1. INTRODUCTION

For more than a few decades it has been well known that supersymmetry(SUSY) is one of the most promising candidates for beyond standard model phisics. Since March 2010, LHC has been running with a center-of-mass energy 7 TeV and is expected to accumulate 1fb$^{-1}$ data by the end of 2011. In both the experiments, ATLAS and CMS are heavily engaged to look for a SUSY signal in the collision data. From negative searches CMS(ATLAS) have predicted a lower bound on gluino mass, $m_{\tilde{g}} > 650(700)$GeV for almost degenerate squark mass($m_{\tilde{q}}$) \cite{1,2} in the framework of the constrained minimal SUSY model (cMSSM). It is now of general interest to address the discovery potential of SUSY at this low energy(7 TeV) and low luminosity(1fb$^{-1}$) option in the LHC experiment. Already quite a few studies have been carried out along this direction \cite{3-5}.

In this present study, we revisit the discovery reach for SUSY at 7 TeV energy with a special effort to control standard model(SM) backgrounds by implementing a different search strategy. In hadron colliders, sparticle production, because of its long cascade decay chain results in events with a multiple number of leptons and jets along with missing transverse energy($E_T^{miss}$) due to the presence of neutralino($\tilde{\chi}_1^0$), assumed to be the lightest sparticle. Since they originate from massive $\tilde{g}$, $\tilde{q}$ states, therefore the final states consist of harder objects. Hence, SUSY is characterized by high transverse momentum($p_T$) events with higher multiplicities. We introduce event-shape variables \cite{6} to exploit these special features of SUSY events to discriminate signal and backgrounds. Moreover, we also try to construct an additional cut based on $p_T$ of jets in the final state. Feasibility of these new sets of cuts are examined by analyzing the following final states, which are thought to be discovery channels for SUSY at the LHC:

- a single lepton + jets(1$\ell$),
- di-leptons+ jets(2$\ell$),
- jets + $E_T^{miss}$.

In a hadron collider machine, measurement of $E_T$ is a nontrivial task due to the presence of other nonphysics sources of $E_T$. However, current studies show that $E_T$ performance in the detector is better than it was thought to be \cite{7}. Nevertheless, we investigate the detection possibility of SUSY signal with and without $E_T$ \cite{8} in the final state.

As is the practice, we simulate signal event in the framework of a minimal supergravity(mSUGRA) based SUSY model described by four parameters, $m_0$, $m_{1/2}$, $A_0$, $\tan \beta$ and sign($\mu$) at the GUT scale. Here $m_0$, $m_{1/2}$ are the unified masses of scalars and fermions, respectively, $A_0$ is the trilinear coupling, $\tan \beta$ is the ratio of two vacuum expectation values and $\mu$ is the Higgs mass parameter. The mSUGRA model is very severely constrained by many low energy experimental data, like direct bounds on sparticles as well as from dark matter experiments \cite{4,9}. Instead of testing the mSUGRA model against all those constraints, we simply use restricted parameter space obtained by other authors \cite{9} and select a few sets of parameters to simulate signal. The sparticle masses at the electroweak scale are obtained by using the renormalization group evolution performed by SuSpect, and decay branching ratios of sparticles are calculated using the SUSY-HIT package \cite{10}. In Table I, four sets of parameters(P1-P4) are presented for fixed values of $A_0=0$, $\tan \beta=45$ and sign($\mu$)=$+1$. Masses of $\tilde{g}$ and $\tilde{q}$ are shown along charginos and neutralinos. In all cases (P1-P4) the lighter chargino state($\tilde{\chi}^+_1$) turns out to be the next-to-lightest supersymmetric particle(NLSP).

|        | P1   | P2   | P3   | P4   |
|--------|------|------|------|------|
| $m_0$  | 500  | 1500 | 500  | 450  |
| $m_{1/2}$ | 200  | 200  | 400  | 500  |
| $m_{\tilde{g}}$ | 524  | 575  | 954  | 1161 |
| $m_{\tilde{q}}$ | 660  | 1535 | 981  | 1133 |
| $m_{\chi^0_{1,2}}$ | 142.296 | 126.241 | 308.515 | 391.623 |
| $m_{\chi^0_{3,4}}$ | 78.143 | 76.130 | 164.309 | 207.392 |
| $m_{\chi^+_{1,2}}$ | 274.295 | 196.240 | 499.514 | 610.623 |
| $\sigma(\text{pb})$ | 2.5  | 0.32 | 0.08 | 0.018 |

TABLE I: Masses(in GeV) of SUSY particles for four sets of $m_0$, $m_{1/2}$ and fixed values of $A_0=0$, $\tan \beta=45$, sign($\mu$)=$+1$. The total cross sections($\sigma$) for SUSY particle production are in the last row.

