Long-lived particle searches by ATLAS and CMS

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on behalf of the ATLAS and CMS collaborations
**Theoretical motivations:**
- No new physics beyond Standard Model (SM) observed looking for promptly decaying new particles
- Several scenarios predict new long-lived particle (LLP) production: R-parity violating supersymmetry, split SUSY, anomaly mediated supersymmetry breaking model or also hidden valley models
- A wider parameter space of physics beyond the Standard Model could be probed

**New experimental signatures:**
- Long lifetimes: starting from picoseconds ... up to days or even more
- Anomalous loss of energy \((dE/dx)\)
- Time of flight in the muon system
- (...)
Displaced vertices

- Predicted in many BSM scenarios
- In the case of RPV SUSY, long-lived particles will be neutralinos, gluinos (l) or top squarks (r)

![Diagrams showing displaced vertices and multijet signals with CMS data]

- Experimental signature: two displaced vertices shifted from beam axis (SM background: single vertex and near beam axis)
- $d_{vv}$: distance between vertices in the orthogonal plane to the beam axis for simulated multijet signals
Displaced vertices

Observed 95% CL upper limits on $\sigma \beta^2$ for the multijet signal as a function of mass and mean proper decay length

- Background template is constructed using control sample
- Systematics uncertainties mainly coming from vertex reconstruction (in overall 24% on signal efficiency)

Observed and expected 95% CL upper limits on $\sigma \beta^2$ for a fixed $c \tau$ value of 1.0 mm, for multijet signal

- $\sigma \beta^2 \sim 0.3$ fb excluded for masses between 800 and 2600 GeV and mean proper decay lengths between 1 and 40 mm

Similar analysis performed in ATLAS: *Phys. Rev. D 97 (2018) 052012*
Displaced leptons

- Search for displaced leptons in CMS (CMS-PAS-EXO-16-022):
  - A search for displaced leptons in the e-mu channel was performed in CMS using first 13 TeV data
  - The typical signature results in a transverse impact parameter in the range 100 µm up to 10 cm
  - For instance in displaced SUSY model, including R-parity violating terms, gives an LSP that can decay into SM particles: pair of top squarks production

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  \end{align*} \]

\[ \begin{align*}
  \text{Dedicated trigger to target displaced e-µ pairs} \\
  \text{For a lifetime hypothesis of 2cm/c, top squarks excluded up to 870 GeV} \\
  \end{align*} \]
Displaced leptons

- Search for displaced muon vertices in ATLAS (arXiv:1808.03057):
  - The ATLAS muon spectrometer allows the search for muon displaced vertices in a large volume, few cm up to few m from the interacting point, corresponding to LLP masses between 20 GeV and 1100 GeV.
  - Several BSM scenarios can produce such displaced muon vertices, general gauge-mediated supersymmetry (left) as well as dark-sector gauge boson model (weakly interacting with SM matter via coupling to the Higgs field, right):

Background contributions (cosmic muons, fake muons or pion/kaon decays) estimated using control regions and inverting some cuts in the offline analysis.
Displaced leptons

- Exclusion region in the plane $\epsilon$ (kinetic mixing parameter) versus $Z_D$ mass, with different assumptions of the BR($H \to Z_D Z_D$)
- Values of $\epsilon$ of the order $10^{-8}$ excluded for $Z_D$ masses in the range 20 GeV to 60 GeV

- Upper cross-section limit (long-lived particle mass = 1000 GeV)
Disappearing tracks

- Disappearing tracks as a signature of new long-lived particles in ATLAS (JHEP 06 (2018) 022):
  - For instance anomaly-mediated supersymmetry breaking (AMSB) scenarios predict a chargino life-time around 1 ns
  - The long-lived chargino decays into a pion (low momentum, not reconstructed) and the lightest supersymmetric particle (LSP), one neutralino:

- Electroweak (left) or strong production (right):

- Experimental signature: pixel track ("tracklet") without associated hits in the rest of the silicon tracker (= disappearing track), large missing transverse momentum and also high energetic jets
Disappearing tracks

- 95% CL electroweak channel exclusion limits in the plane chargino lifetime and mass, using 2015 and 2016 data
  
  \[ B(\tilde{g} \rightarrow q\tilde{\chi}^\pm_1) = 67\%, \quad B(\tilde{t} \rightarrow q\tilde{\chi}^0_1) = 33\% \]

- 95% CL exclusion limit in the strong channel in the plane chargino-gluino masses, using chargino lifetime assumption of 1 ns and a compressed spectra hypothesis (mass difference lower than 200 GeV)

\[ \tan\beta = 5, \quad \mu > 0 \]

Similar analysis performed in CMS: **JHEP 08 (2018) 016**
Stopped LLP

• Decays of stopped exotic long-lived particles in CMS ([JHEP 05 (2018) 127]):
  • A search for heavy exotic LLP was performed, looking for lifetimes between 100 ns up to 10 days
  • Nuclear interactions and/or ionisation can stop completely heavy LLP
  • out-of-collision time used to discriminate these decays, using dedicated trigger to select events away by more than 50 ns from the pp collisions
  • Experimental signature: large energy deposit in calorimeters or displaced muon tracks

