Guillaume CHALONS

Institut für Theoretische Teilchenphysik, KIT

Rencontres de Moriond 2012, La Thuile

based on: G.C, A. Semenov, JHEP 1112 (2011) 055
Theoretically favored:

- DM particle annihilation or decay into primary $\gamma + X$ can produce monochromatic gamma rays
- "Smoking gun" signature
- No known astrophysical source can mimic this signal
- $\gamma$'s point directly to the source $\rightarrow$ no propagation uncertainties.
- Give direct information on $m_\chi$:

$\chi\chi \rightarrow \gamma\gamma : \ E_\gamma \simeq m_\chi$

$\chi\chi \rightarrow \gamma Z : \ E_\gamma \simeq m_\chi \left(1 - \frac{M_Z^2}{4m_\chi^2}\right)$

Experimentally challenging:

- DM is a neutral particle $\rightarrow$ suppressed process
- Very small branching ratio
- Difficult to detect from the overwhelming astrophysical background
- Optimal energy resolution ($\approx 10\%$ at 100 GeV) and calibration very important
LOW MASS NEUTRALINO IN THE NMSSM

NMSSM DM Phenomenology similar to MSSM except in two cases:

- \( \tilde{\chi}_1^0 \sim \tilde{S} \) or significant singlino mixing
- Low mass region: light singlet pseudoscalars and neutralinos are more “natural” than in the MSSM. (Gunion, Hooper, McElrath, 06’)

- Easier to account for recent results of CDMS, CoGeNT, CRESST (Vasquez et al.; Das, Ellwanger; Draper et al.; Kappl, Ratz, Winkler; Cao et al.) with a light NMSSM \( \tilde{\chi}_1^0 \) than a MSSM one.
- Indirect Signals enhanced (\( \rightarrow \propto 1/m_{\chi} \))
- Possibility to have resonant s-channel light singlet pseudoscalar \( A_1 \) exchange (already pointed out by Ferrer, Krauss, Profumo 06’) \( \Rightarrow \) “BOOST” of the signal

S-channel exchange of a scalar Higgs \( H_i^0 \) velocity-suppressed
APPLYING FERMI CONSTRAINTS

- FERMI satellite has a dedicated search for $\gamma$-lines
- Limits on $\langle \sigma v \rangle_{\chi\chi \rightarrow \gamma\gamma}$ published in the range $m_\chi \in [30, 200]$ GeV → We did not model the propagation.
- Limits taken from Vertongen, Weniger 11' : extended range $m_\chi \in [1, 300]$ GeV.
- Rates computed with S1loopS (Baro, Boudjema 07') adapted to the NMSSM case.
APPLYING FERMI CONSTRAINTS

- FERMI satellite has a dedicated search for $\gamma$-lines
- Limits on $\langle \sigma v \rangle_{\chi \chi \to \gamma \gamma}$ published in the range $m_{\chi} \in [30, 200]$ GeV → We did not model the propagation.
- Limits taken from Vertongen, Weniger 11’ : extended range $m_{\chi} \in [1, 300]$ GeV.
- Rates computed with SloopS (Baro, Boudjema 07’) adapted to the NMSSM case.
APPLYING FERMI CONSTRAINTS

- FERMI satellite has a dedicated search for $\gamma$-lines
- Limits on $\langle \sigma v \rangle_{\chi \chi \rightarrow \gamma \gamma}$ published in the range $m_\chi \in [30, 200]$ GeV $\rightarrow$ We did not model the propagation.
- Limits taken from Vertongen, Weniger 11’ : extended range $m_\chi \in [1, 300]$ GeV.
- Rates computed with SloopS (Baro, Boudjema 07’) adapted to the NMSSM case.

\[ \Delta M = \left| 2m_{\tilde{\chi}_1^0} - m_{A_1} \right| / m_{A_1} \]
FURTHER CONSTRAINT ON THE NMSSM?

