Sensitivity of a Prompt CMS Analysis to Long-Lived Models
Overview

The SUSY AlphaT 2016 analysis

Adapting standard simplified models to include LLPs

Results and Sensitivity discussions
The AlphaT analysis

- **Jets + MET search:**
  - Inclusive search over all-hadronic final state
  - Uses $\alpha_T$ (AlphaT) and $\Delta\phi_{\text{min}}^*$ (biased-delta phi) variables to reduce QCD background to negligible levels
  - Fitting over 253 signal bins based on: $H_T$, $H_T^{\text{miss}}$, number of jets, and number of b-tagged jets
  - Additional simplified binning scheme with only 32 bins

- **No specific treatment for long-lived particles**
  - No dedicated reconstruction or object tagging
  - Selections optimised on prompt signals and not changed

- **Access to paper and supplementary material:**
  - Accepted for JHEP to be published very soon
The AlphaT analysis: Selections

<table>
<thead>
<tr>
<th>Physics object acceptances</th>
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<tbody>
<tr>
<td>Jet</td>
</tr>
<tr>
<td>Photon</td>
</tr>
<tr>
<td>Electron</td>
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<tr>
<td>Muon</td>
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<tr>
<td>Single isolated track (SIT)</td>
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<table>
<thead>
<tr>
<th>Baseline event selection</th>
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<tbody>
<tr>
<td>All-jet final state</td>
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<tr>
<td>$p_T^{miss}$ quality</td>
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<tr>
<td>Jet quality</td>
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<tr>
<td>Jet energy and sums</td>
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<tr>
<td>Jets outside acceptance</td>
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<table>
<thead>
<tr>
<th>Signal region</th>
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<tbody>
<tr>
<td>Baseline selection +</td>
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<tr>
<td>$\alpha_T$ threshold ($H_T$ range)</td>
</tr>
<tr>
<td>$\Delta \phi_{\text{min}}^{*}$ threshold</td>
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</tbody>
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- Data-driven background estimations by fitting to sideband and control regions
Results

- **Simplified binning scheme**
- **Predictions for signal region, having fit to control regions**
The T1qqqq model

- Gluino pair production
- Decay gluinos via intermediate, highly virtual squarks
- Final state: four light-flavour quarks, two LSPs
- Gluino production in MadGraph LO, decay using Pythia
Vanilla T1qqqq

- Exclude up to \( M_{\text{gluino}} = 1650 \text{ GeV} \)
- \( M_{\text{LSP}} = 900 \text{ GeV} \)
- Sensitivity driven by high-\( N_{\text{jet}} \), low-\( N_{b\text{-jet}} \) bins

CMS Supplementary 35.9 fb\(^{-1}\) (13 TeV)

Observed ± 1 \( \sigma_{\text{theory}} \)

Expected ± 1 and 2 \( \sigma_{\text{experiment}} \)
**T1qqqqLL: Long-lived gluinos**

- **Take T1qqqq**
  - Immediate long-lived extensions
  - Already has very off-shell squarks
    - $\rightarrow$ decrease gluino width
    - $\rightarrow$ gluino becomes long-lived
    - $\rightarrow$ Split SUSY
  - Implement by adjusting gluino lifetime in Pythia
  - $c\tau_0$: gluino rest-frame lifetime in metres

- **T1qqqqLL**: $c\tau_0$ values from $1 \mu$m to 100 m and "meta-stable" gluinos

- **Use CMS FullSim for T1qqqqLL, compared to FastSim for T1qqqq**

- **R-hadronisation model:**
  - Long-lived gluinos can form meta-stable, bound states with SM contents
  - Particularly important for larger values of $c$-tau
  - Material affects of detector R-hadron interactions could become important
Cross section limits

Best limits achieved when $C\tau_0 = 1 \text{ mm}$
Cross section limits
Up to 100 microns:
Limits as prompt models

CMS

$35.9 \text{ fb}^{-1}$ (13 TeV)

$pp \rightarrow \tilde{g} \tilde{g}, \tilde{g} \rightarrow q \bar{q} \tilde{\chi}_1^0$ NLO+NLL exclusion

c$_{\tilde{t}} = 1 \mu$m

- Observed $\pm 1 \sigma_{\text{theory}}$
- Expected $\pm 1$ and $2 \sigma_{\text{experiment}}$

