Higgs and Dark Matter in Supersymmetry

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CTPG 2012 Grenoble
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.
Introduction

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Calculating Dark Matter observable with \textit{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 a generic automated tool:
  - No need to do the computation by hand
  - Applicable to many models (so far supersymmetry, extra dimensions and technicolor).
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**micrOMEGAs**

- Lagrangian
  - LANHEP...

**CalcHEP**

- Model File
  - Particles
  - Vertices
  - Parameters

- Generate tree-level cross sections

**Auxilliary Routines**

- (Effective couplings,
  - Flavour: \(b \rightarrow s\gamma, (g - 2),\)
  - Collider constraints...)

**Relic Density**

- Annihilation/co-annihilations

**Indirect detection**

- \(\sigma v, v = 0\)

**Direct Detection**

- Wimp-Nucleon/q

**Collider Observables**

- Cross sections
  - Decays

G.Drieu La Rochelle (LAPTh)

Higgs and Dark Matter in Supersymmetry

CTPG 2012 @ Grenoble
The relic density: a precision observable

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

\[ \Omega_h = 0.1123 \pm 0.0036 \quad 3\% \text{ precision!} \]

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

\[ \sigma(DM, DM \rightarrow SM \text{ particles}) \]

- 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 \( \sigma(DM, DM \rightarrow SM \text{ particles}) \)

- 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

**SPheno**

**SUSY Parameters**

W. Porod (2003-2012)

**SPheno**

**SParticle masses, mixings, precision observables**

**INPUT**

**SUSY Parameters**

(CMSSM/mSUGRA, ...)

**SPheno**

**SParticle masses, mixings, precision observables**

**W. Porod (2003-2012)**

**micrOMEGAs**

**Integration of Boltzmann Equation (and more...)**

G. Bélanger, F. Boudjema, A. Pukhov, A. Semenov (2003-2012)

**CalcHEP**

**(Co)Annihilation Processes Tree-Level**

**CalcHEP**

**Cross-Sections replaced by DM@NLO calculation**

**DM@NLO**

**Relevant Processes including full one-loop SUSY-QCD Corrections**

J. Harz, B. Herrmann, M. Klasen, K. Kovarik, Q. Le Boulc’h, M. Meinecke, P. Steppeler (2008-2012)

**OUTPUT**

**Neutralino Relic Rensity**

**G.Drieu La Rochelle (LAPTh)**

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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 $\tilde{\chi}_1^0$
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Blue: One-loop, Green: Tree-level, Red: Tree-level with effective masses.
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)

\[
g_{\chi_1^0 \bar{f}}
\]
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\[
\chi^0 \rightarrow \bar{\mu} \rightarrow \mu^+ \mu^- \quad \rightarrow \quad \chi^0 \rightarrow \bar{\mu} \rightarrow \mu
\]

Effective coupling \( g_{\tilde{\chi}^0 \tilde{\mu} \tilde{f}} \)
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\begin{equation}
\tilde{g}_{\tilde{\chi}_1^0\tilde{f}}
\end{equation}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{chart.png}
\caption{Bino-like case}
\end{figure}
Higgs searches

- Exclusion vs Signal

**ATLAS** Preliminary

95% CL Limit on $\sigma/\sigma_{SM}$

- Obs.
- Exp.

$\pm 1 \sigma$

$\pm 2 \sigma$

2011 Data

$\int L dt = 4.6-4.9$ fb$^{-1}$

$\sqrt{s} = 7$ TeV

**ATLAS** Preliminary

$H \rightarrow \gamma\gamma$

- Best fit
- $-2 \ln \lambda(\mu) < 1$

$\int L dt = 4.9$ fb$^{-1}$

$\sqrt{s} = 7$ TeV
Recasting Standard Model searches (I)

- Neutral channels are

\[
\begin{align*}
VH & \to Vbb & H & \to \tau\tau \\
H & \to ZZ & H & \to WW \\
& & (H \to \gamma\gamma + 2\text{ jets})
\end{align*}
\]

- For neutral bosons $\Phi$ and each final state $XX$ we define

\[
R_{XX} \Phi = \frac{\sigma_{pp \to \Phi \to XX}}{\sigma_{SM pp \to \Phi \to XX}} \quad \& \quad R_{XX}^{\text{Exclusion}} = \frac{\sigma_{pp \to \Phi \to XX}}{\sigma_{95\% \, CL \, pp \to \Phi \to XX}}
\]

- $R_{XX}^{\text{Exclusion}}$ are added in quadrature among all channels to determine whether the point is excluded.

- $R_{XX}^{\text{Exclusion}}$ shows the sensitivity: e.g. $R_{XX}^{\text{Exclusion}} = 0.5 \implies \text{we need } \mathcal{L} \sim 4 \times 5 = 20\text{fb}^{-1}$.

