

TESTS OF THE HIGGS PROPERTIES AT THE NEXT COLLIDERS*

ABDELHAK DJOUADI

LPT, Université Paris-Sud, 91405 Orsay, France

(Received April 13, 2006)

We discuss the tests of the fundamental properties of the Standard Model Higgs boson that can be performed in the next round of experiments.

PACS numbers: 12.15.-y, 12.60.Fr, 14.80.Bn, 13.66.Jn

1. Introduction

The search for Higgs bosons is the primary mission of present and future high-energy colliders. Detailed theoretical and experimental studies performed in the last few years, have shown that the single neutral Higgs boson that is predicted in the Standard Model (SM) [1] could be discovered at the upgraded Tevatron, if it is relatively light and if enough integrated luminosity is collected [2, 3]. It can also be detected at the LHC [3, 4] over its entire mass range $115 \text{ GeV} \lesssim M_H \lesssim 1 \text{ TeV}$ in many redundant channels.

Should we then declare that we have done our homework and wait peacefully for the LHC to start operation? Well, discovering the Higgs boson is not the entire story, and another goal, just as important, would be to probe the electroweak symmetry breaking mechanism in all its facets. Once the Higgs boson is found, the next step would, therefore, be to perform very high precision measurements to explore all its fundamental properties. To achieve this goal in great detail, one needs to measure all possible cross sections and decay branching ratios of the Higgs bosons to derive their masses, their total decay widths, their couplings to the other particles and their self-couplings, their spin-parity quantum numbers, *etc.* This needs very precise theoretical predictions and more involved theoretical and experimental studies. In particular, all possible production and decay channels of the Higgs particles, not only the dominant and widely studied ones allowing for clear discovery,

* Presented at the PLC2005 Workshop (Kazimierz Lecture), 5–8 September 2005, Kazimierz, Poland.

should be investigated. This also requires complementary detailed studies at future e^+e^- linear colliders, where the clean environment and the expected high luminosity allow for very high precision measurements [5,6].

In this talk, I summarize the studies of the Higgs profile that can be performed at the LHC and ILC. Most of the material presented here relies on the detailed discussion given in Refs. [1] to which we refer for details.

2. Higgs production and tests at the LHC

The production mechanisms for the SM Higgs boson at hadron colliders are:

- (a) gluon gluon fusion $gg \rightarrow H$,
- (b) association with W/Z $q\bar{q} \rightarrow V + H$,
- (c) WW/ZZ fusion $VV \rightarrow H$,
- (d) association with $Q\bar{Q}$ $gg, q\bar{q} \rightarrow Q\bar{Q} + H$,

The cross sections are shown in Fig. 1 for the LHC with $\sqrt{s} = 14$ TeV. Let us briefly discuss the main features of each channel at the LHC [for the various Higgs decay modes; see Ref. [7] for details]:

(a) The dominant process, up to masses $M_H \lesssim 700$ GeV, is by far the gg fusion mechanism. The most promising signals are $H \rightarrow \gamma\gamma(WW^*)$ in the mass range below 130 GeV (around 160 GeV); for larger masses it is $H \rightarrow ZZ^{(*)} \rightarrow 4\ell^\pm$, with $\ell = e, \mu$, which from $M_H \gtrsim 500$ GeV can be complemented by $H \rightarrow ZZ \rightarrow \nu\bar{\nu}\ell^+\ell^-$ and $H \rightarrow WW \rightarrow \nu\ell jj$. The higher order QCD corrections should be taken into account since they lead to an increase of the cross sections by a factor of ~ 2 ; see Ref. [1] for a review.

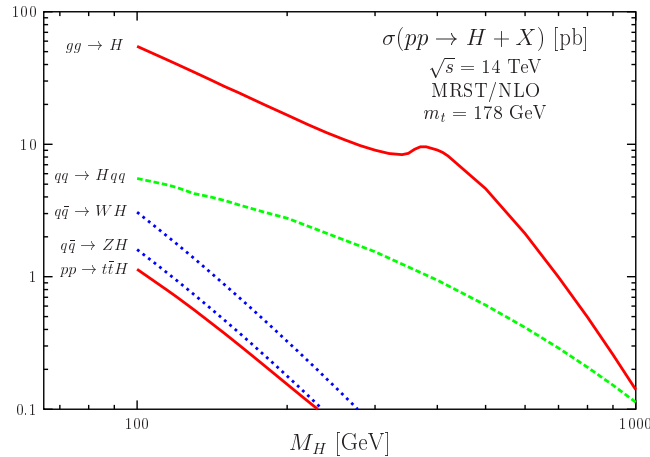


Fig.1. The Higgs boson production cross sections at the LHC in the dominant mechanisms as functions of M_H ; from Ref. [1].

