Simplified models & benchmarks devoted to searches for displaced top-quarks at the LHC 14 TeV Run

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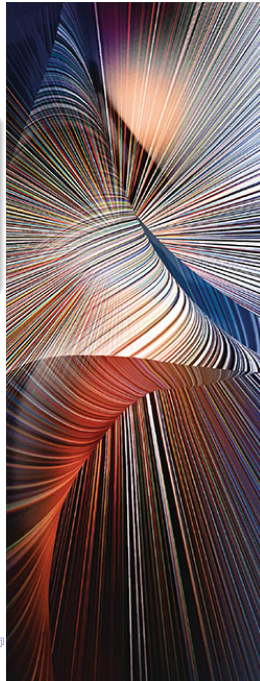


Overview

Introduction

ATLAS & **CMS**:

Search of exotic particles with **long life-times** (decay in the detector volume)
(Difficulties to be observed: detectors are not designed initially for this purpose)

Goal of the project:

Provide simplified models & benchmarks for future searches of **non-prompt top-quarks arising from heavy long-lived particles (LLP)** (3 scenarios)
Identify **observables of interest** for an **offline & online selection**

Why top quarks?

Expertise from CMS Team of IPHC
Investigate CMS & ATLAS algorithms performance to tag/reconstruct those objects
Study the relevance to design a devoted reconstruction/identification algorithm

Our definition of long-lived particle:

Flight distance ct between **4 cm & 100 cm**: "Tracker volume"

Global strategy

Find topologies of events **involving a long-lived mediator** which gives **at least one top quark**

Cross-section of the process must be **independant from the $c\tau$ of the LLP**

Design simplified models corresponding to such topology

Analysing the parameters region & studying:

- cross-section of production at 14 TeV
- average flight-distance of the LLP in the laboratory frame
- relevent geometrical & kinematical observables

Identifying promising benchmarks for each model where the top-quarks decay in the tracker volume

Give some **guidelines for the experimentalists** for online & offline selection

Global strategy

Displaced-tops quarks signatures

Types of mediation studied:

Coloured long-lived particle
(neutral or charged R-hadron)

- R-hadron containing a squark: Simplified model based on **MSSM with GMSB**
- R-hadron containing a gluino: Simplified model based on **MSSM Split-SUSY**

Uncoloured long-lived particle

- Electrically neutral : Simplified model based on **MSSM with RPV**

Events generation & Physical observables definition

Tools for events generation:

- MadGraph_aMC@LNO with PDF *NNPDF30_lo_as_0130* (LHAPDF lhaid=263000)
- Pythia (MCTunes CUETP8M2T4)
- MadAnalysis tunable detector fast-simulation + some improvements
  - FastJet (anti-k_t algorithm, $\Delta R = 0.4$, $p_{T_{min}} = 5$ GeV)
- MadAnalysis in expert mode
  - magnetic field $B = 3.8$ T (CMS value, ATLAS=3.0 T)
  - fiducial acceptance of the tracker
    - cylinder with end-caps (no blind-spot)
  - infinite resolution for observables

Events generation & Physical observables definition

Definition of observables used for these analyses (online/offline selection):

Global observables:

$$\mathrm{MET} = ||\sum_{\text{visible}} \vec{p}_T||, \quad \mathrm{MHT} = ||\sum_{\text{hadronic}} \vec{p}_T||, \quad \mathrm{TET} = \sum_{\text{visible}} ||\vec{p}_T||, \quad \mathrm{THT} = \sum_{\text{hadronic}} ||\vec{p}_T||, \quad \alpha_T = \frac{p_{T_2}}{m_{jj}}$$

If the LLP decays beyond the tracker, it is considered as invisible:

- neutral uncoloured LLP do not interact with calorimeter matter
- energy deposit of R-hadron in the calorimeter is negligeable
- no interaction between R-hadron and matter: "charge sign change" or 'stopped LLP" are not taken into account

