Higgs and Dark Matter in Supersymmetry

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Introduction

- The call for New Physics : Dark Matter and Naturalness. Where do we go?
  - Extra dimensions, extra gauge structure, hidden sector ...
  - Main focus : Supersymmetry
- Working team for the phenomenology of supersymmetry
  - Permanent : F. Boudjema, G.Belanger, B. Herrmann
  - PhD : GDLR, J. Da Silva
  - Collaborators : A.Pukhov, A. Semenov, J. Harz, M. Heikinheimo ...
- New Physics @ Annecy
  - A multi-observables approach : Higgs searches, direct and indirect detection of Dark Matter
  - A multi-tool development : **micrOmegas**, **SloopS**, **DM@NLO**.

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Calculating Dark Matter observable with **micrOmegas**

- Evidence for a new kind of matter : massive and weakly interacting.
- How can we probe such particles ?
  - Interactions with dense materials : direct detection
    Experiments XENON 100, CDMS, COGENT,...
  - Annihilation of dark matter particles to standard particle : indirect detection
    Experiments Fermi, PAMELA, HESS, AMS...

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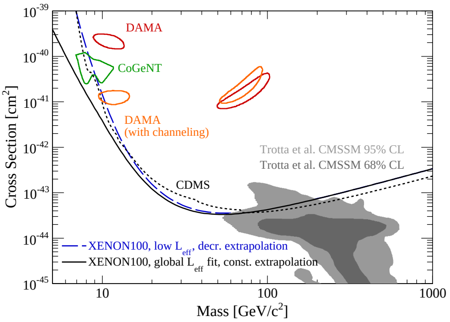

Using **micrOmegas**

- The need for an generic automated tool :
  - No need to do the computation by hand
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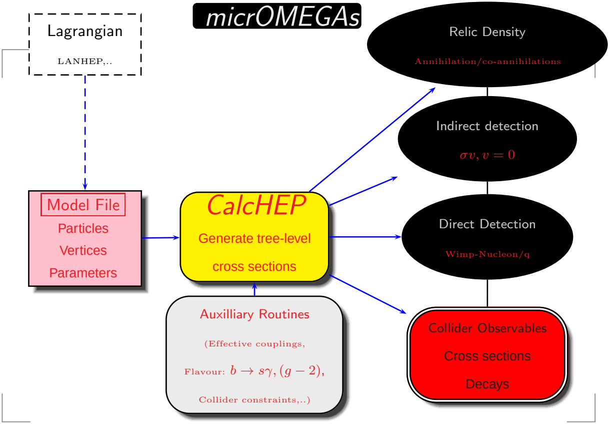

The relic density : a precision observable

- From the observation of the CMB (Cosmic Microwave Background) onde deduces

$$\Omega_h = 0.1123 \pm 0.0036 \qquad \text{3\% precision!}$$

- Assuming a standard cosmological model, it yields an impressive accuracy on

$$\sigma(DM, DM \to SM \text{ particles})$$

- Is the precision obtained from **micrOmegas** sufficient?
  - We expect quantum corrections for most of the processes $\Rightarrow$ those correction can be high
  - Going to the one-loop computation of $\sigma(DM, DM \to SM\text{particles})$
- Different tools to be used :
  - **SloopS**
  - **DM@NLO**
  - Effective approach

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The **SloopS** program : automated full one-loop in Supersymmetry

Strategy: Exploiting and interfacing modules from different codes

Lagrangian of the model defined in LanHEP

- particle content
- interaction terms
- shifts in fields and parameters
- ghost terms constructed by BRST

