# Why July 4th is celebrated (not only in the US):

# Higgs (and DM) Production from SUSY Decays

*Sven Heinemeyer, IFCA (CSIC, Santander)*

Trieste, 08/2013

based on collaboration with

*A. Bharucha, T. Fritzsche, F. v.d. Pahlen, H. Rzehak, C. Schappacher*

1. Introduction
2. SUSY decays to Higgs bosons
3. Effects on SUSY exclusion regions
4. Conclusions

# 1. Introduction

## Production of SUSY particles at the LHC:

$$pp \to \tilde{\chi}_1^{\pm}\, \tilde{\chi}_2^0 \to W^{\pm}\tilde{\chi}_1^0\, \tilde{\chi}_2^0 \to W^{\pm}\tilde{\chi}_1^0\, h\tilde{\chi}_1^0$$

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Focus here: $h_i$ production

$\tilde{\chi}_1^0$ production $\Rightarrow$ no time ...

## 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

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$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$
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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: $\xi$, $\arg(m_{12})$ $\Rightarrow$ can be set/rotated to zero

Input parameters: (to be determined experimentally)

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

Complex parameters:

– $\mu$ : 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

Effects of complex parameters in the Higgs sector:

Complex parameters enter via loop corrections:

Result:

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

with

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

## More on complex phases: Neutralinos and charginos:

Higgsinos and electroweak gauginos mix

charged:

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

$\Rightarrow$ charginos: mass eigenstates

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

neutral:

$$\underbrace{\tilde{\gamma}, \tilde{Z}}, \tilde{h}_u^0, \tilde{h}_d^0 \to \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$$

$$\tilde{W}^0, \tilde{B}^0$$

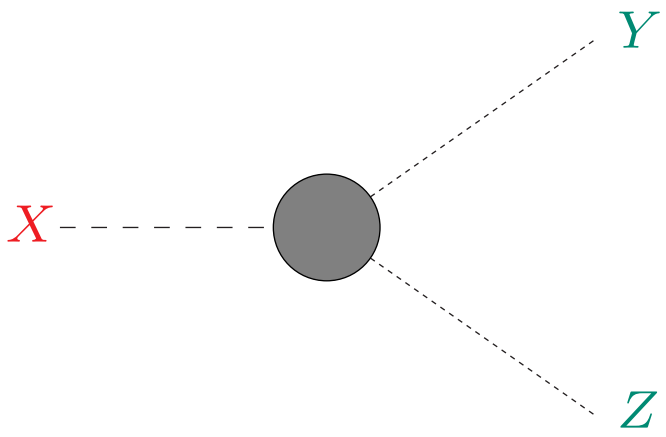
$\Rightarrow$ neutralinos: mass eigenstates

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

$\Rightarrow$ only one new parameter

$\Rightarrow$ MSSM predicts mass relations between neutralinos and charginos

# The bigger picture: SUSY decays in the cMSSM




$\Rightarrow$ to get BRs right $\Rightarrow$ all decays needed

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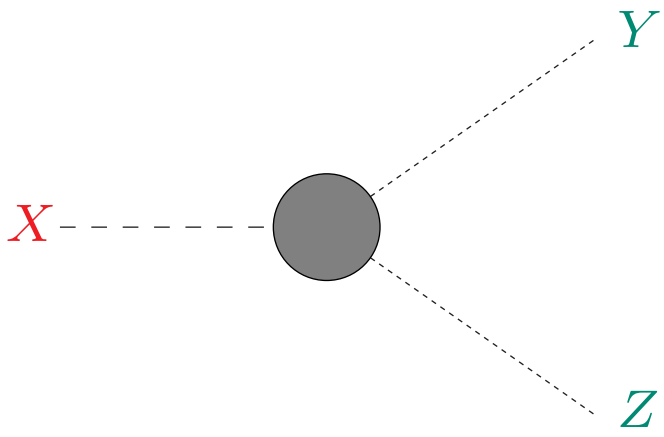


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now ready:

- (heavy) stop, sbottom and stau decays $\Rightarrow$ relevant for Higgs, LSP
- gluino decays
- (non-hadronic) chargino decays $\Rightarrow$ relevant for Higgs, LSP
- (non-hadronic) neutralino decays $\Rightarrow$ relevant for Higgs, LSP

