

Resonant H/A Mixing in CP–Noninvariant 2HDM and MSSM

[SYC, J. Kalinowski, Y. Liao and P.M. Zerwas, to appear in EPJC]

Outline

1. Introduction to CP–violating 2HDM
2. CP Violating Higgs Mixing
 - General structure and resonant H/A mixing
 - MSSM Higgs sector with distinct phenomenology
 - Complex/non-Hermitian Higgs Mixing
3. Signatures at PLC
4. Conclusions

Introduction

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

- The tree-level MSSM 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, Ginzburg and Haber @ CPNSH]

CP Violating Higgs Mixing

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

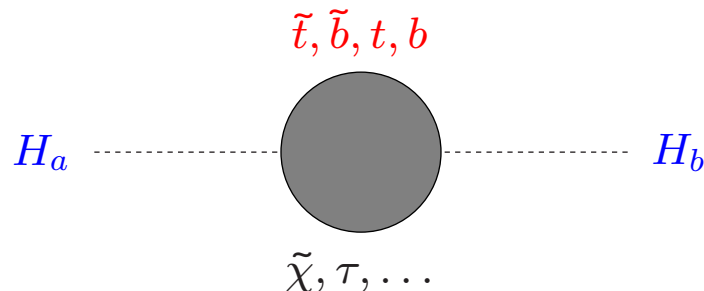
- The most general gauge invariant 2-Higgs potential (m_{12} assumed to be real)

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

- 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 could effectively be non-zero $\in$ the CP-violating 2HDM.

Loop-induced CP-violating Higgs Mixing

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



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

- Large radiative corrections:
 $m_h^{\text{tree}} < m_Z \Rightarrow m_h \lesssim 135 \text{ GeV}$
[\[Okada et al., 1991; ...\]](#)
- 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

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

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

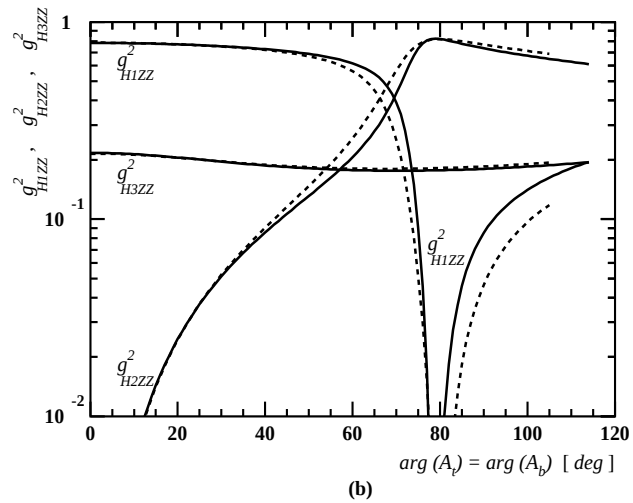
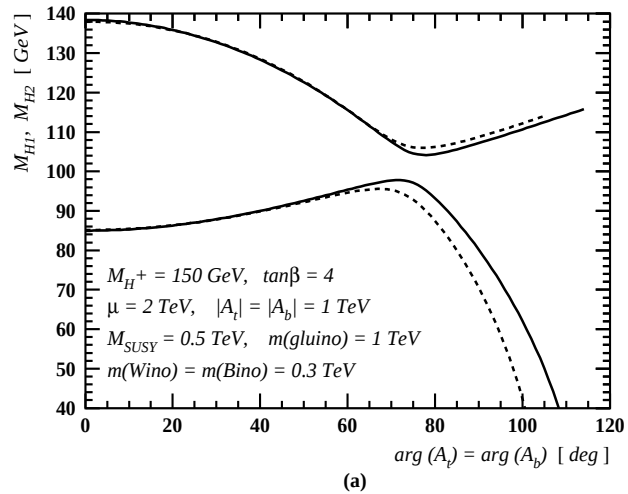
- $\hat{\lambda}_p, \lambda_p, (\lambda_q)$ are combinations of **imaginary** parts of $\lambda_5, \lambda_6, \lambda_7$

$$\hat{\lambda}_p = \Im m(\lambda_5)s_\beta c_\beta + \Im m(\lambda_6)c_\beta^2 + \Im m(\lambda_7)s_\beta^2$$