95% CL upper limit on cross section [pb]
Cross section limits

Around 1 mm

Gluino events become b-tagged
T1qqqqqLL: Signal vs Background

- $\mathcal{CT}_0 = 1$ mm
- $M_{\text{gluino}} = 1800$ GeV
- $M_{\text{LSP}} = 200$ GeV
- Bottom right of observed limit contour
Cross section limits

At 1 m, decaying outside tracker:

- Charged-hadron fraction cut reduces acceptance
Cross section limits

Metastable gluinos
- Depend on ISR jets
- No sensitivity to LSP mass

CMS Supplementary 35.9 fb⁻¹ (13 TeV)

pp → ĝ ĝ  NLO+NLL exclusion

Metastable ĝ

Observed ± 1 σ_{theory}

Expected ± 1 and 2 σ_{experiment}

95% CL upper limit on cross section [pb]
Key sensitivity effects

- **B-tagging rate**
  - Improve sensitivity around b-decay length (~1 mm)

- **Charged hadron fraction of leading jet**
  - Reduces sensitivity once decays outside of the tracker

- **Reliance on ISR as $\cT_0$ becomes large**
  - Gluino escapes undetected
Limit contours for all considered values of $cT_0$
Limits vs $\mathcal{C}\tau_0$

$\tilde{g} \to q\bar{q}\chi^0$

(R-hadron cloud model)

$\tilde{g} \to q\bar{q}\chi^0$

(Jets + $p_T^{\text{miss}}$, arXiv:1802.02110)

- $m_{\chi^0} = 100$ GeV
- $m_{\tilde{g}} - m_{\chi^0} = 100$ GeV

*Limit on gluino mass assuming theoretical cross section for different $\mathcal{C}\tau_0$ values*
Comparing to other results

- **CMS: EXO-16-004**
  - Submitted to JHEP in December
  - A dedicated search for out-of-time calorimeter jets
  - T1qqqqLL where gluinos stop in the calorimeter, then decay out-of-time with collisions

- **HSCP, CMS-PAS-EXO-16-036**
  - dE/dX measurement for hadronised gluinos
  - Complementary sensitivity between methods
    - Prompt AlphaT analysis does well for smaller lifetimes
    - EXO-16-004 and HSCP perform better for much larger lifetimes

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**CMS Preliminary**

13–39 fb$^{-1}$ (13 TeV)

- $\tilde{g} \rightarrow q\bar{q}\chi^0$ (BR=100%)
  - (R-hadron cloud model)
  - Status: February 2018
  - Jets + $p_T^{\text{miss}}$, arXiv:1802.02110
  - $m_{\chi^0} = 100$ GeV, charge suppressed
  - Jets + $p_T^{\text{miss}}$, arXiv:1802.02110
  - $m_{\tilde{g}} - m_{\chi^0} = 100$ GeV, charge suppressed
  - Stopped gluino, arXiv:1801.00359
  - $m_{\tilde{g}} - m_{\chi^0} > 160$ GeV, $f_{\tilde{g}} = 0.1$
  - HSCP, CMS-PAS-EXO-16-036
  - $f_{\tilde{g}} = 0.1$

- Lower limit (95% CL) on $m_{\tilde{g}}$ [GeV] vs. $c\tau$ [m] vs. $\tau$ [ns]
Summary

- First look at extending standard prompt inclusive search to simplified SUSY models to a LLP regime

- Limits from the AlphaT prompt search:
  - Best observed (expected) limits, $C_{T_0} = 1$ mm: $M_{\text{gluino}} = 1750$ (1950) GeV, $M_{\text{LSP}} = 1050$ (1200) GeV

- Sensitivity to full range of $C_{T_0}$ values (prompt to meta-stable)
  - Weak dependence on R-hadronisation model
  - Possible due inclusive nature of search and low selection thresholds

- More on this at the LLP workshop later in the week
  - CMS Material for Reinterpretation ([Juliette Alimena](https://arxiv.org/abs/1802.02110))

- Links to paper and material
Advert: Additional Material

Since this is a reinterprations conference, available online material:

- Covariance matrix (full and simplified binning)
- Bin contents for data and SM background predictions as csv files (full and simplified binning)
- Digital limit and signal acceptance x efficiency mass planes for 7 standard SMS models and T1qqqqLL with 6 $cT_0$ values
- Bin contents for signal from four benchmark models
- Cut flows for four benchmark models

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Table 2: A summary of the cumulative signal acceptance times efficiency, $Ae$ [%], for various benchmark models found in Table 4 of the paper, following the successive application of the event selection criteria used to define the signal region. See discussion and Table 1 in the paper for detailed descriptions of the selection.

