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

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

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\begin{aligned}
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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\end{aligned}
$$

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)

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

Complex parameters:

– 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

$\Rightarrow$ 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, μ, $\tan\beta$

neutral:

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

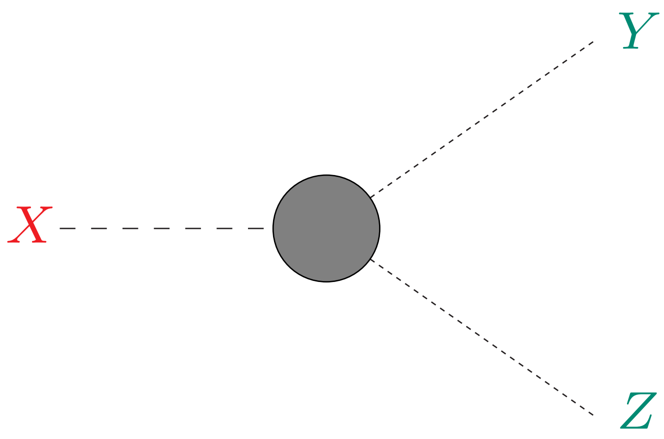
$\Rightarrow$ neutralinos: mass eigenstates

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

$\Rightarrow$ only one new parameter

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

The bigger picture: SUSY 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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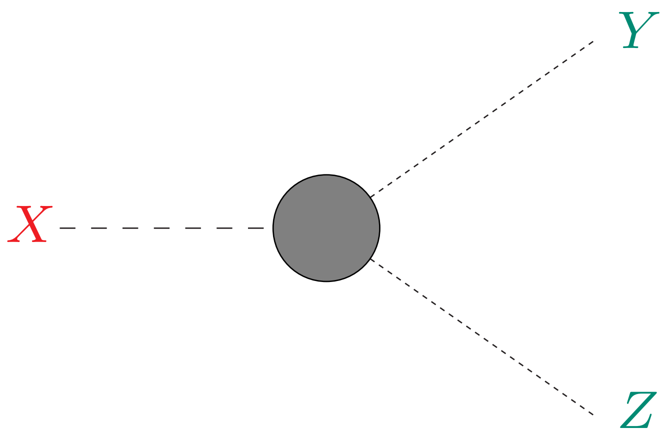

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now ready:

– (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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$$\Gamma(\tilde{\tau}_2 \to \tau \tilde{\chi}_k^0) \qquad (k = 1 \ldots 4) \ ,$$

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2C) Chargino decays

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

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$$\Gamma(\tilde{\chi}_i^\pm \to \tilde{\chi}_j^0 H^\pm) \qquad (i = 1, 2, \; j = 1, 2, 3, 4) \; ,$$

$$\Gamma(\tilde{\chi}_i^\pm \to \tilde{\chi}_j^0 W^\pm) \qquad (i = 1, 2, \; j = 1, 2, 3, 4) \; ,$$

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No hadronic decays yet . . .

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2D) Neutralino decays [A. Bharucha, S.H. F. v.d. Pahlen, C. Schappacher '12]

