GAMMA RAY LINES CONSTRAINTS IN THE NMSSM

Guillaume CHALONS

Institut für Theoretische Teilchenphysik, KIT

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GAMMA-RAY LINES

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
- γ's point directly to the source $\rightarrow$ no propagation uncertainties.
- Give direct information on m_χ :

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

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

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

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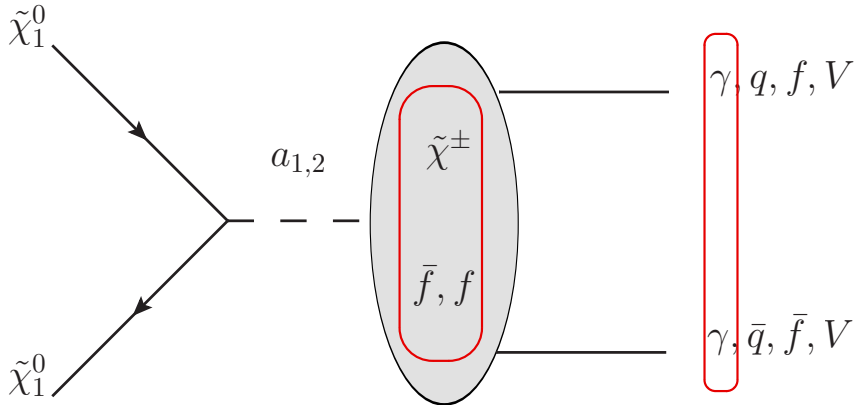
LOW MASS NEUTRALINO IN THE NMSSM

NMSSM DM Phenomenology similar to MSSM except in two cases :

- $\tilde{\chi}_1^0 \sim \widetilde{S}$ 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 γ-lines
- Limits on $\langle \sigma v \rangle_{\chi\chi \to \gamma\gamma}$ 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.

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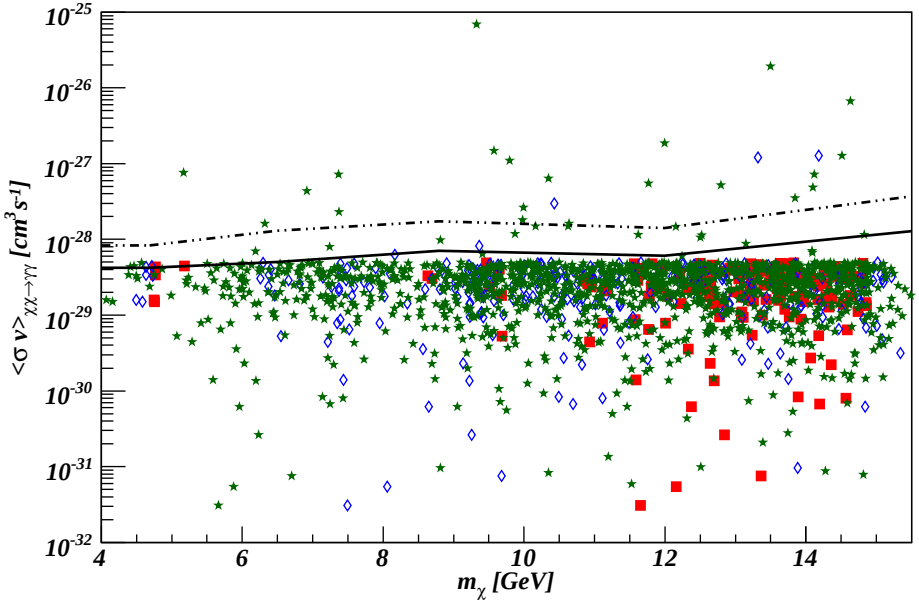

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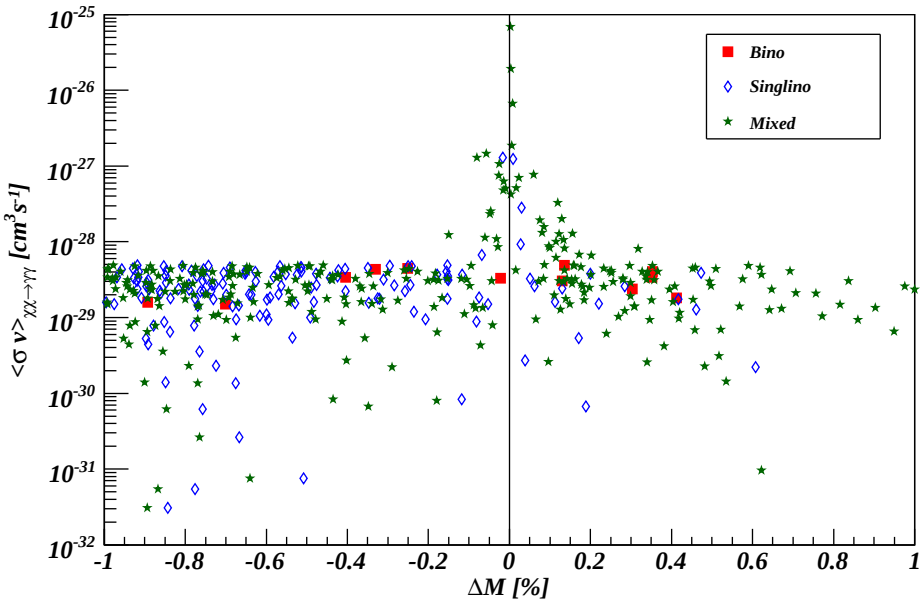

$$\Delta M = |2m_{\tilde{\chi}_1^0} - m_{A_1}|/m_{A_1}$$

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 continous 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'*