# 2. SUSY decays to Higgs bosons

## 2A) Heavy Stop decays

[*T. Fritzsche, S.H., H. Rzehak, C. Schappacher '11*]

$$\Gamma(\tilde{t}_2 \to \tilde{t}_1 h_i) \qquad (i = 1,2,3) \ ,$$
$$\Gamma(\tilde{t}_2 \to \tilde{t}_1 Z) \ ,$$
$$\Gamma(\tilde{t}_2 \to t\tilde{\chi}_k^0) \qquad (k = 1 \ldots 4) \ ,$$
$$\Gamma(\tilde{t}_2 \to t\tilde{g}) \ ,$$
$$\Gamma(\tilde{t}_2 \to \tilde{b}_i H^+) \qquad (i = 1,2) \ ,$$
$$\Gamma(\tilde{t}_2 \to \tilde{b}_i W^+) \qquad (i = 1,2) \ ,$$
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$\Rightarrow$ but no time . . .

## 2B) Heavy Stau decays

[S.H., C. Schappacher '12]

$$\Gamma(\tilde{\tau}_2 \to \tilde{\tau}_1 h_i) \qquad (i = 1,2,3) \ ,$$
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## 2C) Chargino decays

[S.H., F. v.d. Pahlen, C. Schappacher '12]

