Long-Lived $\tilde{t}$ at LHC with or without R-parity

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Based on: L. Covi and F. D - arxiV :1403.4923v1 -

Motivations

- Dark matter is still one of the greatest unsolved mysteries at the present time.
- The most popular idea is that the dark matter consists of particles beyond the Standard Model $\Longrightarrow$ Gravitino LSP
- We focused on the Minimal Supersymmetric extension of the Standard Model (MSSM) $\Longrightarrow$ Stop NLSP
- LHC is still searching for supersymmetric particles.

Outline

1. $\tilde{t}$ displaced vertex analysis at LHC
2. Comparison of the RPC and RPV decays
3. Conclusions

Scenario

We consider:

- the interesting possibility of a MSSM spectrum where the NLSP is $\tilde{t}$. Moreover, to account for DM, we assume that $\psi_{3/2}$ is the LSP.
- both RPC model and RPV model.

but....why do we choose a stop NLSP?

Motivations:

- the stop low abundance makes the Big Bang nucleosynthesis (BBN) bound easier to obey (consistent cosmology)
- the stop particle might be discovered at LHC being it not too heavy (to give right 1-loop corrections to m_H) $\Longrightarrow$ LHC analysis

Scenario

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

- $\tilde{t} \to \psi_{3/2}\, t$ (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) usually before BBN

  The $\tilde{t}$ lifetime:

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

  and the indirect detection (ID) bound on $\psi_{3/2}$ DM: $\epsilon \leq 2 \times 10^{-8}$

  $\Longrightarrow$ BBN bound relevant only for $\epsilon \leq 10^{-11.5}$.

$\tilde{t}$ displaced vertex analysis

We study the stop production at LHC at $\sqrt{s} = 14$ TeV and the prospect for discovery of $\tilde{t}$-displaced vertices 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).

  (MG5 extension to take account of the $\tilde{t}$-decay. Correction of LO stop production with a NLO k-factor of 1.6 given by Prospino for $m_{\tilde{t}} = 800\,\mathrm{GeV}$.)

- 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 via MG5

The numerical approach consists of

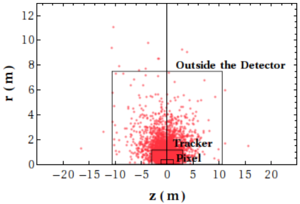
- running MG5 for several $m_{\tilde{t}}$'s and only one $\Gamma_{\tilde{t}}$ so as to generate $10,000$ events every "run" and achieve their kinematics.
- computing the decay length and direction of stop produced.
- circumventing the problem of launching MG5 for all of decay rates we need by rescaling the dimensions of all parts of the detector consistently.

$$\Downarrow$$

Spatial distribution of $10,000$ $\tilde{t}$ vertices for each $\Gamma_{\tilde{t}}$ can be obtained.

- e.g.

$(m_{\tilde{t}} = 800$ GeV, $\Gamma_{\tilde{t}} = 2.0159 \times 10^{-16}$ GeV $)$



Numerical approach via MG5

Assuming the working hypothesis:

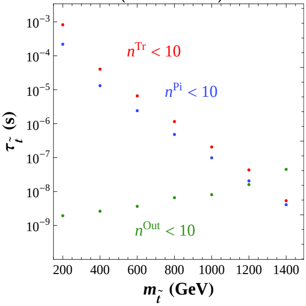
- backgrounds of SM and SUSY particles are both negligible.
- minimum number of observed vertices by CMS: $n_{min} = 10$

at the integrated luminosities $L = 25\,\mathrm{fb}^{-1}$ and $3000\,\mathrm{fb}^{-1}$, we obtain:

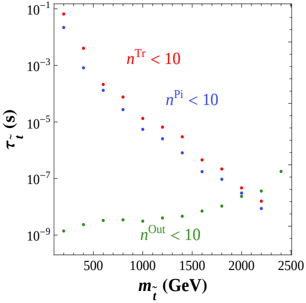
$\Downarrow$

$\boxed{\text{LHC reach in } \tau_{\tilde{t}}\text{-}m_{\tilde{t}} \text{ plane}}$

$(L = 25\,\mathrm{fb}^{-1})$



$(L = 3000\,\mathrm{fb}^{-1})$



Semi-analytic approach

The semi-analytic approach consists of:

- computing the number N_0 of generated $\tilde{t}$'s by the product of cross section (computed by MG5) and integrated luminosity: $N_0 = \sigma L$
- using the exponential decay formula (i.e. $P(r) = \frac{\Gamma_{\tilde{t}}}{\beta\gamma} \exp\left\{-\frac{\Gamma_{\tilde{t}}}{\beta\gamma} r\right\}$)
- assuming the same decay probability for all decaying $\tilde{t}$ particles, i.e. only one value of $\beta\gamma$ (approximation!)

