MSSM Higgs sector with CP Violation

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- *Introduction*
  - CP violation in Higgs sector
    - CPX scenario
    - Masses and couplings g_{H_iVV}
    - Decays
  - CPsuperH
- *Coupled-channel analysis of neutral Higgs bosons*

  J. Ellis, JSL and A. Pilaftsis, hep-ph/0404167

  - Propagator matrix
  - Three-way mixing scenario
- *Production $\to$ Mixing $\to$ Decay at the LHC*
  - $b\bar{b} \to H \to \tau^+_{R,L}\tau^-_{R,L}$
  - $gg \to H \to \tau^+_{R,L}\tau^-_{R,L}$
  - $W^+W^- \to H \to \tau^+_{R,L}\tau^-_{R,L}$
- *Conclusion*
  - Prospects and Visions

♠ *Introduction*

- CP violation in Higgs sector
  - We need soft SUSY breaking terms to construct a phenomenologically viable model

$$
\begin{aligned}
&(M_3\,\widetilde{g}\widetilde{g} + M_2\,\widetilde{W}\widetilde{W} + M_1\,\widetilde{B}\widetilde{B} + \mathrm{c.c.})\\
&(\widetilde{u}_R^*\,\mathbf{A_u}\,\widetilde{Q}H_2 - \widetilde{d}_R^*\,\mathbf{A_d}\,\widetilde{Q}H_1 - \widetilde{e}_R^*\,\mathbf{A_e}\,\widetilde{L}H_1 + \mathrm{c.c.})\\
&-(m_{12}^2 H_1 H_2 + \mathrm{c.c.})\\
&-\widetilde{Q}^\dagger\,\mathbf{M^2_{\widetilde{Q}}}\,\widetilde{Q} - \widetilde{L}^\dagger\,\mathbf{M^2_{\widetilde{L}}}\,\widetilde{L}\\
&-\widetilde{u}_R^*\,\mathbf{M^2_{\widetilde{u}}}\,\widetilde{u}_R - \widetilde{d}_R^*\,\mathbf{M^2_{\widetilde{d}}}\,\widetilde{d}_R - \widetilde{e}_R^*\,\mathbf{M^2_{\widetilde{e}}}\,\widetilde{e}_R\\
&-m_2^2 H_2^* H_2 - m_1^2 H_1^* H_1
\end{aligned}
$$

  * Supersymmetric complex parameter μ

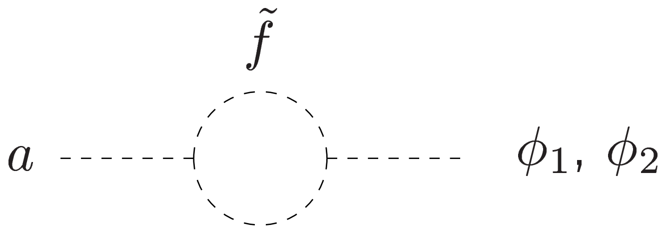
  - The physical observables depends on the phases of the products : arg($M_i\,\mu\,(m_{12}^2)^*$) and arg($\mathbf{A_f}\,\mu\,(m_{12}^2)^*$)
    M. Dugan, B. Grinstein and L. J. Hall, Nucl. Phys. B **255** (1985) 413; S. Dimopoulos and S. Thomas, Nucl. Phys. B **465** (1996) 23

  - Very important radiative corrections

$$
M_h^{\mathrm{tree}} < M_Z \quad \Rightarrow \quad M_h < 135 \text{ GeV}
$$

♠ *Introduction*

- CP violation in Higgs sector (cont'd)
  - Very important radiative corrections with non-vanishing CP phases



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

Mixing among CP–odd and CP–even states !

A. Pilaftsis, Phys. Rev. D **58** 096010 (1998); Phys. Lett. **B435** 88 (1998)

D.A. Demir, Phys. Rev. D **60** 055006 (1999)

A. Pilaftsis and C.E.M. Wagner, Nucl. Phys. **B553** 3 (1999)

S. Y. Choi, M. Drees, and JSL, Phys. Lett. **B481** 57 (2000)

M. Carena, J. Ellis, A. Pilaftsis, C.E.M. Wagner, Nucl. Phys. **B586** 92 (2000)

M. Carena, J. Ellis, A. Pilaftsis, C.E.M. Wagner, Nucl. Phys. **B625** 345 (2002)

♠ *Introduction*

- CP violation in Higgs sector (cont'd)
  - Results of CP-violating mixing among three neutral Higgs bosons
    * The neutral Higgs bosons do not have to carry any definite CP parity
    * 3×3 mixing matrix $O_{\alpha i}$

$$(\phi_1, \phi_2, a)^T = O_{\alpha i}(H_1, H_2, H_3)^T$$

    * Couplings of the Higgs bosons to SM and SUSY particles are significantly modified, for example,

$$\mathcal{L}_{HVV} = gM_W \left(W_\mu^+ W^{-\mu} + \frac{1}{2c_W^2} Z_\mu Z^\mu \right) \sum_i g_{H_iVV} H_i$$

$$g_{H_iVV} = c_\beta O_{\phi_1 i} + s_\beta O_{\phi_2 i}\,; \qquad \sum_{i=1,2,3} g_{H_iVV}^2 = 1$$

♠ *Introduction*

- CP violation in Higgs sector (cont'd)
  - CPX scenario

$$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = M_{\tilde{L}_3} = M_{\tilde{E}_3} = M_{\rm SUSY}$$
$$|\mu| = 4\, M_{\rm SUSY}\,, \quad |A_{t,b,\tau}| = 2\, M_{\rm SUSY}$$
$$|M_3| = 1 \ \ {\rm TeV}$$

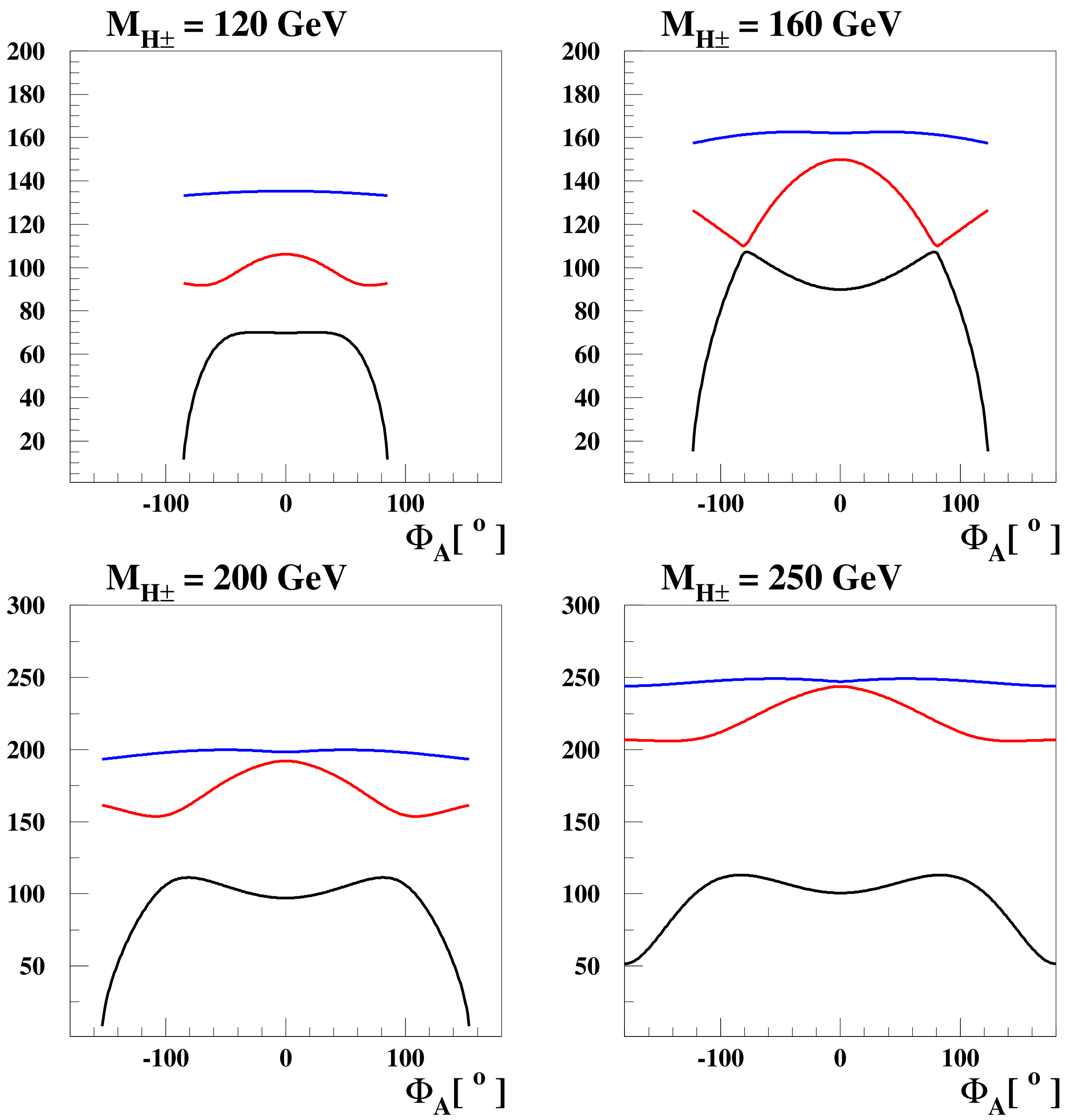
Varying parameters are :

$$\tan\beta\,, \quad M_{H^\pm}^{\rm pole}\,, \quad M_{\rm SUSY}$$
$$(\Phi_\mu)\,, \quad (\Phi_{A_t}\,, \quad \Phi_{A_b}\,, \quad \Phi_{A_\tau})\,, \quad \Phi_3$$

