Searches for Long–lived Particles and Leptoquarks at CMS

James Hirschauer
Fermilab
(for CMS)

Implications of LHC results for TeV–scale physics
26–30 March 2012
CERN
<table>
<thead>
<tr>
<th>Search</th>
<th>Int. Luminosity</th>
<th>Documentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow HSCP</td>
<td>4.7/fb</td>
<td>EXO-11-022</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1.1/fb, 4.7 /fb coming soon)</td>
</tr>
<tr>
<td>Stopped HSCP</td>
<td>0.9/fb</td>
<td>EXO-11-020</td>
</tr>
<tr>
<td>Displaced Leptons</td>
<td>1.1/fb</td>
<td>EXO-11-004</td>
</tr>
<tr>
<td>Displaced Photons (using conversions)</td>
<td>2.1/fb</td>
<td>EXO-11-067</td>
</tr>
<tr>
<td>$2^{nd}$ Generation Leptoquarks ($\mu\mu jj, \mu\nu jj$)</td>
<td>2.0/fb</td>
<td>EXO-11-028</td>
</tr>
<tr>
<td>$3^{rd}$ Generation Leptoquarks (bb$\nu\nu$)</td>
<td>1.8/fb</td>
<td>EXO-11-030</td>
</tr>
</tbody>
</table>

**Updates in progress!**
Introduction: Long-lived Particles

- Many models of new physics predict long-lived massive particles including SUSY, Extra dimensions, Hidden valley.
- Experimentally challenging.
- Detection strategies depend on charge and $\beta\gamma\tau$:

<table>
<thead>
<tr>
<th>Charge</th>
<th>$\beta\gamma\tau$</th>
<th>Example</th>
<th>Detection Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charged</td>
<td>~cm – detector scale</td>
<td>Gluino, stop</td>
<td>Stopped HSCP: Isolated, out-of-time energy in calorimeter.</td>
</tr>
<tr>
<td>Charged</td>
<td>&gt; detector scale</td>
<td></td>
<td>Slow HSCP: Ionization (dE/dx) and time-of-flight.</td>
</tr>
<tr>
<td>Neutral</td>
<td>~cm – detector scale</td>
<td>H→XX→4l, GMSB NLSP neutralino</td>
<td>Displaced photons, Displaced leptons</td>
</tr>
<tr>
<td>Neutral</td>
<td>&gt; detector scale</td>
<td>SUSY LSP</td>
<td>Large MET</td>
</tr>
</tbody>
</table>
Slow HSCP

**Triggers:**
- Single $\mu$, MET (for charge suppression models)
- 75% (10%) efficiency for staus with $\beta = 0.6$ (0.45)

**Two selection strategies:**
- **Tracker-only**: large $dE/dx$ + large $p_T$
- **Tracker+TOF**: Tracker-only + $\mu$-like + long time-of-flight ($\beta^{-1}$ from $\mu$ system)

**Data-driven background estimation:**
From uncorrelated sidebands in $\beta^{-1}$, $dE/dx$, MIP-compatibility ($I_{as^*}$), and $p_T$ (w/ correction for $\eta$-dependence of $dE/dx$).

*Defined in backup slides.*
Slow HSCP

95% CLs mass limits for

- **R–hadrons**: gluino, stop
  - Two interaction models: *cloud* and conservative *charge suppression*
  - R–gluonball fractions: 0.1, 0.5
- **Lepton–like**:
  - *stau* (direct pair production, GMSB)
  - *Hyper-kaon* (DY+range of $M_{\text{hyper-\rho}}$)

\[
\begin{align*}
\text{Mass (GeV/c}^2) & \quad \text{(pb)} \\
\text{Theoretical Prediction} & \quad \text{CMS Preliminary } \sqrt{s} = 7 \text{ TeV } 4.7 \text{ fb}^{-1} \\
\text{Tk + TOF} & \quad \text{Tk - Only}
\end{align*}
\]

- **Kinematic threshold for resonant production.**
Stopped HSCPs

**Trigger**: 50 GeV single jet trigger with BPTX veto in triggered bunch crossing (BX) ±1 BX. 168 hours live time.

**Background rate**:
- 1.7±0.7e−5 Hz from beam-related, cosmic rays, and detector noise.
- Signal efficiency ~13%.
- Noise and cosmic rates from 2010 data (36 pb⁻¹).

