Searches for long-lived particles at CMS

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On behalf of the CMS Collaboration

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Long-Lived particles at CMS

- **Short lifetime ($c\tau < \sim 100\text{cm}$)**
  - Displaced Leptons
  - Displaced Photons
  - Displaced Jets

- **Stable or Long lifetime ($c\tau > \sim 100\text{cm}$)**
  - Long-Lived charged particles
  - Stopped or delayed particles

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j.physletb.2013.04.027
PAS-EXO-12-038

arXiv: 1305.0491
(accepted by JHEP)
JHEP08(2012)026
Search for Displaced Jets
Displaced Jets in a nutshell

- **Signature**: \( \geq 2 \) Jets containing majority of tracks associated to a secondary vertex
- **First CMS results in this channel**
- **Full 8TeV dataset** was used: \( 18.6 \) fb\(^{-1}@8\text{TeV} \)
- **Signal Model**:
  - \( gg \rightarrow H \rightarrow XX \rightarrow (qq) (qq) \)
  - \( M_H = [200, 400, 1000] \text{GeV} \) \( M_X = [50, 150, 350] \text{GeV} \) \( c\tau_X = [3, 30, 300] \text{cm} \)
- **Expected Backgrounds**:
  - Multijet events (mostly QCD), nuclear interactions, B Hadrons, etc.

- **Dedicated Trigger**:
  - Sum Jet \( p_T > 300 \text{GeV} \)
  - \( \geq 2 \) Jets with \( p_T > 60 \text{GeV}, |\eta|<2, \leq 2 \) Prompt Tracks carrying \( \leq 15\% \) of Jet energy (\(|d_{XYZ}|<300 \mu\text{m}\))
- **Pre-Selection** → **Used to populate signal AND control regions**
  - Jet \( p_T > 60 \text{GeV}, |\eta|<2 \)
  - Build a secondary vertex (SV) using jet displaced tracks (\(|d_{XY}|>500 \mu\text{m}\))
  - SV : \( \chi^2 < 5, \text{Mass}>4 \text{GeV}, p_T>8 \text{GeV}, \text{incompatibility with Primary vertex}>8\sigma, \ldots \)
- **Selection**
  - Jet1: #(Prompt Tracks) and Jet energy fraction they carry
  - Jet2: #(Prompt Tracks) and Jet energy fraction they carry
  - Secondary vertex: Likelihood Discriminant (LD) based on 4 vertex variables (#tracks, RMS, ...)
Two variables used in the LD

\[ \int \mathcal{L} \, dt = 17 \, \text{pb}^{-1}, \sqrt{s} = 8 \, \text{TeV} \]

- Data
- QCD
- \( H(1000) \rightarrow 2X(350) \) c.t=35cm
- \( H(400) \rightarrow 2X(150) \) c.t=40cm
- \( H(200) \rightarrow 2X(10) \) c.t=20cm

Vertex Track Multiplicity vs. dijets / bin

Cluster RMS vs. dijets / bin

Data/QCD

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### Search Results

- **Background prediction:**
  - **ABCD technique** used since selection variables are uncorrelated
    - Jet1 properties
    - Jet2 properties
    - Secondary Vertex properties

- **Search**
  - **Cut&count technique** is used
  - Two selections are used
    - optimized for $L_{XY} < 20\text{cm}$
    - optimized for $L_{XY} > 20\text{cm}$
  - Data are compatible with background prediction

<table>
<thead>
<tr>
<th>$L_{XY}$</th>
<th>&lt; 20 cm (low)</th>
<th>&gt; 20 cm (high)</th>
</tr>
</thead>
<tbody>
<tr>
<td>prompt tracks</td>
<td>$\leq 1$</td>
<td>$\leq 1$</td>
</tr>
<tr>
<td>prompt energy fraction</td>
<td>$&lt; 0.15$</td>
<td>$&lt; 0.09$</td>
</tr>
<tr>
<td>vertex/cluster disc.</td>
<td>$&gt; 0.9$</td>
<td>$&gt; 0.8$</td>
</tr>
<tr>
<td>expected background</td>
<td>$1.60 \pm 0.26(\text{stat.}) \pm 0.51(\text{syst.})$</td>
<td>$1.14 \pm 0.15(\text{stat.}) \pm 0.52(\text{syst.})$</td>
</tr>
<tr>
<td>observed</td>
<td><strong>2</strong></td>
<td><strong>1</strong></td>
</tr>
</tbody>
</table>
Limits

