Precise Predictions for Higgs Production in Neutralino Decays

Alison Fowler

IPPP, University of Durham
Work in collaboration with G. Weiglein

Annual HEPP Meeting, IOP, 6-8 April 2009

www.ippp.dur.ac.uk

Outline

1. CP-violating MSSM
   - Higgs sector in the CP-violating MSSM
   - Higgs production in CPX scenario
2. Higher Order Corrections to $\tilde{\chi}_i^0 \tilde{\chi}_j^0 h_k$ vertex
   - Renormalisation and loop corrections
3. Numerical Results
   - $\tilde{\chi}_2^0$ Decay Width
   - $\tilde{\chi}_2^0$ Branching Ratio
4. Summary

CP-violating MSSM

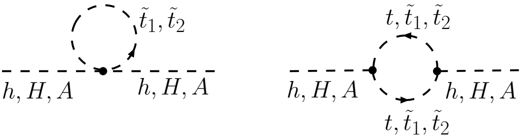
- New source of CP-violating complex phases: A_f, μ, $M_{1,2,3}$

Higgs sector at tree-level:

- Higgs sector is CP-conserving:
  h^0, H^0 (CP-even), A^0 (CP-odd), H^+, H^-

Beyond tree-level: Loop corrections can be large

- Complex parameters $\phi_{A_{t,b,\tau}}$, ϕ_μ, $\phi_{M_{1,2,3}}$ enter via loops
- Mixing between h,H,A $\rightarrow h_1, h_2, h_3$



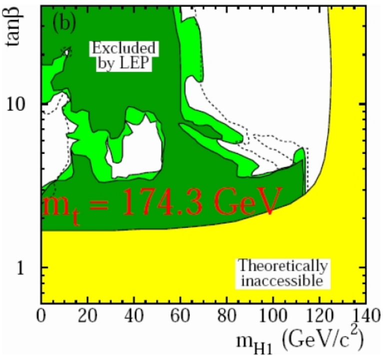
- Higgs sector is CP-violating at 1-loop level
- CP-violating mixing $\propto \mathrm{Im}(A_t \mu)/M^2_{\mathrm{SUSY}}$

CPX Scenario at LEP

Extreme CP violating scenario with large h-H-A mixing.

μ	$M_{\rm SUSY}$	$\lvert M_3 \rvert$	$\lvert A_{\rm t,b,\tau} \rvert$	ϕ_{M_3}	$\phi_{A_{\rm t,b,\tau}}$
2000	500	1000	900 GeV	$\pi/2$	$\pi/2$

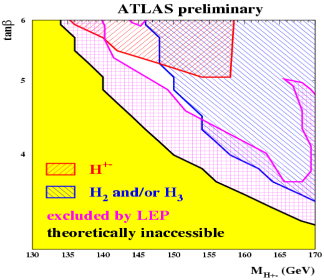
[M. Carena et al. '00]

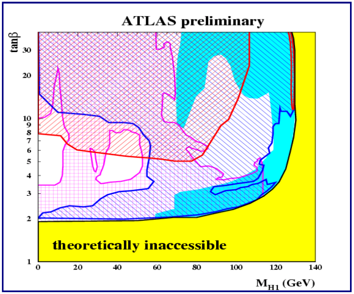


- h_1 mostly CP-odd A^0
- LEP: $e^+e^- \to Z^* \to Zh, hA$
- Suppression of ZZh_1 coupling
- h_2 may be within LEP reach
- $h_2 \to h_1 h_1$: difficult final state
- Light Higgs not excluded!
- CPX hole at $t_\beta \approx 7$, $M_{h_1} \approx 40$GeV
- Genuine vertex corrections to $h_2 \to h_1 h_1$ very important

[LEP Higgs Working Group '06]

CPX scenario at LHC





[M. Schumacher, ATLAS '07]

- CPX holes not covered by conventional channels at LHC
- Need to consider other production methods
- Perhaps involve SUSY particles themselves

