Higgs and Dark Matter Production from SUSY Decays

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Higgs and Dark Matter Production from SUSY Decays

- Introduction
- Renormalization of the cMSSM
- Two-body decays @ 1-loop (widths and BRs)
  - Chargino decays
  - Neutralino decays
  - Stop decays
- Summary and Outlook

Introduction

Cold Dark Matter

- Ordinary matter $< 5\%$ of the Universe!
  $\Omega_{\rm CDM} h^2 \simeq 0.11, \qquad \Omega_{\rm B} h^2 \simeq 0.0224$
- WIMP miracle:
  DM @ e-w scale & weakly interacting $\Rightarrow$ good relic density

CDM $\Rightarrow$ BSM physics

Our candidate: the LSP

Introduction

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CDM $\Rightarrow$ BSM physics

Our candidate: the LSP

LHC may produce DM particles:

$\rightarrow$ neutral particles produced in cascades!

LC necessaray to determine DM properties!

Theoetical calculations must be under control

Introduction

Low Energy Supersymmetry (here MSSM)

- hierarchy/naturalness problem: SM sensitive to $M_{\rm Plank}$
  quadratic divergences to the self energy of scalars cancel out and stabilise the Higgs mass against radiative corrections
- Provides a natural candidate for CDM:
  here the neutralino $\tilde{\chi}_1^0$ (other groups, other candidates)
- Unification of gauge couplings:
  GUT scale $M_{\rm GUT}$ below the Plank mass $M_{\rm Plank}$

CP-violation

- Baryon asymmetry: CP-violation in the SM not large enough

  MSSM with complex couplings (cMSSM)
  $\Rightarrow$ new sources of CP-violation

Complex parameters in the MSSM

Enter at tree-level or 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

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$\Rightarrow$ can induce CP-violating effects

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

with $M_{h_3} > M_{h_2} > M_{h_1}$

$\Rightarrow$ computed by FeynHiggs

cMSSM & one-loop

Aim:

consistent one-loop calculation of all two-body decay widths and BRs in the cMSSM

$\Rightarrow$ need consistent renormalization of the full cMSSM

Previous analyses: restricted to single decay channels.

rMSSM: $\Gamma(\tilde{q} \to q\tilde{\chi}_j^0)$, @1 loop QCD, [Djouadi, Hollik, Junger '96]
rMSSM: $\Gamma(\tilde{q} \to q\tilde{\chi}_j^0)$, @1 loop, [Guasch, Hollik, Sola '01, '02]
rMSSM: $\Gamma(\tilde{\chi}_i^0 \to \tilde{\chi}_j^0 \ell^+ \ell^-)$, $\Gamma_{\rm Tot}(\tilde{\chi}_i^0)$, @1 loop, no QCD [Drees, Hollik, Xu '06]
rMSSM: $\Gamma(\tilde{\chi}_i^{\pm/0} \to W^\pm \tilde{\chi}_j^{0/\mp})$, @1 loop [Liebler, Porod '10]
cMSSM: $\Gamma(\tilde{\chi}_i^0 \to \tilde{\chi}_j^0 h_k)$, full 1 loop [Weiglein, Fowler '09]

Chargino and neutralino sectors

Chargino and neutralino mass matrices:

$$\mathcal{L}_{\tilde{\chi}\text{mass}} = \begin{pmatrix}\tilde{W}^{\pm} & \tilde{H}^{\pm}\end{pmatrix} \cdot \begin{pmatrix} M_2 & \sqrt{2}\sin\beta\, M_W \\ \sqrt{2}\cos\beta\, M_W & \mu \end{pmatrix} \cdot \begin{pmatrix}\tilde{W}^{\pm} \\ \tilde{H}^{\pm}\end{pmatrix}$$

$$+ \begin{pmatrix}\tilde{B}^0 \tilde{W}^0 \tilde{H}_1^0 \tilde{H}_2^0\end{pmatrix} \cdot \begin{pmatrix} M_1 & 0 & -M_Z\, s_W \cos\beta & M_Z\, s_W \sin\beta \\ 0 & M_2 & M_Z\, c_W \cos\beta & -M_Z\, c_W \sin\beta \\ -M_Z\, s_W \cos\beta & M_Z\, c_W \cos\beta & 0 & -\mu \\ M_Z\, s_W \sin\beta & -M_Z\, c_W \sin\beta & -\mu & 0 \end{pmatrix} \cdot \begin{pmatrix}\tilde{B}^0, \\ \tilde{W}^0, \\ \tilde{H}_1^0, \\ \tilde{H}_2^0\end{pmatrix}$$

Diagonalization $\Rightarrow$ Higgsinos and gauginos mix:

$\tilde{W}^{\pm}, \tilde{H}^{\pm} \to \tilde{\chi}_1^{\pm}, \tilde{\chi}_2^{\pm}$: chargino mass eigenstates

$\tilde{B}^0, \tilde{W}^0, \tilde{H}_1^0, \tilde{H}_2^0 \to \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$: neutralino mass eigenstates

Common parameters $\Rightarrow$ relations between masses and couplings

Chargino and neutralino sectors: renormalization

On-shell renormalization:

- renormalize 3 (complex) parameters: $M_1,\ M_2,\ \mu$
- chargino-neutralino sector $\Rightarrow$ 6 mass paramters: $m_{\tilde{\chi}_i^\pm},\ i = 1, 2,\ m_{\tilde{\chi}_j^0},\ j = 1, \ldots, 4$

we choose $m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^\pm}, m_{\tilde{\chi}_1^0}$ as input parameters

$$\left[\widetilde{\mathrm{Re}}\hat{\Sigma}_{\tilde{\chi}_i^\pm}(p)\right]_{ii}\tilde{\chi}_i^\pm(p)\Big|_{p^2=m^2_{\tilde{\chi}_i^\pm}} = 0, \qquad (i = 1, 2),$$

$$\left[\widetilde{\mathrm{Re}}\hat{\Sigma}_{\tilde{\chi}_1^0}(p)\right]_{ii}\tilde{\chi}_j^0(p)\Big|_{p^2=m^2_{\tilde{\chi}_1^0}} = 0,$$

3 eqs. define 3 complex parameters & field renormalization const.

Choose masses of charged particles as input to avoid IR divergencies

Simultaneous renormalization of the full cMSSM

- Higgs wave function renormalization and $\tan\beta$: $\overline{\mathrm{DR}}$
- Higgs masses: on-shell.
  Z_H-matrix: $h, H, A \to h_1, h_2, h_3$ [FeynHiggs]
- electroweak gauge bosons: on-shell
- quark sector: internal m_b $\overline{\mathrm{DR}}$, external m_b on-shell, other quarks on-shell
- squark sector: A_b $\overline{\mathrm{DR}}$, squarks on-shell
- lepton/slepton sector: on-shell
- chargino-neutralino sector: on-shell (next slide)

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  Z_H-matrix: $h, H, A \to h_1, h_2, h_3$ [FeynHiggs]
- electroweak gauge bosons: on-shell
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- squark sector: A_b $\overline{\rm DR}$, squarks on-shell
- lepton/slepton sector: on-shell
- chargino-neutralino sector: on-shell (next slide)

Simultaneous renormalization of the full cMSSM under control!

