“Search for Large Extra Dimensions, Leptoquarks and Heavy Quarks at CMS”

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For the CMS Collaboration

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Outline

✦ Brief introduction and search for large extra dimensions (LED) at CMS:
  ✤ Di-photon, di-electron and di-muon production
  ✤ Photon+MET and jet+MET final states

✦ Introduction and searches for leptoquarks

✦ Heavy quark searches:
  ✤ Di, tri-lepton and lepton+jet channel
  ✤ $t'/b'$ inclusive searches and
  ✤ vector-like quark production

✦ Summary and future prospects

Results in this talk are also available as public results of CMS at the following link:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
Large Extra Dimension (LED)


- Large extra dimensions can explains the large difference between the Plank and electroweak scale, the so-called hierarchy problem

- Gravity could propagate in these extra dimensions while SM particles in 4D space-time

- Introduce a new scale $M_D$:
  \[ M_{Pl}^2 = M_D^{n+2} R^n \]

- At $M_D \sim M_W$, the observed large value of $M_{Pl}$ is only a consequence of large $R$ and it depends on $n$ extra dimensions
The visible signal is two high \( P_T \) isolated photons with modest backgrounds.

Look for excess of events in diphoton invariant mass for ADD.

**ADD Limits:** \( M_s > 2.3-3.8 \) TeV

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**Figure:**
- Plot showing CMS exclusion limits for \( M_\text{eff} \) and coupling \( K \) at 7 TeV.
- Graph displaying CMS data with observed and expected distributions for dijet, diphoton, and \( \gamma+\text{jet} \) channels.

**References:**
Di-lepton Search: LED

- Isolated muons and electrons
  - for di-electron: Opposite charges and at least one barrel electron
  - for muon channel no such requirement

- Non-DY background contributions are small and include: $t\bar{t}$, $\gamma$+jet, $W$+jet etc..

- For DY simulated background the correction factors are estimated in the signal region:
  - Radiation effect, QCD correction (NNLO)

- Main source of systematic uncertainty: PDF and higher orders for DY

**ADD limits: $M_s > 2.5$-$3.8$ TeV**

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CMS Search in 2.3 fb$^{-1}$

**Figures:**
- Data distribution for $M_{\mu\mu}$
- ADD limits for different $n$ values

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CMS EXO-11-087, Accepted by PLB

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Tuesday, March 27, 2012
Photon+MET : LED

- Clean signal with $P_T$ high photon and large missing-$E_T$
- $qqbar \rightarrow \gamma G$

- Event counting to look for an excess in $P_T$ or Missing-$E_T$
- SM $Z(\nu\nu)\gamma$ production is main background, rest comes from QCD, non-collision sources

$\int Ldt = 4.7 \text{ fb}^{-1}$

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

$\sum p_T^\gamma [\text{GeV}]$

$\int Ldt = 4.7 \text{ fb}^{-1}$

CMS Preliminary

$\sum p_T^\gamma [\text{GeV}]$

$\int Ldt = 4.7 \text{ fb}^{-1}$

CMS Preliminary

$\sum p_T^\gamma [\text{GeV}]$

$\int Ldt = 4.7 \text{ fb}^{-1}$

CMS LO ($\gamma + E_T$)

CMS NLO ($\gamma + E_T$)

CDF ($\gamma + E_T$)

D0 ($\gamma + E_T$)

LEP ($\gamma + E_T$)

Lower Limit on $M_{\text{XP}} [\text{TeV}]$

Number of Extra Dimensions

$\sum p_T^\gamma [\text{GeV}]$

$\sum p_T^\gamma [\text{GeV}]$

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$\sum p_T^\gamma [\text{GeV}]$
Jet+ MET : LED

CMS Search in 4.7fb⁻¹

✧ Relatively large production and clean final state with high \( P_T \) jet and large missing-\( E_T \)
✧ \( q\bar{q} \rightarrow gG, qg \rightarrow qG, gg \rightarrow Gg \)
✧ Main background: \( Z \rightarrow \nu\nu \) and \( W+\)jets

