CP violation in charged Higgs production and decays in the Complex 2HDM

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Based on: A.A, H. Eberl, E. Ginina, K. Christova , JHEP'11

Plan

- Complex 2HDM: Motivations
- parametrization of C2HDM and constraints
- CP violation in charged Higgs production $\boxed{bg \to tH^-}$ and decays $\boxed{H^\pm \to tb\ ,\ W^\pm h_{1,2}}$
- CP violation in neutral Higgs decays $h_1 \to \tau^+\tau^-$, ...
- Conclusions

Complex 2HDM: Motivations

In the SM, the amount of $\not{C}P$ in CKM, may be enough to explain the observed size of $\not{C}P$ in B and K meson system.

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Those large CP violating phases can give contributions to the EDM which exceed the experimental upper bound.

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EW phase transition with 4th generation requires 2 $SU(2)$ doublet Higgs fields
[Y.Kikukawa, M. Kohda, J.Yasuda, Prog.Theor.Phys'09]

arameterization of C2HDM and constrain

$$
\begin{aligned}
V &= m_{11}^2(\Phi_1^+\Phi_1) + m_{22}^2(\Phi_2^+\Phi_2) + \lambda_1(\Phi_1^+\Phi_1)^2 + \\
&\quad \lambda_2(\Phi_1^+\Phi_1)^2 + \lambda_3(\Phi_1^+\Phi_1)(\Phi_2^+\Phi_2) + \lambda_4|\Phi_1^+\Phi_2|^2 \\
&\quad +\{m_{12}^2(\Phi_1^+\Phi_2) + h.c\} + [\lambda_5(\Phi_1^+\Phi_2)^2 + h.c]
\end{aligned}
$$

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- One can have: Explicit $\not{C}\not{P}$ if $\Im(m_{12}^4\lambda_5^*) \neq 0$
- For $\Im(m_{12}^4\lambda_5^*) = 0$: we can have Spontaneous $\not{C}\not{P}$ if: $|\frac{m_{12}^2}{\lambda_5 v_1 v_2}| < 1$; $<\Phi_1>= v_1$, $<\Phi_2>= v_2 e^{i\theta}$, the minimum occurs for:

$$\cos\theta = \frac{m_{12}^2}{\lambda_5 v_1 v_2} \ ; \lambda_5 \neq 0$$

Stability condition $\frac{\partial^2 V}{\partial\theta^2} > 0 \Rightarrow \lambda_5 > 0$,

parameterization of C2HDM

$$\Phi_1 = \begin{pmatrix} \varphi_1^+ \\ (v_1 + \eta_1 + i\chi_1)/\sqrt{2} \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \varphi_2^+ \\ (v_2 + \eta_2 + i\chi_2)/\sqrt{2} \end{pmatrix}.$$

The physical Higgs eigenstates are obtained as follows.

The charged Higgs $H^\pm$ and the charged Goldstone fields $G^\pm$ are a mixture of $\varphi^\pm_{1,2}$:

$$\begin{aligned} H^\pm &= -\sin\beta\varphi_1^\pm + \cos\beta\varphi_2^\pm\,, \\ G^\pm &= \cos\beta\varphi_1^\pm + \sin\beta\varphi_2^\pm\,, \end{aligned}$$

$\tan\beta = v_2/v_1$.

The neutral physical Higgs states are obtained:

- One rotates the imaginary parts of: (χ_1, χ_2) into (G^0, η_3):

$$\begin{aligned} G^0 &= \cos\beta \chi_1 + \sin\beta \chi_2\,, \\ \eta_3 &= -\sin\beta \chi_1 + \cos\beta \chi_2\,, \end{aligned}$$

  G^0 is the Goldstone boson. The CP-odd η_3 mixes with the neutral CP-even components $\eta_{1,2}$.

- $\mathcal{M}^2_{ij} = \partial^2 V_{\rm Higgs}/(\partial\eta_i\partial\eta_j) \;\;,\;\; i,j = 1,2,3$
  $\mathcal{R}\mathcal{M}^2\mathcal{R}^T = {\rm diag}({\rm M}^2_{H_1^0}, {\rm M}^2_{H_2^0}, {\rm M}^2_{H_3^0})\,, {\rm M_{H_1^0}} \leq {\rm M_{H_2^0}} \leq {\rm M_{H_3^0}}$
  with $(H_1^0, H_2^0, H_3^0)^T = \mathcal{R}\;\; (\eta_1, \eta_2, \eta_3)^T$
  The mass eigenstates H_i^0 have a mixed CP structure.

$\mathcal{R}$ is parametrized by three rotation angles $\alpha_i, \; i = 1, 2, 3$:

$$\mathcal{R} \;=\; \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_3 & s_3 \\ 0 & -s_3 & c_3 \end{pmatrix} \begin{pmatrix} c_2 & 0 & s_2 \\ 0 & 1 & 0 \\ -s_2 & 0 & c_2 \end{pmatrix} \begin{pmatrix} c_1 & s_1 & 0 \\ -s_1 & c_1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} c_1\, c_2 & s_1\, c_2 & s_2 \\ -\big(c_1\, s_2\, s_3 + s_1\, c_3\big) & c_1\, c_3 - s_1\, s_2\, s_3 & c_2\, s_3 \\ -c_1\, s_2\, c_3 + s_1\, s_3 & -\big(c_1\, s_3 + s_1\, s_2\, c_3\big) & c_2\, c_3 \end{pmatrix},$$

with $s_i = \sin\alpha_i$ and $c_i = \cos\alpha_i$,

$$-\frac{\pi}{2} < \alpha_1 \le \frac{\pi}{2}\,; \quad -\frac{\pi}{2} < \alpha_2 \le \frac{\pi}{2}\,; \quad 0 \le \alpha_3 \le \frac{\pi}{2}\,.$$

Scalar potentiel parameters

The potential has 12 real parameters: 2 real masses: $m^2_{11,\,22}$, 2 VEVs, 4 reals: $\lambda_{1,\,2,\,3,\,4}$, 2 complex: λ_5, m^2_{12}.

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remains: 8 real independent parameters:

$$\boxed{\lambda_{1,2,3,4}, \quad \mathrm{Re}\,(\lambda_5), \quad \mathrm{Re}\,(m^2_{12}), \quad \tan\beta, \quad \mathrm{Im}\,(m^2_{12}).}$$

or

$$\boxed{M_{H_1^0}, \quad M_{H_2^0}, \quad M_{H^+}, \quad \alpha_1, \quad \alpha_2, \quad \alpha_3, \quad \tan\beta, \quad \mathrm{Re}\,(m_{12})\,.}$$

$$M^2_{H_3^0} = \frac{M^2_{H_1^0} R_{13}(R_{12}\tan\beta - R_{11}) + M^2_{H_2^0} R_{23}(R_{22}\tan\beta - R_{21})}{R_{33}(R_{31} - R_{32}\tan\beta)}\,,$$

Higgs couplings to gauge bosons

The interactions relevant to our study are:

$$\begin{aligned}\mathcal{C}(\mathrm{H}_i^0\mathrm{WW}) &= \cos\beta R_{i1} + \sin\beta R_{i2}\,, \\ \mathcal{C}(\mathrm{H}_i^0\,\mathrm{W}^{\pm}\,\mathrm{H}^{\mp}) &= \mp\, i(\sin\beta R_{i1} - \cos\beta R_{i2}) \pm R_{i3}\,.\end{aligned}$$

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One can derives the following sum rules:

$$\mathcal{C}(\mathrm{H}_i^0\mathrm{WW})^2 + |\mathcal{C}(\mathrm{H}_i^0\,\mathrm{W}^{+}\,\mathrm{H}^{-})|^2 = 1 \quad \text{for each i} = 1, 2, 3$$
$$\sum_{i=1}^{3}\mathcal{C}(\mathrm{H}_i^0\mathrm{WW})^2 = 1$$

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For a fixed i, if $|\mathcal{C}(\mathrm{H}_i^0\ \mathrm{W}^{+}\ \mathrm{H}^{-})|^2$ is suppressed, then $(\sin\beta R_{i1} - \cos\beta R_{i2})^2 \approx 0$ and $R_{i3}^2 \approx 0$

$\Rightarrow H_i^0$ is dominantly a CP-even state.

$$\begin{aligned}\mathcal{C}(\mathrm{H}_i^0\mathrm{WW})^2 + |\mathcal{C}(\mathrm{H}_i^0\ \mathrm{W}^+\ \mathrm{H}^-)|^2 &= 1 \quad \text{for each i} = 1, 2, 3 \\ \sum_{i=1}^{3} \mathcal{C}(\mathrm{H}_i^0\mathrm{WW})^2 &= 1\end{aligned}$$

For a fixed i, if $|\mathcal{C}(\mathrm{H}_i^0\ \mathrm{W}^+\ \mathrm{H}^-)|^2$ is suppressed,

the second sum rule $\Rightarrow \mathcal{C}(\mathrm{H}_j^0\mathrm{WW})^2 \approx 0$ for $j \neq i$.

