3 Body Stop decay with Gravitino/Goldstino in the final state

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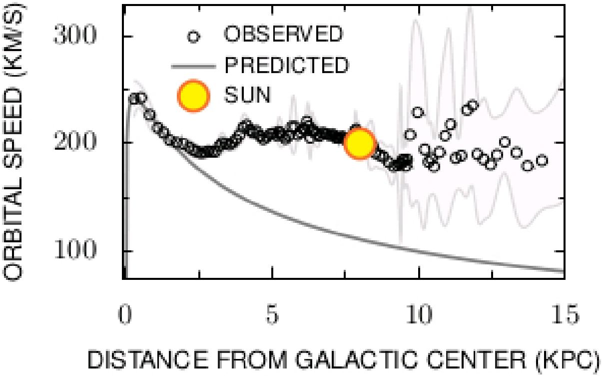
XXIX Reunión Anual de Partículas y Campos

Outline

- Motivation: Dark Matter (DM) and Supersymmetry (SUSY),
  - Gravitino Lightest Supersymmetric Particle (LSP) and Dark Matter,
  - The Next Lightest Supersymmetric Particle (NLSP),
- 3 body Stop decay,
  - With Gravitino
  - With Goldstino
- Conclusions.

Dark Matter



$$F_T = ma$$

$$v = \sqrt{\frac{G_N M}{r}}$$

New Physics: LHC and the Cosmos

- After 30-40 years of Standard Model success (apart from ν hints) something new should happen or else...,
- LHC is expected to find Physics Beyond the SM (BSM),
- At the same time, astro/cosmo phenomena also suggest BSM physics may be needed,
- SUSY is one of the best motivated theories BSM.

Supersymmetry is a symmetry that relates Boson fields degree of freedom with Fermion Fields degree of freedom.

$$|\,Fermions\rangle = \hat{Q}\,|\,Bosons\rangle$$

$$|\,Bosons\rangle = \hat{Q}\,|\,Fermions\rangle$$

There are a lot of SUSY models. We will use the Minimal Supersymmetric Standard Model MSSM (4D) with $\mathcal{N} = 1$.

The MSSM particle content

	SM	Superpartners
SM Bosons	$W^{\pm}, Z, \gamma$ gluon Higgs bosons	Wino, Zino, Photino gluino Higgsinos
SM Fermions	quarks leptons neutrinos	squarks sleptons sneutrinos

The particles in the SM are distinguished from their superparthers from R-Parity. With R-Parity being preserved the (LSP) cannot decay.

What is the LSP?

The lightest Supersymmetric (LSP) particle is suppose to be stable and electrically neutral and to interact weakly with the particles of the SM. These are exactly the characteristic required for DM.

- One option is: Gravitino ($\tilde{\Psi}_\mu$), there are other ones (Neutralino, Sneutrino).

Gravitino $\tilde{\Psi}_\mu$ as LSP in SUGRA models

- One of the candidates for dark matter in Supergravity (local Supersymmetry) is the gravitino. However, the exact relation is uncertain.
- Gravitino is a very weakly interacting particle, with coupling $\simeq 1/M_{Pl} = 0.83 \times 10^{-19} GeV^{-1}$ (in Supergravity).
  - Practically undetectable. (Except for its gravitational effect.)
  - The next lightest SUSY particle (NLSP) could be long lived.
- We have many possibilities for the NLSP: neutralino, stau, stop, sneutrino. Each with its own distinct phenomenology.

NLSP phenomenology with $\tilde{\Psi}_\mu$ as LSP

To determine viability of each scenario one need to:

- Identify Gravitino-MSSM interactions,
- Define the models (CMSSM, NUHM),
- Calculate NLSP lifetime,
- Check consistency with low-energy and collider constraints,
- Verify implications for cosmology.

Gravitino ($\tilde{\Psi}_\mu$) interactions

- All interactions can be derived from SUGRA lagrangian (Wess-Bagger),
- Most relevant terms are:
  - Coupling with chiral superfields:

$$\mathcal{L}_1 = -\frac{1}{\sqrt{2}M}\tilde{D}_\nu^*\phi_i^*\tilde{\Psi}_\mu\gamma^\nu\gamma^\mu\chi_R^i + h.c.(L\to R) \quad (1)$$

  - Coupling with vector superfields:

$$\mathcal{L}_2 = \frac{i}{8M}\bar{\tilde{\Psi}}_\mu[\gamma^\nu,\gamma^\rho]\gamma^\mu\lambda^a F_{\nu\rho}^a \quad (2)$$

3 body Stop decay

To determine viability of the scenario (NLSP) with $\tilde{\Psi}_\mu$ as LSP, we need to calculate NLSP life time.

$$\tau = \frac{1}{\Gamma} \tag{3}$$

The expression for the decay width is (After integration):

$$\frac{d\Gamma}{dxdy} = \frac{m_{\tilde{t}_1}^2}{256\pi^3} \mid \overline{\mathcal{M}} \mid^2$$

- Let's focus on the amplitude for the moment

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- Let's focus on the amplitude for the moment
- (Squaring and summing over final polarizations).

