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The parameter section

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The Night before the LHC
—thoughts about expectations in the early stage and beyond—

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Abstract. I review recent developments on the use of \( m_{T^2} \) variables for SUSY parameter study, which might be useful for analyses of the data in the early stage of the LHC experiments. I also discuss some of recent interesting studies.

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THE NIGHT BEFORE....

'Twas the night before Christmas
when all through the house
Not a creature was stirring, not even a mouse;
The stockings were hung by the chimney with care
In hopes that St. Nicolas soon would be there'

— Clement Clarke Moore
"The Night before Christmas"

Although not in its full scale, the LHC is starting this year. All parts of the accelerator and the detectors will be put together with care, in hopes the beams soon would be there—to reveal the nature of elementary particles at TeV scale. Theorists are waiting something new, the gift (the item may vary from the CMSSM minimum to unparticle), and each of you must have your special plans for the night before the LHC. Most likely, the era of "the freedom of model building" will be over within a few years. There will be more data, more constraints, more handles. But when and how?

For the case of supersymmetric models and its family which predict new colored particles decaying into SM particles and a stable new particle—a dark matter candidate, the discovery channels have been studied intensively. The stable particles, the lightest supersymmetric particle (LSP) in the minimal supersymmetric standard model (MSSM), give a large missing momentum to the events, which is an important signature of the SUSY events. To control the large QCD, \( t\bar{t}, W \) and \( Z \) backgrounds, we require large \( E_{T\text{miss}} \), several high \( p_T \) jets, large effective mass \( m_{\text{eff}} \). The ATLAS and CMS studies show that squarks and gluino with the mass below 1.2 TeV would be explored for \( \int dt \mathcal{L} = 1 \text{fb}^{-1} \) at \( \sqrt{s} = 14 \text{ TeV} \). Note that the integrated luminosity is required to understand the detector and the backgrounds from the data, and the number of SUSY events at 1fb\(^{-1} \) itself may be large enough to allow some kind of model parameter studies.

Because SUSY at the LHC have been discussed in this conference series for years and years, I concentrate on recent developments on the use of \( m_{T^2} \) variable in the first part of my talk. It might be relevant to the early stage analyses of the LHC and has not been systematically studied by the experimental groups yet. At the end of my talk I will also cover other interesting developments.

THE \( m_{T^2} \) DISTRIBUTION AND SPARTICLE MASS DETERMINATION

The Stransverse mass and the LSP mass determination

An important development since SUSY '07 is a new understanding on the role of stransverse mass. The stransverse mass, especially, so called a \( m_{T^2} \) variable has been known for years\(^1\). The \( m_{T^2} \) can be defined when there are two visible objects with momenta \( p_{\text{vis}} \) and the missing momentum \( p_{\text{miss}} \) in an event as follows,

\[
m_{T^2} = \min \left[ \max \left( m_T(p_{\text{vis}}, p^{1}_{T}, m), m_{T}(p_{\text{vis}}, p^{2}_{T}, m) \right), \right],
\]

where the minimum must be taken for the test LSP momenta \( p_1 \) and \( p_2 \) which satisfy following condition,

\[
p^{T}_{\text{miss}} = p^{T}_1 + p^{T}_2,
\]

and \( m \) is a test LSP mass. This quantity is an extension of the transverse mass in the hadron collider analysis, aiming for events with two missing massive particles. For sparticle (co-)production, the true LSP momenta can be a...
trial LSP momenta of Eq. \( \text{Eq. (2)} \), therefore, \( m_{T2} \) is bounded from above,

\[
m_{T2} < \max(m_1, m_2)
\]

(3)

where \( m_1 \) and \( m_2 \) are the masses of the primary produced SUSY particles. This is because the \( m_{T2} \) is defined as the minimum of the \( \text{maximum} \) of the two \( m_T \), therefore it effectively takes the minimum of the transverse mass of the decay products of the heavier particle[5].