↓ ↓

Generic Model
-kinematical structures

Classes Model
-Feynman rules, including CT

⇓

Evaluation via FeynArts-FormCalc

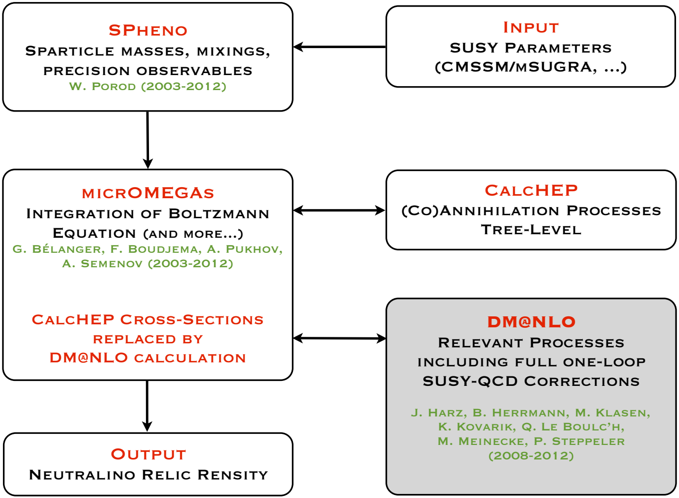
LoopTools modified!!
tensor reduction inappropriate for small relative velocities
(Zero Gram determinants)

⇑

Renormalisation scheme

- definition of renorm. const. in the classes model
Non-Linear gauge-fixing constraints, gauge parameter dependence checks

The **DM@NLO** program : automated QCD one-loop in Supersymmetry



DM@NLO : Features of radiative corrections

- What kind of loop corrections do we expect?
  - Annihilation rate enhanced by up to 50% by QCD corrections
  - Favoured regions of parameter shifted by up to 50 GeV for A_0 or 200 GeV for $\tilde{\chi}_1^0$

- Blue : One-loop, Green : Tree-level, Red : Tree-level with effective masses.

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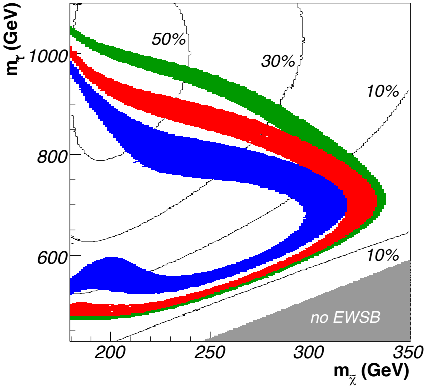

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The effective approach for Supersymmetry

- One loop computations meet technical issues :
  - Loop integration is CPU time consuming
  - Supersymmetric parameter space can be large (19 parameters)
- Solution : tree-level with effective vertices (ref arXiv:1108.4291)

$\Longrightarrow$ Effective coupling $g_{\tilde{\chi}_1^0 \tilde{f} f}$

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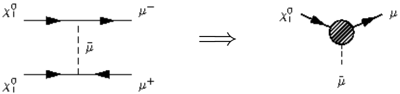

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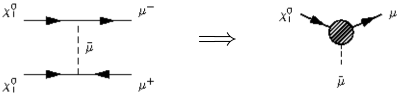

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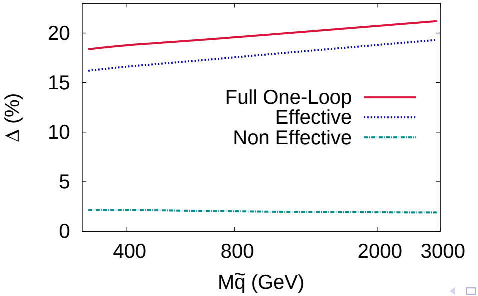
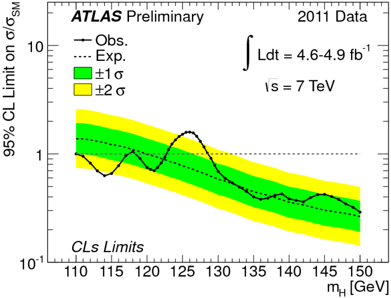
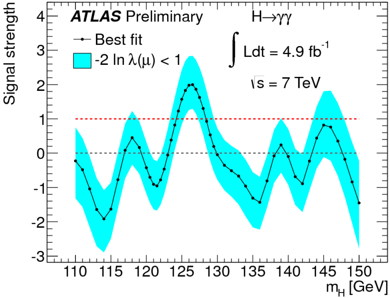


