

DM production from SUSY decays at the LC

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DM production from SUSY decays at the LC

- Introduction
 - The complex MSSM
 - LHC searches for DM
- Decays to neutralinos: precision calculations
 - Our framework
 - Results
- Summary and Conclusions

Introduction

Low Energy Supersymmetry (here MSSM)

- Solves hierarchy/naturalness problem:
Higgs mass stable against rad.corr. $m_H \sim \mathcal{O}(M_Z)$
- Provides a natural candidate for CDM:
here the neutralino $\tilde{\chi}_1^0$ $m_{\tilde{\chi}^0/\tilde{\chi}^\pm} < \mathcal{O}(\text{TeV})$
- Unification of gauge couplings @ M_{GUT} : GUT relations?

CP-violation

- Baryon asymmetry: CP-violation in the SM not large enough
MSSM with complex couplings (cMSSM)
⇒ 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

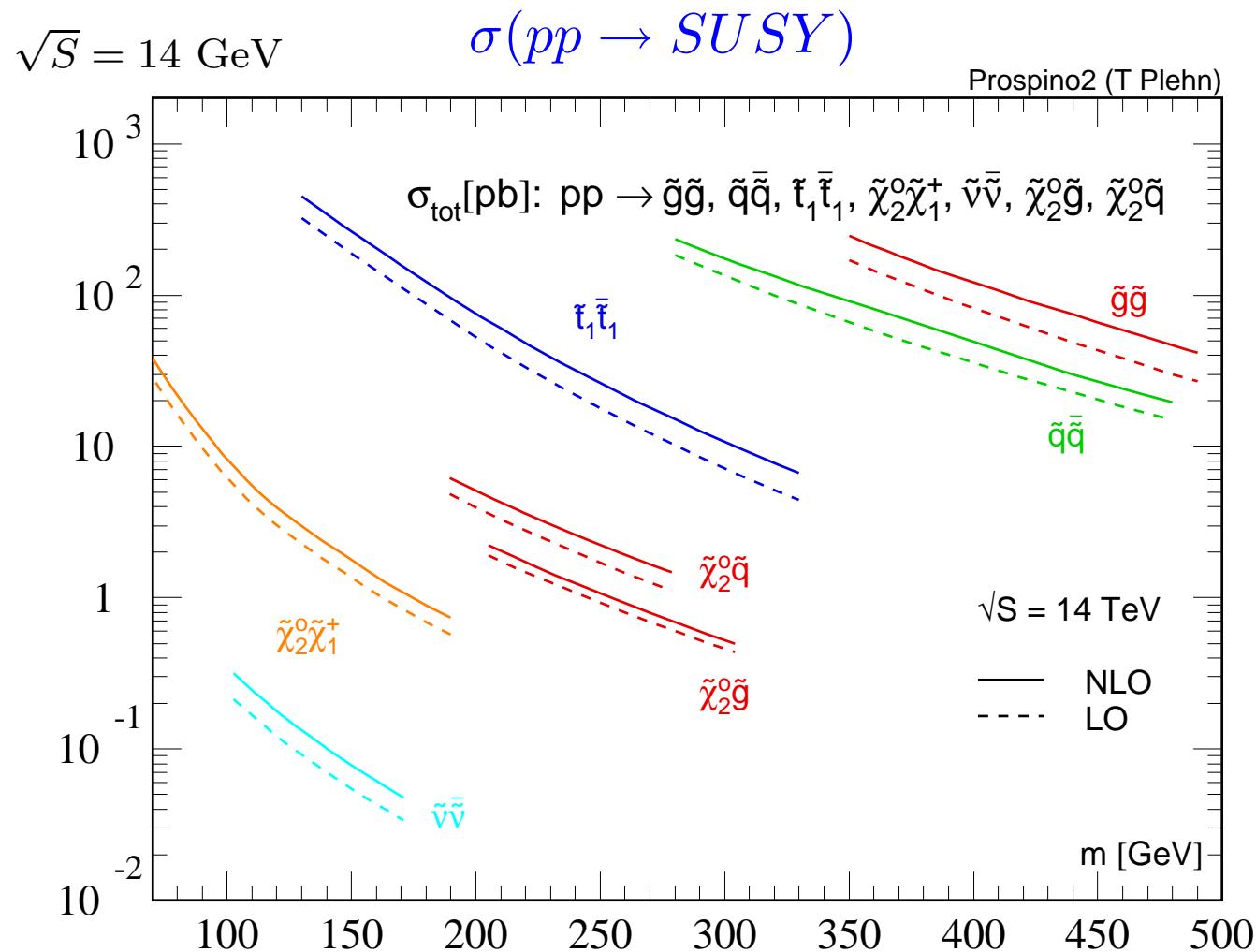
$$(A, H, h) \rightarrow (h_3, h_2, h_1)$$

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

\Rightarrow computed by FeynHiggs

SUSY production @ LHC

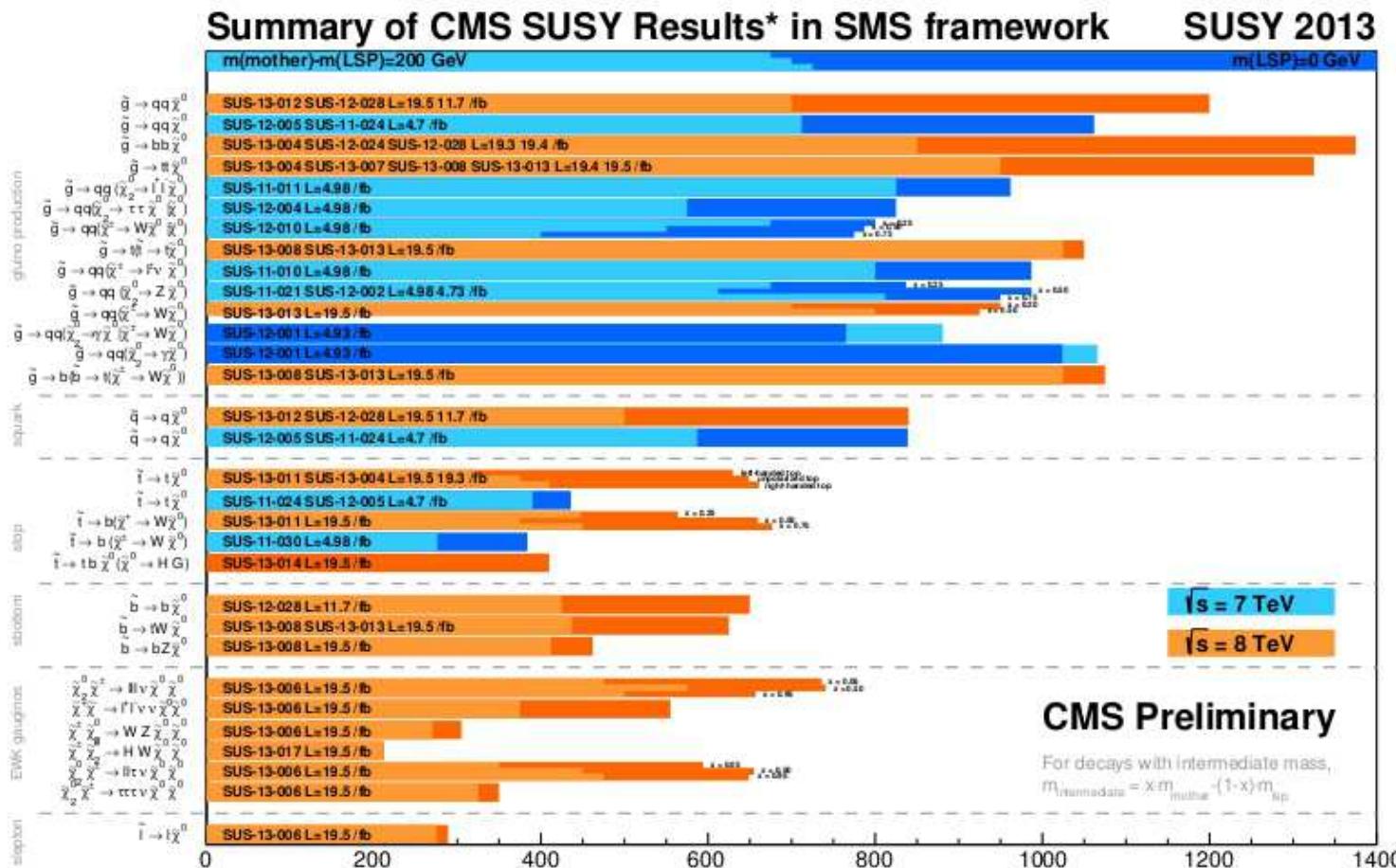
- SUSY cascades to LSP



SUSY production @ LHC

- SUSY cascades to LSP \Rightarrow evaluate decay chains:
 - * Q: determination of fundamental parameters?
 \Rightarrow parameters \leftrightarrow observables
 - * loop corrections must be under control
 - * including effects from CP phases
- @LHC largest production cross sections: colored particles
- Direct $\tilde{\chi}^\pm/\tilde{\chi}^0$ production: LHC sensitive to lower masses
- SUSY production at ILC: EW production

SUSY searches @LHC



- what do these exclusion limits mean?
- $m_{\tilde{\chi}_1^0} > ?$ (which $\tilde{\chi}_1^0$?)

SUSY searches @LHC: interpretation

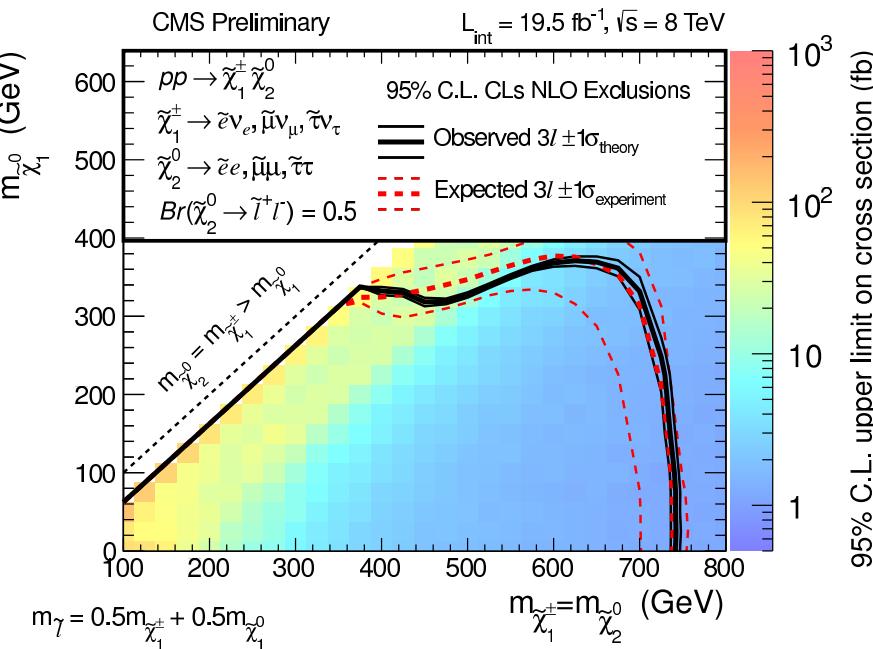
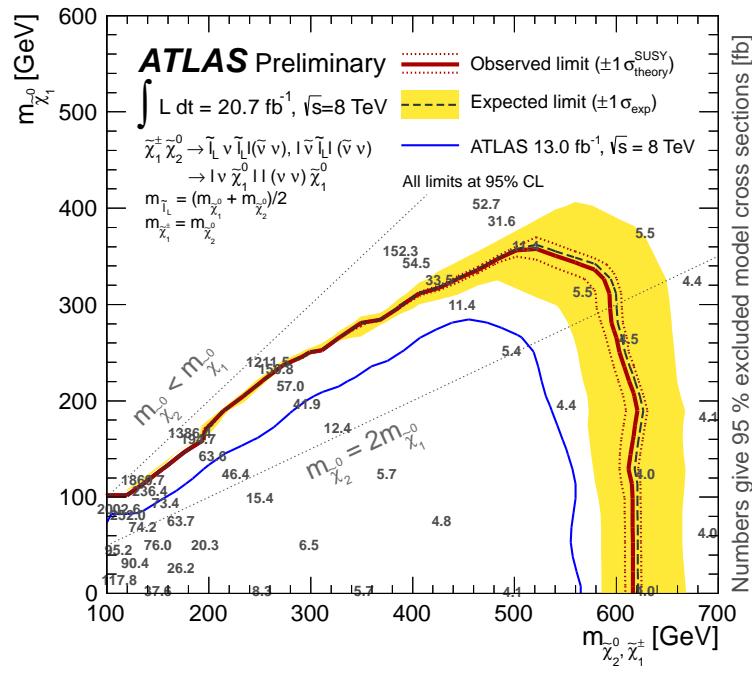
- Searches in specific models (CMSSM, GMSB, etc.)
 - Interpretation of results with more general assumptions difficult/impossible
 - Limits on $\tilde{\chi}^\pm/\tilde{\chi}^0$ reflect searches for colored particles
- Simplified Model Spectra (SMS) analysis
 - Derive limits on maximal production cross sections \times BR as function of particle spectra
 - Allows interpretation of exclusion limits in different models

