

# First LHC Constraints on Neutralinos

Herbi K. Dreiner<sup>1</sup>, Jong Soo Kim<sup>2</sup> and Oleg Lebedev<sup>3</sup>

<sup>1</sup>*Physikalisches Institut & Bethe Center for Theoretical Physics, Nußallee 12, 53115 Bonn, Germany*

<sup>2</sup>*ARC Centre of Excellence for Particle Physics at the Terascale, School of Chemistry and Physics, University of Adelaide, Adelaide, Australia*

<sup>3</sup>*DESY Theory Group, Notkestrasse 85, D-22607 Hamburg, Germany*

## Abstract

The ATLAS and CMS collaborations have recently reported tantalizing hints of the existence of a 125 GeV Higgs-like particle, whose couplings appear to match well the Standard Model (SM) expectations. In this work, we study implications of this observation for the neutralino sector of supersymmetric models, assuming that the Higgs signal gets confirmed. In general, the Higgs decay into neutralinos can be one of its dominant decay channels. Since a large invisible Higgs decay branching ratio would be in conflict with the data, this possibility is now constrained. In particular, we find that most of the region  $\mu < 170$  GeV,  $M_1 < 70$  GeV at  $\tan\beta \sim 10$  and  $\mu < 120$  GeV,  $M_1 < 70$  GeV at  $\tan\beta \sim 40$  is disfavored.

# 1 Introduction

The LHC experiments have given a possible first indication of the Higgs boson at a mass around 125 GeV [1–7]. The main production mechanism in the Standard Model (SM) is gluon fusion  $gg \rightarrow h$  [8]. At the subleading level, vector boson fusion  $qq \rightarrow qqh$  also contributes [9]. The CMS and ATLAS searches are based on several decay channels of the Higgs:  $h \rightarrow \gamma\gamma$  [10],  $h \rightarrow W^+W^-$  [11–13], and  $h \rightarrow ZZ$  [12]. The dominant decay mode of a 125 GeV mass Higgs is  $h \rightarrow b\bar{b}$ , for which the background is however too large. In this paper we are interested in a potential invisible decay width of the Higgs boson. The total decay width of the SM Higgs is about  $\Gamma_h \approx 4.2 \text{ MeV}$  for a Higgs mass of 125 GeV [14]. This is below the resolution of the LHC and can thus not be directly measured in the resonance channels  $h \rightarrow \gamma\gamma$  and  $h \rightarrow ZZ$ , where the final state can be reconstructed. A discrepancy from the theoretical value for the total width would be a direct indication of additional contributions beyond the SM. All the same, in a given production and decay channel, the event rate is proportional to the production cross section times the decay branching ratio, *e.g.*

$$\text{Rate}_{\gamma\gamma} = \sigma(pp \rightarrow h + X) \times \text{BR}(h \rightarrow \gamma\gamma) \times \mathcal{L}, \quad (1)$$

where  $X$  depends on the production mechanism and  $\mathcal{L}$  is the luminosity. Thus, via the branching ratio the total width enters indirectly in the event rate. If we take a given model, for example the SM, and extend it by adding a hypothetical invisible decay width to the Higgs boson as a free parameter  $\Gamma_{\text{inv}} = \Gamma(h \rightarrow \text{inv.})$ , we can perform a fit of  $\Gamma_{\text{inv}}$  to the observed event rates, assuming the Higgs mass and the SM Higgs production mechanisms. Two such global fits have recently been performed in (a) Ref. [15] and (b) Ref. [16], resulting in the upper bounds

$$(a) \quad \text{BR}_{\text{inv}} < 0.15 \text{ (0.30)} \quad (2)$$

$$(b) \quad \text{BR}_{\text{inv}} < 0.37 \text{ (0.69)} \quad (3)$$

at 68% (95%) CL (see also [17]). As the statistics are not sufficient to claim the Higgs boson discovery, these constraints should be interpreted with caution. Nevertheless, one may already explore implications of these results for new physics. For example, the bounds on the invisible Higgs decay set rather strict constraints on Higgs–portal dark matter models [18] where  $\text{BR}_{\text{inv}}$  can be as large as 80% or more [19]. Early work on invisible Higgs decays in minimal extensions of the SM also employed other Higgs production mechanisms:  $t\bar{t}h$  Higgs strahlung [20], associated  $Zh$  or  $Wh$  production [21], [22], and in Ref. [23] vector boson fusion.

