

CP-violation in the NMSSM

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Sources of CP-violation in the NMSSM

Why should we consider CP-violation?

- *Model builder's perspective:* CP-phases are possible + CP is broken
⇒ No reason for discarding CP-phases.
[SM: CP is violated at the first opportunity (CKM).]
- *Phenomenological motivation:* Sources of CP-violation beyond the SM are required in order to explain the Baryogenesis.
- *Other:* explain occasional tensions in flavor observables.

Origin of CP-phases

- *Explicit CP-violation* at high energy → complex input parameters.
- *Spontaneous CP-violation:* minimization of the Higgs potential induces complex Higgs v.e.v.'s.

$$\langle H_u \rangle = (0, v_u e^{i\varphi_u})^T \quad \langle H_d \rangle = (v_d e^{i\varphi_d}, 0)^T \quad \langle S \rangle = s e^{i\varphi_s}$$

- Forbidden at tree-level in the \mathbb{Z}_3 -cons. NMSSM [Romao (1986)].
- Difficult at the radiative level in the \mathbb{Z}_3 -cons. NMSSM.
- Possible in the ‘general’ NMSSM.

- *CP-violation at non-zero temperature:* possible, provided at least one small phase at $T = 0$ [Comelli et al. (1994)].

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Phase-counting (\mathbb{Z}_3 -symmetric NMSSM)

- Superpotential:

$$W_{\text{NMSSM}} = \lambda e^{i\phi_1} \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3} e^{i\phi_2} \hat{S}^3 - \hat{H}_u \cdot \hat{Q}_L [Y_u] \hat{U}_R^c + \hat{H}_d \cdot \hat{Q}_L [Y_d] \hat{D}_R^c + \hat{H}_d \cdot \hat{L}_L [Y_e] \hat{E}_R^c$$

- Soft terms:

$$\begin{aligned} -\mathcal{L}_{\text{soft}} \ni & -M_1 e^{i\phi_{M1}} \tilde{b} \tilde{b} - M_2 e^{i\phi_{M2}} \tilde{w}_\alpha \tilde{w}_\alpha - M_3 e^{i\phi_{M3}} \tilde{g}_a \tilde{g}_a \\ & + \lambda A_\lambda e^{i\phi_{A_\lambda}} S H_u \cdot H_d + \frac{\kappa}{3} A_K e^{i\phi_{A_K}} S^3 \\ & - H_u \cdot Q_L [Y_u A_u] U_R^c + H_d \cdot Q_L [Y_d A_d] D_R^c + H_d \cdot L_L [Y_e A_e] E_R^c + h.c. \\ & + Q_L^\dagger [m_Q^2] Q_L + U_R^{c\dagger} [m_U^2] U_R^c + D_R^{c\dagger} [m_D^2] D_R^c + L_L^\dagger [m_L^2] L_L + E_R^{c\dagger} [m_E^2] E_R^c \end{aligned}$$

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- ‘new’ minimization conditions w.r.t. $\text{Im}[H_u^0]$, $\text{Im}[H_d^0]$, $\text{Im}[S]$.

- Symmetry: $\{\hat{H}_u \mapsto e^{i\varphi} \hat{H}_u, \hat{H}_d \mapsto e^{-i\varphi} \hat{H}_d, \text{etc.}\}$ \rightarrow only 2 min. cond.
- Higgs field re-def.: $\{\hat{S} \mapsto e^{-i\varphi_s} \hat{S}, \hat{H}_{u,d} \mapsto e^{-i\varphi_{u,d}} \hat{H}_{u,d}\}$ $+ \phi_\lambda \mapsto \tilde{\phi}_\lambda$ (etc.)
- Global phase: intervenes only at the topological level.
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Phase-counting (\mathbb{Z}_3 -symmetric NMSSM)