  - * M_1 and M_2

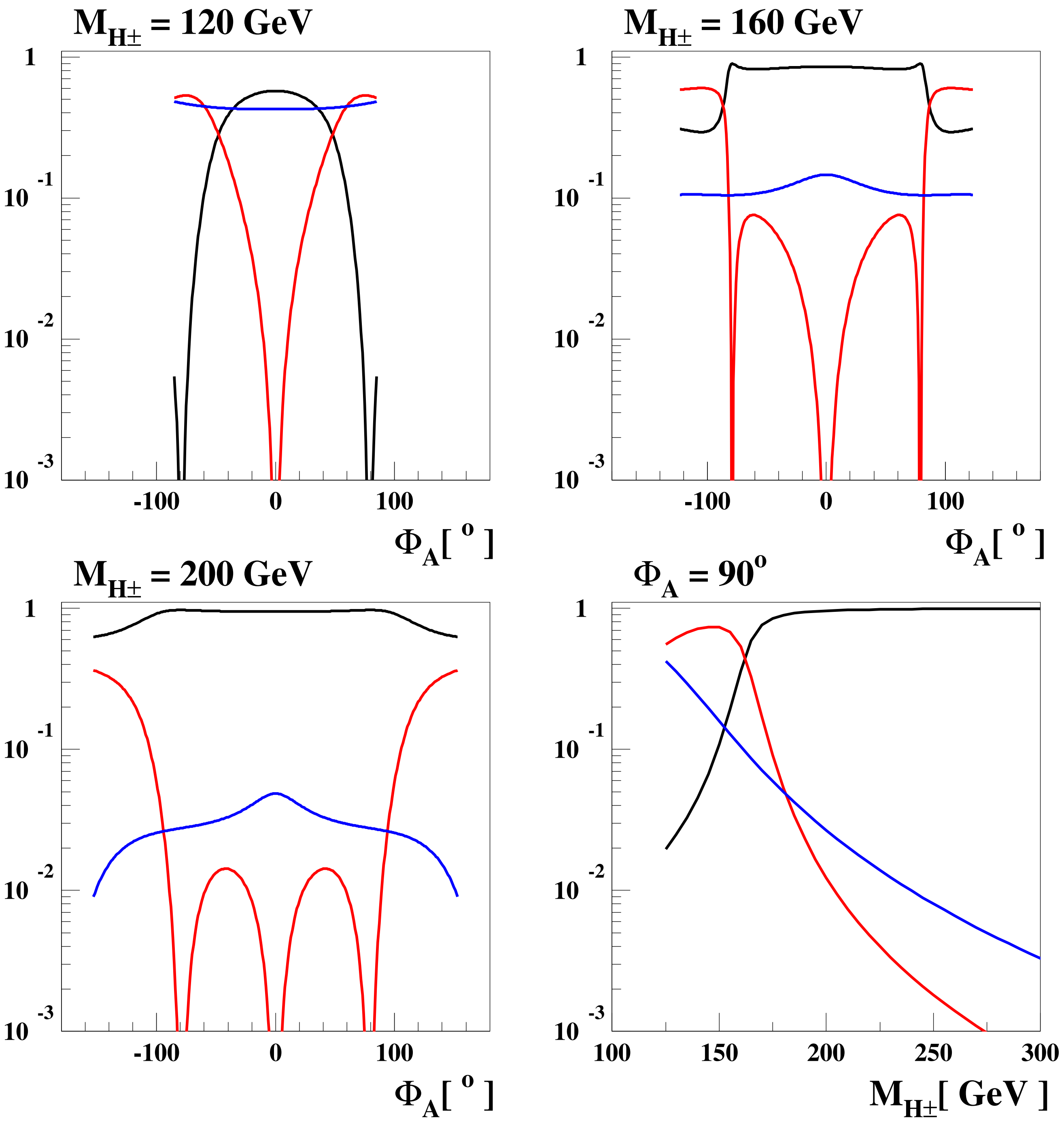
♠ Introduction

- CP violation in Higgs sector (cont'd)
  - Masses M_{H_i} of the neutral Higgs bosons H_1, H_2, and H_3 for CPX scenario varying Φ_A and $M_{H^\pm}^{\rm pole}$ with $\tan\beta = 4$, $\Phi_3 = 0^\circ$ and $M_{\rm SUSY} = 0.5$ TeV



♠ *Introduction*

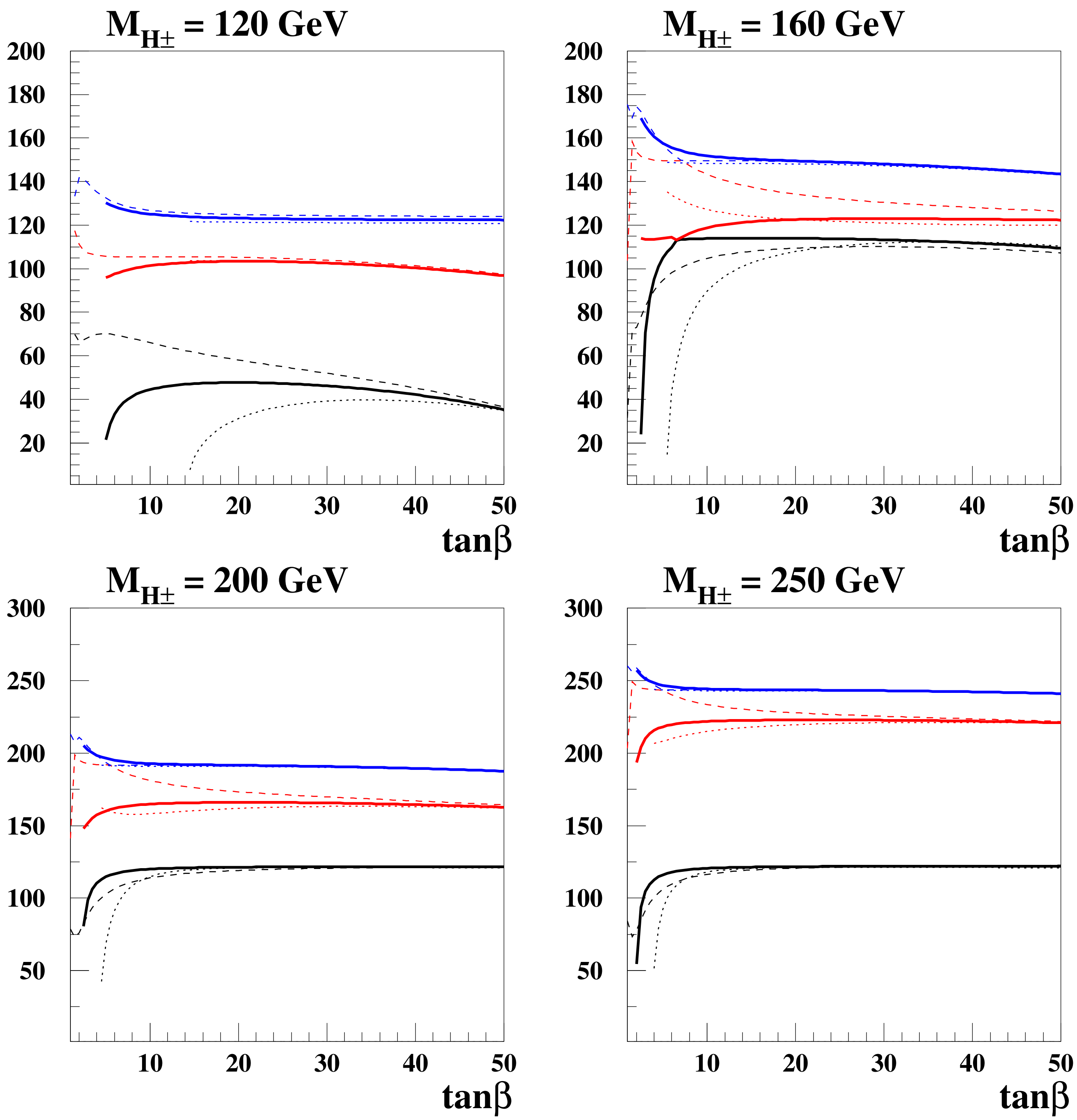
- CP violation in Higgs sector (cont'd)
  - Couplings $g^2_{H_iVV}$ for CPX scenario varying Φ_A and $M^{\rm pole}_{H^\pm}$ with $\tan\beta = 4$, $\Phi_3 = 0^\circ$ and $M_{\rm SUSY} = 0.5$ TeV



♠ *Introduction*

- CP violation in Higgs sector (cont'd)
  - Masses M_{H_i} of the neutral Higgs bosons H_1, H_2, and H_3 for CPX scenario varying $\tan\beta$ and $M_{H^\pm}^{\rm pole}$ with $\Phi_A = 90°$, $\Phi_3 = 0°$ and $M_{\rm SUSY} = 0.5$ TeV

