Searches for unconventional signatures at CMS

Małgorzata Kazana on behalf of the CMS Collaboration

National Centre for Nuclear Research NCBJ – Warsaw, Poland

Phenomenology Symposium, PHENO 2020
4-6 May 2020
University of Pittsburgh, USA
Searches for long-lived particles

- **LLPs** have **unconventional** final states
- **LLPs signature** depend on the **lifetime** $c\tau$:
  - **Cross** the detector: quasi-stable LLP
  - **Decay inside** the detector: displaced, delayed or disappearing objects

- **Challenging** from the experimental point of view:
  - Often difficult triggering
  - Non-standard reconstruction: **displacements, timing** and **ionization**

- **Non-standard backgrounds to challenges**
  detector noise, cosmic rays, reco failures – can be estimated from data
In this talk, the focus is on recent, complementary searches for LLPs that decay hadronically.

CMS data collected at 13 TeV in Run II up to 137/fb:
- 2016 – 36/fb,
- 2017 – 41/fb,
- 2018 – 60/fb

The search strategy for:
- Displaced jets
- Delayed jets
Displaced Jets

- Distinctive **topology:** pair of jets originating at a secondary vertex displaced from the production vertex by up to around 55 cm in the transverse plane
- Inclusive search for LLPs decaying into jets, with at least one displaced vertex

**Reconstructed tracks (and CALO jets) in a simulated LLP event**

**New results with 132/fb!**

**Full Run 2**

- **2017/2018:** 95.9/fb
  - Preliminary: EXO-19-021
  - https://cds.cern.ch/record/2717071

- **2016:** 36/fb

Calo jet is formed from energy deposits in the calorimeters
Displaced Jets - signal

- Distinctive topology: pair of jets originating at a displaced vertex

Hypothetical SIGNAL:

- Long-lived massive neutral particles decaying to quark-antiquark pairs

- Jet-jet benchmark model: $gg \to (\text{non-SM}) H \to 2X, X \to qq$
  where $c\tau_X \sim 1\text{mm to } 10\text{m}$

- BMS models:
  Hidden Valley Higgs, Split SUSY, General Gauge Mediated SUSY, RPV SUSY
Displaced Jets – pre-selection

- Dedicated **triggers:**
  - the *displaced trigger* has better efficiency for low-mass LLPs,
    while the *inclusive trigger* recovers efficiency for high mass LLPs
    with small $c\tau (< \sim 3\text{mm})$ and large $c\tau (> \sim 300\text{mm})$

- with algo for **jet displacement tagging**
  - $H_T > 430$ (650) GeV
    - $H_T$ trigger threshold required if no selection on displaced object is significantly higher
  - $\geq 2$ jets with $p_T > 40$ (60) GeV, $|\eta| < 2.0$
  - $\geq 1$ displaced track (**no requirement on the number of displaced tracks**)
  - $\leq 2$ (**associated**) prompt tracks

- **Basic event selections:**
  - If passes the *displaced (inclusive)* trigger:
    - Calo $H_T > 500$ (700) GeV, Calo jets $p_T > 50$ (80) GeV, $|\eta| < 2.0$
  - Track-jet association, tracks are matched to jets within $R < 0.5$
  - Tracks are required to high-purity and have $p_T > 1\text{GeV}$
**Secondary vertex reconstruction**

- For all possible pairs of jets
- **Tracks associated with the dijet candidate** have $\text{IP}_{2\text{D}} > 0.5\text{mm}$, $\text{Sig}[\text{IP}_{2\text{D}}] > 5.0$ (w.r.t. the leading PV)
- Fit a SV with requirement of $\chi^2/\text{ndof} < 5.0$
- Vertex $\text{Mass}_{\text{inv}} > 4\text{ GeV}$ and vertex $p_T > 8\text{ GeV}$