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

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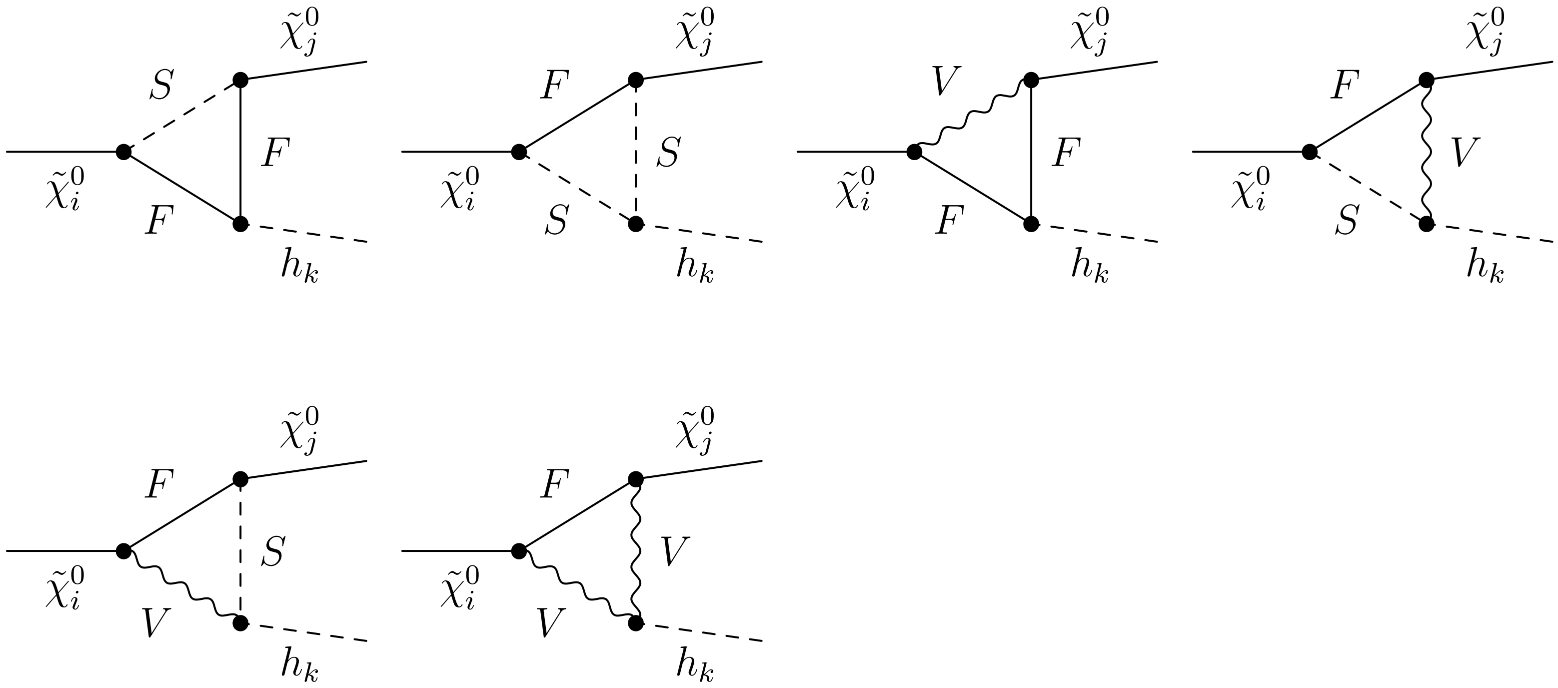
$\tan\beta$	$M_{H^\pm}$	$m_{\tilde{\chi}^\pm_2}$	$m_{\tilde{\chi}^\pm_1}$	$M_{\tilde{l}_L}$	$M_{\tilde{l}_R}$	A_l	$M_{\tilde{q}_L}$	$M_{\tilde{q}_R}$	A_q
20	160	600	350	300	310	400	1300	1100	2000

