Signals of H/A mixing in CP violating SUSY at the Photon Linear Collider

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Outline:

- Motivation
- Complex mass matrix
  - general structure and H/A mixing
  - example: MSSM with CP-violation
- Experimantal signatures at the PLC
- Conclusions

Motivation

Supersymmetry – best motivated extension of the SM; employs two Higgs doublets

- **at tree level the Higgs potential severly constrained**

$\Rightarrow$ **quartic couplings are gauge couplings**

$\Rightarrow$ **no CP violation**

- **however, loop corrections are very important and induce**

$\Rightarrow$ **all possible quartic couplings**

$\Rightarrow$ **and CP-violating effects**

in the effective Higgs potential

- **if low-scale supersymmetry breaking** **[Casas, Espinosa, Hidalgo]**

$\Rightarrow$ **even the tree level effective Higgs potential may assume the most general form**

Therefore

Consider the most general two-Higgs doublet model as a generic model to explore the CP-violating Higgs sector

Complex mass matrix

General two-Higgs doublet model $\ni$ loop-corrected MSSM Higgs sector

- **The most general gauge invariant scalar potential**

$$\begin{aligned}\mathcal{V} &= m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - [m_{12}^2\Phi_1^\dagger\Phi_2 + \mathrm{h.c.}]\\ &+ \tfrac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \tfrac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)\\ &+ \left\{\tfrac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \left[\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)\right]\Phi_1^\dagger\Phi_2 + \mathrm{h.c.}\right\}\end{aligned}$$

- **In many discussions: to avoid tree-level FCNC impose the Z_2 symmetry implying $m_{12} = \lambda_5 = \lambda_6 = \lambda_7 = 0$**
- **conventionally, in the CP-conserving case $\Longrightarrow h, H, A$ base**
- **We take all terms non-zero: the CP-violating 2HDM**

[Gunion et al.'02, Ginzburg et al.,'02,'04, Dubinin et al.,'02,'04, S.Y.Choi et al.,'04]

- the mass matrix M^2 in the h, H, A basis takes the form

$$\begin{bmatrix} \lambda + (m_A^2/v^2 - \lambda_A)c_\gamma^2 c_{2\gamma}^{-1} & 0 & -\hat{\lambda}_p s_\gamma - \lambda_p c_\gamma \\ 0 & \lambda - (m_A^2/v^2 - \lambda_A)s_\gamma^2 c_{2\gamma}^{-1} & -\hat{\lambda}_p c_\gamma + \lambda_p s_\gamma \\ -\hat{\lambda}_p s_\gamma - \lambda_p c_\gamma & -\hat{\lambda}_p c_\gamma + \lambda_p s_\gamma & m_A^2/v^2 \end{bmatrix}$$

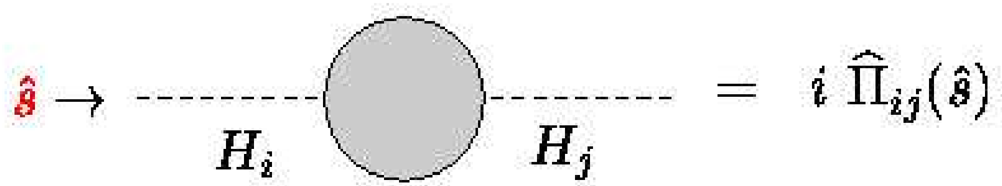
i.e. h, H, A all mix $\Longrightarrow$ H_1, H_2, H_3 mass-eigenstates

- $\hat{\lambda}_p, \lambda_p$ and λ_q are combinations of imaginary parts of λ_5, λ_6 and λ_7