2. SIGNAL AND BACKGROUND

At the LHC, pairs of colored sparticles, viz gluino-gluino, gluino-squark, and squark-squark, are produced copiously and the corresponding total leading order(LO)
cross sections are presented in the last row in Table I for each of the parameter space. We set both the renormalization and factorization scales to $Q^2 = \hat{s}$, defined to be the center-of-mass energy in the partonic frame, and CTEQ6L \[11\] is used for parton distribution function. The dominant SM backgrounds are, $t\bar{t}$+jets, W/Z+jets, $tW+$jets, $tW+$jets, QCD. In addition, we also check contributions due to WW+jets, ZZ+jets and WZ+jets. Since, the background to signal cross section ratio are of several orders of magnitudes, therefore, to identify the SUSY signal, one needs to suppress backgrounds a by huge amount, which is not a formidable task by a suitable choice of kinematical selection cuts \[12\]. However, a continuous effort is always in process to control SM backgrounds to achieve a better signal sensitivity \[13\].

In this current study, our goal is to find a better method to deal with SM backgrounds. We propose a new strategy to suppress backgrounds by using well-known event-shape variable, namely, transverse thrust(T). In addition, we define another new variable taking the ratio($R_T$) of a scalar sum of transverse momentum of lowest number of jets over the sum of all jets present in the event. To the best of our knowledge these two cuts are never used in SUSY searches in the hadron colliders. We observed, which are discussed below, that these two cuts play a very important role in isolating SM backgrounds leading discovery reach signal cross section limited. Importantly, these two cuts are also very easy to implement experimentally once four momenta of jets are reconstructed.

The event generator PYTHIA6 \[13\] is used to generate signal events and background processes due to $t\bar{t}$, WW, WZ, ZZ and QCD. The $t\bar{t}$ and QCD backgrounds are generated by slicing the entire phase space in various $p_T$ bins, where $p_T$ stands for the transverse momentum of final state partons in the partonic center-of-mass frame. For QCD, we present results from $p_T \geq 200$ GeV onwards since contribution due to low $p_T$ bins are expected to be negligible because of strong cuts as can be seen later. The hard scattering process consisting of more than two particles in the final state, like $t\bar{t}$+jets, W/Z+jets, $tW+$jets, $tbW+$jets, are simulated using ALPGEN \[10\] based on the matrix element (ME) calculation and subsequently passed through PYTHIA6 for parton showering (PS). While generating events by ALPGEN, initial selection cuts of $p_T \geq 20$GeV and pseudorapidity, $|\eta| \leq 3$ are applied. We adopt MLM matching \[17\] to avoid double counting while doing parton showering (PS) after performing matrix element (ME) calculation. In the MLM matching, we use the $p_T$ threshold to 20 GeV and $|\eta| \leq 3$ while keeping the default value of $\Delta R = 0.7$ for jet and parton separation. Finally, we multiply matching efficiency with the accepted efficiency to obtain event rates. The jets are reconstructed by FastJet \[18\] using the anti-$K_T$ \[19\] cone algorithm and are preselected with minimum cuts $p_T \geq 50$ GeV and $|\eta| \leq 3$. The total $E_T$ of the event is calculated out of the momentum of all visible particles present in the event with $p_T \geq 1$ GeV and $|\eta| \leq 3$.

In the following we, describe cuts used in the simulation.

- **Leptons(C1):** Leptons, both electron(e) and muon(\(\mu\)) are selected with $p_T \geq 10$ GeV and $|\eta| \leq 3$. In the case of the single lepton final state, we apply $p_T \geq 20$ GeV. Isolation of the lepton is ensured by looking at the total transverse energy, $E_T^{AC} \leq 20\%$ of the $p_T$ of the lepton, where $E_T^{AC}$ is the scalar sum of transverse energies of jets close to the lepton satisfying $\Delta R(t,j) \leq 0.2$.