Higgs couplings to fermions

if Φ_1 and Φ_2 couple to all fermions

$$\mathcal{L}_{Yukawa}^{2HDM} = -h_{ij}^{d,1}(\overline{\Psi_q^L})_i \Phi_1 d_j^R - h_{ij}^{u,1}(\overline{\Psi_q^L})_i \widetilde{\Phi}_1 u_j^R + (\Phi_1 \longleftrightarrow \Phi_2)$$

The mass term is: $M_{ij}^q = h_{ij}^{q,1}\ v_1 + h_{ij}^{q,2}\ v_2$

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up	Φ_2	Φ_2	Φ_2	Φ_2
down	Φ_2	Φ_1	Φ_1	Φ_2
lepton	Φ_2	Φ_1	Φ_2	Φ_1

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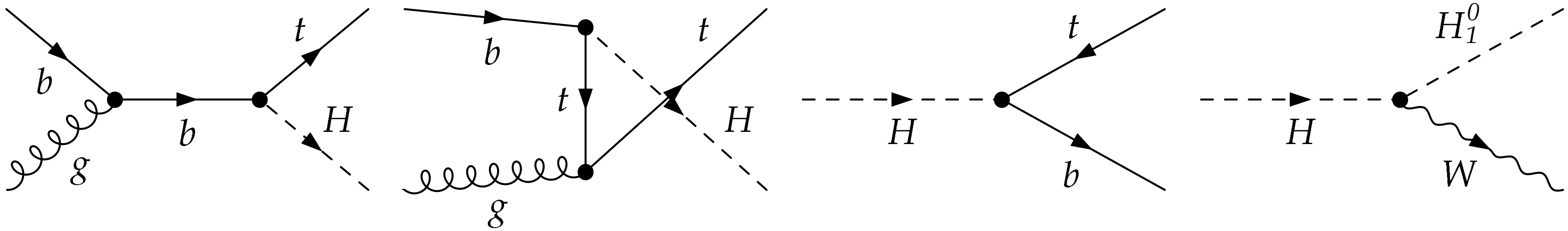
2HDM-IV ou 2HDM-L: (Lepton-specific model)

$$H_i b\bar{b} = -i\frac{gm_b}{2m_W}(\frac{R_{i1}}{\cos\beta} - iR_{i3}\tan\beta\gamma_5)$$

$$H_i t\bar{t} = -i\frac{gm_t}{2m_W}(\frac{R_{i2}}{\sin\beta} - iR_{i3}\cot\beta\gamma_5)$$

Feynman Diagrams



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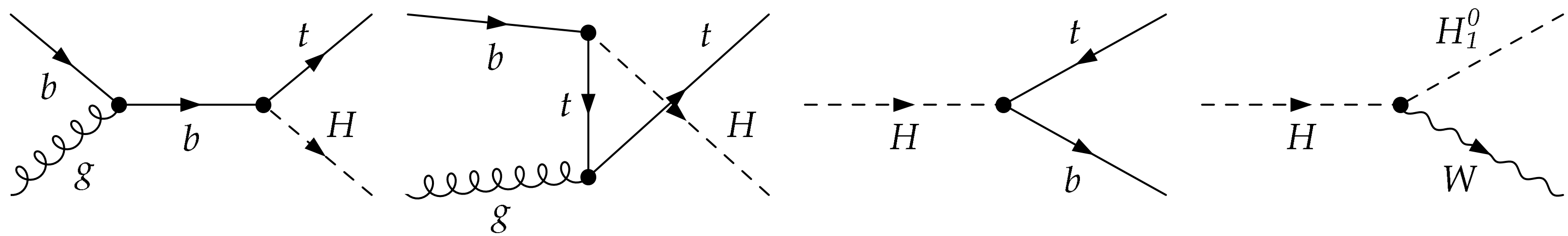

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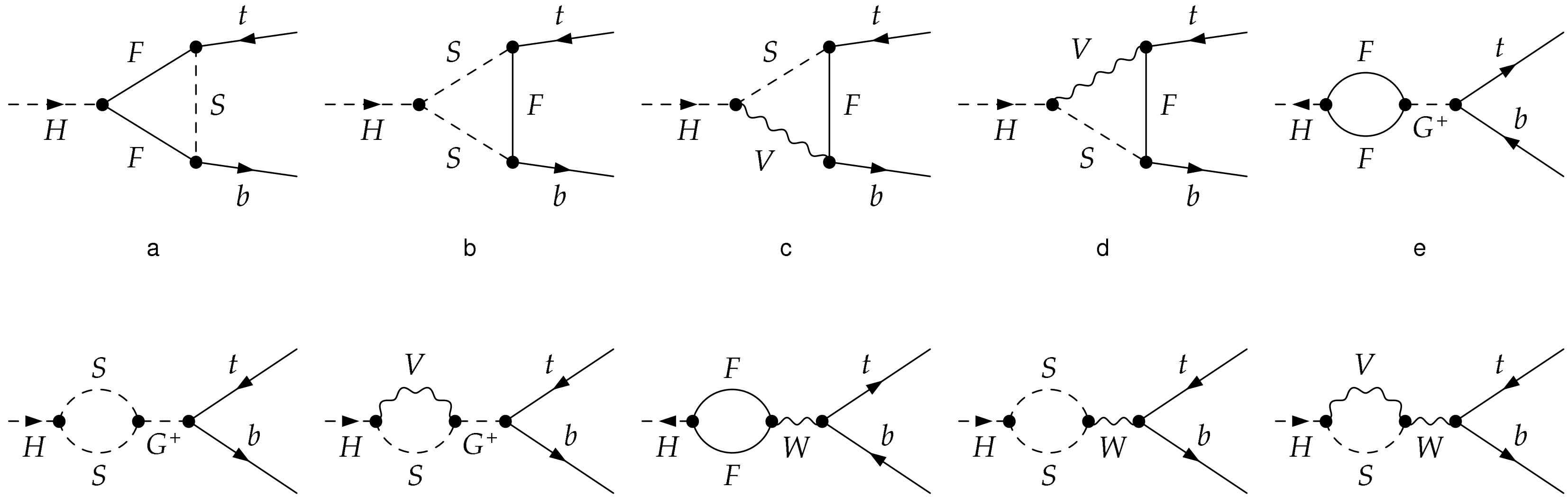
$H^{\pm} \to tb$