- Light neutralinos compatible with DD and RD accompanied by a light pseudoscalar/scalar singlet.
- Pseudoscalar resonance also at play for RD and continuous gamma ray spectrum.
- FERMI collab. published limits on the continuous gamma-ray spectrum (dSph).
- 14 NMSSM parameter space points taken from Vasquez, Belanger, Boehm 11’

<table>
<thead>
<tr>
<th>$m_{\chi_1^0}$ [GeV]</th>
<th>$\langle \sigma v \rangle_{\chi \bar{\chi} \rightarrow q\bar{q},\tau\bar{\tau}} \times 10^{27}$ [cm$^3$ s$^{-1}$]</th>
<th>$\langle \sigma v \rangle_{\gamma\gamma} \times 10^{30}$ [cm$^3$ s$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.976</td>
<td>0.209</td>
<td>0.00008</td>
</tr>
<tr>
<td>2.409</td>
<td>0.297</td>
<td>0.00267</td>
</tr>
<tr>
<td>3.342</td>
<td>0.345</td>
<td>0.00345</td>
</tr>
<tr>
<td>4.885</td>
<td>3.298</td>
<td>0.00262</td>
</tr>
<tr>
<td>5.626</td>
<td>5.389</td>
<td>0.00410</td>
</tr>
<tr>
<td>6.551</td>
<td>3.547</td>
<td>0.00427</td>
</tr>
<tr>
<td>7.101</td>
<td>2.425</td>
<td>0.00664</td>
</tr>
<tr>
<td>8.513</td>
<td>2.161</td>
<td>0.00220</td>
</tr>
<tr>
<td>9.274</td>
<td>2.497</td>
<td>0.00655</td>
</tr>
<tr>
<td>10.27</td>
<td>2.323</td>
<td>0.01881</td>
</tr>
<tr>
<td>11.50</td>
<td>2.575</td>
<td>0.02456</td>
</tr>
<tr>
<td>12.74</td>
<td>3.224</td>
<td>0.02003</td>
</tr>
<tr>
<td>13.51</td>
<td>9.571</td>
<td>0.17487</td>
</tr>
<tr>
<td>14.48</td>
<td>148.4</td>
<td>2.87500</td>
</tr>
</tbody>
</table>
SUMMARY

▶ **Spectacular features** of the gamma ray line
▶ Only suffer from **uncertainties** of the **DM halo**.
▶ Light neutralino **easier to accomodate** in the NMSSM than the MSSM.
▶ Detecting the signal **extremely** challenging and requires a fine-energy resolution.
▶ Rate can be strongly enhanced in the **fine-tuned region** $m_{\tilde{\chi}_1^0} \sim 2m_{A_1}$.
▶ The most extreme points **can be excluded** by $\gamma$-lines limits.
▶ However still not **competing with constraints from dSph** on the continuous spectrum.
▶ Having a dedicated strategy for detecting the gamma lines since it is **too small** to have an visible impact on the continuous spectrum.
▶ At least **one order of magnitude of sensitivity** on $\langle \sigma v \rangle$ should be reached to exclude more featureless region of the NMSSM parameter space.
▶ **FERMI** mission is a long termed one and claims that limits will be **improved**.
▶ **First implementation** of the NMSSM framework in the SloopS code.
BACKUP
AUTOMATIC TOOL FOR ONE-LOOP CALCULATIONS: SLOOPS

LanHEP
MSSM Lagrangian
Counterterms
Renormalisation schemes

MicrOMEGAs @ Tree-Level
FormCalc/FeynArts/LoopTools
Computation of one-loop processes
(cross-sections, decays, mass corrections)

not yet automatised

MicrOMEGAs @ One-Loop

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.
GAUGE FIXING

Linear gauge fixing

\[ \mathcal{L}_{GF} = -\frac{1}{\xi_W} |\partial_\mu W^\mu + i\xi_W \frac{g}{2} \nu G^+|^2 \\
-\frac{1}{2\xi_Z} (\partial_\mu Z^\mu + \xi_Z \frac{g}{2c_w} \nu G^0)^2 \\
-\frac{1}{2\xi_A} (\partial_\mu A^\mu)^2 \]