Chargino/Neutralino searches @LHC

$pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow \text{sleptons} \rightarrow 3\ell \tilde{\chi}_1^0 \tilde{\chi}_1^0$:

most sensitive channel for direct $\tilde{\chi}^\pm \tilde{\chi}^0$ production

Example: interpretation for $m_{\tilde{\ell}_L} = (m_{\tilde{\chi}_1^\pm} + m_{\tilde{\chi}_1^0})/2$



Chargino/Neutralino searches @LHC

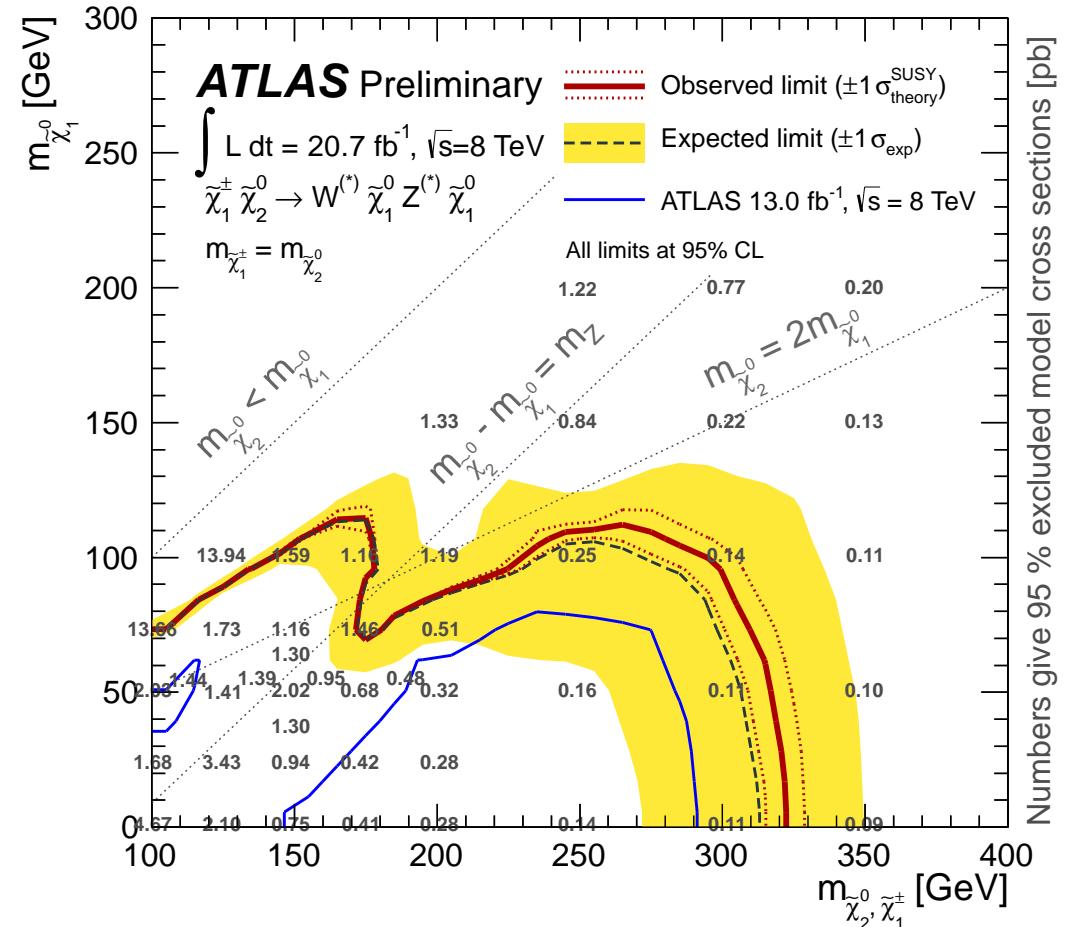
$$pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow W \tilde{\chi}_1^0 Z \tilde{\chi}_1^0$$

Assume:

- $m_{\tilde{\chi}_1^\pm} \simeq m_{\tilde{\chi}_2^0}$
- heavier sleptons

Exclusion limits for:

- gaugino-like $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$
- bino-like $\tilde{\chi}_1^0$
- $\text{BR}(\tilde{\chi}_1^\pm \rightarrow W^\pm \tilde{\chi}_1^0) = 1$
- $\text{BR}(\tilde{\chi}_2^0 \rightarrow Z \tilde{\chi}_1^0) = 1$



Simplified Model Spectra analysis: **interpret carefully**

Chargino/Neutralino searches @LHC

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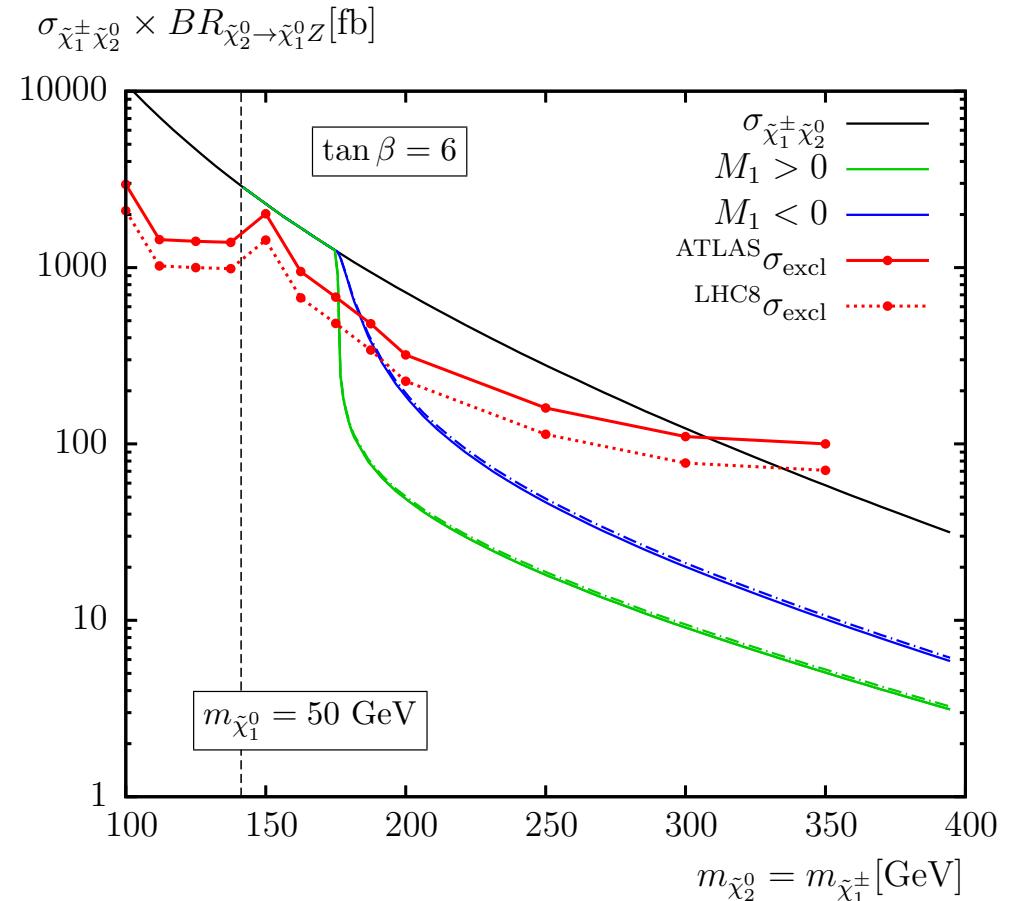
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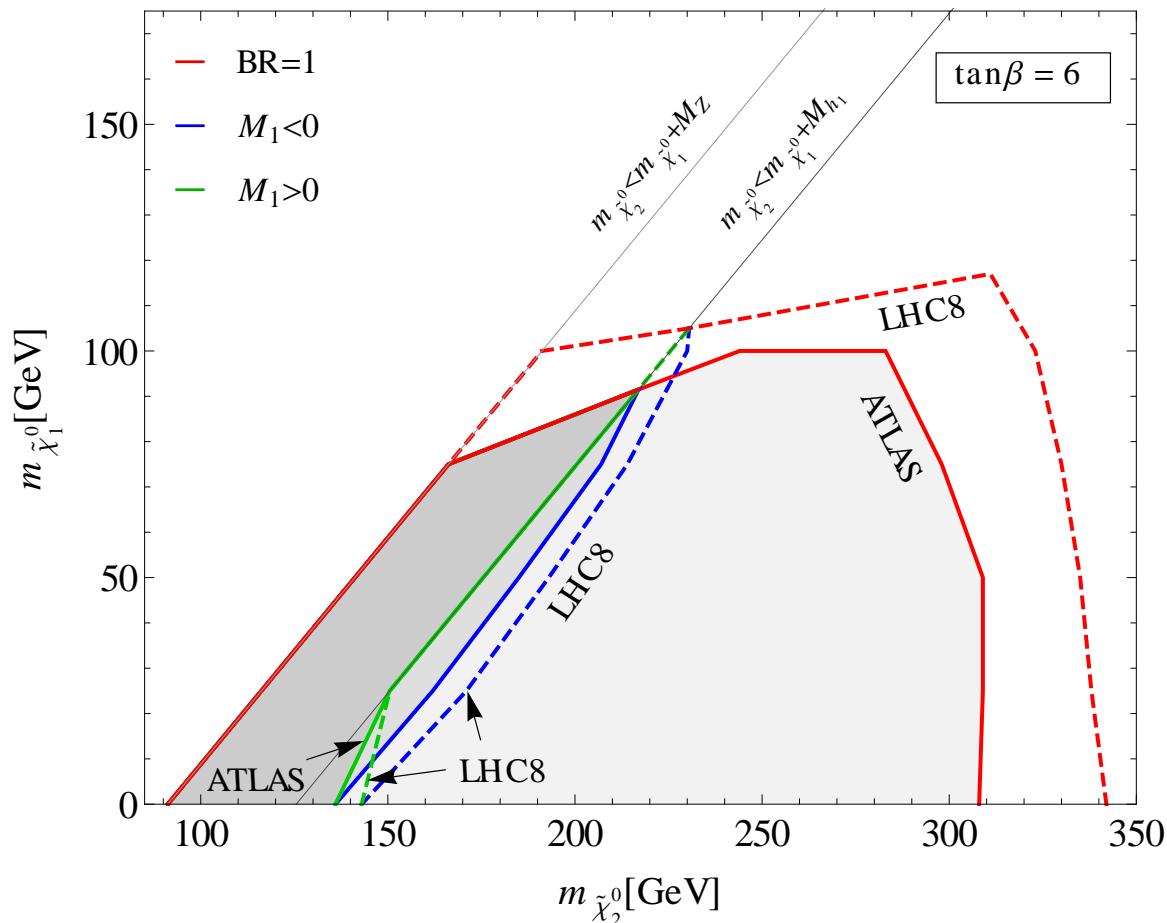
- gaugino-like $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$
- bino-like $\tilde{\chi}_1^0$
- including $(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h_1)$

[Bharucha, Heinemeyer, FP 13]



