Gauge boson fusion as a probe of inverted hierarchies in supersymmetry

Partha Konar*,† and Biswarup Mukhopadhyaya‡

Harish-Chandra Research Institute, Chhatnag Road, Jhusi, Allahabad - 211 019, India

(Received 1 December 2003; published 15 December 2004)

Supersymmetric scenarios with inverted mass hierarchy can be hard to observe at a hadron collider, particularly in the nonstrongly interacting sector. We show how the production of stau pairs via gauge boson fusion, along with hard jets in the high rapidity region, can be instrumental in uncovering the signatures of such scenarios. We demonstrate this both in a model-independent way and with reference to some specific, well-motivated models.

DOI: 10.1103/PhysRevD.70.115011 PACS numbers: 12.60.Jv, 13.35.Dx, 13.85.Rm

Supersymmetry (SUSY) is perhaps the most frequently discussed new physics [1] 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 flavor problem [2], which essentially means the danger of having unacceptable enhancement of flavor-changing neutral current 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 [3], 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 [4].
(c) Nonuniversal boundary conditions at the grand unification scale [5], 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 [6].

Diverse as the phenomenological consequences of the above cases may be, all of them pose a serious question: how can the nonstrongly 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 $m_{\tilde{l}} \simeq 250$–300 GeV [7]. 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 trileptons [8]) 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 [9]. Subsequent studies also have underlined its usefulness for an intermediate mass Higgs, especially for Higgs decay modes such as those into $\tau\tau$, $\gamma\gamma$, or $b\bar{b}$, or for probing couplings which can potentially distinguish a supersymmetric Higgs boson [10]. The characteristic features of such events are two hard forward jets, usually peaking in the rapidity region $3 < |\eta| < 4$, with the lack of color exchange between the jets preventing hadronic activity in the intervening rapidity gap [11]. Tagging the forward jets reduces the backgrounds drastically. Furthermore, such events survive a central jet veto with a high ($\geq 80\%$) efficiency. It is because of all this that the facility of

*Electronic address: konar@theory.tifr.res.in
†Present address: Department of Theoretical Physics, Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai-400005, India
‡Electronic address: biswarup@mri.ernet.in

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 also can be 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 invisible charginos and neutralinos [12] or sleptons [13] 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 additionally can see signals of the stau when the latter is the only nonstrongly interacting supersymmetric particle.

The signal we are suggesting comes from

$$pp \to j_f j_f \tilde{\tau}\tilde{\tau} \to j_f j_f \tau\tau + \not{E}_T, \qquad (1)$$

j_f being a hard forward jet. The missing transverse energy comes from the lightest neutralino due to stau decay. The $\tilde{\tau}$ (and τ) decay products lie in the rapidity gap between the forward jets, with no other color activity in that region. In order to observe the τ'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 $j_f j_f l j_\tau + \not{E}_T$, j_τ being a low-multiplicity jet characteristic of τ decay.

In practice, however, there is a large region of the SUSY parameter space where the stau has a substantial branching ratio for decay into the lighter chargino or the second lightest neutralino. This happens particularly when the stau mass is well above that of the lightest SUSY particle (LSP). In such cases, the loss of signal events due to branching fraction suppression may be partially offset by including events where the stau decays into a chargino and the latter, in the leptonic 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. Gauge invariance requires one to include subprocesses other than those involving gauge boson fusion, although they contribute very little when all the event selection criteria are imposed. In addition to electroweak subprocesses, it is also necessary to take into account the real emission corrections to Drell-Yan production; being strong processes, they have large rates, although the survival probability under a central jet veto is rather low. We have used the survival probability to be 80% (15%) for electroweak (QCD) subprocesses [14].

Our calculation is done in the helicity amplitude formalism, using the subroutine HELAS [15]. All calculations corresponds to the LHC energy ($\sqrt{s} = 14$ TeV), and CTEQ4L structure functions [16] have been used. The following ‘‘basic cuts’’ are employed to ensure the *bona fide* of the gauge boson fusion events:

(a) Two forward jets in opposite hemispheres ($\Delta\eta_{j_f j_f} > 4$), with $p_T > 15$ GeV and $2.0 < |\eta_{j_f}| < 5.0$.
(b) Forward jet invariant mass $M(j_f j_f) > 650$ GeV.
(c) Narrow central jet ($|\eta_{j_\tau}| < 2$) with $p_T > 30$ GeV.
(d) Central lepton ($|\eta_l| < 2$) with $p_T > 10$ GeV.
(e) Lepton isolated from any other jets: $\Delta R_{lj} > 0.4$.