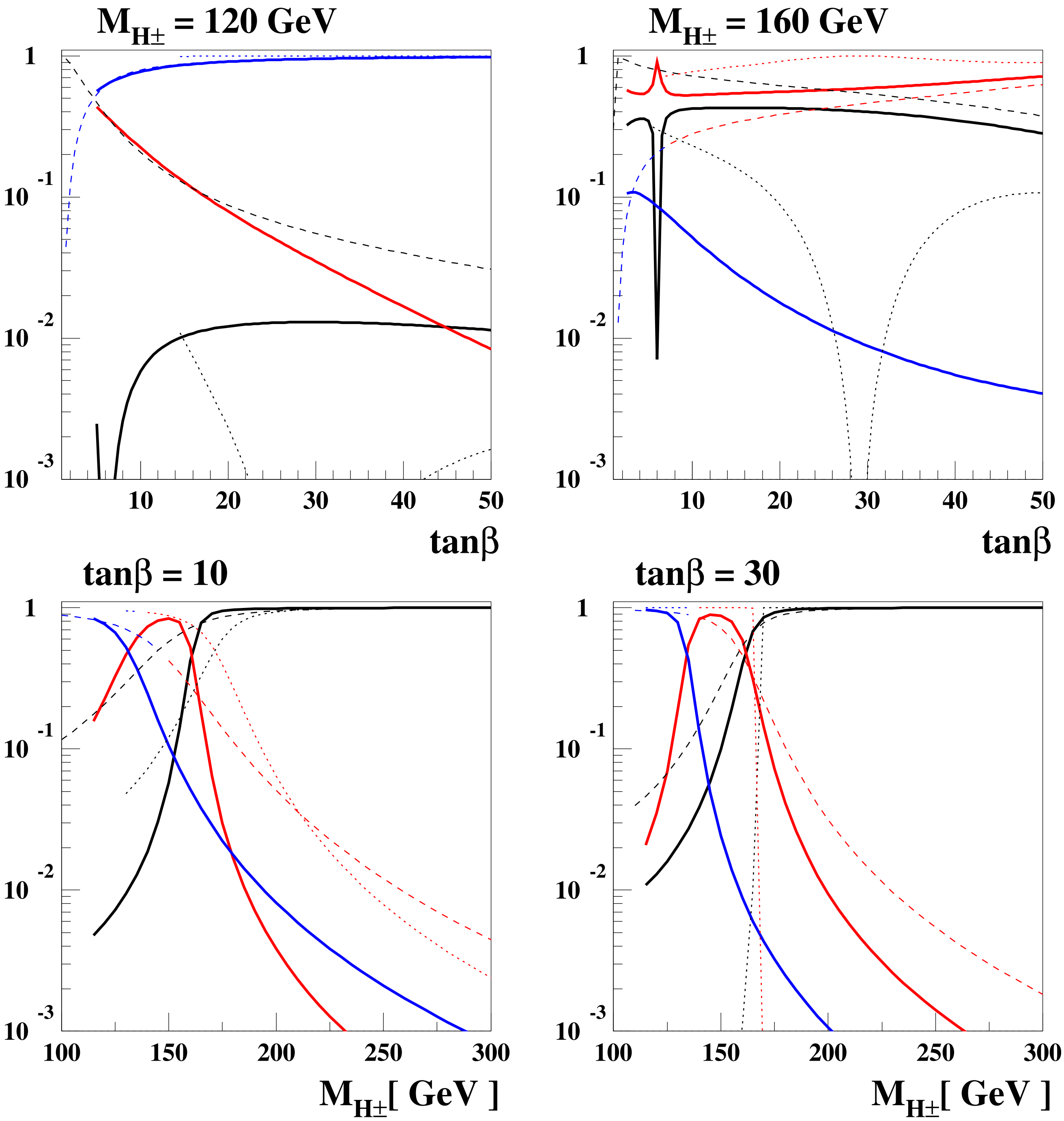
* Dashed : $\Phi_A = 0°$ Dotted : $\Phi_A = 180°$



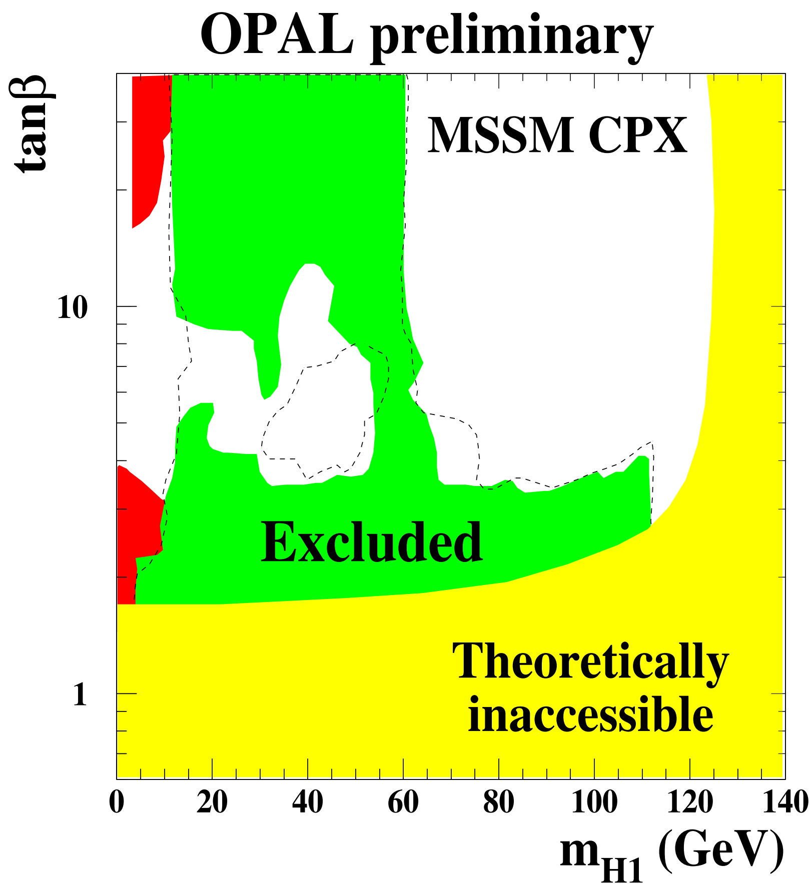
♠ *Introduction*

- CP violation in Higgs sector (cont'd)
  - Couplings $g^2_{H_iVV}$ for CPX scenario varying $\tan\beta$ and $M^{\rm pole}_{H^\pm}$ with $\Phi_A = 90^\circ$, $\Phi_3 = 0^\circ$ and $M_{\rm SUSY} = 0.5$ TeV

* Dashed : $\Phi_A = 0^\circ$ Dotted : $\Phi_A = 180^\circ$



- CP violation in Higgs sector (cont'd)



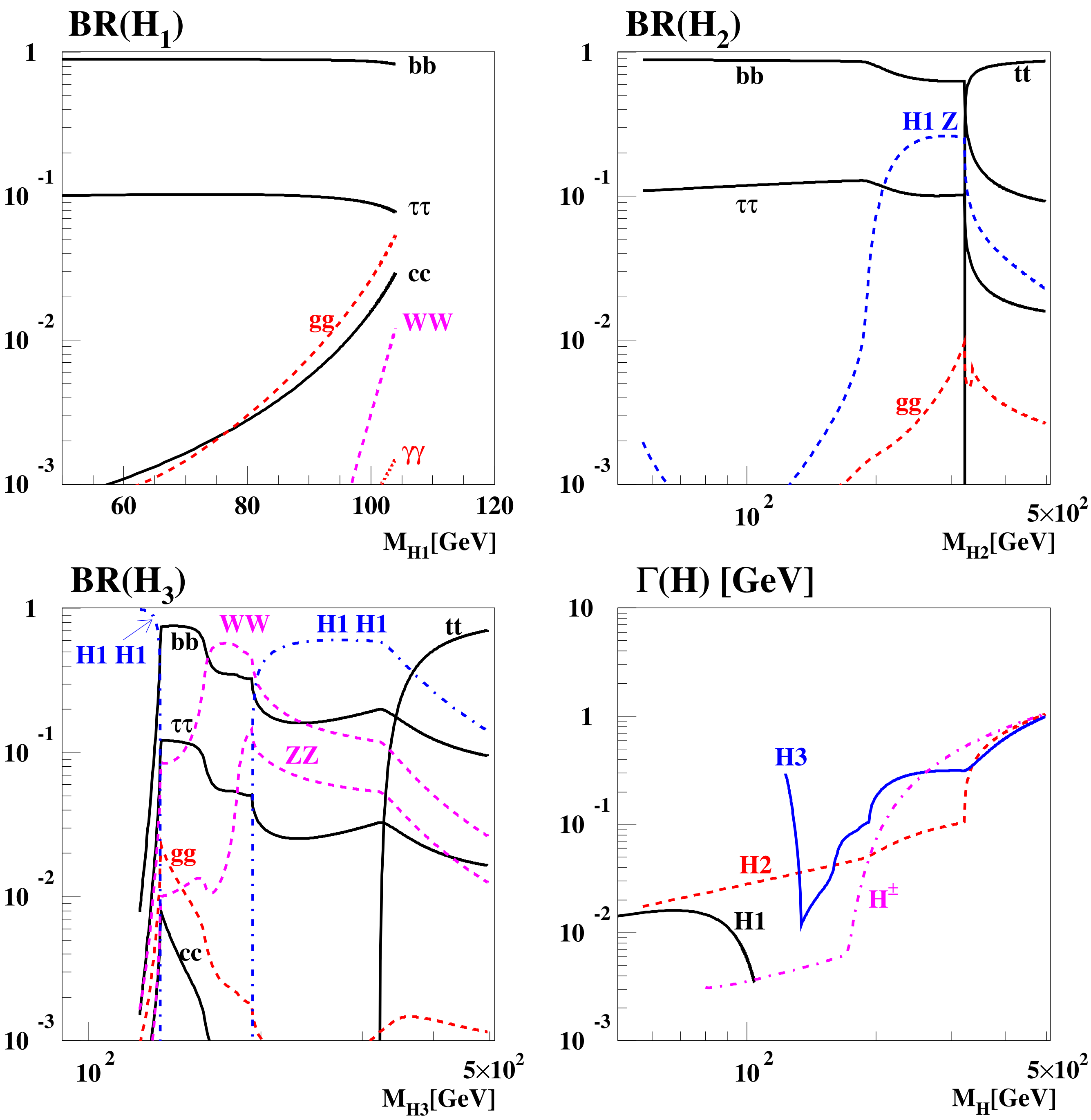
P. Bechtle, hep-ex/0401007

Exclusion area of the CPX scenario in the $\tan\beta$, m_{H_1} projection from OPAL

- CPsuperH : a computational tool for Higgs phenomenology in the MSSM with explicit CP violation JSL, A. Pilaftsis, M. Carena, S. Y. Choi, M. Drees, J. R. Ellis and C. E. M. Wagner, Comput. Phys. Commun. **156** (2004) 283