Chargino decays

$$\Gamma(\tilde{\chi}_i^\pm \to \tilde{\chi}_j^0 H^\pm), \quad i = 1,2,\ j = 1,...,4$$

$$\Gamma(\tilde{\chi}_i^\pm \to \tilde{\chi}_j^0 W^\pm), \quad i = 1,2,\ j = 1,...,4$$

$$\Gamma(\tilde{\chi}_2^\pm \to \tilde{\chi}_1^\pm h_k), \quad k = 1,...,3$$

$$\Gamma(\tilde{\chi}_2^\pm \to \tilde{\chi}_1^\pm Z),$$

$$\Gamma(\tilde{\chi}_i^\pm \to \nu_\ell\, \tilde{\ell}_k^\pm), \quad \ell = \tau, \mu, e,\ k = 1,2$$

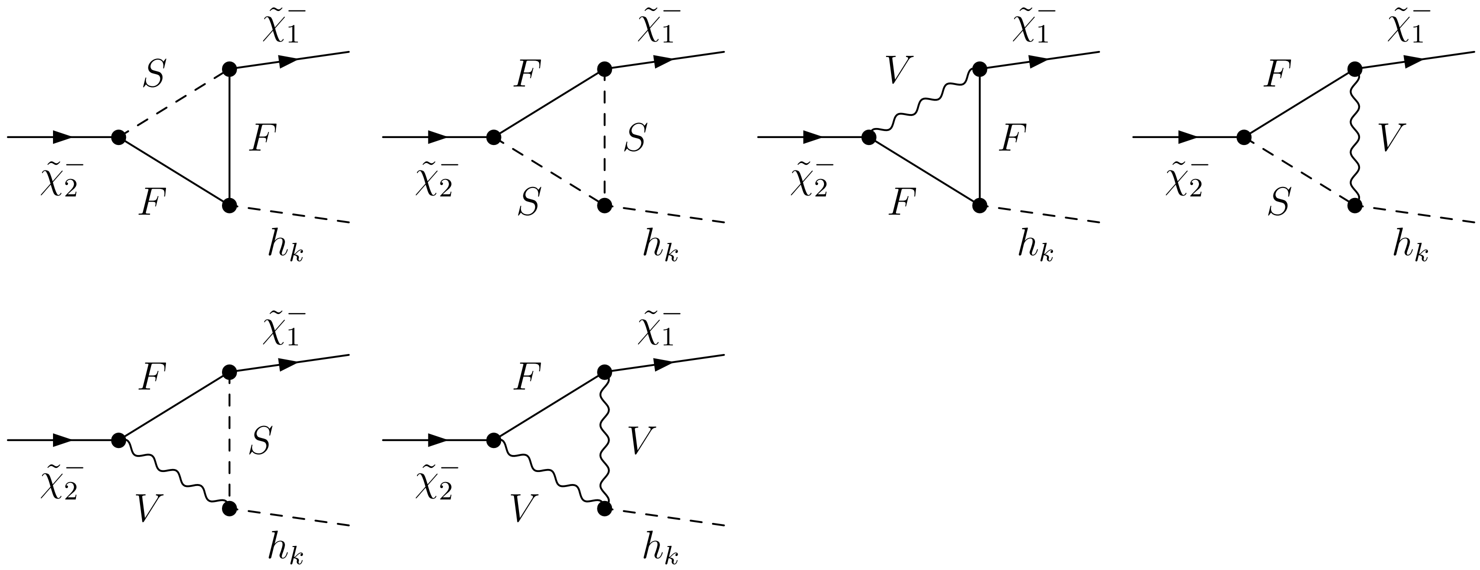
$$\Gamma(\tilde{\chi}_i^\pm \to \ell^\pm\, \tilde{\nu}_\ell) \quad \ell = \tau, \mu, e$$

No hadronic decays yet:

$$\Gamma(\tilde{\chi}_i^\pm \to q\, \tilde{q}_k'), \quad k = 1,2$$

[SH,FP,CS 11]

Feynman diagrams for $\tilde{\chi}_2^- \to \tilde{\chi}_1^- h_k$



$+$ including all hard QED diagrams

(not shown: self energies of initial and final particles)

Calculation of widths and branching ratios

Framework:

- create all diagrams with FeynArts $\longrightarrow$ model file with all counterterms in the cMSSM
- include all soft & hard QED diagrams
- further evaluation with FormCalc and LoopTools
- Dimensional REDuction
- all UV and IR divergencies cancel
- results to be included in FeynHiggs (www.feynhiggs.de)

Numerical results

Parameters for numerical evaluation

- $m_{\tilde{\chi}_1^\pm} = 350$ GeV, $m_{\tilde{\chi}_2^\pm} = 600$ GeV, $\varphi_\mu = 0$ and $\mu > 0$
- μ and M_2 as a function of the chargino masses:

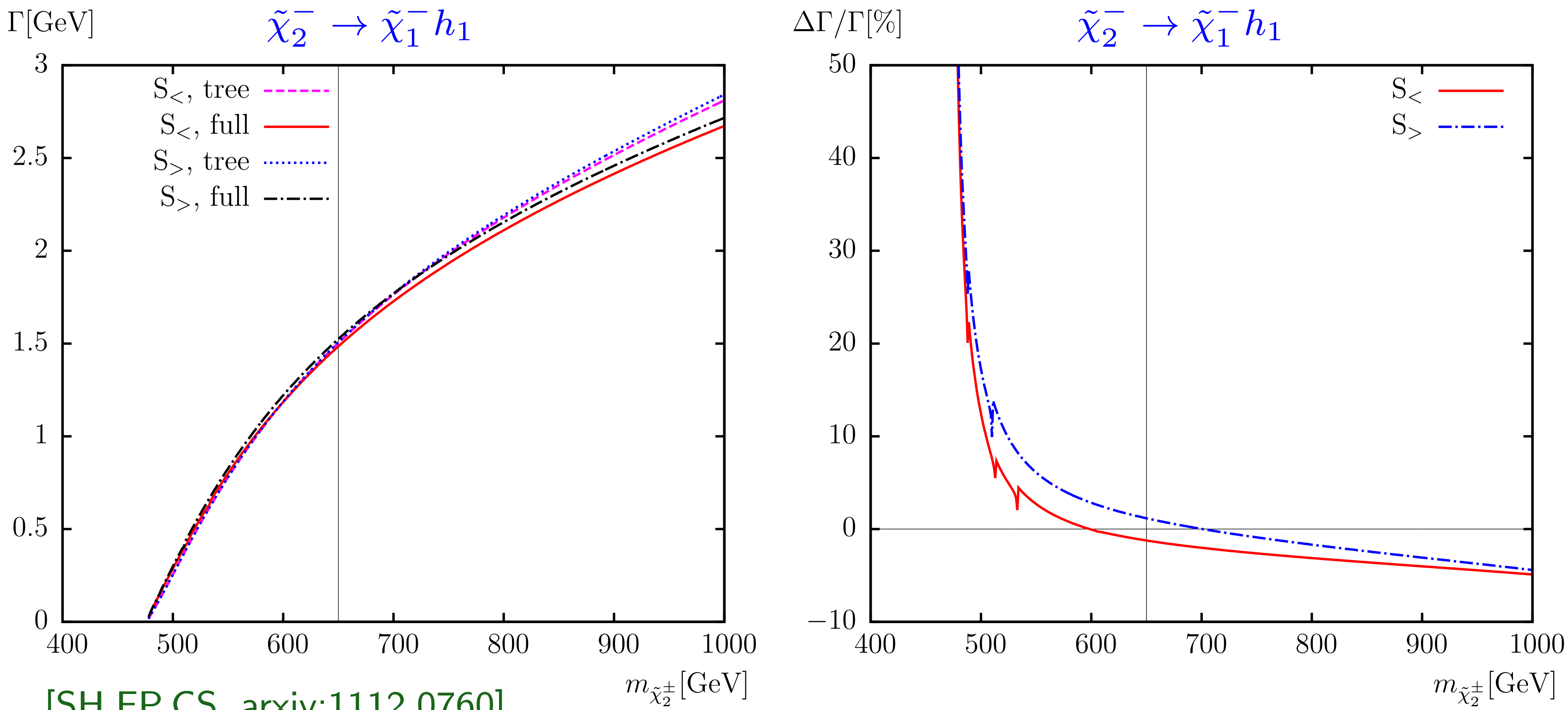
$$S_> := \{\mu > M_2\} \quad \tilde{\chi}_2^\pm \sim \mathrm{Higgsino-like}$$