$\tilde{t}_1 \to b + W + \tilde{\Psi}_\mu$

We are considering the $\tilde{t}$ as NLSP. In what follows we need to consider the following Feynman diagrams:

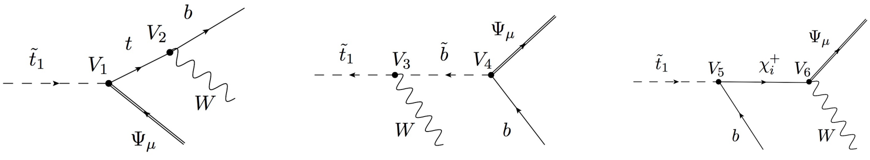

Figure 1. top diagram **Figure 2.** sbotom diagram **Figure 3.** chargino diagram

Where $V_i \ \forall \ i = 1, ..., 6$ are the interactions vertex.

3 body Stop decay

We can write the squared amplitude from the last 3 Feynman diagram.

$$\begin{aligned} |\overline{\mathcal{M}}|^2 = & |\mathcal{M}_t|^2 + |\mathcal{M}_{\tilde{b}}|^2 + |\mathcal{M}_{\chi^+}|^2 \\ & + 2\,\mathrm{Re}(\mathcal{M}_t^\dagger \mathcal{M}_{\tilde{b}} + \mathcal{M}_t^\dagger \mathcal{M}_{\chi^+} + \mathcal{M}_{\tilde{b}}^\dagger \mathcal{M}_{\chi^+}) \end{aligned} \tag{4}$$

In order to keep control of $|\overline{\mathcal{M}}|^2$ we shall write the chargino amplitude as $\mathcal{M}_\chi = \mathcal{M}_{1\chi} + \mathcal{M}_{2\chi}$.
(Because the huge vertex functions in the process.)

The amplitudes are:

$$
\begin{aligned}
\mathcal{M}_t &= C_t P_t(q_1)\,\overline{\Psi}_\mu p^\mu (A_t + B_t\gamma_5)(\not{q}_1 + m_t)\gamma^\rho \epsilon_\rho(k) P_L u(p_2) \\
\mathcal{M}_{\tilde{b}_i} &= C_{\tilde{b}_i} P_{\tilde{b}_i}(q_2)\,\overline{\Psi}_\mu q_2^\mu (a_i P_l + b_i P_R) p^\rho \epsilon_\rho(k) P_L u(p_2) \\
\mathcal{M}_{1\chi_i^+} &= C_{\chi_i^+} P_{\chi_i^+}(q_3)\,\overline{\Psi}_\mu \gamma^\rho \epsilon_\rho(k) \gamma^\mu (V_i + \Lambda_{i5})(q_3 + m_\chi)(S_i + P_{i5}) u(p_2) \\
\mathcal{M}_{2\chi_i^+} &= \underline{C}_{\chi_i^+} P_{\chi_i^+}\,\overline{\Psi}_\mu p^{\rho\mu} (T_i + Q_{i5}) \epsilon_\rho(k)(q_3 + m_\chi)(S_i + P_{i5}) u(p_2)
\end{aligned}
$$

Basically we shall have to compute 4 squared amplitudes and 6 interferences in [4]. ☹

Squared amplitudes can be written as:

$$| \mathcal{M}_{\psi_a} |^2 = C^2_{\psi_a} \, | P_{\psi_a}(q_a) |^2 \, W_{\psi_a \psi_a} \tag{5}$$

where $\psi_a = (t, \tilde{b}_j, \chi^+_k)$, and the functions $W_{\psi_a \psi_a}$ are :

$$W_{\psi_a \psi_a} = \mathsf{w}_{1\psi_a} + m_{\psi_a} \mathsf{w}_{2\psi_a} + m^2_{\psi_a} \mathsf{w}_{3\psi_a} \tag{6}$$

$\mathsf{w}_{i\psi_a} \, \forall \, i = 1, 2, 3, 4$ are functions of the scalar products of the momenta p, p_1, p_2, k.

The interference terms may be written as follows:

$$\mathcal{M}^{\dagger}_{\psi_a}\mathcal{M}_{\psi_b} = C_{\psi_a}C_{\psi_b}P^{*}_{\psi_a}(q_a)P_{\psi_b}(q_b)W_{\psi_a\psi_b} \quad (7)$$

with

$$W_{\psi_a\psi_b} = \mathrm{w}_{1\psi_a\psi_b} + m_{\psi_a}\left(\mathrm{w}_{2\psi_a\psi_b} + m_{\psi_b}\mathrm{w}_{3\psi_a\psi_b}\right) + m_{\psi_b}\mathrm{w}_{4\psi_a\psi_b} \quad (8)$$

Finally we will need to compute the 36 w's. ☹

But it is ok, fortunately we have **Mathematica** ☺

For example by brute force using Mathematica one obtain for the chargino $|\overline{\mathcal{M}_{1\chi}}|^2$.

