed. Among them, the minimal supersymmetric standard model with conserved R-parity (MSSM) is an attractive one. The lightest supersymmetric particle (LSP) is stable and a DM candidate. In the MSSM, quadratic divergences in the Higgs mass radiative corrections cancel each other, therefore the fine tuning problem is solved. At the large hadron collider (LHC), a $pp$ collider with $\sqrt{s} = 14$ TeV starting its operation in 2007 [2, 3], discovery of the squarks $\tilde{q}$ and gluino $\tilde{g}$ – super partners of quarks and gluon – is possible for the masses up to 2.5 TeV by looking for an excess of events with large $E_T$. We can also measure their mass spectrum by studying the decay kinematics of the quarks and gluino decay chains if there are enough events.

However, the discovery of a $E_T$ signature does not necessarily mean the confirmation of the existence of supersymmetry. A similar mass spectrum and decay pattern might be obtained for the Universal Extra Dimension model (UED) [4] and the Littlest Higgs model with T parity (LHT) [5, 6, 7]. To study the origin of the $E_T$ signature, therefore, it is important to measure the other features that are characteristic of the MSSM.

Many analyses have already been carried out in this direction. Recently, processes sensitive to the $\tilde{g}\tilde{q}$ Yukawa type coupling constant have been investigated in [8]. The Yukawa type coupling constant for the $\tilde{g}\tilde{q}$ vertex is the same as the gauge coupling constant due to SUSY. They study the same sign two isolated-lepton (SS2l) channel to estimate the production cross section $\sigma(\tilde{q}_L\tilde{q}_L)$. The SS2l channel is one of the major discovery channels for supersymmetry, which is studied in [9, 10, 11]. The process is in principle sensitive to the coupling, however they found a large background from $\tilde{g}\tilde{q}$ production. To measure the coupling constant, it is important to measure the cross sections of sparticle production processes separately. In this paper, we also focus on the $\sigma(\tilde{q}_L\tilde{q}_L)$. We will give a new method
based on cuts on the numbers of jets in the hemispheres for the purpose of separating $\tilde{q}_L\tilde{q}_L$ production from $\tilde{g}\tilde{q}_L$ production.

The $\tilde{q}_L\tilde{q}_L$ production process occurs through a chirality flip caused by the gluino majorana mass term $m_g\tilde{g}\tilde{g}$. To study the sensitivity to the majorana nature of the gluino mass, we consider a model with an extended gluino sector. This extension is inspired by the model that extends SUSY to $N = 2$ in [12, 13, 14, 15]. In this model, an adjoint matter $\tilde{a}$ is introduced, then the gluino can have a Dirac mass term $m_D\tilde{g}\tilde{a}$. The gluino mass receives a contribution from $m_D$. We also discuss the Littlest Higgs model with T-parity (LHT). This model contains quark partners ($q_-$) and gauge boson partners ($W_H, A_H$) which decay into the stable lightest T-odd particle (LTP) $A_H$ and SM particles as in the MSSM. Then, collider signatures are similar. There is progress concerning spin studies at LHC to distinguish these models [16, 17]. In this paper, however, we focus only on the difference among the production cross sections in these models.

This paper is organized as follows. In Section 2, we first discuss the mass dependencies of the production cross section of $\tilde{q}L$ and $\tilde{g}$ in the MSSM. The $\tilde{u}_L\tilde{u}_L$ production cross section is typically of the order of $100 \text{ fb}$ at $m_{\tilde{q}} \sim m_{\tilde{g}} \sim 1 \text{ TeV}$, which may be detectable at LHC. The production processes of $\tilde{q}_L\tilde{q}_L$ and $\tilde{q}_R\tilde{q}_R$ occur due to the gluino majorana mass, therefore the mass dependencies are different from those of $\sigma(\tilde{q}_L\tilde{q}_L^*)$ and $\sigma(\tilde{g}\tilde{g})$. We compare $\sigma(\tilde{q}_L\tilde{q}_L)$ with $\sigma(\tilde{g}\tilde{g})$ and find that $\sigma(\tilde{q}_L\tilde{q}_L) \ll \sigma(\tilde{g}\tilde{g})$. In this section, we also choose a few model points for later analyses.

For the MSSM with an extended gluino sector, the $\tilde{g}$, $\tilde{q}$ production cross sections are functions of the three mass parameters – two majorana masses $m_g, m_A$ and one Dirac mass $m_D$, where the mass terms are of the form $m_g\tilde{g}\tilde{g} + m_A\tilde{a}\tilde{a} + m_D(\tilde{a}\tilde{g} + \tilde{g}\tilde{a})$. In particular, $\sigma(\tilde{q}_L\tilde{q}_L)$ becomes zero for some particular choice of parameters. We also discuss the LHT model. The production process $q_-q_-$ occurs by heavy SU(2) gauge boson exchange. $\sigma(q_-q_-)$ is large compared with $\sigma(\tilde{q}\tilde{q})$ of the MSSM [18]. On the other hand, because no gluon partner exists in this model, there is no problematic background corresponding to the $\tilde{g}\tilde{g}$ production of the MSSM.

In Section 3, We study SS2l events to estimate $\sigma(\tilde{q}_L\tilde{q}_L)$ in the MSSM. To reduce SS2l events from $\tilde{g}\tilde{q}_L$, we use a $b$-jet veto and the numbers of jets in hemispheres defined following the procedure proposed in [19]. We demonstrate that production processes $\tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q}$ can be distinguished by the efficiency under the cuts. We also discuss the dominant $t\bar{t}$ background.
In Section 4, we calculate the expected number of SS2\ell events in the model with an extended gluino sector considered in Section 2. We discuss the sensitivity of the \( \tilde{q}_L \tilde{q}_L \) production cross section to the majorana gluino mass \( m_\tilde{g} \) at a few model points. We also estimate the number of SS2\ell signature in the LHT model. The efficiency under the cuts to reduce gluino background turns out to be useful to prove the existence of quark partner productions and difference from the MSSM prediction. Section 5 is devoted to the summary.

II. PRODUCTION CROSS SECTIONS AT LHC

A. MSSM production cross sections at LHC

In the MSSM, sparticles are always pair produced at LHC because of R-parity conservation. Production processes \( \tilde{g} \tilde{g}, \tilde{g} \tilde{q}, \tilde{q} \tilde{q} \) occur copiously unless the masses are much heavier than 1 TeV. Because \( u \) quark and \( d \) quark parton distribution functions (PDF) of a proton are much harder than the other partons, \( \tilde{u} \) and \( \tilde{d} \) are mainly produced among squarks. In particular, production processes \( \tilde{u}_L \tilde{u}_L, \tilde{d}_L \tilde{d}_L, \tilde{u}_R \tilde{u}_R, \tilde{d}_R \tilde{d}_R \), etc. require a chirality flip, therefore they do not occur if the gluino mass is not of majorana type \( m_\tilde{g} \lambda \lambda \). Only gluino exchange diagrams contribute to the productions.\(^1\)

If the sparticle mass spectrum is known, the production cross sections at LHC are calculable. The mass dependencies of some sparticle production cross sections are shown in Figures 1\textendash}3. Here, we use CTEQ 6l\(^2\) as the PDF. The horizontal axis is the gluino mass \( m_\tilde{g} \), and the vertical axis is the squark mass \( m_\tilde{q} \). The production cross section of each process is shown in contour lines in units of pb.

\[
\sigma(\tilde{q}_L \tilde{q}_L) (\tilde{q}_L = \tilde{u}_L \text{ or } \tilde{d}_L) \text{ are shown in Figures 1a} \sim c. \ \sigma(\tilde{u}_L \tilde{u}_L) \text{ is 0.05 pb at } m_\tilde{q} = m_\tilde{g} = 1000 \text{ GeV, and 0.12 pb at } m_\tilde{q} = m_g = 800 \text{ GeV. This shows that they strongly depend on the squark mass } m_\tilde{q}. \text{ The mass measurement error at LHC for squarks and gluino can be around a few percent, if the number of events is large enough} \text{[21].} \ \sigma(\tilde{q}_L \tilde{q}_L) \text{ changes by 10% when } m_\tilde{g} \text{ changes by 3% around } m_\tilde{q} = m_g = 1000 \text{ GeV and } m_\tilde{q} = m_g = 800 \text{ GeV. On the other hand, the cross section only weakly depends on gluino mass. This is because the amplitude has a}
\]

\(^1\) Here, we neglect the contributions from neutralino and chargino exchange diagrams. This assumption is reasonable, because \( g^2 < g_s^2, m_W < m_\tilde{g} \) in mSUGRA.

\(^2\) We set \( m_{\tilde{u}_L} = m_\tilde{q}, m_{\tilde{d}_L} = m_\tilde{g} + 6 \text{ GeV, } m_{\tilde{u}_R} = m_\tilde{g} - 19 \text{ GeV.}\)
FIG. 1: Contour plot of a) $\sigma(\tilde{u}_L\tilde{u}_L)$, b) $\sigma(\tilde{d}_L\tilde{d}_L)$, c) $\sigma(\tilde{u}_L\tilde{d}_L)$ and d) $\sigma(\tilde{u}_L\tilde{u}_R)$ as a function of $m_{\tilde{g}}$ and $m_{\tilde{q}}$. Factor of $m_{\tilde{g}}$ from the chirality flip, which compensates the suppression from the t-channel propagator. $\sigma(\tilde{u}_L\tilde{u}_L)$ changes by up to 10% in the range $500 \text{ GeV} < m_{\tilde{g}} < 1100 \text{ GeV}$ around $m_{\tilde{q}} = 800 \text{ GeV}$, and also changes by up to 10% in the range $700 \text{ GeV} < m_{\tilde{g}} < 1300 \text{ GeV}$ around $m_{\tilde{q}} = 1000 \text{ GeV}$ (Figure 1a). In the case of $m_{\tilde{g}} = 3 \text{ TeV}$, $\sigma(\tilde{u}_L\tilde{u}_L)$ is 0.04 pb at $m_{\tilde{q}} = 800 \text{ GeV}$, and 0.02 pb at $m_{\tilde{q}} = 1000 \text{ GeV}$. As a result, even when the accuracy of the mass measurement of the gluino is bad, the $\tilde{q}_L\tilde{q}_L$ production cross section is a useful

FIG. 2: Contour plot of a) $\sigma(\tilde{g}\tilde{u}_L)$ and b) $\sigma(\tilde{g}\tilde{d}_L)$ as a function of $m_{\tilde{g}}$ and $m_{\tilde{q}}$.
observable that can be used to quantitatively test the MSSM. The behavior of the \( \tilde{q}_R\tilde{q}_R \) production cross section is the same.

\( \sigma(\tilde{q}_L\tilde{q}_R) \) (such as \( \sigma(\tilde{u}_L\tilde{u}_R) \) etc.) depends on the gluino mass more sensitively than \( \sigma(\tilde{q}_L\tilde{q}_L) \). It decreases as the gluino mass increases. \( \sigma(\tilde{u}_L\tilde{u}_R) \) drops by half as \( m_{\tilde{g}} \) increases from 500 GeV to 1100 GeV for \( m_{\tilde{q}} = 800 \) GeV, and also drops by half as \( m_{\tilde{g}} \) increases from 700 GeV to 1300 GeV for \( m_{\tilde{q}} = 1000 \) GeV (Figure 1). \( \sigma(\tilde{g}\tilde{g}) \) depends on the gluino mass even more because an onshell gluino has to be produced (Figure 2).

By investigating \( \tilde{q}_L\tilde{q}_L \) production processes, we can probe the majorana nature of gluino mass. To measure the production cross section of \( \tilde{u}_L\tilde{u}_L \) and \( \tilde{d}_L\tilde{d}_L \), same sign two lepton (SS2l) events are useful, which is studied in [8]. This idea is as follows: a \( \tilde{u}_L(\tilde{d}_L) \) may dominantly produces \( l^+(l^-) \) through the decays of

\[
\tilde{u}_L \rightarrow \chi_1^+ d \rightarrow \tilde{l}^+ \nu d \rightarrow \tilde{\nu}_l \tilde{l} \rightarrow \tilde{\nu}_l \tilde{l} \\
\tilde{d}_L \rightarrow \chi_1^- u \rightarrow \tilde{l}^- \tilde{\nu}_l \rightarrow \tilde{\nu}_l \tilde{l} \nu_l \\
\text{or} \rightarrow \chi_1^0 W^+ d \rightarrow \tilde{\nu}_l \tilde{l} \nu_l \\
\text{or} \rightarrow \chi_1^0 W^- u \rightarrow \tilde{\nu}_l \tilde{l} \nu_l.
\]

(1)

Therefore \( l^+l^+ \) events are sensitive to \( \tilde{u}_L\tilde{u}_L \) production and \( l^-l^- \) events to \( \tilde{d}_L\tilde{d}_L \) production. This signature implies the existence of the Yukawa type vertex \( gg\tilde{g} \).

The ratio of \( l^+l^+ \) and \( l^-l^- \) has more information, as studied in [11]. The ratio of the fractions of \( u \) and \( d \) in the PDF is 2:1. Then \( \sigma(\tilde{u}_L\tilde{u}_L) \) is larger than \( \sigma(\tilde{d}_L\tilde{d}_L) \) and their ratio is about 4:1 (Figure 1a,b). Thus the ratio of the number of SS2l events \( N(l^+l^+ \text{ from } \tilde{u}_L\tilde{u}_L) : N(l^-l^- \text{ from } \tilde{d}_L\tilde{d}_L) \) should be 4:1 if leptonic branching ratios of \( \tilde{u}_L \) and \( \tilde{d}_L \) are the same.

The processes involving \( \tilde{u}_L^+ \) and \( \tilde{d}_L^+ \) etc. also become sources of SS2l events although the cross section is not large (\( \sigma(\tilde{u}_L\tilde{d}_L^+) \sim 0.1\sigma(\tilde{u}_L\tilde{u}_L) \) in Figure 3). Since the basic observable is the sign of the leptons, in the following we define \( \tilde{q}_L^+ \) as \( \{\tilde{u}_L, \tilde{d}_L, \tilde{c}_L, \tilde{s}_L^+\} \) which can be a...
parent of $l^+$, and $\tilde{q}_L$ as $\{\tilde{u}_L^*, \tilde{d}_L^*, \tilde{c}_L^*, \tilde{s}_L\}$ which can be a parent of $l^-$.

The mass dependencies of the production cross sections of $\tilde{q}_L^+, \tilde{q}_L$ are shown in Figures 4-6. By comparing Figure 4a with Figure 1a, and Figure 4b with Figure 1b, we can see that $\tilde{u}_L \tilde{u}_L$ ($\tilde{d}_L \tilde{d}_L$) is dominant in $\tilde{q}_L^+ \tilde{q}_L^+ (\tilde{q}_L \tilde{q}_L)$ respectively. By comparing Figure 5a with Figure 2a, and Figure 5b with Figure 2b, we also find that $\tilde{g} \tilde{u}_L$ ($\tilde{g} \tilde{d}_L$), is dominant in $\tilde{q}_L^+ \tilde{q}_L^+ (\tilde{q}_L^- \tilde{q}_L^-)$ respectively.

