



I FOUND THE HUGS BISON.

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Precision calculations in the Higgs sector of the complex MSSM: Towards the LC precision

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

Whistler, 11/2015

1. The Grand Scheme
2. Renormalizing the MSSM
3. Results for the MSSM Higgs at the LC
4. Conclusions

1. The Grand Scheme

The LHC up and running ...
→ discovery of BSM physics in 2016?



The ILC (and CLIC?) 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

⇒ concentrate on the (N)MSSM from now on

(other people ⇒ other guesses ⇒ other priorities . . .)

In any case:

⇒ we have to measure as many observables as possible

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

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⇒ we have to measure as many observables as possible

- masses
- branching ratios
- angular distributions
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⇒ compare with theory calculations at the same level of accuracy

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

$$\begin{array}{llll} [u, d, c, s, t, b]_{L,R} & [e, \mu, \tau]_{L,R} & [\nu_{e,\mu,\tau}]_L & \text{Spin } \frac{1}{2} \\ [\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}]_{L,R} & [\tilde{e}, \tilde{\mu}, \tilde{\tau}]_{L,R} & [\tilde{\nu}_{e,\mu,\tau}]_L & \text{Spin } 0 \\ g & \underbrace{W^\pm, H^\pm}_{\text{Spin } 1} & \underbrace{\gamma, Z, H_1^0, H_2^0}_{\text{Spin } 0} & \text{Spin } 1 / \text{Spin } 0 \\ \tilde{g} & \tilde{\chi}_{1,2}^\pm & \tilde{\chi}_{1,2,3,4}^0 & \text{Spin } \frac{1}{2} \end{array}$$

Enlarged Higgs sector: Two Higgs doublets

⇐ for obvious reasons
some focus here!

Problem in the MSSM: many scales

Problem in the MSSM: complex phases

Where are we? (a selection!)

1. Neutral Higgs boson masses

- $\mathcal{O}(\alpha_t \alpha_s)$ in the cMSSM [S.H., W. Hollik, H. Rzehak, G. Weiglein '07]
- $\mathcal{O}(\alpha_t \alpha_s^2)$, $\mathcal{O}(\alpha_t^2 \alpha_s)$, rMSSM [S. Martin '07]
- $\mathcal{O}(\alpha_t \alpha_s^2)$, rMSSM (incl. fin. terms) [Haarlander, Kant, Mihaila, Steinhauser '08]
- log-resummation, 2L/3L [Hahn et al. '13][Draper et al. '13][E. Bagnaschi et al. '14]
[J. Pardo Vega et al. '14][Lee et al. '15]

2. Charged Higgs mass

- 1-loop [M. Frank et al. '06] $\mathcal{O}(\alpha_t \alpha_s)$ [M. Frank et al. '13] $\mathcal{O}(\alpha_t^2)$ [Hollik, Passehr '14]

3. Production cross sections at the LC

- $e^+e^- \rightarrow h_i h_j, Zh_i, \gamma h_i$, full one-loop, cMSSM [S.H., C. Schappacher '15]
- $e^+e^- \rightarrow H^\pm e^\mp \nu$ at one-loop, rMSSM [O. Brein, T. Figy '07][T. Farris et al. '04]
- Z -factors at 2-loop [M. Frank, T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein '06]

4. Higgs decays

- full 1-loop (depending on final state) [...]
- Z -factors at 2-loop [M. Frank, T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein '06]

5. Decays to Higgs bosons

- full 1-loop, cMSSM [K. Williams et al. '11][S.H., C. Schappacher '14, 15]
[A. Bharucha, T. Fritzsche, S.H., F. v.d. Pahlen, H. Rzehak, C. Schappacher '11 - '13]

What is missing? (a selection!)

1. Neutral Higgs boson masses

- full 2-loop
- more 3-loop (and in “easier accessible” scheme?)
- leading 4-loop
- Improved combination of LL, NLL, ... resummation with diag. calc.

2. Charged Higgs boson mass

- (sub)leading 2-loop

3. Higgs bosons production

- full 1-loop in the cMSSM (some initial states)
- leading 2-loop

4. Higgs decays

- full 1-loop in the r/cMSSM (some final states)
- leading 2-loop

5. Decays to Higgs bosons probably ok now

⇒ provide corresponding codes!

2. Renormalization of the cMSSM

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
- ⇒ this is the biggest issue!

Enlarged Higgs sector: Two Higgs doublets

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

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

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

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

Goldstone bosons: G^0, G^\pm

Input parameters: (to be determined experimentally)

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

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

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

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

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

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

Input parameters: (to be determined experimentally)

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

The Higgs sector of the cMSSM at tree-level:

- phase of m_{12} :

$m_{12} = 0$ and $\mu = 0 \Rightarrow$ additional $U(1)$ (PQ) symmetry

reality: $m_{12} \neq 0, \mu \neq 0$

\Rightarrow perform PQ transformation with ϕ_{PQ}

$$\begin{aligned} m_{12}' &= |m_{12}| e^{i(\phi_{m_{12}} - \phi_{PQ})} \\ \mu' &= |\mu| e^{i(\phi_{\mu} - \phi_{PQ})} \end{aligned}$$

$\Rightarrow m_{12}$ can always be chosen real

- phase of H_2 : ξ :

mixing between \mathcal{CP} -even and \mathcal{CP} -odd states:

$$\mathcal{M}_{\mathcal{CP}\text{-even}, \mathcal{CP}\text{-odd}} = \begin{pmatrix} 0 & m_{12}^2 \sin \xi \\ -m_{12}^2 \sin \xi & 0 \end{pmatrix}$$

Tadpoles have to vanish: $T_A^{\text{tree}} \propto \sin \xi m_{12}^2 \stackrel{!}{=} 0$

$\Rightarrow \xi = 0 \Rightarrow$ no \mathcal{CPV} at tree-level

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:

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

with

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

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

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

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

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

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

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

soft SUSY-breaking parameters A_t, A_b also appear in ϕ - \tilde{t}/\tilde{b} couplings

$$m_{\tilde{t}_{1,2}}^2 = m_t^2 + \frac{1}{2} \left(M_{\tilde{t}_L}^2 + M_{\tilde{t}_R}^2 \mp \sqrt{(M_{\tilde{t}_L}^2 - M_{\tilde{t}_R}^2)^2 + 4m_t^2 |X_t|^2} \right)$$

\Rightarrow independent of ϕ_{X_t}
but $\theta_{\tilde{t}}$ is now complex

$SU(2)$ relation $\Rightarrow M_{\tilde{t}_L} = M_{\tilde{b}_L} \Rightarrow$ relation between $m_{\tilde{t}_1}, m_{\tilde{t}_2}, \theta_{\tilde{t}}, m_{\tilde{b}_1}, m_{\tilde{b}_2}, \theta_{\tilde{b}}$

More on complex phases: Neutralinos and charginos:

Higgsinos and electroweak gauginos mix

charged:

$$\tilde{W}^+, \tilde{h}_u^+ \rightarrow \tilde{\chi}_1^+, \tilde{\chi}_2^+, \quad \tilde{W}^-, \tilde{h}_d^- \rightarrow \tilde{\chi}_1^-, \tilde{\chi}_2^-$$

⇒ charginos: mass eigenstates

mass matrix given in terms of M_2 , μ , $\tan \beta$

neutral:

$$\underbrace{\tilde{\gamma}, \tilde{Z}, \tilde{h}_u^0, \tilde{h}_d^0}_{\tilde{W}^0, \tilde{B}^0} \rightarrow \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$$