In[87]:=

```
TrX3 = trx31 + mχ (trx32 + trx33 + mχ trx34)
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Out[87]=

$$4\Big(-\frac{1}{3\, m_W^2\, m_{\tilde{G}}^2} 8\, (((\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))^2-(\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))^2)(P_i P_j+S_i S_j)-$$
$$(P_j S_i+P_i S_j)((\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))-\nu_j\Lambda_{i1}))(f_3)^4-$$
$$\frac{1}{m_W^2} 4\, (((\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))^2-(\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))^2)(P_i P_j+S_i S_j)-$$
$$(P_j S_i+P_i S_j)((\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))-\nu_j\Lambda_{i1}))(f_3)^3+$$
$$\frac{1}{3\, m_W^2\, m_{\tilde{G}}^2} 4\, f_1\, (((\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))^2-(\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))^2)(P_i P_j+S_i S_j)-$$
$$(P_j S_i+P_i S_j)((\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))-\nu_j\Lambda_{i1}))(f_3)^3+$$
$$\frac{1}{3\, m_W^2\, m_{\tilde{G}}^2} 4\, f_2\, (((\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))^2-(\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))^2)(P_i P_j+S_i S_j)-$$
$$(P_j S_i+P_i S_j)((\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))-\nu_j\Lambda_{i1}))(f_3)^3+$$
$$\frac{1}{3\, m_W^2\, m_{\tilde{G}}^2} 2\, {q_3}^2\, (((\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))^2-(\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))^2)(P_i P_j+S_i S_j)-$$
$$(P_j S_i+P_i S_j)((\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))-\nu_j\Lambda_{i1}))(f_3)^3-$$
$$\frac{1}{3\, m_{\tilde{G}}^2} 4\, (((\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))^2-(\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))^2)(P_i P_j+S_i S_j)-$$
$$(P_j S_i+P_i S_j)((\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))-\nu_j\Lambda_{i1}))(f_3)^3-$$
$$\frac{1}{3\, m_W^2} 4\, m_{\tilde{G}}^2\, (((\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))^2-(\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))^2)(P_i P_j+S_i S_j)-$$
$$(P_j S_i+P_i S_j)((\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))-\nu_j\Lambda_{i1}))(f_3)^2+$$
$$\frac{1}{3\, m_W^2} 4\, f_1\, (((\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))^2-(\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))^2)(P_i P_j+S_i S_j)-$$
$$(P_j S_i+P_i S_j)((\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))-\nu_j\Lambda_{i1}))(f_3)^2+$$

$$\frac{1}{3\, m_W^2} 4\, f_2\, (((\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))^2-(\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))^2)(P_i P_j+S_i S_j)-$$
$$(P_j S_i+P_i S_j)((\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))-\nu_j\Lambda_{i1}))(f_3)^2+$$
$$\frac{1}{3\, m_W^2} 2\, {q_3}^2\, (((\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))^2-(\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))^2)(P_i P_j+S_i S_j)-$$
$$(P_j S_i+P_i S_j)((\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))-\nu_j\Lambda_{i1}))(f_3)^2-$$
$$\frac{1}{3\, m_W^2\, m_{\tilde{G}}^2} 2\, f_2\, {q_3}^2\, (((\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))^2-(\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))^2)(P_i P_j+S_i S_j)-$$
$$(P_j S_i+P_i S_j)((\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))-\nu_j\Lambda_{i1}))(f_3)^2-$$
$$\frac{20}{3}\, (((\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))^2-(\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))^2)(P_i P_j+S_i S_j)-$$
$$(P_j S_i+P_i S_j)((\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))-\nu_j\Lambda_{i1}))(f_3)^2-$$
$$\frac{8}{3}\, m_W^2\, (((\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))^2-(\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))^2)(P_i P_j+S_i S_j)-$$
$$(P_j S_i+P_i S_j)((\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))-\nu_j\Lambda_{i1}))\, f_3-$$