- Superpotential:
$$W_{\text{NMSSM}} = e^{i\tilde{\phi}_\lambda} \left\{ \lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3} e^{i\phi_0} \hat{S}^3 \right. \\ \left. + [\hat{H}_u^0 \hat{U}_L - \hat{H}_u^+ \hat{D}_L V_{CKM}^T] Y_u \hat{U}_R^c + [\hat{H}_d^0 \hat{D}_L - \hat{H}_d^- \hat{U}_L V_{CKM}^*] Y_d \hat{D}_R^c + \hat{H}_d \cdot \hat{L}_L Y_e \hat{E}_R^c \right\}$$
- Soft terms:
$$-\mathcal{L}_{\text{soft}} \ni e^{-i\tilde{\phi}_\lambda} \left\{ -M_1 e^{i\varphi_{M_1}} \tilde{b} \tilde{b} - M_2 e^{i\varphi_{M_2}} \tilde{w}_\alpha \tilde{w}_\alpha - M_3 e^{i\varphi_{M_3}} \tilde{g}_a \tilde{g}_a \right. \\ \left. + \lambda A_\lambda e^{i\varphi_{A_\lambda}} S H_u \cdot H_d + \frac{\kappa}{3} A_\kappa e^{i\varphi_{A_\kappa}} S^3 \right. \\ \left. - H_u \cdot Q_L Y_u [A_u] U_R^c + H_d \cdot Q_L Y_d [A_d] D_R^c + H_d \cdot L_L Y_e [A_e] E_R^c \right\} + h.c. \\ + Q_L^\dagger [m_Q^2] Q_L + U_R^{c\dagger} [m_U^2] U_R^c + D_R^{c\dagger} [m_D^2] D_R^c + L_L^\dagger [m_L^2] L_L + E_R^{c\dagger} [m_E^2] E_R^c$$
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- 2 ‘new’ minimization conditions w.r.t. $Im[H_d^0]$, $Im[S]$.

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Aftermath:

- 1 singlet phase from the superpotential: ϕ_0 ;
 - 3 gaugino phases: φ_{M_1} , φ_{M_2} , φ_{M_3} ;
 - up to 9 sfermion phases (under MFV assumption): $\phi_{A_{t,b,\tau}}$, $\phi_{A_{c,s,\mu}}$, $\phi_{A_{u,d,e}}$.
 - + 2 implicit Higgs phases φ_{A_λ} , φ_{A_κ} ;
 - + global phases $\tilde{\phi}_\lambda$, $\arg\{\det([Y_u], [Y_d], [Y_e])\}$, etc.
- the NMSSM has 1 additional phase w.r.t. the MSSM.

CP-phases and RGE's

Phases from the superpotential

No running (at least up to two-loop order): $\frac{d\phi_0}{d \log(\mu)} = 0$
→ The RGE's of $\lambda, \kappa, Y_{u,d,e}$ is unchanged w.r.t. CP-conservation.

Soft phases

- the gaugino phases do not run at 1L: $\frac{d\varphi_{M_i}}{d \log(\mu)} = O(2L)$
- the phases from trilinear couplings run at 1L: $\frac{d\phi_{A_i}}{d \log(\mu)} = O(1L)$

→ A CP-phase at high-energy will propagate among the soft-terms.

Consequences for the spectrum – SUSY fermions

Gaugino phases

$$\mathcal{L} \ni M_i e^{i\varphi_{M_i}} \tilde{g}_a \tilde{g}_a = -M_i \tilde{\mathcal{G}}_a \tilde{\mathcal{G}}_a \quad , \quad \tilde{\mathcal{G}}_a \equiv -i e^{i\frac{\varphi_{M_i}}{2}} \tilde{g}_a$$

However the phase reappears in the couplings:

$$\mathcal{L} \ni i g_i \tilde{F}^* T_i^a f \tilde{g}_a + h.c. = -e^{-i\frac{\varphi_{M_i}}{2}} g_i \tilde{F}^* T_i^a f \tilde{\mathcal{G}}_a + h.c.$$

Singlino phase

$$\mathcal{L} \ni -2\kappa e^{i\phi_0} S \tilde{s} \tilde{s} = -2\kappa S \tilde{h}_s \tilde{h}_s \quad , \quad \tilde{h}_s \equiv e^{i\frac{\phi_0}{2}} \tilde{s}$$

However the phase reappears in the couplings:

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Charginos and neutralinos

- $\begin{cases} \chi_i^+ = V_{iw}(-i\tilde{w}^+) + V_{iu}\tilde{h}_u^+ \\ \chi_i^- = U_{iw}(-i\tilde{w}^-) + U_{id}\tilde{h}_d^- \end{cases} \quad U, V \text{ are unitary (complex).}$
- $\chi_i^0 = N_{ib}(-i\tilde{b}) + N_{iw}(-i\tilde{w}^0) + N_{id}\tilde{h}_d^0 + N_{iu}\tilde{h}_u^0 + N_{is}\tilde{s} \quad N \text{ complex orthogonal.}$

→ The complex phases appear in the couplings to Higgs / Sfermions / fermions (via U, V, N).

