Relic density at one-loop with neutralino/chargino coannihilation

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ERA OF PRECISION MEASUREMENTS

RELIC DENSITY OF DARK MATTER

- WMAP : $0.098 < \Omega_{DM} h^2 < 0.114$ (10% precision)
- PLANCK : 2% precision

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- At one loop : the Higgs receives huge corrections
- More generally SUSY processes are known to give large radiative corrections.
- Models for the relic abundance valid at tree-level can be excluded at one-loop and vice-versa.

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$\Rightarrow$ RADIATIVE CORRECTIONS ARE IMPORTANT

COSMOLOGY+PARTICLE PHYSICS

RELIC DENSITY

$$\Omega_{DM} h^2 \simeq \frac{3 \times 10^{-27} cm^3 s^{-1}}{\langle \sigma(\chi\chi \to SM) v \rangle}$$

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PRECISION

- Need to know precisely $\sigma \Rightarrow$ one-loop calculations
- Parameters reconstruction at the LHC/LC
- Check the underlying cosmological scenario

SOME PREVIOUS WORK AT 1-L IN SUSY

EW + QCD corrections

$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \gamma\gamma, Z\gamma, gg$: processes only possible at one-loop order

(Boudjema,Semenov,Temes)[hep-ph :0507127]

$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to ZZ, W^+W^-$ (Baro,Boudjema,Semenov)[hep-ph :0710.1821,Phys.Lett B660(2008) 550]

$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \tau^+\tau^-, b\bar{b}$ (Baro,Boudjema,Semenov)[hep-ph :0710.1821,Phys.Lett B660(2008) 550]

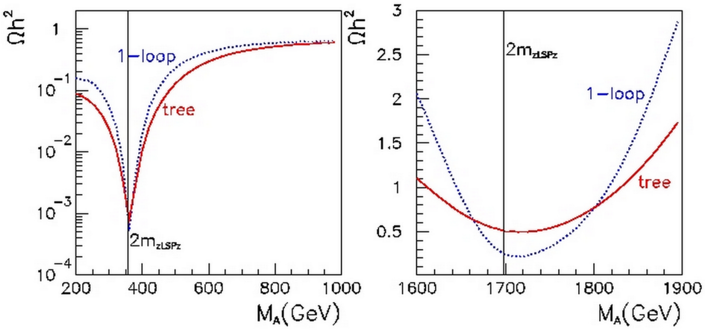
Co-annihilation with $\tilde{\tau}$ (Baro,Boudjema,Semenov)[hep-ph :0710.1821,Phys.Lett B660(2008) 550]

QCD corrections

Co-annihilation with $\tilde{t}$ (Freitas)[Phys.Lett. B652 (2007) 280]

Example with MicrOMEGAs

With one-loop effective lagrangian :



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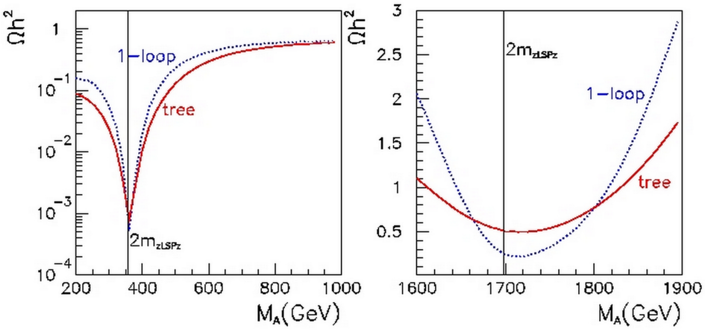
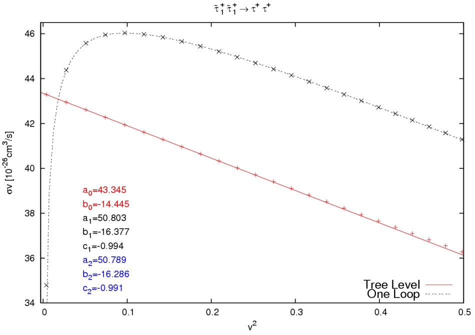


⇒ EXCLUSION OF MODELS AT ONE-LOOP

Example with SloopS

With full one-loop electroweak corrections :



$$\langle \sigma v \rangle \simeq a + b\langle v^2 \rangle$$
$$a = s - wave \;\; coefficient$$
$$b = p - wave \;\; coefficient$$

