# Six-Quark Decays of the Higgs Boson in Supersymmetry with *R*-Parity Violation

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Both electroweak precision measurements and simple supersymmetric extensions of the standard model prefer a mass of the Higgs boson less than the experimental lower limit (on a standard-model-like Higgs boson) of 114 GeV. We show that supersymmetric models with $R$ parity violation and baryon-number violation have a significant range of parameter space in which the Higgs boson dominantly decays to six jets. These decays are much more weakly constrained by current CERN LEP analyses and would allow for a Higgs boson mass near that of the $Z$. In general, lighter scalar quark and other superpartner masses are allowed. The Higgs boson would potentially be discovered at hadron colliders via the appearance of new displaced vertices.

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The standard model of particle physics is arguably the crowning achievement of the last half-century's work towards the understanding of the laws of nature at short distances. However, two somewhat nagging features remain. The first is that while statistical fits of standard model parameters to precision measurements produce a best fit value for the Higgs scalar mass of $76^{+33}_{-24}$ GeV [1], LEP II places a lower bound of 114.4 GeV at 95% C.L. [2]. While there is no discrepancy here, a Higgs boson mass measured below the current LEP bound would have improved the fit to precision data. Additionally, it has been argued that some of the electroweak observables most sensitive to the Higgs boson mass, namely, the leptonic and forward-backward bottom quark asymmetries, are themselves not mutually consistent and may imply a discrepancy with the LEP II bound [3]. The second nagging feature is that the scale of electroweak symmetry breaking is very sensitive to quantum corrections. If the standard model is valid to some very high energy scale $M \gg 1$ TeV, the parameters of the ultraviolet theory would require an unnatural tuning of order one part in $(M/1\ \text{TeV})^2$ to maintain the hierarchy. While this fact alone does not guarantee new physics beyond a Higgs boson at the electroweak scale, it is strongly suggestive of physics at the weak scale which stabilizes scalar masses with respect to radiative corrections.

A well-known solution to the naturalness problem is to impose supersymmetry on the standard model and softly break it at a scale of $M \sim 1$ TeV [4]. Radiative corrections to scalar masses in these theories are proportional to the scale of supersymmetry breaking and therefore naturally stabilize the mass of the Higgs at around the weak scale. A discrete symmetry, $R$ parity, is introduced to forbid dimension-four baryon and lepton number violating operators and avoid proton decay as we discuss below.

While the MSSM (Minimal Supersymmetric Standard Model) contains over a hundred new parameters, it has become tightly constrained. A robust constraint on the MSSM is the bound on the Higgs boson mass. The physical mass gets contributions which depend only logarithmically on superpartner masses (for example, the scalar top quark mass) through corrections to the Higgs quartic interaction [4]. On the other hand, the $Z$ boson mass and the scale of electroweak symmetry breaking gets corrections *proportional* to superpartner masses. To satisfy the current bound on the physical mass, large scalar top masses ($m_{\tilde{t}} \simeq 1$ TeV) are required. For a large cutoff $\Lambda$, say of order the Planck scale, contributions to the (squared) $Z$ mass will be roughly of order the superpartner masses, say $\delta m_Z^2 \sim m_{\tilde{t}}^2$. A cancelation would be required among contributions with a tuning of the order one part in $(m_{\tilde{t}}/m_Z)^2$. Thus, 1 TeV scalar tops would require $\sim$1% tuning. A beautiful discussion of this tension in the MSSM is contained in [5].

One possible resolution to the paradox is that the Higgs boson is in fact light but missed by experiments. The quoted lower bound on the Higgs boson mass comes from analyses assuming a Higgs boson with standard model properties such as a standard model cross section for $Z$-Higgs boson production and standard model branching ratios into bottom quarks and tau leptons. If the branching ratio to standard model final states are uniformly suppressed by, for example, a factor of 5, and the new decay modes are not picked up by any LEP searches, the 95% C.L. lower limit on the Higgs boson mass reduces to roughly 93–95 GeV (see Fig. 2 of [2]). Our model exploits this weakness. Other attempts to modify Higgs boson decays for the purpose of naturalness have been made in the context of the MSSM with an additional singlet [6].