Other observables:

$$d_0 = \mathrm{sgn}\left(\frac{p_T}{q\mathbf{B}}\right)\left(\sqrt{x^2+y^2} - \left|\frac{p_T}{q\mathbf{B}}\right|\right)$$

$$d_z = \mathbf{z_v} + \frac{p_z}{q\mathbf{B}} \arctan\left(\frac{xp_x + yp_y}{yp_x - xp_y}\right)$$

with $\begin{cases} x = \mathbf{x_v} + \frac{p_y}{q\mathbf{B}} \\ y = \mathbf{y_v} - \frac{p_x}{q\mathbf{B}} \end{cases}$, $p_{T\ell}$, p_{Tj}, η_ℓ, η_j

with $\mathbf{B} = 3.8$ T & $(\mathbf{x_v}, \mathbf{y_v}, \mathbf{z_v})$: secondary vertex position

Mediation by a coloured long-lived particle (R-hadron based on a squark)

Model definition

Theoretical foundation

In the context of the **MSSM** with **R-parity conserved**: NLSP $\tilde{t} \to \psi_\mu t$

GMSB (Gauge Mediated Supersymmetry Breaking) : **gravitino is the LSP with a mass**

$$m_{3/2} \propto \frac{F}{m_p} \quad (F\text{: energy scale of messenger fields})$$

$$\mathcal{L} = \mathcal{L}_{\text{MSSM}} + \mathcal{L}^{kin.}_{3/2} + \mathcal{L}^{int.}_{3/2} \quad \text{with:} \quad \mathcal{L}^{int}_{3/2} = -\frac{\sqrt{4\pi}}{\sqrt{m_p}}\left(\mathcal{D}_\nu \phi^i \bar{\chi}_{Li} \gamma^\mu \gamma^\nu \Psi^{(M)}_\mu + \mathcal{D}_\nu \phi^\dagger_i \bar{\Psi}^{(M)}_\nu \gamma^\nu \gamma^\mu \chi^i_R\right)$$

with $\Psi^{(M)}_\mu$ the gravitino

Simplified model definition

- First & second sfermion generations not considered
- stop $\tilde{t}$ = Equal mixing between left & right stop
- Lightest stop $\tilde{t}$ is the NLSP **BR($\tilde{t} \to \psi_\mu t$) = 1**

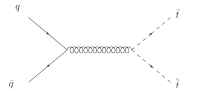
Parameters:

- $m_{\tilde{t}}$
- $ct(\tilde{t})$ or $m_{3/2}$

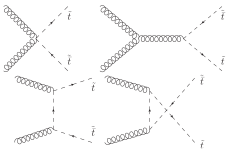
Mediation by a coloured long-lived particle (R-hadron based on a squark)

Production & decay

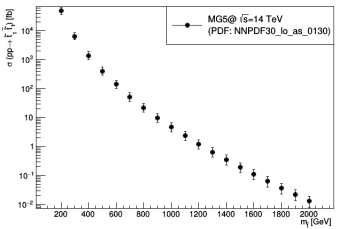
LO QCD production at LHC
Only one parameter: $\mathbf{m_{\tilde{t}}}$

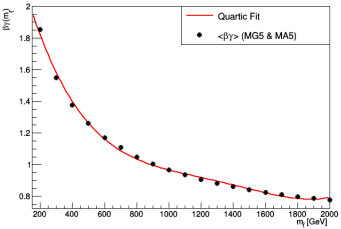


Quark anihilation



Gluon fusion





Values for $\mathbf{m_{\tilde{t}}}$:

- Assuming a hundred of events at $\mathcal{L}_{int.} = 300$ fb^{-1}
  - $\Rightarrow \mathbf{m_{\tilde{t}}^{max}} \approx 1.4$ TeV
- $\mathbf{m_{\tilde{t}}^{min}} \approx 1$ TeV

$\langle\beta\gamma\rangle(\mathbf{m_{\tilde{t}}}) \approx \mathbf{0.9 - 1}$: No large impact on the flight distance of $\tilde{t}$

Mediation by a coloured long-lived particle (R-hadron based on a squark)