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No hadronic decays yet ...

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$$\Gamma(\tilde{\chi}_i^0 \to \tilde{\chi}_j^0 h_k) \qquad (i = 2,3,4;\ j < i;\ k = 1,2,3)\ ,$$
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$$\Gamma(\tilde{\chi}_i^0 \to \bar{\nu}_\ell \tilde{\nu}_\ell / \nu_\ell \tilde{\nu}_\ell^\dagger) \qquad (i = 2,3,4;\ \ell = e,\mu,\tau)\ .$$

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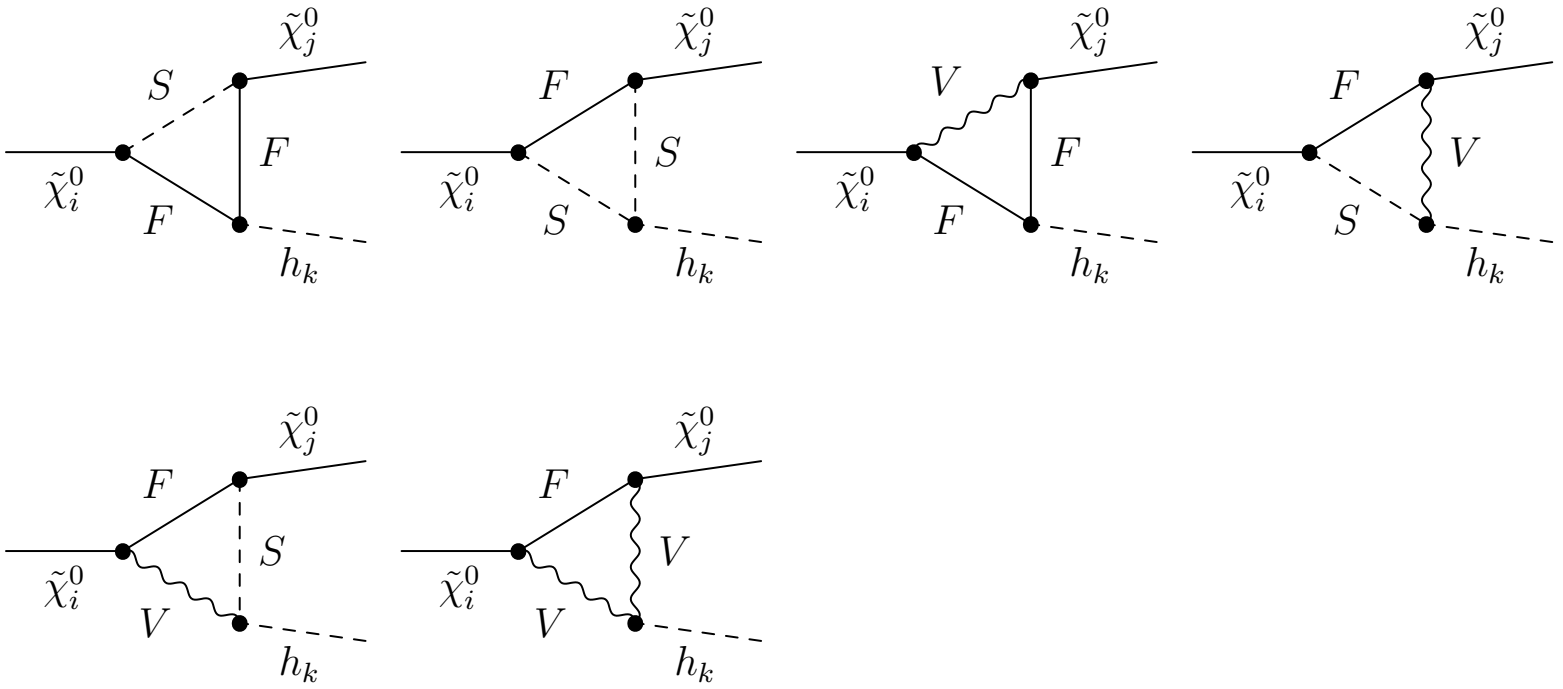
| $\tan\beta$ | $M_{H^\pm}$ | $m_{\tilde{\chi}_2^\pm}$ | $m_{\tilde{\chi}_1^\pm}$ | $M_{\tilde{l}_L}$ | $M_{\tilde{l}_R}$ | $A_l$ | $M_{\tilde{q}_L}$ | $M_{\tilde{q}_R}$ | $A_q$ |
|---|---|---|---|---|---|---|---|---|---|
| 20 | 160 | 600 | 350 | 300 | 310 | 400 | 1300 | 1100 | 2000 |