In this Letter, we show that in the MSSM with $R$ parity violation and nonunified gaugino masses, there is a significant amount of parameter space in which the Higgs boson dominantly decays to a pair of unstable neutralinos, each of which subsequently decays to three quark jets. The parameter space allows, as we detail below, Higgs boson masses around the $Z$ mass even with a standard model production cross section; this is our main result.

$R$ parity is a symmetry under which all superpartners are odd. Superpotential operators which violate $R$ parity (and baryon number) are

 

$$W \supset \lambda''_{ijk} U^c_i D^c_j D^c_k, \tag{1}$$

where $U^c$ and $D^c$ are up-type and down-type quark singlet superfields, respectively, and the $ijk$ are flavor indices. Current bounds on the individual $\lambda''$ couplings are only stringent from neutron-anti-neutron oscillations and double nucleon decay, requiring $\lambda''_{112} \lesssim 10^{-7}$ and $\lambda''_{113} \lesssim 10^{-4}$ for 200 GeV scalar quark and gluino masses. The other seven couplings are less constrained. The tightest bounds are on products of two different couplings which range from $\lambda''_{ijk}\lambda''_{i'j'k'} < 10^{-2}$–$10^{-4}$ and come dominantly from limits on rare hadronic decays of $B$ mesons. For a broad review of $R$ parity violation in supersymmetry, see [7].

Do LEP searches put a bound on a Higgs boson that decays to 6 quarks (via two neutralinos)? No analysis has been performed looking for this exclusive final state. A decay-mode-independent search for a Higgs boson was performed by the OPAL experiment [8] and puts a lower bound of 82 GeV with a standard model production cross section. In addition, the search for $h \to 2b$ could be sensitive to our Higgs boson to six jets when the latter can be forced into a two-jet topology (and when each neutralino decay contains a $b$ quark). An analysis of this type was done by the LEP collaborations, specifically, DELPHI [9] and OPAL [10] in the search for a cascade decay of the Higgs boson to four $b$ quarks via two pseudo scalars, $a$. They modified the search for $e^+e^- \to hZ \to (b\bar{b})Z$ to be sensitive to the cascade $h \to aa \to b\bar{b}b\bar{b}$ by forcing the latter into two jets and estimating the efficiency of the $h \to 2b$ search to pick up $h \to 4b$. Efficiencies ranged from 70% to 30% for masses of the pseudoscalar from 12 GeV to nearly half the Higgs boson mass. DELPHI (the more efficient of the two) relied heavily on $b$-tagging and the existence of 4 $b$'s in the final state, while OPAL relied heavily on both $b$ tagging and mass reconstruction. In the case where the decay is into six quarks (with at most two $b$'s), one expects efficiencies to be significantly lower both because there are fewer $b$'s in the event and because the additional jets in the event makes the mass reconstruction more difficult, both for the Higgs boson and the $Z$. This would also be true of the flavorless search [11], which is similar to the $2b$ search with the $b$-tagging requirement removed. Unfortunately, we cannot make a meaningful statement about the sensitivity, and thus a study of our decay would be useful.

What are the constraints on the mass of the lightest neutralino? The neutralino should be light enough to allow for our Higgs boson decay ($\lesssim$50 GeV), while the lightest chargino must satisfy its current lower bound ($\sim$103 GeV in most of parameter space, even for $R$-parity violating decays [12]). This constrains the MSSM parameters such that $M_1 < M_2$, $\mu$, and the lightest neutralino is mostly bino—although it must have enough of a higgsino component to allow the Higgs boson width to be dominated by this decay, and thus the $\mu$ parameter should not be too much larger than 100 GeV as we see below (see also [13]).

The remaining question then is how could such a light neutralino with strong enough couplings to dominate the Higgs boson width not being detected indirectly by its effect on the $Z$ width or directly in searches at LEP II. There are two reasons: the first is that the width of the $Z$ in the standard model ($\sim$2.5 GeV) is 3 orders of magnitude bigger than the standard model width of a 100 GeV Higgs boson. The second is that in the range of small to moderate bino-higgsino mixing, the Higgs boson decay rate into neutralinos is roughly proportional to the mixing angle squared $\Delta$ (defined in the appendix), while the same rate for the $Z$ goes like $\Delta^2$. The decay width of the $Z$ into the lightest neutralino at tree level is

$$\Gamma_{\chi^0} = \frac{\Gamma_\nu}{3}\Delta^2\sqrt{1-\left(\frac{2m_\chi}{m_Z}\right)^2}\left(1-\left(\frac{m_\chi}{m_Z}\right)^2\right), \tag{2}$$

where $\Gamma_\nu$ is the standard model invisible $Z$ width. We require this contribution to the total and hadronic widths to be less than 0.1%—roughly $1\sigma$ as determined by the electroweak fit [1]. This requirement sets a bound of $\Delta \lesssim 1/10$ for a very light neutralino, and weaker for a heavier neutralino as phase space gets reduced. We find that in most of our parameter space—where the decay to neutralinos dominates the Higgs boson width and the chargino bound is satisfied—we satisfy this constraint.

Searches for neutralinos which decay via baryon-number violation have been performed by ALEPH, DELPHI, and L3 [12]. None of these searches were able to put a bound on the neutralino mass via a direct search, but only through a search for a chargino and the restriction $M_1 = (5/3)\tan^2\theta_W M_2 \sim M_2/2$ relating the two masses through the assumption of gaugino mass unification. The L3 experiment does present cross section bounds for neutralino masses between 30 GeV and roughly 100 GeV of around 0.1 pb. The neutralino cross section through an $s$-channel $Z$ at LEP II is

$$\sigma_{\to\chi^0\chi^0} = \sigma_{\to\nu\bar{\nu}} \times \Delta^2\sqrt{1-\frac{4m_\chi^2}{s}}\left(1-\frac{m_\chi^2}{s}\right), \tag{3}$$

where $\sigma_{\to\nu\bar{\nu}}$, the neutrino pair-production cross section, is $\sim$1 pb at center of mass energy $\sqrt{s} = 200$ GeV. To satisfy the L3 bound, we require $\Delta < 1/3$, which is satisfied in our entire parameter space. However, if scalar leptons are relatively light, a $t$-channel diagram can dominate the cross section and overwhelm the bound. Requiring the cross section to satisfy the L3 constraint places a lower bound of $\sim$300 GeV on scalar electron masses (in the case degenerate scalars). This becomes our strongest constraint on a superpartner mass in the baryon-number violating MSSM. With baryon-number and $R$-parity violating interactions, the direct search bounds on *all* superpartners are below 100 GeV, except for the chargino, whose bound remains roughly the same as the $R$-parity conserving case (102.5 GeV) [14].

The points in parameter space which predict a large Higgs boson to neutralinos branching ratio and satisfy the lower bound on the chargino mass satisfy $M_2 > 3M_1$ [13]. In Fig. 1 we show a plot of different branching ratios of the Higgs boson to neutralinos for fixed $M_2$, $M_1$, and Higgs boson mass. Each point also satisfies the constraint on the contribution to the hadronic $Z$ width and the requirement on the neutralino mass $m_{\chi^0} > 12$ GeV. We see that a large branching ratio requires relatively low values of $\tan\beta$ and $\mu$. In Fig. 2 we scan over $M_1$, $M_2$, $\mu$, and $\tan\beta$ and plot points which satisfy the chargino mass and $Z$ width bounds. For these points, the branching ratio is less than 25% to normal standard model decays, thus lowering the Higgs boson mass bound in this part of parameter space to roughly 95–100 GeV according to Fig. 2 of [2].

The scans are done in the decoupling limit (i.e., the pseudoscalar mass is fixed at 1 TeV), where the heavier CP-even Higgs boson is much more massive and thus all couplings of this lightest Higgs boson are standard-model-like. Away from this limit, the decay width to standard model channels increases while the overall production cross section goes down. Moderate mixing with the heavier Higgs boson does not significantly change the qualitative features of these plots.

The decay length of the neutralino can be long enough to leave a displaced vertex. The average decay length of the lightest neutralino is [15]

$$L \simeq \frac{384\pi^2\cos^2\theta_w}{\alpha|U_{21}|^2\lambda''^2}\frac{m_{\tilde{q}}^4}{m_\chi^5}(\beta\gamma)$$
$$\sim \frac{3\ \mu\text{m}}{|U_{21}|^2}\left(\frac{10^{-2}}{\lambda''}\right)^2\left(\frac{m_{\tilde{q}}}{100\text{ GeV}}\right)^4\left(\frac{30\text{ GeV}}{m_\chi}\right)^5\frac{p_\chi}{m_\chi}, \quad (4)$$

where $|U_{21}|$ is an element of the mixing matrix in the appendix and $p_\chi$ is the neutralino's momentum. Final-state particle masses, Yukawa couplings and QCD corrections have all been neglected. For small $\lambda''$, light neutralinos, or heavy scalar quarks, the decay length could be quite long and might have been seen as anomalous events at LEP if they decay in the tracking chamber, and perhaps by searches for stable squarks and gluinos [16] if they decay in or near the hadronic calorimeter. If their decay length is longer than about a meter, the invisible Higgs boson search would pick up these events and rule out masses up to 114 GeV [17].

An important impact of this model is the allowance of a lighter Higgs boson mass thus reducing the need for large radiative corrections to the quartic potential from the stop loop. For the same value of $\tan\beta = 3$, the allowed lighter Higgs boson mass (say around 96 GeV) requires an enhancement of the quartic of only half as much as in the MSSM with $R$-parity conservation. If instead we compare allowed MSSM Higgs boson masses at large $\tan\beta$ to our model's allowed Higgs boson masses at $\tan\beta = 3$ (since we require low values for our decay to dominate), we still typically require a lower quartic enhancement by roughly 10%–30%. This translates into lower stop masses needed and less tuning. However, while $R$ parity violation and nonunified gaugino masses help to relieve much of the persistent fine tuning in the MSSM, they clearly do not eliminate it [18]. Among the strongest constraints are the chargino mass bound and the restrictions on contributions to $b \to s\gamma$. In addition, avoiding the Higgs boson mass bound requires one to be in a nongeneric part of parameter space in which the Higgs boson decays to neutralinos.

One constraint on models with $R$-parity violation comes from the requirement that the additional baryon-number violation does not wipe out the baryon asymmetry of the universe [19,20], requiring couplings to be very tiny if baryogenesis happens at a high scale. Such constraints would be eliminated in the case of low-scale baryogenesis [21] or in high-scale leptogenesis scenarios [22].

$R$-parity violation can allow for other nonstandard Higgs boson decays which evade LEP searches. For example, one linear combination of scalar bottom squarks can be perhaps as light as 7.5 GeV [23] due to suppressed couplings to the $Z$. With baryon-number violation, and sbottom masses

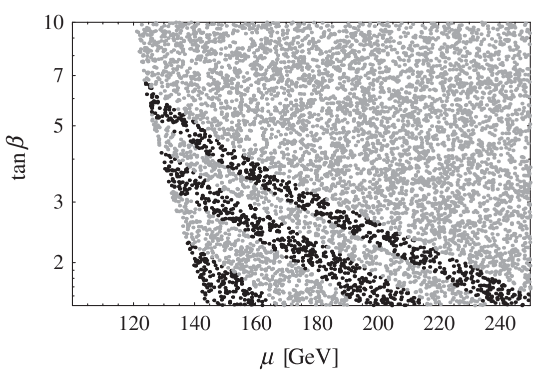


FIG. 1. A random scan of the parameters $\mu$ and $\tan\beta$ with $M_2 = 250$ GeV, $M_1 = 50$ GeV and $m_{\text{higgs}} = 100$ GeV. The borders between the alternating black and gray points represent Higgs boson branching ratios to neutralinos of (from left to right) 90%, 85%, 80%, 75%, and 70%, respectively. The white space to the left is excluded by the chargino mass bound.

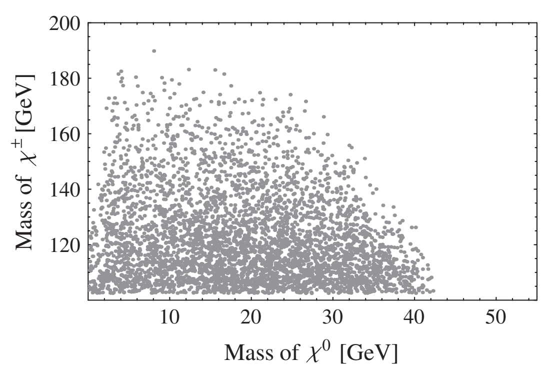


FIG. 2. The lightest chargino mass versus lightest neutralino mass in a scan of $\mu$ (from 120 to 250 GeV), $\tan\beta$ (2 to 5), $M_1$ (10–100 GeV), and $M_2$ (150–400 GeV). For all points, the branching ratio to neutralinos is at least 75%.

below half the Higgs boson mass, this would allow the Higgs boson to decay to four light jets, and the decay would dominate standard Higgs boson decays at moderate to large $\tan\beta$ [24]. On the other hand, violating lepton number instead of baryon number through the superpotential operator $\lambda'_{i33}L_iQ_3D_3^c$ could produce a dominant Higgs boson decay of $h \to 4b + \not{E}$ to which the standard $2b$ and $4b$ searches should have significantly reduced sensitivity.

If the above scenario is correct, searching for the Higgs boson at hadron colliders could pose great difficulty. On the other hand, the International Linear Collider should have no problem seeing such a Higgs boson as it is expected to accurately measure the Higgs boson mass independent of its decay mode. However, if the neutralinos decay at a displaced vertex with a decay length greater than about 50 microns, these events could potentially be picked up by a dedicated search at the Tevatron or LHCb [25,26]. The vertex tagging at LHCb would be well suited for this search, and the statistics high enough—roughly 30% of the Higgs boson bosons produced via gluon fusion are expected to fall in the detector's acceptance range [27]. CDF may be able to use its $b$-physics triggers to pick up such events before the LHC even turns on [25]. In addition, half of these decays would be baryon violating (assuming the lightest neutralino is a Majorana particle) and this could potentially be a striking signal. Finally, the small but nonzero coupling of long-lived neutralinos to the $Z$ may allow them to be discovered by studying the "vertexless" events in LEP I data.

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*Appendix.*—The neutralino mass matrix

$$U\begin{pmatrix} m_{\chi_1} & 0 & 0 & 0 \\ 0 & m_{\chi_2} & 0 & 0 \\ 0 & 0 & m_{\chi_3} & 0 \\ 0 & 0 & 0 & m_{\chi_4} \end{pmatrix}U^T = \begin{pmatrix} M_2 & 0 & m_Z c_w c_\beta & -m_Z c_w s_\beta \\ 0 & M_1 & -m_Z s_w c_\beta & m_Z s_w s_\beta \\ m_Z c_w c_\beta & -m_Z s_w c_\beta & 0 & -\mu \\ -m_Z c_w s_\beta & m_Z s_w s_\beta & -\mu & 0 \end{pmatrix} \tag{A1}$$

is diagonalized from the gauge basis to the mass basis by the orthogonal matrix $U$. The eigenvalues are in ascending order in magnitude. In the gauge basis, the mass matrix above multiplies the vector $\{\tilde{W}, \tilde{B}, \tilde{H}, \tilde{\bar{H}}\}$ corresponding to the $W$-ino, $B$-ino and down- and up-type higgsinos. The bino-higgsino mixing can be characterized by a parameter $\Delta$ (used in the text) defined as

$$\Delta = |U_{13}|^2 - |U_{14}|^2. \tag{A2}$$

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