Invisible Charginos and Neutralinos from Gauge Boson Fusion: A Way to Explore Anomaly Mediation

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(Received 1 November 2001; revised manuscript received 30 January 2002; published 22 April 2002)

We point out that vector boson fusion at the Large Hadron Collider (LHC) can lead to useful signals for charginos and neutralinos in supersymmetric scenarios where these particles are almost invisible. The proposed signals are just two forward jets with missing transverse energy. It is shown that, in this way, one can put by far the strongest constraint on the parameter space of a theory with anomaly mediated supersymmetry breaking at the LHC. In addition, scenarios where the lightest neutralinos and charginos are Higgsino-like can give signals of the above type.

DOI: 10.1103/PhysRevLett.88.181802 PACS numbers: 12.60.Jv, 13.85.Rm, 14.80.Ly

Vector boson fusion (VBF) at hadronic machines such as the Large Hadron Collider (LHC) at CERN has been suggested as a useful channel for studying the signal of the Higgs boson. Characteristic features of this mechanism are two highly energetic quark jets, produced in the forward direction in opposite hemispheres and carrying a large invariant mass. The absence of color exchange between the forward jets ensures a suppression of hadronic activities in the central region [1]. Although it was originally proposed as a background-free signal of a heavy Higgs [2], the usefulness of the VBF channel in uncovering an intermediate mass Higgs has also been subsequently demonstrated [3].

Encouraged by all this, one naturally wants to know whether the VBF channel can be used to unravel other aspects of the basic constituents of nature, especially those bearing the stamp of physics beyond the standard model of elementary particles. It should be emphasized here that the tagging of forward-jet events is part of the experimental program at the LHC, and therefore any new physics contributing to such events is bound to get explored there.

One such candidate scenario, constantly knocking at our door, is supersymmetry (SUSY). While a multitude of signals for SUSY at the up-and-coming accelerators have been proposed [4], here we want to stress the utility of VBF processes to probe the nonstrongly interacting sector of the SUSY standard model. We point out in particular that some of the SUSY theories of considerable current interest can be tested in this way, via signals where nothing except the forward-tagged jets are visible.

When R parity [defined as $R = (-1)^{3B+L+2S}$] is conserved, a conventional method of searching for charginos ($\chi^{\pm}$) and neutralinos (χ^0) at hadron colliders is their direct production. The most convenient channel is $p\bar{p}/pp \to \chi_1^{\pm}\chi_2^0$ followed by the decays $\chi_1^{\pm} \to \chi_1^0 l^{\pm}\nu_l(\bar{\nu}_l)$ and $\chi_2^0 \to \chi_1^0 l^+ l^-$, where χ_1^0 is the lightest SUSY particle (LSP) and hence is invisible. This gives rise to 'hadronically quiet' trilepton signals [5].

It is in cases where the trilepton signal is not expected to be visible that other channels such as VBF must be explored, if one wants to study the nonstrongly interacting sector in isolation. For example, in some of the currently popular SUSY models, the lighter chargino ($\chi_1^{\pm}$) and the lightest neutralino (χ_1^0) are closely degenerate in mass. Then the previously mentioned trilepton signal is no longer detectable, since the chargino decays into either a soft pion (π) or very soft leptons/quarks together with the χ_1^0. This makes the chargino-neutralino pair essentially invisible. Final states comprising them need to be identified with some visible tags. In electron-positron colliders, the use of a photon as such a tag is advocated [6]. However, tagging either photons or gluons at hadronic machines is unlikely to be efficient due to extremely large backgrounds. Under the circumstances, we find it useful to study the production of chargino-neutralino pairs in VBF, since the forward jets themselves act as the necessary tags. In such cases, two $forward\ jets + \not{E}_T$ can be treated as the generic signal of invisibly decaying charginos and neutralinos.

It should be noted that such signals have already been suggested [7] for Higgs bosons decaying invisibly into stable, neutral weakly interacting particles such as a pair of LSP's in the minimal SUSY standard model, or pairs of gravitinos or majorons in some other extended theories. It has also been shown in the above reference that the backgrounds to such a signal can be effectively handled by using suitable event selection criteria. We demonstrate that the partial invisibility of the chargino-neutralino sector of a SUSY model can be used to our advantage using very similar event selection criteria.

