Neutralino decays at NLO

in the complex MSSM

based on: "Neutralino Decays in the Complex MSSM at One-Loop: a Comparison of On-Shell Renormalization Schemes," Phys. Rev. D **86** (2012) 075023 [arXiv:1208.4106 [hep-ph]], A. Bharucha, S. Heinemeyer, F. von der Pahlen and C. Schappacher

and work done in collaboration with A. C. Fowler, G. Moortgat-Pick, G. Weiglein.

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Seminar, Annecy LAPTH, Nov. 29$^{\mathrm{th}}$ 2012

Two clues

two is more than none

A Higgs boson 

Dark Matter 

Refine MSSM predictions for a better analysis of collider data

~~Two~~ Three clues

~~two~~ three is more than ~~none~~ two

A Higgs boson 

Baryon asymmetry →

Dark Matter 

→ Refine MSSM predictions for a better analysis of collider data

....with complex parameters

Neutralino decays at NLO in the cMSSM

Motivation

- Cascades at the LHC lead to LSP
- Important final step often $\tilde{\chi}^0_{2,3,4} \rightarrow \tilde{\chi}^0_1 Z, h$
- Precise predictions for sparticle decays in MSSM requires loop effects: can be very large
- $\Rightarrow$ We calculate NLO corrections to ALL uncoloured $\tilde{\chi}^0_{2,3,4}$ decays
- Various issues concerning renormalisation of the complex MSSM, requires a consistent framework[a]
- Compare two on-shell renormalization schemes, focus on *CP violating phases*

[a] see A. Bharucha, A. Fowler, G. Moortgat-Pick and G. Weiglein, "Consistent on shell renormalisation of electroweakinos in the complex MSSM: LHC and LC predictions," arXiv:1211.3134 [hep-ph].

Outline

a bit of structure

- Quick recap: the Chargino and Neutralino Sector
- Introducing and motivating *CP violation* in the MSSM
- Neutralino decays studied at LO and NLO
- Field renormalisation, issues due to absorptive contributions
- Parameter renormalisation: which masses should be on-shell?
- Comparison of two on-shell renormalization schemes, differing w.r.t. treatment of *CP violating phases*
- Prospects to use our results via direct gaugino production@LHC

Quick recap: Chargino and Neutralino Sector

$$\mathcal{L}_{\tilde{\chi}} = \overline{\tilde{\chi}_i^-}(\not{p}\,\delta_{ij} - \omega_L(U^* X V^\dagger)_{ij} - \omega_R(V X^\dagger U^T)_{ij})\tilde{\chi}_j^- + \frac{1}{2}\overline{\tilde{\chi}_i^0}(\not{p}\,\delta_{ij} - \omega_L(N^* Y N^\dagger)_{ij} - \omega_R(N Y^\dagger N^T)_{ij})\tilde{\chi}_j^0$$

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

diagonalised via $\mathbf{M}_{\tilde{\chi}^+} = U^* X V^\dagger$

[0] where we define $\omega_{L/R} = \frac{1}{2}(1 \mp \gamma_5)$

Quick recap: Chargino and Neutralino Sector

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diagonalised via $\mathbf{M}_{\tilde{\chi}^+} = U^* X V^\dagger$

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

diagonalised via $\mathbf{M}_{\tilde{\chi}^0} = N^* Y N^\dagger$

0 where we define $\omega_{L/R} = \frac{1}{2}(1 \mp \gamma_5)$

CMSSM $\rightarrow$ cMSSM?

- Complex phases in the MSSM result in beyond SM CP violation
- Strong bounds on phase of 1st/2nd generation trilinear couplings via EDMs (n, e, Hg, TI) [1], but not so strict for 3rd generation

Important contributing phases:

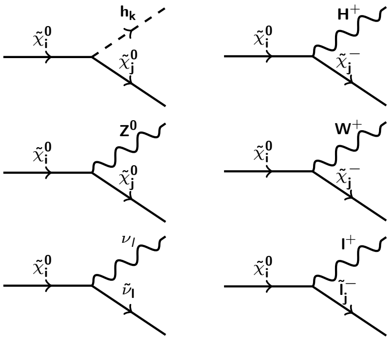
$$\phi_{A_{t/b/\tau}},\ \phi_{\mu},\ \phi_{M_{1/3}}$$

Note that higgsino phase is also tightly constrained by the EDM's, therefore we only consider the phase ϕ_{M_1} for the neutralino decays

[1] for review see J. R. Ellis, J. S. Lee and A. Pilaftsis, [arXiv:0808.1819 [hep-ph]].

Introduction

Calculating neutralino decays in the complex MSSM



- LO results[a] encoded in SDECAY[b]
- Used to distinguish SUSY breaking[c], detect CP violation at LC[d]
- h, H, A mix in cMSSM $\Rightarrow h_1, h_2, h_3$
- If $\tilde{q}$ heavy (as in CMSSM, GMSB or AMSB), $q\,\tilde{q}$ final state forbidden

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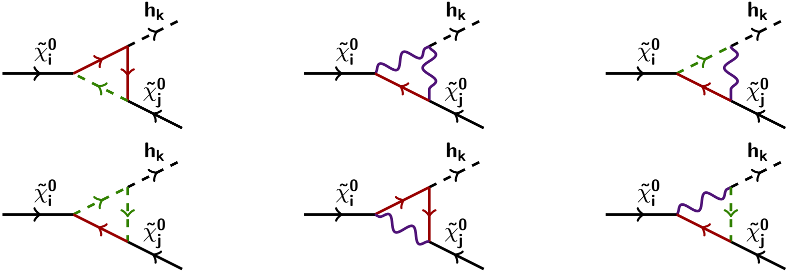
[a] e.g. J. Gunion and H. Haber, Phys. Rev. D 37 (1988) 2515

[b] M. Mühlleitner, A. Djouadi and Y. Mambrini, Comput. Phys. Commun. 168 (2005) 46

[c] K. Huitu et al, Phys. Rev. D 82 (2010) 115003 [arXiv:1006.0661 [hep-ph]]

[d] e.g. H. Dreiner, O. Kittel and F. von der Pahlen, JHEP 0801 (2008) 017 [arXiv:0711.2253 [hep-ph]]

Neutralino decays at one loop



- Calculated in real MSSM and implemented in SloopS/CNNDecays[2]
- Loops contain EW-inos/leptons/quarks, $\tilde{q}$s/$\tilde{l}$s/Hs or Ws or Zs
- Calculate using `FeynArts/LoopTools/FormCalc/FeynHiggs`[3], including hard and soft QED radiation and Renormalize

[2] N. Baro and F. Boudjema, Phys. Rev. D 80 (2009) 076010 [arXiv:0906.1665 [hep-ph]], S. Liebler and W. Porod, Nucl. Phys. B 849 (2011) 213 [arXiv:1011.6163 [hep-ph]]

[3] also see A. C. Fowler and G. Weiglein, JHEP **1001** (2010) 108 [arXiv:0909.5165 [hep-ph]].