Chargino/Neutralino searches: ATLAS exclusion limits

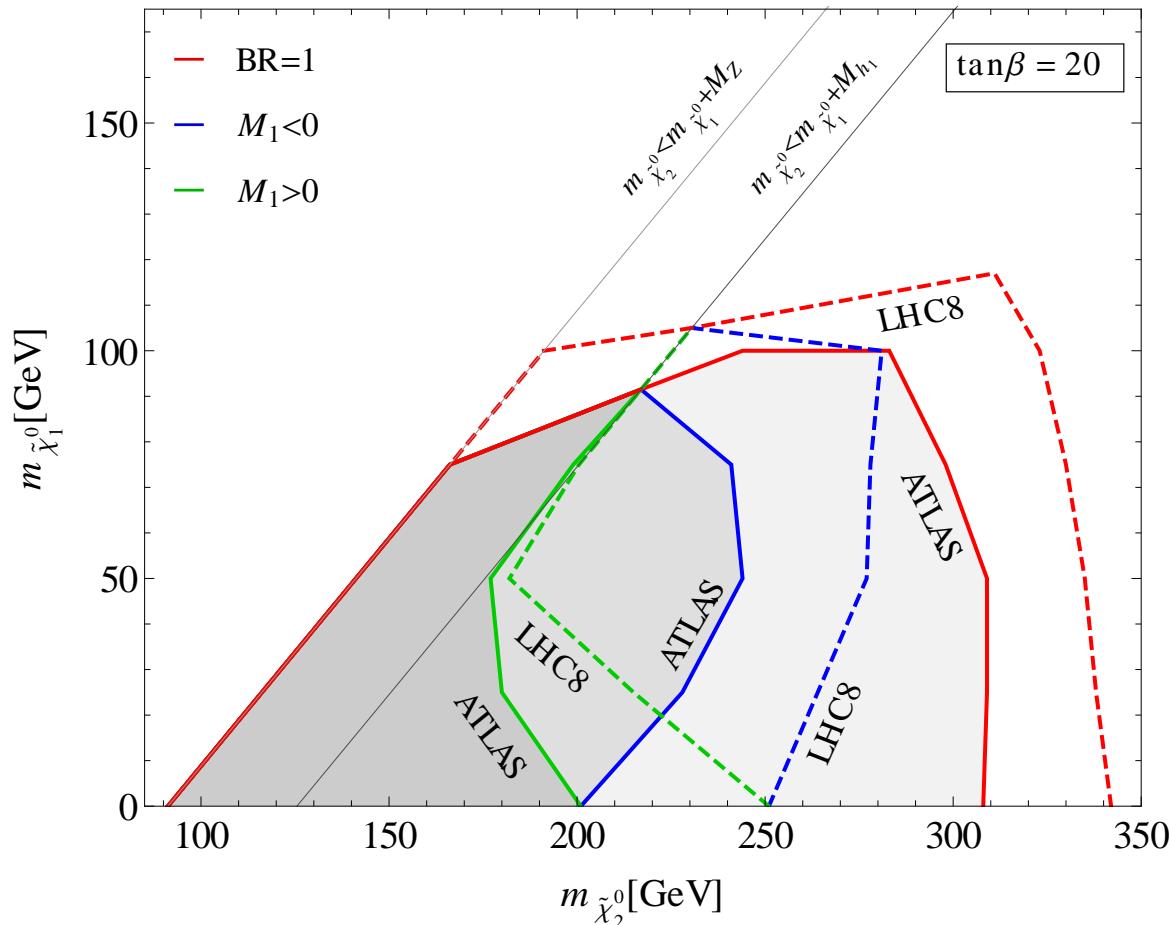
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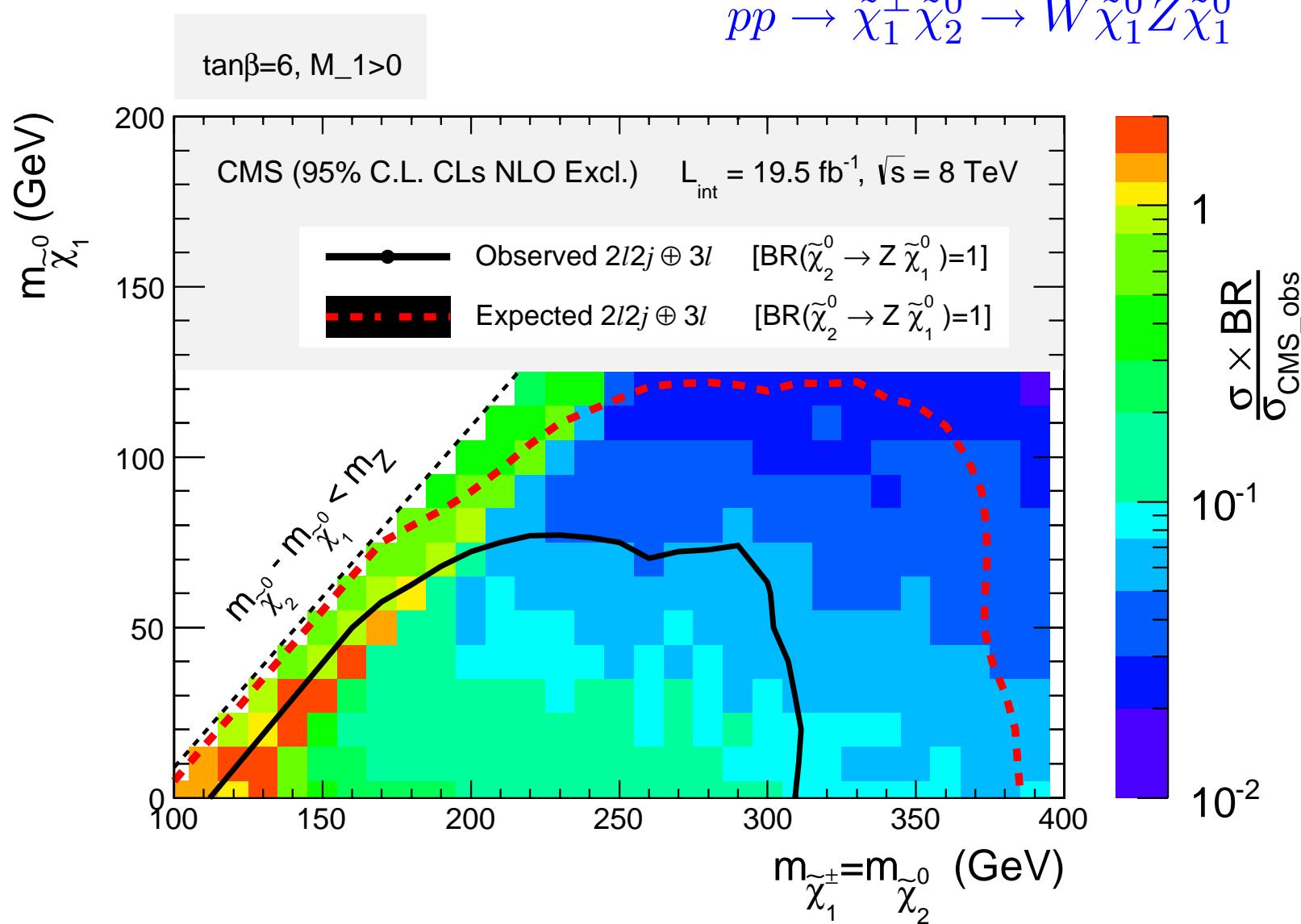
$pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow W \tilde{\chi}_1^0 Z \tilde{\chi}_1^0$ (BR depend on scenario: now $\tan\beta = 20$)



[Bharucha, Heinemeyer, FP 13]

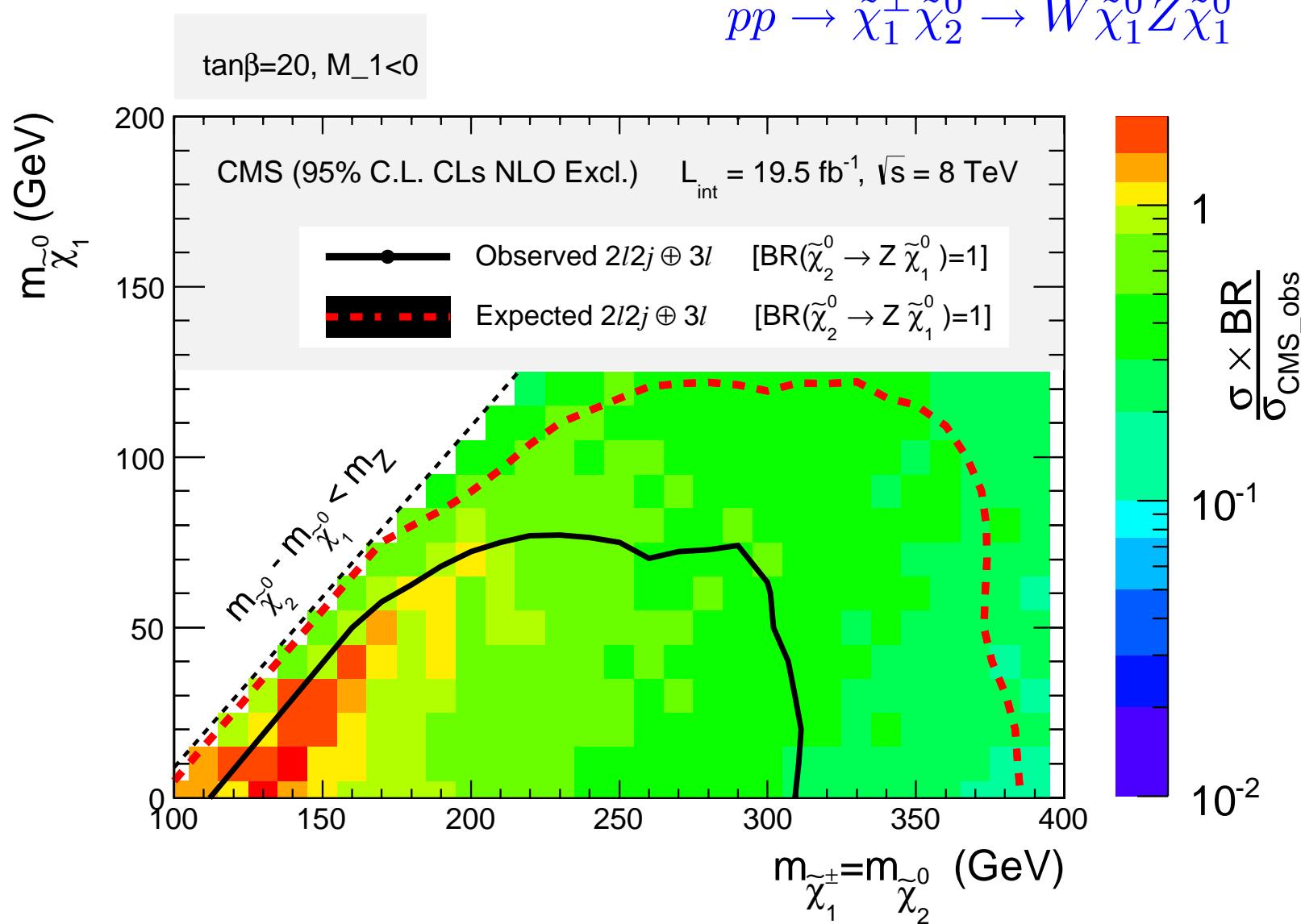
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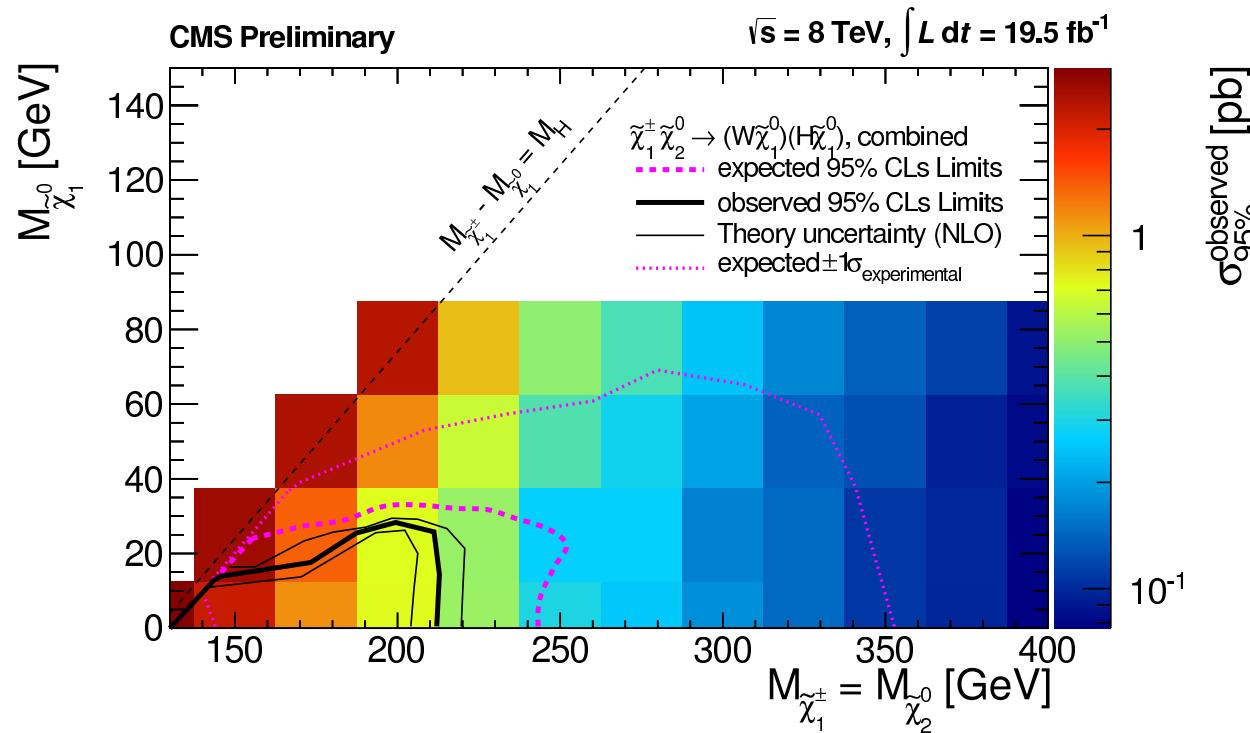
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Chargino/Neutralino searches @LHC: CMS summary