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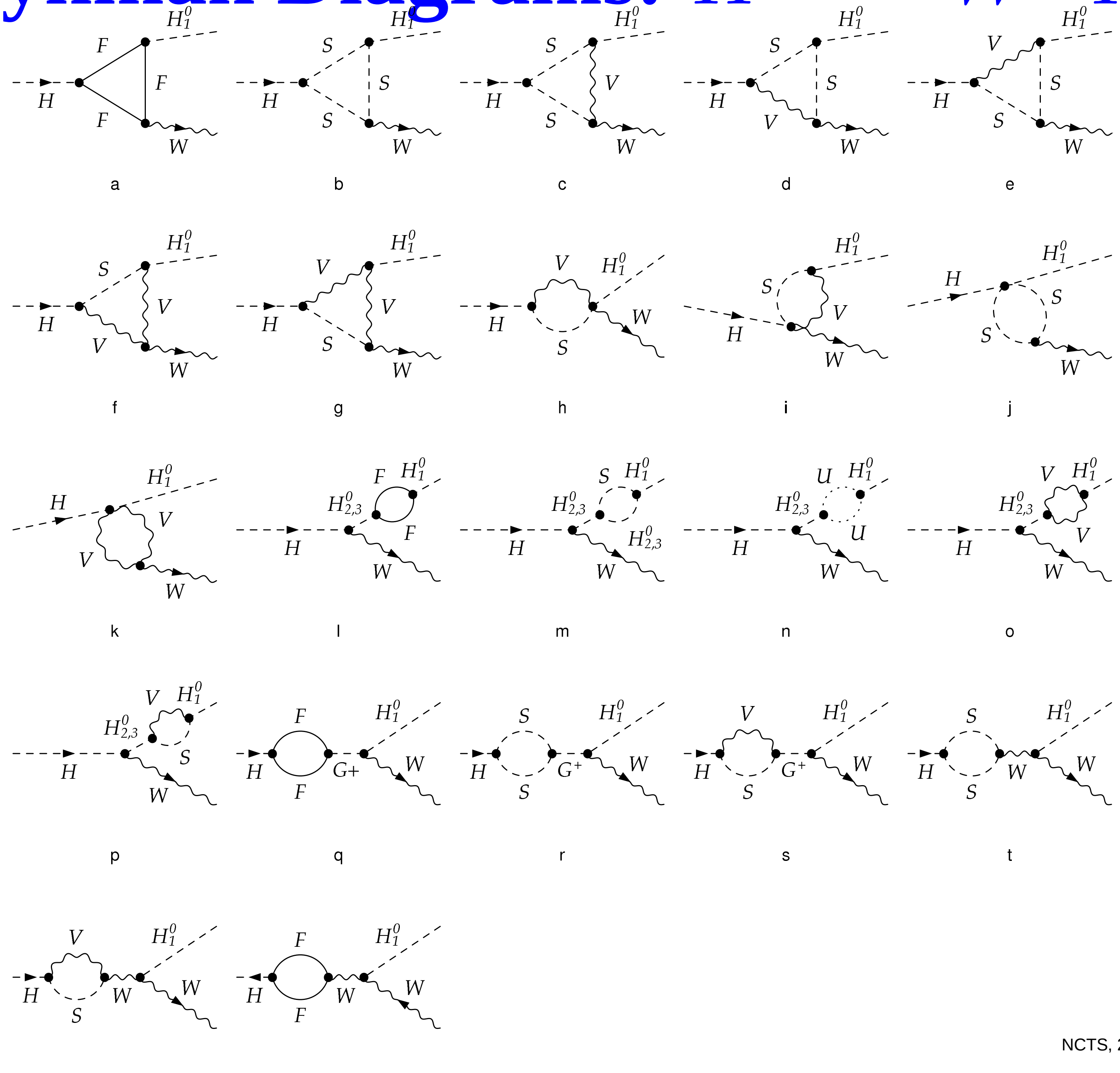
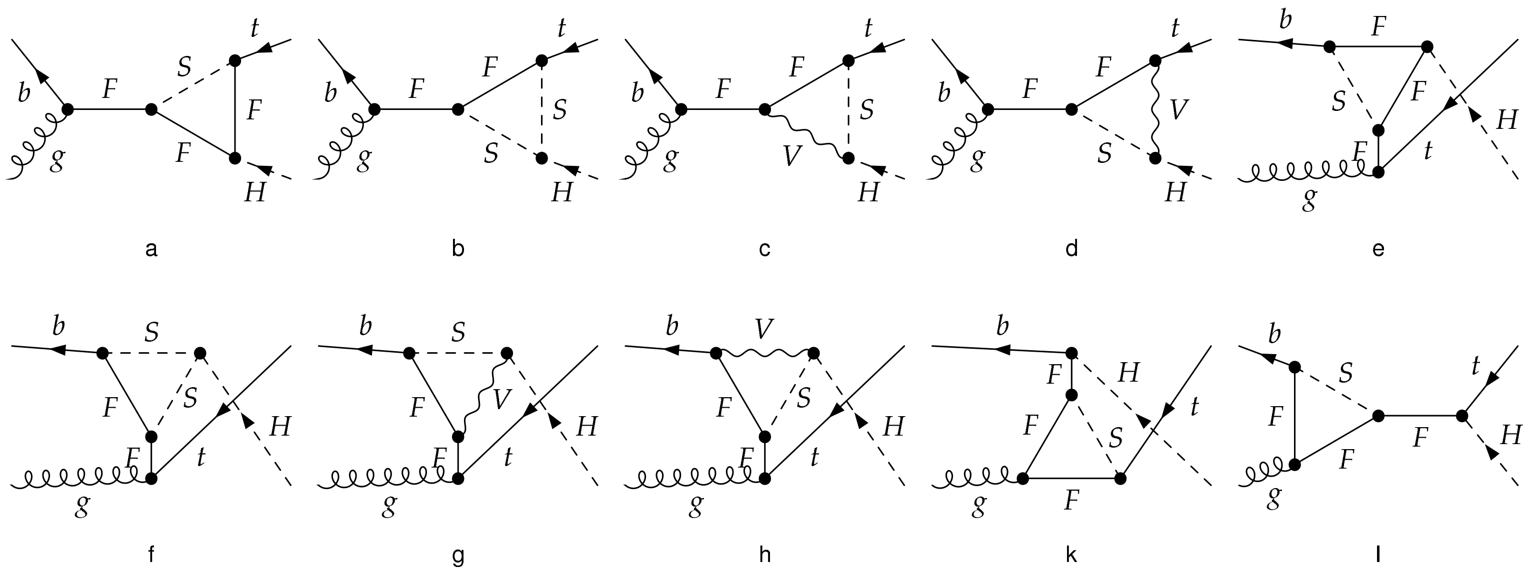
Feynman Diagrams: $H^{\pm} \to W^{\pm} H_i$



Feynman Diagrams: vetex & selfenergies



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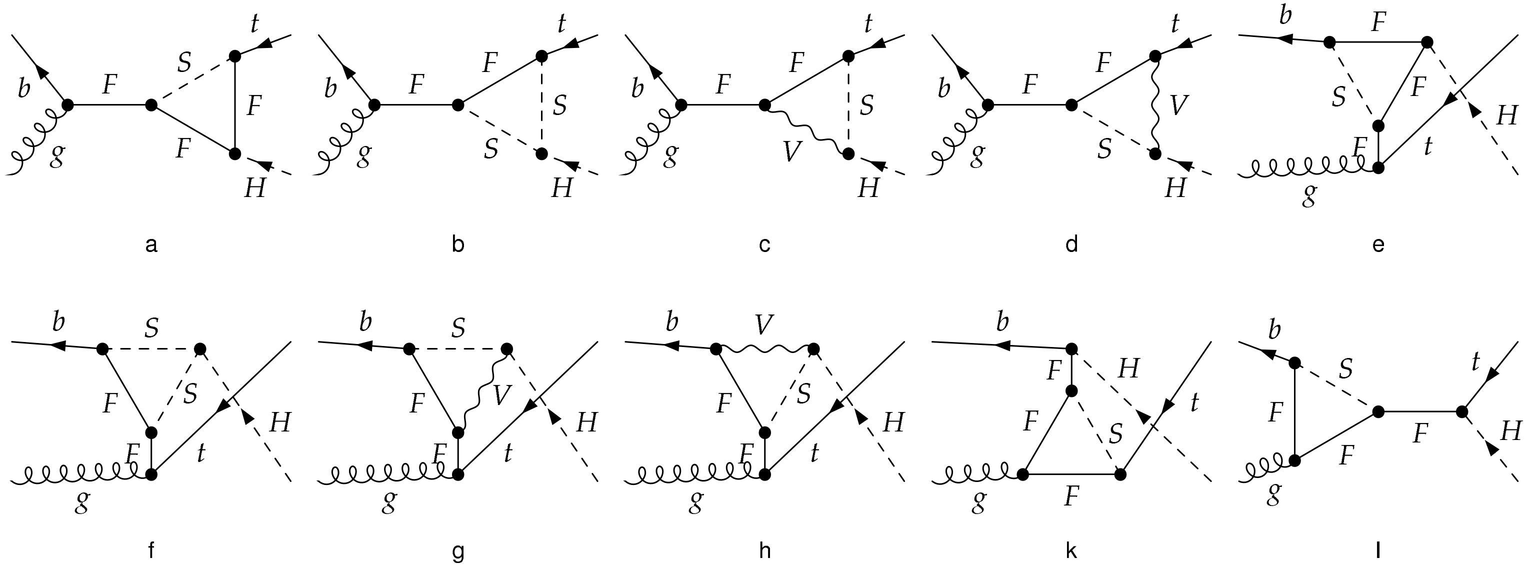
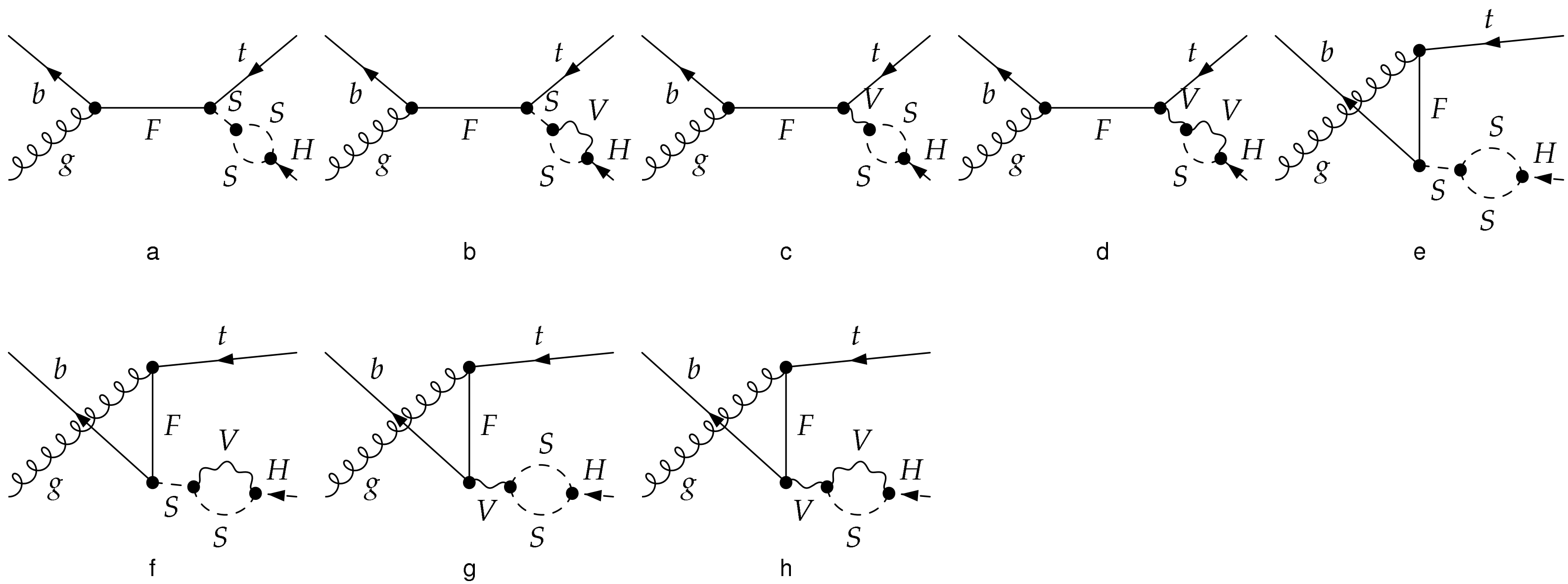
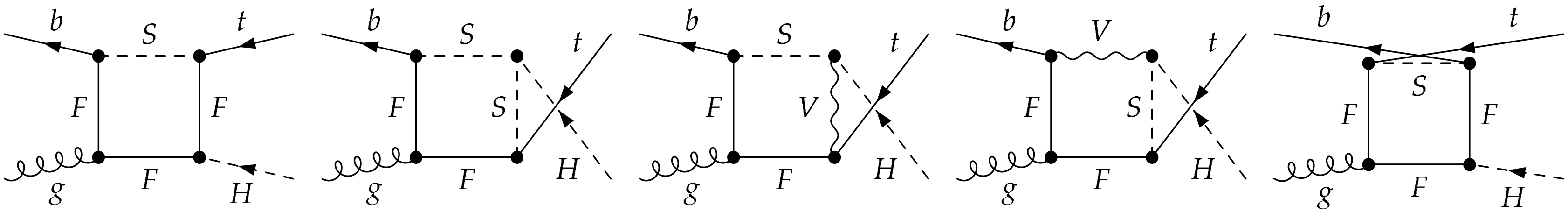




Feynman Diagrams: boxes



a b c d e

CP violating asymmetries

Decay rate asymmetries $A^{CP}_{D,f}$, defined by:

$$A^{CP}_{D,f}\ (H^\pm \to f) = \frac{\Gamma(H^+ \to f) - \Gamma(H^- \to \bar{f})}{2\Gamma^{\rm tree}(H^+ \to f)}\ ,\ \ f = t\bar{b};\ W^\pm H^0_i$$

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In the narow width approximation:

$$A^{CP}_f = A^{CP}_P + A^{CP}_{D,f}$$

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Theoretical constraints:

Potential bounded from bellow:

$$\lambda_1 > 0\,, \quad \lambda_2 > 0\,, \quad \lambda_3 + \sqrt{\lambda_1 \lambda_2} > 0\,, \quad \lambda_4 + \lambda_4 - |\lambda_5| + \sqrt{\lambda_1 \lambda_2} > 0$$

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Perturbative unitarity constraints:

$$\begin{aligned}
\left|\left(\lambda_1 + \lambda_2 \pm \sqrt{(\lambda_1 - \lambda_2)^2 + 4|\lambda_5|^2}\right)\right| &< 16\pi\,, \\
\left|\left(\lambda_1 + \lambda_2 \pm \sqrt{(\lambda_1 - \lambda_2)^2 + 4\lambda_4^2}\right)\right| &< 16\pi\,, \\
\left|3(\lambda_1 + \lambda_2) \pm \sqrt{9(\lambda_1 - \lambda_2^2 + 4(\lambda_3 + \lambda_4)^2)}\right| &< 16\pi\,, \\
|\,\lambda_3 \pm \lambda_4| < 8\pi\,, \quad |\,\lambda_3 \pm |\lambda_5|| < 8\pi\,, \quad |\,\lambda_3 + 2\lambda_4 \pm |\lambda_5|| &< 8\pi\,.
\end{aligned}$$

Only $|\lambda_5|$ is constrained not the CP phase

Numerics: $H^{\pm} \to tb$

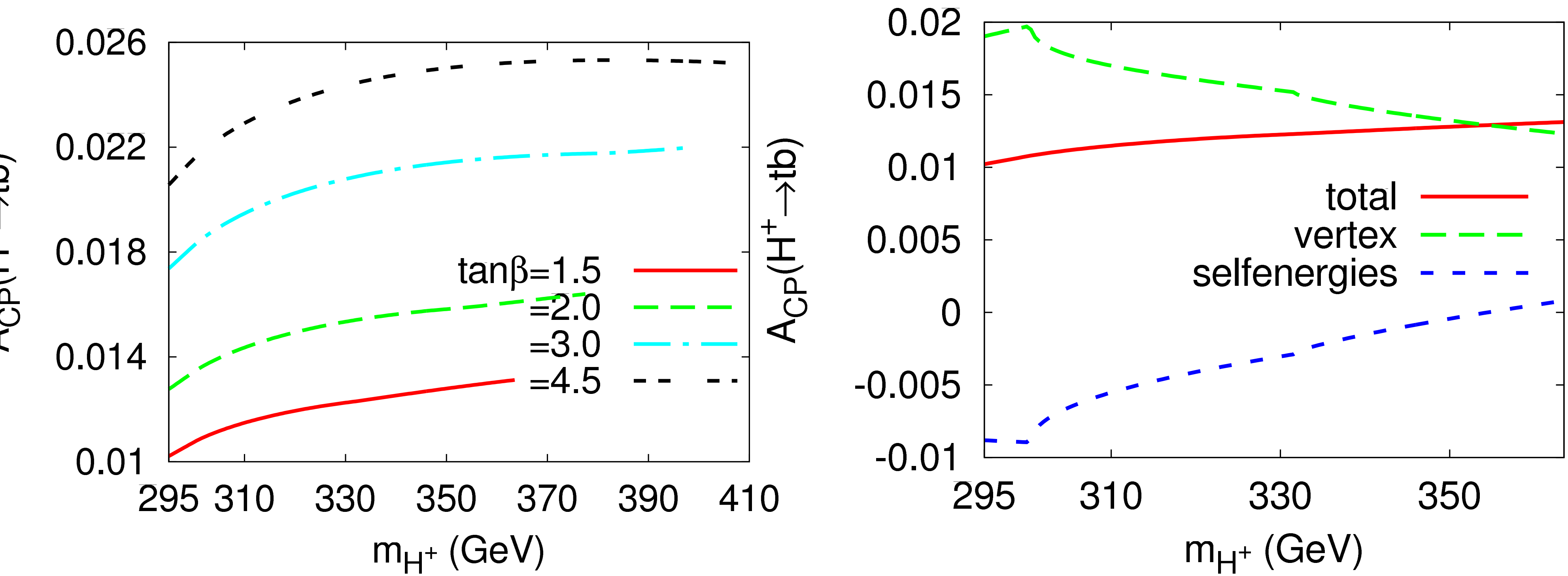


Figure 1: Left: $A^{CP}_{D,tb}$ as a function of M_{H^+}. $M_{H_1^0,H_2^0} = 120, 220$ GeV, $\mathrm{Re}(m_{12}) = 170$ GeV, $\alpha_1 = 0.8$, $\alpha_2 = -0.9$ and $\alpha_3 = \pi/3$. Right: Cancellation for $\tan\beta = 1.5$.

Numerics: $H^{\pm} \to W^{\pm} H_1$

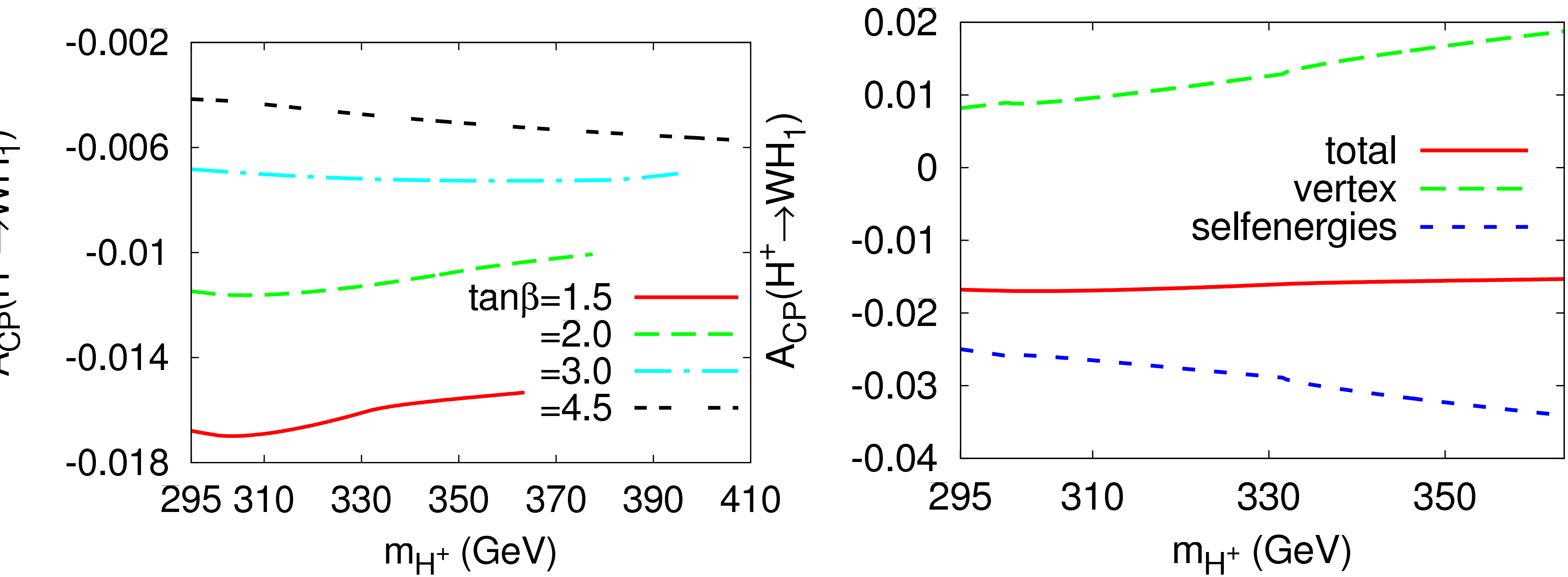


Figure 2: Left: A^{CP}_{D,WH_1^0} as a function of M_{H^+}. Right: Cancellation in A^{CP}_{D,WH_1^0} for $\tan\beta = 1.5$.

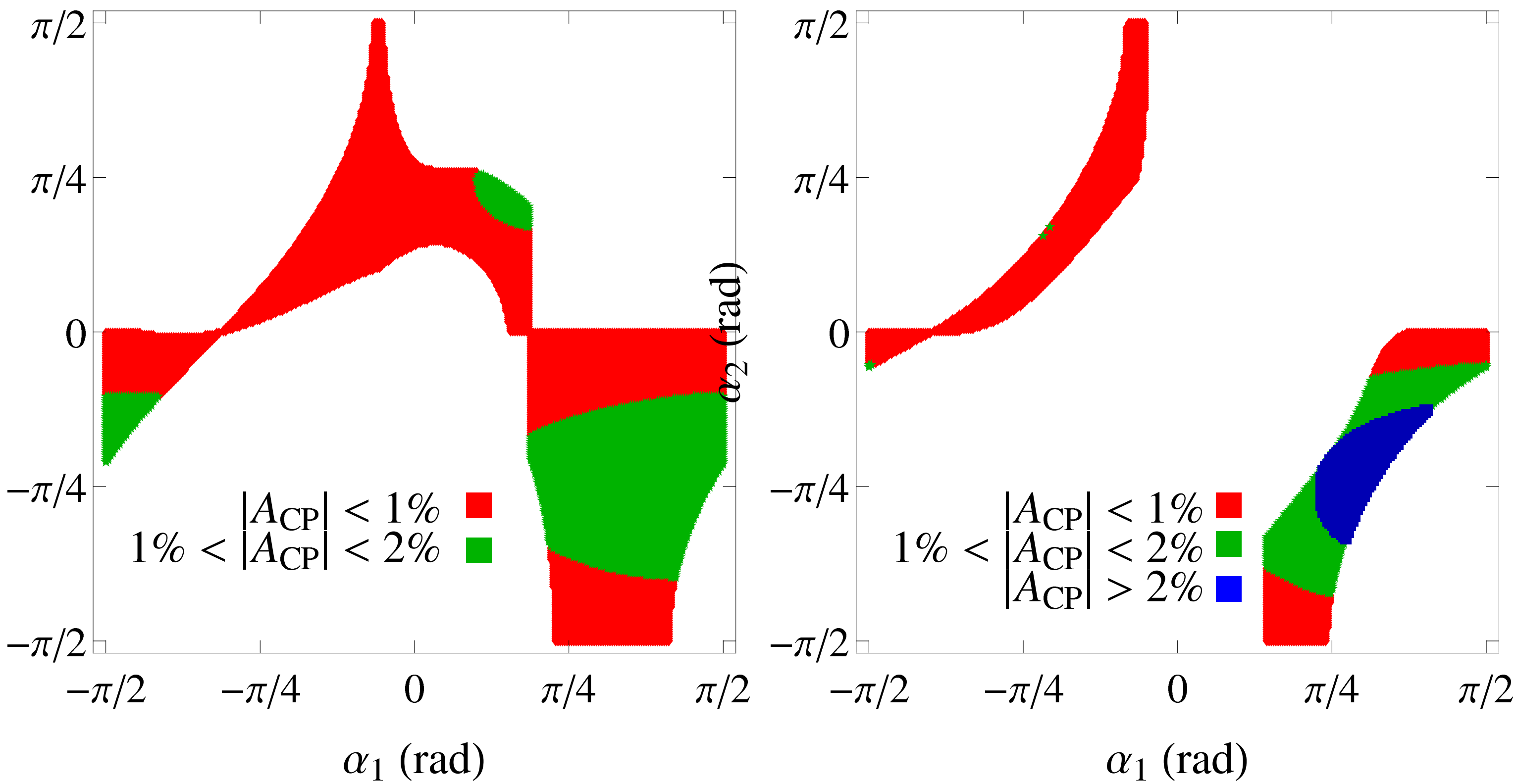


Figure 3: The allowed regions in (α_1, α_2) plan together with $|A^{CP}_{D,tb}|$. $M_{H_1^0, H_2^0, H^\pm} = 120, 220, 350$ GeV, $\mathrm{Re}(m_{12}) = 170$ GeV, and $\alpha_3 = \pi/3$. On the top left plot $\tan\beta = 1.5$ and $\tan\beta = 3$

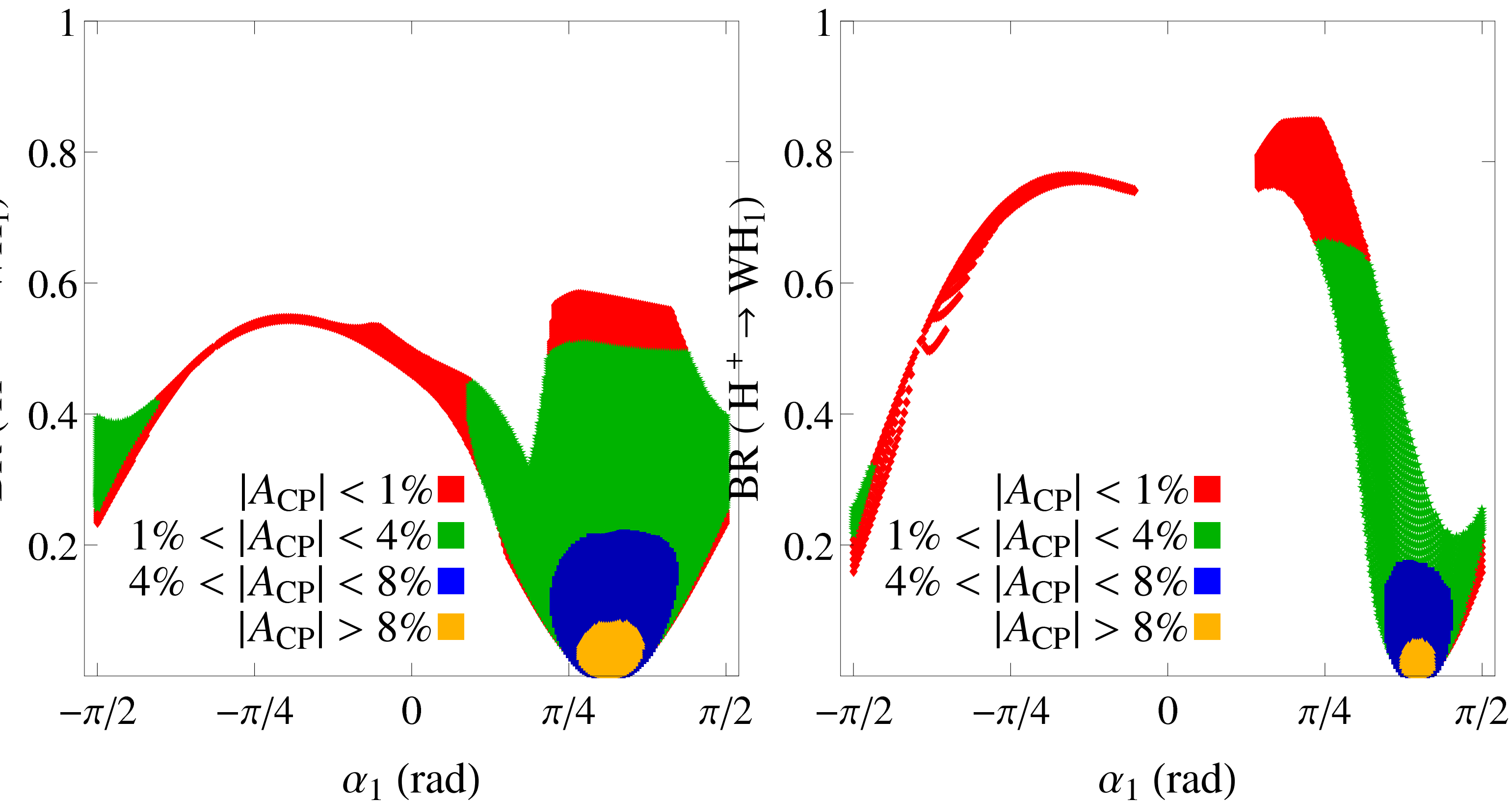


Figure 4: The BR$(H^+ \to W^+ H_1^0)$ as a function of α_1 with α_2 in the allowed parameter range, $\tan\beta = 1.5$ (left), $\tan\beta = 3$ (right)

Production: $pp \to tH^+$

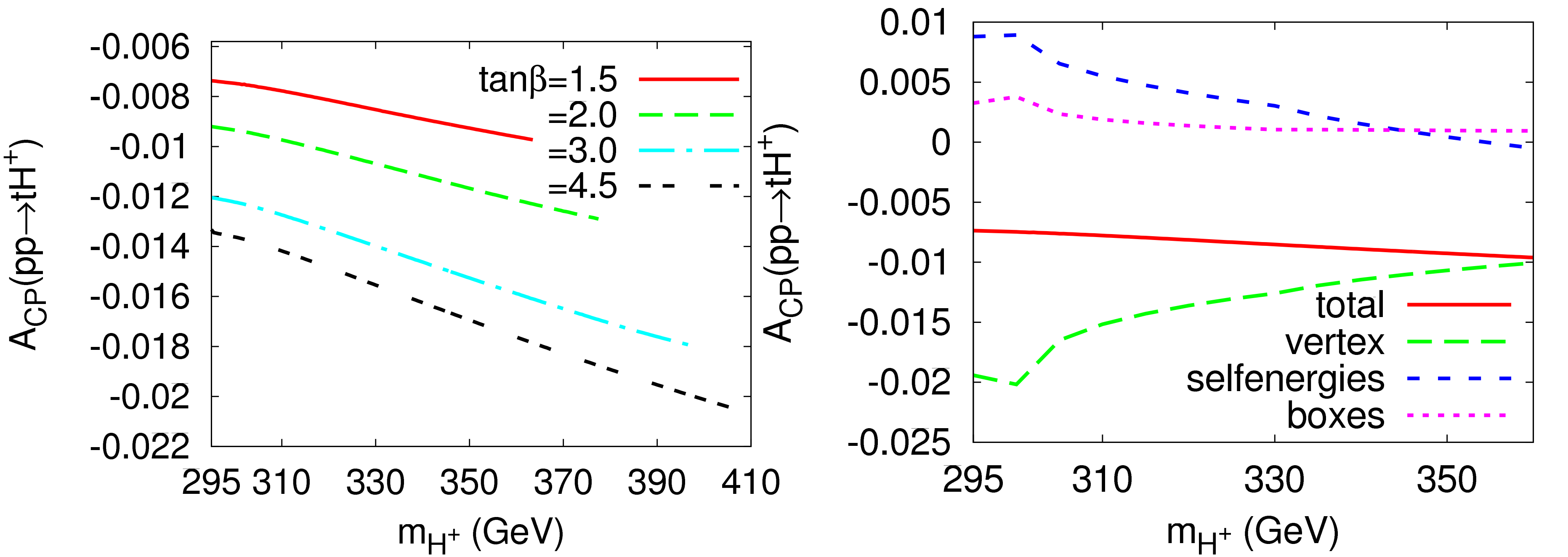


Figure 5: A_P^{CP} as a function of $m_{H\pm}$ with $M_{H_1^0,H_2^0} = 120, 220$ GeV, $\mathrm{Re}(m_{12}) = 170$ GeV, $\alpha_1 = 0.8$, $\alpha_2 = -0.9$ and $\alpha_3 = \pi/3$; Right: cancellation in A_P^{CP} as a function of M_{H^+} for $\tan\beta = 1.5$

Production: $pp \to tH^+$

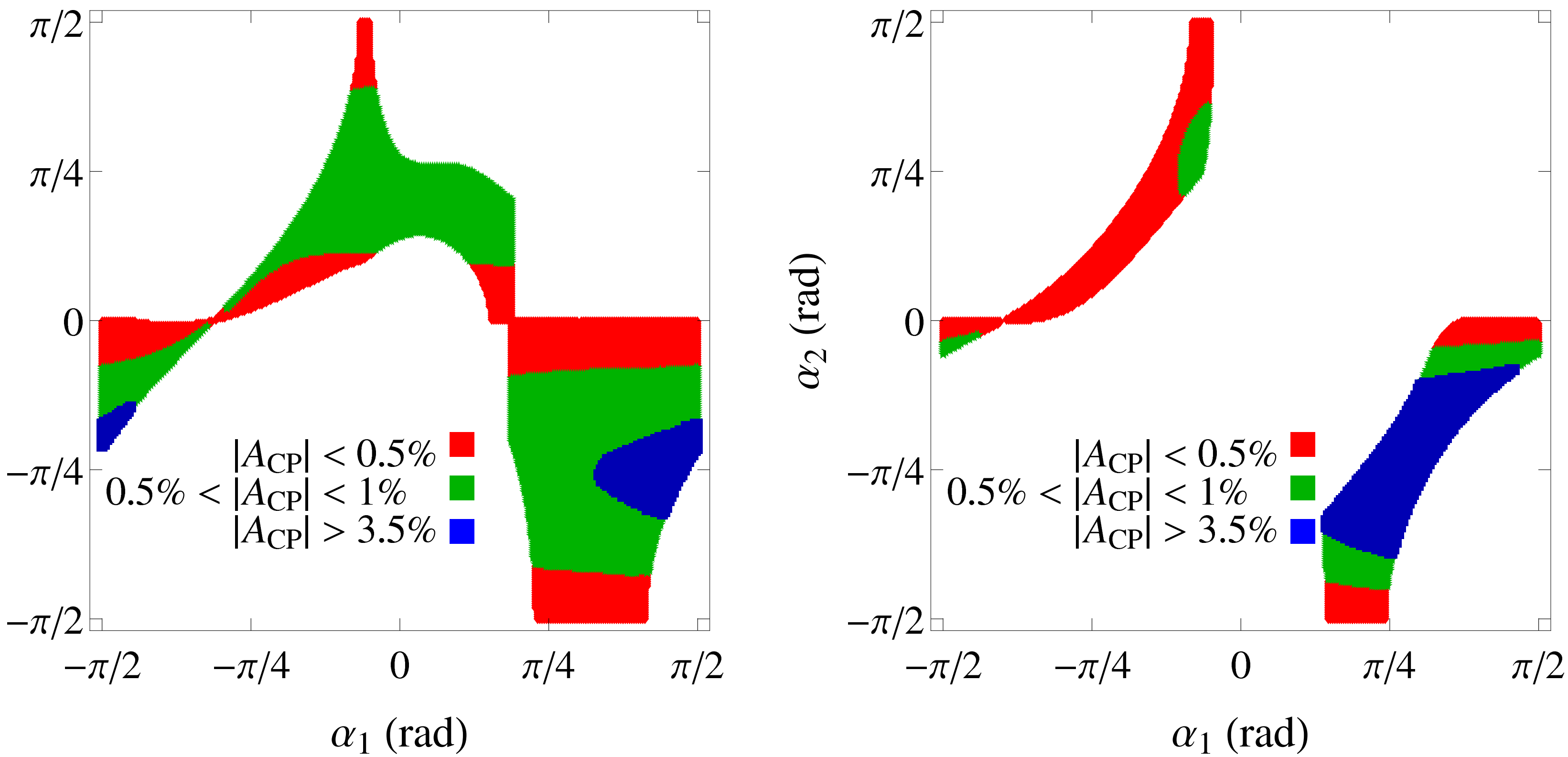
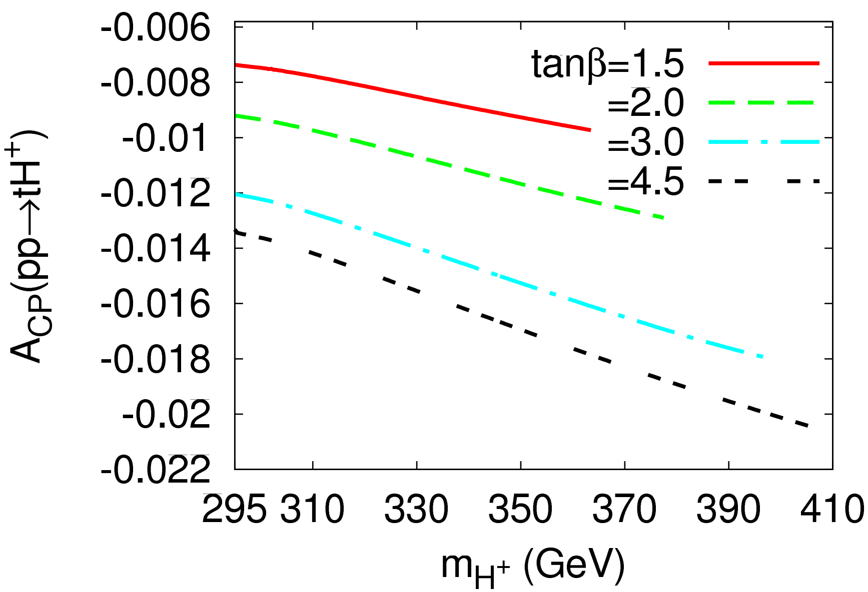
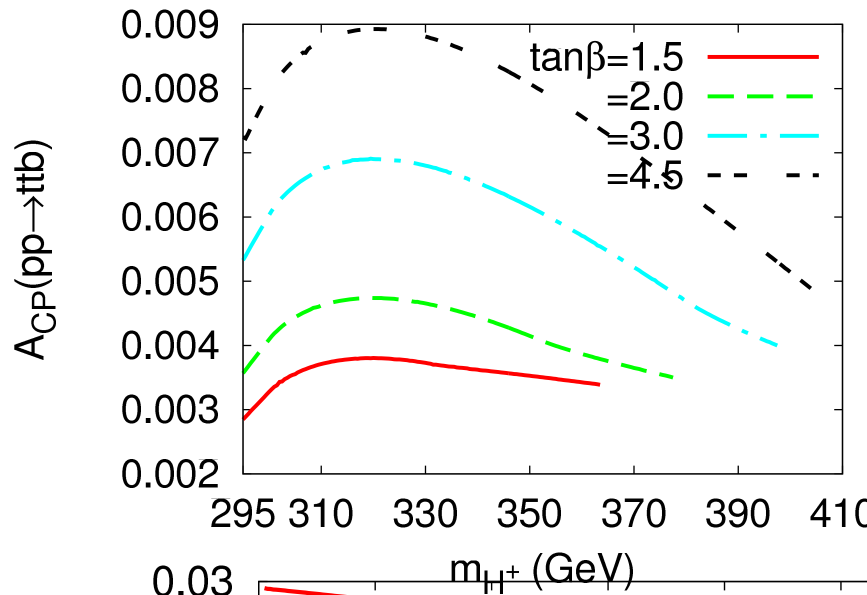
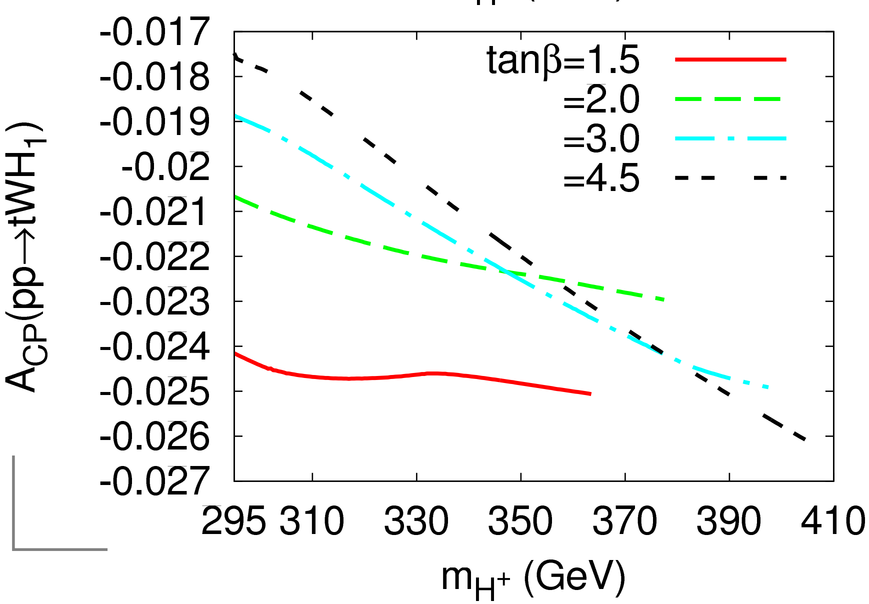


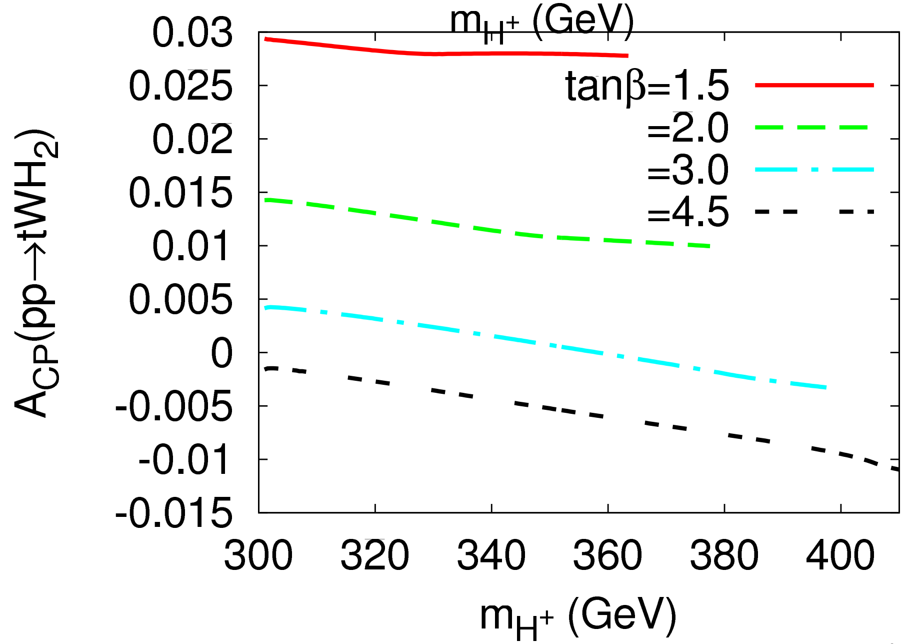
Figure 6: The allowed parameter regions in the (α_1, α_2) plan in the C2HDM together with $|A_P^{CP}|$.