The \( m_{T2} \) distribution can be used for the determination of the right-handed squark mass \( m_R \) in \( j j + E_{T \text{miss}} \) channel[4]. When \( m_R < m_{\tilde{g}}, \tilde{q}_R \) dominantly decays into the lightest neutralino \( \tilde{\chi}_1^0 \) and a jet, therefore \( \tilde{q}_R \tilde{g} \) production can be tagged by requiring two very high \( p_T \) jets in the final state. When \( m = m_{\text{LSP}} \), the endpoint of \( m_{T2} \) is equal to \( m_R \). The selected events are populated near the \( m_{T2} \) endpoint, therefore the SM background is negligible. The right-handed squark mass \( m_R \) is determined with the error of 3% at SPS1a[2].

Recently, Cho et al[5, 6] investigated the \( m_{T2} \) variable as a function of a test LSP mass for gluino pair production and the decay \( pp \rightarrow \tilde{g} \rightarrow jj \tilde{\chi}_1^0 \tilde{\chi}_1^0 \). The \( m_{T2} \) variable is constructed from two jet pairs so that \( p_T^{\text{vis}} \) is a momentum of one of the jet pairs arising from a gluino decay. The endpoint of the \( m_{T2} \) distribution as a function of a test LPS mass has a kink exactly at \( m = m_{\text{LSP}} \). This is because two different sets of the SUSY events contribute to the endpoint of \( m_{T2} \) variable. For \( m < m_{\text{LSP}} \), the events with \( m_{1j} \sim m_{\text{min}}^{1j} \) give \( m_{T2}^{\text{max}} \), while for \( m > m_{\text{LSP}} \), the events with \( m_{1j} \sim m_{\text{max}}^{1j} \) give it, where \( m_{1j}^{\text{min(max)}} \) is the minimum (maximum) jet pair invariant mass arising from \( \tilde{g} \) decay. At \( m = m_{\text{LSP}} \), the endpoints of both of the events should be at \( m_2 \) because the true LSP momenta can be the test momenta that satisfy Eq.(2). Thus, the endpoint becomes a function which has a kink at \( m = m_{\text{LSP}} \). This means that one can determine the LSP mass from the kink position experimentally.

In [5, 6], it is shown that the \( m_{T2} \) endpoint is sensitive to the both LSP and gluino masses for several model points by explicit MC simulations. They select the four highest \( p_T \) jets of the events, and divide them into two jet pairs using some distance measure, and regard the jet pair momentum as two visible momenta \( p_T^{\text{vis}} \) in Eq. (1).

In the previous analyses, the endpoint method has been used to determine the particle masses. In the SUSY cascade decay \( \tilde{g} \rightarrow \tilde{\chi}_{1}^{0} \rightarrow l \rightarrow \tilde{\chi}_{1}^{0} \), the sparticle masses are solved analytically from the endpoints of \( m_{1j}, m_{2j} \) and \( m_{3j} \) distributions. The lepton channel is very clean but the branching ratio is rather small in wide region of the parameter space. This was a problem in the SUSY parameter determination at the LHC—we did not know how to fix the LSP mass kinematically when \( \tilde{\chi}_{1}^{0} \rightarrow j j \tilde{\chi}_{1}^{0} \) is closed. It should be noted that the decay \( \tilde{g} \rightarrow j j \tilde{\chi}_{1}^{0} \) for the \( m_{T2} \) study involves only jets, and it has significant branching ratio. The LSP mass determination using the \( m_{T2} \) kink method could be applied in wider parameter region.

**The inclusive \( m_{T2} \)**

The proposal in [5, 6] is still limited to the case that only a single channel (either gluino-gluino or squark-squark) contributes to the four jet + missing \( E_T \) channel, and a gluino decays dominantly into \( j j \tilde{\chi}_{1}^{0} \). It is not satisfactory because gluino and squark can decay into the channel involving multiple jets. The number of high \( p_T \) jets are larger than four, and there are no good reason to select the first four jets to study \( m_{T2} \) distributions for general MSSM points. They are also generally co-produced. When \( m_2 \sim m_{\tilde{g}} \), the squark-gluino co-production is the dominant part of the colored SUSY particle productions.