✧ \( M_D > 2.49 - 4.44 \) TeV for \( n_{ED} = 2-6 \)

\[ \sigma \left( \frac{pb}{f b} \right) \]

\[ \int L dt = 4.7 \, fb^{-1} \text{ at } \sqrt{s} = 7 \, TeV \]

\[ M_D [TeV/c²] \]

\[ E_T^{miss} [GeV] \]

\[ \nu\nu \rightarrow Z \nu \rightarrow Wt \]

\[ \nu\nu \rightarrow Z \nu \rightarrow Wt \]

\[ qq \rightarrow gG, qg \rightarrow qG, gg \rightarrow Gg \]

\[ Z \rightarrow \nu\nu \] and \( W+\)jets
Leptoquark Searches at CMS

✧ Possibility of a fundamental relationship between quarks and leptons through leptoquarks
  ✧ they are colored and have fractional charge
  ✧ couples to quarks and leptons with coupling $\lambda$
  ✧ branching fractions are denoted as: $\beta(lq)$ and $1 - \beta (vq)$

✧ CMS searched for all 3 generation of leptoquarks with following final states:
  ✧ $llqq$ ($\beta = 1$) where $l = e, \mu$
  ✧ $lvqq$ ($\beta = 0.5$)
  ✧ $bb\nu\nu$

✧ Limits are set on mass of leptoquarks ($M_{LQ}$)
1st Generation Scalar Leptoquarks

- Isolated electron + missing-\(E_T\)
- Main bkg: ttbar, W+jets (for evqq)
  ttbar, Z+jets (for eeqq)

\[ S_T = P_{T(l_1)} + P_{T(l_2)} + P_{T(j_1)} + P_{T(j_2)} \]

- Limits: \(M_{LQ} > 339 \text{ GeV (384 GeV)}\) for evqq (eeqq)

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PRL 106, 201802 (2011)
2\textsuperscript{nd} Generation Scalar Leptoquarks

Final state: $\mu\muqq$ and $\mu\nuqq$

- $P_T(\mu) > 40$ GeV, $P_T(\text{jets}) > 30$ GeV

In addition for $\mu\nuqq$ channel:

- Veto on 2nd muon and 3rd jet and electron
- $\text{missing}-E_T > 45$ GeV

- The dominant backgrounds are estimated from data

- Multi-jet QCD background is negligible in both final states

Limits:

- $M_{LQ} > 632$ GeV for $\beta=1.0$
- $M_{LQ} > 523$ GeV for $\beta=0.5$
3rd Generation Scalar Leptoquarks

**Final state: bbνν**

- Used *razor* variable $R \equiv \frac{M^R_T}{M_R}$
  
  $$M_R \equiv \sqrt{(E_{j1} + E_{j2})^2 - (p_T^{j1} + p_T^{j2})^2}$$
  
  $$M^R_T \equiv \sqrt{\mathcal{H}_T(p_T^{j1} + p_T^{j2}) - \mathcal{H}_T \cdot (\mathcal{p}_T^{j1} + \mathcal{p}_T^{j2})}$$

- Designed to search for a pair of “heavy particles”

- 2 b-tagged jets

- Main Bkg: 1) Heavy Flavor (HF) Multi-jet
  2) ttbar+jets and W/Z+HF jets

- Systematics: background shape and b-tagging efficiency

**Limit:** $M_{LQ} > 350$ @ 95%CL
Heavy Quarks

✦ SM Extension?: Adding one more generation of quarks is an obvious extension of SM and is also not fully excluded by electroweak precision data

✦ Due to heaviness of this new generation of quarks the CP violation can be boosted by large factor and could resolve the matter-antimatter asymmetry in the universe

Decay signatures for direct searches:
✦ $t' \rightarrow bW$, $b' \rightarrow tW(bWW)$: complex final state, $b' \rightarrow qW$
✦ With small mass splitting: $|M_{t'} - M_{b'}| < M_W$
$t' \bar{t}' \rightarrow W^+ bW^- \bar{b} \rightarrow l^+ \nu b l^- \bar{\nu} b$

✦ Signal: 2 leptons + 2 b-jets + missing-$E_T$

✦ Reconstruct "$b$-jet + lepton" masses

$M_{t'} > 552$ GeV @95% CL

CMS Search in 4.7 fb$^{-1}$
Reconstruction of a pair of “heavy tops”:
- 1 lepton + 4 jets + at least 1 b-jet + missing-\(E_T\)

Kinematic fit is applied for mass reconstruction (\(M_{\text{fit}}\)) and look for \(H_T\) and reconstructed mass tail for signal

\[
H_T = p_T^{\text{lepton}} + p_T^{\text{miss}} + \sum p_T^{\text{jets}}
\]

Top towards lower \(H_T\) and \(M_{\text{fit}}\)

Signal towards higher \(H_T\) and \(M_{\text{fit}}\)