The $\tilde{g}$ can decay into $\tilde{q}_L^+ q^+$, therefore $\tilde{g}\tilde{q}_L^+$ production also produces $l^\pm l^\mp$. Moreover, $\sigma(\tilde{g}\tilde{q}_L^+)$ is larger than $\sigma(\tilde{q}_L^+ \tilde{q}_L^+)$ unless the gluino is too heavy (Typically $\sigma(\tilde{g}\tilde{q}) \sim 5\sigma(\tilde{q}^+ \tilde{q}^\mp)$ ), thus the $\tilde{g}\tilde{q}_L^+$ production process becomes background to the $\tilde{q}_L^+ \tilde{q}_L^+$ production process. The ratio $\sigma(\tilde{g}\tilde{q}_L^+)/\sigma(\tilde{g}\tilde{q}_L^-)$ is about 2:1 (Figure 5). Then the ratio of the numbers of SS2l events $N(l^++l^+ \text{ from } \tilde{g}\tilde{q}_L^+): N(l^-l^- \text{ from } \tilde{g}\tilde{q}_L^-)$ should be 2:1.

The $\tilde{g}\tilde{g}$ production process also produces $l^\pm l^\mp$ and $N(l^++l^+ \text{ from } \tilde{g}\tilde{g}): N(l^-l^- \text{ from } \tilde{g}\tilde{g})$ should be 1:1. This process, however, does not produce problematic background because the SS2l branching ratio of $\tilde{g}\tilde{g}$ production is small, although $\sigma(\tilde{g}\tilde{g})$ may be larger than $\sigma(\tilde{g}\tilde{q})$ in the mSUGRA model.

![FIG. 4: Contour plot of a) $\sigma(\tilde{q}_L^+ \tilde{q}_L^+)$, b) $\sigma(\tilde{q}_L \tilde{q}_L)$ and c) $\sigma(\tilde{q}_L^+ \tilde{q}_L^-)$ as a function of $m_{\tilde{g}}$ and $m_{\tilde{q}}$.](image)

The ratio of $\sigma(\tilde{q}_L^+ \tilde{q}_L^+)/\sigma(\tilde{g}\tilde{q}_L^+)$ increases as the gluino gets heavier or the squark gets lighter.
FIG. 5: Contour plot of a) $\sigma(\tilde{g}\tilde{q}_L^\pm)$ and b) $\sigma(\tilde{g}\tilde{q}_L^-)$ as a function of $m_{\tilde{g}}$ and $m_{\tilde{q}}$.

FIG. 6: Contour plot of the $\sigma(\tilde{q}_L^+\tilde{q}_L^-)$ divided by $\sigma(\tilde{g}\tilde{q}_L^-)$ as a function of $m_{\tilde{g}}$ and $m_{\tilde{q}}$.

(Figure 6). When $m_{\tilde{g}} \sim m_{\tilde{q}}$ the ratio is always less than 1/2 for $m_{\tilde{q}} < 1500$ GeV.

B. The MSSM model points

The numbers of SS2\ell events from $\tilde{g}\tilde{q}_L^\pm$ production and from $\tilde{q}_L^\pm\tilde{q}_L^\pm$ production depend on their decay patterns and the branching ratios. For the study in the following sections, we choose a few model points to fix the branching ratios. We consider the model points with $m_{\tilde{g}} > m_{\tilde{q}}$. If $m_{\tilde{q}} > m_{\tilde{g}}$, both of $\tilde{q}_L^\pm$ decay into $\tilde{g}$ and this $\tilde{g}$ can produce a lepton or an anti-lepton with the same probability, and we cannot distinguish $\tilde{q}_L^\pm\tilde{q}_L^\pm$ and $\tilde{q}_L^\pm\tilde{q}_L^\mp$.

We take relatively heavy sparticle masses ($m_{\tilde{q}}, m_{\tilde{g}} \gtrsim 800$ GeV), because $\sigma(\tilde{q}_L^\pm\tilde{q}_L^\pm)$ is too small compared with $\sigma(\tilde{g}\tilde{q}_L^-)$ if the masses are lighter. For example, at SPS1a ($m_{\tilde{q}}, m_{\tilde{g}} \sim 600$ GeV), which is a popular benchmark point defined in [22], $\sigma(\tilde{g}\tilde{q})$ is about ten times as large as $\sigma(\tilde{q}\tilde{q})$. We choose four points A~D shown in Table I so that $\sigma(\tilde{q}_L^\pm\tilde{q}_L^\pm)/\sigma(\tilde{g}\tilde{q}_L^-) \lesssim 1/5$, because we find that one can reduce $\tilde{g}\tilde{q}$ background by factor of 1/10 by applying various cuts in Section 3. The points A~D and SPS1a are also marked in Figure 1~6. We can see
in Figure 6 that the ratio $\sigma(\tilde{q}_L^+\tilde{q}_L^+)/\sigma(\tilde{g}\tilde{q}^+_L)$ is about $1/6, 1/4, 1/3, 1/2, 1/10$ for Points A∼D and SPS1a respectively.

Points A and B are mSUGRA points where $(m_0,m_{\tilde{1/2}})$ are (100GeV,340GeV) and (100GeV, 450GeV), $A_0 = 0$, $\tan \beta = 10$, $\text{sign} \mu > 0$ respectively. At these points, the mass difference of $\tilde{\tau}_1$ and $\tilde{\chi}_1^0$ is small. This feature is favored to reduce the LSP abundance. Points C and D are the mSUGRA points where $(m_0,m_{\tilde{1/2}})$ are (370GeV, 340GeV) and (400GeV, 450GeV), $A_0 = 0$, $\tan \beta = 10$, $\text{sign} \mu > 0$ respectively, except the low energy gluino masses are heavier than the mSUGRA predictions by 300GeV. By increasing the gluino mass, the production cross section of the gluino decreases, therefore $\tilde{g}\tilde{q}$ backgrounds are smaller. Sleptons are heavier than the lighter charginos $\tilde{\chi}_1^\pm$, thus the $\tilde{\chi}_1^\pm$ does not decay into a slepton but decays into a $W^\pm$ boson. These points are not favored cosmologically, however the mass density can be reduced by tuning the mass of the pseudoscalar higgs boson $m_P$ as $m_P \sim 2m_{\text{LSP}}$ without changing the rate of SS2l signal if we go beyond mSUGRA. Moreover, the decay patterns have some similarity to those predicted in the LHT as we will see later. SPS1a is also written in Table I and II for reference.

The masses of some particles at our model points are shown in Table I. These spectra are calculated using ISAJET [23, 24]. The other mass spectra are given in the Appendix A1. The SUSY production cross sections of our model points are also shown in Table II. This is calculated with HERWIG 6.5 [25], where we use the CTEQ 6l PDF [20].

|       | $m_0$ | $m_{\tilde{1/2}}$ | $A_0$ | $m_{\tilde{g}}$ | $m_{\tilde{\chi}_L}$ | $m_{\tilde{\chi}_R}$ | $m_{\tilde{\tau}_1}$ | $m_{\tilde{b}_1}$ | $m_{\tilde{\tau}}$ | $m_{\tilde{\chi}_L}$ | $m_{\tilde{\chi}_1^0}$ |
|-------|-------|-------------------|------|----------------|----------------------|----------------------|----------------------|----------------|----------------|----------------------|----------------------|
| Point A | 100   | 340               | 0    | 809.86        | 737.25               | 714.56               | 559.18               | 683.97           | 160.79          | 256.36               | 132.74               |
| Point B | 100   | 450               | 0    | 1047.83       | 951.16               | 919.51               | 734.57               | 883.16           | 194.28          | 324.47               | 179.11               |
| Point C | 370   | 340               | 0    | 1123.23       | 808.67               | 787.79               | 585.39               | 731.10           | 387.18          | 437.13               | 133.95               |
| Point D | 400   | 450               | 0    | 1360.22       | 1017.91              | 988.10               | 804.20               | 928.37           | 429.40          | 503.38               | 180.54               |
| SPS1a  | 100   | 250               | −100 | 595.19        | 537.04               | 520.45               | 379.14               | 491.92           | 133.39          | 202.12               | 96.05                |

TABLE I: The mass spectra at Point A∼D and SPS1a. Here the unit of masses is GeV.

C. The model with an extended gluino sector

In this section, we consider a model with an extended gluino sector. This model was originally considered in [12, 13, 14, 15] as a model with enhanced particle contents of $N = 2$
SUSY to solve the little hierarchy problem. The model has new fermions $\tilde{a}_i^a$ in adjoint representations of each SM gauge group $G_i$. The majorana gaugino $\lambda_i^a$ has a Dirac mass term with $\tilde{a}_i^a$.

Inspired by the model, we consider phenomenologies of the gluino sector. The mass term of the gluino is extended as follows,

$$- \mathcal{L}^\text{mass}_{\tilde{g}} = \frac{1}{2} m_{\tilde{g}} \tilde{g} \tilde{g} \rightarrow \frac{1}{2} \begin{pmatrix} \tilde{g} & \tilde{a} \end{pmatrix} \begin{pmatrix} m_g & m_D \\ m_D & m_A \end{pmatrix} \begin{pmatrix} \tilde{g} \\ \tilde{a} \end{pmatrix}. \quad (2)$$

Here, $\tilde{g}$ and $\tilde{a}$ are four component spinors that satisfy the majorana condition. The $m_g$ is a majorana mass for $\tilde{g}$, $m_D$ is a Dirac mass between $\tilde{g}$ and $\tilde{a}$, $m_A$ is a majorana mass for $\tilde{a}$. We leave the SU(2) and U(1) gaugino sectors unchanged.

The mass eigenstates $\tilde{g}_1, \tilde{g}_2$ are majorana particles, and the mass eigenvalues are given by

$$m_{\tilde{g}_{1,2}} = \frac{1}{2} \left( m_g + m_A \pm \sqrt{(m_g - m_A)^2 + 4m_D^2} \right), \quad | m_{\tilde{g}_1} | < | m_{\tilde{g}_2} |. \quad (3)$$

The mass eigenstates are defined as follows,

$$\begin{pmatrix} \tilde{g}_1 \\ \tilde{g}_2 \end{pmatrix} = \begin{pmatrix} \cos \phi & \sin \phi \\ -\sin \phi & \cos \phi \end{pmatrix} \begin{pmatrix} \tilde{g} \\ \tilde{a} \end{pmatrix}, \quad (\tan \phi = \frac{m_{\tilde{g}_1} - m_g}{m_D}). \quad (4)$$

In the limit of $m_D \rightarrow 0, m_A \rightarrow \infty$, $\tilde{a}$ decouples from the MSSM fields, then the phenomenology becomes identical to that of the MSSM. In the limit of $m_g = 0, m_A = 0, m_D \neq 0$ (we call this limit the pure Dirac limit), the masses of the two gluinos become the same,

\[ \text{TABLE II: The SUSY production cross sections for some processes at Point A–D and SPS1a. Here the unit of the cross sections is pb.} \]

|             | $\sigma(SUSY)$ | $\sigma(\tilde{q}_L\tilde{q}_L^c)$ | $\sigma(\tilde{q}_L\tilde{q}_L^-)$ | $\sigma(\tilde{q}_L\tilde{q}_L^R)$ | $\sigma(\tilde{g}\tilde{q}_L)$ | $\sigma(\tilde{g}\tilde{q}_L^-)$ | $\sigma(\tilde{g}\tilde{q}_L^-)$ | $\sigma(\tilde{g}\tilde{g})$ |
|-------------|----------------|-----------------------------------|-----------------------------------|-----------------------------------|-------------------------------|---------------------------------|-----------------------------------|--------------------------|
| Point A     | 8.621          | 0.2251                            | 0.0674                            | 0.4247                            | 1.3580                        | 0.6005                         | 0.7134                            | 1.0134                   |
| Point B     | 2.023          | 0.0750                            | 0.0189                            | 0.1309                            | 0.2949                        | 0.1208                         | 0.1389                            | 0.1704                   |
| Point C     | 3.418          | 0.1321                            | 0.0371                            | 0.2572                            | 0.3410                        | 0.1406                         | 0.0989                            | 0.1549                   |
| Point D     | 0.963          | 0.0494                            | 0.0118                            | 0.0875                            | 0.0897                        | 0.0345                         | 0.0280                            | 0.0440                   |
| SPS1a       | 45.890         | 0.8033                            | 0.2868                            | 1.600                             | 7.408                         | 3.544                          | 4.872                             | 5.377                     |

\[ ^3 \text{In Ref. [13], } m_{\tilde{g}} \text{ is taken as zero.} \]
then $\tilde{g}_1$ and $\tilde{g}_2$ interfere strongly so that $\tilde{g}$ and $\tilde{a}$ form a Dirac particle $\tilde{g}_D$ and its anti-particle $\bar{\tilde{g}}_D$. The model has continuous R-symmetry in the pure Dirac limit. We can assign R-charge 1 for $\tilde{g}_D$ and $\tilde{u}_L$, $-1$ for $\tilde{u}_R$ and so on. The pair production of $\tilde{u}_L\tilde{u}_L$, $\tilde{u}_R\tilde{u}_R$ through gluino exchange, which is one of main production process in the MSSM at the LHC, is forbidden by the R-charge conservation law. This can be also understood by the fact that existence of nonzero majorana mass of gluino is necessary for $\tilde{q}_L\tilde{q}_L$, $\tilde{q}_R\tilde{q}_R$ processes. While $\tilde{g}_D\tilde{u}_L$ pair production is allowed, $\tilde{g}_D\tilde{u}_L$ pair production is forbidden in the limit, and once $\tilde{g}_D$ is produced, $\tilde{g}_D$ can decay into $\tilde{u}_L\tilde{u}$ and $\tilde{d}_L\tilde{d}$ but can not decay into $\tilde{u}_L^*u$ nor $\tilde{d}_L^*d$. The difference between the pure Dirac limit and the MSSM is clear. If $m_A$, $m_g \ll m_D$, the mass difference of two gluinos $\Delta m_{\tilde{g}_{1,2}}$ is small, continuous R-symmetry exists approximately, and the phenomenology is similar to that in the pure Dirac limit. We do not investigate the phenomenology of this case any further.