(b) The WW/ZZ fusion mechanism has the second largest cross section (a few pico-barns for $M_H \lesssim 250$ GeV) and rather small backgrounds (comparable to the signal) allowing precision measurements, so that one can use forward-jet tagging, mini-jet veto for low luminosity, and one can trigger on the central Higgs decay products [8]. It has been shown that at least the decay $H \rightarrow \tau^+\tau^-$ as well as $H \rightarrow \gamma\gamma, WW^*$ can be detected and could allow for Higgs coupling measurements [3, 8].

(c) The associated production with gauge bosons, with $H \rightarrow b\bar{b}$, is the most relevant mechanism at the Tevatron [2] but at the LHC, this process (also with the decays $H \rightarrow \gamma\gamma$) is challenging and needs a large luminosity.

(d) Finally, Higgs boson production in association with top quarks, with $H \rightarrow \gamma\gamma$ or $b\bar{b}$, could be observed at the LHC with sufficient luminosity and would allow the measurement of the important top Yukawa coupling.

Let us now turn to the measurements that can be performed at the LHC. We will mostly rely on the summaries given in Refs. [1, 3, 8, 9]. In most cases, a large, $\mathcal{O}(200)$ fb $^{-1}$, integrated luminosity is assumed.

- The Higgs boson mass can be measured with a very good accuracy. For $M_H \lesssim 400$ GeV, where Γ_H is not too large, a precision of $\Delta M_H/M_H \sim 0.1\%$ can be achieved in $H \rightarrow ZZ^{(*)} \rightarrow 4\ell^\pm$. In the “low-mass” range, a slight improvement can be obtained by considering $H \rightarrow \gamma\gamma$. For $M_H \gtrsim 400$ GeV, the precision starts to deteriorate because of the smaller rates. However, a precision of the order of 1% can still be obtained up to $M_H \sim 800$ GeV if theoretical errors, such as width effects, are not taken into account.

- Using the same process, $H \rightarrow ZZ^{(*)} \rightarrow 4\ell^\pm$, the total Higgs width can be measured for masses above $M_H \gtrsim 200$ GeV, when it is large enough. While the precision is very poor near this mass value (a factor of (2), it improves to reach the level of $\sim 5\%$ around $M_H \sim 400$ GeV. Here again, the theoretical errors are not taken into account.

- The Higgs boson spin can be measured by looking at angular correlations between the fermions in the final states in $H \rightarrow VV \rightarrow 4f$. However the cross sections are rather small and the environment too difficult. Only the measurement of the decay planes of the two Z bosons decaying into four leptons seems promising. The Higgs CP properties and the structure of the HVV coupling can be also determined in the fusion process, $qq \rightarrow qqH$, by looking at the azimuthal dependence of the two outgoing forward tagging jets. The analysis is independent of the Higgs mass and decay modes but might be difficult because of background problems.

- The direct measurement of the Higgs couplings to gauge bosons and fermions is possible, but with rather poor accuracy. This is due to the limited statistics, the large backgrounds, and the theoretical uncertainties from the parton densities and the higher-order radiative corrections. To reduce some uncertainties, it is more interesting to measure ratios of cross sections where

the normalization cancels out. The cross sections times branching ratios which can be measured in various channels at the LHC are shown in the left-hand side of Fig. 2 for Higgs masses below 200 GeV [8]. A statistical precision of the order of 10 to 20% can be achieved in some channels, while the vector boson fusion process, $pp \rightarrow Hqq \rightarrow WWqq$, leads to accuracies of the order of a few percent. Under some assumptions, these $\sigma \times \text{BR}$ can be translated into Higgs partial widths in the various decay channels $\Gamma_X \equiv \Gamma(H \rightarrow XX)$ [8], which are proportional to the square of the Higgs couplings, g_{HXX}^2 . The expected accuracies, at the level of 10 to 30%, are shown in the right-hand side of Fig. 2. One can indirectly measure the total Higgs width Γ , and thus derive the absolute values of the partial widths Γ_X , by making additional assumptions, besides g_{HWW}/g_{HZZ} universality