In addition, one has to take into account the τ-identification efficiency in the one-prong channel. Here one is basically looking for a narrow, low-multiplicity jet whose size can be restricted, for example, by using the variable $R_{\rm em}$, the ‘‘jet-radius’’ defined as [17]

$$R_{\rm em} = \frac{\sum E_{T_i}\sqrt{(\eta_i - \eta_c)^2 + (\phi_i - \phi_c)^2}}{\sum E_{T_i}}, \qquad (2)$$

where E_{T_i} is the transverse energy recorded by the ith 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 (η_c, ϕ_c). In addition, one may use the ‘‘isolation criterion’’ or the ‘‘multiplicity criterion’’ as defined in [17]. We have based our results primarily on the variable $R_{\rm em}$. Thus we confine ourselves to $R_{\rm em} < 0.07$ corresponding to the peak of the $R_{\rm em}$ distributions of simulated τ events with p_T in different ranges, thereby obtaining the following τ-identification efficiencies in the hadronic channels [17]:

$$\begin{aligned}\epsilon_\tau &= 0.30 \text{ for } 30 \text{ GeV} \le p_T(j_\tau) < 50 \text{ GeV},\\ &\quad 0.38 \text{ for } 50 \text{ GeV} \le p_T(j_\tau) < 70 \text{ GeV},\\ &\quad 0.46 \text{ for } 70 \text{ GeV} \le p_T(j_\tau).\end{aligned}$$

The $R_{\rm em}$ cuts also give us the factor by which nontau jets faking the signal get reduced. This factor turns out to be about 400 corresponding to the τ-identification efficiencies 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) $pp \to \tau\tau jj$ (including Drell-Yan production with QCD jets as well as electroweak production via gauge boson fusion).
(b) $pp \to Wjjj$, with one jet faking the tau and the W decaying leptonically.
(c) $pp \to WWjj$, with one W decaying into a tau and the other into an electron or a muon.
(d) $pp \to t\bar{t}X$.

Although the $t\bar{t}$ + jets background looks formidable, it can still be brought under control with appropriate cuts as can be seen from Table I. Additionally, we have employed a b veto corresponding to a b-tagging efficiency of 60%.

For the backgrounds, we have assumed a veto on central jets with $p_T \le 30$ GeV and used a veto survival probability of approximately 50% (15%) for color-singlet exchange (color exchange) processes [18]. After this survival probability is folded in, the $\tau\tau$ background retains comparable contributions from electroweak and QCD subprocesses,

TABLE I. Signal and background cross sections surviving each type of cuts, for $M_{\tilde{\tau}_1} = 400$ GeV, $M_{\tilde{\tau}_2} = 430$ GeV, $\cos\theta_\tau = 0.9$, and $M_2 = 400$ GeV. Basic cuts are as specified in the text. The $t\bar{t}$ background includes $t\bar{t}$ + jets.

	Signal (in fb)	Background (in fb)				
		$\tau\tau$	Wj	WW	$t\bar{t}$	Total
Basic cuts	0.73	2.88	2.01	0.37	5.06	10.30
$+M_{j_f j_f} > 1200$ GeV	0.57	1.37	0.63	0.25	1.14	3.41
$+\not{E}_T > 100$ GeV	0.42	0.32	0.09	0.11	0.24	0.77
$+M_{l j_\tau} > 60$ GeV	0.31	0.03	0.08	0.10	0.16	0.38

the electroweak ones being mainly driven by a real Z boson. The $Wjjj$ background comes overwhelmingly from QCD subprocesses, while $WWjj$ has mostly from electroweak contributions. Apart from exploiting the jet reduction factor arising out of the $R_{\rm em}$ cut, we demand additionally that the τ-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 flavor production. Moreover, we have found very little faking of the signal by pair-produced charged Higgs bosons [19].

