Theoretical particle physics seminar
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CP violation in charged Higgs production and decays in the Complex 2HDM

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This talk is based on a recent publication in collaboration with
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Outline

- *Motivation*
- *Short introduction to the notations*
- *CP violation in charged Higgs production and decays*
- *Numerical results*
- *Parameter constraints from theory and experiment*
- *Numerical results on CP asymmetry in H^{+} production and decay at the LHC*
- *Implementation of the complex 2HDM in FeynArts and FormCalc packages*
- *Conclusions*

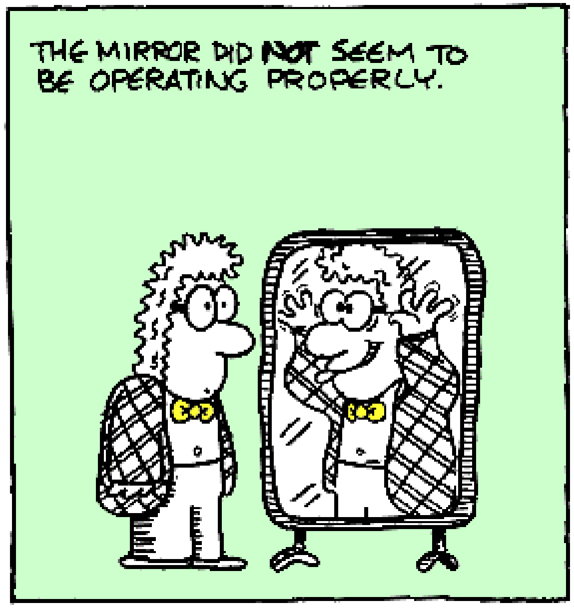
Motivation

- *If a charged Higgs is discovered at the LHC it would be a clear signal for physics beyond the SM*
- *Almost all models beyond the SM predict the existence of a charged Higgs – which one is the right one?*
- *Exploring CP violation could give some hints*
- *One of the favorites is the MSSM: the tree-level Higgs potential is real. CP violation in induced by the non-zero phases of the soft SUSY-breaking parameters*
- *Recently advertised is the general complex 2HDM: CP violation is induced by the complex parameters of the tree-level Higgs potential*
- *Then for example:*

  → CP asymmetry in associated production of a charged Higgs and a t-quark at the LHC can be rather large in the MSSM [E. Christova, H.Eberl, E. Ginina., W. Majerotto, '09]

  → How large can be the CP asymmetry in the Complex 2HDM?

CP violation?



We need sources!

Could it be the Complex 2HDM?

The Higgs sector of a general 2HDM

- *The Higgs sector of a general 2HDM consists of two complex $Y=1$, $SU(2)_L$ doublet scalar fields Φ_1 and Φ_2,*

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

>> $\tan\beta = v_2/v_1$

- *Higgs potential:*

$$\begin{aligned} V = {} & \frac{\lambda_1}{2}(\phi_1^\dagger\phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger\phi_2)^2 \\ & + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) \\ & + \frac{1}{2}\left[\lambda_5(\phi_1^\dagger\phi_2)^2 + \text{h.c.}\right] + \left\{\left[\lambda_6(\phi_1^\dagger\phi_1) + \lambda_7(\phi_2^\dagger\phi_2)\right](\phi_1^\dagger\phi_2) + \text{h.c.}\right\} \\ & - \frac{1}{2}\left\{m_{11}^2(\phi_1^\dagger\phi_1) + m_{22}^2(\phi_2^\dagger\phi_2) + \left[m_{12}^2(\phi_1^\dagger\phi_2) + \text{h.c.}\right]\right\} \end{aligned}$$

- *The parameters: $\lambda_1 \div \lambda_4$, m^2_{11} & m^2_{22} are real;*

$\Lambda_5 \div \lambda_7$ & m^2_{12} can be complex and introduce violation of CP invariance

The Higgs sector of a general 2HDM

- *After symmetry breaking: 5 physical Higgses*
- *CP conserving case: analogous to MSSM: h^0, H^0, A^0, $H^\pm$*
- *CP violating case: all three neutral week states η_1,η_2,η_3 mix to form the physical Higgses H_1, H_2, H_3*

$$\begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = R \begin{pmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \end{pmatrix},$$

$$R\mathcal{M}^2 R^{\mathrm{T}} = \mathcal{M}^2_{\mathrm{diag}} = \mathrm{diag}(M_1^2, M_2^2, M_3^2),$$

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

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

- *Parameters of the rotation matrix R: α_1, α_2, α_3*
- *The limit: α_2, α_3 = 0 & $\alpha = \alpha_1 - \pi/2$ corresponds to the CP conserving tree-level Higgs sector*

Z_2 symmetry and input parameter set

- *To avoid FCNC at tree-level one has to impose discrete Z_2 symmetry on the Lagrangian*
- *Softly broken Z_2 symmetry of the Lagrangian suppresses FCNC and provides CP violation by $m_{12}^2 \neq 0$ and complex*

$$V_{\mathrm{Higgs}}^{\mathrm{soft}}(\Phi_1,\Phi_2) = \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\left[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \mathrm{h.c.}\right] - \frac{1}{2}\left\{m_{11}^2\Phi_1^\dagger\Phi_1 + \left[m_{12}^2\Phi_1^\dagger\Phi_2 + \mathrm{h.c.}\right] + m_{22}^2\Phi_2^\dagger\Phi_2\right\} .$$

→ *We note the relation:* $\mathrm{Im}\,(m_{12}^2) = v_1\, v_2\, \mathrm{Im}\,(\lambda_5)$

- *Input parameter set:* $\{\lambda_{1,2,3,4},\ \ \mathrm{Re}\,(\lambda_5),\ \ \mathrm{Re}\,(m_{12}^2),\ \ \tan\beta,\ \ \mathrm{Im}\,(m_{12}^2)\}$

Yukawa interactions

- *Note that:*

- *We work in the type II 2HDM*
  $\rightarrow$ *down-type quarks and charged leptons only couple to* Φ_1
  $\rightarrow$ *up-type quarks couple to* Φ_2

- *The MSSM Higgs sector is also a type II 2HDM with additional constraints*

Theoretical constraints on the Higgs potential

- *Stable vacuum requirements* *[I. Ginzburg, M.Krawczyk,'05] :*

  the potential has to be positive for large values of $|\Phi_k|$

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

- *Unitarity and perturbativity requirements:*

  [I. Ginzburg, M.Krawczyk,'05]

$$|\Lambda^{Z_2}_{Y\sigma\pm}| < 8\pi$$

$$\Lambda^{even}_{21\pm} = \frac{1}{2}\left(\lambda_1 + \lambda_2 \pm \sqrt{(\lambda_1 - \lambda_2)^2 + 4|\lambda_5|^2}\;\right),$$
$$\Lambda^{odd}_{21} = \lambda_3 + \lambda_4\,, \quad \Lambda^{odd}_{20} = \lambda_3 - \lambda_4\,,$$
$$\Lambda^{even}_{01\pm} = \frac{1}{2}\left(\lambda_1 + \lambda_2 \pm \sqrt{(\lambda_1 - \lambda_2)^2 + 4\lambda_4^2}\right), \quad \Lambda^{odd}_{01\pm} = \lambda_3 \pm |\lambda_5|\,,$$

$$\Lambda^{even}_{00\pm} = \frac{3(\lambda_1 + \lambda_2) \pm \sqrt{9(\lambda_1 - \lambda_2)^2 + 4(2\lambda_3 + \lambda_4)^2}}{2},$$
$$\Lambda^{odd}_{00\pm} = \lambda_3 + 2\lambda_4 \pm 3|\lambda_5|\,.$$

The processes

We consider the following processes involving charged Higgs in the Complex 2HDM:

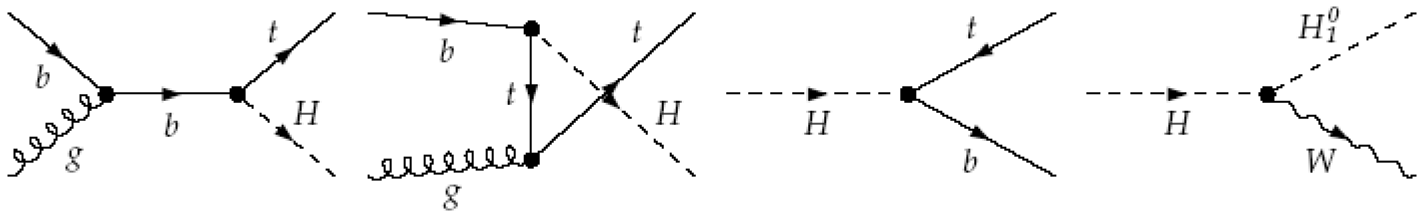
- *Decays:*

  $\rightarrow H^{\pm} \rightarrow t\,\bar{b}$

  $\rightarrow H^{\pm} \rightarrow W^{\pm} H^{0}_{i}$, *I = 1, 2*

- *Associated production with a top quark at the LHC:*

  $\rightarrow pp \rightarrow tH^{\pm} + X$ *(via the partonic process* $bg \rightarrow tH^{\pm}$ *)*



CP violating asymmetries

- *We study CP violating rate asymmetries at one loop level in the complex 2HDM:*

  → In the decays $H^+ \to f$, $f = tb$; $W^+ H_i^0$, $i = 1, 2$

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

  → In the production of a charged Higgs and t-quark at the LHC

$$A^{CP}_P = \frac{\sigma(pp \to H^+\bar{t}) - \sigma(pp \to H^- t)}{2\sigma^{\rm tree}(pp \to H^+\bar{t})}$$

  → In the combination of production and subsequent decay

$$A^{CP}_f = \frac{\sigma(pp \to \bar{t}H^+ \to \bar{t}f) - \sigma(pp \to tH^- \to t\bar{f})}{2\sigma^{\rm tree}(pp \to \bar{t}H^+ \to \bar{t}f)}$$

Tree level CP violating couplings

- *Yukawa couplings of the neutral Higgses:*

$$\mathcal{L}_{\bar{t}tH_j^0} = \bar{t}(h_{t,j}^L P_L + h_{t,j}^R P_R) t H_j^0, \quad j = 1,2,3,$$

$$h_{t,j}^L = -\frac{1}{\sqrt{2}}(R_{j2} + i c_\beta R_{j3}) h_t,$$

$$h_{t,j}^R = -\frac{1}{\sqrt{2}}(R_{j2} - i c_\beta R_{j3}) h_t, \quad h_t = \frac{g m_t}{\sqrt{2} m_W s_\beta}$$

$$\mathcal{L}_{\bar{b}bH_j^0} = \bar{b}(h_{b,j}^L P_L + h_{b,j}^R P_R) b H_j^0, \quad j = 1,2,3,$$

$$h_{b,j}^L = -\frac{1}{\sqrt{2}}(R_{j1} + i s_\beta R_{j3}) h_b,$$

$$h_{b,j}^R = -\frac{1}{\sqrt{2}}(R_{j1} - i s_\beta R_{j3}) h_b, \quad h_b = \frac{g m_b}{\sqrt{2} m_W c_\beta}$$

- *Charged Higgs – Neutral Higgs – gauge boson / Goldstone boson*

$$\mathcal{L}_{H_j^0 H^+ W^-} = \frac{ig}{2}(s_\beta R_{j1} - c_\beta R_{j2} + i R_{j3})[H_j^0 \overleftrightarrow{\partial^\mu} H^+ W^{\mu -} - H_j^0 \overleftrightarrow{\partial^\mu} H^- W^{\mu +}],$$
$$j = 1,2,3\,,$$

$$\mathcal{L}_{H_j^0 H^+ G^-} = \frac{m_W}{g}(f_{H^0 H^+ G^-})_j H_j^0 H^+ G^- + \mathrm{h.c.}, \quad j = 1,2,3\,,$$

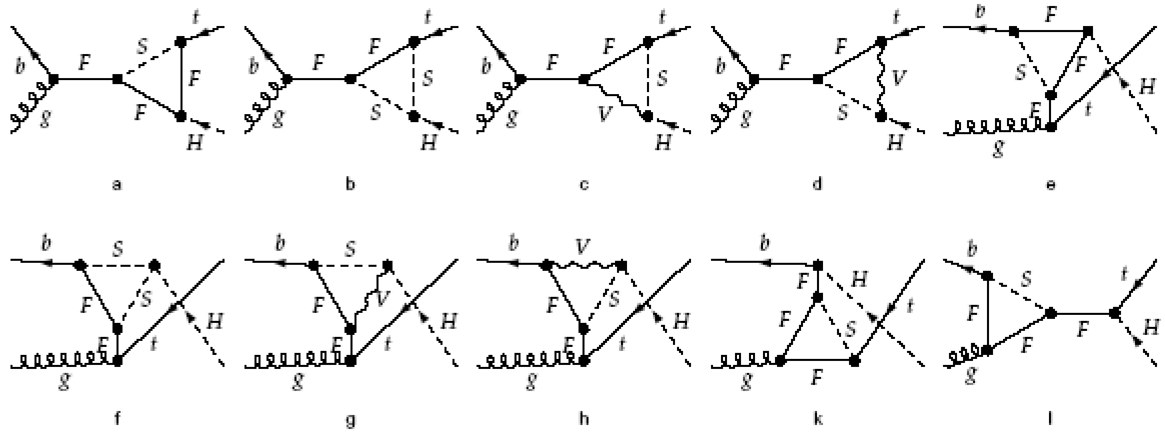
$$\begin{aligned}(f_{H^0 H^+ G^-})_j = {} & s_\beta[s_\beta^2(\lambda_4 + \mathrm{Re}(\lambda_5)) + c_\beta^2(2\lambda_1 - \lambda_3 - \lambda_{345}) - i\mathrm{Im}(\lambda_5)]R_{j1} + \\ & c_\beta[-c_\beta^2(\lambda_4 + \mathrm{Re}(\lambda_5)) - s_\beta^2(2\lambda_2 - \lambda_3 - \lambda_{345}) - i\mathrm{Im}(\lambda_5)]R_{j2} + \\ & [i(\lambda_4 - \mathrm{Re}(\lambda_5)) + (c_\beta^2 - s_\beta^2)\mathrm{Im}(\lambda_5)]R_{j3},\end{aligned}$$

$$\lambda_{345} = \lambda_3 + \lambda_4 + \mathrm{Re}(\lambda_5), \quad j = 1,2,3\,.$$

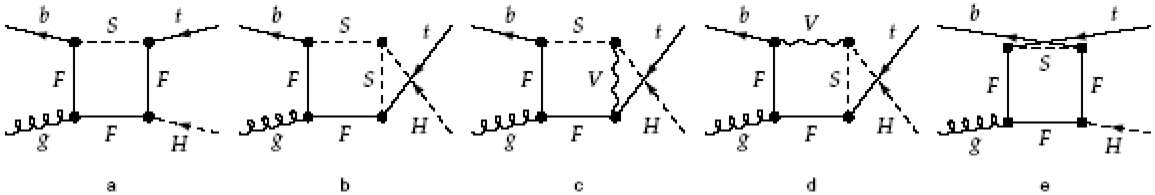
CP violating loop contributions

- The CP violating loop contributions are three types: selfenergies, vertex diagrams and boxes (in the production only)
- Examples: in the production (generic form only)

→ vertexes:



→ boxes:



Numerical results. Input parameters

Further on we set $\lambda_6 = \lambda_7 = 0$ and confine in the case of minimal CP violation provided by $m^2_{12} \neq 0$

* $Im\,(m^2_{12}) = Im\,(\lambda_5)\, v_1 v_2$

- *As input one needs the values of:*

$$\lambda_1, \lambda_2, \lambda_3, \lambda_4, Re(\lambda_5), Re(m^2_{12}), Im(m^2_{12}), \& \tan\beta$$

- *Convinient is to use the following set:*

$$M_1, M_2, M_{H+}, \mu, \tan\beta, \alpha_1, \alpha_2, \alpha_3$$

with $\mu = 1/(2\ v_1^2 v_2^2)Re(m_{12}^2)(v_1^2+v_2^2)$

**Note that the parameter μ here is different than the one in the MSSM*

Numerical results. Parameter constraints

- *From theory – these are the requirements for unitarity and positivity mentioned*
- *From experiment – mostly coming from electroweak precision data at LEP*
  - $B \rightarrow X_s \gamma$
  - ρ *parameter constraint*
  - B_0-$\overline{B}_0$ *mixing*
  - *Direct searches for* H^+
  - *LEP2 non-discovery*
  - *Muon anomalous magnetic moment*
  - *Electron EDM, etc..*

Numerical results. Parameter constraints

- *Lower limit of the M_{H+} mass ($B \to X_s \gamma$)*

$$M_{H^\pm} \geq 295 \text{ GeV}$$

- *ρ parameter constraint (electroweak precision data)*

$$\rho_0 = 1.0004 \,{}^{+0.0029}_{-0.0011}$$

→ Δρ – deviation from the SM should accommodate all new physics contributions

→ We use the calculations of [A.Kaffas, W. Khater, O. Ogreid, P. Osland,'06]

→ The limits are asymmetric (PDG):

$$-0.0011 \leq \Delta\rho \leq 0.0029$$

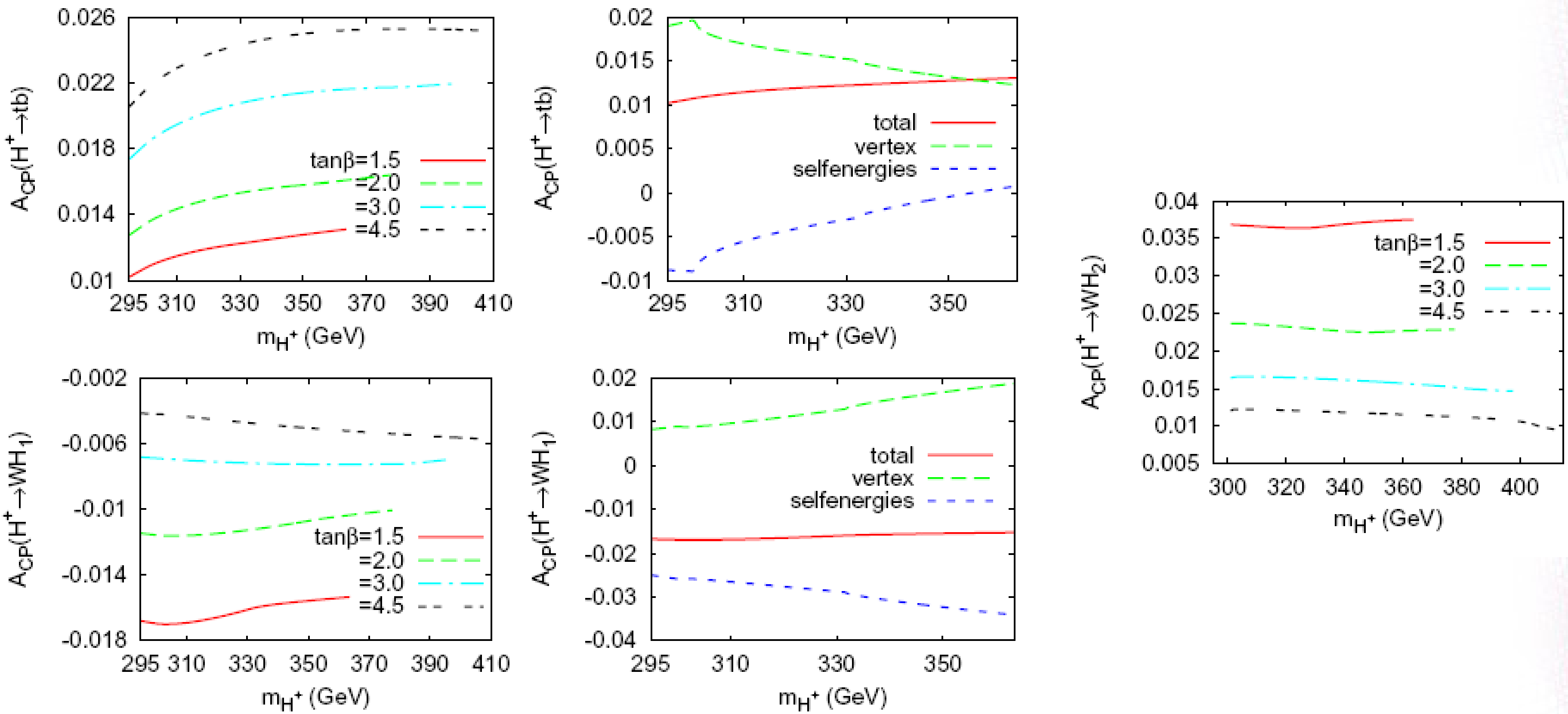
Numerical results. Parameter constraints

- *The theoretical constraints already reduce quite dramatically the complex 2HDM parameter space – they exclude generally "large" value of $\tan\beta$ and the M_{H+} mass*

→ Hard to make a numerical analysis as the parameter space is constantly cut

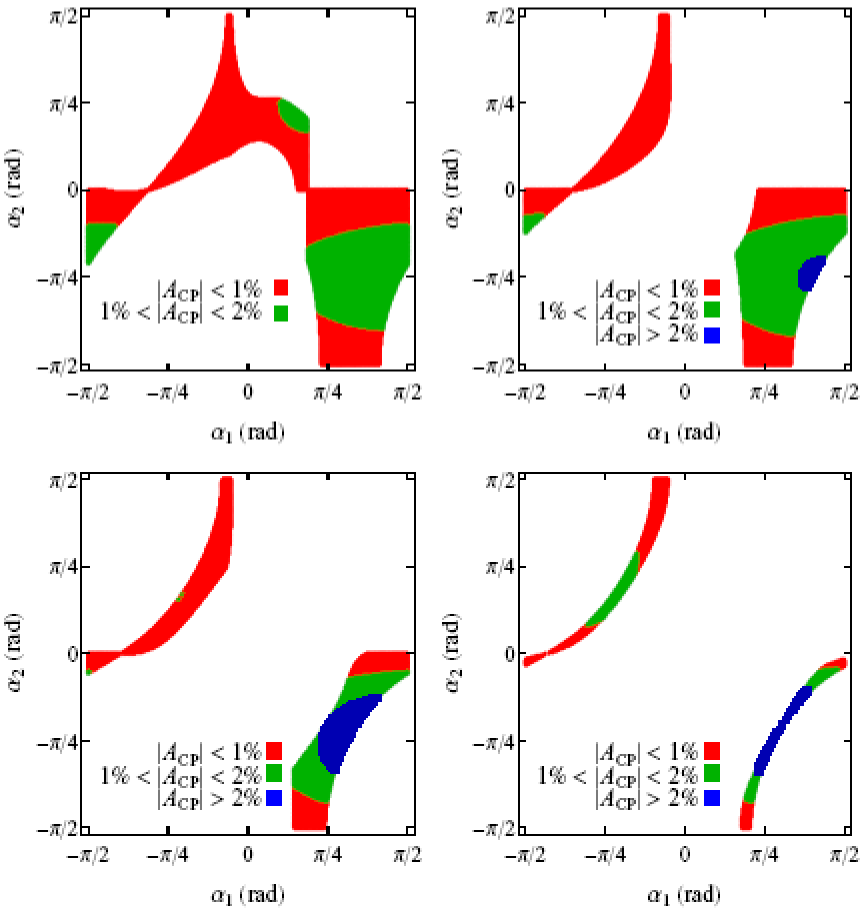
- *Most of the experimental constraints also exclude "large" values of these parameters*
- *We take into account the strongest: ρ parameter constraint and $B \to X_s \gamma$ constraint → "small" values of M_{H+} is already forbidden from B decyas*
- *=> In our analysis we shall consider relatively small values of $\tan\beta$ and moderate values of M_{H+}*