Bino-like case

- Exclusion vs Signal





Recasting Standard Model searches (I)

- Neutral channels are

$VH \to V\bar{b}b$	$H \to \bar{\tau}\tau$	$H \to WW$
$H \to ZZ$	$H \to \gamma\gamma$	($H \to \gamma\gamma$ + 2 jets)

- For neutral bosons Φ and each final state XX we define

$$R_{XX\ \Phi} = \frac{\sigma_{pp\to\Phi\to XX}}{\sigma^{\text{SM}}_{pp\to\Phi\to XX}} \qquad \& \qquad R^{\text{Exclusion}}_{XX\ \Phi} = \frac{\sigma_{pp\to\Phi\to XX}}{\sigma^{95\%\ \text{CL}}_{pp\to\Phi\to XX}}$$

- $R^{\text{Exclusion}}$ are added in quadrature among all channels to determine whether the point is excluded.
  - $R^{\text{Exclusion}}$ shows the sensitivity : e.g. $R^{\text{Exclusion}} = 0.5 \Rightarrow$ we need $\mathcal{L} \sim 4 \times 5 = 20\text{fb}^{-1}$.
- Issues :
  - $\sigma^{\text{inclusive}} \neq \sigma^{\text{exclusive}} = \epsilon_{gg}\sigma^{\text{inclusive}}_{gg} + \epsilon_{vbf}\sigma^{\text{inclusive}}_{VBF} + \epsilon_{vh}\sigma^{\text{inclusive}}_{VH}$
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Hints for non-minimal supersymmetry

- The would be signal is somehow hard to reconcile with MSSM :
  - $m_h = 125$ GeV contradicts Naturalness since it requires heavy stops !
  - The enhancement $R_{\gamma\gamma} \sim 2$ is quite hard to reproduce (light staus).
- MSSM ruled out $\neq$ Susy ruled out, but non-minimal realisations
  - Extensions : NMSSM, U(1)'MSSM...
- Effective Field Theory approach

$$\begin{aligned} M &= 1.5 \text{ TeV} \\ K &= K_{MSSM} + \frac{1}{M}K^{(1)} + \frac{1}{M^2}K^{(2)} + \ldots \\ W &= W_{MSSM} + \frac{1}{M}W^{(1)} + \frac{1}{M^2}W^{(2)} + \ldots \end{aligned}$$

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$$\boxed{h/H,\ A_0,\ H^+}$$

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Higher dimensionnal operators in the Higgs sector

- Include only operators involving Higgs superfields H_1, H_2
- Effective Field Theory expansion on K and W:

$$
\begin{aligned}
K \to K &+ \frac{a_1}{M^2}\left(H_1^\dagger e^{V_1} H_1\right)^2 + \frac{a_2}{M^2}\left(H_2^\dagger e^{V_2} H_1\right)^2 \\
&+ \frac{a_3}{M^2}\left(H_1^\dagger e^{V_1} H_1\right)\left(H_2^\dagger e^{V_2} H_2\right) + \frac{a_4}{M^2}\left(H_1 \cdot H_2\right)^\dagger \left(H_1 \cdot H_2\right) \\
&+ \frac{a_5}{M^2}\left(H_1^\dagger e^{V_1} H_1\right)\left(H_1 \cdot H_2 + h.c.\right) + \frac{a_6}{M^2}\left(H_2^\dagger e^{V_2} H_2\right)\left(H_1 \cdot H_2 + h.c.\right) \\
W \to W &+ \frac{\zeta_1}{M}\left(H_1 \cdot H_2\right)^2
\end{aligned}
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- The effective coefficients can also have susy-breaking parts

$$a_i \to a_{i0} + \theta^2 m_s a_{i1} + \bar{\theta}^2 m_s a_{i1}^* + \theta^2 \bar{\theta}^2 m_s^2 a_{i2}$$

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

with $m_s = 300$ GeV.

