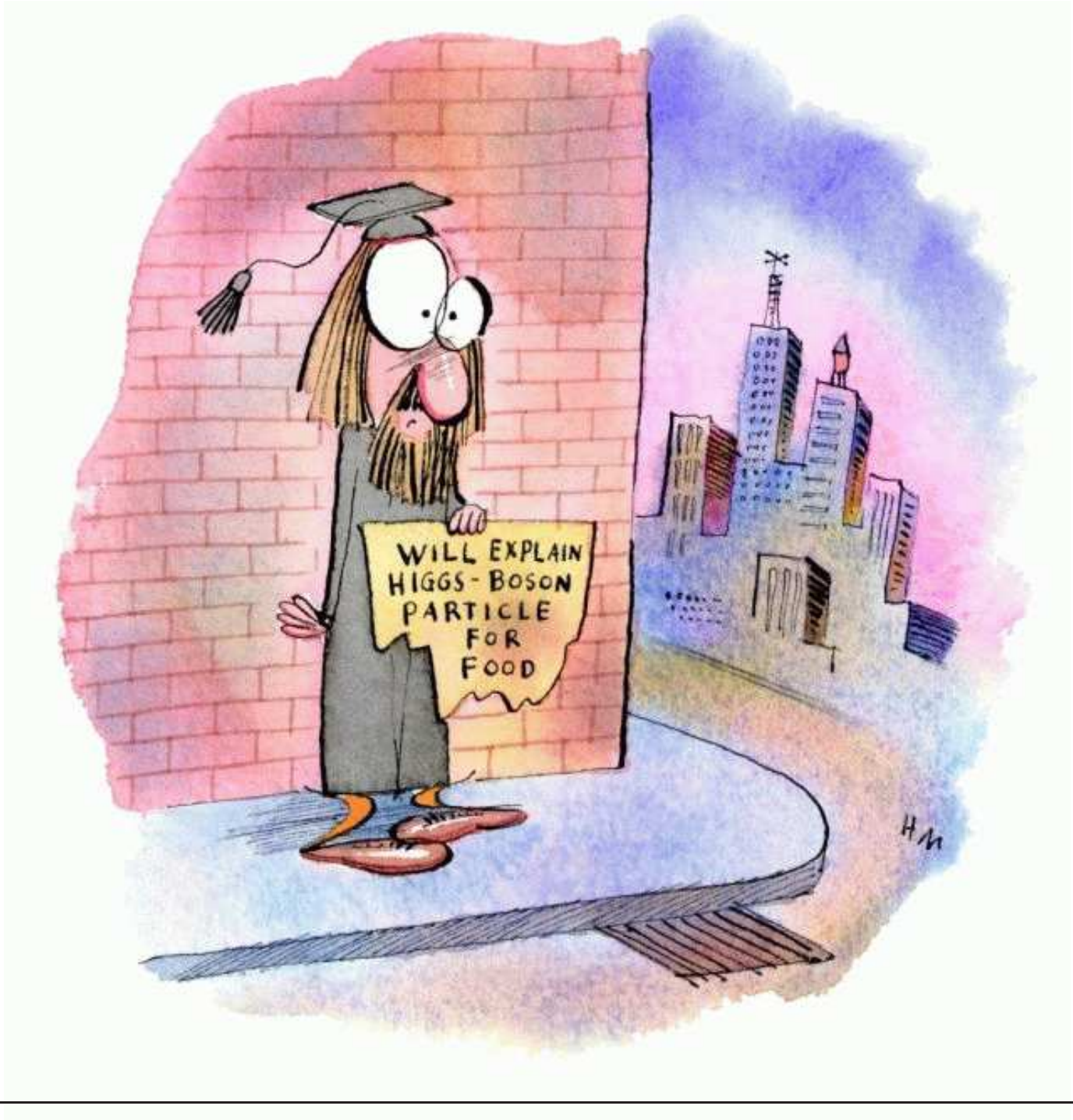

WILL EXPLAIN
HIGGS-BOSON
PARTICLE
FOR
FOOD

Higgs to SUSY Decays at the Full One-Loop Level

Sven Heinemeyer, IFT/IFCA (CSIC, Madrid/Santander)

Melbourne, 06/2016

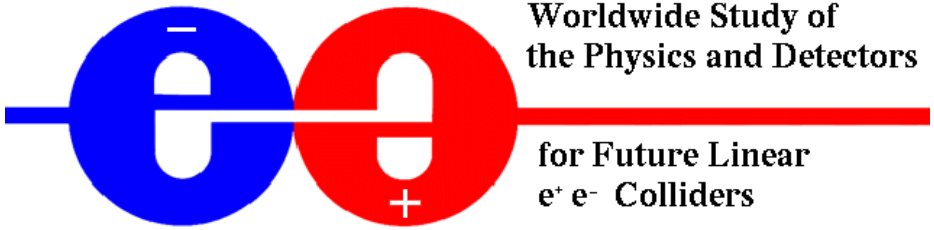
based on collaboration with *C. Schappacher*

1. The Grand Scheme
2. Higgs to chargino/neutralino decays
3. Higgs to Sfermion decays
4. Conclusions

1. The Grand Scheme

The LHC up and running . . .
→ discovery of BSM physics this year?

The ILC is still coming . . .
. . . a bit later than anticipated
→ to investigate BSM physics



⇒ New Physics is certainly around the corner

⇒ Time to get ready for BSM physics

The big question:

Which Lagrangian describes the world?

My guess:

It is a supersymmetric one

$\Rightarrow$ concentrate on the MSSM from now on

(other people $\Rightarrow$ other guesses $\Rightarrow$ other priorities $\Rightarrow$ wrong conference?)

In any case:

$\Rightarrow$ we have to measure as many observables as possible

- masses
- branching ratios
- angular distributions
- cross sections
- ...

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- masses
- branching ratios
- angular distributions
- cross sections
- ...

$\Rightarrow$ compare with theory calculations at the same level of accuracy

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

$$\left[u, d, c, s, t, b\right]_{L,R} \quad \left[e, \mu, \tau\right]_{L,R} \quad \left[\nu_{e,\mu,\tau}\right]_{L} \qquad \text{Spin } \tfrac{1}{2}$$

$$\left[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}\right]_{L,R} \quad \left[\tilde{e}, \tilde{\mu}, \tilde{\tau}\right]_{L,R} \quad \left[\tilde{\nu}_{e,\mu,\tau}\right]_{L} \qquad \text{Spin } 0$$

$$g \quad \underbrace{W^{\pm}, H^{\pm}} \quad \underbrace{\gamma, Z, H_1^0, H_2^0} \qquad \text{Spin 1 / Spin 0}$$

$$\tilde{g} \quad \tilde{\chi}_{1,2}^{\pm} \quad \tilde{\chi}_{1,2,3,4}^{0} \qquad \text{Spin } \frac{1}{2}$$

Enlarged Higgs sector: Two Higgs doublets $\Leftarrow$ for obvious reasons some focus here!

Problem in the MSSM: many scales

Problem in the MSSM: complex phases

Where are we for MSSM Higgs decays?

1. Higgs decays to SM
   - full 1-loop, leading 2-loop, ... (depending on final state)
   - Z-factors at 2-loop

2. Higgs decays to SUSY
   - mostly 1-loop QCD (depending on final state)
   - Z-factors at 2-loop

3. SUSY decays to Higgs bosons
   - full 1-loop in cMSSM

     [*A. Bharucha, T. Fritzsche, S.H., F. v.d. Pahlen, H. Rzehak, C. Schappacer*]

NEW: full 1-loop calculation for Higgs decay to SUSY

Generic problems for SUSY loop calculations:

- SUSY has to be preserved in the calculation
- Many different mass scales
- Many more mass scales than free parameters
- Even more parameters: mixing angles, complex phases
- Renormalization is much more involved than in the SM
  - much less explored than in the SM
  - has to preserve/respect mass relations
  - depend on mass scales realized in Nature
  - sometimes no really good solution exist (e.g. $\tan\beta$)
  - many sectors enter at the same time

  $\Rightarrow$ this is the biggest issue!