This model has two gluino like particles. We may be able to observe two gluinos if the mass difference is large enough compared with the decay widths of the gluinos ($\Gamma_{\tilde{g}_{1,2}} \ll \Delta m_{\tilde{g}_{1,2}}$). In this case, each gluino decay produces $\tilde{q}^+$ and $\tilde{q}^-$ with the same branching ratio. If $\tilde{g}_2$ is too heavy so that the production cross section is too small to be observed at LHC, we can observe only $\tilde{g}_1$. It is not possible in this case to distinguish this model from the MSSM only by the mass spectrum. We focus on this case and study the deviation of the production cross sections from the MSSM predictions. The gluino sector of this model has two degrees of freedom in addition to $m_{\tilde{g}_1}$ and we take them as the other gluino like particle’s mass $m_{\tilde{g}_2}$ and the majorana mass $m_g$.

In Figure 7 we show the production cross sections of SUSY processes such as $\tilde{q}_L^+\tilde{q}_L^+$ and $\tilde{g}\tilde{q}_L^+$ as functions of the majorana gluino mass $m_g$. Here, we fix $m_{\tilde{g}_2} = -3000$ GeV and $m_{\tilde{g}_1} = 1047.83$ GeV, which is the gluino mass at Point B. The $\tilde{g}_2$ cannot be searched for at LHC. We take the mass spectrum of the other sparticles to be the same as that of Point B.

In the limit of $m_g = m_{\tilde{g}_1} = 1047.83$ GeV, $m_D$ is zero and $m_{\tilde{g}_2} = m_A = -3000$ GeV. The $\tilde{g}_2$ decouples from $\tilde{q}$, and the cross sections involving $\tilde{g}_1$ are the same as those of Point B. Changing $m_g$ from this value distorts the model from the MSSM. As the majorana mass $m_g$ decreases keeping $m_{\tilde{g}_1}$ and $m_{\tilde{g}_2}$ fixed, the total SUSY production cross section decreases. In particular, $\sigma(\tilde{q}_L^+\tilde{q}_L^+)$ decreases quickly, while $\sigma(\tilde{g}_1\tilde{q}^+) \sigma(\tilde{g}_1\tilde{q}^+)$ is proportional to $\cos^2\phi$ and $m_g = \cos^2\phi(m_{\tilde{g}_1} - m_{\tilde{g}_2}) + m_{\tilde{g}_2}$. The fraction of $\tilde{g}$ in $\tilde{g}_2$ increases, but $\tilde{g}_2$ is too heavy so that $\sigma(\tilde{g}_1\tilde{q}_1)$ is small. $\sigma(\tilde{g}_1\tilde{g}_1)$ is less sensitive to the majorana mass
follows, by the dependence of the subprocess cross section \( \sigma(m_\theta) \) of one of the initial quarks, coupling. Here \( \sigma \) is dominated by the threshold production. We can calculate that eq.(5) and the last equality in eq.(6), we take the limit that \( |m_\theta| \sim -1500 \text{ GeV} \), while \( \sigma(\tilde{q}_L, \tilde{q}_L) \) is reduced by factor of 3. This behavior can be explained by the dependence of the subprocess cross section \( \sigma(qq \to \tilde{q}_L \tilde{q}_L) \) on the mass parameters as follows,

\[
\sigma(qq \to \tilde{q}_L \tilde{q}_L) = \frac{\beta_f}{64\pi s} \int_1^s d(\cos\theta) \frac{4E^2g_s^4}{9} \times |T_{ij}^a T_{kl}^a| f(m_{\tilde{g}_1}, m_{\tilde{q}}, \mathbf{p}) \cos^2\phi + f(m_{\tilde{g}_2}, m_{\tilde{q}}, \mathbf{p}) \sin^2\phi + T_{d}^a T_{k}^a f(m_{\tilde{g}_1}, m_{\tilde{q}}, -\mathbf{p}) \cos^2\phi + f(m_{\tilde{g}_2}, m_{\tilde{q}}, -\mathbf{p}) \sin^2\phi |^2 \propto \left| \frac{m_{\tilde{g}_1} \cos^2\phi}{m_{\tilde{g}_1}^2 + m_{\tilde{q}}^2} + \frac{m_{\tilde{g}_2} \sin^2\phi}{m_{\tilde{g}_2}^2 + m_{\tilde{q}}^2} \right|^2,
\]

(5)

where, \( f(m_i, m_f, \mathbf{p}) \equiv \frac{m_i}{m_i^2 + m_f^2 + 2|\mathbf{p}|^2 - 2E|\mathbf{p}| \cos\theta} \approx \frac{m_i}{m_i^2 + m_f^2} \).

Here \( \sigma(qq \to \tilde{q}_L \tilde{q}_L) \) is the cross section of the subprocess \( qq \to \tilde{q}_L \tilde{q}_L \) with center of mass energy \( s \). \( \mathbf{p} \) is the momentum of one of the created \( \tilde{q}_L \). We set the z-axis along the momentum of one of the initial quarks, \( \theta \) is the polar angle of \( \mathbf{p} \) from the z-axis, and \( \beta_f \) is the beta factor \( \beta_f = \sqrt{1 - 4m_{\tilde{q}}^2/s} \). \( T^a \) denotes a generator of the SU(3) group and \( g_s \) denotes the gauge coupling. \( \phi \) is the mixing angle between the \( \tilde{g} \) and \( \tilde{a} \) as defined in (4). In the last line in eq.(5) and the last equality in eq.(6), we take the limit that \( |\mathbf{p}| \ll m_{\tilde{q}} \) because \( \sigma(pp \to \tilde{q}_L \tilde{q}_L) \) is dominated by the threshold production. We can calculate that \( \sigma(\tilde{q}_L \tilde{q}_L) \) approaches zero around \( \phi = \phi_0 \) defined as

\[
\tan\phi_0 = \sqrt{-\frac{m_{\tilde{g}_1} m_{\tilde{g}_2}^2 + m_{\tilde{q}}^2}{m_{\tilde{g}_2} m_{\tilde{g}_1}^2 + m_{\tilde{q}}^2}}
\]

(7)

This corresponds to \( m_g = -1516 \text{ GeV} \) for Point B (here, we use the relation \( m_g = \cos^2\phi m_{\tilde{g}_1} + \sin^2\phi m_{\tilde{g}_2} \)). Note that we again neglect the contributions from chargino and neutralino exchange diagrams in the calculation. They are at most of the order of \( 10^{-3} \text{ pb} \), and negligible.

\[
\sigma(\tilde{q}_L \tilde{q}_L)/\sigma(\tilde{q}_L \tilde{q}_L) \text{ is less than 5% in the range of } -1800 \text{ GeV} < m_g < -800 \text{ GeV}, \text{ while } \sigma(\tilde{q}_L \tilde{q}_L)/\sigma(\tilde{q}_L \tilde{q}_L) \text{ is about 25% in the MSSM limit } (m_g = 1047.83 \text{ GeV}). \text{ The production cross
section $\sigma(\tilde{q}_L\tilde{q}_L)$ is reduced by more than factor of 5 compared with $\tilde{g}\tilde{q}_L$ in this range (Figure 8).

As $m_g$ decreases further, $\sigma(\tilde{q}_L^+\tilde{q}_L^+)$ increases again while $\sigma(\tilde{g}_1\tilde{q}_L^\pm)$ keeps decreasing. When $m_g = -3000$ GeV, $\tilde{g}_2$ is $\tilde{g}$ and $\tilde{g}_1$ is $\tilde{a}$. In this limit, $\sigma(\tilde{q}_L\tilde{q}_L)$ is enhanced by the factor of $m_g$ in the amplitude, and $\sigma(\tilde{g}_1\tilde{q}_L^\pm) = 0$ because $\tilde{g}_1$ does not couple to $\tilde{q}$. We do not discuss this region because the production and decay pattern would be significantly different from the MSSM.

Note that the mass spectrum is the same as that at Point B for entire $m_g$ in Figure 7. We can detect the deviation from the MSSM only through measurements of production cross sections such as $\sigma(\tilde{q}_L^\pm\tilde{q}_L^\mp)$, $\sigma(\tilde{g}\tilde{q}_L^\pm)$ or their ratios.

**D. The Littlest Higgs model with T-parity**

The Littlest Higgs model with T-parity (LHT) [5, 6, 7] is an alternative scenario that solves the quadratic divergence problem for Higgs mass and predicts a stable DM candidate. This model is the extension of the Littlest Higgs model [26]. The features of the Littlest Higgs model are:

1. Higgs bosons are introduced as pseudo Nambu-Goldstone bosons of global symmetry
breaking $SU(5)/SO(5)$. The global symmetry is partially gauged, and the gauge symmetry is $[SU(2) \times U(1)]^2$.

2. The gauge groups are spontaneously broken at scale $f$ as $[SU(2) \times U(1)]^2 \rightarrow SU(2)_L \times U(1)_Y$. Heavy gauge bosons of the broken gauge groups are called as $W_H^\pm, Z_H, A_H$. The masses are,

$$M_{Z_H} \sim M_{W_H} \simeq g f \left[ 1 - \frac{v^2}{8f^2} \right], \quad M_{A_H} \simeq \frac{g' f}{\sqrt{5}} \left[ 1 - \frac{5v^2}{8f^2} \right].$$

Here, $v$ is the electroweak symmetry breaking scale, $v \simeq 246$ GeV.

3. To cancel the quadratic divergence of Higgs mass, the third generation fermion sector has to be extended to respect the global symmetry of the theory. In particular, $T_+$ has to be introduced as a partner of the $t$ quark. The $T_+$ is a SU(2)$_L$ singlet Dirac fermion.

However, this model suffers from large tree level corrections to the electroweak parameters. Even if the parameters of the models are tuned to reduce the corrections, $f$ becomes large enough that the fine tuning problem is reintroduced \cite{27,28}. To solve this problem, the LHT model imposes invariance under the T-parity that corresponds to switching the two $[SU(2)\times U(1)]$ gauge groups. Matter sectors are extended so that there is a T-odd partner for each SM fermion.

The T-parity plays a similar role to the R-parity of the SUSY model. The Lightest T-parity odd particle (LTP) cannot decay because T-parity is multiplicatively conserved for all vertices. The LTP can be a candidate for DM. Moreover, T-odd particles can be produced only in pairs in a collider experiment and each of them must decay into final states including an odd number of T-odd particles. As a result, the final states include at least two LTPs. The collider signal at LHC is large transverse missing energy $E_T$, just like SUSY.

This model predicts a set of new particles. Amongst them, the heavy gauge bosons $W_H^\pm, Z_H, A_H$, the SM fermion partners $u_-, d_-, s_-, c_-, b_-, t_-$, and the top partner $T_-$ are T-odd. In the following, $q_+^-$ denotes $\{u_-, c_-, t_-, \bar{d}_-, \bar{s}_-, \bar{b}_-\}$, $q_-^-$ denotes $\{d_-, s_-, b_-, \bar{u}_-, \bar{c}_-, \bar{t}_-\}$, $q_-$ denotes $q_+^-$ and $q_-^-$.

No T-odd partner for the SU(3) gauge boson is introduced. On the other hand, the decay pattern of T-odd $q_-$ is similar to that of $\tilde{q}$ in SUSY. According to Ref.\cite{18}, about 60% of $q_+^-$ decays into $W_H^+$, 100% of $W_H^+$ decays into $W^+$ and 25% of $W^+$ decays into
leptons. Therefore about 15% of $q^+\!\!\!\!_+^-$ decay leptonically. This decay pattern is similar to that of $\tilde{q}_L$ at Point C. Thus, for the LHT model, we obtain SUSY-like signal as if there are only $\tilde{q}\tilde{q}$ and $\tilde{q}\tilde{q}^*$ production at LHC. Although there is no t-channel colored particle exchange, $\sigma(q^-q^-)$ is non zero due to the t-channel exchange of $W_H$ and $A_H$. It is higher than that of the MSSM because $q^-$’s are fermions. For example, $\sigma(q^+q^-)$ is 0.7 pb, $\sigma(q^-q^-)$ is 0.15 pb at $m_{q^-} = 800$ GeV and $f = 560$ GeV, and $\sigma(q^+q^+)$ is 0.2 pb, $\sigma(q^-q^-)$ is 0.04 pb at $m_{q^-} = 1000$ GeV and $f = 700$ GeV. $\sigma(q^+q^+)$ is 4 ~ 5 times as large as $\sigma(\tilde{q}^+\tilde{q}^+)$ at the MSSM model points with the same mass scale (See Figure 4a). The ratio $\sigma(q^+q^-)/\sigma(q^-q^-)$ is similar to $\sigma(\tilde{q}^+\tilde{q}^+)/\sigma(\tilde{q}^-\tilde{q}^-)$ of the MSSM. The ratio $\sigma(l^+l^+)/\sigma(l^-l^-)$ of the LHT is expected to be higher than that of the MSSM, because $\tilde{g}\tilde{q}$ production dominates the total SUSY production.

As we will see later, the production cross sections and their ratios will help to distinguish the LHT and the MSSM.

E. Summary of the production cross sections

There are several models which predict a MSSM-like collider signature with large $E_T$.

In section 2.2 we have shown that the $\tilde{q}_L\tilde{q}_L$ production cross section changes significantly if the majorana mass contribution to the gluino mass is reduced in the model with an extended gluino sector. In particular, in the case of $m_g < m_{\tilde{g}_1}$, $\sigma(\tilde{q}_L\tilde{q}_L)$ can be reduced significantly compared to $\sigma(\tilde{g}\tilde{q}_L)$.

On the other hand, for the LHT model, $q_-$ may have a similar decay pattern to $\tilde{q}$ while there is no particle corresponding to gluino. Hence, the signal is similar than that of the MSSM with an undetectably heavy gluino. $\sigma(q_-q_-)$ is larger than $\sigma(\tilde{q}\tilde{q})$ by a factor of 5.

The signal cross sections of these models are different to those of the MSSM, even if the mass spectrum is the same. Therefore $\sigma(\tilde{q}_L\tilde{q}_L \to l^\pm l^\pm + X)$ is one of the key observables for MSSM studies.

III. SEPARATION OF $\tilde{q}\tilde{q}$ AND $\tilde{g}\tilde{q}$ PRODUCTIONS

A. Branching ratios of $\tilde{q}$, $\tilde{g}$

To identify $\tilde{q}_L\tilde{q}_L$ production (mainly $\tilde{u}_L\tilde{u}_L$ production), $\tilde{q}_L\tilde{q}_L \to 2l + X$ events would be useful because $BR(\tilde{q}_L^\pm \to l^\pm + X) \gg BR(\tilde{q}_L^\pm \to l^\mp + X)$. In this paper, we assume 100%
of $\tilde{q}_R$ decays into q and the LSP $\tilde{\chi}_1^0$. This is indeed realized over most of the mSUGRA parameter space. However, in less constrained models neutralino mixing can be different, such that also $\tilde{q}_R$ has cascade decays involving the heavier neutralinos and charginos. In this case, $\tilde{q}_L\tilde{q}_R$ and $\tilde{q}_R\tilde{q}_R$ production can both produce SS2l events, and the following analyses are more complicated. In particular, $\sigma(\tilde{q}_L\tilde{q}_R)$ is not so sensitive to the majorana nature of gluino, therefore it is more difficult to probe the majorana nature of the gluino using the SS2l channel. We assume that the LSP $\tilde{\chi}_1^0$ is dominantly a Bino and the $\tilde{\chi}_2^0$ a Wino, so $\tilde{q}_R$ does not produce leptons.