- **Event-Shape variable(C2):** These variables describe the shape of the event which is related with the geometry of the final state and, importantly, are safe to use as observables because of its stability against any singularity. For instance, the CMS has used event-shape variables to test models for QCD multijet production by analyzing collision data \[20\]. As discussed before, multiplicity of the final state, which determines the shape of the event, is very different in SUSY and backgrounds. This encouraging observation leads us to use event-shape variables to separate out the signal from the debris of SM backgrounds. There are many event-shape variables out of which we use only the transverse thrust defined in the $(x,y)$ plane transverse to the beam direction, which is along the $z$-axis. The transverse thrust is defined as \[6\],

$$T = \max_{n_T} \sum_{i} |\vec{q}_T,i - \vec{n}_T|,$$

(1)

where the sum runs over all objects in the event, $\vec{q}_T,i$ is the transverse component of each object and $\vec{n}_T$ is the transverse vector that maximizes this ratio. Notice that because of the normalization of $T$ by the hard scale of the event, the effect of systematic uncertainties related with measurements is expected to be less. In Fig. 1, in the left panel, we display the distribution for $\tau = 1 - T$, of signal and the backgrounds for jet plus $B_T$ final state. This distribution is subject to preselection jet cuts i.e. $p_T \geq 50$ GeV and $|\eta| \leq 3$ in conjunction with $E_T \geq 50$ GeV. It clearly demonstrates that events having low multiplicity, like high $p_T$ QCD and Z$(\to \nu \bar{\nu})$+jets processes, are distributed near $\tau \sim 0 (T \sim 1)$ whereas $t\bar{t}$+jets with higher multiplicities are distributed towards comparatively higher(lower) values of $\tau(T)$. As expected, signal events with more multiplicities are distributed towards larger values of $\tau$. This novel feature of transverse thrust between signal and background events is exploited to suppress the latter. For instance, selecting events by demanding $T \leq 0.9 (\tau \geq 0.1)$, QCD background and W/Z+jets are suppressed by more than 90% whereas $t\bar{t}$ and the signal are less affected.

- **$R_T$ (C3):** Events are accepted requiring a number of preselected jets, $n_j \geq n_j^{\text{min}}$, where $n_j^{\text{min}}$ is the lowest number of jets events should have at the least and is the input for event selection. Now we construct a ratio($R_T$) between the scalar sum of $p_T$ for the required lowest number of jets ($n_j^{\text{min}}$) in the event and the scalar sum of $p_T$ of all jets($n_j$) in the same event, i.e,

$$R_T = \frac{\sum_{j} p_T^{j}}{H_T}$$

(2)
with $H_T = \sum p_T^n$. It is obvious that the behavior of this variable is strongly connected with the multiplicity as well as the hardness of the jets in the event. The $R_T$ becomes exact unity for those events with $n_j = n_j^{min}$, otherwise it is expected to be away from unity for those events with $n_j \gg n_j^{min}$. In Fig. 1, we present in the right panel the distribution of $R_T$ of signal along with backgrounds subject to jet selection cuts along with the requirement of $n_j^{min} = 4$. The peak suggests that most of the events in the backgrounds are dominantly 4-jet events. The dip indicates events with relatively softer jets, $p_T^n \sim 50$ GeV(recall that preselection cut on jets $p_T \geq 50$ GeV) along with $n_j$ just above $n_j^{min}$, are present predominantly in backgrounds). On the other hand, for the case $n_j \gg n_j^{min}$ and for comparatively harder jets, which is the case for signal events, $R_T$ is mostly distributed below 0.85. Evidently, the $R_T$ distribution provides us another very robust tool towards the suppression of SM backgrounds by a substantial amount. For instance, restricting $R_T \leq 0.85$ enables to remove backgrounds by $\sim 70\text{-}80\%$ or more with a 10\text{-}20\% loss in signal events.

- $H_T$(C4): As mentioned before, the signal events are expected to be harder in comparison to background events. Therefore, a cut on $H_T \geq 900$ GeV is very effective to get rid of a good fraction of background events.

- $E_T$ cut(C5): In all backgrounds, the lepton mainly comes from W decay except for QCD, hence the transverse mass between the lepton and $E_T$ is expected to be bounded by the W mass, for the single lepton case, in particular. Hence, events with a single lepton case is expected to suffer due to a cut on transverse mass, $M_T = \sqrt{2E_T^l E_T (1-\cos(\phi(l, E_T)))} \geq 60$ GeV [2]1, where $\phi$ is the azimuthal angle between the lepton and the $E_T$ direction. Beside this $M_T$ cut, which is applicable only for one lepton final state, a cut on $E_T \geq 150$ GeV for all cases turns out to be a good criterion to reject backgrounds.