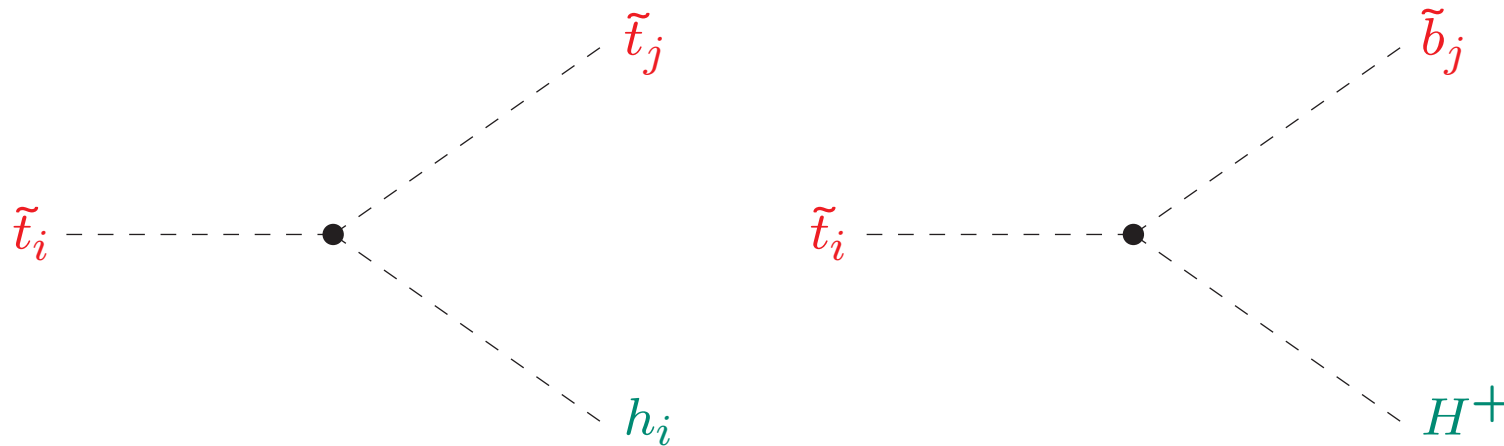
⇒ neutralinos: mass eigenstates

mass matrix given in terms of M_1 , M_2 , μ , $\tan \beta$

⇒ only one new parameter

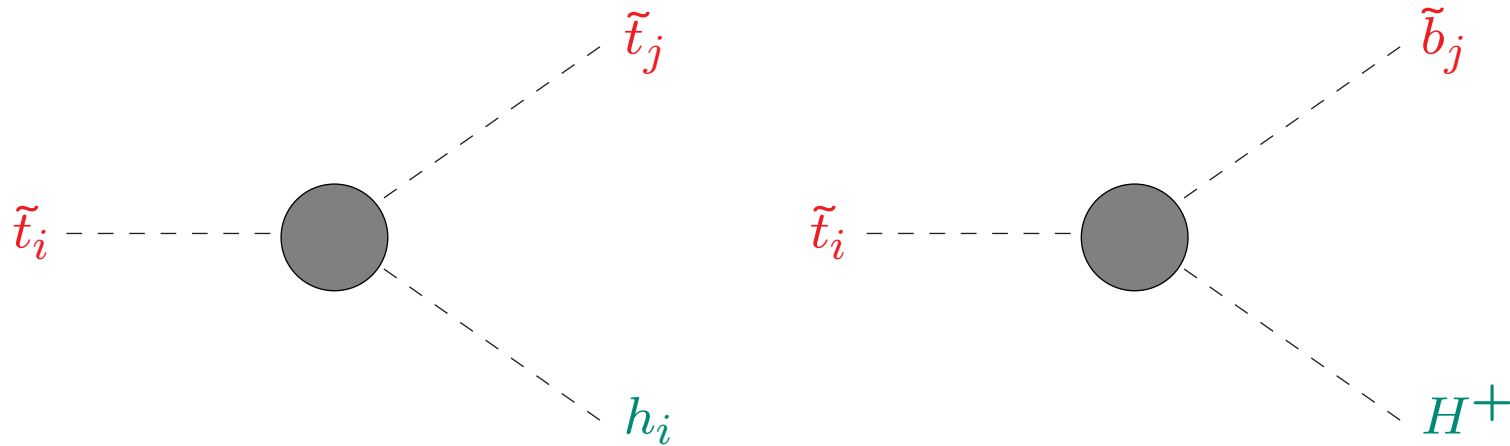
⇒ MSSM predicts mass relations between neutralinos and charginos

Examples for processes with (external) stops and Higgs bosons:



- important decay modes of stops
- A_t and A_b directly enter the vertex
- possible source of Higgs bosons at the LHC/ILC
- . . .

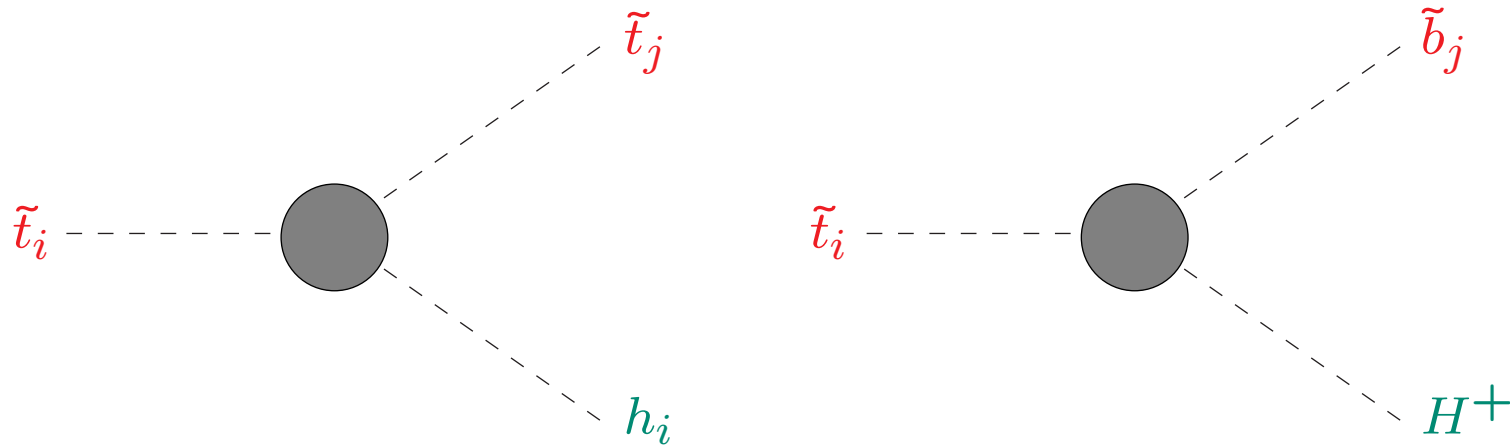
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⇒ higher-order corrections important!

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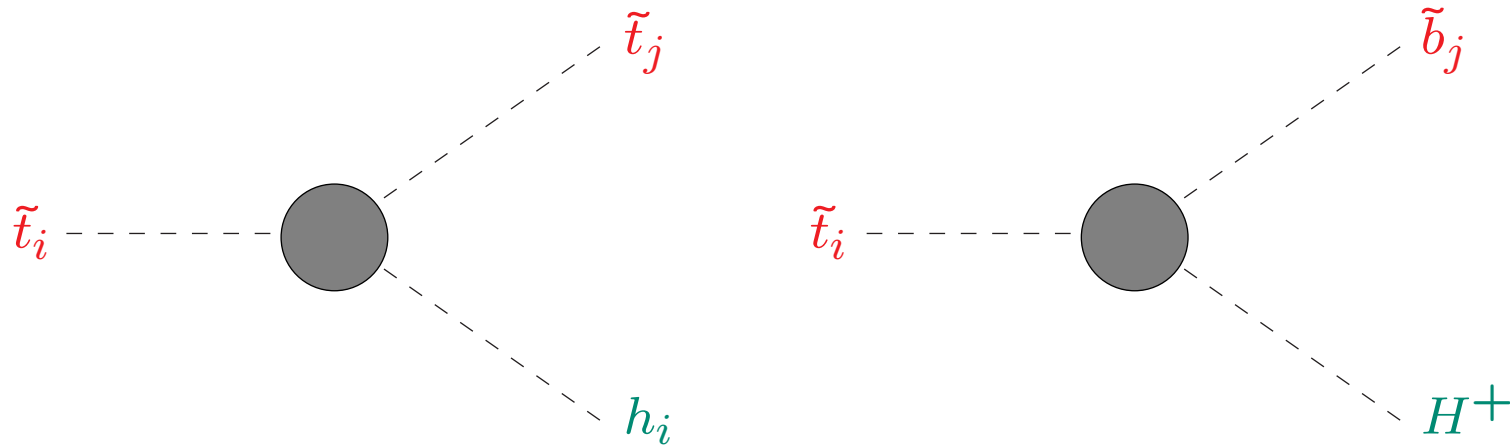


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⇒ simultaneous renormalization of stop and sbottom sector required!

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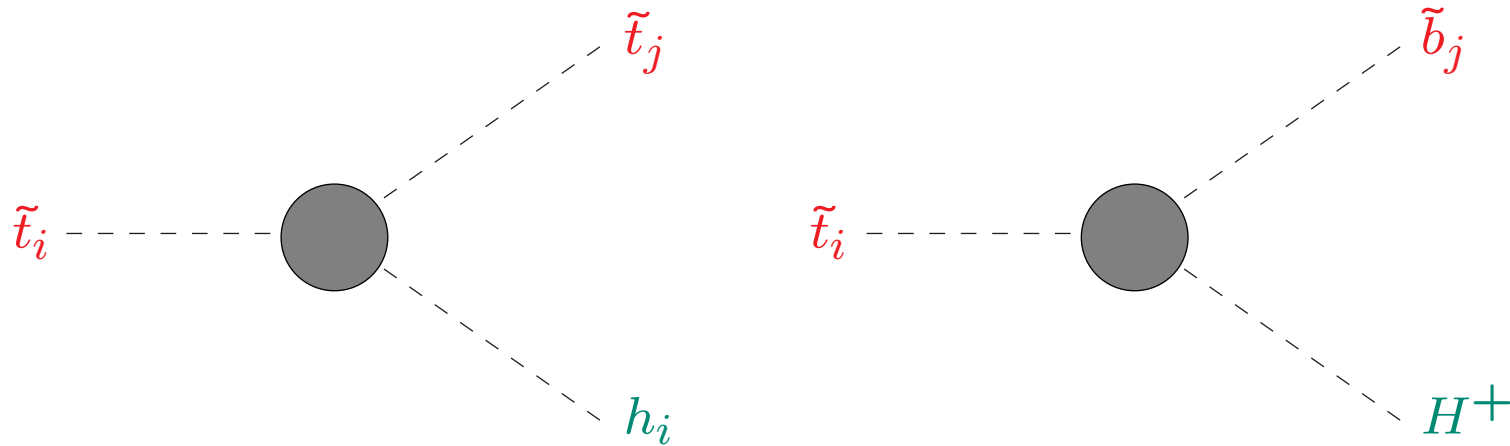
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⇒ with on-shell properties for external particles!