Production & decay

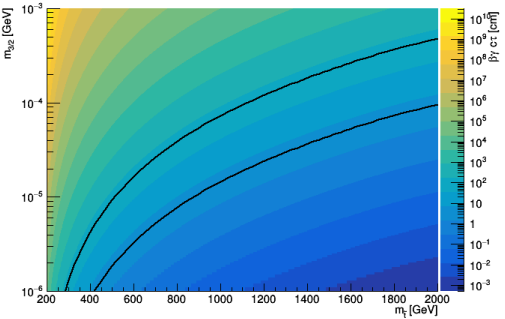
Decay width:

$$\Gamma(\tilde{t} \to \psi_\mu t) = \frac{1}{6 m_p^2 m_{\tilde{t}}^3 m_{3/2}^2} \lambda^{3/2}(m_{\tilde{t}}^2, m_t^2, m_{3/2}^2) \times (m_{\tilde{t}_1}^2 - (m_t - m_{3/2})^2)$$

with $\lambda(x, y, z) = (x - y - z)^2 - 4yz$.

Stop $\tilde{t}$ average flight distance:

$$c t = \langle \beta\gamma \rangle c\tau = \frac{\langle \beta\gamma \rangle \hbar c}{\Gamma(\tilde{t} \to \psi_\mu t)}$$



The black lines delimitate the "Tracker volume" [4 cm, 100 cm]

Definition of eight benchmarks:

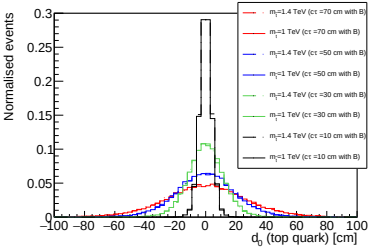
Name	$\tilde{t}_{1.0}^{10}$	$\tilde{t}_{1.0}^{30}$	$\tilde{t}_{1.0}^{50}$	$\tilde{t}_{1.0}^{70}$	$\tilde{t}_{1.4}^{10}$	$\tilde{t}_{1.4}^{30}$	$\tilde{t}_{1.4}^{50}$	$\tilde{t}_{1.4}^{70}$
$m_{\tilde{t}}$[TeV]	1.0	1.0	1.0	1.0	1.4	1.4	1.4	1.4
ct[cm]	10	30	50	70	10	30	50	70

$\mathbf{m_{3/2} \approx 10 - 100}$ keV

Mediation by a coloured long-lived particle (R-hadron based on a squark)

Results

Relevant distributions:

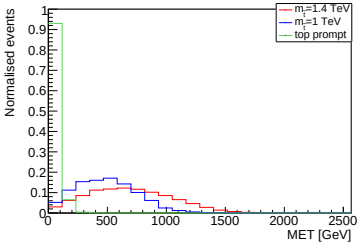


- **Equivalent distributions** for all particles & for d_z
- Same for $m_{\tilde{t}} = 1.0$ TeV & 1.4 TeV

Light gravitino ($m_{3/2} \sim$ keV): Many benchmarks leads to equivalent distributions

$\Rightarrow$ **Reduce to two distributions**

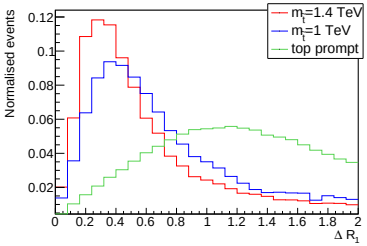
- Highly energetic events
- Main contribution from the gravitino (neutrinos negligible)



Mediation by a coloured long-lived particle (R-hadron based on a squark)

Results

Relevant distributions:



Energetic events: **boosted topologies?**

(Requiring to study the jet substructure?)

Check the indicator $\Delta R(bW)$

A lot of events with $\Delta R < 0.4$

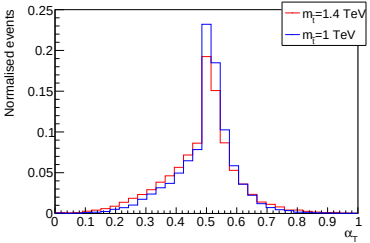
$$\alpha_T = p_{T_2}/m_{jj}$$

(p_{T_2}) transverse impulsion of the second hardest jet

(m_{jj}) invariant mass of the two hardest jets

Background (SM) events with $\alpha_T < 0.5$

α_T: Dependency on the jet reconstruction!