- Issues:
  - $\sigma_{\text{inclusive}} \neq \sigma_{\text{exclusive}} = \epsilon_{gg}\sigma_{gg}^{\text{inclusive}} + \epsilon_{VBF}\sigma_{VBF}^{\text{inclusive}} + \epsilon_{VH}\sigma_{VH}^{\text{inclusive}}$
  - No model independent combinations: SM combination does not apply to BSM!
Neutral channels are

<table>
<thead>
<tr>
<th>$VH \rightarrow V\bar{b}b$</th>
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$$R_{XX} \Phi = \frac{\sigma_{pp \rightarrow \Phi \rightarrow XX}}{\sigma_{SM_{pp \rightarrow \Phi \rightarrow XX}}}$$

and

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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 $\not\Rightarrow$ Susy ruled out, but non-minimal realisations
  - Extensions: NMSSM, U(1)'MSSM...

- Effective Field Theory approach

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

$$K \rightarrow K + \frac{a_1}{M^2} \left( H_1^\dagger e^{v_1} H_1 \right)^2 + \frac{a_2}{M^2} \left( H_2^\dagger e^{v_2} H_1 \right)^2 + \frac{a_3}{M^2} \left( H_1^\dagger e^{v_1} H_1 \right) \left( H_2^\dagger e^{v_2} H_2 \right) + \frac{a_4}{M^2} \left( H_1 \cdot H_2 \right)^\dagger \left( H_1 \cdot H_2 \right) + \frac{a_5}{M^2} \left( H_1^\dagger e^{v_1} H_1 \right) \left( H_1 \cdot H_2 + h.c. \right) + \frac{a_6}{M^2} \left( H_2^\dagger e^{v_2} H_2 \right) \left( H_1 \cdot H_2 + h.c. \right)$$

$$W \rightarrow W + \frac{\zeta_1}{M} \left( H_1 \cdot H_2 \right)^2$$

- The effective coefficients can also have susy-breaking parts

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

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

with $m_s = 300$ GeV.
Higher dimensionnal operators in the Higgs sector

- Include only operators involving Higgs superfields $H_1, H_2$

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K \rightarrow 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) \\
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Non-minimal Higgs Phenomenology

- Main effect: $m_h$ goes up to 250 GeV.
- Couplings also affected

But this was soon constrained by LHC searches ($\mathcal{L} = 2.3 fb^{-1}$)
Non-minimal Higgs Phenomenology

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\frac{\sigma_{gg\rightarrow h}}{\sigma_{gg\rightarrow h}^{SM}} \quad \frac{\sigma_{VBF}}{\sigma_{VBF}^{SM}} \quad \frac{\sigma_{bb\rightarrow h}}{\sigma_{gg\rightarrow h}^{SM}}
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F. Boudjema, G. DLR
arXiv:1112.1434
BR $h \rightarrow \gamma \gamma$

- Effective operators can turn $g_{hbb} = 0$
- Enhance branching ratios in all over channels

- Correlation with the gluon fusion
Effective operators can turn $g_{hbb} = 0$

Enhance branching ratios in all over channels

Correlation with the gluon fusion

$$\frac{\sigma_{gg \rightarrow h}}{\sigma_{gg \rightarrow h}^{SM}} = \frac{|A_t + x A_b|^2}{|A_t + A_b|^2}$$
Signal features : case of the light $h$ (I)

- **Enhancement in the $h \rightarrow \gamma\gamma$ channel**

  ![Graph A) and B) showing enhancement](image)

  - **Blue lines**: $1\sigma$ error band on ATLAS best fit.
  - **Enhancement driven by the suppression of $g_{hbb}$**.
Signal features : case of the light $h$ (II)

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

- Blue : $R_{ZZ}$, Red : $R_{\gamma\gamma + 2 \text{ jets}}$
Signal features: case of the light $h$ (II)

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

\[ m_{\tilde{t}_1} \simeq m_{\tilde{t}_1} \simeq 400 \text{ GeV} \]

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

- Blue: $R_{ZZ}$, Red: $R_{\gamma\gamma} + 2$ jets.
Signal features: stop effects

- Effect of the light stop loop

\[ m_{t_2} \in [300 - 1000] \text{ GeV} \]

- **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 $t_\beta$.
- This constrain the possibility of a large $R_{\gamma\gamma}$ enhancement.
$B \rightarrow X_s\gamma^*$ in model B:

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Prospect for other signals (I)

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

- $t_\beta$ dependence $\Rightarrow$ low $t_\beta$ means low sensitivity.
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  - Example in the degenerate case $m_{A_0} \simeq m_H$

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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?
$VH \rightarrow V\bar{b}b$
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 \( \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \bar{t}t \) by \( A_0 \) resonance
Spin-Independent bounds from XENON 100