Numerical results: $H^{\pm}$ decays



$$M_{H_1^0} = 120 \text{ GeV},\ M_{H_2^0} = 220 \text{ GeV},\ \mathrm{Re}(m_{12}) = 170 \text{ GeV},\ \alpha_1 = 0.8,\ \alpha_2 = -0.9$$
$$\alpha_3 = \pi/3$$

Numerical results: $H^{\pm} \to t\,\bar{b}$ decay



- *A scan over (α_2, α_3)*

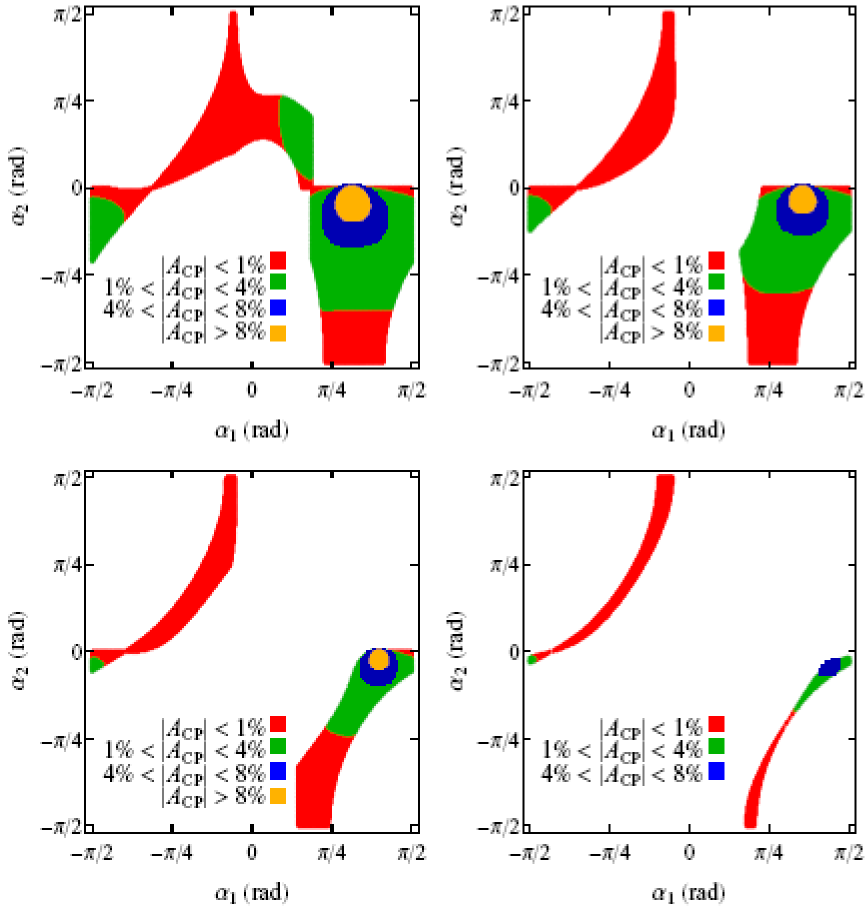
$\tan\beta = 1.5, 2, 3, 4$

$$M_{H_1^0} = 120 \text{ GeV}, \; M_{H_2^0} = 220 \text{ GeV},$$

$$M_{H^\pm} = 350 \text{ GeV}, \; \mathrm{Re}(m_{12}) = 170 \text{ GeV},$$

$$\alpha_3 = \pi/3.$$