Production and decays









CPV in neutral Higgs decays into fermion

At the LHC, the expected accuracy for $h \to \tau^+\tau-$ is about 20% .

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$$A_{CP} = \frac{\Gamma^1(H_1 \to f_L\bar{f}_L) - \Gamma^1(H_1 \to f_R\bar{f}_R)}{\Gamma^0(H_1 \to f_L\bar{f}_L) + \Gamma^0(H_1 \to f_R\bar{f}_R)}$$

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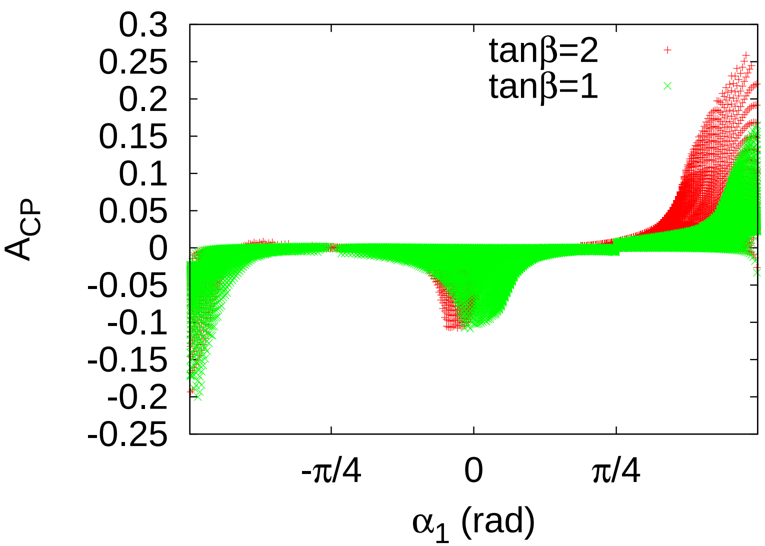
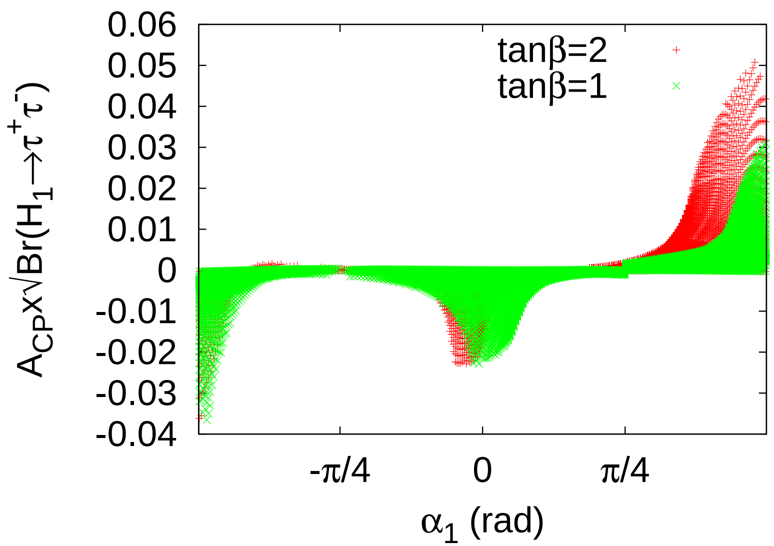
$Br(H_1 \to \tau^+\tau^-\&b\bar{b})$ suppressed for $\alpha_2 \approx 0$ and $\alpha_1 \approx \pm\pi/2$

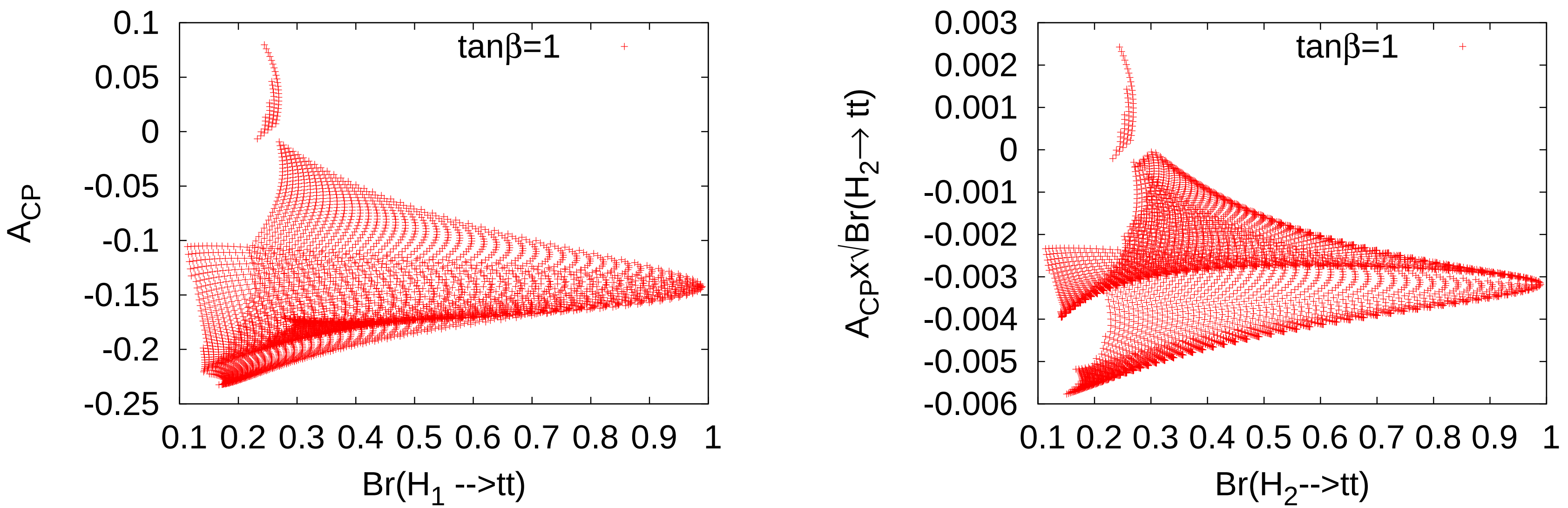
$H_1 b\bar{b} = -i\frac{gm_b}{2m_W c_\beta}(\cos\alpha_1 \cos\alpha_2 - i\sin\alpha_2 \sin\beta\gamma_5)$

$H_1 \to \tau^+\tau-$


tanβ=2
tanβ=1
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
A_CP
-π/4
0
π/4
α_1 (rad)


tanβ=2
tanβ=1
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
A_CP×√Br(H_1→τ^+τ^-)
-π/4
0
π/4
α_1 (rad)

$H_2 \to t\bar{t}$



0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
A_CP
Br(H_1 -->tt)
tanβ=1
0.003
0.002
0.001
0
-0.001
-0.002
-0.003
-0.004
-0.005
-0.006
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
A_CP×√Br(H_2→ tt)
Br(H_2-->tt)
tanβ=1

Production: $pp \to tH^+$

- In C2HDM with softly broken Z_2, the complex m_{12}^2 parameter of the tree-level potential gives CPV in $pp \to H^{\pm}t + X$, and $H^{\pm}$ to tb, and to WH_i, i=1,2
- The parameters space of C2HDM is severely constrained by vacuum stability, perturbative unitarity ... CPA cannot be greater than $\sim$3 %.
- In the CMSSM , the CPVA can reach more than 20%. However, at the LHC they will have roughly same statistical significance. Not enough for a clear observation at the LHC.
- need for SLHC!
- Calculations have been done with FeynArts & FormCalc. A new model file has been created and corresponding fortran drivers have been written and tested.