Searches for New Physics at CMS

Berkeley Workshop for SUSY at the LHC
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For the CMS Collaboration
Outline

• SUSY and Higgs results already covered
• I will cover “exotic” searches:
  – Heavy Resonances
    – dileptons, diphotons,
      dijets, trijets, l+MET, WZ, ttbar
  – Non-Resonant Signatures
    – mono-jet, mono-photon, black-holes
  – 4th Generation Quarks
    – b’, t’
• 20 new physics results this summer with 2011 data
  – Impossible to cover everything
• All CMS new physics results can be found at:
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
Searches for Heavy Resonances

• **Search for excesses in invariant mass spectra**
  - Bump hunt
  - Generic, powerful and track record for discovery in the past
  - Predicted by several BSM models
    with extended gauge symmetries
      - Z’ and W’ with SM-like couplings
      - Kaluza-Klein excitations from RS model of extra dimensions
      - E6 models
      - Technicolor
      - ....
Searches for Non-Resonant Signatures

- Searches non-resonant excess in kinematic distributions and mass spectra
- Predicted by many Extra Dimension Models
  - Universal Extra Dimensions (UED)
    - All particles propagate the bulk
  - Large Extra Dimensions:
    - e.g. ADD
      - Only Graviton propagates the bulk
  - Warped Extra Dimensions:
    - e.g. Randall-Sundrum
      - Warped geometry

\[ M_{Pl}^2 \sim M_D^{2+n} R^n \]
Dilepton Resonances

**di-muons**

**di-electrons**

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

Data

- $Z/\gamma^* \rightarrow \mu^+ \mu^-$
- $t\bar{t} + \text{other prompt leptons}$
- Jets

Events / 5 GeV

- $m(\mu^+ \mu^-)$ [GeV]
Displays of Highest Mass Events

Searches for New Physics at CMS  E. Halkiadakis
Dilepton Resonances

- Published ~40 pb\(^{-1}\) result
  - JHEP 05, 093 (2011)
- 1.1 fb\(^{-1}\) update
- Z’ with SM-like couplings is excluded below 1.94 TeV

<table>
<thead>
<tr>
<th>Z’ SSM</th>
<th>Z’ (\psi)</th>
<th>RS G* (k=0.05)</th>
<th>RS G* (k=0.10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.94 TeV</td>
<td>1.62 TeV</td>
<td>1.45 TeV</td>
<td>1.78 TeV</td>
</tr>
</tbody>
</table>
Dimuons

Search for non-resonant excess in $M_{\mu\mu}$

- Search for excess above 1.1 TeV
- Exclusion limits for ADD models for several parameters (2-3 TeV)

Limits on $M_s$ (no k-factor)

<table>
<thead>
<tr>
<th>$n$</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>TeV</td>
<td>2.6</td>
<td>3.1</td>
<td>2.6</td>
<td>2.3</td>
<td>2.1</td>
<td>2.0</td>
</tr>
</tbody>
</table>
Diphotons

Search for resonant and non-resonant diphoton production

Search for excess above 0.8 TeV
Exclusion limits on RS gravitons (800-1800 GeV) and several ADD models (2.2-3.6 TeV)

Effective Planck scale (TeV) in ADD

<table>
<thead>
<tr>
<th>$k$ factor</th>
<th>$n_{\text{ED}} = 2$</th>
<th>$n_{\text{ED}} = 3$</th>
<th>$n_{\text{ED}} = 4$</th>
<th>$n_{\text{ED}} = 5$</th>
<th>$n_{\text{ED}} = 6$</th>
<th>$n_{\text{ED}} = 7$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>3.2</td>
<td>3.4</td>
<td>2.8</td>
<td>2.6</td>
<td>2.4</td>
<td>2.2</td>
</tr>
<tr>
<td>1.6</td>
<td>3.5</td>
<td>3.7</td>
<td>3.1</td>
<td>2.8</td>
<td>2.6</td>
<td>2.4</td>
</tr>
</tbody>
</table>

RS gravitons: Mass (TeV)

<table>
<thead>
<tr>
<th>$k$</th>
<th>$M_1$ (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>0.77</td>
</tr>
<tr>
<td>0.02</td>
<td>1.05</td>
</tr>
<tr>
<td>0.03</td>
<td>1.20</td>
</tr>
<tr>
<td>0.04</td>
<td>1.31</td>
</tr>
<tr>
<td>0.05</td>
<td>1.41</td>
</tr>
<tr>
<td>0.06</td>
<td>1.49</td>
</tr>
<tr>
<td>0.07</td>
<td>1.57</td>
</tr>
<tr>
<td>0.08</td>
<td>1.63</td>
</tr>
<tr>
<td>0.09</td>
<td>1.69</td>
</tr>
<tr>
<td>0.10</td>
<td>1.74</td>
</tr>
<tr>
<td>0.11</td>
<td>1.78</td>
</tr>
</tbody>
</table>
Dijet Resonances

High sensitivity to strongly produced new resonances decaying to pairs of jets predicted in numerous models: string phenomena, excited quarks, colorons, diquarks
Dijet Resonances

