Signals of CP Violating H/A Mixing at the Photon LC

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Outline

Motivation

SUSY (MSSM) is the best motivated extension of the SM, (with two Higgs doublets).

- The tree–level Higgs potential is severely constrained.
  - Quartic couplings are gauge couplings
  - No CP violation
- Loop corrections are important and the effective potential includes
  - All possible quartic couplings
  - All CP–violating effects

Therefore, the MSSM Higgs–sector CP violation can be described in the context of the general 2–Higgs doublet model. [Gunion et al. '02, Ginzburg et al. '02/04, Dubinin et al. '02/04, S.Y. Choi et al. '04]

CP Violating Higgs Mixing

Loop–corrected MSSM Higgs sector $\in$ General 2–Higgs doublet model

- The most general gauge invariant 2–Higgs potential

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

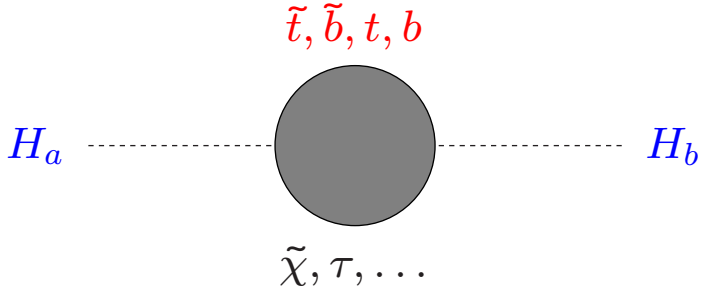
- The imaginary parts of λ_5, λ_6 and λ_7, signalling CP violation, are developed at the loop level with complex parameters in the other SUSY sectors.

- In the CP conserving case we have two CP–even h, H and one CP–odd A mass eigenstates.

- In the MSSM, all terms are effectively non–zero $\in$ the CP–violating 2HDM.

Loop–induced CP–violating Higgs Mixing

CP Mixing of $H_a = h, H, A$



$$\Delta_{Ah,AH} \propto \frac{3m_f^2}{16\pi^2} \frac{\Im\mathrm{m}(A_f \mu)}{m^2_{\tilde{f}_2} - m^2_{\tilde{f}_1}}$$

- Large radiative corrections: $m_h^{\rm tree} < m_Z \Rightarrow m_h \lesssim 135$ GeV [Okada et al., 1991; . . .]
- Large CP mixing among CP–even and CP–odd states

  [Pilaftsis, 1998; Demir, 1999; Pilaftsis and Wagner, 1999; SYC, Drees and J.S.Lee, 1999; Carena et al., 2000; S.W. Ham et al., 2002]
- Higgs couplings to SM and MSSM particles are significantly modified. [CPsuperH: J.S. Lee et al., 2004]

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

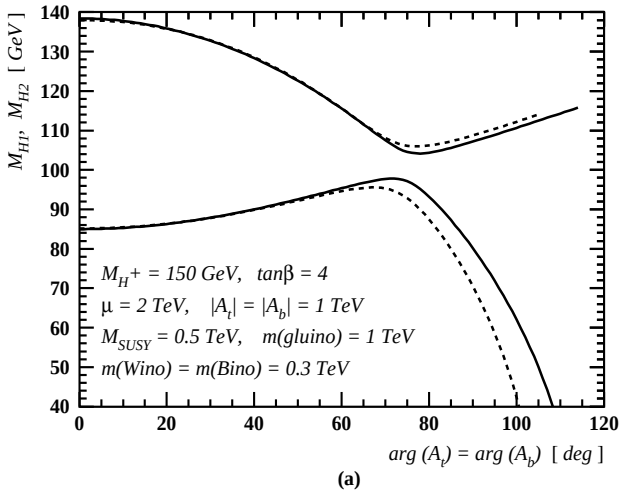
$$\begin{bmatrix} \lambda + (m_A^2/v^2 - \lambda_A) c_\gamma^2 c_{2\gamma}^{-1} & 0 & -\widehat{\lambda}_p\, s_\gamma - \lambda_p\, c_\gamma \\ 0 & \lambda - (m_A^2/v^2 - \lambda_A) s_\gamma^2 c_{2\gamma}^{-1} & -\widehat{\lambda}_p\, c_\gamma + \lambda_p\, s_\gamma \\ -\widehat{\lambda}_p\, s_\gamma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

