Precise Predictions for Higgs Production in Neutralino Decays

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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
   - Improved Born Approximation
   - Renormalisation
   - Full 1-loop vertex correction
3. Numerical Results
   - $\tilde{\chi}_2^0$ Decay Width
   - $\tilde{\chi}_2^0$ Branching Ratio
4. Summary

The CP-violating MSSM

- Every SM particle gets supersymmetric partner
- 2 Higgs doublets $\Rightarrow$ 5 physical Higgs bosons
- Rich mixing structure:
  - $\widetilde{f}_{L,R}$ mix $\Rightarrow$ sfermions $\widetilde{f}_{1,2}$
  - $\widetilde{\mathrm{h}}^{\pm}_{u,d}$,$\widetilde{\mathrm{W}}^{\pm}$ mix $\Rightarrow$ charginos $\tilde{\chi}^{\pm}_{1,2}$
  - $\widetilde{\mathrm{h}}^0_u$,$\widetilde{\mathrm{h}}^0_d$,$\widetilde{\mathrm{B}}$,$\widetilde{\mathrm{W}}^3$ mix $\Rightarrow$ neutralinos $\tilde{\chi}^0_{1,2,3,4}$
- New source of CP-violation: A_f, μ, $M_{1,2,3}$
- May help explain matter-antimatter asymmetry of the universe

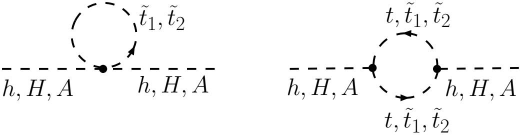
The Higgs Sector

Higgs sector at tree-level:

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

Beyond tree-level: Loop corrections can be large

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



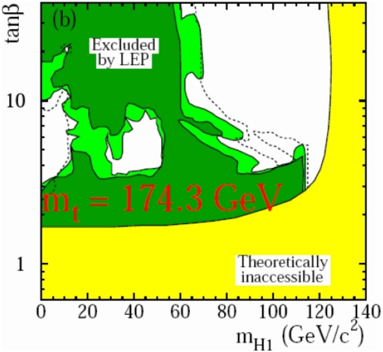
- Higgs sector is CP-violating at 1-loop level
- CP-violating mixing $\propto \mathrm{Im}(A_t\mu)/M^2_{\mathrm{SUSY}}$

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	$\pi/2$	$\pi/2$

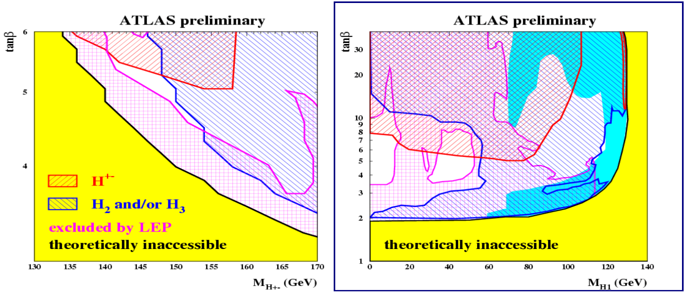
[Carena et al. hep-ph/0009212]



[LEP Higgs Working Group '06]

- h_1 mostly CP-odd A
- LEP: $e^+e^- \to Z^* \to Zh, hA$
- Suppression of ZZh_1 coupling
- Suppression of h_1 production
- h_2 may be within LEP reach
- But $h_2 \to h_1 h_1$: 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

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

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

Higgs in SUSY cascade decays

- SUSY cascade decays: another source of light Higgs

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

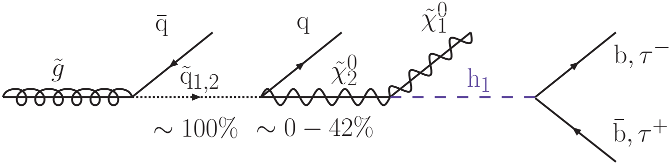
- May complement Higgs searches in conventional channels
- Also a probe to determine parameters of EWSB
- Applicable to both CP-conserving and CP-violating MSSM
- Recent interest in SUSY cascade Higgs production:
  - CP-conserving MSSM *[Datta and Djouadi et al. hep-ph/0303095]*
  - Experimental analyses of $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h$ *[CMS TDR '07]*
  - MSSM with non-universal gaugino masses *[Banyopadhyay et al. arXiv:0806.2367, Huitu et al. arXiv:0808.3094]*
  - NMSSM with light Higgs *[Djouadi '08, Cheung and Hou arXiv:0809.1122]*

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 $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 h_1$?