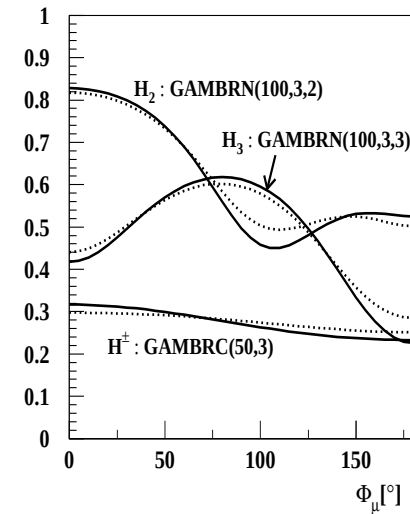
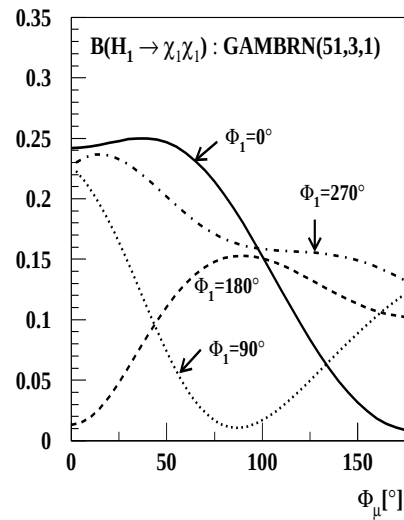
$$\lambda_p = \frac{1}{2}\Im m(\lambda_5)(c_\beta^2 - s_\beta^2) - \Im m(\lambda_6 - \lambda_7)s_\beta c_\beta$$

$$\lambda_q = \Im m(\lambda_5)s_\beta c_\beta - \Im m(\lambda_6)s_\beta^2 - \Im m(\lambda_7)c_\beta^2$$

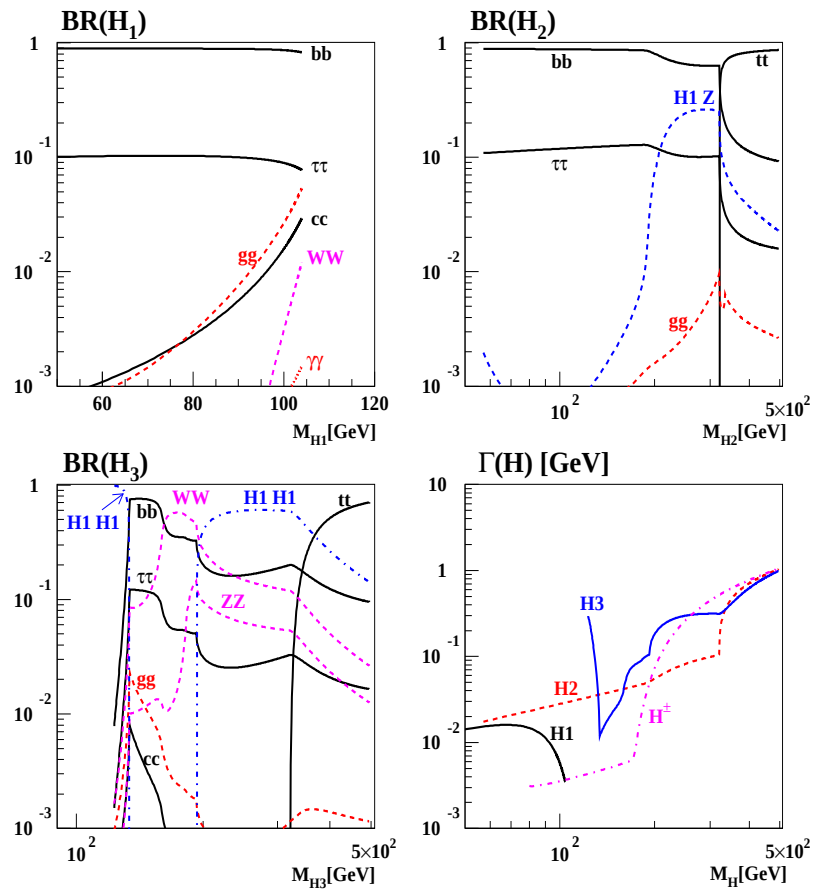
- If $\hat{\lambda}_p = \lambda_p = 0$, but $\lambda_q \neq 0 \Rightarrow$ CP violation via triple/quartic couplings