In [7, 3], we proposed an inclusive definition of \( m_{T2} \), which can be calculated for events with any number of jets in the final state. The quantity is defined first by dividing the jets into two hemisphere which satisfy following conditions,

\[
P_{\text{hem}}^{(i)} = \sum_{k \in H_i} p_k
\]

\[
d(p_k, P_{\text{hem}}^{(i)}) < d(p_k, P_j) \quad \text{where,}
\]

\[
d(p_k, P_j) = \frac{E_k - |p_k \cos \theta_{jk}|}{(E_j + E_k)^2}
\]

(4)

The hemisphere axes (momenta) may be found by taking the highest \( p_T \) jet \( i \) and the jet \( j \) with \( \max(\Delta R_{ij}, p_{Tj}) \) as initial axes. Jets are first associated with one of the initial axes with smaller \( d \). The new hemisphere momenta is calculated under the assignments, and the procedure is
iterated until the assignment converges. Only the jets with $p_T > 50$ GeV and $|\eta| < 3$ GeV are involved in the hemisphere analysis.

The inclusive $m_{T2}$ is defined as $m_{T2}$ for $p_T^{vis} = p_T^{hem}$ in Eq. (4). We study the distribution at the model points with $m_{\tilde{g}} \sim 750$ GeV and $m_{\tilde{q}}$ from 880 GeV to 1516 GeV using HERWIG for event generations. These points are within the reach of ATLAS and CMS at $\int dt Z = 1 fb^{-1}$. Some of the mass parameters of the model points are given in Table 1.

In Fig. 1 we show a parton level inclusive $m_{T2}$ distributions for a model point with $m_{\tilde{g}} = 1342$ GeV and $m_{\tilde{q}} = 785$ GeV. By using the generator information, we find that our hemisphere algorithm reconstruct only 1/4 of the events without any mis-assignment. However, the mis-reconstructed events tend to have smaller $m_{T2}$ value so that the endpoint of the $m_{T2}$ distribution coincides with that of the correct hemisphere assignment shown in the dotted line. We also find the endpoint of $m_{T2}^{end}$ agree with $m_{\tilde{q}}$ for $m_{test} = m_{LSP}$ for the model points we have studied. We also show the signal $m_{T2}$ distribution using HERWIG for event generation and parton shower, with a toy detector simulator using AcerDET in Fig. 2. The obtained distribution is consistent with the parton level distribution in Fig 1.

The merits of the inclusive approach are 1) one can use all events available at the early stage of the experiment 2) The end point is least biased. However, there are some demerits co-exist as well. For example, the kink of the inclusive $m_{T2}$ distribution is studied in [7], and the result is mixed. The kink method is most effective when the particle contributes to the endpoint follow the three body decay, when the difference between $m_{min}$ and $m_{max}$ is large. It is not always guaranteed for the inclusive approach. In addition, the distributions show tails arising from the contamination of jets coming from the radiation from the initial state quarks and gluon. When enough luminosity is available, selecting clean decay chain would give a better results.

Both the effective mass $m_{eff} = \sum p_T^{eff} + E_{Tmiss}$ and the inclusive $m_{T2}$ involve the missing transverse momentum in their definitions. It has been known that a peak of $m_{eff}$ distribution of SUSY events has strong correlation with the parent sparticle masses. This is because the SUSY production occurs dominantly at its threshold, therefore the sum of the $p_T$ of the jets and leptons reflects the sum of the parent sparticle masses. Obviously, this is a phenomenological relation. Moreover, there are SM backgrounds which is not negligible at the peak position. Therefore, some systematics is expected in the extraction of the peak positions of the signal.

On the other hand, the inclusive $m_{T2}$ distribution has a clear kinematical interpretation; the endpoint should exactly coincide with the parent sparticle mass when $m_{test} = m_{LSP}$. Furthermore, the SM background tends to be suppressed near the $m_{T2}$ endpoint. The background $m_{T2}$ distribution are shown with the signal distribution in Fig. 3. The $S/N$ ratio near the $m_{T2}$ endpoint is large near the endpoint. Here the background distribution contain contributions from $t\bar{t} + n$ jets($n \leq 2$), $Z^0 + n$ jets($n \leq 5$), and $W^\pm + n$ jets ($n \leq 4$) generated and matched using ALPGEN.