$\mathcal{S}_h : \mu > M_2$ ($\tilde{\chi}_4^0$ more higgsino-like)

$\mathcal{S}_g : \mu < M_2$ ($\tilde{\chi}_4^0$ more gaugino-like)

# Feynman diagrams for $\tilde{\chi}_i^0 \to \tilde{\chi}_j^0 h_k$

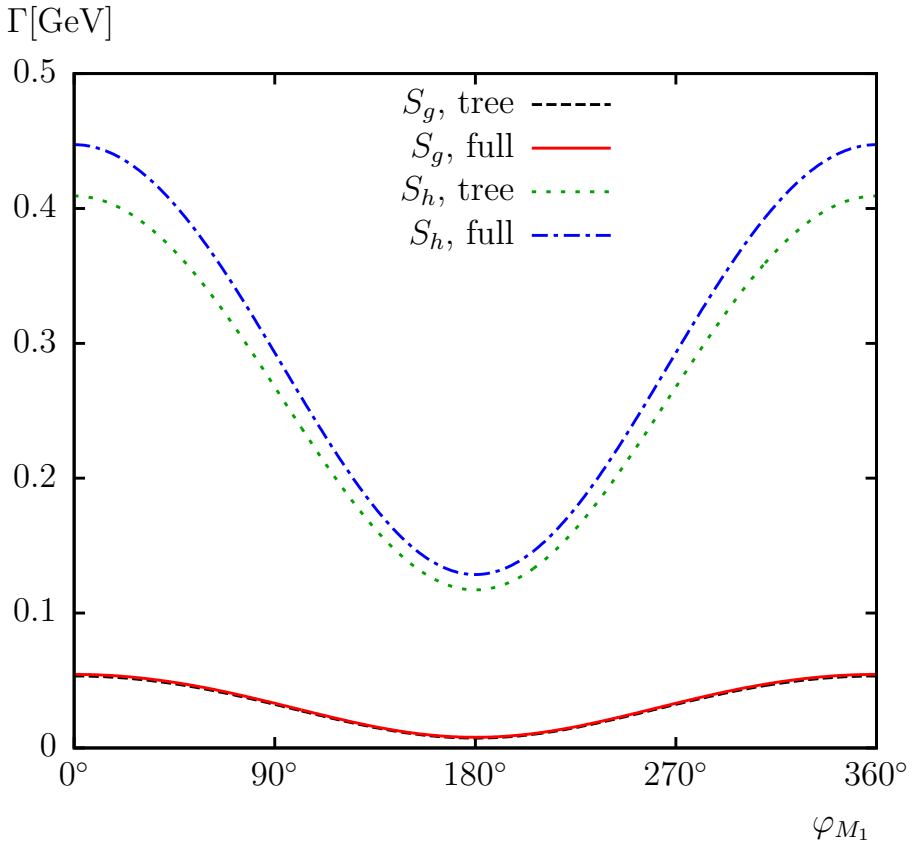


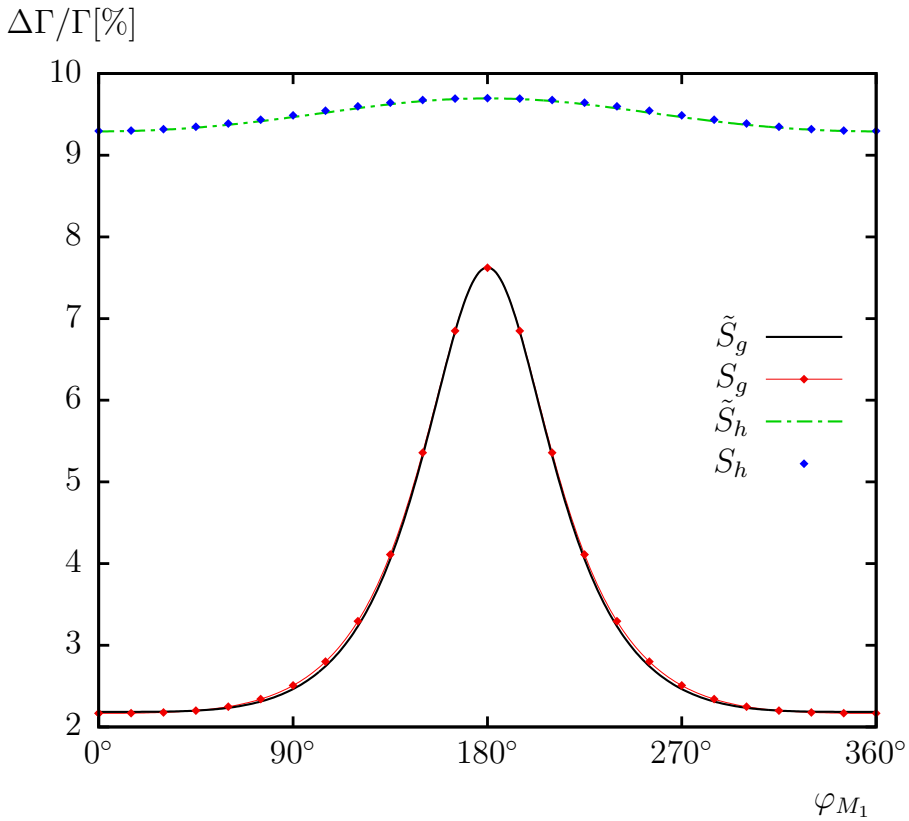

– including $Z$–$A$ or $G$–$A$ transition contribution on the external Higgs boson leg

– including all soft/hard QED diagrams

# $\Gamma(\tilde{\chi}_4^0 \to \tilde{\chi}_1^0 h_1)$: dependence on $\varphi_{M_1}$

[*A. Bharucha, S.H., F. v.d. Pahlen, C. Schappacher '12*]