Mediation by a coloured long-lived particle (R-hadron based on a squark)

Results

Summary table: Geometrical quantities

	$\tilde{t}^{10}_{1.0}$	$\tilde{t}^{30}_{1.0}$	$\tilde{t}^{50}_{1.0}$	$\tilde{t}^{70}_{1.0}$	$\tilde{t}^{10}_{1.4}$	$\tilde{t}^{30}_{1.4}$	$\tilde{t}^{50}_{1.4}$	$\tilde{t}^{70}_{1.4}$
% events with exactly two tops decaying in the "Tracker Volume"	58.8	92.7	96.7	95.1	60.6	93.1	97.1	96.7
% events with at least one top decaying in the "Tracker Volume"	69.9	97.6	99.0	97.2	70.0	97.1	99.1	98.3
$\langle MET \rangle$ [GeV]	506.4	507.4	508.4	507.8	704.2	707.9	712.9	695.5
$\langle TET \rangle$ [GeV]	1202.2	1202.0	1201.4	1202.0	1524.0	1522.8	1525.0	1568.6
$\langle THT \rangle$ [GeV]	1117.8	1117.0	1118.2	1117.0	1410.9	1411.4	1412.2	1416.7
$\langle MHT \rangle$ [GeV]	488.9	489.6	490.9	489.5	676.2	676.7	682.8	680.4
$\langle p_T(j_1) \rangle$ [GeV]	579.2	581.6	583.0	580.3	784.8	785.0	787.1	786.1
$\langle p_T(\ell) \rangle$ [GeV]	130.6	133.5	134.5	132.3	174.5	176.9	176.2	176.7
$\langle \lvert d_0 \rvert \rangle$ [cm]	3.1	9.4	15.6	21.6	3.1	9.2	15.4	21.4
$\langle \lvert d_z \rvert \rangle$ [cm]	6.8	18.9	28.3	34.4	6.0	16.7	25.8	32.4

("Tracker Volume": distance in the transverse plane between 4 cm & 100 cm)

Mediation by a coloured long-lived particle (R-hadron based on a squark)

Results

Summary table: Global Observables

	$\tilde{t}^{10}_{1.0}$	$\tilde{t}^{30}_{1.0}$	$\tilde{t}^{50}_{1.0}$	$\tilde{t}^{70}_{1.0}$	$\tilde{t}^{10}_{1.4}$	$\tilde{t}^{30}_{1.4}$	$\tilde{t}^{50}_{1.4}$	$\tilde{t}^{70}_{1.4}$
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Mediation by a coloured long-lived particle (R-hadron based on a squark)

Results

Summary table: Transverse impulsion

	$\tilde{t}^{10}_{1.0}$	$\tilde{t}^{30}_{1.0}$	$\tilde{t}^{50}_{1.0}$	$\tilde{t}^{70}_{1.0}$	$\tilde{t}^{10}_{1.4}$	$\tilde{t}^{30}_{1.4}$	$\tilde{t}^{50}_{1.4}$	$\tilde{t}^{70}_{1.4}$
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Mediation by a coloured long-lived particle (R-hadron based on a squark)

Results

Summary table: Impact parameters

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Mediation by a coloured long-lived particle (R-hadron based on a squark)

Discussion

Associated background

If "short-lived":

Background equivalent to stop pair search:

- $t\bar{t}$, DY with MET, tW, $\cdots$

If "long-lived":

- cosmic rays
- algorithmic
- detector (nuclear interactions)

Guidelines for experimentalists

Possible trigger path for Long-lived (Run 2):

- All top decay channels: **MET** $>$ **170** GeV
- Few displacement: (Leptonic top decay channel) muon with $\mathbf{p_T} > \mathbf{50}$ GeV or isolated leptons with $\mathbf{p_T} > \mathbf{23}, \mathbf{17}$ GeV
- Specific long-lived trigger

