CP violation in SUSY

Sabine Kraml[1,2] [a]

[1] CERN PH-TH, 1211 Geneva 23, Switzerland
[2] LPSC, 53 Av des Martyrs, 38026 Grenoble, France

Abstract. CP violation in supersymmetric models is reviewd with focus on explicit CP violation in the MSSM. The topics covered in particular are CP-mixing in the Higgs sector and its measurement at the LHC, CP-odd observables in the gaugino sector at the ILC, EDM constraints, and the neutralino relic density.

PACS. 12.60.Jv Supersymmetric models – 11.30.Er Charge conjugation, parity, time reversal, and other discrete symmetries

1 Introduction

Test of the discrete symmetries, charge conjugation C, parity P, and time-reversal T, have played an important role in establishing the structure of Standard Model (SM). In particular, CP violation has been observed in the electroweak sector of the SM in the K and B systems. It is linked to a single phase in the unitary Cabbibo-Kobayashi-Maskawa (CKM) matrix describing transitions between the three generations of quarks; see e.g. [1] for a detailed review. It is important to note that this source of CP violation is strictly flavour non-diagonal.

The strong sector of the SM also allows for CP violation through a dimension-four term $\theta G\tilde{G}$, which is of topological origin. Such a term would lead to flavour-diagonal CP violation and hence to electric dipole moments (EDMs). The current experimental limits on the EDMs of atoms and neutrons [2,3,4]

$$\begin{aligned} |d_{\rm Tl}| &< 9\times10^{-25}\,e\,{\rm cm} \qquad (90\%\ {\rm C.L.})\\ |d_{\rm Hg}| &< 2\times10^{-28}\,e\,{\rm cm} \qquad (95\%\ {\rm C.L.})\\ |d_n| &< 6\times10^{-26}\,e\,{\rm cm} \qquad (90\%\ {\rm C.L.}) \end{aligned} \tag{1}$$

however constrain the strong CP phase to $|\theta| < 10^{-9}$! A comprehensive discussion of this issue can be found in [5]. While θ appears to be extremly tuned, the CKM contribution to the EDMs is several orders of magnitude below the experimntal bounds, e.g. $d_n^{\rm CKM} \sim 10^{-32}\,e\,{\rm cm}$. Therefore, while providing important constraints, the current EDM bonds still leave ample room for new sources of CP violation beyond the SM.

Such new sources of CP violation are indeed very interesting in point of view of the observed baryon asymmetry of the Universe

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.14\pm0.25)\times10^{-10} \tag{2}$$

with n_B, $n_{\bar{B}}$ and n_γ the number densities of baryons, antibaryons and photons, respectively; see [6,7] for recent reviews. The necessary ingredients for baryogenesis [8] i) baryon number violation, ii) C and CP violation and iii) departure from equilibrium are in principle present in the SM, however not with sufficient strength. In particular, the amount of CP violation is not enough. This provides a strong motivation to consider CP violation in extensions of the SM, as reviewed e.g. in [9].

In general, CP violation in extensions of the SM can be either explicit or spontaneous. Explicit CP violation occurs through phases in the Lagrangian, which cannot be rotated away by field redefinitions. This is the standard case in the MSSM, on which I will concentrate in the following. Spontaneous CP violation, on the other hand, occurs if an extra Higgs field develops a complex vacuum expectation value. This can lead to a vanishing θ term as well as to a complex CKM matrix. Spontaneous CP violation is a very interesting and elegant idea, but difficult to realize in SUSY and obviously not possible in the MSSM (where the Higgs potential conserves CP). There has, however, been very interesting new work on left-right symmetric models and SUSY GUTs. For instance, models based on supersymmetric SO(10) may provide a link with the neutrino seesaw and leptogenesis. I do not follow this further in this talk but refer to [9] for a review.

2 CP violation in the MSSM

In the general MSSM, the gaugino mass parameters M_i $(i = 1, 2, 3)$, the higgsino mass parameter μ, and the trilinear couplings A_f can be complex,

$$M_i = |M_i|\,e^{i\phi_i}, \quad \mu = |\mu|\,e^{i\phi_\mu}, \quad A_f = |A_f|\,e^{i\phi_f}, \tag{3}$$

(assuming $B\mu$ to be real by convention) thus inducing explicit CP violation in the model. Not all of the

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[a] *Email:* sabine.kraml@cern.ch

phases in eq. (3) are, however, physical. The physical combinations indeed are $\mathrm{Arg}(M_i\mu)$ and $\mathrm{Arg}(A_f\mu)$. They can

- affect sparticle masses and couplings through their mixing,
- induce CP mixing in the Higgs sector through radiative corrections,
- influence CP-even observables like cross sections and branching ratios,
- lead to interesting CP-odd asymmetries at colliders.

