Supersymmetry in astrophysics and at colliders

G. Drieu La Rochelle

LAPTh

06/10/2011

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- fundamental issue : hierarchy problem
- experimental outcome : a dark matter candidate

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Plenty of measurements (flavor, superpartners)

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This is an heavy task

Research status

- contributions from a large community since a few decades
- But things remains to be done
- **My aim** : adding a bit of insight on those two subjects

Constraints

- Flavor physics
- Superpartners searches
- Relic density
- Higgses searches
- Precision test

One of the most stringent

accuracy of the %
(WMAP 7-year + Planck)

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This is hampered by radiatives corrections !

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- Some points could be lost/gained.

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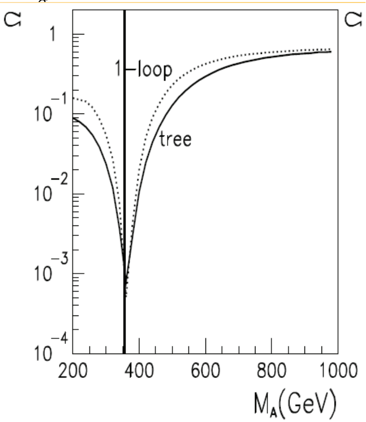

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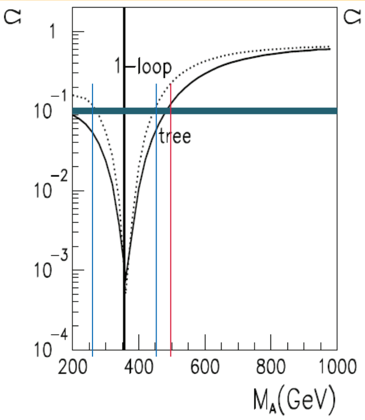

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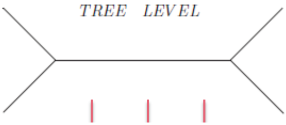
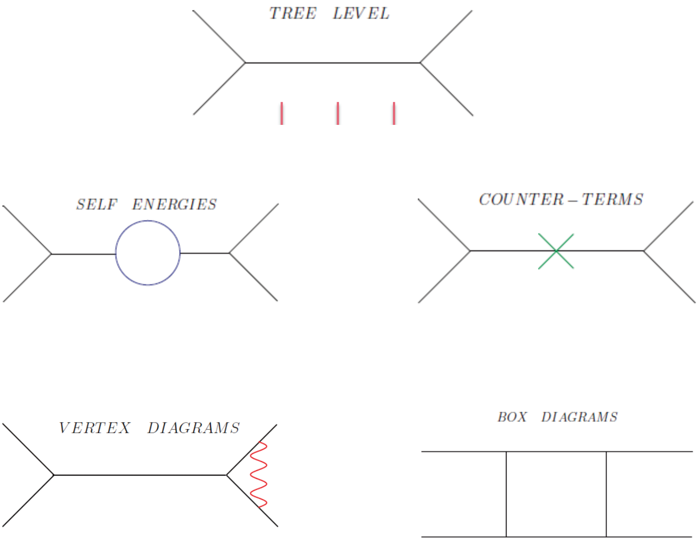

TREE LEVEL

What is in the loop ?



We know it to be feasible :

- Automated tools are quite efficient
  - FeynArts/FormCalc, Grace, SloopS
- The renormalisation part is well understood
  - We can simply treat all particles On-Shell, as in the Standard Model

- It is a process-by-process method, to compute Ω.
  Whereas the tree-level is computed all at once.
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  - From 6 at tree-level to more than 1000 at the one-loop level.

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- but different schemes exist : t_β
  - from M_H
  - from $A_0 \to \tau\tau$
- neutralino chargino sector

MSSM@one-loop : do we really want to ?

Technically contrived

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Selecting par of the diagrams the α_{QED} contribution

- universal diagrams (independent of external legs)
- Hence can be taken by simply shifting $\alpha_{QED} \rightarrow \alpha_{QED} + \Delta\alpha_{QED\ eff}(Q)$

$\alpha_{QED}(Q)$ stands for a small number of diagrams $\longrightarrow$ quick computation !