**Methods**: Counting experiment and timing profile analysis (for τ<0.7ms).

**95% C.L. Limits**:

<table>
<thead>
<tr>
<th>Lifetime</th>
<th>$L_{\text{eff}}(pb^{-1})$</th>
<th>Expected $B_g$</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>75 ns</td>
<td>4.3</td>
<td>0.11 ± 0.05</td>
<td>0</td>
</tr>
<tr>
<td>100 ns</td>
<td>12.5</td>
<td>0.35 ± 0.14</td>
<td>0</td>
</tr>
<tr>
<td>1 μs</td>
<td>139</td>
<td>3.3 ± 1.3</td>
<td>4</td>
</tr>
<tr>
<td>10 μs</td>
<td>352</td>
<td>10.1 ± 4.1</td>
<td>9</td>
</tr>
<tr>
<td>30 μs - 10³ s</td>
<td>360</td>
<td>10.4 ± 4.2</td>
<td>10</td>
</tr>
<tr>
<td>10⁴ s</td>
<td>268</td>
<td>10.4 ± 4.2</td>
<td>10</td>
</tr>
<tr>
<td>10⁵ s</td>
<td>65</td>
<td>10.4 ± 4.2</td>
<td>10</td>
</tr>
<tr>
<td>10⁶ s</td>
<td>7.5</td>
<td>10.4 ± 4.2</td>
<td>10</td>
</tr>
</tbody>
</table>

**Figure 8**: /ν C₄L₄ limits on HSCP pair production cross-section times the probability of either HSCP to stop, as a function of HSCP lifetime. Including the stopping probability obtained from simulation, we then place limits on the particle production cross-section. Figures 6 and 7 show the observed /ν C₄L₄ limits on gluino and stop pair production cross-sections, for different models of R₃hadron interactions, as a function of particle lifetime assuming /ν branching ratio and fixed visible energy of m_{HSCP}−M_χ^6 > 766 GeV. The stopping probability used to construct these limits assume m_~g = 66 GeV and m_~t = 966 GeV. The variation of the limit with HSCP mass may be inferred from Figures 6 and 7.
Stopped HSCP

- 95% CL mass exclusion limits assuming $10^{-6} < \tau < 10^3$ s:
  - $m_{\text{gluino}} < 601$ GeV
  - $m_{\text{stop}} < 337$ GeV
- 95% CL limits on cross section $\times$ BR $\times$ stopping efficiency are independent of interaction model.

![Graph](image-url)

CMS Preliminary 2011

$\int L \, dt = 886$ pb$^{-1}$

$\sqrt{s} = 7$ TeV

$95\%$ C.L. Limits

- NLO+NLL $\tilde{g}$
- Obs.: $10 \, \mu$s - 1000 s Counting Exp. ($\tilde{g}$)
- Obs.: $10 \, \mu$s Timing Profile ($\tilde{g}$)
- NLO+NLL $\tilde{t}$
- Obs.: $10 \, \mu$s - 1000 s Counting Exp. ($\tilde{t}$)
- Obs.: $10 \, \mu$s Timing Profile ($\tilde{t}$)

Model Independent Cross-section [pb]

$\left[ \frac{\text{GeV}}{c^2} \right]^2$

$\int L \, dt = 886$ pb$^{-1}$

$95\%$ C.L. Limits:

- Gluino: $m_{\tilde{g}} = 500$ GeV/$c^2$, $m_{\tilde{g}} = 400$ GeV/$c^2$
- Stop: $m_{\tilde{t}} = 300$ GeV/$c^2$, $m_{\tilde{t}} = 100$ GeV/$c^2$

$\sqrt{s} = 7$ TeV

Thursday, March 29, 2012
Displaced Lepton Pair

New physics model:
• $gg \rightarrow H^0 \rightarrow 2X, X \rightarrow l^+l^-$
• $X$ is long-lived, spin 0
• Consider $200 < M_{H^0} < 1000$ GeV and $20 < M_X < 500$ GeV.
• Assume $ee/\mu\mu$ are each 50% of $l^+l^-$ width.

