Search for new phenomena in diboson final states in ATLAS and CMS

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EPS-HEP 2015
25/07/2015
Diboson resonances

- Several extensions of the SM predict new resonances decaying into pairs of bosons (including the Higgs)

\[ W', G^* \ldots ? \to W/Z/H \]

- Clear experimental signature
  - Known properties and decay kinematics

<table>
<thead>
<tr>
<th>M</th>
<th>M</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>W-&gt;qq ~67%</td>
<td>Z-&gt;qq ~70%</td>
<td>H-&gt;bb ~57%</td>
</tr>
<tr>
<td>W-&gt;lv ~33%</td>
<td>Z-&gt;vv ~20%</td>
<td>H-&gt;WW ~21.5%</td>
</tr>
<tr>
<td></td>
<td>Z-&gt;ll ~10%</td>
<td>H-&gt;ZZ ~2.5%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H-&gt;\tau \tau ~6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H-&gt;\gamma \gamma ~0.2%</td>
</tr>
</tbody>
</table>

To fully exploit potential signatures (at high mass) from new physics at LHC

**novel reconstruction techniques to handle highly boosted objects**
Resonance models

**Charged ( WZ )**

Sequential Standard Model \((W', \text{spin-1})\)

- Trilinear \(W'WZ\) coupling set by Extended Gauge Model: \(~ (M_W/M_{W'})^2\)

**Neutral ( WW,ZZ,HH )**

Randall-Sundrum graviton \((RS G^*, \text{spin-2})\)

- Traditional benchmark model with extra dimensions

Bulk RS graviton \((Bulk G^*, \text{spin-2})\)

- Graviton couples more with heavy particles \((W, Z, t)\)
- Smaller \(\sigma\), but larger branching ratio to WW, ZZ

**Minimal Walking Technicolor \((R_1,R_2, \text{charged and neutral})\)**

- Technicolor with minimal ingredients, can decay to ZH and WH

**HVT (Simplified Lagrangian)**

**Model A**

- weakly coupled vector resonances from extension of the gauge group

**Model B**

- produced in a strong scenario e.g. composite higgs model
Summary of diboson analysis

<table>
<thead>
<tr>
<th>Final State</th>
<th>Channel</th>
<th>Reference (ATLAS)</th>
<th>Reference (CMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>lγ,lγ</td>
<td>Zγ, Wγ</td>
<td>ATLAS:arxiv.1407.8150</td>
<td></td>
</tr>
<tr>
<td>llqq</td>
<td>ZZ</td>
<td>ATLAS:arxiv.1409.6190</td>
<td>CMS: arxiv1405.3447</td>
</tr>
<tr>
<td>lvbb/lbvb/vvb</td>
<td>WH/ZH</td>
<td>ATLAS: arxiv1503.08089</td>
<td>CMS PAS EXO-14-010</td>
</tr>
<tr>
<td>qqbb</td>
<td>WH/ZH</td>
<td>ATLAS</td>
<td>CMS: arxiv1506.01443</td>
</tr>
<tr>
<td>bbbb</td>
<td>HH</td>
<td>ATLAS: arxiv. 1506.00285</td>
<td></td>
</tr>
<tr>
<td>bbγγ</td>
<td>HH</td>
<td>ATLAS: arxiv. 1406.5053</td>
<td>CMS-HIG-13-032</td>
</tr>
</tbody>
</table>

All results based on full Run1 dataset
Final states

- Fully leptonic $\rightarrow$ Low backgrounds, high purity, low branching fraction
- Semileptonic final states
- Fully hadronic
  - Advantages:
    - good kinematic resolution
    - High branching fractions
    - Access to $H\rightarrow bb$
  - Disadvantages:
    - higher background although steeply falling at high mass
- Physics observable: invariant mass of diboson system

Signal (BR)  
Background

• 3 leptons $E_{T}^{\text{miss}}$  
$m(l_1,l_2) - m_Z$  
$m_T(l_3,\nu) - m_W$

background (data-driven or MC based)
Boson jets

- “Natural” angular separation $dR \sim 2m/p_T$
- Resolved regime: the boson has relative low momentum in the lab frame so we are able to reconstruct one jet for each quark
- Boosted Regime: the boson has high momentum in the lab frame - the outgoing quarks are very close so the jets begin to merge

1. Fat jet: large distance parameter to pick up all the radiation from the original decay
2. Grooming:
   - Signal: take out jet constituents that don’t belong to the signal decay
   - Background: Preserve background characteristics in the jet
3. Tagging:
   - Use differences in Signal and Background jet characteristics to reject background jets

Boson jets

QCD jets
Jet substructure

**Jet Pruning:** (Phys. Rev. D 80 051501, arXiv:0912.0033)

- Recluster jet constituents, applying additional conditions at each recombination
  \[
  z = \frac{\min(p_{T,i}, p_{T,j})}{p_{T,\text{jet}}} > 0.1 \quad \Delta R < 0.5 \frac{M_{\text{jet}}}{p_{T,\text{jet}}}
  \]
- Filter out soft and large angle QCD emissions

**Mass Drop:** (PRL 100 240001)

- de-cluster jet by stopping jet algo before last iteration \(\rightarrow\) two subjets
- jet is V-tagged if its mass drop \(\mu_D\) < (analysis dependent) cut value

\[
\mu_D = \frac{M_1}{M_{\text{jet}}}
\]

**N-subjettiness:** (JHEP03(2011)240001)

- Topological compatibility with hyp of N subjets
- \(\tau_N\) : pT-weighted sum over jet constituents of distances from closest subjet axis

**Momentum balance:** (PRL 100(2008)24200)

- boson jets tend to have symmetric momentum distribution among the two quarks

Plenty of alternatives at CMS-JME-13-006 and ATL-PHYS-PUB-2014-004
**ZV→llqq**

**Z→ll:**
- 2 leptons, same flavor, compatible with the Z mass
- Leptons are collimated and interfere with each other’s isolation cones
  - Subtract the other lepton’s track pT from the isolation cone

**Z/W→hadronic:**

**ATLAS:**
- Low pt resolved: 2 jets with pt > 100 GeV
- High pt resolved
  - 2 jets with pt > 250 GeV to gain efficiency in the intermediate region
  - Merged Region: 1 fat jet with pt > 400 GeV

**CMS:**
- high-purity (HP) category: $\tau_{21} \leq 0.5$;
- low-purity (LP) category: $0.5 < \tau_{21} < 0.75$.
- ATLAS: Use C/A $R=1.2$ jets with modified BDRS filtering
- CMS: Use C/A $R=0.8$ pruned jets

---

**Diboson Final States**

- $WW$ (5 fb$^{-1}$)  
- $ZZ$ (1 fb$^{-1}$)  
- $WZ$ (1 fb$^{-1}$)  

**2 leptons**

- $E_T$ miss
- $m(l_1,l_2) \sim m_Z$

**3 leptons**

- $E_T$ miss
- $m(l_1,l_2) \neq m_Z$
- No b-jets

**4 leptons**

- $E_T$ miss
- $m(l_1,l_2) \sim m(l_3,l_4) \sim m_Z$

---

**ΔR > jet radius**  
ΔR < jet radius
No significant deviations from Standard Model expectation observed

- $M(G^*) > 730$ GeV, $M(W') > 1590$ GeV
**WV->lvqq**

**W-> lnu selection**: MET > 30 GeV (100 GeV for CMS) and exactly one lepton

Hadronic side, same selection as for llqq

**Main Backgrounds:**

MC: W/Z+jets, ttbar

Data driven: Multijet QCD → loosened lepton selection to extract template and fit to the Met to extract normalization

Since no excess is seen, limits are set using \( W' \) and \( G \)
VV->qqqq

- **ATLAS**: Trigger on a jet with pt > 360 GeV
- CMS: Trigger on HT
- Only boosted region considered (low mass QCD dominated)
- Select events with Mj within the W/Z mass window
  - **ATLAS**: $|y_1 - y_2| < 1.2$, Pt Asymmetry < 0.15 to reject events where one of the jets is poorly measured
  - 3 overlapping signal regions/non statistically independent
- Additional cuts to reduce QCD (ntrk, nsubjettiness...)
- The background is estimated by fitting the data