Here we wish to explore the implications of the constraints in Eqs. (2), (3) for the minimal supersymmetric standard model (MSSM) [24] and, in particular, for the neutralino sector thereof. Due to LEP, Tevatron and LHC constraints it is clear that if supersymmetry exists, most of the

superpartners are heavy, *i.e.* well above the purported Higgs mass scale. However, it is well known, that there is no lower limit on the mass of the lightest neutralino [25–28]. Therefore, the invisible decay of the Higgs boson to two neutralinos is open and can even be dominant. In the next section we discuss the Higgs decay to neutralinos and the constraints on the supersymmetric parameter space resulting from Eqs. (2), (3). In Sect. 3 we conclude.

## 2 Higgs decay into neutralinos

The Higgs decay into neutralinos has been studied in Refs. [29–32] (see also [33, 34]). In general, it can be the dominant decay channel if kinematically allowed. The main constraint on this scenario comes from the invisible Z–decay, which has been measured very precisely. However, the uncertainty in the invisible Z–decay width  $\Delta\Gamma_Z^{\text{inv}} = \mathcal{O}(1 \text{ MeV})$  is comparable to the total SM Higgs width  $\Gamma_h$ ,

$$\Delta\Gamma_Z^{\text{inv}} \sim \Gamma_h. \quad (4)$$

Therefore,  $\mathcal{O}(1)$  invisible Higgs decay branching ratio can be compatible with the Z–pole data. (Further constraints are imposed if the neutralino is assumed to be thermal dark matter [32]).

To make our analysis more transparent, we will assume that the sfermions, gluinos and charged Higgses are sufficiently heavy (TeV–scale) so that the production cross section for the lightest Higgs  $h$  is SM–like. This is certainly consistent with (and perhaps hinted by) the current LHC bounds on superpartners (see also [35]). Specifically, in terms of the FeynHiggs [36] variables, we choose  $M_{\text{SUSY}} = M_A = 1 \text{ TeV}$  and adjust  $A_t$  for a given  $\tan\beta$  to obtain  $m_h = 125 \pm 1 \text{ GeV}$ . We use the FeynHiggs version 2.8.6 with the default settings and  $m_t = 172 \text{ GeV}$ .

The Higgs decay width into the lightest neutralinos  $\chi_1^0$  is given by [29]

$$\Gamma(h \rightarrow \chi_1^0 \chi_1^0) = \frac{G_F M_W^2 m_h}{2\sqrt{2}\pi} \left(1 - 4m_{\chi_1^0}^2/m_h^2\right)^{3/2} |C_{h\chi_1^0 \chi_1^0}|^2, \quad (5)$$

with

$$C_{h\chi_1^0 \chi_1^0} = (N_{12} - \tan\theta_W N_{11}) (\sin\beta N_{14} - \cos\beta N_{13}). \quad (6)$$

Here  $\tan\beta = \langle H_2^0 \rangle / \langle H_1^0 \rangle$  and  $N_{ij}$  is the orthogonal<sup>1</sup> matrix which diagonalizes the neutralino mass matrix [24]:

$$N M_{\chi^0} N^T = \text{diag} (m_{\chi_1^0}, m_{\chi_2^0}, m_{\chi_3^0}, m_{\chi_4^0}) \quad (7)$$

with

$$M_{\chi^0} = \begin{pmatrix} M_1 & 0 & -M_Z \sin\theta_W \cos\beta & M_Z \sin\theta_W \sin\beta \\ 0 & M_2 & M_Z \cos\theta_W \cos\beta & -M_Z \cos\theta_W \sin\beta \\ -M_Z \sin\theta_W \cos\beta & M_Z \cos\theta_W \cos\beta & 0 & -\mu \\ M_Z \sin\theta_W \sin\beta & -M_Z \cos\theta_W \sin\beta & -\mu & 0 \end{pmatrix}. \quad (8)$$

---

<sup>1</sup>We assume CP–conserving soft terms.