Numerical results: $H^{\pm} \to W^{\pm} H^0_1$ decay



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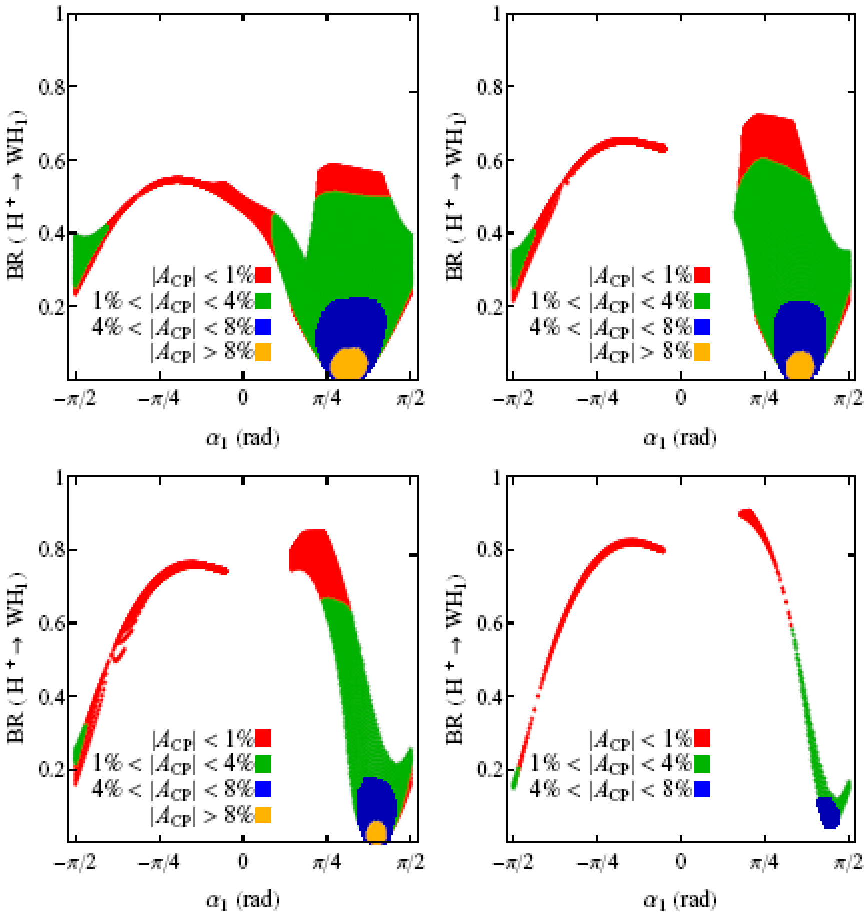
Numerical results: $H^{\pm} \rightarrow W^{\pm} H^0_{\ 1}$ decay



- *Branching ratio of $H^{\pm} \rightarrow W^{\pm} H^0_{\ 1}$ decay*

  $\tan\beta = 1.5 , 2 , 3 , 4$

$$M_{H_1^0} = 120 \text{ GeV}, \; M_{H_2^0} = 220 \text{ GeV},$$

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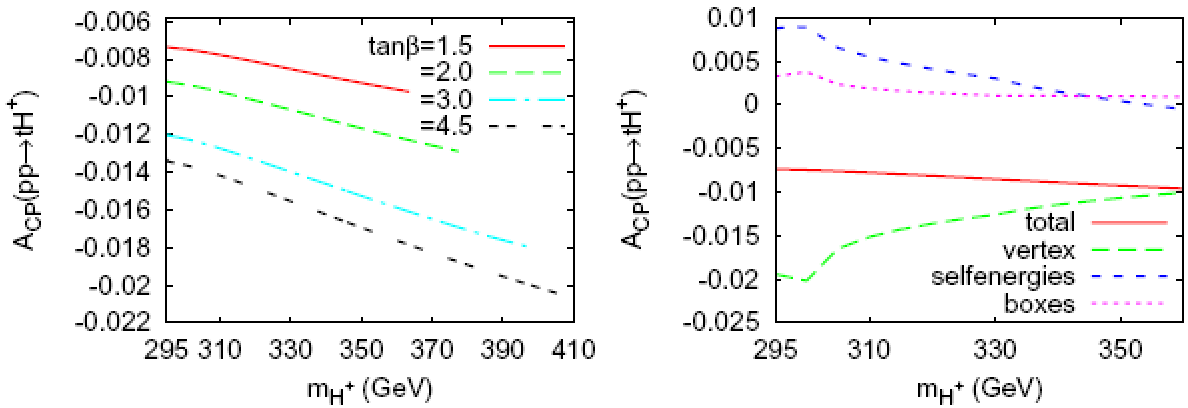
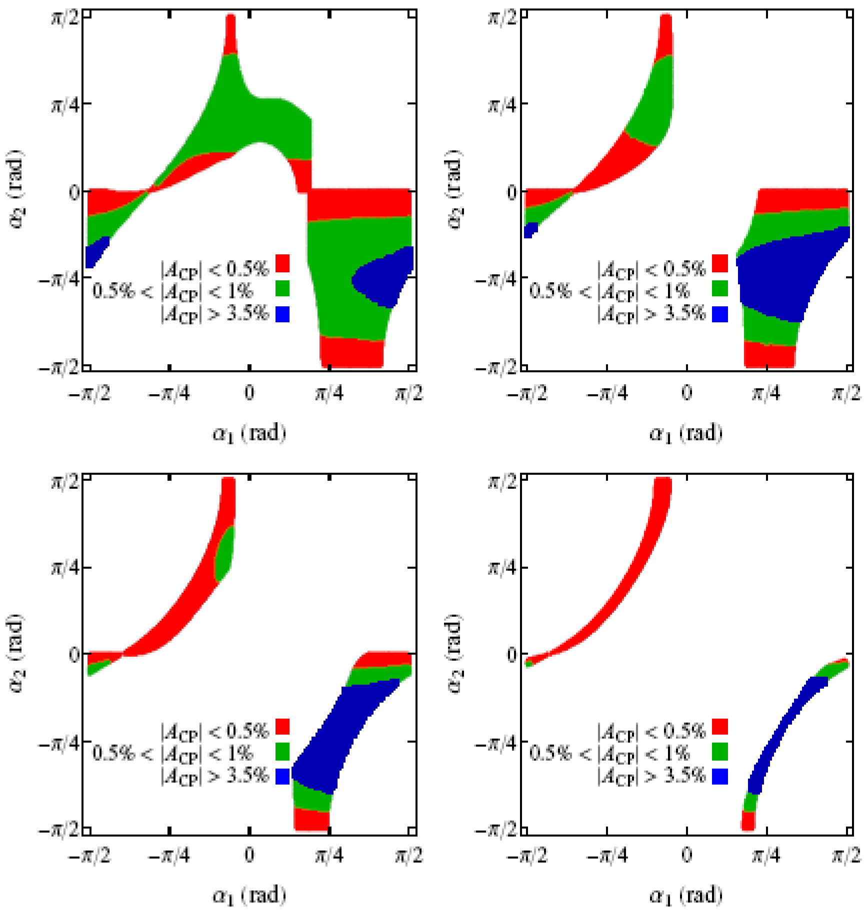
$$\alpha_3 = \pi/3.$$