See eg. $H^+ \rightarrow W^+ h_1$ *Ghosh, Godbole and Roy [hep-ph/0412193]*

and $\tilde{t}\tilde{t}h_1$ *Bandyopadhyay, Datta et al. [0710.3016]*

Higgs in SUSY cascade decays

- SUSY cascade decays: another source of light Higgs

  [Datta and Djouadi et al. hep-ph/0303095]

  $$pp \;\rightarrow\; \tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{g}\tilde{q} \;\rightarrow\; \tilde{\chi}_i^0, \tilde{\chi}_i^+ + X \;\rightarrow\; \tilde{\chi}_j^0, \tilde{\chi}_j^+ + X + h, H, A, H^\pm$$

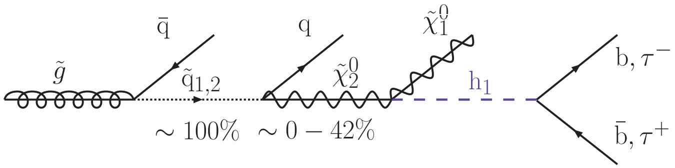
- May complement Higgs searches in conventional channels
- Also a probe to determine parameters of EWSB
- Recent interest in SUSY cascade Higgs production:
  - MSSM with non-universal gaugino masses
    [Banyopadhyay et al. 0806.2367, Huitu et al. 0808.3094]
  - NMSSM with light Higgs *[Djouadi '08, Cheung and Hou 0809.1122]*
  - Experimental analyses of $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h$ *[CMS TDR '07]*

CPX Cascades

CPX with $M_2 = 200\,\text{GeV}$, $\tan\beta = 5.5$:

Masses in GeV:

$M_{\tilde{\chi}^0_{3,4},\tilde{\chi}^+_2}$	$M_{\tilde{g}}$	$M_{\tilde{u},\tilde{d},\tilde{c},\tilde{s}}$	$M_{\tilde{t}_{1,2}}$	$M_{\tilde{b}_{1,2}}$	$M_{\tilde{\chi}^0_2,\tilde{\chi}^+_1}$	$M_{\tilde{\chi}^0_1}$
$\simeq$2000	1000	$\simeq$500	332,667	471,531	198.5	95.1



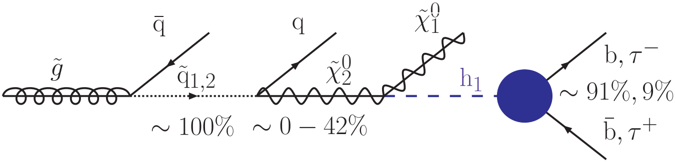
Total: 18% of all gluinos decay to $\tilde{\chi}_2^0$, which may decay to h_1.
What is branching ratio for $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h_1$?

CPX Cascades

CPX with $M_2 = 200\,\text{GeV}$, $\tan\beta = 5.5$:

Masses in GeV:

$M_{\tilde{\chi}^0_{3,4},\tilde{\chi}^+_2}$	$M_{\tilde{g}}$	$M_{\tilde{u},\tilde{d},\tilde{c},\tilde{s}}$	$M_{\tilde{t}_{1,2}}$	$M_{\tilde{b}_{1,2}}$	$M_{\tilde{\chi}^0_2,\tilde{\chi}^+_1}$	$M_{\tilde{\chi}^0_1}$
$\simeq$2000	1000	$\simeq$500	332,667	471,531	198.5	95.1



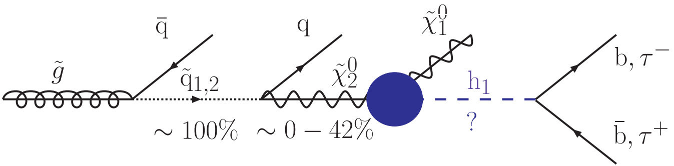
Total: 18% of all gluinos decay to $\tilde{\chi}_2^0$, which may decay to h_1.
What is branching ratio for $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h_1$?

