Recent Results in the cMSSM Higgs Sector:

A complete 1-loop calculation

S. Heinemeyer, LMU München

DESY, 06/02

based on collaboration with
M. Frank, W.Hollik, G. Weiglein

1. Introduction
2. The Higgs boson sector at 1-loop in the cMSSM
3. Status of *FeynHiggs*
4. Conclusions

Stringent direct test of SUSY:

Light Higgs boson h required

Tree level: $m_h < M_Z$

Yukawa couplings: $\frac{e\, m_t}{2 M_W s_w}, \; \frac{e\, m_t^2}{M_W s_w}, \; \ldots$

Dominant corrections to m_h from $t - \tilde{t}$-sector :

$$\Delta m_h^2 \sim \frac{m_t^4}{M_W^2} \log\left(\frac{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}{m_t^4}\right)$$

$$\approx \frac{m_t^4}{M_W^2} \log\left(\frac{(M_{\text{SUSY}}^2 + m_t^2)^2 - m_t^2 X_t^2}{m_t^4}\right)$$

$\tilde{t}$ -masses:

$$(\tilde{t}_L, \tilde{t}_R) \begin{pmatrix} M_{\text{SUSY}}^2 + m_t^2 + DT_1 & m_t X_t \\ m_t X_t^* & M_{\text{SUSY}}^2 + m_t^2 + DT_2 \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}$$

High-precision measurement of m_h:

$$\begin{aligned} \text{LHC}: &\quad \delta m_h \approx 0.2 \text{ GeV} \\ \text{LC}: &\quad \delta m_h \approx 0.05 \text{ GeV} \\ \text{Muon Collider}: &\quad \delta m_h \approx 0.1 \text{ MeV} \end{aligned}$$

$\Rightarrow$ m_h will be precision observable!

1.) From unknown higher-order corrections:

$\Rightarrow \Delta m_h \approx 3$ GeV

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

2.) From uncertainties in input parameters

$m_t, \ldots, M_A, \tan\beta, m_{\tilde{t}_1}, m_{\tilde{t}_2}, \theta_{\tilde{t}}, m_{\tilde{g}}, \ldots$

$\Delta m_t \approx 5$ GeV $\Rightarrow \Delta m_h \approx 5$ GeV

Needed for LC physics:

$$\Delta m_h^{\text{theo}} \lesssim 0.5 \text{ GeV}$$

Upper bound on m_h in the "unconst. MSSM":

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

Diagrammatic result: *FeynHiggs*1.2.2 (see sect. 3)

[*S.H., W. Hollik, G. Weiglein '99/'01*]

$$m_h \lesssim 134 \text{ GeV}$$

($m_t = 175$ GeV, $M_{\text{SUSY}} \leq 1000$ GeV,
no theoretical uncertainties included)

$\rightarrow$ holds also for $\mathcal{CP}$-violation

[*A. Pilaftsis, C. Wagner '99*]

MSSM can have complex phases ⇒ cMSSM

Higgs sector of the cMSSM:

Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1^0 + i\chi_1^0)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = e^{i\xi} \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2^0 + i\chi_2^0)/\sqrt{2} \end{pmatrix}$$

Higgs potential:

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

2 $\mathcal{CP}$-violating phases: ξ, m_{12}

⇒ can compensate each other

⇒ no $\mathcal{CP}$V at tree-level

$$\phi_1, \phi_2 \rightarrow h, H \quad (\mathcal{CP}-\text{even})$$
$$\chi_1, \chi_2 \rightarrow A, G \quad (\mathcal{CP}-\text{odd})$$
$$\phi_1^\pm, \phi_2^\pm \rightarrow H^\pm, G^\pm$$

$\Rightarrow$ 3 neutral, 2 charged physical Higgs bosons

Input parameters:

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_{H^\pm}$$

$\Rightarrow m_h, m_H, M_A$

calculable in terms of other parameters

Other complex parameters:

- μ : Higgs mixing parameter
- $A_{t,b}$: trilinear couplings
  $\Rightarrow X_{t,b} = A_{t,b} - \mu^* \{\cot\beta, \tan\beta\}$ complex
- $M_{1,2}$: gaugino mass parameter
- $m_{\tilde{g}}$: gluino mass

