Search for long-lived particles at CMS

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Outline

• Brief introduction to long-lived particle
• Neutral long-lived particles
  – Search for displaced lepton pair CMS-PAS-EXO-11-004
  – Search for displaced photon CMS-PAS-EXO-11-067
• Heavy stable charged particles
  ▪ Stopped gluino/stop search CMS-PAS-EXO-11-020
  ▪ Slowly moving gluino/stop/stau/hyperk searches CMS-PAS-EXO-11-022
• Conclusions
Introduction
Long-lived massive particle

- **Neutral**
  - $\sim \text{cm} < \beta\gamma c\tau < \text{detector scale: non-prompt decay to}$
    - displaced leptons
    - displaced photon+X
    - displaced jets, top, W, Z.....
  - $\beta\gamma c\tau > \text{detector scale: decay outside detector}$
    - MET, covered by SUSY/DM searches.

- **Charged**
  - $\sim \text{cm} < \beta\gamma c\tau < \text{detector scale: kink/fork track}$
  - $\beta\gamma c\tau > \text{detector scale: decay outside detector or readout time window} \rightarrow \text{Heavy Stable Charged Particle (HSCP)}$

**Theoretical Motivation:**
SUSY, Extra Dimension, Hidden Valley and other BSMs.
Neutral long-lived particles searches at CMS

- displaced leptons CMS-PAS-EXO-11-004
- displaced photon CMS-PAS-EXO-11-067
**Displaced Lepton Pair**

Model considered:

\[ gg \rightarrow H^0 \rightarrow 2X, \ X \rightarrow l^+l^- \]  
\( X \) being long-lived spin 0 particle.

- Different Higgs (200-1000 GeV) and \( X \) boson (20-500 GeV) masses, with \( X \) boson lifetimes \( c\tau = 1.5-40 \) cm
- \( \text{Br}(X \rightarrow ee/\mu\mu) \) is set to 50\% each

\[
\begin{array}{c}
H^0 \\
\rightarrow \ X \\
\rightarrow \ X \\
\rightarrow \ l^+ \\
\rightarrow \ l^- \\
\rightarrow \ l^+ \\
\rightarrow \ l^- \\
\end{array}
\]
Displaced Lepton Pair

- Dataset: 1.1~1.2 fb^{-1} from 2011 run
- Trigger: di-\(\mu(e)\) each with \(p_T>33(23)\) GeV

- Displaced track reco: seeding from SST stereo layers, can reconstruct tracks missing the primary vertex by nearly half a meter

- Selection:
  - primary vertex; isolated, high purity track
  - opposite charged pair with well fitted common secondary vertex
  - collinearity angle< 0.2(0.8) between di-lepton total momentum and vector from primary to secondary vertex
  - lepton-id: only trigger matching required
Displaced Lepton Pair

- Signal MC: $H^0 \rightarrow 2X, X \rightarrow l^+l^-$
- Look for one or two displaced vertices from oppositely charged leptons, the vertex significance ($L_{xy}/\sigma$) > 8(5) (e/µ)
Displaced Lepton Pair

- Reconstructed di-lepton mass
Displaced Lepton Pair

- Background is estimated with fit in control region of MC, extrapolating to signal region
- Difference to direct MC prediction as systematic
Displaced Lepton Pair

• For $H^0 \rightarrow 2X$, $X \rightarrow l^+l^-$, selection efficiency
  – 20-30% (mu channel)
  – 10-20% (electron channel)

• Interpret 95% CL limits in mass of X boson for fixed $H^0$ mass
Displaced Lepton Pair

Limits for other H^0 masses
Displaced Photon

- GMSB motivation
- Long-lived 140 GeV neutralino with $2\text{cm} < c\tau < 25\text{cm}$
Displaced Photon

