Supersymmetry (SUSY) is perhaps the most frequently discussed new physics \footnote{Electronic address: konar@theory.tifr.res.in} that is expected to exist around the TeV scale. Such a scale is attributed to SUSY because that is how it can aspire to lend naturalness to the electroweak theory. The fact remains, however, that neither have we found any experimental signal of SUSY yet, nor is there an unambiguous guideline on the superparticle spectrum or the mechanism of SUSY breaking which is so essential to make the theory realistic. Still, the very necessity of solving the naturalness problem raises hopes of discovering superparticles at TeV scale colliders such as the Large Hadron Collider (LHC).

On the other hand, most SUSY theories are beset with the flavour problem \footnote{Electronic address: biswarup@mri.ernet.in}, which essentially means the danger of having unacceptable enhancement of flavour-changing neutral current (FCNC) processes. One way to avoid this difficulty is to have the mass scale of superparticles raised to several, often tens of, TeV. However, this largely defeats the purpose of introducing SUSY to solve the naturalness problem. A possible way out lies in theories which have the third family of scalar fermions light, against the backdrop of a heavy matter sector in the first two families. Such ‘inverted hierarchy’ has been achieved in a number of theoretical frameworks. This can be done, for example, through

(a) SUSY breaking induced by modular and dilaton fields \footnote{Present address: Department of Theoretical Physics, Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai-400005, India}, with the modular weight being different for different families, thus leading to a lower scalar mass for the third family at high scale itself.

(b) Introducing some additional (anomalous) $U(1)$ symmetry, with family-dependent $U(1)$ charges, thus allowing the consequent D-terms to lower the third family scalar masses \footnote{Electronic address: biswarup@mri.ernet.in}.

(c) Non-universal boundary conditions at the Grand Unification (GUT) scale \footnote{Electronic address: konar@theory.tifr.res.in}, with other high-scale boundary conditions suitably adjusted, and by demanding Yukawa coupling unification (thus allowing third family scalars to be affected by large Yukawa couplings as they run).

(d) Arranging SUSY parameters in such a way that the third family masses have fixed points below a TeV \footnote{Present address: Department of Theoretical Physics, Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai-400005, India}.

Diverse as the phenomenological consequences of the above cases may be, all of them pose a serious question: how can the non-strongly interacting sfermion sector be revealed in experiments? This is because sleptons are usually expected to be seen in the Drell-Yan channel, where the production rates fall to rather low values for $m_\tilde{f} \approx 250 \text{–} 300$ GeV \footnote{Electronic address: konar@theory.tifr.res.in}. Stau’s ($\tilde{\tau}$) in inverted hierarchy scenarios, even if still marginally accessible in the Drell-Yan channel, have their signals further suppressed because of the complications involved in identifying tau’s. The resulting difficulties are again twofold. First of all, if charginos and neutralinos, too, are almost as heavy as the staus, their detectability (in hadronically quiet channels such as tripletinos \footnote{Electronic address: konar@theory.tifr.res.in}) falls below the threshold of detection at the LHC. Alternatively, if charginos and neutralinos are relatively light, then they may be detected, while we have little information on the SUSY particle spectrum, and cannot even confirm an inverted hierarchy.

Here we suggest a new search channel for SUSY scenarios with inverted hierarchy, using gauge boson fusion at the LHC to produce stau-pairs. We show that this not only makes the stau signals relatively background-free, but also enhances the mass reach for the stau’s, thus opening a gateway to scenarios of this kind.