  All h, H, A mix $\Rightarrow$ H_1, H_2, H_3 mass eigenstates w/o definite CP parities

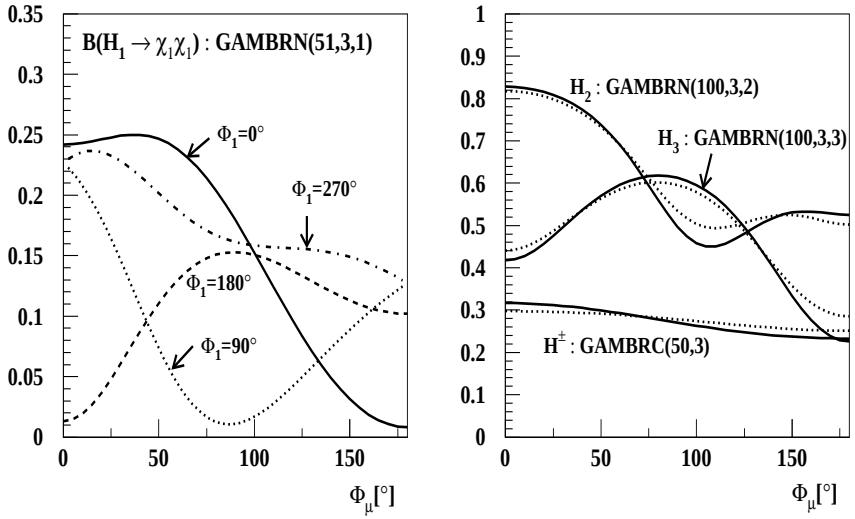
- $\widehat{\lambda}_p, \lambda_p, (\lambda_q)$ are combinations of imaginary parts of $\lambda_5, \lambda_6, \lambda_7$

$$\widehat{\lambda}_p = \Im\mathrm{m}(\lambda_5) s_\beta c_\beta + \Im\mathrm{m}(\lambda_6) c_\beta^2 + \Im\mathrm{m}(\lambda_7) s_\beta^2$$
$$\lambda_p = \frac{1}{2}\Im\mathrm{m}(\lambda_5)(c_\beta^2 - s_\beta^2) - \Im\mathrm{m}(\lambda_6 - \lambda_7) s_\beta c_\beta$$
$$\lambda_q = \Im\mathrm{m}(\lambda_5) s_\beta c_\beta - \Im\mathrm{m}(\lambda_6) s_\beta^2 - \Im\mathrm{m}(\lambda_7) c_\beta^2$$

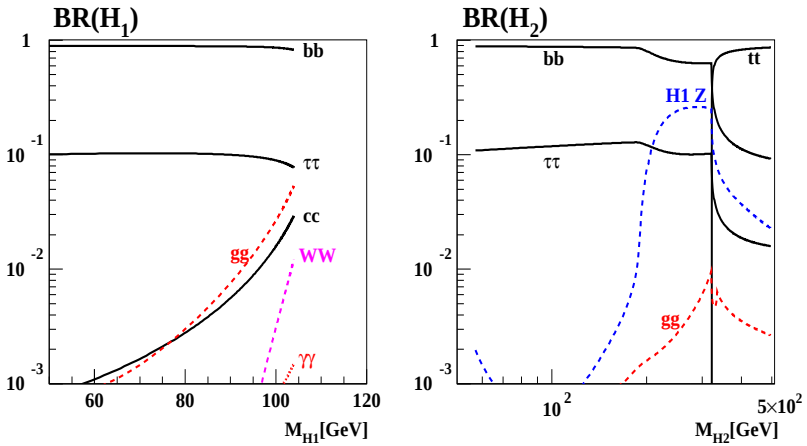
- If $\widehat{\lambda}_p = \lambda_p = 0$, but $\lambda_q \neq 0 \Rightarrow$ CP violation via triple/quartic couplings



