Exploring Phases of the cMSSM at Future Colliders

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based on collaboration with
M. Velasco et al.

1. Motivation

2. Higgs physics in the cMSSM

3. Exploring the phases

4. Conclusions

1. Motivation

One of the main tasks of future colliders:

$\Rightarrow$ find the Higgs boson
$\Rightarrow$ determine its properties
$\Rightarrow$ explore the underlying model

Simplest solution: Higgs in the Standard Model (SM)

Attractive solution:
Higgs in the Minimal Supersymmetric Standard Model (MSSM)

Large efforts to extract Lagrangian parameters from exp. measurements
– Fittino [*P. Bechtle, K. Desch, P. Wienemann '04*]
– SFitter [*R. Lafaye, T. Plehn, D. Zerwas '04*]

$\rightarrow$ so far restricted to real parameters

However: we have to be prepared for a variety of models:
real MSSM, complex MSSM, non-minimal flavor violation MSSM, . . .

Focus here: sensitivity to complex MSSM parameters

2. Higgs physics in the cMSSM

Higgs potential of the cMSSM contains two Higgs doublets:

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

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

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

gauge couplings, in contrast to SM

Five physical states: $h^0, H^0, A^0, H^\pm$ (no $\mathcal{CP}$V at tree-level)

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

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

$\tilde{t}/\tilde{b}$ sector of the MSSM: (scalar partner of the top/bottom quark)

Stop, sbottom mass matrices ($X_t = A_t - \mu^*/\tan\beta$, $X_b = A_b - \mu^* \tan\beta$):

$$\mathcal{M}^2_{\tilde{t}} = \begin{pmatrix} M^2_{\tilde{t}_L} + m_t^2 + DT_{t_1} & m_t X_t^* \\ m_t X_t & M^2_{\tilde{t}_R} + m_t^2 + DT_{t_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{t}}} \begin{pmatrix} m^2_{\tilde{t}_1} & 0 \\ 0 & m^2_{\tilde{t}_2} \end{pmatrix}$$

$$\mathcal{M}^2_{\tilde{b}} = \begin{pmatrix} M^2_{\tilde{b}_L} + m_b^2 + DT_{b_1} & m_b X_b^* \\ m_b X_b & M^2_{\tilde{b}_R} + m_b^2 + DT_{b_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{b}}} \begin{pmatrix} m^2_{\tilde{b}_1} & 0 \\ 0 & m^2_{\tilde{b}_2} \end{pmatrix}$$

mixing important in stop sector (also in sbottom sector for large $\tan\beta$)

complex soft SUSY-breaking parameters A_t, A_b and μ

$\Rightarrow$ comples phases enter via $\tilde{t}/\tilde{b}$ sector

Contrary to the SM: m_h is not a free parameter

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

Large radiative corrections:

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

> The MSSM Higgs sector is connected to all other sector via loop corrections (especially to the scalar top sector)
>
> $\Rightarrow$ complex phases enter

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

LHC: $\Delta m_h \approx 0.2$ GeV
ILC: $\Delta m_h \approx 0.05$ GeV

$\Rightarrow$ m_h will be (the best?) electroweak precision observable

Status of calculations in the cMSSM and uncertainties:

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

– some leading logs from remaining sectors

– leading 2-loop corrections

[*A. Pilaftsis '98*] , [*A. Pilaftsis, C. Wagner '99*] , [*A. Demir '99*] , [*S.H. '01*]
[*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. Martin '01-'05*] [*S.H., W. Hollik, H. Rzehak, G. Weiglein '05*]
(→ see talk by S. Heinemeyer ;-)

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

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

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

Effects of complex parameters 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

Result:

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

with

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

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

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

Two codes on the market:

CPsH:
– (leading) log approx. for one-loop
– approx. for momentum dependence (at one-loop)
– (leading) log approx. for $\mathcal{O}\left(\alpha_s\alpha_t, \alpha_t^2\right)$ including full complex phase dependence
– $\mathcal{O}(\alpha_s\alpha_b)$: $(\alpha_s \tan\beta)^n$ resummation including full complex phase dependence

FeynHiggs: (www.feynhiggs.de, see talk by T. Hahn)
– full one-loop including full complex phase dependence
– full momentum dependence (at one-loop)
– full $\mathcal{O}\left(\alpha_s\alpha_t, \alpha_t^2\right)$, but with approx. for complex phase dependence
– $\mathcal{O}(\alpha_s\alpha_b)$: $(\alpha_s \tan\beta)^n$ resummation including full complex phase dependence + subleading terms (without phase dependence)

⇒ not trivial to disentangle where possible differences in the complex case come from

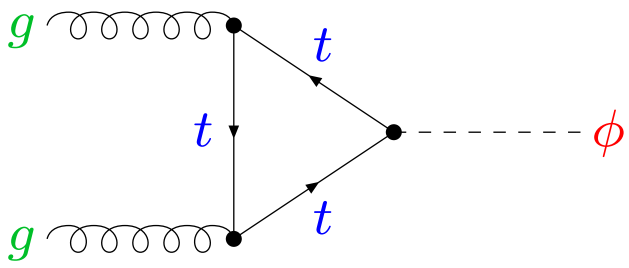
⇒ use FeynHiggs2.2 for the following results

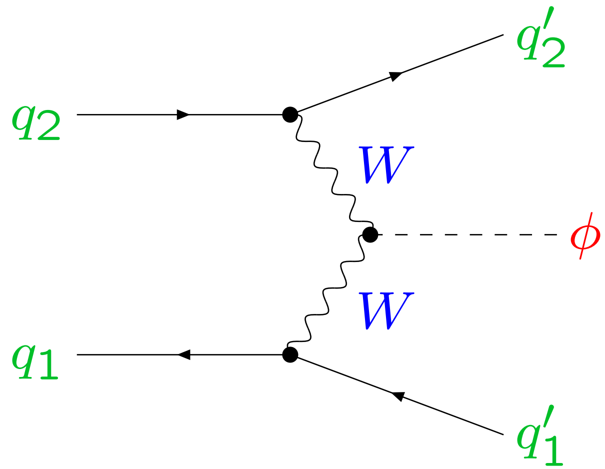
3. Exploring the phases in the cMSSM

3. A) The colliders

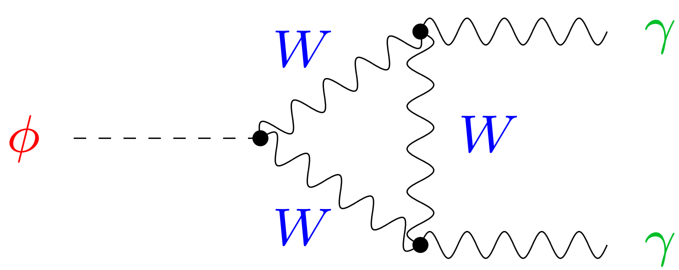
LHC:

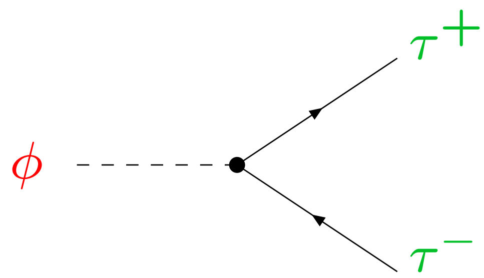
– Higgs production:





– Higgs decays:





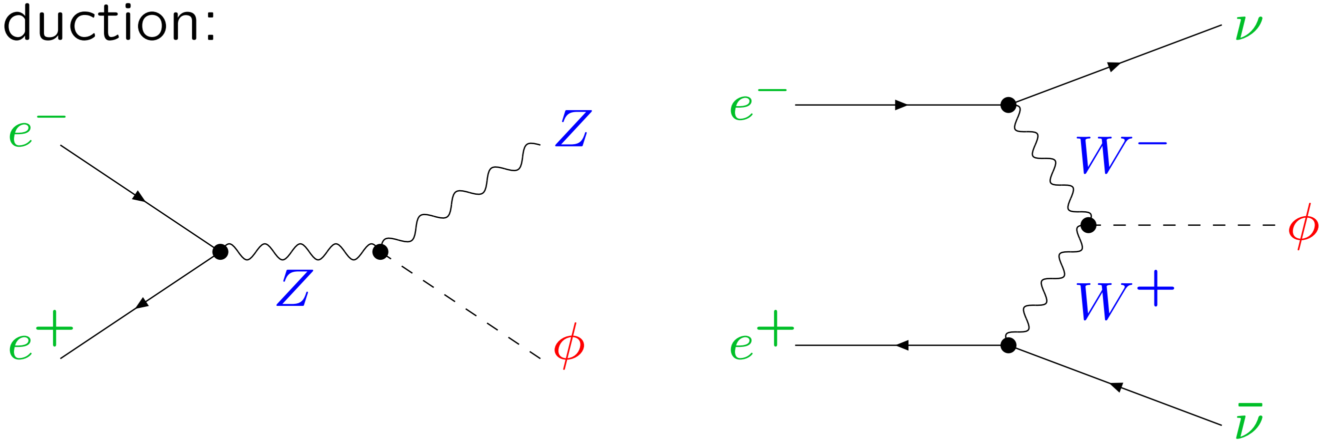
– Precisions for $m_h = 120$ GeV (300 fb^{-1}):

[*M. Dührssen, S.H., H. Logan, D. Rainwater, G. Weiglein, D. Zeppenfeld '04*]

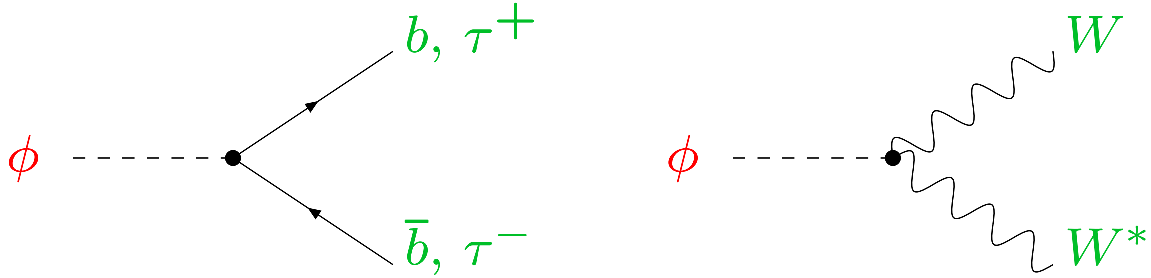
BR($h \to \gamma\gamma$), BR($h \to \tau^+\tau^-$) $= \mathcal{O}\,(10 - 20\%)$

ILC:

– Higgs production:



– Higgs decays:



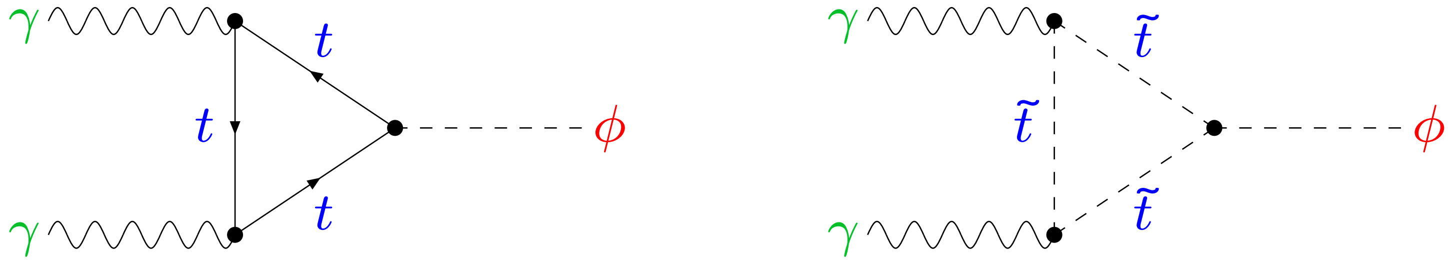
– Precisions for $m_h = 120$ GeV (500 fb^{-1} @ $\sqrt{s} = 350$ GeV):

[*TESLA TDR '01*]

BR($h \to b\bar{b}$) $\approx$ 2%, BR($h \to \tau^+\tau^-$) $\approx$ 5%, BR($h \to WW^*$) $\approx$ 5%

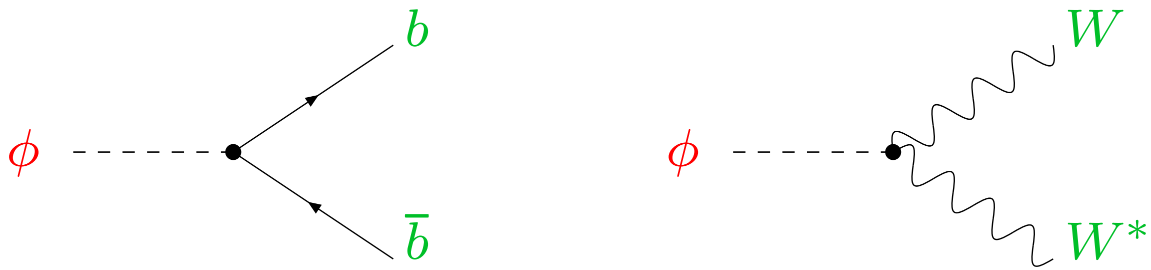
γC:

– Higgs production:



$\Rightarrow$ complex phases enter Higgs production

– Higgs decays:



– Precisions for $m_h = 120$ GeV (one year @ $\sqrt{s} = 160$ GeV):

[*D. Asner et al. '01, '02*]

BR($h \to b\bar{b}$) $\approx$ 2%, BR($h \to WW^*$) $\approx$ 5%, BR($h \to \gamma\gamma$) $\approx$ 8%

3. B) The scenarios

CPX scenario: $\to$ emphasize "possible" large effects:

[*M. Carena, J. Ellis, A. Pilaftsis, C. Wagner '01*]

