SLOOPS

An automatic program for full one-loop calculations in the SM/MSSM

Guillaume CHALONS
LAPTH, Annecy-le-Vieux

The SloopS team :
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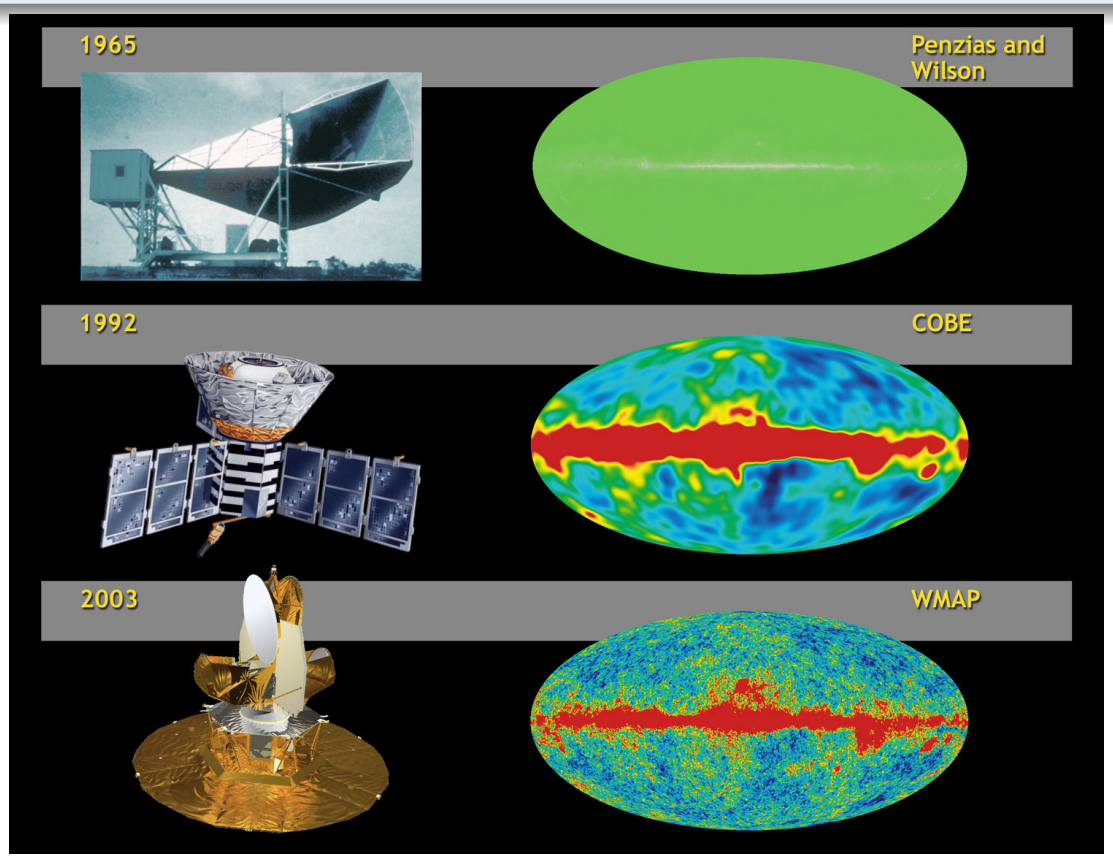
IWLC 2010

NEED FOR PRECISE THEORETICAL PREDICTIONS

RELIC DENSITY OF DARK MATTER

- WMAP : $0.0975 < \Omega_{DM} h^2 < 0.1223$ (10% precision)
- PLANCK : 2% precision



PRECISION MEASUREMENTS

RELIC DENSITY IN THE STANDARD SCENARIO

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

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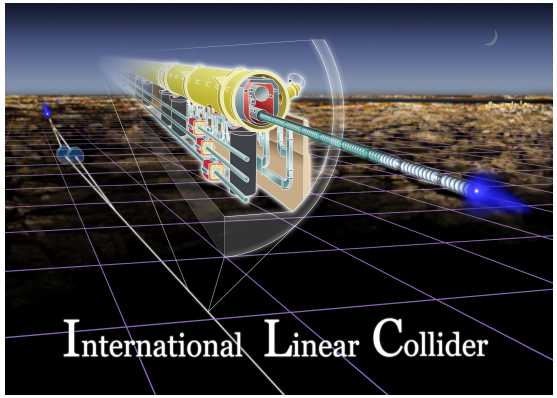
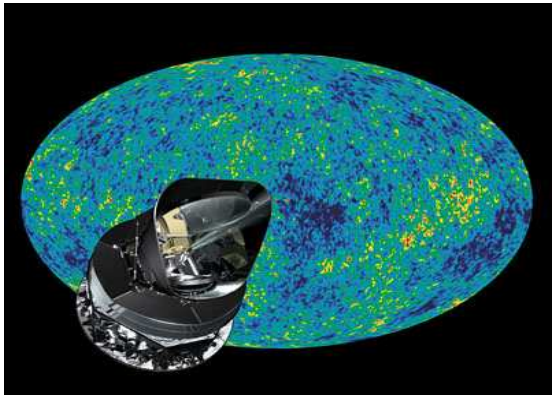
PRECISION

- Need for precise theoretical predictions w.r.t experimental measurements.
- Precision needed at the level of $\sigma \Rightarrow$ One-loop calculations (at least).
- Reconstruction of fundamental underlying parameters at LHC and LC.
- Radiative corrections must be under control to be able to constrain the cosmological underlying scenario.
- What precision required at colliders and theory to constrain cosmology ?