<table>
<thead>
<tr>
<th>Event Selection</th>
<th>Benchmark Model</th>
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<tbody>
<tr>
<td>$m_{SUSY}$ (GeV)</td>
<td>T2bb T2cc T1bb66 T1qqqqLL</td>
</tr>
<tr>
<td>$m_{A^0}$ (GeV)</td>
<td>550 500 1900 1800</td>
</tr>
<tr>
<td>$cT_0$ (mm)</td>
<td>200 200 200 1</td>
</tr>
</tbody>
</table>

Before selection  
100.0 100.0 100.0 100.0

Single isolated track, muon, electron, & photon veto:  
94.6 97.2 99.4 86.0

Event veto for jets failing ID:  
94.3 96.8 98.7 85.7

$\rho^2 > 100$ GeV:  
62.9 84.3 98.7 85.7

$0.1 < \rho^2 < 0.95$:  
59.8 77.4 93.9 82.1

$H_T > 200$ GeV:  
49.5 64.5 93.9 82.1

$H_T^{miss} > 200$ GeV:  
18.8 48.3 88.5 77.4

Event veto for forward jets ($\eta > 2.4$):  
13.6 35.8 69.9 63.7

$H_T^{miss}/E_T^{miss} < 1.25$:  
12.9 34.1 69.3 60.3

$\Delta R_{min} > 0.5$:  
8.3 24.9 69.2 60.1

$\Delta R_{min} > 0.5$:  
5.7 20.5 25.1 22.9

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Back-ups
**AlphaT**

\[ \alpha_T = \frac{E_{j2}^T}{M_T} \]

- **In dijet events:**
  - AlphaT is the ratio between the sub-leading jet’s transverse energy and the dijet mass
  - With no Etmiss in event, cannot exceed 0.5 even with jet energy mis-measurements
  - Robust to detector effects on jet energy resolutions

- **Generalising to multi-jet events**
  - Cluster all jets into two large pseudo-jets such that difference in scalar ET sums for each pseudo-jet is minimised
Biased delta-phi

- Minimum for all jets of the angle between the jet and the vector sum of all others
- Peaks close to zero for mismeasured multi-jet events
- Can reach up to 180°

\[
\Delta \phi_{\text{min}}^* = \min_i \left( \Delta \phi \left( \vec{p}_T^i, \sum_{j \neq i} \vec{p}_T^j \right) \right)
\]
Full binning results (1)
Full binning results (2)
Full binning results (1)
## Cut flow

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</tr>
<tr>
<td>550</td>
<td>500</td>
</tr>
<tr>
<td>$m_{\text{LSP}}$ (GeV)</td>
<td>450</td>
</tr>
<tr>
<td>$c\tau_0$ (mm)</td>
<td>–</td>
</tr>
<tr>
<td><strong>Before selection</strong></td>
<td>100.0</td>
</tr>
<tr>
<td>Single isolated track, muon, electron, &amp; photon vetos</td>
<td>94.6</td>
</tr>
<tr>
<td>Event veto for jets failing ID</td>
<td>94.3</td>
</tr>
<tr>
<td>$p_T^{j_1} &gt; 100$ GeV</td>
<td>62.9</td>
</tr>
<tr>
<td>$0.1 &lt; f_{j_1}^{j_1} &lt; 0.95$</td>
<td>59.8</td>
</tr>
<tr>
<td>$H_T &gt; 200$ GeV</td>
<td>49.5</td>
</tr>
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<td>\eta</td>
</tr>
<tr>
<td>$H_T^{\text{miss}} / E_T^{\text{miss}} &lt; 1.25$</td>
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<tr>
<td>$n_{\text{jet-}}$ and $H_T$-dependent $\alpha_T$ thresholds</td>
<td>8.3</td>
</tr>
<tr>
<td>$\Delta \phi^*_\text{min} &gt; 0.5$</td>
<td>5.7</td>
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Signal acceptance x efficiency

In general, flat for all model points until about $10^{-2}$ m, start to decay outside of the tracker

*Depends on mass values*