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

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

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

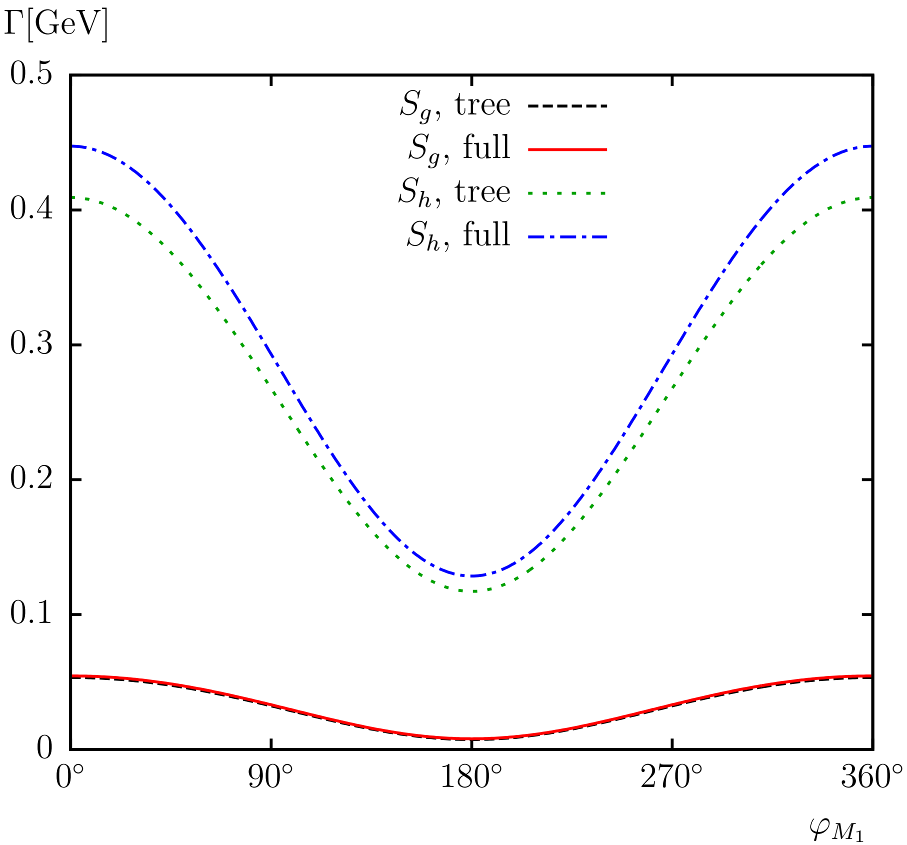


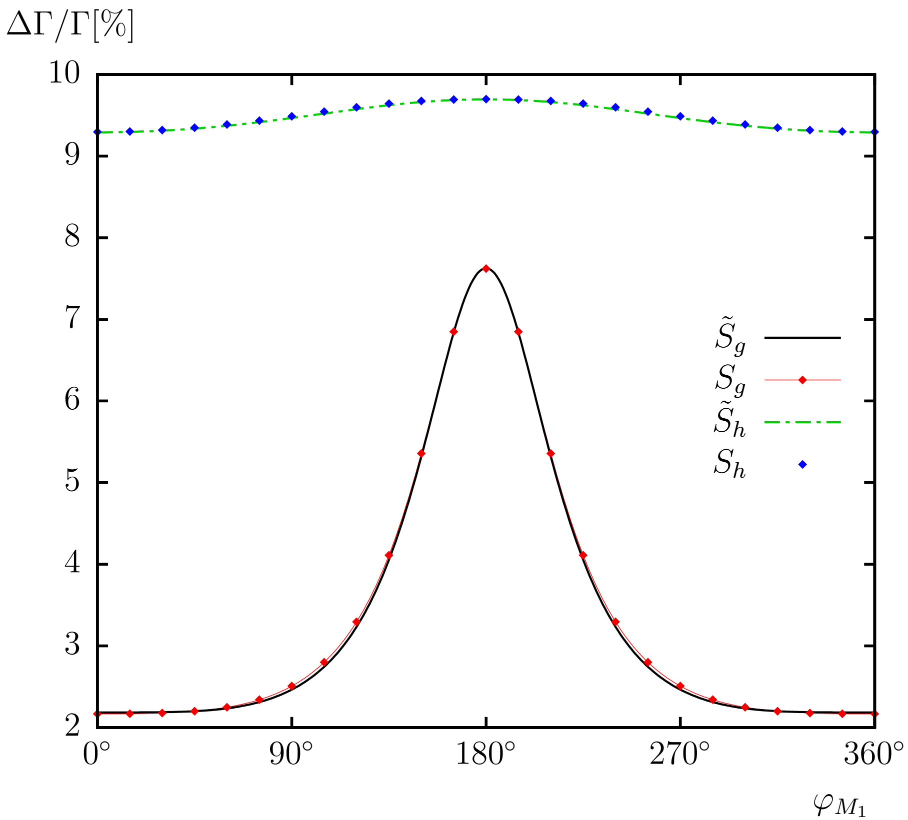
– including Z–A or G–A transition contribution on the external Higgs boson leg