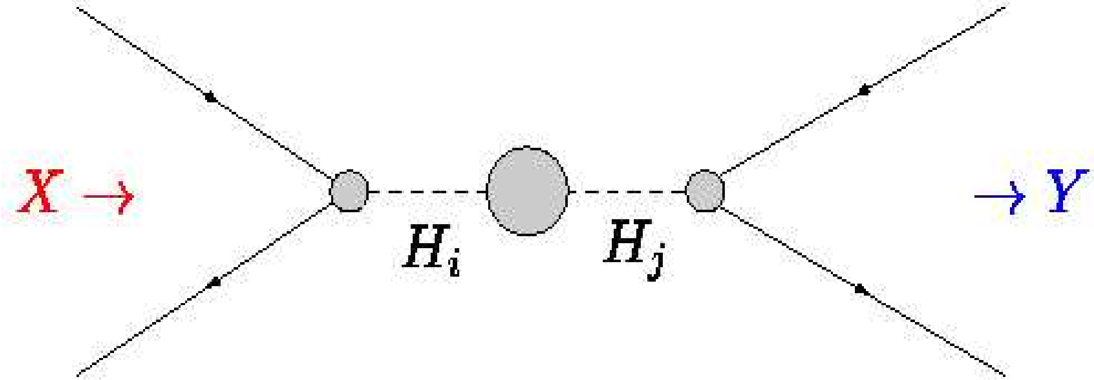
$$\begin{aligned} \hat{\lambda}_p &= \lambda_5^I s_\beta c_\beta + \lambda_6^I c_\beta^2 + \lambda_7^I s_\beta^2 \\ \lambda_p &= \tfrac{1}{2}\lambda_5^I (c_\beta^2 - s_\beta^2) - s_\beta c_\beta (\lambda_6^I - \lambda_7^I) \\ \lambda_q &= \lambda_5^I s_\beta c_\beta - \lambda_6^I s_\beta^2 - \lambda_7^I c_\beta^2 \end{aligned}$$

- even if $\hat{\lambda}_p$=λ_p=0, but $\lambda_q \neq 0$ $\Longrightarrow$ CP–mixing via triple and quartic couplings

Moreover, the hermitian M^2 must be supplemented with anti-hermitian $M\Gamma$ built up by loops



As a result, the Higgs formation process, e.g.



must include off-diagonal $H_i \Rightarrow H_j$ transitions

Two approaches:

- Coupled–channel analysis has recently been employed [Ellis, Lee, Pilaftsis '04]
- diagonalize the complex matrix given by the Weisskopf-Wigner sum

$$\mathcal{M}_c^2 = M^2 - iM\Gamma$$

[Choi, Liao, Zerwas, JK, hep-ph/0407347]

Interesting physics case the decoupling limit: $m_A^2 \gg |\lambda_i| v^2$

- H_1 must be the CP-even SM–like $\Longrightarrow$ it decouples from the H/A system
- H/A almost degenerate $\Longrightarrow$ mixing between H and A can be finite and large

$$\mathcal{M}_c^2 = \begin{bmatrix} m_H^2 - i m_H \Gamma_H & \delta m_{HA}^2 \\ \delta m_{HA}^2 & m_A^2 - i m_A \Gamma_A \end{bmatrix} \Longrightarrow \mathcal{M}^2 = C\, \mathcal{M}_c^2\, C^{-1}$$

- the C and the complex mixing angle θ are given by [Güsken, Kühn, Zerwas '85]

$$C = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}, \quad X \equiv \frac{1}{2}\tan 2\theta = \frac{\delta m_{HA}^2}{m_H^2 - m_A^2 - i(m_H \Gamma_H - m_A \Gamma_A)}$$

- the mass eigenstates H_2 and H_3 no longer orthogonal; need to use bra and ket states

$$|H_2> = \cos\theta |H> + \sin\theta |A>, \qquad <\tilde{H}_2| = \cos\theta <H| + \sin\theta <A|$$

$$|H_3> = -\sin\theta |H> + \cos\theta |A>, \quad <\tilde{H}_3| = -\sin\theta <H| + \cos\theta <A|$$

- correspondingly, the transition amplitudes are modified, $e.g.$ for $X \Rightarrow H \Rightarrow Y$

$$<Y|H|X> = \sum_{i=2,3} <Y|H_i> \frac{1}{s - m_{H_i}^2 + i m_{H_i} \Gamma_{H_i}} <\tilde{H}_i|X>$$