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 I 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. Furthermore, the strong missing-E_T cut and the invariant mass cut for the τ-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 Fig. 1 we present our results by considering the SUSY parameter space in a model-independent manner, assuming the two stau mass eigenstates to be the only "light"

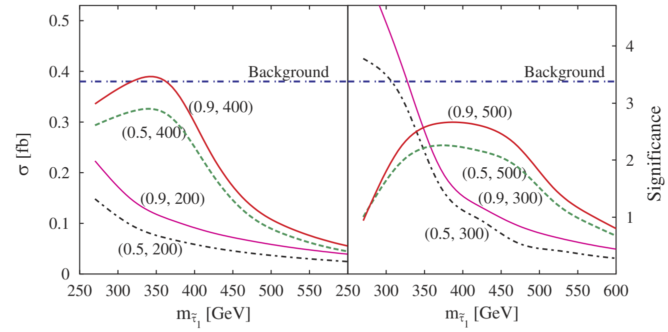

FIG. 1 (color online). Variation of signal cross section with lighter stau mass in a model-independent study, with $\Delta M_{\tilde{\tau}_1\tilde{\tau}_2} = 30$ GeV. The parameters ($\cos\theta_\tau$, M_2 in GeV) are as shown in the labels. We show too the background cross section and significance ($S/\sqrt{B}$). We have used $\mu = 500$ GeV and $\tan\beta = 35$.

sfermions. The real and symmetric stau mass matrix is fixed in terms of its two eigenvalues and the left-right mixing angle θ_τ. Two values of the mixing angle have been considered, along with different values of the SU(2) gaugino mass M_2 (assuming gaugino mass unification). The behavior of the graphs can be traced to the interplay of a number of factors. First, SU(2) gauge 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 stau, and therefore a suppression in its branching ratio for decay into the LSP. Third, for any value of M_2, higher values of $m_{\tilde{\tau}_1}$ leads to the opening of the decay channels into $\chi_1^\pm$ or χ_2^0, and a consequent dilution of the signal. Fourth, as the signal level itself, there is a further θ_τ dependence in the W/Z-induced diagrams. And finally, the signal falls for smaller mass difference between the decaying stau and χ_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 σ level with an integrated luminosity of 30 fb^{-1}, for $\tilde{\tau}$ masses ranging from 250 GeV to nearly 500 GeV. We also have checked that the lighter stau, so long as it is within 425 (450) GeV, can be detected at the $3\sigma(2\sigma)$ level even if the $\tilde{\tau}_2$ is much heavier. To show the results in specific models, we present in Fig. 2 the estimated signal rates for a scenario of the kind studied in [5], where specific boundary conditions at the grand unification scale have been assumed. The third generation scalar mass parameter $m_0(3)$ is here lower than that corresponding to the first two, and consequently, the two stau eigenstates emerge as the only nonstrongly interacting sfermions in the detectable range. For a large gaugino mass parameter, it is not possible to go to very small $m_0(3)$ 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 sym-

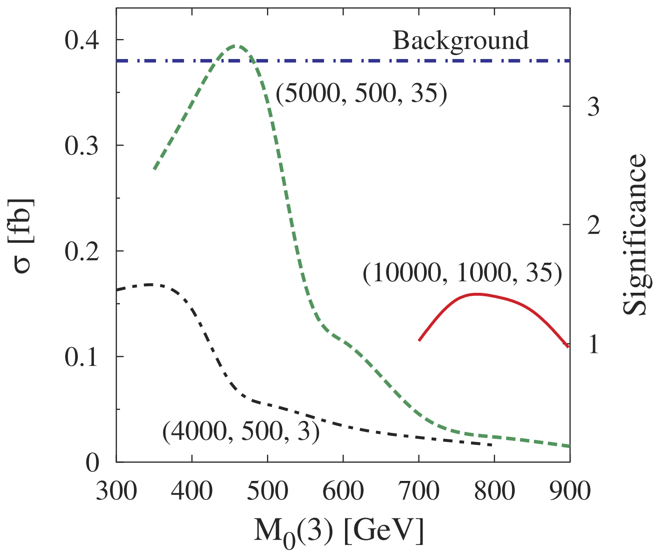

FIG. 2 (color online). Variation of signal cross section with lighter stau mass for the scenario in [5]. The parameters [$m_0(1)$ in GeV, $m_{1/2}$ in GeV, $\tan\beta$] are as shown in the labels. We have used $m_0(1) = m_0(2)$ and Sign(μ) = +1.

metry breaking. Thus the parameter space of this kind of a scenario is more constrained than in the ''model-independent'' cases of Fig. 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 favorable 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 $m_0(3)$ up to 550–600 GeV at the 2σ 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 nonstrongly interacting matter sector here.