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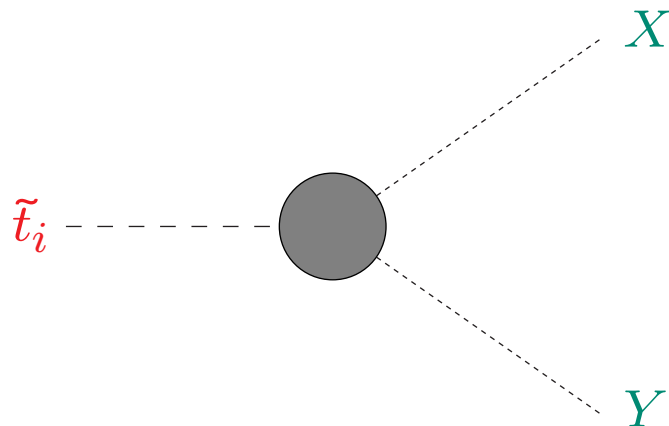
- important decay modes of stops
- A_t and A_b directly enter the vertex **incl. complex phases!**
- possible source of Higgs bosons at the LHC/ILC
- . . .

⇒ higher-order corrections important!

⇒ simultaneous renormalization of stop and sbottom sector required!

⇒ including complex phases!

The bigger picture: stop decays in the cMSSM

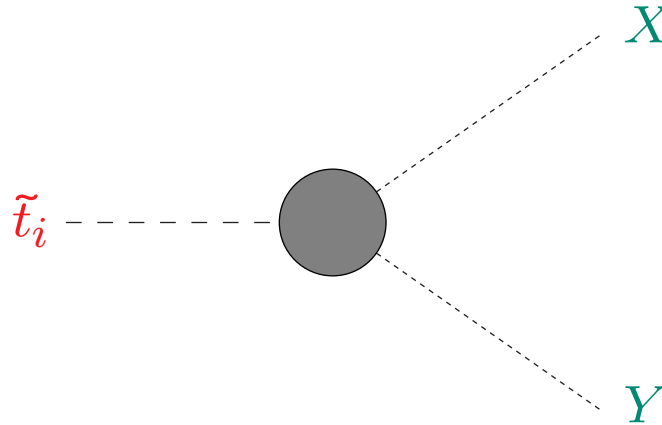


⇒ to get BRs right ⇒ all decays needed

⇒ (nearly) all sectors of the cMSSM enter as external particles

⇒ (nearly) all sectors of the cMSSM have to be renormalized simultaneously

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Available for LC precision: cMSSM full one-loop:

- SUSY decays to Higgs
- Higgs decays to SM fermions, Higgs Higgs
- Higgs decays to SUSY particles
- $e^+e^- \rightarrow h_i h_j, Zh_i, \gamma h_i$

LC potential:

The clean environment of the ILC would permit a detailed study of the SUSY decays

The ILC environment would result in an accuracy of the relative branching ratio

$$BR^{\text{full}} \equiv \frac{\Gamma^{\text{full 1L}}(\text{SUSY} \rightarrow xy)}{\Gamma_{\text{tot}}^{\text{full 1L}}}$$

$$\frac{\delta BR}{BR} \equiv \frac{BR^{\text{full}} - BR^{\text{tree}}}{BR^{\text{full}}}$$

close to the statistical uncertainty

⇒ Precision at the per-cent level possible!

⇒ theory precision at the per-cent level required!

Renormalization status:

- 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
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⇒ **go and make your prediction!**

⇒ and so we did :-)

3. Results for the MSSM Higgs at the LC

- A. Status and latest results for M_h prediction
⇒ still far away from LC precision!
- B. Status for the charged Higgs boson mass predictions
- C. Status of $e^+e^- \rightarrow h_i h_j, Zh_i, \gamma h_i$
⇒ see talk by S.H. yesterday :-)
- D. Recent results for Higgs boson decays
- E. Recent results for decays to Higgs bosons

3A/B) MSSM Higgs mass prediction: The embarrassing situation

The light CP -even Higgs mass accuracy in the MSSM:

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Experiment:

ATLAS: $M_h^{\text{exp}} = 125.36 \pm 0.37 \pm 0.18 \text{ GeV}$

CMS: $M_h^{\text{exp}} = 125.03 \pm 0.27 \pm 0.15 \text{ GeV}$

combined: $M_h^{\text{exp}} = 125.09 \pm 0.21 \pm 0.11 \text{ GeV}$

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$$\delta M_h^{\text{theo}} \sim 3 \text{ GeV}$$

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to match the experimental accuracy!

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⇒ dedicated working group has been formed to take care ... (KUTS)

Katharsis of Ultimate Theory Standards

4th meeting: 20.-22. January 2016, Heidelberg University

Precise Calculation of

(N)

Higgs Boson masses

Lokal organization: L. Mihaila

Organized by:
M. Carena, H. Haber
R. Harlander, S. Heinemeyer
W. Hollik, P. Slavich, G. Weiglein

3D) Higgs to SUSY decays

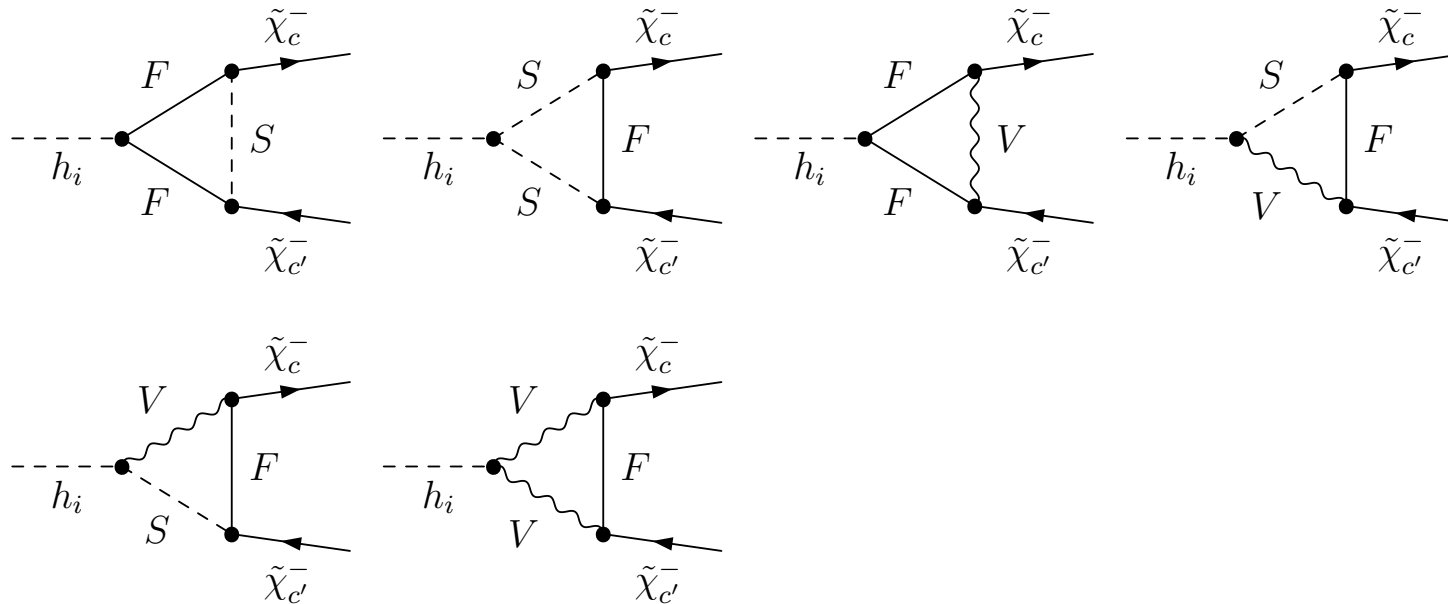
3D-1) Higgs decays to charginos/neutralinos

[arXiv:1503.02996]