Numerical results: $H^{\pm}$ production



$$M_{H_1^0} = 120 \text{ GeV}, \; M_{H_2^0} = 220 \text{ GeV}, \; \mathrm{Re}(m_{12}) = 170 \text{ GeV}, \; \alpha_1 = 0.8, \; \alpha_2 = -0.9$$
$$\alpha_3 = \pi/3$$

Numerical results: $H^{\pm}$ production



- *A scan over (α_2, α_3)*

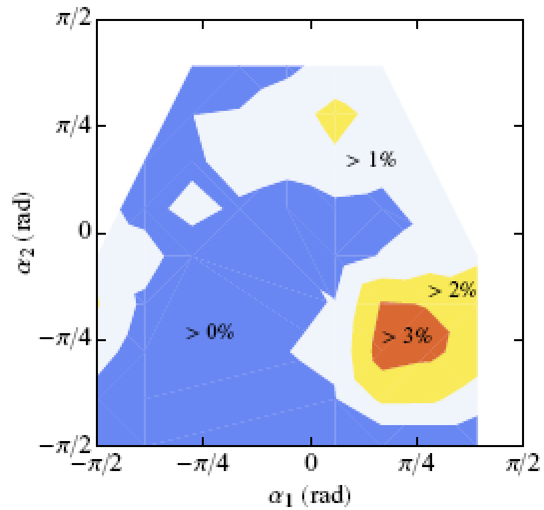
  $\tan\beta$ = 1.5 , 2 , 3 , 4

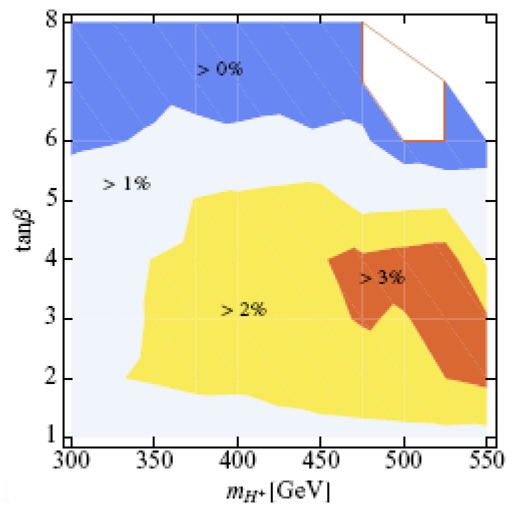
$$M_{H_1^0} = 120\ \text{GeV},\ M_{H_2^0} = 220\ \text{GeV},$$

$$M_{H^\pm} = 350\ \text{GeV},\ \text{Re}(m_{12}) = 170\ \text{GeV},$$

$$\alpha_3 = \pi/3.$$

Numerical results: $H^{\pm}$ production

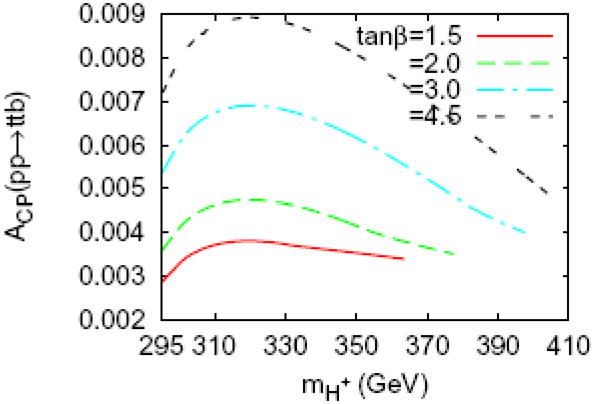




- *For the production process we perform the following scan using GRID computing:*

$$
\begin{aligned}
M_{H_1^0} &= 115 \div 125 \text{ GeV}, \text{ with step size 5 GeV}, \\
M_{H_2^0} &= 150 \div 400 \text{ GeV}, \text{ with step size 50 GeV}, \\
M_{H^+} &= 300 \div 550 \text{ GeV}, \text{ with step size 25 GeV}, \\
\mathrm{Re}\,(m_{12}) &= 10 \div 460, \text{ with step size } 50\,, \\
\tan\beta &= 1 \div 8, \text{ with step size } 1\,, \\
\alpha_1 &= \pi/2 \div \pi/2, \text{ with step size } \pi/9\,, \\
\alpha_2 &= \pi/2 \div \pi/2, \text{ with step size } \pi/9\,, \\
\alpha_3 &= 0 \div \pi/2, \text{ with step size } \pi/9\,,
\end{aligned}
$$