- **One lepton + jets(1ℓ):** The event with the final state having only a single lepton(e or $\mu$) along with at least 3 jets($n_j^{min}=3$) are simulated applying a sequential set of cuts C1-C5 and the results are presented in Table II using P1 parameter space for signal. The second and third columns display the raw production cross sections and the simulated number of events($N_{EV}$), respectively, for each process. The numbers in the third column corresponding to $t\bar{t}$+jets and $W/Z$+jets represent the number of events with jet-parton MLM matching. We observe that, in general, about 20\%\text{-}25\% of the events are lost due to the isolation requirement of the lepton, with the exception of the QCD background with more($\sim 50\%$) loss. In the 5th column, the numbers after thrust(Eq.1) cut(C2) $T \leq 0.90$, clearly indicate that the QCD background is eliminated by a huge amount whereas other backgrounds suffer by about 50\%\text{-}70\% with a modest loss in the signal event. Requirement of at least 3 jets with a restriction on $R_T \leq 0.85$(C3) results in a substantial suppression of backgrounds, particularly processes with low jet multiplicity. Subsequently, a cut(C4) on $H_T \geq 900$ GeV removes a significant fraction of backgrounds. The resulting cross sections($\sigma_{H_T}$) due to cuts C1-C4 i.e without the $E_T$ requirement turn out to be 179fb for the signal and 101fb for the total background leading to $S/\sqrt{B} \sim 17$. However, for other sets of SUSY parameters P3-P4, this ratio is $\lesssim 1$. We check that the contributions due to backgrounds $t\bar{t}W$+jets, $tbw$+jets and $VV$+jets($V=W,Z$) are negligible after applying all cuts. Finally, $E_T$ is considered to suppress the remaining backgrounds to gain in signal-to-background ratio. Demand(C5)
The final state with two leptons(1) for the single lepton(1) case. For QCD and \( t\bar{t}+\)jets, events are simulated for different \( \tilde{g}\) masses up to \( M_{\tilde{g}} \geq 60\) GeV and \( E_T \geq 150\) GeV it is possible to further isolate backgrounds to an almost negligible level(\( \sigma_{g_T} \sim 2.65\) fb). Note that due to the cuts C4 and C5, the signal suffers substantially because of comparatively softer cut on the 4th subleading jet, \( p_T^4 \sim 10\) GeV and \( E_T^4 \sim 10\) GeV are acceptable. However, for higher masses, the losses are minimal. In Table III, we show the total signal(P1-P4) and background cross sections after cuts C1-C4(\( \sigma_{g_T} \)) and C1-C5(\( \sigma_{g_T} \)). This table predicts that the single lepton channel alone can explore \( \tilde{g} \) and \( \tilde{q} \) masses up to \( \sim 1\) TeV for \( \mathcal{L} = 10^{33}\) fb^{-1} requiring a signal(S) to a background(B) ratio, \( S/\sqrt{B} \geq 5\).

**Di-lepton +jets(2\ell):** The final state with two leptons of any type and of any charge combinations are accepted along with at least 3 jets(\( n_{\text{jet}}^{\text{min}} \)). In the simulation, a softer cut on the lepton, \( p_T^\ell \geq 10\) GeV (\( \ell = e, \mu \)) is imposed along with the isolation requirement. In this case one of the most dominant backgrounds appears to be due to \( Z+\)jets. A good fraction of \( Z+\)jets events can be removed by an additional requirement on the di-lepton invariant mass, \( m_{\ell+\ell^-} \geq 10\) GeV and \( m_{\ell+\ell^-} \neq 70-120\) GeV. We find that the patterns of background suppression due to cuts C2-C4 are more or less the same as a single lepton case. In Table III, we present the total cross section for both the signal and the backgrounds with C1-C4 cuts (\( \sigma_{0g_T} \)) and including \( E_T \) cut(C1-C5) (\( \sigma_{g_T} \)). This table depicts that, without \( E_T \) cut it is difficult to observe any signal event in the di-lepton channel except for light \( \tilde{g} \) and \( \tilde{q} \) masses(P1). Therefore, including \( E_T \) cut(C5) it may be possible to detect signal events for \( \tilde{g} \) and \( \tilde{q} \) masses \( \sim 700\) GeV with \( \mathcal{L} = 10^{33}\) fb^{-1}.