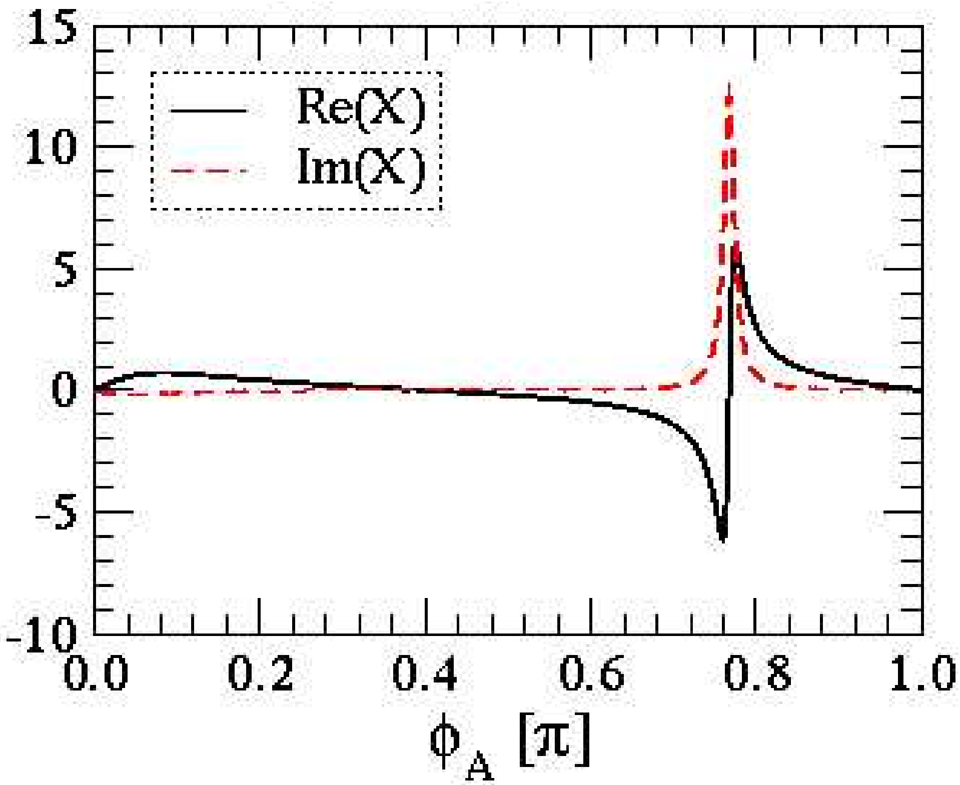
Example: **an MSSM with CP-violation**

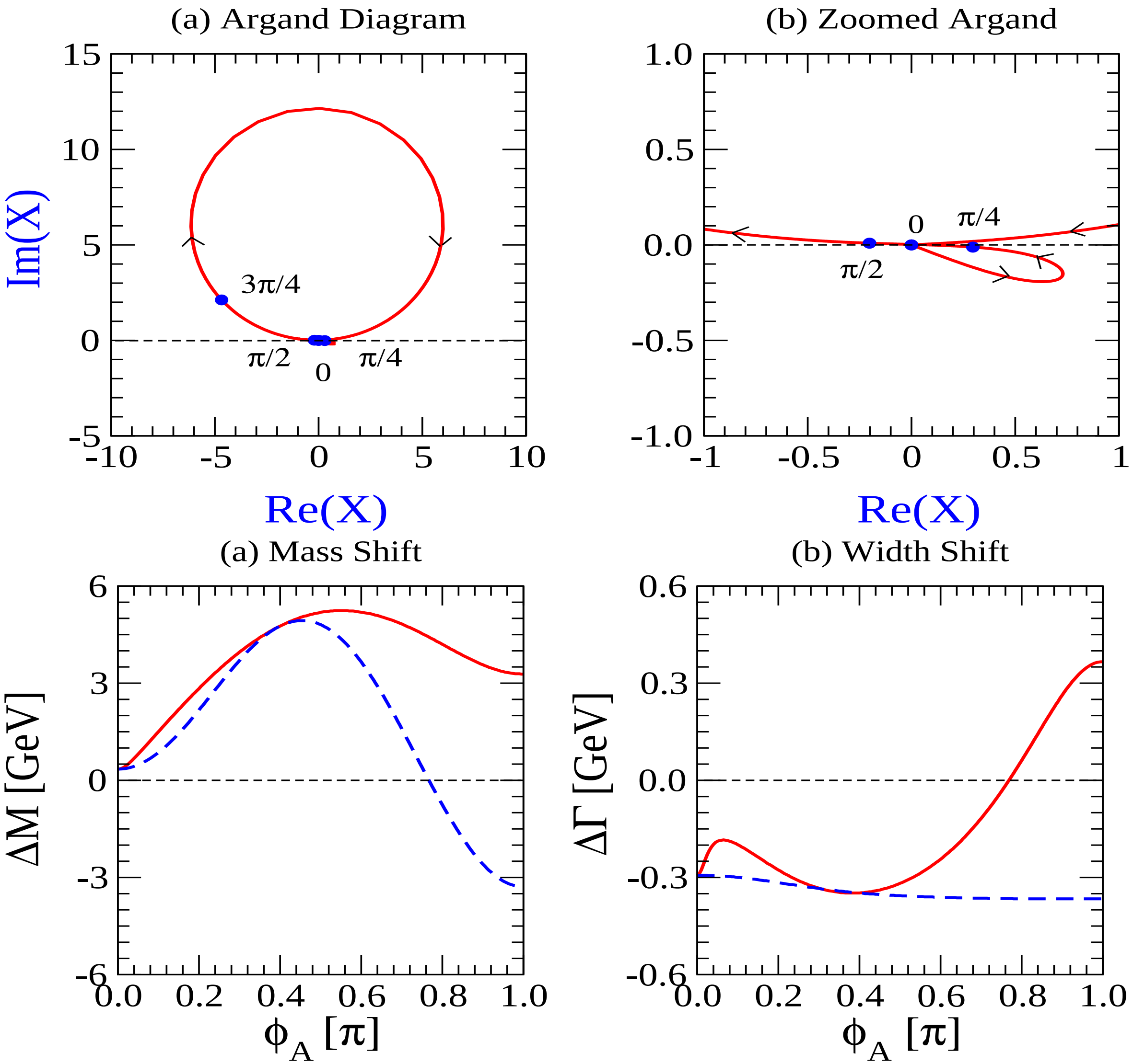
$M_S = 0.5$ TeV, $|A_t| = 1.0$ TeV, $|\mu| = 1.0$ TeV, $\phi_\mu = 0$; $\tan\beta = 5$

for this set: $M_h = 129.6$ **GeV**

with $\Phi_A = 0$: $M_H = 500.3$ **GeV,** $M_A = 500.0$ **GeV,** $\Gamma_H = 1.2$ **GeV,** $\Gamma_A = 1.5$ **GeV**

turning on the phase ϕ_A **of** A_t **with only** $t/\tilde{t}$ **and** h **in the loops**





Mixing parameter as a function of ϕ_A

Mass and width shifts for $\phi_A = 3\pi/4$

Experimental signatures at a photon LC

(A) **Higgs formation in polarized $\gamma\gamma$ collisions**

$$\gamma\gamma \to H_i \to Y \quad [i = 2, 3]$$

with the following CP-even and CP-odd asymmetries

$$\mathcal{A}_{\rm lin} = \frac{\sigma_\parallel - \sigma_\perp}{\sigma_\parallel + \sigma_\perp} \qquad \text{and} \qquad \mathcal{A}_{\rm hel} = \frac{\sigma_{++} - \sigma_{--}}{\sigma_{++} + \sigma_{--}}$$