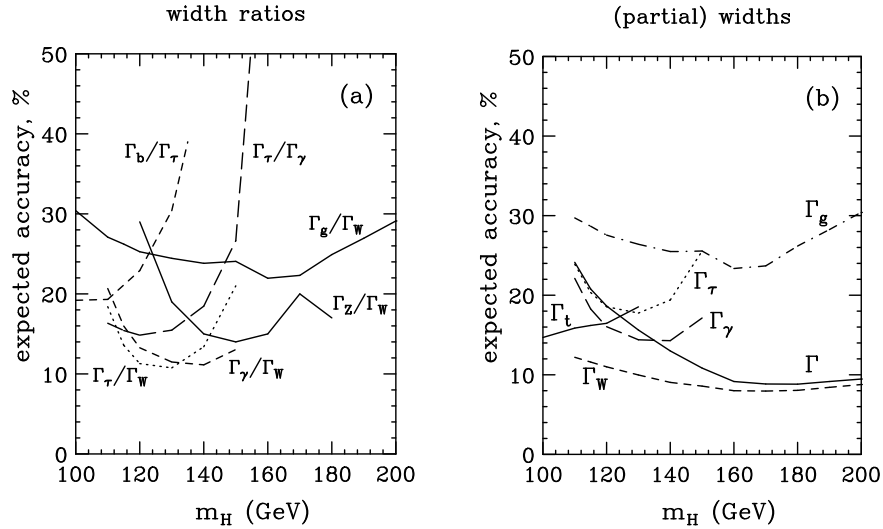


Fig. 2. Relative accuracy expected at the LHC with a luminosity of 200 fb^{-1} for various ratios of Higgs partial widths (left) and indirect determination of partial and total widths $\tilde{\Gamma}_i$ and Γ (right); from Ref. [8].

- The trilinear Higgs boson self-coupling λ_{HHH} is too difficult to be measured at the LHC because of the smallness of the $gg \rightarrow HH$ (and *a fortiori* the $VV \rightarrow HH$ and $qq \rightarrow HHV$) cross sections and the very large backgrounds; see Refs. [1, 9] for a recent work and references.

Note that some of the measurements discussed previously would greatly benefit from an increase of the LHC luminosity (SLHC) or from an increase of the energy (VLHC); see Ref. [10] for details.

3. Higgs production and tests at the ILC

At e^+e^- linear colliders operating in the 300–1000 GeV energy range, the main production mechanisms for SM-like Higgs particles are

- | | | |
|-----|-------------------------|--|
| (a) | Higgs-strahlung process | $e^+e^- \rightarrow (Z) \rightarrow Z + H,$ |
| (b) | WW fusion process | $e^+e^- \rightarrow \bar{\nu} \nu (WW) \rightarrow \bar{\nu} \nu + H,$ |
| (c) | ZZ fusion process | $e^+e^- \rightarrow e^+e^- (ZZ) \rightarrow e^+e^- + H,$ |
| (d) | radiation off tops | $e^+e^- \rightarrow (\gamma, Z) \rightarrow t\bar{t} + H,$ |
| (e) | double Higgs-strahlung | $e^+e^- \rightarrow (Z) \rightarrow Z + HH.$ |

The Higgs-strahlung cross section scales as $1/s$ and, therefore, dominates at low energies, while the WW fusion mechanism has a cross section that rises like $\log(s/M_H^2)$ and dominates at high energies. At $\sqrt{s} \sim 500$ GeV, the two processes have approximately the same cross sections, $\mathcal{O}(100$ fb) for the interesting range $100 \text{ GeV} \lesssim M_H \lesssim 200 \text{ GeV}$, as shown in Fig. 3. With $\mathcal{L} \sim 500 \text{ fb}^{-1}$, as it was expected *e.g.* in the TESLA design [6], approximately 25.000 events per year can be collected in each channel for a $M_H \sim 150$ GeV. This sample is more than sufficient to discover the Higgs boson and to study its properties in detail. Higgs masses of the order of 80% of the c.m. energy can be probed, which means that a 800 GeV collider can cover almost the entire mass range in the SM, $M_H \lesssim 650$ GeV. The subleading processes (c)–(e) have orders of magnitude smaller rates but they are very important for precision tests of the Higgs properties as discussed below.