Non-trivial phases, although constrained by EDMs, can hence significantly influence the collider phenomenology of Higgs and SUSY particles, and as we will see also the properties of neutralino dark matter.

Let me note here that CP violation in the MSSM alone is a large field with a vast amount of literature; it is essentially impossible to give a complete review in 25 min. I will hence not try a *tour de force* but rather present some selected examples, and I apologize to those whose work is not mentioned here. This said, let us begin with the MSSM Higgs sector:

2.1 Higgs-sector CP mixing

The neutral Higgs sector of the MSSM consists in principle of two CP-even states, h^0 and H^0, and one CP-odd state, A^0. Complex parameters, eq. (3), here have a dramatic effect, inducing a mixing between the three neutral states through loop corrections [10,11, 12]. The resulting mass eigenstates H_1, H_2, H_3 (with $m_{H_1} < m_{H_2} < m_{H_3}$ by convention) are no longer eigenstates of CP. Owing to the large top Yukawa coupling, the largest effect comes from stop loops, with the size of the CP mixing proportional to [13]

$$\frac{3}{16\pi^2}\,\frac{\Im m(A_t\mu)}{m^2_{\tilde t_1}-m^2_{\tilde t_2}}\,. \tag{4}$$

CP mixing in the Higgs sector can change the collider phenomenology quite substantially. For example, it is possible for the lightest Higgs boson to develop a significant CP-odd component such that its coupling to a pair of vector bosons becomes vanishingly small. This also considerably weakens the LEP bound on the lightest Higgs boson mass [14], as illustrated in Fig. 1, which shows the LEP exclusions at 95% CL (medium-grey or light-green) and 99.7% CL (dark-grey or dark-green) for the CPX scenario with maximal phases; the top mass is taken to be $m_t = 174.3$ GeV. The CPX scenario [15] is the default benchmark scenario for studying CP-violating Higgs-mixing phenomena. It is defined as

$$\begin{aligned} &M_{\tilde Q_3} = M_{\tilde U_3} = M_{\tilde D_3} = M_{\tilde L_3} = M_{\tilde E_3} = M_{\rm SUSY}\,, \qquad (5)\\ &|\mu| = 4\,M_{\rm SUSY}\,,\ \ |A_{t,b,\tau}| = 2\,M_{\rm SUSY}\,,\ \ |M_3| = 1\ \mathrm{TeV}\,. \end{aligned}$$

The free parameters are $\tan\beta$, the charged Higgs-boson pole mass $M_{H^\pm}$, the common SUSY scale $M_{\rm SUSY}$, and the CP phases. Typically one chooses $\phi_\mu = 0$, which leaves $\phi_{t,b}$ and ϕ_3 as the relevant ones. The ATLAS discovery potential [16] for Higgs bosons in the CPX scenario with $\phi_{t,b,3} = \pi/2$ is shown in Fig. 2. As can be seen, also here there remains an uncovered region at small $\tan\beta$ and small Higgs masses, comparable to the holes at small m_{H_1} in Fig. 1,

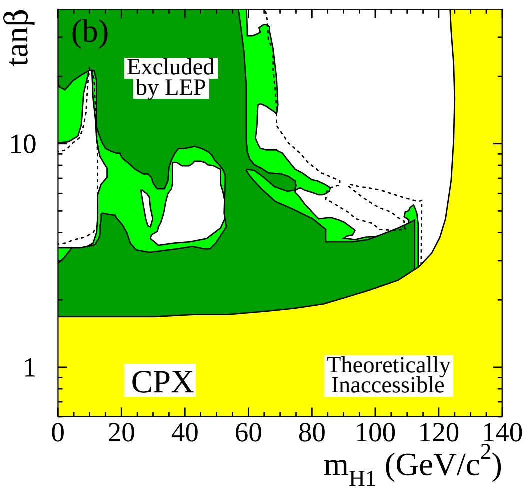

Fig. 1. LEP limits in the CPX scenario, from [14].

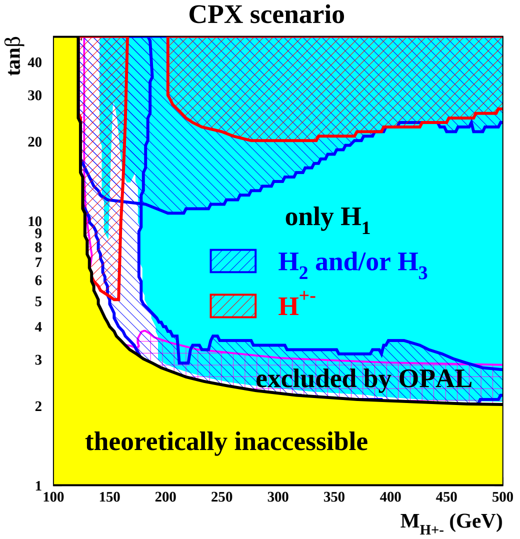

Fig. 2. ATLAS discovery potential for Higgs bosons in the CPX scenario, from [16].

