Searches for Heavy Resonances at ATLAS and CMS

Koji Terashi
(ICEPP, University of Tokyo)

on behalf of the ATLAS and CMS Collaborations
Resonant Signature

- Powerful, model-independent probe to new physics
- Predicted in many BSM scenarios
- “Relatively simple”: Reconstruct invariant mass and look for “bump”
Resonant Signature

Powerful, model-independent probe to new physics
Predicted in many BSM scenarios
"Relatively simple" : Reconstruct invariant mass and look for “bump”

Bump at $m_{ff} > m_Z$ or $m_H$ $\Rightarrow$ New Physics!
Exotics Search

Final States
- Dijet
- Dilepton
- Diboson
- Diphoton
- Photon+Jet
- Multi-jets
- Jet/Photon/X+E_{T}^{miss}
- Top/W/Z/H+Jet
- Ditop
- Multi-leptons
- Same-sign dilepton
- Long-lived, Lepton-jets

BSM Scenarios
- Supersymmetry
- Extra dimensions
- Technicolor
- Little Higgs
- Heavy gauge boson (GUT, ...)
- Left-right symmetry
- Compositeness
- Vector-like quark, 4th gen.
- Heavy neutrino
- Hidden Valley

Signature-based searches

"Illustrative" view
Exotics Search

Dijet
Dilepton
Diphoton
Photon+Jet
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Supersymmetry
Extra dimensions
Technicolor
Little Higgs
Heavy gauge boson (GUT, ...)
Left-right symmetry
Compositeness

Covered by other talks
F. Santanastasio, N. Zhou, S. Lowette
T. Andeen, R. Kogler, L. Fiorini,
P. Martinez Ruiz Del Arbol, M. King, P. Lujan

Non-resonant ED signatures covered by J. Kretzschmar

"Illustrative" view
Dilepton

2 isolated leptons: \(E_{T}^{\text{electron}} > 40/30 \text{ GeV}, \ p_{T}^{\text{muon}} > 25 \text{ GeV}\)

- Drell-Yan background estimated with POWHEG at NLO
- \(m_{ll}\)-dependent NNLO QCD corrections (by FEWZ) included
- Total simulated background scaled to data at Z-peak (80<\(m_{ll}\)<110 GeV)
Dilepton

- Likelihood scan with $Z'_{SSM}$ template over $m_\ll$ range
  - Obs. $p$-value = 27(28)% for $ee(\mu\mu)$
  - No significant excess

- Interpretation on various models:
  - SSM $Z'$, Minimal $Z'$, Chiral excited $Z$ ($Z^*$)
  - $E_6$-motivated $Z'_\psi$ and $Z'_\chi$
  - Randall-Sundrum graviton, MWT

95% CL lower mass limit (in TeV)

<table>
<thead>
<tr>
<th>Model</th>
<th>Obs</th>
<th>Exp</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z'_{SSM}$</td>
<td>2.90</td>
<td>2.87</td>
</tr>
<tr>
<td>$Z'_\psi(\chi)$</td>
<td>2.51(2.62)</td>
<td>2.46(2.60)</td>
</tr>
<tr>
<td>RS1 $G^*$</td>
<td>2.68</td>
<td>2.67</td>
</tr>
<tr>
<td>MWT A</td>
<td>1.96</td>
<td>1.93</td>
</tr>
</tbody>
</table>

- CMS limit on $Z'_{SSM}$ : 2.90 TeV

CMS PAS EXO-12-061

\[ \frac{\kappa}{\bar{M}_{PL}} = 0.1 \]
\[ \bar{g} = 2 \]
Dijet resonance search updated with full 8 TeV data

- Largest dijet mass range (0.25-4.5 TeV) combined with new online selection
- Model-(in)dependent interpretations with various initial/final state partons

2 R=0.6 jets: $p_T > 50$ GeV, $|y_{1,2}| < 2.8$
$|y_1 - y_2| < 1.2$, $m_{jj} > 250$ GeV

Use “delayed” stream data:
- Additional ~100 Hz data recorded in 2012
- Increased statistics at $m_{jj} = 0.75-1.0$ TeV

$\Rightarrow$ No significant excess
Interpretation on various models:
- Excited quark q*
- Color-octet scalar
- SSM W', Chiral excited W (W*)
- Quantum black holes

95% CL lower mass limit (in TeV)

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<tbody>
<tr>
<td>q*</td>
<td>qg</td>
<td>4.09</td>
<td>3.99</td>
</tr>
<tr>
<td>color-octet scalar</td>
<td>gg</td>
<td>2.72</td>
<td>2.83</td>
</tr>
<tr>
<td>W'</td>
<td>q\bar{q}'</td>
<td>2.45</td>
<td>2.51</td>
</tr>
<tr>
<td>QBH</td>
<td>q,g</td>
<td>5.82</td>
<td>5.82</td>
</tr>
</tbody>
</table>

Model-independent interpretation:
- Gaussian shape
- Breit-Wigner shape **NEW!**
  - \( \Gamma/M = 0.5\% - 5\% \)
  - \( qq, qg, gg, q\bar{q} \) initial states
Lepton + $E_T^{\text{miss}}$

