Searches for long-lived particles with the CMS detector

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**Outline**

- **Highlights** from *signature-driven searches for LLPs* in the LHC Run 2 at CMS
- The search strategy for:
  - **Displaced** vertices or jets
  - **Emerging** jets (presented by J. Duatre)
  - **Disappearing** tracks
  - **Delayed** jets
  - **Stopped** particles
- Results and limits on xsec, mass & lifetime

- **CMS data collected at 13 TeV** in Run II up to **137/fb**
- In this talk, the focus is on recently published CMS results
LLPs have non conventional final states

LLPs signature depend on the lifetime $\tau$:

Cross the detector quasi-stable LLP

Decay or are produced inside the detector
Displaced or disappearing objects, stopped particles

Challenging from the experimental point of view:

Often difficult triggering

Non-standard reconstruction:

displacements, timing and ionization

Not much SM background, no such objects in SM, mostly detector noise, cosmic rays, reco failures – can be estimated from data
**Displaced vertices in multijet events**

- **Signature:** displaced jets in the region of a beam pipe

- **Analysis strategy:**
  - reconstruct displaced vertices from tracks in events with jets
  - focus on intermediate lifetimes $c\tau$ (100 $\mu$m to 10 cm)
    - first tracking (pixel) layer: 4.4 cm radius
  - distinguish **signal in two-vertex events** using the distance $d_{vv}$ between vertices
  - SM background: prompt vertices in events with lots of jets

- **Benchmark:**
  - Pair-produced long-lived neutralinos/gluinos or stops in RPV SUSY
Displaced vertices in multijet events

- **Search variable**: $d_{VV}$ – $xy$ distance between vertices

- **Search regions**: 3 bins
  - 0.0 – 0.4 mm
  - 0.4 – 0.7 mm
  - 0.7 – 40 mm
Displaced vertices in multijet events

- **Trigger:**
  standard HT = $\Sigma^{N\text{jets}}E_T > 800$ GeV

- **Selection:** $\geq 4$ jets

- **Signal region:**
  - $\geq 5$-track two-vertex events

- **Background:**
  - estimated from $\geq 5$-track one-vertex

- **Control samples:**
  - events with 3-track and 4-track vertices

- **Results:** 1 event observed ($\geq 5$-track two-vertex) with $d_{VV} = 396$ $\mu$m

<table>
<thead>
<tr>
<th>$d_{VV}$ range</th>
<th>Fitted background yield</th>
<th>Observed</th>
<th>Predicted multijet signal yields</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–0.4 mm</td>
<td>0.51 ± 0.01 (stat) ± 0.13 (syst)</td>
<td>1</td>
<td>2.8 ± 0.7 3.5 ± 0.8 1.0 ± 0.2</td>
</tr>
<tr>
<td>0.4–0.7 mm</td>
<td>0.37 ± 0.02 (stat) ± 0.09 (syst)</td>
<td>0</td>
<td>2.0 ± 0.5 3.7 ± 0.9 0.5 ± 0.1</td>
</tr>
<tr>
<td>0.7–40 mm</td>
<td>0.12 ± 0.02 (stat) ± 0.08 (syst)</td>
<td>0</td>
<td>1.1 ± 0.3 11 ± 3 31 ± 7</td>
</tr>
</tbody>
</table>
Displaced vertices in multijet events

**Inclusive displaced jets**

- **Signature:** displaced jets in the tracker
- **Analysis strategy:** utilize the properties of jets, tracks and secondary vertices to tag displaced jet signatures

- **Inclusive analysis:**
  - one displaced vertex is sufficient
  - not requires SV containing tracks from both jets
  - no missing hit requirement, therefore LLPs could be charged

- **Benchmark:**
  pair produced LLP with \(ct\) from 1mm to 1m decaying to jets or leptons which are displaced

- **GMSB gluino**
  \(\tilde{g} \rightarrow g \tilde{G}\)

- **RPV stop quarks**
  \(\tilde{t} \rightarrow t \tilde{G}\)

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M. Kazana

LLP @ CMS, 7th LHCP, 23.05.2019
Dedicated **displaced** trigger:
- Calo HT $> 350$ GeV
- $\geq 2$ calo jets with $p_T > 40$ GeV, $|\eta| < 2.0$
- $\geq 1$ displaced track for each jet pair
- $\leq 2$ prompt tracks for each jet pair