An overview of the implications for Higgs searches at different colliders is given in [17], and a review of MSSM Higgs physics at higher orders, for both CP-conserving and CP-violating cases, in [18]. For an extensive discussion of Higgs-sector CP violation, see the CPNSH report [19].

A question that naturally arises is whether and how the CP properties of the Higgs boson(s) can be determined at the LHC. (At the ILC, which is a high-precision machine in particular for Higgs physics, this can be done quite well, see [20] and references therein).

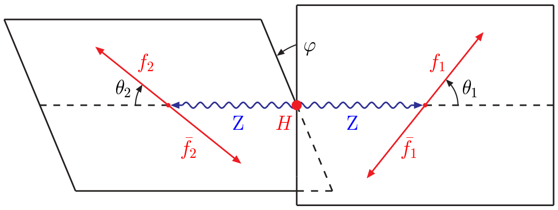

Fig. 3. Definition of the polar angles θ_i ($i = 1,2$) and the azimuthal angle φ for the sequential decay $H \to Z^{(*)}Z \to (f_1\bar{f}_1)(f_2\bar{f}_2)$ in the rest frame of the Higgs boson.

A very promising channel is $H \to ZZ \to 4$ leptons; cf. the contributions by Godbole *et al.*, Buszello and Marquard, and Bluj in [19]. Were here follow Godbole *et al.* [19,21]: The HZZ coupling can be written as in the general form

$$g_{HZZ} \sim [\,a\, g_{\mu\nu} + b\,(k_{2\mu}k_{1\nu} - k_1\cdot k_2 g_{\mu\nu}) + c\,\epsilon_{\mu\nu\alpha\beta}\,{k_1}^{\alpha}{k_2}^{\beta}\,], \qquad (6)$$

up to a factor $ig/(m_Z\cos\theta_W)$, where k_1 and k_2 the four-momenta of the two Z bosons. The terms associated with a and b are CP-even, while that associated with c is CP-odd. $\epsilon_{\mu\nu\alpha\beta}$ is totally antisymmetric with $\epsilon_{0123} = 1$. CP violation is be realized if at least one of the CP-even terms is present (i.e. either $a \neq 0$ and/or $b \neq 0$) and c is non-zero. This can be tested through polar and azimuthal angular distributions in $H \to Z^{(*)}Z \to (f_1\bar{f}_1)(f_2\bar{f}_2)$, c.f. Fig. 3. Denoting the polar angles of the fermions f_1, f_2 in the rest frames of the Z bosons by θ_1 and θ_2, we have e.g.

$$\cos\theta_1 = \frac{(\boldsymbol{p}_{\bar{f}_1} - \boldsymbol{p}_{f_1})\cdot(\boldsymbol{p}_{\bar{f}_2} + \boldsymbol{p}_{f_2})}{|\boldsymbol{p}_{\bar{f}_1} - \boldsymbol{p}_{f_1}||\boldsymbol{p}_{\bar{f}_2} + \boldsymbol{p}_{f_2}|} \qquad (7)$$

where $\boldsymbol{p}_f$ are the three-vectors of the corresponding fermions with $\boldsymbol{p}_{f_1}$ and $\boldsymbol{p}_{\bar{f}_1}$ in their parent Z's rest frame but $\boldsymbol{p}_{f_2}$ and $\boldsymbol{p}_{\bar{f}_2}$ in the Higgs rest frame, see Fig. 3. The angular distribution in θ_i ($i = 1,2$) for a CP-odd state is $\sim (1+\cos^2\theta_i)$, corresponding to transversely polarized Z bosons, which is very distinct from the purely CP-even distribution proportional to $\sin^2\theta_i$ for longitudinally polarized Z bosons in the large Higgs mass limit.$\Im m(c) \neq 0$ will introduce a term linear in $\cos\theta_i$ leading to a forward-backward asymmetry. The distribution for $\cos\theta_1$ is shown in Fig. 4 for a Higgs mass of 200 GeV and a purely scalar, purely pseudoscalar and CP-mixed scenario. The asymmetry is absent if CP is conserved (for both CP-odd and CP-even states) but is non-zero if $\Im m(c) \neq 0$ while simultaneously $a \neq 0$. Another probe of CP violation is the azimuthal angular distribution $d\Gamma/d\varphi$ with φ the angle between the planes of the fermion pairs, see Fig. 3. For a detailed discussion of various distributions and asymmetries sensitive to CP violation in $H \to ZZ \to 4$ leptons, see [21].