$M_{\text{SUSY}} = 500$ GeV, $|A_t| = 1000$ GeV, $A_b = A_\tau = A_t$,
$M_2 = 500$ GeV, $|m_{\tilde{g}}| = 1000$ GeV, $\mu = 2000$ GeV
$\Phi = \Phi_{A_{t,b,\tau}} = \Phi_{m_{\tilde{g}}}$
$M_{H^\pm}$, $\tan\beta$ varied

BGX scenario: $\to$ allows for baryogenesis (more "realistic"?):
based on: [*C. Balazs, M. Carena, A. Menon, D. Morissey, C. Wagner '04*]

$M_{\tilde{t}_L} = 1.5$ TeV, $M_{\tilde{t}_R} = 0$, $M_{\tilde{Q}_{1,2}} = 1.2$ TeV, $M_{\tilde{L}_{1,2}} = 1.0$ TeV
$|X_t| = 0.7$ TeV, $A_b = A_\tau = A_t$
$M_2 = 220$ GeV, $m_{\tilde{g}} = 1$ TeV, $\mu = 200$ GeV
$\Phi = \Phi_{A_{t,b,\tau}} = \Phi_{m_{\tilde{g}}}$
$M_{H^\pm}$, $\tan\beta$ varied

Some remarks/warnings:

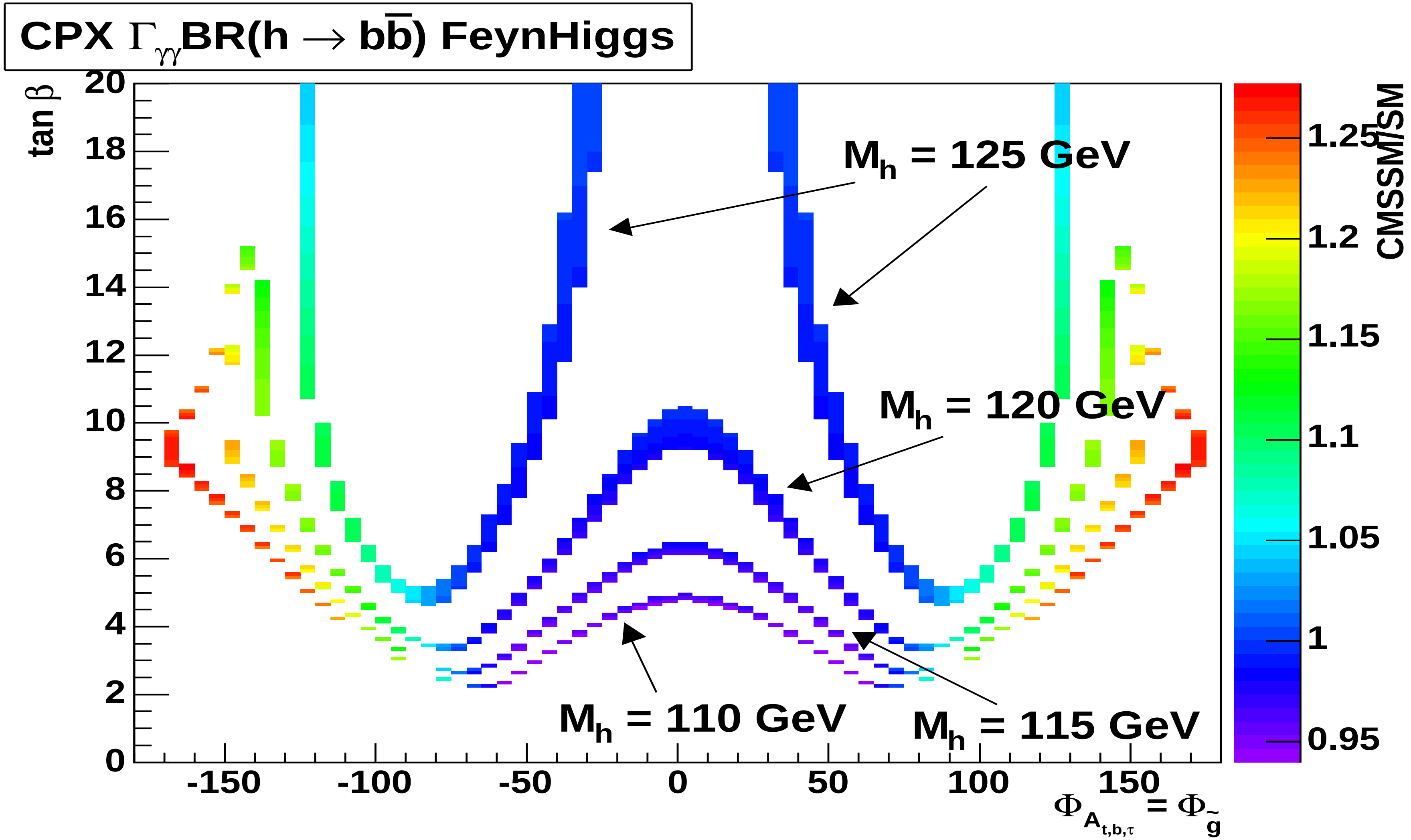
- EDM constraints forbid too large values of $\tan\beta$: $\tan\beta \lesssim 15 - 20$!
- in reality parameters will enter with their experimental errors
  $\rightarrow$ not included

  $\Rightarrow$ plots show best possible results
- also not included: theory uncertainties

  New routine in *FeynHiggs*: theory error evaluation
  (not completely thoroughly tested yet, but . . .)

