Relic density at one-loop with gauge boson pair production

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RELIC DENSITY OF DARK MATTER

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

ERA OF PRECISION MEASUREMENTS

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- 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

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

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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

EW + QCD corrections

- $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \gamma\gamma, Z\gamma, gg$: Boudjema,Semenov,Temes, *Phys. Rev.* **D72**, 055024 (2005), hep-ph/0507127
- $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to ZZ, W^+W^-$: Baro,Boudjema,Semenov, *Phys. Lett.* **B660** (2008) 550, hep-ph/0710.1821
- $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \tau^+\tau^-, b\bar{b}$: Baro,Boudjema,Semenov, *Phys. Lett* **B660** (2008) 550, hep-ph/0710.1821
- Co-annihilation with $\tilde{\tau}$: Baro,Boudjema,Semenov, *Phys. Lett* **B660** (2008) 550, hep-ph/0710.1821

QCD corrections

- Co-annihilation with $\tilde{t}$ Freitas *Phys. Lett.* **B652** (2007) 280
- Annihilation into massive quarks Hermann,Klasen,Kovarik *Phys. Rev.* **D79** (2009), hep-ph/0901.0481

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A coherent renormalisation scheme and a choice of input parameters

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

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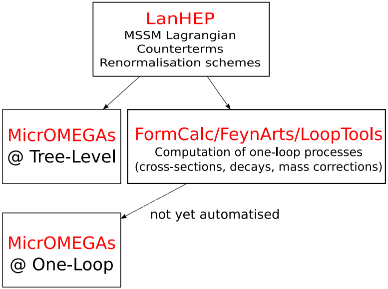
$\Rightarrow$ NEED FOR AUTOMATION



- A code for the calculation of loop diagrams in the MSSM with application to collider physics, astrophysics and cosmology.
- Evaluation of one-loop diagrams including a complete and coherent renormalisation of each sector of the MSSM with an OS scheme.
- Modularity between different renormalisation schemes.

OVERVIEW

- Mass matrix

$$Y = \begin{pmatrix} M_1 & 0 & -c_\beta s_W M_Z & s_\beta s_W M_Z \\ 0 & M_2 & c_\beta c_W M_Z & -s_\beta c_W M_Z \\ -c_\beta s_W M_Z & c_\beta c_W M_Z & 0 & -\mu \\ s_\beta s_W M_Z & -s_\beta c_W M_Z & -\mu & 0 \end{pmatrix}, \quad X = \begin{pmatrix} M_2 & \sqrt{2} s_\beta M_W \\ \sqrt{2} c_\beta M_W & \mu \end{pmatrix}$$

- Diagonalisation and Decomposition

$$\hookrightarrow \boxed{\tilde{\chi}_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W} + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0}$$

- At one-loop : 3 counterterms $(\delta M_1, \delta M_2, \delta\mu)$ $\longrightarrow$ 3 renormalisation conditions
- Our choice : $\boxed{\text{ON-SHELL}}$ scheme with 3 masses $\boxed{m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_1^+}, m_{\tilde{\chi}_2^+}}$.
- Other schemes/definitions possible
- Remaining counter-terms are determined in the gauge and higgs sector$\left(\alpha(0), M_W, M_Z, \delta t_\beta\right)$

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

PARTICLE PHYSICS (SloopS)

GAUGE BOSON PRODUCTION

- $SU(2)_L$ type couplings
- Channels contributions $> 5\%$ to Ωh^2 at TL corrected at one-loop
- Coannihilation channels

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COSMOLOGY (MicrOmegas)

THERMAL RELIC DENSITY

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

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

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

$g_{j,eff} = \frac{g_1}{g_{\tilde{\chi}_j^+}} \left(1 + \frac{\delta m}{m_1} \right)^{\frac{3}{2}} e^{-x \frac{\delta m}{m_1}}$

MIXED-BINO NEUTRALINO

Parameter	M_1	M_2	μ	t_β	M_3	$M_{\tilde{L},\tilde{Q}}$	A_i	M_{A^0}
Value	110	134.5	-245	10	600	600	0	600

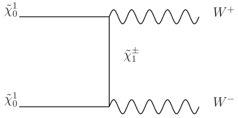
$$\tilde{\chi}_1^0 = 0.94\tilde{B} - 0.20\tilde{W} - 0.27\tilde{H}_1^0 - 0.10\tilde{H}_2^0$$

- $m_{\tilde{\chi}_1^0} = 107$ GeV
- $\delta(m_{\tilde{\chi}_1^+} - m_{\tilde{\chi}_1^0}) = 18$ GeV