Probe to heavy charged gauge boson decaying to lepton+neutrino

- 1 electron(muon) : $p_T > 100(45)$ GeV
- $0.4 < p_T^{\text{lepton}}/E_T^{\text{miss}} < 1.5$
- $\Delta \phi(\text{lepton},E_T^{\text{miss}}) > 0.8\pi$

Look for Jacobian-Peak in $m_T$

$$m_T = \sqrt{2p_T E_T^{\text{miss}} (1 - \cos \Delta \phi_{\ell\nu})}$$

95% CL lower mass limit (in TeV)

<table>
<thead>
<tr>
<th>Model</th>
<th>Obs</th>
<th>Exp</th>
<th>Interference with SM $W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W'_{\text{SSM}}$</td>
<td>3.35</td>
<td>3.40</td>
<td>No</td>
</tr>
<tr>
<td>$W'_{\text{SSMO(S)}}$</td>
<td>3.60(3.10)</td>
<td>3.60(3.20)</td>
<td>Yes : OS(SS) as SM $W$-fermion coupling</td>
</tr>
</tbody>
</table>

Interpreted for UED and contact interaction as well
First CMS $\gamma$+jet resonance search **NEW!** with full 8 TeV data

- Interpretations for excited quarks with varied coupling strength
  - $\geq1$ photon + $\geq1$ jet $p_T > 170$ GeV
  - $\Delta R(\gamma, \text{jet}) > 0.5$
  - $\Delta\eta(\gamma, \text{jet}) < 2.0, \Delta\phi(\gamma, \text{jet}) > 1.5$

$\rightarrow$ **No significant deviation…**
Multi-Jets

Model independent search for pair-produced 3-jet narrow resonances

- Gluinos with R-parity violating decay used as signal model
- Background estimate largely data-driven

Pair-produced gluinos decaying into 3 quarks with RPV coupling $\lambda''_{udd}$

Two approaches:

- **Inclusive analysis**
  Light-flavor dominant $\Rightarrow$ probing $\lambda''_{uds}$

- **Heavy Flavor analysis**
  $\geq 1$ b-tagged jet in triplet $\Rightarrow$ probing $\lambda''_{udb}$ or $\lambda''_{csb}$
  Split into low-mass and high-mass

20 triplet combinations from 6-jets

Select correct combination using

$$M_{jjj} < \left( \sum_{i=1}^{3} p_T^i \right) - \Delta$$

Set $\Delta = 110$ GeV

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PLB 730, 193 (2014)
Multi-Jets

CMS, L = 19.4 fb⁻¹ at √s = 8 TeV

Δ = 110 GeV, 6ᵗʰ jet p_T ≥ 110 GeV
Sphericity ≥ 0.4, ≥ 1 b tag in triplet

Data Fit to the data

\[ \chi^2 / \text{ndf} = 13.7 / 19 \]

Signal M_{gluino} = 500 GeV

High-mass HF search with background estimate from fit to data → No significant excess

95% CL lower mass limit (in GeV)

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<tbody>
<tr>
<td>RPV gluino Light-flavor</td>
<td>650</td>
<td>755</td>
</tr>
<tr>
<td>RPV gluino Heavy-flavor</td>
<td>835</td>
<td>825</td>
</tr>
</tbody>
</table>

Theory, hadronic RPV
\( \lambda''_{113} \) or \( \lambda''_{223} \) (\( \tilde{g} \to qqb \))
**$W\gamma, Z\gamma$**

**NEW!**

Searches for narrow resonances decaying to $W\gamma$ or $Z\gamma$ with full 8 TeV data

- 1 (2) electron/muon $p_T > 25$ GeV for $W\gamma$ ($Z\gamma$)
- 1 photon $E_T > 40$ GeV
- $E_T^{miss} > 35$ GeV, $m_T^{W} > 40$ GeV ($W\gamma$)
- $65 < m_{ll} < 115$ GeV ($Z\gamma$)

Likelihood scan over $m_T^{lv\gamma}$ or $m_{ll\gamma}$ distributions with narrow signal and background spectra

- *largest deviation* $< 2.5\sigma$ (local)
- *No significant excess*
Search results interpreted for

- spin-0 resonances (composite scalar $\phi$)
  
  2 parameter sets for $\phi$-gauge boson couplings:
  
  (a) $c_g = c_W = -c_B = 1/4\pi$
  
  (b) $c_g = 1/2\pi, c_W = -c_B = 1/\pi$

- spin-1 resonances (LSTC $a_T \rightarrow W\gamma$, $\omega_T \rightarrow Z\gamma$)

95% CL excluded mass range (in GeV)

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<tbody>
<tr>
<td>LSTC $a_T \rightarrow W\gamma$</td>
<td>[275, 960]</td>
</tr>
<tr>
<td>LSTC $\omega_T \rightarrow Z\gamma$</td>
<td>[200, 700] [750, 890]</td>
</tr>
<tr>
<td>Composite Scalar $\rightarrow Z\gamma$</td>
<td>[200, 1180] for (b)</td>
</tr>
</tbody>
</table>
Reviewed latest results on heavy resonance searches with

- Dilepton : heavy gauge bosons, RS graviton, walking technicolor, …
- Dijet : excited quarks, colored scalar, heavy gauge bosons, QBH, …
- Lepton+E_{T}^{\text{miss}} : heavy gauge bosons
- Photon + Jet : excited quarks
- Multi-jets : gluinos with R-parity violating decay
- W/Z boson + Photon : narrow heavy scalar/vector
  - Diphoton : narrow heavy scalar ➔ See S. Laplace’s H→γγ talk

No indication of new physics yet, but...

