Higgs physics in the MSSM: News from FeynHiggs

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based on collaboration with
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3. The code *FeynHiggs2.1*
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1. Introduction

Higgs potential of the MSSM contains two Higgs doublets:

$$
\begin{aligned}
H_1 &= \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix} \\
H_2 &= \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = e^{i\xi} \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2^+ i\chi_2)/\sqrt{2} \end{pmatrix}
\end{aligned}
$$

$$
\begin{aligned}
V &= m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) \\
&\quad + \underbrace{\frac{g'^2 + g^2}{8}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} |H_1 \bar{H}_2|^2
\end{aligned}
$$

gauge couplings, in contrast to SM

Five physical states: $h^0, H^0, A^0, H^\pm$

2 $\mathcal{CP}$-violating phases: ξ, m_{12} $\Rightarrow$ can compensate each other

$\Rightarrow$ no $\mathcal{CP}$V at tree-level

Input parameters: $\tan\beta = \frac{v_2}{v_1}$, M_A or $M_{H^\pm}$

$\Rightarrow$ Prediction for m_h:

MSSM tree-level bound: $m_h < M_Z$, excluded by LEP Higgs searches

Large radiative corrections:

Dominant one-loop corrections: $\sim G_\mu m_t^4 \ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$

Measurement of m_h, Higgs couplings $\Rightarrow$ test of the theory

LHC: $\Delta m_h \approx 0.2$ GeV, LC: $\Delta m_h \approx 0.05$ GeV

$\Rightarrow$ m_h will be precision observable

Present status of m_h prediction in the MSSM:

Complete one-loop result $+$ all presumably dominant two-loop corrections known for MSSM with real parameters

Used for LEP analyses: *FeynHiggs* (Feynman-diagrammatic result: complete one-loop, leading + subleading two-loop)
[*S. Heinemeyer, W. Hollik, G. W. '98, '00, '02*]

Upper bound on m_{h} in the MSSM:

"Unconstrained MSSM":

M_{A}, $\tan\beta$, 5 parameters in $\tilde{\mathrm{t}}$–$\tilde{\mathrm{b}}$ sector, μ, $m_{\tilde{\mathrm{g}}}$, M_2

FeynHiggs $\Rightarrow$ $m_{\mathrm{h}} \lesssim 135$ GeV

[*S. Heinemeyer, W. Hollik, G. W. '99*], [*M. Frank, S. Heinemeyer, W. Hollik, G. W. '02*]

for $m_{\mathrm{t}} = 175$ GeV, no theoretical uncertainties included

Remaining theoretical uncertainties in prediction for m_{h}:

[*G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich, G. W. '02*]

– From unknown higher-order corrections:

$\Rightarrow$ $\Delta m_{\mathrm{h}} \approx 3$ GeV

– From uncertainties in input parameters

$m_{\mathrm{t}}, \ldots, M_{\mathrm{A}}, \tan\beta, m_{\tilde{\mathrm{t}}_1}, m_{\tilde{\mathrm{t}}_2}, \theta_{\tilde{\mathrm{t}}}, m_{\tilde{\mathrm{g}}}, \ldots$

$\Delta m_{\mathrm{t}} \approx 5$ GeV $\Rightarrow$ $\Delta m_{\mathrm{h}} \approx 5$ GeV

Treatment of MSSM Higgs sector has recently been updated in various codes, but still sizable numerical deviations:

Example: *HDECAY3.0* with option *subhpole* or *FeynHiggsFast*

$\Rightarrow$ deviations in $m_{\rm h}$ of $\mathcal{O}(5\,\text{GeV})$

$m_{\rm h}^{\rm max}$ benchmark scenario:

$M_{\rm A}$ (GeV), $\tan\beta$	*HD3.0* (*subhpole*)	*HD3.0* (*FeynHiggsFast*)	*FeynHiggs*
250, 7.8	125.1	128.7	129.5
600, 6.9	125.2	130.0	129.7

2. Higgs physics in the cMSSM

$\mathcal{CP}$ violation in the Higgs sector:

Complex parameters enter via loop corrections:

– μ: Higgsino mass parameter

– $A_{t,b,\tau}$: trilinear couplings $\Rightarrow$ $X_{t,b,\tau} = A_{t,b} - \mu^* \{\cot\beta\,,\tan\beta\}$ complex

– $M_{1,2}$: gaugino mass parameter (one phase can be eliminated)

– $m_{\tilde{g}}$: gluino mass

$\Rightarrow$ can induce $\mathcal{CP}$-violating effects

$\Rightarrow$ Mixing between neutral Higgs bosons h_1, h_2, h_3

Status of calculations in the cMSSM:

– fermion/sfermion corrections at 1-loop, $q^2 = 0$

– leading 2-loop corrections

[*A. Pilaftsis '98*], [*A. Pilaftsis, C. Wagner '99*], [*A. Demir '99*]
[*S. Choi, M. Drees, J. Lee '00*], [*M. Carena, J. Ellis, A. Pilaftsis, C. Wagner '00, '01*]
[*T. Ibrahim, P. Nath '01, '02*], [*S. Ham, C. Kim, S. Oh, D. Son, E. Yoo '02*]

– remaining sectors at 1-loop (rMSSM: 5 GeV)

– q^2 dependence at 1-loop (rMSSM: $\sim$ 2 GeV)

[*M. Frank, S. Heinemeyer, W. Hollik, G. W. '02*]

Inclusion of higher-order corrections:

($\to$ Feynman-diagrammatic approach)

Propagator / mass matrix with higher-order corrections:

$$\begin{pmatrix} q^2 - M_{\mathrm{A}}^2 + \hat{\Sigma}_{AA}(q^2) & \hat{\Sigma}_{AH}(q^2) & \hat{\Sigma}_{Ah}(q^2) \\ \hat{\Sigma}_{HA}(q^2) & q^2 - m_{\mathrm{H}}^2 + \hat{\Sigma}_{HH}(q^2) & \hat{\Sigma}_{Hh}(q^2) \\ \hat{\Sigma}_{hA}(q^2) & \hat{\Sigma}_{hH}(q^2) & q^2 - m_{\mathrm{h}}^2 + \hat{\Sigma}_{hh}(q^2) \end{pmatrix}$$

$\hat{\Sigma}_{ij}(q^2)$ $(i, j = h, H, A)$: renormalized Higgs self-energies

$\hat{\Sigma}_{Ah}, \hat{\Sigma}_{AH} \neq 0 \;\Rightarrow\; \mathcal{CP}$V, $\mathcal{CP}$-even and $\mathcal{CP}$-odd fields can mix

Our result for $\hat{\Sigma}_{ij}$:

– full 1-loop evaluation: dependence on all possible phases included

– most up-to-date 2-loop corrections in rMSSM (complex phases neglected at two-loop level)

– momentum dependence fully included at 1-loop

– on-shell renormalisation scheme

Result: $(A, H, h) \to (h_3, h_2, h_1)$ with $m_{\mathsf{h}_3} > m_{\mathsf{h}_2} > m_{\mathsf{h}_1}$

Higgs boson couplings:

(in $q^2 = 0$ approximation)

$$\begin{pmatrix} h_3 \\ h_2 \\ h_1 \end{pmatrix} = \begin{pmatrix} u_{11} & u_{12} & u_{13} \\ u_{21} & u_{22} & u_{23} \\ u_{31} & u_{32} & u_{33} \end{pmatrix} \cdot \begin{pmatrix} A \\ H \\ h \end{pmatrix}$$

– h_1, h_2, h_3: neutral Higgs boson with $\mathcal{CP}$V couplings

– $u_{12}, u_{13}, u_{21}, u_{31}$: $\mathcal{CP}$V mixings

– u_{ij} determine Higgs-fermion and Higgs-gauge boson couplings

3. The code FeynHiggs2.1

[*M. Frank, T. Hahn, S. Heinemeyer, W. Hollik, G. W. '03*]

Latest version: (05/03)

contains all above described results

- evaluation of the Higgs sector of the (c)MSSM:
  - full 1-loop, $q^2 \neq 0$
  - leading/subleading 2-loop
- full 1-loop corrections for charged Higgs sector