– including all soft/hard QED diagrams

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

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





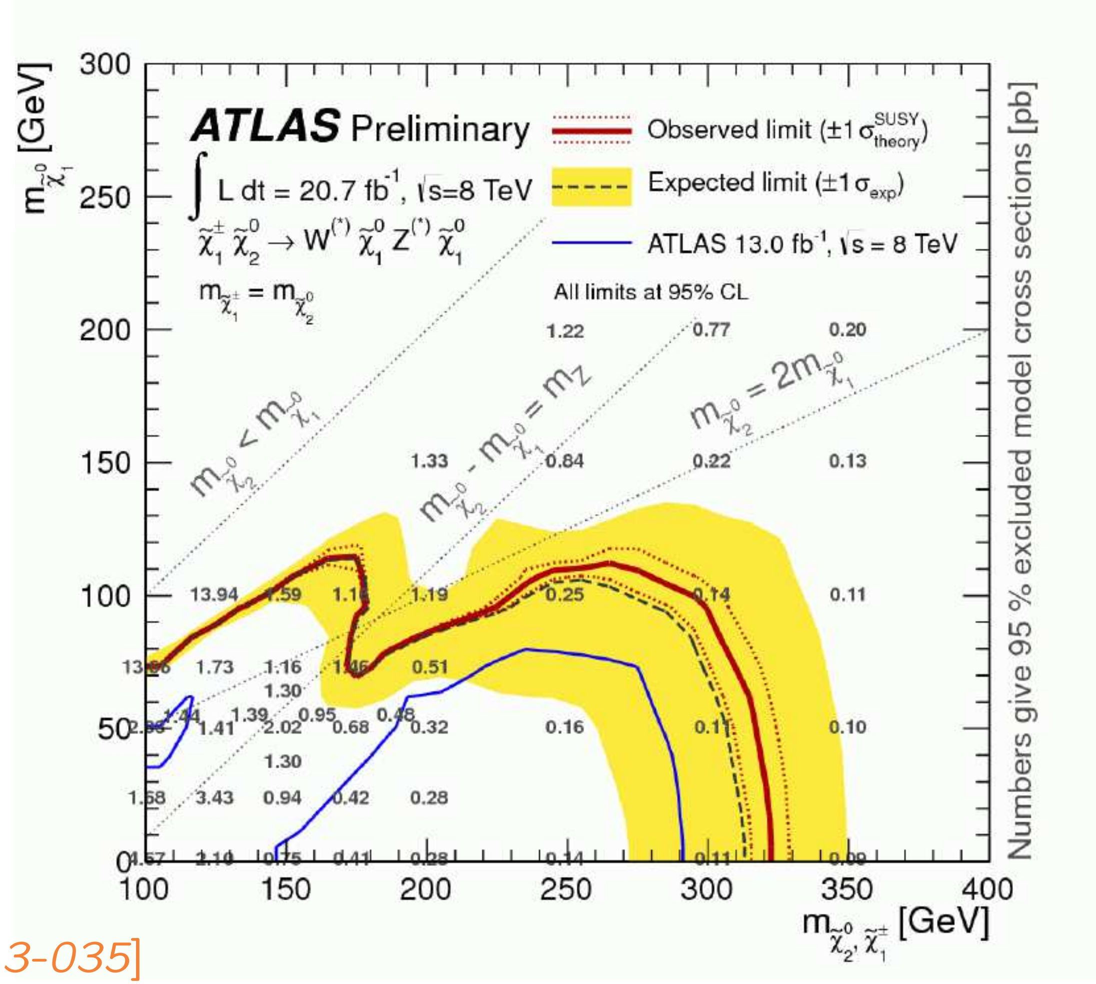
⇒ one-loop corrections under control and non-negligible

⇒ 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]

Assumptions in the limit setting:

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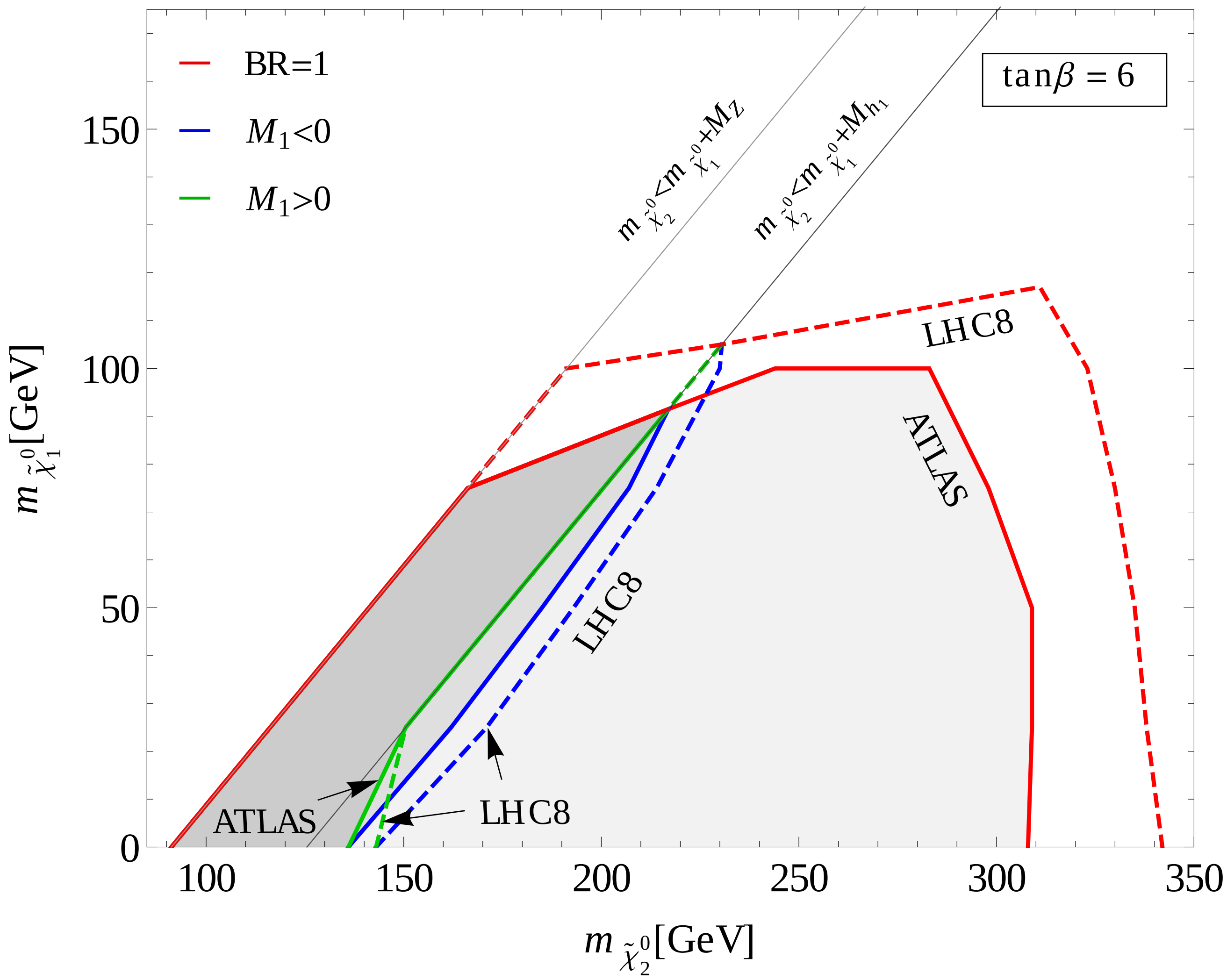
$\Rightarrow$ more details in Aoife's talk on Thursday afternoon

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

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



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

Comparison of ATLAS vs. “real” exclusion (II)

