Effect of Large Supersymmetric Phases on Higgs Production

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If the soft supersymmetry (SUSY) breaking masses and couplings are complex and cancellations do take place in the SUSY induced contributions to the fermionic electric dipole moments, then the *CP*-violating soft phases can drastically modify much of the known phenomenological pattern of the minimal supersymmetric standard model. In particular, the squark loop content of the dominant Higgs production mechanism at the Large Hadron Collider, the gluon-gluon fusion mode, could be responsible for large corrections to the known cross sections.

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The strong constraints arising from the measurements of the electron and neutron electric dipole moments (EDMs) on the size of the CP-violating phases associated with the soft supersymmetry (SUSY) Lagrangian [1] can be evaded, if the corresponding masses and couplings arrange themselves so that the SUSY contributions to the EDMs cancel out. This has been proved to occur over a sizable area of the minimal supersymmetric standard model (MSSM) parameter space [2,3]. Under these circumstances, one ought to consider possible phenomenological effects of such "explicit" CP violation in the soft SUSY breaking sector [4].

Higgs physics is perhaps the primary interest behind the construction of the Large Hadron Collider (LHC). Within the MSSM, with or without phases, the mass of the lightest Higgs boson, h^0, is expected to be well within the reach of the future CERN hadron collider. However, the dominant production mode of this particle (and of the other two neutral Higgs bosons of the theory, H^0 and A^0) can be affected by a nonzero value of either of the two independent phases, ϕ_μ and ϕ_A, associated with the (complex) Higgsino mass term, μ, and trilinear scalar couplings $A \equiv A_u = A_d$, where u and d refer to all flavors of up- and down-type (s)quarks, respectively. In fact, the production of one on-shell Higgs boson via gluon-gluon fusion [5] proceeds through loops of both quarks and squarks (primarily, those of top and bottom flavor). By a close look at the squark-squark-Higgs vertices (which we collectively denote by $\lambda_{\Phi^0\tilde{q}_\chi\tilde{q}^*_{\chi'}}$, with $\Phi^0 = h^0, H^0, A^0$ and $q = u, d$—here, we are interested only in vertices involving neutral Higgs bosons and the combination $\chi = \chi'$; see [6] for $\chi \neq \chi'$ and/or charged Higgs scalars) in the chiral (or weak) basis of Ref. [5] (i.e., $\chi, \chi' = L, R$) and at the mixing relations (these originally appeared in the first paper of Ref. [7]) converting the latter into the mass basis (i.e., $\chi, \chi' = 1, 2$), i.e.,

$$\begin{aligned}\lambda_{\Phi^0\tilde{q}_1\tilde{q}_1^*} &= c_{\tilde{q}}c_{\tilde{q}}\lambda_{\Phi^0\tilde{q}_L\tilde{q}_L^*} + s_{\tilde{q}}s_{\tilde{q}}\lambda_{\Phi^0\tilde{q}_R\tilde{q}_R^*} \\ &\quad + c_{\tilde{q}}s_{\tilde{q}}e^{i\phi_{\tilde{q}}}\lambda_{\Phi^0\tilde{q}_L\tilde{q}_R^*} + s_{\tilde{q}}c_{\tilde{q}}e^{-i\phi_{\tilde{q}}}\lambda_{\Phi^0\tilde{q}_R\tilde{q}_l^*}, \\ \lambda_{\Phi^0\tilde{q}_2\tilde{q}_2^*} &= s_{\tilde{q}}s_{\tilde{q}}\lambda_{\Phi^0\tilde{q}_L\tilde{q}_L^*} + c_{\tilde{q}}c_{\tilde{q}}\lambda_{\Phi^0\tilde{q}_R\tilde{q}_R^*} \\ &\quad - s_{\tilde{q}}c_{\tilde{q}}e^{i\phi_{\tilde{q}}}\lambda_{\Phi^0\tilde{q}_L\tilde{q}_R^*} - c_{\tilde{q}}s_{\tilde{q}}e^{-i\phi_{\tilde{q}}}\lambda_{\Phi^0\tilde{q}_R\tilde{q}_l^*}, \quad (1)\end{aligned}$$