@ SUSY2013: ATLAS & CMS added search of Higgs channel
 $(\text{BR}(\tilde{\chi}_2^0 \rightarrow h_1 \tilde{\chi}_1^0) = 1)$



Any interpretation of limits should combine Z and h_1 channels
→ pheno analysis for boosted Higgs @LHC14 [1309.5966]

SUSY searches @LHC: Summary

Interpret bounds with care (especially for electroweakinos)

- Should consider realistic BR
- Experimental bounds for wino → bino
- compressed spectra ($m_{\tilde{\chi}_2^0} \approx m_{\tilde{\chi}_1^0}$) may be naturally realized
(f.i. higgsino dark matter)
⇒ need the ILC (see f.i. [Berggren et al. 1307.3566])

How good is the ILC?

Expect precision at the $\mathcal{O}(\%)$ level

⇒ need precision calculations to match experimental accuracy!

(see f.i. talk from M.Chera @ECFA DESY13): $\tilde{\chi}_2^0/\tilde{\chi}_1^\pm$ in hadronic
decays to W, Z

- * $\mathcal{L} = 500 \text{ fb}^{-1}$ @500 GeV, $P(e^+e^-) = (30\%, -80\%)$
- * $m_{\tilde{\chi}_1^0} \simeq 115 \text{ GeV}$, $m_{\tilde{\chi}_2^0} \simeq m_{\tilde{\chi}_1^\pm} \simeq 215 \text{ GeV}$
(not excluded by naive ATLAS & CMS searches)
- * $\sigma(\tilde{\chi}_1^+\tilde{\chi}_1^-) \simeq 130 \text{ fb}$, $\sigma(\tilde{\chi}_2^0\tilde{\chi}_2^0) \simeq 23 \text{ fb}$

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Changing $m_{\tilde{\chi}_1^0} < 90 \text{ GeV} \Rightarrow$ decay to h_1 opens up

- * $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h_1$ possibly dominant channel, $h_1 \rightarrow b\bar{b}$ main channel
LC could analyze Higgs-DM interactions w/ high precision

@LC need precision calculations for SUSY

Our framework:

Simultaneous renormalization of the full cMSSM @ one-loop

On-shell renormalization scheme (up to $\tan \beta$, m_b , A_b in $\overline{\text{DR}}$)

Precision calculations: cMSSM @ one-loop

Aim: consistent one-loop calculation of all two-body decay widths and BRs in the cMSSM to be implemented in FeynHiggs

⇒ need consistent renormalization of the full cMSSM

Previous analyses: restricted to single decay channels.

rMSSM: $\Gamma(\tilde{q} \rightarrow q \tilde{\chi}_j^0)$, @1 loop QCD [Djouadi, Hollik, Junger '96]

rMSSM: $\Gamma(\tilde{q} \rightarrow q \tilde{\chi}_j^0)$, @1 loop [Guasch, Hollik, Sola '01, '02]

rMSSM: $\Gamma(\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_j^0 \ell^+ \ell^-)$, $\Gamma_{\text{Tot}}(\tilde{\chi}_i^0)$, @1 loop, no QCD [Drees, Hollik, Xu '06]

rMSSM: $\Gamma(\tilde{\chi}_i^{\pm/0} \rightarrow W^\pm \tilde{\chi}_j^{0/\mp})$, @1 loop [Liebler, Porod '10]

cMSSM: $\Gamma(\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_j^0 h_k)$, full 1 loop [Fowler, Weiglein, '09]

Precision calculations: cMSSM @ one-loop

Aim: consistent one-loop calculation of all two-body decay widths and BRs in the cMSSM to be implemented in FeynHiggs

⇒ need consistent renormalization of the full cMSSM

Two-body decays in the cMSSM:

\tilde{t} decays [Fritzsche, Heinemeyer, Rerezak, Schappacher '11]

\tilde{g} decays [Heinemeyer, Schappacher '11]

$\tilde{\tau}$ decays [Heinemeyer, Schappacher '12]

$\tilde{\chi}^\pm$ decays [Heinemeyer, Schappacher, FP '11]

$\tilde{\chi}^0$ decays [Bharucha, Heinemeyer, Schappacher, FP '12]

Simultaneous renormalization of the full cMSSM under control!

Calculation of widths and branching ratios

Framework:

- * create all diagrams with FeynArts
 - model file with all counterterms in the cMSSM
`MSSMCT.mod` now included in FeynArts [arXiv:1309.1692]
- * 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)

Renormalization Scheme comparison

- evaluate with FeynArts/FormCalc/LoopTools/FeynHiggs
- for charged processes: include all hard QED diagrams

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

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

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

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

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

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

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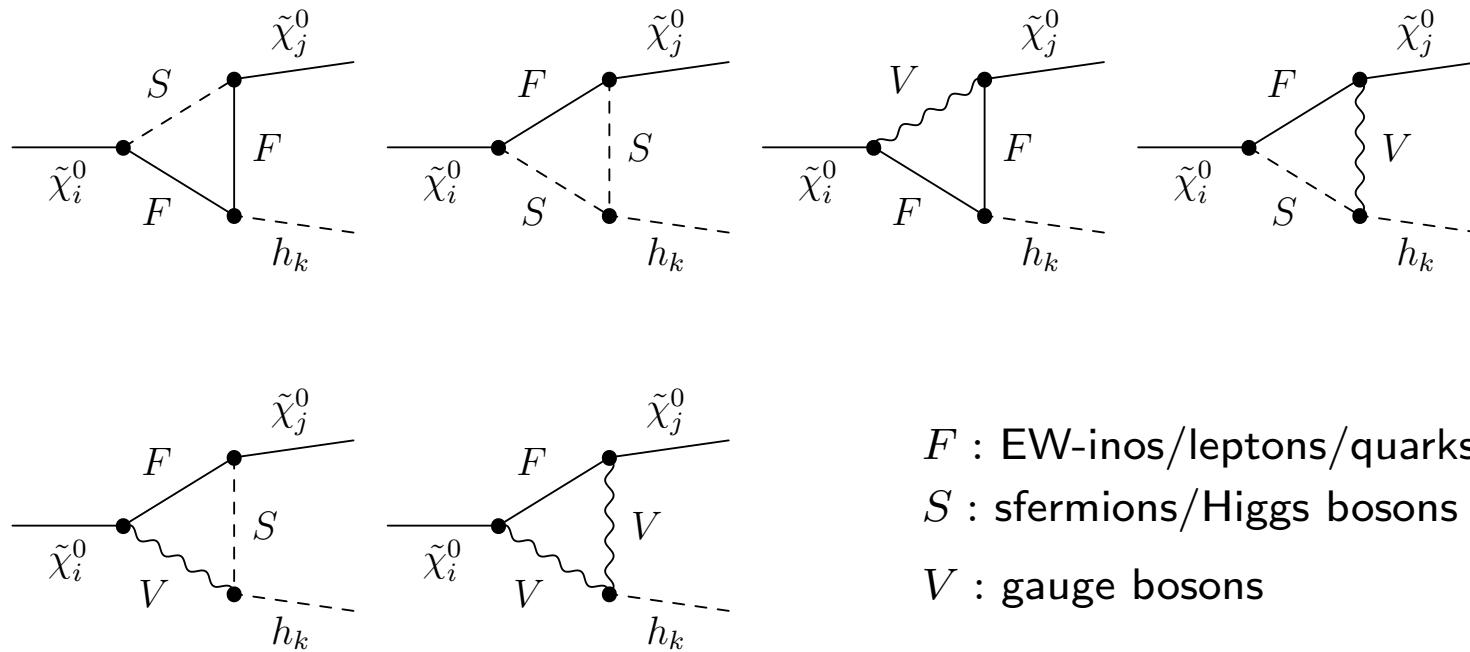
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$$\Gamma(\tilde{\chi}_i^0 \rightarrow \nu_\ell \tilde{\nu}_\ell), \quad i = 1, \dots, 4, \quad \ell = \tau, \mu, e$$

- Numerical comparison of all decay channels in both RS
[Bharucha, Heinemeyer, FP, Schappacher '12]

One loop diagrams: $\tilde{\chi}_4^0 \rightarrow \tilde{\chi}_1^0 h_k$



- evaluate with FeynArts/FormCalc/LoopTools/FeynHiggs
- for charged processes: include all hard QED diagrams