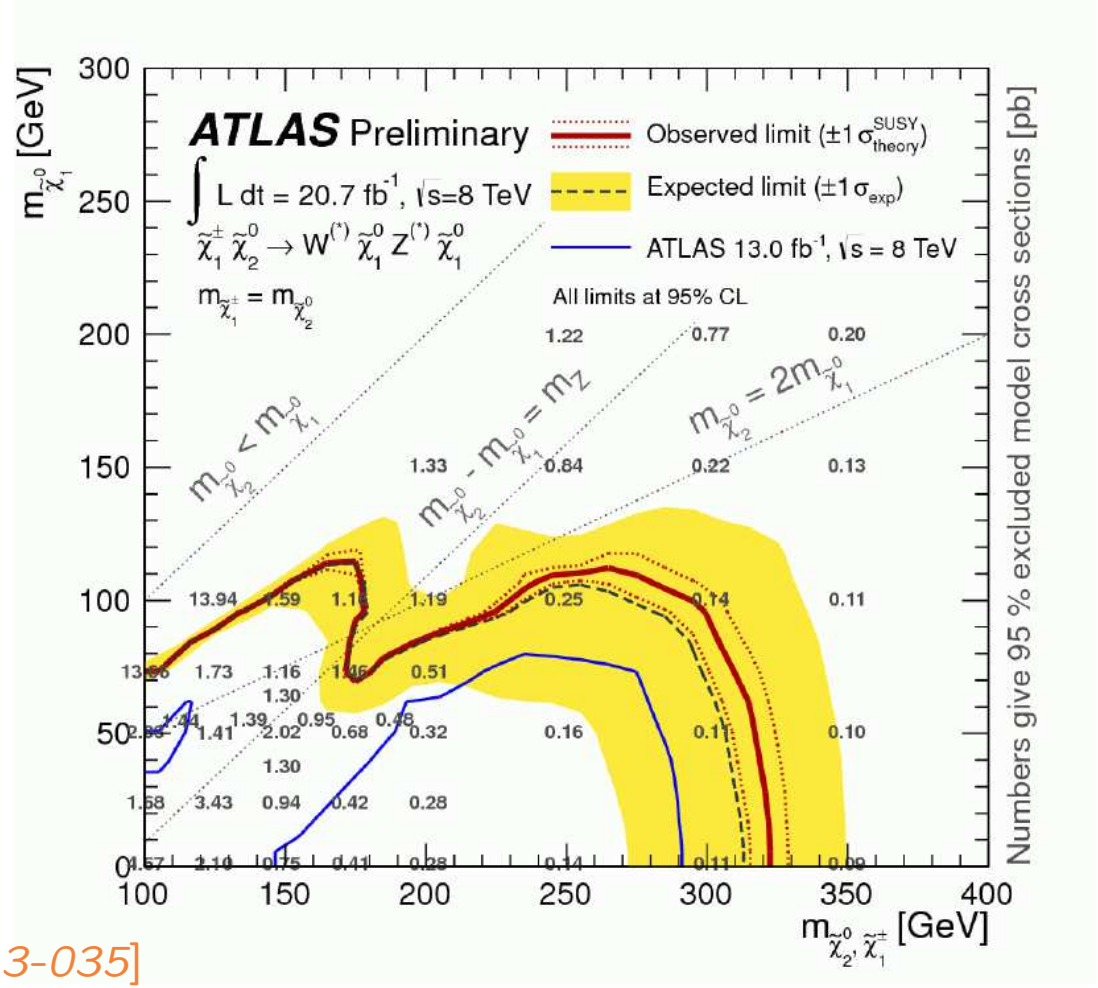

$\Rightarrow$ one-loop corrections under control and non-negligible

$\Rightarrow$ size of BR highly scenario dependent

# 3. Effects on SUSY exclusion regions

$(g-2)_\mu$ tells us: there should be light EW SUSY particles!

LHC is looking for $pp \to \tilde{\chi}_1^\pm \, \tilde{\chi}_2^0 \to W^\pm \tilde{\chi}_1^0 \, Z \tilde{\chi}_1^0$




[ATLAS-CONF-2013-035]

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## Procedure:

based on [*ATLAS-CONF-2013-035*]

- start with ATLAS scenario
  ($M_{\mathrm{SUSY}} = 2000$ GeV, $\mu = 1000$ GeV, $\tan\beta = 6$) $\to$ vary $M_2$ and $M_1$
- use ATLAS result as cross section limit on $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production
- as ATLAS (and CMS): display results in $m_{\tilde{\chi}_2^0}$–$m_{\tilde{\chi}_1^0}$ plane
- compare ATLAS exclusion to "real" exclusion
  including precision calculation for $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h$
- vary parameters: phase of $M_1$, $\tan\beta$, ...