Selection:
• track and event quality,
• isolated tracks,
• transverse decay length significance $> 8$ (5)*,
• no back-to-back tracks,
• dilepton $p_T$ collinear with primary and displaced vertices,
• signal efficiency $= 20–30\%$ (10–20%)*

* for muon (electron)
Displaced Lepton Pair

- Background estimate from fit to MC.
- $L_{XY} \approx 4\text{cm}$ for backgrounds.
- 95% CLs cross section limits vs. $c\tau$
  - Typically $3-30\text{ fb}$ for $c\tau \approx 1\text{ meter}$.

Assume $\text{BR}(X \rightarrow \ell\ell) = 1\%$

$$m_h = 200\text{ GeV}/c^2$$
- $m_x = 50\text{ GeV}/c^2$
- $m_x = 20\text{ GeV}/c^2$
- Expected limit ($\pm 1\sigma$)

CMS Preliminary $\sqrt{s}=7\text{ TeV}\ L=1.2\text{ fb}^{-1}$

Signal Region

Entries

CMS Preliminary $\sqrt{s}=7\text{ TeV}\ L=1.2\text{ fb}^{-1}$

Cross Section $\times$ BR [pb] (95% CL)

$\mu^+\mu^-$
Displaced Photons

New physics model:
- GMSB SPS8: $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$
- $2 < \text{neutralino}\ c\tau < 25\text{cm}$
- high $p_T$ jets, MET, displaced diphotons

Conversion Reconstruction:
- Determine photon impact parameter ($d_{XY}$) from $\gamma \rightarrow \text{ee}$ conversions in tracker.
  - Complementary to analysis of timing/shape of showers in EM calorimeter (for signals with $c\tau \sim 1\text{m}$).
- Reco efficiency of 6–7%.
- $Z \rightarrow \mu\mu\gamma$ studies:
  - $\sim 20\%$ uncertainty on efficiency
  - Negligible uncertainty on $d_{XY}$ resolution.

$$d_{XY} = -L_X \cdot \sin \phi + L_Y \cdot \cos \phi$$
Displaced Photons

New physics model:
- GMSB SPS8: $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$
- $2 < \text{neutralino } c\tau < 25 \text{ cm}$
- high $p_T$ jets, MET, displaced diphotons

Conversion Reconstruction:
- Determine photon impact parameter ($d_{XY}$) from $\gamma \rightarrow \text{ee conversions in tracker}$.
  - Complementary to analysis of timing/shape of showers in EM calorimeter (for signals with $c\tau \sim 1 \text{ m}$).
- Reco efficiency of 6–7%.
- $Z \rightarrow \mu\mu\gamma$ studies:
  - $\sim 20\%$ uncertainty on efficiency
  - Negligible uncertainty on $d_{XY}$ resolution.

\[
d_{XY} = -L_X \cdot \sin \phi + L_Y \cdot \cos \phi
\]
Displaced Photons

Data-Driven Bkg. Estimation:
- Compare $d_{XY}$ in isolated/non-isolated and high-MET/low-MET regions $\rightarrow$ $d_{XY}$ shape independent of MET and isolation.
- Use low-MET control sample for background shape.

Cross section limits
- 95% CLs, 0.1–0.25 pb depending on $cT$:

![Cross section plot](image1)

![Data vs. Expected limits](image2)
Introduction: Scalar Leptoquarks

• Predicted by many BSM theories including versions of GUTs, technicolor, and superstring-inspired $E_6$.
  ‣ Natural explanation for observed quark–lepton symmetry of SM.
• Carry both baryon and lepton number.
• Assume coupling only within a single generation.
• Produced dominantly via $qq$ and $gg$ annihilation.
  ‣ Cross section determined by model-independent LQ–gluon coupling.
• Today, discuss $\mu\mu jj/\nu\nu jj$ and $bb\nu\nu$ final states.
  ‣ $eejj/evjj$ results from 2010 data; update coming soon.
2\textsuperscript{nd} Generation Leptoquarks