$$S_< := \{\mu < M_2\} \quad \tilde{\chi}_2^\pm \sim \mathrm{wino-like}$$

- $|M_1|$ fixed by GUT relation: $|M_1|/M_2 = 5/3 \tan^2\theta_W \simeq 0.5$
- $\tan\beta = 20$, $\varphi_{M_1} = 0$

Choice of scenario: so that most chargino decay channels are open

Chargino decays: $m_{\tilde{\chi}_2^\pm}$-dependence



[SH,FP,CS, arxiv:1112.0760]

⇒ one-loop corrections under control and non-negligible

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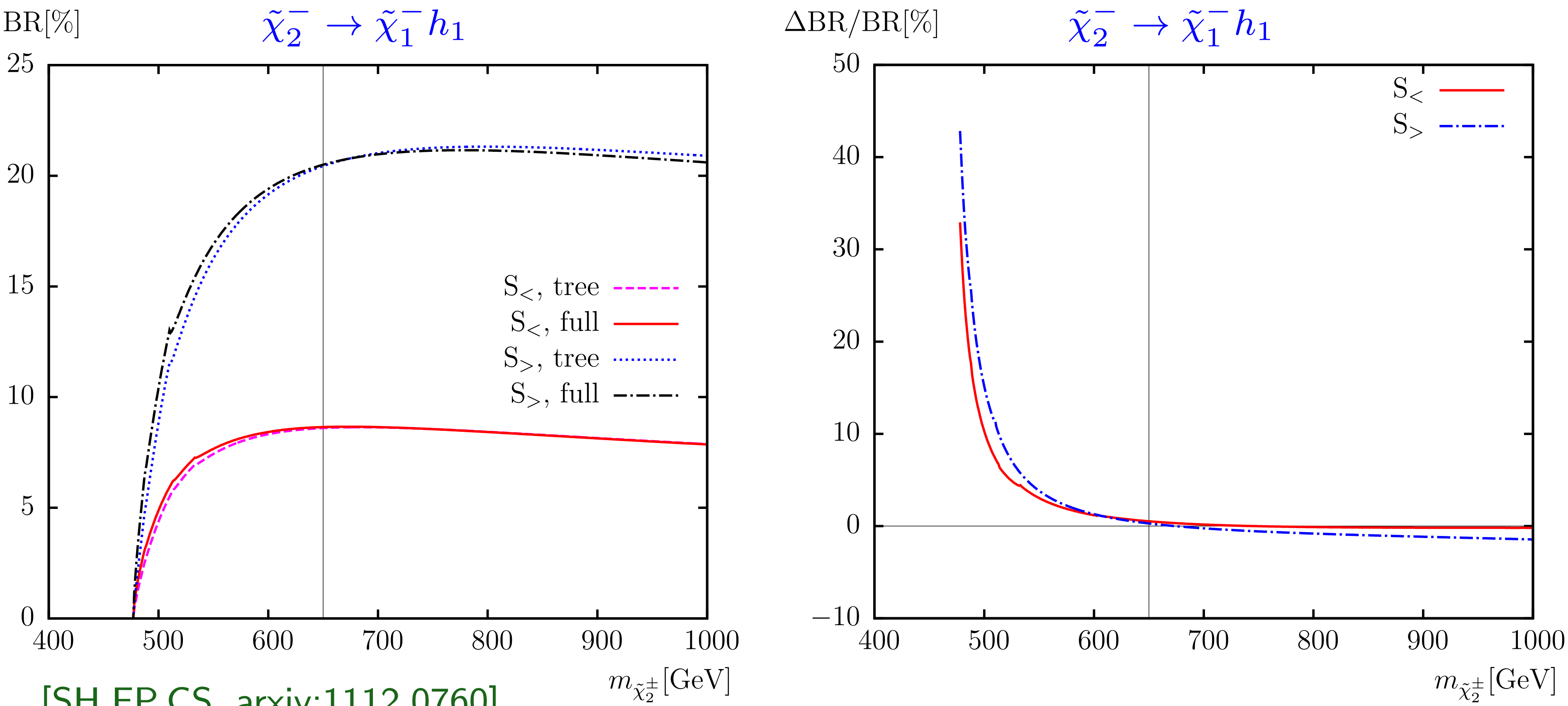

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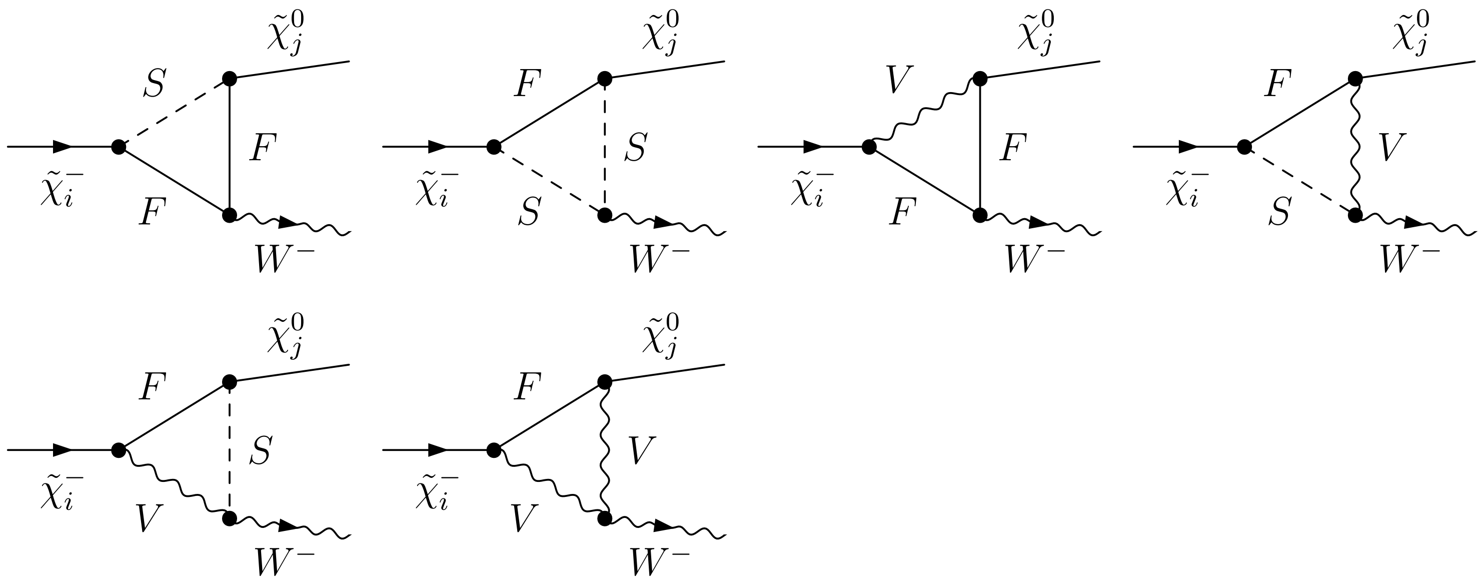
⇒ one-loop corrections under control and non-negligible