Another possibility to test Higgs CP mixing at the LHC are correlations arising in the production process. Here the azimuthal angle correlations between the two additional jets in Hjj events have emerged as a promising tool [22]. Higgs boson production in association with two tagging jets, analysed in detail in [23], is mediated by electroweak vector boson fusion and by gluon fusion. The latter proceeds through top-quark loops, which induce an effective Hgg vertex. Writing the Htt Yukawa coupling as $\mathcal{L}_Y = y_t H\bar{t}t + i\tilde{y}_t A\bar{t}\gamma_5 t$, where H and A denote scalar and pseudoscalar Higgs fields, the tensor structure of the effective Hgg vertex has the form [24,25]

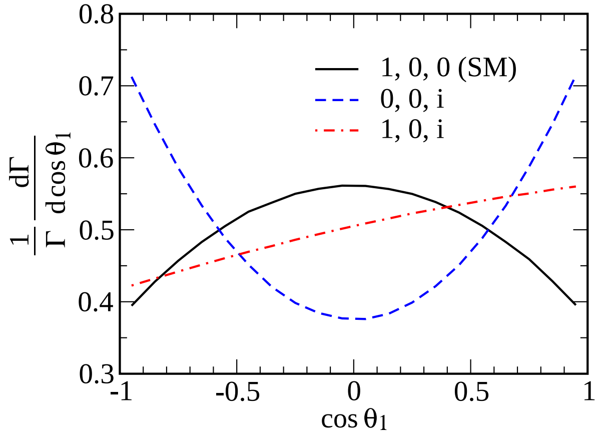

Fig. 4. The normalized differential width for $H \to ZZ \to (f_1\bar{f}_1)(f_2\bar{f}_2)$ with respect to the cosine of the fermion's polar angle. The solid (black) curve shows the SM ($a = 1$, $b = c = 0$) while the dashed (blue) curve is a pure CP-odd state ($a = b = 0$, $c = i$). The dot-dashed (red) curve is for a state with a CP violating coupling ($a = 1$, $b = 0$, $c = i$). One can clearly see an asymmetry in $\cos\theta_1$ for the CP-violating case.

$$T^{\mu\nu} = a_2\,(q_1\cdot q_2\, g^{\mu\nu} - q_1^{\nu}q_2^{\mu}) + a_3\,\varepsilon^{\mu\nu\rho\sigma}q_{1\rho}q_{2\sigma}\,, \qquad (8)$$

with

$$a_2 = \frac{y_t}{y_t^{SM}}\cdot\frac{\alpha_s}{3\pi v} \quad \text{and} \quad a_3 = -\frac{\tilde{y}_t}{y_t^{SM}}\cdot\frac{\alpha_s}{2\pi v}\,. \qquad (9)$$

The azimuthal angle correlation of the two jets is hence sensitive to the CP-nature of the Htt Yukawa coupling. To resolve interference effects between the CP-even coupling a_2 and the CP-odd coupling a_3 it is, however, important to measure the sign of $\Delta\Phi_{jj}$. This can be done by defining $\Delta\Phi_{jj}$ as the azimuthal angle of the “away” jet minus the azimuthal angle of the “toward” jet with respect to the beam direction [24]. The corresponding distributions, for two jets with $p_{Tj} > 30$ GeV, $|\eta_j| < 4.5$, and $|\eta_{j_1} - \eta_{j_2}| > 3.0$, are shown in Fig. 5 for three scenarios of CP-even and CP-odd Higgs couplings [25]. All three cases are well distinguishable, with the maxima in the distributions directly connected to the size of the scalar and pseudoscalar contributions, a_2 and a_3.

2.2 Gauginos and sfermions

The CP-violating phases in (3) directly enter the neutralino, chargino, and sfermion mass matrices, hence

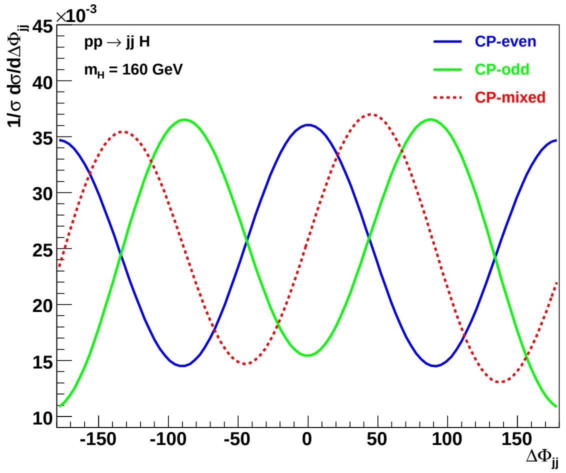

Fig. 5. Normalized distributions of the jet-jet azimuthal angle difference, for the SM CP-even case ($a_3 = 0$), a pure CP-odd ($a_2 = 0$) and a CP-mixed case ($a_2 = a_3 \neq 0$); from [25].