$m_{\tilde{\chi}_1^0}$ [GeV]	$\langle \sigma v \rangle_{\chi\bar{\chi}\to q\bar{q},\tau\bar{\tau}} \times 10^{27}$ [$cm^3\,s^{-1}$]	$\langle \sigma v \rangle_{\gamma\gamma} \times 10^{30}$ [$cm^3\,s^{-1}$]
0.976	0.209	0.00008
2.409	0.297	0.00267
3.342	0.345	0.00345
4.885	3.298	0.00262
5.626	5.389	0.00410
6.551	3.547	0.00427
7.101	2.425	0.00664
8.513	2.161	0.00220
9.274	2.497	0.00655
10.27	2.323	0.01881
11.50	2.575	0.02456
12.74	3.224	0.02003
13.51	9.571	0.17487
14.48	148.4	2.87500

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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 γ-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.

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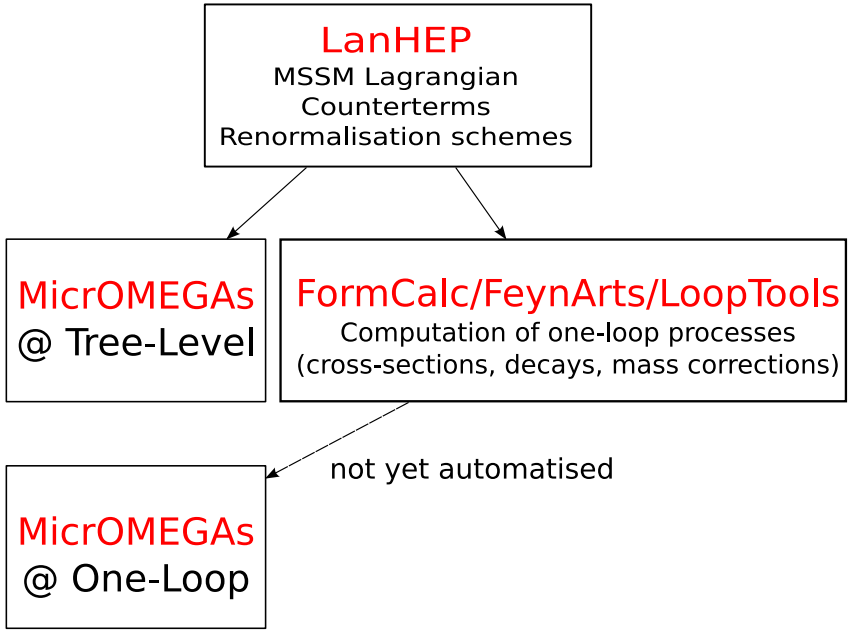
BACKUP

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.

GAUGE FIXING

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)

GAUGE FIXING

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}^0_H)G^0)^2 \\
& -\frac{1}{2\xi_A}(\partial_\mu A^\mu)^2
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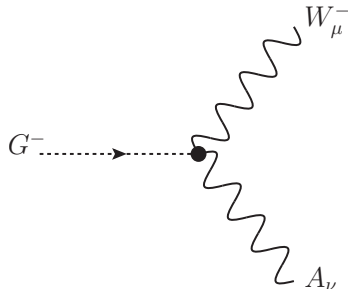

$$eM_W(1 + \tilde{\alpha}g_{\mu\nu})$$

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

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

SEGMENTATION

- $detG_{box} = m^6_{\tilde{\chi}^0_1} v^2 \frac{\sin^2\theta}{(1-v^2/4)^3}$, $detG_{vert} = -m^4_{\tilde{\chi}^0_1} v^2 \frac{1}{(1-v^2/4)^2}$
- Segmentation has been used to study the analytical and numerical behaviour for $v \longrightarrow 0$.

$$\begin{aligned}
\frac{1}{D_0 D_1 D_2 D_3} &= \left(\frac{1}{D_0 D_1 D_2} - \alpha \frac{1}{D_0 D_2 D_3} - \beta \frac{1}{D_0 D_1 D_3} + (\alpha+\beta-1)\frac{1}{D_1 D_2 D_3}\right) \times \\
&\quad \frac{1}{A + 2\ell \cdot (s_3 - \alpha s_1 - \beta s_2)} \\
A &= (s_3^2 - M_3^2) - \alpha(s_1^2 - M_1^2) - \beta(s_2^2 - M_2^2) - (\alpha+\beta-1)M_0^2. \\
D_i &= (\ell + s_i)^2 - M_i^2, \; s_i = \sum_{j=1}^{i} p_j
\end{aligned}$$

- For any graph if $\det G(s_1, s_2, s_2) \simeq 0$, construct all 3 sub-determinants $\det G(s_1, s_2)$ and take the couple s_i, s_j (as independant basis) that corresponds to $\mathrm{Max}|\det G(s_i, s_j)|$.Then

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

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

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

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