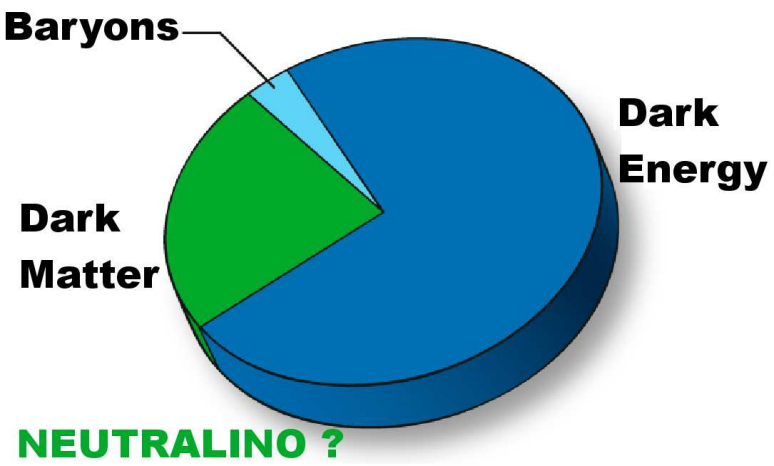
$\Longleftrightarrow$

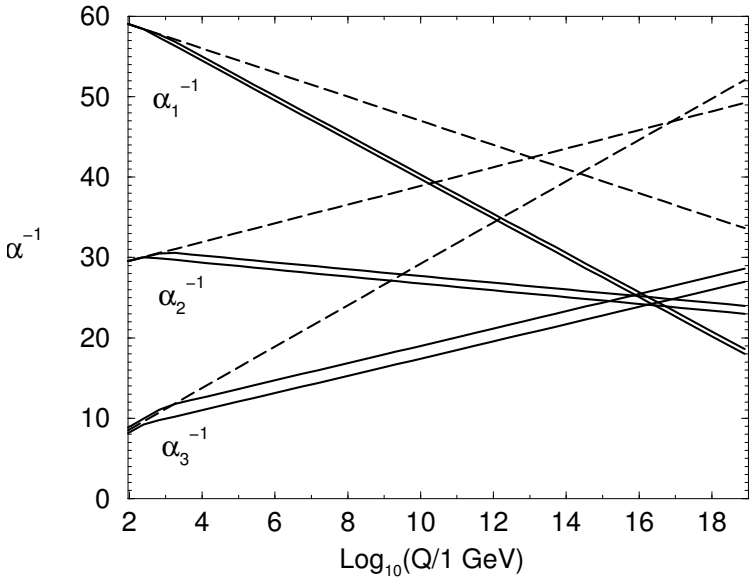


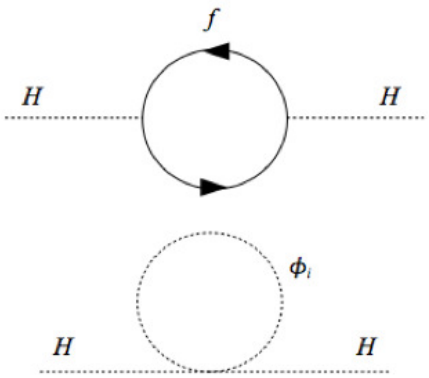
A PARADIGM OF BSM MODELS : SUSY AND THE MSSM

ATTRACTIVE FEATURES

- Stabilization of the scalar sector
- Better Unification of coupling constants
- Dark Matter Candidate(s)
- ...







$$\Delta M_H^2 \sim \frac{\lambda_f^2}{4\pi^2}\left[(m_f^2 - m_S^2)\log\left(\frac{\Lambda}{m_S}\right)\right]$$

COMPLICATIONS

- Not observed yet, neither the Higgs boson...
- $\mathcal{L}_{soft}$ unkown.
- Lots of free parameters ($\simeq 105$).
- Calculations become extremely tedious and involved.