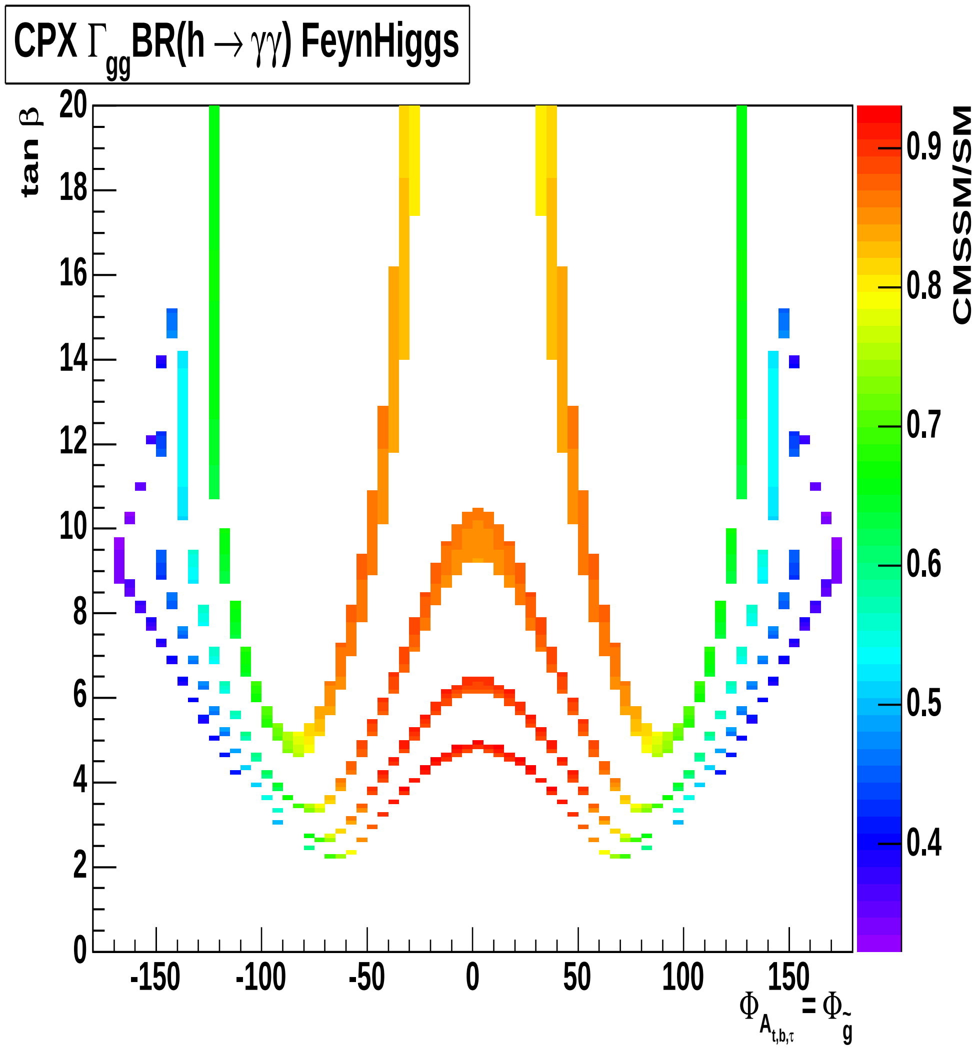
  CPX: $\delta M_h^{\text{theo}} \gtrsim 5$ GeV for not too small $\tan\beta$

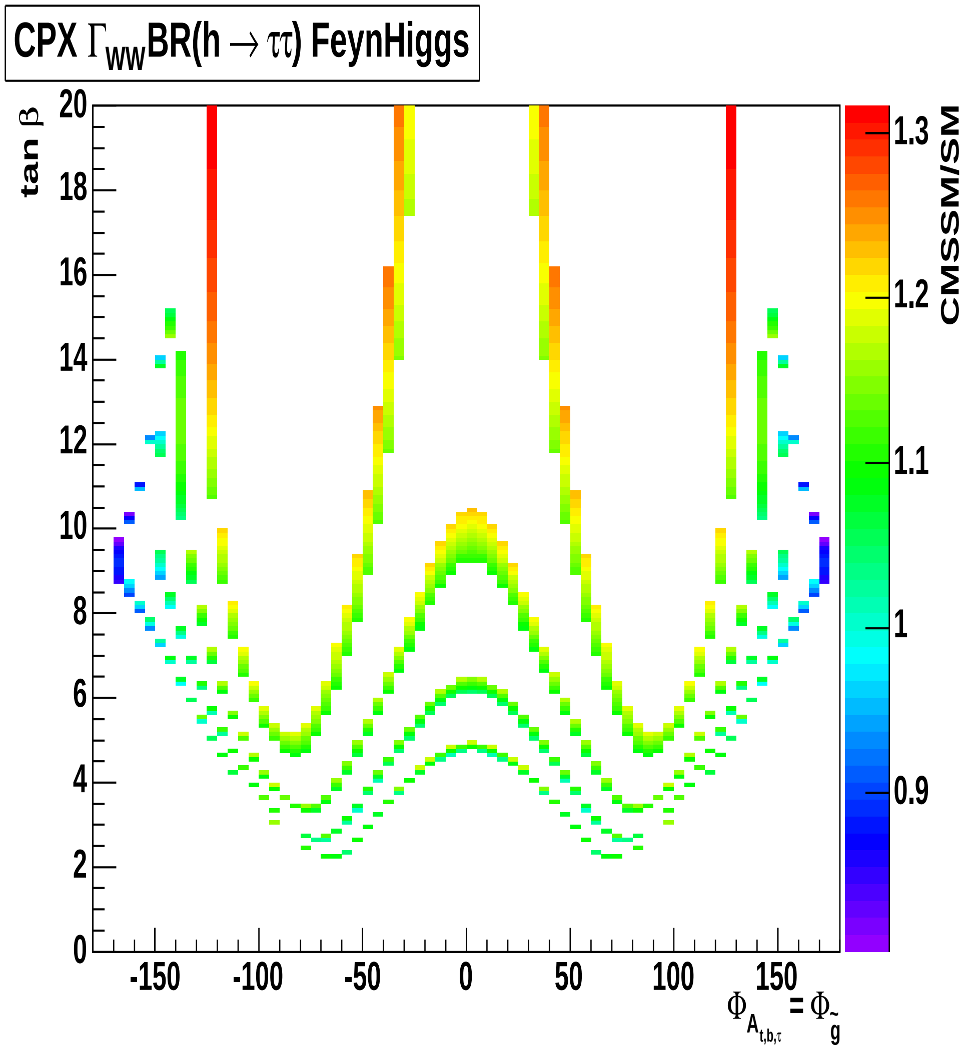
Results are shown for fixed m_h values: γC/CPX:



⇒ looks very promising

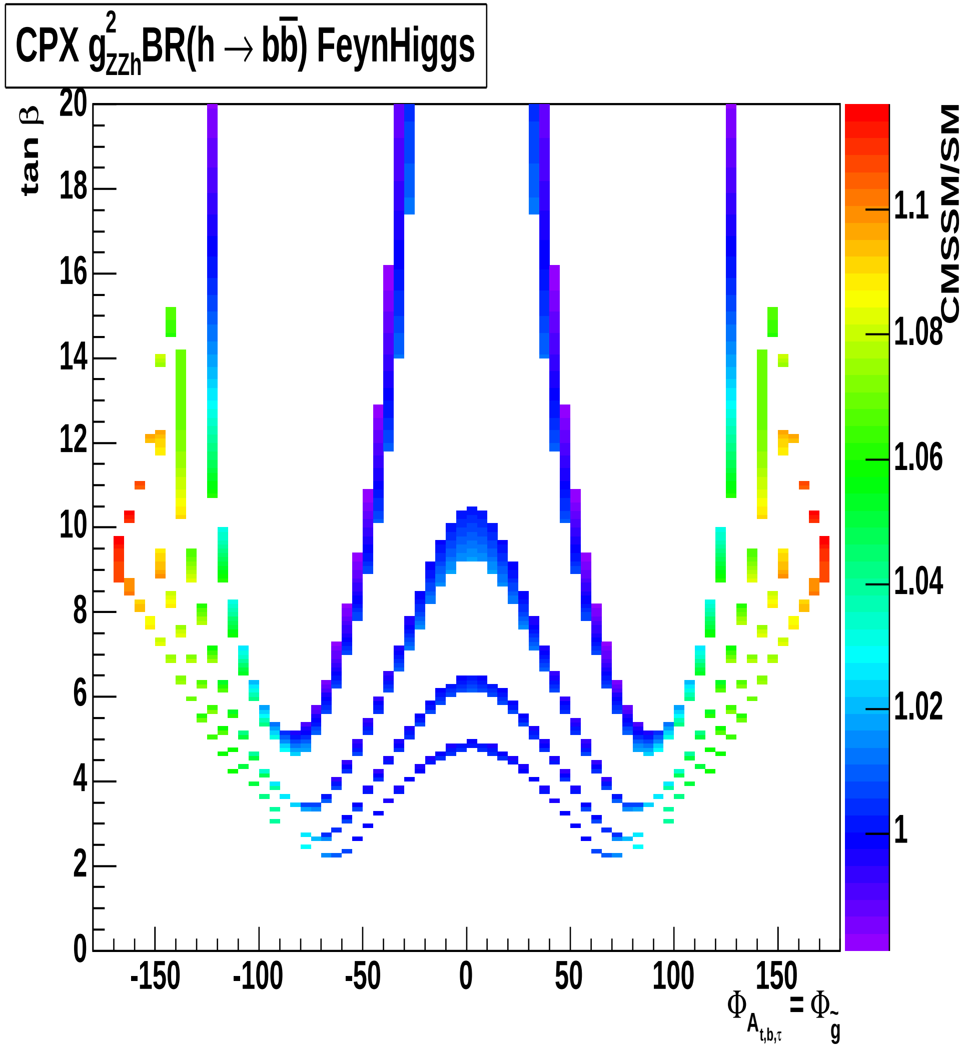
Results are shown for fixed m_h values: LHC/CPX:

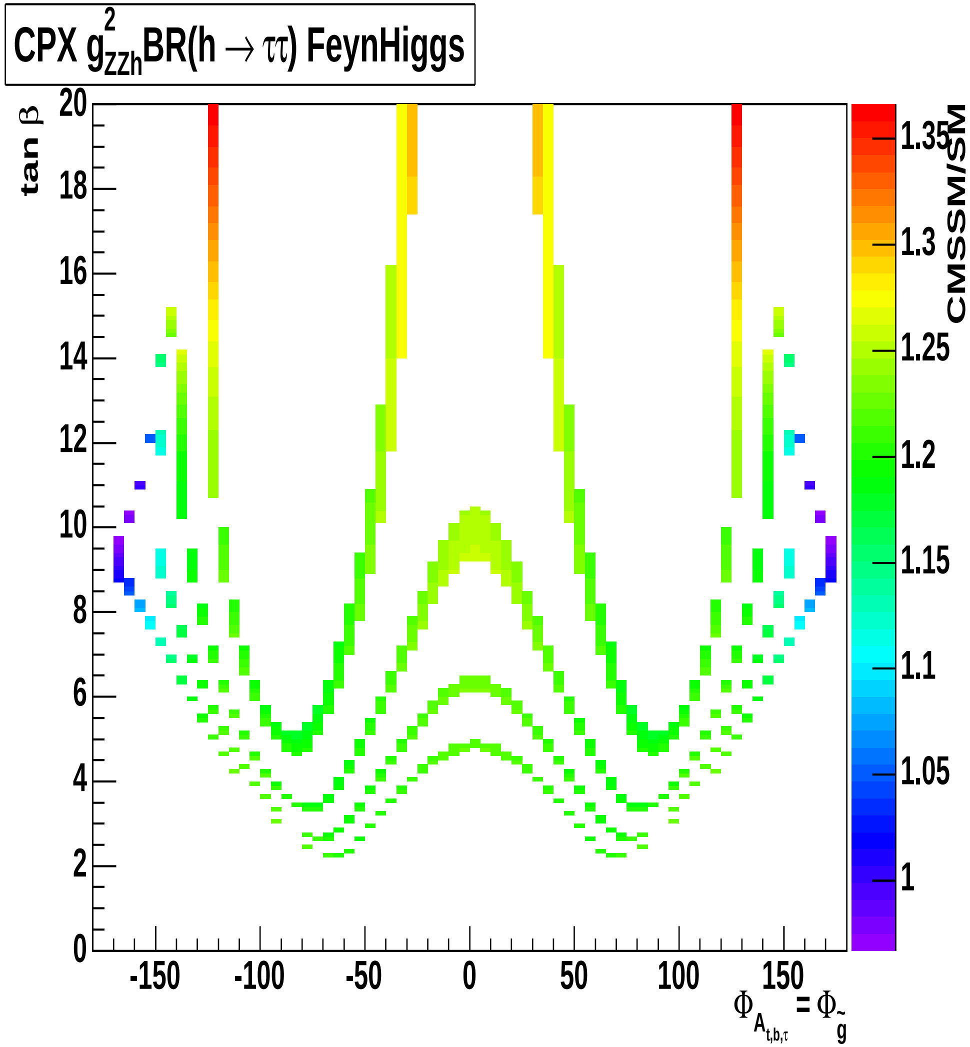




⇒ interesting, but probably not precise enough . . .

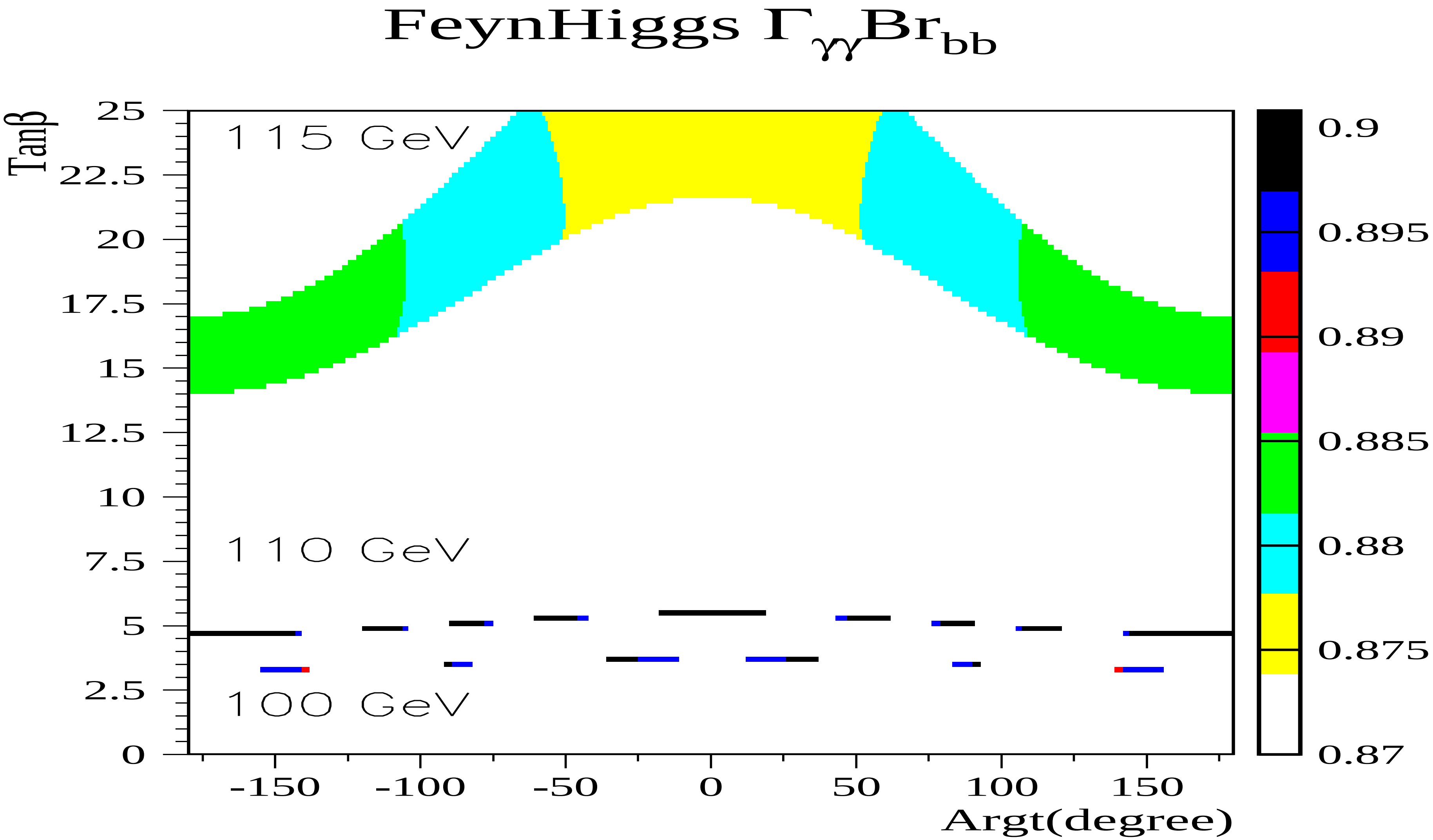
Results are shown for fixed m_h values: ILC/CPX:





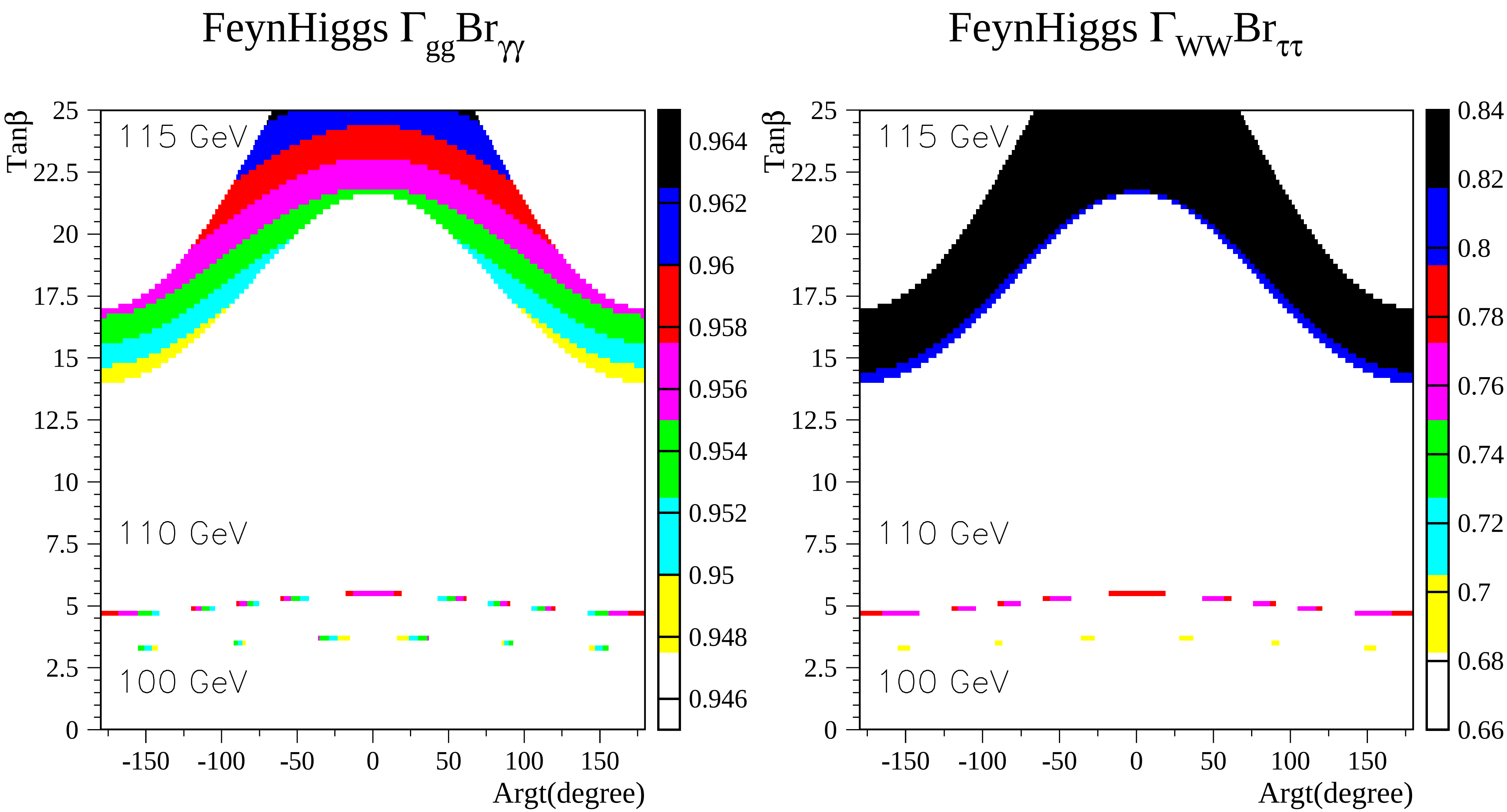
⇒ interesting, . . .

Results are shown for fixed m_h values: γC/BGX:



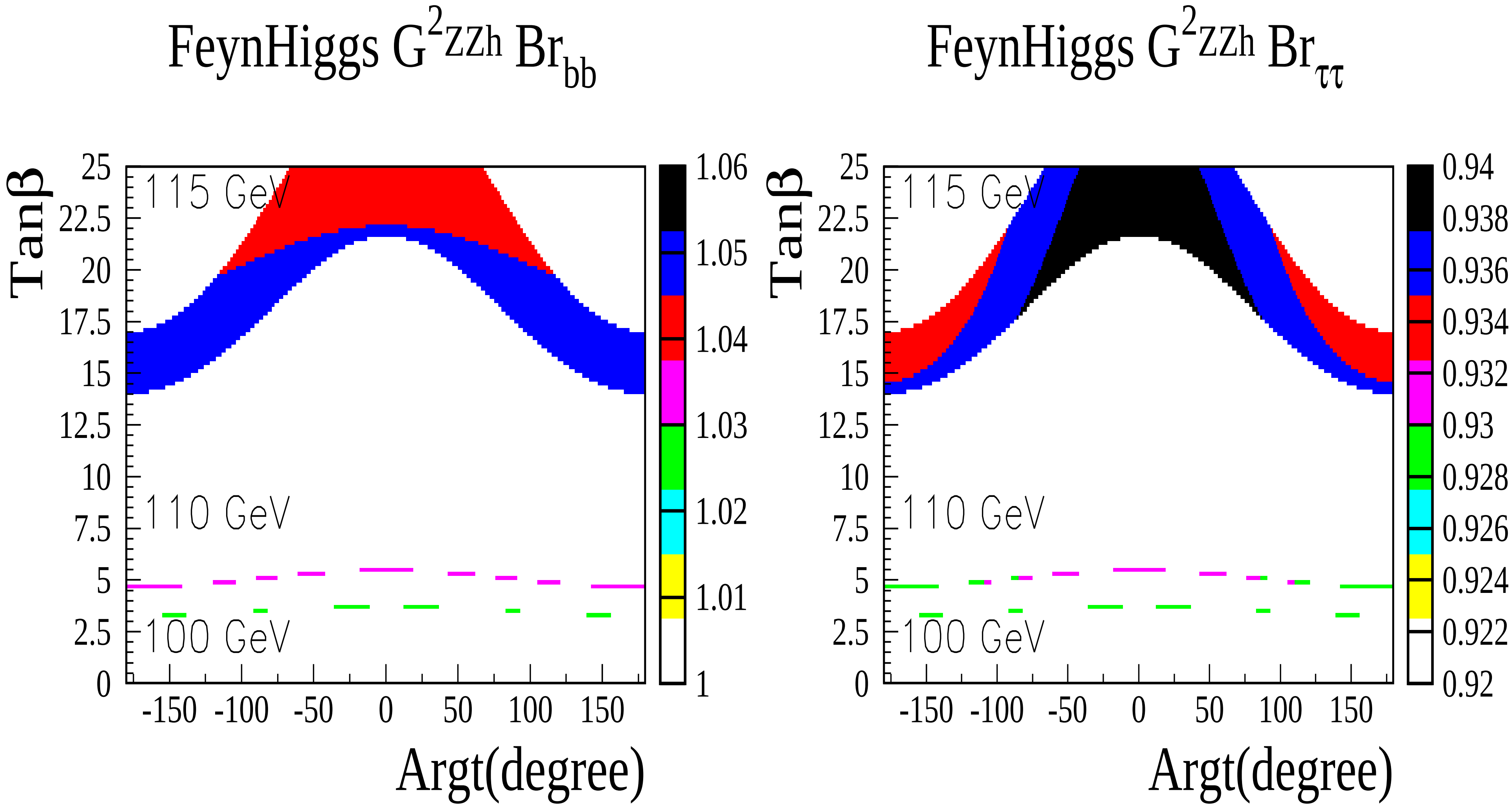
⇒ strong deviation from SM, but does not look good for ϕ determination:-(

Results are shown for fixed m_h values: LHC/BGX:



⇒ hopeless

Results are shown for fixed m_h values: ILC/BGX:



⇒ deviation from the SM possible, but not too good for ϕ determination

4. Conclusinos

- One of the main tasks of future colliders:
  determine the SUSY model parameters

- Especially interesting: complex parameters

- Comparison of LHC, ILC and γC for CPX and BGX scenario
  (experimental errors neglected so far)

- Advantage of γC: complex phases enter substantially also in
  Higgs production

- CPX scenario: ("maximum" effects):
  γC shows largest variation for the mode $\gamma\gamma \to h \to b\bar{b}$
  $\Rightarrow$ good prospects for parameter determination

  ILC offers good channel with $e^+e^- \to Z\,h \to Z\,b\bar{b}$

- BGX scenario (more "realistic"?)
  $\Rightarrow$ more or less hopeless

- Nevertheless: Theory/parametric uncertainty has to get under control!

0. Back-up slides

1. Comparison with other calculations

Other calculations/codes:

– Hdecay3.0 (pure real case) [*M. Spira et al.*]
– CPsH (real and complex MSSM) [*J. Lee, A. Pilaftsis et al. '03*]
(rMSSM: CPsH and Hdecay3.0(default) should agree)

Comparison in the rMSSM:

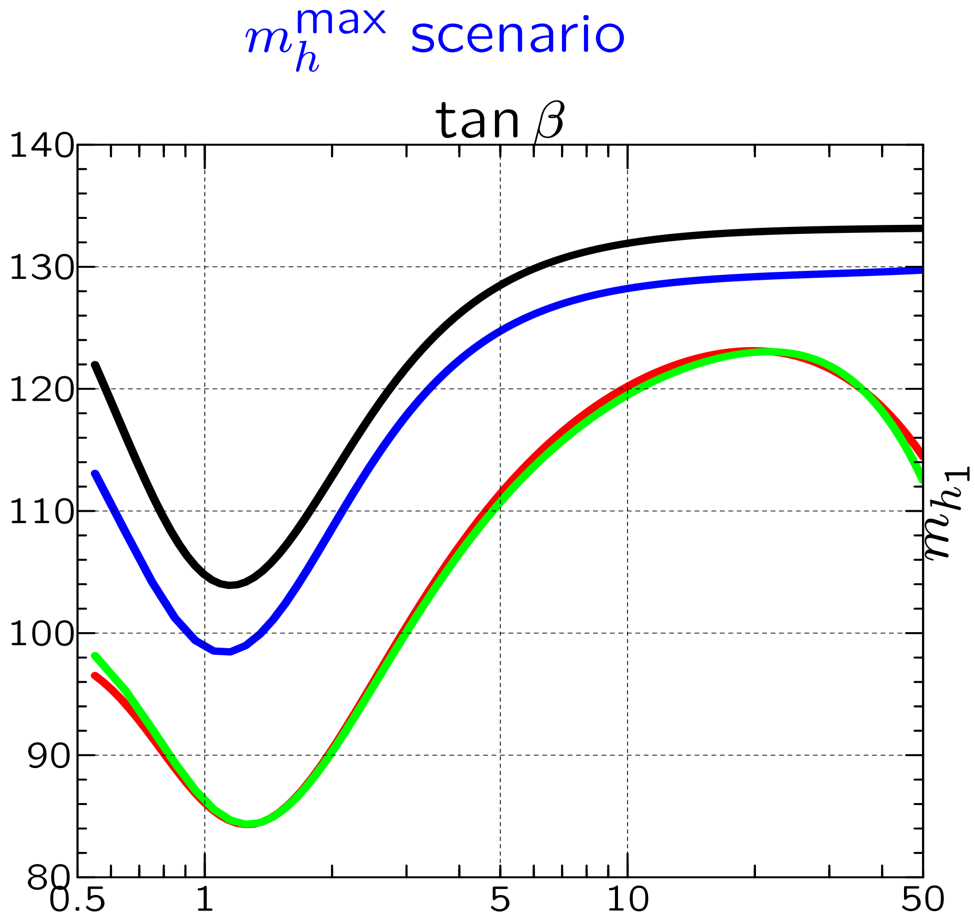
masses, mixings, . . . : more included in *FeynHiggs*2.2
⇒ compare with CPsH/Hdecay3.0