$$\Downarrow$$

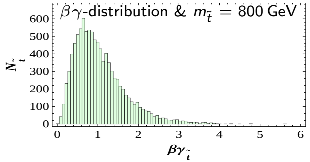
we can find the analytic expression for the number of $\tilde{t}$-displaced vertices inside the detector (In) and outside the detector (Out):

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

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

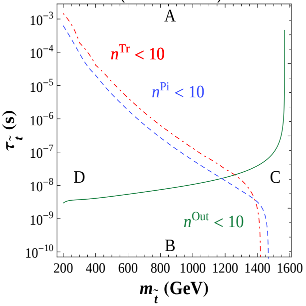
Semi-analytic approach

If the value $\langle \beta\gamma^{peak} \rangle = 0.66$ is used for all masses – good approximation, see e.g.

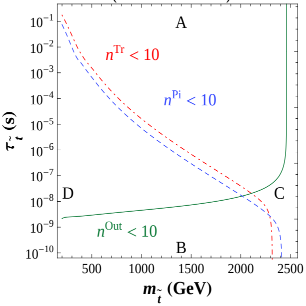


– we obtain: $\Longrightarrow$ $\boxed{\text{LHC reach in } \tau_{\tilde{t}}\text{-}m_{\tilde{t}} \text{ plane}}$

$(L = 25\ \text{fb}^{-1})$



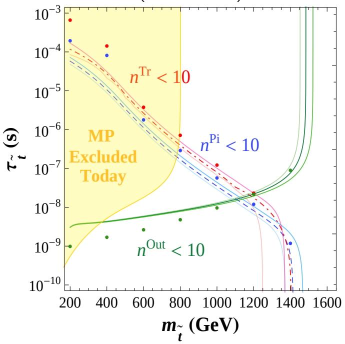
$(L = 3000\ \text{fb}^{-1})$



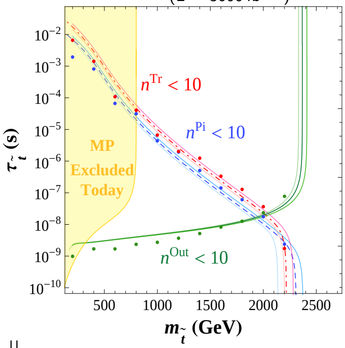
LHC reach in the plane "$\tau_{\tilde{t}}$ vs $m_{\tilde{t}}$" - comparison

To compare the numerical LHC reaches with the analytical ones, we plot all together along with the current CMS excluded region for metastable particles (MP) and the uncertainly $\pm 1\sigma$ for the analytical curves:

$(L = 25\ \mathrm{fb}^{-1})$



$(L = 3000\ \mathrm{fb}^{-1})$



$\Downarrow$

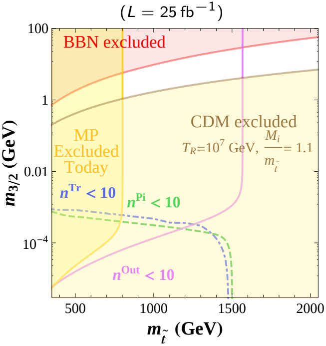
Good agreement between MG data and semi-analytic curves & complementarity Pixel-Tracker VS Out!!

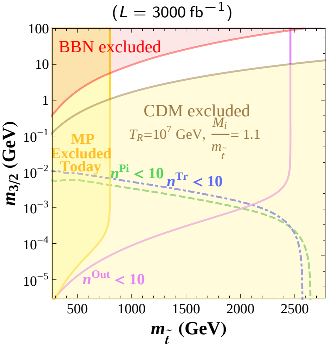
LHC reach for the RPC stop decay ($\tilde{t} \to \psi_{3/2} t$)

For the RPC $\tilde{t}$ decay into $\psi_{3/2}$ and t, the LHC reach can be reformulated in $m_{\tilde{t}}$-$m_{3/2}$ parameter space by using the analytical expression of $\tau_{\tilde{t}}$.

$$\Downarrow$$

RPC LHC reach in $m_{\tilde{t}}$-$m_{3/2}$ plane





where the BBN and CDM excluded regions and the current CMS excluded region for MP are also drawn.