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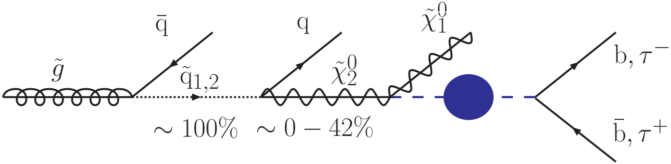

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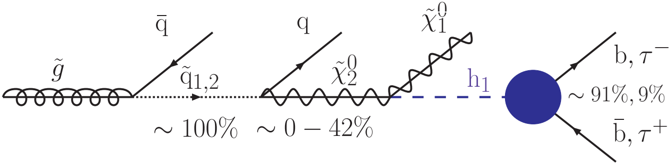

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Masses in GeV:

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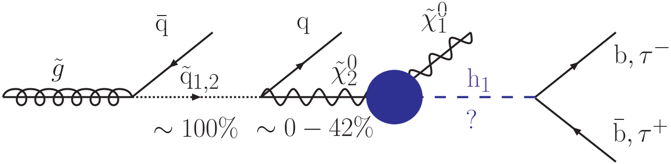
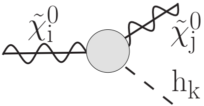


Total: 18% of all gluinos decay to $\tilde{\chi}_2^0$, which may decay to h_1.
What is branching ratio for $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h_1$?

$\tilde{\chi}_i^0 \tilde{\chi}_j^0 h_k$ 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 and Weiglein arXiv:0710.5320]
- Large μ, A_t may also enhance loop contributions

Already available:

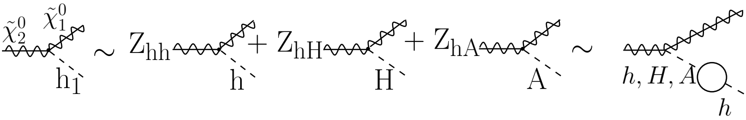
- 1-loop (s)fermion corrections to $h, H, A \to \tilde{\chi}_i^0 \tilde{\chi}_j^0$ in rMSSM

  [Eberl et al. hep-ph/0111303, Ren-You et al. hep-ph/0201132]
- 1-loop effective Lagrangian for $h_k \to \tilde{\chi}_i^0 \tilde{\chi}_j^0$ in cMSSM

  [Ibrahim arXiv:0803.4134]
- 2-loop Higgs propagator corrections in `FeynHiggs` at $\mathcal{O}(\alpha_s \alpha_t)$ in cMSSM *[Heinemeyer et al. arXiv:0705.0746]*

Loop Corrections in the Higgs Sector

Step 1: Improved Born Approximation incorporating existing 2-loop Higgs propagator corrections

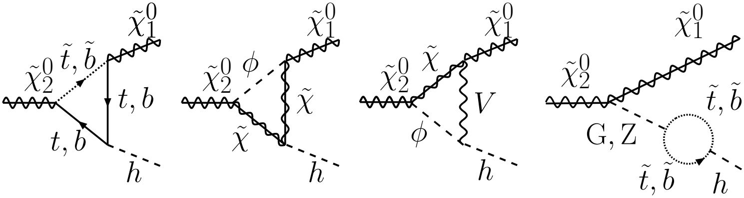


- Finite wavefunction normalisation factors Z_{ij} include mixing between h, H, A (i.e. h-H-A self-energy diagrams).
- We evaluate M_{h_i}, Z_{ij} using `FeynHiggs2.6.5`, which contains the leading 2-loop corrections.

Genuine vertex corrections in Higgs/Neutralino sectors

Step 2: Full 1-loop vertex correction

We evaluate triangle and self-energy diagrams: eg.



- We implement our own renormalisation scheme into `FeynArts` and also use `FormCalc/LoopTools`

Renormalisation in the Higgs Sector

We implement the same scheme used in `FeynHiggs`:

See [Frank et al. hep-ph/0611326] and [Williams and Weiglein arXiv:0710.5320] for details

- Charged Higgs boson mass, $M_{H^\pm}$, is fixed on-shell
- M_{h_1}, M_{h_2}, M_{h_3} derived from poles of loop-corrected 3x3 propagator matrix $\Delta_{hHA}(p^2)$
- $\overline{\text{DR}}$ renormalisation for $\tan\beta$
- $\overline{\text{DR}}$ renormalisation for fields: $\delta Z^{\overline{\text{DR}}}_{\mathcal{H}_{1,2}}$
- To obtain correct on-shell properties of neutral Higgs bosons, we then introduce finite normalisation factors Z_{ij}
- Convenient for including CP-violating mixing effects beyond one-loop order