- Background events arise from nuclear interactions (NI) with the inner tracker material
- NI vertex candidates reflect a structure of the pixel tracking system and beam pipe
- **Any secondary vertex candidate that overlaps with the NI-veto map is rejected**
- The loss of the fiducial volume within $r < 30\text{ cm}$ is around 4%
- Efficiencies for signal events to pass this selection are generally well above 90%
QCD multijet process dominates the background given the large cross section (≈4 × 10⁴ pb for Hₜ > 500 GeV)

Gradient Boosted Decision Tree (GBDT) as the discriminant on four variables:
1. vertex track multiplicity
2. cluster RMS
3. vertex Lxy significance
4. |κ|

Control region for GBDT training:
- selection on the SV track energy fraction inverted
- NI-veto removed

Signal distributions almost do not depend on mass and ctau
Displaced Jets – bckg. prediction

- **Background is purely data-driven**

- With extended ABCD method predictions in 8 regions for 3 selection options:
  - No of prompt tracks for 1st jet ≤ 2
  - No of prompt tracks for 2nd jet ≤ 2
  - GBDT > 0.988

- **Signal region:**
  - All selection criteria applied
  - No of prompt tracks for both jets ≤ 2
  - GBDT > 0.988

- Offline selections:
  - Provide an extremely strong background rejection power of ~ 2 \times 10^7
  - Are highly efficient for signals (can be ~70% - 80%)
  - Inclusive to different long-lived models with different final-state topologies

- Predicted background in the final signal region: **0.75 ± 0.44(stat) ± 0.39(syst)**

- Number of observed events: **1 event** \((H_T = 570 \text{ GeV}, SV \text{ with } Lxy \sim 26 \text{ cm and 8 assigned tracks})**
New limits with displaced jets

Combined results for Full Run 2 data (2016 + 2017/18):

- Exclusion limits on the cross-section on **new neutral LLPs** decaying to two jets, 0.04 fb at high mass ($m_\chi>1000$ GeV) for $c\tau_0 = 30$ mm
- **GMSB**: pair-produced **LL gluinos** lighter than **2450 GeV** are excluded for $c\tau_0$ between 6 and 550 mm
- **RPV SUSY**: pair-produced **LL top squarks** lighter than $\sim$1600 GeV are excluded for $c\tau_0$ between 2 and 1320 mm
**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, $\Delta R(\text{cell, jet}) < 0.4$
  - time resolution per cell (crystal+APD) ~200 ps

---

M. Kazana

Unconventional Signatures @ CMS, PHENO, 5.05.2020
### Delayed Jets

- **Signal:** GMSB long-lived gluinos or Split SUSY R-hadrons decaying to displaced jets + MET

- **Selection:**
  - $\geq 1$ delayed calo jet
    - $(t > 3\text{ ns}, p_T > 30\text{ GeV}, E > 70\text{ GeV}, |\eta| < 1.48)$
  - MET $> 300\text{ GeV}$

- **Trigger:** MET $> 120\text{ GeV}$

- **Candidate event cleaning:**
  - beam halo rejected by muon CSC & HCAL
  - satellite bunches & mismeasurements veto
  - cosmics vetoed by muon DT and RPC
  - pileup & APD hits rejected by ECAL timing

- **Background:**
  Data-driven by invert cleaning cuts to form data CRs

- **Search region:** $N_{\text{jet}} \geq 1$, $t_{\text{jet}} > 3\text{ ns}$
**Observed:** 0 events in agreement with bckg. 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)

<table>
<thead>
<tr>
<th>Background source</th>
<th>Events predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam halo muons</td>
<td>$0.02^{+0.06}<em>{-0.02}$ (stat) $^{+0.05}</em>{-0.01}$ (syst)</td>
</tr>
<tr>
<td>Core and satellite bunch collisions</td>
<td>$0.11^{+0.09}<em>{-0.05}$ (stat) $^{+0.02}</em>{-0.02}$ (syst)</td>
</tr>
<tr>
<td>Cosmic ray muons</td>
<td>$1.0^{+1.8}<em>{-1.0}$ (stat) $^{+1.8}</em>{-1.0}$ (syst)</td>
</tr>
</tbody>
</table>