The signal rate depends on the leptonic branching ratios of sparticles. The branching ratios at Points A~D are shown in Appendix A2. We summarize them in Table III.

| mode               | BR(%) |
|--------------------|-------|
|                    | Point A | Point B | Point C | Point D |
| $\tilde{g} \rightarrow \tilde{q}_L^\pm q$ | 11     | 10     | 14     | 13     |
| $\rightarrow \tilde{q}_L^\pm$ | 11     | 10     | 14     | 13     |
| $\rightarrow \tilde{q}_R q$       | 38     | 36     | 32     | 32     |
| $\rightarrow \tilde{q}_3q_3$      | 41     | 45     | 40     | 41     |
| $\tilde{u}_L \rightarrow l^+X$    | 31     | 46     | 18     | 17     |
| $\tilde{d}_L \rightarrow l^-X$    | 30     | 44     | 17     | 17     |
| $\tilde{b}_1 \rightarrow l^-X$    | 28     | 39     | 17     | 20     |
| $\tilde{b}_2 \rightarrow l^-X$    | 22     | 27     | 11     | 12     |
| $\tilde{t}_1 \rightarrow l^+X$    | 29     | 37     | 17     | 10     |
| $\tilde{t}_2 \rightarrow l^+X$    | 18     | 23     | 6.3    | 11     |

TABLE III: Branching ratios of squarks and gluinos at Point A~D. These are calculated by ISAJET. Here, $\tilde{q}_L^\pm$ denotes $\{\tilde{u}_L, \tilde{d}_L^*, \tilde{c}_L, \tilde{s}_L^*\}$, $\tilde{q}_L$ denotes the antiparticles of $\tilde{q}_L^\pm$, $\tilde{q}_R$ denotes $\{\tilde{u}_R, \tilde{d}_R, \tilde{c}_R, \tilde{s}_R\}$ and their antiparticles. $\tilde{q}_3$ denotes $\{\tilde{b}_1, \tilde{b}_2, \tilde{t}_1, \tilde{t}_2\}$ and their antiparticles. X means LSP and other SM particles.

We can see that $\tilde{q}_L^\pm$ produces $l^\pm$ when $\tilde{q}_L^\pm$ decays through a chargino. $\text{BR}(\tilde{q}_L^\pm \rightarrow l^\pm)$ is about 30% at Point A. If $\tilde{q}_L^\pm$ decays through a neutralino, $\tilde{q}_L^\pm$ may also produce $l^\pm$.

On the other hand, a gluino decays into third generation squarks $\tilde{q}_3$ more than the 1st and 2nd generation squarks $\tilde{q}_L$, and also decays into $\tilde{q}_R$ more than $\tilde{q}_L$ at these points, because gluino and squark masses are close and the phase space of the gluino decay is sensitive to the small differences of squark masses. (The third generation squarks $\tilde{t}, \tilde{b}$ are lighter than the 1st, 2nd generation $\tilde{q}_L$, and $\tilde{q}_R$ is lighter than $\tilde{q}_L$.) We also find that $\text{BR}(\tilde{g} \rightarrow l^\pm) = \text{BR}(\tilde{g} \rightarrow l^-)$ and they are small (8%), because $\tilde{g}$ decays dominantly into $\tilde{q}_R$. 

16
As a result, $\mathcal{BR}(\tilde{q}_L^+\tilde{q}_L^+ \to l^+l^+)$ is 9%, $\mathcal{BR}(\tilde{g}\tilde{q}_L^+ \to l^+l^+)$ is 2.4%, $\mathcal{BR}(\tilde{g}\tilde{g} \to l^+l^+)$ is 0.6% at Point A.

To measure $\sigma(\tilde{q}_L^+\tilde{q}_L^+)$, we need to reduce the events involving $\tilde{g}$ by means of appropriate cuts. We can achieve this in part by rejecting events with $b$-tagged jets because $\mathcal{BR}(\tilde{g} \to \tilde{t} \text{ or } \tilde{b})$ is large; $\mathcal{BR}(\tilde{g} \to l^+l^+ \text{ without } b$-quark) is only 6%. For pair production processes, $\mathcal{BR}(\tilde{q}_L^+\tilde{q}_L^+ \to l^+l^+ \text{ without } b$-quark) is $\sim$ 9%, $\mathcal{BR}(\tilde{g}\tilde{q}_L^+ \to l^+l^+ \text{ without } b$-quark) $\sim$ 1%, $\mathcal{BR}(\tilde{g}\tilde{g} \to l^+l^+ \text{ without } b$-quark) $\sim$ 0.1%. However, the efficiency of $b$-veto is at most 60%.

In the following, we neglect $SS2l$ events from $\tilde{g}\tilde{g}$ production. This is reasonable if squark and gluino masses are sufficiently large, such as at Points A $\sim$ D, because $\sigma(\tilde{g}\tilde{g})$ is small (Table II) and $\mathcal{BR}(\tilde{g} \to \tilde{q}_L) \ll 1$. Furthermore, the events contain more $b$-jets on average.

### B. Event generation and detector simulation

We generate about 300,000 SUSY events using HERWIG 6.5 \[25\] at Points A $\sim$ D and SPS1a. The number of events actually produced by HERWIG and the corresponding integrated luminosities are listed in Table IV. $N(\tilde{q}_L^+\tilde{q}_L^+) : N(\tilde{q}_L^-\tilde{q}_L^-) \text{ is about 4:1 and } N(\tilde{g}\tilde{q}_L^+) : N(\tilde{g}\tilde{q}_L^-) \text{ is about 2:1 for these model points as discussed in Sec II A.}$

|              | $N(SUSY)$ | $N(\tilde{q}_L^+\tilde{q}_L^+)$ | $N(\tilde{q}_L^+\tilde{q}_L^-)$ | $N(\tilde{q}_L^-\tilde{q}_L^-)$ | $N(\tilde{g}\tilde{q}_L^+)$ | $N(\tilde{g}\tilde{q}_L^-)$ | $N(\tilde{g}\tilde{g})$ | $\int dt L$ |
|--------------|-----------|-------------------------------|-------------------------------|-------------------------------|-----------------------------|-----------------------------|---------------------------|---------|
| Point A      | 289906    | 7865                          | 10698                         | 2197                          | 44007                       | 19330                       | 21065                     | 33.63   |
| Point B      | 284544    | 10601                         | 11115                         | 2526                          | 39208                       | 15818                       | 13242                     | 140.65  |
| Point C      | 295042    | 11411                         | 14666                         | 3072                          | 25793                       | 10729                       | 4748                      | 86.32   |
| Point D      | 295695    | 14505                         | 14394                         | 3279                          | 23589                       | 8982                        | 3333                      | 307.06  |
| SPS1a        | 293161    | 5412                          | 10423                         | 1849                          | 46072                       | 22241                       | 31371                     | 6.39    |

TABLE IV: Numbers of events generated by HERWIG 6.5. Here, the unit of the integrated luminosities is fb$^{-1}$.

We use AcerDET \[29\] for event reconstruction. AcerDET is a fast simulation and reconstruction package. It finds jets, isolated electrons, muons, photons and calculates the missing transverse energy from particles in the events. The granularity of the calorimetric cells is assumed as $(0.1 \times 0.1)$ in $(\eta \times \phi)$ coordinates for $|\eta| < 3.2$. The clusters with $p_T > 15$ GeV for $\Delta R_{\text{cone}} = 0.4$ are classified as jets. It also labels a jet as a $b$-jet if a $b$-quark with momentum $p_T > 5$ GeV is found within the cone $\Delta R = 0.2$. The tagging efficiency of the algorithm is
about 80% and it is too high compared with the full simulation result of 60% in ATLAS. Therefore we assume that 60% of the \(b\)-labeled jets are tagged. Isolation criteria for muons, electrons and photons are \(p_T > 10 \text{ GeV}\) and \(|\eta| < 2.5\), separation by \(\Delta R > 0.4\) from other clusters and \(\sum E_T < 10 \text{ GeV}\) in a cone \(\Delta R < 0.2\) around them. For electrons and photons, we require \(\Delta R_{\text{cluster}} < 0.1\). The \(E_T\) is defined as

\[
E_T = \left| \sum_{\text{visible}} p_T \right|,
\]

and calculated by summing the transverse momenta of all cells as follows,

\[
E_T = \left| \sum_{\text{cells}} p_T \right|.
\]

The numbers of SS2\(l\) events from each production process are shown in Table \(V\) for Point B.

| Point B | generated | \(l^+l^+\) | \(l^-l^-\) |
|---|---|---|---|
|   | all | \(c_0\) | \(c_1\) | all | \(c_0\) | \(c_1\) |
| total | 284544 | 4363 | 2573 | 1680 | 2231 | 1288 | 749 |
| \(q_Lq_L\) | 10601 | 1410 | 967 | 958 | 6 | 2 | 2 |
| \(q_L\bar{q}_L\) | 2526 | 1 | 1 | 1 | 399 | 264 | 258 |
| \(\bar{q}_Lq_L\) | 11115 | 88 | 54 | 52 | 112 | 70 | 68 |
| \(\bar{g}\bar{q}_L\) | 39208 | 1720 | 1067 | 467 | 149 | 84 | 31 |
| \(\bar{g}q_L\) | 15818 | 46 | 31 | 14 | 732 | 469 | 235 |
| \(\bar{g}\bar{g}\) | 13242 | 220 | 117 | 22 | 225 | 121 | 26 |

**TABLE V:** Numbers of SS2\(l\) events from each production process at Point B

Here, \(c_0\) and \(c_1\) denote the different cuts applied to the events,

- all : all SS2\(l\) events generated by HERWIG 6.5.
  - \(c_0\) : basic cuts, \(E_T > 200 \text{ GeV}\), \(M_{\text{eff}} > 500 \text{ GeV}\), \(\sum_{\text{leptons}} |p_T| > 0.2M_{\text{eff}}\) and \(n_{100} \geq 2\)
    - \(n_{100}\) is the number of jets with \(p_T \geq 100 \text{ GeV}\)
  - \(c_1\) : \(c_0\) and \(n_b = 0\). \((n_b\) is the number of \(b\)-tagged jets.\))

\(M_{\text{eff}}\) is defined as

\[
M_{\text{eff}} = \sum_{|p_T| \geq 50 \text{ GeV}} |p_T| + \sum_{|p_T| \geq 10 \text{ GeV}} |p_T| + E_T.
\]
The SS2l events are mainly produced by $\tilde{q}_L^\pm \tilde{q}_L^\pm$, $\tilde{g} \tilde{q}_L^\pm$, $\tilde{g} \tilde{g}$. We find that $N(l^+l^+)$ from $\tilde{q}_L^\pm \tilde{q}_L^\pm$; $N(l^-l^-)$ from $\tilde{q}_L^- \tilde{q}_L^-$ is nearly 4:1 and $N(l^+l^+)$ from $\tilde{g} \tilde{q}_L^\pm$; $N(l^-l^-)$ from $\tilde{g} \tilde{g}^-$ is nearly 2:1. Note that $l^\pm l^\pm$ events are also produced from $\tilde{q} \tilde{q}^\pm$, if $\tilde{q}$ decays into a neutralino and the neutralino decays into $\tau^+ \tau^-$. After the $c_0$ cut, contributions from $\tilde{q}_L^\pm \tilde{q}_L^\pm$, $\tilde{q}_L^- \tilde{q}_L^-$, $\tilde{g} \tilde{q}_L^\pm$ dominate the SS2l events. We describe the number of generated $l^\pm l^\pm$ events after cut $c_1$ as $N(l^\pm l^\pm; c_1)$. Comparing $N(l^\pm l^\pm; c_0)$ with $N(l^\pm l^\pm; c_1)$, we see that the $b$-veto cut ($c_1$) reduces only events involving $\tilde{g}$. The $l^\pm l^\pm$ events from $\tilde{g} \tilde{q}^\pm$ are reduced by half. The $l^\pm l^\pm$ events from $\tilde{g} \tilde{g}$ are reduced by one fifth. After the $c_1$ cut, $l^\pm l^\pm$ events from $\tilde{q}^+ \tilde{q}^+$ are 60% of all $l^\pm l^\pm$ events, while they are 40% under the $c_0$ cut.

### C. Hemisphere cuts

To further reduce events involving $\tilde{g}$, we next study the number of jets emitted from $\tilde{q}$ and $\tilde{g}$. A gluino decays into a squark and a quark, and the squark decays into a chargino or a neutralino and a quark. Thus, a gluino usually emits at least two jets while a squark emits at least one jet. We can distinguish the parent particles by the number of high $p_T$ jets in the events. In this paper, we divide the final state particles into two groups called hemispheres, then we investigate the number of jets and the invariant masses in each hemisphere.

SUSY production processes always occur in pairs due to R-parity conservation. Particles from each sparticle decay with momentum $p_i, p_j, \ldots$ are kinematically constrained so that $(p_i + p_j + \ldots)^2 = m^2$ where $m$ is the mass of the parent sparticle. When the parent sparticle is boosted the decay products are boosted in the same direction. We therefore divide all high $p_T$ objects into two groups: hemisphere 1 $\{p_{1k}\}$, hemisphere 2 $\{p_{2k}\}$, which satisfy the following conditions.

Any $p_{1i} \in \{p_{1k}\}$, $p_{2i} \in \{p_{2k}\}$ satisfy the conditions

$$d(p_{1ax}, p_{1i}) \leq d(p_{2ax}, p_{1i}),$$
$$d(p_{2ax}, p_{2i}) \leq d(p_{1ax}, p_{2i}).$$

(12)

We define the axis of hemisphere $p_{ax}$ and the distance between two 4-vectors $d(p_1, p_2)$

---

4 The other SS2l events come mainly from productions involving third generation squarks, charginos and gluino.
as follows.

\[ p_{1,ax} \equiv \sum_i p_{1i}, \quad p_{2,ax} \equiv \sum_i p_{2i}, \quad (13) \]

\[ d(p_{ax}, p_i) \equiv \frac{(E_{ax} - |p_{ax}| \cos \theta_i) E_{ax}}{(E_{ax} + E_i)^2} \quad (\text{Here}, \ \theta_i \ \text{is the angle between} \ p_{ax} \ \text{and} \ p_i). \quad (14) \]

Here, high \( p_T \) objects mean jets with \( p_T \geq 50 \text{ GeV} \) and \( \eta \leq 3 \), leptons, photons with \( p_T \geq 10 \text{ GeV} \) and \( \eta \leq 2.5 \).