Renormalisation of the Electroweakino sector I[4]

Field renormalisation:

Require correct on-shell properties for:

- renormalised two point functions:

$$\hat{\Gamma}^{(2)}_{ij}(p^2) = i(\not{p} - m_i)\delta_{ij} + i\hat{\Sigma}_{ij}(p^2)$$

- renormalised propagator:

$$\hat{S}^{(2)}_{ij}(p^2) = -(\hat{\Gamma}^{(2)}_{ij}(p^2))^{-1}$$

Note that the self energy can be expressed in terms of coefficient:
$\Sigma_{ij}(p^2) = \not{p}\omega_L \Sigma^L_{ij}(p^2) + \not{p}\omega_R \Sigma^R_{ij}(p^2) + \omega_L \Sigma^{SL}_{ij}(p^2) + \omega_R \Sigma^{SR}_{ij}(p^2)$,
where of course $\omega_{L/R} = \frac{1}{2}(1 \mp \gamma_5)$

[4] see A. C. Fowler, PhD Thesis, 2010

Renormalisation of the Electroweakino sector I[5]

Definitions and on-shell conditions:

The neutralino field RCs are defined as above:

$$\omega_L\tilde{\chi}_i^0 \to (1+\tfrac{1}{2}\delta Z_0^L)_{ij}\omega_L\tilde{\chi}_j^0, \qquad \overline{\tilde{\chi}_i^0}\omega_R \to \overline{\tilde{\chi}_i^0}(1+\tfrac{1}{2}\delta \bar{Z}_0^L)_{ij}\omega_R,$$
$$\omega_R\tilde{\chi}_i^0 \to (1+\tfrac{1}{2}\delta Z_0^R)_{ij}\omega_R\tilde{\chi}_j^0, \qquad \overline{\tilde{\chi}_i^0}\omega_L \to \overline{\tilde{\chi}_i^0}(1+\tfrac{1}{2}\delta \bar{Z}_0^R)_{ij}\omega_L.$$

One must impose the on-shell conditions:

- $\hat{\Gamma}_{ij}^{(2)}$ should be diagonal, e.g. $\hat{\Gamma}_{ij}^{(2)}\tilde{\chi}_i(p)\big|_{p^2=m^2_{\tilde{\chi}_j}} = 0$
- $\hat{S}_{ij}^{(2)}$ should have a unity residue,

  e.g. $\lim_{p^2\to m^2_{\tilde{\chi}_i}} \frac{1}{\not{p}-m_{\tilde{\chi}_i}}\hat{\Gamma}_{ii}^{(2)}\tilde{\chi}_i(p) = i\tilde{\chi}_i$

[5] see A. C. Fowler, PhD Thesis, 2010

Where does our approach differ?

Usual approach: Assume $\delta\bar{Z}_{ij} = \delta Z^{\dagger}_{ij}$
$\Rightarrow$ Expressions for the wave-function renormalisation e.g. for charginos

$$\delta Z^{L/R}_{-,ij} = \frac{2}{m^2_{\tilde{\chi}^\pm_i} - m^2_{\tilde{\chi}^\pm_j}} \widetilde{\mathrm{Re}} \left[m^2_{\tilde{\chi}^\pm_j} \Sigma^{L/R}_{-,ij}(m^2_{\tilde{\chi}^\pm_j}) + m_{\tilde{\chi}^\pm_i} m_{\tilde{\chi}^\pm_j} \Sigma^{R/L}_{-,ij}(m^2_{\tilde{\chi}^\pm_j}) + m_{\tilde{\chi}^\pm_i} \Sigma^{SL/SR}_{-,ij}(m^2_{\tilde{\chi}^\pm_j}) + m_{\tilde{\chi}^\pm_j} \Sigma^{SR/SL}_{-,ij}(m^2_{\tilde{\chi}^\pm_j}) - m_{\tilde{\chi}^\pm_{i/j}} (U^* \delta X V^\dagger)_{ij} - m_{\tilde{\chi}^\pm_{j/i}} (V \delta X^\dagger U^T)_{ij} \right],$$

$$\delta\bar{Z}^{L/R}_{-,ij} = \frac{2}{m^2_{\tilde{\chi}^\pm_j} - m^2_{\tilde{\chi}^\pm_i}} \widetilde{\mathrm{Re}} \left[m^2_{\tilde{\chi}^\pm_i} \Sigma^{L/R}_{-,ij}(m^2_{\tilde{\chi}^\pm_i}) + m_{\tilde{\chi}^\pm_i} m_{\tilde{\chi}^\pm_j} \Sigma^{R/L}_{-,ij}(m^2_{\tilde{\chi}^\pm_i}) + m_{\tilde{\chi}^\pm_i} \Sigma^{SL/SR}_{-,ij}(m^2_{\tilde{\chi}^\pm_i}) + m_{\tilde{\chi}^\pm_j} \Sigma^{SR/SL}_{-,ij}(m^2_{\tilde{\chi}^\pm_i}) - m_{\tilde{\chi}^\pm_{i/j}} (U^* \delta X V^\dagger)_{ij} - m_{\tilde{\chi}^\pm_{j/i}} (V \delta X^\dagger U^T)_{ij} \right]$$

Only consistent soln. to OS eqs using $\widetilde{\mathrm{Re}}$ $\Rightarrow$ drop absorptive part

Additional finite renormalisation term required to restore on-shell properties of external states

Where does our approach differ?