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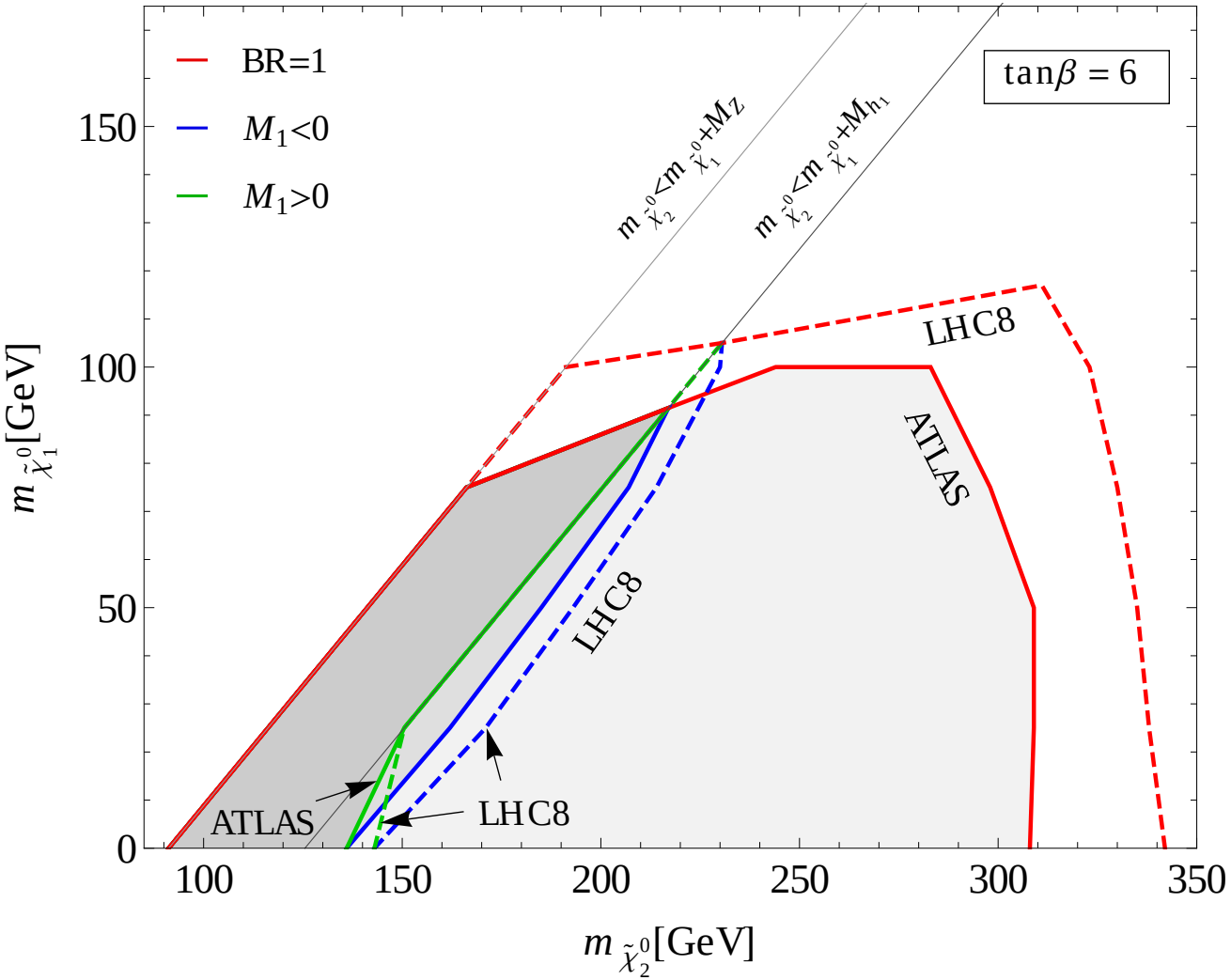
$\Rightarrow$ more details in Aoife's talk on Thursday afternoon