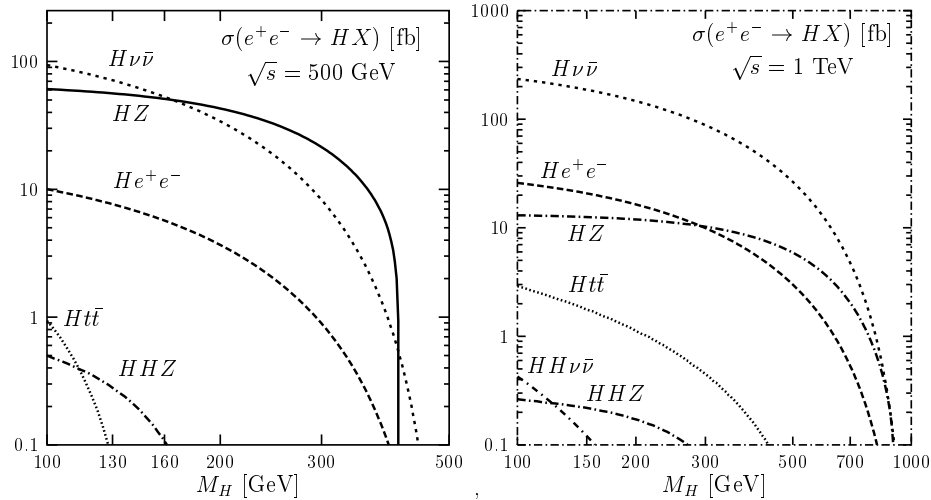


Fig. 3. Production cross sections of the SM Higgs boson in e^+e^- collisions in the main and subdominant processes at $\sqrt{s} = 500$ GeV (left) and 1 TeV (right) [1].

The determination of the Higgs properties can be done in great detail in the clean environment of the ILC [5,6]. In the following, relying on analyses done for TESLA [6] (where the references for the original studies can be found), we summarize the measurements in the case of the SM Higgs.

- The measurement of the recoil $f\bar{f}$ mass in the strahlung process, $e^+e^- \rightarrow ZH \rightarrow Hf\bar{f}$ allows a very good determination of M_H : at $\sqrt{s} = 350$ GeV with $\mathcal{L} = 500 \text{ fb}^{-1}$, a precision of $\Delta M_H \sim 50$ MeV can be reached for $M_H \sim 120$ GeV. Accuracies $\Delta M_H \sim 80$ MeV can also be reached for $M_H = 150$ and 180 GeV when the Higgs decays mostly into gauge bosons.

- The angular distribution of the Z/H in the strahlung process, $\propto \sin^2 \theta$ at high energy, characterizes the production of a $J^P = 0^+$ particle. The Higgs spin-parity quantum numbers can also be checked by looking at correlations in the production $e^+e^- \rightarrow HZ \rightarrow 4f$ or decay $H \rightarrow WW^* \rightarrow 4f$ processes, as well as in the channel $H \rightarrow \tau^+\tau^-$ for $M_H \lesssim 140$ GeV. An unambiguous test of the Higgs CP nature can be made by analyzing the spin-correlation in $H \rightarrow \tau^+\tau^-$ and possibly in the process $e^+e^- \rightarrow t\bar{t}H$ (or at laser photon colliders in the loop-induced process $\gamma\gamma \rightarrow H$).

- The Higgs couplings to ZZ/WW bosons (which are predicted to be proportional to the masses) can be directly determined by measuring the production cross sections in the $e^+e^- \rightarrow H\ell^+\ell^-$ and $H\nu\bar{\nu}$ processes. A precision less than $\sim 3\%$ at $\sqrt{s} \sim 500$ GeV with $\mathcal{L} = 500 \text{ fb}^{-1}$ can be achieved. This leads to an accuracy of $\lesssim 1.5\%$ on the HVV couplings.