We conclude by summarizing 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 nonstrongly 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 one hundred to three hundred GeV's compared to the conventional strategies.

[1] For introductory reviews see, for example, H. P. Nilles, Phys. Rep. **110**, 1 (1984); H. Haber and G. Kane, Phys. Rep.. **117**, 75 (1985); *Perspectives on Supersymmetry*, edited by G. Kane, (World Scientific, Singapore, 1998).
[2] See, for example, F. Gabbiani *et al.*, Nucl. Phys. B **477**, 321 (1996).
[3] A. Brignole *et al.*, Z. Phys. C **74**, 157 (1997); V. Barger, C. Kao, and R. Zhang, Phys. Lett. B **483**, 184 (2000).
[4] G. Dvali and A. Pomarol, Phys. Rev. Lett. **77**, 3728 (1996); P. Binetruy and E. Dudas, Phys. Lett. B **389**, 503 (1996).
[5] H. Baer *et al.*, Phys. Rev. D **63**, 015011 (2000); Phys. Lett. B **475**, 289 (2000); T. Blazek *et al.*, Phys. Rev. D **65**, 115004 (2002); S. Raby, hep-ph/0304074.
[6] J. Bagger *et al.*, Phys. Lett. B **473**, 264 (2000).
[7] H. Baer *et al.*, Phys. Rev. D **49**, 3283 (1994); D. Denegri, L. Rurua, N. Stepanov, CMS CERN Report No. CMS notes-1996/059; CMS Collaboration, S. Abdullin *et al.*, CMS CERN Report No. CMS notes-1998/006; S. Abdullin *et al.*, J. Phys. G **28**, 469 (2002); ATLAS Collaboration, Report No. ATL-PHYS-97-111 (1997).
[8] W. Beenakker *et al.*, Phys. Rev. Lett. **83**, 3780 (1999); K. Matchev and D. Pierce, Phys. Rev. D **60**, 075004 (1999); H. Baer *et al.*, Phys. Rev. D **61**, 095007 (2000).
[9] R. N. Cahn and S. Dawson, Phys. Lett. B **136**, 196 (1984).
[10] R. Godbole and S. Rindani, Z. Phys. C **36**, 395 (1987); D. Rainwater and D. Zeppenfeld, J. High Energy Phys. 12, 005 (1997); Phys. Rev. D **60**, 113004 (1999); D. Rainwater, D. Zeppenfeld, and K. Hagiwara, Phys. Rev. D **59**, 014037 (1999); T. Plehn, D. Rainwater, and D. Zeppenfeld, Phys. Rev. D **61**, 093005 (2000).
[11] J. D. Bjorken, Phys. Rev. D **47**, 101 (1993).
[12] A. Datta, P. Konar, and B. Mukhopadhyaya, Phys. Rev. D **65**, 055008 (2002); Phys. Rev. Lett. **88**, 181 802 (2002).
[13] D. Choudhury *et al.*, Phys. Rev. D **68**, 075007 (2003).
[14] D. Rainwater, Ph.D. thesis, Wisconsin University (hep-ph/9908378).
[15] K. Hagiwara, H. Murayama, and I. Watanabe, KEK Report No. 91-11 (1991).
[16] H. Lai *et al.*, Phys. Rev. D **55**, 1280 (1997).
[17] ATLAS Detector and Physics Performance Technical Design Report: Vol. I, see http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/TDR/access.html.
[18] See D. Rainwater, D. Zeppenfeld, and K. Hagiwara in [10].
[19] S. Moretti, J. Phys. G **28**, 2567 (2002).