Offline kinematics selection:
- Calo HT $> 400$ GeV
- $p_T > 50$ GeV, $|\eta| < 2.0$ for calo jets in dijet candidates

Background:
- Data driven estimate using control regions built from track, secondary vertex and jet information as a likelihood discriminant

4 Signal Regions:
Inclusive displaced jets

Limits:

**GMSB**: pair-produced LL gluinos $< 2300$ GeV are excluded for $c\tau_0$ between 20 and 110 mm

**RPV SUSY**: pair-produced LL top squarks $< 1350$ GeV are excluded for $c\tau_0$ between 7 and 110 mm

Exclusion limits on the cross-section on **new neutral LLPs** decaying to two jets, eg 0.2 fb at high mass ($m_X > 1000$ GeV) for $c\tau_0$ from 3 to 130 mm
Disappearing tracks

- **Signature** of short track (ST) in the tracker → charged soft pion hard to be reconstructed

- **Benchmark:** compressed SUSY where in a decay chain long-lived charginos will be seen as STs in the tracker because of small mass splitting with the LSP neutralino, $\Delta m(\tilde{\chi}^{\pm}_1,\tilde{\chi}^0_1) \sim 100$ MeV, $c\tau(\tilde{\chi}^{\pm}_1) \sim 50$ cm

- **Analysis strategy:** classic SUSY inclusive $M_{T2}$ search adopted to disappearing track search for events with at least 2 jets

- **Profit:** SM background is significantly further suppressed by presence of disappearing tracks
Disappearing tracks

- **Short Track:** high quality track with missing outer hits w/o associated calo or muon hits

- **Selection:** ≥2 jets, events converted to 2 pseudo-jets with $M_{T2} > 200$ GeV and at least 1 ST

- **Trigger:** identical to inclusive $M_{T2}$ search based on $p_T$, MET, HT and HTM

- **Background:**
  Data-driven estimation for main backgrounds:
  fake rate applied to ST events from poorly reconstructed charged pions and leptons

- **Search regions:**
  68 regions in Njet, HT, the ST length, the ST $p_T$
**Delayed Jets**

**NEW! Usage of ECAL timing for calo jets**

- **Signature:** Calorimeter deposits of displaced jets from massive LLPs are **delayed** wrt. jets from prompt decays.

- **Strategy:** use ECAL timing to find **delayed jets**

- **Profit:** increased acceptance for decays beyond tracker (0.3 - 1.5 m)

- **ECAL:** jet time is a median time of all ECAL cells in jet with energy > 0.5 GeV and |time| < 20ns, ΔR(cell, jet) < 0.4
  
  - time resolution per cell (crystal+APD) ~200 ps
Delayed Jets

- **Benchmark model:**
  
  GMSB *long-lived gluino* → gluon + gravitino

**Selection SR:**

- ≥ 1 delayed calo jet
  
  \[(t > 3\text{ ns}, \ pT > 30 \text{ GeV}, \ E > 70 \text{ GeV}, \ |\eta| < 1.48)\]
- Calo MET > 300 GeV
- **Trigger:** MET > 120 GeV

**Background:**

- Cleaning selections reject contributions from dominant backgrounds:
  beam halo, cosmics, satellite bunches
- Bkg. prediction from data using ABCD (not modelled in MC)
- **Observed:** 0 events in agreement with bkg. prediction of 1 evt

- **Results (GMSB):**
  
  Exclude $m_{\tilde{g}} < 2.50$ TeV for $c\tau_{0} \sim 1$ m
  
  or $m_{\tilde{g}} < 2.15$ TeV for $c\tau_{0} \sim 30$ m

→ **Significantly extends reach for $c\tau_{0} \geq 1$ m**

(vs. tracker-based searches)
Stopped particles

- **R-hadrons from Split SUSY** (gluino or $|Q|=2e$) are **stopped inside the detector** and **decay to muons or have hadronic decays** from rest after unknown time (sensitivity to lifetimes between 0.1 $\mu$s and $10^6$ s)
- Events recorded **out-of-time with collisions** with the custom trigger

**Cosmics**

**Signal**

- **No events** observed
- **13 orders of magnitude of the lifetime** tested
- **Excluded gluinos** with mass between 400 and 970 GeV, assuming 100% BF to muons