		Tree-Level
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to W^+W^-$ [44%]	a	$+0.81$
	b	$+1.219$
$\tilde{\chi}_1^0\tilde{\chi}_1^+ \to u\bar{d}/c\bar{s}$ [8%]	a	$+15.61$
	b	-5.81
$\tilde{\chi}_1^0\tilde{\chi}_1^+ \to Z^0W^+$ [5%]	a	$+8.26$
	b	$+1.42$
$\tilde{\chi}_1^0\tilde{\chi}_2^0 \to W^+W^-$ [5%]	a	$+17.81$
	b	$+11.86$
Ωh^2		0.108

- $\sigma v^2 = a + bv^2$ works well

- Annihilations driven by the s-wave coefficient



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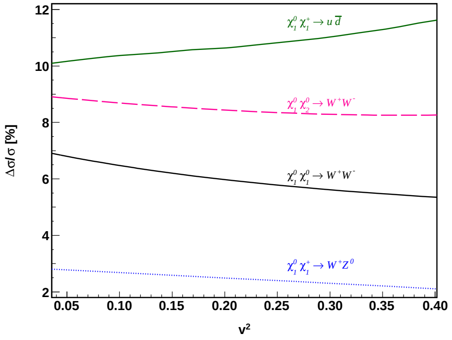
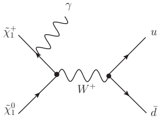
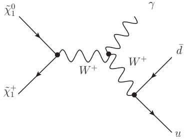


	$A_{\tau\tau}$	$\overline{\text{DR}}$	MH
$\delta\Omega h^2/\Omega h^2$	-2.8%	-5.6%	-10.2%

- Bulk of corrections to the s-wave coefficient
- Large δt_β scheme dependence
- Careful treatment of hard radiation during integration of photon momenta $\longrightarrow$ Internal W boson ON-SHELL
- QCD corrections to $u\bar{d} \simeq 2.5$ %





HIGGSINO NEUTRALINO

Parameter	M_1	M_2	μ	t_β	M_3	$M_{\tilde{L},\tilde{Q}}$	A_i	M_{A^0}
Value	400	350	-250	4	1000	650	0	800

$$\tilde{\chi}_1^0 = 0.11\tilde{B} - 0.31\tilde{W} - 0.70\tilde{H}_1^0 - 0.63\tilde{H}_2^0$$

		Tree
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to W^+W^-$ [26%]	a	$+11.84$
	b	$+4.17$
$\tilde{\chi}_1^0\tilde{\chi}_1^+ \to u\bar{d}$ [12%]	a	$+15.28$
	b	-5.31
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to Z^0Z^0$ [9%]	a	$+4.28$
	b	$+1.83$
$\tilde{\chi}_1^0\tilde{\chi}_1^+ \to Z^0W^+$ [6%]	a	$+6.99$
	b	-0.51
$\Omega_\chi h^2$		0.00931

- $m_{\tilde{\chi}_1^0} \simeq m_{\tilde{\chi}_1^+} \simeq |\mu|$

- $m_{\tilde{\chi}_1^0} = 234$ GeV
- $\delta(m_{\tilde{\chi}_1^+} - m_{\tilde{\chi}_1^0}) = 9$ GeV

- Annihilations driven by the s-wave coefficient and too efficient because of strong $\tilde{\chi}_1^0\tilde{\chi}_1^\pm W^\pm$, $\tilde{\chi}_1^0\tilde{\chi}_2^0 Z^0$ vertices.

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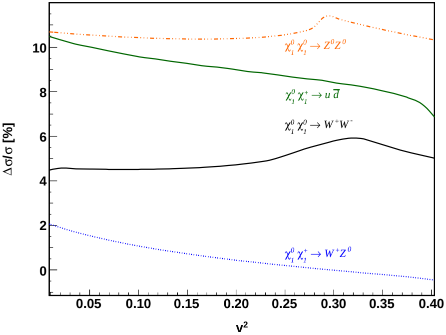
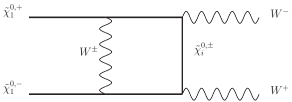


	$A_{\tau\tau}$	$\overline{\mathrm{DR}}$	MH
$\delta\Omega h^2/\Omega h^2$	-2.4%	-2.5%	-3.3%

- Bulk of corrections to the s-wave coefficient
- Small δt_β scheme dependence
- QCD corrections to $u\bar{d} \simeq 3$ %
- Bump $= \tilde{\chi}_1^\pm$ threshold in boxes, not present at Tree-Level



Parameter	M_1	M_2	μ	t_β	M_3	$M_{\tilde{u}_L}$	$M_{\tilde{e}_L}$	$M_{\tilde{u}_R,\tilde{e}_R}$	A_i	M_{A^0}
Value	550	210	-600	30	1200	387	360	800	0	700

$$\tilde{\chi}_1^0 = 0.005\tilde{B} - 0.99\tilde{W} - 0.15\tilde{H}_1^0 - 0.05\tilde{H}_2^0$$

