LHC constraints on long-lived $\tilde{t}$

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Motivations

- Dark matter is one of the greatest unsolved mysteries today.
  - We know it exists but we don't know what it is and how it is generated in the Universe.
- The most popular idea is that the dark matter consists of particles beyond the Standard Model $\Longrightarrow$ Gravitino $\tilde{G}$
  - A model Beyond the Standard Model of particle physics is necessary.
- We focused on the Minimal Supersymmetric extension of the Standard Model (MSSM)
  - LHC is still searching for supersymmetric particles.

Outline

Scenario

We are working with a stop $\tilde{t}$ NLSP and a gravitino LSP $\tilde{G}$ and DM candidate in both RPC and RPV models.

We concentrate on a Bilinear RPV model.

Why do we choose a $\tilde{t}$ NLSP?

Motivations:

- $\tilde{t}$-low abundance makes the Big Bang nucleosynthesis (BBN) bound easier to obey $\Longrightarrow$ Cosmological analysis
- $\tilde{t}$ might be discovered at LHC since it must not be too heavy to give the right 1-loop corrections to m_H $\Longrightarrow$ LHC analysis

Scenario

The $\tilde{t}$ NLSP decay channels are:

- $\tilde{t} \to \tilde{G}\, t$ (RPC decay) after BBN $\Longrightarrow$ BBN bound

  The $\tilde{t}$ lifetime (arXiv:0807.0211v2 [hep-ph]):

$$\tau_{\tilde{t}}^{cm} \approx (18.8\, sec) \left(\frac{500\ GeV}{m_{\tilde{t}}} \right)^5 \left(\frac{m_{3/2}}{1\ GeV} \right)^2$$

- $\tilde{t} \to \ell^+ b$ (BRPV decay) before BBN $\Longrightarrow$ No BBN bound

  The $\tilde{t}$ lifetime:

$$\tau_{\tilde{t}}^{cm} \approx (10^{-7} \mathrm{sec}) \left(\frac{\epsilon \sin\theta}{10^{-8}} \right)^{-2} \left(\frac{500\ GeV}{m_{\tilde{t}}} \right) \left(\frac{1\ GeV}{m_b} \right)^2 .$$

Here, we also consider the indirect detection (ID) bound on $\tilde{G}$ DM: $\epsilon \leq 10^{-8}$.

$\tilde{t}$ RPC Cosmological analysis & BBN bound

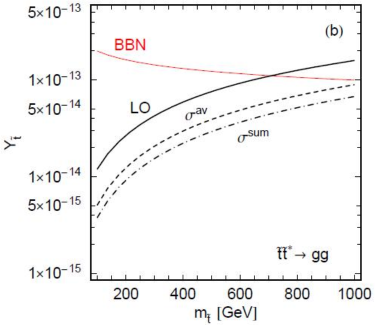
Imposing the BBN bound on $\tau_{\tilde{t}}$ so that it is consistent with the observed light element abundances and the CDM density bound Ω_{CDM} on gravitino density $\Omega_{\tilde{G}}$ so that it is really CDM, we get an excluded region in the plane "$m_{\tilde{t}}$ vs $m_{3/2}$". To obtain BBN bound on $\tau_{\tilde{t}}$, we compare:

- The abundance $Y_{\tilde{t}}(m_{\tilde{t}})\,(:= n_{\tilde{t}}/s)$ computed by C. Berger, L. Covi et al. via Boltzmann equation for the Stop number density $n_{\tilde{t}}$:

$$\dot{n}_{\tilde{t}} + 3Hn_{\tilde{t}} = \int \frac{d^3p_{\tilde{t}}}{(2\pi)^3\, 2E_{\tilde{t}}}\, C\,[f_{\tilde{t}}]$$

with collision integral C, phase space $f_{\tilde{t}}$ and H Hubble constant.

arXiv:0807.0211v2 [hep-ph]



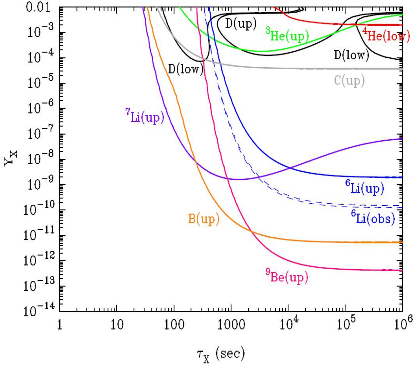
BBN bound

- The limits of abundance $Y_x(\tau_x)\,(:= n_x/n_b)$ computed by M. Kusakabe et al. for a hypothetical long-lived colour charged massive particle X, existed during the BBN epoch and then decayed before it could be detected.