EXO-17-004, EXO-16-004, JHEP 05 (2018) 127
Re-interpretation of prompt SUSY searches

- A fraction of **long-lived particles** can be detected in **prompt searches**
  - If the reco object is not too much displaced or delayed
- **Prompt searches complement the sensitivity** to **dedicated LLP searches**

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**Figure:**
- **Expected** and **Observed** limits on the mass of long-lived particles
- **Status:** February 2018
- **Jets + \( p_T \text{miss} \), arXiv:1802.02110**
  - \( m_{\chi^0} = 100 \text{ GeV}, \text{charge suppressed} \)
  - \( m_{\tilde{g}} - m_{\chi^0} = 100 \text{ GeV}, \text{charge suppressed} \)
- **Stopped gluino, arXiv:1801.00359**
  - \( m_{\tilde{g}} - m_{\chi^0} > 160 \text{ GeV}, f_{\tilde{g}g} = 0.1 \)
- **HSCP, CMS-PAS-EXO-16-036**
  - \( f_{\tilde{g}g} = 0.1 \)

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**Legend:**
- **HSCP**
- **Stopped particles**
- **Multijet SUSY**
LLP at CMS summary

- **CMS** has an **extensive search program** for **different signatures** of LLPs
  - CMS provides **HepData records** with tables of acceptances, efficiencies and signal cross sections, etc. for the **model independent** studies

- **No LLP particle has been observed... yet...**
  - Exclude LLPs with masses up to 1 – 2.5 TeV
  - Sensitive to proper decay lengths from 1 mm
  - Any detected signal of LLP would be a clear indication of a new physics

- **Improvements** on sensitivity to LLP is expected with
  - **Advanced techniques of reconstruction**
    displacement, timing and ionization and triggering
  - **New topologies** are being included
  - **Complementary prompt searches**
  - Increasing luminosity – Run II dataset (~140/ fb in total) coming soon

- SUSY CMS public results:
  [https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO)
Thank you!

Supported in part by the NCN grant: 2014/15/B/ST2/03998
Secret life of Long-Lived Particles

**LLPs sources:**

- Small couplings in decay chain
  - **RPV SUSY**
  - **GMSB** small coupling to the lightest gravitino
- Small phase space/mass splitting (**AMSB**)
- Massive particle mediating the decay (**Split SUSY**, R-hadrons (gluino/stop))
- Hidden sectors (**Hidden Valley**)
- **Dark QCD** and more
The **Dark QCD** model with long-lived dark-pions, which can decay to SM particles

**Signal:**

2 prompt jets and **2 emerging jets**

Emerging jets are produced in the hadronization of $Q_{DK}$ to dark hadrons ($\pi_{DK}$) which form dark jets, and contain multiple displaced vertices from the decay of dark-pions

<table>
<thead>
<tr>
<th>Signal model parameters</th>
<th>List of values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark mediator mass $m_{X_{DK}}$ [GeV]</td>
<td>400, 600, 800, 1000, 1250, 1500, 2000</td>
</tr>
<tr>
<td>Dark pion mass $m_{\pi_{DK}}$ [GeV]</td>
<td>1, 2, 5, 10</td>
</tr>
<tr>
<td>Dark pion decay length $c\tau_{\pi_{DK}}$ [mm]</td>
<td>1, 2, 5, 25, 45, 60, 100, 150, 225, 300, 500, 1000</td>
</tr>
</tbody>
</table>

focus on lifetimes of $1 \text{ mm} < c\tau < 1 \text{ m}$

336 signal hypotheses
Emerging jets

- **Data:** 16/fb – part of 2016 due to saturation-induced dead time present in the readout of the silicon strip tracker

- **HLT Trigger:** HT > 900 GeV

- **Strategy:** extension of the displaced jet search and tagger for emerging jets – *emerging jets identification:*

- **7 Different selections sets** are used with:
  - optimized kinematic cuts on HT, $p_T$ of jets, MET
  - optimized emerging jet tag cuts
Emerging jets

- **Results:** Observed events agree with bkg. expectation in all 7 selection sets