We do not require hermiticity condition:

$$\delta Z^{L/R}_{-,ij} = \frac{2}{m^2_{\tilde{\chi}^\pm_i} - m^2_{\tilde{\chi}^\pm_j}} \cancel{\widetilde{\mathrm{Re}}} \Big[m^2_{\tilde{\chi}^\pm_j} \Sigma^{L/R}_{-,ij}(m^2_{\tilde{\chi}^\pm_j}) + m_{\tilde{\chi}^\pm_i} m_{\tilde{\chi}^\pm_j} \Sigma^{R/L}_{-,ij}(m^2_{\tilde{\chi}^\pm_j}) + m_{\tilde{\chi}^\pm_i} \Sigma^{SL/SR}_{-,ij}(m^2_{\tilde{\chi}^\pm_j})$$

$$+ m_{\tilde{\chi}^\pm_j} \Sigma^{SR/SL}_{-,ij}(m^2_{\tilde{\chi}^\pm_j}) - m_{\tilde{\chi}^\pm_{i/j}} \left(U^* \delta X V^\dagger\right)_{ij} - m_{\tilde{\chi}^\pm_{j/i}} \left(V \delta X^\dagger U^T\right)_{ij} \Big],$$

$$\delta \bar{Z}^{L/R}_{-,ij} = \frac{2}{m^2_{\tilde{\chi}^\pm_j} - m^2_{\tilde{\chi}^\pm_i}} \cancel{\widetilde{\mathrm{Re}}} \Big[m^2_{\tilde{\chi}^\pm_i} \Sigma^{L/R}_{-,ij}(m^2_{\tilde{\chi}^\pm_i}) + m_{\tilde{\chi}^\pm_i} m_{\tilde{\chi}^\pm_j} \Sigma^{R/L}_{-,ij}(m^2_{\tilde{\chi}^\pm_i}) + m_{\tilde{\chi}^\pm_i} \Sigma^{SL/SR}_{-,ij}(m^2_{\tilde{\chi}^\pm_i})$$

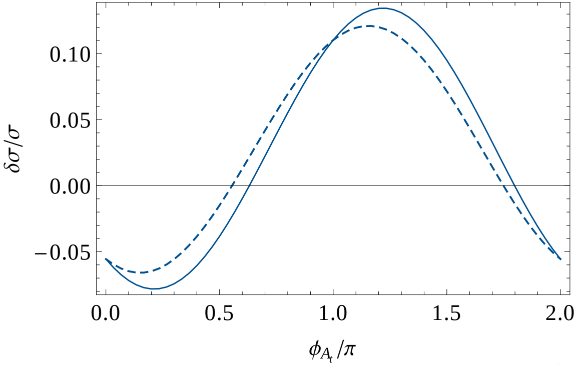
$$+ m_{\tilde{\chi}^\pm_j} \Sigma^{SR/SL}_{-,ij}(m^2_{\tilde{\chi}^\pm_i}) - m_{\tilde{\chi}^\pm_{i/j}} (U^* \delta X V^\dagger)_{ij} - m_{\tilde{\chi}^\pm_{j/i}} (V \delta X^\dagger U^T)_{ij} \Big]$$

In the CP-conserving case one can choose a scheme where (up to purely imaginary terms that do not contribute to squared matrix elements at 1-loop) the hermiticity relation holds: $\delta \bar{Z}_{ij} = \delta Z^\dagger_{ij}$

Keep absorptive parts of loop integrals

Illustration of effect of absorptive parts

for the case of chargino production at a linear collider



- $\delta\sigma/\sigma$ for $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_2^-$ as a function of ϕ_{A_t}
- Absorptive part of loop integrals is included (solid) and ignored (dashed) for field RCs

Illustration of effect of absorptive parts

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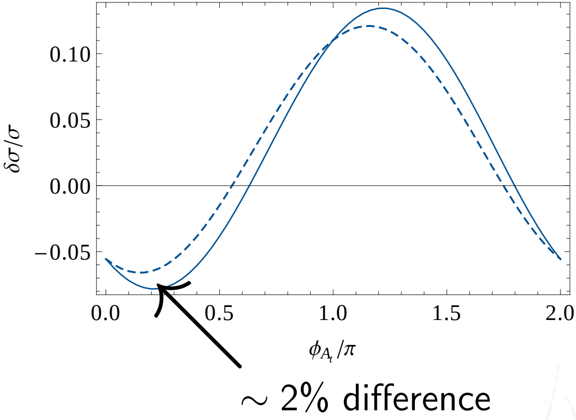

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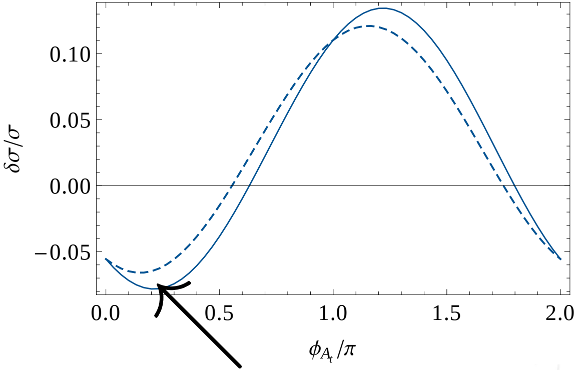

$\sim$ 2% difference

- $\delta\sigma/\sigma$ for $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_2^-$ as a function of ϕ_{A_t}
- Absorptive part of loop integrals is included (solid) and ignored (dashed) for field RCs

Important effect at linear collider precision

Renormalisation of the Electroweakino sector II[6]

Parameter renormalisation:

- $X + \delta X$, $Y + \delta Y \Rightarrow M_1 + \delta M_1$, $M_2 + \delta M_2$ and $\mu + \delta\mu$
  Note $\overline{\mathrm{DR}}$ renormalisation for $\tan\beta$ (δt_β) as in Higgs sector, i.e. like $\overline{\mathrm{MS}}$ with Dim. Reduction instead of Dim. Reg. suitable for SUSY[a]
- e.g. $$\delta X = \begin{pmatrix} \delta M_2 & \frac{\delta M_W^2 s_\beta}{\sqrt{2} M_W} + M_W s_\beta c_\beta^2 \delta t_\beta \\ \frac{\delta M_W^2 c_\beta}{\sqrt{2} M_W} - M_W c_\beta s_\beta^2 \delta t_\beta & \delta\mu \end{pmatrix}$$
- Fix $\delta|M_1|$,$\delta|M_2|$ and $\delta|\mu|$ by choosing three (of six) masses on-shell