The analogous Z-width is given by [37]

$$\Gamma(Z \rightarrow \chi_1^0 \chi_1^0) = \frac{\alpha}{3} M_Z \left(1 - 4m_{\chi_1^0}^2/M_Z^2\right)^{3/2} |C_{Z\chi_1^0\chi_1^0}|^2, \quad (9)$$

where

$$C_{Z\chi_1^0\chi_1^0} = \frac{1}{2 \cos \theta_W \sin \theta_W} (N_{14}^2 - N_{13}^2). \quad (10)$$

The relevant LEP constraint is [38]

$$\Gamma(Z \rightarrow \chi_1^0 \chi_1^0) < 3 \text{ MeV} \quad (11)$$

at 95% CL. We observe that both the Higgs and Z decay rates involve couplings to the Higgsino components of the neutralino  $N_{13}, N_{14}$  and as such vanish in the pure bino limit. For typical values of  $\tan \beta \sim 10$ , the Higgs decay is controlled by the  $H_2$  Higgsino component  $N_{14}$ , whereas the Z decay involves both  $N_{13}$  and  $N_{14}$ . As the bino mass  $M_1$  decreases,  $N_{14}$  becomes small whereas  $N_{13}$  remains substantial<sup>2</sup>. In this limit, the Z-width imposes a strict constraint. On the other hand, for higher  $M_1$  and especially above the kinematic limit for  $Z \rightarrow \chi_1^0 \chi_1^0$ , the Higgs invisible width can be comparable to the SM Higgs width without violating the Z-bound. Here we treat  $M_1$  and  $M_2$  as free parameters and do not impose the supersymmetric grand unified theory constraint  $M_1 = (5/3) \tan^2 \theta_W M_2$ . Therefore, the stricter PDG bound  $m_{\chi_1^0} > 46 \text{ GeV}$  [39] does not apply.

The other relevant collider constraints are imposed by the chargino mass bound

$$m_{\chi^+} > 94 \text{ GeV} \quad (12)$$

and the LEP bound on the neutralino production [40]

$$\sigma(e^+ e^- \rightarrow \chi_1^0 \chi_2^0) \times \text{BR}(\chi_2^0 \rightarrow q \bar{q} \chi_1^0) < 50 \text{ fb}. \quad (13)$$

The dominant neutralino production mechanism is due to the  $t$ -channel slepton exchange [41]. This is however strongly suppressed for slepton masses close to 1 TeV. The  $s$ -channel production mediated by the Z-boson is insignificant and, in the parameter region of interest, we find that the constraint (13) is never violated once the other bounds are satisfied. A similar conclusion was reached in [27, 42].

In the left plot of Fig. 1, we present our results in the  $(M_1, \mu)$  plane for  $\tan \beta = 10$  and  $M_2 = 300 \text{ GeV}$ . The thick (red) lines represent constraints from  $\Gamma_Z^{\text{inv}}$  (solid) and the chargino mass (dashed) such that the area below them is excluded. For fixed  $M_2$ , the chargino constraint is a bound on  $\mu$  which only allows for values of  $\mu$  above approximately 106 GeV.  $\Gamma_Z^{\text{inv}}$  excludes

---

<sup>2</sup>Unlike  $N_{14}$ ,  $N_{13}$  does not vanish as  $M_1 \rightarrow 0$ ,  $\cos \beta \rightarrow 0$ . This limit corresponds to the massless bino- $H_1$ -Higgsino  $\chi_1^0$ .