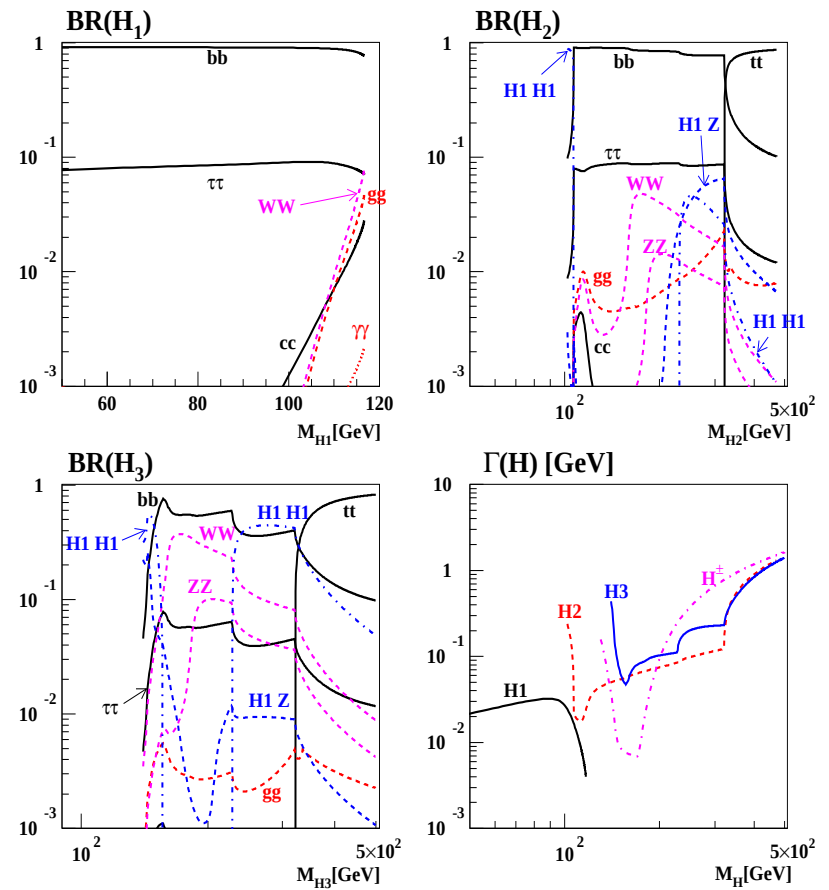
SUSY Modes: $|M_{1,2}| = 50/150 \text{ GeV}$