A solution : Effective operators

A situation analogous to the LEP measurements

- a % precision
- non decoupling effect from heavy particle

Tree-level couplings : $\tilde{\chi}_1^0\tilde{\chi}_1^0 Z$, $\tilde{\chi}_1^0 f\!f$, $\tilde{\chi}_1^0\tilde{\chi}_1^0 h$, $\tilde{\chi}_1^0\chi^+ W^-$

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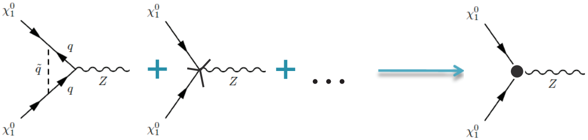

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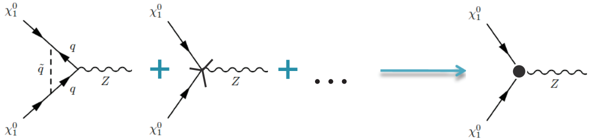

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We are shifitng $\mathcal{L} \to \mathcal{L}_{eff}$

- Easy to do for counterterms such as δZ (include δZ for each leg)
- Possible for triangles (limited number)

Those are universal, in the sense process-independent.

- Not so straightforward for boxes

Ω is mainly driven by the nature of $\tilde{\chi}_1^0$

$$\tilde{\chi} = Z^{-1} \begin{pmatrix} \tilde{B} \\ \tilde{W} \\ \tilde{H}_1^0 \\ \tilde{H}_2^0 \end{pmatrix}$$

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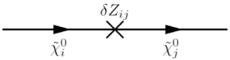
But some of the loops play a nature-changing role



Hence we expect δZ corrections to give a significant contribution to Ω

Which effective operators?

coupling $\tilde{\chi}_1^0 \tilde{f} f$

$$\begin{aligned}
\Delta N_{i1}^{\chi f \tilde{f}} &= \frac{\delta g'}{g'} N_{i1} + \frac{1}{2}\sum_j N_{j1}\delta Z_{ji}, \\
\Delta N_{i2}^{\chi f \tilde{f}} &= \frac{\delta g}{g} N_{i2} + \frac{1}{2}\sum_j N_{j2}\delta Z_{ji}, \\
\Delta N_{i3}^{\chi f \tilde{f}} &= \left(\frac{\delta g}{g} - \frac{1}{2}\frac{\delta M_W^2}{M_W^2} - \frac{\delta c_\beta}{c_\beta}\right) N_{i3} + \frac{1}{2}\sum_j N_{j3}\delta Z_{ji}, \\
\Delta N_{i4}^{\chi f \tilde{f}} &= \left(\frac{\delta g}{g} - \frac{1}{2}\frac{\delta M_W^2}{M_W^2} - \frac{\delta s_\beta}{s_\beta}\right) N_{i4} + \frac{1}{2}\sum_j N_{j4}\delta Z_{ji}.
\end{aligned} \tag{1}$$

Only the counterterms (without leg corrections)

coupling $\tilde{\chi}_1^0 \tilde{\chi}_1^0 Z$

Now the set of counterterms is not finite

We must include the genuine triangle contribution

Tree level $\frac{g_Z}{4}\left(N_{13}N_{13} - N_{14}N_{14}\right)\tilde{\chi}_1^0 \gamma_\mu \gamma_5 \tilde{\chi}_1^0 Z^\mu$

Effective

$$g^{\text{eff}}_{\tilde{\chi}_1^0 \tilde{\chi}_1^0 Z} = g_Z(1 + \Delta g_Z(Q^2) + \Delta g^{\triangle}_{\tilde{\chi}_1^0 \tilde{\chi}_1^0 Z}(Q^2)); \quad (2)$$

$$\Delta N_{ij}^{\tilde{\chi}_1^0 \tilde{\chi}_1^0 Z} = \frac{1}{2}\sum_k N_{kj}\delta Z_{ki}, \quad (i,j,k) = 1\ldots 4. \quad (3)$$

coupling Zff

Numerical study

Model : pMSSM (19 parameters)

- at one-loop
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- Generically heavy sfermions ($M_l \sim 500$ GeV, $M_q \sim 800$ GeV), idem for A_0 ($\sim$1 TeV)
- moderate t_β ($t_\beta \sim 4$)
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Process