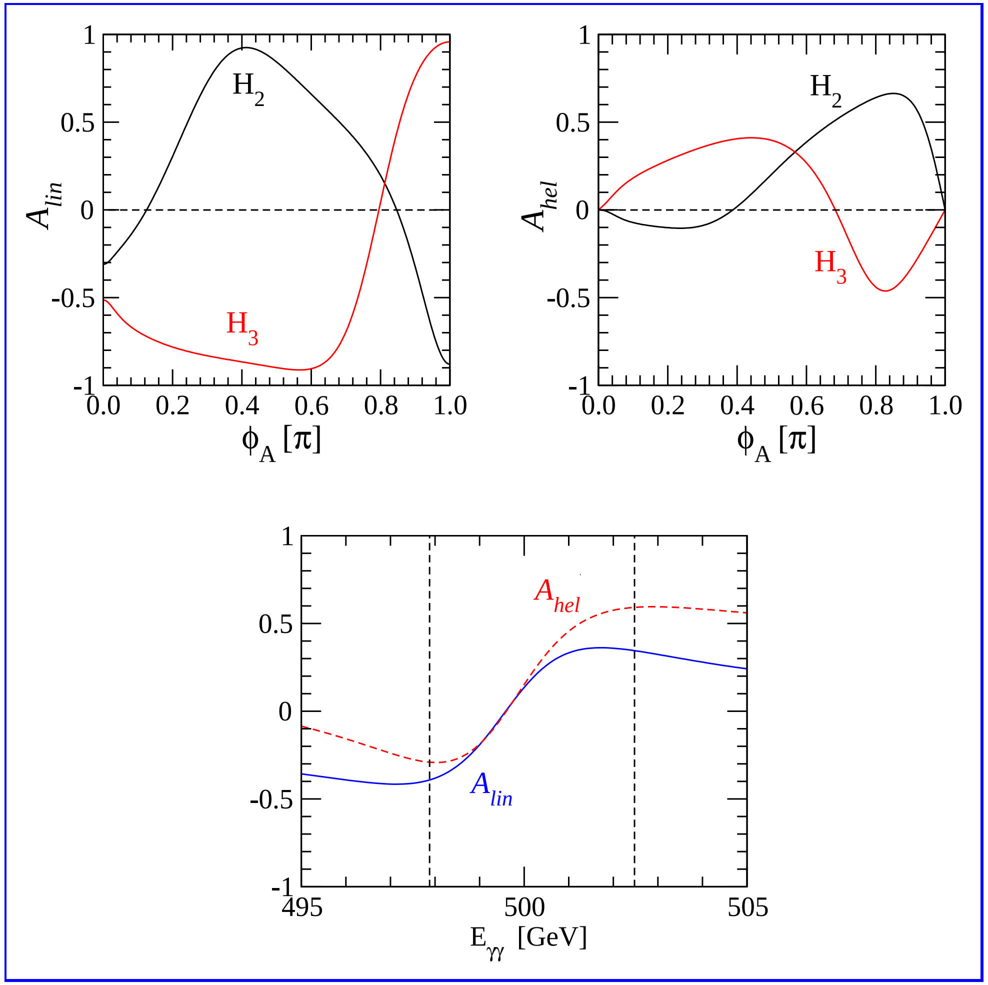
(B) **polarization of top quarks in $H_i \Rightarrow t\bar{t}$** [ϕ^* – angle between $t\bar{t}$ decay planes]