  Authors computed it, taking into account:

  - X-nuclei bound states and reactions involving them
  - X-nucleon interactions comparable to those between nucleons.

arXiv:0906.3516v1 [hep-ph]

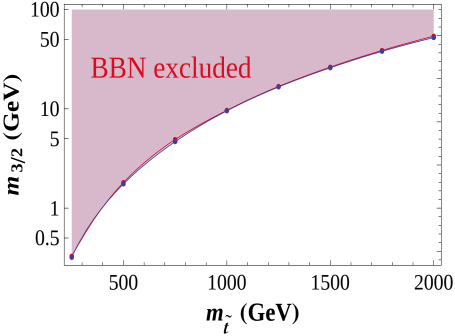


BBN bound

In this way we determine the $\tau_{\tilde{t}}$-maximal values: $\tau_{\tilde{t}}^{max}(m_{\tilde{t}})$, which, using the $\tau_{\tilde{t}}$-analytical formula: $\tau_{\tilde{t}}^{cm} = (2.36 \times 10^3\, s) \left(\frac{500 \text{ GeV}}{m_{\tilde{t}}}\right)^5 \left(\frac{m_{3/2}}{1 \text{ GeV}}\right)^2$ lead to the corresponding maximal values for $m_{3/2}$: $m_{3/2}^{max}(m_{\tilde{t}})$.

$$\Downarrow$$

BBN bound on $\tilde{t}$ converts in a bound on $m_{3/2}$:



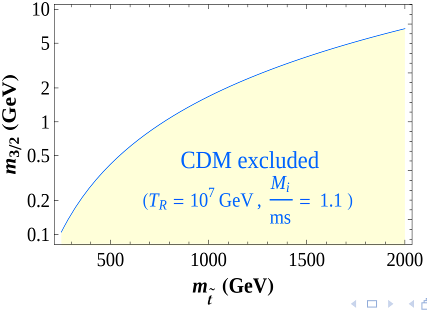
CDM bound

We impose the CDM density bound $\Omega_{CDM} h^2$ ($\leqslant 0.11$) on the $\tilde{G}$ density $\Omega_{\tilde{G}}\, h^2$, in a scenario where $\tilde{G}$ can be produced in the thermal plasma via scattering of energetic particles after inflation and its $\Omega_{\tilde{G}}\, h^2$ reads

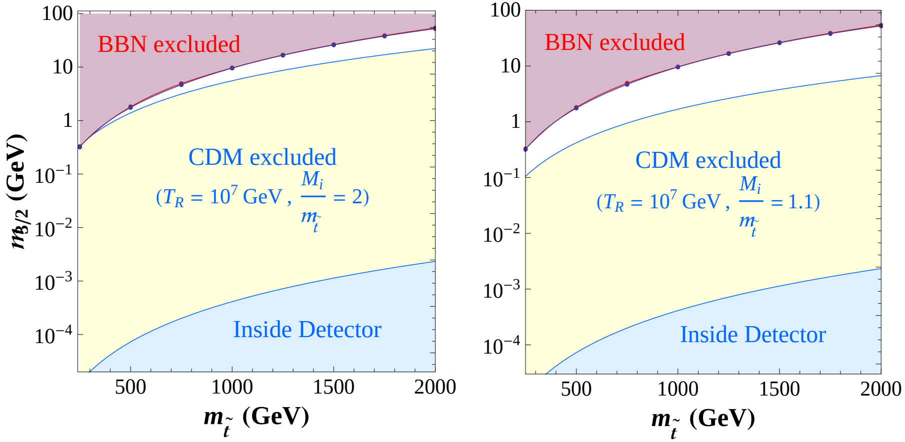
$$\Omega_{\tilde{G}}\, h^2 \approx \frac{T_R}{10^9\; GeV}\, \beta \left(\frac{m_{\tilde{t}}}{300\; GeV}\right)^2 \left(\frac{m_{3/2}}{1\; GeV}\right)^{-1} \quad \text{with} \quad \beta = \sum_{i=1}^{3} \gamma_i \left(\frac{M_i}{m_{\tilde{t}}}\right)^2 .$$