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BEYOND LEADING ORDER IN SUSY

- At LO : $m_h < m_Z$ but no Higgs found !
- LEP Bound on Higgs mass $\boxed{m_h > 114\text{GeV}}$
- At higher orders : Higgs mass can get large corrections.
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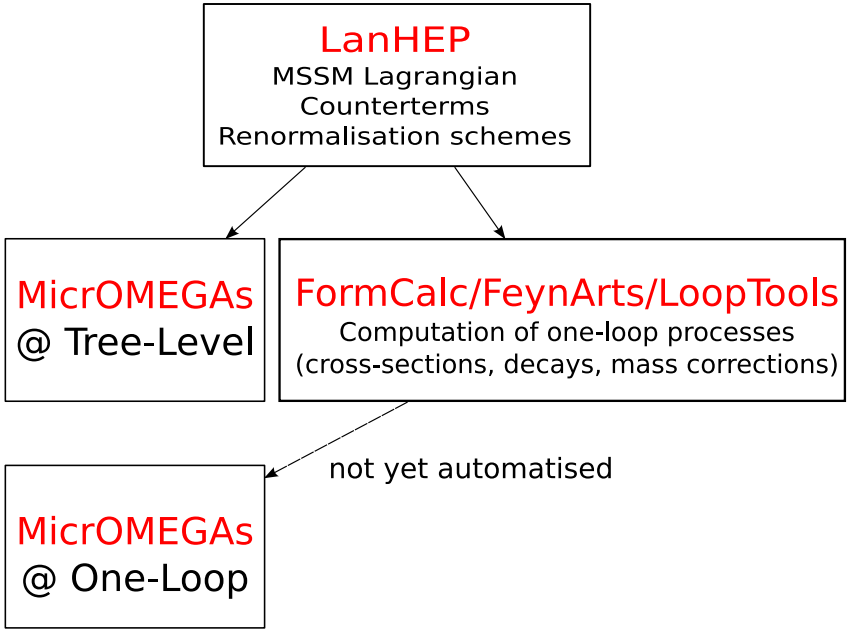
RADIATIVE CORRECTIONS ARE IMPORTANT

AUTOMATION NEEDED

AUTOMATIC TOOL FOR ONE-LOOP CALCULATIONS : SLOOPS



SLOOPS

A code for calculation of loops diagrams in the MSSM with application to colliders, 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.
- Non-linear gauge fixing.
- Checks : results UV,IR finite and gauge independent.

http://code.sloops.free.fr/

ON-SHELL RENORMALISATION OF THE MSSM SECTORS

FERMION + GAUGE SECTOR

Input parameters as in the Standard Model $\boxed{m_f, \alpha(0), M_W, M_Z}$

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NEUTRALINOS/CHARGINOS SECTOR

Input parameters : 2 charginos $m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^\pm}$ and 1 neutralino $\tilde{\chi}_1^0$

Linear gauge fixing

$$\begin{aligned}\mathcal{L}_{GF} \quad = \quad & -\frac{1}{\xi_W}|\partial_\mu W^{\mu +} + i\xi_W \frac{g}{2} v G^+ |^2 \\ & -\frac{1}{2\xi_Z}(\partial_\mu Z^\mu + \xi_Z \frac{g}{2c_w} v G^0)^2 \\ & -\frac{1}{2\xi_A}(\partial_\mu A^\mu)^2\end{aligned}$$

$$\Gamma^{VV} = \frac{-i}{q^2 - M_V^2 + i\epsilon}\left[g_{\mu\nu} + (\xi_V - 1)\frac{q_\mu q_\nu}{q^2 - \xi_V M_V^2}\right]$$

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$\xi_{W,Z,A} = 1$ (Feynman gauge)

Non-Linear gauge fixing

$$
\begin{aligned}
\mathcal{L}_{GF} \quad = \quad & -\frac{1}{\xi_W}|(\partial_\mu - ie\tilde{\alpha}A_\mu - igc_w\tilde{\beta}Z_\mu)W^{\mu +} \\
& +i\xi_W\frac{g}{2}(v + \tilde{\delta}h^0 + \tilde{\omega}H^0 + i\tilde{\kappa}G^0 + i\tilde{\rho}A^0)G^+ \,|^2 \\
& -\frac{1}{2\xi_Z}(\partial_\mu Z^\mu + \xi_Z\frac{g}{2c_w}(v + \tilde{\epsilon}h^0 + \tilde{\gamma}_H^0)G^0)^2 \\
& -\frac{1}{2\xi_A}(\partial_\mu A^\mu)^2
\end{aligned}
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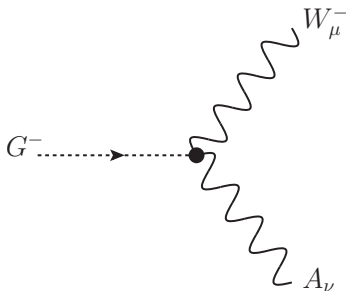
\end{aligned}
$$



$$eM_W(1+\tilde{\alpha}g_{\mu\nu})$$

$\xi_{W,Z,A} = 1$ (Feynman gauge)

→ Gauge parameter dependence in gauge/Goldstone/ghost vertices.
→ No "unphysical" threshold, no higher rank tensor.