Enlarged Higgs sector: Two Higgs doublets

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

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

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

$$+ \underbrace{\frac{g'^2 + g^2}{8}}_{} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}_{} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM

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

Goldstone bosons: $G^0, G^\pm$

Input parameters: (to be determined experimentally)

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_A^2 = -m_{12}^2(\tan\beta + \cot\beta)$$

Enlarged Higgs sector: Two Higgs doublets with $\mathcal{CP}$ violation

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

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

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$
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gauge couplings, in contrast to SM

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

2 $\mathcal{CP}$-violating phases: ξ, $\arg(m_{12})$ $\Rightarrow$ can be set/rotated to zero

Input parameters: (to be determined experimentally)

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_{H^\pm}^2$$

The Higgs sector of the cMSSM at the loop-level:

Complex parameters enter via loop corrections:

– μ : Higgsino mass parameter

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

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

– M_3 : gluino mass parameter

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

Result:

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

with

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

$\Rightarrow$ strong changes in Higgs couplings to SM gauge bosons and fermions

Renormalization summary:

– LHC/LC precision requires all calculations at the per-cent level

– full complex MSSM renormalized

[*A. Bharucha, T. Fritzsche, T. Hahn, S.H., F.v.d. Pahlen, H. Rzehak, C. Schappacher '11 - '13*]

– stable and well behaved results over nearly complete parameter space

– available as FeynArts model file

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– full one-loop calculations possible with FeynArts/FormCalc/LoopTools

– set-up includes full one-loop corrections (hard/soft QED/QCD radiation)

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– full one-loop calculations possible with FeynArts/FormCalc/LoopTools

– set-up includes full one-loop corrections (hard/soft QED/QCD radiation)

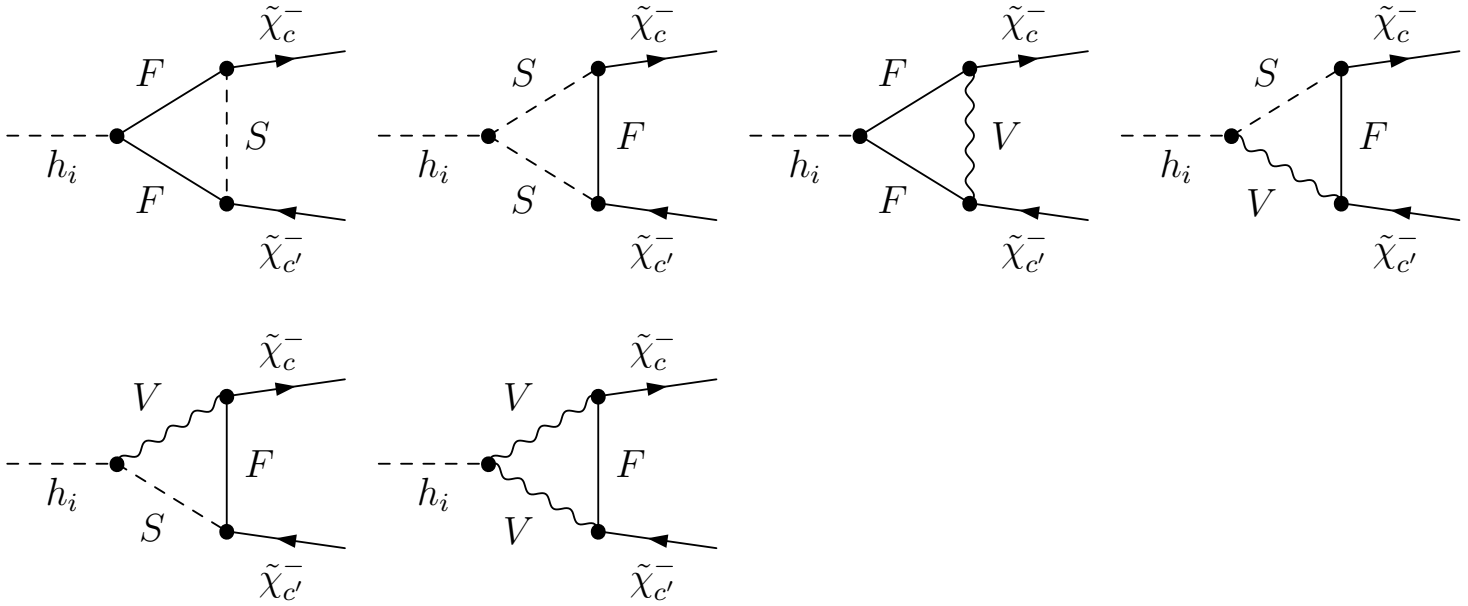
⇒ **go and make your prediction!**

2. Higgs decays to charginos/neutralinos

$$\Gamma(h_i \to \tilde{\chi}_c^- \tilde{\chi}_{c'}^+) \quad (i = 1,2,3;\ c, c' = 1,2)$$

$$\Gamma(h_i \to \tilde{\chi}_n^0 \tilde{\chi}_{n'}^0) \quad (i = 1,2,3;\ n, n' = 1,2,3,4)$$

$$\Gamma(H^\pm \to \tilde{\chi}_n^0 \tilde{\chi}_c^\pm) \quad (n = 1,2,3,4;\ c = 1,2)$$



Numerical example scenario:

$\tan\beta$	μ	A_{u_g}	A_{d_g}	A_{e_g}	$\lvert M_1\rvert$	M_2	M_3	$m_{\tilde{t}_1}$	$m_{\tilde{t}_2}$	$m_{\tilde{b}_2}$	$m_{\tilde{\nu}_\tau}$	$m_{\tilde{\tau}_1}$
10	500	1200	600	1000	300	600	1500	394	771	582	280	309