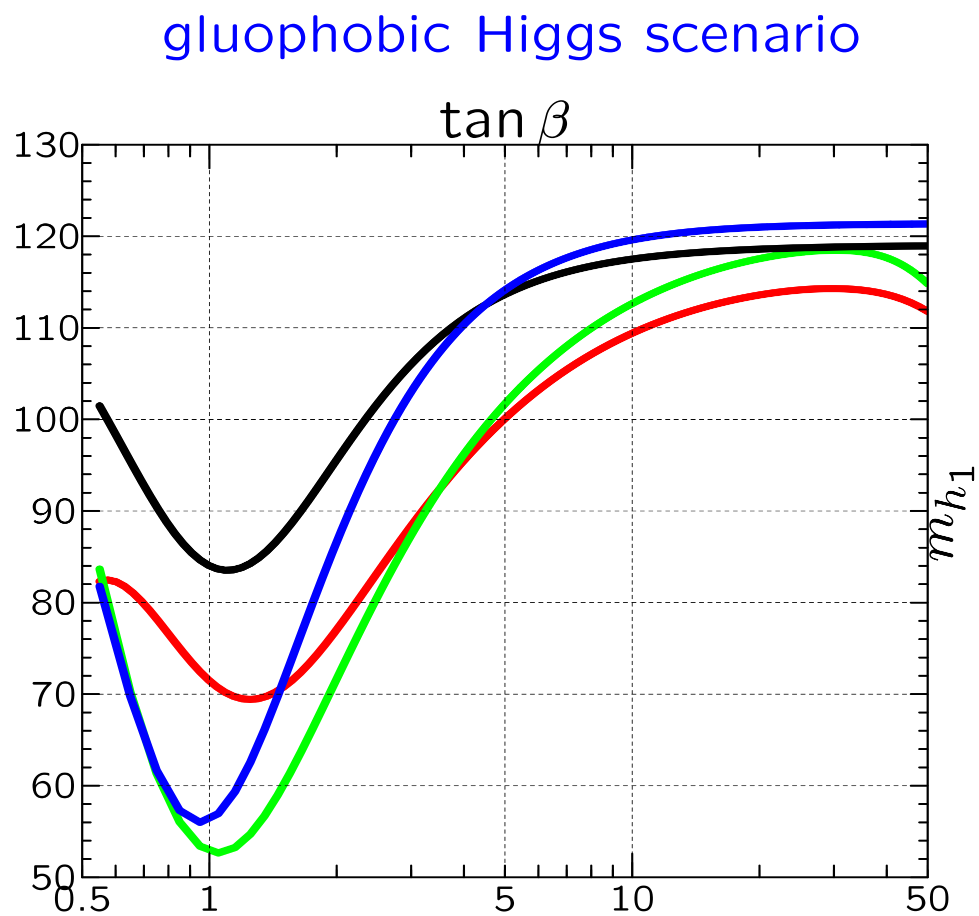
Comparison in the cMSSM:

analysis more involved:
some corrections included in *FeynHiggs*, but not in CPsH (one-loop)
some corrections included in CPsH, but not in *FeynHiggs* (two-loop)
⇒ not completely clear what causes differences
(but differences from real MSSM also present here)

→ qual. /quant. agreement for BRs with CPsH

Compare m_{h_1} in the two scenarios:

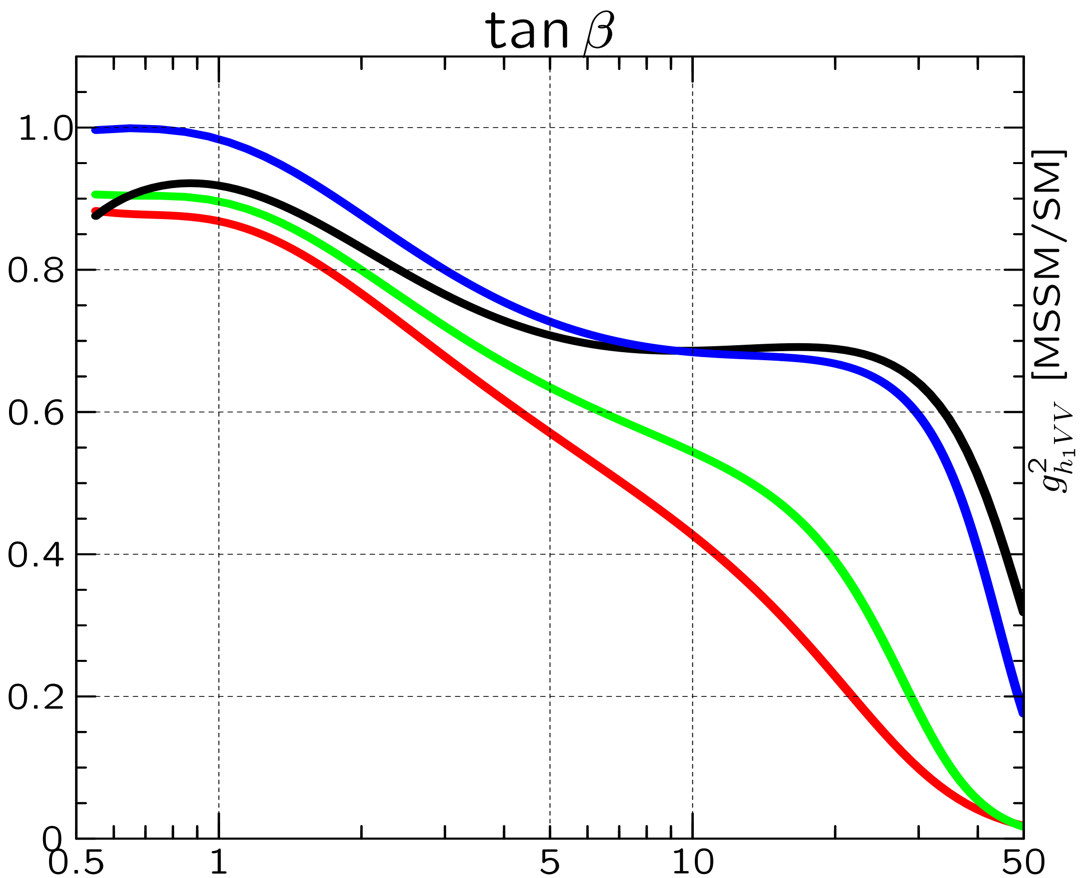




FeynHiggs, $M_{H^\pm} = 150$ GeV , CPsH, $M_{H^\pm} = 150$ GeV
FeynHiggs, $M_{H^\pm} = 500$ GeV , CPsH, $M_{H^\pm} = 500$ GeV

$\Rightarrow$ large differences, but understood

Compare h_1ZZ in the two scenarios for $M_{H^\pm} = 150$ GeV :



FeynHiggs, $m_h^{\rm max}$, CPsH, $m_h^{\rm max}$

FeynHiggs, gluophobic Higgs , CPsH, gluophobic Higgs

⇒ large differences, but understood