$$8\, m_{\tilde{G}}^2\, (((\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))^2-(\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))^2)(P_i P_j+S_i S_j)-$$
$$(P_j S_i+P_i S_j)((\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))-\nu_j\Lambda_{i1}))\, f_3+$$
$$\frac{8}{3}\, f_1\, (((\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))^2-(\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))^2)(P_i P_j+S_i S_j)-$$
$$(P_j S_i+P_i S_j)((\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))-\nu_j\Lambda_{i1}))\, f_3+$$
$$\frac{8}{3}\, f_2\, (((\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))^2-(\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))^2)(P_i P_j+S_i S_j)-$$
$$(P_j S_i+P_i S_j)((\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))-\nu_j\Lambda_{i1}))\, f_3+$$
$$\frac{4}{3}\, {q_3}^2\, (((\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))^2-(\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))^2)(P_i P_j+S_i S_j)-$$
$$(P_j S_i+P_i S_j)((\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))-\nu_j\Lambda_{i1}))\, f_3-$$
$$\frac{8}{3}\, m_{\tilde{G}}^4\, (((\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))^2-(\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))^2)(P_i P_j+S_i S_j)-$$
$$(P_j S_i+P_i S_j)((\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))-\nu_j\Lambda_{i1}))-$$
$$\frac{8}{3}\, m_W^2\, m_{\tilde{G}}^2\, (((\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))^2-(\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))^2)(P_i P_j+S_i S_j)-$$
$$(P_j S_i+P_i S_j)((\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))-\nu_j\Lambda_{i1}))+$$
$$\frac{8}{3}\, f_1\, m_{\tilde{G}}^2\, (((\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))^2-(\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))^2)(P_i P_j+S_i S_j)-$$
$$(P_j S_i+P_i S_j)((\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))-\nu_j\Lambda_{i1}))+$$
$$\frac{8}{3}\, f_2\, m_{\tilde{G}}^2\, (((\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))^2-(\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))^2)(P_i P_j+S_i S_j)-$$
$$(P_j S_i+P_i S_j)((\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))-\nu_j\Lambda_{i1}))+$$
$$\frac{4}{3}\, {q_3}^2\, m_{\tilde{G}}^2\, (((\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))^2-(\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))^2)(P_i P_j+S_i S_j)-$$
$$(P_j S_i+P_i S_j)((\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))-\nu_j\Lambda_{i1}))-$$
$$\frac{4}{3}\, f_2\, {q_3}^2\, (((\mathrm{Ui2}\cos(\beta)+\mathrm{Vi2}\sin(\beta))^2-(\mathrm{Vi2}\sin(\beta)-\mathrm{Ui2}\cos(\beta))^2)(P_i P_j+S_i S_j)-$$

$$(P_j S_i + P_i S_j)((\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta)) - \nu_j \Lambda_{i1}))\Big) +$$

$$m_\chi \Big(4 m_\chi \Big(-\frac{1}{3 m_W^2 m_{\tilde{G}}^2} 2 (((\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta))^2 - (\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))^2)(P_i P_j + S_i S_j) -$$
$$(P_j S_i + P_i S_j)((\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta)) - \nu_j \Lambda_{i1}))(f_3)^3 -$$
$$\frac{1}{3 m_W^2} 2 (((\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta))^2 - (\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))^2)(P_i P_j + S_i S_j) -$$
$$(P_j S_i + P_i S_j)((\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta)) - \nu_j \Lambda_{i1}))(f_3)^2 +$$
$$\frac{1}{3 m_W^2 m_{\tilde{G}}^2} 2 f_2 (((\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta))^2 - (\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))^2)(P_i P_j + S_i S_j) -$$
$$(P_j S_i + P_i S_j)((\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta)) - \nu_j \Lambda_{i1}))(f_3)^2 -$$