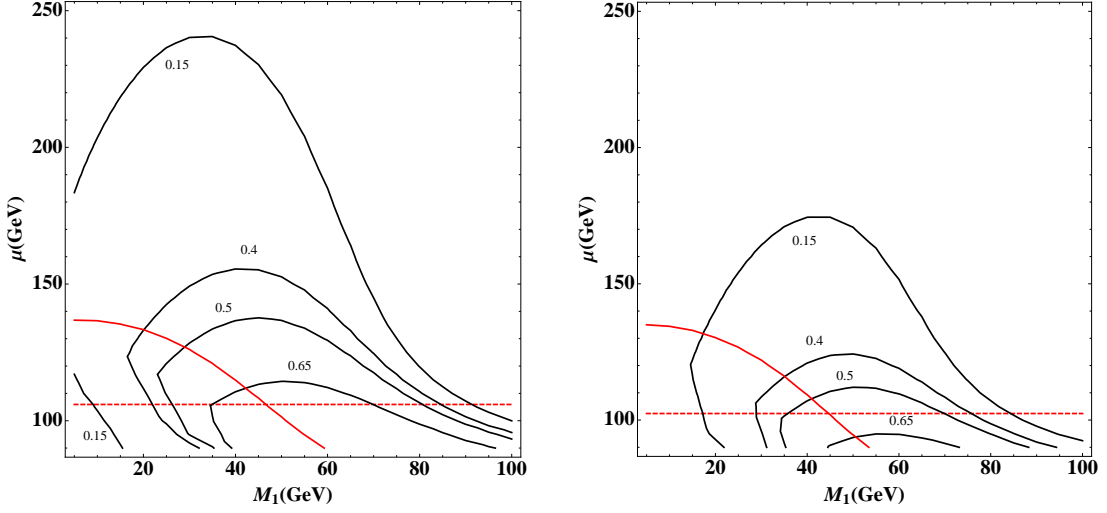


Figure 1: Left: contours of  $\text{BR}(h \rightarrow \chi_1^0 \chi_1^0) = 0.15, 0.4, 0.5, 0.65$  for  $\tan \beta = 10$  and  $M_2 = 300$  GeV. The area below the thick (red) lines is excluded by the  $\Gamma_Z^{\text{inv}}$  (solid) and chargino mass (dashed) constraints. Right: same for  $\tan \beta = 40$ .

low  $M_1$  and  $\mu$  values, where the lightest neutralino has a substantial Higgsino component. Given the constraints, we see that  $\text{BR}_{\text{inv}}$  can still be significantly above 65%. The shape of the constant  $\text{BR}_{\text{inv}}$  contours can be easily understood. At low  $M_1$ , the Higgs decay into the lightest neutralinos is suppressed due to the small  $N_{14}$ . If  $\mu$  is also relatively small, decays  $h \rightarrow \chi_1^0 \chi_2^0$  and  $h \rightarrow \chi_1^0 \chi_3^0$  become kinematically available, which reduces  $\text{BR}(h \rightarrow \chi_1^0 \chi_1^0)$  further and accounts for the kinks in the  $\Gamma_Z^{\text{inv}}$ -excluded region.  $\text{BR}_{\text{inv}}$  peaks at  $M_1 \sim 30 - 60$  GeV, where  $N_{14}$  is still significant and the kinematic suppression  $\left(1 - 4m_{\chi_1^0}^2/m_h^2\right)^{3/2}$  has not yet set in. In this range,  $m_{\chi_1^0}$  varies between 20 and 50 GeV. For  $M_1 > 80$  GeV, the invisible Higgs decay is strongly constrained by the chargino mass bound and becomes insignificant. In summary, we find that if we take  $\text{BR}_{\text{inv}} < 40\%$  as the bound, most of the region  $\mu < 170$  GeV and  $M_1 < 70$  GeV is disfavored by the invisible Higgs decay.

We conclude that the Higgs decay bound is stronger than the  $Z$ -bound for intermediate  $M_1 \sim 30 - 70$  GeV. The reason for this is two-fold: (a) kinematic suppression of  $Z \rightarrow \chi_1^0 \chi_1^0$  in this range, (b) linear dependence of the Higgs-neutralino coupling on the Higgsino component ( $N_{14}, N_{13}$ ) as opposed to the quadratic suppression in the  $Z$  case. Therefore, the Higgs decay covers a new territory, not explored by other experiments.