Numerical analysis

Parameters for numerical evaluation

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

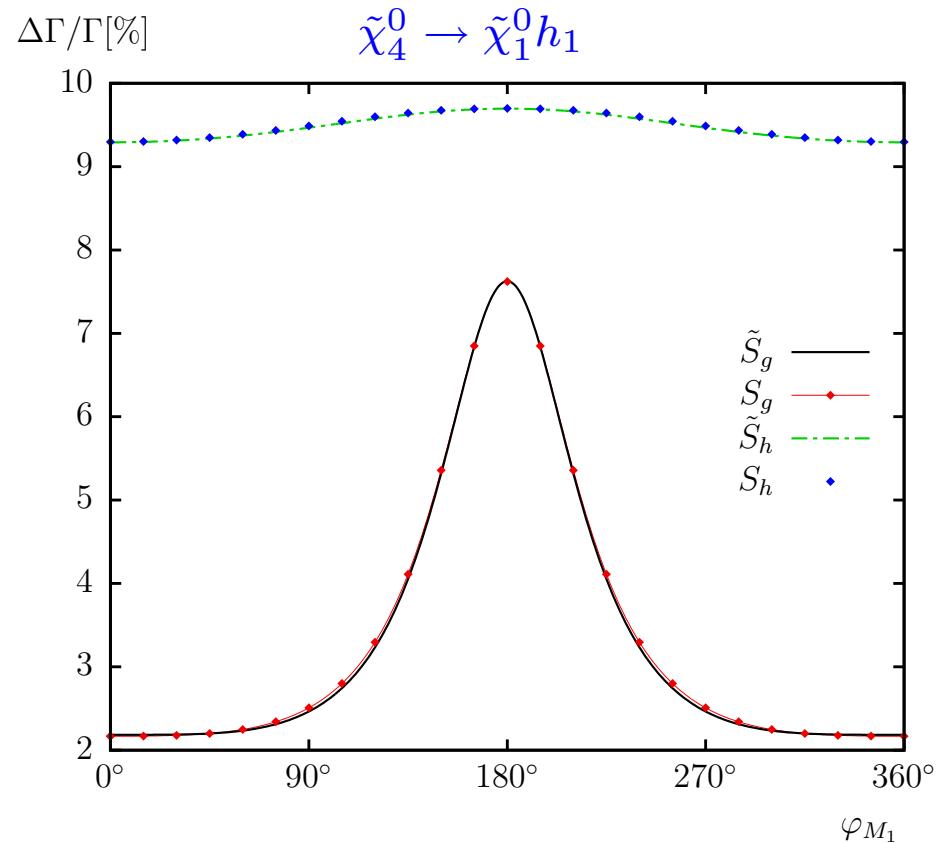
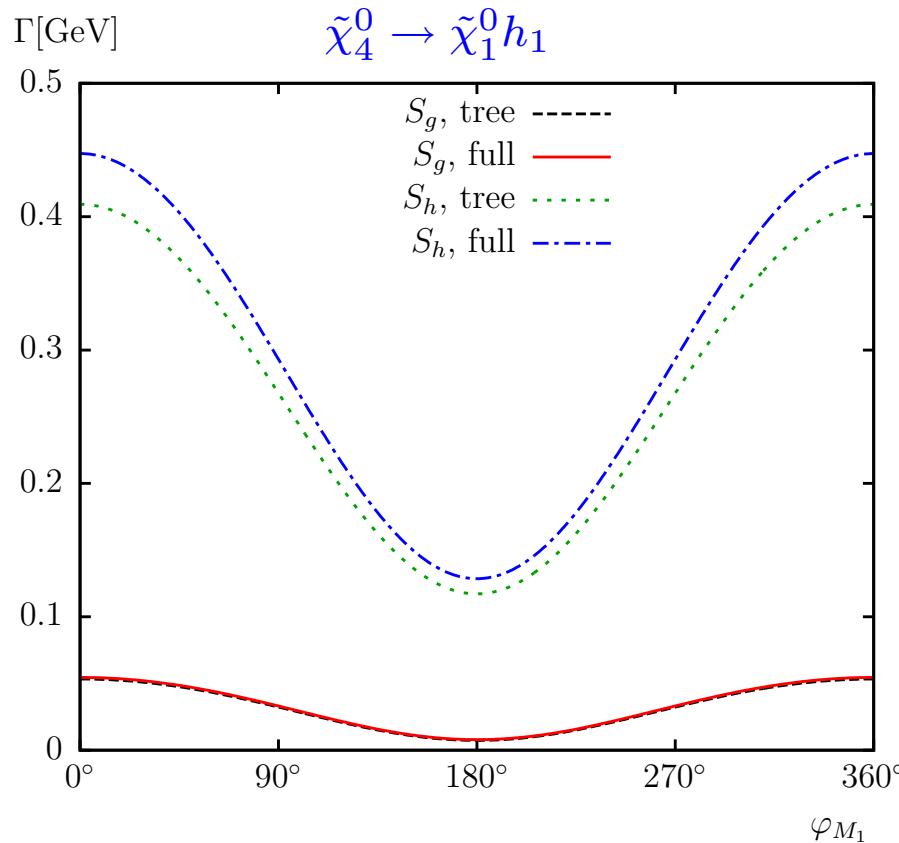
$$S_> = S_h := \{\mu > M_2\} \quad \tilde{\chi}_2^\pm \sim \text{Higgsino-like}$$

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

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

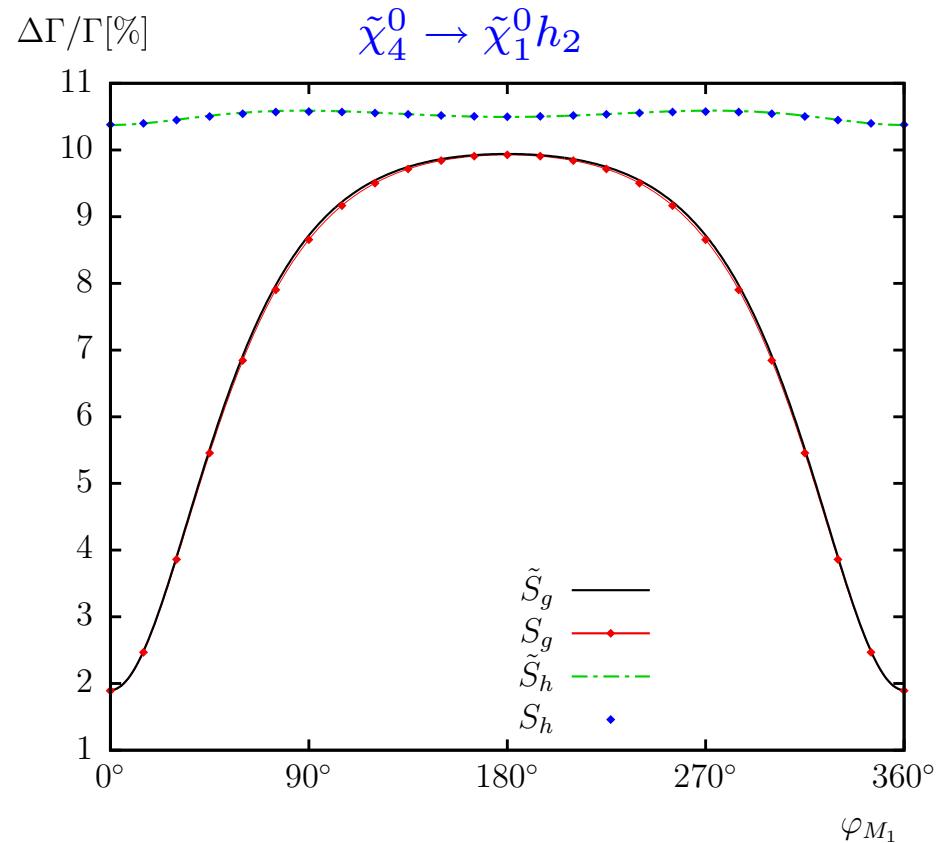
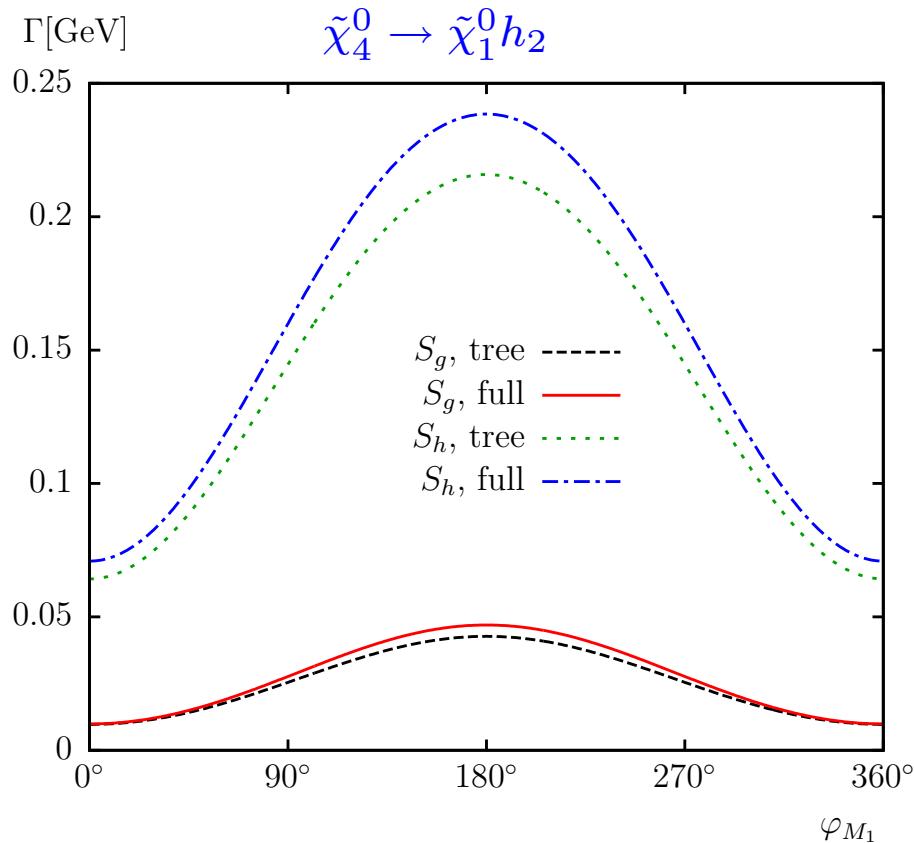
Choice of scenario: so that most neutralino decay channels are open

Neutralino decays: φ_{M_1} -dependence



- ⇒ one-loop corrections under control and non-negligible
- ⇒ size of BR highly scenario dependent
- Very good agreement between RS

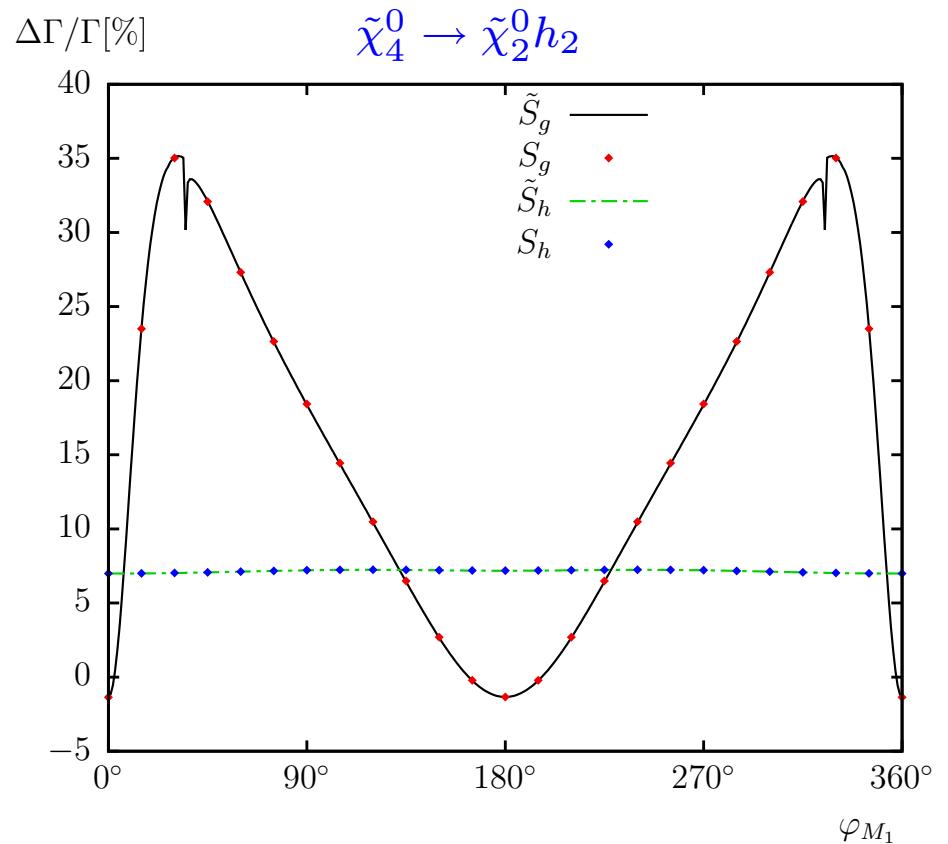
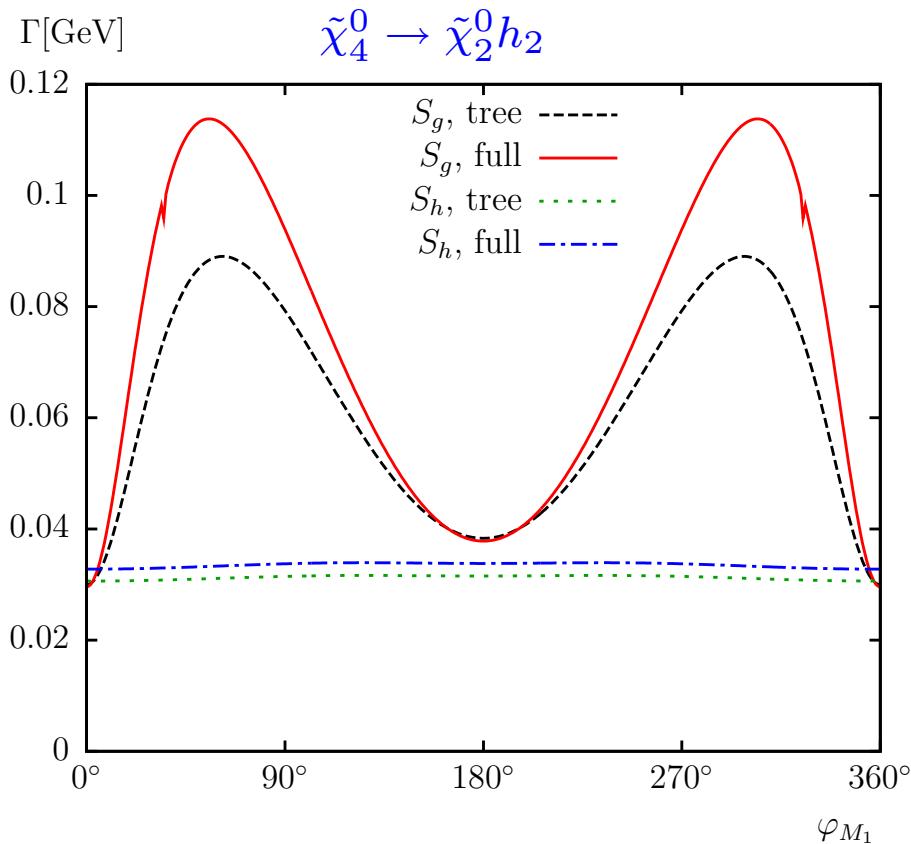
Neutralino decays: φ_{M_1} -dependence