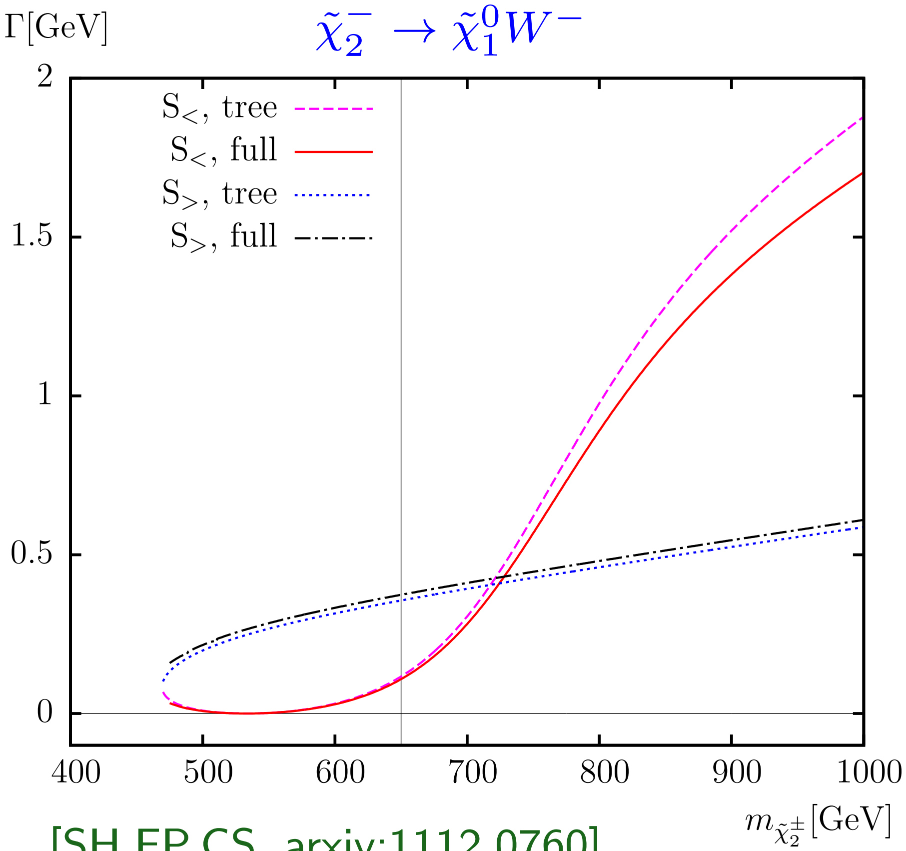
⇒ size of BR highly scenario dependent

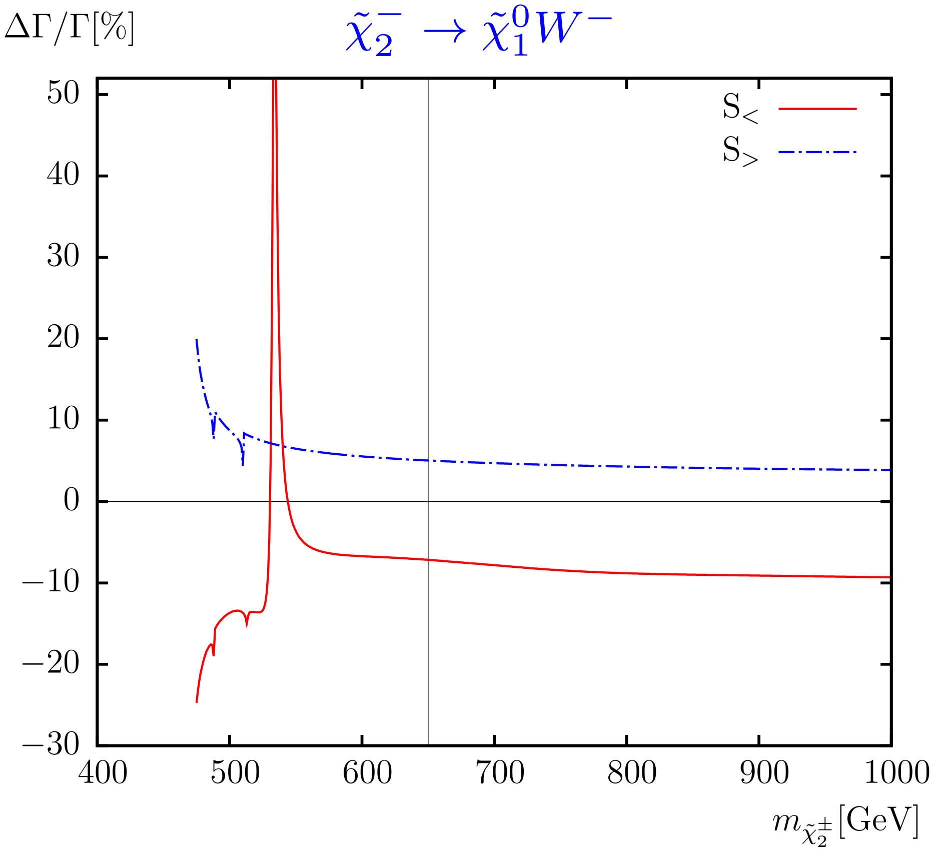
Feynman diagrams for $\tilde{\chi}_i^- \to \tilde{\chi}_j^0 W^-$



$+$ including all hard QED diagrams

Chargino decays: $m_{\tilde{\chi}_2^{\pm}}$-dependence





[SH,FP,CS, arxiv:1112.0760]