The effectiveness of the VBF technique has also been demonstrated by us in an R-parity violating scenario where it is rather difficult to distinguish the final states obtained via $p\bar{p}/pp \to \chi_1^{\pm}\chi_2^0$ against cascades coming from the strongly interacting sector [8]. In VBF channel, charginos and neutralinos produced with the help of the W boson, the Z boson, and the photon lead to signatures of such models in the form of like- and unlike-sign dileptons in background-free environments.

We will consider two specific examples which are of interest for the present purpose. The first one of these is a theory with anomaly mediated supersymmetry breaking

(AMSB) [9], where $\chi_1^\pm \chi_1^0$ are both winolike and therefore very closely degenerate. The second instance is that of a SUSY grand unified theory (GUT) with $M_2 \gg \mu$, where M_2 is the SU(2) gaugino mass and μ is the Higgsino mass parameter occurring in the superpotential. In that case, χ_1^0, $\chi_1^\pm$, and χ_2^0 are all Higgsino-like and have small mass separations. We show below how it is possible to constrain both of these scenarios at the LHC using the VBF mechanism.

AMSB models attempt to link the SUSY-breaking mechanism to scenarios with extra compactified dimensions. The SUSY-breaking sector is confined to a 3-brane separated from the one on which the standard model fields reside. SUSY breaking is conveyed to the observable sector by a super-Weyl anomaly term, and the gaugino and scalar masses are given by

$$\begin{aligned} M_i &= b_i \frac{g_i^2}{16\pi^2} m_{3/2}, \\ M_{\rm scalar}^2 &= c^2 \frac{m_{3/2}^2}{(16\pi^2)^2} + m_0^2. \end{aligned} \tag{1}$$

Here b_i's are coefficients occurring in the β functions of the appropriate gauge couplings and c's are combinations of β functions and anomalous dimensions (of gauge and Yukawa couplings). Explicit expressions for these can be obtained, for example, from [10]. m_0 is a scalar mass parameter introduced to prevent sleptons from becoming tachyonic.

Since the gaugino masses are proportional to the beta functions of the corresponding gauge couplings, both the lightest neutralino (which is the LSP) and the lighter chargino turn out to be dominated by the wino, with their masses separated by a few hundred MeV. The second lightest neutralino, on the other hand, is about 3 times larger in mass and is Bino dominated.

This type of spectrum implies that the dominant decay mode for the lighter chargino is $\chi_1^\pm \to \pi^\pm \chi_1^0$. The pion in such cases is too soft to be detected, making the chargino essentially invisible. There are suggested ways of looking for this type of spectrum in high-energy e^+e^- colliders [6,10]. Studies to probe AMSB at hadron colliders using different superparticle decay cascades are also found in the literature [11]. We, on the other hand, exploit the invisibility of the lighter chargino and tagging of the forward jets in the VBF channel to explore or exclude this type of theory at the LHC. Our analysis is based on the processes $pp \to \chi_1^\pm \chi_1^0 jj$, $pp \to \chi_1^+ \chi_1^- jj$, and $pp \to \chi_1^0 \chi_1^0 jj$, driven by the fusion of gauge bosons, which give rise to just two visible forward jets with missing transverse energy. Similar final states may also arise from $\chi_1^\pm \chi_2^0$ production, but the contribution to the events of our interest is small, since (i) the Bino-dominated character of χ_2^0 makes the production rate low, and (ii) the invisible final states can arise only from $\chi_2^0 \to \nu\bar{\nu}\chi_1^0$, where a further suppression by the branching fraction takes place.

The signals, however, are not background-free. As has already been discussed in Ref. [7], such events can be faked by the pair production of neutrinos along with two forward jets. In addition, two forward jets together with a soft lepton and missing E_T (due to a neutrino) can also fake the signal. Such final states can arise in the standard model from real emission corrections to the Drell-Yan process as well as from electroweak W and Z production along with two jets.

