Searches for Heavy Resonances with CMS

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Heavy Resonances at CMS

- Heavy resonances theorized in BSM physics
  - Little Higgs, extra dimensions, etc.

- Focus:
  - $W' \rightarrow \text{lepton} + \text{MET}$
  - $Z' \rightarrow \tau\tau$
  - top pair resonances

- Up to 2.6 fb$^{-1}$ of 13 TeV data

- Lastest identification techniques for higher energy decay products
  - E.g. jet substructure

See Also:
- SUSY: J. Schulte
- Higgs: H. Ohman, M. Pickering, A. Tuna, A. De Wit
$W' \rightarrow \text{lepton} + \text{MET}$

- $\mu$, e, and $\tau_h$ channels
  - Look for a high $p_T$ lepton and missing energy

- Background rejection
  - $\Delta\phi(p_T^{\text{lep}}, p_T^{\text{miss}})$ and $p_T^{\text{lep}}/E_T^{\text{miss}}$ cuts
  - Veto other high $p_T$ leptons
  - QCD estimated from data
W' → lepton + MET

- Good discrimination with sensitive variable:

\[ M_T = \sqrt{2p_T^l E_T^{\text{miss}} (1 - \cos[\Delta\phi(p_T^l, p_T^{\text{miss}})])} \]
**W' → lepton + MET**

- **Improved limits since Run I**
  - $e/\mu$: 4.4 TeV with 2.2 fb$^{-1}$ of data; previously 3.28 TeV
  - $\tau$: 3.3 TeV with 2.3 fb$^{-1}$ of data; previously 2.7 TeV
Z’ → ττ

- Z’ coupling preferentially to 3rd gen.
- \(\tau_\mu \tau_\mu, \tau_e \tau_\mu, \tau_\mu \tau_e, \tau_\mu \tau_\mu\) channels

- Selection:
  - High \(p_T\) lepton
  - \(E_T^{\text{miss}} > 30\) GeV
  - Back-to-back \(\tau\) events:
    - \(\tau_e/\tau_\mu\): isolated lepton
    - \(\cos\Delta\phi(\tau_1, \tau_2) < -0.95\)
    - \(p_\zeta - 3.1*p_\zeta^{\text{vis}} > -50\) GeV

- Backgrounds
  - QCD, W + jets, DY + jets estimated from data
  - ttbar - require 0 b-tagged jets
$Z' \rightarrow \tau\tau$

- **Sensitive variable:** $m(\tau_1, \tau_2, \slashed{E}_T) = \sqrt{(E_{\tau_1} + E_{\tau_2} + \slashed{E}_T)^2 - (p_{\tau_1} + p_{\tau_2} + \slashed{p}_T)^2}$

- **Strictest limits set so far!**
  - First 13 TeV exotic $\tau\tau$ results!
Top Pair Resonances

- Event categories
  - All-hadronic:
    - 2 top-tags $\Delta y < 1.0$
    - 0 b-tags
    - 1 b-tag
    - 2 b-tags
  - Semileptonic:
    - $\mu/e +$ jets
    - 1 top-tag
    - 0 top-tags, 1 b-tag
    - 0 top-tags, 0 b-tags

- Run II t-tagging - boosted tops!
  - Soft drop jet mass $= [110, 210]$ GeV
    - Removes soft and collinear radiation
  - N-subjettiness ($\tau_{32}$) $< 0.69$
    - Distinguishes 3-prong jet substructure (top) from non-top jet

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**All-hadronic**

**Semileptonic**

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**CMS Preliminary 2.6 fb$^{-1}$ (13 TeV)**

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**Semileptonic**

**Jet softdrop mass [GeV]**
Top Pair Resonances

- All-hadronic: QCD background estimated from data
- Semileptonic background:
  - $\ell\bar{\ell}$, $W + \text{jets}$, single top, Drell-Yan + jets, $VV$, QCD
  - Rejection methods
    - $\Delta R_{\min}(l,j) > 0.4 \| p_{T,\text{rel}}(l,j) > 20 \text{ GeV}$
    - $\chi^2 < 30$

\[
\chi^2 = \left[ \frac{M_{\text{lep}}^\text{top} - M_{\text{lep}}^\text{top}}{\sigma_M^\text{lep}} \right]^2 + \left[ \frac{M_{\text{had}}^\text{top} - M_{\text{had}}^\text{top}}{\sigma_M^\text{had}} \right]^2
\]
Top Pair Resonances

- Sensitive variable: ttbar invariant mass
Top Pair Resonances

- $g_{KK}; Z' \Gamma = 1\%, 10\%, \text{NEW: 30}\%$
- Stricter limits with $2.6 \text{ fb}^{-1}$ of data!