Gauge boson fusion has been found to be a useful channel for exploring the signals of a heavy Higgs boson \footnote{Electronic address: konar@theory.tifr.res.in}. Subsequent studies have also underlined its usefulness for an intermediate mass Higgs, especially for Higgs decay modes such as those into $\tau\tau$, $\gamma\gamma$ or $bb$, or for probing couplings which can potentially distinguish a supersymmetric Higgs boson \footnote{Electronic address: konar@theory.tifr.res.in}. The characteristic features of such events are two hard forward jets, usually peaking in the rapidity region $3 < |\eta| < 4$, with the lack of colour exchange between the jets preventing hadronic activity in the intervening rapidity gap \footnote{Electronic address: konar@theory.tifr.res.in}. Tagging the forward jets reduces the backgrounds drastically. Also, such events survive a central jet veto with a high ($\geq 80\%$) efficiency. It is because of all this that the facility of forward jet tagging is going to be an integral part of detector design at the LHC.
It has been shown in a series of recent studies that
gauge boson fusion can be also very helpful in unraveling
the signatures of physics beyond the standard model.
This has been demonstrated mostly in the context of
supersymmetric theories, for example, ones with invis-
cible charginos and neutralinos \( \tilde{\chi}_2 \) or sleptons \( \tilde{\ell} \) with
masses on the heavier side. Gauge boson fusion lends
visibility to the latter situation when the conventional
Drell-Yan signal becomes too small to be detectable. In
the same way, one can also see signals of the stau when
the latter is the only non-strongly interacting supersym-
metric particle.

The signal we are suggesting comes from
\[
pp \rightarrow j_f j_f \tilde{\tau}_1 \rightarrow j_f j_f \tau \tau + E_T \tag{1}
\]
\( j_f \) being a hard forward jet. The missing transverse en-
ergy comes from the lightest neutralino due to stau-decay.
The \( \tilde{\tau} \) (and \( \tau \)) decay products lie in the rapidity gap be-
tween the forward jets, with no other colour activity in
that region. In order to observe the \( \tau \)'s, we suggest the
events where one of them decays leptonically and the
other, into the one-prong hadronic channel. Therefore,
the final state in this channel consists of \( j_f j_f \eta j \rightarrow \eta j \gamma \),
\( j \gamma \) being a low-multiplicity jet characteristic of \( \tau \)-decay.

In practice, however, there is a large region of the
Susy parameter space where the stau has a substan-
tial branching ratio for decay into the lighter chargino
or the second lightest neutralino. This happens particu-
larly when the stau mass is well above that of the light-
est Susy particle (LSP). In such cases, the loss of signal
events due to branching fraction suppression may be par-
tially offset by including events where the stau decays
into a chargino and the latter, in the lepton channel.
Such a possibility has been included in our calculation.

A large number of diagrams contribute to the above
process. Stau-pair production in the desired form can
take place through the fusion of the W, the Z as well
as the photon. All the production modes, namely, \( \tilde{\tau}_1 \),
\( \tilde{\tau}_1 \), \( \tilde{\tau}_2 \), \( \tilde{\tau}_2 \) and \( \tilde{\tau}_1 \), \( \tilde{\tau}_2 \) are included in the general analysis.



| Signal | Background (in fb) |
|--------|--------------------|
| \( \tau \tau \) | 0.73 2.88 2.01 0.37 5.06 10.30 |
| \( W j \) | 0.57 1.37 0.63 0.25 1.14 3.41 |
| \( WW \) | 0.42 0.32 0.09 0.11 0.24 0.77 |
| \( t \bar{t} \) | 0.31 0.03 0.08 0.10 0.16 0.38 |