It should be noted that the massless neutralino scenario of [27] is not excluded by these considerations. Choosing

$$M_1 = \frac{M_2 M_Z^2 \sin 2\beta \sin^2 \theta_W}{\mu M_2 - M_Z^2 \sin 2\beta \cos^2 \theta_W}, \quad (14)$$

one finds that  $m_{\chi_1^0} = 0$  at tree level. For values of  $\mu$  allowed by the  $\Gamma_Z^{\text{inv}}$ -bound, the massless neutralino is mostly a bino and  $\text{BR}(h \rightarrow \chi_1^0 \chi_1^0)$  is typically around 10-20% for  $\tan \beta \sim 10$ . A

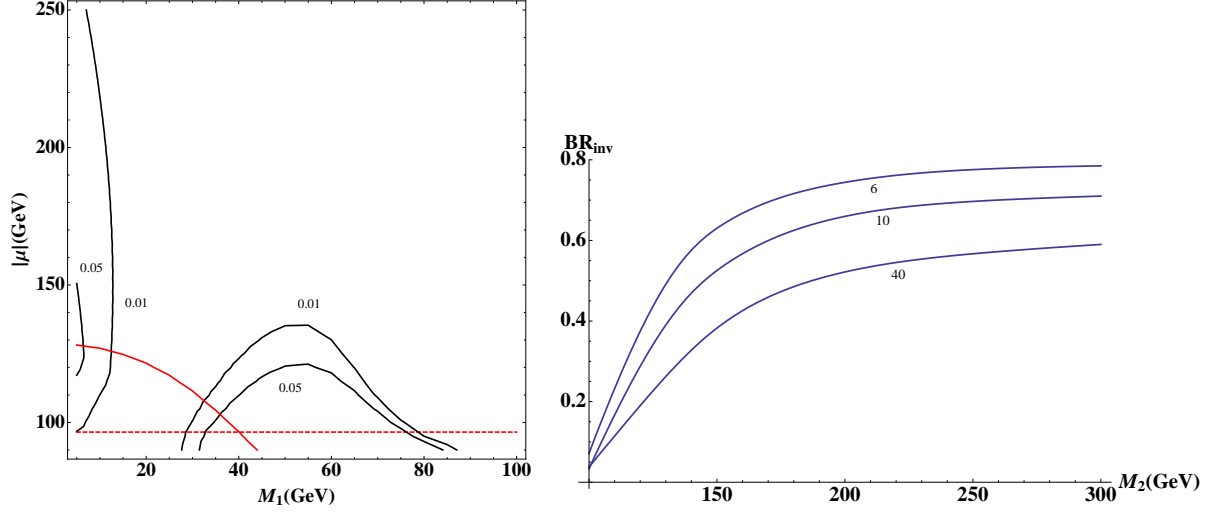


Figure 2: Left: as in Fig. 1 for  $\tan \beta = 10$  and  $\mu < 0$ . Right: maximal allowed  $\text{BR}_{\text{inv}}$  as a function of  $M_2$  for  $\tan \beta = 6, 10, 40$  (top to bottom).

stronger experimental bound on  $\text{BR}_{\text{inv}}$  is necessary to constrain this scenario.

Below we summarize the dependence of  $\text{BR}_{\text{inv}}$  on the other parameters:

- $M_2$ : lowering  $M_2$  pushes up the chargino bound on  $\mu$  thus eliminating parameter space with the largest  $\text{BR}_{\text{inv}}$ .
- $\tan \beta$ : increasing  $\tan \beta$  reduces the Higgs coupling to  $\chi_1^0$ , mostly due to the term  $\cos \beta N_{13}$ . As a result,  $\text{BR}_{\text{inv}}$  decreases. For example, at  $\tan \beta = 40$ , the disfavored region reduces to  $\mu < 120$  GeV and  $M_1 < 70$  GeV (Fig. 1, right panel).
- $\text{sign } \mu$ : for  $\mu < 0$ , the lighter chargino mass increases, relaxing the chargino bound. On the other hand, the Higgs–neutralino coupling decreases due to a partial cancellation between  $\sin \beta N_{14}$  and  $\cos \beta N_{13}$ .  $\text{BR}_{\text{inv}}$  drops below 10-20% (Fig. 2, left panel) imposing no significant constraint on parameter space. Around  $M_1 \sim 20$  GeV, the cancellation is almost perfect and  $\text{BR}_{\text{inv}}$  is negligible.