it is clear that ϕ_μ and ϕ_A end up into the squark loop contributions to $gg \to \Phi^0$, via $\phi_{\tilde{q}}$, the phases associated to the soft squark masses, in turn expressed in terms of the previous two. (We follow the notation of Ref. [6].) Here, $c_{\tilde{q}}$ and $s_{\tilde{q}}$ are the cosine and sine of the mixing angle $\theta_{\tilde{q}}$ entering the unitary transformation that diagonalizes the squark mass matrix (alongside $\phi_{\tilde{q}}$). It is the purpose of this Letter to assess the extent of the corrections induced to the total cross sections of $gg \to \Phi^0$ (for any Higgs state) at the LHC by finite values of ϕ_μ and ϕ_A.

In order to do so, we proceed as follows. First, we establish which are the combinations of MSSM parameters that guarantee the mentioned cancellations among the SUSY contributions to the EDMs. Then, we enforce the current collider limits on the squark and Higgs masses and couplings concerned: primarily, those of the lightest Higgs scalar, h^0, and squark, $\tilde{t}_1$. Finally, we compute the $gg \to \Phi^0$ rates with and without phases and plot the ratio between the two results. We do so at leading order (LO) and include only the top and bottom (i.e., t and b) and stop and sbottom (i.e., t_1, t_2 and b_1, b_2, with $1, 2$ in order of increasing mass) loops, indeed the dominant terms [8]. At this accuracy, such a ratio coincides with that taken between the matrix elements themselves, as the dependence upon the gluon distribution functions cancels out (further assuming that the relevant hard scale is the same in both cases, e.g., $Q \equiv M_{\Phi^0}$). We are, of course, aware that higher order QCD corrections to the gluon-gluon fusion mode are very large in the MSSM [8]. However, it has been shown that they affect the quark and squark contributions very similarly [8]. Thus, we leave them aside for the time being. (A two-loop analysis is performed in Ref. [6].)

Before proceeding to the computation though, a subtlety should be noted. The production of the pseudoscalar Higgs boson, A^0, proceeds at LO via quark loops only, if $\phi_\mu = \phi_A = 0$. In fact, for a "phaseless" MSSM, one gets that $\lambda_{A^0\tilde{q}_1\tilde{q}_1^*} = \lambda_{A^0\tilde{q}_2\tilde{q}_2^*} = 0$, as can be deduced from Eq. (1) if one recalls that reverting the chirality flow in the vertex $\lambda_{A^0\tilde{q}_\chi\tilde{q}_{\chi'}}$, with $\chi \neq \chi' = L, R$, corresponds to changing the sign in the Feynman rule [5]: $\lambda_{A^0\tilde{q}_L\tilde{q}_R} = -\lambda_{A^0\tilde{q}_R\tilde{q}_L}$. That the above couplings are identically zero is no longer

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true if either ϕ_μ or ϕ_A is nonzero. Therefore, a novel effect in the case $\Phi^0 = A^0$, due to the presence of CP-violating phases, is the very existence of squark loop contributions to the amplitude associated to pseudoscalar Higgs boson production:

$$\mathcal{M}_{ab}^{A^0} \propto \frac{\alpha_s(Q)}{2\pi}\,\delta_{ab}\epsilon_\mu(P_1)\epsilon_\nu(P_2) \times \left\{ i\varepsilon^{\mu\nu\rho\sigma}P_{1\rho}P_{2\sigma}\sum_q \frac{\lambda_{A^0q\bar{q}}}{m_q}\,\tau_q[f(\tau_q)] + \sum_{\tilde{q}} \frac{\lambda_{A^0\tilde{q}\tilde{q}^*}}{4m_{\tilde{q}}^2}\,(g^{\mu\nu}P_1\cdot P_2 - P_1^\nu P_2^\mu)\tau_{\tilde{q}}[1-\tau_{\tilde{q}}f(\tau_{\tilde{q}})]\right\}. \quad (2)$$