Renormalisation in the Neutralino/Chargino Sector

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

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

- We renormalise the 3 independent parameters: M_1, M_2, μ
- We fix masses of $\tilde{\chi}_{1,2}^0$, $\tilde{\chi}_2^+$ on-shell $\Rightarrow \delta M_1$, δM_2, $\delta\mu$
- Other 3 masses of $\tilde{\chi}_{3,4}^0$, $\tilde{\chi}_1^+$ receive loop corrections
- Convenient for $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h_k$ with $M_1 < M_2 \ll \mu$
- For other processes and parameters we found different choices can be more convenient and numerically stable.

Renormalisation in the Neutralino/Chargino Sector

- We fix the field renormalisation constants, $\delta\tilde{Z}$, by requiring correct on-shell properties of 2-pt vertex functions and correct normalisation of the S-matrix[1]
- CP-violation makes this non-trivial rel. to SM or real MSSM
- Complex phases may combine with absorptive parts of loop integrals to contribute to real parts of amplitudes at 1-loop level
- Investigated scheme where field renormalisation constants for incoming particles and outgoing antiparticles do not coincide[2]
- Correct structure of on-shell propagator
  $\Rightarrow$ renormalisation conditions for $\mathrm{Im}\,\delta\tilde{Z}$, $\delta\phi_{M_1}$, $\delta\phi_{M_2}$, $\delta\phi_\mu$
- Other possibility: $\overline{\mathrm{DR}}$ renormalisation of phases (in progress)

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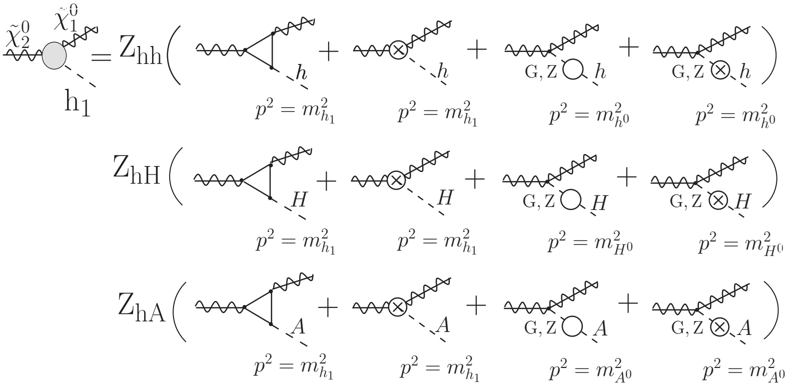
[1] See *[Fritzsche and Hollik hep/ph-0203159] for chargino/neutralino field renormalization in real MSSM*

[2] See *[Espriu et al. hep-ph/0204085] and [Denner et al. hep-ph/0402130] for discussion for CKM matrix*

Step 3: We combine our complete 1-loop result with existing 2-loop Higgs-propagator corrections from the literature:



The most precise prediction for the process $\tilde{\chi}_i^0 \to \tilde{\chi}_j^0 h_k$.