Very good agreement between RS

φ_{M_1} -dependence opposite for h_1 ($\sim h$) and h_2 ($\sim A$) !

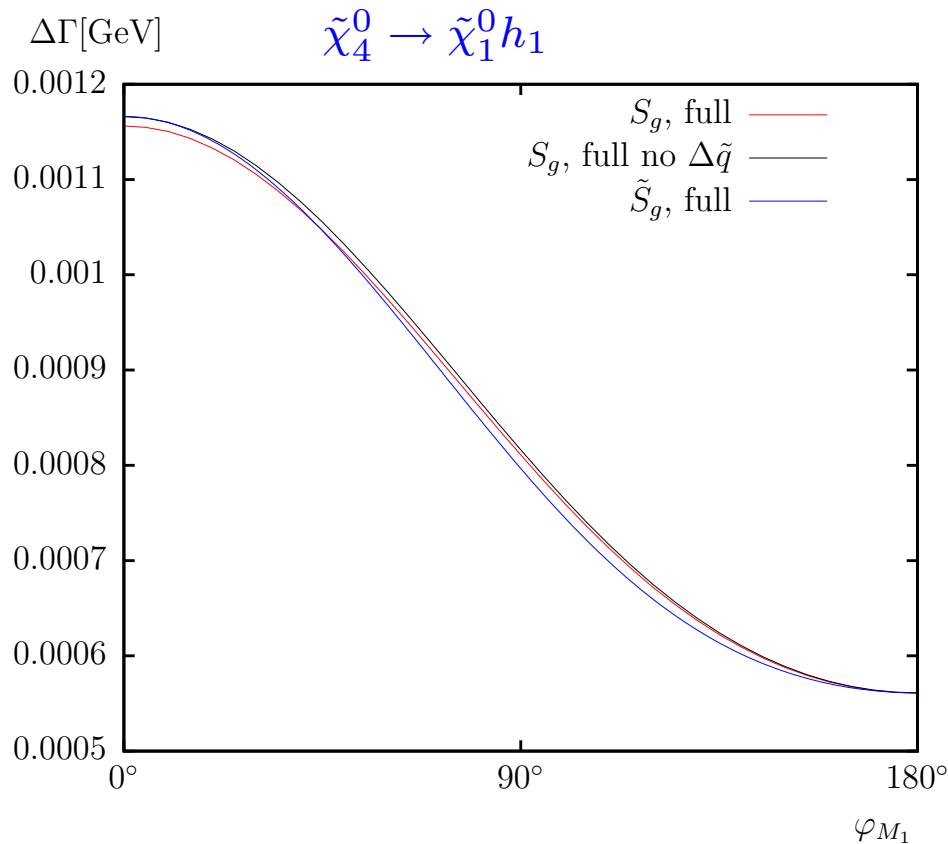
Neutralino decays: φ_{M_1} -dependence



Eventually large corrections to neutralino mixing!

Very good agreement between RS

Neutralino decays: comparison of the schemes



Difference of two-loop order

In CP-conserving limit ($\varphi_{M_1} = 0, \pi$), schemes identical

Recap: chargino and neutralino sectors

Chargino and neutralino mass matrices:

$$\begin{aligned}\mathcal{L}_{\tilde{\chi} \text{mass}} &= (\tilde{W}^\pm \ \tilde{H}^\pm) \cdot \begin{pmatrix} M_2 & \sqrt{2} \sin \beta M_W \\ \sqrt{2} \cos \beta M_W & \mu \end{pmatrix} \cdot \begin{pmatrix} \tilde{W}^\pm \\ \tilde{H}^\pm \end{pmatrix} \\ &+ (\tilde{B}^0 \tilde{W}^0 \tilde{H}_1^0 \tilde{H}_2^0) \cdot \begin{pmatrix} M_1 & 0 & -M_Z s_w \cos \beta & M_Z s_w \sin \beta \\ 0 & M_2 & M_Z c_w \cos \beta & -M_Z c_w \sin \beta \\ -M_Z s_w \cos \beta & M_Z c_w \cos \beta & 0 & -\mu \\ M_Z s_w \sin \beta & -M_Z c_w \sin \beta & -\mu & 0 \end{pmatrix} \cdot \begin{pmatrix} \tilde{B}^0, \\ \tilde{W}^0, \\ \tilde{H}_1^0, \\ \tilde{H}_2^0 \end{pmatrix}\end{aligned}$$

Diagonalization \Rightarrow Higgsinos and gauginos mix:

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

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

Common parameters (M_1, M_2, μ), 2 independent CP

ses

Chargino and neutralino sectors: renormalization

On-shell renormalization (Santander-Karlsruhe Scheme):

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

CCN_j scheme: choose $m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^\pm}, m_{\tilde{\chi}_j^0}$ on-shell $\Rightarrow \delta M_1, \delta M_2, \delta \mu$

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

$$\left[\widetilde{\text{Re}}\hat{\Sigma}_{\tilde{\chi}_j^0}(p) \right]_{jj} \tilde{\chi}_j^0(p) \Big|_{p^2=m_{\tilde{\chi}_j^0}^2} = 0,$$

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

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

CCN: masses of charged particles as input to avoid IR divergencies

Chargino and neutralino sectors: renormalization

3 masses not fixed by OS conditions:

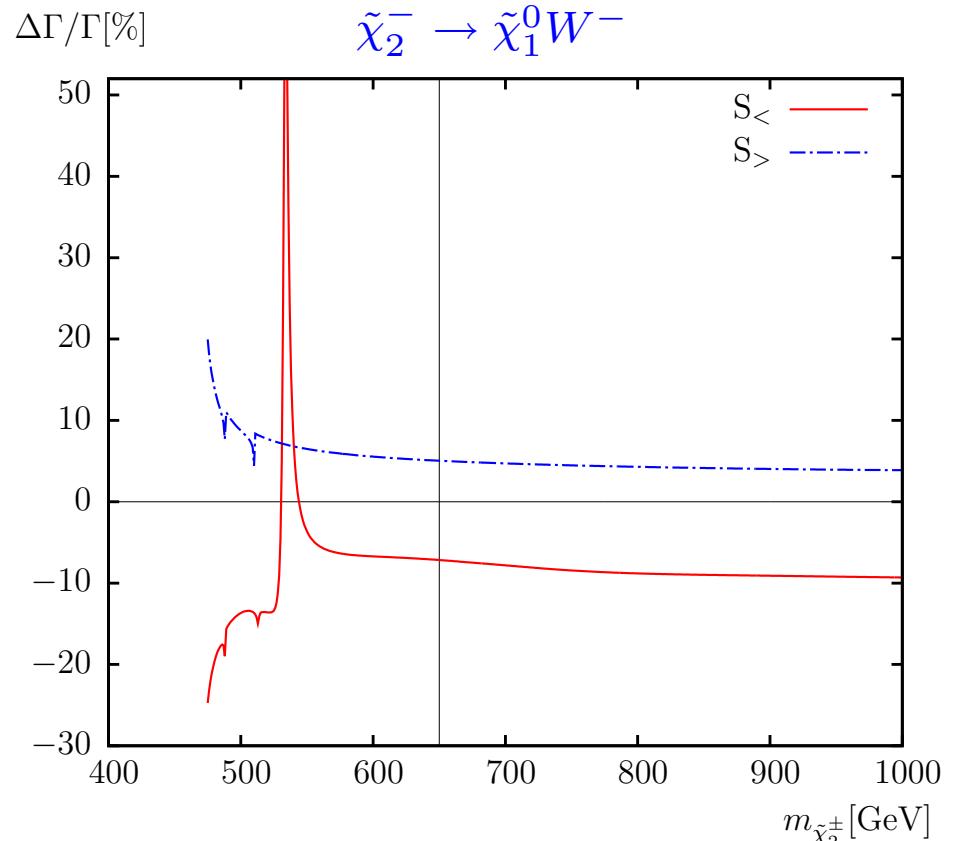
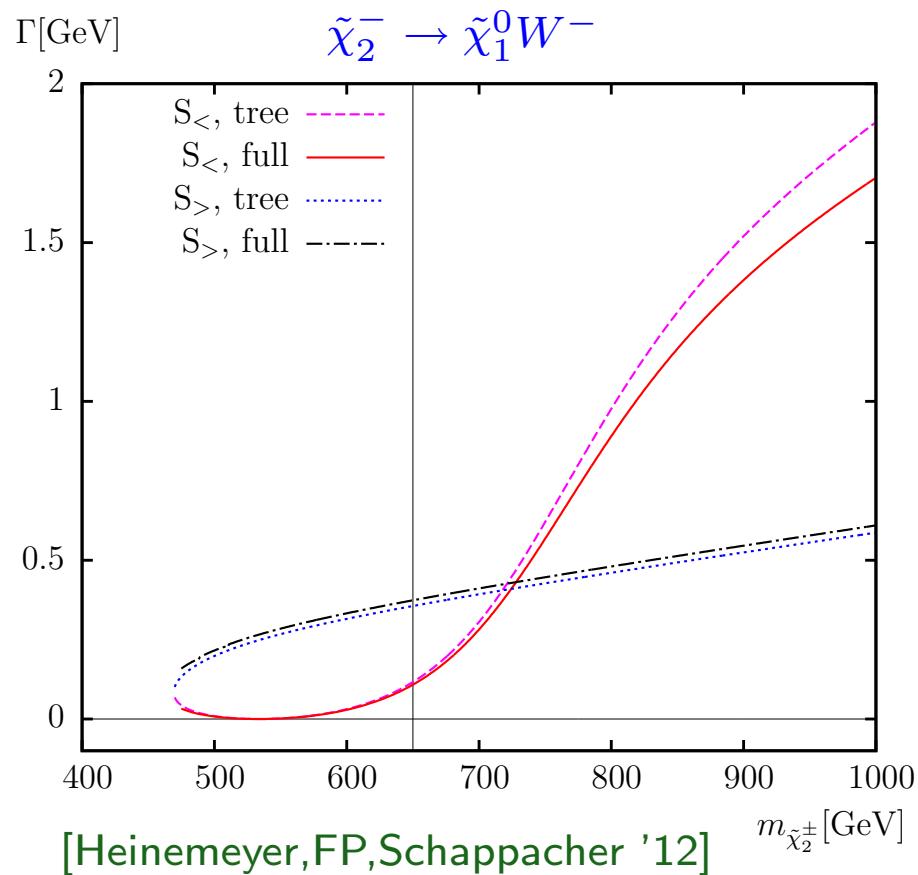
Mass shifts (in CCN₁ Scheme)

