Determining SUSY Particle Masses at LHC

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ABSTRACT

Some possible methods to determine at the LHC masses of SUSY particles are discussed.


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ABSTRACT

Some possible methods to determine at the LHC masses of SUSY particles are discussed.

I. INTRODUCTION

If supersymmetry (SUSY) exists at the electroweak scale, it should be easy at the LHC to observe deviations from the Standard Model (SM) such as an excess of events with multiple jets plus missing energy $E_T$ or with like-sign dileptons $\ell^+\ell^+$ plus $E_T$ [1, 2, 3]. Determining SUSY masses is more difficult because each SUSY event contains two missing lightest SUSY particles $\tilde{g}$,1, and there are not enough kinematic constraints to determine the momenta of these. This note describes two possible approaches to determining SUSY masses, one based on a generic global variable and the other based on constructing particular decay chains.

The ATLAS and CMS Collaborations at the LHC are considering five points in the minimal supergravity (SUGRA) model listed in Table I below [4]. Point 4 is the comparison point extensively discussed elsewhere in these Proceedings. For this point a good strategy at the LHC is to use the decays $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\ell^+\ell^-$ to determine the mass difference $M(\tilde{\chi}_2^0) - M(\tilde{\chi}_1^0)$ [4]. For higher masses, e.g., Points 1-3, this decay is small, but $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_2^0h \rightarrow \tilde{\chi}_1^0bb$, $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0W^\pm \rightarrow \tilde{\chi}_1^0q\bar{q}$, and $\tilde{\chi}_2^0 \rightarrow \tilde{\ell}\tilde{\ell}$ provide alternative starting points for detailed analysis.

Table I: SUGRA parameters for the five LHC points.

<table>
<thead>
<tr>
<th>Point</th>
<th>$m_0$ (GeV)</th>
<th>$m_{1/2}$ (GeV)</th>
<th>$A_0$ (GeV)</th>
<th>$\tan\beta$</th>
<th>sign $\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>300</td>
<td>300</td>
<td>2.1</td>
<td>+</td>
</tr>
<tr>
<td>2</td>
<td>400</td>
<td>400</td>
<td>0</td>
<td>2.0</td>
<td>+</td>
</tr>
<tr>
<td>3</td>
<td>400</td>
<td>400</td>
<td>0</td>
<td>10.0</td>
<td>+</td>
</tr>
<tr>
<td>4</td>
<td>200</td>
<td>100</td>
<td>0</td>
<td>2.0</td>
<td>–</td>
</tr>
<tr>
<td>5</td>
<td>800</td>
<td>200</td>
<td>0</td>
<td>10.0</td>
<td>+</td>
</tr>
</tbody>
</table>

II. EFFECTIVE MASS ANALYSIS

The first step after discovering a deviation from the SM is to estimate the mass scale. SUSY production at the LHC is dominated by gluinos and squarks, which decay into jets plus missing energy. The mass scale can be estimated using the effective mass, defined as the scalar sum of the $p_T$'s of the four hardest jets and the missing transverse energy $E_T$,

$$M_{\text{eff}} = p_{T,1} + p_{T,2} + p_{T,3} + p_{T,4} + E_T.$$
Point 5

Figure 3: Signal and SM backgrounds for Point 3. See Fig. 1 for symbols.

Figure 4: Signal and SM backgrounds for Point 4. See Fig. 1 for symbols.

Figure 5: Signal and SM backgrounds for Point 5. See Fig. 1 for symbols.

$s$, $c$, or $b$ jets, in five bins covering $50 < p_T < 2400$ GeV. The detector response was simulated using a toy calorimeter with

- **EMCAL**: $10\%/\sqrt{E} + 1\%$
- **HCAL**: $50\%/\sqrt{E} + 3\%$
- **FCAL**: $100\%/\sqrt{E} + 7\%$, $|\eta| > 3$

Jets were found using a simple fixed-cone algorithm (GETJET) with $R = [(\Delta \eta)^2 + (\Delta \phi)^2]^{1/2} = 0.7$. To suppress the SM background, the following cuts were made:

- $E_T > 100$ GeV
- $\geq 4$ jets with $p_T > 50$ GeV and $p_T,1 > 100$ GeV

- Transverse sphericity $S_T > 0.2$
- Lepton veto
- $E_T > 0.2M_{\text{eff}}$

With these cuts and the idealized detector assumed here, the signal is much larger than the SM backgrounds for large $M_{\text{eff}}$, as is illustrated in Figs. 1–5.