- Limits on $\sigma(gg \rightarrow H \rightarrow XX) \times B(X \rightarrow qq) \times B(X \rightarrow qq)$
- Signal acceptance and reconstruction efficiency for $X \rightarrow qq$ are provided for results reinterpretation in different models
  - Efficiencies available for $q='uds'$, $q='c'$ and $q='b'$

$m_H = 1000\text{GeV}$
$m_X = 350\text{GeV}$

$m_H = 400\text{GeV}$
$m_X = 150\text{GeV}$

$m_H = 200\text{GeV}$
$m_X = 50\text{GeV}$

- Many more results in [PAS-EXO-12-038](#)
Long-Lived Charged Particles
Long-Lived Charged Particles

- **Signature**
  - **Heavy and (Quasi-)Stable** → Slowly moving particles ($\beta<1$)
  - **Charged** → High dE/dx in the Tracker → Long TimeOfFlight to the Muon System

- **Signal Models**
  - **Stau particles**
    - $|Q|=e$ in GMSB (SPS7)
    - $e/3 \leq |Q| \leq 8e$ pair production (neutral under SU(2)$_L$)

  - **Gluino (spit SUSY) and Stop (large gluino masses limit)**
    - Form R-hadrons containing a massive parton,
    - Large uncertainty on the hadronization model (fraction of gluino balls, $f=10\%$?) and on charge flipping
    - **Electric charge can change while interacting with the detector**
      - → Specific searches are needed
Search for particles with $|Q|=e$

- **Tracker+TOF**
  - **Global Muons**
  - $p_T + dE/dx + TOF$
  - particles staying charged

- **Tracker-Only**
  - **Tracks**
  - $p_T + dE/dx$
  - particles becoming neutral

- **Muon-only**
  - **Stand alone muon (STA)**
  - $p_T (\muon) + TOF$
  - particles becoming charged

--- HSCP
--- HSCP (becoming neutral)
--- HSCP (neutral in tracker)
Search for particles with $|Q| \neq e$

**Multiply charged particles**
- Global Muons
- $dE/dx + TOF$
- Do not use $p_T$
  - $p_T^{\text{reco}} \sim p_T^{\text{true}} / Q$

**Fractionnaly charged particles**
- Tracks
- $p_T + dE/dx$
- $dE/dx$ lower than for SM particles
- Do not use TOF to remain as inclusive as possible
The search in a nutshell

- Full datasets were used: 5.0 fb\(^{-1}\)@7TeV + 18.8 fb\(^{-1}\)@8TeV

- Triggers:
  - Mu \(p_T > 40\) → for always charged HSCPs
  - MET > 150 → for neutral or delayed HSCPs
  - STA Mu \(p_T > 70\) & MET > 65 → for neutral in tracker HSCPs (only used for Muon-only ana.)

- Pre-selection
  - Basic cleaning done to get reasonable candidates
  - Main goal is to get good control samples to be used for background prediction.
  - \(p_T > 45\text{GeV}, |\eta| < 2.1, |dxy|\) and \(|dz| < 0.5\text{cm}, \#\text{Hits} > 7\), very loose isolation, cosmic veto, etc…

- Selection
  - \textbf{Track} \(p_T\): Inner tracker transverse momentum
  - \textbf{Muon} \(1/\beta\): measured by muon system (DT+CSC):
  - \textbf{Track} \(I_{as}\): Incompatibility of the track energy loss w.r.t MIP expected \(dE/dx\)
    (Could be higher or lower \(dE/dx\) than a MIP)

- Actual thresholds optimized to lead to best discovery reach for a class of models
Background prediction

- ABCD-technique used
  - $p_T$, $dE/dx$ and $1/\beta$ variables
  - Uncorrelated for backgrounds
  - Fully correlated for signal...