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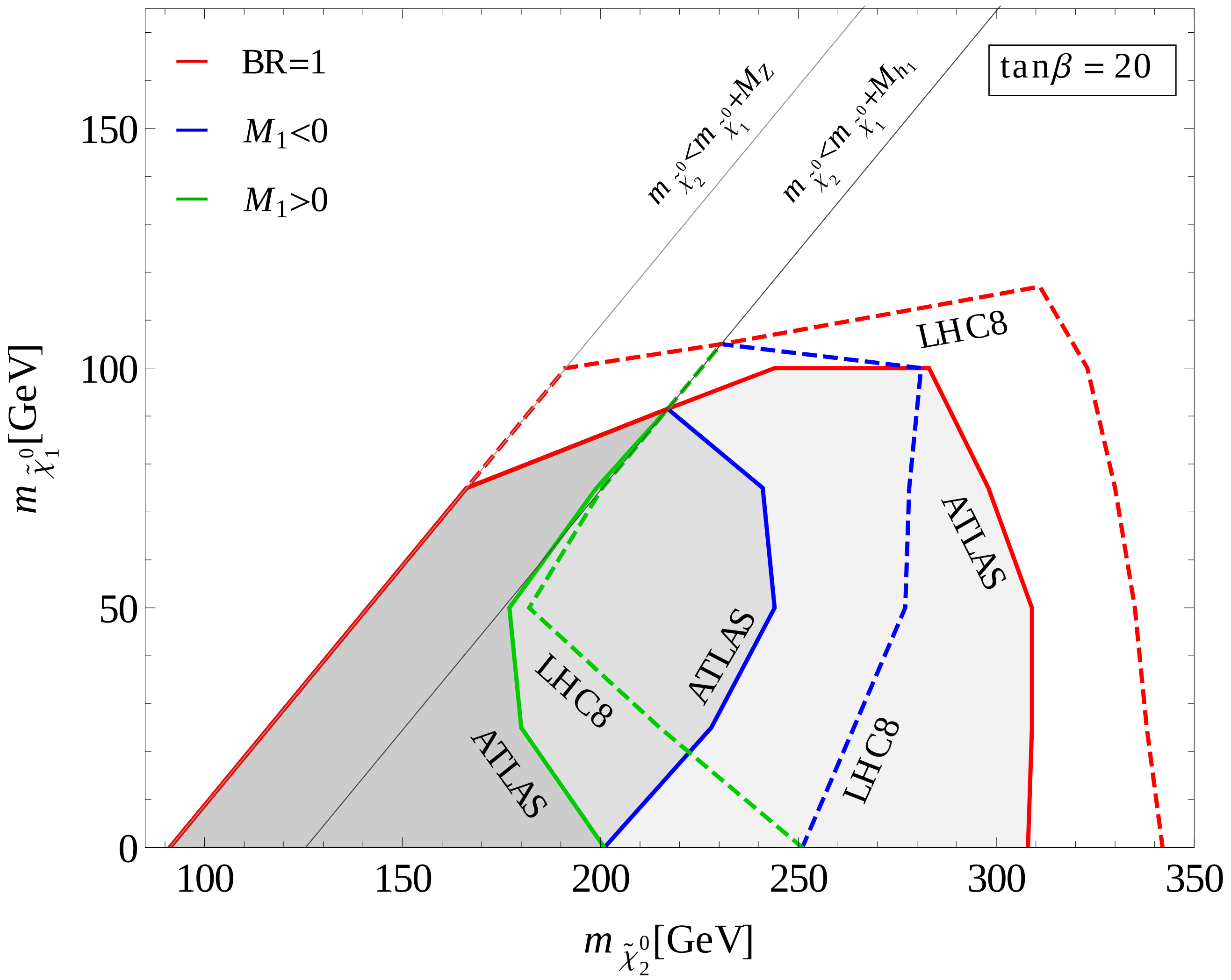