FIRST CHECKS ON THE CODE

TREE LEVEL CALCULATIONS

Comparison with public codes : `Grace` and `CompHEP`

Nans Baro PhD Thesis

Cross-section [pb]	SloopS	CompHEP	Grace
$h^0 h^0 \to h^0 h^0$	3.932×10^{-2}	3.932×10^{-2}	3.929×10^{-2}
$W^+ W^- \to \tilde{t}_1 \bar{\tilde{t}}_1$	7.082×10^{-1}	7.082×10^{-1}	7.083×10^{-1}
$e^+ e^- \to \tilde{\tau}_1 \bar{\tilde{\tau}}_2$	2.854×10^{-3}	2.854×10^{-3}	2.854×10^{-3}
$H^+ H^- \to W^+ W^-$	6.643×10^{-1}	6.643×10^{-1}	6.644×10^{-1}
Decay [GeV]			
$A^0 \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$	1.137×10^{0}	1.137×10^{0}	1.137×10^{0}
$\tilde{\chi}_1^+ \to t \bar{\tilde{b}}_1$	5.428×10^{0}	5.428×10^{0}	5.428×10^{0}
$H^0 \to \tilde{\tau}_1 \bar{\tilde{\tau}}_1$	7.579×10^{-3}	7.579×10^{-3}	7.579×10^{-3}
$H^+ \to \tilde{\chi}_1^+ \tilde{\chi}_1^0$	1.113×10^{-1}	1.113×10^{-1}	1.113×10^{-1}

... ... # 200 processes checked

ONE-LOOP PROCESSES THAT DO NOT NEED RENORMALISATION

Comparison with public codes : `PLATON` and `DarkSUSY`

Implementation of a special routine for loop integrals at $v = 0$

Boudjema,Semenov,Temes, *Phys. Rev.* **D72**, 055024 (2005)

- $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to \gamma\gamma$
- $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to gg$
- $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to \gamma Z^0$

APPLICATIONS IN THE HIGGS SECTOR

N. Baro., F. Boudjema, A. Semenov, *Phys. Lett.* **B660** (2008) 550, 0710.1821 [hep-ph]

- One-loop corrections to Higgs masses H^+, h^0 Freitas, Stockinger, *Phys. Rev.* **D66** (2002) 095014, hep-ph/0205281

$t_\beta = 3$	*mhmax*	*large* μ	*nomix*
Tree Level	72.51	72.51	72.51
DCPR	134.28	97.57	112.26
MH	140.25	86.68	117.37
$A\tau\tau$	134.25	97.59	112.27
$\overline{\mathrm{DR}}$ $\overline{\mu} = m_{A^0}$	134.87	98.10	112.86

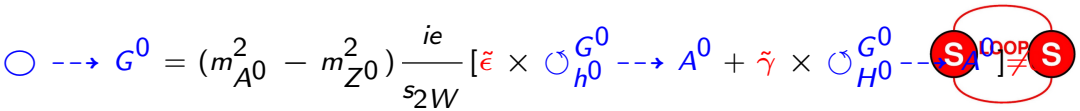
Light Higgs mass m_{h^0}

- $A^0 \to \tau^+\tau^-$, $A^0 \to Z^0 h^0$, $H^0 \to Z^0 Z^0$, $H^0 \to \tau^+\tau^-$

$t_\beta = 3$	*mhmax*	*large* μ	*nomix*
Tree Level	9.35×10^{-3}	9.35×10^{-3}	9.35×10^{-3}
DCPR	-1.09×10^{-4}	-7.96×10^{-5}	-1.09×10^{-4}
MH	$+6.28\times10^{-3}$	-7.91×10^{-3}	$+4.47\times10^{-3}$
$A\tau\tau$	-1.45×10^{-4}	-7.09×10^{-5}	-1.01×10^{-4}
$\overline{\mathrm{DR}}$ $\overline{\mu} = m_{A^0}$	$+5.08\times10^{-4}$	$+3.24\times10^{-4}$	$+4.17\times10^{-4}$