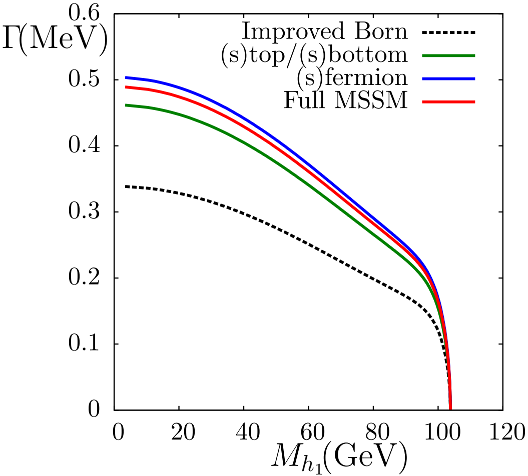
$\tilde{\chi}_2^0$ Decay Width

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

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

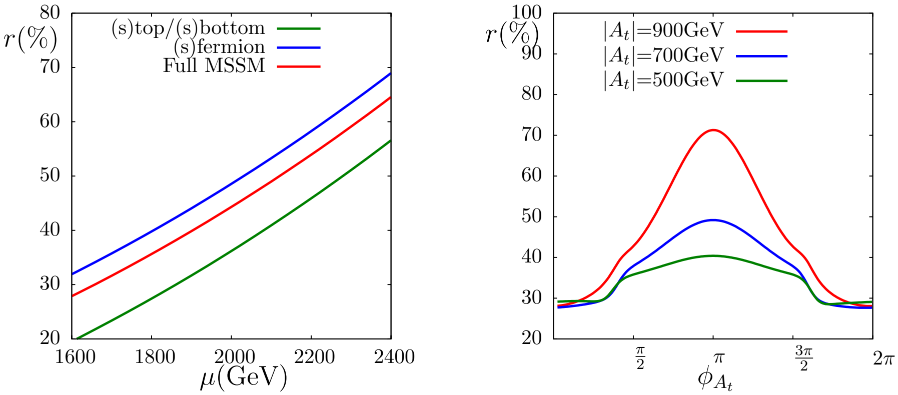
[A.F, G.Weiglein, in preparation '09]

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



Variation with μ and $Arg(A_t)$

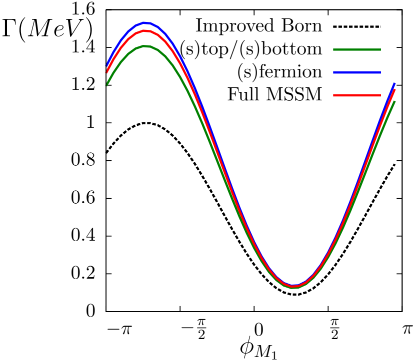
$\Gamma(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \mathrm{h}_1)$: CPX with $M_{h_1} = 40$, $M_2 = 200\,\mathrm{GeV}$, $\tan\beta = 5.5$

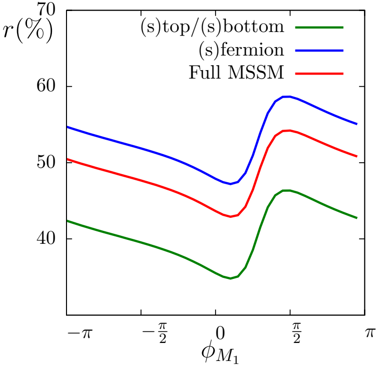


- Large μ, $|A_t|$ in CPX scenario enhance vertex corrections
- Correction largest for $\phi_{A_t} = \pi$, where h_1 is mostly h (experimentally excluded at 40 GeV)

Variation with ϕ_{M_1} (*Preliminary Results:*)

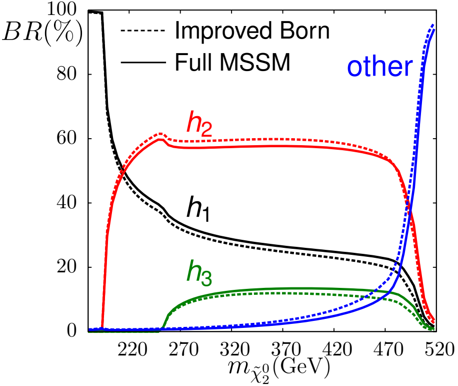
$\Gamma(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h_1)$: CPX with M_{h_1}=60, M_2=200 GeV, $M_1 = \frac{5}{3}\frac{s_W}{c_W} M_2\, e^{i\phi_{M_1}}$

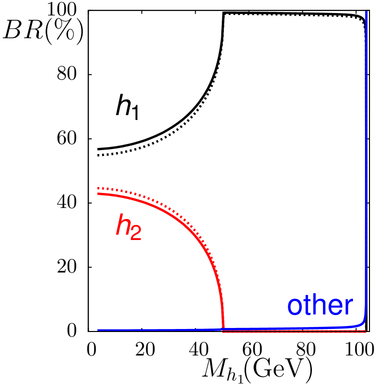




- ϕ_{M_1} plays large role for neutralino sector at Born level
- Can also enhance effect of vertex corrections
- Asymmetry due to CP-violating *h*-*H*-*A* mixing

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

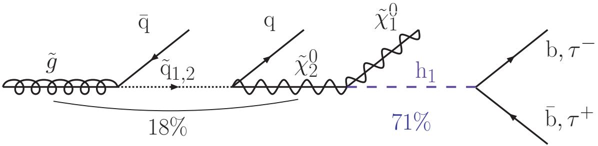




- $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\, h_1,\, h_2,\, h_3$ have similar $\mathcal{O}(50\%)$ vertex corrections which cancel to $\mathcal{O}(3\%)$ for BRs
- Other decays ($\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \bar{f} f, \tilde{\chi}_1^0 Z, \tilde{f}_{1,2} f$) only important for $m_{\tilde{\chi}_2^0} \gtrsim m_{\tilde{f}}$
- Improved Born approx. works well for this branching ratio