having an important impact on the masses and couplings of these particles. This is particularly interesting for the precision measurements envisaged at the ILC. The effects of CP phases in measurements of neutralinos, charginos, and sfermions at the ILC have been studied in great detail by various groups; see below as well as references in [9,26]. They fall into two different classes. On the one hand, there are CP-even observables: spartice masses, cross sections, branching ratios, etc.. If measured precisely enough, they allow for a parameter determination, either analytically [27, 28] or through a global fit [29]. Beam polarization [26] is essential, but some ambiguities in the phases always remain. We do not discuss this in more detail here. On the other hand, there are CP-odd (or T-odd) observables, e.g. rate asymmetries or triple-product asymmetries, which are a direct signal of CP violation. Indeed the measurement of CP-odd effects is necessary to prove that CP is violated, and to determine the model parameters, including phases, in an unambiguous way.

An expample for a rate asymmetry is the chargino decay into a neutralino and a W boson, $\tilde\chi^\pm_i \to \tilde\chi^0_j W^\pm$. Here, non-zero phases can induce an asymmetry between the decay rates of $\tilde\chi^+_i$ and $\tilde\chi^-_i$,

$$A_{\rm CP} = \frac{\Gamma(\tilde\chi^+_i \to \tilde\chi^0_j W^+) - \Gamma(\tilde\chi^-_i \to \tilde\chi^0_j W^-)}{\Gamma(\tilde\chi^+_i \to \tilde\chi^0_j W^+) + \Gamma(\tilde\chi^-_i \to \tilde\chi^0_j W^-)}\,, \qquad (10)$$

through absorptive parts in the one-loop corrections [30]. Figure 6 shows the dependence of $A_{\rm CP}$ on $\phi_A \equiv \phi_{t,b,\tau}$ for $M_2 = 500$ GeV, $|\mu| = 600$ GeV, $|A| = 400$ GeV, $M_{\tilde Q} = 400$ GeV, and various ϕ_{M_1}. $A_{\rm CP}$ has its maximum at $|\phi_A| \sim \pi/2$ and is larger at large negative values of the phase of M_1. The obvious advantage of such a rate asymmetry is that it can be measured in a 'simple' counting experiment. Analogous asymmetries have been computed for $H^\pm$ in [31,32,33]. Ref. [32] also discusses CP-violating forward-backward asymmetries.

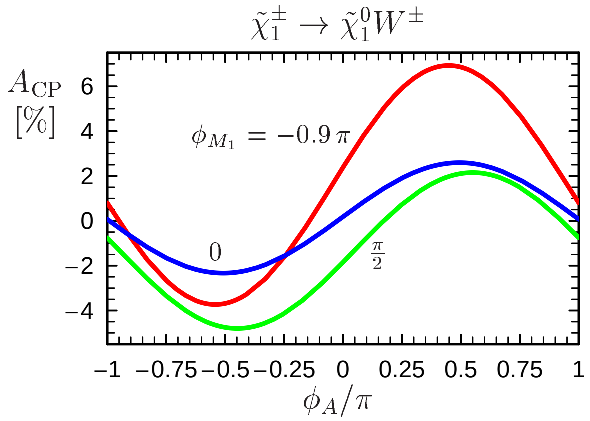

Fig. 6. The dependence of $A^{\tilde\chi^\pm}_{CP}$ on ϕ_A, and various values of ϕ_{M_1}, from [30].

Triple-product asymmetries rely on spin correlations between sparticle production and decay processes. They have been computed for neutralino [34,35,36, 37,38,39,40,41] and chargino [42,43,44] production in e^+e^- followed by two- or three-body decays. Let me take the most recent work [44] on chargino-pair production with subsequent three-body decay as an illustrative example. The processes considered are $e^+e^- \to \tilde\chi^+_1\tilde\chi^-_j$ $(j = 1, 2)$ at a linear collider with longitudinal beam polarizations, followed by three-body decays of the $\tilde\chi^+_1$,

$$\tilde\chi^+_1 \to \tilde\chi^0_1\, \nu\, \ell^+ \quad \text{or} \quad \tilde\chi^+_1 \to \tilde\chi^0_1\, \bar s\, c\,, \qquad (11)$$

where $\ell = e, \mu$. It is assumed that the momenta $\boldsymbol{p}_{\tilde\chi^+_1}$, $\boldsymbol{p}_\ell$, $\boldsymbol{p}_c$ and $\boldsymbol{p}_s$ of the associated particles can be measured or reconstructed. The relevant triple products are:

$$\mathcal{T}_\ell = \boldsymbol{p}_{\ell^+} \cdot (\boldsymbol{p}_{e^-} \times \boldsymbol{p}_{\tilde\chi^+_1})\,, \qquad (12)$$

$$\mathcal{T}_q = \boldsymbol{p}_{\bar s} \cdot (\boldsymbol{p}_c \times \boldsymbol{p}_{e^-})\,. \qquad (13)$$