Numerical results: $H^{\pm}$ production and decay



$$M_{H_1^0} = 120 \text{ GeV}, \ M_{H_2^0} = 220 \text{ GeV},$$

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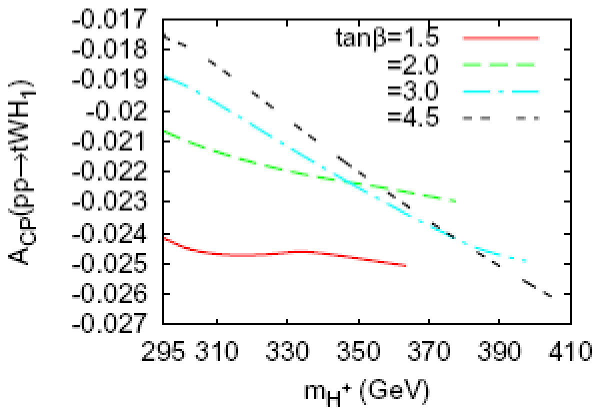
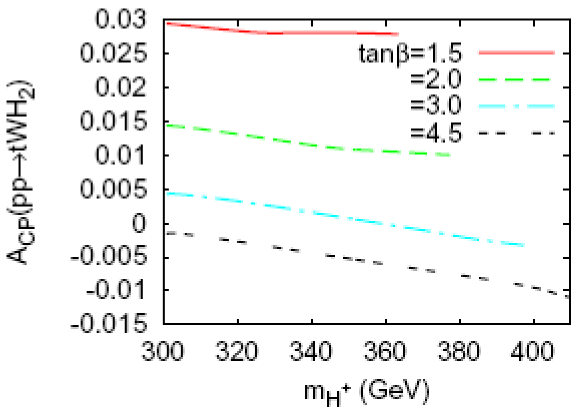


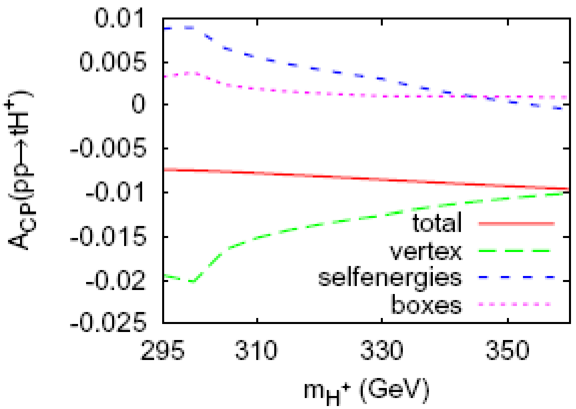


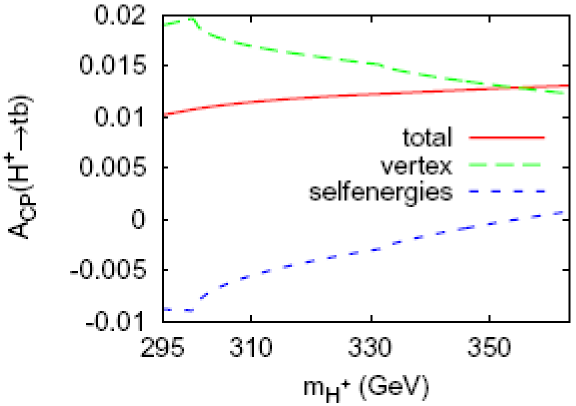
Numerical results: cancelations

$$M_{H_1^0} = 120 \text{ GeV}, \ M_{H_2^0} = 220 \text{ GeV},$$

$$M_{H^\pm} = 350 \text{ GeV}, \ \mathrm{Re}(m_{12}) = 170 \text{ GeV},$$

$$\alpha_3 = \pi/3.$$





Conclusions

- *A complete FeynArts model file for Complex 2HDM, CTHDM.mod has been generated*
- *Fully working FormCalc Fortan drivers have been established*
- *Theoretical and experimental constraints have been included*
- *Due to these constraints the free parameter space is very narrow*
- *The CP asymmetry in associated production of a charged Higgs and a t-quark at the LHC, as well as in the subsequent decay of the charged Higgs is in the range of 1to 3 per cent*
- *This result is in contrast to the MSSM result, where the asymmetry can go up to ~10% [E. Christova, H.Eberl, E. Ginina., W. Majerotto, '09]*
- *However, eventually, taking into account the BRs, the cross sections and the LHC integrated luminocity, the mesurability of the studied asymmetries in the complex 2HDM and in the MSSM has roughly the same statistical significance, which is not enouph to be measure at the LHC first stage*
- *At the Super LHC such a measurment would be worth of being measured*

Thank you!

& Have a nice rest of the day! :)

Implementation of the Complex 2HDM in FA / FC

Generating complete FeynArts model file for the complex 2HDM

- *For studying particular processes usage of FeynArts/ FormCalc/ LoopTools packages is quite convenient*
- *The CP conserving 2HDM is implemented in FeynArts/ FormCalc: needs to be extended to the complex case*
- *Steps:*
  → Generating complete FeynArts model file for the complex 2HDM, CTHDM.mod
  → Extending the existing 2HDM FormCalc Fortran drivers for the complex case

Implementation of the Complex 2HDM in FA / FC

Generating complete FeynArts model file for the complex 2HDM

- *Higgs potential → Calculation of complete Lagrangian & all coupling vectors for the complex 2HDM with Mathematica → collecting this information into a new model file: CTHDM.mod*
- *Usage:*
  - For generating amplitudes with FeynArts for processes in the complex 2HDM
  - For generating Fortran codes with FormCalc for processes in the complex 2HDM

Implementation of the Complex 2HDM in FA / FC

Generating complete FeynArts model file for the complex 2HDM

- *The model file CTHDM.mod consists of 265 couplings, including:*

→ *All terms arising from the covariant derivative*

→ *Yukawa interactions*

→ *Three and four Higgs self interactions*

→ *Interaction of Higgses with Fadeev-Popov ghosts*

- *CTHDM.mod is independently built and checked between the collaboration*

Implementation of the Complex 2HDM in FA / FC

Extending the existing 2HDM FormCalc drivers for the complex case

- *Establishing a fully working Fortran code requires*

  → Modifying the existing model_thdm.F to the new model_cthdm.F :

- *Defining the new parameters and relations*
- *Including the relevant parameter constraints*

  → Usage of LoopTools for loop integrals

  ** Exporting results back to Mathematica via MathLink*