Keeping all these in mind, we have applied the following event selection criteria: (i) two forward jets in opposite hemispheres, with $E_T > 40$ GeV and $2.0 \leq |\eta_j| \leq 5.0$; (ii) $\Delta\eta_{jj} > 4$; (iii) $M_{\rm inv}(jj) > 1200$ GeV; (iv) $\not{E}_T > 100$ GeV; (v) $\Delta\phi_{jj} < 57°$.

The first three cuts establish the *bona fides* of the VBF events. All the criteria enhance the signal-to-background ratio, since the background events are in general found to have smaller missing E_T and tend to have back-to-back orientations in the transverse plane. Also, we have required the pions to have E_T less than 20 GeV to be really undetected. The leading order estimate of backgrounds depends on the choice of the renormalization scale. Estimates with different choices are found in Ref. [7]. The range over which such estimates vary in our case, with and without the rapidity and azimuthal angle cuts, are shown in Table I. The purpose of this table is to show the dependence on the renormalization scale choice and the effects of kinematic cuts (especially the lower cut on rapidity and the upper cut on the azimuthal angle). Both the azimuthal angle cut and the lower cut on jet rapidity cause a substantial reduction of the background rate. As has already been mentioned, the backgrounds can have their origin in both QCD and electroweak interactions. For the choice of higher α_s in Table I, for example, one has 168 fb of QCD contribution and 21 fb from electroweak processes. The numbers in the first column of the table are obtained when all the cuts specified earlier in the text are applied, except the one on $\Delta\phi_{jj}$. Similarly, for the second column, we remove only the lower cut on the rapidity of the forward jets ($|\eta_j| > 2$). Therefore, a comparison of the numbers in the first two

TABLE I. Backgrounds for different choices of the renormalization scales with and without the rapidity and azimuthal angle cuts (the remaining cuts as specified in the text are retained in each case).

Choice of the renormalization scale	Background (in fb) Without $\Delta\phi_{jj} < 57°$ cut	 Without $\lvert\eta_j\rvert \geq 2$	 With all cuts
$\alpha_s = \alpha_s(\min\{p_{T_{j1}}, p_{T_{j2}}\})$	984	452	189
$\alpha_s = \alpha_s(\sqrt{\hat{s}}/4)$	334	193	72

columns with the corresponding entries in the third column also gives us an estimate of the efficiencies of these cuts individually. Furthermore, one multiplies the cross sections with the survival rates on the application of the central jet veto. The survival probabilities have been taken as 0.9, 0.28, and 0.82, respectively, for the signal, QCD backgrounds, and electroweak backgrounds [12].

The amplitudes for all the processes of our interest have been calculated using the HELAS (helicity amplitude subroutines) [13]. We have used CTEQ4L parton distribution functions [14].

In Fig. 1 we plot the number of signal events, calculated for an integrated luminosity of 100 fb^{-1} at the LHC, against the chargino mass for $\mu > 0$ and $\tan\beta = 10$. The rates, essentially dependent on the chargino mass, are, by and large, insensitive to $\tan\beta$ and m_0.

In estimating the detectability of the signal against the backgrounds, we have chosen a renormalization scale that keeps α_s on the high side. Thus we have taken $\alpha_s = \alpha_s(\min\{p_{Tj_1}, p_{Tj_2}\})$. By performing an analysis similar to that in [7], we have utilized the fact that the backgrounds can be estimated to a fairly high precision ($\sim$1.2%) at the high-luminosity option of the LHC, from the visible decay products of the W and the Z. The above uncertainty has been added in quadrature with the Gaussian fluctuation in the background itself. It is then possible to identify those regions of the parameter space where the signal survives at different confidence levels.

It may be mentioned that another way of handling the backgrounds in such a case has been suggested in the literature [15]. This consists of identifying the track left by a possibly long-lived chargino. However, further studies are required to ascertain whether this is a viable option at the high-luminosity version of the LHC.