Here, P_1, P_2 are the gluon four-momenta, $\epsilon_\mu(P_1)$, $\epsilon_\nu(P_2)$ their polarization four-vectors and a, b their colors, $\alpha_s(Q)$ is the strong coupling constant, $\lambda_{A^0u\bar{u}} = -gm_u\cot\beta/2M_W$, and $\lambda_{A^0d\bar{d}} = -gm_d\tan\beta/2M_W$ are the standard MSSM quark-quark-Higgs couplings (they are affected by the presence of the phases only in higher orders [7]), $g^2 = e^2/\sin^2\theta_W = 4\pi\alpha_{\rm EM}/\sin^2\theta_W$, $\tau_{q,\tilde{q}} = 4m_{q,\tilde{q}}^2/M_{A^0}^2$ with m_q and $m_{\tilde{q}}$ the quark and squark masses entering the loops, respectively, whereas $f(\tau)$ can be found in [8]. Furthermore, there exist no interference terms between quark and squark loops if $\Phi^0 = A^0$. In fact, in Eq. (2), one can recognize an antisymmetric part—ε is the Levi-Civita tensor, generated by the γ^5 matrix in the quark-quark-Higgs vertex—associated to the former (first term on the right-hand side) and a symmetric one associated to the latter (second term on the right-hand side). In other words, in the case of pseudoscalar Higgs boson production, the SUSY corrections are always positive. In contrast, see Ref. [8], the SUSY terms can interfere with the standard model ones in scalar Higgs boson production, i.e., $\Phi^0 = h^0, H^0$, so that finite values of ϕ_μ and ϕ_A can either enhance or deplete the phaseless MSSM production rates.

The current limits—at 90% confidence level (C.L.)—on the electron, d_e [9], and neutron, d_n [10], EDMs are $|d_e| \le 4.3\times10^{-27}e$ cm and $|d_n| \le 6.3\times10^{-26}e$ cm. Large values of ϕ_μ and ϕ_A are consistent with these bounds (both in the "constrained" and "unconstrained" MSSM) provided cancellations take place between the contributions proportional to the former and those proportional to the latter [2,3]. This certainly requires a certain amount of "fine tuning" among the soft SUSY masses and couplings [3]. However, it has recently been suggested that such cancellations occur naturally in the context of Superstring models [11]. Here we should point out that we are working in the region of the parameter space where the phases of the gaugino masses and those of the vacuum expectation values are zero. Also, for the neutron EDM calculation we take into account the electric, chromoelectric and gluon-chromoelectric dipole moment contributions evaluated at the electroweak (EW) scale [2,3]. To search for those combinations of soft sparticle masses and couplings that guarantee vanishing SUSY contributions to the EDMs for each possible choice of the CP-violating phases, we scan over the (ϕ_μ, ϕ_A) plane and use the program of Ref. [3]. This returns those minimum values of the modulus of the common trilinear coupling, $|A|$, above which the cancellations work. These can be found in Fig. 1 in the form of a contour plot over the (ϕ_μ, ϕ_A) plane. There, we have also superimposed those regions (to be excluded from further consideration) over which the observable MSSM parameters assume values that are either forbidden by collider limits or for which the squared squark masses become negative, for a given combination of the other soft SUSY breaking parameters. These are $|\mu|$, which is taken to be 500 GeV, the soft squark masses of the three generations $M_{\tilde{q}_{1,2,3}}$, for which we assume—in the notation of Ref. [5]—$M_{\tilde{q}_{1,2}} \gg M_{\tilde{q}_3}$, $M_{\tilde{q}_{1,2}} \equiv M_{\tilde{Q}_{1,2}} = M_{\tilde{U}_{1,2}} = M_{\tilde{D}_{1,2}} = 2$ TeV, and , $M_{\tilde{q}_3} \equiv M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 300$ GeV and the gluino soft mass $M_{\tilde{g}} = 1$ TeV. In addition, in order to completely define our model for the calculation of the $gg \to \Phi^0$ processes, we also have introduced a possible choice of the Higgs sector parameters: i.e., the mass of one physical state, e.g., $M_{A^0} = 200$ GeV, and the ratio of the vacuum expectation values of the two doublet fields, e.g.,