**Jets +\( E_T \):** It is well known that SUSY searches in jets plus the missing energy channel offer the highest reach of gluino and squark masses \(^1\). We revisit this final state to examine the effects of transverse thrust(Eq.1) and \( R_T \) (eq.2) selection cuts in tandem with the other set of cuts. A substantial number of background events(\( \sim 50\%-80\% \)) or more are rejected by thrust cut(C2) costing about 20% of the signal events. Furthermore, events with at least 4(\( \geq n_{\text{jet}}^{\text{min}} \)) jets with a softer cut on the 4th subleading jet, \( p_T^4 \geq 70\) GeV are selected and a requirement on \( R_T \leq 0.85 \) turns out to be very useful to get rid of a good amount of \( W/Z+jets \) and \( t\bar{t}W+jets \) events. However, C1-C5 cuts are not enough to kill backgrounds completely, a good amount of \( t\bar{t}+\)jets remains. Therefore, in addition, we adopt a selection cut on the transverse mass \( m_{T}\) between two leading jets. The demand of \( m_{T}\geq 450\) GeV is very effective in suppressing \( t\bar{t}+\)jets events by almost a factor 10, of course, with a substantial loss(\( \sim 60\%-70\% \)) of signal cross section as well. However, for higher masses of \( \tilde{g} \) and \( \tilde{q} \) i.e for parameter sets P3 and P4, we find this loss is less than 5%. The cut \( H_T \geq 1050\) GeV removes the remaining background events from \( W/Z+jets \), whereas high \( p_T \) QCD and \( t\bar{t} \) events are eliminated by the \( E_T \geq 150\) GeV cut. We find after all cuts the total background cross section mainly due to the \( t\bar{t} \) and QCD is \( \sim 3.7\) fb out of which \( t\bar{t}+\)jets contributes about 70%. In Table III the total signal (P1-P4) and background cross sections are presented. It reflects that at \( \tilde{g} \) and \( \tilde{q} \) masses up to \( \sim 1.1\) TeV can be explored with \( 10^{33}\) fb^{-1} luminosity. We find that the signal efficiency for low mass point (P1) is about 10% and for higher mass(P4) it turns out to be \( \sim 30\%-40\% \).

### Table II: Event summary for the signal and the backgrounds after each set of cuts(C1-C5) described in the text for the single lepton(\( t\ell \)) case. For QCD and \( t\bar{t}+\)jets, events are simulated for different \( \tilde{g} \) masses.
TABLE III: Total signal (P1-P4) and background cross sections(fb) after cuts C1-C4 ($\sigma_0 E / T$) and C1-C5 ($\sigma E / T$) for the single lepton(1\text{\ell}), di-lepton(2\text{\ell}) and jets plus $E_T$ case.

|                | Total Bg | P1     | P2     | P3     | P4     |
|----------------|----------|--------|--------|--------|--------|
| $1(\sigma_0 E_T)$ | 101      | 179    | 20     | 7      | 2      |
| $2(\sigma_0 E_T)$ | 2.65     | 70.8   | 8      | 5      | 1.3    |
| $2(\sigma E_T)$  | 5.43     | 7.5    | 2      | 0.5    |        |
| $0.97$           | 31       | 4      | 1.8    | 0.5    |        |
| Jets($\sigma E / T$) | 3.7      | 271    | 32.5   | 21.8   | 4.63   |

estimate predicts that in the single lepton channel and as well as the jet plus $E_T$ channel, it is possible to achieve a reasonable signal-to-background ratio for $\tilde{g}$ and $\tilde{q}$ masses up to $\sim 1.1$ TeV whereas the di-lepton channel alone is not very encouraging. It is to be noted that our conclusion is based on LO signal cross sections whereas in background evaluation the higher order effects are taken into account to a certain extent by considering hard emission of partons(jets), which is the real part of the NLO correction. We check using Prospino [22] that NLO cross sections for SUSY are about 50%-70% higher than LO cross sections resulting in an enhancement in signal-to-background ratio than our present conservative estimate. Clearly, the discovery reach is signal rate limited rather than background limited, which is almost negligible after all cuts. Evidently, this is a very powerful result based on our search strategy, which can be implemented experimentally very easily. For illustration purposes, we mention that the total SM background cross section corresponding to the jet plus missing energy final state is 3.7 fb, as shown in Table III, and which is 2.42 pb for same final states as reported in the paper of Ref. [23]. We observe that our analysis predicts better sensitivity than others in the literature [3, 4]. Note that in our simulation $\tau$ leptons are not considered in final states, which will be simulated in the future along with a detailed scan of parameter space [24].

4. ACKNOWLEDGMENT

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