CPX Cascades

CPX with $M_2 = 200\,\text{GeV}$, $\tan\beta = 5.5$:

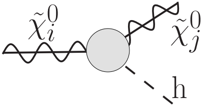
Masses in GeV:

$M_{\tilde{\chi}^0_{3,4},\tilde{\chi}^+_2}$	$M_{\tilde{g}}$	$M_{\tilde{u},\tilde{d},\tilde{c},\tilde{s}}$	$M_{\tilde{t}_{1,2}}$	$M_{\tilde{b}_{1,2}}$	$M_{\tilde{\chi}^0_2,\tilde{\chi}^+_1}$	$M_{\tilde{\chi}^0_1}$
$\simeq$2000	1000	$\simeq$500	332,667	471,531	198.5	95.1



Total: 18% of all gluinos decay to $\tilde{\chi}^0_2$, which may decay to h_1.
What is branching ratio for $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 h_1$?

$\tilde{\chi}_i^0 \tilde{\chi}_j^0$ h_k vertex: Why study?



- Higgs propagator corrections already known to be large
- Vertex corrections to $\Gamma(h_2 \to h_1 h_1)$ were $\mathcal{O}(400\%)$ for CPX

  [Williams et al. arXiv:0710.5320]
- Large μ & A_t may also enhance neutralino contributions

Already available:

- 1-loop (s)fermion corrections to $h, H, A \to \tilde{\chi}_i^0 \tilde{\chi}_j^0$ in rMSSM
- 1-loop effective Lagrangian for $h_k \to \tilde{\chi}_i^0 \tilde{\chi}_j^0$ in cMSSM

  [Eberl et al. hep-ph/0111303, Ren-You et al. hep-ph/0201132, Ibrahim 0803.4134]
- 2-loop Higgs propagator corrections in `FeynHiggs` at $\mathcal{O}(\alpha_s \alpha_t)$ in cMSSM (we use same Higgs renormalisation)

Renormalisation in the Neutralino/Chargino Sector

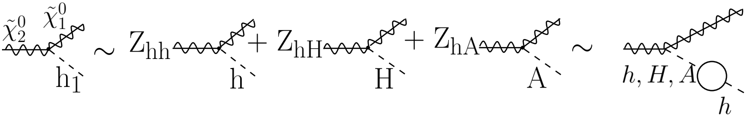
$$X = \begin{pmatrix} M_2 & \sqrt{2} M_W \sin\beta \\ \sqrt{2} M_W \cos\beta & \mu \end{pmatrix}$$

$$Y = \begin{pmatrix} M_1 & 0 & -M_Z c_\beta s_W & M_Z s_\beta s_W \\ 0 & M_2 & M_Z c_\beta c_W & -M_Z s_\beta c_W \\ -M_Z c_\beta s_W & M_Z c_\beta c_W & 0 & -\mu \\ M_Z s_\beta s_W & -M_Z s_\beta c_W & -\mu & 0 \end{pmatrix}$$

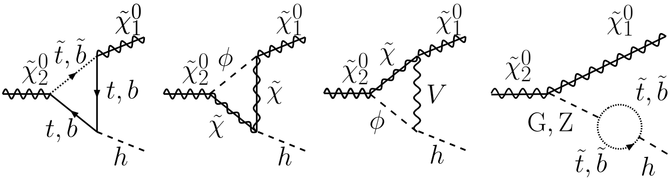
- 3 independent parameters: M_1, M_2, μ
- 6 masses: we fix masses of $\tilde{\chi}^0_{1,2}$, $\tilde{\chi}^+_2$ on-shell
- Other 3 masses receive corrections
- We allow CPV phases of $A_{t,b,\tau}$ and M_3 to vary
- Renormalisation of CPV phases of M_1, M_2, μ in progress

Loop Corrections

Step 1: Improved Born Approximation using 2-loop masses and Z-factors from `FeynHiggs2.6.5`



Step 2a: Full 1-loop vertex correction using own counterterms and `FeynArts/FormCalc/LoopTools`



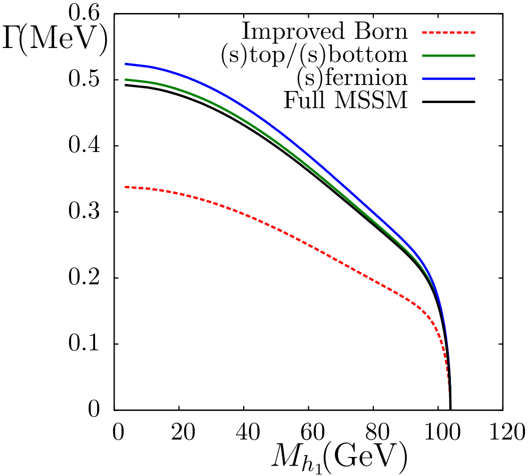
Step 2b: Combine to obtain most precise $\Gamma(\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_j^0 h_k)$