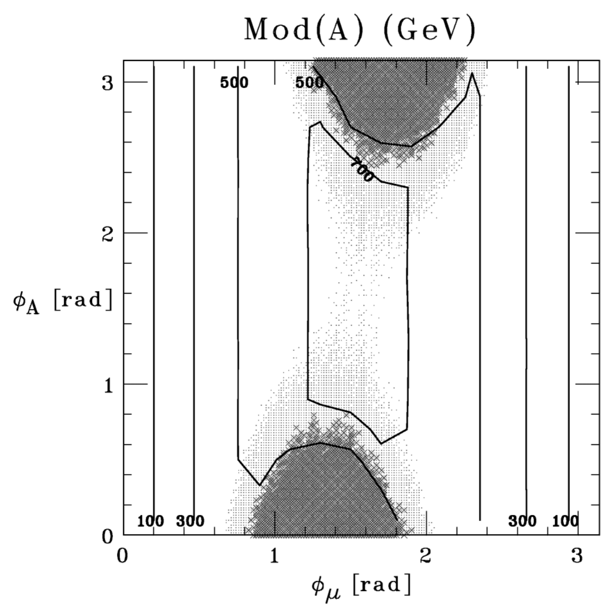

FIG. 1. Contour plot illustrating the minimum values of the modulus of the common trilinear coupling $|A|$ (consistent with cancellations taking place in the MSSM contributions to the EDMs), for any combination of ϕ_μ and ϕ_A. Dotted and crossed points indicate—here and in the following figures—regions which are excluded from direct searches and negativity of the squared squark masses, respectively.

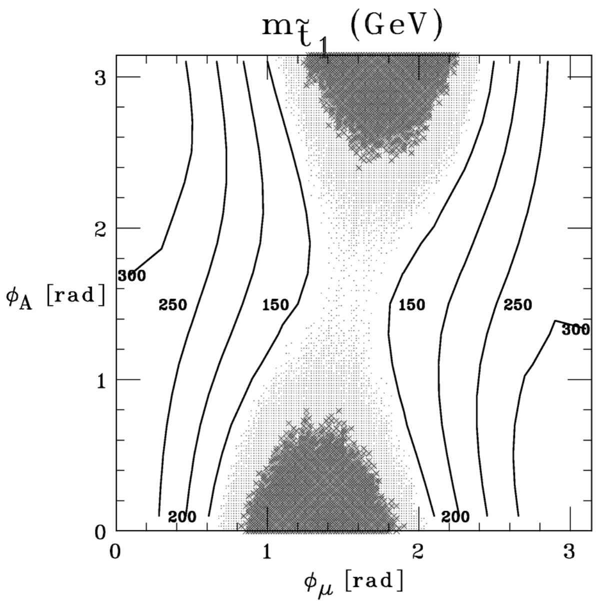

FIG. 2. Contour plot illustrating the values of the lightest stop mass, $m_{\tilde{t}_1}$, for any combination of ϕ_μ and ϕ_A.

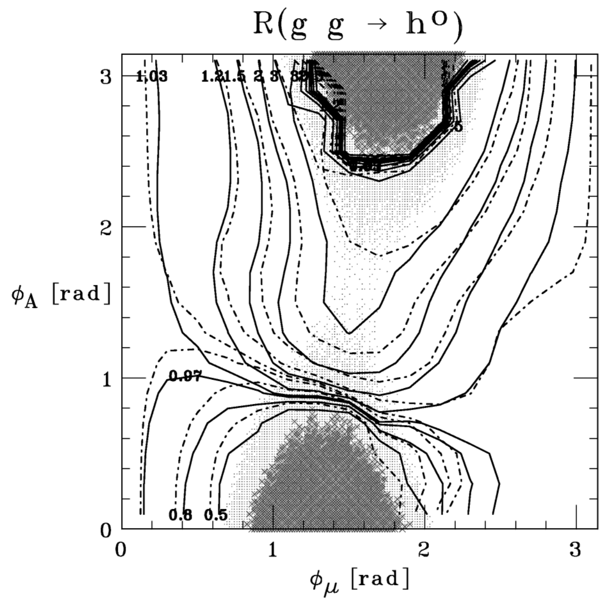

FIG. 3. Contour plot illustrating the values of the ratio in Eq. (3) for the case $\Phi^0 = h^0$, for any combination of ϕ_μ and ϕ_A, when $M_{h^0} = 90$ (solid lines) and 100 (dot-dashed lines) GeV.