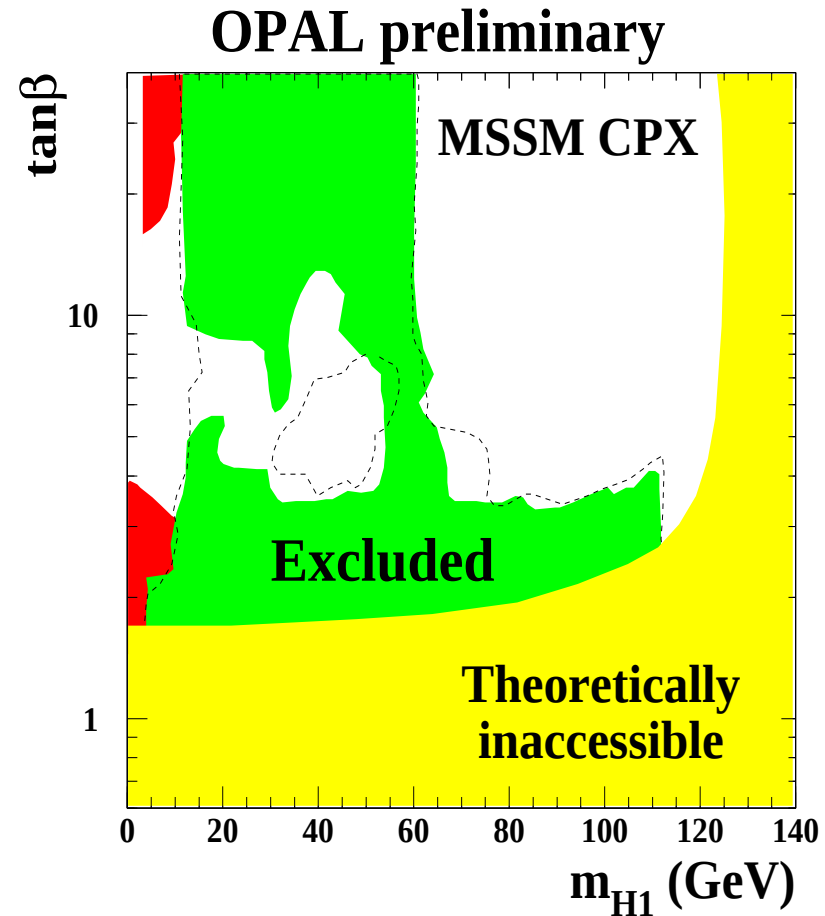
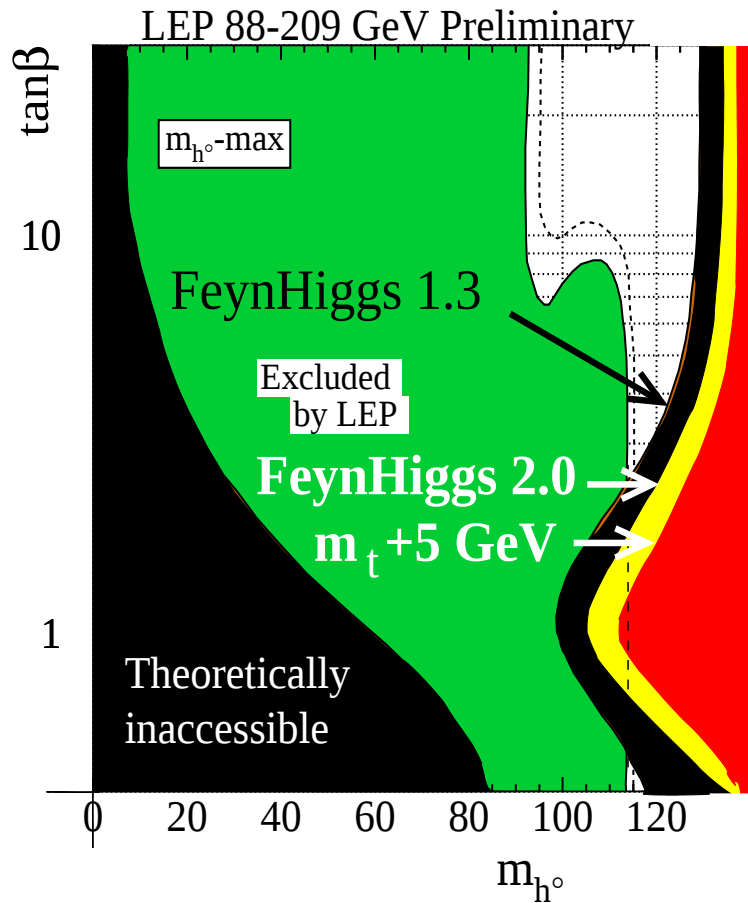
$$\Phi_A = \Phi_3 = 0^\circ$$