<table>
<thead>
<tr>
<th>Set number</th>
<th>Expected</th>
<th>Observed</th>
<th>Signal</th>
<th>Model parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$m_{X_{DK}}$ [GeV]</td>
</tr>
<tr>
<td>1</td>
<td>168 ± 15 ± 5</td>
<td>131</td>
<td>36.7 ± 4.0</td>
<td>600</td>
</tr>
<tr>
<td>2</td>
<td>31.8 ± 5.0 ± 1.4</td>
<td>47</td>
<td>(14.6 ± 2.6) × 10^2</td>
<td>400</td>
</tr>
<tr>
<td>3</td>
<td>19.4 ± 7.0 ± 5.5</td>
<td>20</td>
<td>15.6 ± 1.6</td>
<td>1250</td>
</tr>
<tr>
<td>4</td>
<td>22.5 ± 2.5 ± 1.5</td>
<td>16</td>
<td>15.1 ± 2.0</td>
<td>1000</td>
</tr>
<tr>
<td>5</td>
<td>13.9 ± 1.9 ± 0.6</td>
<td>14</td>
<td>35.3 ± 4.0</td>
<td>1000</td>
</tr>
<tr>
<td>6</td>
<td>9.4 ± 2.0 ± 0.3</td>
<td>11</td>
<td>20.7 ± 2.5</td>
<td>1000</td>
</tr>
<tr>
<td>7</td>
<td>4.40 ± 0.84 ± 0.28</td>
<td>2</td>
<td>5.61 ± 0.64</td>
<td>1250</td>
</tr>
</tbody>
</table>

- First emerging jets search at colliders!
- First Dark QCD results
- Limits do not depend strongly on mass of dark pion $\pi_{DK}$
- Exclude dark-mass mediator $X_{DK}$ mass between 400 and 1250 GeV for $c\tau (\pi_{DK})$ between 5 and 225 mm
Heavy quasi-stable charged particles

- HSCPs (R-hadrons, GMSB staus and MCHAMPs) cross the detector
- **Signature:** high ionization (dE/dx) in the tracker delay in the muon system – long-time of flight (TOF: 1/\(\beta\) measured) → **mass measurement** from dE/dx
- **Trigger:** MET (>170 GeV) or single muon (pT > 50 GeV)
- **Background** estimated from data using pT, dE/dx discriminator, 1/\(\beta\)

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**HSCP stau**

**Mass limit on GMSB stau > 660 GeV**

**HSCP Gluino**

**Stop > 1250 GeV**

**Gluino > 1850 GeV**

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EXO-16-036, PRD 94 (2016) 112004
LLP limits

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

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

- **H → XX (10%), X → ee, m(H) = 125 GeV, m(X) = 20 GeV**
  - $6$ TeV, $19.0$ fb$^{-1}$ (displaced leptons)

- **H → XX (10%), X → $\mu\nu, m(H) = 125$ GeV, m(X) = 20 GeV**
  - $6$ TeV, $20.5$ fb$^{-1}$ (displaced leptons)

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

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

- **RPV SUSY, m(\tilde{q}) = 1000 GeV, m(\tilde{\chi}^0_1) = 150$ GeV**
  - $8$ TeV, $18.5$ fb$^{-1}$ (displaced jets)

- **RPV SUSY, m(\tilde{q}) = 1000 GeV, m(\tilde{\chi}^0_1) = 500$ GeV**
  - $8$ TeV, $18.5$ fb$^{-1}$ (displaced jets)

- **AMSB $\chi^0_1, \tilde{\chi}^0_1 \to \tilde{\chi}^0_0 + \pi^0, m(\tilde{\chi}^0_1) = 200$ GeV**
  - $8$ TeV, $19.5$ fb$^{-1}$ (disappearing tracks)

- **cloud model R-hadron, m(\tilde{q}) = 1000$ GeV**
  - $8$ TeV, $18.6$ fb$^{-1}$ (stopped particle)

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

- **AMSB $\tilde{\chi}_1^0$, tan(β) = 5, $\mu > 0, m(\tilde{\chi}^0_1) = 200$ GeV**
  - $8$ TeV, $18.8$ fb$^{-1}$ (tracker + TOF)

Aug 2016
Regions of LLP decay/production in CMS

Pixels 20 cm Strips

tracker 1 m calorimeters 3 m

Si

Iron return yoke interspersed with Muon chambers

muon system 7 m

CMS