Note that $\mathcal{T}_\ell$, relates momenta of initial, intermediate and final particles, whereas $\mathcal{T}_q$, uses only momenta from the initial and final states. Therefore, both triple products depend in a different way on the production and decay processes. From $\mathcal{T}_{\ell,q}$ one can define T-odd asymmetries

$$A_T(\mathcal{T}_{\ell,q}) = \frac{N[\mathcal{T}_{\ell,q} > 0] - N[\mathcal{T}_{\ell,q} < 0]}{N[\mathcal{T}_{\ell,q} > 0] + N[\mathcal{T}_{\ell,q} < 0]}\,, \qquad (14)$$

where $N[\mathcal{T}_{\ell,q} > (<)\ 0]$ is the number of events for which $\mathcal{T}_{\ell,q} > (<)\ 0$. A genuine signal of CP violation is obtained by combining $A_T(\mathcal{T}_{\ell,q})$ with the corresponding asymmetry $\bar A_T(\mathcal{T}_{\ell,q})$ for the charge-conjugated processes:

$$A_{\rm CP}(\mathcal{T}_{\ell,q}) = \frac{A_T(\mathcal{T}_{\ell,q}) - \bar A_T(\mathcal{T}_{\ell,q})}{2}\,. \qquad (15)$$

Figure 7 shows the phase dependence of $A_{\rm CP}(\mathcal{T}_q)$ for $e^+e^- \to \tilde\chi^+_1\tilde\chi^-_2$ followed by $\tilde\chi^+_1 \to \tilde\chi^0_1 \bar s c$ for $\sqrt{s} =$

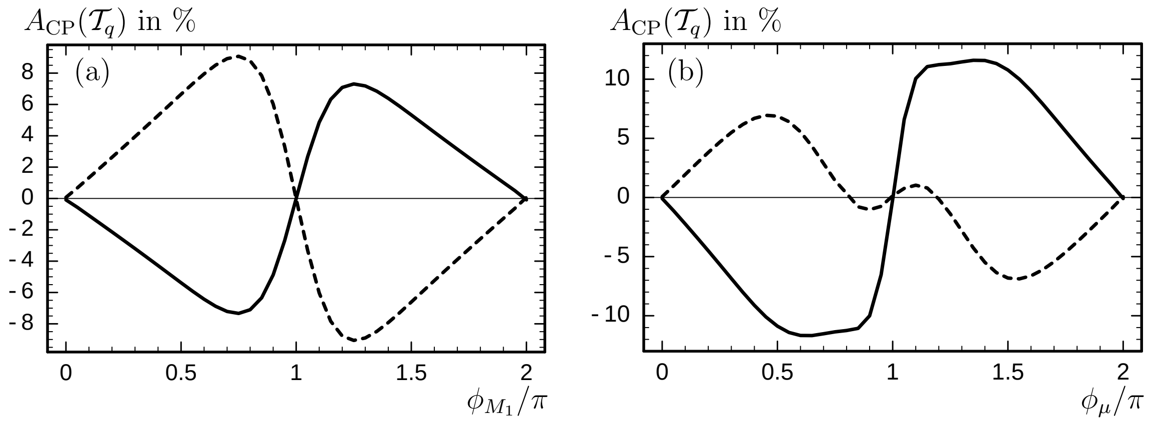

Fig. 7. CP asymmetry $A_{\rm CP}(\mathcal{T}_q)$ for $e^+e^- \to \tilde\chi_1^+\tilde\chi_2^-$ with subsequent decay $\tilde\chi_1^+ \to \tilde\chi_1^0 \bar s c$ for $\sqrt{s} = 500$ GeV and beam polarizations $(P_{e^-}, P_{e^+}) = (-0.8, +0.6)$ (solid), $(P_{e^-}, P_{e^+}) = (+0.8, -0.6)$ (dashed); the parameters are $M_2 = 280$ GeV, $|\mu| = 200$ GeV, $\tan\beta = 5$, with $\phi_\mu = 0$ in (a) and $\phi_1 = 0$ in (b); from [44].

500 GeV and polarized $e^\pm$ beams. The authors conclude that $A_{\rm CP}(\mathcal{T}_q)$ can be probed at the 5σ level in a large region of the MSSM parameter space, while $A_{\rm CP}(\mathcal{T}_\ell)$ has a somewhat lower sensitivity.

