Searches for BSM physics in final states with jets and leptons+jets at CMS

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Large Hadron Collider (LHC)

- Still many unanswered questions in Standard Model (SM)
  - what is dark matter? where is all the antimatter in the universe? why gravity is so weak? etc..
- LHC is the ideal place to find new physics beyond SM at the TeV scale
Physics beyond SM

Many theory predictions

Many searches in CMS

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• Searches for new physics produce the largest number of publications in CMS
  - ~100 from Exotica
  - ~65 from Supersymmetry
  - ~15 from B2G

• In this talk, focus on some Exotica signatures of new physics in jets and leptons +jets final state
  - selection of few recent results
Dijet resonances

- Nearly any new resonance that might be seen at LHC should couple to quarks/gluons
  - dijet final state

- Search strategy
  - look of narrow bump in dijet invariant mass spectrum

- High-mass search using standard data stream (mass > 1 TeV)
- Low-mass search using special data stream (mass < 1 TeV)
Highest dijet mass event (~6 TeV)
High-mass dijet search

- Trigger selection
  - $H_T = \sum_{jets} p_T^j > 800\text{GeV}$

- Wide jets (R=1.1) used to recover final state radiation
  - improve energy scale and resolution

- Fit data with smoothly falling background function
  - same parameterization successfully used in previous searches

- No new resonance observed, set limits

\[
\frac{d\sigma}{dm_{jj}} = \frac{p_0 (1-x)p_1}{x^{p_2 + p_3 \ln(x)}} \quad x = \frac{M_{jj}}{13000}
\]
High-mass limits at 13 TeV

- Different final states considered: $qq$, $qg$, $gg$ resonances
- More sensitive than Run1 for resonance masses $>2$ TeV

Low-mass dijet search

- Important to cover the full mass range in BSM searches

- Hot topic
  - diphoton excess at 750 GeV [2]
  - decays to jets are expected

- Experimental difficulties
  - large dijet cross section at hadron colliders at low-mass
  - limited resources to process and store data
  - trigger thresholds raise with increasing inst. luminosity($\mathcal{L}$)

\[ \frac{dN}{dt} = \sigma \times \mathcal{L} \]
“Data scouting” in CMS

First introduced by CMS in 2011 [3,4]

**Physics Goal:** recover sensitivity to new physics in phase space not accessible via the standard trigger selection

<table>
<thead>
<tr>
<th>Trigger selection</th>
<th>Main data stream</th>
<th>Data scouting</th>
</tr>
</thead>
<tbody>
<tr>
<td>All CMS triggers ex. for dijet</td>
<td>$H_T &gt; 800\text{GeV}$</td>
<td>Low-pT jet triggers</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Event rate</th>
<th>~1 KHz</th>
<th>~4 KHz</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Event content</th>
<th>FULL (RAW data + offline reconstruction)</th>
<th>REDUCED (store calo jets reconstructed at trigger level)</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Bandwidth</th>
<th>~1 GB/s</th>
<th>~0.01 GB/s</th>
</tr>
</thead>
</table>

1 calo scouting event $\sim 3\text{KB} \sim \frac{1}{10}$

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Low-mass limits at 8 TeV

- Best limits in the 500-800 GeV region
- Recently ATLAS released similar analysis with 13 TeV data (called “TLA”, trigger level analysis) [6]
  - similar sensitivity of CMS 8 TeV, no excess
Leptoquarks (LQ)

- Predicted by many BSM theories: grand unified theories, composite models, technicolor, superstring-inspired, SUSY RPV, and others

- Possible *explanation for observed quark-lepton symmetry of SM*

- Spin 0 or 1, coloured, fractional electric charge, carry both baryon and lepton number
  - proton is stable $\rightarrow$ baryon and lepton number conserved separately
  - FCNC suppressed in SM $\rightarrow$ only coupling within each generation
LQ model and signatures

- Pair-production cross section known at NLO
  - independent of unknown l-q-LQ coupling
- Several different final states
  - rich physics program in CMS
  - interesting signatures also beyond leptoquark models