Further features:

- New renormalization ($\overline{\mathrm{MS}}$/OS) for 1-loop result
  [*M. Frank, S. Heinemeyer, W. Hollik, G. W. '02*]
- "Δm_{b}" corrections for Higgs masses
  $\Rightarrow$ leading $\mathcal{O}(\alpha_{\mathrm{b}}\alpha_s)$ terms included
  [*M. Carena, D. Garcia, U. Nierste, C. Wagner '00*]
- most recent: subleading $\mathcal{O}(\alpha_{\mathrm{t}}\alpha_{\mathrm{b}}, \alpha_{\mathrm{b}}^2)$ terms
  [*A. Dedes, G. Degrassi, P. Slavich '03*]

Output:

Higgs boson masses, mixing matrix
effective couplings for

$h \to f\bar{f}$, $h_{2,3} \to h_1 h_1$, ZZh, ...

Latest version can be obtained from www.feynhiggs.de

$\Rightarrow$ type `configure`, `make` $\to$ library is created
$\to$ check with stand-alone version/front-end

Link *FeynHiggs* as a subroutine:

`call FHSetFlags` $\to$ specification of accuracy etc.

`call FHSetPara` $\to$ specify input parameters

`call FHHiggsCorr`, `call FHCouplings`

Additional options:

man pages give detailed instructions, Stand alone version for single points
M*FeynHiggs* to obtain results within *Mathematica*

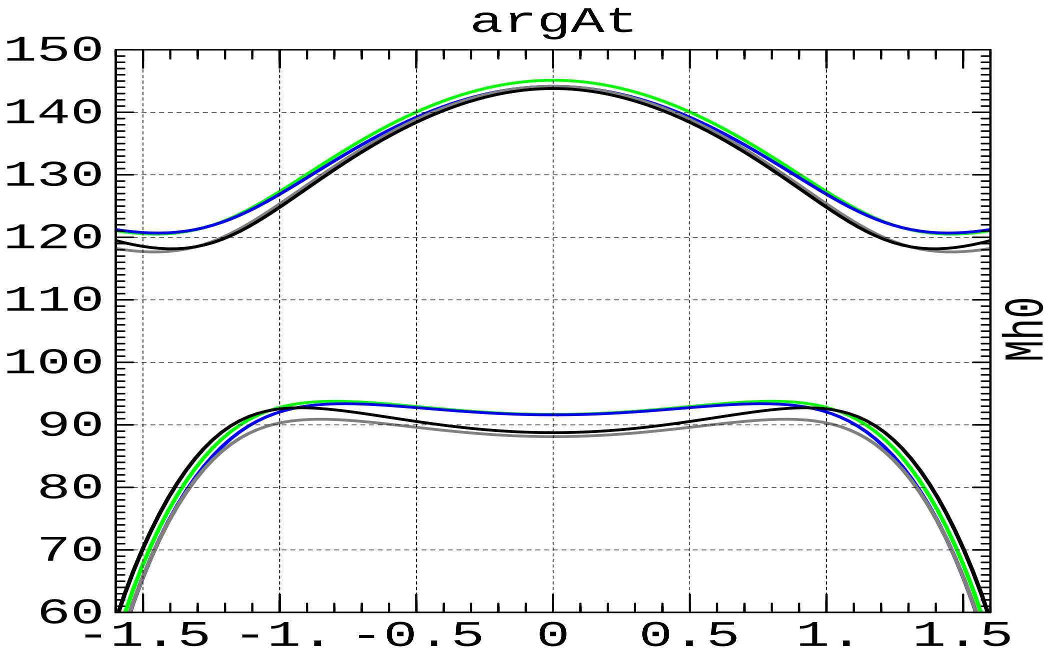
FeynHiggs is used for final evaluations of of LEP Higgs WG for evaluating $\mathcal{CP}$V scenario (together with CPH)
[*P. Bechtle, K. Desch, priv. comm.*]