$$\Phi_A = \Phi_3 = 90^\circ$$

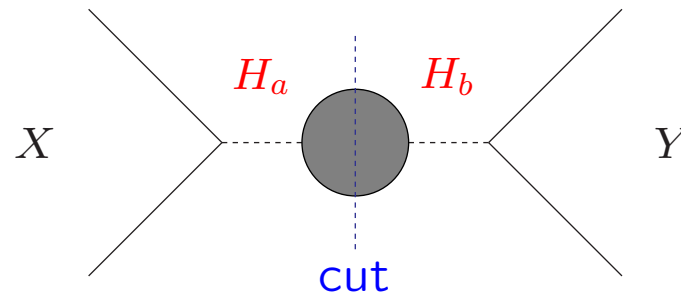


[P. Bechtle, hep-ex/0401007]



Non-Hermitian Mixing

- The hermitian M^2 must be supplemented with anti-hermitian $-iM\Gamma$ built up by loops!, particularly crucial 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

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

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

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

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

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

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

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

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

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

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

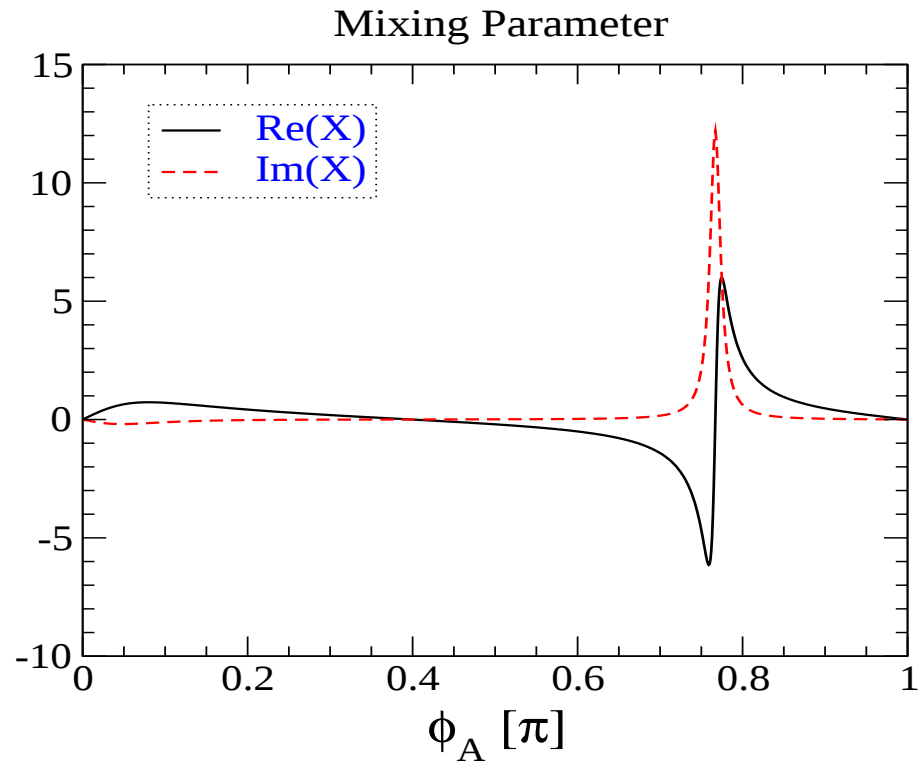
- Correspondingly, the transition amplitudes for $X \Rightarrow H \Rightarrow Y$ are given by

