Search for Heavy Resonances with CMS

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On behalf of the CMS collaboration

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OUTLINE

Searches for:

1. **Narrow, new resonances (Z', RS)**
   - EXO-11-009 with 4.7 fb$^{-1}$ (dileptons)
   - EXO-11-061 with 4.7 fb$^{-1}$ (jet + MET)

2. **Heavy, charged bosons W'**
   - EXO-11-024 with 4.7 fb$^{-1}$ (lv)
   - EXO-11-041 with 4.7 fb$^{-1}$ (WZ)

3. **2nd generation Leptoquarks**
   - EXO-11-028 with 2 fb$^{-1}$

4. **3rd generation Leptoquarks**
   - EXO-11-030 with 1.8 fb$^{-1}$

5. **Summary**
High $p_T$ Muon Selection

High redundancy of mu system, 4 stations along track
Iron between stations may cause bremsstrahlung
for O(TeV) muons
$p_T$<200 GeV tracker in B=3.8T, $p_T$>200 GeV mu+tracker

Dedicated muon selection:

- Special algorithm to consider showering
- At least 1 pixel hit
- Number of measured tracker layers $>8$
- Transverse impact parameter $d0 < =0.2\text{cm}$
  $(Z')$, $0.02\text{cm}$ $(W')$ reject cosmics, value for $W'$ tighter than
  other analyses, $Z'$ rejects in addition back-to-back muons
- $\geq 2$ matched muon segments
- Relative track isolation $<0.10$ in $\Delta R < 0.3$
- No cut on chi2 cut introduces a 4-6% inefficiency for
  muons $>500$ GeV
High Energy Electron Selection

ECAL made of matrix of fully active crystals. Measured energy resolution \( \sim 2\% \)

Electrons are reconstructed from energy clusters in the ECAL and tracks from the silicon tracker. Electron ID optimized for high \( E_T \) requires:

- \( E_T > 85 \) GeV
- \( |\eta| < 1.442 \) (barrel) or \( 1.56 < |\eta| < 2.5 \) (endcap)
- Good quality of track and cluster
- Matching between the two
- Isolation
Signature: two isolated high energy electrons or two isolated, opposite-sign muons; forming a resonance

Also searches with dijets and boosted top-pairs, see other CMS talks
Assume **similar decays as for Standard Model** (plus decay into top quarks)

**Generic** search for new physics: extra high-mass **resonances** in dilepton spectrum: e.g. new gauge bosons $Z'$, Randall-Sundrum gravitons (RSG)

**Channels**

$Z' \rightarrow \text{ee}$

$Z' \rightarrow \mu\mu$

**Signature**

- **Z'**
  - RS
  - $q'\rightarrow e$
  - $q'\rightarrow \mu^+$

- **RS**
  - $q\rightarrow e$
  - $q\rightarrow \mu^-$

- **Signature**
  - two isolated high energy electrons
  - two isolated, opposite-sign muons

**Forming a resonance**

**Triggered by single lepton** trigger with increasing threshold

**One common offline** $p_T$ cut, above highest trigger threshold

**BR ~8% per channel**
Method of Analysis

- Use **dedicated high** $p_T$ **lepton ID** to avoid mis-reconstruction
- Reconstruct **invariant mass** $M_{ll}$
- Search for **generic excess** in invariant dielectron and dimuon mass spectra
- Many studies concerning efficiencies etc. at such high invariant masses

Generic shape-based search: no assumptions on absolute background rate, with **results normalized to the Z$^0$ peak**

Differences $\rightarrow$ small extra systematic uncertainties.

$$\frac{\sigma \times BR(Z')}{\sigma \times BR(Z^0)} = \frac{N(Z')}{N(Z^0)} \times \frac{A(Z^0)}{A(Z')} \times \frac{\epsilon(Z^0)}{\epsilon(Z')}$$
Sources of Background

Dominant irreducible SM DY
- From POWHEG MC, normalized to data at Z-peak
- PDF uncertainties 5-20%

Jets faking electrons (ee)
- From $\gamma$-triggered events. Subtract $W/\gamma$+jets using MC.
- Ratio GSF/HEEP
- Max. fake rate ~2% (barrel), 3% (EC). Decreasing with $E_T$

Cosmics ($\mu\mu$)
- Largely reduced by back-to-back cut

emu method
Data-MC comparison incl. SF, no charge req.

tt and tt-like background
- main bkgr in $M_{ll}$ tail
- With emu method from MC
- Shape and normalization checked in data
4.7/fb Dielectron mass spectrum

- At least one electron has to be in the barrel
- 70% acceptance * efficiency
- Main background due to DY, NLO uncertainties ~6%, PDF uncertainties <20%
- Some contribution from tt and jets faking electrons

The uncertainties on the data points (statistical only) represent 68% confidence intervals for the Poisson means.
4.9/fb Dimuon mass spectrum

CMS PAS EXO-11-019

- Taking full acceptance, up to $\eta<2.4$
- 85% acceptance * efficiency
- Main background due to DY, NLO uncertainties like electron channel

The uncertainties on the data points (statistical only) represent 68% confidence intervals for the Poisson means.
Exclusion limit on ratio of cross sections using Bayesian method.

- Cross check with simple cut-and-count method

**Limit input:**
- Bkgr shape (exponential above Z-peak), 15% error [200-2000]
- Z peak [60-120] ~0.5 mill events, 10% acc x eff
- $\Delta M$ as function of mass

Also search for excess. LEE by bkgr-only pseudoexperiments

- Highest local significance at M=963 GeV is 2.4 going down to 0.3 when including LEE

<table>
<thead>
<tr>
<th>model</th>
<th>exclude mass (GeV/c²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSM $Z'$</td>
<td>2120</td>
</tr>
<tr>
<td>$Z'_{\Psi}$</td>
<td>1805</td>
</tr>
<tr>
<td>RS Grav ($k/M_{pl} = 0.1$)</td>
<td>1950</td>
</tr>
<tr>
<td>RS Grav ($k/M_{pl} = 0.05$)</td>
<td>1630</td>
</tr>
</tbody>
</table>
Exclusion limits

Same strategy as electrons adapted to muon channel.

\[ R_\sigma = \text{ratio of xsec } Z' / Z \]

Limit input:
- Exponential bkgr shape
- \#Z from pre-scaled trigger ~700, 27% acc x eff
- \( \Delta M \) as function of mass, lower for muons

Excess search:
Highest local significance at \( M=1004 \) GeV at 1.2 which reduces to -0.7 when incl. LEE
Combined Exclusion Limit 95\% C.L.

CMS preliminary

\[ \mu^+ \mu^- (4.9 \text{ fb}^{-1}) \]

- median expected
- 68\% expected
- 95\% expected
- \( Z_{\text{SSM}}' \)
- \( Z_{\psi}' \)
- \( G_{\text{KK}} \ k/M_{\text{Pl}} = 0.1 \)
- \( G_{\text{KK}} \ k/M_{\text{Pl}} = 0.05 \)
- \( Z_{\text{Stu}}' \ c = 0.02 \)
- \( Z_{\text{Stu}}' \ c = 0.03 \)
- \( Z_{\text{Stu}}' \ c = 0.04 \)
- \( Z_{\text{Stu}}' \ c = 0.05 \)
- \( Z_{\text{Stu}}' \ c = 0.06 \)

- 95\% C.L. limit

\[ \frac{1}{\sigma} \times 10^{-4} \]

\[ 500 \quad 1000 \quad 1500 \quad 2000 \quad 2500 \]

\[ M [\text{GeV}] \]

\[ M_{\mu^+ \mu^-} \quad M_{ee} \quad M_{ll, \text{combined}} \]

\begin{align*}
Z_{\text{SSM}}' & : 2150 \quad 2120 \quad 2320 \\
Z_{\phi}' & : 1830 \quad 1810 \quad 1990 \\
G_{\text{KK}}, c = 0.1 & : 1980 \quad 1940 \quad 2140 \\
G_{\text{KK}}, c = 0.05 & : 1620 \quad 1630 \quad 1810
\end{align*}
RS graviton $G^* \rightarrow ZZ \rightarrow qar{q}var{v}$ with boosted $Z$ yielding signal of jet + MET

Search is signature oriented, RS model serves as a benchmark model

- Trigger: jet + MET (fully efficient for $p_T > 200$ GeV, MET > 300 GeV)
- Signal: single jet (particle flow jet, $M_{\text{inv}} \sim Z$) and MET

Use correlation $m_J - M_T(j-MET)$ to suppress SM background
RS graviton $\rightarrow$ Jet + MET

95% C.L. exclusion limits

Systematic uncertainties $\sim$5% (4% PDF, 1% JES, 3% MET)

$\sigma \times BR$ (pb)

$\int L \, dt = 4.7 \, fb^{-1}, \, \sqrt{s} = 7 \, TeV$

$G^*, k/M_{pl} = 0.1$

$G^*, k/M_{pl} = 0.2$

$G^*, k/M_{pl} = 0.3$

$\mathcal{O}(M_{pl})$ coupling to SM

$m_G = \text{Mass of lightest Graviton excitation}$
Analysis 1) **no interference with SM W** (right-handed W'). Signal samples generated individually with PYTHIA6. Limit = f(m_{W'})

Analysis 2) including W-W' **interference**. Signal samples are generated with Madgraph as W+W' \rightarrow requires M_{T} threshold. Cross section limit as function of MT threshold.
For experimental search:

- Assume **SM-like couplings**
  (+ tb-channel), \(\sim8\%\) per channel
- SM-like coupling strength \(g'/g_{SM}\) \(\sim1\)
- Impact of detector resolution.

Channels: \(W' \rightarrow e\nu\) and \(W' \rightarrow \mu\nu\)

\(W' \rightarrow\) dijets see hadronic talk

<table>
<thead>
<tr>
<th>M(W') [TeV]</th>
<th>NNLO xsec x BR W'(\rightarrow)lv</th>
<th># Events for 4/fb full MT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.88 pb</td>
<td>3520</td>
</tr>
<tr>
<td>1.5</td>
<td>0.095 pb</td>
<td>380</td>
</tr>
<tr>
<td>2.0</td>
<td>0.0135 pb</td>
<td>54</td>
</tr>
<tr>
<td>3.0</td>
<td>0.00071 pb</td>
<td>2.8</td>
</tr>
</tbody>
</table>
Analysis Cuts


Kinematic cuts in addition to e/mu selection:

- Only 1 lepton with $p_T > 45$ GeV or high quality electron with $E_T > 85$ GeV.
- $0.4 < p_T/MET < 1.5$
- $\Delta \phi(p_T, MET) > 2.5$

Analysis also possible with only the lepton signal, ~10% less sensitivity
Methods:

- **Fit to data.** Fit lower $M_T$ sideband ($M_T \sim 200 - 650$ GeV) with different functions and varying sideband width. Uncertainties: from variations + extrapolation uncertainty + fit errors.

- **Fit full** $M_T$ distribution (up to 2500 GeV) with simulation. Normalization from data. Uncertainties from fit.
Average signal efficiency ~80% including ~90% geometrical acceptance

<table>
<thead>
<tr>
<th>$M_T$ &gt; [GeV]</th>
<th>Data</th>
<th>SM expected from bkgr fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$600$</td>
<td>$83$</td>
<td>$76.7 +/- 10.5$</td>
</tr>
<tr>
<td>$700$</td>
<td>$41$</td>
<td>$37.51 +/- 4.9$</td>
</tr>
<tr>
<td>$800$</td>
<td>$22$</td>
<td>$20.0 +/- 2.7$</td>
</tr>
<tr>
<td>$900$</td>
<td>$12$</td>
<td>$11.4 +/- 1.6$</td>
</tr>
<tr>
<td>$1000$</td>
<td>$8$</td>
<td>$6.8 +/- 1.1$</td>
</tr>
<tr>
<td>$1100$</td>
<td>$6$</td>
<td>$4.3 +/- 0.8$</td>
</tr>
<tr>
<td>$1200$</td>
<td>$3$</td>
<td>$2.8 +/- 0.6$</td>
</tr>
</tbody>
</table>
Acceptance * efficiency ~80%, comparable to electron channel

<table>
<thead>
<tr>
<th>Mt &gt; [GeV]</th>
<th>600</th>
<th>700</th>
<th>800</th>
<th>900</th>
<th>1000</th>
<th>1100</th>
<th>1200</th>
<th>1300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>62</td>
<td>36</td>
<td>16</td>
<td>11</td>
<td>6</td>
<td>4</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>SM expected from bkgr fit</td>
<td>67.9+/7.6</td>
<td>32.6+/5.0</td>
<td>17.0+/3.3</td>
<td>9.5+/2.3</td>
<td>5.6+/1.6</td>
<td>3.4+/1.1</td>
<td>2.2+/0.8</td>
<td>1.5+/0.6</td>
</tr>
</tbody>
</table>
Max. $M_T$ Event ($M_T \sim 2.4$ TeV, $\mu \nu$)

Uncertainty on muon $p_T \sim 70$ GeV, on $M_T \sim 130$ GeV

Jet 1, $p_T$: 44.5 GeV
Jet 2, $p_T$: 43.9 GeV
$p_f$Jet: 1204.6 GeV
Muon Cocktail $p_T$: 1195.6 GeV
Exclusion Limits 95% C.L.

- Single bin counting experiment
  - Search window optimized for **best expected limit** for each mass point
  - Optimization independently in each channel

Limits per channel $\sim 2.4$ TeV

Combining LLH of both channels ($W'\rightarrow ev$ and $\mu\nu$) $\sim 2.5$ TeV

Systematic uncertainties on signal mainly related to detector performance. Largest contributions from mu and MET resolution (10% each, impact on signal $<0.5\%$)

In orange: Interpretation in terms of UED

$W' \ xsec \ NNLO \ with \ mass-dependent \ k-factor$

$\mathcal{BR}(W' \rightarrow e/\mu + v) (fb)$

$\mathcal{BR}(W' \rightarrow e/\mu + v) (fb)$

CMS Preliminary

$\sqrt{s} = 7$ TeV

$\int L dt = 4.7 \ fb^{-1}$

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Including W-W' Interference

- If W' is left-handed, expect interference with SM W → modulation of transverse mass spectrum and impact on mass limits (~10%)
- First time simulated and considered in leptonic W' channels (Madgraph)

![Graph showing cross section vs. M_T](image)

No interference, model used until now by Tevatron and LHC

Destructive interference would impact SM W-tail
Channel (with public result):
\[ WZ \rightarrow \ell^+ \nu \ell'^+ \ell'^- (\ell, \ell' = e, \mu) \]

Recently added channels:
\[ WZ \rightarrow lljj, W\gamma \rightarrow e\nu\gamma \]

Clear signature of three high momentum leptons (e,\(\mu\))
$W' / \rho_{TC} \rightarrow WZ \rightarrow 3 \text{ leptons} + \text{MET}$

For experimental search

- **For $W'$ complementary** to lepton channels (e.g. fermiophobic models). Assume WZ as an additional channel.
- $\text{BR} \sim 2x$ less than $W' \rightarrow l\nu$. Further reduced by requiring leptonic decay of $W,Z$
- Signal generated individually in PYTHIA, no interference
- Same k-factors as $W' \rightarrow l\nu$

- **“Technicolor Strawman Model” (TCSM)**
  - $M(\rho_{TC}) < 1 \text{ TeV}$
  - $M(\rho_{TC}) \sim M(\pi_{TC}) \rightarrow \text{BR}(\rho_{TC} \rightarrow WZ) \sim 100%$
  - $\Gamma < 5 \text{ GeV}$, $\rho_{TC}$ much narrower than $W'$

**Main background is SM diboson** production. CMS diboson xsec measurement used for background prediction (spin-off).
Analysis Steps

Remove everything but SM WZ. Then add further cuts to suppress SM WZ.

- Reconstruct Z mass [60-120] for 1 Z
- Reconstruct W $M_T$ 
- Reconstruct $M_{WZ}$. WZ accounts for 90% of bkgr. Good agreement data-MC

- To discriminate signal from bkgr:
  $$H_T \equiv \sum p_T^\ell$$

- Search for bump in WZ mass distr.
- Optimize search window for W' masses
Exclusion Limits 95\% C.L.

CMS PAS EXO-11-041

CMS Preliminary 2011

Mass of $W'$ or Technicolor rho

Technicolor parameter space

CMS Preliminary 2011

$\sqrt{s} = 7 \text{ TeV}$

$\int L \, dt = 4.7 \text{ fb}^{-1}$
2nd generation Leptoquarks
EXO-11-028 with 2 fb⁻¹

3rd generation Leptoquarks
EXO-11-030 with 1.8 fb⁻¹

Signatures:
2nd generation: $\mu^+\mu^- + \text{jets}$, $\mu \nu + \text{jets}$

3rd generation: $\nu_\tau \bar{\nu}_\tau + \text{b-jets}$, using Razor variable

1st generation: $e^+e^- + \text{jets}$, $e \nu + \text{jets}$ (released soon for 2011)
2nd Generation LQ, Strategy

Object reconstruction and event selection $\mu\mu jj$ channel:

- **Muons** as before, with $p_T > 40$ GeV, separated by $\Delta R > 0.3$
- **Particle flow jets** (see hadronic talk) with anti-$k_T$ algorithm $R=0.5$, $p_T > 30$ GeV
- Scalar sum $S_T (\mu\mu jj) > 250$ GeV
- Optimize for each LQ mass:

  ![Table 1: Optimization thresholds for different mass hypothesis of the $\mu\mu jj$ signal.](image)

Event selection $\mu\nu jj$ channel where different from above:

- **MET** > 45 GeV. Veto events with 2nd muon or electron.
- MET separated from leading jet by $\Delta \phi > 0.5$ and from muon by $\Delta \phi > 0.8$

  ![Table 2: Optimization thresholds for different mass hypothesis of the $\mu\nu jj$ signal.](image)

e$\mu jj$ for ttbar background (emu method see $Z'$)
After Final Selection 2/fb

**μμjj channel**

![Graph showing the distribution of events after selection for the μμjj channel.](image)

**μνjj channel**

![Graph showing the distribution of events after selection for the μνjj channel.](image)

Main background after selection Z+jets and ttbar
Statistical analysis using CLs modified frequentist approach
Syst. Uncertainties on $\mu \mu jj$ ~28% (dominated by bkgr modelling).
In $\mu \nu jj$ channel ~30% (mainly JES)
**Signal:** LQ LQ $\rightarrow$ $v \, v \, b \, b = 2$ b-jets and MET

- Jets reconstructed with anti-kT ($R=0.5$). Forcing them into two “mega-jets” with $E_{j1}$ and $E_{j2}$ taking the combination where $M_{\text{inv}}$ is minimal.
- Include b-tagging (“track counting high efficiency”)
- Define dimensionless **Razor kinematic variable** $M_R$ incl. MET (PF MET) without assumptions on MET shape or details of decay chain.
- Reduce QCD by $R>\text{threshold}$. For signal $\max R=1$ and distribution peaks $\sim 0.5$, while QCD peaks $\sim 0$.