Offline selection

- Search at least 1 displaced top (displaced jets, leptons, vertices)
- Boosted top: jets substructure analysis
- Cut on α_T ($\alpha_T > 0.5$)
- If R-hadron & long-lived enough: track

Mediation by an electrically neutral and uncoloured long-lived particle

Model definition

Theoretical foundation

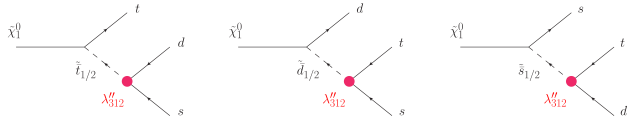
Based on **MSSM** with **R-Parity Violation**: LSP χ_1^0

$$W = W_{MSSM} + W_{RPV} \text{ with}$$

$$W_{RPV} = \epsilon_i (H_u \cdot L_i) + \frac{1}{2}\lambda_{ijk} (L_i \cdot L_j) E_k^c + \lambda'_{ijk} (L_i \cdot Q_j) D_k^c + \frac{1}{2}\lambda''_{ijk} U_i^c D_f^c D_k^c$$

Baryonic & leptonic number violation from λ, λ', λ'' (+ sym. properties $\lambda_{ijk} = -\lambda_{jik}$ & $\lambda''_{ijk} = -\lambda''_{jik}$)

Only λ'_{i3k}, λ''_{312}, λ''_{313}, λ''_{323} allow top quark in the final state $\Rightarrow$ **Only consider** $\lambda''_{312} \neq 0$: $\chi_1^0 \to tds$



Simplified model definition

- Equal mixing between gaugino & higgsino states
- No mixing of different generations & Equal mixing left & right squark
- All squarks have the same mass

Parameters:

- $m_{\chi_1^0}$ & $m_{\tilde{\mu}}$ & $m_{\tilde{q}}$

Mediation by an electrically neutral and uncoloured long-lived particle

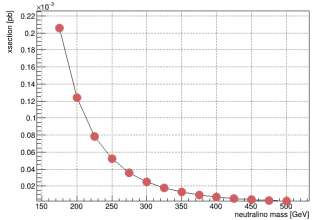
Production & decay

Two hard processes considered for production:

Direct neutralino production
$(pp \to \chi_1^0\chi_1^0)$

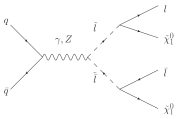
Dependancy of σ:

- $m_{\chi_1^0}$



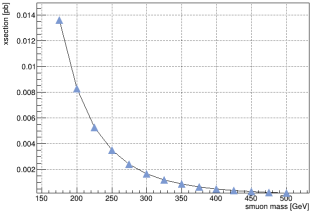
NLSP smuon production $(pp \to \tilde{\mu}^+\tilde{\mu}^-)$

Smuon decay: $\tilde{\mu}^\pm \to \chi_1^0\mu^\pm$ with $BR(\tilde{\mu}^\pm \to \chi_1^0\mu^\pm) = 1$



Dependancy of σ:

- Smuon mass $m_{\tilde{\mu}}$

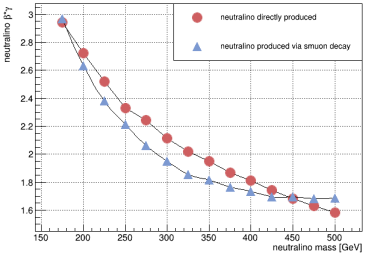


Mediation by an electrically neutral and uncoloured long-lived particle

Production & decay

Flight distance $ct \propto 1/(\lambda'')^2$

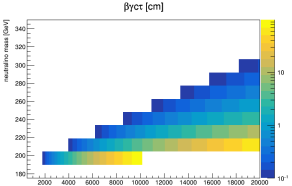
$m_{\tilde{\mu}}^{max.} = 500$ GeV for sufficient data signal



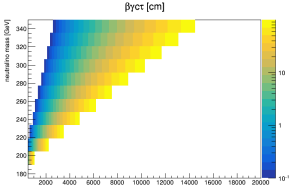
Lorentz factor $\langle\beta\gamma\rangle \approx 1.6 - 3$