Still many to come from full data analysis at 8 TeV and more exciting 13/14 TeV run at 2015!!

Era of Tera-scale physics has just begun!

Future prospects for BSM searches by F. Ruehr and L. Shchutska tomorrow
Backup
Dijet

CMS PAS EXO-12-059

- Model-independent search for narrow dijet resonance
- Data-driven background estimate by a smooth function fit to data

\[ \frac{dN}{dx} = p_1 \frac{(1 - x)p^2}{x p^3 + p^4 \ln x} \]

- Look for local excess in \( m_{jj} \) spectrum

Add “gluon radiation” back to the energy of leading jets

\( \geq 2 \) \( R=0.5 \) jets \( p_T > 30 \) GeV

Merge all jets to closest leading jets if they are within \( \Delta R < 1.1 \)

\( |y_{1,2}| < 2.5, |y_1 - y_2| < 1.3, m_{jj} > 890 \) GeV

95% CL lower mass limit (in TeV)

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<td>3.50</td>
<td>3.75</td>
</tr>
<tr>
<td>color-octet</td>
<td>gg</td>
<td>2.79</td>
<td>2.74</td>
</tr>
<tr>
<td>scalar</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W'</td>
<td>q\bar{q}'</td>
<td>2.29</td>
<td>2.28</td>
</tr>
<tr>
<td>RS1 G*</td>
<td>q,g</td>
<td>1.58</td>
<td>1.43</td>
</tr>
</tbody>
</table>
**Lepton + E_T^{miss}**

- 1 electron(muon) : p_T >125(45) GeV
- E_T^{miss}>125(45) GeV for e(μ) channel

![Graph showing data and expected limits](image)

- Likelihood scan at m_T tail (m_T>m_T^{min})
  - No excess...

- Interpretation on:
  - SSM W'
  - Chiral excited boson W*
  - Dark matter with EFT

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<tr>
<td>W'_{SSM}</td>
<td>3.27</td>
<td>3.19</td>
</tr>
<tr>
<td>W*</td>
<td>3.17</td>
<td>3.08</td>
</tr>
<tr>
<td>DM</td>
<td>~0.3</td>
<td>-</td>
</tr>
</tbody>
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95% CL lower mass limit (in TeV)

M* (m_χ=100GeV)
Diphoton

Method used in SM $H \rightarrow \gamma\gamma$ extended to search for diphoton resonances

- fit to $m_{\gamma\gamma}$ spectrum using analytical functions for narrow ($\Gamma \ll M$) signal and BG
- Limit set on fiducial cross section times $\text{BR}(X \rightarrow \gamma\gamma)$

Split into two regions

- **Low-mass**: $65 < m_{\gamma\gamma} < 110$ GeV
  - DY $Z \rightarrow \text{ee}$ misidentified as $\gamma\gamma$
  - Classified as unconv-unconv, unconv-conv and conv-conv pairs

- **High-mass**: $110 < m_{\gamma\gamma} < 600$ GeV
  - $E_T^{\gamma^{1(2)}}/m_{\gamma\gamma} > 0.4(0.3)$ required
  - Fit within a sliding $m_{\gamma\gamma}$ window
  - SM Higgs modeled by a double-sided Crystal Ball function

$\geq 2$ photons : $E_T > 22$ GeV

$\sqrt{s} = 8$ TeV

$\int L \, dt = 20.3 \, \text{fb}^{-1}$

$\text{No significant excess}$
95% CL limit on $\sigma_{\text{fid}} \cdot \text{BR}(X \rightarrow \gamma\gamma) = \frac{N_{\text{data}}}{C_X \cdot \mathcal{L}}$

$C_X = \frac{N_{\text{reco}}^{\text{MC}}}{N_{\text{fid}}^{\text{MC}}}$

Fiducial region:
- $E_T^{\gamma} > 22$ GeV, $|\eta_\gamma| < 2.37$
- $E_T^{\gamma^{(1,2)}/m_{\gamma\gamma}} > 0.4(0.3)$ for $m_{\gamma\gamma} > 110$ GeV
- Photons are isolated ($\Delta R < 0.4$)

$\sigma_{\text{fid}} \cdot \text{BR}(X \rightarrow \gamma\gamma)$ limit for additional scalar:

$\Rightarrow$ 90 (1) fb at $\sim$65 (600) GeV