The $m_{T2}$ of jet subsystem is also useful. When squarks heavier than a gluino, a squark decay into a high $p_T$ quark and gluino/neutralinos. We constructed hemispheres for the jet system without the highest $p_T$ jet and calculate the subsystem $m_{T2}$ ($m_{T2}^{sub}$) distributions. The $m_{T2}^{sub}$ distribution has an endpoint consistent with gluino mass when $m_{\tilde{g}} < m_{\tilde{q}}$. (See Fig. 4). This shows that one can extract both squark and gluino masses in the event by looking jet distribution in terms of $m_{T2}$ and $m_{T2}^{sub}$. The endpoint values of the $m_{T2}$ and $m_{T2}^{sub}$ distributions are obtained by a linear fit, and they are compared with input

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**FIGURE 2.** The inclusive $m_{T2}$ distribution at the model point of Fig. 1 for $\int dt Z = 1 fb^{-1}$. The distribution is after the standard SUSY cuts. See [3] for details.

**TABLE 1.** Some of the mass parameters of our model points. We take the scalar masses of sfermions and gaugino masses to be universal. We tune the higgsino mass parameter $\mu$ by allowing non-universal GUT scale Higgs masses parameters so that $m^2 \sim 0.1$. All mass parameters are given in GeV.

| $m_0$ (GeV) | $A_0$ (GeV) | $m_{\tilde{g}}$ (GeV) | $m_{\tilde{q}}$ (GeV) | $m_{LSP}$ (GeV) | $\mu$ (GeV) |
|----------|--------|----------------|----------------|----------------|---------|
| a        | 1400   | -1400         | 1516           | 795.7          | 107.9   | 180     |
| b        | 1200   | -1200         | 1342           | 785.0          | 107.4   | 180     |
| c        | 1100   | -1100         | 1257           | 779.5          | 107.1   | 180     |
| d        | 1000   | -1000         | 1175           | 773.2          | 106.8   | 180     |
| e        | 820    | -750          | 1035           | 761.7          | 106.1   | 180     |
| f        | 600    | -650          | 881.0          | 745.4          | 107.8   | 190     |
FIGURE 3. The signal(solid) and background(dashed) distributions at the same model point. Here we apply a cut $m_{\text{hemi}}^{(2)} > 200$ GeV. We produced 50,000 SUSY events for this study, and the distribution is normalized to $1\text{fb}^{-1}$.

FIGURE 4. The $m_{T_2}$ distributions at the same model point. The endpoint is consistent with the input gluino mass $m_{\tilde{g}} = 785$ GeV. The distribution is normalized to $1\text{fb}^{-1}$.

squark and gluino masses in Fig. 5.

Exact relations

In the endpoint method, endpoints of the several distributions are solved to obtain the sparticle masses involved in the events. Each endpoint gives one constraint among the sparticle masses. It is known that a decay cascade involving at least three SUSY cascade decays are required to determine the all sparticle masses from the endpoints.

The results in [5, 6] shows that $E_{\text{miss}}$ constrain the LSP momenta, and the sparticle masses are solved even though there are only two sparticles involved in the decays. In general, $p_{\text{Tmiss}}$ provides an independent constraint to the sparticle mass determination when both of the pair produced sparticle decays are identified. Several groups studied the case involving $\tilde{q} \rightarrow \tilde{\chi}_2^0 \rightarrow \tilde{l} \rightarrow \tilde{\chi}_1^0$. By using the exact relation among the visible and missing momenta event by event, the errors on the LSP mass is improved by factor of 30% in [8].

MORE FAVORITE TOYS

If SUSY particles are found in the early phase of the LHC experiments, we would be able to access various decay chains of SUSY particles in the later stage of the experiment.