Existing corrections 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*]

[*S.H. '01*]

Missing:

– remaining sectors at 1-loop (rMSSM: 5 GeV)
– q^2 dependence at 1-loop (rMSSM: $\sim$ 2 GeV)
– non-leading 2-loop corrections (rMSSM: 3 GeV)

New calculation:

complete 1-loop evaluation in the
Feynman-diagrammatic approach, $q^2 \neq 0$

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

Propagator/Mass matrix at tree-level:

$$\begin{pmatrix} q^2 - M_A^2 & 0 & 0 \\ 0 & q^2 - m_H^2 & 0 \\ 0 & 0 & q^2 - m_h^2 \end{pmatrix}$$

with higher-order corrections:

$$\begin{pmatrix} q^2 - M_A^2 + \hat{\Sigma}_{AA}(q^2) & \hat{\Sigma}_{AH}(q^2) & \hat{\Sigma}_{Ah}(q^2) \\ \hat{\Sigma}_{HA}(q^2) & q^2 - m_H^2 + \hat{\Sigma}_{HH}(q^2) & \hat{\Sigma}_{Hh}(q^2) \\ \hat{\Sigma}_{hA}(q^2) & \hat{\Sigma}_{hH}(q^2) & q^2 - m_h^2 + \hat{\Sigma}_{hh}(q^2) \end{pmatrix}$$

$\hat{\Sigma}_{Ah}, \hat{\Sigma}_{AH} \neq 0 \;\Rightarrow\; \mathcal{CP}$V

New calculation:

$\hat{\Sigma}_{AA}, \hat{\Sigma}_{HH}, \hat{\Sigma}_{hh}, \hat{\Sigma}_{hH}, \; \hat{\Sigma}_{Ah}, \hat{\Sigma}_{AH}$:

– full 1-loop evaluation
  dependence on all possible phases included
  $\Rightarrow$ uncertainties of up to 5 GeV eliminated

– momentum dependence fully included
  $\Rightarrow$ uncertainties of up to 2 GeV eliminated

– On-shell renormalization scheme

$$(A, H, h) \to (h_3, h_2, h_1)$$

with

$$m_{h_3} > m_{h_2} > m_{h_1}$$

Higgs boson couplings:

(only in $q^2 = 0$ approximation)

[*A. Pilaftsis, C. Wagner '99*]

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

– 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

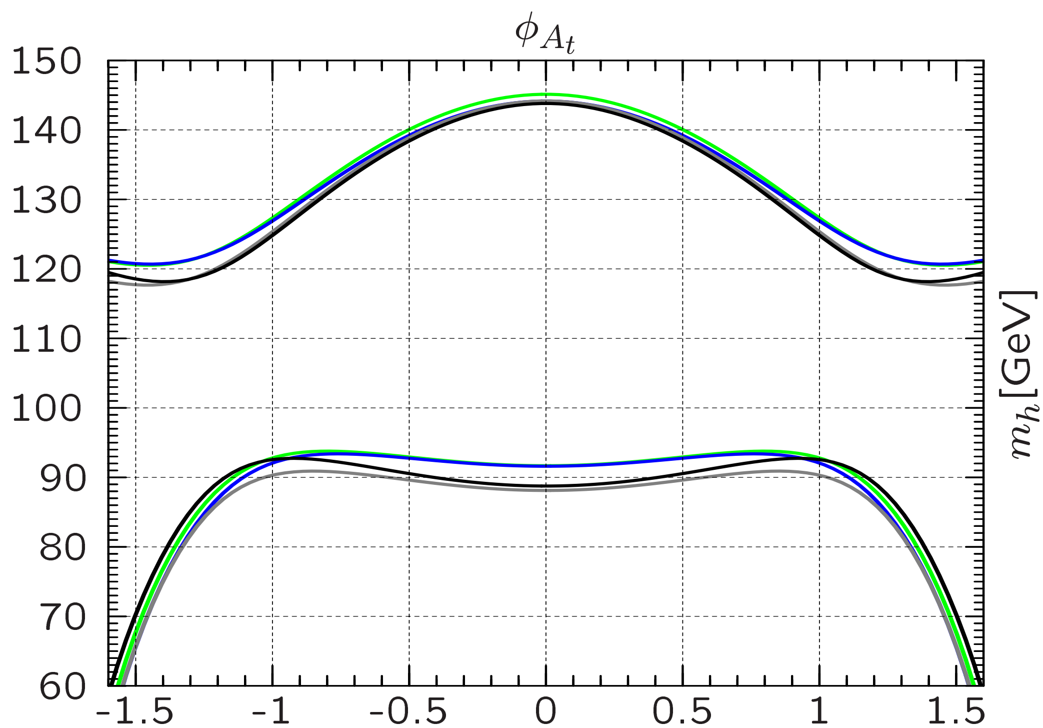
To show “possible” large effects:

CPX scenario:

$M_{\text{SUSY}} = 500$ 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}:

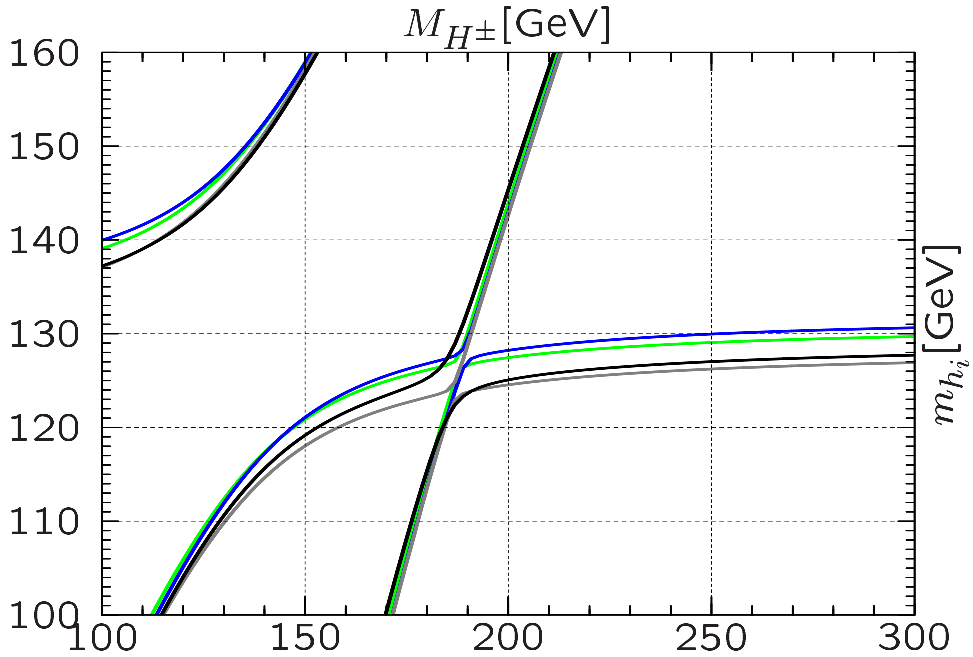
($\phi_\mu = 0$, $|A_t| = 2\,M_{\text{SUSY}}$)