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

Example: CP-violating MSSM

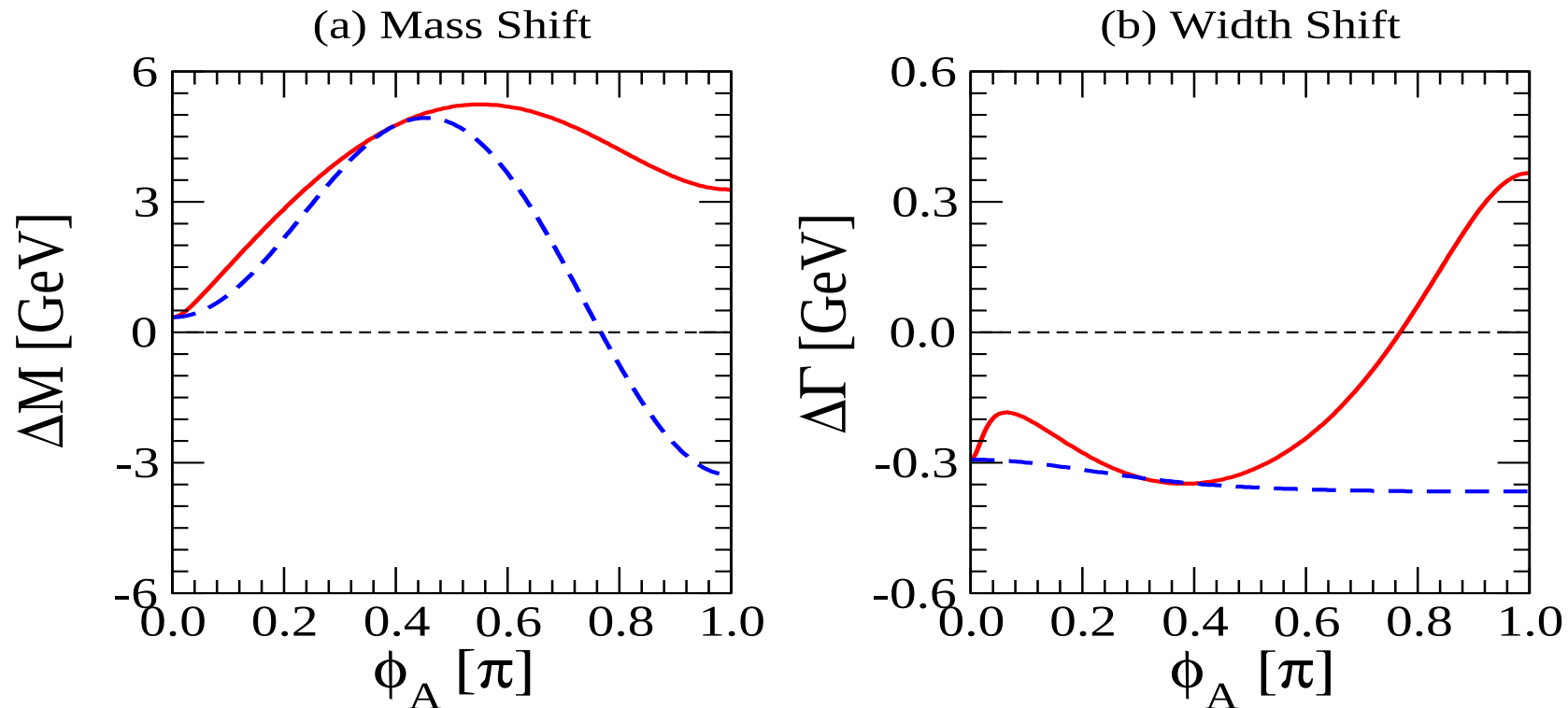
$$M_S = 0.5 \text{ TeV}, \quad |A_t| = 1.0 \text{ TeV}, \quad |\mu| = 1.0 \text{ TeV}, \quad \phi_\mu = 0; \quad \tan \beta = 5$$