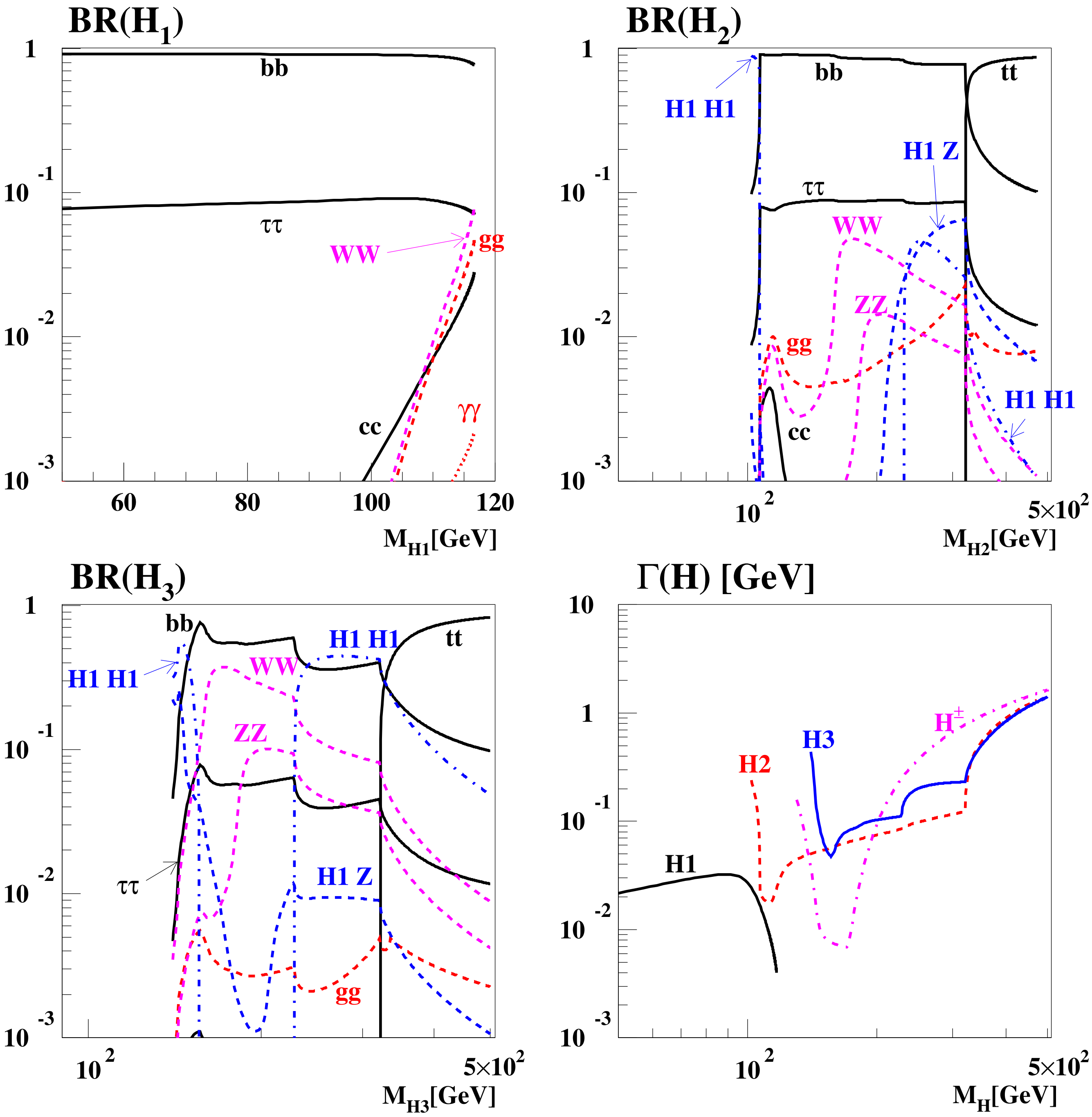
  * Higgs decay patterns strongly depend on CP-violating Higgs mixing S.Y. Choi and JSL, Phys.Rev. **D61** (2000) 015003; S.Y. Choi, K. Hagiwara, and JSL, Phys. Rev. **D64** (2001) 032004; S. Y. Choi, M. Drees, JSL and J. Song, Eur. Phys. J. C **25**, 307 (2002)

- CPsuperH (cont'd)
  - Br's and decay widths for CPX scenario varying $M_{H^\pm}^{\rm pole}$ with $\Phi_A = \Phi_3 = 0^\circ$, $\tan\beta = 4$, $M_{\rm SUSY} = 0.5$ TeV



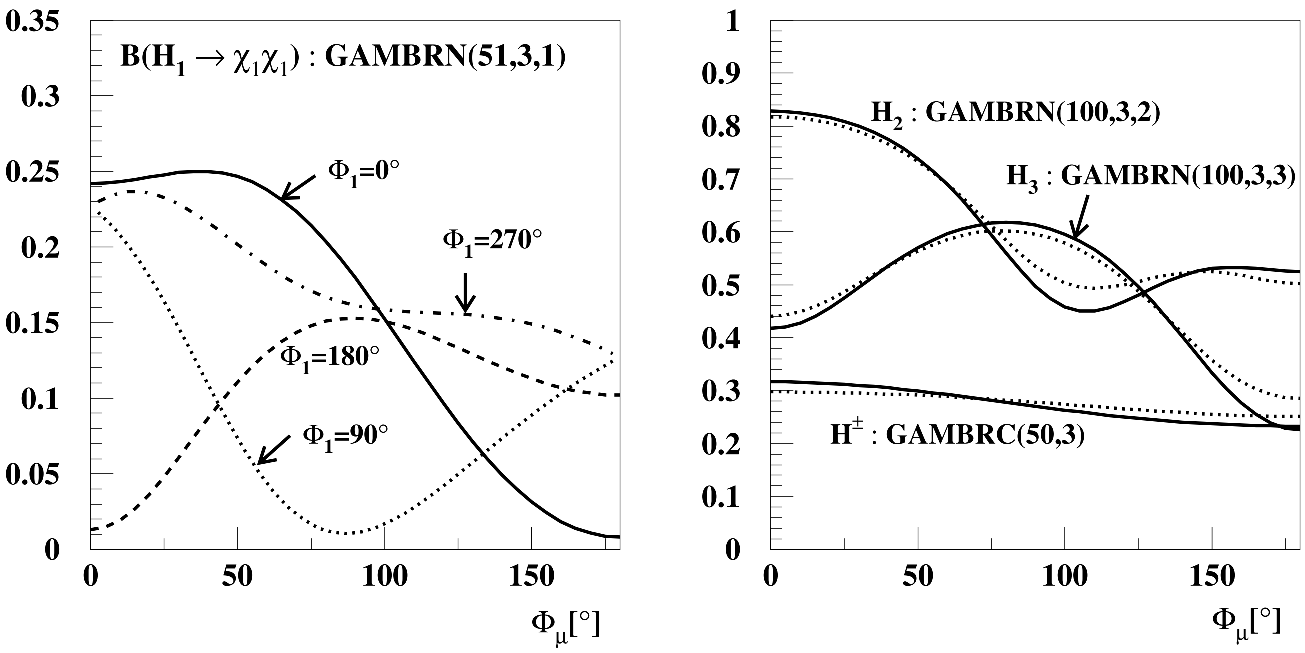
♠ *Introduction*

- CPsuperH (cont'd)
  - Br's and decay widths for CPX scenario varying $M_{H^\pm}^{\rm pole}$ with $\Phi_A = \Phi_3 = 90^\circ$, $\tan\beta = 4$, $M_{\rm SUSY} = 0.5$ TeV



♠ *Introduction*

- CPsuperH (cont'd)
  - Decays into SUSY particles with $\tan\beta = 5$ and $M_{H^+}^{\rm pole} = 0.3$ TeV



$$M_{\rm SUSY} = 0.5 \ \ {\rm TeV}\,, \quad |\mu| = 250 \ \ {\rm GeV},$$
$$|A_t| = |A_b| = |A_\tau| = 1.2 \ \ {\rm TeV}\,, \quad |M_3| = 0.5 \ \ {\rm TeV}$$
$$|M_1| = 50 \ \ {\rm GeV}\,, \quad |M_2| = 150 \ \ {\rm GeV}$$
$$\Phi_2 = \Phi_3 = 0\,, \quad \Phi_{A_t} = \Phi_{A_b} = \Phi_{A_\tau} = -\Phi_\mu$$

♠ *Coupled-channel analysis of neutral Higgs bosons*

- The full 3×3 Higgs boson propagator matrix : $D(\hat{s})$

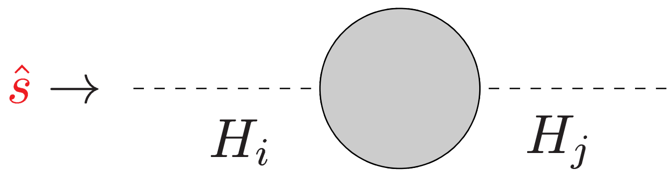
We consider a situation where two or more Higgs bosons are simultaneously involved in a process

$$D(\hat{s}) = \hat{s} \times$$
$$\begin{pmatrix} \hat{s} - M_{H_1}^2 + i\Im\mathrm{m}\widehat{\Pi}_{11}(\hat{s}) & i\Im\mathrm{m}\widehat{\Pi}_{12}(\hat{s}) & i\Im\mathrm{m}\widehat{\Pi}_{13}(\hat{s}) \\ i\Im\mathrm{m}\widehat{\Pi}_{21}(\hat{s}) & \hat{s} - M_{H_2}^2 + i\Im\mathrm{m}\widehat{\Pi}_{22}(\hat{s}) & i\Im\mathrm{m}\widehat{\Pi}_{23}(\hat{s}) \\ i\Im\mathrm{m}\widehat{\Pi}_{31}(\hat{s}) & i\Im\mathrm{m}\widehat{\Pi}_{32}(\hat{s}) & \hat{s} - M_{H_3}^2 + i\Im\mathrm{m}\widehat{\Pi}_{33}(\hat{s}) \end{pmatrix}^{-1}$$

A. Pilaftsis, Nucl. Phys. B **504** (1997) 61

– M_{H_i} : One-loop Higgs-boson pole mass
$\rightarrow M_{H_i}\Gamma_{H_i}\Im\mathrm{m}\widehat{\Pi}'(M_{H_i}^2)$ and $\Re\mathrm{e}\widehat{\Pi}(\hat{s}) - \Re\mathrm{e}\widehat{\Pi}(M_{H_i}^2)$ are neglected.
M. Carena, J. Ellis, A. Pilaftsis and C.E.M. Wagner, Nucl. Phys. B **625** (2002) 345

– $\Im\mathrm{m}\widehat{\Pi}_{ij}(\hat{s})$: absorptive parts of the Higgs-boson self-energies $\rightarrow \Im\mathrm{m}\widehat{\Pi}_{ii}(\hat{s} = M_{H_i}^2) = M_{H_i}\Gamma_{H_i}$



$$= \quad i\, \widehat{\Pi}_{ij}(\hat{s})$$

♠ *Coupled-channel analysis of neutral Higgs bosons*

- The full 3×3 Higgs boson propagator matrix : $D(\hat{s})$ (cont'd)

  – Contributions from loops of fermions $(b, t, \tau, \tilde{\chi}^0, \tilde{\chi}^{\pm})$, vector bosons (ZZ, WW), pairs of Higgs and vector bosons $(H_k Z, H^{\pm} W^{\mp})$, Higgs-boson pairs $(H_k H_l)$, and sfermions $(\tilde{b}, \tilde{t}, \tilde{\tau})$ have been considered.