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

$$\Delta m_{\tilde{\chi}_j^0} = -\frac{1}{2} \text{Re} \left\{ \widetilde{\text{Re}} \left[m_{\tilde{\chi}_j^0} \hat{\Sigma}_{\tilde{\chi}_j^0}^L(m_{\tilde{\chi}_j^0}^2) + \hat{\Sigma}_{\tilde{\chi}_j^0}^{SL}(m_{\tilde{\chi}_j^0}^2) + (L \leftrightarrow R) \right] \right\}$$

Shift masses of neutral particles to avoid IR-divergencies
(formally of higher order)

Chargino decays



- ⇒ one-loop corrections under control and non-negligible
- ⇒ in $|\mu| \approx |M_2|$ region need different choice of input parameters

Chargino and neutralino sectors: renormalization

- On-Shell scheme have num. instabilities for some parameters:
no fundamental problem \Rightarrow need alternative RS conditions
- Pert. expansion converges better if
starting point lies near true solution
 \Rightarrow appropriate RS conditions depend on parameter point

Chargino and neutralino sectors: renormalization

CCN_j scheme: ($m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^\pm}, m_{\tilde{\chi}_j^0}$ on-shell)

Mass shifts at one-loop

$$m_{\tilde{\chi}_k^0} = m_{\tilde{\chi}_k^0}^{(0)} + \Delta m_{\tilde{\chi}_k^0}, \quad (k \neq j)$$

Shift masses of neutral particles to avoid IR-divergencies
(formally of higher order)

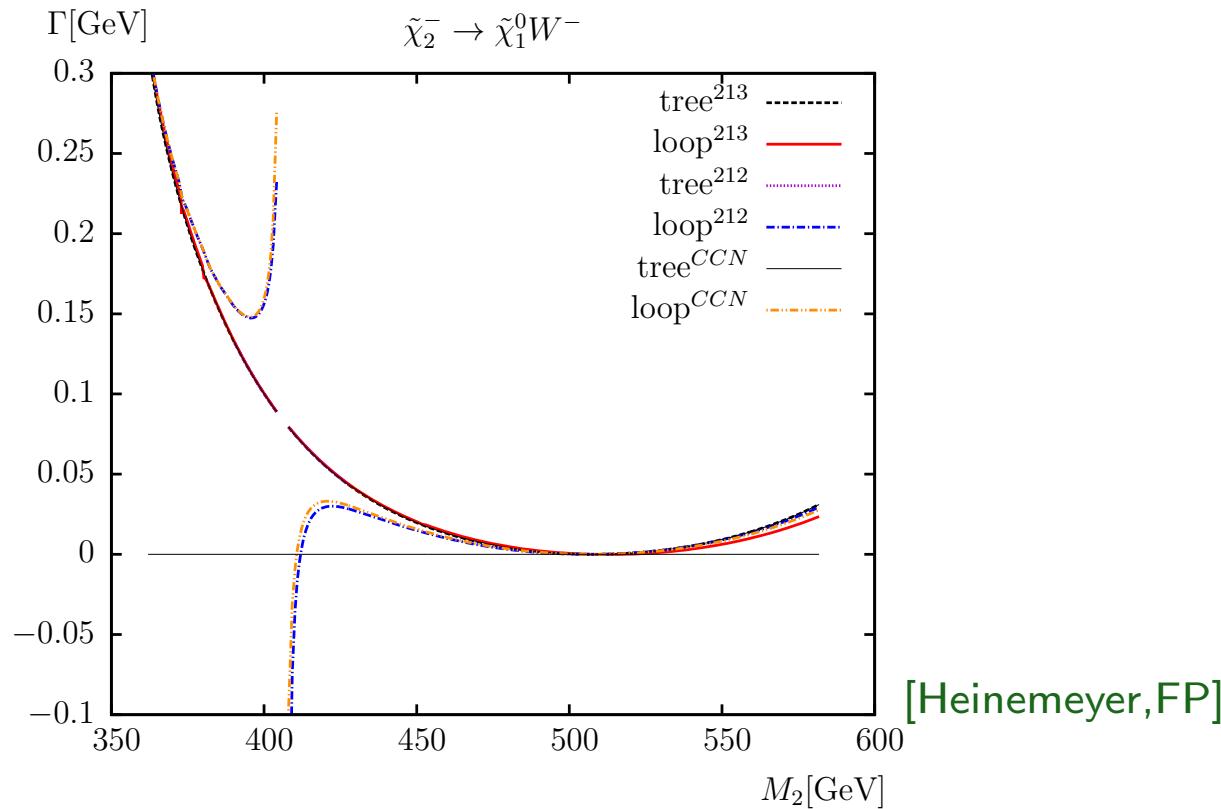
CNN_{i,j,k} scheme: ($m_{\tilde{\chi}_i^\pm}, m_{\tilde{\chi}_j^0}, m_{\tilde{\chi}_k^0}$ on-shell)

Finite mass shifts for one chargino, two neutralinos

Shift mass of chargino only if not an external particle!

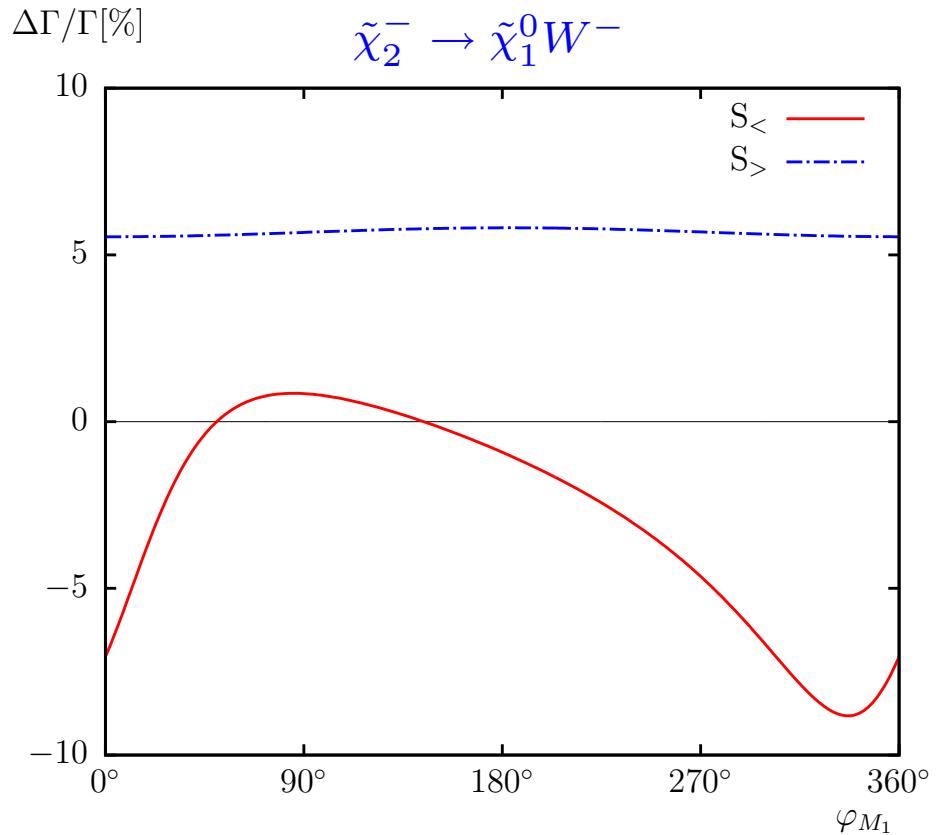
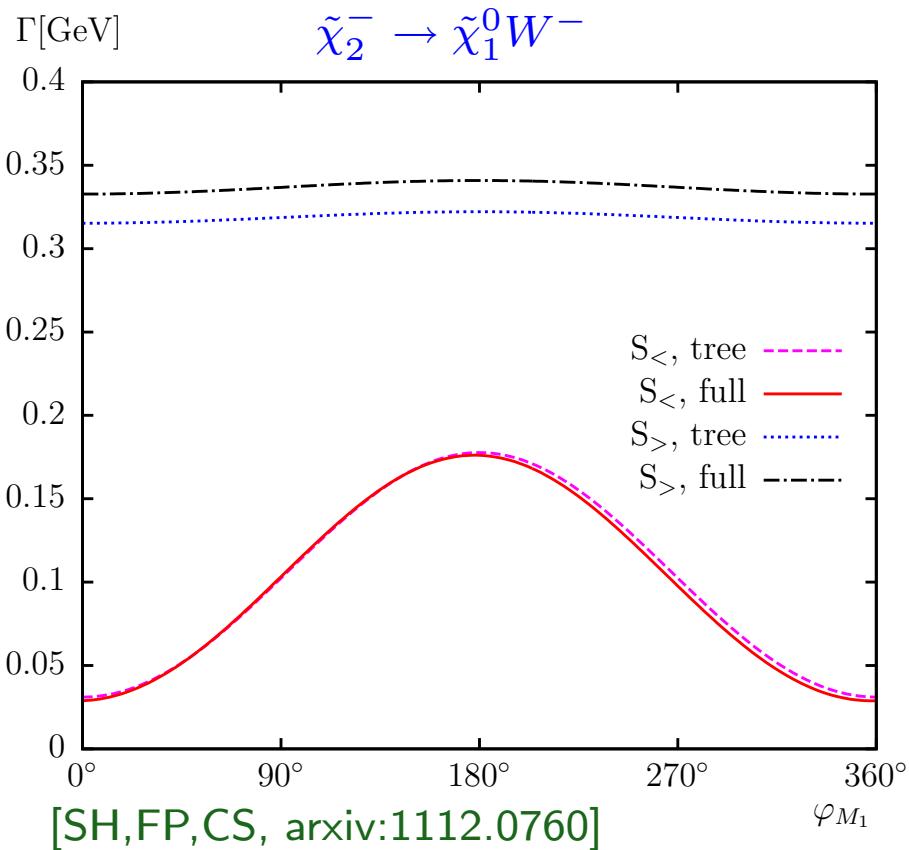
Renormalization schemes: matching

no on-shell scheme works everywhere: here $\mu \simeq M_2$ region
test convergence of perturbative expansion



- different schemes \Rightarrow theory uncertainty of phys. processes
- implement results in HepTools: matching of Ren.Schemes

Chargino decays: φ_{M_1} -dependence



- ⇒ one-loop corrections under control and non-negligible
- ⇒ absorptive contributions → CP violating effects