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

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

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



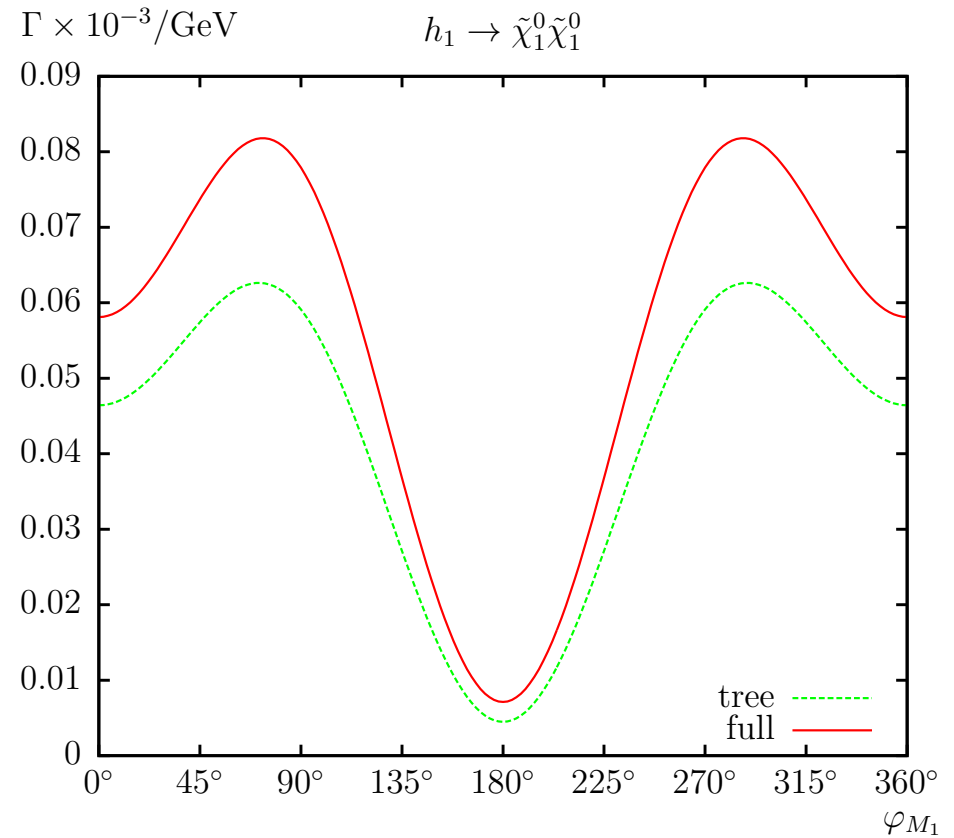
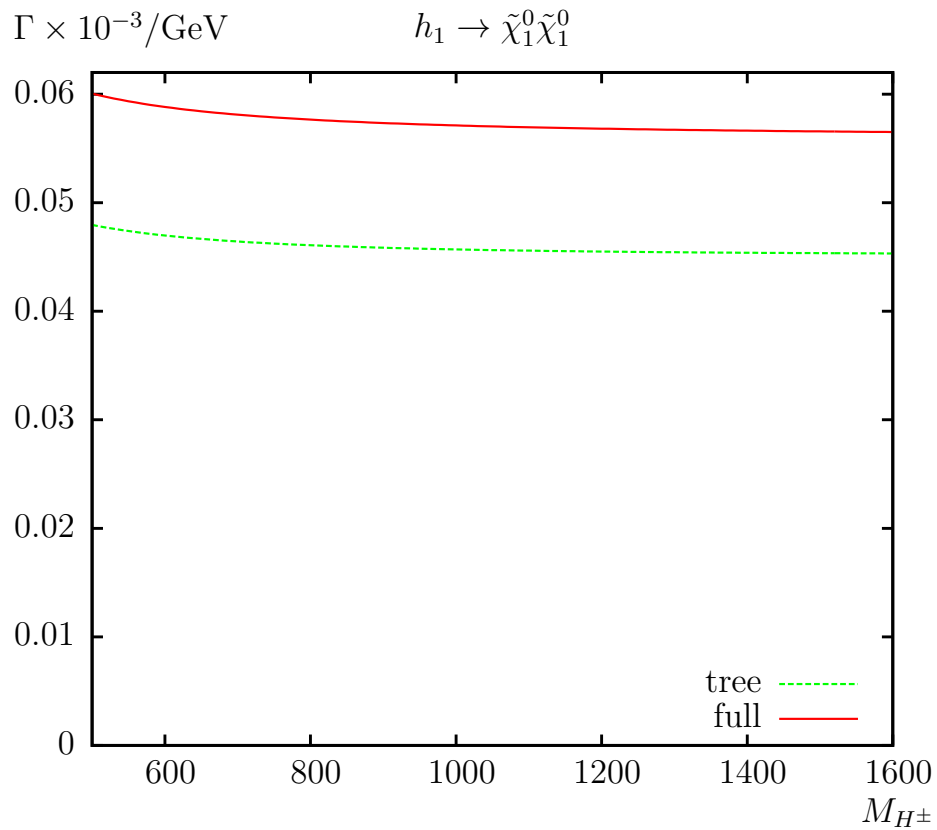
Numerical example scenario:

$\tan \beta$	μ	A_{u_g}	A_{d_g}	A_{e_g}	$ M_1 $	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}

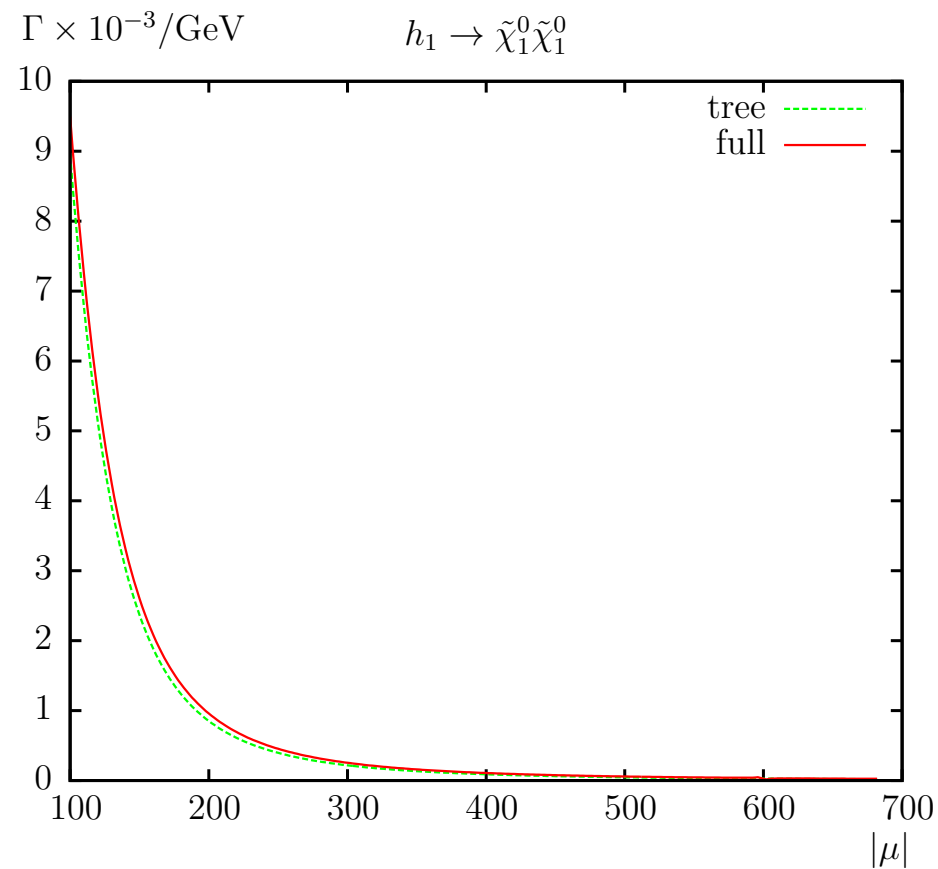
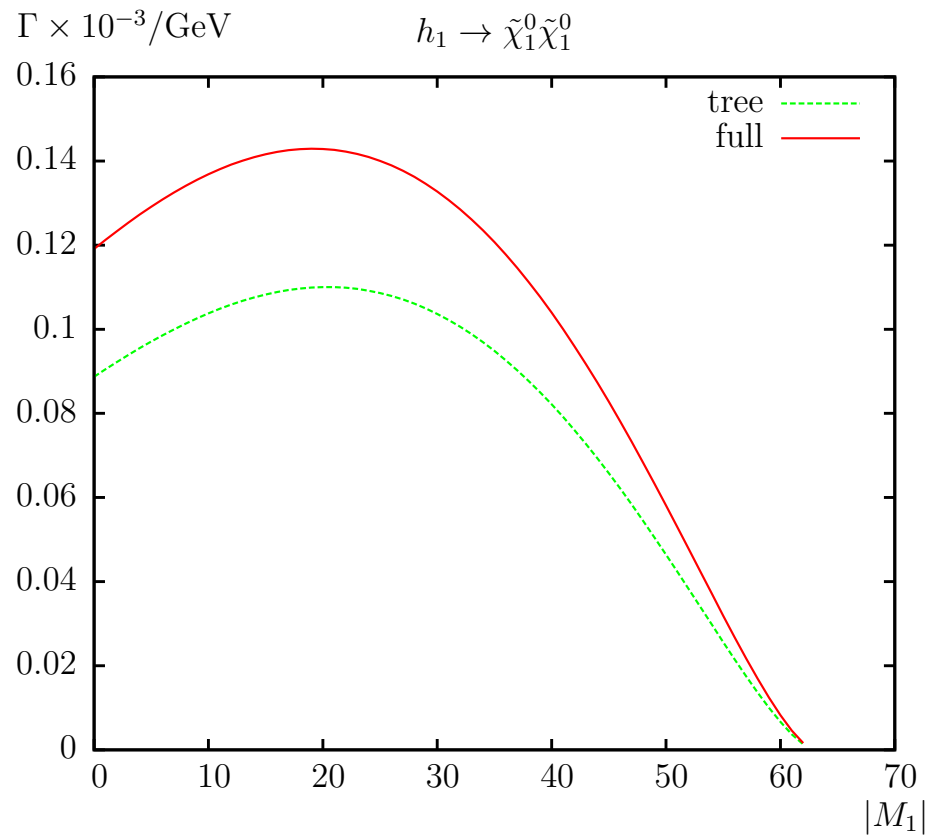
- in agreement with exp. data
- opens up many (all) decay channels
- relevant parameters varied
- . . .