PRESENT STUDY : COANNIHILATION WITH CHARGINOS/NEUTRALINOS

- It is already known that calculating the relic density including coannihilation effects can significantly change the results.
- Regions of parameters difficult to probe (in mSUGRA) in colliders are regions where coannihilation comes into account for the relic density.
- Coannihilation can be important for Higgsino-like, mixed or gaugino-like neutralino.
- It should be included in calculation whenever $|\mu| \lesssim 2|M_1|$
- Can push the relic density in or out the cosmologically interesting region, as one-loop calculations do.

To deal with radiative corrections we need :

BATTLE PLAN

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A coherent renormalisation scheme and a choice of input parameters

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Loop Integrals to handle Gram determinant when v$\longrightarrow$0

To deal with IR and collinear divergencies$\longrightarrow$ include bremsstrahlung.

INPUT PARAMETERS IN CHARGINO/NEUTRALINO SECTOR

AT TREE-LEVEL...

- The 4x4 neutralino mass matrix is defined as :

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

- The 2x2 chargino mass matrix is :

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

INPUT PARAMETERS IN CHARGINO/NEUTRALINO SECTOR

AND AT ONE-LOOP

- The 4x4 neutralino CT mass matrix is defined as :

$$\delta Y = \begin{pmatrix} \delta M_1 & 0 & \delta Y_{13} & \delta Y_{14} \\ 0 & \delta M_2 & \delta Y_{23} & \delta Y_{24} \\ \delta Y_{13} & \delta Y_{23} & 0 & -\delta\mu \\ \delta Y_{14} & \delta Y_{24} & -\delta\mu & 0 \end{pmatrix}$$

- The 2x2 CT chargino mass matrix is :

$$\delta X = \begin{pmatrix} \delta M_2 & \sqrt{2} s_\beta M_W \left(\frac{1}{2}\frac{\delta M_W^2}{M_W^2} + c_\beta^2 \frac{\delta t_\beta}{t_\beta}\right) \\ \sqrt{2} c_\beta M_W \left(\frac{1}{2}\frac{\delta M_W^2}{M_W^2} - s_\beta^2 \frac{\delta t_\beta}{t_\beta}\right) & \delta\mu \end{pmatrix}$$

- With this sector we can determine M_1, M_2, μ and the corresponding counter-terms $\delta M_1, \delta M_2, \delta\mu$
- Remaining counter-terms are determined in the gauge and higgs sector$\left(\delta\alpha(\text{defined with } \alpha(0)), \delta M_W^2, \delta s_W^2, \delta t_\beta\right)$.
- To determine it we trade these parameters to physical observables (input parameters like masses)
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$\Longrightarrow$ DIFFERENT PREDICTIONS
(different $\delta M_1, \delta M_2, \delta\mu$)

SOME REMARKS

- For general purpose the first input scheme is well adapted :
  - only diagonalisation of a 2x2 matrix
  - for a mSUGRA type model we can reconstruct easily the fundamental parameters (provided that $M_1 \ll M_2 \ll |\mu|$)

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- For general purpose the first input scheme is well adapted :
  - only diagonalisation of a 2x2 matrix
  - for a mSUGRA type model we can reconstruct easily the fundamental parameters (provided that $M_1 \ll M_2 \ll |\mu|$)
- But some drawbacks :
  - $\delta' s \propto \frac{1}{\mu^2 - M_2^2}$
  - $\tilde{\chi}_2^0$ gets a correction at one-loop $\Rightarrow$ care must be taken if it's on an external leg
- For calculation of relic density at one-loop the 2^{nd} input scheme is better suited in case of coannihilation between $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$

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Only MH,$A^0\tau\tau$ are gauge independent

$\Rightarrow$ MIXED CASE to have coannihilation channels
$M_1 = 110\,GeV, M_2 = 127\,GeV, \mu = -245\,GeV$
$\tan\beta = 10, M_A = 600\,GeV$
$m_{\tilde{f}} = 600\,GeV$, $m_{\chi_1^0} = 106\,GeV$

At tree-level :