2.3 EDM constraints

Let us next discuss the EDM constraints in some more detail. The constraints eq. (1), especially the one on $d_{\rm Tl}$, translate into a tight bound on the electron EDM,

$$|d_e| < 1.6 \times 10^{-27}\, e\,{\rm cm}. \qquad (16)$$

Setting all soft breaking parameters in the selectron and gaugino sector equal to $M_{\rm SUSY}$, one can derive a simplified formula for the one-loop contributions [45]

$$d_e = f_{\rm S}\Big[\Big(\frac{5g_2^2}{24} + \frac{g_1^2}{24}\Big)\sin[{\rm Arg}(\mu M_2)]\tan\beta + \frac{g_1^2}{12}\sin[{\rm Arg}(M_1^* A_e)]\Big]\,, \qquad (17)$$

where $f_{\rm S} = (e m_e)/(16\pi^2 M_{\rm SUSY}^2)$, and ${\rm Arg}(B\mu) = 0$ by convention. Note the $\tan\beta$ enhancement of the first term. It is the main reason why the phase of μ is more severely constrained than the phases of the A parameters. The phases of the third generation, $\phi_{t,b,\tau}$, only enter the EDMs at the two-loop level. However, there can be a similar $\tan\beta$ enhancement for these two-loop contributions [46], so they have to be taken into account as well.

Indeed, the EDM constraints pose a serious problem in the general MSSM: for $O(100)$ GeV masses and $O(1)$ phases, the EDMs are typically three(!) orders of magnitude too large [47,48,49,50]. Some efficient suppression mechanism is needed to satisfy the experimental bounds. The possibilities include

- small phases,
- heavy sparticles [51,52,53,54],
- accidental cancellations [55,56,57,58,59,60,61],
- flavour off-diagonal CP phases [63],
- lepton flavour violation [64].

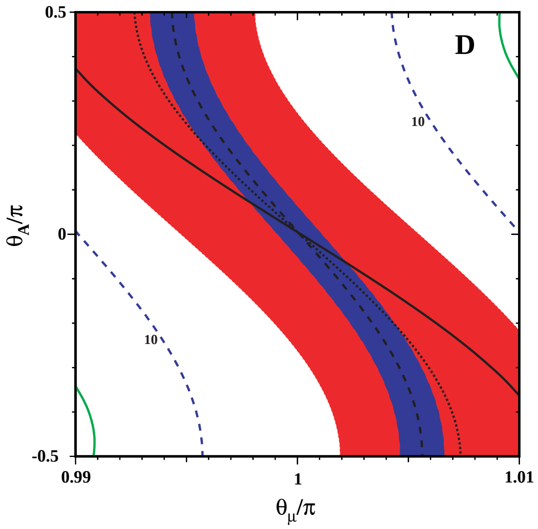

Fig. 8. The Tl (blue dashed) and neutron (red dotted) EDMs relative to their respective experimental limits in the θ_μ, θ_A plane for benchmark point D of [65]. Inside the shaded regions, the EDMs are less than or equal to their experimental bounds. Each of the EDMs vanish along the black contour within the shaded region; from [65].

Detailed analyses of the EDM constraints have recently been performed e.g. in [5,65,62]. As example that large phases can be in agreement with the current EDM limits, Fig. 8 shows the results for the CMSSM benchmark point D of [65], which has $(m_{1/2}, m_0, \tan\beta) = (525, 130, 10)$. The strongest constraint comes from the EDM of Tl; that of Hg is not shown because it is satisfied over the whole plane. As can be seen, for this benchmark point there is no limit to θ_A, while $|\theta_\mu - \pi| \leq 0.065\pi$.