- \(M_{t'} > 560\) GeV @95% CL

CMS Search in 4.7 fb\(^{-1}\)

CMS preliminary \(\sqrt{s} = 7\) TeV, 4.7 fb\(^{-1}\), e+jets

CMS preliminary \(\sqrt{s} = 7\) TeV

CMS simulation \(\sqrt{s} = 7\) TeV

CMS simulation \(\sqrt{s} = 7\) TeV

CMS simulation \(\sqrt{s} = 7\) TeV

CMS simulation \(\sqrt{s} = 7\) TeV

CL\(_S\): \(\mu +\text{jets (4.6fb}^{-1}\), e+jets (4.7fb\(^{-1}\)

- observed 95% C.L.
- expected
- ±1\(\sigma\) expected
- ±2\(\sigma\) expected
- \(t'_\text{THEORY}\)

Tuesday, March 27, 2012
b' Search (di-lepton, tri-lepton)

- 3 leptons + 2jets OR 2 same sign leptons + 4jets
- at least 1 b-jet, missing-$E_T$
- $S_T > 500$ GeV where,
  $$S_T = |E_T^{miss}| + \sum |p_T^l| + \sum |p_T^{jet}|$$
- Almost no background

$M_{b'} > 600$ GeV @ 95% CL

CMS EXO-11-036
Why not look for $b'$ and $t'$ at the same time with a single production?

- For simplicity degenerate masses are assumed and no $t' \leftrightarrow b'$ transition
- A convenient way to express the CKM4 matrix is to express it in terms of free parameter $A$ where $A = |V_{tb}|^2 = |V_{t'b'}|^2$

These channels will be possible:

\[
\begin{align*}
t'b & \rightarrow bWb \\
b't & \rightarrow tWbW \rightarrow bWWbW \\
t't' & \rightarrow bWbW \\
b'b' & \rightarrow tWtW \rightarrow bWWbWW
\end{align*}
\]

- Look for 1 isolated muon ($W \rightarrow \mu \nu$), missing-$E_T$ and at least one jet with $P_T(jet) > 30$ GeV

- Classify events by number of $b$-jets and $W$ multiplicity
b′/t′ Inclusive Search (2)

\[ H_T = p_T^l + \sum p_T^{jet} + E_T^{miss} \]

Scanning of mass limit as a function of \( A \)

\[ M_{b'} = M_{t'} > 590 \text{ GeV} @ 95\% \text{ CL} \]
Vector-like Heavy Quarks: \( T \rightarrow tZ \)

- **Pair production of** \( T \rightarrow tZ \)
  - tag a \( Z(\ell\ell) \) + an isolated lepton + \( \geq 2 \) jets

- **Define:** \( R_T = \sum p_T \) (jets, excluding leading two) 
  + \( \sum p_T \) (leptons, excluding leading two)

- **Assuming 100% branching fraction**
  - \( M_T > 475 \) GeV @ 95% CL

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PRL 107, 271802 (2011)
2011 data taking at CMS was very successful. Many analyses with different final states have set the most stringent limits. In a nutshell:

- for LED the limits are extend up to $M_D > 2.49 - 4.44$ TeV for $n_{ED} = 2-6$

- for leptoquarks the lower limits on mass are set to $M_{LQ} > 632(523)$ GeV for $\beta=1.0(0.5)$ from 2nd generation searches

- the limits on heavy quark masses are extended to $M_{t'} > 560$ GeV and $M_{b'} > 600$ GeV from pair production searches
Future Prospects

- Analyses to cover a wider parameter space
- Combine limits from many different final states to improve sensitivity
- Some heavy quark analyses based on 100% branching fraction, what if we relax this assumption?
  - e.g., for $T \to tZ$ determine limits as function of BF and T mass and low BF could be cover with $t' \to bW$
  - a combined limit

- If we see signal then how to discriminate it from similar signatures e.g., SUSY etc.

Thank you!
Selection for muon and electron:
- Isolated muons and electrons
- $P_T(\mu) > 45$ GeV, $|\eta| < 2.1$
- $P_T(e) > 35$ GeV ($45$ GeV) for barrel/endcap
- opposite charge and at least one barrel electron

The main source of systematic uncertainty
- Trigger and reconstruction efficiency: Signal: $\sim 3$-$4\%$, Background: $\sim 3\%$
- Electron energy scale: $1$-$3 \%$
- PDF and higher order (for DY):
  - Background: $\sim 10$-$13 \%$
Table 2: Comparison of the observed and expected number of events in control and signal regions for the dimuon and dielectron mass distributions. Expected signal contributions are shown for $\Lambda_T = 2.8$ TeV (ADD K-factor 1.0, signal truncation at $M_{\text{max}} = \Lambda_T$).