Our algorithm to find the hemisphere axes is as follows. We take the highest \( p_T \) object in the event and regard its momentum as \( p_{1,ax} \). Next, \( p_{2,ax} \) is taken as the momentum of the object which has largest \( |p| \Delta R \), where \( p \) is the momentum of an object, \( \Delta R \equiv \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} \), and \( \Delta \eta \) and \( \Delta \phi \) are the differences of the pseudo-rapidity and azimuthal angle of \( p \) from \( p_{1,ax} \) respectively. We calculate \( d(p_{1,ax}, p) \) and \( d(p_{2,ax}, p) \) for all high \( p_T \) objects. We identify it to hemisphere 1 if \( d(p_{1,ax}, p) < d(p_{2,ax}, p) \). Otherwise, to hemisphere 2. After that, we redefine \( p_{1,ax} \) and \( p_{2,ax} \) as the new hemisphere axes by using eq.\((13)\). We iterate the same operation using new \( p_{1,ax} \) and \( p_{2,ax} \) five times.

After determination of two hemispheres, we calculate the maximum invariant mass \( m_{jj} \) of all jet pairs in a hemisphere. We call it \( m_{jj1} \) for hemisphere 1 and \( m_{jj2} \) for hemisphere 2. When a hemisphere has only one or zero jets, we define \( m_{jj} = 0 \).

The 2-dim plots of \( m_{jj1} \) vs. ~\( m_{jj2} \) for production processes \( \tilde{g}\tilde{g}, \tilde{g}\tilde{u}_L, \tilde{u}_L\tilde{u}_L \) at Point B are shown in Figure 9a~c. Here, the plotted events are not only SS2l events but all events after imposing \( c_0 \) cut.

We find \( \tilde{g}\tilde{g} \) events are mainly distributed in the region of \( m_{jj1} \neq 0 \) and \( m_{jj2} \neq 0 \), \( \tilde{g}\tilde{q} \) events are mainly distributed in the region of either \( m_{jj1} = 0 \) or \( m_{jj2} = 0 \), \( \tilde{q}\tilde{q} \) events are mainly distributed in the region of \( m_{jj1} = m_{jj2} = 0 \). This is because \( \tilde{g} \) produces two high \( p_T \) jets while \( \tilde{q} \) produces only one high \( p_T \) jet. Therefore we require \( m_{jj1} = m_{jj2} = 0 \) as the cut to reduce \( \tilde{g} \) production events.

**D. Numerical results after hemisphere cuts**

We apply the cuts \( m_{jji} = 0 \) and/or a \( b \)-veto on the SS2l events and investigate the efficiencies for each production channel. We subsequently apply the cuts to remove the
contributions from $\tilde{g}\tilde{q}$ production, while keeping the contributions from $\tilde{q}\tilde{q}$. We define cuts $c_2 \sim c_5$ in addition to $c_0$ and $c_1$ as follows,

$$c_2 : c_0 \text{ with } \min(m_{jj1}, m_{jj2}) = 0.$$  
$$c_3 : c_0 \text{ with } m_{jj1} = m_{jj2} = 0.$$  
$$c_4 : c_0, n_b = 0 \text{ and } \min(m_{jj1}, m_{jj2}) = 0.$$  
$$c_5 : c_0, n_b = 0 \text{ and } m_{jj1} = m_{jj2} = 0.$$ 

ratio : $N(c_5)/N(c_0)$. This describes the efficiency for $c_5$ cut.

The number of the SS2l events after these cuts are shown in the Table. The cut requiring $m_{jj1} = 0$ or $m_{jj2} = 0 \ (c_2, c_4)$ reduces $\tilde{g}\tilde{g}$ events drastically and $\tilde{g}\tilde{q}$ events moderately. The cut requiring $m_{jj1} = 0$ and $m_{jj2} = 0 \ (c_3, c_5)$ further reduces $\tilde{g}\tilde{q}$ events. On the other hand, $\tilde{q}\tilde{q}$ events survive under the cut $c_5$ compared with $\tilde{g}\tilde{g}, \tilde{g}\tilde{q}$ events. Note that a $b$-veto cut is not essential to reduce the gluino contribution. The cut $c_3$ reduces events involving gluino less than $\tilde{q}_L\tilde{q}_L$ events although the $b$-veto is not applied. $\tilde{g}\tilde{q}$ events are dominant under the $c_0$ cut and $\tilde{q}\tilde{q}$ events are dominant under the $c_5$ cut.

The ratio of $N(l^+l^+; c_5)/N(l^+l^+; c_0)$ for $\tilde{q}\tilde{q}$ productions is more than 30% at our model points. It is $3 \sim 5\%$ for $\tilde{g}\tilde{q}$ productions at Point A and B and about 1% at Point C and D. We can obtain a pure SS2l event set from $\tilde{q}\tilde{q}$ production by the $c_5$ cut. Dominant contributions to $N(l^+l^+)$ from $\tilde{q}\tilde{q}$ are from $\tilde{q}_L\tilde{q}_L$ production (mainly $\tilde{u}_L\tilde{u}_L$). We can see in Appendix A.3, $N(l^+l^+ \text{ from } \tilde{u}_L\tilde{u}_L \text{ and } \tilde{u}_L\tilde{c}_L)=1256, N(l^+l^+ \text{ from } \tilde{u}_L\tilde{d}_L^* \text{ and } \tilde{u}_L\tilde{s}_L^*)=138, N(l^+l^+ \text{ from } \tilde{u}_L\tilde{d}_L)=84$ are obtained among $N(l^+l^+ \text{ from all } \tilde{q}\tilde{q})=1479$ at Point B. In Table VII, we also show the results at SPS1a for a reference. The efficiencies of these cuts are similar to the other points. However contamination from $\tilde{g}\tilde{q}$ production is larger.
Experimentally, we can only observe the total number of SS2l events. The ratio $N(l^+l^+; c_5)/N(l^+l^+; c_0)$ for total events is $13\sim17\%$ at our points. If there is no $\tilde{q}_L\tilde{q}_L$ production, it becomes less than 5%. If the efficiency of $N(l^+l^+; c_5)/N(l^+l^+; c_0)$ for $\tilde{q}\tilde{q}$ and $\tilde{g}\tilde{q}$ can be obtained by MC simulations and from the other constraints, we may estimate $\sigma(\tilde{q}_L\tilde{q}_L)$ from $N(l^\pm l^\pm)$. The model parameters we need are the gluino, squark masses to constrain the branching ratio of the gluino, leptonic branching ratios of squarks and their decay kinematics. The ratio of events with 2 leptons to events with 1 lepton should be useful to estimate the leptonic branching ratio of $\tilde{q}$. The decay cascade $\tilde{g} \rightarrow \tilde{b}\bar{b}((\tilde{t}t) \rightarrow \tilde{\chi}^- t\bar{b}(\tilde{\chi}^+ t\bar{b})$ also emits leptons from $W^\pm$ decays. The branching ratio must be estimated carefully from $b$-tagged samples. Estimation of the errors on the branching ratio is beyond the scope of this paper. Information on the mass would be obtained from various end points of the decay distribu-

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|}
\hline
& Point A & all & $c_0$ & $c_1$ & $c_2$ & $c_3$ & $c_4$ & $c_5$ & ratio \\
\hline
\hline
& $l^+l^+$ total & 1519 & 716 & 349 & 463 & 114 & 267 & 94 & 0.131 \\
& $\tilde{q}\tilde{q}$ & 235 & 140 & 132 & 123 & 57 & 117 & 56 & 0.400 \\
& $\tilde{g}\tilde{q}$ & 618 & 333 & 125 & 205 & 27 & 83 & 16 & 0.048 \\
& $\tilde{g}\tilde{g}$ & 184 & 79 & 14 & 27 & 2 & 5 & 0 & 0.000 \\
\hline
\hline
& $l^-l^-$ total & 1213 & 610 & 286 & 368 & 89 & 216 & 75 & 0.123 \\
& $\tilde{q}\tilde{q}$ & 151 & 92 & 90 & 83 & 42 & 81 & 41 & 0.446 \\
& $\tilde{g}\tilde{q}$ & 472 & 262 & 108 & 159 & 19 & 75 & 13 & 0.050 \\
& $\tilde{g}\tilde{g}$ & 172 & 93 & 20 & 31 & 1 & 6 & 0 & 0.000 \\
\hline
\end{tabular}
\end{table}

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|c|}
\hline
& Point B & all & $c_0$ & $c_1$ & $c_2$ & $c_3$ & $c_4$ & $c_5$ & ratio \\
\hline
\hline
& $l^+l^+$ total & 4363 & 2573 & 1612 & 1765 & 465 & 1293 & 441 & 0.171 \\
& $\tilde{q}\tilde{q}$ & 1479 & 1014 & 1001 & 894 & 363 & 883 & 361 & 0.356 \\
& $\tilde{g}\tilde{q}$ & 1765 & 1098 & 433 & 613 & 52 & 279 & 36 & 0.033 \\
& $\tilde{g}\tilde{g}$ & 220 & 117 & 18 & 26 & 1 & 5 & 0 & 0.000 \\
\hline
\hline
& $l^-l^-$ total & 2231 & 1288 & 708 & 809 & 187 & 561 & 171 & 0.133 \\
& $\tilde{q}\tilde{q}$ & 499 & 326 & 316 & 286 & 122 & 278 & 121 & 0.371 \\
& $\tilde{g}\tilde{q}$ & 861 & 541 & 237 & 304 & 23 & 169 & 15 & 0.028 \\
& $\tilde{g}\tilde{g}$ & 225 & 121 & 22 & 32 & 0 & 11 & 0 & 0.000 \\
\hline
\end{tabular}
\end{table}
| Point C | all | $c_0$ | $c_1$ | $c_2$ | $c_3$ | $c_4$ | $c_5$ | ratio |
|---------|-----|-------|-------|-------|-------|-------|-------|-------|
| $l^+l^+$ total | 1081 | 467 | 242 | 284 | 66 | 186 | 62 | 0.133 |
| $\bar{q}\bar{q}$ | 259 | 154 | 144 | 133 | 57 | 127 | 57 | 0.370 |
| $\bar{g}\bar{g}$ | 327 | 165 | 55 | 69 | 3 | 29 | 2 | 0.012 |
| $\bar{g}\bar{g}$ | 47 | 10 | 1 | 20 | 0 | 0 | 0 | 0.000 |
| $l^-l^-$ total | 618 | 233 | 110 | 134 | 20 | 83 | 17 | 0.073 |
| $\bar{q}\bar{q}$ | 77 | 40 | 39 | 12 | 36 | 12 | 0 | 0.300 |
| $\bar{g}\bar{g}$ | 164 | 66 | 23 | 29 | 2 | 14 | 0 | 0.000 |
| $\bar{g}\bar{g}$ | 32 | 11 | 3 | 6 | 0 | 2 | 0 | 0.000 |

| Point D | all | $c_0$ | $c_1$ | $c_2$ | $c_3$ | $c_4$ | $c_5$ | ratio |
|---------|-----|-------|-------|-------|-------|-------|-------|-------|
| $l^+l^+$ total | 1157 | 571 | 318 | 335 | 82 | 243 | 78 | 0.137 |
| $\bar{q}\bar{q}$ | 356 | 216 | 207 | 182 | 72 | 179 | 72 | 0.333 |
| $\bar{g}\bar{g}$ | 333 | 169 | 56 | 64 | 2 | 26 | 2 | 0.012 |
| $\bar{g}\bar{g}$ | 35 | 18 | 5 | 7 | 0 | 4 | 0 | 0.000 |
| $l^-l^-$ total | 588 | 263 | 116 | 128 | 27 | 83 | 24 | 0.091 |
| $\bar{q}\bar{q}$ | 84 | 55 | 47 | 45 | 16 | 40 | 16 | 0.291 |
| $\bar{g}\bar{g}$ | 131 | 63 | 25 | 23 | 1 | 14 | 1 | 0.016 |
| $\bar{g}\bar{g}$ | 27 | 9 | 0 | 0 | 0 | 0 | 0 | 0.000 |

| sps1a | all | $c_0$ | $c_1$ | $c_2$ | $c_3$ | $c_4$ | $c_5$ | ratio |
|--------|-----|-------|-------|-------|-------|-------|-------|-------|
| $l^+l^+$ total | 1314 | 461 | 250 | 326 | 80 | 193 | 63 | 0.137 |
| $\bar{g}\bar{g}$ | 164 | 72 | 71 | 59 | 29 | 58 | 28 | 0.389 |
| $\bar{g}\bar{g}$ | 550 | 226 | 106 | 150 | 22 | 75 | 15 | 0.066 |
| $\bar{g}\bar{g}$ | 155 | 58 | 15 | 32 | 2 | 9 | 2 | 0.034 |
| $l^-l^-$ total | 1070 | 345 | 180 | 242 | 64 | 147 | 46 | 0.133 |
| $\bar{g}\bar{g}$ | 109 | 47 | 45 | 41 | 16 | 40 | 16 | 0.340 |
| $\bar{g}\bar{g}$ | 394 | 156 | 64 | 109 | 27 | 51 | 16 | 0.103 |
| $\bar{g}\bar{g}$ | 147 | 39 | 9 | 17 | 2 | 7 | 0 | 0.000 |

TABLE VI: Numbers of SS2$l$ events after the cuts for Point A~D and SPS1a. Here, $c_0$ is set to $p_T > 200$ GeV, $M_{\text{eff}} > 500$ GeV, $p_T > 0.2M_{\text{eff}}, n_{100} \geq 2$. 

23
In addition, there are various sources of systematic errors for the cross sections such as the PDF, NNLO corrections and so on. Following the arguments in [8], we assume that the overall uncertainty on the total production cross section is 17%, which comes from 10% PDF uncertainty, 8% NNLO corrections and 10% \( \sigma(\tilde{q}\tilde{q}_L) \) error from a 3% squark mass uncertainty. If the squark mass error is 10%, \( \sigma(\tilde{q}\tilde{q}_L) \) error is 40%, and this uncertainty dominates the systematic errors.

Uncertainties on the cross sections may partly cancel in \( N(l^\pm l^\pm; c_5)/N(l^\pm l^\pm; c_0) \) ratios. The errors on the absolute sparticle masses are common for both \( \sigma(\tilde{q}\tilde{q}_L) \) and \( \sigma(\tilde{g}\tilde{q}_L) \), and \( m_{\tilde{g}} - m_{\tilde{q}} \) may be known precisely. If the cross section errors cancel, the total systematic error becomes 14%. Uncertainties on leptonic branching ratios of squarks may also partly cancel because the gluino emits leptons through its decay into a squark.