  – The PT is applied for VV and HV cases to obtain gauge-independent result and to remove the badly high-energy-behaved $\hat{s}^2$ terms consistently J. Papavassiliou and A. Pilaftsis, Phys. Rev. Lett. **80** (1998) 2785; Phys. Rev. D **58** (1998) 053002

  – Note the relation

$$\widehat{\Pi}_{ij}(\hat{s}) = \sum_{\alpha,\beta=\phi_1,\phi_2,a} O_{\alpha i} O_{\beta j} \widehat{\Pi}_{\alpha\beta}(\hat{s})$$

♠ *Coupled-channel analysis of neutral Higgs bosons*

- Three-way mixing scenario

$$\tan\beta = 50, \quad M_{H^\pm}^{\rm pole} = 155 \;\; {\rm GeV},$$
$$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = M_{\tilde{L}_3} = M_{\tilde{E}_3} = 0.5 \;\; {\rm TeV},$$
$$|\mu| = 0.5 \;\; {\rm TeV}, \quad |A_{t,b,\tau}| = 1 \;\; {\rm TeV}, \quad |M_{1,2}| = 0.3 \;\; {\rm TeV},$$
$$|M_3| = 1 \;\; {\rm TeV},$$

For the choice of phases:

$$\Phi_\mu = 0^\circ, \quad \Phi_{A_t,A_b,A_\tau} = 90^\circ, \quad \Phi_{1,2} = 0^\circ, \quad \Phi_3 = -90^\circ,$$

we have (in GeV)

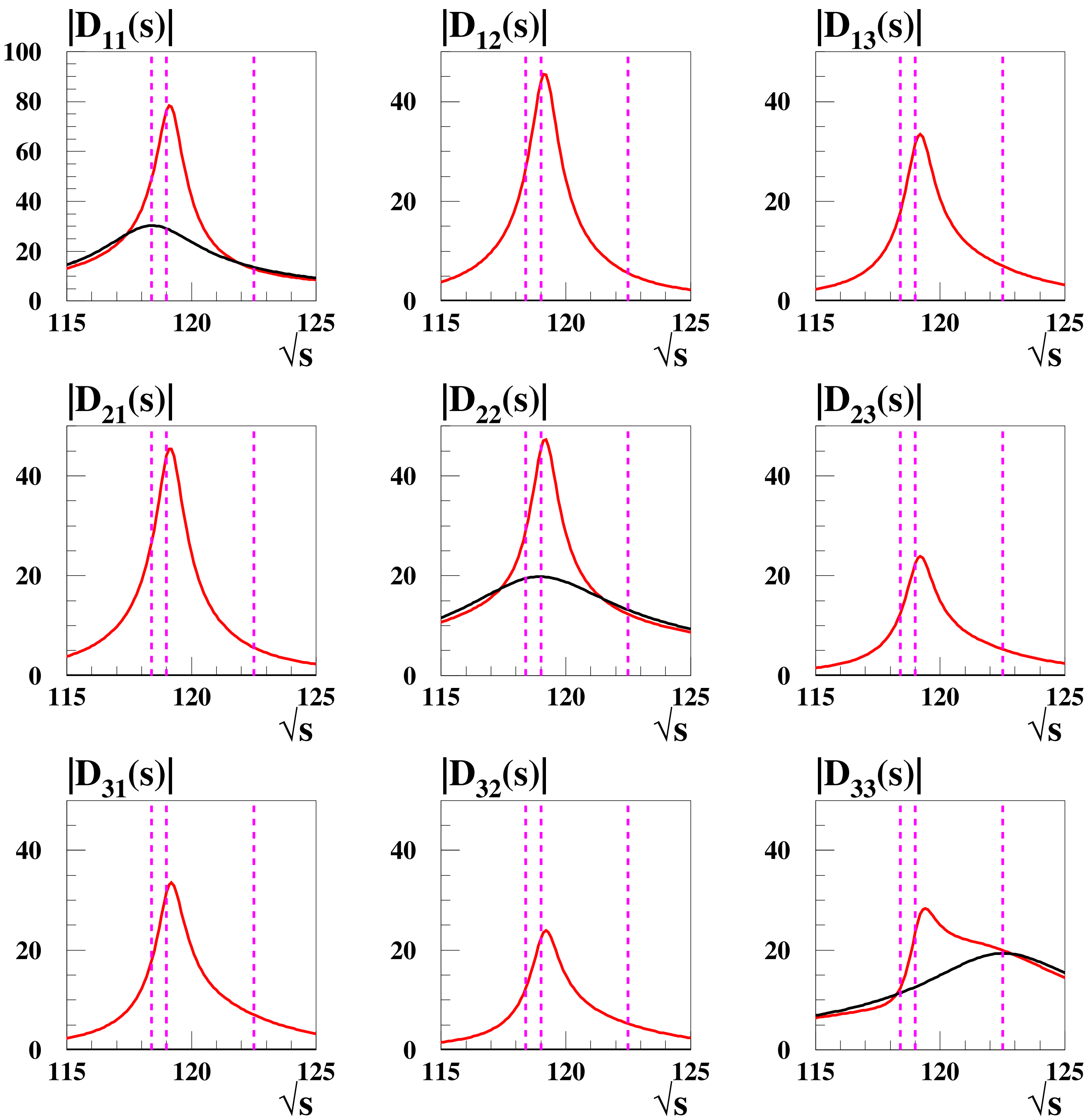
$$M_{H_1} = 118.4, \quad M_{H_2} = 119.0, \quad M_{H_3} = 122.5,$$
$$\Gamma_{H_1} = 3.91, \quad \Gamma_{H_2} = 6.02, \quad \Gamma_{H_3} = 6.34.$$

The branching ratios are

$$\begin{aligned}
B(H_1 \to b\bar{b}/\tau^+\tau^-) &= 0.908/0.09 \\
B(H_2 \to b\bar{b}/\tau^+\tau^-) &= 0.909/0.09 \\
B(H_3 \to b\bar{b}/\tau^+\tau^-) &= 0.908/0.09
\end{aligned}$$

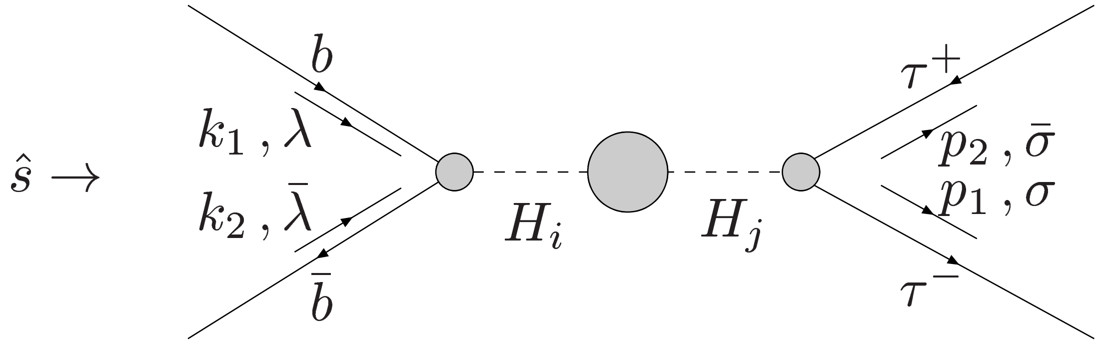
♠ *Coupled-channel analysis of neutral Higgs bosons*

- $|D_{ij}(s)|$ for three-way mixing scenario with $\Phi_A \equiv \Phi_{A_t,A_b,A_\tau} = 90^\circ$ and $\Phi_3 = -90^\circ$
  - Black Line : Set $i\Im\mathrm{m}\widehat{\Pi}_{ij} = 0$ when $i \neq j$
  - Red Line : Absorptive parts fully considered