$\tan\beta = 3$. We will adopt the above numbers as default in the reminder of our analysis. Apart from complying with the limits on the two-loop Barr-Zee type graphs [12], they should serve the sole purpose of being an example of the rich phenomenology that can be induced by the CP-violating phases in the MSSM, rather than a benchmark case. Indeed, similar effects to those illustrated below can be observed for other choices of $|\mu|$, $M_{\tilde{q}_{1,2,3}}$, M_{A^0}, and $\tan\beta$ [6]. As for the lightest stop, we display in Fig. 2 the values attained by $m_{\tilde{t}_1}$ over the usual (ϕ_μ, ϕ_A) plane. As a matter of fact, over most of the latter, $m_{\tilde{t}_1}$ is well above the current experimental reach, whose upper limit can safely be drawn at 120 GeV or so, given our $\tan\beta$ [13]. Also, for the above choice of $\tan\beta$ and M_{A^0}, one gets that $M_{h^0} \gtrsim 90$ GeV, in accordance with the latest bound from LEP, of about 85.5 GeV for $\tan\beta \geq 1$ at 95% C.L. [14], whereas M_{H^0} is approximately degenerate with M_{A^0}. In this respect, notice that, since the SUSY loop corrections to the lightest Higgs boson mass are significant, M_{h^0} in general depends upon A (see the last paper of [7]). As such dependence is not yet known explicitly, we have mimicked it by adopting two values for M_{h^0}, within 10 GeV of the one-loop result, for each $|A|$ over the (ϕ_μ, ϕ_A) plane. In contrast, one may assume little dependence of M_{H^0} upon A, and thus use a unique value for it, given the negligible size of the higher order corrections here. We now proceed to displaying the ratio:

$$R(gg \to \Phi^0) = \frac{\sigma_{\rm LO}^{\rm MSSM^*}(gg \to \Phi^0)}{\sigma_{\rm LO}^{\rm MSSM}(gg \to \Phi^0)}, \qquad (3)$$

where MSSM* refers to the case of the MSSM in the presence of CP-violating phases. [Of course, if $\phi_\mu = \phi_A = 0$, then $R(gg \to \Phi^0)$ is equal to 1.]

Figure 3 shows the ratio in Eq. (3) for the case $\Phi^0 = h^0$, again as a contour plot over the (ϕ_μ, ϕ_A) plane. One can see that the effects of the CP-violating phases are large indeed. Over the allowed (ϕ_μ, ϕ_A) regions, they deplete or increase the cross section obtained in the phaseless MSSM by as much as a factor of 2 and 3, respectively. In fact, one can distinguish two complementary regions: $\phi_A \lesssim \pi/3$ and $\phi_A \gtrsim \pi/3$ (for any ϕ_μ). In the first one, the effects of the phases are destructive; in the second one, constructive. A simple explanation for this is that $\lambda_{h^0\tilde{t}_1\tilde{t}_1^*}$ changes its sign when $\phi_A \approx \pi/3$. Figure 4 presents the rates for

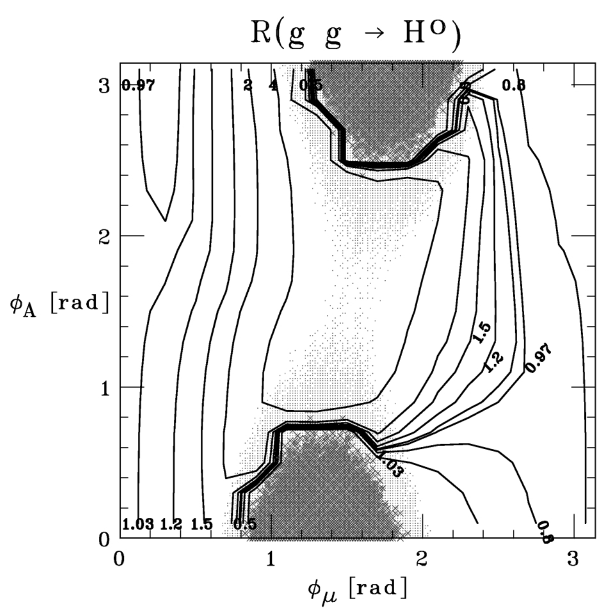

FIG. 4. Same as in Fig. 3 for the case $\Phi^0 = H^0$.