Numerical computation of $ct = \langle\beta\gamma\rangle c\tau$

Wide region allowed depending on the λ''-value



$\lambda'' = 10^{-1}$



$\lambda'' = 10^{-3}$

Benchmarks definition:

Name	$\tilde{\mu}^{10}$	$\tilde{\mu}^{30}$	$\tilde{\mu}^{50}$	$\tilde{\mu}^{70}$
$m_{\tilde{q}}$[TeV]	7.2	10.3	2.35	3.7
$m_{\chi_1^0}$[GeV]	200	250	225	200
$m_{\tilde{\mu}}$[GeV]	250	300	275	250
ct[cm]	10	30	50	70

Long-lived gluinos produced in Split SUSY models

Model definition

Theoretical foundation

Split-SUSY: based on the paradigm that the naturalness problem is ignored (anthropic principle)

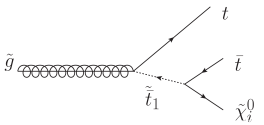
Squark & **slepton** masses can be as large as the GUT scale M_{GUT}
Fermions ($\{\chi_i^0, \chi_j^\pm\}$) remain near the EW scale

If neutralino χ_1^0 LSP & gluino $\tilde{g}$ NLSP:

Long-lived process (LO) $\tilde{g} \to \bar{\tilde{t}}_1 t \to t\bar{t}\chi_1^0$ due to heavy-massive mediator

Simplified model definition

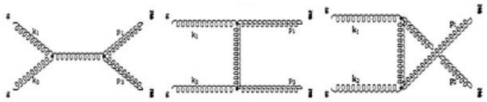
- Equal mixing between left & right stops
- χ_1^0: Only the gauge states
- $BR(\tilde{g} \to \tilde{t}\bar{t}) = 1$

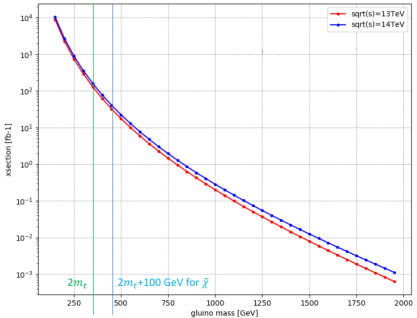


Long-lived gluinos produced in Split SUSY models

Production & decay

Production LO QCD: gluino pair production
(other contribution including $\tilde{q}$ negligeable)





Benchmarks definition

Name	$\tilde{g}^{10}_{1.0,0.4}$	$\tilde{g}^{30}_{1.0,0.4}$	$\tilde{g}^{50}_{1.0,0.4}$	$\tilde{g}^{70}_{1.0,0.4}$
$m_{\tilde{g}}$[TeV]	1.0	1.0	1.0	1.0
$m_{\chi^0_1}$[TeV]	0.4	0.4	0.4	0.4
$c\tau$[cm]	10	30	50	70

Name	$\tilde{g}^{10}_{1.0,0.1}$	$\tilde{g}^{30,0}_{1.0,0.1}$	$\tilde{g}^{50}_{1.0,0.1}$	$\tilde{g}^{70}_{1.0,0.1}$
$m_{\tilde{g}}$[TeV]	1.0	1.0	1.0	1.0
$m_{\chi^0_1}$[TeV]	0.1	0.1	0.1	0.1
$c\tau$[cm]	10	30	50	70

Conclusion & Outlook

Summary:

Goal: models & benchmarks devoted to searches for displaced top-quarks using charged particles (decay in tracker volume)

Mediation by different type of LLP: R-hadrons (squark or gluino) & uncoloured neutral particle (neutralino)

For each model, some benchmarks have been defined and can be used by ATLAS/CMS collaboration

Guidelines for offline & online selection

Perspective:

A paper in preparation

Work for gluino-based R-hadron & uncoloured LLP must be finalized

Why not electrically charged and uncoloured LLP?

Begin to investigate specific LLP signature like displaced vertex with Delphes

THANK YOU FOR YOUR ATTENTION