<table>
<thead>
<tr>
<th>Model parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{LQ}$</td>
</tr>
<tr>
<td>$\beta$</td>
</tr>
<tr>
<td>$\lambda$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2 leptons + 2 jets</th>
<th>1 lepton + 2 jets + MET</th>
<th>2 jets + MET</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EXO-16-007:</strong> $\mu\mu jj$ (13 TeV)</td>
<td><strong>EXO-12-041:</strong> evjj, $\mu\nu jj$ (8 TeV)</td>
<td><strong>EXO-11-030:</strong> $\nu\nu bb$ (7 TeV)</td>
</tr>
<tr>
<td><strong>EXO-16-016:</strong> $\tau\tau + jj$ (13 TeV)</td>
<td><strong>Final state covered also by CMS SUSY searches</strong></td>
<td><strong>Final state covered also by CMS SUSY searches</strong></td>
</tr>
<tr>
<td><strong>EXO-12-041:</strong> eejj, $\mu\mu jj$ (8 TeV)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>EXO-14-008:</strong> $\tau\tau + tt$ (8 TeV)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>EXO-12-032:</strong> $\tau\tau + bb$ (8 TeV)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>EXO-12-043:</strong> singleLQ eej, $\mu\mu j$ (8 TeV)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
LQ2 - $\mu\mu qq$

- 2 muons + 2 jets [7]
- Selection optimized for each LQ mass hypothesis
  - $M_{\mu\mu}$: dimuon invariant mass
  - $S_T$: $p_T(\mu_1) + p_T(\mu_2) + p_T(jet_1) + p_T(jet_2)$
  - $M_{\mu j}^{\text{min}}$: smaller of two LQ masses which minimizes LQ-LQ mass difference

- Counting experiment
  - no excess in data
- Exclude scalar LQ2 with mass < 1150 GeV and $\beta=1$
  - exceeding 8 TeV limits
• First search for LQ3 at 13 TeV LHC
  • 2 taus + 2 jets [8]
    - hadronic tau decays (BR = 42%)
    - no explicit jet b-tagging (model independent)
  • Main physics observable
    - $S_T : p_T(\tau_1) + p_T(\tau_2) + p_T(jet_1) + p_T(jet_2)$
  • Shape analysis
    - data in agreement with predictions
  • Exclude scalar LQ3 with mass < 740 GeV and $\beta=1$
Run 1 fluctuations

- **2-3σ excess in electron+jets final states**
- No excess in muon channels
- Looking for analysis with 13 TeV data
Conclusions

- Search for BSM physics continues at CMS
  - rich physics program in final states with jets and leptons+jets (covered small part in this talk)
- Dijet resonances
  - new energy territory for masses > 2 TeV
  - novel data scouting technique extend search in sub-TeV mass region; can confirm 750 GeV diphoton excess
- Leptons+jets searches
  - many different final states covered in CMS
  - 2-3σ excess in evjj and eejj Run 1 searches
- Excellent LHC performance in 2016
  - expect ~10 fb⁻¹ for ICHEP2016 in August
  - maybe 40 fb⁻¹ by the end of the year
- Keep eyes open for LHC results !!!
References

CMS Exotica Public Results

- [3] **Data Scouting and Data Parking**: CMS collaboration, CMS-DP-2012-022
Backup slides
Data Scouting in 2015
(next 3 slides)
Event Content

• Calo Scouting
  • Four-momenta of Calojets with $p_T > 20$ GeV
  • Vertices (when available), “opportunistically” from other paths in the trigger table
  • Event information
    • energy density $\rho$ (for pile-up subtraction)
    • Missing transverse energy

• PF Scouting
  • Four-momenta of relevant physics objects
    • $e$, $\mu$, $\gamma$, PFJets, PF candidates, vertices
  • Event information (as for Calo Scouting, but with tracking)
**Trigger Algorithms**

- **Hadronic triggers**
  - collect events with HT above some threshold (PF/Calo scouting)
  - collect events in bins of HT (parking)

- **Muon Trigger**
  - collect events with muon pair having mass > 10 GeV

- **Auxiliary triggers**
  - measure L1-seed turn-on curve
  - measure efficiency of HLT selection