Light Higgs decay to Dark Matter (I):



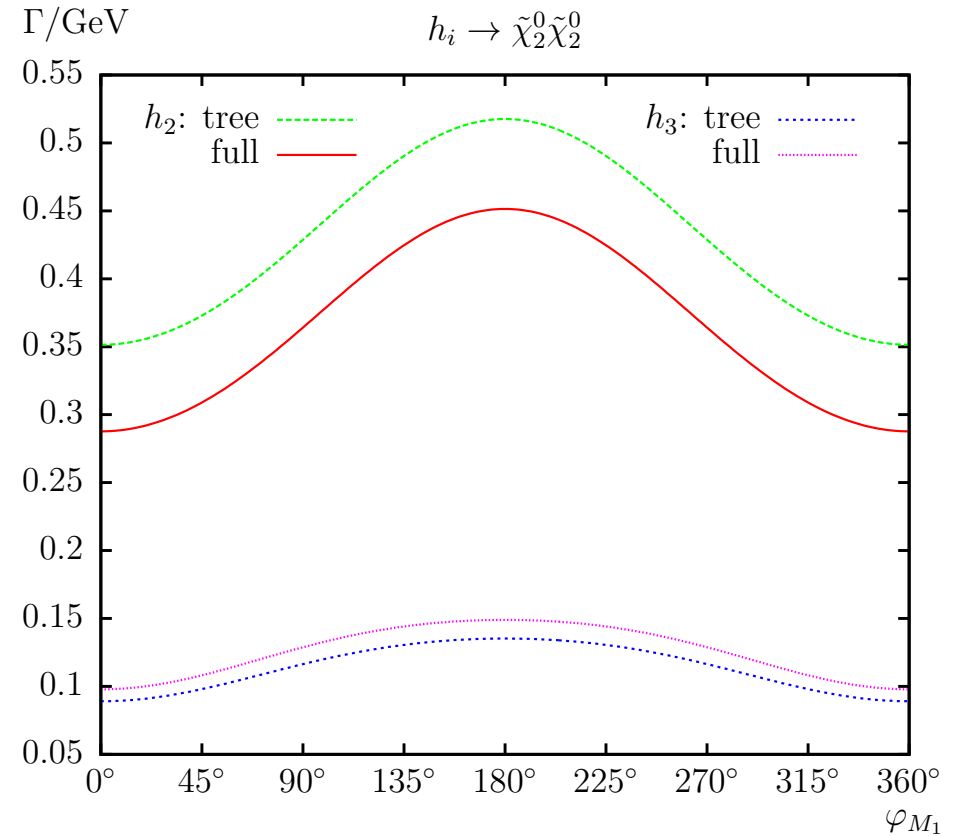
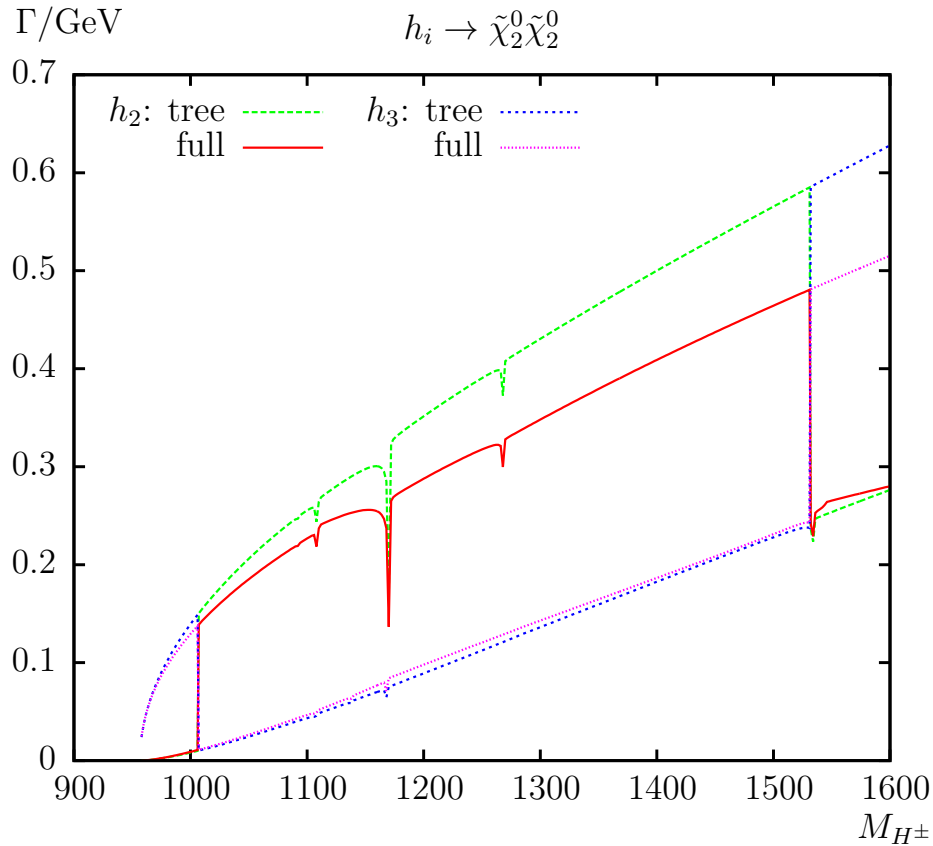
- ⇒ loop corrections $\sim 20\%$
- ⇒ strong phase dependence

Light Higgs decay to Dark Matter (II):



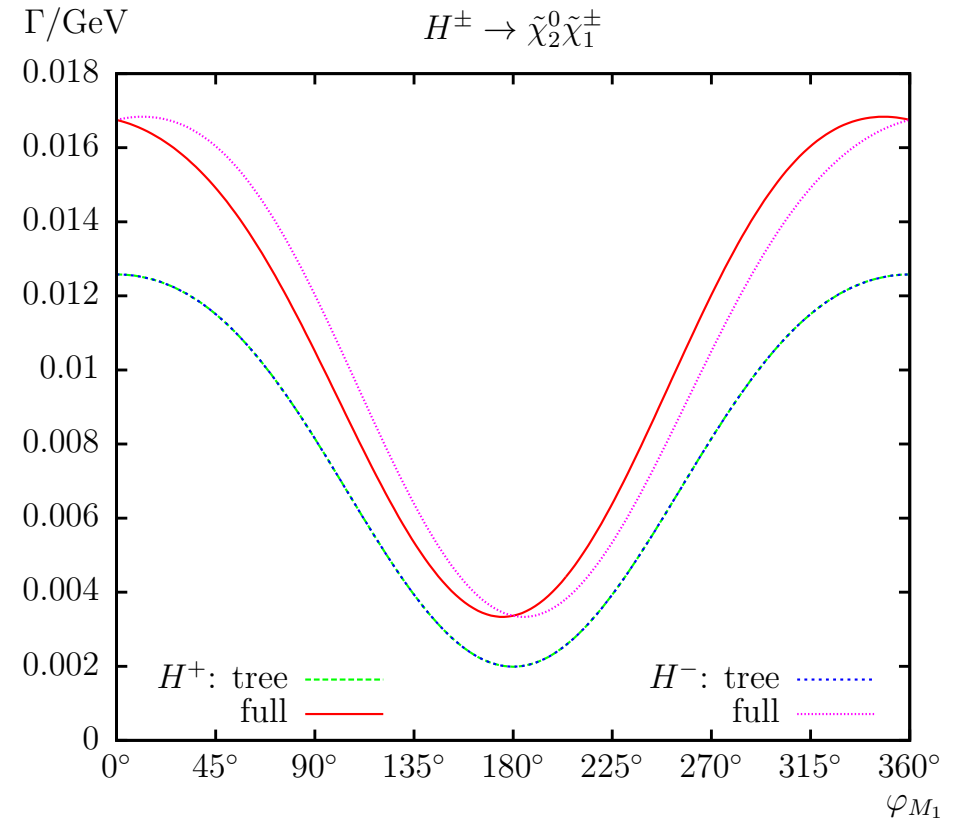
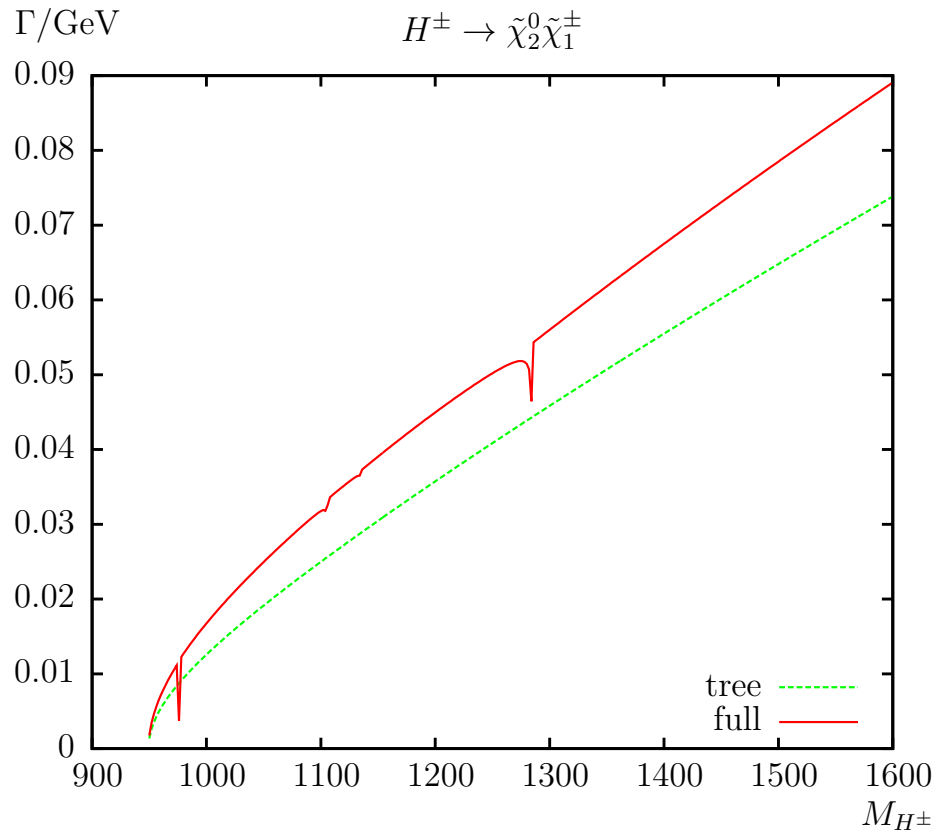
\Rightarrow strong dependence on $|M_1|, \mu$

Heavy Higgs decay to heavier neutralinos:



- ⇒ loop corrections up to $\sim 20\%$
- ⇒ strong phase dependence
- ⇒ level crossing, thresholds, ...