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Consequences for the spectrum – Scalars

Sfermions

Hermitic mass matrix

(ϕ_{A_f} in off-diagonal terms)

$$\rightarrow \tilde{F}_i = U_{iL}^{\tilde{F}} \tilde{F}_L + U_{iR}^{\tilde{F}} \tilde{F}_R^{c*} \quad U^{\tilde{F}} \text{ unitary.}$$

$\rightarrow \phi_{A_f}$ appear in couplings to Higgs bosons;

+ in couplings to SM-fermions/chargino-neutralinos (through $U^{\tilde{F}}$).

Higgs sector

- No phase in the charged-Higgs sector (gauge invariance).
- Mixing of CP-even and CP-odd neutral components.
 - No CP-mixing in the doublet sector at tree-level (= MSSM).
 - $\phi_0 \Rightarrow$ singlet-singlet + singlet-doublet CP-mixing.
 - doublet-doublet mixing at the radiative level.
 - ⇒ Higgs mass-matrix 5×5 symmetric.

Mass-states are superpositions of CP-even + CP-odd components.

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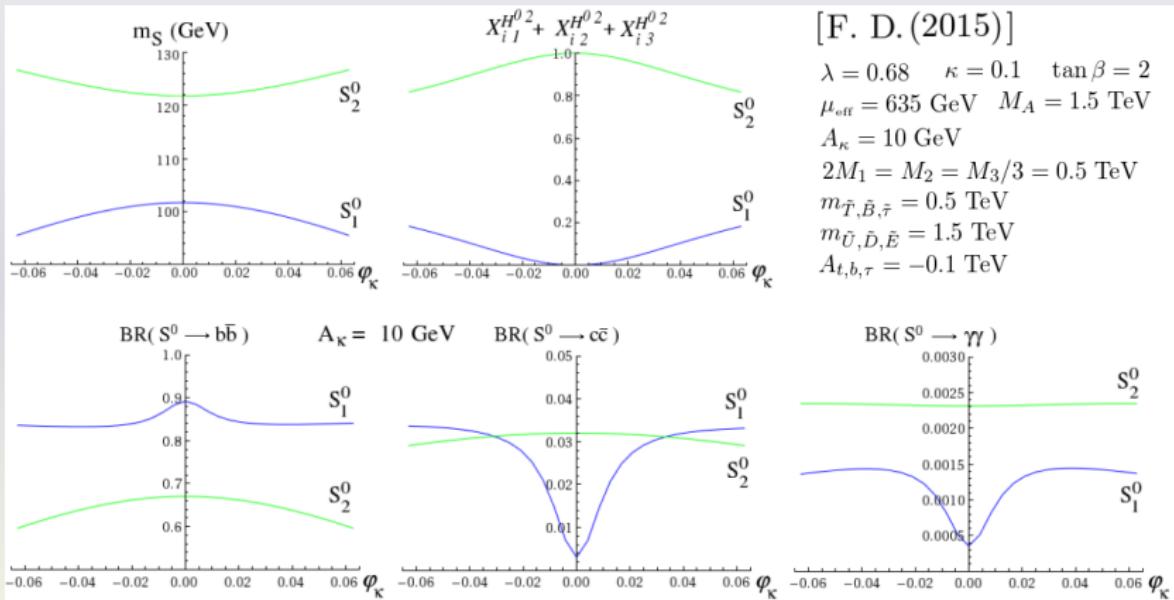
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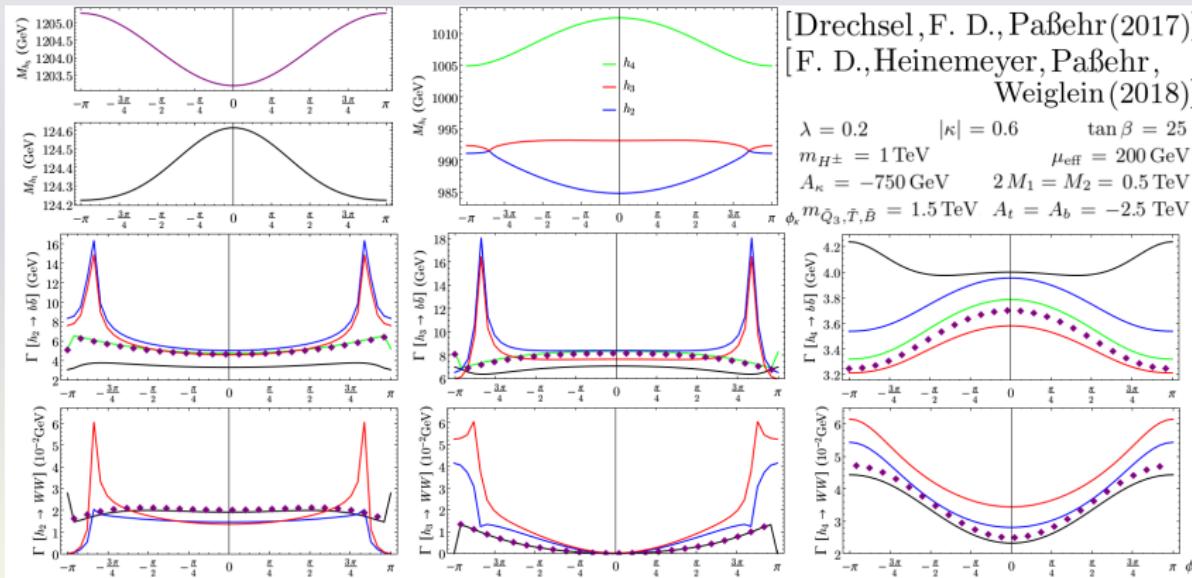
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Consequences for the spectrum – Higgs-mixing