<table>
<thead>
<tr>
<th>Model</th>
<th>All-Hadronic</th>
<th>Semileptonic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Narrow $Z'$ (1%)</td>
<td>1.4 - 1.6</td>
<td>0.6 - 2.3</td>
</tr>
<tr>
<td>Wide $Z'$ (10%)</td>
<td>1.0 - 3.3</td>
<td>0.5 - 3.4</td>
</tr>
<tr>
<td>Extra Wide $Z'$ (30%)</td>
<td>1.0 - 3.8</td>
<td>0.5 - 4.0</td>
</tr>
<tr>
<td>RS KK Gluon</td>
<td>1.0 - 2.4</td>
<td>0.5 - 2.9</td>
</tr>
</tbody>
</table>

Combination coming soon!
Conclusions

- Many new heavy resonance search results from CMS
  - BSM W’ and Z’ models
- Run II analyses setting strictest limits so far!
  - With only 10% of the 8 TeV dataset!
- No signs of new physics yet
- Looking forward to more data in 2016!
BACKUP
W' → lepton + MET: QCD Estimation

- **Method:**
  - $P(\text{fake}) = D/C$
  - QCD estimate = $P(\text{fake}) \times A$

- **Signal Region:**
  - $\tau$: one $\tau$
  - $\mu/e$: $0.4 < \frac{p_{\text{lep}}^T}{E_{\text{miss}}^T} < 1.5$

- **Signal Region:**
  - $\tau$: one $\tau$ + one $\mu/e$
  - $\mu/e$: $0.4 < \frac{p_{\text{lep}}^T}{E_{\text{miss}}^T} > 1.5$
Z’ → ττ: Invariant Mass Plots

τ_{μh} channel

τ_{eμ} channel

τ_{e_h} channel

τ_{h_h} channel

CMS Preliminary 2.2 fb⁻¹ (13 TeV)

Events / GeV

Obs / Bkg

m(τ_{μ}, τ_{μ}, \slashed{E}_T) [GeV]

Observed
Z/γ⁺ → μ⁺μ⁻
QCD
t\bar{t}
W+Jets
VV
10 x Z(1500) → ττ

CMS Preliminary 2.2 fb⁻¹ (13 TeV)

Events / GeV

Obs / Bkg

m(τ_{e}, τ_{μ}, \slashed{E}_T) [GeV]

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CMS Preliminary 2.2 fb⁻¹ (13 TeV)

Events / GeV

Obs / Bkg

m(τ_{μ}, τ_{μ}, \slashed{E}_T) [GeV]

Observed
Z/γ⁺ → μ⁺μ⁻
QCD
t\bar{t}
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CMS Preliminary 2.2 fb⁻¹ (13 TeV)

Events / GeV

Obs / Bkg

m(τ_{e}, τ_{μ}, \slashed{E}_T) [GeV]

Observed
Z/γ⁺ → e⁺e⁻
QCD
t\bar{t}
W+Jets
VV
10 x Z(1500) → ττ

CMS-PAS-EXO-16-008
Z' → ττ: Limit Plots by Decay Channel

τ_{μh} channel

τ_{μh} channel

τ_{eμ} channel

τ_{hh} channel
Soft Drop Algorithm

- Recursively decluster jet. Remove the softer component unless the soft drop condition is satisfied.

\[
\text{Soft Drop Condition:} \quad \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \left( \frac{\Delta R_{12}}{R_0} \right)^\beta
\]

- Soft wide angle radiation fails the condition
  - As \( z_{\text{cut}} \uparrow \) ⇒ more aggressive grooming
  - As \( \beta \downarrow \) ⇒ more aggressive grooming

- Example (\( z_{\text{cut}} = 0.1 \)):
  - If \( \beta = 0 \), remove softer subjet if \( p_T \) fraction < 0.1
    (≈equivalent to MMDT)
  - If \( \beta > 0 \), remove softer subjet if \( p_T \) fraction < \( x \), where \( x \) increases with \( \Delta R \) and has maximum value 0.1
  - \( \beta \to \infty \) no grooming
  - \( \beta < 0 \) soft drop becomes a tagger instead of a groomer
    (finds jets with hard, large angle subjets)
N-subjettiness

- Jet shape variable to measure consistency of jet to have N subjets

\[ \tau_N = \frac{1}{d_0} \sum_k p_{Tk} \times \Delta R_{k_{\text{min}}} \]

With

\[ d_0 \equiv \sum_k p_{Tk} \times R \]

- Distance between constituent k & axis of closest subjet
- Large-R jet distance parameter

13 TeV

CMS
Simulation Preliminary

110 < m_{sp} < 210 GeV

AK8, flat p_T, \eta

<\eta>=20, 25ns

- Top, 470<p_T<600 GeV, 69%
- Top, 600<p_T<800 GeV, 68%
- Top, 800<p_T<1000 GeV, 72%
- Top, 1000<p_T<1400 GeV, 68%
- QCD, 470<p_T<600 GeV, 14%
- QCD, 600<p_T<800 GeV, 15%
- QCD, 800<p_T<1000 GeV, 14%
- QCD, 1000<p_T<1400 GeV, 12%
Top Pair Resonances

- All-hadronic QCD background estimation
  - Model $t\bar{t}$ invariant mass spectrum
  - Anti-tag: $\tau_{32} > 0.69$, $m_{SD} = [110, 210]$ GeV

![Graph showing mistag rate versus jet momentum with Data and QCD Simulation (Pythia 8) comparisons.](image)
Top Pair Resonances: All-hadronic Limits
Top Pair Resonances: Semileptonic Limits

CMS Preliminary

2.6 fb⁻¹ (13 TeV)

Upper limit on \( \sigma \times B(\text{Z} \rightarrow \ell \nu \to t \bar{t}) \) [pb]

- **Narrow Z’**
  - Expected (95% CL)
  - Observed (95% CL)
  - Z’ 1% width (NLO)
  - \( \pm 1\sigma \) Expected
  - \( \pm 2\sigma \) Expected

- **Wide Z’**
  - Expected (95% CL)
  - Observed (95% CL)
  - Z’ 10% width (NLO)
  - \( \pm 1\sigma \) Expected
  - \( \pm 2\sigma \) Expected

- **Extra Wide Z’**
  - Expected (95% CL)
  - Observed (95% CL)
  - Z’ 30% width (NLO)
  - \( \pm 1\sigma \) Expected
  - \( \pm 2\sigma \) Expected

- **RS Gluon**
  - Expected (95% CL)
  - Observed (95% CL)
  - KK gluon (LO \( \times 1.3 \))
  - \( \pm 1\sigma \) Expected
  - \( \pm 2\sigma \) Expected
Z’ → leptons

- Search for Z’ → μμ/ee
  - Sensitive variable: dilepton invariant mass
  - electron channel divided into barrel and endcap categories
- Limits surpass Run I results
$W'\rightarrow tb$ Search

- Search for $W'_R$ decaying to top, bottom pair
  - Semileptonic channel
- New: no isolated lepton requirement due to boost
- At least one b-tagged jet
- Limits increased: $2.15 \text{ TeV} \rightarrow 2.38 \text{ TeV}$; $2.2 \text{ fb}^{-1}$ of data

![Graphs and plots showing event distributions and pull analyses for $W'\rightarrow tb$ search.](Graphs)

CMS Preliminary, $L = 2.2 \text{ fb}^{-1}$, $\sqrt{s} = 13 \text{ TeV}$

- Invariant Mass Analysis
- $\sigma(pp\rightarrow W'_R) \times B(W'_R \rightarrow tb)$ vs. $W'$ Mass [GeV]

CMS Preliminary, L=2.2 fb$^{-1}$ at $\sqrt{s} = 13$ TeV

- Theory $M_{W'_R} << M_{W'_R}$
- Theory $M_{W'_R} > M_{W'_R}$
- 95% CL observed
- 95% CL expected
- ±1σ expected
- ±2σ expected