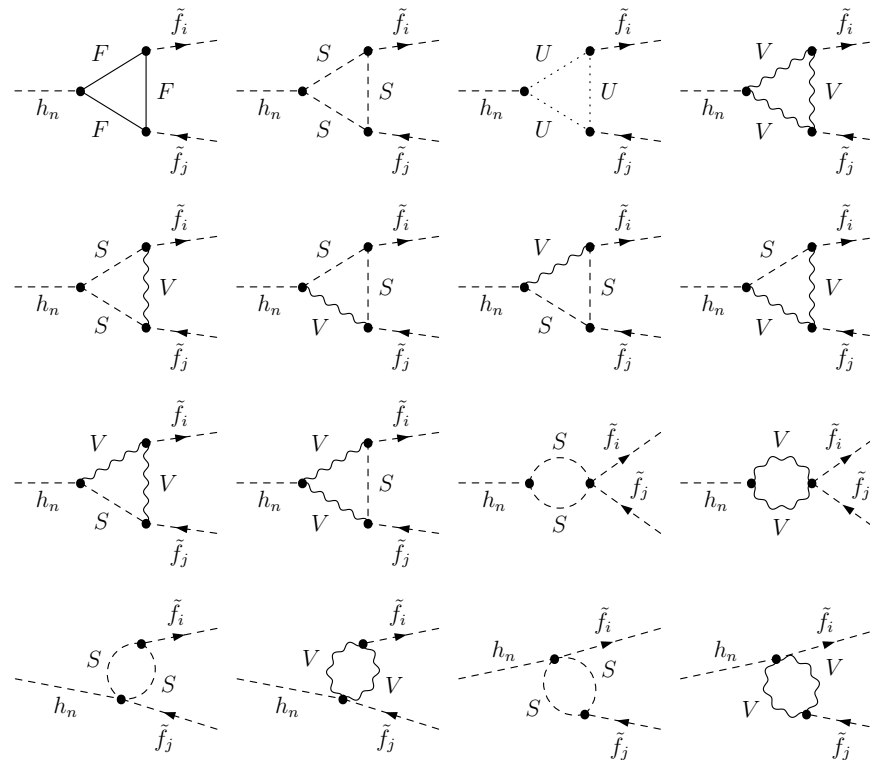
Charged Higgs decay:



- ⇒ loop corrections up to $\sim 20\%$
- ⇒ strong phase dependence
- ⇒ small difference between H^+ and H^- decay

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

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



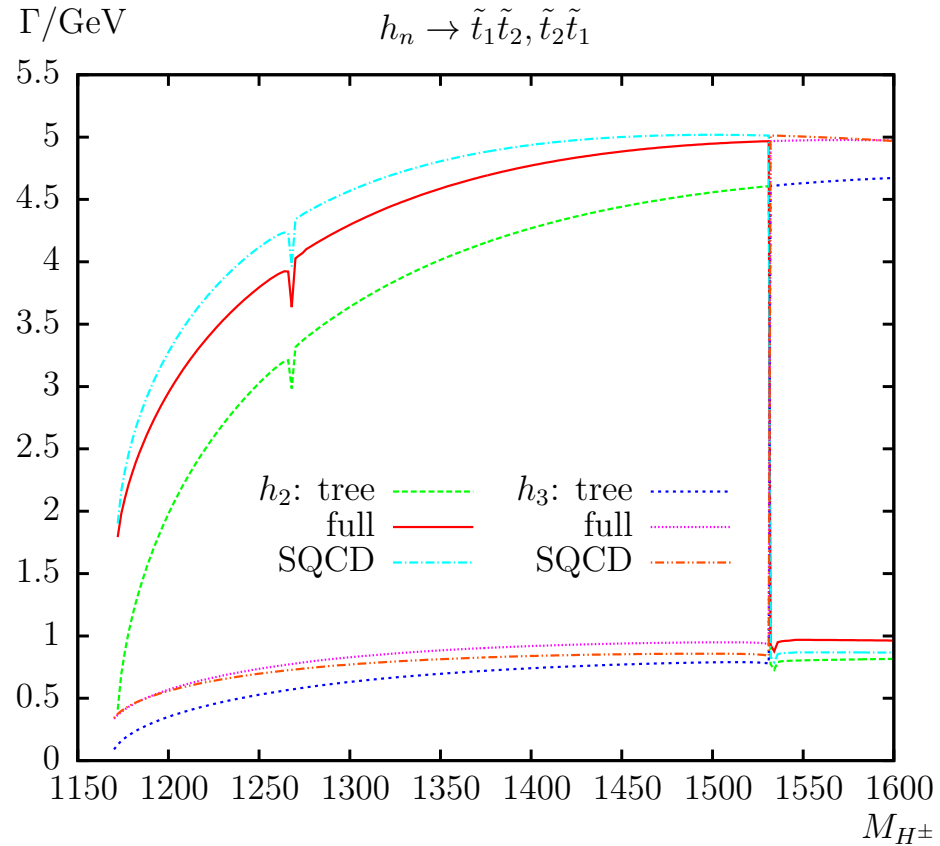
Numerical example scenario:

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

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

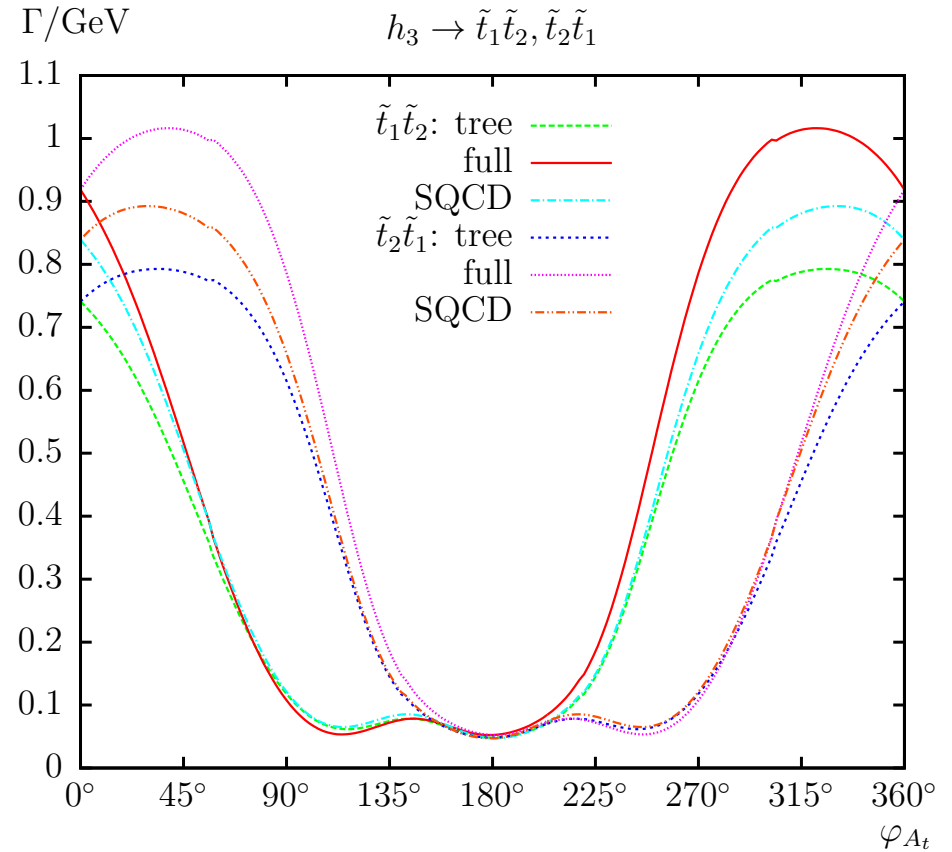
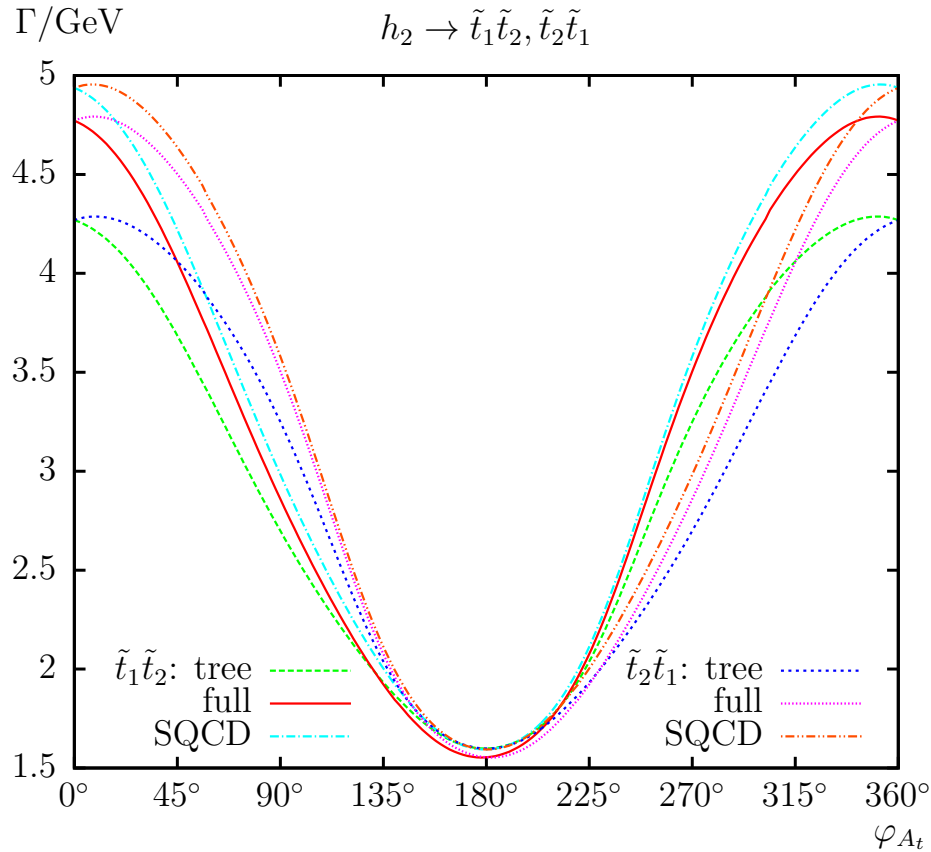
- in agreement with exp. data
- opens up many (all) decay channels
- relevant parameters varied
- . . .