[a] see e.g. D. Stockinger, "Regularization by dimensional reduction: Consistency, quantum action principle, and supersymmetry," JHEP **0503** (2005) 076 [arXiv:hep-ph/0503129]

[6] see A. C. Fowler, PhD Thesis, 2010

Renormalisation of the Electroweakino sector II[7]

Parameter renormalisation:

- Fix $\delta|M_1|$,$\delta|M_2|$ and $\delta|\mu|$ by choosing three (of six) masses on-shell:
- More physical masses than independent parameters $\Rightarrow$ can only choose three masses on-shell:
  - $\tilde{\chi}^{\pm}_{1,2}$, $\tilde{\chi}^0_{1(2/3)}$:NCC(b/c)
  - $\tilde{\chi}^0_{1,2}$, $\tilde{\chi}^{\pm}_2$: NNC or
  - $\tilde{\chi}^0_{1,2}$, $\tilde{\chi}^0_3$: NNN

[7] see A. C. Fowler, PhD Thesis, 2010

Renormalisation of the Electroweakino sector II[7]

Parameter renormalisation:

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  - $\tilde{\chi}^{\pm}_{1,2}$, $\tilde{\chi}^{0}_{1(2/3)}$:NCC(b/c)
  - $\tilde{\chi}^{0}_{1,2}$, $\tilde{\chi}^{\pm}_{2}$: NNC or
  - $\tilde{\chi}^{0}_{1,2}$, $\tilde{\chi}^{0}_{3}$: NNN

Does it make a difference?

[7] see A. C. Fowler, PhD Thesis, 2010

Parameter renormalisation cont'd[8]

	NNN	NNC	NCC	
$\delta\|M_1\|$	-1.468	-1.465	-1.468	
$\delta\|M_2\|$	-9.265	-9.265	-9.410	
$\delta\|\mu\|$	-18.494	-18.996	-18.996	
$\Delta m_{\tilde{\chi}_1^0}$	0	0	0	
$\Delta m_{\tilde{\chi}_2^0}$	0	0	-0.1446	
$\Delta m_{\tilde{\chi}_3^0}$	0	-0.5012	-0.5016	
$\Delta m_{\tilde{\chi}_4^0}$	0.3237	-0.1775	-0.1775	
$\Delta m_{\tilde{\chi}_1^\pm}$	0.1446	0.1445	0	
$\Delta m_{\tilde{\chi}_2^\pm}$	0.5012	0	0	

- Finite parts of parameter renormalisation constants (RCs) and mass corrections in GeV for the gaugino-like CPX scenario: $|M_2|$=200 GeV, $M_3 = 1000e^{i\pi/2}$ GeV, $|A_f|$=900 GeV, $\phi_{f1,2} = \pi$, $\phi_{f3} = \pi/2$, M_{SUSY}=500 GeV, $\mu = 2000$ GeV with $M_{H^\pm} = 132.1\,\mathrm{GeV}$ and $\tan\beta = 5.5$
- Last two columns, denoted with an asterisk, show the results for a higgsino-like CPX scenario, with $\mu = 200\,\mathrm{GeV}$, $M_1 = (5/3)(s_W^2/c_W^2)M_2$ and $M_2 = 1000\,\mathrm{GeV}$, and all other parameters the same as the CPX scenario

[8] A. C. Fowler, PhD Thesis, 2010, also see A. Chatterjee, M. Drees, S. Kulkarni, Q. Xu, "On the On-Shell Renormalization of the Chargino and Neutralino Masses in the MSSM," [arXiv:1107.5218 [hep-ph]].

Parameter renormalisation cont'd[8]

	NNN	NNC	NCC	NCCb	NCCc	
$\delta\|M_1\|$	-1.468	-1.465	-1.468	2518.7	-3684.6	
$\delta\|M_2\|$	-9.265	-9.265	-9.410	-9.410	-9.410	
$\delta\|\mu\|$	-18.494	-18.996	-18.996	-18.996	-18.996	
$\Delta m_{\tilde{\chi}_1^0}$	0	0	0	2518.8	-3681.1	
$\Delta m_{\tilde{\chi}_2^0}$	0	0	-0.1446	0	0.356	
$\Delta m_{\tilde{\chi}_3^0}$	0	-0.5012	-0.5016	-0.8446	0	
$\Delta m_{\tilde{\chi}_4^0}$	0.3237	-0.1775	-0.1775	0.6851	-1.439	
$\Delta m_{\tilde{\chi}_1^\pm}$	0.1446	0.1445	0	0	0	
$\Delta m_{\tilde{\chi}_2^\pm}$	0.5012	0	0	0	0	

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Parameter renormalisation cont'd[8]

	NNN	NNC	NCC	NCCb	NCCc	NCCb*	NCCc*
$\delta\|M_1\|$	-1.468	-1.465	-1.468	2518.7	-3684.6	-355.6	-4.642
$\delta\|M_2\|$	-9.265	-9.265	-9.410	-9.410	-9.410	10.683	10.683
$\delta\|\mu\|$	-18.494	-18.996	-18.996	-18.996	-18.996	-5.136	-5.136
$\Delta m_{\tilde{\chi}_1^0}$	0	0	0	2518.8	-3681.1	-11.44	-0.636
$\Delta m_{\tilde{\chi}_2^0}$	0	0	-0.1446	0	0.356	0	-0.671
$\Delta m_{\tilde{\chi}_3^0}$	0	-0.5012	-0.5016	-0.8446	0	-339.5	0
$\Delta m_{\tilde{\chi}_4^0}$	0.3237	-0.1775	-0.1775	0.6851	-1.439	-0.0794	-0.0328
$\Delta m_{\tilde{\chi}_1^\pm}$	0.1446	0.1445	0	0	0	0	0
$\Delta m_{\tilde{\chi}_2^\pm}$	0.5012	0	0	0	0	0	0

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Parameter renormalisation: phases

A comparison of the two approaches

Scheme I:

- Find that imaginary part of field RC is UV convergent $\mathrm{Im}\delta[Z^{L/R}_{\pm,11}]^{\mathrm{div}} \overset{\mathrm{S_I}}{:=} 0$
- Obtain $\delta\phi s$ from three additional conditions: $\mathrm{Im}\delta Z^{L/R}_{\pm,11/22} \overset{\mathrm{S_I}}{:=} 0$, $\mathrm{Im}\delta Z^{L/R}_{0,11} \overset{\mathrm{S_I}}{:=} 0$
- $\Rightarrow$ $\delta\phi_{M_2}$ also renormalised

Scheme II:

- Assume $\delta\phi_{M_2} = 0$ as $\phi_{M_2} = 0$
- Find on-shell expression for $\delta\phi_\mu$, $\delta\phi_{M_1}$ UV-convergent $\delta\phi^{\mathrm{div}}_\mu \overset{\mathrm{S_{II}}}{:=} 0, \quad \delta\phi^{\mathrm{div}}_{M_1} \overset{\mathrm{S_{II}}}{:=} 0$ $\Rightarrow$ Phases do not require renormalization
- Phases remain at tree-level value

NLO result for neutralino decays

Scenarios chosen to ensure all colourless channels are open

MSSM parameters for the initial numerical investigation

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

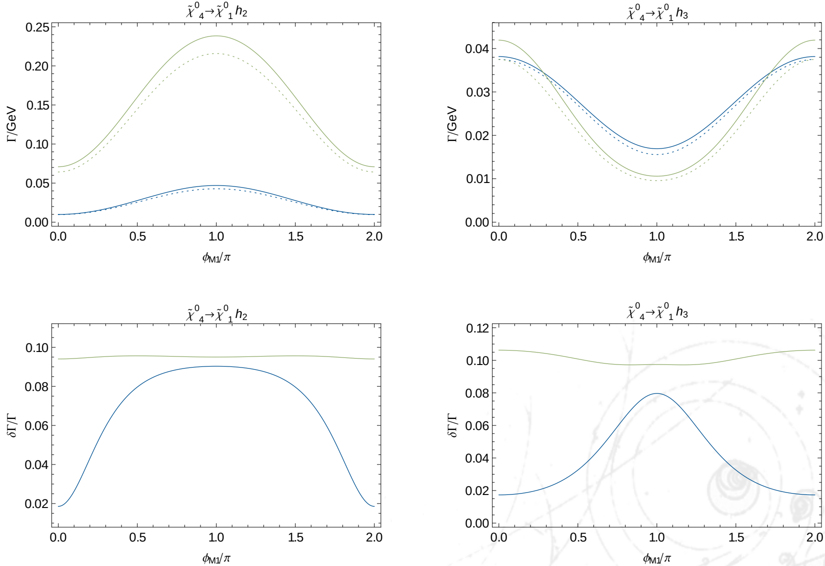
The chargino and neutralino masses in S_g and S_h

Scenario	$m_{\tilde{\chi}_2^\pm}$	$m_{\tilde{\chi}_1^\pm}$	$m_{\tilde{\chi}_4^0}$	$m_{\tilde{\chi}_3^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\chi}_1^0}$	μ	M_2	M_1
S_g	600.0	350.0	600.0	364.2	359.6	267.2	362.1	581.8	277.7
S_h	600.0	350.0	600.1	586.2	349.9	171.4	581.8	362.1	172.8

(masses are in GeV)

Results

Decays to the LSP and neutral Higgs bosons ($\mu < M_2$, $\mu > M_2$)



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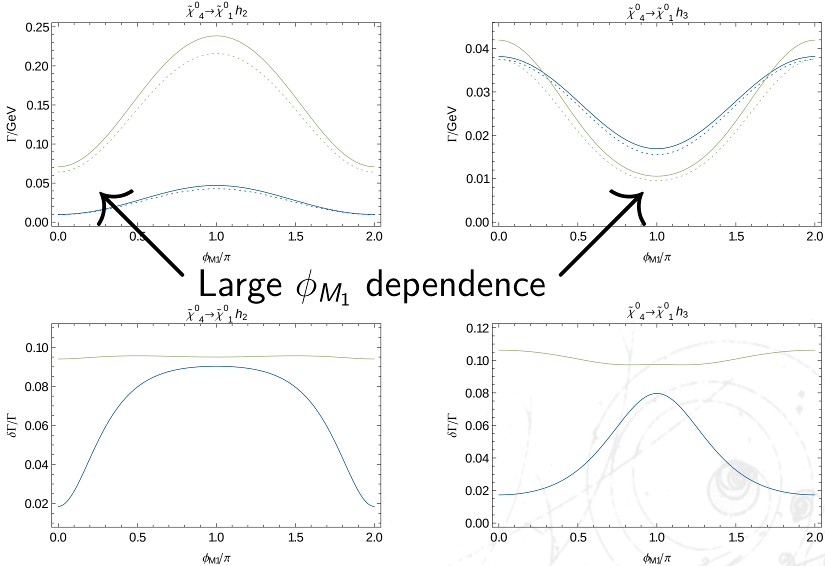
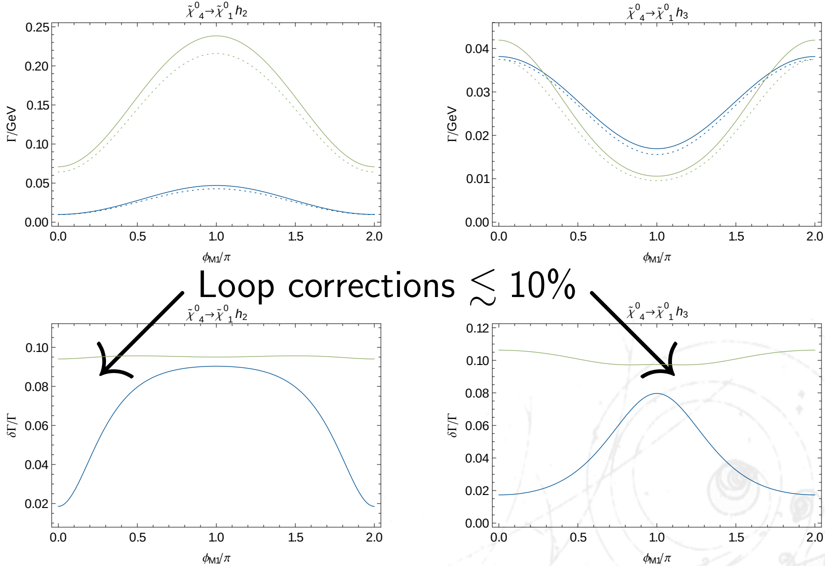