The following 'basic cuts' are employed to ensure the
\( \tau \) identification efficiencies in the hadronic channels \([17]\):
\[
R_{em} = \frac{\sum E_{Ti}(\eta_i - \eta_e)^2 + (\phi_i - \phi_e)^2}{\sum E_{Ti}} \tag{2}
\]
\( E_{Ti} \) is the transverse energy recorded by the \( i \)th
cell of the electromagnetic calorimeter, and \( i \) runs over
all such cells contained in a cone of size \( \Delta R = 0.7 \) (with
\( \Delta R^2 = \Delta \eta^2 + \Delta \phi^2 \)) around the jet axis, defined
by \( (\eta_e, \phi_e) \). In addition, one may use the 'isolation criterion'
the 'multiplicity criterion' as defined in \([17]\). We have
based our results primarily on the variable \( R_{em} \).
Thus we confine ourselves to \( R_{em} < 0.07 \) corresponding to the
peak of the \( R_{em} \) distributions of simulated \( \tau \)-events with
\( p_T \) in different ranges, thereby obtaining the following
\( \tau \)-identification efficiencies in the hadronic channels \([17]\):
\[
\epsilon_\tau = 0.30 \text{ for } 30 \text{ GeV} \leq p_T(j_\tau) < 50 \text{ GeV}
0.38 \text{ for } 50 \text{ GeV} \leq p_T(j_\tau) < 70 \text{ GeV}
0.46 \text{ for } 70 \text{ GeV} \leq p_T(j_\tau)
\]
The \( R_{em} \) cuts also give us the factor by which non-tau
jets faking the signal get reduced. This factor turns out
to be about 400 corresponding to the \( \tau \)-identification ef-
ciciencies listed above, and it has a big role in handling
the backgrounds.

The following backgrounds are found to pose the
largest threat to our suggested signals:
(a) \( pp \rightarrow \tau \tau jj \) (including Drell-Yan production with
QCD jets as well as electroweak production via gauge
boson fusion)
(b) \( pp \rightarrow W jjj \), with one jet faking the tau and the W
decaying leptonically.
(c) \( pp \rightarrow WWjjj \), with one W decaying into a tau and
the other, into an electron or a muon.
(d) \( pp \rightarrow t \bar{t}X \)
Although the \( t \bar{t} + j \) background looks formidable, it
can still be brought under control with appropriate cuts.
as can be seen from table 1. We have also employed a b-veto corresponding to a b-tagging efficiency of 60%.

For the backgrounds, we have also assumed a veto on central jets with $p_T \leq 30$ GeV, and used a veto survival probability of approximately 50% (15%) for colour-singlet exchange (colour exchange) processes [18]. After this survival probability is folded in, the $\tau\tau$ background retains comparable contributions from electroweak and QCD subprocesses, while $WWjj$ has mostly from electroweak contributions. Apart from exploiting the jet reduction factor arising out of the $R_{em}$-cut, we also demand that the $\tau$-induced central jet and the central lepton have opposite electric charges, whereby the $Wjjj$ background gets further halved. The lepton isolation cut, imposed from the very beginning, effectively suppresses backgrounds from heavy flavour production. We have also found very little faking of the signal by pair-produced charged Higgs bosons [10].

In order to reduce the still remaining backgrounds, we have adopted the following criteria in addition to the basic cuts:
(a) The forward jet pair invariant mass has to be greater than 1200 GeV
(b) Missing $E_T$ must be greater than 100 GeV
(c) Invariant mass of the central lepton and the tau-jet has to be greater than 60 GeV.

In table 1 we indicate how the different types of background as well as the signal are affected by the additional cuts. The signal includes contributions of comparable orders from electroweak gauge boson fusion and real emission corrections to Drell-Yan processes, after the central jet veto survival probabilities are folded in. Backgrounds arising from sources other than gauge boson fusion undergo a drastic reduction on raising the invariant mass cut on the forward jet pair. Also, the strong missing-$E_T$ cut and the invariant mass cut for the $\tau$-jet-lepton pair strongly suppress backgrounds. In fact, we found by explicit analysis that the $b\bar{b}$ background (with two forward jets) which can be menacing for Higgs detection is eliminated via the missing-$E_T$ cut together with the demand that no jet with $E_T \geq 5$ GeV is to be found within a cone of $\Delta R = 0.4$ around the central lepton. On the other hand, both the above cuts are survived with relative ease by the signal, especially when the LSP is heavy. This immediately identifies the scenarios where signals of the suggested type have higher chances of detection.