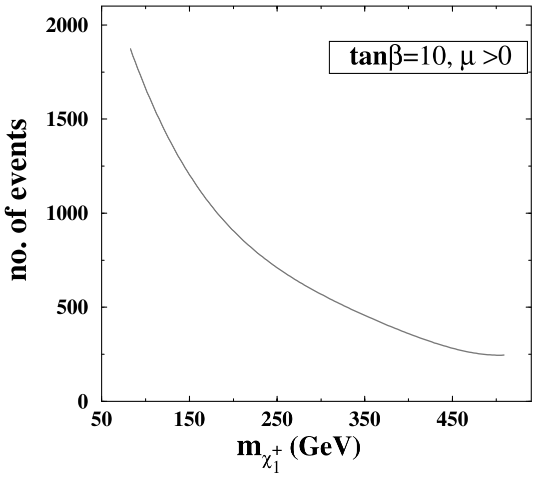

FIG. 1. Variation of a number of (2 *forward jets* + $\not\!\!E_T$) events (after applying cuts as specified in the text) with the lighter chargino mass ($m_{\chi_1^+}$) in AMSB with $\tan\beta = 10$ and $\mu > 0$. An integrated luminosity of 100 fb^{-1} has been assumed.

Figure 2 shows the regions in the $m_0 - m_{3/2}$ plane corresponding to 2σ and 5σ detectability of the signal against the backgrounds estimated above. Again, an integrated luminosity of 100 fb^{-1} has been assumed. We also show the regions already excluded by CERN Large Electron-Positron Collider (LEP) data [16] as well as those forbidden by the possibility of tachyonic sleptons (or $\tilde{\tau}$-LSP) and the impossibility of electroweak symmetry breaking. The signal event rates are independent of m_0 and highly insensitive to $\tan\beta$.

It is clear from Fig. 2 that the entire AMSB parameter space for $m_{3/2} \leq 190$ TeV can be probed at 95% confidence level, corresponding to a lighter chargino of mass up to about 500 GeV. Moreover, chargino masses upto 300 GeV can be explored at the 5σ level. The results are very similar for negative values of μ. The above predictions, it should be emphasized, correspond to a case where backgrounds are assumed to be of the largest possible magnitude. Therefore, *although our predictions are related to processes involving charginos and neutralinos only, the signals to be looked for can have wider implications, since the fundamental parameters of AMSB can be constrained through them.*

It may be noted that general strategies for AMSB search at hadronic machines have been reported in earlier works (for example, in the first reference of [11]) using superparticle cascades of various types. For $m_{3/2} > 80$ TeV, such signals have limited reach for $m_0 > 1.2$ TeV. Our results, on the other hand, essentially depend on direct chargino production and therefore are independent of m_0. As can be seen from Fig. 2, the overall reach of our suggested signal in $m_{3/2}$ space, even at the 5σ level, is also higher.

We now come to the situation where the gaugino masses are large compared to the μ parameter in a SUSY GUT. Treating μ as a free parameter, one can have as small a

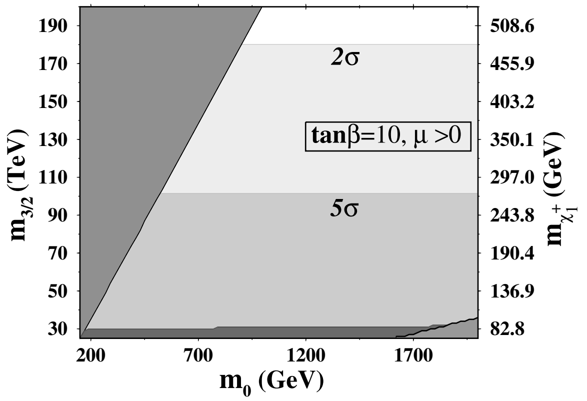

FIG. 2. 5σ and 2σ discovery regions in the $m_0 - m_{3/2}$ plane for $\mu > 0$ and $\tan\beta = 10$ in an AMSB scenario. The upper-left shaded region is excluded to prevent the lighter $\tilde{\tau}$ from becoming first the LSP and then the tachyonic. The dark shaded region parallel to the m_0 axis in low $m_{3/2}$ is disallowed from LEP data. The light shaded portion in the lower-right corner is excluded to ensure electroweak symmetry breaking.