<table>
<thead>
<tr>
<th>Mass region [TeV]</th>
<th>$N_{\text{obs}}$</th>
<th>Background expectation</th>
<th>Signal exp. $\Lambda_T = 2.8$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control regions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.14–0.20</td>
<td>3723</td>
<td>3690±300</td>
<td>-</td>
</tr>
<tr>
<td>0.20–0.40</td>
<td>1674</td>
<td>1605±160</td>
<td>-</td>
</tr>
<tr>
<td>0.40–0.60</td>
<td>131</td>
<td>122±13</td>
<td>-</td>
</tr>
<tr>
<td>0.60–0.80</td>
<td>16</td>
<td>21±3</td>
<td>-</td>
</tr>
<tr>
<td>0.80–1.10</td>
<td>8</td>
<td>5±1</td>
<td>0.8</td>
</tr>
<tr>
<td>Signal region</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$&gt; 1.10$</td>
<td>0</td>
<td>1.0±0.2</td>
<td>3.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mass region [TeV]</th>
<th>$N_{\text{obs}}$</th>
<th>Background expectation</th>
<th>Signal exp. $\Lambda_T = 2.8$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control regions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.12–0.20</td>
<td>6592</td>
<td>6598±530</td>
<td>-</td>
</tr>
<tr>
<td>0.20–0.40</td>
<td>1413</td>
<td>1301±120</td>
<td>-</td>
</tr>
<tr>
<td>0.40–0.60</td>
<td>88</td>
<td>103±11</td>
<td>-</td>
</tr>
<tr>
<td>0.60–0.80</td>
<td>21</td>
<td>18±3</td>
<td>-</td>
</tr>
<tr>
<td>0.80–1.10</td>
<td>7</td>
<td>6±1</td>
<td>0.6</td>
</tr>
<tr>
<td>Signal region</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$&gt; 1.10$</td>
<td>0</td>
<td>1.3±0.2</td>
<td>2.7</td>
</tr>
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</table>
CMS Search in 4.7 fb$^{-1}$

<table>
<thead>
<tr>
<th>Source</th>
<th>Estimate</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Halo</td>
<td>11.1</td>
<td>5.6</td>
</tr>
<tr>
<td>Jet Fakes Photon</td>
<td>11.2</td>
<td>2.8</td>
</tr>
<tr>
<td>Electron Fakes Photon</td>
<td>4.1</td>
<td>2.4</td>
</tr>
<tr>
<td>$W\gamma$</td>
<td>2.8</td>
<td>0.9</td>
</tr>
<tr>
<td>$\gamma+\text{jet}$</td>
<td>0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>$\gamma\gamma$</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>$Z(\nu\bar{\nu})+\gamma$</td>
<td>42.4</td>
<td>6.3</td>
</tr>
<tr>
<td>Total Background</td>
<td>72.5</td>
<td>9.2</td>
</tr>
</tbody>
</table>

- $M_D \approx 1.59$-$1.66$ TeV for $3 \leq n_{ED} \leq 6$

CMS EXO-11-096
Jet+ MET: LED

- Relatively large production and clean final state with high $p_T$ jet and large Missing-$E_T$
- $q\bar{q} \to gG, qg \to qG, gg \to Gg$

- Main background: $Z \to \nu\nu$ and $W+$jets

- Limits are set on $M_D$, the Planck scale $M_s$ for extra dimensions $n_{\text{ED}}$

<table>
<thead>
<tr>
<th>Background process</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \to \nu\bar{\nu}$</td>
<td>$900 \pm 94$</td>
</tr>
<tr>
<td>W+jets</td>
<td>$312 \pm 35$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$8 \pm 8$</td>
</tr>
<tr>
<td>$Z(\ell\ell)$+jets</td>
<td>$2 \pm 2$</td>
</tr>
<tr>
<td>QCD multijet</td>
<td>$1 \pm 1$</td>
</tr>
<tr>
<td>Single $t$</td>
<td>$1 \pm 1$</td>
</tr>
<tr>
<td>Total background</td>
<td>$1224 \pm 101$</td>
</tr>
<tr>
<td>Observed in data</td>
<td>$1142$</td>
</tr>
</tbody>
</table>