$$\Downarrow$$

The bound on $\Omega_{CDM} h^2$ converts in a bound on $m_{3/2}$:



"$m_{\tilde{t}}$ vs $m_{3/2}$" - all bounds



$\Longrightarrow$ BBN and CDM have a strong impact on the RPC $\tilde{t}$ decay.
RPV scenario is less constrained.

$\tilde{t}$ displaced vertex analysis

We study the stop $\tilde{t}$ production at the LHC at $\sqrt{s} = 14\ TeV$ leading to displaced vertices because the discovery of $\tilde{t}$ might be observed as a $\tilde{t}$-displaced vertex inside the detector.

Our analysis studies the number of $\tilde{t}$ displaced vertices in the Pixel, Tracker and Outside CMS detector. It uses 2 different approaches:

- Numerical approach via "MadGraph5" (MG5).

  (Since MG5 is a matrix element generator at tree-level for a given Model)

- Semi-analytic approach via MG5 and analytical considerations for $\tilde{t}$-decay.

  (Since the semi-analytic method gives us a better control on physical parameters and a useful check of MG5.)

Numerical approach

Running MG5 for several $m_{\tilde{t}}$'s and $\Gamma_{\tilde{t}}$'s, and demanding that it generates 10000 events every "run", MG5 output - e.g.

(1 MG-event, $m_{\tilde{t}} = 800\ GeV$, $\Gamma_{\tilde{t}} = 10^{-10}\ GeV$)

pid	in/out	mother1	mother2	color1	color2	px	py	pz	p0	mass	distance	hel
uBar	in	0	0	0	501	0.	0.	576.918	576.918	0.	0.	-1.
u	in	0	0	502	0	0.	0.	-1681.09	1681.09	0.	0.	1.
$\tilde{t}_1$	decayed	1	2	502	0	237.699	484.863	-776.314	1238.65	800.	0.000185211	0.
$(\tilde{t}_1)^*$	decayed	1	2	0	501	-237.699	-484.863	-327.855	1019.35	800.	0.000554574	0.
b	out	3	3	502	0	503.895	242.913	-279.689	625.433	4.88992	0.	1.
μ^+	out	3	3	0	0	-266.195	241.95	-496.626	613.219	0.	0.	1.
bBar	out	4	4	0	501	112.019	-452.578	88.5704	474.598	4.88992	0.	-1.
particle[15]	out	4	4	0	0	-349.718	-32.2848	-416.425	544.755	1.777	0.	-1.

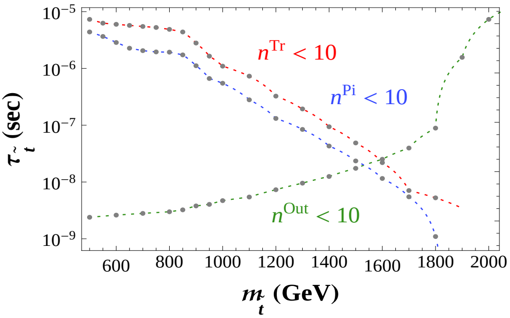
- provides us with the kinematics of all particles in the process, among which decay length of $\tilde{t}$'s, ("distance" in the table above), and then:

$\Longrightarrow$ Spatial distribution of 10000 $\tilde{t}$-vertices

Numerical approach

Assuming that the backgrounds of SM and SUSY particles are both negligible, requiring the minimum number of observed vertices by CMS is 10 for the maximum expected LHC luminosity $L = 3000\, fb^{-1}$, we plot the LHC reach in the plane "$\tau_{\tilde{t}}$ vs $m_{\tilde{t}}$" for studied detector parts:

$\Downarrow$



Semi-Analytic approach

Using the formula (in space) of exponential decay $\left(P(x) = \exp\left\{-\frac{\Gamma^{cm}_{\tilde{t}}}{\beta\gamma}x\right\}\right)$, assuming the same decay probability for all decaying particles, i.e. only one value of $\beta\gamma$ (approximation!) and, finally, computing the number of generated particles $N_0\,(=\sigma L)$

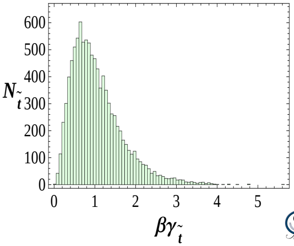
$$\Downarrow$$

we can find the analytic expression for the number of $\tilde{t}$-displaced vertices inside the detector (In) and outside the detector (Out):

$$N(x_i, x_f) = -N_0\left(\exp\left\{-\frac{\Gamma^{cm}}{\beta\gamma}x_f\right\} - \exp\left\{-\frac{\Gamma^{cm}}{\beta\gamma}x_i\right\}\right) \qquad \text{(In)}$$

$$N(x_f) = N_0 \exp\left\{-\frac{\Gamma^{cm}}{\beta\gamma}x_f\right\}. \qquad \text{(Out)}$$

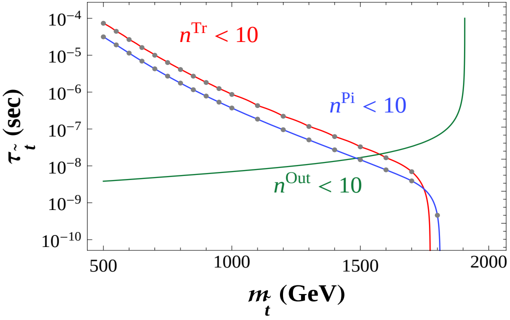
If we use $\beta\gamma = \langle\beta\gamma^{peak}\rangle = 0.66$ for all masses - good approximation, see e.g. ($\beta\gamma$-distribution for $m_{\tilde{t}} = 800\ GeV$), and...



Semi-Analytic approach

...the previous hypothesis, we get the LHC reach in the plane "$\tau_{\tilde{t}}$ *vs* $m_{\tilde{t}}$":

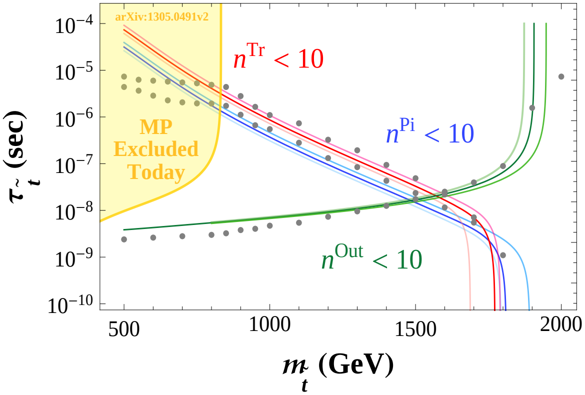
$$\Downarrow$$



Now, in order to compare the numerical analysis with the semi-analytic analysis, we plot all together...

"$\tau_{\tilde{t}}$ vs $m_{\tilde{t}}$" - comparison

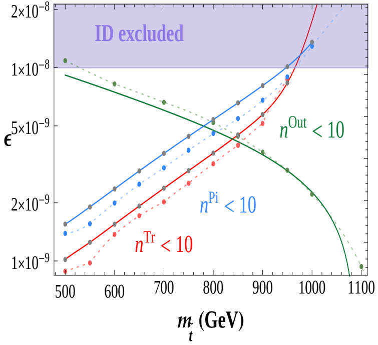
$L = 3000\ fb^{-1}$ & $\beta\gamma^{max} = 0.66$:



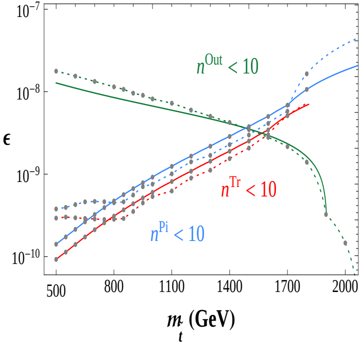
Good agreement between MG data and Semi-Analytic curves!