$$\frac{4}{3} (((\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta))^2 - (\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))^2)(P_i P_j + S_i S_j) -$$
$$(P_j S_i + P_i S_j)((\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta)) - \nu_j \Lambda_{i1})) f_3 -$$
$$\frac{4}{3} m_{\tilde{G}}^2 (((\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta))^2 - (\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))^2)(P_i P_j + S_i S_j) -$$
$$(P_j S_i + P_i S_j)((\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta)) - \nu_j \Lambda_{i1})) +$$
$$\frac{4}{3} f_2 (((\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta))^2 - (\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))^2)(P_i P_j + S_i S_j) -$$
$$(P_j S_i + P_i S_j)((\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta)) - \nu_j \Lambda_{i1}))\Big) +$$

$$4 \Big(-\frac{1}{3 m_W^2 m_{\tilde{G}}} 4 (((\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta))^2 - (\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))^2)(P_i P_j + S_i S_j) -$$
$$(P_j S_i + P_i S_j)((\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta)) - \nu_j \Lambda_{i1}))(f_3)^3 -$$
$$\frac{1}{3 m_W^2} 2 m_{\tilde{G}} (((\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta))^2 - (\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))^2)(P_i P_j + S_i S_j) -$$
$$(P_j S_i + P_i S_j)((\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta)) - \nu_j \Lambda_{i1}))(f_3)^2 +$$
$$\frac{1}{3 m_W^2 m_{\tilde{G}}} 2 f_1 (((\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta))^2 - (\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))^2)(P_i P_j + S_i S_j) -$$
$$(P_j S_i + P_i S_j)((\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta)) - \nu_j \Lambda_{i1}))(f_3)^2 +$$
$$\frac{1}{3 m_W^2 m_{\tilde{G}}} 2 f_2 (((\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta))^2 - (\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))^2)(P_i P_j + S_i S_j) -$$
$$(P_j S_i + P_i S_j)((\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta)) - \nu_j \Lambda_{i1}))(f_3)^2 -$$
$$\frac{1}{3 m_{\tilde{G}}} 2 (((\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta))^2 - (\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))^2)(P_i P_j + S_i S_j) -$$
$$(P_j S_i + P_i S_j)((\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta)) - \nu_j \Lambda_{i1}))(f_3)^2 -$$
$$\frac{8}{3} m_{\tilde{G}} (((\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta))^2 - (\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))^2)(P_i P_j + S_i S_j) -$$
$$(P_j S_i + P_i S_j)((\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta)) - \nu_j \Lambda_{i1})) f_3 -$$
$$\frac{4}{3} m_{\tilde{G}}^3 (((\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta))^2 - (\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))^2)(P_i P_j + S_i S_j) -$$
$$(P_j S_i + P_i S_j)((\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta)) - \nu_j \Lambda_{i1})) -$$
$$\frac{4}{3} m_W^2 m_{\tilde{G}} (((\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta))^2 - (\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))^2)(P_i P_j + S_i S_j) -$$
$$(P_j S_i + P_i S_j)((\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta)) - \nu_j \Lambda_{i1})) +$$
$$\frac{4}{3} f_1 m_{\tilde{G}} (((\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta))^2 - (\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))^2)(P_i P_j + S_i S_j) -$$
$$(P_j S_i + P_i S_j)((\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta)) - \nu_j \Lambda_{i1})) +$$
$$\frac{4}{3} f_2 m_{\tilde{G}} (((\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta))^2 - (\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))^2)(P_i P_j + S_i S_j) -$$
$$(P_j S_i + P_i S_j)((\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta)) - \nu_j \Lambda_{i1}))\Big) +$$