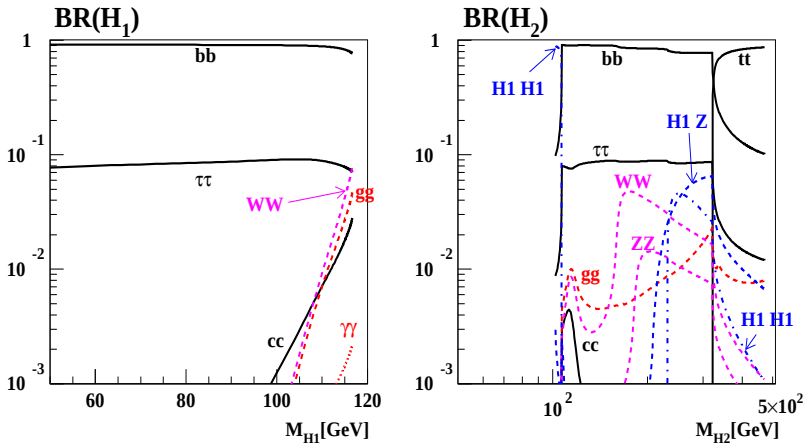
SUSY Modes: $|M_{1,2}| = 50/150$ GeV



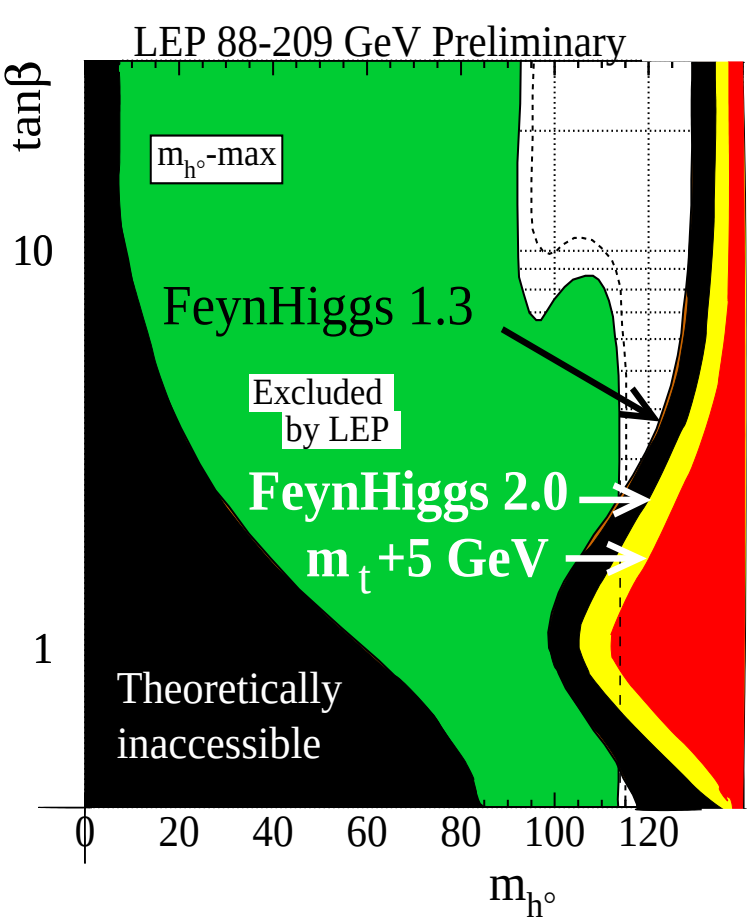
$\Phi_A = \Phi_3 = 0^o$

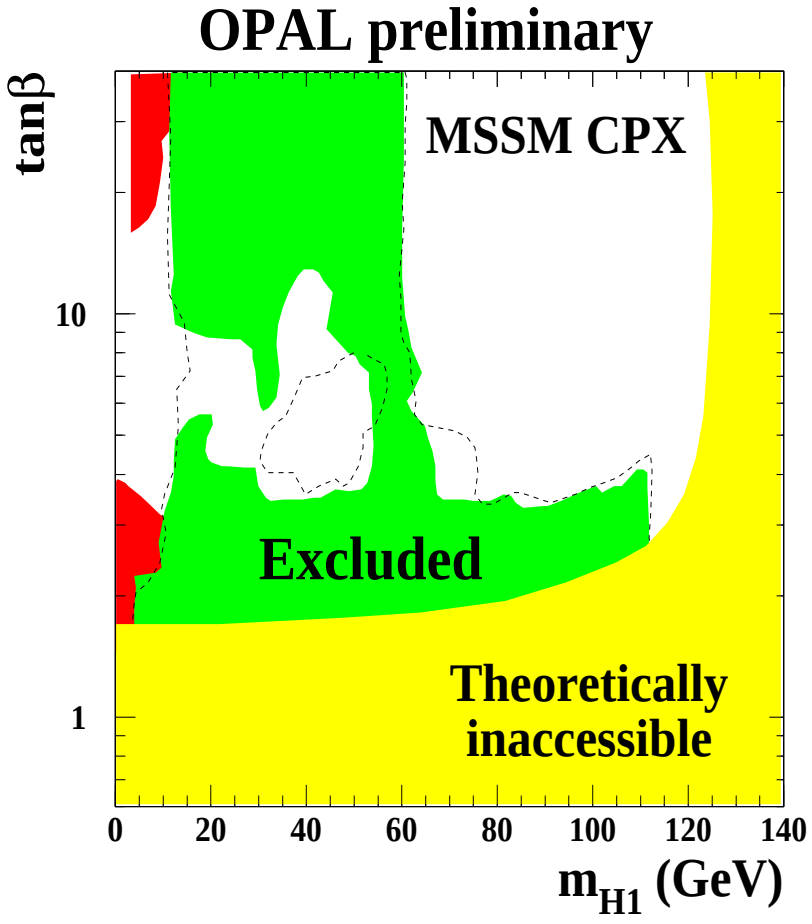


$\Phi_A = \Phi_3 = 90^o$



[P. Bechtle, hep–ex/0401007]

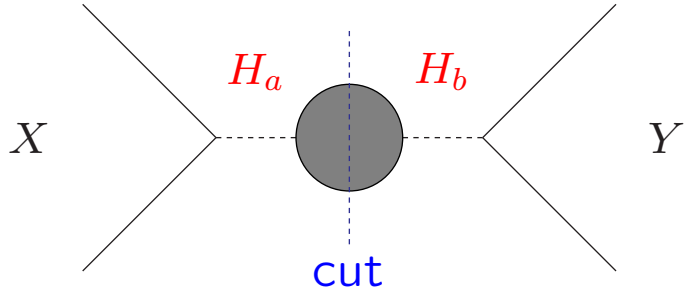




Non–Hermitian Mixing

- The hermitian M^2 must be supplemented with anti–hermitian $-i\mathsf{M}\Gamma$ built up by loops!, important for degenerate states [K–$\bar{K}$, B–$\bar{B}$, n–$\bar{n}$ mixing]

- As a result of the complex mixing, the Higgs–exchange process must include both diagonal and off–diagonal $H_a \Rightarrow H_b$ complex transitions. [$H_{a,b} = h, H, A$]



- Diagonalize the complex/symmetric Weisskopf–Wigner matrix

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

[SYC, Kalinowski, Liao, Zerwas, '04; Ellis, J.S. Lee, Pilaftsis, '04]

Decoupling Limit: $m_A^2 \gg |\lambda_i| v^2$

- H_1 becoms the CP–even SM–like and decouples from the H/A system.
- H and A almost degenerate $\Rightarrow$ The 2–state H/A mixing can be large.

$$\mathcal{M}_c^2 = \begin{bmatrix} m_H^2 - i m_H \Gamma_H & \delta m_{HA}^2 \\ \delta m_{HA}^2 & m_A^2 - i m_A \Gamma_A \end{bmatrix} \quad \Rightarrow \quad \mathcal{M}_{\rm diag}^2 = C \mathcal{M}_c^2 C^T$$

- The rotation matrix C with a complex mixing angle θ is given by

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

- H_2 and H_3 no longer orthogonal $\Rightarrow$ Need to use both bra and ket states!

$$|H_2\rangle = \cos\theta\,|H\rangle + \sin\theta\,|A\rangle, \quad \langle\tilde{H}_2| = \cos\theta\,\langle H| + \sin\theta\,\langle A|$$
$$|H_3\rangle = -\sin\theta\,|H\rangle + \cos\theta\,|A\rangle, \quad \langle\tilde{H}_3| = -\sin\theta\,\langle H| + \cos\theta\,\langle A|$$