Mixing of the CP-odd singlet with the SM-like Higgs:
 → Uplift of the mass of the SM-like state.
 → Possible ‘CP-even’ signature of the singlet.

Consequences for the spectrum – Higgs-mixing (continued)



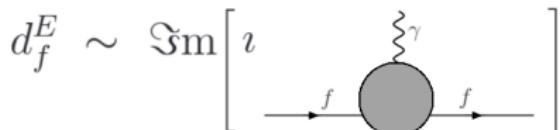
Mixing of the CP-even singlet with the heavy CP-even and odd doublets.

Electric Dipole Moments

$$\mathcal{L}_{\text{EDM}} = -\frac{i}{2} d_f^E F^{\mu\nu} \bar{f} \sigma_{\mu\nu} \gamma_5 f$$

$E_\gamma \ll m_f$

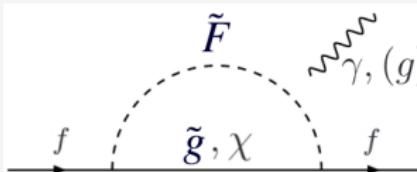
Sensitive to imaginary parts
of couplings.



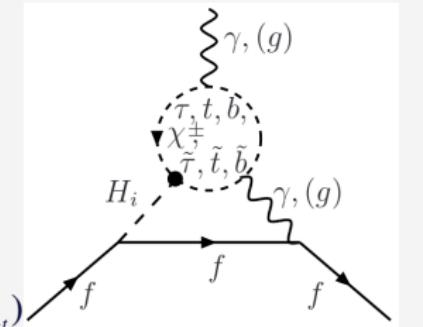
Experimental limits

- Thallium EDM: $d_{Tl}^E \sim 585 d_e^E$
 $d_{Tl}^E \leq 10^{-24} e \text{ cm}$ (90% CL) [Regan et al. (2002)]
- Neutron EDM: $d_n^E \sim (d_u^{E,C}, d_d^{E,C}, d_s^{E,C}, \dots)$
 $d_n^E \leq 3 \cdot 10^{-26} e \text{ cm}$ (90% CL) [Baker et al. (2006)]
- Mercury EDM: $d_{Hg}^E \sim (d_e^E, d_u^{E,C}, d_d^{E,C}, \dots)$
 $d_{Hg}^E \leq 3.1 \cdot 10^{-29} e \text{ cm}$ (95% CL) [Griffith et al. (2009)]
- Thorium monoxide: $d_{ThO}^E \sim (d_e^E, \dots)$
 $d_e^E \leq 10^{-28} e \text{ cm}$ (90% CL) [Baron et al. (2013)]
 → No evidence for EDMs of elementary particles.

NMSSM contributions to the EDMs



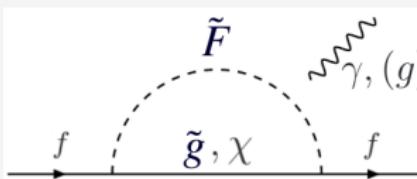
- φ_{M_i} and $\phi_{A_{e,u,d,s}}$ generate $d_{e,u,d,s}^{E,C}$ at 1-loop.
- Large Bar-Zee contributions at 2-loop:
→ sensitive to phases in the Higgs sector (ϕ_0, ϕ_{A_t})



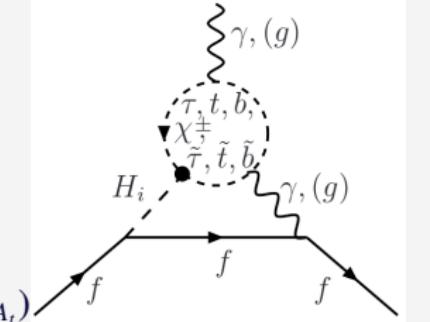
Constraining New Physics contributions to EDMs – Caveat

- Connection between $d_{e,u,d,s}^{E,C}$ and experimental results interpreted by atomic/nuclear models. → are they reliable?
[For instance, the transition SM \rightarrow chiral for $s \rightarrow d$ operators fails.]
- What about the “Old Physics” contributions to the EDMs?
 - Phase shifts of any QCD-charged fermion $\rightarrow L_\mu = \theta \bar{q}_\mu G_\mu^\alpha \tilde{G}_{\alpha\mu}$
 - θ contributes to d_e^C [Baluni (1979), Crewther et al. (1979)]
 - Does it make sense to take EDMs into account without introducing (low-energy) new-physics addressing the strong CP-problem?

NMSSM contributions to the EDMs



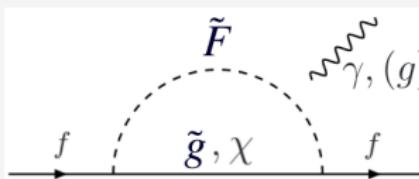
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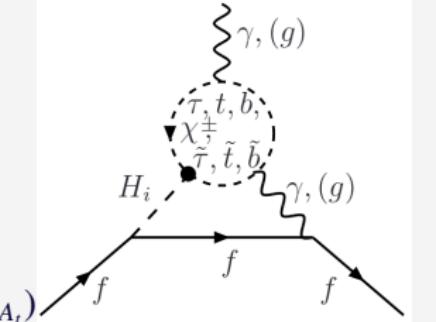
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NMSSM contributions to the EDMs