$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \mu\mu$, focus on EW corrections

Bino case

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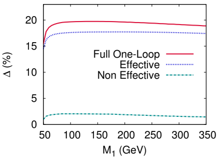

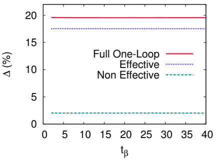

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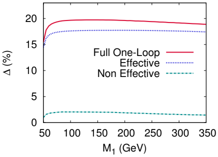
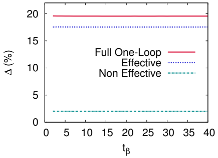
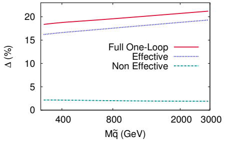




Non decoupling of the squark mass



Higgsino case

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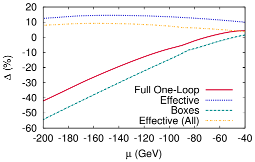

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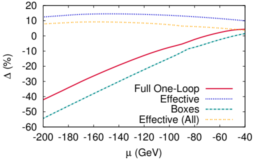
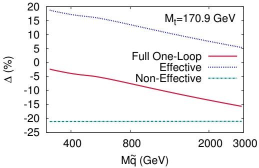
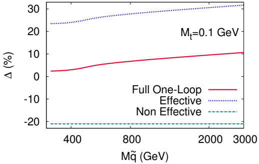


Squark non-decoupling





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But not for the second one

- Those effective couplings apply to any susy model.
- But additional particles will modify the relic density
  - NMSSM, U(1)' MSSM

What can we do for it ?

There is a way not to choose a specific model :

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Beyond the MSSM

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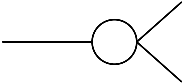
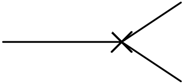
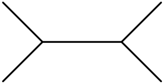
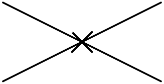
But instead of









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$\rightarrow$

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Is it enough ?

- Not if an accidental cancellation occurs

$$\mathcal{O} = \mathcal{O}^{(0)} + \frac{1}{M}\mathcal{O}^{(1)} + \frac{1}{M^2}\mathcal{O}^{(2)} + \dots$$

well suited only if $\frac{1}{M^n}\mathcal{O}^{(n)}$ small compared to previous orders.

New effective operators

Generic $\rightarrow$ include all possible operators

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Retriction to the Higgs sector
also done by Antoniadis et al., Carena et al.

Operators basis

Dimension 5	Dimension 6
	$\frac{a_i}{M^2}\left(H_i^\dagger e^{2gV_i} H_i\right)^2$
$\frac{\zeta_1}{M}\left(H_1\cdot H_2\right)^2$	$\frac{a_3}{M^2}\left(H_1^\dagger e^{2gV_1} H_1\right)\left(H_2^\dagger e^{2gV_2} H_2\right)$
	$\frac{a_4}{M^2}\left(H_1\cdot H_2\right)\left(H_1^\dagger\cdot H_2^\dagger\right)$
	$\frac{a_5}{M^2}\left(H_1^\dagger e^{2gV_1} H_1\right)\left(H_1\cdot H_2\right)+h.c.$
	$\frac{a_6}{M^2}\left(H_2^\dagger e^{2gV_2} H_2\right)\left(H_1\cdot H_2\right)+h.c.$

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	$\frac{a_4}{M^2}(H_1 \cdot H_2)\left(H_1^\dagger \cdot H_2^\dagger\right)$
	$\frac{a_5}{M^2}\left(H_1^\dagger e^{2gV_1} H_1\right)(H_1 \cdot H_2) + h.c.$
	$\frac{a_6}{M^2}\left(H_2^\dagger e^{2gV_2} H_2\right)(H_1 \cdot H_2) + h.c.$

Susy breaking

$$\zeta_1 = \zeta_{10} + \theta^2 m_s \zeta_{11}$$

$$a_i = a_{i0} + \theta^2 m_s a_{i1} + \theta^2 m_s a_{i1} + \theta^2 \theta^2 m_s^2 a_{i2}$$

Operators basis

Dimension 5	Dimension 6
	$\frac{a_i}{M^2}\left(H_i^\dagger e^{2gV_i} H_i\right)^2$
$\frac{\zeta_1}{M}\left(H_1 \cdot H_2\right)^2$	$\frac{a_3}{M^2}\left(H_1^\dagger e^{2gV_1} H_1\right)\left(H_2^\dagger e^{2gV_2} H_2\right)$
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Effective coeefficients $\zeta_{10}, \zeta_{11}, a_{10}, a_{11}, a_{12} \ldots.$

Aim of these operators

Initially, those operators were introduced for the following reasons

- raising M_h without tuning the loops.
- modifying the higgs decays.