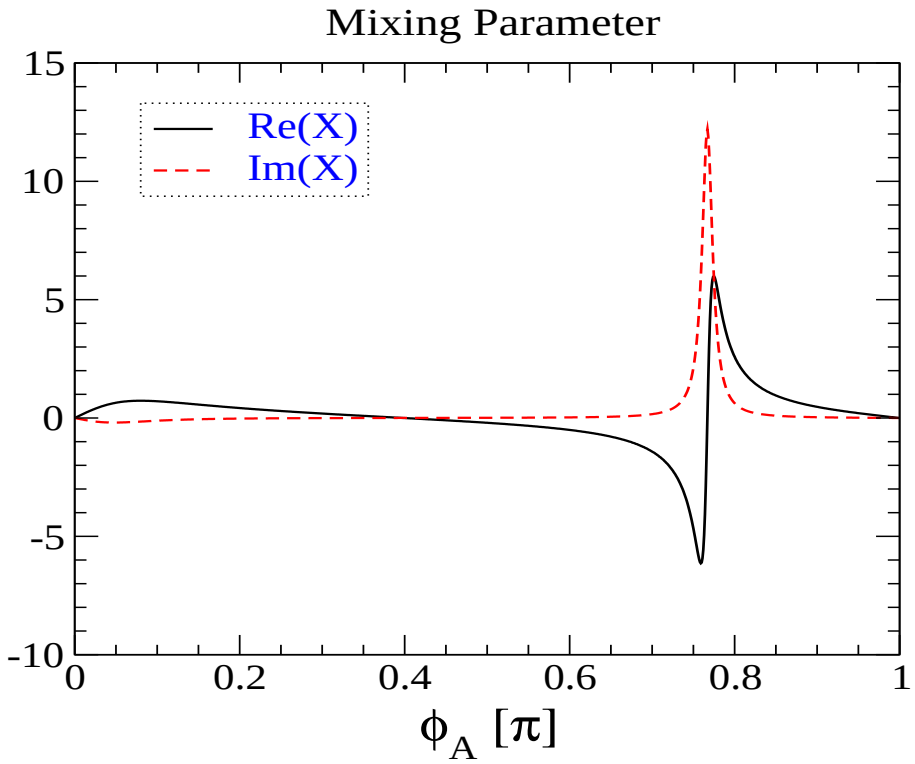
- Correspondingly, the transition amplitudes for $X \Rightarrow H \Rightarrow Y$ are given by