- **Dataset:** 2.1 fb\(^{-1}\) from 2011 run.
- **Trigger:** di-photon \(E_T > 32(22)\) to 40(28) GeV for leading (sub-leading) photon.
- **Offline Selection:**
  - isolated photon \(E_T > 45\) GeV; jets: \(p_T^1 > 80, p_T^2 > 50\) GeV in \(|\eta| < 2.6\); MET > 30 GeV
- **Converted photon selection:**
  - Transverse impact parameter \(d_{xy} > 0.6\) cm.
- **Background:**
  - data driven estimation

\[
d_{xy} = -L_X \cdot \sin \phi + L_Y \cdot \cos \phi \\
d_Z = L_Z - \frac{L_X \cdot p_X + L_Y \cdot p_Y}{p_T} \cdot \frac{p_Z}{p_T}
\]
Displaced Photon

d_{XY} distribution for data with MET>30 GeV vs. signal simulation for cτ = 5 cm, normalized to luminosity
Displaced Photon

- Photon $d_{XY}$ comparison for
  - non-isolated (fake) photons in low/high MET region.
  - isolated photons, fake photons in same low MET region.
- $d_{XY}$ independent of MET
- Background can be predicted using MET < 20 control sample.
Displaced Photon

- Isolated photon $d_{XY}$ for MET<20 GeV (background region) and MET>30 GeV (signal region)

Data vs background prediction
Displaced Photon

- conversion reco systematic 20% from $Z \rightarrow \mu \mu \gamma$ data-MC comparison

- 95% C.L. upper limits on neutralino productions cross section as a function of neutralino lifetime.

- Event selection efficiency vs neutralino lifetime.
Heavy Stable Charged Particles

- stopped HSCP search \textit{CMS-PAS-EXO-11-020}

- slow moving HSCP search \textit{CMS-PAS-EXO-11-022}
Model Considered:
- pair produced gluino/stop (R-hadrons)
- pair produced stau (lepton-like)
- stau from GMSB SPS7 cascade decay
- pair produced hyper-k (through DY + hyper-rho resonance)

Lepton-like HSCPs behave like (heavy) muons with large ionization energy loss

R-Hadron, also has hadronic interactions
- Charge suppression interaction scenario: all R-baryons become neutral after a hadronic interaction
HSCPs can possibly stop inside ($\beta<0.4$) or slowly escape ($0.4<\beta<0.9$) detector

**Stopped HSCP**: look for energetic hadronic jet from HSCPs decaying when beam off or during beams collisions intervals

**Slowly moving HSCP**: measure $\beta$ from delayed time of flight (T.O.F) and tracker $dE/dx$ (ionization energy loss per path length)
  - Can measure mass from $p/(\beta\gamma c)$

Two searches are complimentary
Stopped HSCP

Data Samples:
- 168 hours of trigger live-time LHC fills, peak luminosity up to $10^{33}$ cm$^{-2}$ s$^{-1}$
- 2010 data with peak luminosity of $10^{28}$~$10^{32}$ cm$^{-2}$ s$^{-1}$, as background control sample

Selection:
- dedicated 50 GeV jet trigger: no signals from beam position and timing (BPTX) monitors in a window of ±1 Bunch Crossing (BX)
- 70 GeV jet energy requirement
- beam-related, cosmic and instrumental background rejection
Stopped HSCP