Results

Decays to the LSP and neutral Higgs bosons ($\mu < M_2$, $\mu > M_2$)



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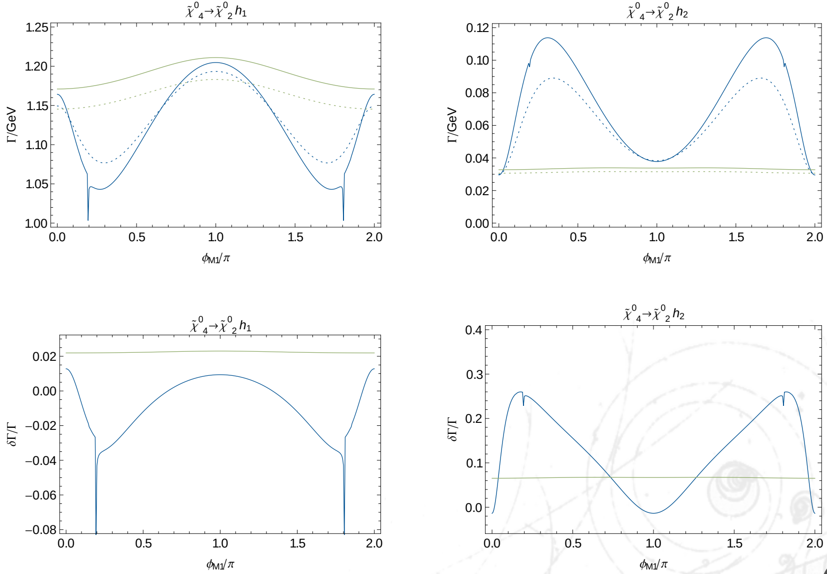

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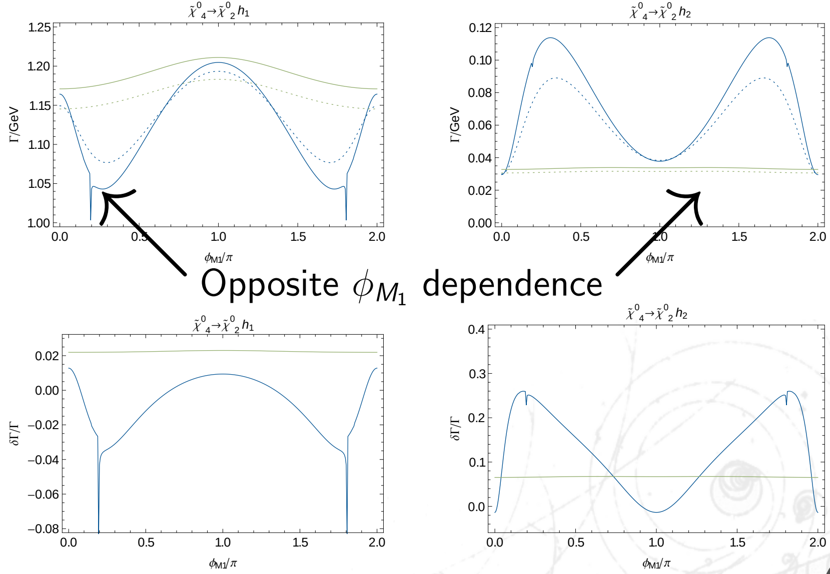

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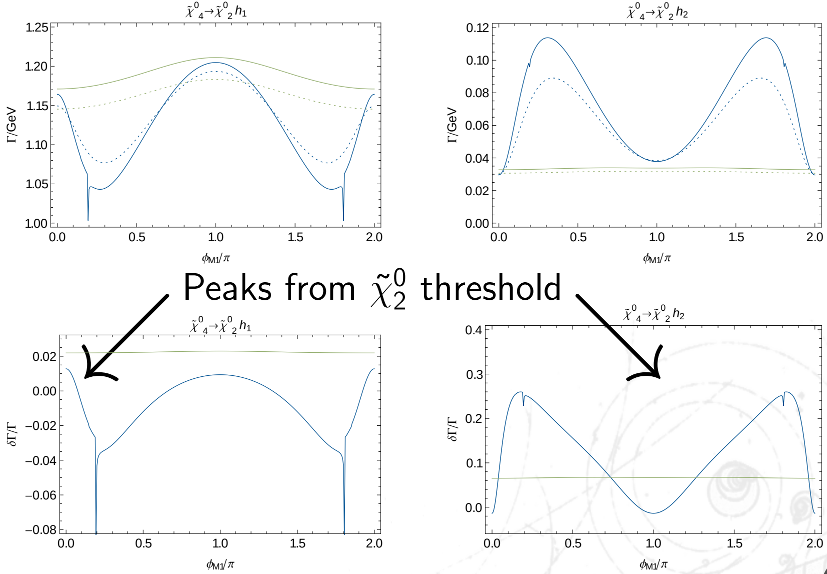


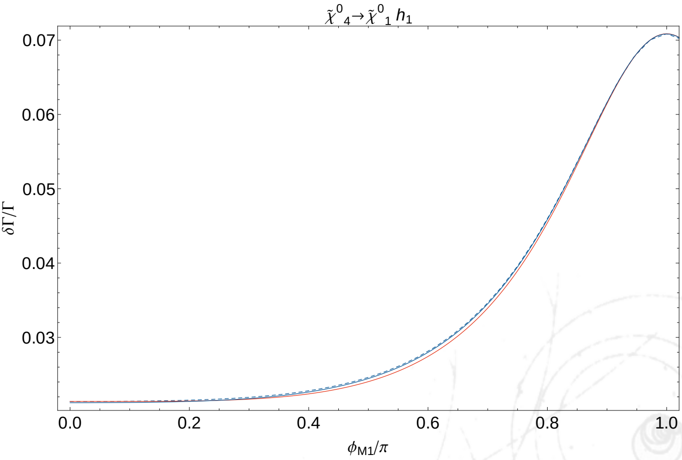
Numerical comparison of the schemes

Difference between $\delta\Gamma/\Gamma$ for $\mathcal{S}_I$ and $\mathcal{S}_{II}$