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

$m_{h_1}, m_{h_2}, m_{h_3}$

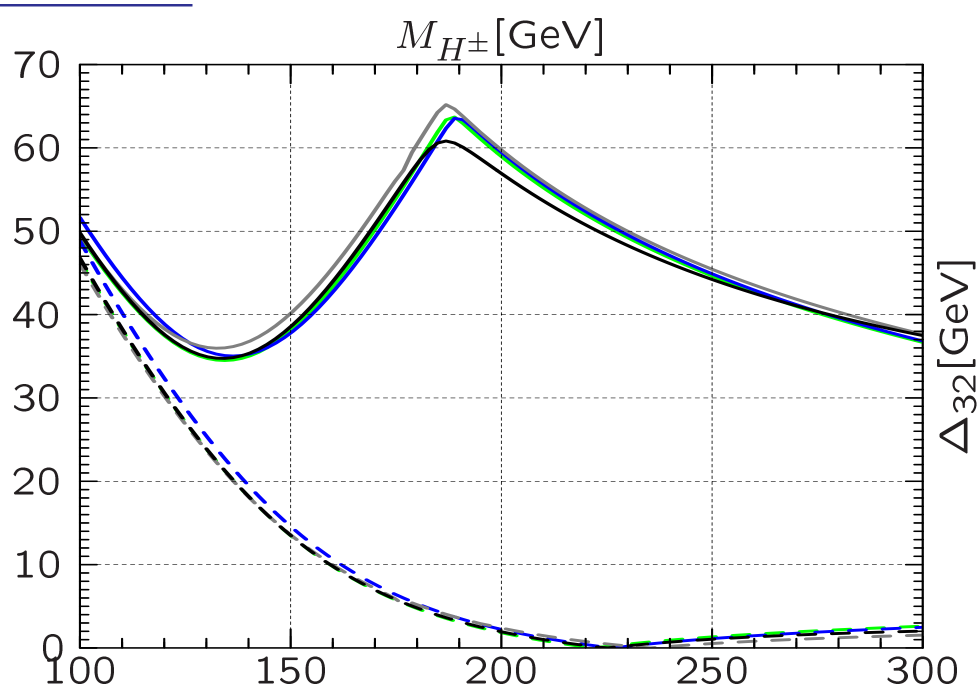
$(\phi_\mu = 0, \phi_{A_t} = \pi/2)$



$t/\tilde{t}, b/\tilde{b},\ q^2 = 0$ (s)fermion, $q^2 = 0$

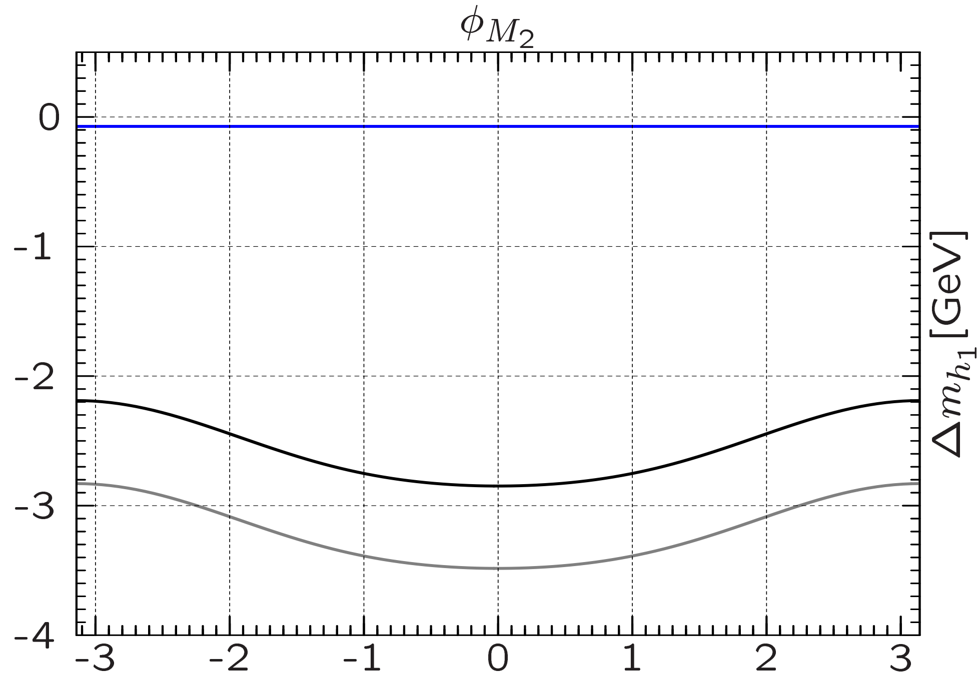
full MSSM, $q^2 = 0$ full MSSM, $q^2 \neq 0$ (pole masses)