$\tilde{\chi}_2^0$ Decay Width

$$\Gamma(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h_1)$$

CPX: $\tan\beta = 5.5$, $M_2 = 200$ GeV

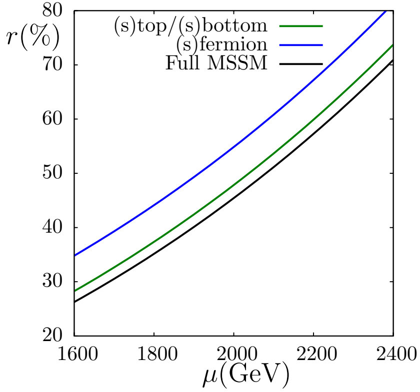
- Improved Born: $Z_{ij}^{(2)} \Gamma_j^{tree}$
- Full result: $Z_{ij}^{(2)} \Gamma_j^{(1)}$
- $t, \tilde{t}, b, \tilde{b}$ dominant
- $r = \frac{\Gamma^{\text{loop}} - \Gamma^{\text{improved born}}}{\Gamma^{\text{improved born}}}$
- Genuine vertex corrections $r \sim \mathcal{O}(50\%)$ in (extreme) CPX scenario

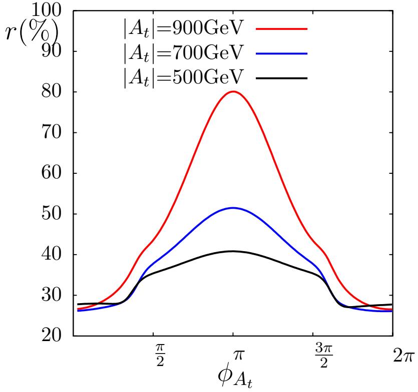


[A.F, G.Weiglein, in preparation '09]

Variation with μ and $Arg(A_t)$

$\Gamma(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \mathrm{h}_1)$: CPX with $M_{h_1} = 40$, $M_2 = 200$ GeV, $\tan\beta = 5.5$

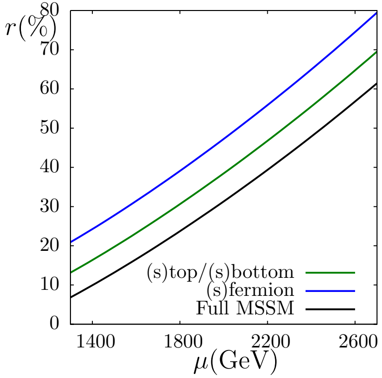




- Large μ in CPX scenario enhances vertex corrections
- Correction largest for $\phi_{A_t} = \pi$, where h_1 is mostly h^0 (experimentally excluded at 40 GeV)

CP-conserving case: Small $\alpha_{\rm eff}$ scenario

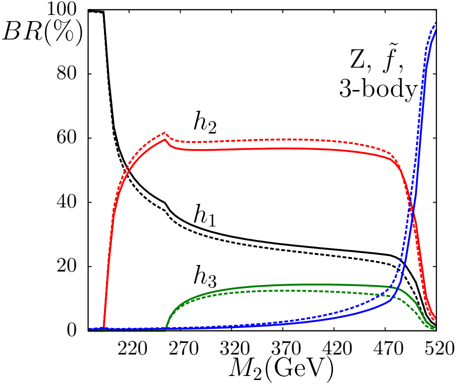
$\Gamma(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h_1)$: Small $\alpha_{\rm eff}$ scenario