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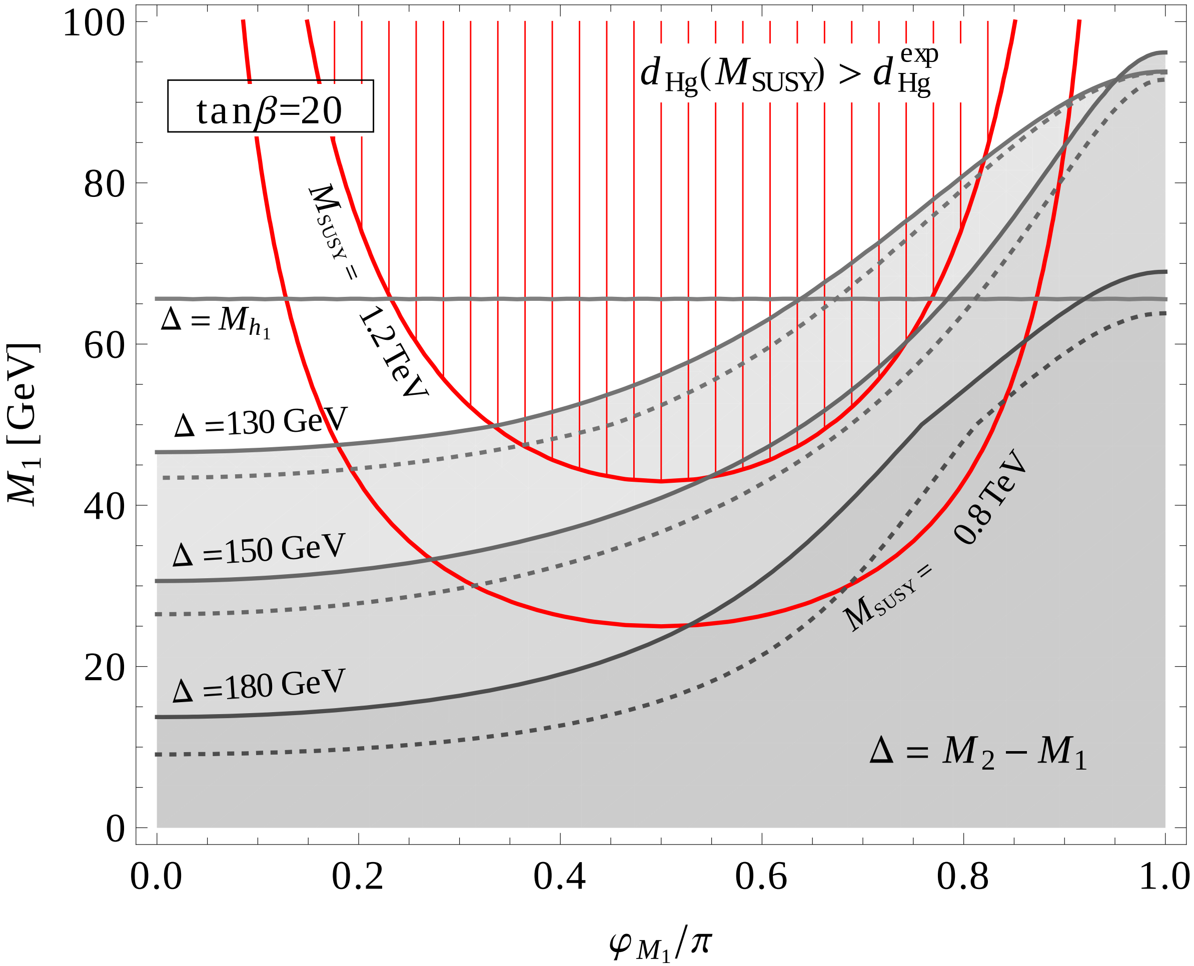
Effects of complex M_1 and higher-order corrections:

[*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 φ_{M_1}

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

  Used for interpretation so far: $\text{BR}(\tilde{\chi}_1^{\pm} \to W^{\pm} \tilde{\chi}_1^0) = \text{BR}(\tilde{\chi}_2^0 \to Z \tilde{\chi}_1^0) = 1$

  $\Rightarrow$ 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