Channel	S_g		S_h	
	45°	90°	45°	90°
$\tilde{\chi}_4^0 \to \tilde{\chi}_1^0 h_1$	-1.92×10^{-4}	-6.09×10^{-4}	-6.29×10^{-5}	-1.8×10^{-4}
$\tilde{\chi}_4^0 \to \tilde{\chi}_1^0 h_2$	4.46×10^{-4}	5.18×10^{-4}	1.54×10^{-4}	1.74×10^{-4}
$\tilde{\chi}_4^0 \to \tilde{\chi}_1^0 h_3$	-1.35×10^{-4}	-3.6×10^{-4}	-9.13×10^{-5}	-2.21×10^{-4}
$\tilde{\chi}_4^0 \to \tilde{\chi}_2^0 h_1$	-1.15×10^{-5}	5.38×10^{-5}	2.67×10^{-6}	6.07×10^{-6}
$\tilde{\chi}_4^0 \to \tilde{\chi}_2^0 h_2$	1.32×10^{-4}	-4.88×10^{-4}	6.02×10^{-6}	7.08×10^{-6}
$\tilde{\chi}_4^0 \to \tilde{\chi}_2^0 h_3$	5.51×10^{-5}	1.04×10^{-4}	4.46×10^{-6}	8.63×10^{-6}
$\tilde{\chi}_4^0 \to \tilde{\chi}_3^0 h_1$	2.39×10^{-4}	-7.2×10^{-4}	– –	– –
$\tilde{\chi}_4^0 \to \tilde{\chi}_3^0 h_2$	-2.84×10^{-5}	3.22×10^{-5}	– –	– –
$\tilde{\chi}_4^0 \to \tilde{\chi}_3^0 h_3$	-5.07×10^{-5}	-1.58×10^{-4}	– –	– –
$\tilde{\chi}_4^0 \to \tilde{\chi}_1^0 Z$	1.15×10^{-3}	7.48×10^{-4}	1.18×10^{-4}	1.74×10^{-4}
$\tilde{\chi}_4^0 \to \tilde{\chi}_2^0 Z$	2.16×10^{-4}	-3.44×10^{-4}	9.51×10^{-6}	7.26×10^{-6}
$\tilde{\chi}_4^0 \to \tilde{\chi}_3^0 Z$	-4.51×10^{-5}	1.23×10^{-5}	– –	– –
$\tilde{\chi}_4^0 \to \nu_\tau \tilde{\nu}_\tau^\dagger$	-3.45×10^{-6}	-7.03×10^{-6}	-8.93×10^{-6}	-1.93×10^{-5}
$\tilde{\chi}_4^0 \to \tilde{\chi}_1^+ H^-$	1.53×10^{-5}	1.97×10^{-5}	-6.91×10^{-6}	-4.81×10^{-6}
$\tilde{\chi}_4^0 \to \tilde{\chi}_1^+ W^-$	3.44×10^{-6}	6.14×10^{-6}	9.87×10^{-5}	9.74×10^{-5}
$\tilde{\chi}_4^0 \to \tau^- \tilde{\tau}_1^+$	-1.33×10^{-6}	3.65×10^{-6}	-3.47×10^{-5}	-1.07×10^{-5}
$\tilde{\chi}_4^0 \to \tau^- \tilde{\tau}_2^+$	-6.45×10^{-5}	-6.15×10^{-5}	-1.09×10^{-4}	-1.05×10^{-4}

Results

Differentiating between renormalisation schemes (S_I, S_{II})



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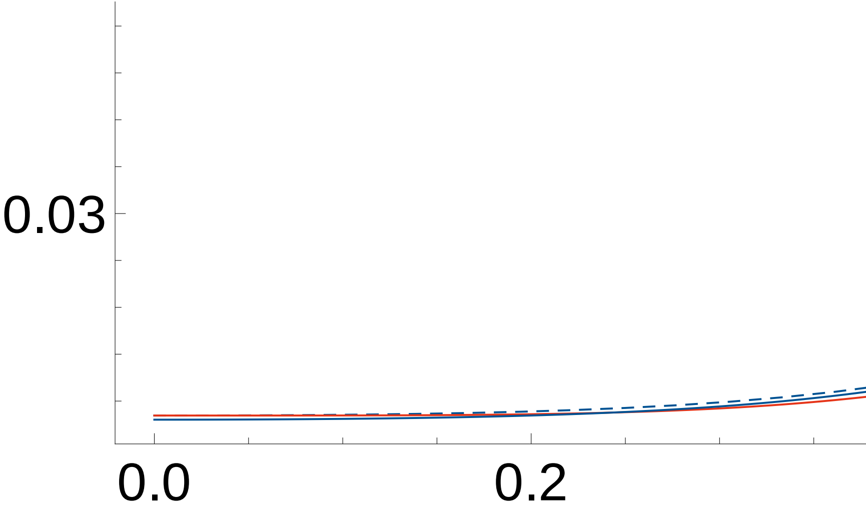
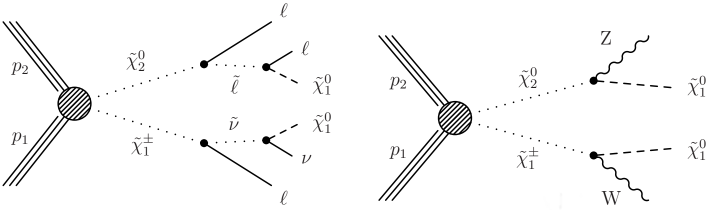


Prospects for direct EWino production@LHC

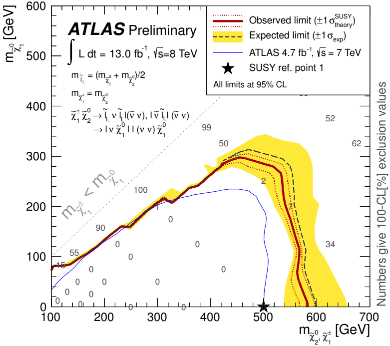
Clues about parameters? (work in progress)