**Data driven background estimation:**
- Normalization for Z+jets.
- Norm and shape for \(t\bar{t}\)bar.

**Selection:**
- \(\mu\mu jj\)
  - \(p_{T\mu}>40\text{GeV}, |\eta_\mu|<2.1, p_{Tj}>30\text{GeV}\)
  - \(M_{\mu\mu}\) (remove Z+jets),
  - Scalar sum of \(\mu\mu jj\) \(p_T\),
  - Smaller \(M_{\mu j}\) in \(M_{\mu j}\)-pair that minimizes LQ–LQ mass difference.
- \(\mu\nu jj\)
  - 2nd \(\mu\) veto, electron veto,
  - \(p_{T\mu}>80\text{GeV}\),
  - MET (remove W+jets),
  - Scalar sum of \(\mu\nu jj\) \(p_T\),
  - \(M_{\mu j}\) that minimizes \(\Delta M(\text{LQ},\overline{\text{LQ}})\)
2nd Generation Leptoquarks

- Statistics dominated; background modeling systematic uncertainty is largest.

- 95% CL$_S$ limits (crosscheck with Bayesian+MCMC method).
  - $M_{LQ} > 632$ (523) GeV, assuming $\beta = 1.0$ (0.5).

![Graph 1: 2Q(1-$\beta$)$\times$$\sigma$ (pb) vs. $M_{LQ}$ (GeV)]

![Graph 2: $\beta^2$ $\times$ $\sigma$ (pb) vs. $M_{LQ}$ (GeV)]
3rd Generation Leptoquarks

- **Razor-based analysis**: Model-independent variables to search for pair-produced particles with masses larger than those of SM particles and MET.

\[
M_R \equiv \sqrt{(E_{j_1} + E_{j_2})^2 - (p^1_z + p^2_z)^2}.
\]

\[
M_T^R \equiv \sqrt{\frac{E_T(p^1_T + p^2_T) - \vec{p}_T \cdot (\vec{p}^1_T + \vec{p}^2_T)}{2}}
\]

\[
R \equiv \frac{M_T^R}{M_R}
\]
3rd Generation Leptoquarks

- **Data-driven background estimation** using R sidebands and signal-depleted samples from lepton triggers.

- Signal efficiency 1–10% for 200<\(M_{\text{LQ}}\)<600 GeV.
Summary

- CMS has an active search program for the “most exotic” new physics signals.
- Updates in progress and new analyses planned.

**HSCP Mass Limits**

- gluino, $R_{gluonball}=0.5$
- gluino, $R_{gluonball}=0.1$
- gluino, charge suppression
- stop
- stop, chg. sppn.
- stop, GMSB
- stop, pair production
- Hyper-K, $M_\rho=800\text{GeV}$
- Hyper-K, $M_\rho=1200\text{GeV}$
- Hyper-K, $M_\rho=1600\text{GeV}$
- Stopped gluino
- Stopped stop

**Leptoquark Mass Limits**

- LQ1, $\beta=1.0$
- LQ1, $\beta=0.5$
- LQ2, $\beta=1.0$
- LQ2, $\beta=0.5$
- LQ3, $\beta=1.0$

$gg \rightarrow H^0 \rightarrow 2X, X \rightarrow l^+l^-$

$\sigma \times \text{BR} < 3-30 \text{ fb for } c\tau \approx 1 \text{ meter}$

**GMSB neutralino**

$\sigma < 0.12-0.24 \text{ pb for } c\tau = 2-25 \text{ cm}$
Additional Material
As an estimator of the degree of compatibility of the observed charge measurements with the MIP hypothesis, a modified version of the Smirnov-Cramer-von Mises [18, 19] discriminant is used (the modification applied to the original form of the discriminant eliminates the sensitivity to incompatibility with the MIP hypothesis due to low ionization):

\[ I_{as} = \frac{3}{N} \times \left( \frac{1}{12N} + \sum_{i=1}^{N} \left[ P_i \times \left( P_i - \frac{2i - 1}{2N} \right)^2 \right] \right), \]

where \( N \) is the number of charge measurements in the silicon-strip detectors, \( P_i \) is the probability for a MIP to produce a charge smaller or equal to the \( i^{th} \) charge measurement for the observed path length in the detector, and the sum is over the track measurements ordered in terms of increasing \( P_i \). The charge probability density function used to calculate \( P_i \) is obtained using tracks with \( p > 5 \) GeV/c in events collected with a minimum bias trigger. Non-relativistic HSCP candidates will have the value of the discriminant \( I_{as} \) approaching unity.
Slow HSCP : \( I_h \)