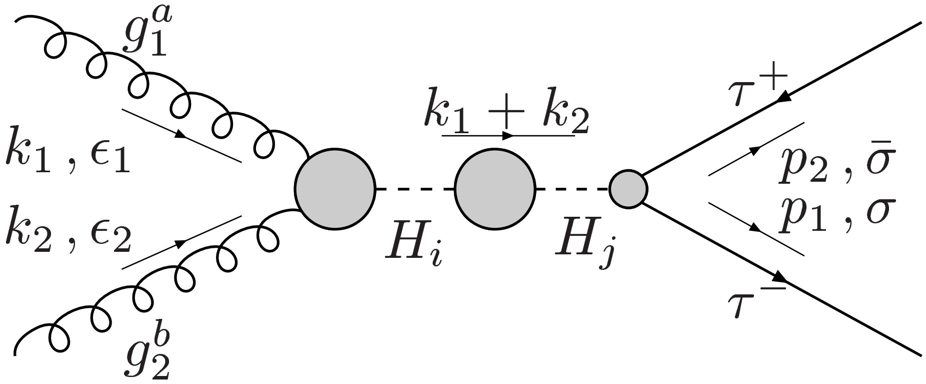


♠ Production → Mixing → Decay

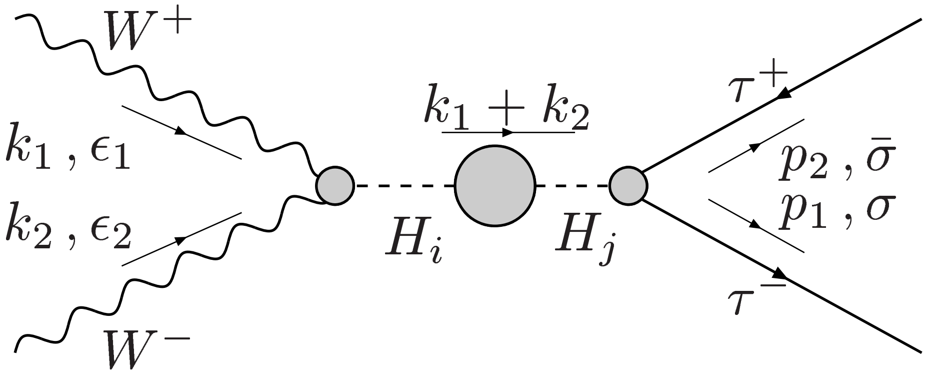
- $b\bar{b} \to H \to \tau^+_{R,L}\tau^-_{R,L}$



- $gg \to H \to \tau^+_{R,L}\tau^-_{R,L}$



- $W^+W^- \to H \to \tau^+_{R,L}\tau^-_{R,L}$



♠ *Production* $\rightarrow$ *Mixing* $\rightarrow$ *Decay*

- The (differential) total cross section : $\tau = \hat{s}/s$

$$\sigma_{\rm tot} = \sigma_{RR} + \sigma_{LL} \, ; \qquad \tau \frac{{\rm d}\sigma_{\rm tot}}{{\rm d}\tau}$$

$$\sigma_{RR} \equiv \sigma(pp \rightarrow H \rightarrow \tau^+_R \tau^-_R X)$$

$$\sigma_{LL} \equiv \sigma(pp \rightarrow H \rightarrow \tau^+_L \tau^-_L X)$$

- The (differential) CPV cross section : $\tau = \hat{s}/s$

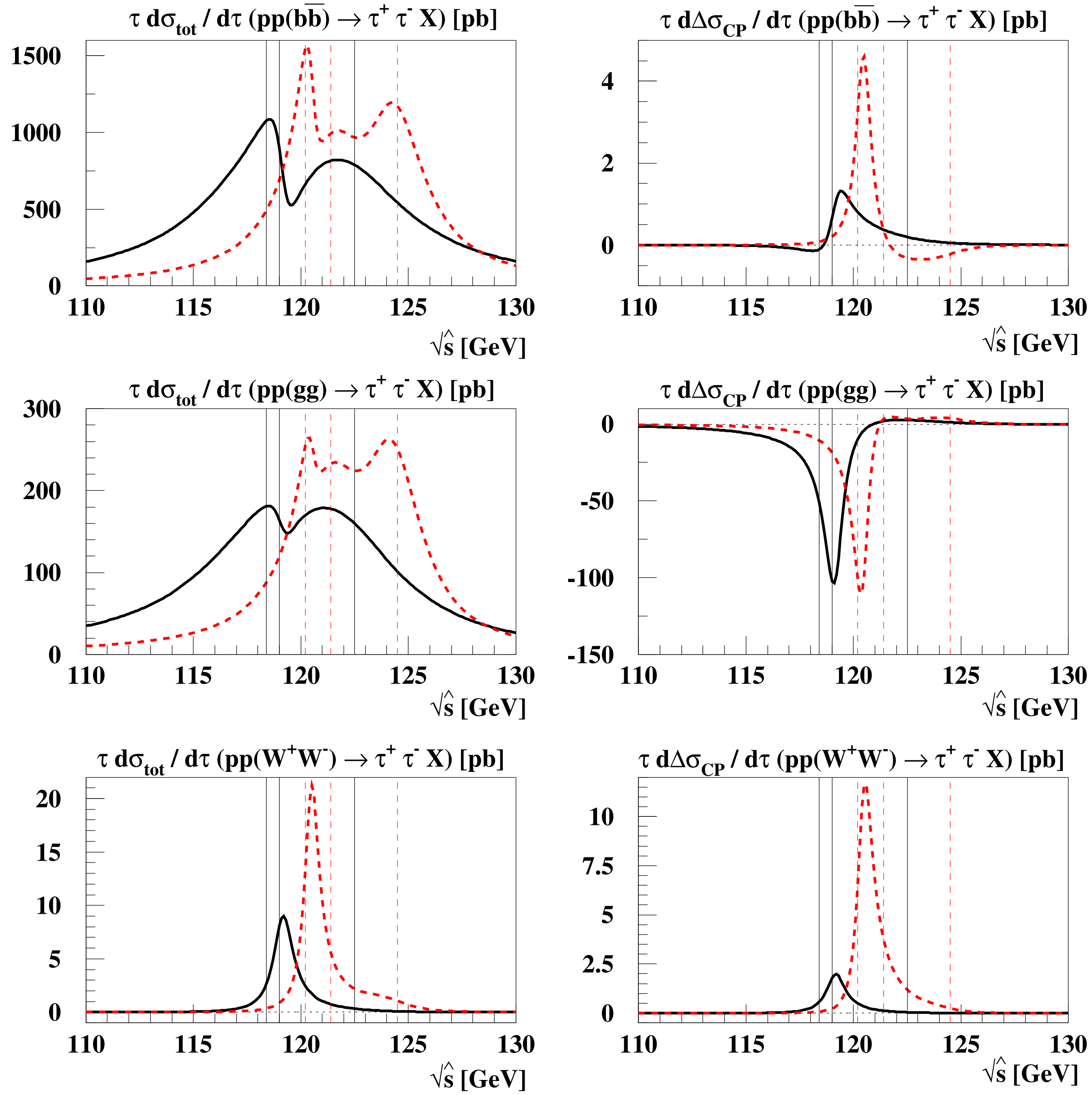
$$\Delta\sigma_{\rm CP} = \sigma_{RR} - \sigma_{LL} \, ; \qquad \tau \frac{{\rm d}\Delta\sigma_{\rm CP}}{{\rm d}\tau}$$

♠ Production $\rightarrow$ Mixing $\rightarrow$ Decay

- $\tau \, \frac{d\sigma_{\rm tot}}{d\tau}$ and $\tau \, \frac{d\Delta\sigma_{\rm CP}}{d\tau}$ for three-way mixing scenario

– Black Line : $\Phi_A = 90^\circ$ and $\Phi_3 = -90^\circ$

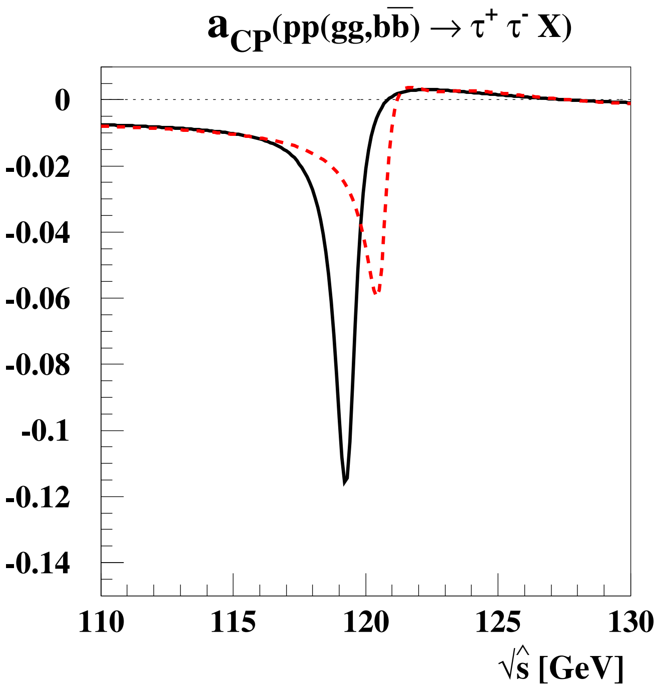
– Red Dashed Line : $\Phi_A = 90^\circ$ and $\Phi_3 = -10^\circ$

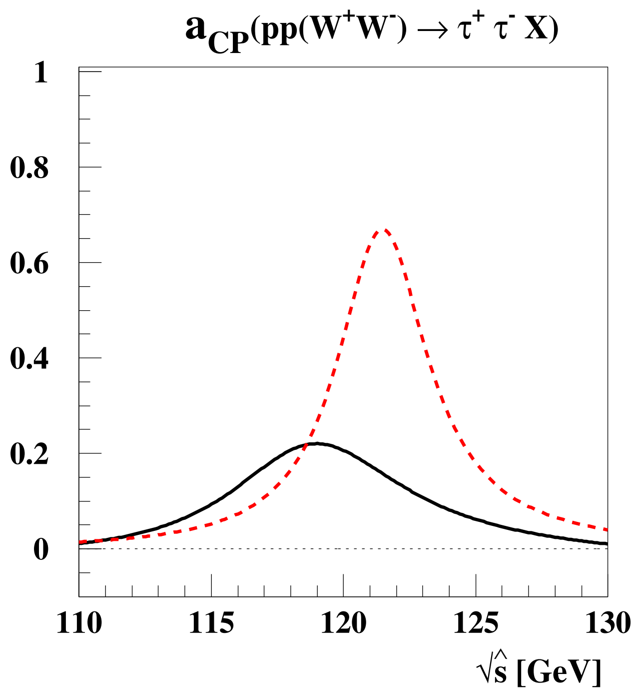


♠ *Production* → *Mixing* → *Decay*

- CP asymmetry : $a_{\rm CP}$ and $\mathcal{A}_{\rm CP}$

$$a_{\rm CP}(\tau) \equiv \frac{\tau \dfrac{d\Delta\sigma_{\rm CP}}{d\tau}}{\tau \dfrac{d\sigma_{\rm tot}}{d\tau}}\,, \qquad \mathcal{A}_{\rm CP} \equiv \frac{\Delta\sigma_{\rm CP}}{\sigma_{\rm tot}}$$