Mass limits up to 4 TeV

<table>
<thead>
<tr>
<th>Model</th>
<th>Excluded Mass (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
</tr>
<tr>
<td>String Resonances</td>
<td>4.00</td>
</tr>
<tr>
<td>$E_6$ Diquarks</td>
<td>3.52</td>
</tr>
<tr>
<td>Excited Quarks</td>
<td>2.49</td>
</tr>
<tr>
<td>Axigluons/Colorons</td>
<td>2.47</td>
</tr>
<tr>
<td>$W'$ Bosons</td>
<td>1.51</td>
</tr>
</tbody>
</table>

1 fb$^{-1}$ results published in: PLB 704, 123 (2011)
Trijet Resonances

• **Model-independent search for:**
  - $p \bar{p} \rightarrow X \ X'$, where $X, X' \rightarrow 3\text{jets}$
    - 6 jet final state
    - Large QCD multijets background

• **NEW Technique**
  - Make use of kinematic features and an *ensemble* of jet combinations
  - Build triplets out of all final state jets and calculate
    - Invariant mass $M_{jjj}$
    - Scalar sum $p_T \Sigma |p_T|_{jjj}$
  - Plot one vs. the other for each combination (at least 20 combinations for each event)
Trijet Resonances

- Search $M_{jjj}$ 200-500 GeV
- Interpretation:
  - RPV SUSY
  - gluino $\rightarrow$ 3jets

• Hypothetical gluino signal for mass 250 GeV shown, normalized to data
• No significant excess observed
Trijet Resonances

- Exclusion for masses $200 < M_{jjj} < 280$ GeV
- Largest excess seen at 390 GeV corresponding to $1.9\sigma$ (with “look-elsewhere effect”)
- 1st search for 3-jet resonances at the LHC
- Highest limits to date
- Published in PRL
Lepton+MET

Look for an excess in the transverse mass spectrum

\[ M_T = \sqrt{2 \cdot p_T^\ell \cdot E_T^{\text{miss}} \cdot (1 - \cos \Delta\phi_{\ell,\nu})} \]
Lepton+MET

- Published $\sim 36 \text{ pb}^{-1}$ results
  - PLB 698, 21 (2011)
  - PLB 701, 160 (2011)
- $\sim 1 \text{ fb}^{-1}$ update
- $W'$ with SM-like couplings is excluded below 2.4 TeV
WZ Resonances

Search for Gauge-Boson-like objects.
Predicted by many BSM models:
e.g. Extra dimensions, technicolor.
Search done in 3lepton+MET channel.

$H_T$ (scalar sum of leptons) cut optimized for each mass point
WZ Resonances

Limits on $W'$ and technicolor production

$W'$ SSM

<table>
<thead>
<tr>
<th>$\rho_{TC}$</th>
<th>$M(\pi_{TC}) = \frac{3}{4} M(\rho_{TC}) - 25\text{GeV}$</th>
<th>$M(\rho_{TC}) &lt; M(\pi_{TC}) + M_W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>784 GeV</td>
<td>382 GeV</td>
<td>436 GeV</td>
</tr>
</tbody>
</table>

CMS PAS-EXO-11-041
ttbar Resonances

Boosted All-Hadronic State

Top decay products either partially or fully merged into one jet.
Top-tagging tools using jet substructure with Cambridge-Aachen R=0.8 jets.
ttbar Resonances

Boosted Semi-leptonic State

- Again, top daughter products are collimated
- Use $\mu + \geq 2$ jets + MET
- Kinematic variables used:
  - $H_{T,lep}$: scalar sum of muon $p_T$ and MET
  - $M_{ttbar}$

**Graph**

- L = 1.14/fb
- $\sqrt{s} = 7$ TeV
- $\sigma_{Z'} = 1$ pb
- CMS preliminary
- QCD $t\bar{t}$
- $W \rightarrow l\nu$
- $Z/\gamma^* \rightarrow t\bar{t}$
- Single-Top
- QCD multijet
- $Z'$, $M=2$ TeV/$c^2$
- CMS data 2011
ttbar Resonances

Exclusion limits on SSM, KK and topcolor models

**W' SSM**  
1.1 TeV

**KK Gluon**  
1.0 < M < 1.5 TeV

**Topcolor Z'**

850 < M_{Z'} < 935 GeV  
960 < M_{Z'} < 1060 GeV

CMS PAS-EXO-11-006  
CMS PAS-EXO-11-055
Mono-jet + MET

Search for excess in events with 1 jet + MET
Irreducible background from $Z$(invisible) + jets

Limits on ADD models for several parameters

<table>
<thead>
<tr>
<th>ADD $K$ factor</th>
<th>$\delta = 2$</th>
<th>$\delta = 3$</th>
<th>$\delta = 4$</th>
<th>$\delta = 5$</th>
<th>$\delta = 6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LO: 1.0</td>
<td>3.67</td>
<td>2.96</td>
<td>2.66</td>
<td>2.41</td>
<td>2.25</td>
</tr>
<tr>
<td>NLO: 1.5</td>
<td>4.03</td>
<td>3.21</td>
<td>2.80</td>
<td>2.55</td>
<td>2.36</td>
</tr>
</tbody>
</table>
Mono-photon + MET