### Scouting Trigger Paths

<table>
<thead>
<tr>
<th>Path</th>
<th>Rate [Hz] @3.2e33 cm^-2 s^-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>DST_HT450_PFS</td>
<td>100</td>
</tr>
<tr>
<td>DST_HT250_Calo</td>
<td>1000</td>
</tr>
<tr>
<td>DST_DoubleMu6</td>
<td>140</td>
</tr>
</tbody>
</table>

### Parking Trigger

<table>
<thead>
<tr>
<th>Path</th>
<th>Rate [Hz] @3.2e33 cm^-2 s^-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>HLT_HT450to470</td>
<td>17</td>
</tr>
<tr>
<td>HLT_HT470to500</td>
<td>20</td>
</tr>
<tr>
<td>HLT_HT500to550</td>
<td>22</td>
</tr>
<tr>
<td>HLT_HT550to650</td>
<td>23</td>
</tr>
<tr>
<td>HLT_HT650</td>
<td>21</td>
</tr>
</tbody>
</table>

### Prescaled Paths (10 Hz each)

<table>
<thead>
<tr>
<th>Path</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>DST_L1HT_PFS</td>
<td>Measure HLT turn-ons</td>
</tr>
<tr>
<td>DST_L1HT_Calo</td>
<td>Measure HLT turn-ons</td>
</tr>
<tr>
<td>DST_CaloJet40_PFS</td>
<td>Measure L1 turn-ons</td>
</tr>
<tr>
<td>DST_CaloJet40_Calo</td>
<td>Measure L1 turn-ons</td>
</tr>
</tbody>
</table>
EXAMPLE: The HT events

- **250 GeV**: Calo Scouting
  - Peak rate: 3.8 kHz (too high for parking)

- **450 GeV**: Parking
  - Peak rate: 420 Hz

- **450 GeV**: PF Scouting
  - Scouting with PF candidates
  - Peak rate: 420 Hz

- **800 GeV**: Lowest unprescaled HT trigger

Rate estimates assume a luminosity of 7e33 cm\(^{-2}\) s\(^{-1}\) (Not to scale)
Dijet scouting limits

- Exclude “cross section X branching ratio X acceptance” of about 2 pb at 750 GeV for gg resonances
  - acceptance ~ 60% for scalar resonances
Leptoquark constraints

Proton is stable

\begin{tikzpicture}
  \node (u) at (0,0) {$u$};
  \node (d) at (0,-1) {$d$};
  \node (p) at (0,-2) {$p$};
  \node (LQ) at (1,0) {LQ};
  \draw (u) -- (LQ);
  \draw (d) -- (LQ);
  \draw (p) -- (LQ);
  \node at (1,1) {$e^+$};
  \node at (1,-1) {$\bar{d}$};
  \node at (1,-2) {$d$};
\end{tikzpicture}

- $\Rightarrow$ LQ must vertices must conserve separately baryon and lepton number

FCNC suppressed in SM

\begin{tikzpicture}
  \node (D) at (0,0) {$D^+$};
  \node (c) at (-1,0) {$c$};
  \node (u) at (1,0) {$u$};
  \node (d) at (-1,-1) {$d$};
  \node (LQ) at (0,-1) {LQ};
  \draw (D) -- (c);
  \draw (D) -- (u);
  \draw (LQ) -- (d);
  \draw (D) -- (d);
  \node at (0,1) {$\gamma/Z^0$};
  \node at (0,-2) {$\pi^+$};
\end{tikzpicture}

- $\Rightarrow$ LQ only couple within a single generation

\begin{tikzpicture}
  \node (D) at (0,0) {$D^+$};
  \node (c) at (-1,0) {$c$};
  \node (u) at (1,0) {$u$};
  \node (d) at (-1,-1) {$d$};
  \node (LQ) at (0,-1) {LQ};
  \draw (D) -- (c);
  \draw (D) -- (u);
  \draw (LQ) -- (d);
  \draw (D) -- (d);
  \node at (0,1) {$\gamma/Z^0$};
  \node at (0,-2) {$\pi^+$};
\end{tikzpicture}

(SM)
LQ1 and LQ2 limits
M(lljj) spectra