**Razor dimensionless ratio**

$$R = \frac{M^R}{2} = \frac{\sqrt{E_T (p_T^1 + p_T^2) - p_T^1 \cdot p_T^2}}{2}$$

$$M_R = \sqrt{(E_{j1} + E_{j2})^2 - (p_Z^1 + p_Z^2)^2}$$

- Set threshold on $R^2>0.25$ (and higher) and $M_R>400$ GeV
Search Strategy

Define “boxes” of

- **MU or ELE**: with one loose lepton with $p_T > 20$ GeV, $M_R > 400$ GeV and $R^2 > 0.14$ plus 2 jets with $p_T > 60$ GeV
- **HADRONIC**: without leptons, $M_R > 400$ GeV and $R^2 > 0.2$
- Use **lepton boxes for background determination** and control regions
- Shapes for $R$, $M_R$ for main backgrounds (heavy flavor QCD, tt) from data

Search **signal in Hadronic** with $R^2 > 0.25$ (and increasing for larger LQ masses) and at least 2 b-tagged jets and no leptons

<table>
<thead>
<tr>
<th>LQ3 mass</th>
<th>$R/M_R$</th>
<th>Expected Number of Events</th>
<th>Observed Number of Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>$M_R &gt; 400$, $R^2 &gt; 0.25$</td>
<td>$326.98 \pm 30.98$</td>
<td>295</td>
</tr>
<tr>
<td>330</td>
<td>$M_R &gt; 400$, $R^2 &gt; 0.30$</td>
<td>$195.49 \pm 25.58$</td>
<td>172</td>
</tr>
<tr>
<td>340</td>
<td>$M_R &gt; 400$, $R^2 &gt; 0.35$</td>
<td>$121.88 \pm 21.51$</td>
<td>107</td>
</tr>
<tr>
<td>340</td>
<td>$M_{LQ}$ [GeV]</td>
<td>Signal Efficiency</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>$0.64 \pm 0.08$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>$1.85 \pm 0.22$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>280</td>
<td>$3.04 \pm 0.36$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>320</td>
<td>$5.29 \pm 0.62$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>340</td>
<td>$4.96 \pm 0.58$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>450</td>
<td>$9.64 \pm 1.11$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>600</td>
<td>$11.38 \pm 1.32$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Largest uncertainties from b-tagging (~10%).
Signal PDF 3.5% to 26% (depending on LQ mass)
SUMMARY

Many searches for new heavy resonances beyond SM (Z’, RS, W’, LQ) ongoing in CMS.

No indications for new physics yet...

<table>
<thead>
<tr>
<th></th>
<th>95% C.L. exclusion</th>
<th>Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z’$_{SSM}$</td>
<td>2.3 TeV</td>
<td>ee + $\mu\mu$</td>
</tr>
<tr>
<td>Z’$_{\phi}$</td>
<td>2.0 TeV</td>
<td>ee + $\mu\mu$</td>
</tr>
<tr>
<td>W’</td>
<td>2.5 TeV 1.2 TeV</td>
<td>ee + $\mu\nu$, WZ$\rightarrow$ leptons</td>
</tr>
<tr>
<td>G$_{KK}$</td>
<td>2.1 TeV (c=0.1)</td>
<td>ee + $\mu\mu$</td>
</tr>
<tr>
<td>$\rho_{TC}$ TCSM</td>
<td>0.7 TeV</td>
<td>WZ</td>
</tr>
<tr>
<td>LQ 2$^{nd}$ GEN</td>
<td>0.6 TeV (\beta=1), 0.5(\beta=0.5)</td>
<td>$\mu\mu jj$, $\mu \nu jj$</td>
</tr>
<tr>
<td>LQ 3$^{rd}$ GEN</td>
<td>0.35 TeV (\beta=0)</td>
<td>$\nu\nu jj$</td>
</tr>
</tbody>
</table>

Projections for 2012: increase to 8 TeV and roughly tripling the statistics.