# Comparison of ATLAS vs. "real" exclusion (I)

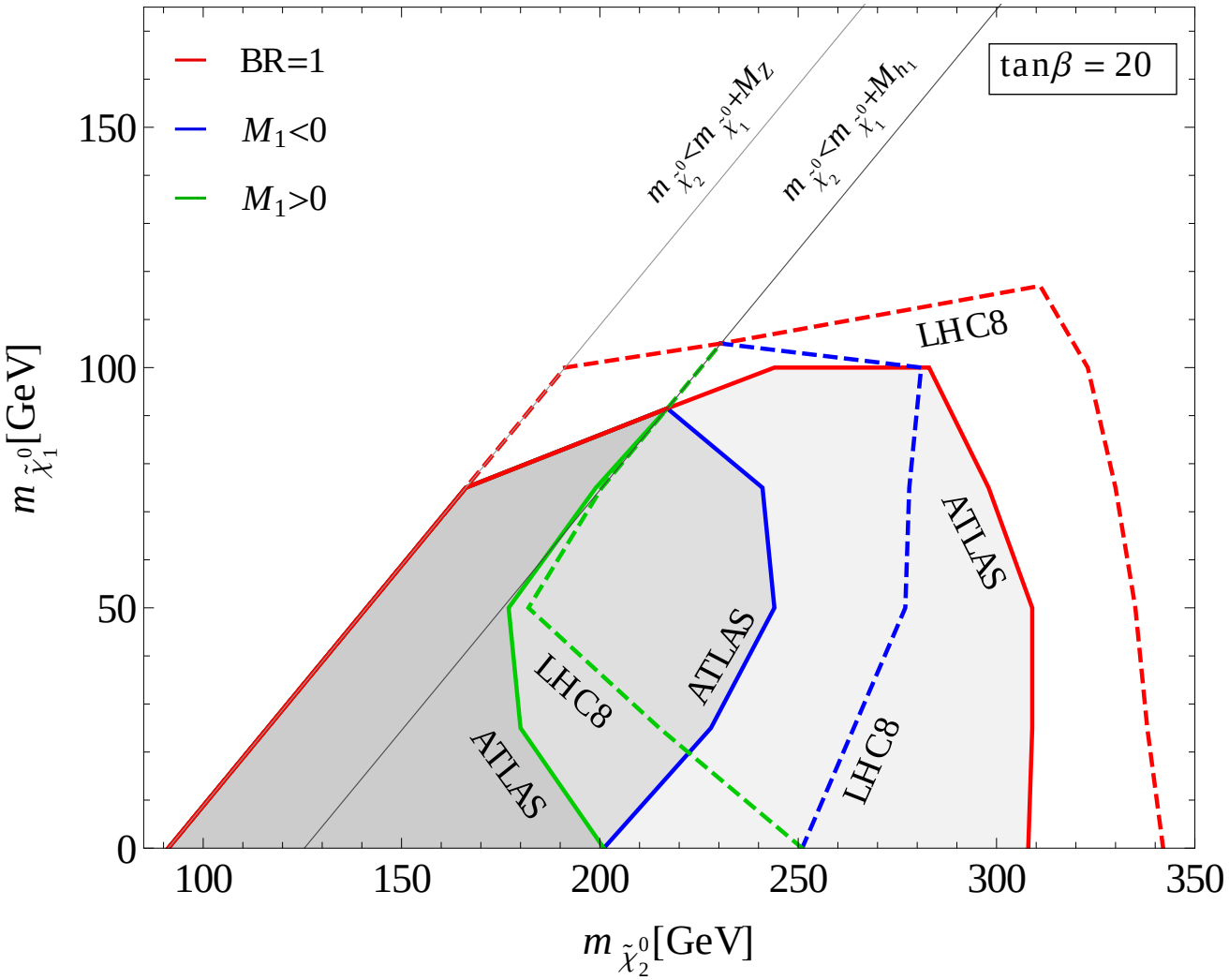
[*A. Bharucha, S.H., F. v.d. Pahlen '13*]




$\Rightarrow$ huge reduction of exclusion region (where $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h$ allowed)

# Comparison of ATLAS vs. "real" exclusion (II)

[*A. Bharucha, S.H., F. v.d. Pahlen '13*]