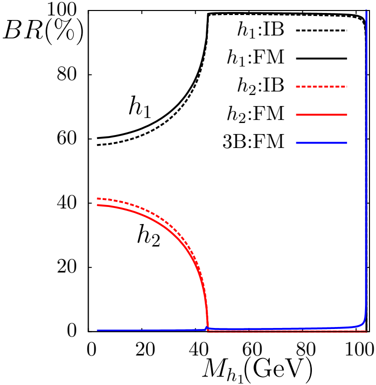


- $M_{H^\pm} = 220$ GeV, $\tan\beta = 10$
- $\mu = 2$ TeV, $X_t = -1.1$ TeV
- Large vertex corrections also found in CP-conserving scenarios with large μ and A_t

[A.F, G.Weiglein, in preparation '09]

CPX scenario: $\tilde{\chi}_2^0$ Branching Ratio

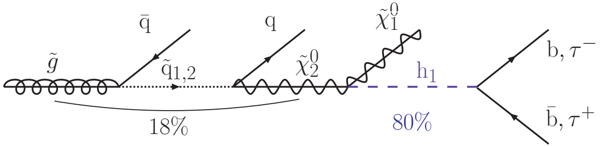




- Improved Born approx. works well for this branching ratio
- h_1, h_2, h_3 have similar $\mathcal{O}(50\%)$ vertex corrections which cancel to $\mathcal{O}(3\%)$ for BRs

CPX Cascades

Eg. CPX hole with $\tan\beta = 5.5$, $M_2 = 200$, $M_{h_1} = 40\,\text{GeV}$:



Rough estimate:

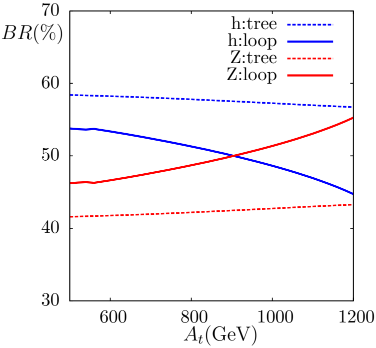
- Produce $\tilde{g}$ ($\sigma_{\tilde{g}\sim 1\text{TeV}} \sim 1\text{pb}$) $\rightarrow$ 14% cascade decay to h_1
- Or produce $\tilde{q}$ ($\sigma_{\tilde{q}\sim 500\text{GeV}} \sim 50\text{pb}$) $\rightarrow$ up to 42% decay to h_1

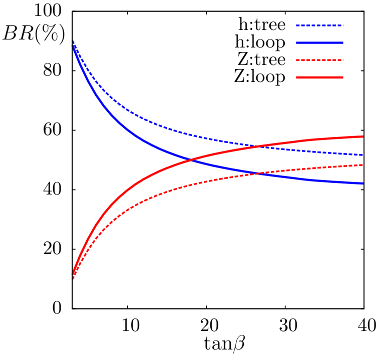
Can one dig such a signal out of SM/SUSY backgrounds?

c.f. *[CMS TDR '07]* Reconstruction of mass of 115 GeV Higgs boson (mSUGRA) in similar cascade by requiring multiple hard jets, 2 b-tagged jets and missing transverse energy.

Light $\tilde{\chi}_1^0$ scenario

$m_{\tilde{\chi}_1^0} \approx 0$ (not phenom. excluded) *[see Dreiner et al. 0901.3485]*
$M_2 = 400$, $\mu = 600$, $M_{\rm SUSY} = 500\,$GeV, ($A_f = 1$ TeV, $\tan\beta = 20$)





- Large vertex corrections for both $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h$ and $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z$ can have $\mathcal{O}(10\%)$ effect if BRs are of similar magnitude.

[A.F, G.Weiglein, in preparation '09]

Summary

- Complete 1-loop result for $\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_j^0 h_k$ was presented, supplemented by 2-loop propagator-type corrections: the most precise prediction for this process in both real and complex MSSM with non-zero Φ_{A_t}.
- Genuine vertex corrections seen to be as large as 50%.
- These results have particular relevance to CP-violating scenarios, where h_1 may be as light as $30 - 40$ GeV.
- Such a light h_1 may be significantly produced via $\tilde{\chi}^0$ decay.
- Outlook:
  - Results will be provided as a public tool so that experimental studies can be carried out.
  - Effect of additional CP-violating phases will be studied.