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

Example: CP–violating MSSM

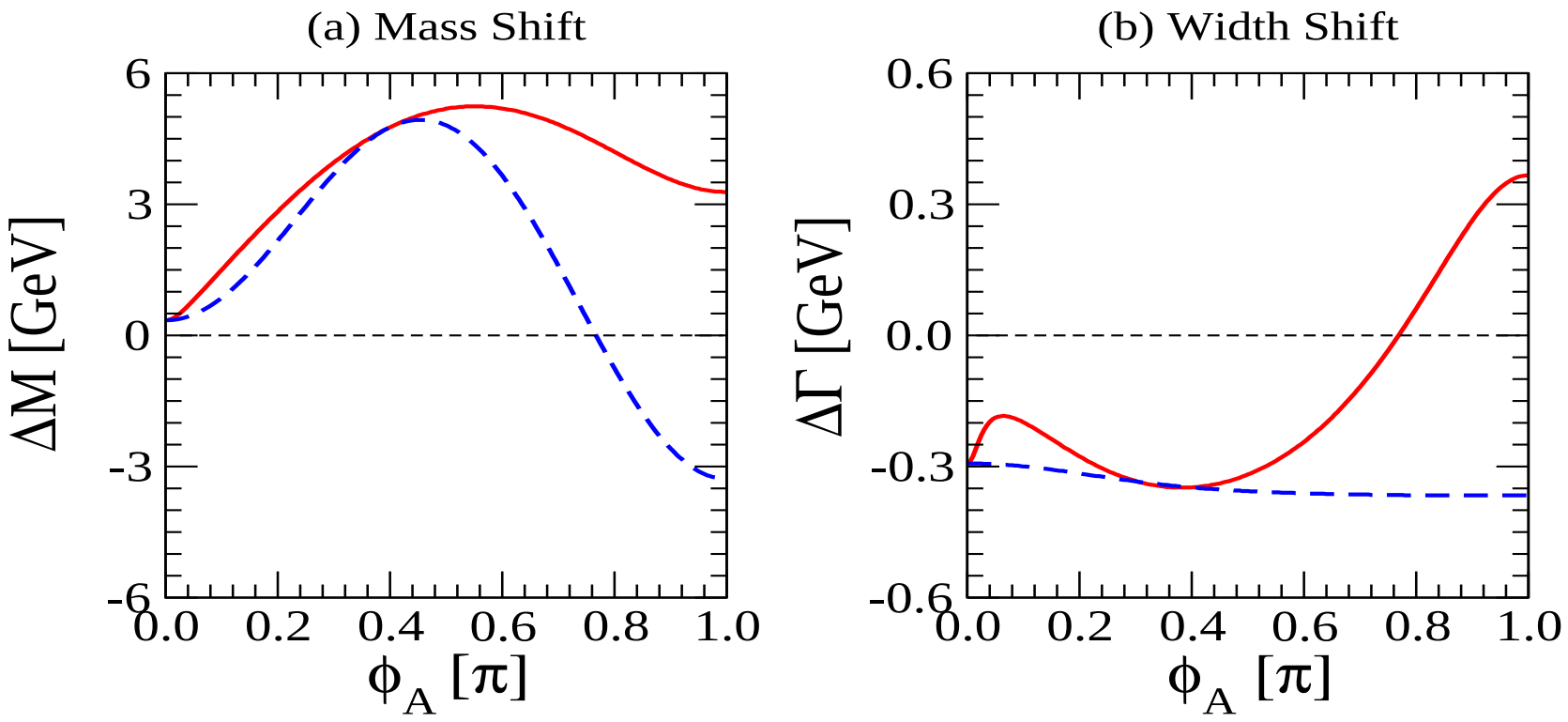
$M_S = 0.5\,\text{TeV}, \quad |A_t| = 1.0\,\text{TeV}, \quad |\mu| = 1.0\,\text{TeV}, \quad \phi_\mu = 0; \quad \tan\beta = 5$

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



- For $\phi_A = 0$, $M_H/M_A = 500.3/500.0$ GeV and $\Gamma_H/\Gamma_A = 1.2/1.5$ GeV

Mass and Width Shifts



Signatures at the Photon LC

(1) 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

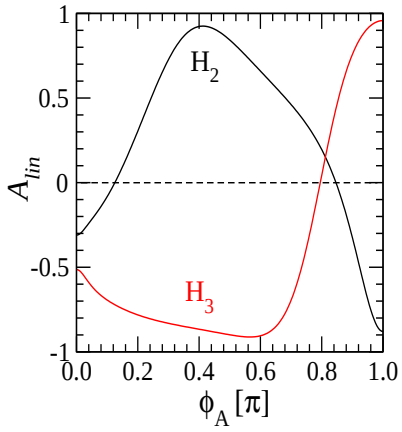
$$\mathcal{A}_{\rm lin} = \frac{\sigma_{\parallel} - \sigma_{\perp}}{\sigma_{\parallel} + \sigma_{\perp}} \qquad \text{and} \qquad \mathcal{A}_{\rm hel} = \frac{\sigma_{++} - \sigma_{--}}{\sigma_{++} + \sigma_{--}}$$

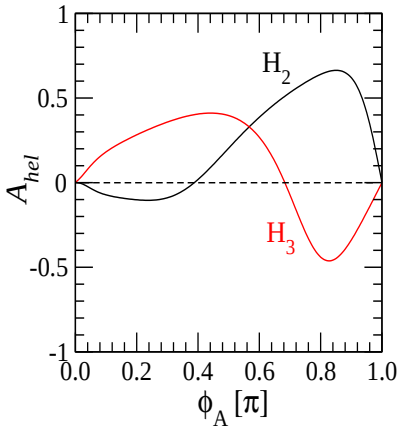
(2) Top polarization in $(\gamma\gamma \to) H_i \to t\bar{t}$ [ϕ_*–angle between t and $\bar{t}$ decay planes]