We thus find that  $\text{BR}_{\text{inv}}$  imposes a significant constraint on the neutralino sector of SUSY models, assuming that the Higgs signal gets confirmed.  $h \rightarrow \chi_1^0 \chi_1^0$  can be the dominant Higgs decay channel with  $\text{BR}_{\text{inv}}$  reaching 75% for moderate  $\tan \beta$  and  $M_2 > 200$  GeV (Fig. 2, right panel). Values above 40% are disfavored by the LHC Higgs signal which allows us to place constraints on  $\mu$  and  $M_1$ . These constraints are the strongest for  $\mu > 0$  and low  $\tan \beta$ , covering the  $M_1$  values in the kinematically allowed range for  $h \rightarrow \chi_1^0 \chi_1^0$  up to 80 GeV, and values of  $\mu$  up to 200 GeV.

It is clear that the constraints will get significantly stronger when the experimental limit on  $\text{BR}_{\text{inv}}$  reaches a 10% level. For example, most of the parameter region shown in Fig. 1 (left) would be excluded. The massless neutralino scenario would also be strongly constrained since the typical  $\text{BR}_{\text{inv}}$  is around 10-20% in this case. Further bounds on invisible Higgs decay can come from monojet analyses (see e.g. [43]), although their impact is expected to be less significant.

### 3 Conclusion

The tentative Higgs signal reported by the LHC collaborations appears to agree well with the SM expectations. In this paper, we have studied implications of this observation for the neutralino sector of SUSY models. The SM-like Higgs can decay into a pair of the lightest neutralinos with the branching ratio up to 75%. As invisible Higgs decay is constrained by the existing data, we find that most of the parameter region  $\mu < 170$  GeV,  $M_1 < 70$  GeV at  $\tan\beta \sim 10$  and  $\mu < 120$  GeV,  $M_1 < 70$  GeV at  $\tan\beta \sim 40$  is disfavored.

This conclusion depends only weakly on the other SUSY parameters. In particular, the current bounds on superpartners suggest that the sfermion/gluino masses are in the TeV range. It is therefore a good approximation to assume that the lightest MSSM Higgs is very similar to the SM Higgs. The drastic difference however could appear in its invisible decays, if the decay into neutralinos is kinematically allowed. This allows us to set constraints on the Higgs-neutralino coupling, which is controlled mostly by  $\mu$  and  $M_1$ . It is important to note that these constraints are “direct” in the sense that they do not rely on further assumptions such as gaugino mass unification or specific SUSY decay chains, unlike many previous analyses [39].

**Acknowledgements.** The work of JSK is supported by the ARC Centre of Excellence for Particle Physics at the Terascale. The work of HKD was supported by the BMBF Verbundprojekt HEP-Theorie under the contract 0509PDE. JSK thanks A. Williams for reading the manuscript.

### References

- [1] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **710** (2012) 403.
- [2] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **710** (2012) 26.
- [3] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **710** (2012) 91.
- [4] S. Chatrchyan *et al.* [CMS Collaboration], arXiv:1202.1997 [hep-ex].
- [5] G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **710** (2012) 49.