![Graph of CMS data]

• Specific cosmic runs with these dedicated triggers were taken several days after the beams stopped to get a control sample
• Main backgrounds are the cosmic muons, beam halo and hadronic calorimeter noise
• Split SUSY model: two candidates as LLP (gluino and/or top squarks) and BSM scenarios predict some doubly-charged LLP, that could decay into a pair of same-sign muons
- Calorimeter search results: lifetimes between 10 µs and 1000 s excluded for $m_{\tilde{g}} < 1385$ GeV and $m_{\tilde{t}} < 744$ GeV

- Muon pairs search results: gluino mass excluded between 400 and 980 GeV for $c\tau$ in the range 10 µs and 1000 s

• Search for heavy stable charged particles in ATLAS (arXiv:1808.04095):
• Several SUSY models (split SUSY, AMSB) predict the production of R-hadrons, composite colourless states of a gluino together with SM quarks or gluon
• Heavy charged long-lived particles are supposed to travel well below c, giving higher ionisation than SM particles

- Pixel detector is used to measure the ionisation energy loss of charged particles (dE/dx)
- For metastable R-hadrons, large transverse missing momentum from neutralinos, while stable R-hadrons will not decay inside the detector
Heavy charged LLP

- Gluino masses excluded up to 1809 GeV for stable LLP

- Observed 95% CL limits on gluinos masses and lifetimes, using 8 TeV data (blue), first 13 TeV data (pink) and finally full 2015/2016 datasets (red)

- Sensitivity for shorter than 1ns lifetimes falls sharply and will be complemented by displaced vertices/disappearing tracks searches
Heavy charged LLP

- Both tracker and muon system combined in CMS search for HSCP
- dE/dx from silicon tracker:

• New mass limits for long-lived gluinos, top squarks, tau sleptons and multiply charged LLP derived, improving Run 1 of LHC limits
• R-hadron like HSCP limits given for several gluino-gluon hadronization fractions and two different interaction models
• Gluino mass limit up to 1610 GeV
Reinterpretation

• Reinterpretation of (prompt decay) SUSY searches in ATLAS ([ATLAS-CONF-2018-003]):
  • A set of nine ATLAS SUSY searches were reinterpreted in the context of long-lived particle searches
  • RPV coupling strength could be varied: LSP could be stable/long-lived particle

95% CL exclusion limits of R-hadron lifetimes vs. gluino mass (region under curves is excluded)

Escaping the detector
### ATLAS Long-lived Particle Searches* - 95% CL Exclusion

**Status:** July 2018

<table>
<thead>
<tr>
<th>Model</th>
<th>Signature</th>
<th>ATLAS Preliminary ( \mathcal{L} , dt = (3.2 - 36.1) \text{ fb}^{-1} )</th>
<th>Lifelong limit ( \Delta R )</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPV ( X_1 \to \nu \nu \nu \nu )</td>
<td>displaced lepton pair</td>
<td>20.3</td>
<td>( \tau ) lifetime</td>
<td>( \tau ) lifetime</td>
</tr>
<tr>
<td>GGM ( X_1 \to Z \ell )</td>
<td>displaced ( \ell \ell ) + jets</td>
<td>20.2</td>
<td>( \tau ) lifetime</td>
<td>( \tau ) lifetime</td>
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<tr>
<td>GGM ( X_2 \to Z \ell )</td>
<td>displaced dimuon</td>
<td>32.9</td>
<td>( \tau ) lifetime</td>
<td>( \tau ) lifetime</td>
</tr>
<tr>
<td>GMSB</td>
<td>non-pointing or delayed ( \gamma )</td>
<td>20.3</td>
<td>( \tau ) lifetime</td>
<td>( \tau ) lifetime</td>
</tr>
<tr>
<td>AMSB</td>
<td>( p \bar{p} \to X_1 X_1 X_1 X_1 )</td>
<td>20.5</td>
<td>( \tau ) lifetime</td>
<td>( \tau ) lifetime</td>
</tr>
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<td>( p \bar{p} \to X_1 X_1 X_1 X_1 )</td>
<td>20.5</td>
<td>( \tau ) lifetime</td>
<td>( \tau ) lifetime</td>
</tr>
<tr>
<td>AMSB</td>
<td>( p \bar{p} \to X_1 X_1 X_1 X_1 )</td>
<td>26.1</td>
<td>( \tau ) lifetime</td>
<td>( \tau ) lifetime</td>
</tr>
<tr>
<td>AMSB</td>
<td>( p \bar{p} \to X_1 X_1 X_1 X_1 )</td>
<td>18.4</td>
<td>( \tau ) lifetime</td>
<td>( \tau ) lifetime</td>
</tr>
<tr>
<td>Stealth SUSY</td>
<td>2 ID/MS vertices</td>
<td>19.5</td>
<td>( \tau ) lifetime</td>
<td>( \tau ) lifetime</td>
</tr>
<tr>
<td>Split SUSY</td>
<td>large pixel dE/dx</td>
<td>26.1</td>
<td>( \tau ) lifetime</td>
<td>( \tau ) lifetime</td>
</tr>
<tr>
<td>Split SUSY</td>
<td>displaced ( \ell \ell ) + ( E_T^{miss} )</td>
<td>32.6</td>
<td>( \tau ) lifetime</td>
<td>( \tau ) lifetime</td>
</tr>
<tr>
<td>Split SUSY</td>
<td>0 ( \ell ), 2 - 6 jets + ( E_T^{miss} )</td>
<td>36.1</td>
<td>( \tau ) lifetime</td>
<td>( \tau ) lifetime</td>
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<tr>
<td>H \to \gamma \gamma</td>
<td>2 low BMF trackless jets</td>
<td>20.3</td>
<td>( \tau ) lifetime</td>
<td>( \tau ) lifetime</td>
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<tr>
<td>FRVZ</td>
<td>( H \to 3 \gamma \to X )</td>
<td>20.3</td>
<td>( \gamma ) lifetime</td>
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<tr>
<td>FRVZ</td>
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<td>3.4</td>
<td>( \gamma ) lifetime</td>
<td>( \gamma ) lifetime</td>
</tr>
<tr>
<td>H \to Z_0 Z_0</td>
<td>displaced dimuon</td>
<td>32.9</td>
<td>( \gamma ) lifetime</td>
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*Only a selection of the available lifetime limits on new states is shown.