Note that the ratio of the production cross sections of \( \tilde{g}\tilde{u}_L \) to \( \tilde{g}\tilde{d}_L \) is 2:1, and that of \( \tilde{u}_L\tilde{u}_L \) to \( \tilde{d}_L\tilde{d}_L \) is 4:1. Indeed, at Points C and D, the ratio \( N(l^+l^+; c_5)/N(l^-l^-; c_5) \) is 4:1, while that is 2:1 for \( c_0 \). At Point A (B), the ratio of \( N(l^+l^+; c_5) \) to \( N(l^-l^-; c_5) \) is 5:4 (5:2), while the ratio of \( N(l^+l^+; c_0) \) to \( N(l^-l^-; c_0) \) is 7:6 (2:1). These discrepancies from \( \sigma(\tilde{q}^\pm\tilde{q}^+)/\sigma(\tilde{q}^-\tilde{q}^-) \) or \( \sigma(\tilde{q}^+/\sigma(\tilde{q}^-) \) in Table IV are caused by decays of the second lightest neutralinos from \( \tilde{q}_L^\pm \). According to Appendix A.2, the left handed squark can decay into \( \tilde{\chi}_1^0\tau^+\tau^- \) through \( \tilde{\chi}_2^0 \) with a large branching ratio at Point A (B). Therefore there is a contamination from \( \tilde{q}_L^\pm\tilde{q}_L^- \) (mainly \( \tilde{u}_L\tilde{d}_L \)) production to SS2l events and the ratio of \( N(l^+l^+) \) to \( N(l^-l^-) \) gets closer to 1:1. Therefore the charge of the hard lepton does not reflect the sign of the parent particle.

E. Tight cut for heavy mass spectrum

We now consider the SM background to SS2l events. Here we only consider \( t\bar{t} \) production which is found as dominant background in [8]. The background comes from the events where one lepton comes from the leptonic decay of a top quark while the other lepton comes from accidental sources such as \( b \) quark decays. The \( BR(t \rightarrow l^-) \) is small, however the total number of \( t\bar{t} \) events is significantly larger than the signal (\( \sigma(t\bar{t}) = 400 \text{ pb at tree level} \)). The \( t\bar{t} \) events corresponding to 100 fb\(^{-1} \) are also generated by HERWIG 6.5, and the result is shown in Table VII.

At Points A and B, \( N(l^+l^+ \text{ from } t\bar{t}; c_0) \) is less than 8% of \( N(l^+l^+ \text{ from SUSY}; c_0) \) and \( N(l^+l^+ \text{ from } t\bar{t}; c_5) \) is about 5% of \( N(l^+l^+ \text{ from SUSY}; c_5) \). At Point C, it is 30% after \( c_0 \),
TABLE VII: Numbers of SS2l events from $t\bar{t}$ production after the cuts $c_0 \sim c_5$ for $\int dt\mathcal{L} = 100\,\text{fb}^{-1}$. Here, $c_0 \sim c_5$ are the same as Table 6.

and 25% after $c_5$. At Point D, they are $\sim 1$. In that case, more strict $E_T^l$ and $M_{\text{eff}}$ cuts are needed.

In Table VI we have taken $E_T^l > 200\,\text{GeV}$, $M_{\text{eff}} > 500\,\text{GeV}$ and $E_T^l > 0.2M_{\text{eff}}$ as the $c_0$ cut. Numbers of $t\bar{t}$ after various $E_T^l$ and $M_{\text{eff}}$ cuts are shown in Table VIII. The $t\bar{t}$ background is dramatically reduced if high $E_T^l$ cuts are applied for large $M_{\text{eff}}$ [37]. Here, we change the $c_0$ cut as follows.

**$E_T^l$ and $M_{\text{eff}}$ cuts**

$c^{(1)}$: $E_T^l > 200\,\text{GeV}$, $E_T^l > 0.2M_{\text{eff}}$, $M_{\text{eff}} > 500\,\text{GeV}$

$c^{(2)}$: $E_T^l > 250\,\text{GeV}$, $E_T^l > 0.2M_{\text{eff}}$, $M_{\text{eff}} > 750\,\text{GeV}$

$c^{(3)}$: $E_T^l > 300\,\text{GeV}$, $E_T^l > 0.2M_{\text{eff}}$, $M_{\text{eff}} > 1000\,\text{GeV}$

**Number of high $p_T$ jets**

$n_{100} \geq 2$: at least two jets with $p_T > 100\,\text{GeV}$

$n_{200} \geq 2$: at least two jets with $p_T > 200\,\text{GeV}$

We also show $N(l^\pm l^\pm; c_5)/N(l^\pm l^\pm; c_0)$ after the cut $c^{(i)}$ and the cuts on the number of high $p_T$ jets at Point D in Table IX. The numbers of events correspond to $307.06\,\text{pb}^{-1}$. We
can see that the efficiency $N(l^\pm l^\pm; c_5)/N(l^\pm l^\pm; c_0)$ for $\tilde{q}\tilde{q}$ production and the efficiency for $\tilde{g}\tilde{q}$ production only weakly depend on the basic cut $c^{(i)}$ and the cuts on the number of high $p_T$ jets. The $c_5$ cut is still useful to reduce $\tilde{g}\tilde{q}$ productions.

We can drop the $t\bar{t}$ background without reducing the signal from SUSY events so much by taking $c^{(3)}$ and $n_{200} \geq 2$ as $c_0$. However, it has recently been pointed out that the number of high $p_T$ jets increases significantly if matrix element (ME) corrections are included [38]. On the other hand, the $E_T$ cut is not affected by ME corrections. The $c^{(3)}$ cut reduces background efficiently.

| number of jets | all | $n_{100} \geq 2$ | $n_{200} \geq 2$ |
|---------------|-----|----------------|----------------|
| $E_T$, $M_{\text{eff}}$ cut | all | $c^{(1)}$ | $c^{(2)}$ | $c^{(3)}$ | $c^{(1)}$ | $c^{(2)}$ | $c^{(3)}$ |
| $N(l^+l^+ \text{ from } \tilde{q}\tilde{q}; c_0)$ | 356 | 216 | 211 | 197 | 162 | 159 | 150 |
| $N(l^+l^+ \text{ from } \tilde{g}\tilde{q}; c_0)$ | 333 | 169 | 169 | 161 | 122 | 122 | 119 |
| $N(l^+l^+ \text{ from } \tilde{q}\tilde{q}; c_5)$ | * | 72 | 67 | 61 | 59 | 56 | 52 |
| $N(l^+l^+ \text{ from } \tilde{g}\tilde{q}; c_5)$ | * | 2 | 2 | 2 | 2 | 2 | 2 |
| $N(l^+l^+; c_5)/N(l^+l^+; c_0)$ for $\tilde{q}\tilde{q}$ | * | 0.333 | 0.318 | 0.310 | 0.364 | 0.352 | 0.347 |
| $N(l^+l^+; c_5)/N(l^+l^+; c_0)$ for $\tilde{g}\tilde{q}$ | * | 0.012 | 0.012 | 0.012 | 0.016 | 0.016 | 0.017 |
| $N(l^-l^- \text{ from } \tilde{q}\tilde{q}; c_0)$ | 84 | 55 | 54 | 50 | 38 | 37 | 36 |
| $N(l^-l^- \text{ from } \tilde{g}\tilde{q}; c_0)$ | 131 | 63 | 60 | 56 | 47 | 47 | 46 |
| $N(l^-l^- \text{ from } \tilde{q}\tilde{q}; c_5)$ | * | 16 | 15 | 15 | 14 | 13 | 13 |
| $N(l^-l^- \text{ from } \tilde{g}\tilde{q}; c_5)$ | * | 1 | 1 | 1 | 1 | 1 | 1 |
| $N(l^-l^-; c_5)/N(l^-l^-; c_0)$ for $\tilde{q}\tilde{q}$ | * | 0.291 | 0.278 | 0.300 | 0.368 | 0.351 | 0.361 |
| $N(l^-l^-; c_5)/N(l^-l^-; c_0)$ for $\tilde{g}\tilde{q}$ | * | 0.016 | 0.017 | 0.018 | 0.021 | 0.021 | 0.022 |

TABLE IX: Number of SS2l events at Point D after various $c_0$ cuts for 307.06 fb$^{-1}$

F. Summary of the cuts

It is important to reduce the background from $\tilde{g}\tilde{q}$ production to measure the $\tilde{q}_L\tilde{q}_L$ production cross section using SS2l events. We give a systematic procedure to separate $\tilde{g}$ and $\tilde{q}$ based on the number of jets in a hemisphere, and demonstrate that it works well to separate $\tilde{q}_L\tilde{q}_L$ from $\tilde{g}\tilde{q}$ for our model points. The hemisphere cut should work provided that $m_{\tilde{q}} - m_{\tilde{q}}$
is sufficiently large that a jet from the decay $\tilde{g} \rightarrow \tilde{q}q$ is detectable.

Using the cut on the number of jets in a hemisphere and the $b$-jet veto, SS2l events from $\tilde{g}\tilde{q}$ production are reduced by more than 95% while SS2l events from $\tilde{q}_L\tilde{q}_L$ are selected with an efficiency of more than 30% at our model points. Moreover, these efficiencies depend only weakly on the basic cuts on $E_T$ and $M_{\text{eff}}$.

Evidence of squark pair production can be seen in the ratio of the events before and after the hemisphere cuts, because it is significantly different from that of $\tilde{g}\tilde{q}$ production. At Point B, the ratio $N(l^+l^+; c_5)/N(l^+l^+; c_0)$ is 0.171 with a statistical error of $\sim 0.01$. If $\tilde{g}\tilde{q}$ production does not occur, $N(l^+l^+; c_0)$ becomes 1559, $N(l^+l^+; c_5)$ becomes 80 and the ratio becomes 0.051 with a statistical error of $\sim 0.006$. Actually, there are various sources of systematic errors such as uncertainties on the PDF, NNLO corrections and so on. The total systematic error is 14% if the uncertainties from squark and gluino mass errors cancel in the ratio and we ignore errors on the branching ratios. However we think there is enough margin to identify $\tilde{q}_L\tilde{q}_L$ production if careful analyses are done at LHC.

IV. COMPARISON OF OTHER MODELS WITH THE MSSM

A. The model with an extended gluino sector

The model with an extended gluino sector has been discussed in section 2.2. In this model, a gluino acquires a Dirac mass term with an adjoint fermion $\tilde{a}$. As the majorana gluino mass parameter decreases from the MSSM value for the same gluino mass, the total SUSY production cross section decreases. In particular, $\sigma(\tilde{q}_L\tilde{q}_L)$ decreases more rapidly than $\sigma(\tilde{g}\tilde{q}_L)$ when the majorana gluino mass parameter is reduced. Then SS2l events from $\tilde{q}_L\tilde{q}_L$ decrease more than those from $\tilde{g}\tilde{q}_L$. Figure 10 shows $N(l^\pm l^\pm; c_0)$ as a function of the majorana gluino mass. Here, we set the mass spectrum of this model as that of Point B and $m_{\tilde{g}_1} = m_{\tilde{g}}$ and $m_{\tilde{g}_2} = -3000$ GeV, and branching ratios and efficiencies of cuts are the same as in the previous section. Moreover, we simplify our calculation by assuming that all $l^\pm l^\pm$ events from $\tilde{g}\tilde{q}$ production occur from $\tilde{q}_L\tilde{q}_L$ productions (see Appendix A.3) and that the non-$\tilde{g}$, non-$\tilde{q}_L$ contribution does not depend on $m_g$. We show $N(l^+l^+; c_0)$ as a bold solid line, $N(l^-l^-; c_0)$ as a bold dashed line, $N(l^+l^+ \text{ from } \tilde{q}\tilde{q}; c_0)$ as a thin solid line and $N(l^-l^- \text{ from } \tilde{q}\tilde{q}; c_0)$ as a thin dashed line.
Figure 10b shows \(N(l^\pm l^\pm; c_5)\). SS2\(l\) events from \(\tilde{q}_L^+ \tilde{q}_L^+\) are dominant in the total SS2\(l\) events after the \(c_5\) cut, and that the dependency on the majorana gluino mass of the total number of SS2\(l\) events is nearly the same as the \(\sigma(\tilde{q}_L \tilde{q}_L)\) dependence shown in Figure 7. On the other hand, the \(\tilde{g}\tilde{q}\) contribution is dominant in Figure 10a.

We show the \(\pm 1\sigma\) statistical error for the MSSM limits with a dark gray zone. The absolute numbers of SS2\(l\) events after the cut \(c_0, c_5\) depend on various parameters, acceptance and so on. We assume the total uncertainty is 17% as discussed in the previous section. This is also shown in Figure 10 with a light gray zone.

The \(N(l^\pm l^\mp; c_0)\) shows more than 17% deviation from the MSSM in case of \(m_g \leq 606\,\text{GeV}\) \((m_g \leq 459\,\text{GeV})\). This means \(m_D \geq 1262\,\text{GeV}\) \((m_D \geq 1427\,\text{GeV})\). It is \(m_g \leq 936\,\text{GeV}\) \((m_g \leq 730\,\text{GeV})\) for \(N(l^+l^+(l^-l^-); c_5)\). This means \(m_D \geq 664\,\text{GeV}\) \((m_D \geq 1089\,\text{GeV})\).

As discussed in the previous section, the uncertainties on the leptonic branching ratios, PDF, QCD NNLO corrections and squark mass errors partly cancel by taking the ratio \(N(l^+l^+; c_5)/N(l^+l^+; c_0)\). Roughly speaking, \(N(l^\pm l^\pm; c_5)/N(l^\pm l^\pm; c_0)\) depends linearly on \(\sigma(\tilde{q}_L^+ \tilde{q}_L^+)/\sigma(\tilde{g}\tilde{q}_L)\). In this model, the ratio \(\sigma(\tilde{q}_L^+ \tilde{q}_L^+)/\sigma(\tilde{g}\tilde{q}_L)\) decreases as the majorana gluino mass decreases from the MSSM value. The ratios \(N(l^\pm l^\pm; c_5)/N(l^\pm l^\pm; c_0)\) as a function of the majorana gluino mass are plotted for Points A∼D in Figure 11a∼d. We show only the statistical error of \(\pm 1\sigma\) in the MSSM limit for \(3 \times 10^5\) events with a gray zone. For example, the ratio \(N(l^\pm l^\pm; c_5)/N(l^\pm l^\pm; c_0)\) has a statistically significant difference from Pont B for \(m_g \leq 850\,\text{GeV}\) at the 1\(\sigma\) level. Because \(\sigma(\tilde{q}^- \tilde{q}^-) \ll \sigma(\tilde{q}^+ \tilde{q}^+\) the sensitivity to \(l^-l^-\) is worse.

### B. The Littlest Higgs model with T-parity

We now consider the case where the \(E_T\) signature arises from decays of the quark partner \(q_-\) in the LHT model. The \(q_-\) has a similar decay pattern to the \(\tilde{q}\). Indeed, the leptonic branching ratio of \(q_-^+\) is \(\sim 15\%\), which is almost the same as that of \(\tilde{q}^+\) at Point C and D. The acceptance should be similar to that of the MSSM, because the acceptance depends on the decay kinematics, namely on the mass difference between \(\tilde{q}\) or \(q_-\) mass and the lightest R-odd or T-odd particle.

