Searches for long-lived particles at CMS

A. Hart for the CMS collaboration

The Ohio State University

May 16, 2017
Why long-lived particles (LLP)?

- Dozens of searches over past 6 years have failed to find evidence of BSM physics at the LHC.
- More important than ever to explore ways new physics could have escaped the attention of all these searches.

- LLPs is one such way.
- Most searches assume promptly decaying new particles.

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CMS already has a rich programme of LLP searches. Several searches place limits on models with baryon/lepton number violation, typically as R-parity violation (RPV):

- very small RPV couplings is a well-motivated way of making the LSP long-lived in SUSY models

CMS long-lived particle searches, lifetime exclusions at 95% CL
Types of LLP searches – direct

- observe LLP directly
- better for **long lifetimes**
- good for **charged LLPs**

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Diagram:
- Neutral, charged, any charge
- Direct Searches
- Disappeared conversion
- Displaced photon
- Displaced jet
- Displaced dilepton
- Displaced lepton
- HSCP

Legend:
- BSM
- Lepton
- Quark
- Photon
- Anything

Not pictured:
- Stopped HSCP
Types of LLP searches – indirect

- observe LLP decay products
  - better for **short lifetimes**
  - good for **neutral LLPs**

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**Indirect Searches**

- displaced vertex
- displaced jet
- displaced photon
- displaced dilepton
- disappearing track
- HSCP

**Not pictured:**

- BSM
- lepton
- quark
- photon
- anything

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Searches for long-lived particles  
May 16, 2017
Heavy stable charged particle (HSCP) search

- neutral
- charged
- any charge

displaced vertex

HSCP

disappearing track

displaced conversion

BSM
lepton
quark
photon
anything

displaced photon

displaced jet

displaced dilepton

displaced lepton

Not pictured:
Stopped HSCP
Most mature LLP search at CMS:

- results at 7, 8, and 13 TeV

Two main discriminating variables:

- \( I_h \) (a.k.a. \( dE/dx \)): ionization energy loss in tracker
- \( \beta^{-1} \): time of flight (TOF) to muon chambers

Two channels maximize sensitivity to strongly-interacting HSCPs that may become neutral via interactions in the tracker:

- tracker-only
- tracker + TOF

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No excess at high mass in either channel.

Limits placed on wide range of models:
- cross section limits down to $1\sim10\ fb$
- mass limits up to 1.8 TeV

<table>
<thead>
<tr>
<th>Selection cuts</th>
<th>Numbers of events 2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T$ (GeV)</td>
<td>$I_{as}$</td>
</tr>
<tr>
<td>Trk-only</td>
<td>&gt; 65</td>
</tr>
<tr>
<td></td>
<td>&gt; 100</td>
</tr>
<tr>
<td></td>
<td>&gt; 200</td>
</tr>
<tr>
<td></td>
<td>&gt; 300</td>
</tr>
<tr>
<td></td>
<td>&gt; 400</td>
</tr>
<tr>
<td>Trk+TOF</td>
<td>&gt; 65</td>
</tr>
<tr>
<td></td>
<td>&gt; 100</td>
</tr>
<tr>
<td></td>
<td>&gt; 200</td>
</tr>
<tr>
<td></td>
<td>&gt; 300</td>
</tr>
<tr>
<td></td>
<td>&gt; 400</td>
</tr>
</tbody>
</table>
Stopped particles

- neutral
- charged
- any charge

Not pictured: Stopped HSCP
Stopped particles

- Update of mature search done at 7 TeV and 8 TeV.
- Out-of-time events selected with a high-$p_T$ jet.
- Vetoes applied to reject dominant sources of out-of-time calo. activity:
  - calo. noise
  - bremsstrahlung from beam halo muons
  - bramsstrahlung from cosmic muons
Limits placed up to $\tau \gtrsim 11$ days

- Observed numbers of events consistent with expected backgrounds.
- Limits placed on long-lived gluinos and stops:
  - mass limits up to $1.4$ TeV ($740$ GeV) for long-lived gluinos (stops)
  - limits placed over 13 decades of $\tau$

<table>
<thead>
<tr>
<th>Period</th>
<th>Livetime (hrs)</th>
<th>Noise</th>
<th>Cosmics</th>
<th>Halo</th>
<th>Total</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015 control</td>
<td>-</td>
<td>$0.3^{+2.4}_{-0.3}$</td>
<td>$1.7 \pm 0.6$</td>
<td>0</td>
<td>$4.1^{+3.0}_{-1.0}$ (the median is 6.2)</td>
<td>2</td>
</tr>
<tr>
<td>2015</td>
<td>135</td>
<td>$0.4^{+2.9}_{-0.4}$</td>
<td>$2.6 \pm 0.9$</td>
<td>$1.1 \pm 0.1$</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td>2016 control</td>
<td>-</td>
<td>$0^{+2.2}_{-0}$</td>
<td>$2.5 \pm 0.9$</td>
<td>0</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>2016</td>
<td>586</td>
<td>$0^{+9.8}_{-0}$</td>
<td>$8.8 \pm 3.1$</td>
<td>$2.6 \pm 0.2$</td>
<td>$11.4^{+10.3}_{-3.1}$ (the median is 17.4)</td>
<td>13</td>
</tr>
</tbody>
</table>
Displaced $e\mu$ search