The most probable value of the particle \( \frac{dE}{dx} \) is determined using a harmonic estimator \( I_h \) of grade \( k = -2 \):

\[
I_h = \left( \frac{1}{N} \sum_i c_i^k \right)^{1/k},
\]

where \( c_i \) is the charge per unit path length in the detector of the \( i \)th measurement for a given track. In order to estimate the mass \( m \) of highly ionizing particles, the following relationship between \( I_h \), \( p \), and \( m \) is assumed:

\[
I_h = K \frac{m^2}{p^2} + C.
\]

Equation 3 reproduces the Bethe-Bloch formula with an accuracy of better than 1% in the range \( 0.4 < \beta < 0.9 \), which corresponds to \( 1.1 < (\frac{dE}{dx})/(\frac{dE}{dx})_{MIP} < 4.0 \). The empirical parameters \( K \) and \( C \) are determined from data using a sample of low-momentum protons.
Table 2: Sources of systematic uncertainties and corresponding relative uncertainties.

<table>
<thead>
<tr>
<th>Source of systematic uncertainty</th>
<th>Relative uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal acceptance:</td>
<td></td>
</tr>
<tr>
<td>- Trigger efficiency</td>
<td>5</td>
</tr>
<tr>
<td>- Track momentum scale</td>
<td>&lt; 4</td>
</tr>
<tr>
<td>- Ionization energy loss</td>
<td>2</td>
</tr>
<tr>
<td>- Time-of-flight</td>
<td>2</td>
</tr>
<tr>
<td>- Track reconstruction efficiency</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>- Muon reconstruction efficiency</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>- Pile-up</td>
<td>&lt; 0.5</td>
</tr>
<tr>
<td>Total uncertainty on signal acceptance</td>
<td>7</td>
</tr>
<tr>
<td>Expected background</td>
<td>10</td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td>4.5</td>
</tr>
</tbody>
</table>
Displaced Lepton Pair

- Electron channel results

CMS Preliminary $\sqrt{s}=7$ TeV $L=1.1$ fb$^{-1}$

Assume $\text{BR}(X \rightarrow \ell\ell) = 1\%$

Expected limit (± 1 σ)
$3^{rd}$ Gen LQ : Data Samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>$R^2$ cut</th>
<th>leptons</th>
<th># $b$-tagged jets</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>W/Z MC</td>
<td>$R^2 &gt; 0.07$</td>
<td>tight $\mu$</td>
<td>$\geq 2$</td>
<td>shape of $W/Z+HF$ jets</td>
</tr>
<tr>
<td>MU</td>
<td>$R^2 &gt; 0.14$</td>
<td>tight $\mu$</td>
<td>$\geq 2$</td>
<td>shape of $t\bar{t}+jets$</td>
</tr>
<tr>
<td>MU</td>
<td>$R^2 &gt; 0.14$</td>
<td>loose $\mu$</td>
<td>$\geq 1$</td>
<td>shape of HF multijets</td>
</tr>
<tr>
<td>ELE</td>
<td>$0.2 &lt; R^2 &lt; 0.25$</td>
<td>tight $e$</td>
<td>$= 1$</td>
<td>$M_R &lt; 600$, sideband to extract $SF_{ELE}$</td>
</tr>
<tr>
<td>ELE</td>
<td>$R^2 &gt; 0.25$</td>
<td>tight $e$</td>
<td>$\geq 2$</td>
<td>ELE “signal-like” control region</td>
</tr>
<tr>
<td>HAD</td>
<td>$0.2 &lt; R^2 &lt; 0.25$</td>
<td>veto leptons</td>
<td>$= 1$</td>
<td>$M_R &lt; 600$, sideband to extract $SF_{HAD}$</td>
</tr>
<tr>
<td>HAD</td>
<td>$R^2 &gt; 0.25$</td>
<td>veto leptons</td>
<td>$\geq 2$</td>
<td>signal box, search for LQ signal</td>
</tr>
</tbody>
</table>

Table 1: Summary of various samples used in the search, with a short description of their specific purpose. $M_R > 400$ is always applied in all boxes. The cuts on $R^2$ listed in the table are after recalculating $E_T$ and $R$ when leptons are treated as neutrinos. Definitions of muons ($\mu$) and electrons ($e$) are listed in Sec. 3.1.