Parameters varied: $M_{H^\pm}$, M_1, φ_{M_1}

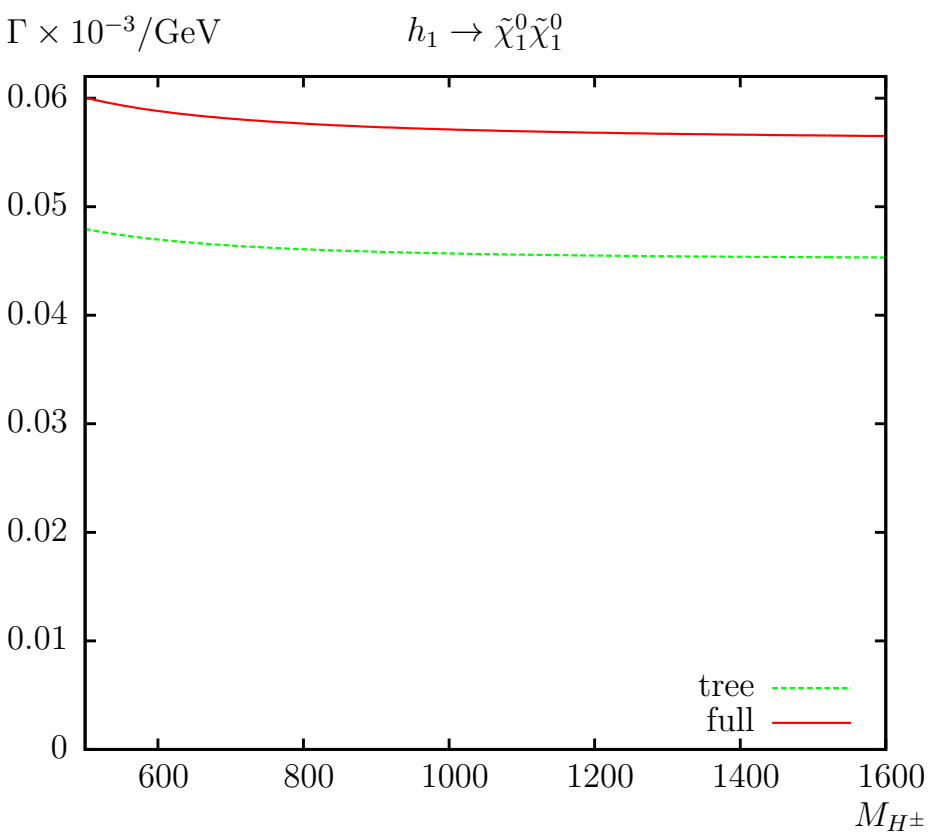
– in agreement with exp. data

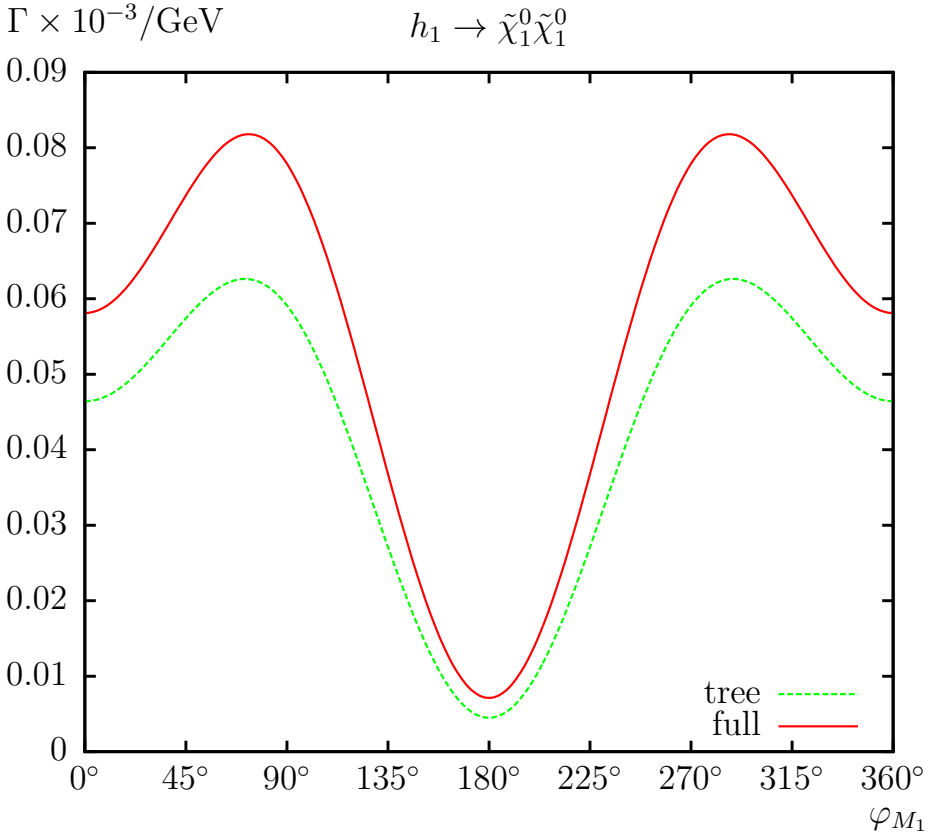
– opens up many (all) decay channels

– relevant parameters varied

– . . .

Light Higgs decay to Dark Matter (I):