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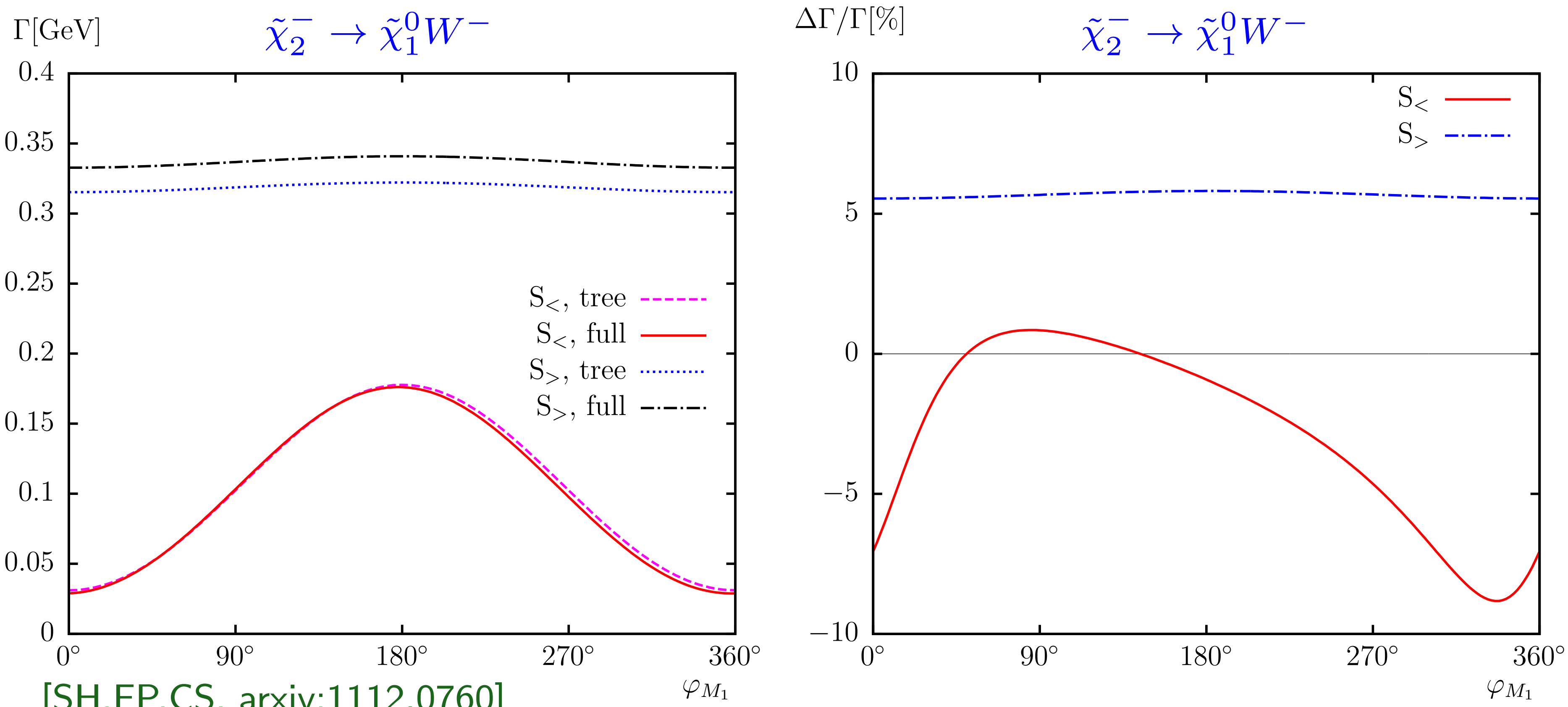
Chargino decays: φ_{M_1}-dependence



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$\Rightarrow$ one-loop corrections under control and non-negligible

$\Rightarrow$ size of BR highly scenario dependent

Chargino decays: φ_{M_1}-dependence: $\mathcal{CP}$ Asymmetry

$$\mathcal{A}_{\mathcal{CP}} = \frac{\Gamma(\tilde{\chi}_2^- \to \tilde{\chi}_1^0 W^-) - \Gamma(\tilde{\chi}_2^+ \to \tilde{\chi}_1^0 W^+)}{\Gamma(\tilde{\chi}_2^- \to \tilde{\chi}_1^0 W^-) + \Gamma(\tilde{\chi}_2^+ \to \tilde{\chi}_1^0 W^+)}$$

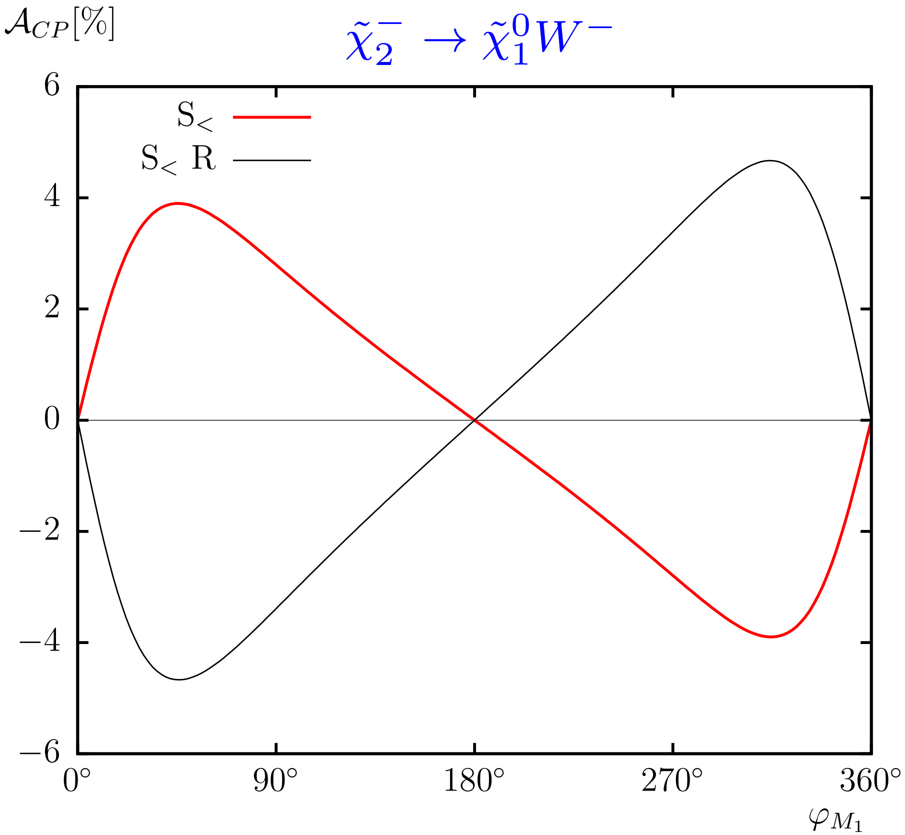
$$\mathcal{A}_{\mathcal{CP}} \propto \mathcal{M}^*_{\rm tree} \times (\mathcal{M}^{\rm loop}_{\tilde{\chi}^-} - \mathcal{M}^{\rm loop}_{\tilde{\chi}^+})$$

$\mathcal{A}_{\mathcal{CP}} \neq 0 \Rightarrow$

absorptive contributions

& complex couplings

$\Rightarrow \mathcal{A}_{\mathcal{CP}} \sim \mathcal{O}(\%)$



f.i.: $\mathrm{Im} B_i(m^2_{\tilde{\chi}_2^\pm}, m_a^2, m_b^2) \times \mathrm{Im(couplings)} \neq 0 \quad (m_{\tilde{\chi}_2^\pm} > m_a + m_b)$

Neutralino decays (preliminary)

$$\Gamma(\tilde{\chi}_i^0 \to \tilde{\chi}_j^0 h_k), \quad i,j=1,...,4,\ k=1,...,3,$$

$$\Gamma(\tilde{\chi}_i^0 \to \tilde{\chi}_j^0 Z), \quad i,j=1,...,4,$$

$$\Gamma(\tilde{\chi}_i^0 \to \tilde{\chi}_j^\pm H^\mp), \quad i=1,2,\ j=1,...,4,$$

$$\Gamma(\tilde{\chi}_i^0 \to \tilde{\chi}_j^\pm W^\mp),$$

$$\Gamma(\tilde{\chi}_i^0 \to \ell^\mp \tilde{\ell}_k^\pm), \quad i=1,...,4,\ \ell=\tau,\mu,e,\ k=1,2$$

$$\Gamma(\tilde{\chi}_i^0 \to \nu_\ell \tilde{\nu}_\ell), \quad i=1,...,4,\ \ell=\tau,\mu,e$$