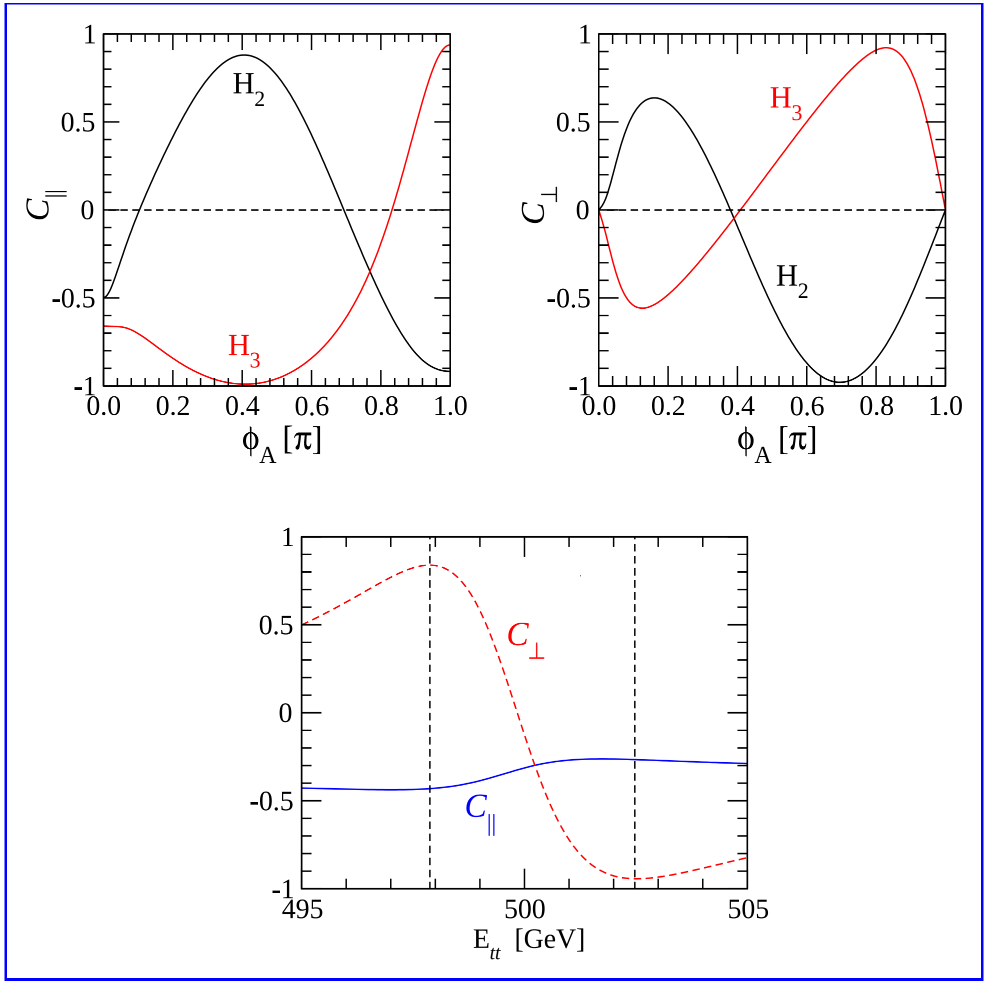
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\phi^*} = \frac{1}{2\pi}\left[1 - \frac{\pi^2}{16}\frac{(m_t^2 - 2m_W^2)^2}{(m_t^2 + 2m_W^2)^2}\left(C_\parallel \cos\phi^* + C_\perp \sin\phi^*\right)\right]$$

with the following CP–even and CP–odd azimuthal correlators

$$\mathcal{C}_\parallel = \langle s_\perp \cdot \bar{s}_\perp \rangle \qquad \text{and} \qquad \mathcal{C}_\perp = \langle \hat{p}_t \cdot (s_\perp \times \bar{s}_\perp) \rangle$$

$\gamma\gamma \Rightarrow H$ $\qquad\qquad$ $H \Rightarrow t\,\bar{t}$





(A): $\mathcal{A}_{\rm lin}$ and $\mathcal{A}_{\rm hel}$ $\qquad$ **(B): $\mathcal{C}_{||}$ and $\mathcal{C}_{\perp}$**

large asymmetries can be expected

Conclusions:

A general CP-violating model with two Higgs doublets studied:

- **important to include decay widths in the mixing formalism**
- **the mixing can be large if masses and decay widths are degenerate**
- **particularly interesting case: the decouplig limit**

Example: an MSSM model in the decoupling limit

- **top squark sector as a source of CP violation**
- **the lightest H_1 is a CP-even SM-like Higgs**
- **large mixing between H and A**
- **mass and decay width shifts calculated**
- **mixing can be investigated in $\gamma\gamma \Rightarrow H_i$, and in $H_i \Rightarrow t\bar{t}$**
- **large effects can be expected**

$\Rightarrow$ Encouraging results to perform detailed experimental simulations