Counting experiment and time-profile analysis are performed

<table>
<thead>
<tr>
<th>Lifetime</th>
<th>$L_{\text{eff}} \ (pb^{-1})$</th>
<th>Expected Bg</th>
<th>Observed</th>
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<tbody>
<tr>
<td>75 ns</td>
<td>4.3</td>
<td>$0.11 \pm 0.05$</td>
<td>0</td>
</tr>
<tr>
<td>100 ns</td>
<td>12.5</td>
<td>$0.35 \pm 0.14$</td>
<td>0</td>
</tr>
<tr>
<td>1 $\mu$s</td>
<td>139</td>
<td>$3.3 \pm 1.3$</td>
<td>4</td>
</tr>
<tr>
<td>10 $\mu$s</td>
<td>352</td>
<td>$10.1 \pm 4.1$</td>
<td>9</td>
</tr>
<tr>
<td>30 $\mu$s - $10^3$ s</td>
<td>360</td>
<td>$10.4 \pm 4.2$</td>
<td>10</td>
</tr>
<tr>
<td>$10^4$ s</td>
<td>268</td>
<td>$10.4 \pm 4.2$</td>
<td>10</td>
</tr>
<tr>
<td>$10^5$ s</td>
<td>65</td>
<td>$10.4 \pm 4.2$</td>
<td>10</td>
</tr>
<tr>
<td>$10^6$ s</td>
<td>7.5</td>
<td>$10.4 \pm 4.2$</td>
<td>10</td>
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</table>

Counting Exp.
Stopped HSCP

- **Gluino**
  - $M_{\text{gluino}} - M_{\text{neutralino}} > 100$ GeV, $\text{Br}(\text{gluino} \rightarrow g + \text{neutralino}) = 100\%$, $m_{\text{gluino}} < 601$ GeV are excluded @95% C.L. for lifetimes from 10 $\mu$s to 1000 s

- **Stop**
  - For $M_{\text{stop}} - M_{\text{neutralino}} > 200$ GeV, $\text{Br}(\text{stop} \rightarrow \text{top} + \text{neutralino}) = 100\%$, $m_{\text{stop}} < 337$ GeV are excluded @95% C.L. for lifetimes from 10 $\mu$s to 1000 s

- 95% C.L. limits are also set for cross-section $\times$ BR $\times$ stopping efficiency to be interaction model independent
Slowly Moving HSCP

4.7 fb$^{-1}$ data used with Muon40 and MET150 trigger
- Two analysis methods
  - Tracker-only (discriminator $I_{as}$ from tracker dE/dx measurement)
  - Tracker+TOF ($\beta^{-1}$ measurement from muon system in addition)
- Look for enhancement in high $I_{as}$, high $\beta^{-1}$ and high $p_T$ region.
Slowly Moving HSCP

Background estimation:
• utilizing the non-correlation between $I_\text{as}$, $\beta^{-1}$ and $p_T$,
• mass prediction from pseudo-exp, using $p$, $I_h$, and $\beta^{-1}$ PDF from non-signal region

Counting experiment:
• in mass window $[M_{\text{reco}} - 2\sigma_{M_{\text{reco}}}, 2 \text{ TeV}]$
• optimized $I_{\text{as}}$, $\beta^{-1}$ and $p_T$ selection for best reach
Slowly Moving HSCP

95% C.L. mass limits are set for

- Cloud model interaction scenario
  - Gluino (10% ~gg): 1091 GeV, Stop: 735 GeV
- Charge suppression interaction scenario
  - Gluino (10% ~gg): 923 GeV, Stop: 623 GeV

- Direct pair produced stau: 232 GeV
- hyper-kaon: 482, 599, and 747 GeV for hyper-ρ masses of 800, 1200, and 1600 GeV
Summary

• With 1-4.7 fb\(^{-1}\) integrated luminosity, CMS searched various long-lived particle signatures.
  – displaced di-lepton
  – displaced di-photon
  – stopped and slow moving HSCPs
  – **No significant excess observed**

• 95% C.L. cross section limits are set on
  – Various BSM models
  – Significant improvement over our 2010 data limits
  – **New displaced lepton/photon results**
  – new models studied for HSCP analysis

• Results shown are available
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO

*Stay tuned for more exciting long-lived particle searches*
Back Up
Displaced Lepton

- Limits for $Z'$. 