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Although the initial motivaiton is the relic density

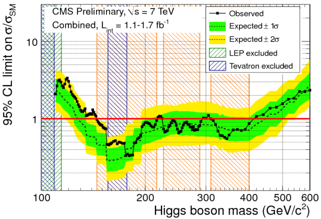
There will also be lots of constraints from Higgs searches.

Hence the analysis will be two-fold

- modification in the relic density
- constraints on the higgs searches at colliders

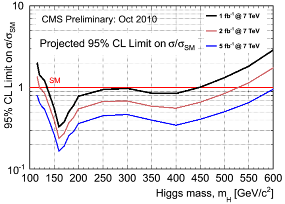
Higgs searches at the LHC have excluded most of the Standard Model mass range

current data



$\longrightarrow$

5 fb^{-1} expectations



Feynman double expansion : Loops and $\frac{1}{M}$

- The loops are compulsory for higgs interactions
  - Depending on the observable zero, one or two loops will be computed
- Effective expansion truncated at order two

We do not consider interference

$$\mathcal{O} = \mathcal{O}_{tree} + \delta\mathcal{O}_{loop} + \delta\mathcal{O}_{eff}$$

Computation

Feynman double expansion : Loops and $\frac{1}{M}$

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Precision of the computation

- EFT theorem imply that we could reach any accuracy
- Loop corrections are expected to be under control
- Effective corrections can go wrong !

Interactions	Observables
$(h_1, h_2)(W, Z)$	W,Z masses
$(h_1, h_2)(h_1, h_2)$	Higgs masses
	Higgs coupling to matter
$(\tilde{h}, \tilde{W}, \tilde{Z})(\tilde{h}, \tilde{W}, \tilde{Z})$	neutralino/chargino masses
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MZ,MW

They are taken as experimental input.
Hence the weak couplings will be changed
Zff coupling change, allowing for changes in EW precision test

Electroweak precision test :$\epsilon_{1,2,3}$ variables

$$\epsilon_{1,2,3} \propto \left(a_{10} - a_{30} t_\beta^2 + a_{20} t_\beta^4\right)$$

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Relic density

- Not included in the first version

Codes and approximations

The following codes are used

- *lanHEP* to derive Feynman rules
- *Mathematica* to extract initial parameters and fields
- *CalcHEP/Suspect/HDecay* for Higgs phenomenology
- *micrOmegas* relic density

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Higgs decay/production computation can be long

Hence need for approximations

- Decays : form factor rescaled by $\left(\frac{g_{eff}}{g_{SM}}\right)$.
  Caution for loop-indued decays.
- VBF and associated production
  $\sigma_{eff} = \sigma_{SM}\left(\frac{g_{VVh\ eff}}{g_{VVh\ SM}}\right)^2$
- gluon fusion
  $\sigma_{gg\to h} = \frac{\Gamma_{h\to gg}}{\Gamma_{h\to gg\ SM}}\sigma_{gg\to h\ SM}$

Benchmarks

- i) $M_{h\ max}$
- ii) no-mixing
- iii) gluephobic
- iv) no-trilinear couplings

Characterised by

- $M_{\tilde{f}} = 1$ Tev
- $\mu = M_2 \sim 200$ GeV (except iv) $M_2 = 1$ TeV)
- $M_3 = 800$ GeV

Away from susy direct searches.