CPX Cascades

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



Rough estimate:

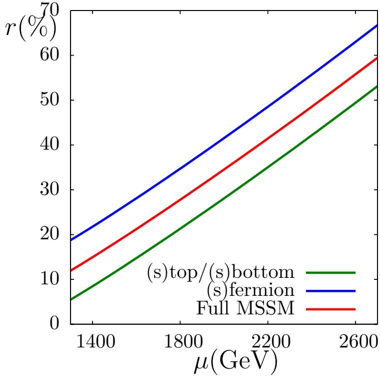
- Produce $\tilde{g}$ ($\sigma_{\tilde{g}\sim 1\text{TeV}} \sim 1\text{pb}$) $\Rightarrow$ 13% cascade decay to h_1

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.

CP-conserving case: Small α_{eff} scenario

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

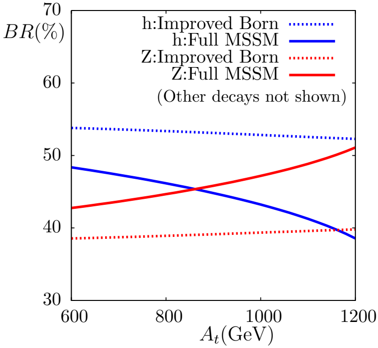


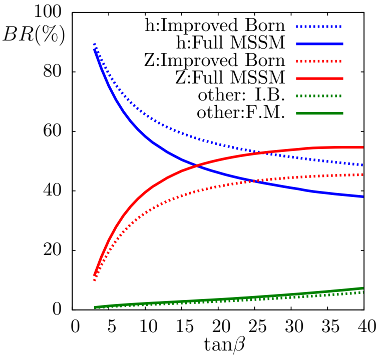
- $M_{H^\pm}$=220 GeV, tan β=10
- μ=2 TeV, X_t=$-$1.1 TeV
- Large vertex corrections also found in CP-conserving scenarios with large μ and A_t

CP-conserving case: Light $\tilde{\chi}_1^0$ scenario

M_1 with $m_{\tilde{\chi}_1^0} \approx 0$ (not experimentally excluded) *[Dreiner et al. 0901.3485]*

M_2=400, μ=600, M_A=500, $M_{\rm SUSY}$=500 GeV, (A_f=1 TeV, tan β=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.

Summary

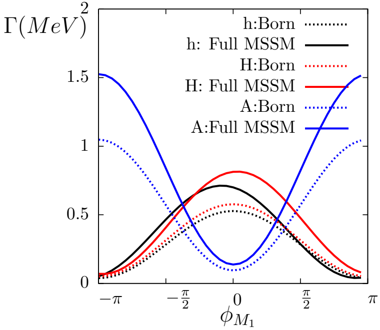
- Complete 1-loop result for $\tilde{\chi}_i^0 \to \tilde{\chi}_j^0 h_k$ was derived, supplemented by 2-loop propagator-type corrections: Most precise prediction for this process in complex MSSM.
- Genuine vertex corrections to decay width found to be as large as 50% in some scenarios.
- Effect on branching ratio can be large if $\tilde{\chi}_i^0 \to \tilde{\chi}_j^0 h_k$ is competing with other decay modes, $\tilde{\chi}_i^0 \to \tilde{\chi}_j^0 Z,\ \tilde{f}_{1,2} f$.
- These results have particular relevance to CP-violating scenarios, where h_1 may be as light as $30 - 40\,\text{GeV}$.
- 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 for $\tilde{\chi}_i^0 \to \tilde{\chi}_j^0 h_k$.
- Effects of CP-violating phases from the chargino-neutralino sector will be studied in more detail.
- Different renormalisation schemes for the complex MSSM will be further investigated and compared.
- These results may also be applied to Higgs searches and bounds which use $h_i \to \tilde{\chi}_j^0 \tilde{\chi}_k^0$, $\tilde{\chi}_j^+ \tilde{\chi}_k^-$ and also to dark matter annihilation.

Back-up slide

Variation with ϕ_{M_1} (*Preliminary Results*)
Why asymmetry about $\phi_{M_1} = 0$?



When a linear combination weighted by Z matrix elements of h, H, A is taken, an asymmetric variation wrt ϕ_{M_1} for h_1 is found already at the Improved Born level.