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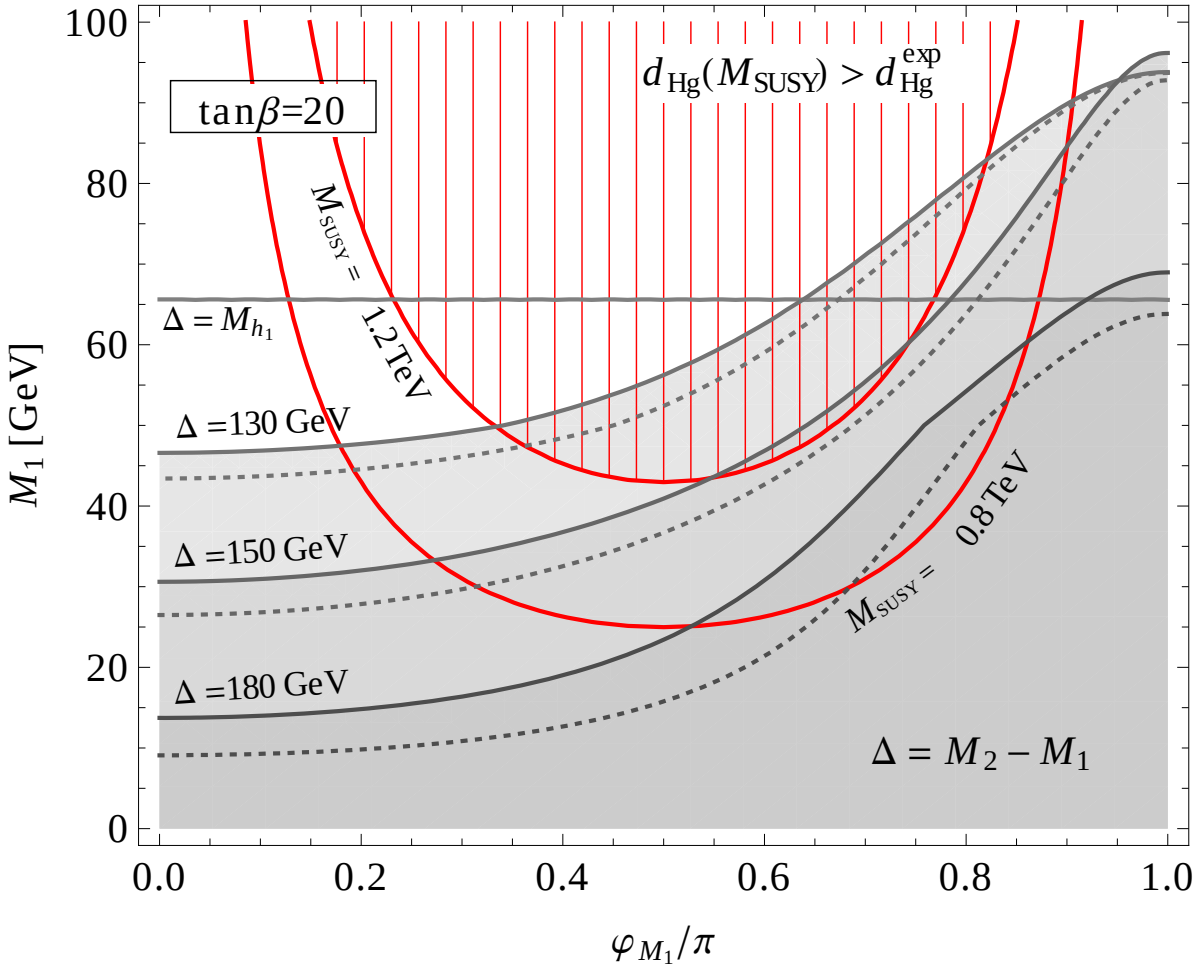
# Effects of complex $M_1$ and higher-order corrections:

[*A. Bharucha, S.H., F. v.d. Pahlen '13*]




$\Delta := M_2 - M_1$, solid: NLO, dotted: tree

$\Rightarrow$ strong phase dependence, NLO not negligible

# 4. Conclusinos

- Needed: reliable prediction for SUSY decays at the LHC/LC

  Of special interest: decays involving Higgs (or LSP)

- Our work: Calculation of decay widths and branching ratios
  - all two-body decays of
    scalar top, scalar bottom, scalar tau, gluino, chargino, neutralino
  - full one-loop (incl. hard QED/QCD radiation)
  - in the complex MSSM for arbitrary parameters
  - renormalization of the full cMSSM!

- Higgs from neutralino decays: $\tilde{\chi}_4^0 \to \tilde{\chi}_1^0 h_1$: $\sim 10\%$ effects, dep. on $\varphi_{M_1}$

- Effects on SUSY exclusion regions: $pp \to \tilde{\chi}_1^\pm \tilde{\chi}_2^0$

  Used for interpretation so far: $\mathrm{BR}(\tilde{\chi}_1^\pm \to W^\pm \tilde{\chi}_1^0) = \mathrm{BR}(\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0) = 1$
  $\Rightarrow$ take all decay channels into account: $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h$

  $\Rightarrow$ huge reduction of excluded parameter space
  $\Rightarrow$ strong dependence on phase of $M_1$