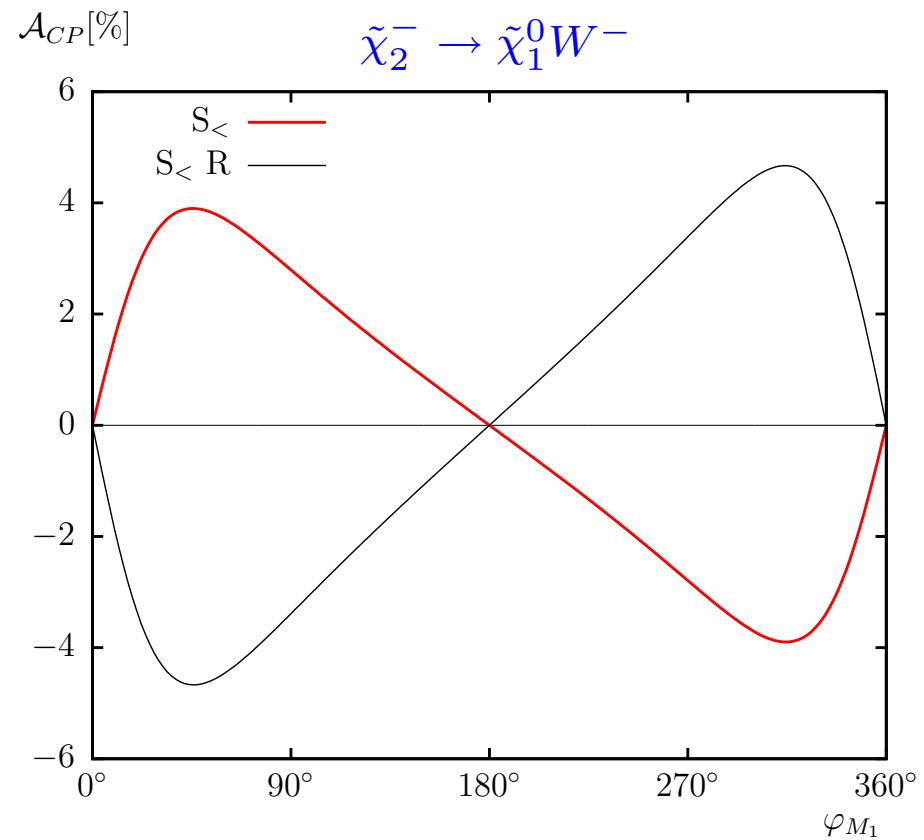
Chargino decays: φ_{M_1} -dependence: \mathcal{CP} Asymmetry

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

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

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

absorptive contributions
and complex couplings



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

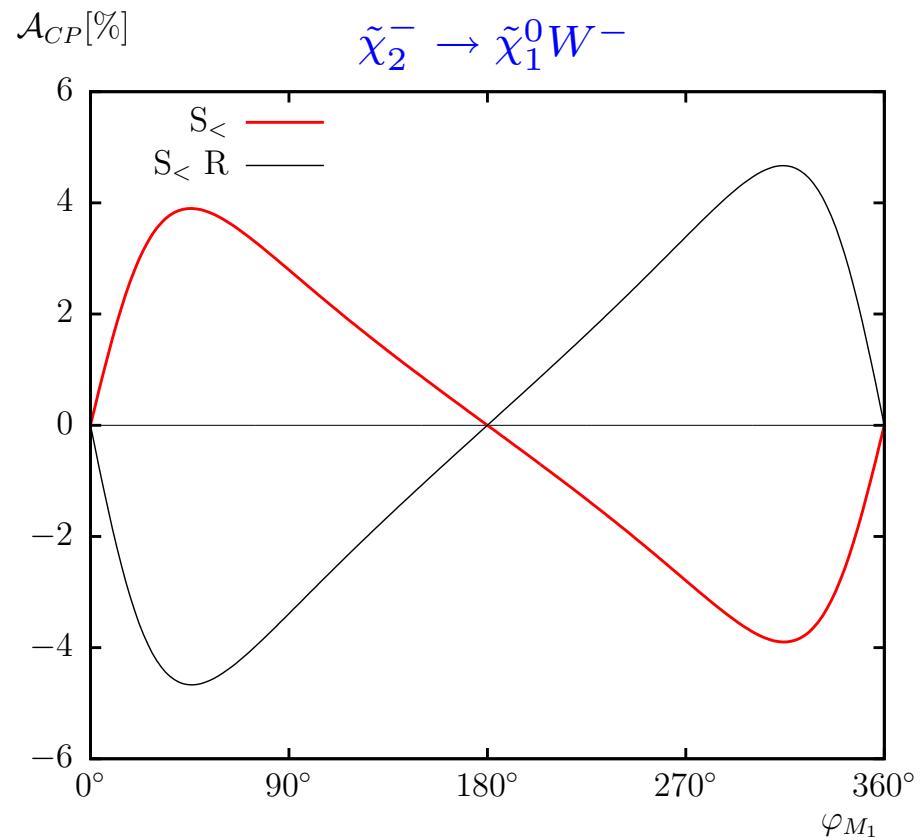
$$\mathcal{A}_{\mathcal{CP}} = \frac{\Gamma(\tilde{\chi}_2^- \rightarrow \tilde{\chi}_1^0 W^-) - \Gamma(\tilde{\chi}_2^+ \rightarrow \tilde{\chi}_1^0 W^+)}{\Gamma(\tilde{\chi}_2^- \rightarrow \tilde{\chi}_1^0 W^-) + \Gamma(\tilde{\chi}_2^+ \rightarrow \tilde{\chi}_1^0 W^+)}$$

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

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

absorptive contributions
and complex couplings

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



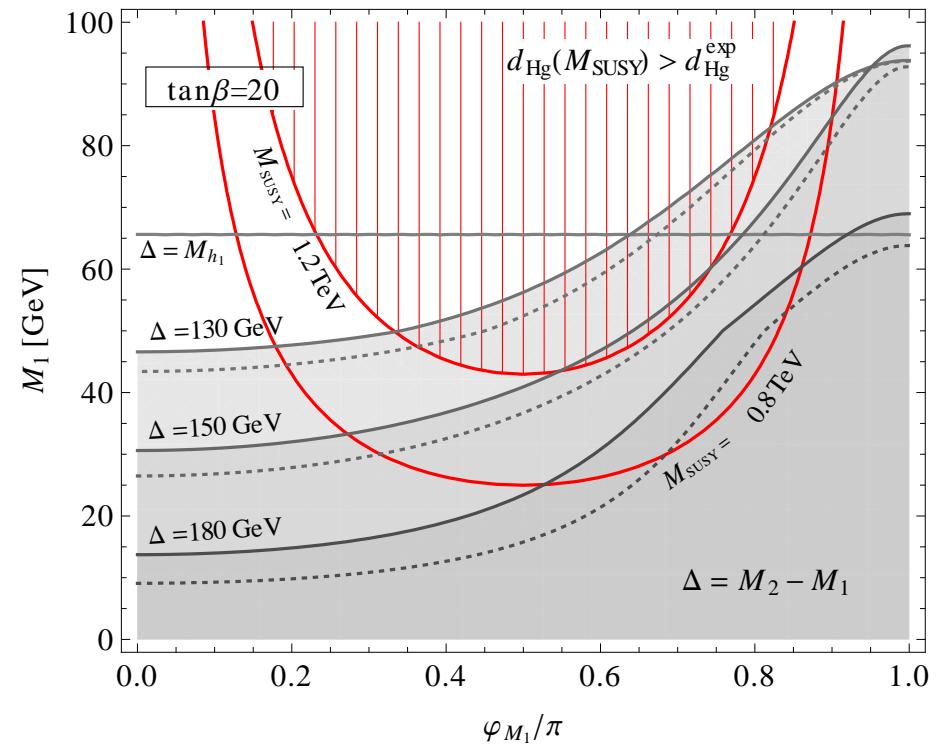
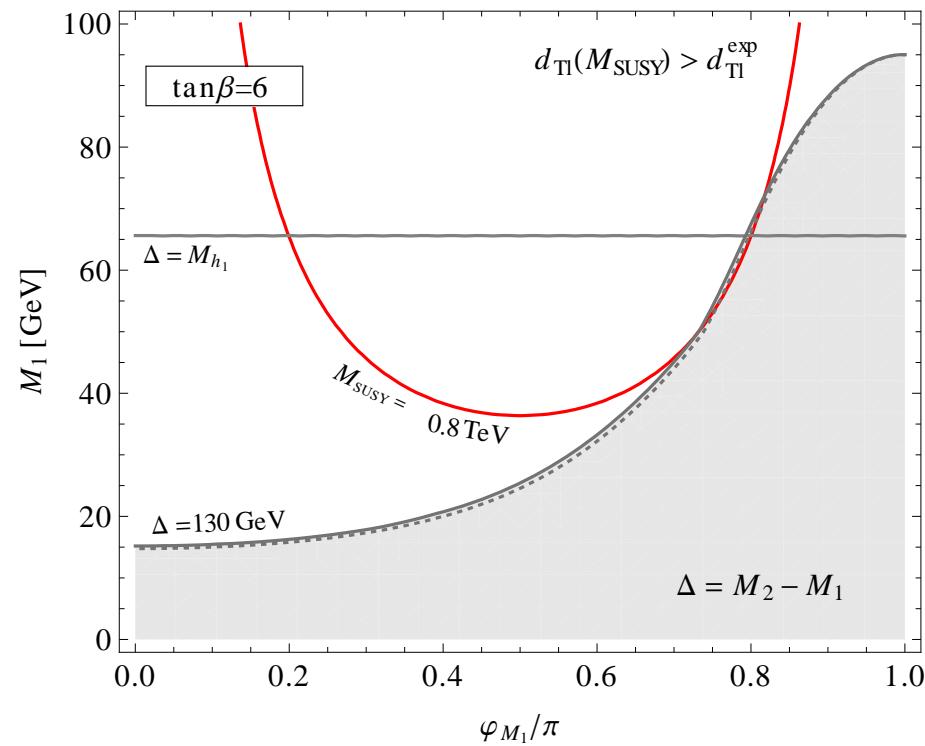
Conclusions

- LHC: EWkino bounds still weak
- DM production @ LC: need precision calculations
- Consistent framework for 1-loop calculations in the complex MSSM
 - * Chargino/Neutralino: compared two on-shell RS
→ perfect agreement
 - * loop corrections for EW decays of $\sim 10\%$
 - * FeynArts modelfile as public code: MSSMCT.mod

backup transparencies

Chargino/Neutralino searches: ATLAS exclusion limits

$|M_1| - \varphi_{M_1}$ plane w/ EDM constraints



[Bharucha, Heinemeyer, FP 13]

Chargino and neutralino sectors: renormalization

Unity residuum of renormalized propagator \Rightarrow

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

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

Combine with on-shell conditions ($i = 1, 2, j = 1$) $\Rightarrow \delta M_1, \delta M_2, \delta \mu$ with, f.i.,

$$\delta M_2 = f(U, V, \widetilde{\text{Re}}[\Sigma_{\tilde{\chi}_i^\pm}^{L/R/SL/LR}])$$

\Rightarrow diagonal field renormalization constants

$$\text{Im } \delta Z_{(\tilde{\chi}_i^\pm)^{L/R}} := 0, \quad \text{Im } \delta Z_{(\tilde{\chi}_1^0)^{L/R}} := 0$$

Chargino and neutralino sectors: renormalization

Off-diagonal renormalized self energies:

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

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

⇒ fix off-diagonal field RC

Chargino and neutralino sectors: renormalization

Mass shifts (in CCN₁ Scheme)

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

$$\Delta m_{\tilde{\chi}_j^0} = -\frac{1}{2} \text{Re} \left\{ \widetilde{\text{Re}} \left[m_{\tilde{\chi}_j^0} \hat{\Sigma}_{\tilde{\chi}_j^0}^L(m_{\tilde{\chi}_j^0}^2) + \hat{\Sigma}_{\tilde{\chi}_j^0}^{SL}(m_{\tilde{\chi}_j^0}^2) + (L \leftrightarrow R) \right] \right\}$$

Shift masses of neutral particles to avoid IR-divergencies
(formally of higher order)

Chargino and neutralino sectors: renormalization

Scheme II (Durham-Hamburg): Take real part only:

$$[\text{Re} \hat{\Sigma}_{\tilde{\chi}_i^\pm}(p)]_{ii} \tilde{\chi}_i^\pm(p) \Big|_{p^2=m_{\tilde{\chi}_i^\pm}^2} = 0, \quad (i = 1, 2),$$

$$[\text{Re} \hat{\Sigma}_{\tilde{\chi}_1^0}(p)]_{ii} \tilde{\chi}_j^0(p) \Big|_{p^2=m_{\tilde{\chi}_1^0}^2} = 0,$$

Only 3 real conditions:

Compute $\delta|M_1|, \delta|M_2|, \delta|\mu|$,

set $\delta\varphi_{M_1} = \delta\varphi_{M_2} = \delta\varphi_\mu = 0$, (phase CT's must be finite)

$\text{Im } \delta\mathbf{Z}(\tilde{\chi}_i^\pm)^{L/R} \neq 0, \text{ Im } \delta\mathbf{Z}(\tilde{\chi}_1^0)^{L/R} \neq 0$

- Ren.Schemes are equal in the rMSSM
- difference of two-loop order → see numerical results