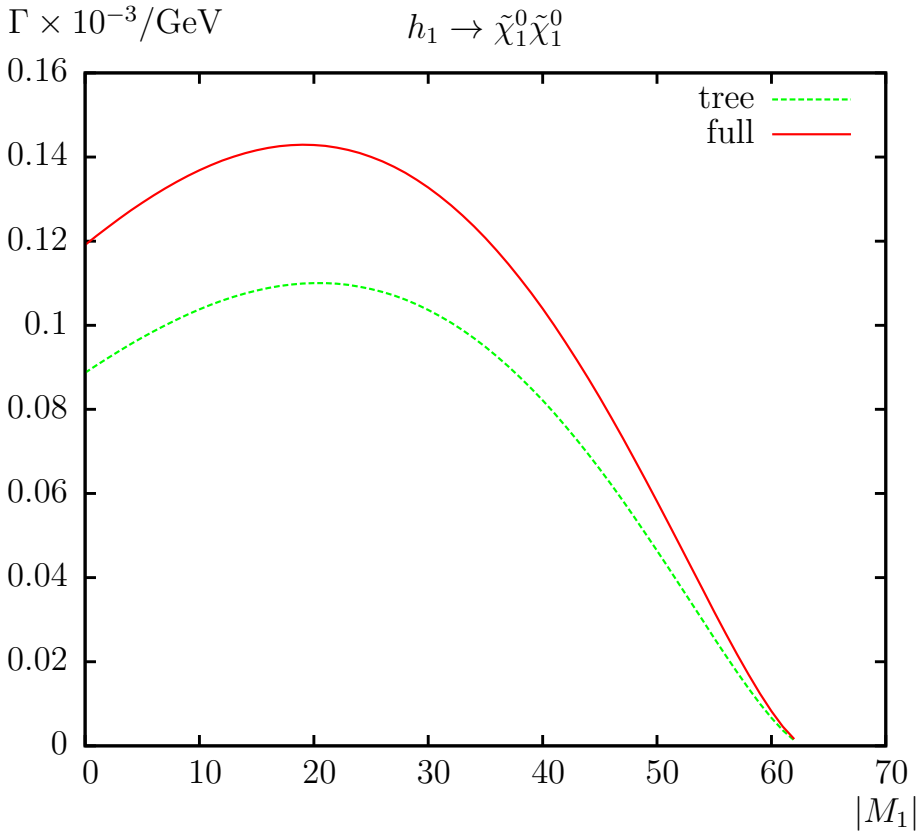


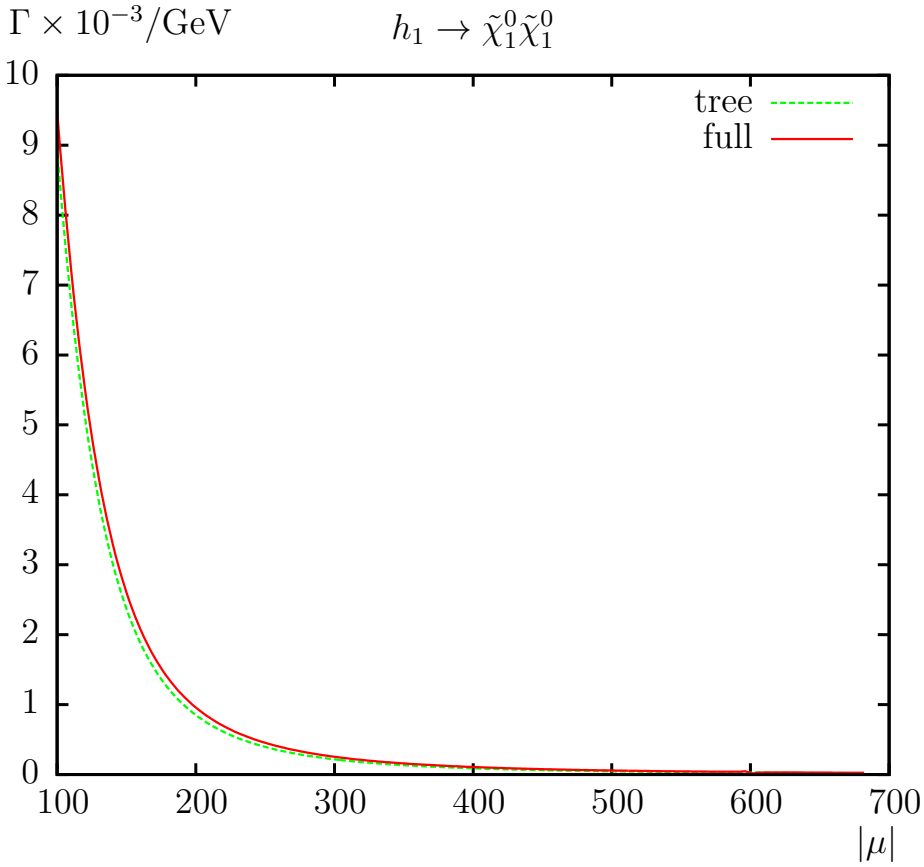


$\Rightarrow$ loop corrections $\sim 20\%$

$\Rightarrow$ strong phase dependence

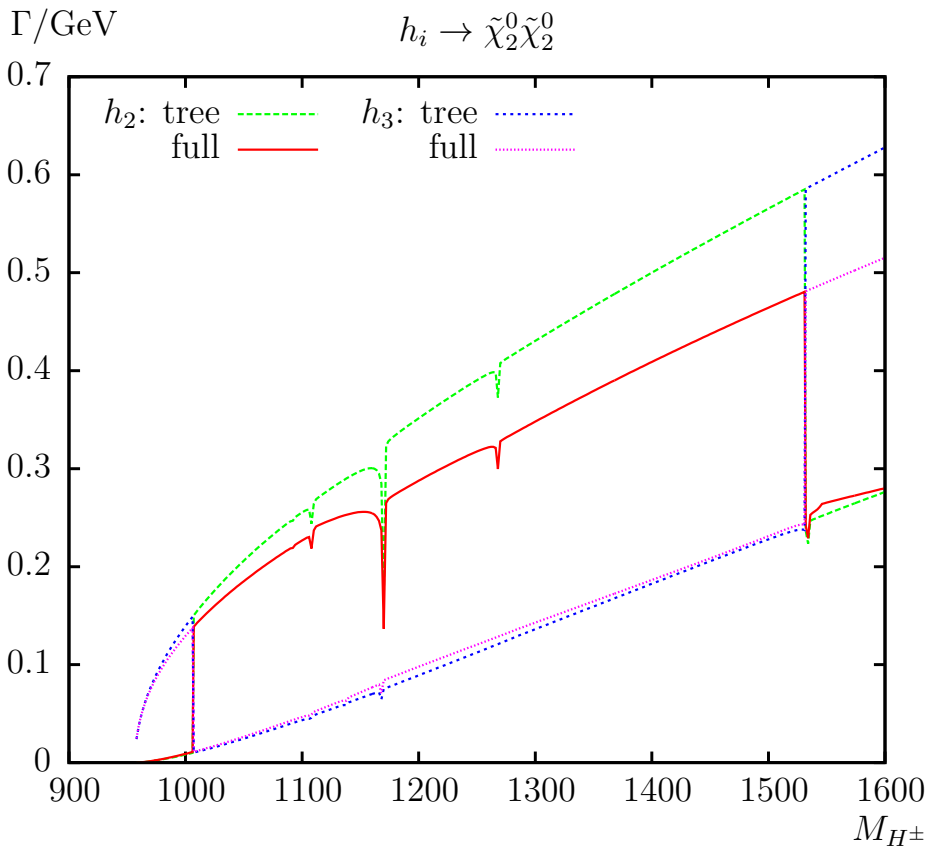
Light Higgs decay to Dark Matter (II):

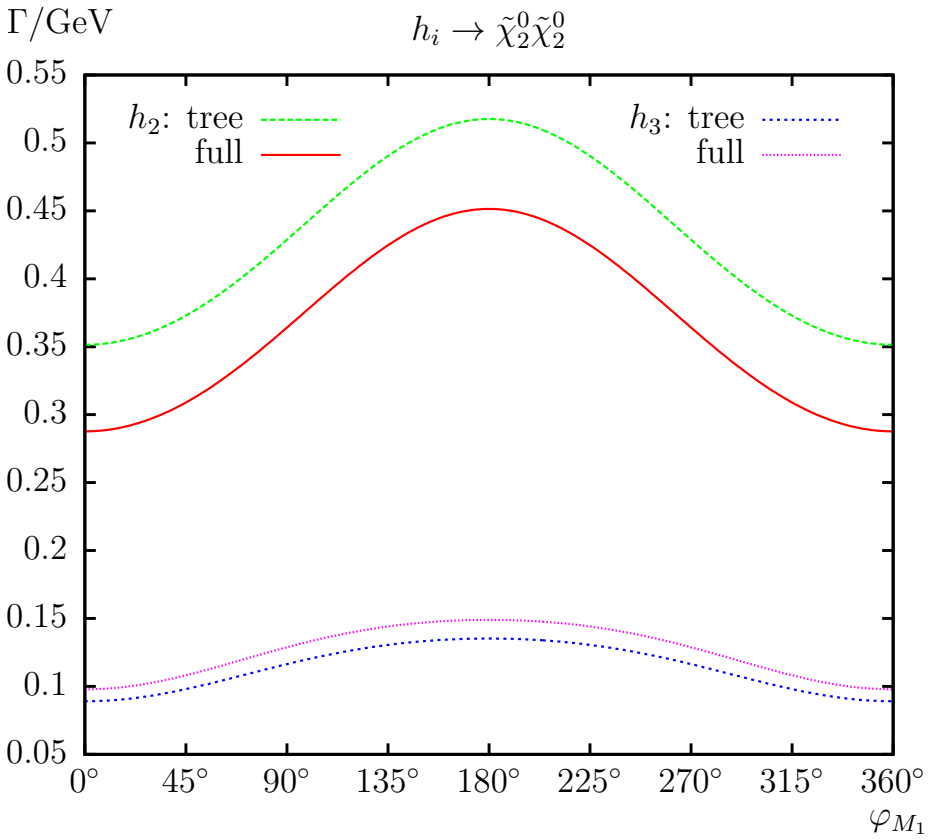




$\Rightarrow$ strong dependence on $|M_1|$, μ

Heavy Higgs decay to heavier neutralinos:



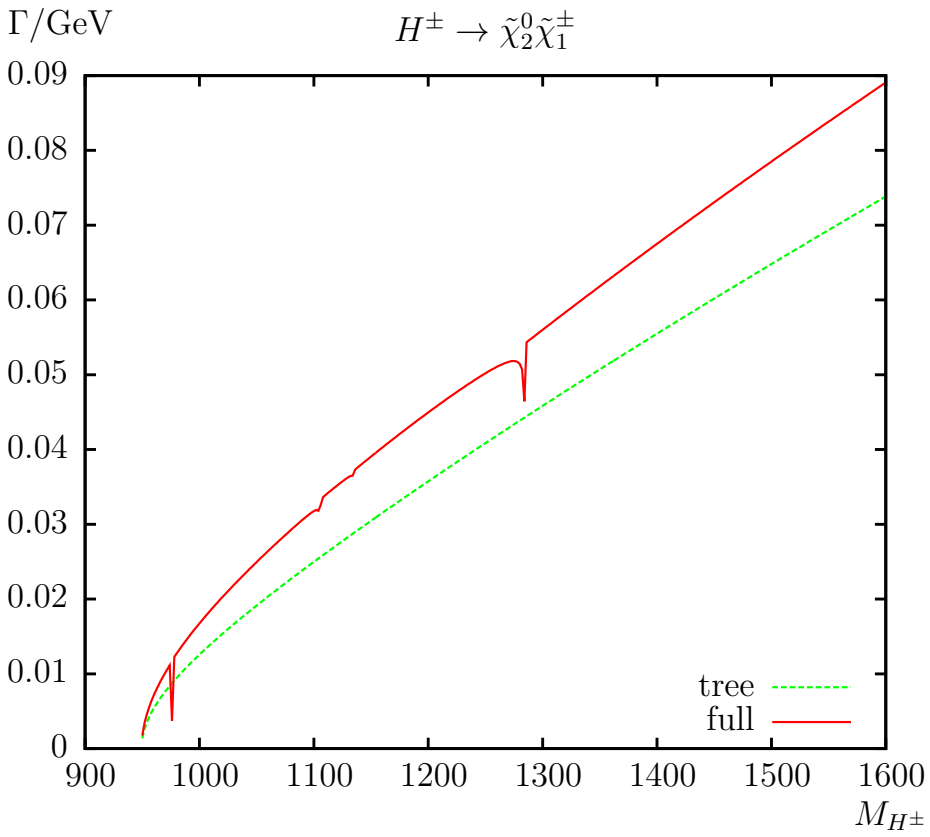


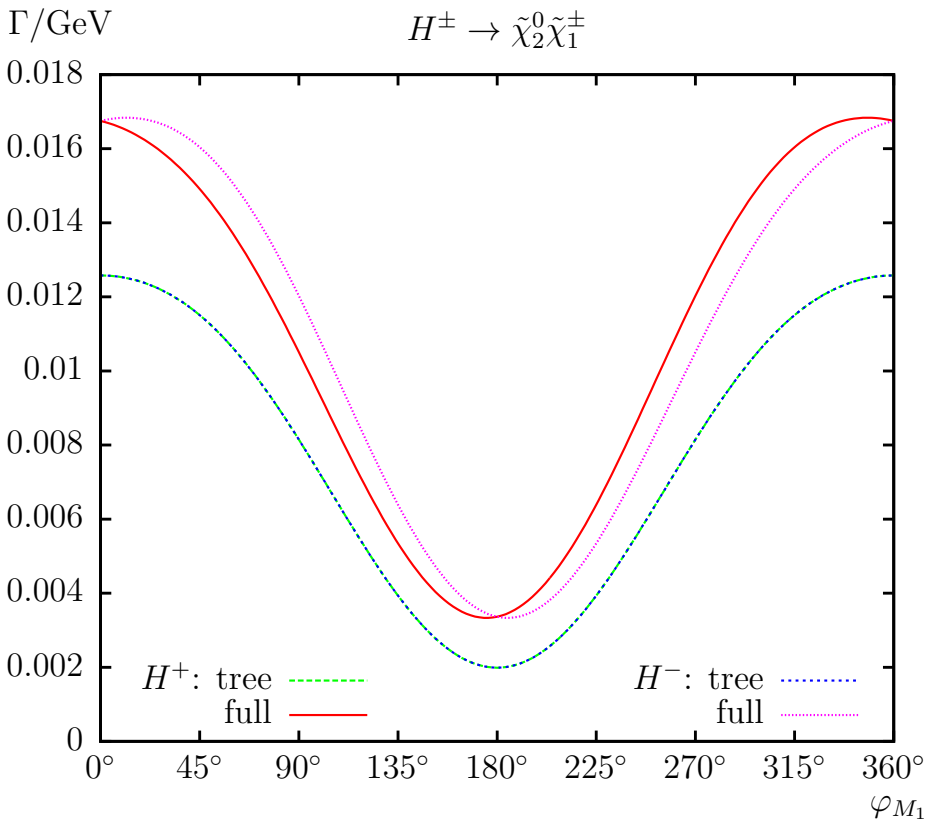
⇒ loop corrections up to ∼ 20%

⇒ strong phase dependence

⇒ level crossing, thresholds, . . .

Charged Higgs decay:





⇒ loop corrections up to $\sim 20\%$

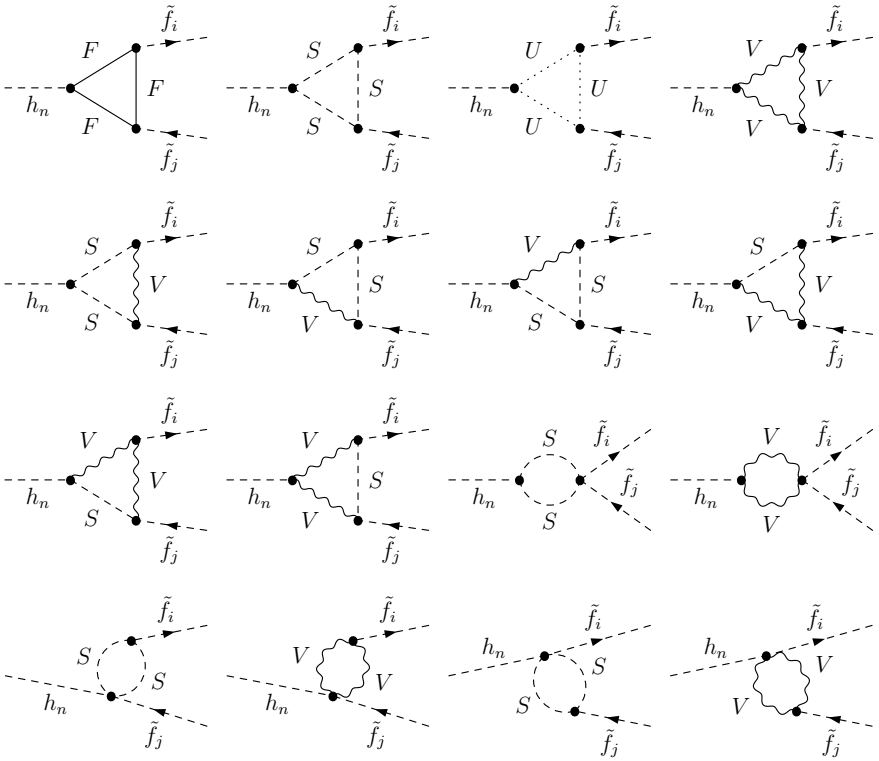
⇒ strong phase dependence

⇒ small difference between H^+ and H^- decay

3. Higgs decays to sfermions

$$\Gamma(h_n \to \tilde{f}_i \tilde{f}_j^\dagger) \quad (n = 2,3;\ i,j = 1,2)$$

$$\Gamma(H^\pm \to \tilde{f}_i \tilde{f}_j'^\dagger) \quad (i,j = 1,2)$$



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Parameters varied: $M_{H^\pm}$, ϕ_{A_t}, ϕ_{A_b}, ϕ_{A_τ}

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– opens up many (all) decay channels

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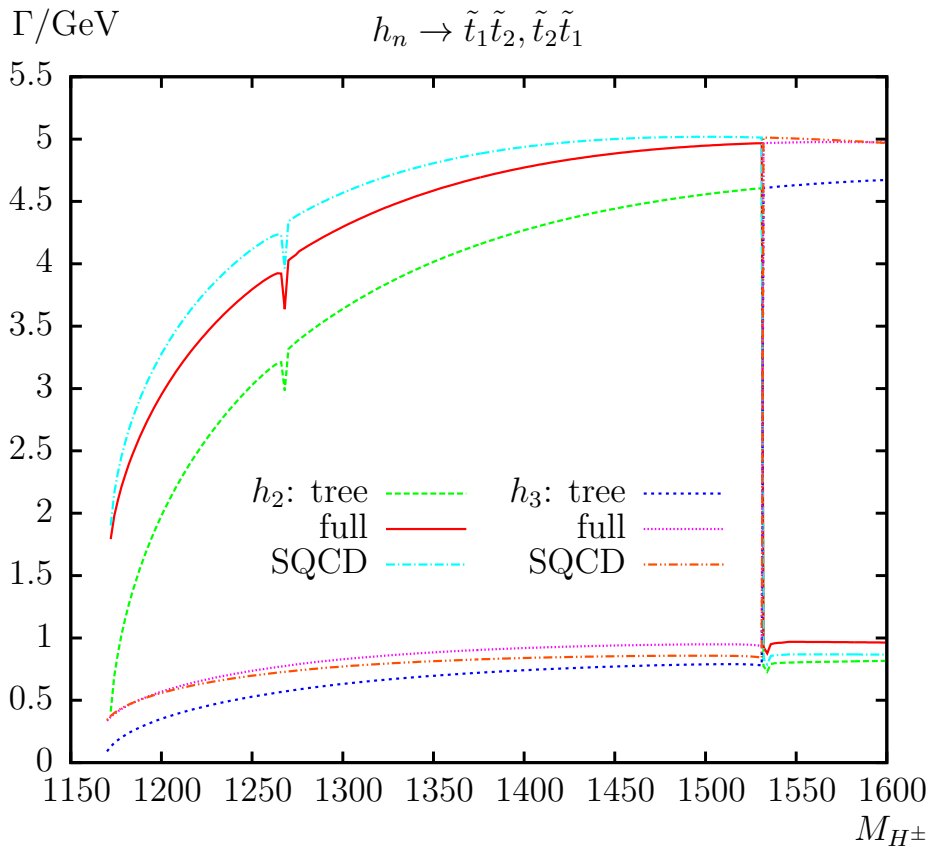
Heavy Higgs decay to stops:



⇒ loop corrections up to $\sim 30\%$

⇒ SUSY QCD not sufficient

⇒ level crossing, thresholds, . . .

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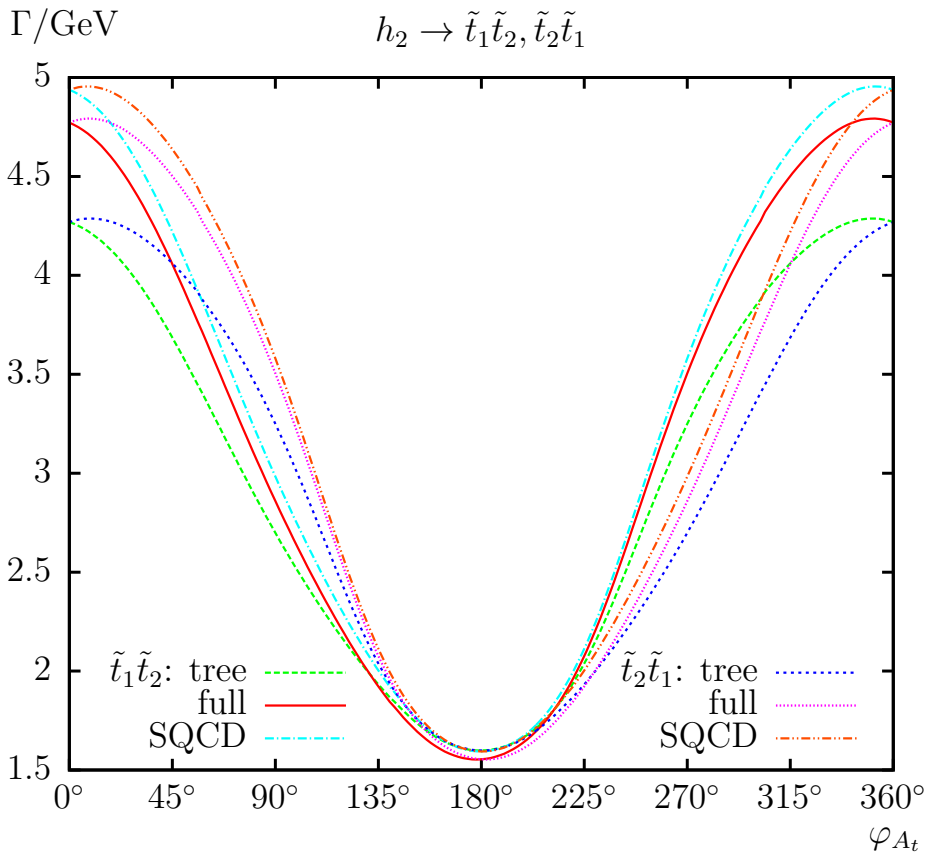
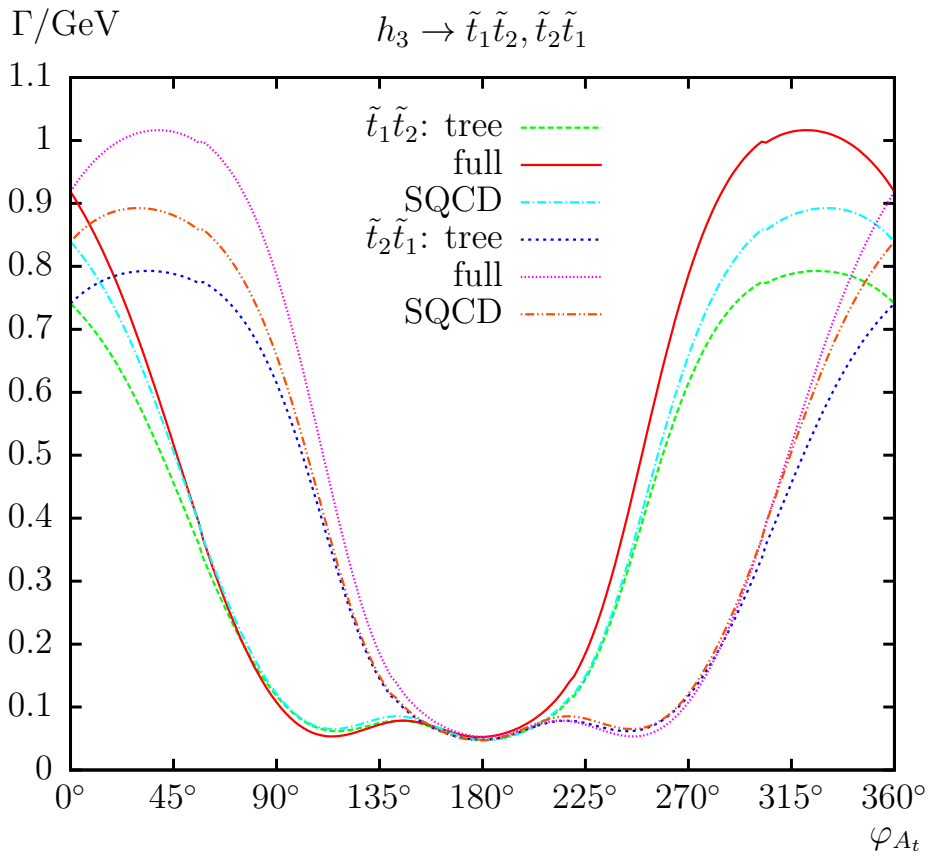