Numerical examples

To emphasize effects new calculations: focus on 1-loop results below

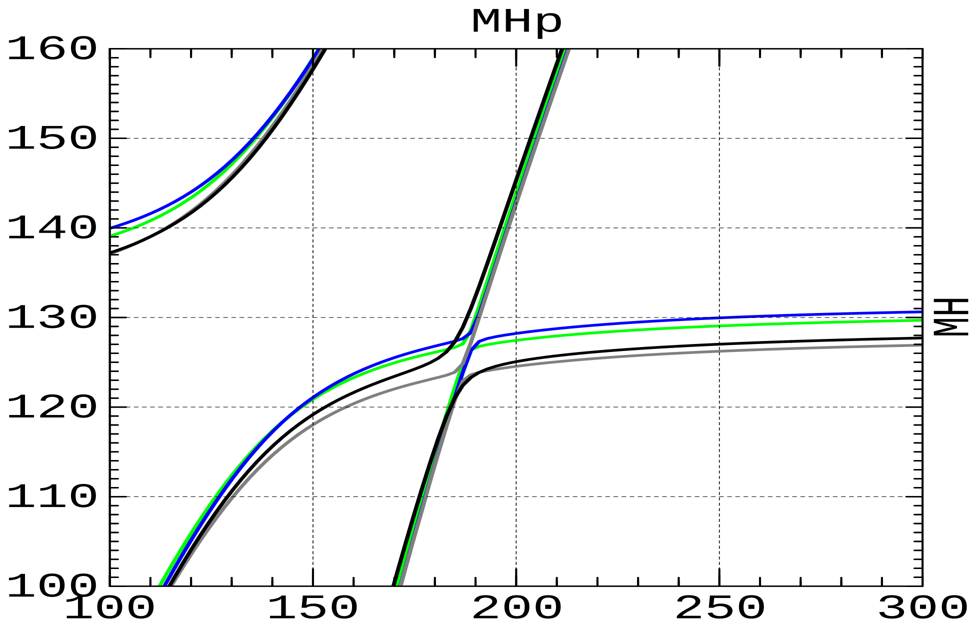
To emphasize "possible" large effects: CPX scenario:
$M_{\mathrm{SUSY}} = 500$ GeV, $M_2 = 500$ GeV, $|\mu| = 2000$ GeV, $|A_t| = 1000$ GeV
$M_{H^\pm} = 150$ GeV, $\tan\beta = 5$
[*M. Carena, J. Ellis, A. Pilaftsis, C. Wagner '01*]

ϕ_{A_t} dependence of m_{h_1}, m_{h_2} ($\phi_\mu = 0$, $|A_t| = 2\,M_{\mathrm{SUSY}}$):



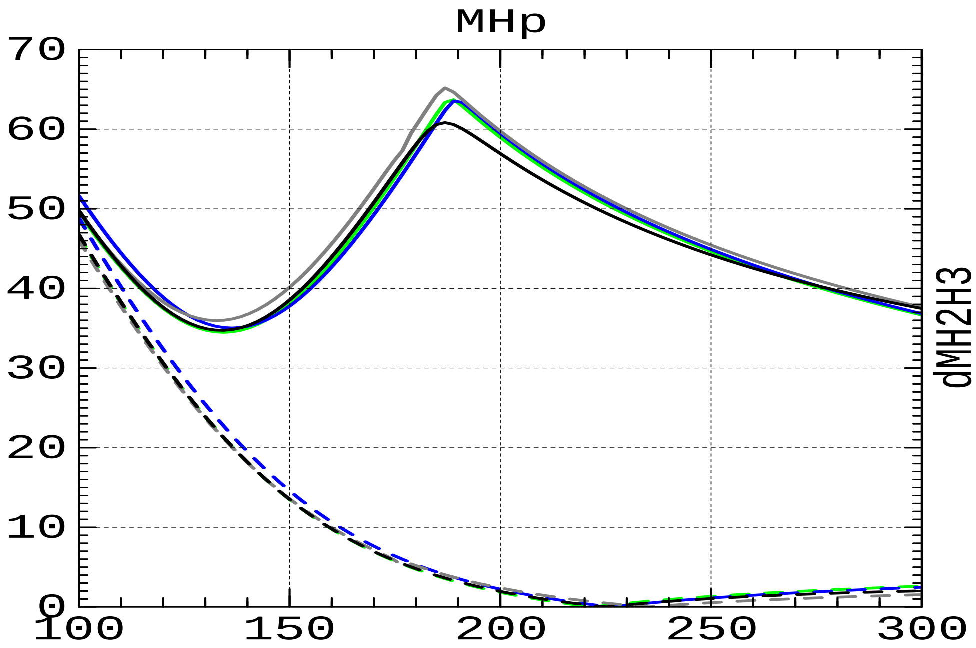
$t/\tilde{t}, b/\tilde{b}$, $q^2 = 0$, (s)fermion, $q^2 = 0$, full MSSM, $q^2 = 0$, full MSSM, $q^2 \neq 0$ (pole masses)