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

\[ \mathcal{L}_{GF} = -\frac{1}{\xi_W} |\partial_\mu W^\mu + i\xi_W \frac{g}{2} \nu G^+|^2 \]

\[ -\frac{1}{2\xi_Z} (\partial_\mu Z^\mu + \xi_Z \frac{g}{2c_w} \nu G^0)^2 \]

\[ -\frac{1}{2\xi_A} (\partial_\mu A^\mu)^2 \]

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

\[ \xi_W, Z, A = 1 \text{ (Feynman gauge)} \]
Non-Linear gauge fixing

\[ \mathcal{L}_{GF} = -\frac{1}{\xi_W} \left| \left( \partial_\mu - i e \tilde{\alpha} A_\mu - i g c_w \tilde{\beta} Z_\mu \right) W^\mu + i \xi_W \frac{g}{2} \left( \nu + \tilde{\delta} h^0 + \bar{\omega} H^0 + i \bar{\kappa} G^0 + i \bar{\rho} A^0 \right) G^+ \right|^2 \]

\[ - \frac{1}{2 \xi_Z} \left( \partial_\mu Z^\mu + \xi_Z \frac{g}{2 c_w} \left( \nu + \tilde{\epsilon} h^0 + \tilde{\gamma}_H^0 \right) G^0 \right)^2 \]

\[ - \frac{1}{2 \xi_A} \left( \partial_\mu A^\mu \right)^2 \]

\[ \xi_{W,Z,A} = 1 \] (Feynman gauge)
GAUGE FIXING

Non-Linear gauge fixing

\[ \mathcal{L}_{GF} = -\frac{1}{\xi_W} \left| (\partial_\mu - ie\tilde{\alpha}A_\mu - igc_\beta Z_\mu) W^\mu + i\xi_W \frac{g}{2} (v + \tilde{\delta} h^0 + \tilde{\omega} H^0 + i\tilde{\kappa} G^0 + i\tilde{\rho} A^0) G^+ \right|^2 
+ \frac{1}{2\xi_Z} (\partial_\mu Z^\mu + \xi_Z \frac{g}{2c_W} (v + \tilde{\varepsilon} h^0 + \tilde{\gamma}_H^0) G^0)^2 
+ \frac{1}{2\xi_A} (\partial_\mu A^\mu)^2 \]

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

→ Gauge parameter dependence in gauge/Goldstone/ghost vertices.
→ No "unphysical" threshold, no higher rank tensor.
\[ \text{Segmentation has been used to study the analytical and numerical behaviour for } v \to 0. \]

\[ \frac{1}{D_0 D_1 D_2 D_3} = \left( \frac{1}{D_0 D_1 D_2} - \alpha \frac{1}{D_0 D_2 D_3} - \beta \frac{1}{D_0 D_1 D_3} + (\alpha + \beta - 1) \frac{1}{D_1 D_2 D_3} \right) \times \frac{1}{A + 2 \ell \cdot (s_3 - \alpha s_1 - \beta s_2)} \]

\[ A = (s_3^2 - M_3^2) - \alpha (s_1^2 - M_1^2) - \beta (s_2^2 - M_2^2) - (\alpha + \beta - 1) M_0^2. \]

\[ D_i = (\ell + s_i)^2 - M_i^2, \quad s_i = \sum_{j=1}^{i} p_j \]

\[ \text{For any graph if } \det G(s_1, s_2, s_3) \approx 0, \text{ construct all 3 sub-determinants } \det G(s_1, s_2) \text{ and take the couple } s_i, s_j \text{ (as independant basis) that corresponds to } \max |\det G(s_i, s_j)|. \text{ Then} \]

\[ s_3 = \alpha s_1 + \beta s_2 + \varepsilon_T \quad \text{with} \quad s_1 \cdot \varepsilon_T = s_2 \cdot \varepsilon_T = 0 \]

\[ \alpha = \frac{s_2^2 (s_3 \cdot s_1) - (s_1 \cdot s_2) (s_2 \cdot s_3)}{\det G(s_1, s_2)}, \quad \beta = \alpha(s_1 \leftrightarrow s_2) \]

\[ \det G(s_1, s_2, s_3) = \varepsilon_T^2 \det G(s_1, s_2) \]