– The b-quark fusion can not be distinguished from gluon fusion : $\mathcal{A}_{\rm CP}^{b\bar{b}+gg} = -1.4\,(-1.0)\,\%$ for $\Phi_3 = -90^\circ\,(-10^\circ)$

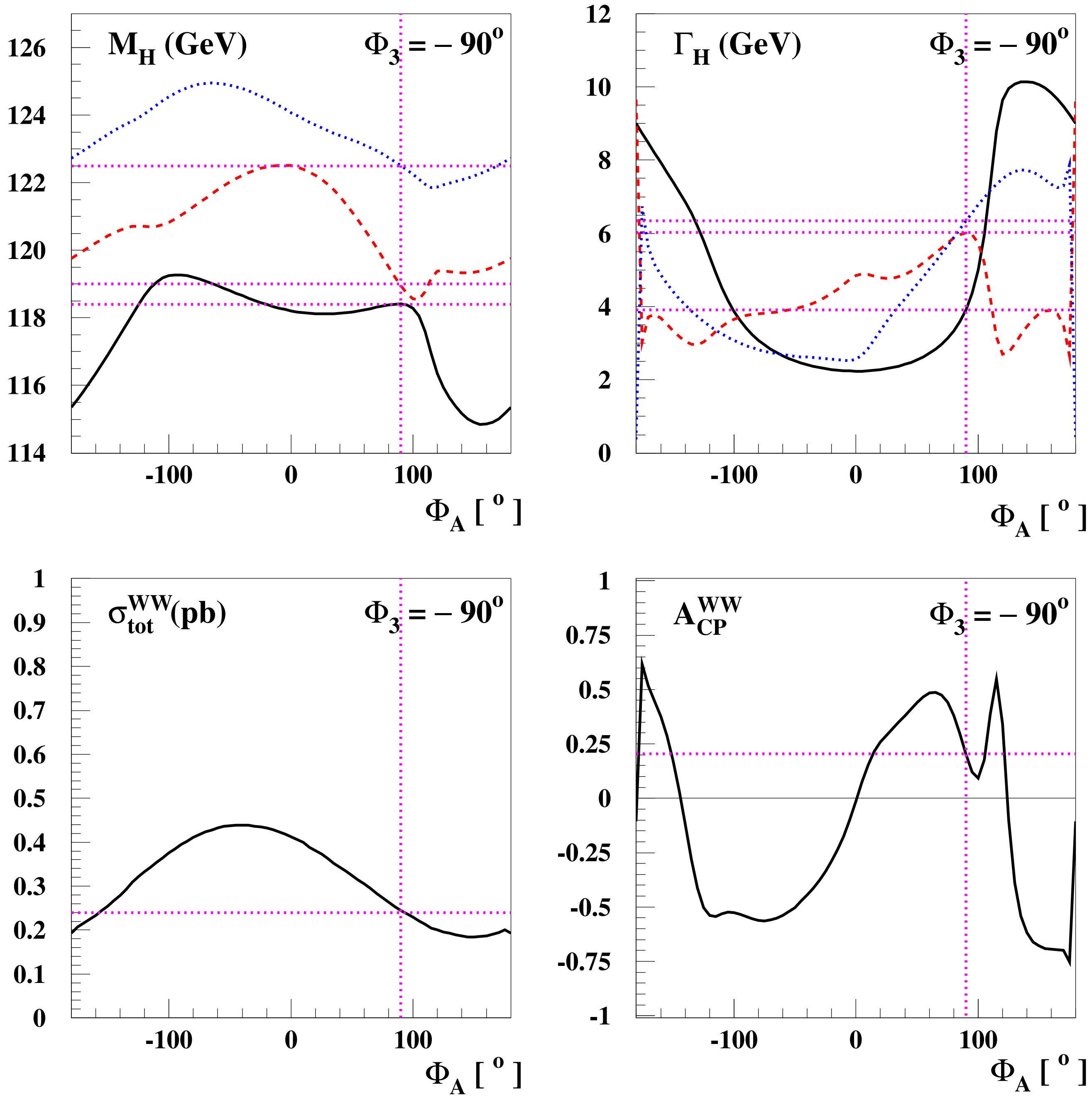
$[\mathcal{A}_{\rm CP}^{gg} = -8.4\,(-6.2)\,\%]$

– The W^+W^--fusion can be distinguished from b-quark and gluon fusions

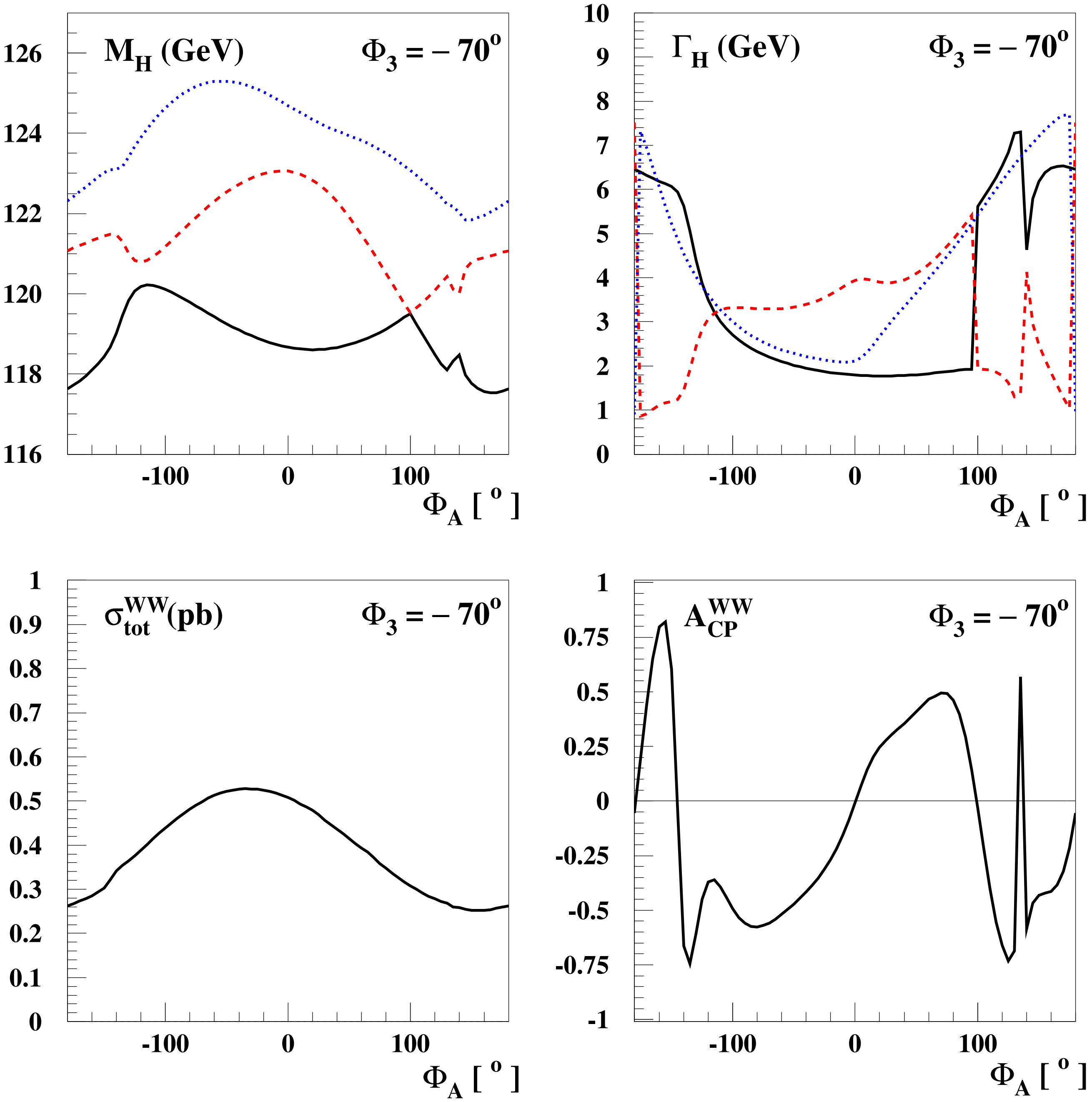
$\longrightarrow$ CONCENTRATE ON W^+W^- FUSION !!!