### Additional Notes
- ATLAS summary LLP searches:
- ATLAS Long-lived Particle Searches with 95% CL Exclusion

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**ATLAS summary**

10/22/2018

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**ICPPA-2018 - Daniel Teyssier**

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Conclusion

• Long-lived new particle searches are complementary to prompt decay searches
• A lot of new experimental signatures emerge from several theoretical scenarios
• No deviations from SM background observed
• New lower mass limits were set in different SUSY or BSM scenarios
• Several order of magnitude of LLP lifetimes probed by both ATLAS and CMS
• Sensitivity will be improved using latest run 2 of LHC data and/or next run 3 data
Backup
CMS summary LLP searches:

- CMS long-lived particle searches, lifetime exclusions at 95% CL

- RPV SUSY, $\tilde{t} \rightarrow b l$, $m(\tilde{t}) = 420$ GeV
  - $8$ TeV, $19.7$ fb$^{-1}$ (displaced leptons)

- $H \rightarrow XX$ (10%), $X \rightarrow ee$, $m(H) = 125$ GeV, $m(X) = 20$ GeV
  - $8$ TeV, $19.6$ fb$^{-1}$ (displaced leptons)

- $H \rightarrow XX$ (10%), $X \rightarrow \mu\nu$, $m(H) = 125$ GeV, $m(X) = 20$ GeV
  - $8$ TeV, $20.5$ fb$^{-1}$ (displaced leptons)

- GMSB SPS8, $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \gamma$, $m(\tilde{\chi}_2^0) = 250$ GeV
  - $8$ TeV, $19.7$ fb$^{-1}$ (disp. photon conv.)

- GMSB SPS8, $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \gamma$, $m(\tilde{\chi}_2^0) = 250$ GeV
  - $8$ TeV, $19.1$ fb$^{-1}$ (disp. photon timing)

- RPV SUSY, $m(\tilde{g}) = 1000$ GeV, $m(\tilde{\chi}_2^0) = 150$ GeV
  - $8$ TeV, $18.5$ fb$^{-1}$ (displaced dijets)

- RPV SUSY, $m(\tilde{g}) = 1000$ GeV, $m(\tilde{\chi}_2^0) = 500$ GeV
  - $8$ TeV, $18.5$ fb$^{-1}$ (displaced dijets)

- AMSB $\tilde{t}_1^\pm \rightarrow \tilde{\chi}_1^0 + \pi^+$, $m(\tilde{\chi}_1^0) = 200$ GeV
  - $8$ TeV, $19.5$ fb$^{-1}$ (disappearing tracks)

- cflud model $R$-hadron, $m(\tilde{g}) = 1000$ GeV
  - $8$ TeV, $18.5$ fb$^{-1}$ (stopped particle)

- AMSB $\tilde{\tau}_1^\pm$, $\tan(\beta) = 5$, $\mu > 0$, $m(\tilde{\chi}_2^0) = 800$ GeV
  - $8$ TeV, $18.8$ fb$^{-1}$ (tracker + TOF)

- AMSB $\tilde{\tau}_1^\pm$, $\tan(\beta) = 5$, $\mu > 0$, $m(\tilde{\chi}_2^0) = 200$ GeV
  - $8$ TeV, $18.8$ fb$^{-1}$ (tracker + TOF)
Improved sensitivity @ HL-LHC for displaced muons:

**CMS-TDR-016**

**FTR-18-002**

GMSB-SUSY smuons are LLP

Dark SUSY (dark) photons are LLP