- [6] G. Aad *et al.* [ATLAS Collaboration], Phys. Rev. Lett. **108** (2012) 111803.
- [7] G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **710** (2012) 383.
- [8] H. M. Georgi, S. L. Glashow, M. E. Machacek and D. V. Nanopoulos, Phys. Rev. Lett. **40** (1978) 692.
- [9] R. N. Cahn and S. Dawson, Phys. Lett. B **136** (1984) 196 [Erratum-ibid. B **138** (1984) 464].
- [10] J. R. Ellis, M. K. Gaillard and D. V. Nanopoulos, Nucl. Phys. B **106** (1976) 292.
- [11] T. G. Rizzo, Phys. Rev. D **22** (1980) 722.
- [12] J. Fleischer and F. Jegerlehner, Phys. Rev. D **23** (1981) 2001.
- [13] M. Dittmar and H. K. Dreiner, Phys. Rev. D **55** (1997) 167; M. Dittmar and H. K. Dreiner, In \*Tegernsee 1996, The Higgs puzzle\* 113-121 [hep-ph/9703401].
- [14] P. Bechtle, O. Brein, S. Heinemeyer, G. Weiglein and K. E. Williams, Comput. Phys. Commun. **182** (2011) 2605.
- [15] P. P. Giardino, K. Kannike, M. Raidal and A. Strumia, arXiv:1203.4254 [hep-ph]; arXiv:1207.1347 [hep-ph].
- [16] J. R. Espinosa, M. Muhlleitner, C. Grojean and M. Trott, arXiv:1205.6790 [hep-ph]; arXiv:1207.1717 [hep-ph].
- [17] V. Barger, M. Ishida and W. -Y. Keung, Phys. Rev. Lett. **108**, 261801 (2012).
- [18] A. Djouadi, O. Lebedev, Y. Mambrini and J. Quevillon, Phys. Lett. B **709**, 65 (2012).
- [19] O. Lebedev, H. M. Lee and Y. Mambrini, Phys. Lett. B **707**, 570 (2012).
- [20] J. F. Gunion, Phys. Rev. Lett. **72** (1994) 199.
- [21] D. Choudhury and D. P. Roy, Phys. Lett. B **322** (1994) 368.
- [22] S. G. Frederiksen, N. Johnson, G. L. Kane and J. Reid, Phys. Rev. D **50** (1994) 4244.
- [23] O. J. P. Eboli and D. Zeppenfeld, Phys. Lett. B **495** (2000) 147.
- [24] H. E. Haber and G. L. Kane, Phys. Rept. **117**, 75 (1985).
- [25] D. Choudhury, H. K. Dreiner, P. Richardson and S. Sarkar, Phys. Rev. D **61** (2000) 095009.



- [26] H. K. Dreiner, C. Hanhart, U. Langenfeld and D. R. Phillips, Phys. Rev. D **68** (2003) 055004.
- [27] H. K. Dreiner, S. Heinemeyer, O. Kittel, U. Langenfeld, A. M. Weber and G. Weiglein, Eur. Phys. J. C **62**, 547 (2009).
- [28] H. K. Dreiner, M. Hanussek, J. S. Kim and S. Sarkar, Phys. Rev. D **85**, 065027 (2012).
- [29] K. Griest and H. E. Haber, Phys. Rev. D **37**, 719 (1988).
- [30] A. Djouadi, J. Kalinowski and P. M. Zerwas, Z. Phys. C **57** (1993) 569.
- [31] A. Djouadi, Mod. Phys. Lett. A **14**, 359 (1999).
- [32] G. Belanger, F. Boudjema, A. Cottrant, R. M. Godbole and A. Semenov, Phys. Lett. B **519**, 93 (2001).
- [33] D. A. Vasquez, G. Belanger, C. Boehm, J. Da Silva, P. Richardson and C. Wymant, arXiv:1203.3446 [hep-ph].
- [34] N. Desai, B. Mukhopadhyaya and S. Niyogi, arXiv:1202.5190 [hep-ph].
- [35] S. Heinemeyer, O. Stal and G. Weiglein, Phys. Lett. B **710**, 201 (2012); A. Arbey, M. Battaglia, A. Djouadi, F. Mahmoudi and J. Quevillon, Phys. Lett. B **708**, 162 (2012).
- [36] S. Heinemeyer, W. Hollik and G. Weiglein, Comput. Phys. Commun. **124**, 76 (2000).
- [37] S. Heinemeyer, W. Hollik, A. M. Weber and G. Weiglein, JHEP **0804**, 039 (2008).
- [38] [ALEPH and DELPHI and L3 and OPAL and SLD and LEP Electroweak Working Group and SLD Electroweak Group and SLD Heavy Flavour Group Collaborations], Phys. Rept. **427**, 257 (2006).
- [39] K. Nakamura *et al.* [Particle Data Group Collaboration], J. Phys. G **37** (2010) 075021.
- [40] G. Abbiendi *et al.* [OPAL Collaboration], Eur. Phys. J. C **35**, 1 (2004).
- [41] J. R. Ellis, J. M. Frere, J. S. Hagelin, G. L. Kane and S. T. Petcov, Phys. Lett. B **132**, 436 (1983).
- [42] H. K. Dreiner, O. Kittel and U. Langenfeld, Phys. Rev. D **74** (2006) 115010.
- [43] A. Djouadi, A. Falkowski, Y. Mambrini and J. Quevillon, arXiv:1205.3169 [hep-ph].