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Non-minimal Higgs Phenomenology

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- Couplings also affected
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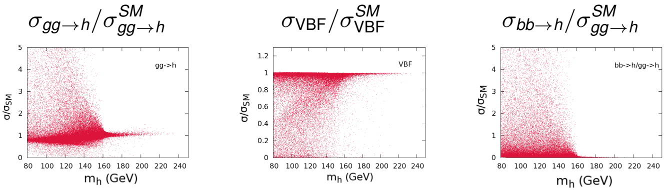

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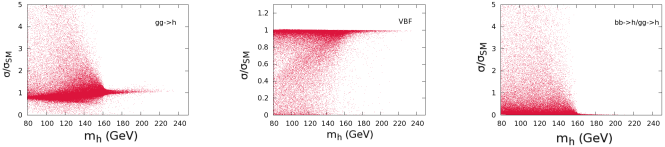

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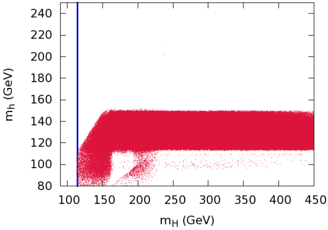

F. Boudjema, G. DLR

arXiv:1112.1434

BR $h \to \gamma\gamma$

- Effective operators can turn $g_{h\bar{b}b} = 0$
- Enhance branching ratios in all over channels

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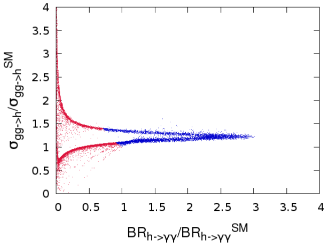
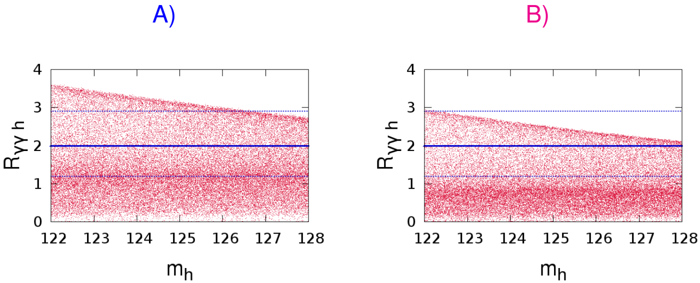


- Correlation with the gluon fusion

$$\frac{\sigma_{gg\to h}}{\sigma^{\mathrm{SM}}_{gg\to h}} = \frac{|\mathcal{A}_t + x\mathcal{A}_b|^2}{|\mathcal{A}_t + \mathcal{A}_b|^2}$$

- Enhancement in the $h \to \gamma\gamma$ channel



  - Blue lines : 1σ error band on ATLAS best fit.

- Enhancement driven by the suppression of $g_{h\bar{b}b}$.

Signal features : case of the light h (II)

- Correlations between ZZ,$\gamma\gamma$ (inclusive) and $\gamma\gamma$+2 jets

- Blue : R_{ZZ}, Red : $R_{\gamma\gamma\,+\,2\,\text{jets}}$.

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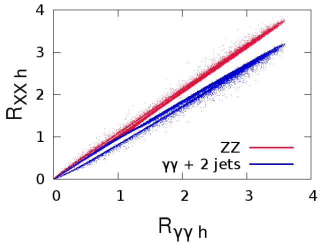
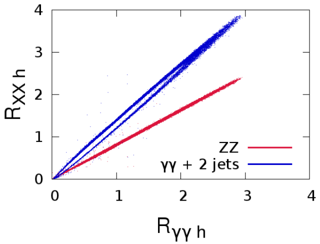
A)



$$m_{\tilde{t}_1} \simeq m_{\tilde{t}_1} \simeq 400 \text{ GeV}$$

B)



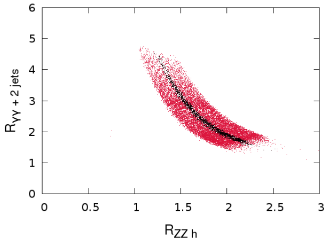
$$m_{\tilde{t}_1} = 200 \text{ GeV}$$
$$m_{\tilde{t}_2} = 600 \text{ GeV}$$

- Blue : R_{ZZ}, Red : $R_{\gamma\gamma\ +2\ \text{jets}}$.

Signal features : stop effects

- Effect of the light stop loop

$m_{\tilde{t}_2} \in [300 - 1000]$ GeV



- **Black** : $R_{\gamma\gamma} = 2.0 \pm 1\%$
- Red : $R_{\gamma\gamma} = 2.0 \pm 10\%$

$B \to X_s\gamma^*$ in model B :

- To lower the supersymmetric contribution, either reduce $s_{2\theta_t}$, or reduce t_β.
- This constrain the possibility of a large $R_{\gamma\gamma}$ enhancement.

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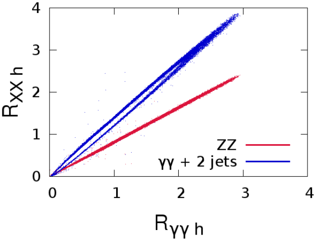
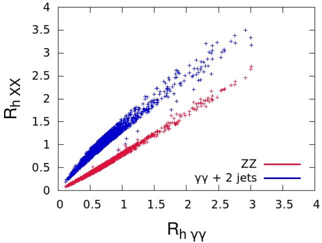


$\overrightarrow{B \to X_s\gamma^*}$



Prospect for other signals (I)

- There is more to see in the $\overline{\tau}\tau$ channel
  - Example in the degenerate case $m_{A_0} \simeq m_H$

- t_β dependence $\Rightarrow$ low t_β means low sensitivity.

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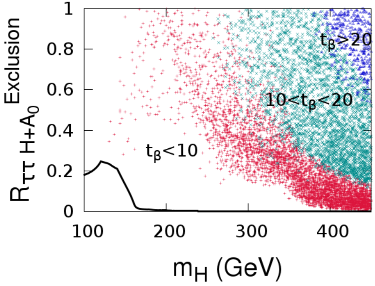

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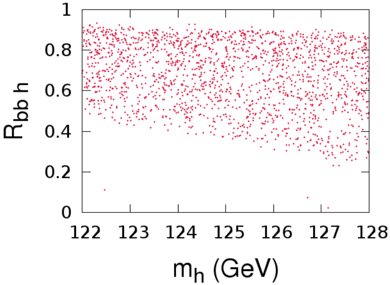
Conclusions

- Dark Matter tools :
  - Multi-use tool : **micrOmegas**(many different models and observables)
  - Precision tool for the Relic Density
    - **SloopS**
    - **DM@NLO**
    - **micrOmegas** with effective couplings
- Higgs searches : the hot spot
  - Recasting exclusion bounds and signal strengths in BSM models
  - Non-minimal susy : what if the Higgs is non-standard like?

Questions

$VH \to V\bar{b}b$

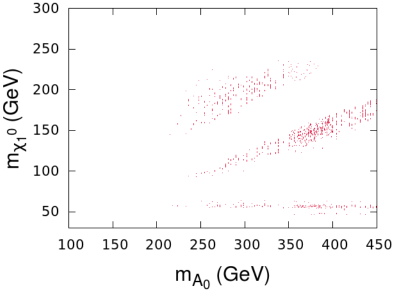


Dark Matter observables : Relic density

- Relic density with WMAP7 :

$$\Omega_h = 0.1126 \pm 15\%$$

- The LSP is $\tilde{\chi}_1^0$, which is a mixture of bino and higgsino.
- Mostly accounted for by $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \bar{f} f$ by A_0 resonance



- Spin-Independent bounds from XENON 100