		Tree
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to W^+W^-$ [13%]	a	$+161.8$
	b	$+53.52$
$\tilde{\chi}_1^+\tilde{\chi}_1^+ \to W^+W^+$ [12%]	a	$+80.75$
	b	$+26.83$
$\tilde{\chi}_1^0\tilde{\chi}_1^+ \to Z^0W^+$ [12%]	a	$+37.50$
	b	$+10.15$
$\tilde{\chi}_1^0\tilde{\chi}_1^+ \to u\bar{d}$ [7%]	a	$+24.44$
	b	-12.62
$\tilde{\chi}_1^+\tilde{\chi}_1^- \to Z^0Z^0$ [7%]	a	$+47.08$
	b	$+17.71$
$\tilde{\chi}_1^+\tilde{\chi}_1^- \to W^+W^-$ [7%]	a	$+46.49$
	b	$+14.01$
$\Omega_\chi h^2$		0.00215

- $m_{\tilde{\chi}_1^0} = 206.6$ GeV
- $\delta(m_{\tilde{\chi}_1^+} - m_{\tilde{\chi}_1^0}) = 0.05$ GeV

- $m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_1^\pm}$ almost degenerate
- Coannihilation very important
- Degeneracy between processes $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to W^+W^-$ and $\tilde{\chi}_1^+\tilde{\chi}_1^+ \to W^+W^+$
- Relic density too low $\to$ non-thermal scenarios
- Claim that a wino could explain positron excess (PAMELA)

LIGHT-WINO NEUTRALINO

Parameter	M_1	M_2	μ	t_β	M_3	$M_{\tilde{u}_L}$	$M_{\tilde{e}_L}$	$M_{\tilde{u}_R,\tilde{e}_R}$	A_i	M_{A^0}
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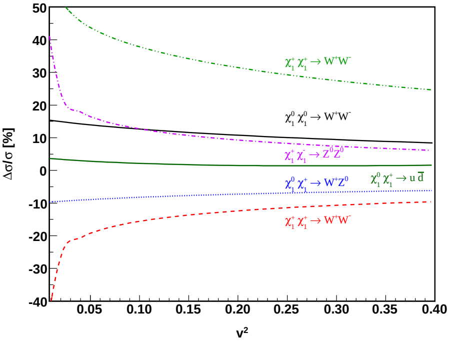
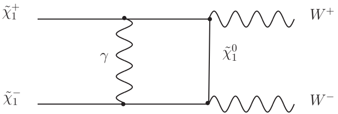


- At 1-L new feature appear for $v \longrightarrow 0$: Coulomb effect
- Possible to capture its one-loop manifestation
- Degeneracy lifted between processes
- Large corrections
- Almost no δt_β scheme dependence
- Strong cancellations between QCD/EW corrections



	$A_{\tau\tau}$	$\overline{\text{DR}}$	MH
$\delta\Omega h^2/\Omega h^2$	-1.9%	-1.9%	-1.9%

LIGHT-WINO NEUTRALINO : ONE-LOOP vs RESUMMATION

Parameter	M_1	M_2	μ	t_β	M_3	$M_{\tilde{u}_L}$	$M_{\tilde{e}_L}$	$M_{\tilde{u}_R,\tilde{e}_R}$	A_i	M_{A^0}
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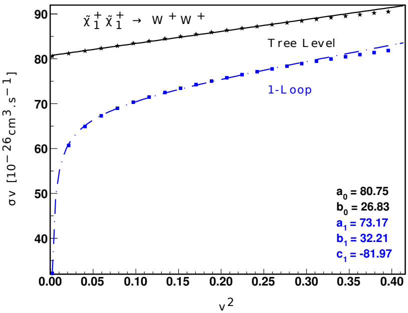

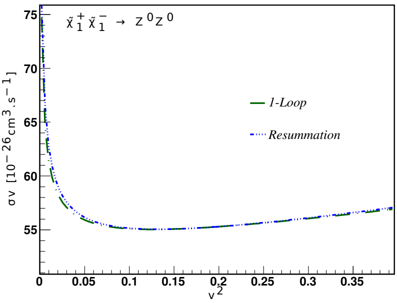

$$\sigma_1 v = a_1 + b_1 v^2 - \pi\alpha a_0 Q_i Q_j / v$$

$$S_{nr} = X_{nr}/(1 - e^{-X_{nr}}) \quad X_{nr} = -2\pi\alpha Q_i Q_j / v$$

CONCLUSION AND PERSPECTIVES

- Complete renormalisation of the MSSM and modularity between different schemes
- Investigation of scenarios where gauge boson pair production dominates
- A lot of processes to correct to have a full $\mathcal{O}(\alpha)$ relic density
- For light-wino case no need for resummation
- Future study of a scenario with a heavy wino $\rightarrow$ QED+EW Sommerfeld enhancement
- Influence of the gaugino scheme
- To be published in *Phys. Rev.* **D**