- 2 or 3 variables are used
  - Tk-Only $\rightarrow p_T+dE/dx$
  - Tk+TOF $\rightarrow p_T+dE/dx+1/\beta$
  - Mu-Only $\rightarrow p_T + 1/\beta$
  - multi. charged $\rightarrow dE/dx+1/\beta$
  - frac. charged $\rightarrow p_T+dE/dx$

- For Tk-Only and Tk+TOF analyses,
  - Predict the mass spectrum using particle momentum and $dE/dx$ P.D.F.

$$dE/dx \approx K \frac{m^2}{p^2} + C$$
Results → No evidences of signal

- **Counting experiment**
- **No evidences for new physics**

<table>
<thead>
<tr>
<th>Selection criteria</th>
<th>Number of events $\sqrt{s} = 7$ TeV</th>
<th>$\sqrt{s} = 8$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T$ (GeV/c)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$I_{as}^{(t)}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$1/\beta$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass (GeV/c²)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tracker-only</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$&gt;70$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$&gt;0.4$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$&gt;0$</td>
<td>7.1 ± 1.5</td>
<td>8</td>
</tr>
<tr>
<td>$&gt;100$</td>
<td>6.0 ± 1.3</td>
<td>7</td>
</tr>
<tr>
<td>$&gt;200$</td>
<td>0.65 ± 0.14</td>
<td>0</td>
</tr>
<tr>
<td>$&gt;300$</td>
<td>0.11 ± 0.02</td>
<td>0</td>
</tr>
<tr>
<td>$&gt;400$</td>
<td>0.030 ± 0.006</td>
<td>0</td>
</tr>
<tr>
<td>Tracker+TOF</td>
<td></td>
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<tr>
<td>$&gt;70$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$&gt;0.125$</td>
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<tr>
<td>$&gt;1.225$</td>
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</tr>
<tr>
<td>$&gt;0$</td>
<td>8.5 ± 1.7</td>
<td>7</td>
</tr>
<tr>
<td>$&gt;100$</td>
<td>1.0 ± 0.2</td>
<td>3</td>
</tr>
<tr>
<td>$&gt;200$</td>
<td>0.11 ± 0.02</td>
<td>1</td>
</tr>
<tr>
<td>$&gt;300$</td>
<td>0.020 ± 0.004</td>
<td>0</td>
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<tr>
<td>Muon-only</td>
<td></td>
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</tr>
<tr>
<td>$&gt;230$</td>
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</tr>
<tr>
<td>$&gt;1.40$</td>
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<td>$&gt;0$</td>
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<td>$&gt;100$</td>
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<td>$&gt;200$</td>
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</tr>
<tr>
<td>$&gt;300$</td>
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<tr>
<td>$</td>
<td>Q</td>
<td>&gt; 1e$</td>
</tr>
<tr>
<td>$</td>
<td>Q</td>
<td>&lt; 1e$</td>
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<td>$&gt;125$</td>
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<td></td>
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<tr>
<td>$&gt;0.275$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$0.15 ± 0.04$</td>
<td>0</td>
<td>0.52 ± 0.11</td>
</tr>
<tr>
<td>0.12 ± 0.07</td>
<td>0</td>
<td>1.0 ± 0.2</td>
</tr>
</tbody>
</table>

- **Set limits on**
  - Cross-sections at 7TeV and 8TeV
  - Mass
Mass Limit Summary

- Best limits to date on several long-lived particle classes
- \( M_{\text{Gluino}} > 1322 \text{GeV} \), \( M_{\text{Stop}} > 935 \text{GeV} \)
- First CMS limits on gluino fully hadronizing into gluino balls (\( f=100\% \)).
- Many more results in arXiv: 1305.0491
Conclusion
CMS has a strong research program for Long-lived particles

**Displaced Jets (18.6fb^{-1}@8TeV )**
- First CMS results on displaced jets
- No excess observed
- Set limit on a $H\rightarrow XX\rightarrow (qq)(qq)$ (benchmark)
- PAS contains material for results reinterpretation

**Long-Lived Charged Particles (18.8fb^{-1}@8TeV + 5fb^{-1}@7TeV)**
- Analyses performed using $pT$, $dE/dx$, TOF variables
- No excess observed
- Most stringent limits to date were set on
  - Leptons with $e/3 \leq |Q| \leq 8e$
  - Gluino (split SUSY) and Stop
    - Charge flipping, 10 to 100% Gluino-balls, 2 nuclear interaction scenarios

**Results shown are available** [https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO)

**Stay tuned for more long-lived physics results**
Thank you....
Backups
Background prediction

- 3D-ABCD-technique used since the 3 selection variables are uncorrelated for backgrounds and fully correlated for signal.
  - Jet1 properties
  - Jet2 properties
  - Secondary Vertex properties
- Signal region H is predicted using control regions: \( H = \frac{BCD}{A^2} \)
  - Systematic uncertainty evaluated using other combination of regions:
    - \( H = \frac{FG}{B} \) or \( \frac{EG}{C} \) or \( \frac{EF}{D} \) or \( \frac{DG}{A} \) or \( \frac{BE}{A} \) or \( \frac{CF}{A} \)
- A control region is used to check the background prediction on data
- Consider dijet pairs that have \(<\text{# missing hits per track}> > 2\) instead of \(<\text{# missing hits per track}> < 2\) for the signal region
- A good agreement is found between data and background prediction
Systematic uncertainties on Signal Efficiency