- Neutral
- Charged
- Any charge

- Displaced vertex
- HSCP
- Disappearing track
- Displaced photon
- Displaced jet
- Displaced dilepton
- Displaced lepton

BSM
Lepton
Quark
Photon
Anything

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May 16, 2017
Displaced $e\mu$ search

- Update of 8 TeV search.
- Benchmark model of RPV $\tilde{t} \rightarrow b l^\pm$ pair production.
- $d_0$ of electron and muon used as discriminating variables.
- Events selected with one oppositely-charged $e\mu$ pair.
Limits placed over 4 decades in $c\tau$

- Three mutually exclusive search regions: $200 \mu m < d_0 < 10 \text{ cm}$.
- Observation consistent with expected background in each region.
- Sensitivity limited by:
  - prompt backgrounds and $d_0 > 200 \mu m$ criterion at small $c\tau$
  - lepton reco. eff. at large $c\tau$

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Event Source | Search Region I | Search Region II | Search Region III
--- | --- | --- | ---
non-HF sum | $(203 \pm 26) \times 10^{-3}$ | $(410 \pm 170) \times 10^{-5}$ | $(82 \pm 71) \times 10^{-5}$
data-driven HF | $< 3.0$ | $< 0.50$ | $< 0.019$
total background | $< 3.2$ | $< 0.50$ | $< 0.020$
observation | 1 | 0 | 0

$pp \rightarrow t_1 \bar{t}_1'$ ($M_{t_1} = 700 \text{ GeV}$)

- $c\tau = 0.1 \text{ cm}$: $3.8 \pm 0.2$, $0.94 \pm 0.06$, $0.16 \pm 0.02$
- $c\tau = 1 \text{ cm}$: $5.2 \pm 0.4$, $4.1 \pm 0.3$, $7.0 \pm 0.3$
- $c\tau = 10 \text{ cm}$: $0.8 \pm 0.1$, $1.0 \pm 0.1$, $5.8 \pm 0.2$
- $c\tau = 100 \text{ cm}$: $0.009 \pm 0.005$, $0.03 \pm 0.01$, $0.27 \pm 0.03$
Displaced jet search

CMS-EXO-16-003

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Searches for long-lived particles

May 16, 2017
Search for dijets sharing a common, displaced vertex.

Generated a lot of interest from the pheno. community:
  - able to exclude huge swaths of parameter space for several models

Displaced jet-based tagging strategy developed:
  - sensitive now to single displaced jets
  - able to place limits on RPV $\tilde{t} \rightarrow b l^\pm$ model from displaced $e\mu$ search
Jet tagging variables

- vertex $\alpha$: fraction of jet’s track $p_T$ associated to vertex
  - cut on highest $\alpha$ vertex
- track $IP^{2D}_{\text{sig}}$: transverse impact parameter of track wrt. PV divided by its error
  - cut on median $IP^{2D}_{\text{sig}}$ for jet
- track $\Theta^{2D}$: angle between track $p_T$ and vector from PV to track’s innermost hit
  - cut on median $\Theta^{2D}$ for jet
Lot of parameter space excluded

- Expected backgrounds are very small:
  - observation is consistent
- Limits placed on multiple models as a function of LLP mass and lifetime.

<table>
<thead>
<tr>
<th>$N_{\text{tags}}$</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>$1.09 \pm 0.16$</td>
<td>1</td>
</tr>
<tr>
<td>$\geq 3$</td>
<td>$(4.9 \pm 1.0) \times 10^{-4}$</td>
<td>0</td>
</tr>
</tbody>
</table>
Conclusion

- Many more results with current 38.5 fb\(^{-1}\) 13 TeV dataset in pipeline.
- The 2017 run will offer even more interesting possibilities for some analyses:
  - CMS now has an upgraded pixel detector with a new 4th barrel layer and 3rd endcap disk on each side.

<table>
<thead>
<tr>
<th>final state</th>
<th>13 TeV result</th>
</tr>
</thead>
<tbody>
<tr>
<td>displaced ee/(\mu\mu) pairs</td>
<td></td>
</tr>
<tr>
<td>displaced (\mu\mu) pairs in muon sys.</td>
<td></td>
</tr>
<tr>
<td>displaced (e\mu) pairs</td>
<td>CMS-EXO-16-022</td>
</tr>
<tr>
<td>displaced (\mu\mu) pairs (dark photons)</td>
<td>CMS-HIG-16-035</td>
</tr>
<tr>
<td>displaced (\gamma) using ECAL timing</td>
<td></td>
</tr>
<tr>
<td>displaced (\gamma) using conversions</td>
<td></td>
</tr>
<tr>
<td>displaced vertices</td>
<td></td>
</tr>
<tr>
<td>displaced jets</td>
<td>CMS-EXO-16-003</td>
</tr>
<tr>
<td>disappearing tracks</td>
<td></td>
</tr>
<tr>
<td>short, highly ionizing disapp. trks.</td>
<td></td>
</tr>
<tr>
<td>kinked tracks</td>
<td></td>
</tr>
<tr>
<td>fractionally charged particles</td>
<td></td>
</tr>
<tr>
<td>stopped particles</td>
<td>CMS-EXO-16-036 (2016)</td>
</tr>
<tr>
<td>delayed muons</td>
<td>CMS-EXO-16-004</td>
</tr>
</tbody>
</table>

- Many well-motivated LLP topologies have yet to be explored.
- Big discoveries could be lurking in the data, just waiting to be found!