Search for excess in events with 1 photon + MET
Similar challenges as in mono-jet + MET

Limits on ADD models for several parameters

<table>
<thead>
<tr>
<th>M_D (TeV) [no k-factor]</th>
<th>n=2</th>
<th>n=3</th>
<th>n=4</th>
<th>n=5</th>
<th>n=6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.30</td>
<td>1.07</td>
<td>1.12</td>
<td>1.16</td>
<td>1.21</td>
</tr>
</tbody>
</table>
Highest Photon $P_T$ Event
Black Holes

BH production in ADD model (large flat extra spatial dimensions)
- Democratic and isotropic decay
- High $S_T$ events (total transverse energy)
- High total multiplicity (e.g. $\geq 4$)

Use $N=2, 3$ for background model.

CMS Preliminary
$\sqrt{s} = 7$ TeV, 1.09 $fb^{-1}$

N=10 $S_T = 1.1$ TeV
Black Holes

Model-specific limits on minimum black hole (ADD) and string balls masses 4 – 5 TeV range for large variety of model parameters

Also model-independent limits

![Graph of theoretical cross section and non-rotating black holes](image)

![Graph of observed 95% confidence level limits](image)
Searches for 4\textsuperscript{th} Generation Quarks
Heavy Bottom-like Quarks

Search for production of: $b'b' \rightarrow t W^- \bar{t} W^+ \rightarrow b W^+ W^- \bar{b} W^- \bar{W}^+$

Signatures: 3-lepton and same-sign dileptons + $\geq 1$ bjet

$S_T > 500$ GeV (scalar sum of jets, leptons and MET)
Heavy Bottom-like Quarks

Dilepton channel

<table>
<thead>
<tr>
<th>Signal (400GeV)</th>
<th>Bkg</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>4.4 ± 1.4</td>
<td>5</td>
</tr>
</tbody>
</table>

Trilepton channel

<table>
<thead>
<tr>
<th>Signal (400GeV)</th>
<th>Bkg</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.7</td>
<td>0.16 ± 0.09</td>
<td>1</td>
</tr>
</tbody>
</table>

b’ excluded below 495 GeV

Significant improvement over 2010 analysis

PLB 701, 204 (2011)
Heavy Top-like Quark

Search for production of: \( t^\prime \bar{t}^\prime \rightarrow bW^+\bar{b}W^- \)
in \( l+jets \) and dilepton channels

**l+jets:** Uses \( H_T \) and reconstructed mass

**Dilepton:** Uses \( M_{lb} \) (two combinations with smallest \( \Delta R(l,b) \))

Searches for New Physics at CMS

E. Halkiadakis

CMS PAS-EXO-11-050

CMS PAS-EXO-11-051
Heavy Top-like Quark

**I+jets**

- CMS preliminary
- $e$+jets (573pb$^{-1}$), $\mu$+jets (821pb$^{-1}$)

- 95% expected
- 68% expected
- median expected
- 95% CL observed
- $t'$ THEOREY

- $t'$ excluded below 450 GeV

**dileptons**

- CMS Preliminary 1.14 fb$^{-1}$ s=7 TeV
- NLO Theory
- 95% CL$_s$ Expected Limits
- 95% CL$_s$ Observed Limits
- $CL_s \geq 1\sigma$
- $CL_s \geq 2\sigma$

- $t'$ excluded below 422 GeV
Inclusive Search for 4\textsuperscript{th} Generation Quarks

Inclusive search for t' and b' quarks, produced singly or in pairs

- **Muon + jets channel**
  - Classify events according to:
    - Number of hadronically decaying W’s
    - Number of b-tags
    - Discriminating variable $H_T$ distribution
    - Scalar sum $p_T$ of muon, MET, b-jets and W(jj)
Inclusive Search for 4\textsuperscript{th} Generation Quarks

- Assume a simplified model, where t' and b' masses are degenerate and:

$$\text{CMS PAS-EXO-11-054}$$

$$\begin{align*}
\text{CMS Preliminary} & \quad L = 1.1 \text{fb}^{-1} \quad \sqrt{s} = 7 \text{TeV} \\
m_{t'} = m_{b'} & \quad (\text{GeV}/c^2) \\
\end{align*}$$

Limits a function mass and parameter A.

For minimal off-diagonal mixing ($A \approx 1$) between 3\textsuperscript{rd} and 4\textsuperscript{th} generations, observed mass limit

$$> 490 \text{GeV}$$
Conclusions

• Rich program of searches for physics beyond the SM
• Many analyses performed with $> 1 \text{ fb}^{-1}$
  – Lots more data in the can
• Advanced analysis techniques
• Stringent limits on many benchmark models
• No evidence of new physics yet
  – Keep looking until either we find something
  – The exploration of Terascale physics has only just started!

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO