

# Charged Higgs production in the flavored MSSM

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**Abstract.** In the Minimal Supersymmetric Standard Model squark mixing can significantly change the pattern of charged-Higgs production. We find that non-minimal flavor structures can have a sizeable impact on the charged-Higgs production cross section, whereas charged-Higgs searches may be able to probe flavor structures not accessible to rare kaon, bottom or charm experiments, and can invalidate the assumption of minimal flavor violation.

**PACS.** 14.80.Cp Non-standard-model Higgs bosons – 12.60.Jv Supersymmetric models

## 1 Introduction

The main task in high-energy physics over the coming years is to understand the nature of electroweak symmetry breaking. In the Minimal Supersymmetric Standard Model (MSSM) two Higgs doublets are needed to give mass to all fermions. Such an extended model with each Higgs doublet coupling exclusively to up-type or down-type fermions is generally referred to as a two-Higgs-doublet model (2HDM) of type II. It predicts two  $CP$ -even neutral Higgs bosons ( $h^0$  and  $H^0$ ), one  $CP$ -odd neutral Higgs boson ( $A^0$ ) and a charged Higgs boson pair ( $H^\pm$ ). Because of the absence of a  $H^\pm W^\mp Z$  vertex at tree level, the production of a single charged Higgs and its decay operate foremost via Yukawa couplings, whereas the heavy-quark Yukawa couplings to the heavy Higgs states are governed by  $y_b \tan \beta$  and by  $y_t / \tan \beta$ . Unfortunately, for  $2 \leq \tan \beta \leq 20$  the rates are small and no promising detection channel is known [1].

Within the Standard Model flavor symmetry breaking is governed solely by the Yukawa interactions, the spurions of flavor symmetry breaking. Applying this concept to extensions of the Standard Model leads to the notion of minimal flavor violation (MFV) [2]: in an MFV model there are no other sources of flavor violation than the Yukawa couplings. However, general soft SUSY breaking introduces new sources of flavor violation. In MFV (i) all soft scalar squark masses need to be diagonal in flavor space and (ii) all tri-scalar  $A$ -terms describing the squark–squark–Higgs couplings have to be proportional to the Yukawas.

$$\mathcal{L}_{\text{soft}} = -\tilde{U}^* m_{\tilde{U}}^2 \tilde{U} - \tilde{D}^* m_{\tilde{D}}^2 \tilde{D} - \tilde{Q}^\dagger m_{\tilde{Q}}^2 \tilde{Q} - \left[ \tilde{Q} \tilde{A}^u \tilde{U}^* H_u - \tilde{Q} \tilde{A}^d \tilde{D}^* H_d + \text{h.c.} \right]. \quad (1)$$

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The hermitian  $6 \times 6$  squark mass matrices  $\mathcal{M}_q^2$  for up and down-type squarks collect  $D$ ,  $F$  and soft terms from the SUSY breaking Lagrangian Eq.(1). They are composed out of the left and right-handed blocks  $M_{qAB}^2$ . Each block is a  $3 \times 3$  matrix in generation space:

$$\mathcal{M}_q^2 = \begin{pmatrix} M_{qLL}^2 & M_{qLR}^2 \\ M_{qLR}^{2\dagger} & M_{qRR}^2 \end{pmatrix} (q = u, d; A, B = L, R). \quad (2)$$

The explicit expressions for the  $M_{qAB}^2$  are given in [3]. To trace back and discuss the sources of new-physics flavor violation, it is useful to define the dimensionless mass insertions  $\delta_{AB,ij}^q \equiv \frac{M_{qAB,ij}^2}{\tilde{m}^2}$  [4,5]. The denominator is the geometric mean  $\tilde{m}^2 = m_{Aii} m_{Bjj}$  of the squared scalar masses of  $\tilde{q}_{Ai}$  and  $\tilde{q}_{Bj}$ . The off-diagonal entries of  $\delta_{AB}^q$  are significant only in non-MFV models and can be complex, inducing  $CP$  violation. We confine ourselves to real  $\delta_{AB}^q$ . Note that in our numerical calculations we diagonalize the squark mass matrices and do not employ a perturbative expansion in the  $\delta_{AB}^q$ , avoiding the calculation of the squark unitary transformations [4].

## 2 Constraints on parameter space

Especially flavor physics can strongly constrain the free parameters from the soft-breaking lagrangian, relevant for the enhancement of the charged-Higgs production. Flavor violation among down squarks is more severely constrained, because in  $K$  and  $B$  physics down-squark effects can be mediated by strongly interacting gluino loops, while up-squark effects are mediated by the weak interaction. Furthermore, mixing between first and second generation squarks is tightly constrained by  $K$ -physics [5,6] and by the recent measurements of  $D^0 \bar{D}^0$ -mixing [7]. Hence, we can limit our analysis to up-squark mixing between the first/second and

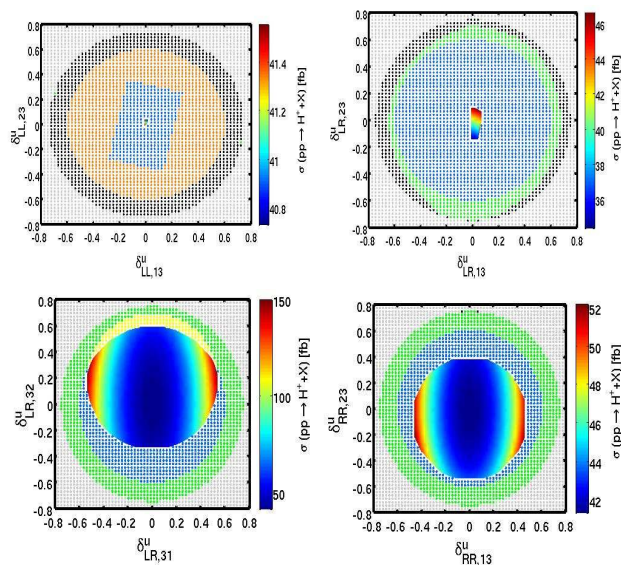
third generation while neglecting down-squark mixing, as long as it is not required by  $SU(2)$ . Particularly constraining are the radiative decays  $B \rightarrow X_s \gamma$  [8,9] and  $B \rightarrow \rho \gamma$  [10], the semileptonic decays  $B \rightarrow X_s \ell^+ \ell^-$  [9,11,12] and  $B \rightarrow \pi \ell^+ \ell^-$  [13], and the  $B_{d,s} - \bar{B}_{d,s}$  mass differences [14,15,16]. All constraints on the supersymmetric flavor sector we implement at 90 % C.L.:

- $A_{ii}^{u,d}$ : diagonal  $A$ -term entries contribute to up and down-quark masses at one loop. We require perturbativity of SUSY-QCD corrections  $\delta m_q \leq m_q$ .
- $A_{33}^{u,d}$ : loop corrections lift the lighter MSSM Higgs mass from  $m_Z$  to above the LEP2 limits.
- $A_{13}^d, A_{23}^d, A_{31}^d, A_{32}^d$ : general vacuum stability constraints limit the inter-generational  $A$ -terms [17].
- $A_{23}^{u,d}, (m_{\tilde{U}_{L,R}}^2, m_{\tilde{D}_{L,R}}^2)_{23}$ : constrained by ( $b \rightarrow s$ )-type measurements.  $\bar{B}_s - B_s$  mixing mass difference  $\Delta m_s$  implies  $\frac{\Delta m_s}{\Delta m_s^{\text{SM}}} = 1.00 \pm 0.44$ . For the semileptonic and radiative decays we demand  $2.94 \cdot 10^{-4} < \text{BR}(B \rightarrow X_s \gamma) < 4.14 \cdot 10^{-4}$  and  $2.8 \cdot 10^{-6} < \text{BR}(B \rightarrow X_s \ell^+ \ell^-) < 6.2 \cdot 10^{-6}$ .
- $A_{13}^{u,d}, (m_{\tilde{U}_{L,R}}^2, m_{\tilde{D}_{L,R}}^2)_{13}$ : similarly, mixing between the first and third generation in the up and the down sector is constrained by  $b \rightarrow d$  transitions:  $\frac{\Delta m_d}{\Delta m_d^{\text{SM}}} = 1.00 \pm 0.54$ ,  $0.63 \cdot 10^{-6} < \text{BR}(B \rightarrow \rho \gamma) < 1.24 \cdot 10^{-6}$  and  $\text{BR}(B \rightarrow \pi \ell^+ \ell^-) < 9.1 \cdot 10^{-8}$ .
- $m_{\tilde{U}_L}^2$  and  $m_{\tilde{D}_L}^2$ : because SUSY breaking respects the  $SU(2)$  gauge symmetry, the doublet soft-breaking masses are identical. In the super-CKM basis this means  $m_{\tilde{U}_L}^2 = V \cdot m_{\tilde{D}_L}^2 \cdot V^\dagger$ .
- Inter-generational mixing involving the third generation always affects the lightest Higgs mass and the  $\rho$  parameter [18].
- Tevatron searches for mass-degenerate first- and second-generation squarks require  $m_{\tilde{q}} > 200$  GeV [19].

The corresponding mass-matrix entries  $A_{3i}^u$  and  $m_{\tilde{U}_R i3}^2$  are only very loosely bounded by flavor physics<sup>1</sup>. The reason is that they involve right-handed squarks  $\tilde{u}_R$  and  $\tilde{c}_R$ ; those enter FCNC processes with external down quarks only via higgsino vertices proportional to the small up and charm Yukawa. Hence, the  $\delta_{LR 3i}^u$  and  $\delta_{RR i3}^u$ , ( $i = 1, 2$ ) are currently the least constrained flavored SUSY couplings. In the following we investigate the potential impact of these relevant  $\delta_{3i}^u$  on charged-Higgs collider searches.

### 3 Single-Charged-Higgs Production

We start by considering single-charged-Higgs production at tree level from quark–antiquark scattering,  $q\bar{q}' \rightarrow H^\pm$ , at the LHC. The amplitude for single-Higgs production in the type-II two-Higgs-doublet model is proportional to the quark Yukawa, thus small unless third-generation quarks are involved [20]. This chiral suppression is generic and with proper assumptions



**Fig. 1.** Single-charged-Higgs production rates at the LHC. In the rainbow-colored area we include beyond-MFV parameters around the parameter point Table 1. Two  $\delta_{AB,i,j}^u$  are varied in each panel, all others are set to zero. The area outside the rainbow is ruled out experimentally

survives radiative corrections. For  $\tan \beta = 7$  and a charged-Higgs mass of  $m_{H^\pm} = 188$  GeV the  $H^+$  production cross section at the LHC in the 2HDM is 41.2 fb, using the  $\overline{\text{MS}}$  quark masses given in [3].

The irreducible background to our searches is single- $W$  production,  $q\bar{q}' \rightarrow W^\pm$ . The  $W^+$  production cross section of  $90 \cdot 10^6$  fb will be a serious challenge to our  $H^+$  search in the two-Higgs-doublet model.

Not assuming MFV has serious impact on the production rate for  $q\bar{q}' \rightarrow H^\pm$ . Squark loops will weaken the CKM suppression at the charged-Higgs–bottom vertex through flavor mixing. The dominant one-loop corrections are due to gluino vertex and self-energy diagrams. Beyond MFV, the loop diagrams do not have to include a (Dirac) quark mass to ensure the chiral limit of the theory. Instead, we can for example combine a Majorana mass with a left-right mixing  $\delta_{LR}$  among the squarks. This combination can lift the supersymmetric charged Higgs production rate above the two-Higgs-doublet model prediction, despite its loop suppression. The MSSM Lagrangian we define at the weak scale, so all parameters are evaluated at the scale of the charged Higgs mass.

To test the effects of flavor structures on the single-Higgs cross section we start with a generic MFV SUSY parameter point which does not violate any current bounds. We then allow for flavor violation beyond MFV by  $\delta_{AB}^q$ . Because of current experimental and theoretical constraints discussed in Section 2, the up-squark parameters  $\delta_{LR,3i}^u$  and  $\delta_{RR,3i}^u$  involving 1-3 and 2-3 mixing are the least constrained and therefore expected to cause the biggest effects.

Our starting parameter point is given in Table 1.  $m_A$  denotes the mass of the CP-odd Higgs leading to  $m_{H^+} = 188$  GeV.  $M_2$  is the SUSY-breaking wino

<sup>1</sup> We strictly use the convention  $A_{ij} = A_{L_i R_j} \neq A_{ji}$ .

$\tan\beta = 7$	$m_A = 170 \text{ GeV}$	$\mu = -300 \text{ GeV}$
$m_{\tilde{q}_{AA}ii} = 600 \text{ GeV}$	$M_2 = 700 \text{ GeV}$	$m_{\tilde{g}} = 500 \text{ GeV}$
$A^{u,c} = 0$	$A^{d,s,b} = 0$	$A^t = 1460 \text{ GeV}$

**Table 1.** Generic parameter point

mass. The diagonal soft-breaking entries in the squark mass matrices we choose universal. All parameters are given at a scale of order  $m_{H^+}$ . The large value of  $A^t$  (corresponding to  $\delta_{LR,33}^u$ ) increases the light Higgs mass to 119.9 GeV at two loops. The production cross sections as a function of the three dominant beyond-MFV mass insertions in the up-sector are shown in Figure 1. Beyond-MFV effects can enhance the single-Higgs rate to values above 100 fb. The size of the production cross section is encoded in the rainbow scale in all panels of Fig. 1, while the parameter choices outside this area are ruled out. The different experimental constraints impacting the parameter point shown in Fig. 1 include:

- Tevatron searches rule out the yellow points.
- squark searches and radiative and semileptonic decay limits rule out the green points.
- black points are forbidden by the squark–mass limits,  $B$  mixing, and radiative and semileptonic decays.
- blue points indicate a violation of the radiative and semileptonic decay bounds only.
- orange points correspond to a violation of the  $B$  mixing and radiative and semileptonic decay limits.
- grey points on the outside of the panels indicate a negative squark mass square after diagonalizing the squark mass matrix.

In Fig. 1 we see that the limits on radiative and semileptonic decays followed by the Tevatron limit on light-flavor squark masses define two distinct boundaries of forbidden parameter space. After taking into account all limits, the off-diagonal entry  $\delta_{LR,31}^u$  has the strongest impact on the rate. It yields a maximal single-Higgs rate at  $|\delta_{LR,31}^u| \sim 0.6$ .

## 4 Charged-Higgs Production with a hard Jet

The generic chiral suppression that characterizes single-Higgs production and limits the cross section at tree level can be removed by simply adding an external gluon to the operator basis. Such operators can be of the form  $i\bar{Q}\gamma_\mu Q H_u \leftrightarrow D^\mu H_u^C$ , leading to higher-dimensional  $q\bar{q}'Hg$  operators after electroweak symmetry breaking [21]. To probe such operators at the LHC, we study charged-Higgs searches in association with a hard jet. Simple diagrams for this process can be derived from all single-Higgs production diagrams just radiating an additional gluon. These are infrared divergent, which is no problem once we require a hard jet with a typical  $p_{T,j} > 100 \text{ GeV}$ .

$m_{H^+}$	$\tan\beta$	$\sigma_{2\text{HDM}}$	$\sigma_{\text{MFV}}$	$\sigma_{\text{MFV}}^{(m_f=0)}$
188 GeV	3	$2.5 \cdot 10^{-1}$	$2.6 \cdot 10^{-1}$	$6.7 \cdot 10^{-4}$
188 GeV	7	$9.9 \cdot 10^{-1}$	$1.1 \cdot 10^0$	$1.5 \cdot 10^{-4}$
400 GeV	3	$4.0 \cdot 10^{-2}$	$4.2 \cdot 10^{-2}$	$4.2 \cdot 10^{-4}$
400 GeV	7	$1.6 \cdot 10^{-1}$	$1.7 \cdot 10^{-1}$	$9.1 \cdot 10^{-5}$

$m_{H^+}$	$\tan\beta$	$\sigma_{\text{SUSY}}$	$\sigma_{\text{SUSY}}^{(m_f=0)}$
188 GeV	3	$14.3 \cdot 10^0$	$13.9 \cdot 10^0$
188 GeV	7	$4.6 \cdot 10^0$	$3.0 \cdot 10^0$
400 GeV	3	$2.4 \cdot 10^0$	$2.3 \cdot 10^0$
400 GeV	7	$7.9 \cdot 10^{-1}$	$5.4 \cdot 10^{-1}$

**Table 2.** Production rates (in fb) for the associated production of a charged Higgs with a hard jet:  $p_{T,j} > 100 \text{ GeV}$ . The label 2HDM denotes a two-Higgs-doublet of type II, while MFV and SUSY refer to the complete set of supersymmetric diagrams, assuming MFV and beyond. Beyond MFV we choose  $\delta_{LR,31}^u = 0.5$ .

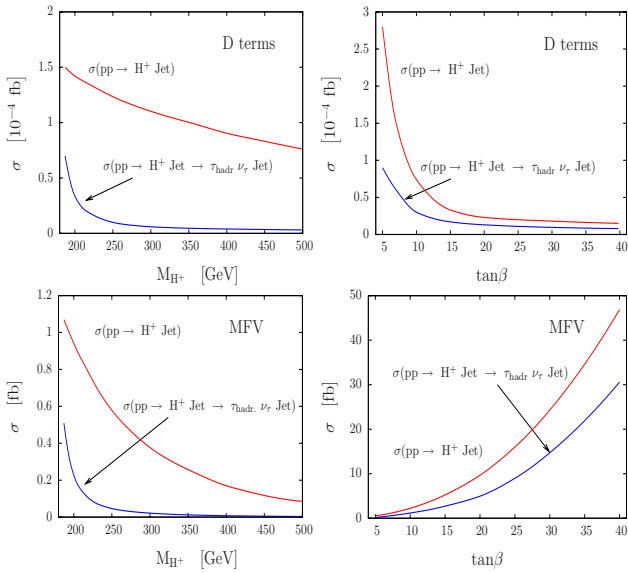
Similar to single-Higgs production we are interested in supersymmetric loop corrections in and beyond MFV. We know from single-Higgs production that the flavor effects we are interested in can be much larger than we expect next-to-leading order QCD effects to be. Therefore, we ignore all gluonic next-to-leading order corrections to charged-Higgs production with a hard jet and limit our analysis to tree-level rates in the two-Higgs-doublet model and additional supersymmetric one-loop corrections with and without the MFV assumption.

### 4.1 MFV and beyond

Assuming MFV,  $F$ -term and  $A$ -term couplings of the Higgs to two squarks are proportional to the quark masses, which means that supersymmetric one-loop amplitudes are expected to be of the size of typical supersymmetric NLO corrections. In the first column of Table 2 we list the hadronic tree level cross sections for charged Higgs plus jet production for a non-supersymmetric two-Higgs-doublet type-II model. Numerical results for hadronic charged Higgs plus jet production in MFV we present in the second column in Table 2.

In the limit  $m_f \rightarrow 0$  just the  $D$ -terms do contribute. Although chirally not suppressed and enhanced for small  $\tan\beta$ , the  $D$ -term contribution is only a small fraction of the supersymmetric amplitude (see Fig. 2 and Tab. 2), due to its faster decoupling with heavy superpartner masses  $\sigma \propto 1/M_{\text{SUSY}}^8$ .

In Fig. 2 we include Higgs decays as indicated and vary  $\tan\beta$  and  $m_{H^+}$ . As long as the Higgs mass is small,  $m_{H^+} \leq 200 \text{ GeV}$ , the Higgs decay into a hadronic  $\tau$  lepton is the most promising [22]. The rates drop dramatically for heavier Higgs masses, even worse once we include the Higgs decay. Furthermore, with  $m_f \neq 0$ , the rates are not enhanced for small  $\tan\beta$ . The dominant background to this signature is clearly  $W$ +jet



**Fig. 2.** Production rates for a charged Higgs with a hard jet including SUSY loops in MFV, assuming  $m_f \rightarrow 0$  (upper panel) and  $m_f \neq 0$  (lower panel).

production  $\sigma(pp \rightarrow W^+ \text{ Jet}) \approx 1$  nb, with the  $W$  decaying to a hadronic  $\tau$ .

Possible large supersymmetric corrections in this process can only occur beyond MFV — just like for single-Higgs production.

Although the operator basis does not get significantly extended when we include beyond-MFV effects, the effective couplings will get enhanced once we allow for sizeable  $\delta_{AB,ij}^u$ . We respect the results from Section 3, where we found  $\delta_{RL,13}^u$  to amplify the charged-Higgs cross section most. In the lower pattern of Tab. 2 we see, that, independent of the Yukawa couplings, beyond MFV can enhance the rate in the region of small  $\tan\beta$  significantly, compared to the tree-level or MFV process.

## 5 Conclusion

We find that if we allow for general squark mixing the cross sections for single-charged-Higgs production and charged-Higgs production in association with a hard jet can be enhanced by an order of magnitude, even after including all current experimental bounds.

The dominant source of genuine supersymmetric flavor enhancement in the charged-Higgs production rate is the soft-breaking  $A$  term for up-type squarks  $A_{i3}^u$ , which is invisible to kaon, charm and  $B$ -experiments. Hence, collider searches for enhanced charged-Higgs production rates can probe a unique sector of flavor. A discovery would besides a breakdown of the Standard Model also signal a non-standard solution to the flavor puzzle beyond the minimal-flavor-violation hypothesis. Unfortunately, at present, we cannot firmly claim that these flavor-induced charged-Higgs production rates at small  $\tan\beta$  rates lead to observable signals over the large  $W$ -production backgrounds.

## References

1. CMS Collaboration, Nucl. Part. Phys. **34**, 995 (2007)
2. G. D’Ambrosio, G. F. Giudice, G. Isidori and A. Strumia, Nucl. Phys. B **645**, 155 (2002).
3. S. Dittmaier, G. Hiller, T. Plehn and M. Spannowsky, arXiv:0708.0940 [hep-ph].
4. L. J. Hall, V. A. Kostelecky and S. Raby, Nucl. Phys. B **267**, 415 (1986).
5. J. S. Hagelin, S. Kelley and T. Tanaka, Nucl. Phys. B **415**, 293 (1994); F. Gabbiani, E. Gabrielli, A. Masiero and L. Silvestrini, Nucl. Phys. B **477**, 321 (1996);
6. G. Colangelo and G. Isidori, JHEP **9809**, 009 (1998).
7. Y. Nir, JHEP **0705**, 102 (2007).
8. B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. D **72**, 052004 (2005); P. Koppenburg *et al.* [Belle Collaboration], Phys. Rev. Lett. **93**, 061803 (2004); H. F. A. Group(HFAG), arXiv:hep-ex/0505100.
9. P. L. Cho, M. Misiak and D. Wyler, Phys. Rev. D **54**, 3329 (1996); F. M. Borzumati and C. Greub, Phys. Rev. D **58**, 074004 (1998) and Phys. Rev. D **59**, 057501 (1999); G. Hiller and F. Krüger, Phys. Rev. D **69**, 074020 (2004).
10. K. Abe *et al.*, Phys. Rev. Lett. **96**, 221601 (2006); B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **98**, 151802 (2007).
11. B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **93**, 081802 (2004). K. Abe *et al.* [Belle Collaboration], arXiv:hep-ex/0408119; A. Ali, E. Lunghi, C. Greub and G. Hiller, Phys. Rev. D **66**, 034002 (2002); B. Grinstein, M. J. Savage and M. B. Wise, Nucl. Phys. B **319**, 271 (1989); D. Guetta and E. Nardi, Phys. Rev. D **58**, 012001 (1998).
12. G. Buchalla, G. Hiller and G. Isidori, Phys. Rev. D **63**, 014015 (2001);
13. B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **99**, 051801 (2007). A. Ali, P. Ball, L. T. Handoko and G. Hiller, Phys. Rev. D **61**, 074024 (2000); P. Ball and R. Zwicky, Phys. Rev. D **71**, 014015 (2005).
14. V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **97**, 021802 (2006); A. Abulencia *et al.* [CDF Collaboration], Phys. Rev. Lett. **97**, 242003 (2006).
15. S. Bertolini, F. Borzumati, A. Masiero and G. Ridolfi, Nucl. Phys. B **353**, 591 (1991);
16. D. Becirevic *et al.*, Nucl. Phys. B **634**, 105 (2002); T. Goto, T. Nihei and Y. Okada, Phys. Rev. D **53**, 5233 (1996) [Erratum-ibid. D **54**, 5904 (1996)].
17. J. A. Casas and S. Dimopoulos, Phys. Lett. B **387**, 107 (1996).
18. J. Cao, G. Eilam, K. i. Hikasa and J. M. Yang, Phys. Rev. D **74**, 031701 (2006).
19. V. M. Abazov *et al.* [D0 Collaboration], Phys. Lett. B **638**, 119 (2006).
20. J. L. Diaz-Cruz, H. J. He and C. P. Yuan, Phys. Lett. B **530**, 179 (2002); H. J. He and C. P. Yuan, Phys. Rev. Lett. **83**, 28 (1999);
21. C. N. Leung, S. T. Love and S. Rao, Z. Phys. C **31**, 433 (1986); W. Buchmüller and D. Wyler, Nucl. Phys. B **268**, 621 (1986).
22. K. A. Assamagan and Y. Coadou, Acta Phys. Polon. B **33**, 707 (2002); R. Kinnunen and A. Nikitenko, report CMS note 2003/006.