<table>
<thead>
<tr>
<th>$M_{Z'}$ or $M_{H^0}$ (GeV/c$^2$)</th>
<th>$M_X$ (GeV/c$^2$)</th>
<th>Dielectron channel</th>
<th>Dimuon channel</th>
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<tbody>
<tr>
<td>1000</td>
<td>350</td>
<td>0.86</td>
<td>0.87</td>
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<td>1000</td>
<td>150</td>
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<td>0.80</td>
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<tr>
<td>200</td>
<td>20</td>
<td>0.134</td>
<td>0.32</td>
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</table>
Displaced Lepton

- The efficiency to select \( X \rightarrow l^+l^- \) decay as a function of transverse decay length for dielectron (left) and dimuon candidates (right), shown for the case \( M_H = 1000 \text{ GeV}, M_X = 150 \text{ GeV/c}^2 \).
Displaced Lepton

- Efficiency of finding a tracker track, given a cosmic muon reconstructed in the muon chambers. Data vs. Simulation
- Good understanding of displaced track reconstruction.
### Displaced Lepton

<table>
<thead>
<tr>
<th>$M_{H^0}$ (GeV/c²)</th>
<th>$M_X$ (GeV/c²)</th>
<th>$c\tau$ (cm)</th>
<th>Dielectron channel</th>
<th>Dimuon channel</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\epsilon_1$</td>
<td>$\epsilon_2$</td>
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<tr>
<td>1000</td>
<td>350</td>
<td>11.7</td>
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<td>0.11</td>
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<td></td>
<td></td>
<td>105.0</td>
<td>0.038</td>
<td>0.045</td>
</tr>
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<td>150</td>
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<td>0.32</td>
<td>0.34</td>
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<td></td>
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<td>10.0</td>
<td>0.20</td>
<td>0.20</td>
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<td>30.0</td>
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<td>0.11</td>
<td>0.11</td>
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<td>120.0</td>
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<td>2.7</td>
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<td>0.16</td>
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<td>8.0</td>
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<td>12.0</td>
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<td>0.044</td>
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<td>50</td>
<td>6.7</td>
<td>0.018</td>
<td>0.022</td>
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<td>20.0</td>
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<td>0.11</td>
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<td>0.003</td>
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<td>2.3</td>
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<td>0.029</td>
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<td>7.0</td>
<td>0.019</td>
<td>0.019</td>
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<td></td>
<td></td>
<td>21.0</td>
<td>0.007</td>
<td>0.010</td>
</tr>
</tbody>
</table>

- Final selection efficiency of Higgs -> XX, both for events in which only one long-lived exotic decays to the chosen lepton species $\epsilon_1$ and for the case where both decay to the chosen lepton species $\epsilon_2$.

- The uncertainties on efficiencies are dominated by the 20% relative uncertainty related to the tracking performance.
Displaced Photon

- Signal selection flow for $c\tau = 5$ cm.

<table>
<thead>
<tr>
<th>Selection</th>
<th>Events in Monte Carlo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>45057</td>
</tr>
<tr>
<td>DiPhoton trigger</td>
<td>39988</td>
</tr>
<tr>
<td>Photon $E_T &gt; 45$ GeV and $E_T &gt; 30$ GeV</td>
<td>37398</td>
</tr>
<tr>
<td>Any ECAL barrel photon $E_T &gt; 45$ GeV and Photon identification</td>
<td>27766</td>
</tr>
<tr>
<td>Jets $p_T &gt; 80$ GeV and $p_T &gt; 50$ GeV</td>
<td>26229</td>
</tr>
<tr>
<td>Conversion selection</td>
<td>1602</td>
</tr>
<tr>
<td>$E_T^{\text{miss}} &gt; 30$ GeV</td>
<td>1542</td>
</tr>
<tr>
<td>$d_{XY} &gt; 0.6$ cm</td>
<td>711</td>
</tr>
</tbody>
</table>
Slow moving HSCP

- Tk+only Analysis
Previous CMS Limits

- CMS HSCP published results from 2010 dataset  
  Gluino exclusion: $m < 398, 370$ GeV/c$^2$

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