- $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow W^+ W^-$: 40%
- $\tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow W^+ W^-$: 6%
- $\tilde{\chi}_1^0 \tilde{\chi}_1^+ \rightarrow W^+ Z$: 5%
- $\tilde{\chi}_1^0 \tilde{\chi}_1^+ \rightarrow u\bar{d}$: 9%
- $\tilde{\chi}_1^0 \tilde{\chi}_1^+ \rightarrow c\bar{s}$: 9%

OVERVIEW OF THE CALCULATION

At tree-level we have for process involving W's 7 diagrams

At one-loop we have $\simeq$ 7000 diagrams $\longrightarrow$ need for automation

SLOOPS

A code for calculating one-loop diagrams including a complete and coherent renormalisation of the MSSM with an OS scheme (cf Nans Baro's talk).

OVERVIEW OF THE CALCULATION

Using this program we calculated the one-loop cross section in the 2 schemes presented above :

- $m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_1^+}, m_{\tilde{\chi}_2^+}$ (o1c1c2 scheme)
- $m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_1^+}$ (o1o2c1 scheme)

And for both schemes we analyzed the t_β scheme dependence

For one-loop calculations several checks have to be done :

- UV finiteness
- IR safety (for process involving quarks we used the soft approximation to deal with g emission)
- gauge independence

To calculate the relic density we had to :

- use an approximation for thermal average :
  $\langle \sigma_{ij} v_{ij} \rangle = a_{ij} + 6(b_{ij} - a_{ij}/4)/x \quad (x = m_{\tilde{\chi}_1^0}/T)$
- include coannihilation (Boltzmann factor $\propto e^{-(m_{NLSP} - m_{LSP})}$)

Our final formula is :

$$\Omega h^2 = \left(\frac{10}{\sqrt{g_*(x_F)}} \frac{x_F}{24} \right) \frac{0.237 \times 10^{-26} cm^3.s^{-1}}{x_F J}$$

$$J = \int_{x_F}^{\infty} \langle \sigma v \rangle_{eff} dx/x^2$$

$$\langle \sigma v \rangle_{eff} = \sum_{ij} \frac{g_{i,eff} g_{j,eff}}{g_{eff}^2} \langle \sigma_{ij} v_{ij} \rangle$$

THEORETICAL DIFFERENCES BETWEEN THE TWO SCHEMES

Tree-level masses(GeV) :

$M_1 = 110, M_2 = 127, \mu = -245$

$m_{\chi_1^0} = 106.47, m_{\chi_2^0} = 119.34, m_{\chi_1^+} = 118.20, m_{\chi_2^+} = 274.06$

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$m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_1^+}, m_{\tilde{\chi}_2^+}$

$$m_{\tilde{\chi}_1^+}, m_{\tilde{\chi}_2^+} \longrightarrow M_2, \mu$$

$$m_{\tilde{\chi}_1^0} \longrightarrow M_1$$

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$$m_{\tilde{\chi}_1^0} \rightarrow M_1$$

$\Rightarrow \mu$ is difficult to reconstruct in the 2^{nd} scheme

CORRECTED MASSES

$m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_1^+}, m_{\tilde{\chi}_2^+}$

Masses	$m_{\chi_1^0}$	$m_{\chi_2^0}$	$m_{\chi_3^0}$	$m_{\chi_4^0}$	$m_{\chi_1^+}$	$m_{\chi_2^+}$
TL (Gev)	106.474	119.345	258.291	269.471	118.203	274.061
1-L (Gev) $A_{\tau\tau}$		119.210	258.707	269.453		
1-L (Gev) $\overline{DR}$		119.264	258.594	269.506		
1-L (Gev) MH		119.448	258.211	269.686		

$m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_1^+}$

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TL (Gev)	106.474	119.345	258.291	269.471	118.203	274.061
1-L (Gev) $A_{\tau\tau}$			254.959	270.802		266.254
1-L (Gev) $\overline{DR}$			256.347	272.107		267.588
1-L (Gev) MH			261.068	276.545		272.125