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pile-up modelling</td>
<td>2%</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>3–5%(*)</td>
</tr>
<tr>
<td>Jet momentum bias</td>
<td>1–5%</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>6%</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>4%</td>
</tr>
<tr>
<td>Total</td>
<td>8–10%</td>
</tr>
</tbody>
</table>

CMS Preliminary, $\sqrt{s} = 8$ TeV

Data/Sim: Ks/Lxy [cm]

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Passing low and high $L_{XY}$ selections

Displaced Jets: Syst. Event Display
### HSCP: Uncertainties

- **Uncertainty is evaluated model by model**

| Signal acceptance                  | $|Q| < 1\epsilon$ | Tracker-only | Tracker+TOF | $|Q| > 1\epsilon$ | Muon-only |
|------------------------------------|------------------|--------------|-------------|------------------|-----------|
| Trigger acceptance                 | <16%             | <7%          | <7%         | <6%              | 7%        |
| Track momentum scale               | < 10%            | <4%          | < 3%        | <10%             | <10%      |
| Track reconstruction eff.          | <25%             | <2%          | <2%         | <2%              | –         |
| Ionization energy loss             | <18%             | <15%         | <12%        | –                | –         |
| Time-of-flight                     | –                | –            | <2%         | <15%             | <3%       |
| Muon reconstruction eff.           | –                | –            | 2%          | 2%               | 2%        |
| Pile-up                            | <2%              | <2%          | <2%         | <2%              | <4%       |
| Detector material                  | <1%              | <1%          | <1%         | 20%              | <1%       |
| Total signal acceptance            | <31%             | <32%         | <31%        | <29%             | <13%      |
| Expected collision bckg.           | 20%              | 20%          | 20%         | 20%              | 20%       |
| Expected cosmic ray bckg.          | 50%              | –            | –           | –                | 80%       |
| Integrated luminosity              | 2.2% (4.4%) for $\sqrt{s} = 7$ (8) TeV |             |             |                  |           |
HSCP Limit setting

- Counting experiment
  - For Tk-Only and TkTOF, counts in a mass window $[M_{\text{reco}} - 2\sigma_{\text{reco}}, +\infty]$.
  - Set limit on cross-sections (at 7 and 8 TeV) and on Signal Stength.

TK-Only

TK+TOF

Muon-Only
HSCP Limit setting

|Q| < e

|Q| = e

|Q| > e

(Stau in GMSB)

CMS √s = 7 TeV, L = 5.0 fb⁻¹ √s = 8 TeV, L = 18.8 fb⁻¹

at 95% CL limit on σ/(σ_{th})

- |Q| < e
- |Q| = e
- |Q| > e

Mass (GeV/c²)

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HSCP Limit setting

- Counting experiment
  - For Tk-Only and TkTOF, counts in a mass window $[M_{\text{reco}} - 2\sigma_{\text{reco}}, +\infty]$.

- Set limit on cross-sections (at 7 and 8 TeV) and on Signal Stength.

TK-Only

TK+TOF

Muon-Only
HSCP Limit setting

$|Q| < e$

$|Q| < 1e$  CMS  $\sqrt{s} = 8$ TeV, $L = 18.8$ fb$^{-1}$

Theoretical Prediction
- $|Q| = e/3$
- $|Q| = 2e/3$

$95\%$ CL limit on $\sigma$ (pb)

$\log_{10}(95\%$ CL limit on $\sigma$ (pb))

Mass (GeV/c$^2$)

$|Q| > e$

$|Q| > 1e$  CMS  $\sqrt{s} = 8$ TeV, $L = 18.8$ fb$^{-1}$

Theoretical Prediction
- $|Q| = 1e$
- $|Q| = 2e$
- $|Q| = 3e$
- $|Q| = 4e$
- $|Q| = 5e$
- $|Q| = 6e$
- $|Q| = 7e$
- $|Q| = 8e$

$95\%$ CL limit on $\sigma$ (pb)

$\log_{10}(95\%$ CL limit on $\sigma$ (pb))

Mass (GeV/c$^2$)