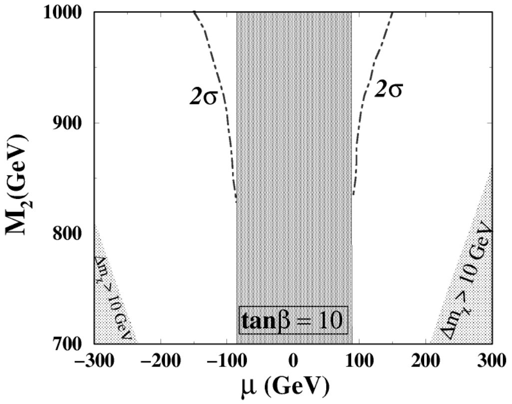

FIG. 3. 2σ significance contours in a SUSY GUT scenario for $\tan\beta = 10$ in the $\mu - M_2$ plane. The dark shaded regions are disallowed from LEP data. The shaded portions in two corners indicate the regions where $(m_{\chi_1^\pm} - m_{\chi_1^0}) > 10$ GeV.

separation as about 5 GeV between $\chi_1^\pm$ and χ_1^0 in such cases, while χ_2^0 can be within about 15 GeV of $\chi_1^\pm$, as long as one is within the region allowed by the LEP data. The branching ratio for such a $\chi_1^\pm$ going to a pion is within about 10%. Invisibility of the chargino mostly hinges on the ensuing leptons and quarks produced in three-body decays being sufficiently soft. Very similar considerations apply to the decay of the χ_2^0 as well.

Since both of the two lightest neutralinos and the lighter chargino are Higgsino dominated in this case, the production rates for $\chi_1^\pm\chi_1^0$, $\chi_1^\pm\chi_2^0$, and $\chi_1^+\chi_1^-$ in gauge boson fusion are of comparable magnitudes. Thus the computation of the *forward jets* + $\not{E}_T$ has to take into account all the above channels, with the three-body decay products sufficiently degraded to escape detection.

We have used similar criteria for tagging the forward jets as in the AMSB case, and the same $E_T/$ and ϕ_{jj} cuts, with the additional demand that the E_T of jets, leptons, or pions in the central region be less than 10 GeV. Events are seen to pass these criteria only if the mass difference between $\chi_1^\pm$ and χ_1^0 is less than 10 GeV. This region has been identified in Fig. 3 with 2σ exclusion contours. The relative dilution of the results compared to the AMSB scenario is due to the fact that only a finite fraction of the three-body decay products are really soft enough to be undetected, unlike the very soft pions that are inexorably produced in the AMSB scenario. Also, since $\chi_1^\pm$ and χ_1^0 here are Higgsino-like, their gauge couplings are smaller than their gauginolike counterparts which belong to the adjoint representation of SU(2). This causes a further reduction compared to AMSB.

Squark and slepton masses on the order of 400 GeV have been assumed in the above analysis. This prevents two-body decays of $\chi_1^\pm$ and χ_2^0 over most of the parameter space involved here. If the sfermions are light enough to allow such decays, χ_2^0, for example, can decay into a sneutrino and a neutrino, both of which can be invisible. The exclusion of such decays from our calculation makes our estimates conservative.

In conclusion, invisibly decaying charginos can be used to our advantage at the LHC if one concentrates on the chargino-pair and chargino-neutralino productions via vector boson fusion. Tagging of the two forward jets, with no other visible particle in the final state, will allow us to constrain a large part of the parameter space in AMSB at the 5σ level, and a still larger region at the 2σ level. Also, a SUSY GUT scenario, where the lighter neutralinos and charginos are Higgsino dominated, can be subjected to similar, though less stringent, constraints. Thus the vector boson fusion channel can offer a major improvement in the search strategies for the chargino-neutralino sector of SUSY theories, where such particles turn out difficult to detect otherwise.

The work of B. M. was partially supported by the Board of Research in Nuclear Sciences, Government of India.

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