$$4 \Big(-\frac{1}{3 m_W^2 m_{\tilde{G}}} 4 (((\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta))^2 - (\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))^2)(P_i P_j + S_i S_j) +$$
$$(P_j S_i + P_i S_j)((\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta)) - \nu_j \Lambda_{i1}))(f_3)^3 -$$
$$\frac{1}{3 m_W^2} 2 m_{\tilde{G}} (((\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta))^2 - (\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))^2)(P_i P_j + S_i S_j) +$$
$$(P_j S_i + P_i S_j)((\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta)) - \nu_j \Lambda_{i1}))(f_3)^2 +$$
$$\frac{1}{3 m_W^2 m_{\tilde{G}}} 2 f_1 (((\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta))^2 - (\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))^2)(P_i P_j + S_i S_j) +$$
$$(P_j S_i + P_i S_j)((\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta)) - \nu_j \Lambda_{i1}))(f_3)^2 +$$
$$\frac{1}{3 m_W^2 m_{\tilde{G}}} 2 f_2 (((\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta))^2 - (\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))^2)(P_i P_j + S_i S_j) +$$
$$(P_j S_i + P_i S_j)((\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta)) - \nu_j \Lambda_{i1}))(f_3)^2 -$$
$$\frac{1}{3 m_{\tilde{G}}} 2 (((\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta))^2 - (\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))^2)(P_i P_j + S_i S_j) +$$
$$(P_j S_i + P_i S_j)((\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta)) - \nu_j \Lambda_{i1}))(f_3)^2 -$$
$$\frac{8}{3} m_{\tilde{G}} (((\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta))^2 - (\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))^2)(P_i P_j + S_i S_j) +$$
$$(P_j S_i + P_i S_j)((\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta)) - \nu_j \Lambda_{i1})) f_3 -$$
$$\frac{4}{3} m_{\tilde{G}}^3 (((\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta))^2 - (\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))^2)(P_i P_j + S_i S_j) +$$
$$(P_j S_i + P_i S_j)((\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta)) - \nu_j \Lambda_{i1})) -$$
$$\frac{4}{3} m_W^2 m_{\tilde{G}} (((\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta))^2 - (\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))^2)(P_i P_j + S_i S_j) +$$
$$(P_j S_i + P_i S_j)((\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta)) - \nu_j \Lambda_{i1})) +$$
$$\frac{4}{3} f_1 m_{\tilde{G}} (((\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta))^2 - (\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))^2)(P_i P_j + S_i S_j) +$$
$$(P_j S_i + P_i S_j)((\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta)) - \nu_j \Lambda_{i1})) +$$
$$\frac{4}{3} f_2 m_{\tilde{G}} (((\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta))^2 - (\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))^2)(P_i P_j + S_i S_j) +$$
$$(P_j S_i + P_i S_j)((\mathrm{Vi2}\sin(\beta) - \mathrm{Ui2}\cos(\beta))(\mathrm{Ui2}\cos(\beta) + \mathrm{Vi2}\sin(\beta)) - \nu_j \Lambda_{i1}))\Big)\Big)$$

With Mathematica help but also with human intuition (hand Working), we obtain for the same last squared amplitude:

We have

$$\mathcal{M}^{\dagger}_{\chi_i^+} = C_{\chi_i^+} P^*_{\chi_i^+}(q_3)\overline{u}(p_2)(S_j - P_j\gamma_5)(\not{q}_3 + m_\chi)(V_j - \Lambda_j\gamma_5)\epsilon_\sigma(k)\Psi^\sigma$$

Squaring and summing over final polarization we obtain:

$$|\overline{\mathcal{M}}_{\chi_i^+}|^2 = C^2_{\chi_i^+}|P_{\chi_i^+}(q_3)|^2 W_{\chi_i^+\chi_i^+}$$

where

$$\begin{aligned} W_{\chi_i^+\chi_i^+} &= \mathbf{Tr}\Big[M_{\rho\sigma}D^{\rho\sigma}(V_i + \Lambda_i\gamma_5)(\not{q}_3 + m_\chi)(S_i + P_i\gamma_5)\not{p}_2 \\ &\quad (S_j - P_j\gamma_5)(\not{q}_3 + m_\chi)(V_j - \Lambda_j\gamma_5)\Big] \\ &= \mathrm{w}_{1\chi_i^+\chi_i^+} + m_{\chi_i^+}\mathrm{w}_{2\chi_i^+\chi_i^+} + m^2_{\chi_i^+}\mathrm{w}_{3\chi_i^+\chi_i^+} \end{aligned}$$

with

$$w_{1\chi_i^+\chi_i^+} = -\frac{8\Sigma_{\mathrm{ij}1} h_2}{3m_W^2 m_{\tilde{G}}^2}\left(\left(m_{\tilde{G}}^2 + f_3\right)\left(2\left(m_{\tilde{G}}^2 + m_W^2\right) + 4f_3 - q_3\right)\right.$$
$$\left. + f_2\left(-2m_{\tilde{G}}^2 - 2f_3 + q_3\right) - 2f_1\left(m_{\tilde{G}}^2 + f_3\right)\right)$$
$$w_{2\chi_i^+\chi_i^+} = -\frac{8(\Sigma_{\mathrm{ij}1} + \Sigma_{\mathrm{ij}2}) h_2}{3m_W^2 m_{\tilde{G}}}\left(m_{\tilde{G}}^2 - f_1 - f_2 + 2f_3 + m_W^2\right)$$
$$w_{3\chi_i^+\chi_i^+} = -\frac{8\Sigma_{\mathrm{ij}3} h_2}{3m_W^2 m_{\tilde{G}}^2}\left(m_{\tilde{G}}^2 - f_2 + f_3\right)$$

with $h_2 = \left(2m_W^2 m_{\tilde{G}}^2 + (f_3)^2\right)$ and also we have used the substitutions:

$$\Sigma_{ij1} = (S_iS_j + P_iP_j)(V_iV_j - \Lambda_i\Lambda_j) - (S_iP_j + P_iS_j)(\Lambda_iV_j - V_i\Lambda_j)$$
$$\Sigma_{ij2} = (S_iS_j + P_iP_j)(V_iV_j - \Lambda_i\Lambda_j) + (S_iP_j + P_iS_j)(\Lambda_iV_j - V_i\Lambda_j)$$
$$\Sigma_{ij3} = (S_iS_j + P_iP_j)(V_iV_j + \Lambda_i\Lambda_j) + (S_iP_j + P_iS_j)(\Lambda_iV_j + V_i\Lambda_j)$$

Goldstino Approximation

In spontaneously broken SUSY models, the massless gravitino field $\tilde{\Psi}_\mu$ acquires mass by absorbing goldstino modes. For the case $\sqrt{s} \gg m_{\tilde{G}}$, the wave function of the gravitino of helicity $\pm\frac{1}{2}$ components is approximately proportional to $p_\mu/m_{\tilde{G}}$ where p_μ is a momentum of the gravitino. In this case the helicity $\pm\frac{1}{2}$ component of the gravitino field can be written as:

$$\tilde{\Psi}_\mu \sim \sqrt{\frac{2}{3}} \frac{1}{m_{\tilde{G}}} \partial_\mu \Psi \quad (9)$$

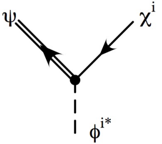
Goldstino Approximation

Ψ represents the spin $\frac{1}{2}$ fermionic field which can be interpreted as the goldstino. Substituting [9] into gravitino interaction lagrangian, one can obtain the effective interaction lagrangian for the godstino components Ψ.

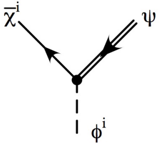
We would like to explore in which case the Goldstino is a good approximation to the Gravitino.

Goldstino Approximation

From the Feynman diagram we can obtain the amplitudes for the stop decay in the case that we have a Goldstino in the final state.



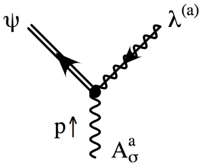
$$\frac{m_\chi^2 - m_\phi^2}{2\sqrt{3}M m_{3/2}}(1+\gamma_5)$$



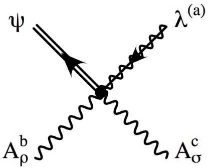
$$\frac{m_\chi^2 - m_\phi^2}{2\sqrt{3}M m_{3/2}}(1-\gamma_5)$$

Goldstino Approximation

Because we are considering the same decay $\tilde{t} \to b + W + \Psi$, we will have to compute 21 amplitudes. Although they are far simpler, compare with the gravitino case.☺



$\frac{-im_\lambda}{2\sqrt{6}Mm_{3/2}}[\gamma_\rho, \gamma_\sigma]p^\rho$



$\frac{-m_\lambda}{2\sqrt{6}Mm_{3/2}} g f^{abc}[\gamma_\rho, \gamma_\sigma]$

Numerical Results

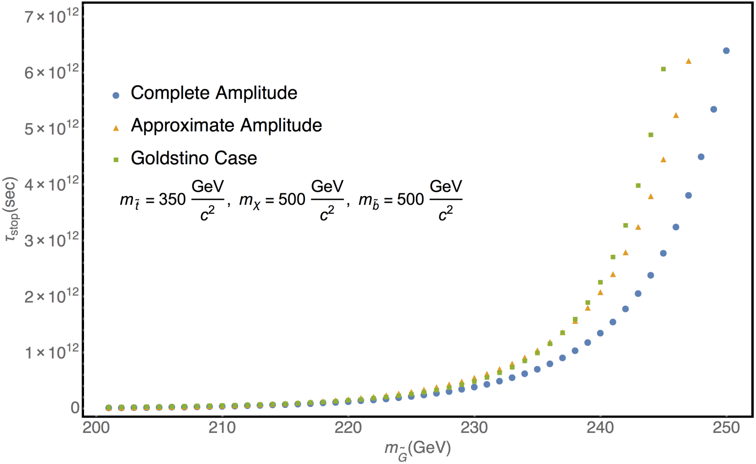
It is more illustrative get some graphs from all these large analytical results.
We need to integrate the decay width

$$\frac{d\Gamma}{dxdy} = \frac{m_{\tilde{t}_1}^2}{256\pi^3} \mid \overline{\mathcal{M}} \mid^2$$

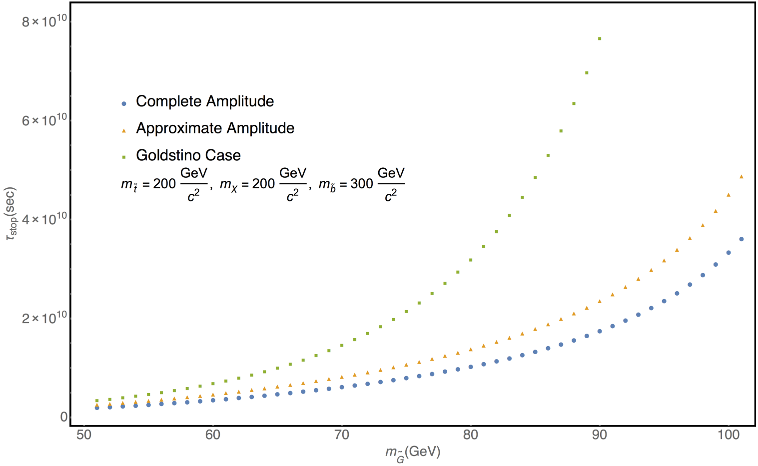
the integration limits are: $2\mu_G < x < 1 + \mu_G - \mu_W$ and $y_- < y < y_+$, where

$$y_\pm = \frac{1 + \mu_G + \mu_W - x}{2(1 + \mu_G - x)} [(2 - x) \pm (x - 4\mu_G)^{1/2}]$$

Numerical Results



Numerical Results



Conclusions

- Amplitude approximations in previous work is not so bad, but now we have the complete result, that refine the range of the stop's life-time.
- Gravitino LSP is an interesting and viable scenario,
- Also possible that stop may be the NLSP,
- A distictive signature of such scenario is the large life-time of the stop $\simeq 10^8 - 10^{12}$ secs., which has interesting implications for nucleosinthesis and collider physics.
- Goldstino is good approximation in the low gravitino mass limit.

THANKS..

Why is SUSY attractive?

- Offers the possibility to stabilize the Higgs mass and induce radiatively
- Improves Unification and o.k. with proton decay,
- Favors a light Higgs boson, in agreement with precision analysis,
- New sources of flavor and CP violation may help to get
- R-parity → Lightest SUSY particle is stable (LSP),
- LSP is a good Dark matter candidate.
- It could be the low limit energy of a fundamental theory of Quantum Gravity.

The MSSM

The minimal extension of the Standard Model (SM) consistent with SUSY (MSSM), is based on:

- Gauge supermultiplets
  - SM Gauge Group → gauge bosons (and gauginos),
- Chiral supermultiplets
  - 3 families of fermions (and sfermions),
  - Two Higgs doublets (and Higgsinos),
- Soft-breaking of SUSY,
  - gaugino and scalar masses,
  - bilinear and trilinear terms,
- R-parity distinguish SM and their superpartners → LSP is stable and good DM candidate.

The models (a): CMSSM

Models at TeV scale are derived from SUGRA models through RGE,

- CMSSM = Constrained Minimal Supersymmetric Standard Model.
- In the CMSSM one takes (at M_{pl}):
  - Universal scalar masses (=$\widetilde{m}_0$)
  - redUniversal gaugino masses (=$\tilde{m}_{1/2}$)
  - Universal trilinear terms (=A_0)
- Also $\tan\beta = v_2/v_1$ and $sgn(mu)$.
- Use RGE to get weak-scale parameters.

The models (b): NUHM

- NUHM = Non-universal Higgs Masses Model.
- Same parameters as in CMSSM, except that the Higgs masses $m_{1,2}$ are not equal to m_0.
- We can trade $m_{1,2}$ with μ and m_A, as our free parameters through the electroweak symmetry breaking condition.
- Thus the NUHM parameters are: m_0,$m_{1/2}$ A_0, $\tan\beta = v_2/v_1$, μ and m_A.

NLSP scenarios and Constraints

Several constraints are required for consistency of this scenario. SUSY parameters must satisfy:

- LHC limits on Higgs mass ($m_h = 125$ GeV),
- Current bounds on $b \to s + \gamma$,
- Correct induced radiative EWSB,
- LHC limits on stable charged particles, e.g. $m_{\tilde{t}} \geq 200$ GeV.

Stop mass matrix

$$\widetilde{\mathcal{M}}_{\tilde{t}}^2 = \begin{pmatrix} M_{LL}^2 & M_{LR}^2 \\ M_{LR}^{2\dagger} & M_{RR}^2 \end{pmatrix}, \qquad (10)$$

where

$$\begin{aligned} M_{LL}^2 &= M_{\tilde{t}_L}^2 + m_t^2 + \frac{1}{6}\cos 2\beta\,(4m_w^2 - m_z^2)\,, \\ M_{RR}^2 &= M_{\tilde{t}_R}^2 + m_t^2 + \frac{2}{3}\cos 2\beta\sin^2\theta_w\, m_z^2\,, \\ M_{LR}^2 &= A_t v\sin\beta/\sqrt{2} - m_t\,\mu\cot\beta\,, \end{aligned} \qquad (11)$$

1

[1] J. L. Diaz-Cruz, J. R. Ellis, K. A. Olive and Y. Santoso, "On the feasibility of a stop NLSP in gravitino dark matter scenarios," JHEP **0705**, 003 (2007) [arXiv:hp-ph/0701229].

Stop mass matrix

The stop mass eigenvalues are given by:

$$m_{\tilde{t}_1}^2 = m_t^2 + \frac{1}{2}(M_{\tilde{t}_L}^2 + M_{\tilde{t}_R}^2) + \frac{1}{4}m_Z^2 \cos 2\beta - \frac{\Delta}{2} \quad (12)$$

$$m_{\tilde{t}_2}^2 = m_t^2 + \frac{1}{2}(M_{\tilde{t}_L}^2 + M_{\tilde{t}_R}^2) + \frac{1}{4}m_Z^2 \cos 2\beta + \frac{\Delta}{2} \quad (13)$$

where:
$\Delta^2 = M_{\tilde{t}_L}^2 - M_{\tilde{t}_R}^2 + \frac{1}{6}\cos 2\beta(8m_W^2 - 5m_Z^2) + 4m_t(A_t - \mu\cot\beta)$.

The mixing angle to go from the weak $(\tilde{t}_L, \tilde{t}_R)$ to the mass eigenstates $(\tilde{t}_1, \tilde{t}_2)$, is given by: $\tan\theta_{\tilde{t}} = (m_{\tilde{t}_1}^2 - M_{LL}^2)/M_{LR}^2$.

A.1 Relevant interactions

Stop-top-gravitino interactions:

$$\tilde{t}_1^*(p)\bar{\Psi}_\mu t \rightarrow -\frac{1}{\sqrt{2}M}\gamma^\nu\gamma^\mu p_\nu(\sin\theta_{\tilde{t}}P_R + \cos\theta_{\tilde{t}}P_L) \quad (14)$$

and similar expression holds for the Bottom-sbottom-gravitino interaction.
Chargino-W-gravitino:

$$\chi_i^- \bar{\Psi}_\mu W^-(k) \rightarrow -\frac{m_W}{M}\gamma^\nu\gamma^\mu(A_{Li}P_R + A_{Ri}P_L) \quad (15)$$

where: $A_{Li} = V_{i2}\sin\beta$, $A_{Ri} = V_{i2}\cos\beta$, and U, V are the matrices that diogonalize the charginos.