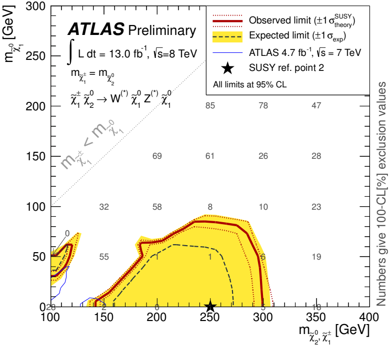
Channel with possibly large cross-section is $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$



- Channels of interest: $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z$, $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h_1$, $\tilde{\chi}_2^0 \to \tau^- \, \tilde{\tau}_1^+$
- Main players: $|M_1|$, ϕ_{M_1}, $|M_2|$, $|\mu|$, $M_{\tilde{\tau}_R}$

Latest news from HCP





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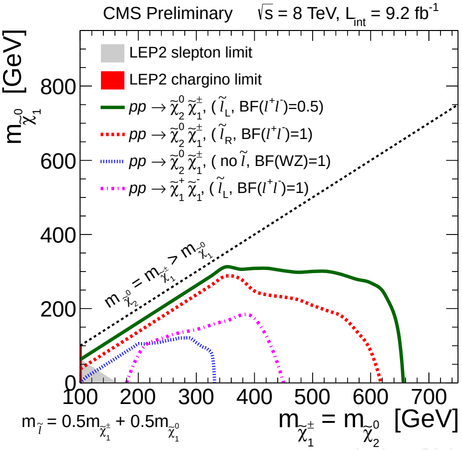
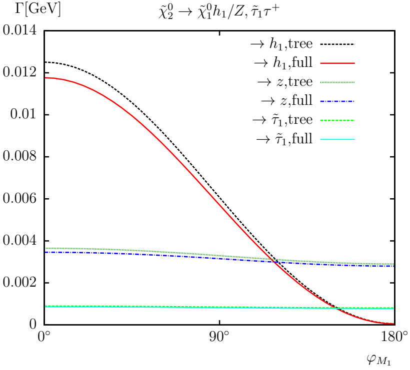
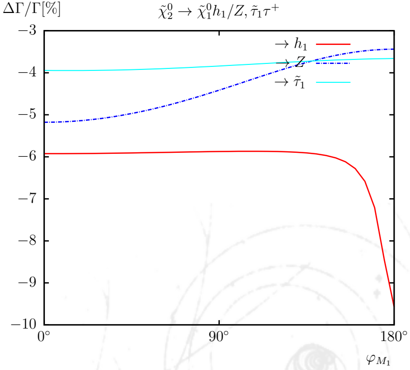


Results for benchmark scenario 1

scenario 2 in progress

$$\mu = 400 \text{ GeV},\ M_2 = 300 \text{ GeV},\ M_1 : \mathrm{GUT},\ m_{\tilde{\tau}_R} = m_{\tilde{\chi}_2^0} - 25 \text{ GeV}$$





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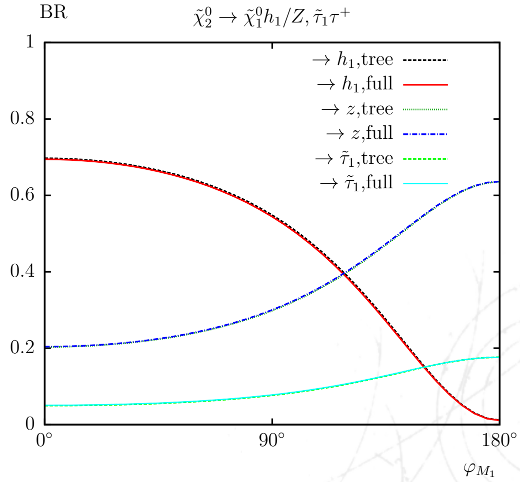

Summary

and Outlook

Neutralino decays at 1-loop in the complex MSSM:

- Calculated all neutralino decays to uncoloured final states
- Effects can be large, easily 20-30% in decays to Higgses, crucial to include
- CP effects can also be very large, espeically when external neutralino is bino-higgsino mixture

[9] and to Flip Tanedo for letting me use his beamer theme

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Renormalization of the electroweakino sector of the cMSSM

- Absorptive parts should be included ($\sim$ 2% effects) + on-shell masses chosen carefully
- Renormalization of phases tricky: what does on-shell mean?
- Difference between relative size of the corrections in two treatments of CP phases is $\lesssim$ 0.1%, largest for channels with strong ϕ_{M_1} dependence.

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Things for the future:

- Important for LHC analyses, and more for LC analyses, where % level precision anticipated for $\tilde{\chi}^0$ BRs
- Same vertices important for calculation of relic density
- The results for the neutralino decays will be implemented into the code FeynHiggs.

Thanks for listening![9]

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Why calculate loop effects

and why the on-shell scheme?

SUSY loop effects known to be large:

- Particularly in the Higgs sector
  $\Rightarrow$ 1-loop effects for $h_a \to \tilde{\chi}_i^+ \tilde{\chi}_j^-$ likely to be sizeable

- Fundamental parameter determination possible at LC to % level, loop effects critical so theory meets experimental accuracy

- CP violation strongly restricted in chargino sector at tree-level, can arise via loops, e.g. in stop sector

Use of on-shell scheme:

- Parameters have a clear physical meaning, experimentally measuremable

- safe-guard infra-red properties of the result

Analogy to the CKM Matrix

- On-shell conditions result in inconsistent equations due to branch cuts in self energies[10]
- Ignore absorptive parts $\Rightarrow$ gauge dependence of δV_{CKM}
- Possible solutions via mass renormalization[11], but not fully on-shell
- Require separate incoming and out-going wfr constants [12], 0.5% observable difference

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[10] A. Denner and T. Sack, Nucl. Phys. B **347** (1990) 203

[11] B. A. Kniehl and A. Sirlin, Phys. Rev. D **74** (2006) 116003, B. A. Kniehl and A. Sirlin, Phys. Lett. B **673** (2009) 208

[12] D. Espriu, J. Manzano and P. Talavera, Phys. Rev. D **66**, 076002 (2002)