**CMS**

137 fb$^{-1}$ (13 TeV)

95% CL upper limit on cross section (fb)

95% CL upper limit on cross section (fb)

95% CL observed ± 1 $\sigma_{\text{theory}}$

95% CL expected ± 1 $\sigma_{\text{experiment}}$

Approx. NNLO+NNLL $\sigma(pp \to \tilde{g} \tilde{g})$
Unconventional signatures of displaced or delayed jets is a powerful tool in searches different LLPs in a model independent way

Searches are complementary

New results for full Run 2 data pushed limits on LLPs

- Exclude new LLPs with masses up to 2.5 TeV
- Sensitive to decay lengths from 1 mm
- Any detected signal of LLP would be a clear indication of a new physics

EXO CMS public results:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
Thank you!

Supported in part by the NCN grant: 2014/15/B/ST2/03998
Backup
New limits with displaced jets

Combined results for Full Run 2 data (2016 + 2017/18):
- Exclusion limits on the cross-section on **new neutral LLPs** decaying to two jets, 0.04 fb at high mass ($m_X > 1000$ GeV) for $c\tau_0 = 30$ mm
New limits with displaced jets

Combined results for Full Run 2 data (2016 + 2017/18):
- For SM Higgs boson decays $2$ LL Scalars and each LLS decays to a qq pair, the branching fractions for the exotic Higgs decay larger than 1% are excluded at 95% CL for $c\tau_0$ between 1mm and 1m when scalar mass is 40 or 55GeV.
New limits with displaced jets

- **GMSB:** pair-produced **LL gluinos** lighter than 2450 GeV are excluded for \( c\tau_0 \) between 6 – 550 mm
- gluino pair production \( x\text{-sec} > 0.1 \text{ fb} \) are excluded for \( c\tau_0 \) between 7 – 600 mm
- the largest gluino mass excluded is 2560 GeV with a \( c\tau_0 \) of 30 mm
New limits with displaced jets

- **Mini Split**: pair-produced **LL gluinos** lighter than **2500 GeV**
  are excluded for $c\tau_0$ between 5 – 520 mm
- gluino pair production $\chi$-sec $> 0.1$ fb are excluded for $c\tau_0$ between 3 – 900 mm
- the largest gluino mass excluded is 2610 GeV with a $c\tau_0$ of 30 mm
New limits with displaced jets

- **RPV tbs**: pair-produced LL gluinos lighter than 2400 GeV are excluded for $c\tau_0$ between 3 – 1000 mm.
- Gluino pair production x-sec > 0.1 fb are excluded for $c\tau_0$ between 3 – 1490 mm.
- The largest gluino mass excluded is 2640 GeV with a $c\tau_0$ of 30 mm.
New limits with displaced jets

- **RPV bl**: pair-produced **LL gluinos** lighter than **1600 GeV** are excluded for $c\tau_0$ between $3 - 340$ mm
- gluino pair production x-sec > 0.1 fb are excluded for $c\tau_0$ between $8 - 160$ mm
- the largest gluino mass excluded is 1720 GeV with a $c\tau_0$ of 30 mm

![Graph showing 95% CL upper limits for RPV ll gluinos](image)

- 132 fb$^{-1}$ (13 TeV)

![Graph showing CMS expected and observed cross sections](image)

- 132 fb$^{-1}$ (13 TeV)
New limits with displaced jets

- **RPV dl:** pair-produced LL gluinos lighter than 1600 GeV are excluded for $c\tau_0$ between 3 – 430 mm
- gluino pair production $\Delta$-sec > 0.1 fb are excluded for $c\tau_0$ between 7 – 220 mm
- the largest gluino mass excluded is 1740 GeV with a $c\tau_0$ of 30 mm