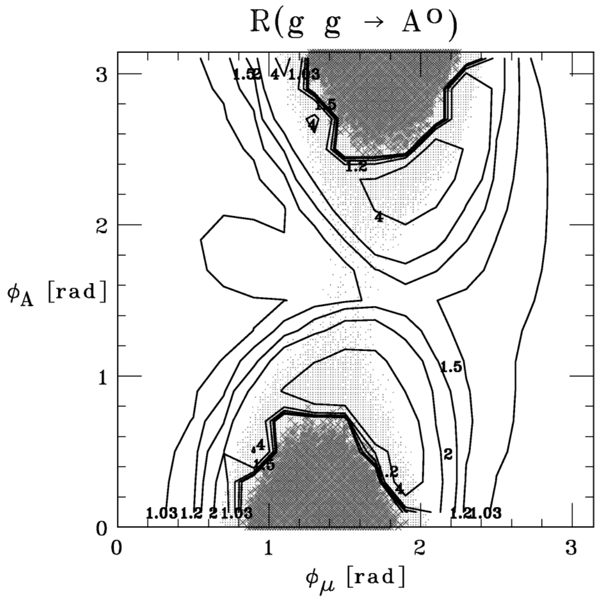

FIG. 5. Same as in Fig. 3 for the case $\Phi^0 = A^0$.

the case $\Phi^0 = H^0$. Here too, effects of finite values of ϕ_μ and ϕ_A can be dramatic, no less than in the previous case. The typical rates for the ratio in Eq. (3) are in the interval $0.5 \lesssim R(gg \to H^0) \lesssim 4$. The dependence of the H^0 cross section on the relative value of ϕ_μ and ϕ_A is difficult to discern. In Fig. 5, we display the pattern of Eq. (3) when $\Phi^0 = A^0$. As already explained, one always has that $R(gg \to A^0) \geq 1$. Once again, the ratio can become as large as 4. In this case, a visible trend is that R approaches 1 when $\phi_A = \phi_\mu \simeq \pi/2$, as the coupling $\lambda_{A^0\tilde{t}_1\tilde{t}_1^*}$ intervening in the lightest stop squark loop becomes zero. Three general remarks for all three ratios are the following. First, we have explicitly verified that significant contributions to the total cross sections come only from top, bottom, and lightest stop loops. Second, the effects of the phases are more evident where $|A|$ is larger, because of its intervention in the $\lambda_{\Phi^0\tilde{t}_1\tilde{t}_1^*}$ couplings of Eq. (1), through the $\theta_{\tilde{t}}$ mixing angle, and because of the form of the squark-squark-Higgs vertices. Third, all $R(gg \to \Phi^0)$ values are close to unity (i.e., negligible effects of the CP-violating phases) when ϕ_μ is small for every value of ϕ_A. This can be easily understood from Fig. 1, since when $\phi_\mu \to 0$ also $|A|, \phi_{\tilde{t}} \to 0$, so that no enhancement occurs in the $\lambda_{\Phi^0\tilde{t}_1\tilde{t}_1^*}$ couplings of Eq. (1)). The same does not happen for the opposite condition ($\phi_A \to 0$ for any ϕ_μ), since $|\mu|$ here is fixed and thus $\phi_{\tilde{t}}$ is always finite when ϕ_A approaches zero; see Ref. [6].

In conclusion, we have demonstrated the potentially dramatic effects that the presence of unconstrained (from the fermionic EDMs) CP-violating phases in the soft SUSY sector of the MSSM can have on the dominant—over most of the parameter space of the model—production mode of all neutral Higgs bosons at the LHC. In fact, corrections induced to the total production cross sections by finite values of ϕ_μ and ϕ_A have been seen to be much larger than any other known effect, such as higher order EW and QCD corrections, at least for certain combinations of soft SUSY masses and couplings. We feel that the matter raised here deserves further attention, both theoretically and experimentally. To this end, a more complete analysis, including a wider selection of combinations of MSSM parameters as well as the incorporation of the dominant two-loop QCD effects, is now under completion [6]. Similarly, one should investigate the effect of the CP-violating phases in the decay process $h^0 \to \gamma\gamma$ [15], as it represents the most promising discovery channel of the lightest Higgs boson.

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