Table of result for $\langle \sigma v \rangle$

$$(\times 10^{-26} cm^3/s)$$

$\chi_1^0 \chi_1^0 \to W^+ W^-$	Tree Level	ATT o1o2c1	ATT o1c1c2	$\overline{\text{DR}}$ o1o2c1	$\overline{\text{DR}}$ o1c1c2	MH o1o2c1	MH o1c1c2
a	3.37	+24.6%	+6.8%	+23.1%	+12.8%	+18.7%	+30.6%
b	4.8	+18.8%	+4.2%	+18.8%	+8.3%	+12.5%	+25%
$\chi_1^0 \chi_2^0 \to W^+ W^-$							
a	32	+16.3%	+10%	+15.6%	+11.9%	+14.1%	+18.8%
b	26	+15.3%	+7.7%	+15.3%	+11.5%	+15.3%	+13.3%
$\chi_1^0 \chi_1^+ \to W^+ Z$							
a	13.5	+10.4%	+2.2%	+9.3%	+3.7%	+3.7%	+10.4%
b	4.3	+2.3%	-4.6%	+2.3%	-2.3%	+4.7%	+9.3%
$\chi_1^0 \chi_1^+ \to u\bar{d}$							
a	31.6	+15.5%	+7.3%	+14.9%	+9.8%	+12.3%	+15.7%
b	-12.3	+12.2%	+4.1%	+11.4%	+6.7%	+8.9%	+15.4%

Table of result for $\langle \sigma v \rangle$ with $\alpha(0) \to \alpha(M_Z^2)$

$(\times 10^{-26} cm^3/s)$

$\chi_1^0\chi_1^0 \to W^+W^-$	Tree Level	ATT		$\overline{\text{DR}}$		MH	
		o1o2c1	o1c1c2	o1o2c1	o1c1c2	o1o2c1	o1c1c2
a	3.82	+9.9%	-2.6%	+8.6%	+0%	+4.7%	+15.8%
b	5.4	+5.6%	-7.4%	+5.6%	-3.7%	+0%	+11%
$\chi_1^0\chi_2^0 \to W^+W^-$							
a	36.3	+2.5%	-3%	+1.9%	-1.4%	+0.6%	+4.7%
b	30	+0%	-6.7%	+0%	-3.3%	-3.3%	+2.7%
$\chi_1^0\chi_1^+ \to W^+Z$							
a	15.2	-2.3%	-9.2%	-3.3%	-7.9%	-3.7%	-2%
b	4.9	-10%	-16.3%	-10%	-14.3%	-8.2%	-4.1%
$\chi_1^0\chi_1^+ \to u\bar{d}$							
a	35.8	+1.9%	-5.3%	+1.4%	-3.1%	-0.8%	+4.7%
b	-13.9	-0.7%	-7.9%	-1.4%	-5.6%	-3.6%	+2.2%

RELIC DENSITY

Correction to Ωh^2 with $\alpha(0)$

	ATT		DR		MH	
	o1o2c1	o1c1c2	o1o2c1	o1c1c2	o1o2c1	o1c1c2
$\frac{\delta\Omega h^2}{\Omega h^2}$	-11.3%	-3.8%	-10.6%	-6.3%	-8.8%	-13.1%

RELIC DENSITY

Correction to Ωh^2 with $\alpha(M_Z^2)$

	ATT		DR		MH	
	o1o2c1	o1c1c2	o1o2c1	o1c1c2	o1o2c1	o1c1c2
$\frac{\delta\Omega h^2}{\Omega h^2}$	+1.7%	+9.2%	+2.4%	+6.7%	+4.2%	-0.1%

UNDERSTANDING THE CORRECTIONS

- With $\alpha(0) \to \alpha(M_Z^2)$ we reabsorb $\simeq 13\%$ of corrections
- The $m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_1^+}$ scheme is sensitive to δt_β whereas the cross-section is not and conversely for the other scheme.
- Constructive/Destructive effect of the various $\delta t_\beta / t_\beta$ contribution
- Most important channel is the exchange of the $\tilde{\chi}_1^+$ (strong $g_{\tilde{\chi}_1^+ \tilde{\chi}_1^0 W^+}$ coupling)
- Strong dependence of the tree-level cross-section with respect to M_2 (compared to the one in μ)

CONCLUSION

- Complete one-loop renormalisation of MSSM and modularity with different schemes
- Full understanding of the underlying physics of the radiative corrections in the chargino/neutralino sector.
- Reconstruction of fundamental parameters at one-loop.
- Introduce effective couplings ?
- Connection with `MicrOMEGAs`