$H^0 \to \tau^+\tau^-$ at one-loop with no QED

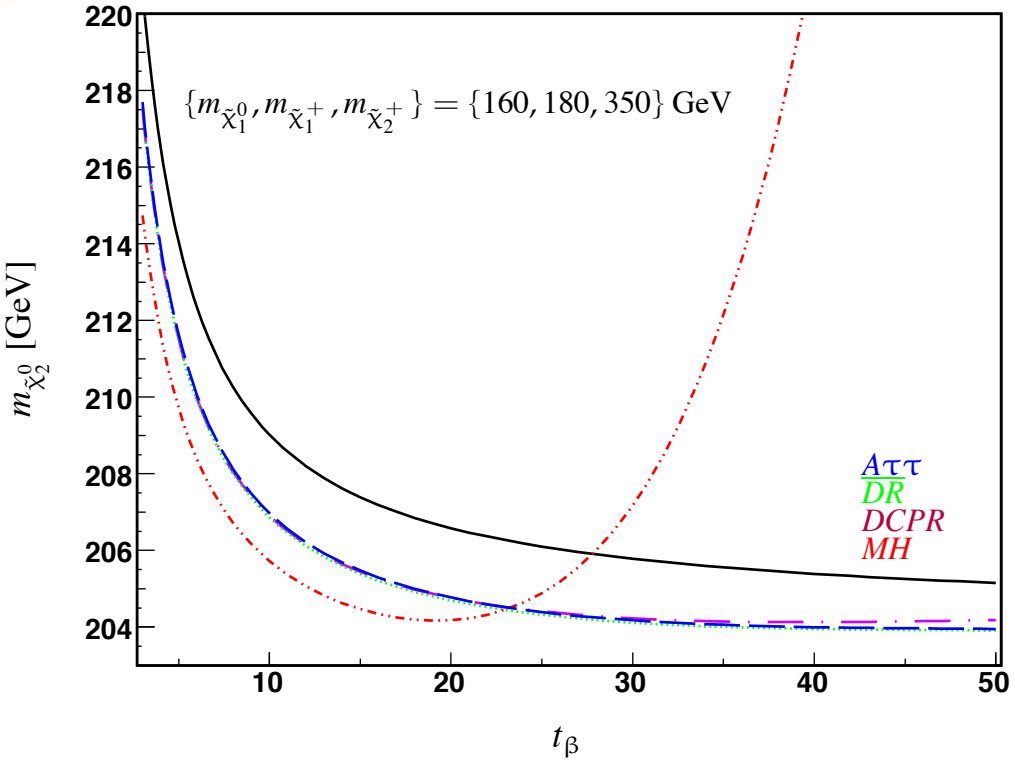
- Theoretical issue due to non-linear gauge fixing and modified Ward-Slavnov-Taylor Identity in the Higgs sector :



APPLICATIONS IN THE CHARGINO/NEUTRALINO SECTOR

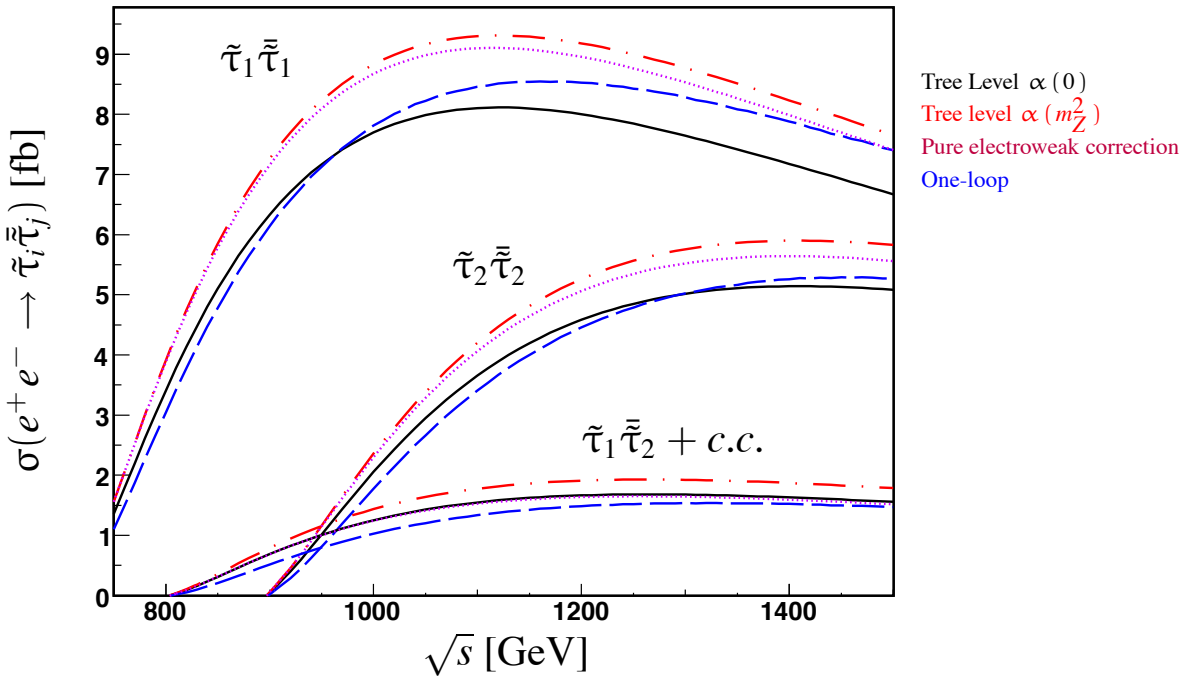
N. Baro, F. Boudjema, *Phys. Rev.* **D80** (2009) 076010, arXiv :0906.1665[hep-ph].

- One-loop corrections to neutralino masses $\tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$
  (see also T. Fritzsche, W. Hollik, *Eur. Phys. J.* **C24** (2002) 619, hep-ph/0203159.)



- Chargino decays at one-loop
  (comparison with J. Fujimoto *et al.*, *Phys. Rev.* **D75** (2007) 113002, hep-ph/0701200.)