$m_{h_1}, m_{h_2}, m_{h_3}$
$(\phi_\mu = 0, \phi_{A_t} = \pi/2)$



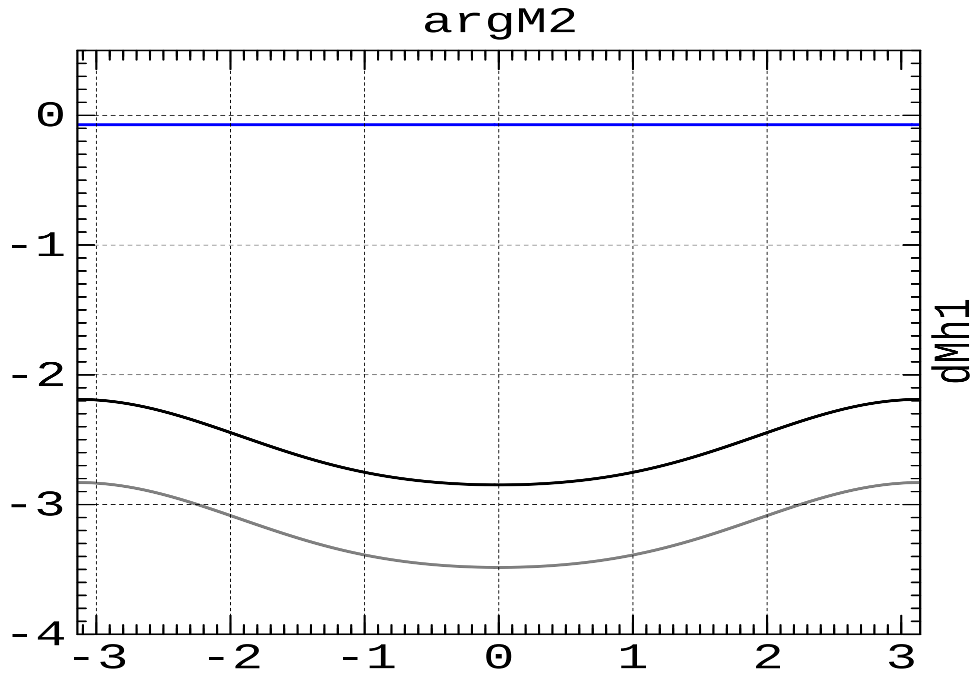
$t/\tilde{t}, b/\tilde{b},\ q^2 = 0$ (s)fermion, $q^2 = 0$, full MSSM, $q^2 = 0$, full MSSM, $q^2 \neq 0$ (pole masses)

$\Delta_{32} = m_{h_3} - m_{h_2}$:



solid: $\phi_{A_t} = \pi/2$,
dashed: $\phi_{A_t} = 0$, real case

Absolute effect beyond $f/\tilde{f}$ contributions ($\phi_\mu = 0, \phi_{A_t} = 0$):