"ϵ vs $m_{\tilde{t}}$"

For the RPV case we can riformulate the curves in the plane "ϵ vs $m_{\tilde{t}}$" for the 1° LHC Phase $\left(L = 25\ fb^{-1},\ \sqrt{s} = 14\ TeV\ \right)$ with the ID bound for $\tilde{G}$ DM decay and for the last LHC Phase $\left(L = 3000\ fb^{-1}\right)$:



$\epsilon = \left\{10^{-9}, 10^{-8}\right\}$



$\epsilon = \left\{10^{-10}, 10^{-8}\right\}$

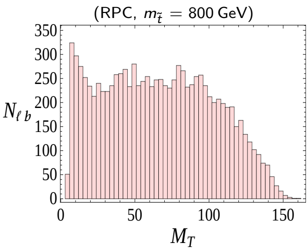
Comparison RPC-RPV models

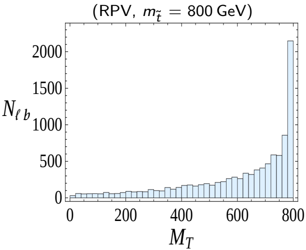
Since the displaced vertex analysis is independent from the $\tilde{t}$ decay channel, it will identical for:

$$\tilde{t} \to \ell^+ b \qquad \text{(2 body RPV decay)}$$
$$\tilde{t} \to \tilde{G} t \to \tilde{G} W^+ b \to \tilde{G} b \ell^+ \nu_\ell \qquad \text{(4 body RPC decay)}$$

where the visible particles are the same.
Can we distinguish RPC and RPV decays? Yes...

- Transverse mass M_T $(= (E_1 + E_2)^2 - (p_{T1} + p_{T2})^2)$)

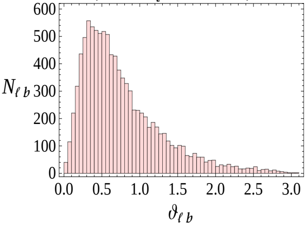




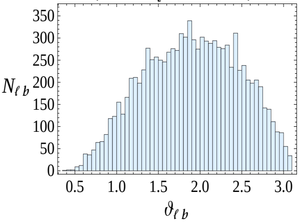
Comparison RPC-RPV models

- Angle $\vartheta_{\ell b}$ $(= \widehat{p_\ell, p_b})$

(RPC, $m_{\tilde{t}} = 800$ GeV)

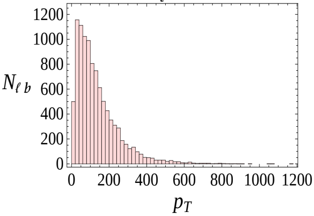


(RPV, $m_{\tilde{t}} = 800$ GeV)

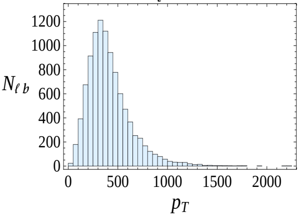


- Transverse momentum P_T $(= \sqrt{p_x + p_y})$

(RPC, $m_{\tilde{t}} = 800$ GeV)



(RPV, $m_{\tilde{t}} = 800$ GeV)



Conclusions

The RPV and RPC scenarios are interesting theoretical possibilities to search SUSY particles with a consistent cosmology and gravitino DM.

For the RPC decay "$\tilde{t} \to \tilde{G} t$" with BBN and CDM bounds we obtain an allowed region in the plane "$m_{\tilde{t}}$ vs $m_{3/2}$".

For the $\tilde{t}$ displaced vertex analysis we can obtain the future LHC reach in the plane "$\tau_{\tilde{t}}$ vs $m_{\tilde{t}}$".

The 2 body RPV $\tilde{t}$ decay and the 4 body RPC $\tilde{t}$ decay decays can be distinguished via their p_T, m_T and $\vartheta_{\ell b}$ distributions of ℓ^+ and b.

Thank you!