- The measurement of the Higgs branching ratios (BRs) is of utmost importance. For $M_H \lesssim 130$ GeV a large variety of ratios can be measured: the $b\bar{b}, c\bar{c}$ and $\tau^+\tau^-$ BRs allow us to derive the relative Higgs-fermion couplings and to check the prediction that they are proportional to the masses. $\text{BR}(gg)$ is sensitive to the $t\bar{t}H$ coupling and to new strongly interacting particles. $\text{BR}(WW)$ allows an indirect measurement of the HWW coupling, while $\text{BR}(\gamma\gamma)$ is also important since it is sensitive to new particles. Measurements at the level of a few percent for most of the BRs at $M_H \sim 130$ GeV can be made (except for $\gamma\gamma$ and ZZ^* where the errors are of $\mathcal{O}(20\%)$).

- The Higgs coupling to top quarks, which is the largest coupling in the SM, is directly accessible in the $e^+e^- \rightarrow t\bar{t}H$ process, although the rates are low (see Fig. 3). For $M_H \lesssim 130$ GeV, g_{Htt} can be measured with a precision of less than 5% at $\sqrt{s} \sim 800$ GeV with $\mathcal{L} \sim 1 \text{ ab}^{-1}$.

- The total width of the Higgs boson, for masses less than ~ 200 GeV, is so small that it cannot be resolved experimentally. However, the measurement of $\text{BR}(H \rightarrow WW)$ allows an indirect determination of Γ_H , since the HWW coupling can be determined from the measurement of the Higgs cross section in the WW fusion process. (Γ_{tot} can also be derived by measuring the $\gamma\gamma \rightarrow H$ cross section at a $\gamma\gamma$ collider or $\text{BR}(H \rightarrow \gamma\gamma)$ in e^+e^- .)

• Finally, the measurement of the trilinear Higgs self-coupling, which is the first non-trivial test of the Higgs potential, is accessible in the double Higgs production processes $e^+e^- \rightarrow ZHH$ (and in the $e^+e^- \rightarrow \nu\bar{\nu}HH$ process at high energies). Despite its smallness [see Fig. 3], the cross section can be determined with an accuracy of the order of 20% at a 500 GeV collider if a high luminosity, $\mathcal{L} \sim 1 \text{ ab}^{-1}$, is available.

An illustration of the experimental accuracies that can be achieved in the determination of the mass, CP nature, total decay width and the various couplings of the Higgs boson for $M_H = 120$ and 140 GeV is shown in Table I for $\sqrt{s} = 350$ GeV (for M_H and the CP nature) and 500 GeV (for Γ_{tot} and all couplings except for g_{Htt}) and for $\int \mathcal{L} = 500 \text{ fb}^{-1}$ (except for g_{Htt} where $\sqrt{s} = 1 \text{ TeV}$ and $\int \mathcal{L} = 1 \text{ ab}^{-1}$ are assumed).

TABLE I

Relative accuracies (in %) on the Higgs boson mass, its CP mixture and total width (top) and on its couplings (bottom) obtained at TESLA with $\sqrt{s} = 350, 500$ GeV and $\int \mathcal{L} = 500 \text{ fb}^{-1}$ (except for top); Ref. [6].

M_H [GeV]	ΔM_H	ΔCP	Γ_{tot}
120	± 0.033	± 3.8	± 6.1
140	± 0.05	—	± 4.5

M_H [GeV]	g_{HWW}	g_{HZZ}	g_{Htt}	g_{Hbb}	g_{Hcc}	$g_{H\tau\tau}$	g_{HHH}
120	± 1.2	± 1.2	± 3.0	± 2.2	± 3.7	± 3.3	± 17
140	± 2.0	± 1.3	± 6.1	± 2.2	± 10	± 4.8	± 23

4. Conclusions

The detection of a Higgs particle is possible at the upgraded Tevatron for $M_H \lesssim 130 \text{ GeV}$ and is not a problem at the LHC where even much heavier Higgs bosons can be probed. Relatively light Higgs bosons can also be found at future e^+e^- colliders with c.m. energies $\sqrt{s} \gtrsim 350 \text{ GeV}$; the signals are very clear, and the expected high luminosity allows a thorough investigation of their fundamental properties. Some of this discussion can of course be extended to the lightest Higgs particle of the minimal SUSY extension of the SM (MSSM), which is expected to have a mass smaller than 140 GeV; see Ref. [11]. In fact, a very important issue once Higgs particles are found, will be to probe in all its facets the electroweak symmetry breaking mechanism. In many aspects, the searches and tests at future e^+e^- colliders are complementary to those that will be performed at the LHC. An example can be given in the context of the MSSM.