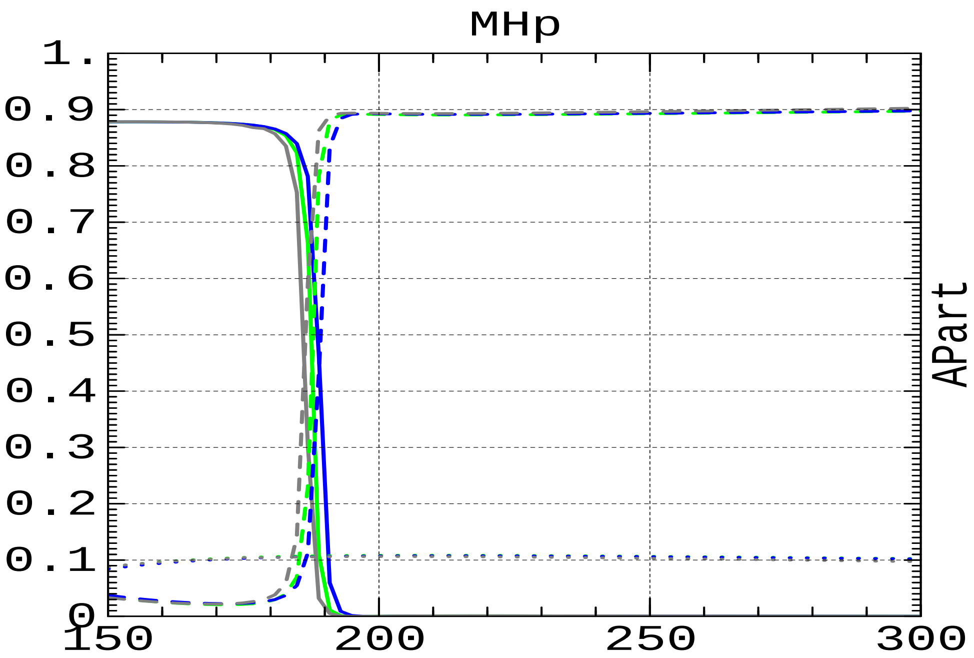


$$\left.\begin{array}{l}\text{full MSSM, } q^2 \neq 0\\ \text{full MSSM, } q^2 = 0\\ \text{(s)fermion, } q^2 = 0\end{array}\right\} - \; t/\tilde{\mathrm{t}}, b/\tilde{\mathrm{b}},\ q^2 = 0$$

Findings:

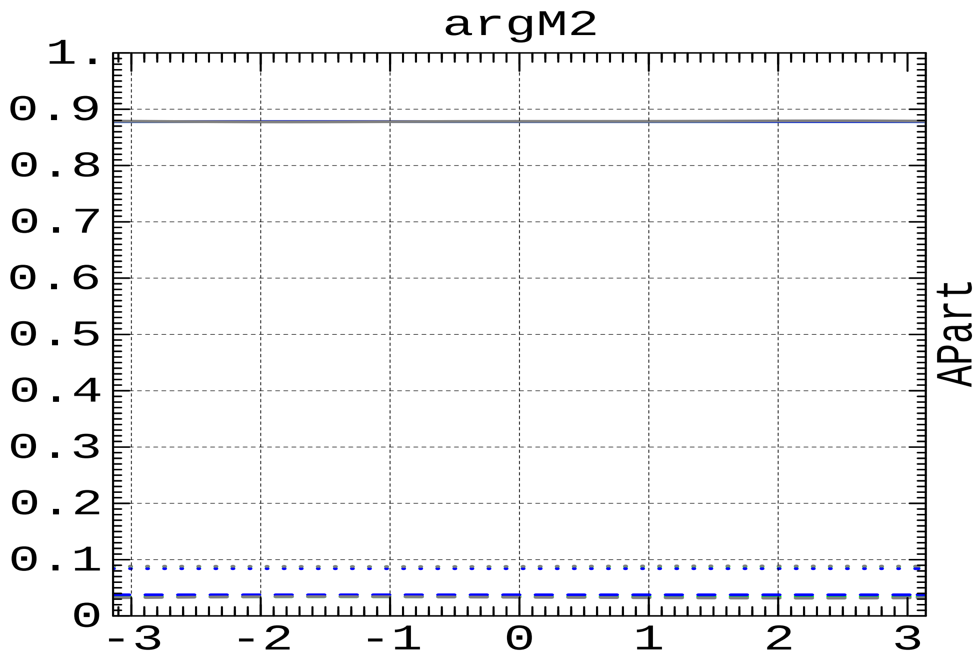
- non-(s)fermion part relevant, $\Delta m_{h_1} \lesssim 4$ GeV
- Impact of phases on non-(s)fermion part: ~ 1 GeV
- momentum dependence relevant, $\Delta m_{h_1} \sim 1.5$ GeV