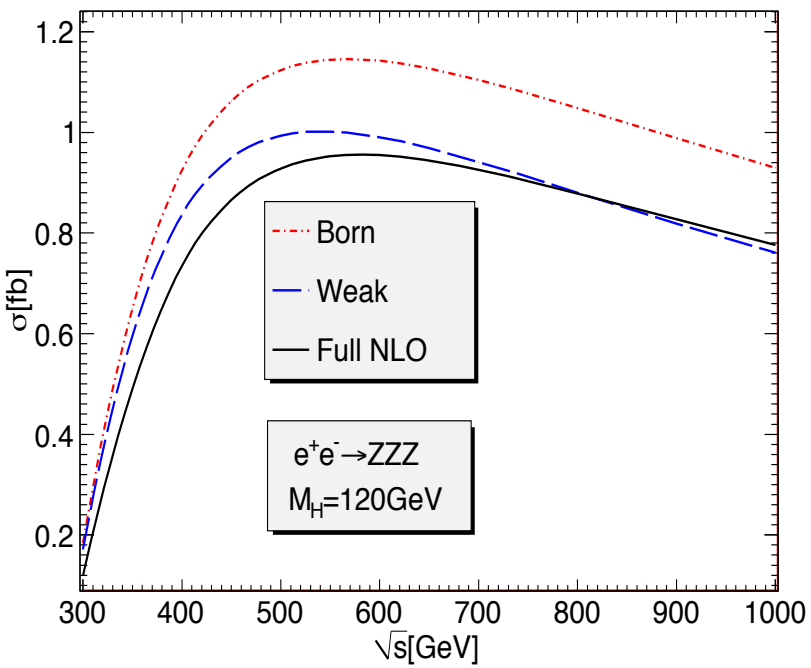
- $e^+e^- \longrightarrow \tilde{\chi}_1^+\tilde{\chi}_1^-$ J. Fujimoto *et al.*, *Phys. Rev.* **D75** (2007) 113002, hep-ph/0701200.
- $e^+e^- \longrightarrow \tilde{\tau}_i\tilde{\tau}_j{}^*$ K. Kovarik *et al.*, *Phys. Rev.* **D72** (2005) 053010, hep-ph/0506021.

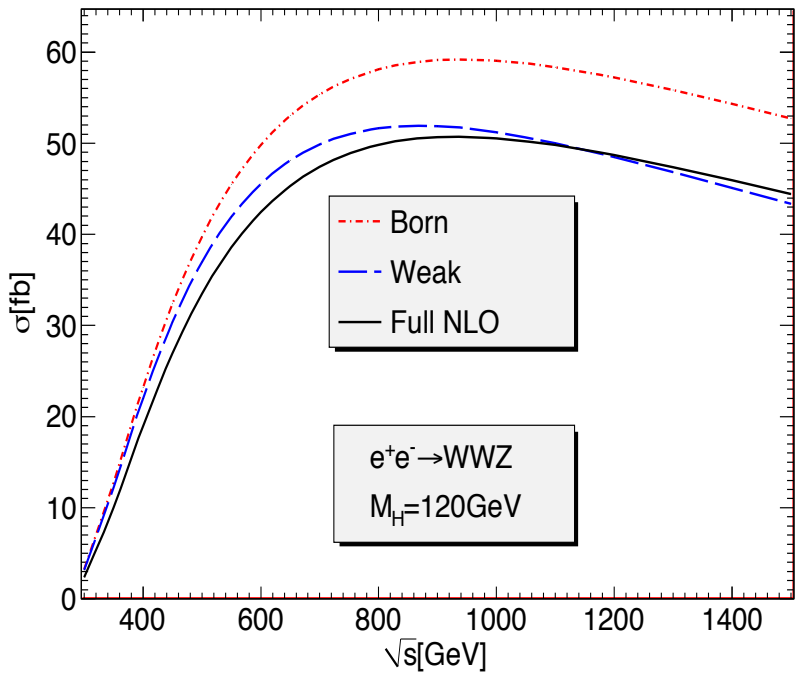


APPLICATIONS TO PURE STANDARD MODEL PROCESSES

F. Boudjema, Le Duc Ninh, Sun Hao, M. M. Weber, *Phys. Rev.* **D81** 073007 (2010)

- $e^+e^- \to W^+W^-Z^0$
- $e^+e^- \to Z^0Z^0Z^0$
- Important processes to test the quartic gauge couplings and Higgs mechanism



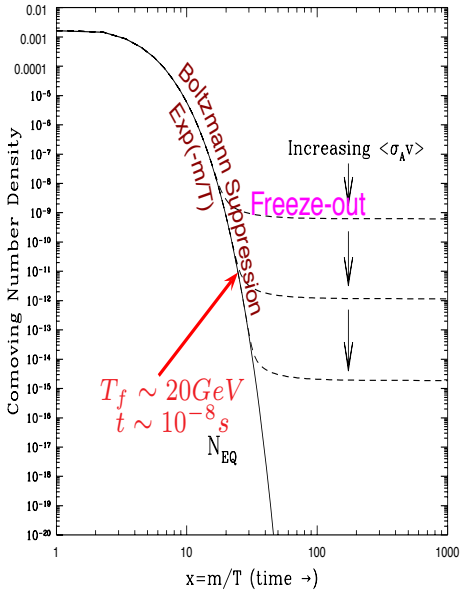


See also Su Ji-Juan *et al. Phys.Rev* **D78** 016007, Sun Wei *et al. Phys.Lett* **B680**, 321