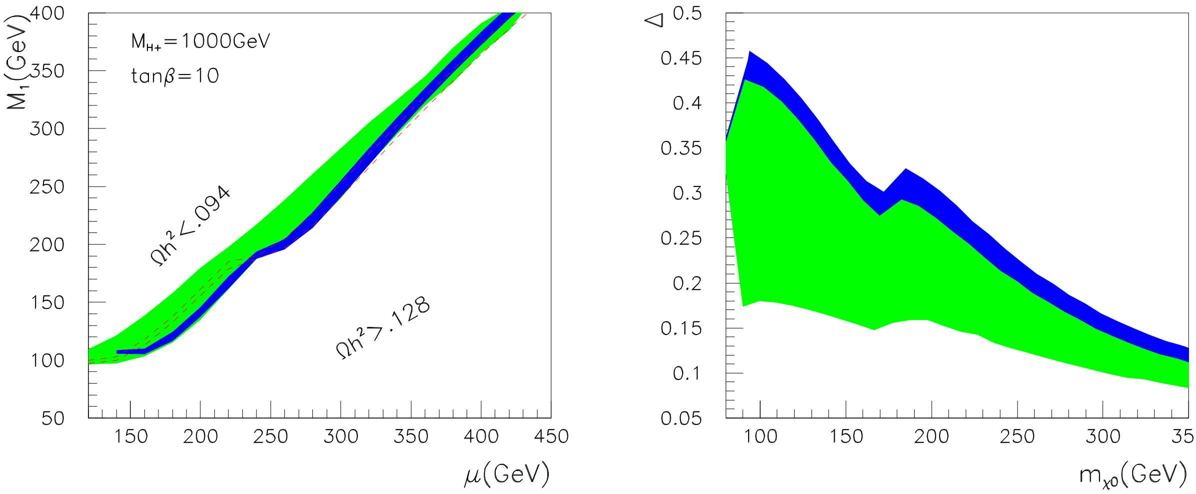

Fig. 9. Left: The 2σ WMAP bands in the M_1–μ plane for $\tan\beta = 10$, $m_{H^+} = M_S = A_t = 1$ TeV, for all phases zero (blue/dark grey band), for $\phi_\mu = 180°$ (or $\mu < 0$) and all other phases zero (dashed red lines) and for arbitrary phases (green/light grey band). Right: The corresponding relative mass difference $\Delta \equiv (m_{\tilde\chi_1^\pm} - m_{\tilde\chi_1^0})/m_{\tilde\chi_1^0}$ as function of $m_{\tilde\chi_1^0}$ for all phases zero (blue/dark grey band) and for arbitrary phases (green/light grey band). From [74].

2.4 Neutralino relic density

If the $\tilde\chi_1^0$ is the lightest supersymmetric particle (LSP) and stable, it is a very good cold dark matter candidate. In the framework of thermal freeze-out, its relic density is $\Omega h^2 \sim 1/\langle\sigma_A v\rangle$, where $\langle\sigma_A v\rangle$ is the thermally averaged annihilation cross section summed over all contributing channels. These channels are: annihilation of a bino LSP into fermion pairs through t-channel sfermion exchange in case of very light sparticles; annihilation of a mixed bino-Higgsino or bino-wino LSP into gauge boson pairs through t-channel chargino and neutralino exchange, and into top-quark pairs through s-channel Z exchange; and annihilation near a Higgs resonance (the so-called Higgs funnel); and finally coannihilation processes with sparticles that are close in mass with the LSP. Since the neutralino couplings to other (s)particles sensitively depend on CP phases, the same can be expected for $\langle\sigma_A v\rangle$ and hence Ωh^2.

The effect of CP phases on the neutralino relic density was considered in [54,66,67,68,69,70,71,72,73], although only for specific cases. The first general analysis, (i) including all annihilation and coannihilation processes and (ii) separating the phase dependece of the couplings from pure kinematic effects, was done in [74].

It was found that modifications in the couplings due to non-trivial CP phases can lead to variations in the neutralino relic density of up to an order of magnitude. This is true not only for the Higgs funnel but also for other scenarios, like for instance the case of a mixed bino-higgsino LSP. Even in scenarios which feature a modest phase dependence once the kinematic effects are singled out, the variations in Ωh^2 are comparable to (and often much larger than) the $\sim 10\%$ range in Ωh^2 of the WMAP bound. Therefore, when aiming at a precise prediction of the neutralino relic density from collider measurements, it is clear that one does not only need precise sparticle spectroscopy but one also has to precisely measure the relevant couplings, including possible CP phases.

This is illustrated in Fig. 9, which shows the regions where the relic density is in agreement with the 2σ WMAP bound, $0.0945 < \Omega_{\rm CDM}h^2 < 0.1287$, for the case of a mixed bino-higgsino LSP. When all phases are zero, only the narrow blue (dark grey) band is allowed. When allowing all phases to vary arbitrarily, while still satisfying the EDM constraints, the allowed band increases to the the green (light grey) region. In the $|M_1|$–$|\mu|$ plane (left panel), the allowed range for μ increases roughly from $\delta\mu \sim 10$ GeV to $\delta\mu \sim 50$ GeV for a given $|M_1|$. In terms of relative mass differences (right panel) this means that in the CP-violating case much smaller $\tilde\chi_1^\pm$–$\tilde\chi_1^0$ mass differences can be in agreement with the WMAP bound than in the CP-conserving case.

3 Conclusions

The observed baryon asymmetry of the Universe necessiates new sources of CP violation beyond those of the SM. I this talk, I have discussed effects of such new CP phases, focussing on the case of the MSSM. The topics covered include CP-mixing in the Higgs sector and its measurement at the LHC, CP-odd observables in the gaugino sector at the ILC, EDM constraints, and the neutralino relic density. Each topic was discussed by means of some recent example(s) from the literature. For a more extensive discussion, in particular of topice that could not be covered here, I refer the reader to the recent review by Ibrahim and Nath [9].

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