The peak of the $M_{\text{eff}}$ mass distribution, or alternatively the point at which the signal and background are equal, provides a good first estimate of the SUSY mass scale, which is defined to be

$$M_{\text{SUSY}} = \min(M_{\tilde{g}}, M_{\tilde{\alpha}})$$

(The choice of $M_{\tilde{g}}$ as the typical squark mass is arbitrary.) The ratio of the value $M_{\text{eff}}$ for which $S = B$ to $M_{\text{SUSY}}$ was calculated by fitting smooth curves to the signal and background and is given in Table II. To see whether the approximate constancy of this ratio might be an accident, 100 SUGRA models were chosen at random with $100 < m_0 < 500$ GeV, $100 < m_1 < 500$ GeV, $-500 < A_0 < 500$ GeV, $1.8 < \tan \beta < 12$, and $\text{sgn} \mu = \pm 1$ and compared to the assumed signal, Point 1. The light Higgs was assumed to be known, and all the comparison

<table>
<thead>
<tr>
<th>Point</th>
<th>$M_{\text{eff}}$ (GeV)</th>
<th>$M_{\text{SUSY}}$ (GeV)</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>980</td>
<td>663</td>
<td>1.48</td>
</tr>
<tr>
<td>2</td>
<td>1360</td>
<td>926</td>
<td>1.47</td>
</tr>
<tr>
<td>3</td>
<td>1420</td>
<td>928</td>
<td>1.53</td>
</tr>
<tr>
<td>4</td>
<td>470</td>
<td>300</td>
<td>1.58</td>
</tr>
<tr>
<td>5</td>
<td>980</td>
<td>586</td>
<td>1.67</td>
</tr>
</tbody>
</table>
models were required to have $M_h = 100.4 \pm 3$ GeV. A sample of 1K events was generated for each point, and the peak of the $M_{\text{eff}}$ distribution was found by fitting a Gaussian near the peak. Figure 6 shows the resulting scatter plot of $M_{\text{SUSY}}$ vs. $M_{\text{eff}}$. The ratio is constant within about $\pm 10\%$, as can be seen from Fig. 7. This error is conservative, since there considerable contribution to the scatter from the limited statistics and the rather crude manner in which the peak was found.

III. SELECTION OF $h \rightarrow b\bar{b}$

For Point 1 the decay chain $\tilde{q}_{\tilde{1}} \rightarrow \tilde{\chi}_{\tilde{1}}^0 h, h \rightarrow b\bar{b}$ has a large branching ratio, as is typical if this decay is kinematically allowed. The decay $h \rightarrow b\bar{b}$ thus provides a handle for identifying events containing $\tilde{\chi}_1^0$'s [6]. Furthermore, the gluino is heavier than the squarks and so decays into them. The strategy for this analysis is to select events in which one squark decays via

\[ \tilde{q} \rightarrow \tilde{\chi}_1^0 q, \quad \tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^{0} h, \quad h \rightarrow b\bar{b}, \]

and the other via

\[ \tilde{q} \rightarrow \tilde{\chi}_1^0 q, \]

giving two $b$ jets and exactly two additional hard jets.

ISAJET 7.22 [5] was used to generate a sample of 100K events for Point 1, corresponding to about 5.6 fb$^{-1}$. Background samples of 250K each for $t\bar{t}$, $Wj$, and $Zj$, and 5000K for QCD jets were also generated, equally divided among five $p_T$ bins. The background samples generally represent a small fraction of an LHC year. The detector response was simulated using the toy calorimeter described above. Jets were found using a fixed cone algorithm with $R = 0.4$. The following cuts were imposed:

- $E_T > 100$ GeV
- $\geq 4$ jets with $p_T > 50$ GeV and $p_{Tj} > 100$ GeV
- Transverse sphericity $S_T > 0.2$
- $M_{\text{eff}} > 800$ GeV
- $E_T > 0.2M_{\text{eff}}$

Jets were tagged as $b$'s if they contained a $B$ hadron with $p_T > 5$ GeV and $\eta < 2$; no other tagging inefficiency or $b$ mistagging was included. Figure 8 shows the resulting $bb$ mass distributions for the signal and the sum of all SM backgrounds with $p_{Tb} > 25$ GeV together with a Gaussian plus quadratic fit to the signal. The light Higgs mass is 100.4 GeV.
giving two hard jets and two softer jets from the $W$. The branching ratio for $q_L \rightarrow \tilde{\chi}^0_1 q$ is small for Point 1, so the contributions from $g \rightarrow q_L \tilde{q}$ and from $q_L q_L$ pair production are suppressed.