In figure 1 we present our results by considering the signal rates ranging from 250 GeV to nearly 500 GeV. We have also checked that the lighter stau, so long as it is within 425 (450) GeV, can be detected at the $3\sigma$ level with an integrated luminosity of 30 $fb^{-1}$, for $\tau$-masses ranging from 250 GeV to nearly 500 GeV. We have also checked that the lighter tau, so long as it is within 425 (450) GeV, can be detected at the $3\sigma$ level even if the $\tau_2$ is much heavier. To show the results coupling causes an enhancement at the production level if the lighter stau eigenstate has a larger component of $\tilde{\tau}_L$ (larger $\cos\theta_\tau$). Secondly, a larger $\cos\theta_\tau$ means less Bino component in the lighter tau, and therefore a suppression in its branching ratio for decay into the LSP. Thirdly, for any value of $M_2$, higher values of $m_{\tilde{\tau}_1}$ lead to the opening of the decay channels into $\chi_1^0$ or $\chi_2^0$, and a consequent dilution of the signal. Fourthly, as the signal level itself, there is a further $\theta_\tau$ dependence in the W/Z-induced diagrams. And finally, the signal falls for smaller mass difference between the decaying stau and $\chi_1^0$, since the decay leptons become too soft to pass the $p_T$ cuts. On the whole, however, the signal rates are quite encouraging. In terms of $S/\sqrt{B}$ (S/B being the number of signal/background events), the signal can be seen at 2-4 $\sigma$ level with an integrated luminosity of 30 $fb^{-1}$, for $\tau$-masses ranging from 250 GeV to nearly 500 GeV. We have also checked that the lighter tau, so long as it is within 425 (450) GeV, can be detected at the $3\sigma$ level even if the $\tau_2$ is much heavier. To show the results

Figure 1: Variation of signal cross section with lighter stau mass in a model independent study, with $\Delta M_{\tilde{\tau}_1,\tilde{\tau}_2} = 30$ GeV. The parameters $(\cos\theta_\tau, M_2$ in GeV) are as shown in the labels. We have also checked that the background cross section and significance $(S/\sqrt{B})$. We have used $\mu = 500$ GeV and $\tan\beta = 35$.
in specific models, we present in figure 2 the estimated signal rates for a scenario of the kind studied in \cite{1}, where specific boundary conditions at the GUT scale have been assumed. The third generation scalar mass parameter $m_{q}(3)$ is here lower than that corresponding to the first two, and consequently the two stau eigenstates emerge as the only non-strongly interacting sfermions in the detectable range. For a large gaugino mass parameter, it is not possible to go to very small $m_{q}(3)$ since it will lead to a stau LSP. Thus we are restricted in such cases to large stau masses whose production rates are kinematically suppressed. A very small gaugino mass parameter, on the other hand, leads to problems with radiative electroweak symmetry breaking. Thus the parameter space of this kind of a scenario is more constrained than in the ‘model-independent’ cases of figure 1. Just as in the previous case, the fall in the event rates for lower mass difference between the stau and the LSP is due to the reduction of hardness of the decay leptons. The region most favourable for detection here turns out to be one where the gaugino mass is on the order of 500 GeV, leading to an LSP in the mass range 200 - 250 GeV. In such cases, particularly for large values of $\tan \beta$, one can probe values of $m_{q}(3)$ up to 550 - 600 GeV at the 2$\sigma$ level. This corresponds to the mass of the lighter stau being up to about 500 GeV. The gauge boson fusion channel, therefore, appears to be the best way of uncovering the non-strongly interacting matter sector here.

We conclude by summarising our main observations. Supersymmetric scenarios with inverted mass hierarchy often have the stau as the only sfermion within the search limits of the LHC, and its mass reach via Drell-Yan production can be severely limited. It is difficult in such cases to get unambiguous signatures of the non-strongly interacting sector of the SUSY scenario. We have shown that the gauge boson fusion channel provides a rather spectacular way of increasing the visibility of the superparticle spectrum in such situations. Such visibility is at its maximum when the lighter stau eigenstate is able to decay into only the lightest neutralino which is sufficiently massive to carry away an appreciable amount of missing $p_T$. On the whole, channels of the type explored here can raise the search limits for inverted mass hierarchy scenarios by a hundred to three hundred GeV’s compared to the conventional strategies.

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