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

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

with the following CP-even and CP-odd asymmetries

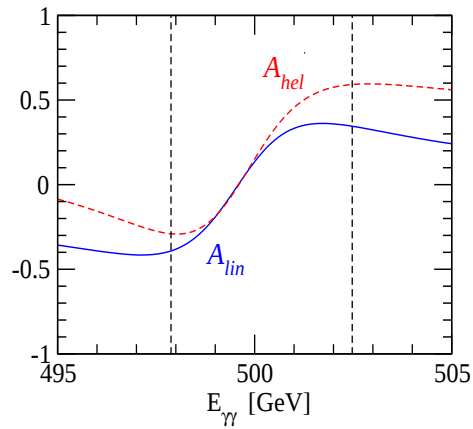
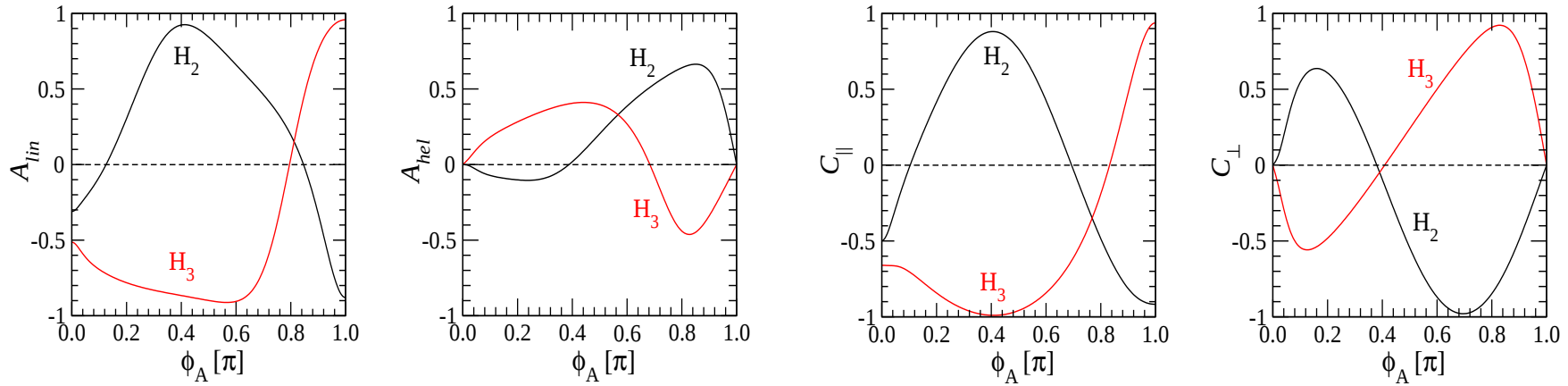
$$\mathcal{A}_{\text{lin}} = \frac{\sigma_{\parallel} - \sigma_{\perp}}{\sigma_{\parallel} + \sigma_{\perp}} \quad \text{and} \quad \mathcal{A}_{\text{hel}} = \frac{\sigma_{++} - \sigma_{--}}{\sigma_{++} + \sigma_{--}}$$

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

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

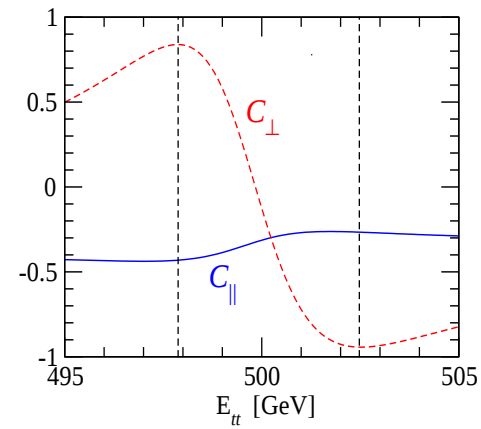
with the following CP-even and CP-odd azimuthal correlators

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



$$\gamma\gamma \rightarrow H$$

$$\phi_A = 3\pi/4$$



$$H \rightarrow t\bar{t}$$

Conclusions

A general CP-violating two Higgs doublet model

Need to include decay widths in the mixing formalism
The complex mixing can be large for (nearly) degenerate states.
An 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.
Complex mixing can be investigated in $\gamma\gamma \rightarrow H_i \rightarrow t\bar{t}$ with large CP effects.

Encouraging results!! Do detailed expt'l simulations!
Extensions to NMSSM and Application to $\chi\chi \rightarrow H/A$