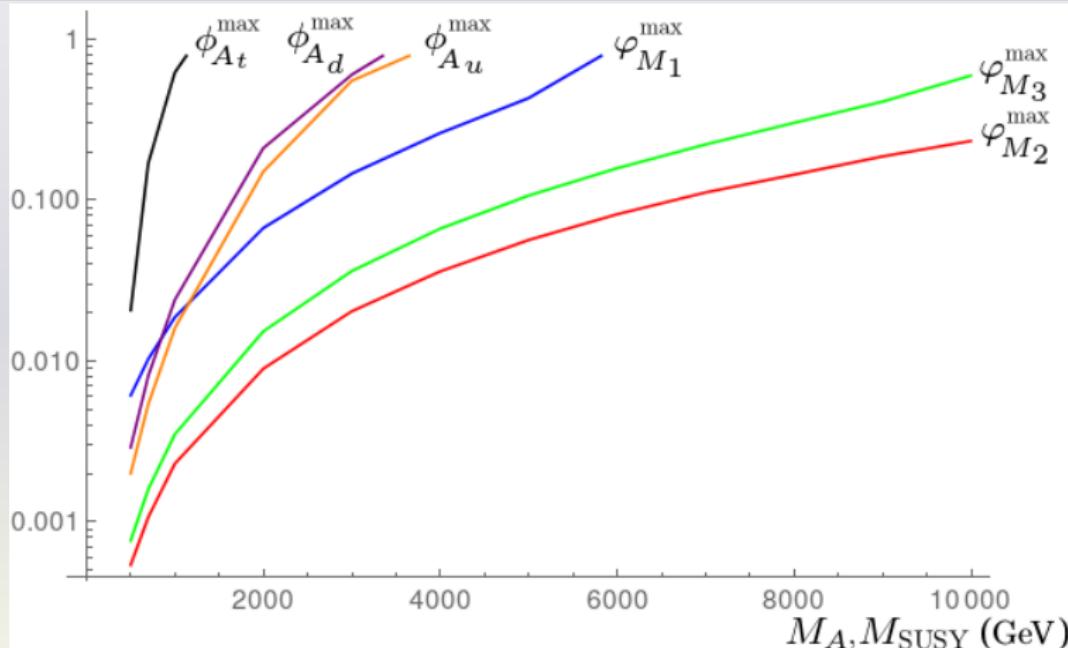
- φ_{M_i} and $\phi_{A_{e,u,d,s}}$ generate $d_{e,u,d,s}^{E,C}$ at 1-loop.
- Large Bar-Zee contributions at 2-loop:
→ sensitive to phases in the Higgs sector (ϕ_0, ϕ_{A_t})



Constraining New Physics contributions to EDMs – Caveat

- Connection between $d_{e,u,d,s}^{E,C}$ and experimental results interpreted by atomic/nuclear models:
→ are they reliable?
[For instance, the transition SM → chiral for $s \rightarrow d$ operators fails.]
- What about the “Old Physics” contributions to the EDMs?
→ Phase shifts of any QCD-charged fermion $\Rightarrow \mathcal{L}_\theta = \theta \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}_{a\mu\nu}$
→ θ contributes to d_n^E [Baluni (1979), Crewther et al. (1979)]
⇒ Does it make sense to take EDMs into account without introducing (low-energy) new-physics addressing the strong CP-problem?

EDM constraints on soft phases



Small phases favored for light spectra. → A sign that M_{SUSY} large?
→ Or new fine-tuning?

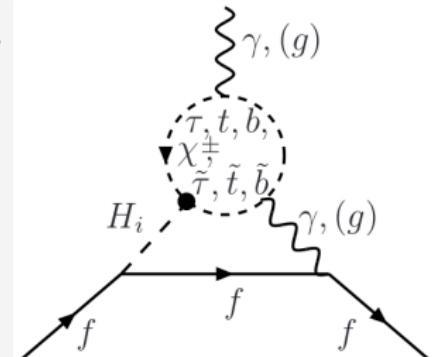
In fact, comparable to the SUSY Flavor problem:
maybe the SUSY breaking mechanism does not generate new phases.

EDMs and the singlet phase

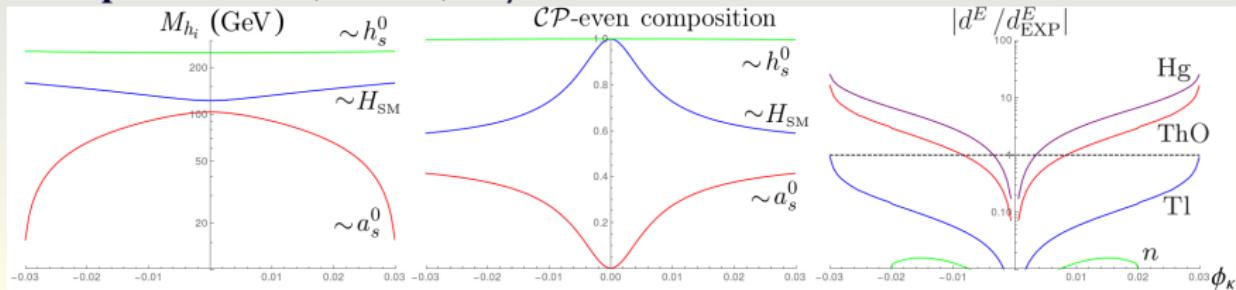
- ϕ_0 induces CPV mixing in the Higgs sector.
- Bar-Zee graph sensitive to Higgs CPV.
- CPV related to singlet-doublet mixing.
- EDMs mostly involve doublet Higgs.

Weak constraints

- if singlets decouple ($\lambda \rightarrow 0$).
- if singlets far from doublet states.
- if BSM Higgs heavy.

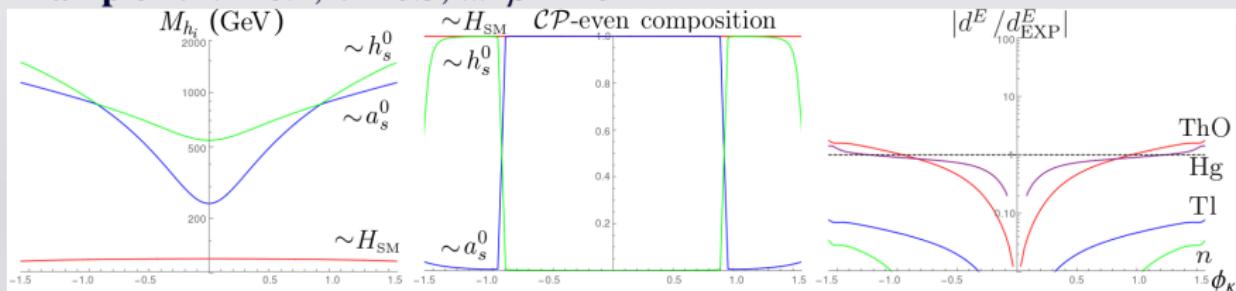


Example 1: $\lambda = 0.7$, $\kappa = 0.1$, $\tan\beta = 2$

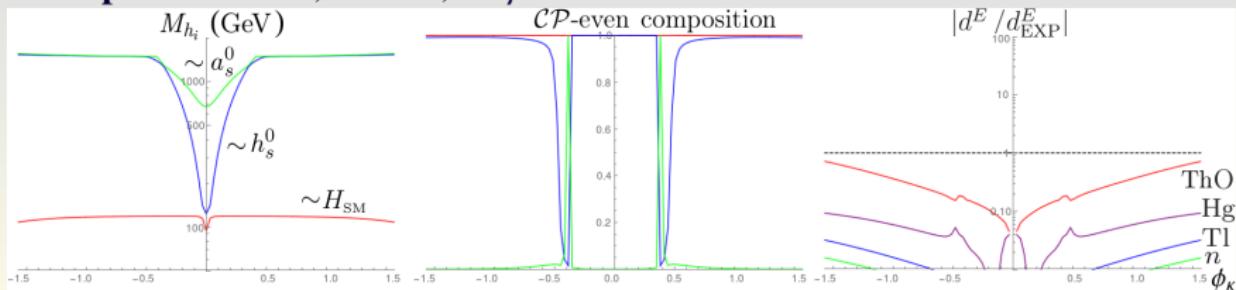


EDMs and the singlet phase (continued)

Example 2: $\lambda = 0.4$, $\kappa = 0.3$, $\tan\beta = 10$



Example 3: $\lambda = 0.1$, $\kappa = 0.1$, $\tan\beta = 10$



Conclusions

- CP-violation can enter the NMSSM at the level of
 - soft terms (MSSM-like);
 - the superpotential (singlet).
- It is motivated by considerations of fine-tuning + Baryogenesis.
- It opens the possibility to CP-even / CP-odd mixing.
- EDMs place strong constraints at low-mass / for large mixing.
 - However, the strong CP-problem may suggest the need for physics beyond the (NMS)SM.