No hadronic decays yet:

$$\Gamma(\tilde{\chi}_i^\pm \to q\,\tilde{q}_k), \quad k=1,2$$

Neutralino decays (preliminary)

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$$\Gamma(\tilde{\chi}^0_i \to \ell^{\mp}\, \tilde{\ell}^{\pm}_k), \quad i=1,...,4, \; \ell=\tau,\mu,e, \; k=1,2$$

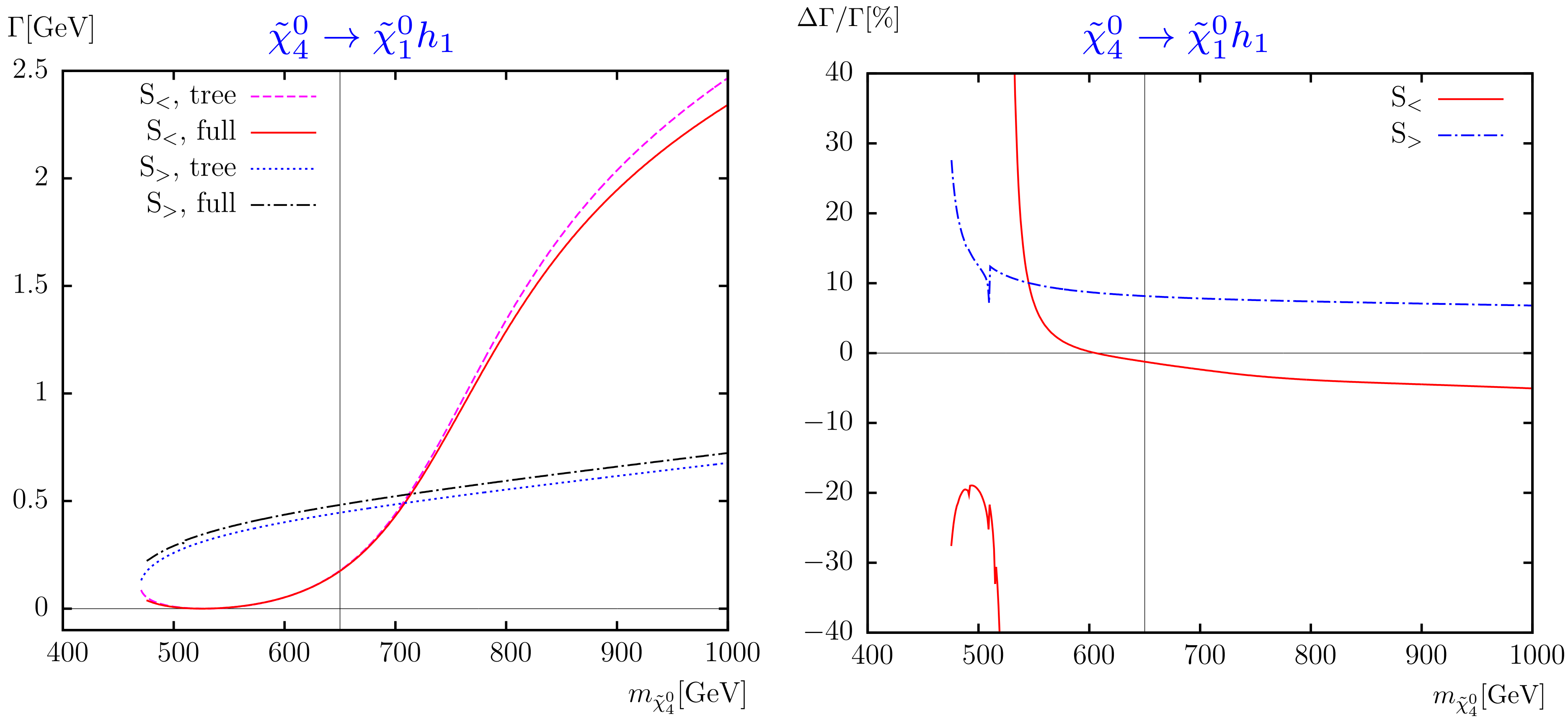
$$\Gamma(\tilde{\chi}^0_i \to \nu_\ell\, \tilde{\nu}_\ell), \quad i=1,...,4, \; \ell=\tau,\mu,e$$

No hadronic decays yet:

$$\Gamma(\tilde{\chi}^{\pm}_i \to q\, \tilde{q}_k), \quad k=1,2$$

- Comparison w/ different RS w/ DESY group

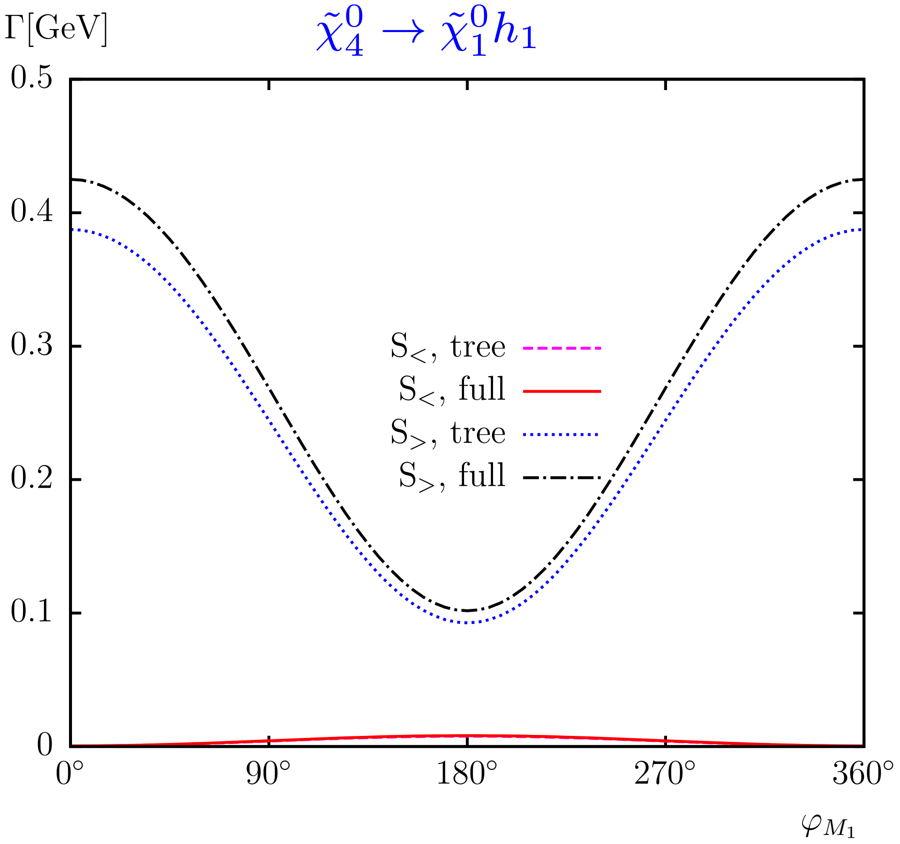
Neutralino decays: $m_{\tilde{\chi}_4^0}$-dependence (preliminary)