♠ Production → Mixing → Decay

- $\sigma^{WW}_{\rm tot}$ and CP asymmetry $\mathcal{A}^{WW}_{\rm CP}$ in W^+W^- fusion for three-way mixing scenario with $\Phi_3 = -90^\circ$ as functions of Φ_A
  - Black : H_1 Red Dashed : H_2 Blue Dotted : H_3

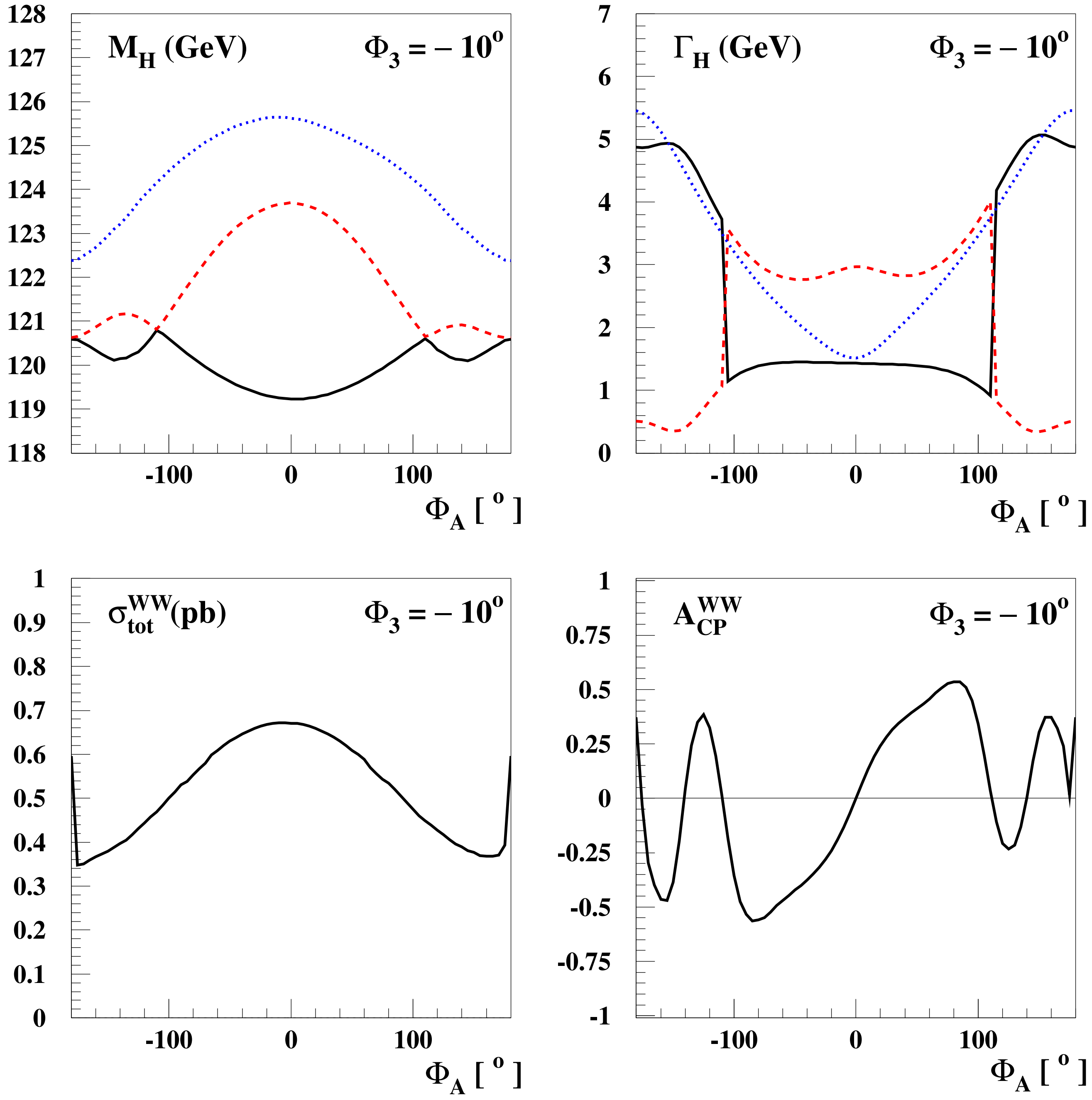


- $\sigma_{\rm tot}^{WW}$ and CP asymmetry $\mathcal{A}_{\rm CP}^{WW}$ in W^+W^- fusion for three-way mixing scenario with $\Phi_3 = -70^\circ$ as functions of Φ_A
  - Black : H_1 Red Dashed : H_2 Blue Dotted : H_3



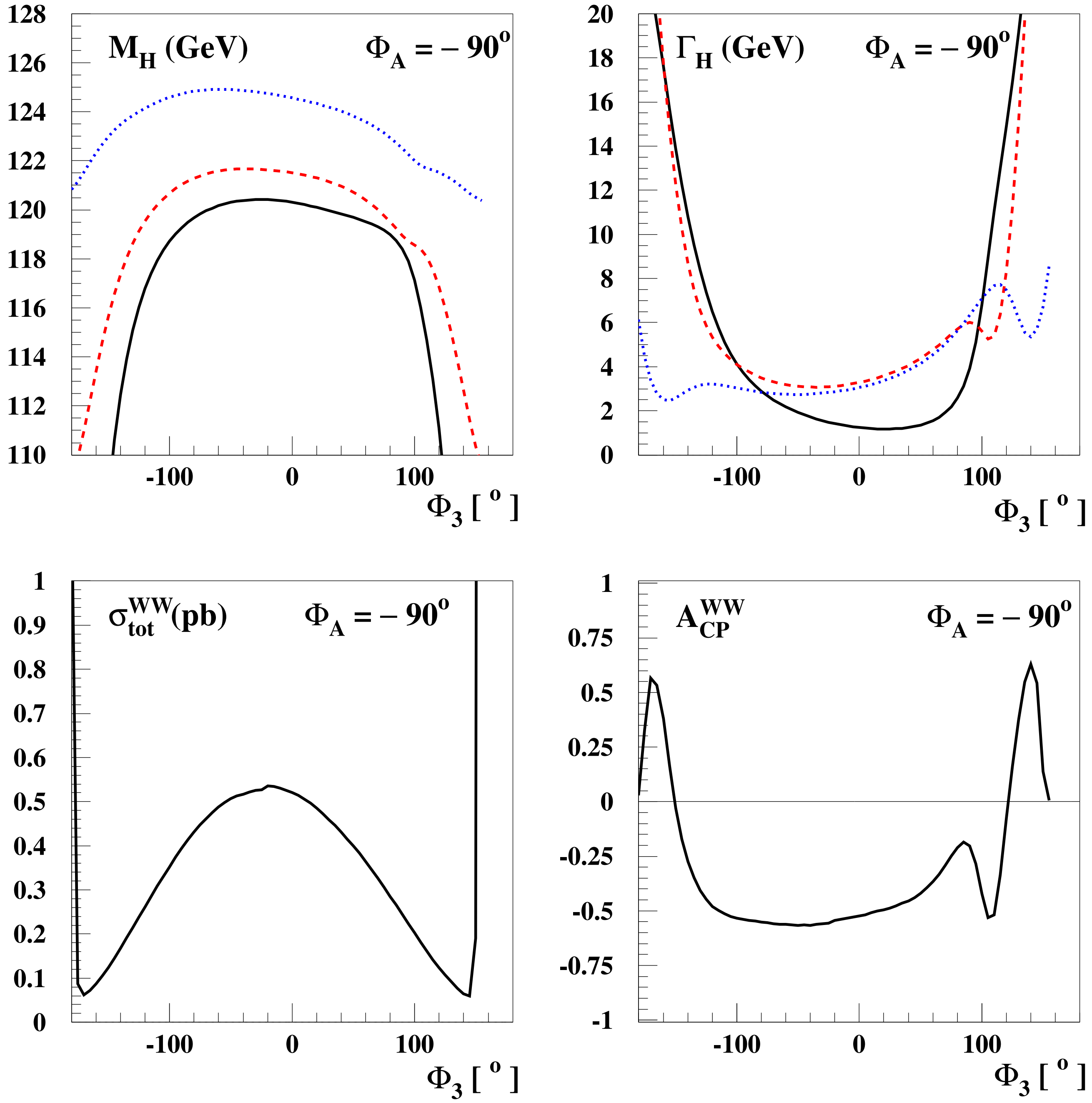
♠ Production → Mixing → Decay

- $\sigma_{\rm tot}^{WW}$ and CP asymmetry $\mathcal{A}_{\rm CP}^{WW}$ in W^+W^- fusion for three-way mixing scenario with $\Phi_3 = -10^\circ$ as functions of Φ_A
  - Black : H_1 Red Dashed : H_2 Blue Dotted : H_3



♠ Production → Mixing → Decay

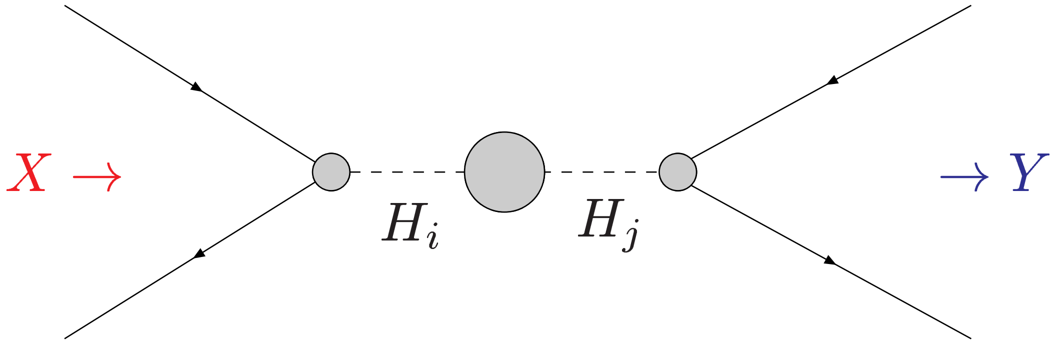
- $\sigma^{WW}_{\rm tot}$ and CP asymmetry $\mathcal{A}^{WW}_{\rm CP}$ in W^+W^- fusion for three-way mixing scenario with $\Phi_A = -90^\circ$ as functions of Φ_3
  - Black : H_1 Red Dashed : H_2 Blue Dotted : H_3



♠ *Conclusion*

- CPsuperH is ready for a Higgs phenomenology in the MSSM with explicit CP violation

- We have developed a general formalism for studying CP-violating phenomena in the production, mixing and decay of a coupled system of CP-violating neutral Higgs boson at high-energy colliders



$$X = b\bar{b}\,, gg\,, WW\,, ZZ\,, \gamma\gamma\,, \tau\tau\,, \mu\mu\,, \cdots$$
$$Y = \tau^+\tau^-\,, t\bar{t}\,,\ \tilde{\chi}_i^0\tilde{\chi}_j^0\,,\ \tilde{\chi}_i^+\tilde{\chi}_j^-\,,\ \cdots$$

$\Longrightarrow$ <u>*Let's do it now !*</u>