Analysis Set-up

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Free parameters

- t_β, M_{A_0}
- $c_i \in [-1, 1]$

Scan over the parameter space

(20+2)-dimensional space $\rightarrow$ Need for efficient methods

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Scanning techniques

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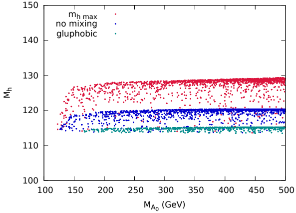
Difficulties

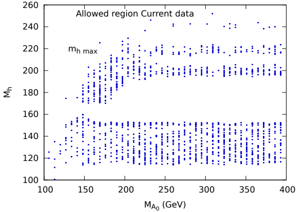
- Random efficiency $\sim 0.01\%$
- Computation time (hdecay running)
- Zone finding with MCMC

MSSM predictions

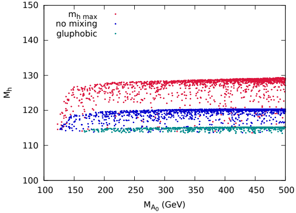
MSSM predictions



Effective MSSM prediction ($t_\beta = 2$)

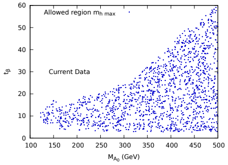


MSSM predictions

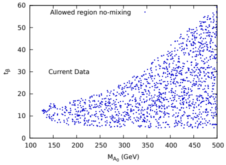


Limits on the the benchmarks i), ii) and iii)

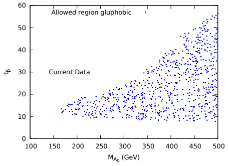
$M_{h\ max}$



no-mixing



gluphobic



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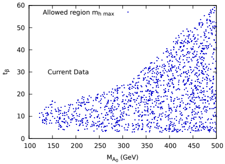

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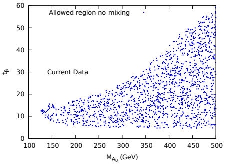

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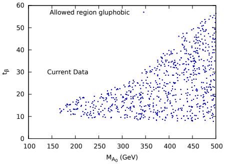
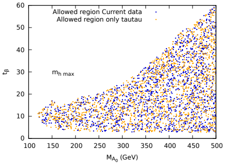
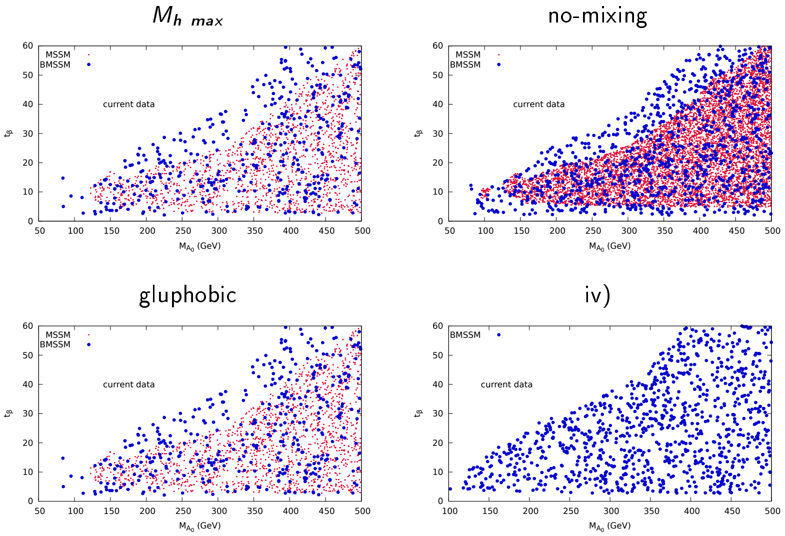


Exclusion identical to $h \to \tau\tau$ only



Limits on t_β, M_{A_0} in BMSSM



Conclusions

A very interesting path into susy

- To constrain efficiently susy, we need
  - a reliable computation method
  - a way to deal with the many different realisaitons of susy
- Effective Field Theory can be used for both, since they avoid many issues

Conclusions

A very interesting path into susy

- To constrain efficiently susy, we need
  - a reliable computation method
  - a way to deal with the many different realisaitons of susy
- Effective Field Theory can be used for both, since they avoid many issues

But the best is yet to come

- Evaluate all constraints together (with Relic density)
- enlarge the EFT to difeerent sectors, to broaden its use
- include some non-standard decays, as $h \to$invisible (for light $\tilde{\chi}^0_1$).