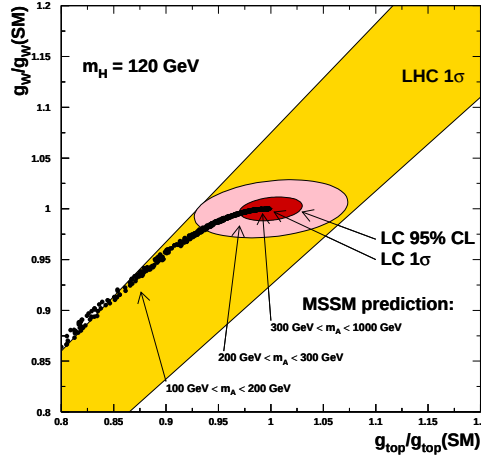


Fig. 4. Higgs boson coupling determinations at TESLA for $M_H = 120$ GeV with 500 fb^{-1} of data, the 1σ LHC constraint and the expected deviations in the MSSM for various M_A ranges are also shown; from Ref. [6].

In constrained scenarios, such as the minimal supergravity model, the heavier H, A and $H^\pm$ bosons tend to have masses of the order of several hundred GeV and, therefore, will escape detection at both the LHC and linear collider. In this parameter range, the h boson couplings to fermions and gauge bosons will be almost SM-like and, because of the relatively poor accuracy of the measurements at the LHC, it would be difficult to resolve between the SM and MSSM (or extended) scenarios. At the ILC, the Higgs couplings can be measured with a great accuracy, allowing a distinction between the SM and the MSSM Higgs boson to be made close to the decoupling limit, *i.e.* for pseudoscalar boson masses, which are not accessible at the LHC. This is exemplified in Fig. 4, where the accuracy in the determination of the Higgs couplings to $t\bar{t}$ and WW states are displayed at LHC and ILC, together with the predicted values in the MSSM for different values of M_A . At the ILC, the two scenarios can be distinguished for pseudoscalar Higgs masses up to 1 TeV and, thus, beyond the LHC reach.

I thank the organizers of the conference, in particular Maria Krawczyk, for the invitation and for the nice atmosphere.

REFERENCES

- [1] For recent reviews on the Higgs sector in the SM and MSSM and a complete set of references, see: A. Djouadi, [hep-ph/0503172](#) and [hep-ph/0503173](#).
- [2] M. Carena *et al.*, [hep-ph/0010338](#).
- [3] A. Djouadi *et al.*, [hep-ph/0002258](#); D. Cavalli *et al.*, [hep-ph/0203056](#); K. Assamagan *et al.*, [hep-ph/0406152](#).
- [4] CMS TR, CERN/LHCC/94-38; ATLAS TDR, CERN/LHCC/99-15; G. Branson *et al.* (CMS and ATLAS), *Eur. Phys. J.* **C4**, N1 (2002); V. Büsher, K. Jakobs, [hep-ph/0504099](#).
- [5] E. Accomando, *Phys. Rept.* **299**, 1 (1998); American LC WG, [hep-ex/0106057](#); ACFA LC Higgs WG, [hep-ph/0301172](#).
- [6] TESLA Technical Design Report, Part III, [hep-ph/0106315](#). For updates see, K. Desch *et al.*, [hep-ph/0311092](#); T. Barklow, [hep-ph/0312268](#); J.-C. Brient, Note LC-PHSM-2002-03; S. Kanemura, [hep-ph/0410133](#).
- [7] A. Djouadi *et al.*, *Z. Phys.* **C70**, 427 (1996); *Z. Phys.* **C70**, 435 (1996); *Comput. Phys. Commun.* **108**, 56 (1998).
- [8] D. Zeppenfeld *et al.*, *Phys. Rev.* **D62**, 013009 (2000); M. Dührssen *et al.* *Phys. Rev.* **D70**, 113009 (2004); M. Dührssen, ATLAS Note PHYS-2003-030.
- [9] G. Weiglein *et al.* (LHC–LC Study Group), [hep-ph/0410364](#).
- [10] F. Gianotti *et al.*, [hep-ph/0204087](#); U. Baur *et al.*, [hep-ph/0201227](#).
- [11] For recent discussions, see G. Degrandi *et al.*, *Eur. Phys. J.* **C28**, 133 (2003); B. Allanach *et al.*, *J. High Energy Phys.* **0409**, 044 (2004).