**CMS Search in 4.7 fb$^{-1}$**

**CMS EXO-11-059**
Selection: 1st generation
- $P_T(e) > 35 \text{ GeV}, P_T(\text{jets}) > 30 \text{ GeV}$ and
- Missing-$E_T > 45 \text{ GeV}$
- Main bkg: ttbar, W+jets
- Main systematic from W+Jet bkg shape

Selection: 2nd Generation
- $P_T(\mu) > 40 \text{ GeV}, P_T(\text{jets}) > 30 \text{ GeV}$
- $\Delta R(\mu-\mu) > 0.3$
- $S_T > 250 \text{ GeV}$ (at preselection level)

In addition for $\mu\nu qq$ channel:
- Veto on 2nd muon and 3rd Jet(and electron) with $P_T > 15, 25 \text{ GeV}$ respectively
- Missing-$E_T > 45 \text{ GeV}$
- $\Delta \phi(\text{MET-jet})$ and $\Delta \phi(\text{MET-}\mu) > 0.5$

PLB 706(2011) 246-266, CMS EXO-11-028
The analysis is designed to kinematically discriminate the pair production of heavy particle from SM background with making strong assumption about missing-

Force every event to *dijet-topology* by combining all jets in the event into two *mega jets* and defined Razor variable as

$$R \equiv \frac{M_T^R}{M_R}$$

Where,

$$M_R \equiv \sqrt{(E_{j1} + E_{j2})^2 - (p_T^{j1} + p_T^{j2})^2}$$

Peaks at leptoquark mass

$$M_T^R \equiv \sqrt{\not{E}_T(p_T^{j1} + p_T^{j2}) - \not{E}_T \cdot (\vec{p}_T^{j1} + \vec{p}_T^{j2})}$$
t' \rightarrow bW (di-lepton)

CMS Search in 4.7 fb$^{-1}$

- **Signal**: 2 leptons + Jets + Missing-$E_T$
- **Reconstruct** "$b$-jet + lepton" masses

**Limit**: $M_{t'} > 552$ GeV @95% CL
$t' \rightarrow bW$ (leptons+jets)

CMS Preliminary $\sqrt{s} = 7$ TeV $e$+jets

CMS Preliminary $\sqrt{s} = 7$ TeV $\mu$+jets

Events / 20 GeV

M$_{fit}$ [GeV]

H$_T$ [GeV]
b’/t’ Inclusive Search: Classification

CMS Search in 1.1 fb⁻¹
**b' Search**

Full decay chain: $b' b' \rightarrow tWtW \rightarrow bWWbWW$: 2 b-jets + 4 Ws

Possible channels:

1L + 8Jet + MET
2L + 6jet + MET
3L + 4jet + MET
4L + 2jet + MET

Clean signatures: *tri-leptons and opposite signe di-lepton events*
Full decay chain: $b'b' \rightarrow 2 \text{ b-jets} + 4 \text{ Ws}$

- **Clean signal:** 3 leptons + 2 jets
  - OR 2 same sign leptons + 4 jets
- at least 1 b-jet, $E_T^{\text{miss}}$
- $P_T(e, \mu) > 20 \text{ GeV}$ and $P_T(\text{each jet}) > 25 \text{ GeV}$, $S_T > 500 \text{ GeV}$
- Very less or almost no backgrounds

$M_{b'} > 600 \text{ GeV} @ 95\% \text{ CL}$
### T→tZ: Decay Modes

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>BF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1L+4-8J (1Wlv)</td>
<td>324/900</td>
</tr>
<tr>
<td>2L+2-6J (2Wlv)</td>
<td>81/900</td>
</tr>
<tr>
<td>2L+6-8J (1Zll)</td>
<td>72/900</td>
</tr>
<tr>
<td>3L+4-6J (1Wlv+ 1Zll)</td>
<td>72/900</td>
</tr>
<tr>
<td>4L+2-4J (2Wlv+ 1Zll)</td>
<td>18/900</td>
</tr>
<tr>
<td>4L+6J (2Zll)</td>
<td>4/900</td>
</tr>
<tr>
<td>5L+4J (1Wlv+ 2Zll)</td>
<td>4/900</td>
</tr>
<tr>
<td>6L+2J (2Wlv+ 2Zll)</td>
<td>1/900</td>
</tr>
</tbody>
</table>

**2W bosons + 2 Z bosons + 2 jets**

- **BF 5.4 % for e, µ**
- Clean signature, includes 3 leptons (two coming from Z) and at least 2 jets