While the collider signal is similar to that of \(\tilde{q}\tilde{q}\) production in the MSSM, the LHT
FIG. 10: Number of SS2l events as a function of the gluino majorana mass at Point B a) after the cut $c_0$, b) after the cut $c_5$. Dark gray zones show 1σ statistical errors for $3\times10^5$ events. Light gray zones show 17% errors.

The model predicts different production cross sections from that of the MSSM. The cross section $\sigma(q^+\bar{q}^-)$ is 0.70 pb and $\sigma(q^-\bar{q}^-)$ is 0.15 pb for $M_{\tilde{q}} \sim 800$ GeV. On the other hand, $\sigma(\tilde{q}_L\tilde{q}_L^-)$ is 0.13 pb and $\sigma(\tilde{q}_L^+\tilde{q}_L^-)$ is 0.037 pb at Point C ($m_{\tilde{q}} \sim 800$ GeV). For $M_{\tilde{q}} = 1000$ GeV, $\sigma(q^+\bar{q}^-)$ is 0.22 pb and $\sigma(q^-\bar{q}^-)$ is 0.045 pb, while $\sigma(\tilde{q}_L^+\tilde{q}_L^-)$ is 0.049 pb and $\sigma(\tilde{q}_L\tilde{q}_L^-)$ is 0.012 pb at Point D ($m_{\tilde{q}} \sim 1000$ GeV). $\sigma(q^+\bar{q}^-)$ is about 4~5 times larger than $\sigma(\tilde{q}_L\tilde{q}_L^-)$ at each point. Note that $\sigma(\tilde{q}_L\tilde{q}_L^-)$ is always significantly smaller than $\sigma(q^-\bar{q}^-)$ of the LHT model no matter how heavy or light the $\tilde{g}$ is. Moreover, there is no $\tilde{g}$ production in the LHT model. If the excess of the production cross section is established and the existence of a light gluino is excluded, we can claim the LHT signature is observed.

At Point C, $N(l^+l^+; c_0) = 467$, $N(l^-l^-; c_0) = 233$, $N(l^+l^+; c_5) = 62$ and $N(l^-l^-; c_5) = 17$ for an integrated luminosity of $86 \text{ fb}^{-1}$. To study $N(l^+l^+)$ or $N(l^-l^-)$, we need to simulate all LHT production processes, which is beyond the scope of this paper. We assume the number of signal events from $q^-q^-$ production process is the number of signal events from $\tilde{q}\tilde{q}$ production process scaled by the ratio of cross sections $\sigma(q^-q^-)/\sigma(\tilde{q}_L\tilde{q}_L)$, and the other production processes are ignored for simplicity. We expect $N(l^+l^+; c_0) \sim 816$, $N(l^-l^-; c_0) \sim 162$, $N(l^+l^+; c_5) \sim 302$ and $N(l^-l^-; c_5) \sim 49$ in the LHT model of $M_{\tilde{q}} \sim 800$ GeV for the same integrated luminosity.

At Point D, we find $N(l^+l^+; c_0) = 571$, $N(l^-l^-; c_0) = 263$, $N(l^+l^+; c_5) = 78$ and $N(l^-l^-; c_5) = 24$ for an integrated luminosity of $307 \text{ fb}^{-1}$. We expect $N(l^+l^+; c_0) \sim 962$, $N(l^-l^-; c_0) \sim 210$, $N(l^+l^+; c_5) \sim 321$ and $N(l^-l^-; c_5) \sim 61$ in the LHT model of
FIG. 11: $N(c_5)/N(c_0)$ dependence on the majorana gluino mass $m_g$ at a) Point A, b) Point B, c) Point C and d) Point D. Gray zones show 1σ statistical errors for $3 \times 10^5$ events.

$M_{q_-} \sim 1000$ GeV for the same integrated luminosity. We can see that in the LHT models, $N(l^+l^+; c_0) : N(l^-l^-; c_0)$ would be about 4:1. This is different from the cases at the MSSM models Point C and D.

If there is no particle production except $q_-$ the ratio $N(l^+l^+; c_5)/N(l^+l^+; c_0)$ is expected to be around 0.37 in the LHT model of $M_{q_-} \sim 800$ GeV, which is larger than the value at Point C (0.133). The ratio $N(l^+l^+; c_5)/N(l^+l^+; c_0)$ is expected to be around 0.33 for $M_q = 1000$ GeV, and the value is larger than that at Point D (0.137).

Finally we comment on the case where $\bar{q}$ and $\bar{g}$ are highly degenerate so that we cannot detect the jets from $\bar{g} \to \bar{q}q$ decay by hemisphere analysis. Note that $\sigma(\bar{g}q) \gg \sigma(\bar{q}q)$, therefore the rate of the SS2l events could be as large as the LHT prediction. However, even in this case, $N(l^+l^+; c_0) : N(l^-l^-; c_0)$ in the MSSM is $\sim 2:1$ and cannot be 4:1 because there are $\bar{g}\bar{g}$ and $\bar{q}\bar{q}$ contributions.
V. CONCLUSION

Information on the fundamental Lagrangian of SUSY model can be extracted from each SUSY production process at LHC. For example, \( \tilde{q}_L \tilde{q}_L \) production cannot occur without a majorana gluino mass, because a chirality flip is required. Thus the majorana nature of gluino mass can be extracted from this process.

This process can be investigated using the SS2\( l \) events because \( \text{BR}(\tilde{q}_L^{\pm} \to l^\pm + X) \gg \text{BR}(\tilde{g}_L^{\pm} \to l^\mp + X) \). At LHC, however, mixed production with other sparticles \( \tilde{g}, \tilde{q}, \) etc. make it difficult to interpret the signal. In particular, \( \tilde{g}\tilde{q} \) production also contributes to the SS2\( l \) channel.

In this paper, we have discussed a systematic method to separate the production modes. When we measure \( \sigma(\tilde{q}_L \tilde{q}_L \to l^\pm l^\pm + X) \) in the MSSM, we suffer from a problematic background from \( \tilde{g}\tilde{q}_L \) production. We have proposed a new method based on a hemisphere analysis as a solution to this problem. In the hemisphere analysis, we assign high \( p_T \) objects into two hemispheres, where each hemisphere contains high \( p_T \) objects from the same parent particle with high probability. Then we require that there is only one jet with \( p_T > 50 \) GeV in a hemisphere. For the sample after some basic cuts, 30\~40\% for \( \tilde{q}_L \tilde{q}_L \) and 1\~3\% for \( \tilde{g}\tilde{q}_L \) remain after the hemisphere cut. Therefore we can obtain SS2\( l \) events with enhanced \( \tilde{q}_L \tilde{q}_L \) contribution, which may be used to estimate \( \sigma(\tilde{q}_L \tilde{q}_L) \).

We have also discussed two models which have similar collider signals to the MSSM but whose relevant production cross sections are dramatically different.

One of the models is the MSSM with an extended gluino sector, where the gluino can have a Dirac mass with an adjoint fermion \( \tilde{a} \). \( \sigma(\tilde{q}_L \tilde{q}_L) \) is sensitive to the fraction of majorana mass terms in the gluino mass. In the case where the gluino is pure Dirac, \( \tilde{q}_L \tilde{q}_L \) production cross section becomes zero.

We have applied our analysis to the model points with an extended gluino sector which have the same mass spectra of some MSSM model points except for an additional heavy adjoint particle. We estimate the number of SS2\( l \) events as a function of the majorana gluino mass, and estimate the sensitivity to the Dirac gluino mass. We take only the statistical error into account and assume that the masses of the squarks and the branching ratios are known. We find that the ratio \( \sigma(\tilde{q}_L^+ \tilde{q}_L^+) / \sigma(\tilde{g}\tilde{q}_L^+) \) that can be estimated from the acceptance under the hemisphere cut is useful because this quantity should be less sensitive to the error.
on the parameters and the acceptance and uncertainties of the PDF and QCD corrections.

We have also considered the LHT model. In this model, a set of T-odd partners is introduced to the SM matter particles and the EW gauge bosons. The quark partner production cross section $\sigma(q_-q_-)$ is 4~5 times as large as the production cross section $\sigma(\tilde{q}_L\tilde{q}_L)$ in the MSSM. The $q_-$ and $\tilde{q}$ have similar decay patterns and branching ratios. Thus, the number of SS2l events from $q_-q_-$ productions in the LHT model is expected 4~5 times larger if patterns of the mass spectra are the same. Moreover, the LHT model has no process corresponding to the process $\tilde{g}\tilde{q}$ nor $\tilde{g}\tilde{g}$ production in the MSSM. To exclude gluino productions is important to identify the LHT model. This can be done by investigating $N(l^+l^+)/N(l^-l^-)$.

It is generally important to measure the production cross sections of sparticles separately to verify the MSSM and distinguish various models. In this paper, we develop a method to identify gluino and squark production separately for SS2l channel. The method is based on the cuts on the kinematical configuration of the jets and can be applied to the other models. More development is needed for the model independent study of physics beyond the SM.

**Acknowledgement**

This work is supported in part by the Grant-in-Aid for Science Research, Ministry of Education, Culture, Sports, Science and Technology, Japan (No.16081207, 18340060 for M.M.N.).
APPENDIX A: APPENDIX

1. Mass spectra at our model points

We show mass spectra for the selected model points which have been analyzed. They are calculated by ISAJET 7.72. They are all mSUGRA mass spectra except that gluino masses of Points C and D are 300 GeV larger than mSUGRA predictions.
### TABLE X: Mass spectra of sparticles for the selected model points

| Mass parameter | Point A | Point B | Point C | Point D | SPS1a  |
|----------------|--------|--------|--------|--------|--------|
| $m_0$          | 100    | 100    | 370    | 400    | 100    |
| $m_1$          | 340    | 450    | 340    | 450    | 250    |
| $A_0$          | 0      | 0      | 0      | 0      | $-100$ |
| tan $\beta$    | 10     | 10     | 10     | 10     | 10     |
| sign $\mu$     | +      | +      | +      | +      | +      |

| Particle | Point A | Point B | Point C | Point D | SPS1a  |
|----------|--------|--------|--------|--------|--------|
| $\tilde{g}$ | 809.86 | 1047.83 | 1123.23 | 1360.22 | 595.19 |
| $\tilde{d}_L$ | 741.58 | 954.53 | 812.70 | 1021.11 | 543.04 |
| $\tilde{u}_L$ | 737.25 | 951.16 | 808.67 | 1017.91 | 537.25 |
| $\tilde{d}_R$ | 712.94 | 916.48 | 786.98 | 986.09  | 520.14 |
| $\tilde{u}_R$ | 714.56 | 919.51 | 787.79 | 988.10  | 520.45 |
| $\tilde{b}_1$ | 683.97 | 883.16 | 731.10 | 928.37  | 491.92 |
| $\tilde{t}_1$ | 559.18 | 734.57 | 585.39 | 804.20  | 379.14 |
| $\tilde{b}_2$ | 708.33 | 909.55 | 776.58 | 973.96  | 524.58 |
| $\tilde{t}_2$ | 738.66 | 929.69 | 780.92 | 946.08  | 574.64 |
| $\tilde{e}_L$ | 256.36 | 324.47 | 437.13 | 503.38  | 202.12 |
| $\tilde{e}_R$ | 168.27 | 201.70 | 393.09 | 435.59  | 143.00 |
| $\tilde{\nu}_e$ | 243.67 | 314.44 | 429.70 | 496.84  | 186.00 |
| $\tilde{\tau}_1$ | 160.79 | 194.28 | 387.18 | 429.40  | 133.39 |
| $\tilde{\tau}_2$ | 258.50 | 325.66 | 437.28 | 503.05  | 206.02 |
| $\tilde{\nu}_\tau$ | 242.89 | 313.50 | 428.00 | 495.00  | 185.06 |
| $\tilde{\chi}_1^0$ | 132.74 | 179.11 | 133.95 | 180.54  | 96.05  |
| $\tilde{\chi}_2^0$ | 253.87 | 345.39 | 256.39 | 348.15  | 176.80 |
| $\tilde{\chi}_3^0$ | $-448.66$ | $-575.60$ | $-451.46$ | $-577.05$ | $-358.82$ |
| $\tilde{\chi}_4^0$ | 467.28 | 591.37 | 470.52 | 592.66  | 377.84 |
| $\tilde{\chi}_1^+$ | 254.13 | 345.95 | 256.71 | 348.72  | 176.37 |
| $\tilde{\chi}_2^+$ | 466.48 | 590.74 | 469.74 | 592.56  | 378.26 |
2. Branching ratios at our model points