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



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

$(\phi_\mu = 0, \phi_{A_t} = 0)$



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

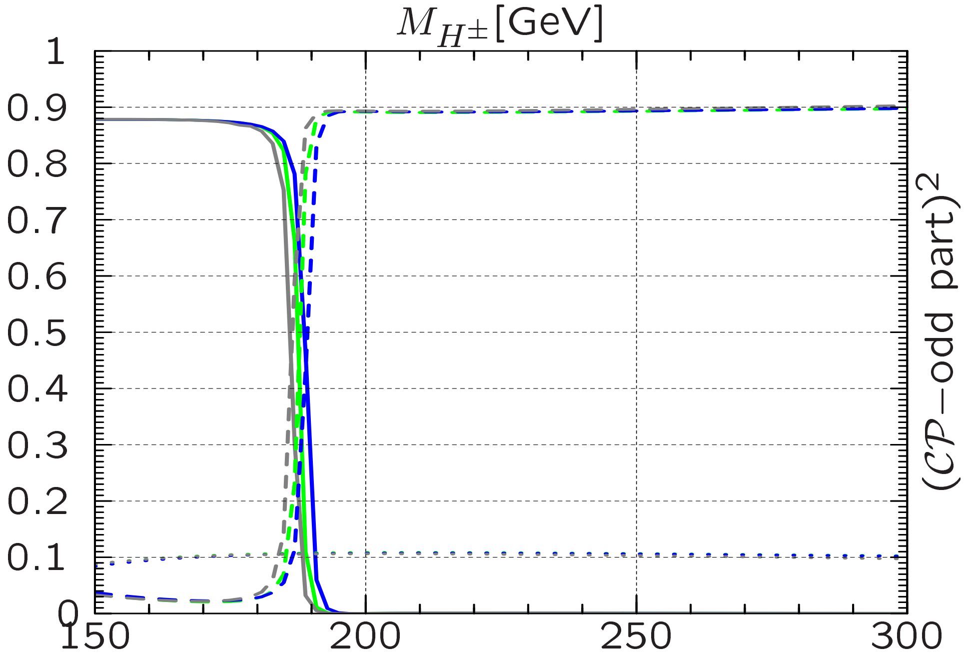
Findings:

– 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

$(\phi_\mu = 0,\ \phi_{A_t} = \pi/2\text{:})$

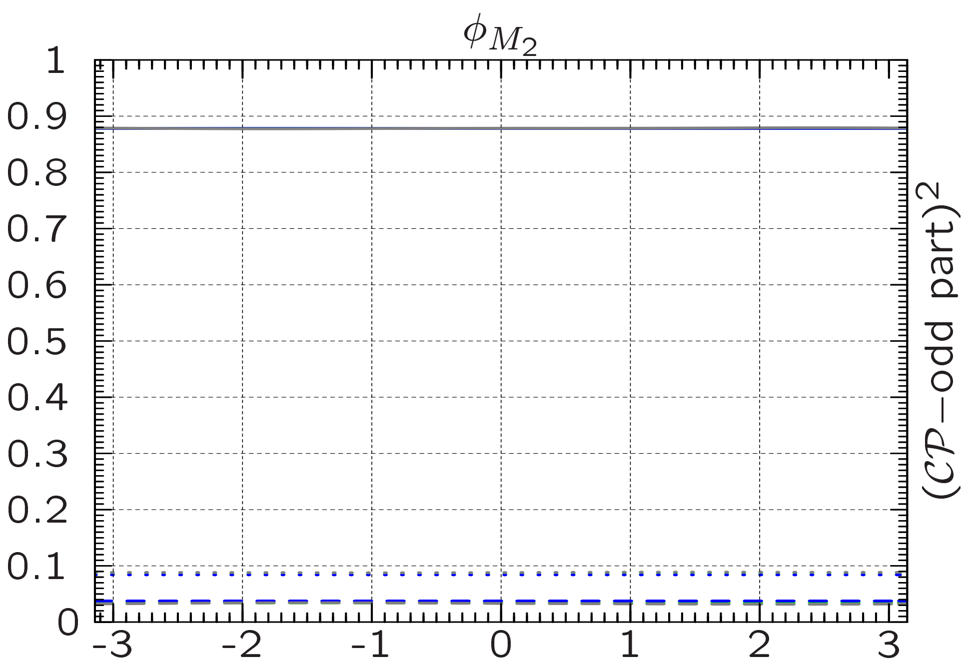


full: h_1 : u_{13}^2

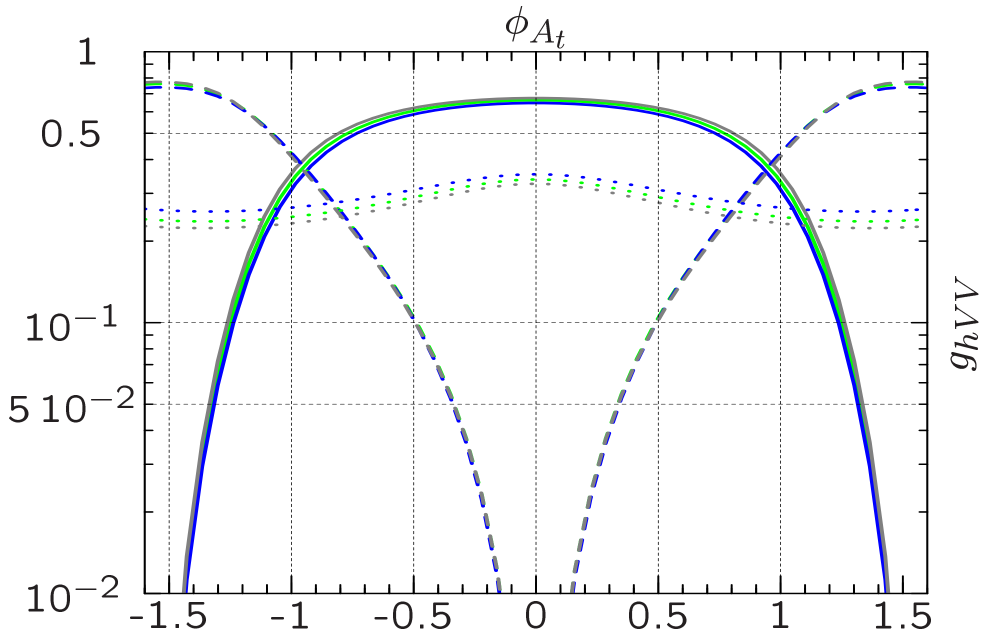
dashed: h_2 : u_{23}^2

dotted: h_3 : u_{33}^2

Dependence on ϕ_{M_2}:



$(\phi_\mu = 0)$



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$)$ $\rightarrow$ 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

Latest version: (03/25/02)

*FeynHiggs*1.2.2 :

– New renormalization ($\overline{\text{MS}}$/OS) for 1-loop result
[*M. Frank, S.H., W. Hollik, G. Weiglein '02*]

– subleading non-log $\mathcal{O}\left(\alpha_t^2\right)$ terms
[*A. Brignole, G. Degrassi, P. Slavich, F. Zwirner '01*]
[*J. Espinosa, R. Zhang '01*]

– "Δm_b" corrections for Higgs masses
$\Rightarrow$ leading $\mathcal{O}\left(\alpha_b\alpha_s\right)$ terms included
[*M. Carena, D. Garcia, U. Nierste, C. Wagner '00*]

– SPS (Snowmass points and slopes) implemented
[*B. Allanach et al. '02*]

– Les Houches BMS for Higgs searches at Tev/LHC implemented
[*M. Carena, S.H., C. Wagner, G. Weiglein '02*]

Obtainable at: www.feynhiggs.de

*FeynHiggs*1.2.2 used for final evaluations of LEP Higgs WG

*FeynHiggs*2.0 :

– 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

– completely new Fortran/C/Mathematica code

– Higgs decays in FD calculation for rMSSM

– Higgs production and decay as u_{ij} for cMSSM

available: $\sim$ 09/2002

- complete 1-loop evaluation for masses and couplings in the cMSSM Higgs boson sector

- q^2 dependence included

- reduction of m_{h_1} uncertainties reduced:
  – non (s)fermion sector: $1-5$ GeV
  – q^2 dependence: $1-2$ GeV

- everything will be included in *FeynHiggs*2.0

- Latest version: *FeynHiggs*1.2.2
  – new renormalization
  – non-log $\mathcal{O}\left(\alpha_t^2\right)$ terms
  – Δm_b corrections for Higgs masses
  ($\to \mathcal{O}\left(\alpha_b \alpha_s\right)$)
  – SPS + Les Houches BMS included

  available at www.feynhiggs.de