APPLICATIONS TO DARK MATTER

THERMAL RELIC

- $\Omega_\chi h^2 \propto 1/(\sigma(\chi\chi \to \mathrm{SM}))$
- Relic density calculated through the interface of `SloopS` with `micrOMEGAs` (Bélanger *et al.*)



BUNCH OF FULL ONE-LOOP PROCESSES CALCULATED

Baro,Boudjema,Semenov, *Phys. Lett* **B660**

Baro, Boudjema, G.C, Sun Hao, *Phys. Rev.* **D81** 015005 (2010) (2008) 550

- $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to f\bar{f}$ (bino)
- $\tilde{\chi}_1^0\tilde{\tau}_1^+ \to \tau^+\gamma(Z^0)$ (bino)
- $\tilde{\tau}_1^+\tilde{\tau}_1^+ \to \tau^+\tau^+$ (bino)
- $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to W^+W^-, Z^0Z^0$ (bino-wino, bino-higgsino, higgsino, higgsino-bino, wino)
- $\tilde{\chi}_1^0\tilde{\chi}_1^+ \to u\bar{d}, t\bar{b}$ (bino-wino, higgsino, higgsino-bino, wino)
- $\tilde{\chi}_1^+\tilde{\chi}_1^- \to W^+W^-, Z^0Z^0$ (wino)

INTERPLAY BETWEEN ILC AND COSMOLOGY

- What is required from collider data to get a precise prediction of $\Omega_\chi h^2$? (see Allanach *et al.* JHEP 0412 :020,2004.)
- What are the relevant observables to control the uncertainty on the predicted $\Omega_\chi h^2$?
- What is the required accuracy in order to achieve PLANCK precision ?

Basic example as an illustration

- Typical mSUGRA scenario : LSP is $\tilde{\chi}_1^0$ in the bulk region
- $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to \ell\bar{\ell}$ through R-sleptons for $\Omega_\chi h^2$
- At tree-level $\boxed{m_{\tilde{\chi}_1^0}, m_{\tilde{\ell}}(m_{\tilde{\tau}_1})}$ + mixing matrix of neutralinos and in the $\tilde{\tau}_1$ sector needed to reconstruct $\Omega_\chi h^2$.

At one-loop level ?

- Sensitivity to parameters entering in loops ? (non decoupling corrections, thresholds...)
- Sensitivity to renormalisation schemes ?

SENSITIVITY TO SQUARKS MASSES

	M_1	M_2	μ	t_β	$M_{\tilde{e}_R}$	$M_{\tilde{e}_L}$	M_3	M_{A^0}
Masses (GeV)	90	200	-600	5	110	250	800	500

$$250 \text{ GeV} \leq M_{\widetilde{Q}} \leq 800 \text{ GeV}$$

- At tree-level $\Omega_\chi h^2$ sensitive to $M_{\widetilde{Q}}$ when $M_{\widetilde{Q}} \simeq 300$ GeV (new channels open).
- Effects of squarks relevant in loops for $M_{\widetilde{Q}} \geq 300$ GeV ?

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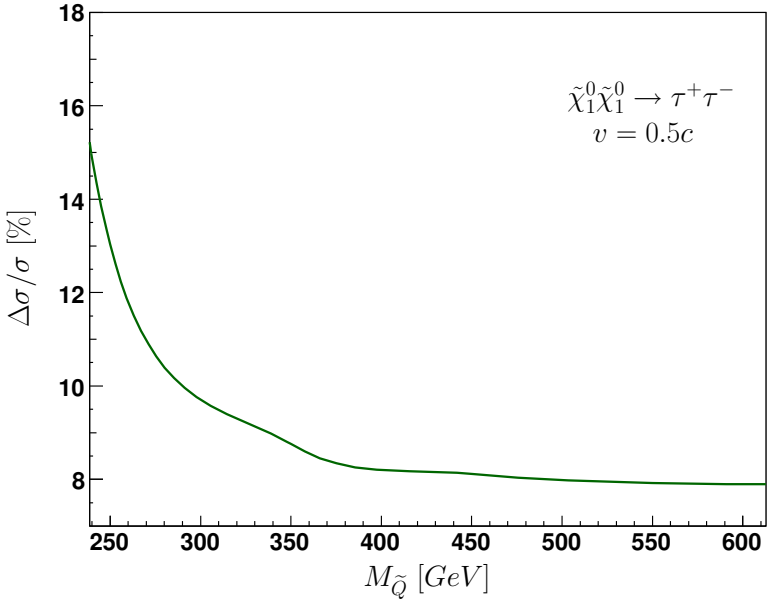