We also show the branching ratios of the selected points. They are also calculated by ISAJET. Squarks mainly decay into charginos $\tilde{\chi}^\pm$ and the second lightest neutralino $\tilde{\chi}_2^0$ at each point. Note that, at Points C and D, $\tilde{\chi}_2^0$ does not decay into sleptons. On the other hand, at Points A, B and SPS1a, $\tilde{\chi}_2^0$ decays into $\tilde{\chi}_1^0l^+l^-$ or $\tilde{\chi}_1^0\tau^+\tau^-$. 
| mode                  | BR(%)      | mode                  | BR(%)      |
|-----------------------|------------|-----------------------|------------|
| $g \rightarrow \tilde{d}_L q$ | 11 10 14 13 12 | $\tilde{t}_1 \rightarrow \tilde{\chi}_1^+ b$ | 49 39 43 6.9 73 |
| $\rightarrow \tilde{d}_L q$ | 11 10 14 13 12 | $\rightarrow \tilde{\chi}_2^0 b$ | 13 21 20 41 0 |
| $\rightarrow \tilde{u}_R q$ | 38 36 32 32 41 | $\rightarrow \tilde{\chi}_1^0 t$ | 22 26 22 24 18 |
| $\rightarrow \tilde{t}_1 \tilde{t}_1^t(t_1^t)$ | 7.1 9.6 5.3 7 4.1 | $\rightarrow \tilde{\chi}_2^0 t$ | 15 14 14 3 9.5 |
| $\rightarrow \tilde{b}_1 \tilde{b}_1^b(b_1^b b)$ | 7.7 6.9 5.1 5 8.9 | $\rightarrow \tilde{\chi}_3^0 t$ | 0 0 0 15 0 |
| $\rightarrow \tilde{b}_2 \tilde{b}_2^b(b_2^b b)$ | 5.5 5.2 4.2 4.2 4.9 | $\rightarrow \tilde{\chi}_4^0 t$ | 0 0 0 10 0 |
| $\rightarrow \tilde{t}_2 \tilde{t}_2(t_2^t t)$ | 0 0 5.4 4.5 0 | $\tilde{t}_2 \rightarrow \tilde{\chi}_1^+ b$ | 23 25 22 41 19 |
| $\tilde{u}_L \rightarrow \tilde{\chi}_1^0 d$ | 65 65 64 64 65 | $\rightarrow \tilde{\chi}_2^0 b$ | 16 12 1.5 2.8 22 |
| $\rightarrow \tilde{\chi}_2^0 d$ | 1.6 1.4 1.9 1.5 1.2 | $\rightarrow \tilde{\chi}_2^0 t$ | 9.7 11 9.5 18 7.6 |
| $\rightarrow \tilde{\chi}_1^0 u$ | 0 1.1 0 1 0.6 | $\rightarrow \tilde{\chi}_3^0 t$ | 8.5 10 11 18 3.7 |
| $\rightarrow \tilde{\chi}_2^0 u$ | 32 32 32 32 32 | $\rightarrow \tilde{\chi}_4^0 t$ | 24 23 25 19 18 |
| $\rightarrow \tilde{\chi}_1^0 u$ | 1.2 0.9 1.4 1.1 1.0 | $\rightarrow \tilde{t}_1 X$ | 17 17 17 0 27 |
| $\tilde{d}_L \rightarrow \tilde{\chi}_1^0 u$ | 61 62 60 62 61 | $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1 X$ | 44 48 54 55 41 |
| $\rightarrow \tilde{\chi}_2^0 u$ | 4.4 3.3 5.3 3.6 4.1 | $\rightarrow \tilde{\chi}_1^0 W^-$ | 37 38 45 42 36 |
| $\rightarrow \tilde{\chi}_1^0 d$ | 2.1 8.1 1.9 1.7 2.4 | $\rightarrow \tilde{t}^- X$ | 12 6.7 0 0 14 |
| $\rightarrow \tilde{\chi}_2^0 d$ | 31 32 31 31 31 | $\rightarrow \tau^- X$ | 7.2 5.4 0 0 6.6 |
| $\rightarrow \tilde{\chi}_4^0 d$ | 1.6 1.2 1.9 1.4 1.4 | $\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 W^-$ | 21 7.7 100 100 1.1 |
| $\tilde{b}_1 \rightarrow \tilde{\chi}_1^0 t$ | 38 36 33 38 43 | $\rightarrow \tilde{\chi}_1^0 t^- \tilde{\nu}_t$ | 24 54 0 0 0.4 |
| $\rightarrow \tilde{\chi}_2^0 t$ | 24 28 31 37 0 | $\rightarrow \tilde{\chi}_1^0 t^- \tilde{\nu}_t$ | 54 38 0 0 98 |
| $\rightarrow W^- \tilde{t}_1$ | 10 12 12 0 14 | $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 X$ | 45 55 100 100 0.8 |
| $\rightarrow \tilde{\chi}_2^0 b$ | 24 21 20 22 36 | $\rightarrow \tilde{\chi}_1^0 t^- \tilde{t}^- t$ | 7.6 18 0 0 13 |
| $\tilde{b}_2 \rightarrow \tilde{\chi}_1^0 t$ | 15 14 4.9 4.4 21 | $\rightarrow \tilde{\chi}_1^0 t^- \tau^-$ | 46 20 0 0 87 |
| $\rightarrow \tilde{\chi}_2^0 t$ | 34 35 39 41 0 | $\tilde{\chi}_3^0 \rightarrow \tilde{\chi}_1^0 X$ | 14 13 14 14 13 |
| $\rightarrow W^- \tilde{t}_1$ | 13 13 13 0 35 | $\rightarrow \tilde{\chi}_2^0 X$ | 24 26 25 27 23 |
| $\rightarrow \tilde{\chi}_1^0 b$ | 19 21 23 31 15 | $\rightarrow \tilde{\chi}_1^0 W^+$ | 29 29 30 30 60 |
| $\rightarrow \tilde{\chi}_2^0 b$ | 9.6 8.3 3.2 5.7 17 | $\tilde{\chi}_4^0 \rightarrow \tilde{\chi}_1^0 X$ | 21 19 12 13 8.5 |
| $\rightarrow \tilde{\chi}_3^0 b$ | 3.7 3.5 7.9 9.4 5.4 | $\rightarrow \tilde{\chi}_2^0 X$ | 18 22 22 25 15 |
| $\rightarrow \tilde{\chi}_4^0 b$ | 5.6 5.2 9.6 11 7.4 | $\rightarrow \tilde{\chi}_1^0 W^+$ | 26 26 32 30 52 |

TABLE XI: Branching ratios of sparticles for our model point: here, X means some SM particles.
3. Dominant processes contributing to SS2l events

Here we show the numbers of SS2l events from each production process at Point B. Note that SS2l ($l^\pm l^\pm$) signals come not only from $\bar{q}_L^+ q_L^+$ production but also from $\bar{q}_L^+ \bar{q}_L^-$ (mainly $u_L d_L$) production. For $l^+ l^+$ events, about 6% of total $l^+ l^+$ events are from $\bar{q} q$ production. The $l^+ l^+$ events from $\bar{q}_L q_L^+$ production are 10% of total $l^+ l^+$ events from $\bar{q} q$ production.
| Point B | all | $c_0$ | $c_1$ | $c_2$ | $c_3$ | $c_4$ | $c_5$ | ratio |
|---------|-----|------|------|------|------|------|------|------|
| $l^+l^+$ | $\tilde{q}\tilde{q}$ | 1479 | 1014 | 1001 | 894 | 363 | 383 | 361 | 0.356 |
|         | $\tilde{u}_L\tilde{u}_L$ | 1161 | 788 | 778 | 701 | 291 | 692 | 289 | 0.367 |
|         | $\tilde{u}_L\tilde{c}_L$ | 95 | 68 | 68 | 58 | 22 | 58 | 22 | 0.324 |
|         | $\tilde{u}_L\tilde{d}_L$ | 84 | 58 | 56 | 51 | 17 | 50 | 17 | 0.293 |
|         | $\tilde{u}_L\tilde{d}^*_L$ | 90 | 62 | 61 | 54 | 19 | 53 | 19 | 0.306 |
|         | $\tilde{u}_L\tilde{s}^*_L$ | 48 | 37 | 37 | 29 | 13 | 29 | 13 | 0.351 |
| $l^+l^+$ | $\tilde{g}\tilde{q}$ | 1765 | 1098 | 433 | 613 | 52 | 279 | 36 | 0.033 |
|         | $\tilde{g}\tilde{u}_L$ | 1581 | 974 | 388 | 538 | 41 | 252 | 30 | 0.031 |
|         | $\tilde{g}\tilde{c}_L$ | 22 | 18 | 8 | 8 | 2 | 3 | 1 | 0.056 |
|         | $\tilde{g}\tilde{d}_L$ | 32 | 22 | 8 | 11 | 2 | 5 | 1 | 0.045 |
|         | $\tilde{g}\tilde{d}^*_L$ | 78 | 53 | 17 | 38 | 6 | 12 | 3 | 0.057 |
|         | $\tilde{g}\tilde{s}^*_L$ | 39 | 22 | 9 | 13 | 0 | 6 | 0 | 0 |
| $l^-l^-$ | $\tilde{q}\tilde{q}$ | 519 | 333 | 323 | 293 | 123 | 285 | 122 | 0.366 |
|         | $\tilde{d}_L\tilde{d}_L$ | 280 | 188 | 181 | 164 | 74 | 159 | 73 | 0.388 |
|         | $\tilde{d}_L\tilde{s}_L$ | 87 | 62 | 61 | 56 | 31 | 55 | 31 | 0.5 |
|         | $\tilde{u}_L\tilde{d}_L$ | 106 | 67 | 65 | 57 | 16 | 55 | 16 | 0.239 |
|         | $\tilde{d}_L\tilde{u}_L$ | 20 | 7 | 7 | 7 | 0 | 7 | 0 | 0 |
|         | $\tilde{d}_L\tilde{c}^*_L$ | 10 | 7 | 7 | 7 | 1 | 7 | 1 | 0.143 |
| $l^-l^-$ | $\tilde{g}\tilde{q}$ | 881 | 553 | 241 | 310 | 23 | 172 | 15 | 0.027 |
|         | $\tilde{g}\tilde{d}_L$ | 615 | 396 | 184 | 232 | 21 | 132 | 14 | 0.035 |
|         | $\tilde{g}\tilde{s}_L$ | 30 | 18 | 8 | 9 | 0 | 5 | 0 | 0 |
|         | $\tilde{g}\tilde{u}_L$ | 135 | 75 | 23 | 40 | 2 | 17 | 1 | 0.013 |
|         | $\tilde{g}\tilde{u}_L^*$ | 67 | 43 | 19 | 21 | 0 | 13 | 0 | 0 |
|         | $\tilde{g}\tilde{c}^*_L$ | 20 | 12 | 4 | 6 | 0 | 3 | 0 | 0 |

TABLE XII: Contributions from each production process to SS2l events at Point B.
[1] D. N. Spergel et al. [WMAP Collaboration], Astrophys. J. Suppl. 148, 175 (2003) arXiv:astro-ph/0302209.
  D. N. Spergel et al., arXiv:astro-ph/0603449.

[2] ALTAS Technical Design Report, CERN/LHCC-99-15, ATL-PHYS-98-131 (1998).

[3] CMS Physics Technical Design Report, CERN/LHCC 2006-001, CMS TDR 8.1 02 February 2006.

[4] I. Antoniadis, Phys. Lett. B 246, 377 (1990).
  T. Appelquist, H. C. Cheng and B. A. Dobrescu, Phys. Rev. D 64, 035002 (2001) arXiv:hep-ph/0012100.

[5] H. C. Cheng and I. Low, JHEP 0309, 051 (2003) arXiv:hep-ph/0308199.

[6] H. C. Cheng and I. Low, JHEP 0408, 061 (2004) arXiv:hep-ph/0405243.

[7] J. Hubisz and P. Meade, Phys. Rev. D 71, 035016 (2005) arXiv:hep-ph/0411264.

[8] A. Freitas and P. Z. Skands, JHEP 0609, 043 (2006) arXiv:hep-ph/0606121.

[9] H. Baer et al., FSU-HEP-901110 To be publ. in Proc. of 1990 DPF Summer Study on High Energy Physics, Snowmass, CO, Jun 25 - Jul 13, 1990

[10] H. Baer, X. Tata and J. Woodside, Phys. Rev. D 45, 142 (1992).

[11] H. Baer, C. h. Chen, F. Paige and X. Tata, Phys. Rev. D 53, 6241 (1996) arXiv:hep-ph/9512383.

[12] P. J. Fox, A. E. Nelson and N. Weiner, JHEP 0208, 035 (2002) arXiv:hep-ph/0206096.

[13] Z. Chacko, P. J. Fox and H. Murayama, Nucl. Phys. B 706, 53 (2005) arXiv:hep-ph/0406142.

[14] L. M. Carpenter, P. J. Fox and D. E. Kaplan, arXiv:hep-ph/0503093.

[15] J. Hisano, M. Nagai, T. Naganawa and M. Senami, Phys. Lett. B 644, 256 (2007) arXiv:hep-ph/0610383.

[16] A. J. Barr, Phys. Lett. B 596, 205 (2004) arXiv:hep-ph/0405052.

[17] C. Athanasiou, C. G. Lester, J. M. Smillie and B. R. Webber, JHEP 0608, 055 (2006) arXiv:hep-ph/0605286.

[18] A. Belyaev, C. R. Chen, K. Tobe and C. P. Yuan, Phys. Rev. D 74, 115020 (2006) arXiv:hep-ph/0609179.

[19] F. Moortgat and L. Pape, CMS Physics TDR Chapter 13.4, p.400-403, CERN/LHCC/2006-
021 (26 June 2006).

[20] S. Kretzer, H. L. Lai, F. I. Olness and W. K. Tung, Phys. Rev. D 69, 114005 (2004) arXiv:hep-ph/0307022.

[21] G. Weiglein et al. [LHC/LC Study Group], Phys. Rept. 426, 47 (2006) arXiv:hep-ph/0410364.

[22] B. C. Allanach et al., in Proc. of the APS/DPF/DPB Summer Study on the Future of Particle Physics (Snowmass 2001) ed. N. Graf, In the Proceedings of APS / DPF / DPB Summer Study on the Future of Particle Physics (Snowmass 2001), Snowmass, Colorado, 30 Jun - 21 Jul 2001, pp P125 arXiv:hep-ph/0202233.

[23] H. Baer, F. E. Paige, S. D. Protopopescu and X. Tata, arXiv:hep-ph/9305342.

[24] F. E. Paige, S. D. Protopopescu, H. Baer and X. Tata, arXiv:hep-ph/0312045.

[25] G. Corcella et al., arXiv:hep-ph/0210213.

[26] N. Arkani-Hamed, A. G. Cohen, E. Katz and A. E. Nelson, JHEP 0207, 034 (2002) arXiv:hep-ph/0206021.

[27] C. Csaki, J. Hubisz, G. D. Kribs, P. Meade and J. Terning, Phys. Rev. D 67, 115002 (2003) arXiv:hep-ph/0211124.

[28] J. L. Hewett, F. J. Petriello and T. G. Rizzo, JHEP 0310, 062 (2003) arXiv:hep-ph/0211218.

[29] E. Richter-Was, arXiv:hep-ph/0207355.

[30] I. Hinchliffe, F. E. Paige, M. D. Shapiro, J. Soderqvist and W. Yao, Phys. Rev. D 55, 5520 (1997) arXiv:hep-ph/9610544.

[31] H. Bachacou, I. Hinchliffe and F. E. Paige, Phys. Rev. D 62, 015009 (2000) arXiv:hep-ph/9907518.

[32] I. Hinchliffe and F. E. Paige, Phys. Rev. D 61, 095011 (2000) arXiv:hep-ph/9907519.

[33] I. Hinchliffe and F. E. Paige, Phys. Rev. D 60, 095002 (1999) arXiv:hep-ph/9812233.

[34] J. Hisano, K. Kawagoe and M. M. Nojiri, Phys. Rev. D 68, 035007 (2003) arXiv:hep-ph/0304214.

[35] K. Kawagoe, M. M. Nojiri and G. Polesello, Phys. Rev. D 71, 035008 (2005) arXiv:hep-ph/0410160.

[36] W. Beenakker, R. Höpker, M. Spira and P. M. Zerwas, Nucl. Phys. B 492, 51 (1997); T. Plehn, Prospino 2.0 [pheno.physics.wisc.edu/~plehn/prospino/prospino.html].

[37] S. Matsumoto, M. M. Nojiri and D. Nomura, arXiv:hep-ph/0612249.
[38] S. Asai, talk in 4th TEV4LHC, Oct 20-22, 2005 at FermiLab.

http://conferences.fnal.gov/tev4lhc/