$\mathcal{CP}$-odd part of h_1, h_2, h_3 ($\phi_\mu = 0$, $\phi_{A_t} = \pi/2$):

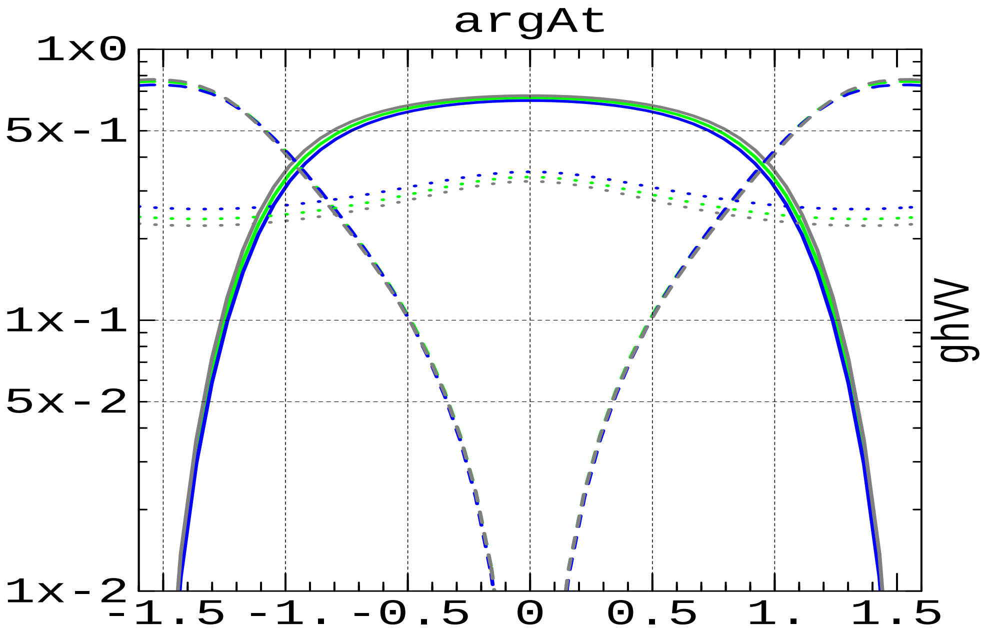


full: h_1: u_{13}^2, dashed: h_2: u_{23}^2, dotted: h_3: u_{33}^2

Dependence on ϕ_{M_2}:



g_{hVV} of h_1, h_2, h_3 ($\phi_\mu = 0$):



full: h_1, dashed: h_2, dotted: h_3, $t/\tilde{t}, b/\tilde{b}$, $q^2 = 0$, (s)fermion, $q^2 = 0$, full MSSM, $q^2 = 0$

Findings:

– Impact on u_{ij}: small for h_1, larger for $h_{2,3}$ ($M_{H^\pm} \gtrsim 200$ GeV)
  $\to$ h_2 and h_3 can possess non-negligible $\mathcal{CP}$-odd part

– Impact of new contributions small (but non-negligible off-set)

– no impact from ϕ_{M_2} in CPX

4. Conclusions

- *FeynHiggs2.1* provides Higgs masses, mixing angles, couplings in the MSSM with complex parameters

- Beyond existing calculations:
  - full one-loop evaluation
  - q^2 dependence included

  $\Rightarrow$ effects non-negligible: 1–5 GeV for subleading 1-loop,
  1–2 GeV for q^2 dependent corrections

- Inclusion of complex phases at two-loop level in preparation

- Work on *FeynHiggsDecay* is on the way

- *FeynHiggs2.1* is available at `www.feynhiggs.de`