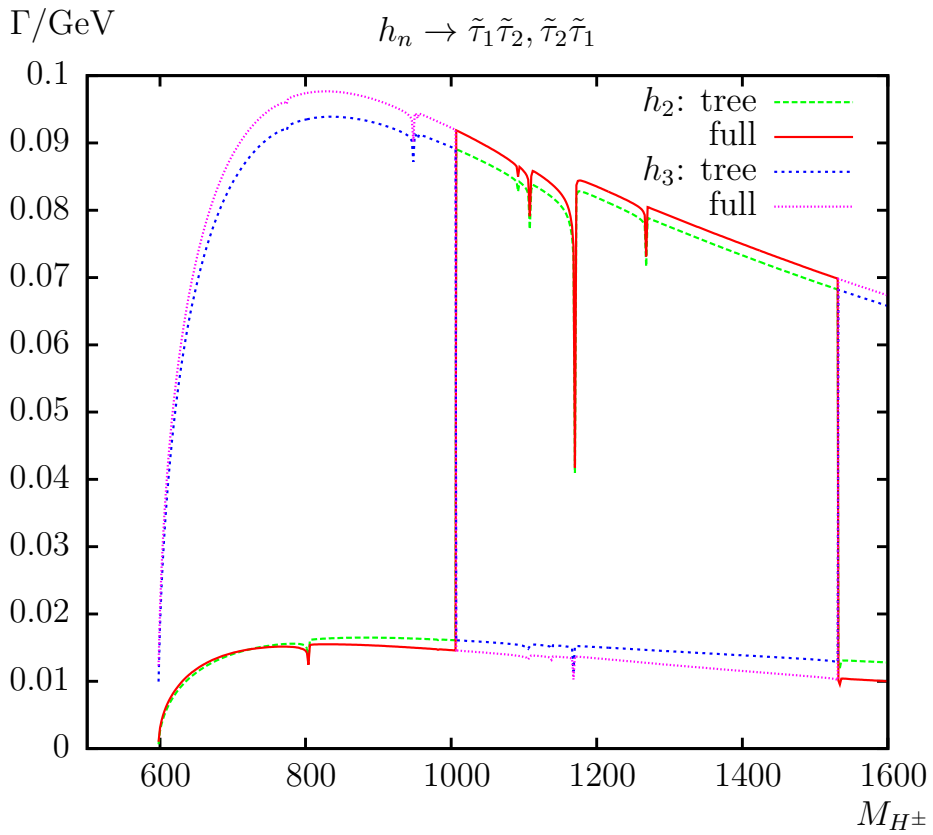


$\Rightarrow$ loop corrections up to $\sim 30\%$, SUSY EW important

$\Rightarrow$ strong phase dependence

$\Rightarrow$ difference between charge conjugated decays

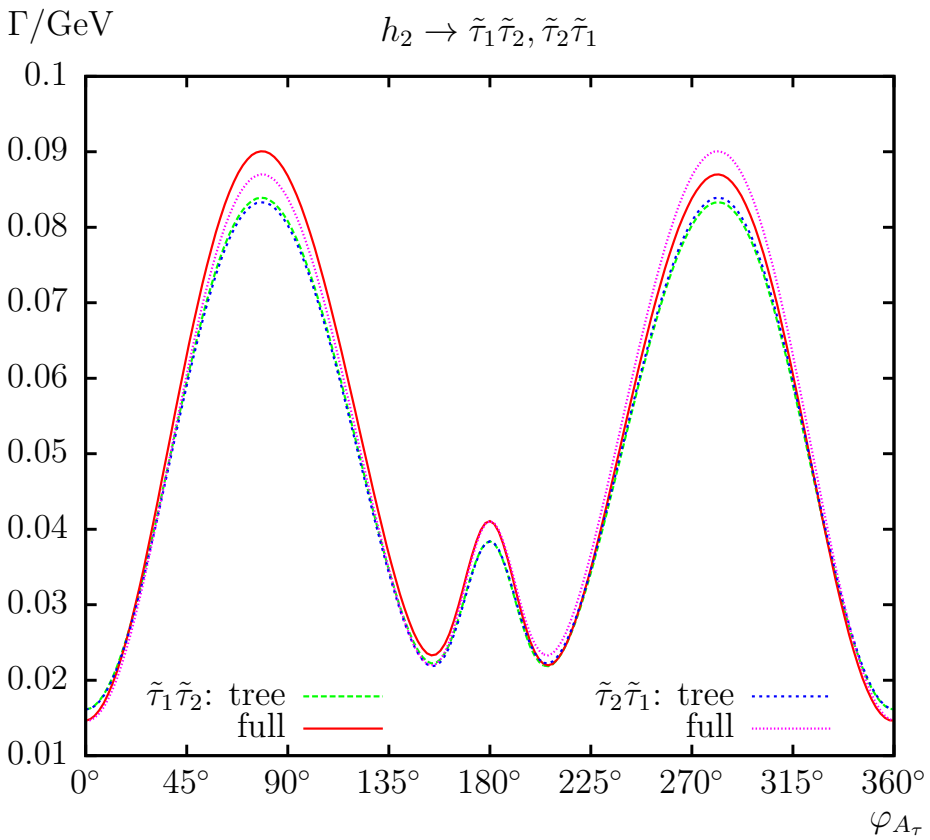
Heavy Higgs decay to staus:

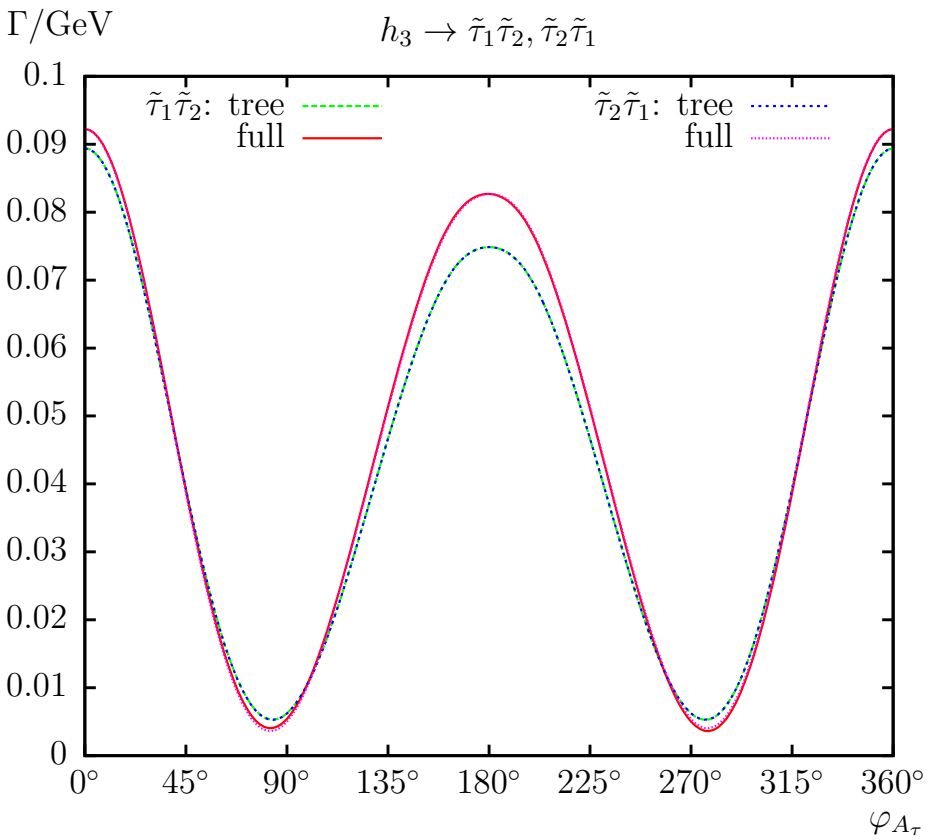


$\Rightarrow$ loop corrections up to $\sim 10\%$, purely EW

$\Rightarrow$ level crossing, thresholds, ...

Heavy Higgs decay to staus:



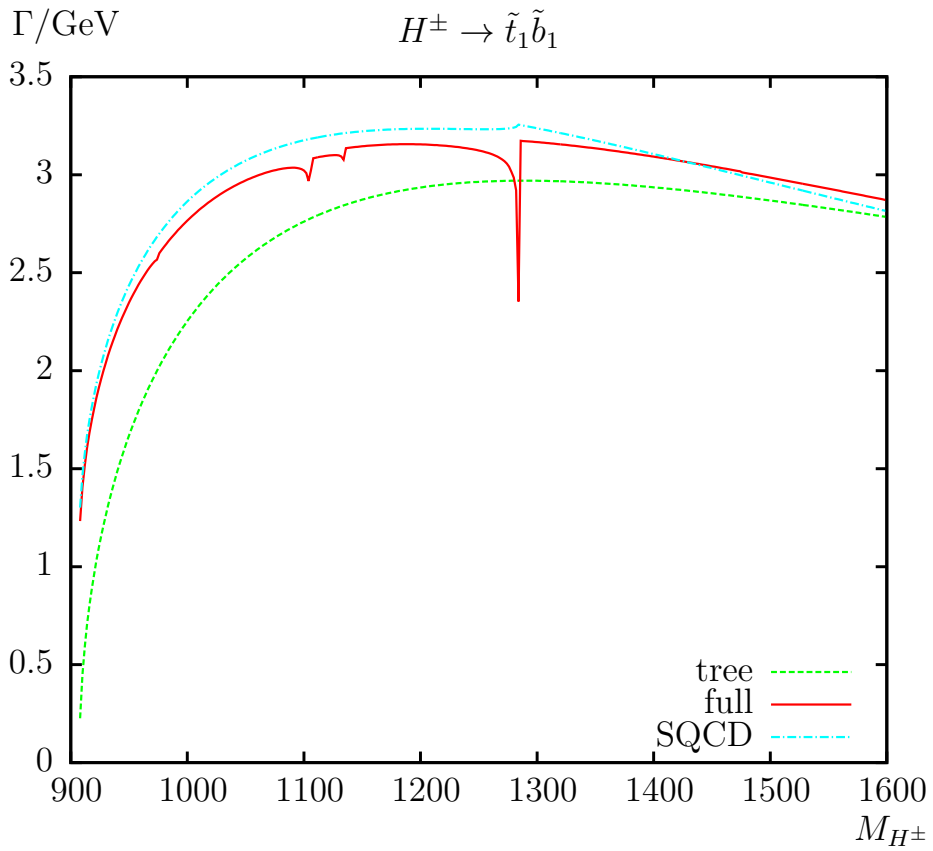


⇒ loop corrections up to ∼ 10%, purely EW

⇒ strong phase dependence

⇒ small difference between charge conjugated decays

Charged Higgs decay to stop/sbottom:



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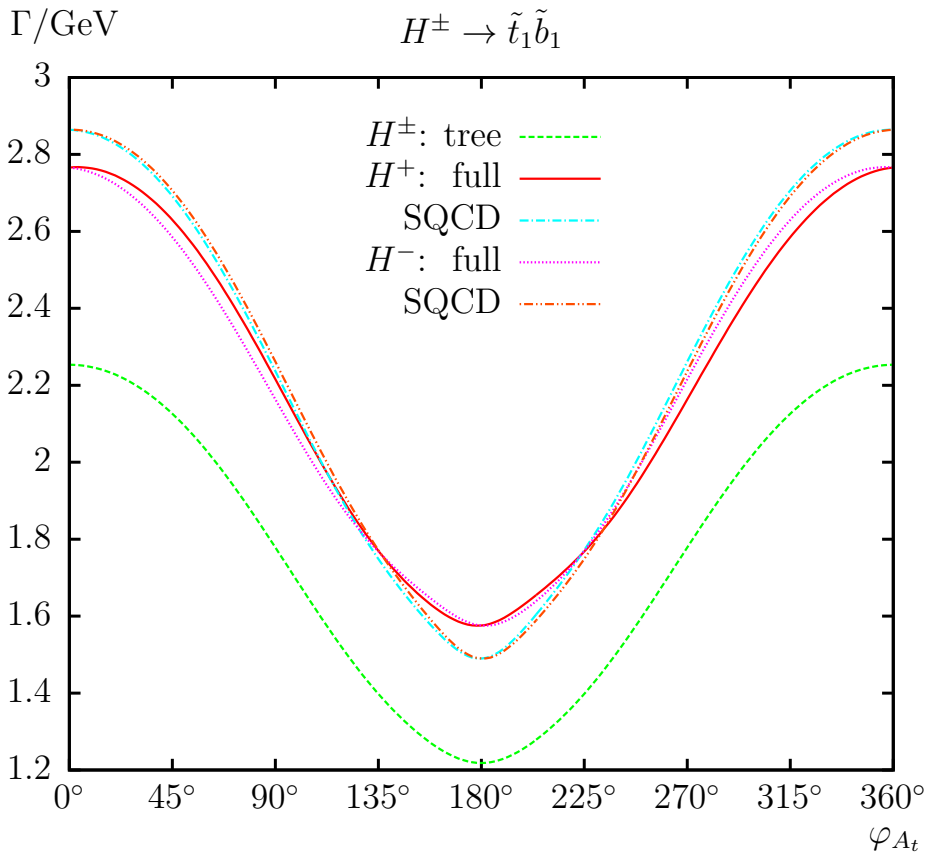

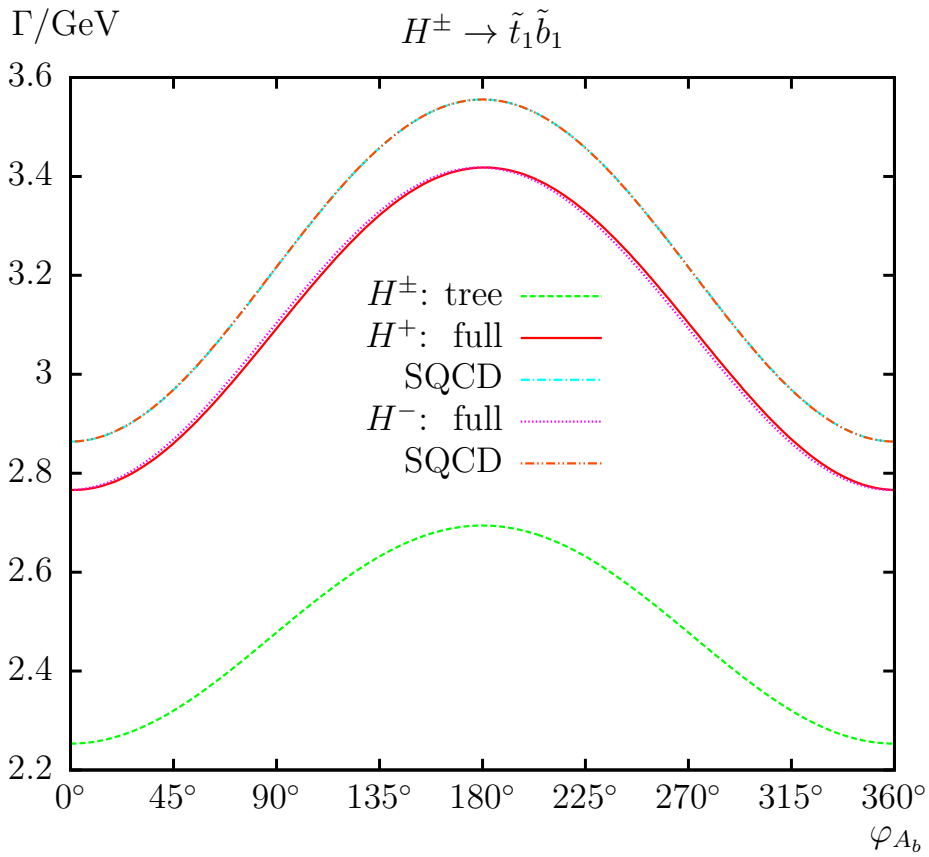

⇒ loop corrections up to ∼ 30%, SUSY EW important

⇒ strong phase dependence

⇒ small difference between charge conjugated decays

4. Conclusinos

- Loop corrections in BSM models are clearly important now
- MSSM: renormalization is still a (the) big(gest) issue
- FeynArts, FormCalc: model file incl. complex renormalization ready (one-loop, thoroughly tested!)
- Calculated:
  decays of Higgs to charginos/neutralinos and to sfermions
  including complex phases (+ hard/soft QED/QCD, . . .)
  $\Rightarrow$ corrections relevant for LHC/ILC/CLIC
- Examples shown:
  - Light Higgs decay to Dark Matter:
    correction up to $\sim 20\%$, strong phase dependence
  - Heavy Higgs decays to charginos/neutralinos:
    correction up to $\sim 20\%$, strong phase dependence
  - Heavy Higgs decay to squarks/sleptons:
    corrections up to $\sim 30\%$, SUSY QCD not sufficient