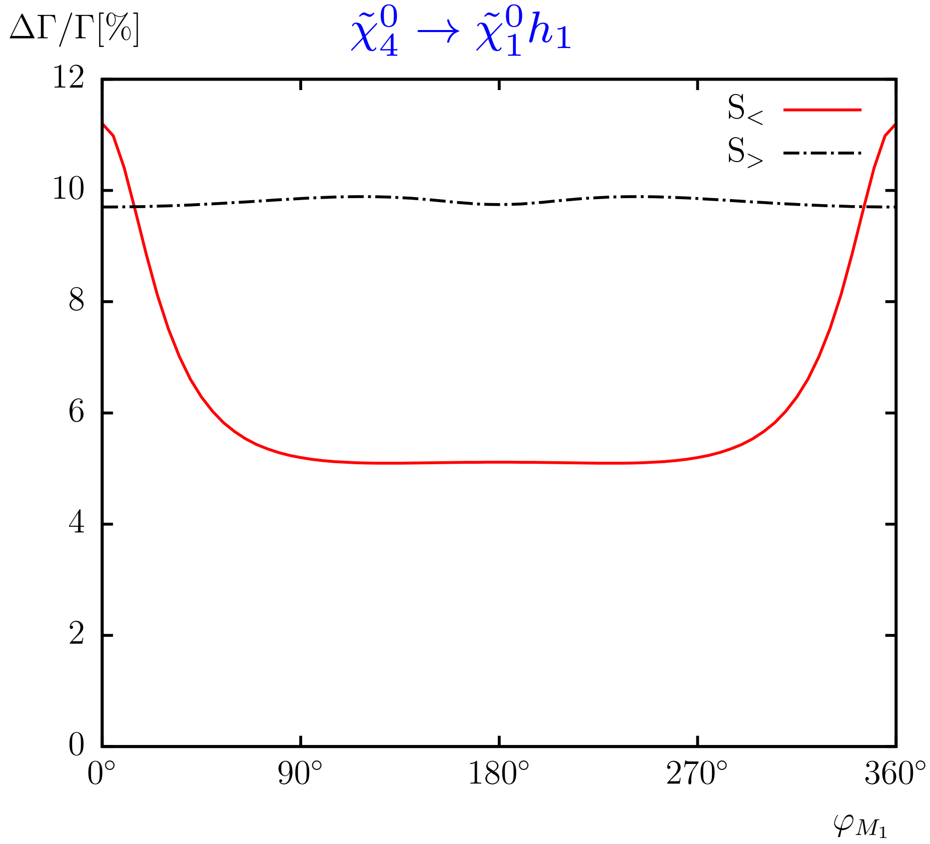


$\Rightarrow$ one-loop corrections under control and non-negligible

$\Rightarrow$ size of BR highly scenario dependent

Neutralino decays: φ_{M_1}-dependence (preliminary)





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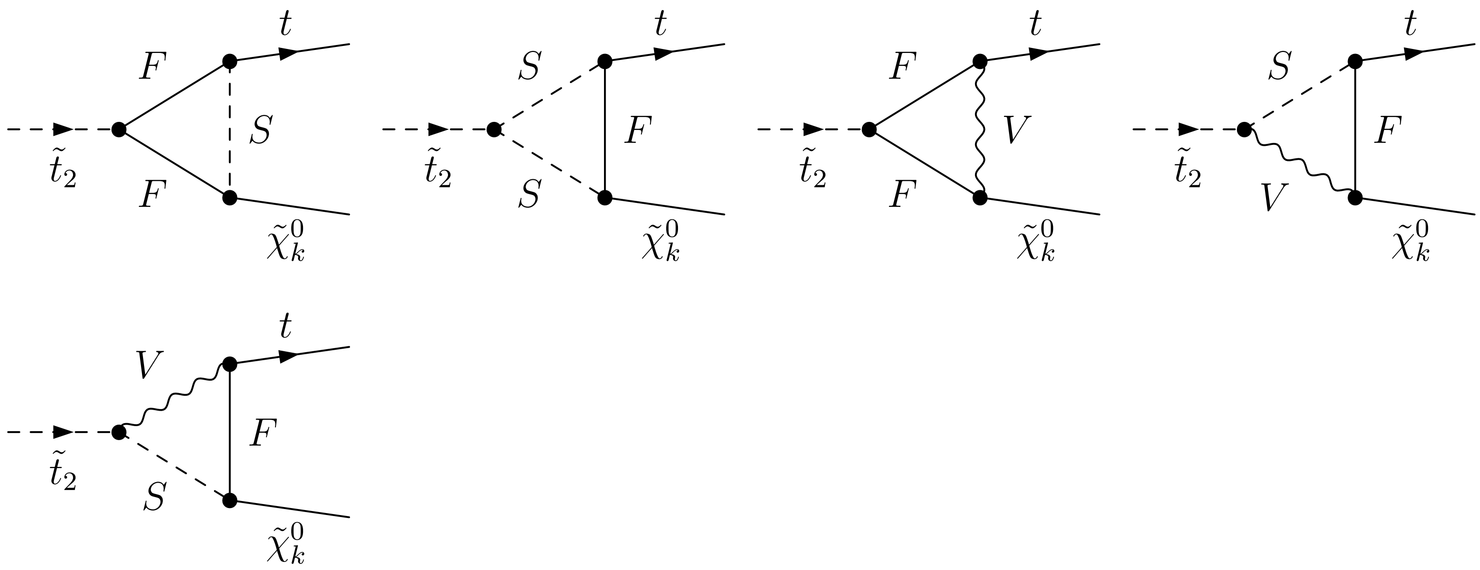
Stop decays

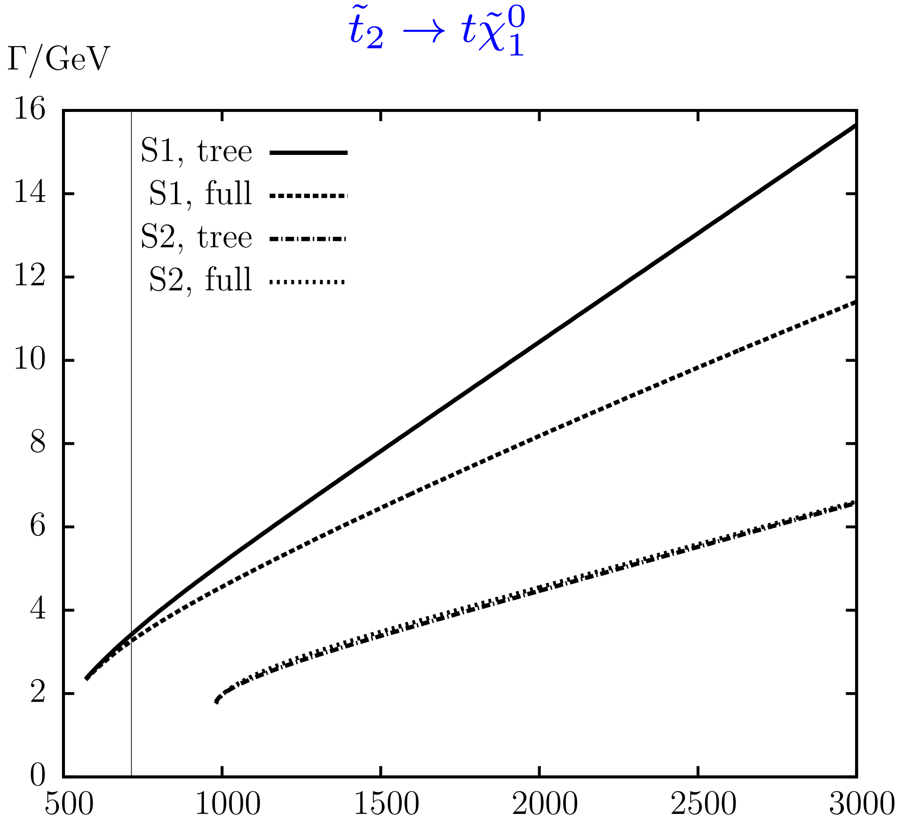
$$\Gamma(\tilde{t}_2 \to t\tilde{\chi}^0_j),\ j = 1, ..., 4$$