The channel involving $\chi_i^0 \rightarrow \tilde{l}l$ is experimentally clean, therefore search of lepton flavor violation (LFV) in neutralino cascade decays are experimentally promising. The LFV in SUSY processes might come from right-handed neutrino Yukawa couplings. Gauge mediation models may also lead experimentally acceptable LFV if the planck scale soft masses violate lepton flavor [9].

By measuring difference of the two lepton endpoints $\Delta m_{ll} = m_{\tilde{e}e} - m_{\tilde{\mu}\mu}$ arising from $\tilde{\chi}_2^0 \rightarrow \tilde{l}l \rightarrow \tilde{\chi}_1^0$, one can detect/set the lower limit to the slepton mass difference $\Delta m_{\tilde{l}} = m_{\tilde{e}} - m_{\tilde{\mu}}$. The $\Delta m_{\tilde{l}}$ is expected to be non-zero in models with non-zero LFV. The sensitivity to the mass difference is recently discussed in [10].

The masses of the third generation squarks and sleptons are also important in distinguishing SUSY models. They are expected to be lighter than the first and second generation squarks if the SUSY mediation scale is near the planck scale. In addition, stop mass and its mixing
are important parameters for Higgs mass radiative corrections. The sbottom and stop masses may be obtained by studying the gluino decays $\tilde{g} \to t\tilde{t}$, $\tilde{b}\tilde{b}$. The $\tilde{g} \to bb\chi^0_2$ channel has been studied and it has been shown that the lighter sbottom mass can be obtained from $bbll$ channel. A recent ATLAS full simulation study confirms the earlier fast simulation study\cite{11} on the $\tilde{g} \to t\tilde{t} \to tb\chi^\pm$ reconstruction in a model point. The hadronic top decay is reconstructed correctly and the $m_{tb}$ endpoint is seen\cite{12}.

Finally, there appeared a few interesting attempts to improve reconstruction of the boosted $W$ and $H$ which decays hadronically\cite{13, 14}. The sparticle decays sometimes produce $W$ or $H$ bosons, and it decays dominantly into jets. One may look for the jet pairs with $m_{\text{pair}}$ consistent with them, however there are other jet pairs or fat jets within the same mass range. It is pointed out that these background can be reduced by looking into the jet substructure. The proposed procedure is 1) reconstruct jets with the $k_T$ algorithm with somewhat large $R(\sim 1)$. 2) Take a hard jet $i$, break it into two subjets $j$ and $k$ by undoing its last stage of clustering. 3) If there is significant mass drop for the subjet and $y = \min(p_T^2/p_T^2)\Delta R_{jk}^2/m_T^2 > y_{\text{cut}}$, then treat it as heavy particle neighborhood. The initial studies show the cut on $y$ is useful in reducing the background to the heavy particles. Jet substructure or jet-jet correlation in SUSY processes and its SM background would be important issues that has not been fully investigated yet.

**CONCLUSION**

It is likely that particle physics will undergo big changes in next few years. LHC will turn on, and we are finally able to work toward the theory of elementary particles—not just one of the possible beyond the standard models.

Although the hadron collider is not a perfect place to do precise new physics measurements compared with high energy $e^+e^-$ colliders, we now think it is possible to do some kind of measurements at the LHC. This “common sense” has been built through continuous efforts to find clear-cut procedures to study the new physics in the LHC environment. The $m_{T^2}$ study discussed in this review is an example that finding a new analysis method greatly improve our understanding on new physics processes. It is worth pushing this efforts further, rather than judging/estimating the LHC ability based on our current knowledge, or just worrying about “empty stockings”.

At this moment, it is probably wise to discuss issues on the discovery of new physics and the initial data analysis. However once some signature of new physics is discovered, we can focus our attention on specific channels which are sensitive to the nature of new physics sectors. In particular, I hope flavor structures of the new physics sector emerge from the data at the later stage of LHC. Let’s hope that there will be more experimental plenary talks next year, starting to prove the physics beyond the standard model.

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