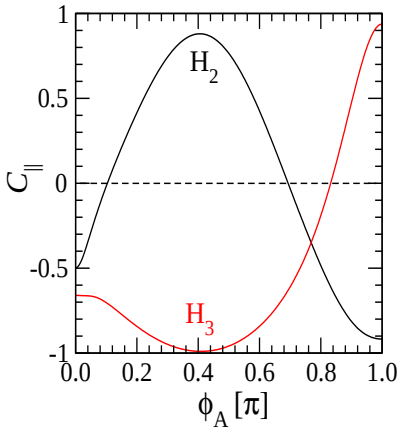
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\phi_*} = \frac{1}{2\pi}\left[1 - \frac{\pi^2}{16}\frac{(m_t^2 - 2m_W^2)^2}{(m_t^2 + 2m_W^2)^2}\left(C_{\parallel}\cos\phi_* + C_{\perp}\sin\phi_*\right)\right]$$

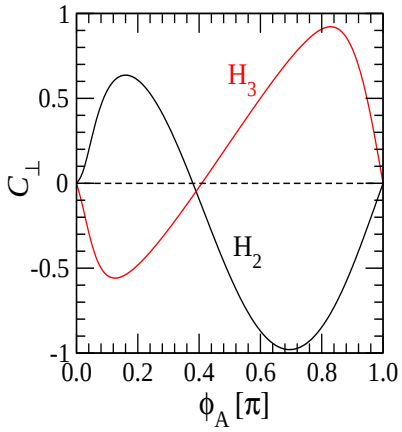
with the following CP–even and CP–odd azimuthal correlators

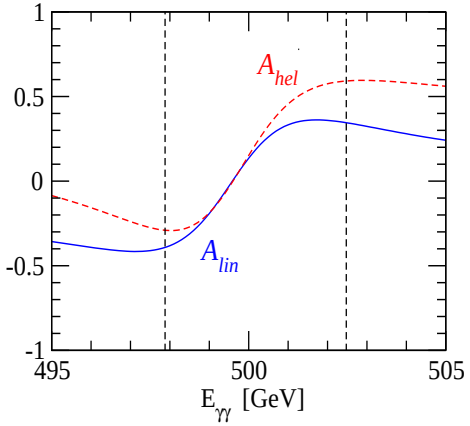
$$C_{\parallel} = \langle s_{\perp} \cdot \bar{s}_{\perp} \rangle \qquad \text{and} \qquad C_{\perp} = \langle \hat{p}_t \cdot (s_{\perp} \times \bar{s}_{\perp}) \rangle$$

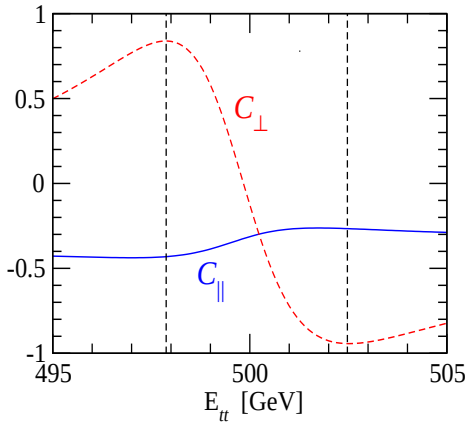












$\gamma\gamma \to H$ $\phi_A = 3\pi/4$ $H \to t\bar{t}$

Conclusions

© A general CP–violating two Higgs doublet model

- Need to include decay widths in the mixing formalism
- The mixing can be large for (nearly) degenerate states.
- A interesting case: the decoupling limit in the 2HDM

© MSSM Higgs bosons in the decoupling limit with $M_A \gtrsim 2M_Z$

- The lightest H_1 is a CP–even SM–like Higgs boson.
- Naturally, H and A become nearly degenerate in the limit.
- CP violating loop corrections lead to large complex H/A mixing.
- Mixing can be investigated in $\gamma\gamma \to H_i \to t\bar{t}$ with large CP effects.

Encouraging results!! Do detailed expt'l simulations!