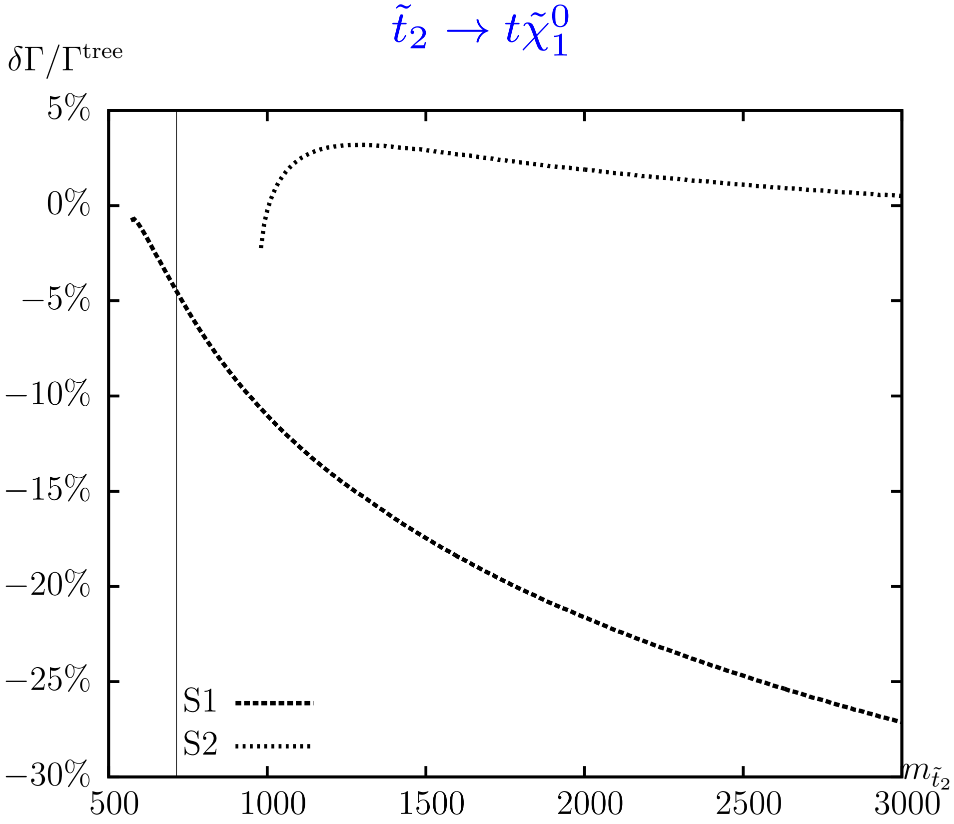
[Fritzsche,Heinemeyer, Rhehak, Schappacher '11]



+ including all hard QCD and QED diagrams

Stop decays: $m_{\tilde{t}}$-dependence





[Fritzsche,Heinemeyer, Rhehak, Schappacher '11]

$\Rightarrow$ one-loop corrections under control and non-negligible

Conclusions

- Aim: consistent one-loop calculation of
  all two-body decay widths and BRs in the cMSSM
  Necessary for the precise parameter extraction
  at LHC/ILC measurements
  Results to be implemented into FeynHiggs
- Chargino decays:
  - $\sim 10\%$ loop corrections for EW decays
  - hadronic decays: work in progress
  - $\mathcal{CP}$ asymmetries
- Neutralino decays:
  - Similar to chargino results
  - Comparison with different on-shell RS w/ DESY group
- Stop decays

backup transparencies

Chargino and neutralino sectors: renormalization

On-shell renormalization (cont.): mass shifts

$$m_{\tilde{\chi}_j^0} = m_{\tilde{\chi}_j^0}^{(0)} + \Delta m_{\tilde{\chi}_j^0}, \qquad (j = 2, 3, 4)$$

$$\Delta m_{\tilde{\chi}_j^0} = -\mathrm{Re}\Big[m_{\tilde{\chi}_j^0} \hat{\Sigma}^L_{\tilde{\chi}_j^0}(m^2_{\tilde{\chi}_j^0}) + \hat{\Sigma}^{SL}_{\tilde{\chi}_j^0}(m^2_{\tilde{\chi}_j^0})\Big],$$

where

$$\hat{\Sigma}_{\tilde{\chi}_j^0}(p) = \not{p}\,\omega_L \hat{\Sigma}^L_{\tilde{\chi}_j^0}(p^2) + \omega_L \hat{\Sigma}^{SL}_{\tilde{\chi}_j^0}(p^2) + (L \leftrightarrow R)$$

Chargino and neutralino sectors: renormalization

On-shell renormalization: field renormalization constants

$$\lim_{p^2 \to m^2_{\tilde{\chi}_i^\pm}} \frac{(\not{p} + m_{\tilde{\chi}_i^\pm}) \left[\widetilde{\text{Re}}\hat{\Sigma}_{\tilde{\chi}_i^\pm}(p)\right]_{ii}}{p^2 - m^2_{\tilde{\chi}_i^\pm}} \tilde{\chi}_i^\pm(p) = 0, \qquad (i = 1, 2)$$

$$\lim_{p^2 \to m^2_{\tilde{\chi}_j^0}} \frac{(\not{p} + m_{\tilde{\chi}_j^0}) \left[\widetilde{\text{Re}}\hat{\Sigma}_{\tilde{\chi}_j^0}(p)\right]_{jj}}{p^2 - m^2_{\tilde{\chi}_j^0}} \tilde{\chi}_j^0(p) = 0, \qquad (j = 1, 2, 3, 4)$$

Off-diagonal field renormalization constants:

$$\left[\widetilde{\text{Re}}\hat{\Sigma}_{\tilde{\chi}_i^\pm}(p)\right]_{ij} \tilde{\chi}_i^\pm(p)\Big|_{p^2 = m^2_{\tilde{\chi}_j^\pm}} = 0, \qquad (i, j = 1, 2),\ i \neq j$$

$$\left[\widetilde{\text{Re}}\hat{\Sigma}_{\tilde{\chi}_j^0}(p)\right]_{ij} \tilde{\chi}_j^0(p)\Big|_{p^2 = m^2_{\tilde{\chi}_1^0}} = 0, \qquad (i, j = 1, 2, 3, 4),\ i \neq j$$