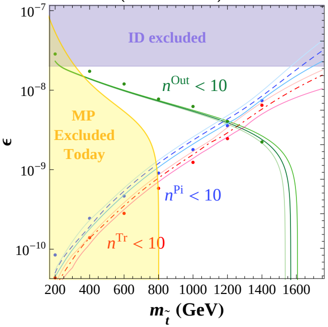
LHC reach for the RPV stop decay ($\tilde{t} \to \ell^+ b$)

For the RPV $\tilde{t}$ decay into ℓ^+ and b, the LHC reach can be reformulated in ϵ-$m_{\tilde{t}}$ parameter space by using the analytical expression of $\tau_{\tilde{t}}$. If we plot such curves along with indirect detection (ID) excluded region for $\psi_{3/2}$ DM decay and the current CMS excluded region for MP, we get:

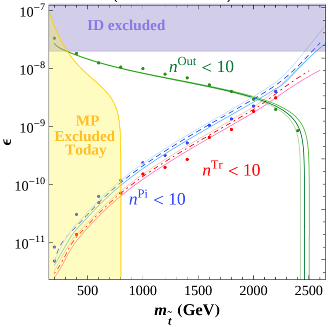
$$\Downarrow$$

$$\boxed{\text{RPV LHC reach in } \epsilon\text{-}m_{\tilde{t}} \text{ plane}}$$

($L = 25\ \mathrm{fb}^{-1}$)



($L = 3000\ \mathrm{fb}^{-1}$)



Comparison RPC-RPV models

Since the displaced vertex analysis is independent from the $\tilde{t}$ decay channel, such an analysis will be identical for the two $\tilde{t}$-decay chains:

$$\tilde{t} \to \ell^+ b \qquad \text{(2 body RPV decay)}$$

$$\tilde{t} \to \psi_{3/2} t \to \psi_{3/2} W^+ b \to \psi_{3/2} b\, \ell^+ \nu_\ell \qquad \text{(4 body RPC decay)}$$

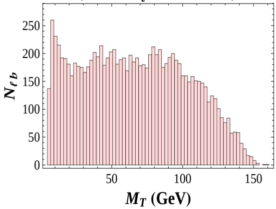
which contain the same visible particles (ℓ^+, b) in the final state... ...are we able to distinguish in some way these two decay chains?

$\Downarrow$

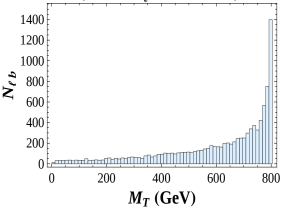
Yes! In fact, being their kinematics different, we can use:

- ℓ^+ transverse mass distribution ($M_{\ell T} = \sqrt{(E_\ell + E_b)^2 - (p_{\ell T} + p_{bT})^2}$)

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



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



Background and coincidence counting

In this talk the background (b.g.) of SM and SUSY particles is neglected. This is a optimistic hypothesis because a background is always present.

Such an hypothesis is supported by the long-lived nature of our stop decay and its kinematics (e.g. t-prompt decay: $t \to W^+ b \to \ell^+ \nu_\ell b$).

Harder is to reduce the sources of background coming from b-decays that occur away from the primary vertex (e.g. $b\bar{b}Z \to b\bar{b}\ell^+\ell^-$)

$$\Downarrow$$

A strategy to eliminate such kind of reducible b.g. is via the coincidence counting (c.c.) of events which is particularly useful for short $\tau_{\tilde{t}}$:

$m_{\tilde{t}} = 800$ GeV & $\tau_{\tilde{t}} = 3.254 \times 10^{-9}$ s

$\tilde{t}$ \ $\tilde{t}^*$	Bp	Pi	Tr	Ib	Out	Tot
Bp	2.84%	5.69%	2.91%	0.97%	0.01%	12.42%
Pi	5.84%	18.15%	12.09%	5.27%	0.06%	41.41%
Tr	3.11%	12.34%	10.25%	4.98%	0.06%	30.74%
Ib	1.13%	5.05%	5.42%	3.66%	0.02%	15.28%
Out	0.02%	0.00%	0.07%	0.05%	0.01%	0.15%
Tot	12.94%	41.23%	30.74%	14.93%	0.16%	100%

Conclusions

The RPV and RPC scenarios with stop NLSP are interesting theoretical possibilities with a consistent cosmology and gravitino DM.

For the NLO long-lived $\tilde{t}$-production at LHC and $\sqrt{s} = 14$TeV, a $m_{\tilde{t}}$-reach of 1600 GeV (2500 GeV) is obtained for $L = 25\,\mathrm{fb}^{-1}$ ($3000\,\mathrm{fb}^{-1}$).

Such a LHC reach can be translated in both $m_{\tilde{t}}$-$m_{3/2}$ (RPC model) and ϵ-$m_{\tilde{t}}$ (RPV model) parameter spaces.

- In RPC $\tilde{t}$-decay with high T_R (10^6–10^7 GeV), only MP are allowed.
- In RPV $\tilde{t}$-decay, the displaced-vertex analysis allows to close the gap between MP and ID bounds at low stop masses.

The final visible particle kinematics allows to distinguish between RPC and RPV stop decays.

Thank you!