The same signal sample was used as in Section III, and jets were again found using a fixed cone algorithm with $R = 0.4$. The combinatorial background for this decay chain is much larger than for the previous one, so harder cuts are needed:

- $E_T > 100$ GeV
- $\geq 4$ jets with $p_T^{1,2} > 200$ GeV, $p_T^{3,4} > 50$ GeV, and $\eta_{3,4} < 2$
- Transverse sphericity $S_T > 0.2$
- $M_{\text{eff}} > 800$ GeV
- $E_T > 0.2 M_{\text{eff}}$

The same $b$-tagging algorithm was applied to tag the third and fourth jets as not being $b$ jets. Of course, this is not really feasible; instead one should measure the $b$-jet distributions and subtract them.

The mass distribution $M_{34}$ of the third and fourth highest $p_T$ jets with these cuts is shown in Fig. 10 for the signal and the sum of all backgrounds. A peak is seen a bit below the $W$ mass with a fitted width surprisingly smaller than that for the $h$ in Fig. 8, note that the $W$ natural width has been neglected in the simulation of the decays. The SM background is more significant here than for $h \rightarrow bb$. Events from this peak can be combined with another jet as was done for $h \rightarrow bb$ in Fig. 9, providing another determination of the quark mass. Figure 10 also provides a starting point for measuring $W$ decays separately from other sources of leptons such as gaugino decays into sleptons.
V. SELECTION OF $\tilde{\chi}_2^0 \rightarrow \tilde{\ell}\ell \rightarrow \tilde{\chi}_1^0\ell\ell$

Point 1 has relatively light sleptons, which is generically necessary if the $\tilde{\chi}_2^0$ is to provide acceptable cold dark matter [7]. Hence the two-body decay

$$\tilde{\chi}_2^0 \rightarrow \tilde{\ell}_R\ell \rightarrow \tilde{\chi}_1^0\ell^+\ell^-$$

is kinematically allowed and competes with the $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h$ decay, producing opposite-sign, like-flavor dileptons. The largest SM background is $t\bar{t}$. To suppress this and other SM backgrounds the following cuts were made on the same signal and SM background samples used in the two previous sections:

- $M_{\text{eff}} > 800$ GeV
- $E_T > 0.2 M_{\text{eff}}$
- $\geq 1 \ R = 0.4$ jet with $p_T,j > 100$ GeV
- $\ell^+\ell^-$ pair with $p_T,\ell > 10$ GeV, $\eta_\ell < 2.5$
- $\ell$ isolation cut: $E_T < 10$ GeV in $R = 0.2$
- Transverse sphericity $S_T > 0.2$

With these cuts very little SM background survives, and the $M_{tt}$ mass distribution shown in Fig. 11 has an edge near

$$M_{\text{eff}}^\text{max} = M_{\tilde{\chi}_2^0} \left(1 - \frac{M_{\tilde{\ell}}^2}{M_{\tilde{\chi}_2^0}^2} \right) \left(1 - \frac{M_{\tilde{\chi}_1^0}^2}{M_{\tilde{\ell}}^2} \right) \approx 112 \text{ GeV},$$

If $M_{tt}$ is near its kinematic limit, then the velocity difference of the $\ell^+\ell^-$ pair and the $\tilde{\chi}_1^0$ is minimized. Having both leptons hard requires $M_{\tilde{\ell}}/M_{\tilde{\chi}_2^0} \sim M_{\tilde{\chi}_1^0}/M_{\tilde{\ell}}$. Assuming this and $M_{\tilde{\chi}_2^0} = 2M_{\tilde{\chi}_1^0}$ implies that the endpoint in Fig. 11 is equal to the $\tilde{\chi}_1^0$ mass. An improved estimate could be made by detailed fitting of all the kinematic distributions. Events were selected with $M_{\text{eff}}^\text{max} - 10$ GeV $< M_{tt} < M_{\text{eff}}^\text{max}$, and the $\tilde{\chi}_1^0$ momentum was calculated using this crude $\tilde{\chi}_1^0$ mass and

$$p_{\tilde{\chi}_1^0} = (M_{\tilde{\chi}_1^0}/M_{tt}) \ p_{tt}.$$ 

The invariant mass $M_{tt}\tilde{\chi}_1^0$ of the $\ell^+\ell^-$, the highest $p_T$ jet, and the $\tilde{\chi}_1^0$ was then calculated and is shown in Fig. 12. A peak is seen near the light squark masses, 660–688 GeV. More study is needed, but this approach looks promising.

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VI. REFERENCES