Heavy Higgs decay to stops:



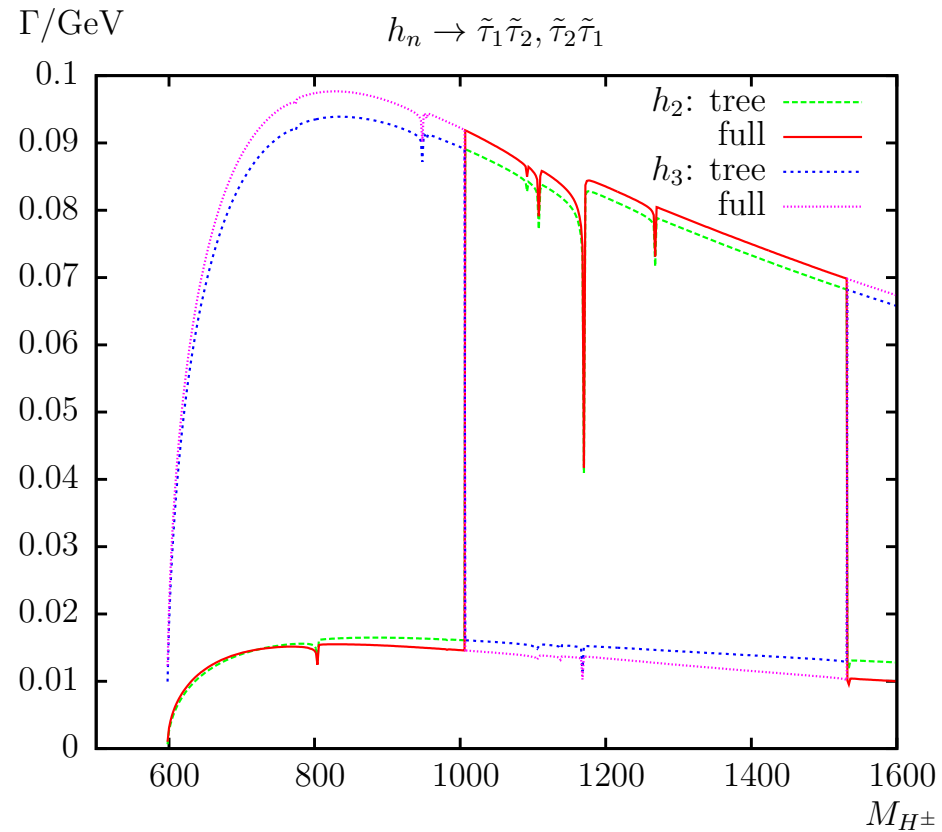
- ⇒ loop corrections up to $\sim 30\%$
- ⇒ SUSY QCD not sufficient
- ⇒ level crossing, thresholds, ...

Heavy Higgs decay to stops:



- ⇒ loop corrections up to $\sim 30\%$, SUSY EW important
- ⇒ strong phase dependence
- ⇒ difference between charge conjugated decays

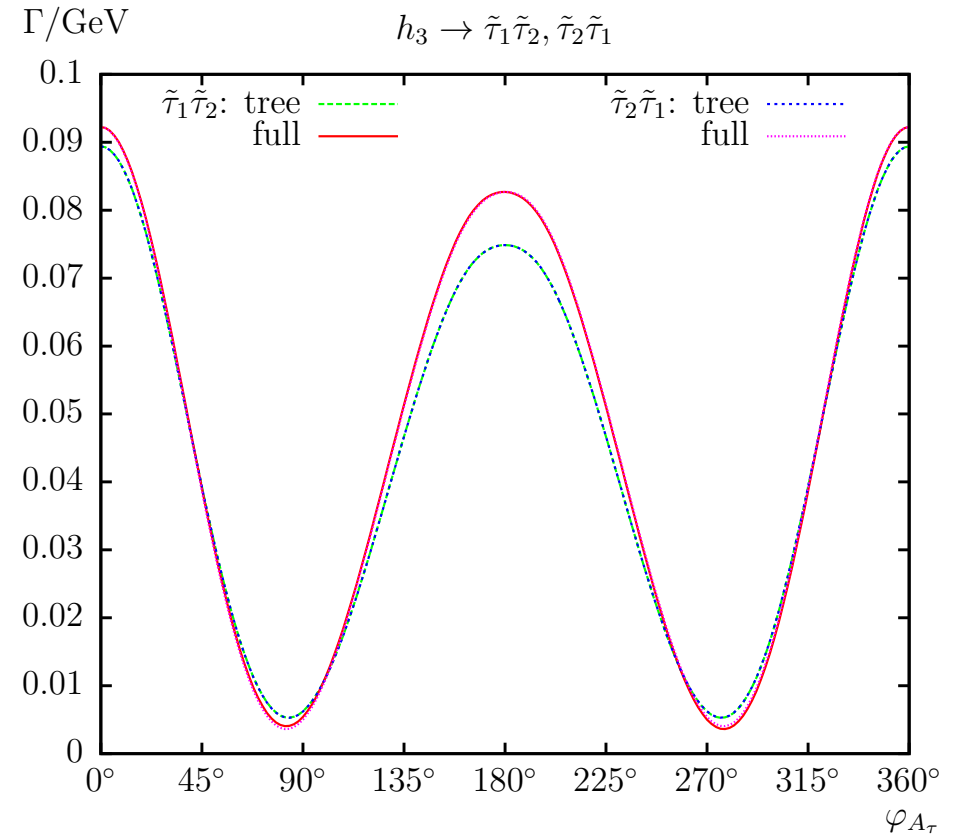
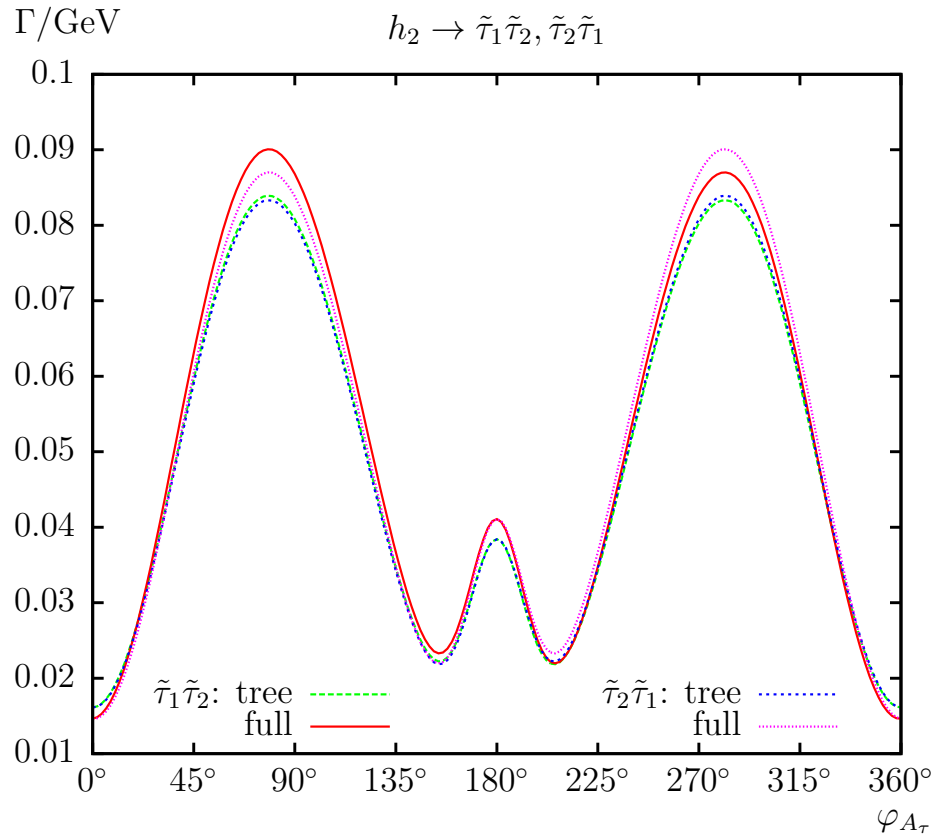
Heavy Higgs decay to staus:



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

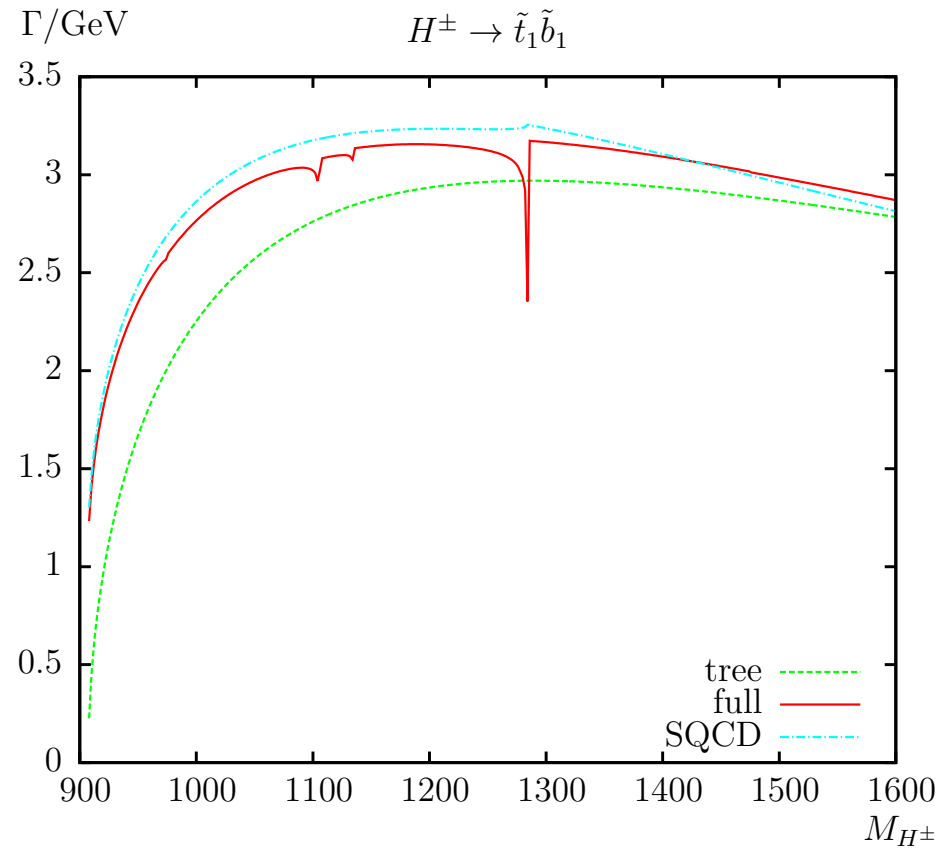
⇒ level crossing, thresholds, ...

Heavy Higgs decay to staus:



- ⇒ loop corrections up to $\sim 10\%$, purely EW
- ⇒ strong phase dependence
- ⇒ small difference between charge conjugated decays

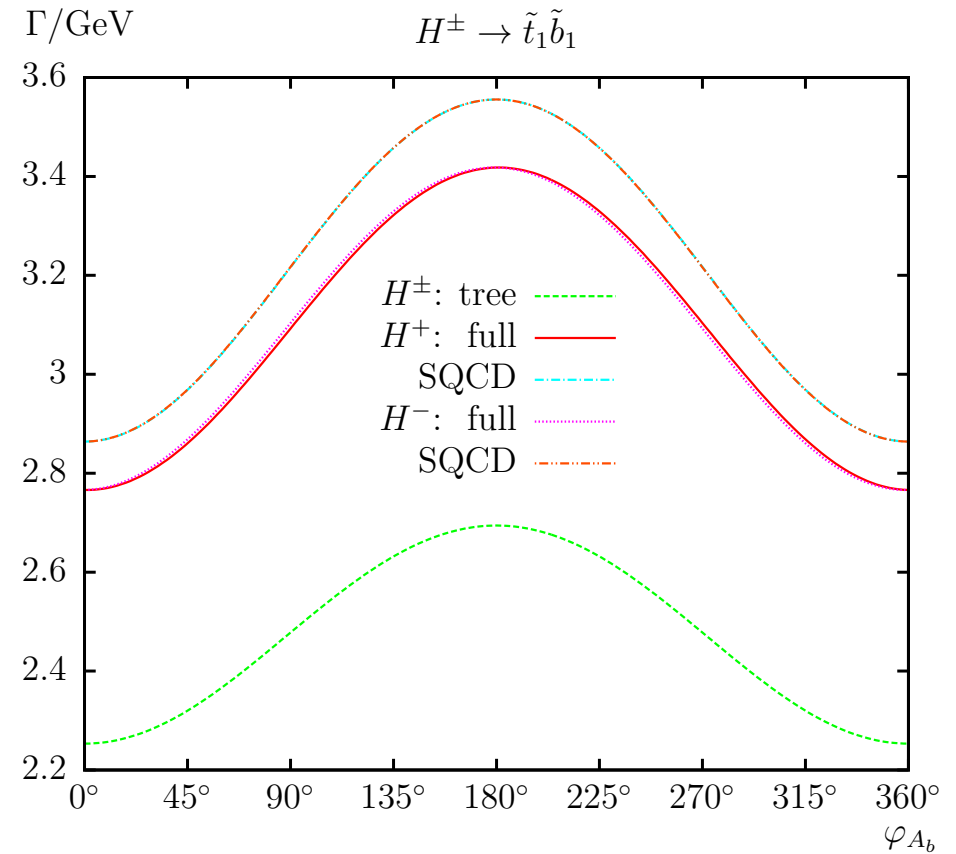
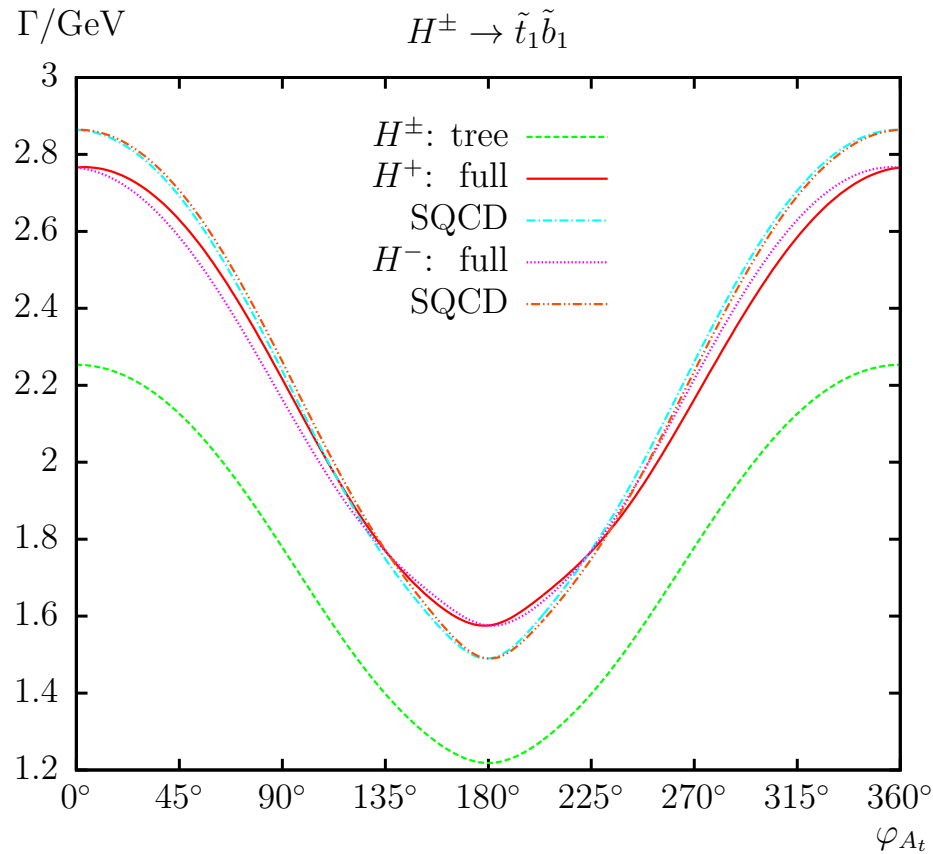
Charged Higgs decay to stop/sbottom:



⇒ loop corrections up to $\sim 30\%$

⇒ SUSY QCD not sufficient

Charged Higgs decay to stop/sbottom:



- \Rightarrow loop corrections up to $\sim 30\%$, SUSY EW important
- \Rightarrow strong phase dependence
- \Rightarrow small difference between charge conjugated decays

3E) SUSY decays to/involving also Higgs bosons

Calculated in the cMSSM full one-loop:

[A. Bharucha, S.H., F. v.d. Pahlen, H. Rzehak, C. Schappacher '11 - '15]

- stop/sbottom decays
- stau decays
- chargino decays
- neutralino decays
- gluino decays

Anything relevant missing?

⇒ effects always relevant for LC precision!

4. Conclusinos

- The **Higgs** will be explored at the **LC**
SUSY will be explored at the **LC**
- **LC precision** often is in the **per-cent range**
⇒ **theory precision has to match!**
⇒ **many corrections still missing**, in particular for **Higgs**
- Problem in the **MSSM**, in particular with **complex parameters**:
consistent renormalization of the whole model (simultaneously)
⇒ **now solved!**
⇒ model file available for **FeynArts/FormCalc/LoopTools**
⇒ full one-loop calculations of any SUSY process possible
- (Updated) results available for:
 - Higgs boson masses
 - Higgs boson production cross sections
 - Higgs decays and decays to Higgs bosons
 - production of **Dark Matter** at the LC
- **Always(?) more higher-order corr. necessary to match LC precision!**