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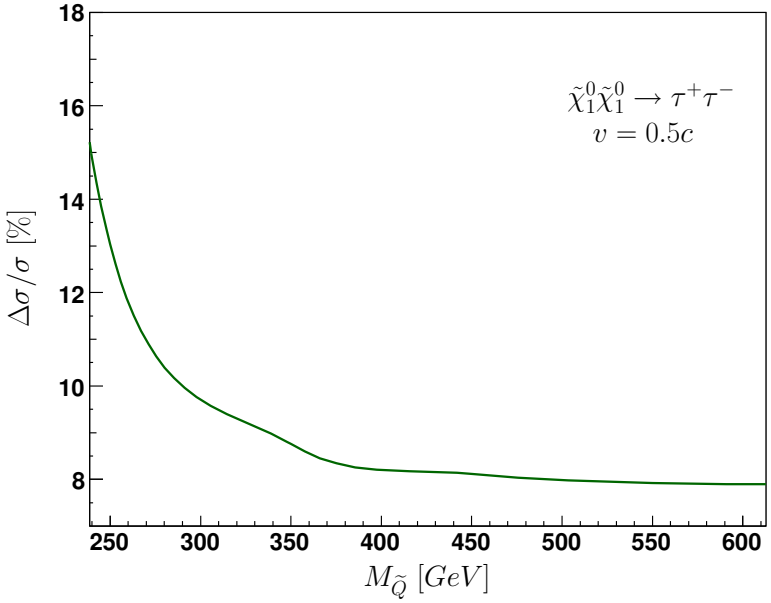
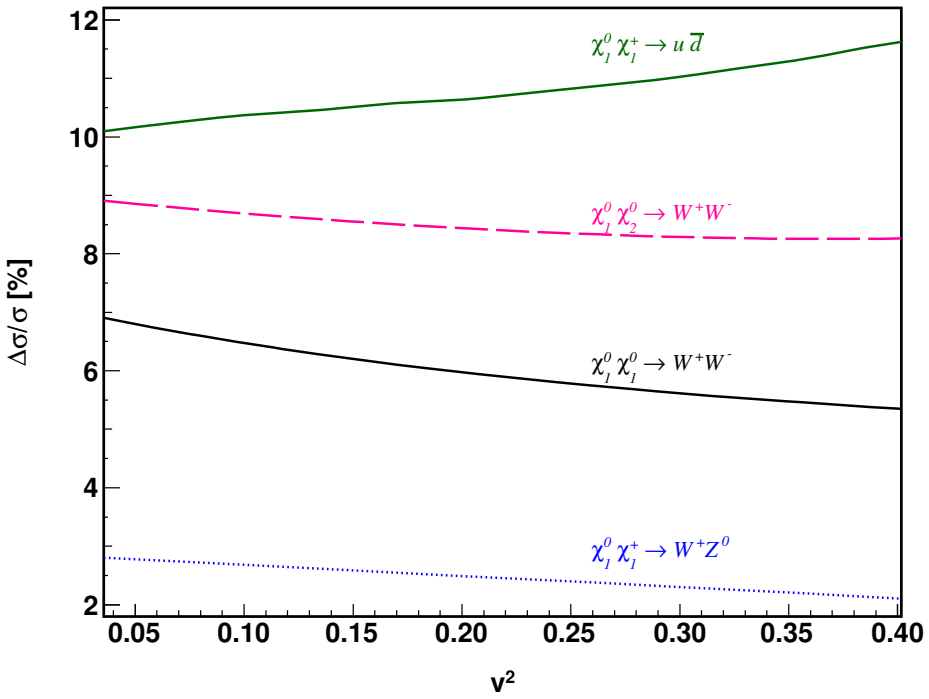


More or less the same conclusion at one-loop level. This may not be the case for other set of parameters.

SENSITIVITY TO RENORMALISATION SCHEME

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

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



	$A_{\tau\tau}$	$\overline{\mathrm{DR}}$	MH
$\Omega_\chi h^2$	0.105	0.102	0.097
$\delta\Omega h^2/\Omega h^2$	-2.8%	-5.6%	-10.2%

- Bulk of corrections to the s-wave coefficient
- Large δt_β scheme dependence
- QCD corrections to $u\bar{d} \simeq 2.5$ %

CONCLUSIONS AND PERSPECTIVES

- Complete EW renormalisation of the MSSM and modularity with different schemes.
- One-loop corrections to masses, decays, cross sections at colliders.
- One-loop corrections to neutralino annihilation relevant for relic density and indirect detection.
- First steps done for the connection with `micrOMEGAs` .
- In any case for $\Omega_\chi h^2$ @ 1-2% $\Rightarrow$ one-loop corrections mandatory.
- Then at one-loop level more input is needed for an efficient reconstruction of parameters compared to the tree level case.
- Gather all available data to construct efficient renormalisation schemes.
- Implementation of QCD renormalisation in `SloopS` ongoing.