*ATLAS: arxiv:1506.00962*  

$\frac{d\sigma}{dm} = p_1(1 - x)^{p_2 - x}p_3 x^p_3$,  

### Significance

- **ATLAS**: arxiv:1405.1994
- CMS, $L = 19.7 \text{ fb}^{-1}$
- **High-purity doubly W/Z-tagged data**
- **WW (1.5 TeV)**
- **ZZ Selection**

### Events / 100 GeV

- **WW Selection**
- **ZZ Selection**
- **WZ Selection**

### Significance

- **VV->qqqq**
- **3.4\sigma local**
- **2.6\sigma local**
- **2.9\sigma local**
**VV→qqqq**

- **ATLAS**: Trigger on a jet with pt>360 GeV  
**CMS**: Trigger on HT
- Only boosted region considered (low mass QCD dominated)
- Select events with Mj within the W/Z mass window
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  - 3 overlapping signal regions/non statistically independent
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- The background is estimated by fitting the data

**ATLAS: arxiv:1506.00962**

**CMS: arxiv:1405.1994**

CMS, L = 19.7 fb⁻¹, √s = 8 TeV

- Observed
- Expected (68%)
- Expected (95%)

- **G_{RS} → WW (k/\Pi) = 0.1**

**2.5σ global significance in WZ selection**

See Attilio Picazio Poster on ATLAS result!
**VH—→ lν/ll/νν/bb (ATLAS)**

- Discovery of the Higgs opened up other final states to look for diboson resonances
  - Examine the VH mass and look for a localized excess
- Categorize events according to the number of charged leptons
- Further subdivision according to number of b-tagged jets (1 to 2 btags)
- Only antikt0.4 jets considered

**Higgs as a discovery tool**

- Dominant background is W/Z+j; simulation with data-based corrections
- Multi-jet background; data driven
- tt/single top; normalized using control region fit
VH—> lv/ll/vv/bb (ATLAS)

- Discovery of the Higgs opened up other final states to look for diboson resonances
  - Examine the VH mass and look for a localized excess
- Categorize events according to the number of charged leptons
- Further subdivision according to number of b-tagged jets (1 to 2 btags)

**ATLAS: arxiv1503.08089**

- for each line corresponding to a $M_{V'}$ mass, the area outside the curves is excluded
WH-\rightarrow l\nu bb (CMS)

- 1 lepton +MET + reconstruct H-\rightarrow bb using pruned jets
- 1 CA0.8 jet
- 110 < m_{jet} < 135 GeV.
- Split pruned jet:
  - if the subjets' \Delta R>0.3 b-tagging applied to individual sub-jets
  - if the subjets' \Delta R<0.3 b-tagging applied to the CA0.8 jet
- Special topological requirements to avoid possible instrumental backgrounds
- The shape of the m_{WH} distribution of the W+jets background in the signal region is estimated from data from the lower sideband region while correction for the extrapolation are taken from the simulation.
W/ZH→hadronic (CMS)

- First analysis to include H→WW→4 q decays
- 2 CA0.8 jet, 70 < m_j < 100 GeV/c^2 for W/Z, 110 < m_j < 135 GeV/c^2 for H
- Split pruned jet:
  - if the subjets' ΔR>0.3 b-tagging applied to individual sub-jets
  - if the subjets' ΔR<0.3 b-tagging applied to the CA0.8 jet
- \tau_{42} used to discriminate H→WW→4q from QCD jets

\begin{table}
\begin{tabular}{|c|c|c|}
\hline
Categories & V tag & H tag \\
\hline
V^{HP}H_{bb} & \tau_{21} \leq 0.5 & b tag \\
V^{LP}H_{bb} & 0.5 < \tau_{21} < 0.75 & b tag \\
V^{HP}H^{WW}_{WW} & \tau_{21} \leq 0.5 & \tau_{42} \leq 0.55 \\
V^{LP}H^{WW}_{WW} & 0.5 < \tau_{21} < 0.75 & \tau_{42} \leq 0.55 \\
V^{HP}H^{WW}_{WW} & \tau_{21} \leq 0.5 & 0.55 < \tau_{42} < 0.65 \\
\hline
\end{tabular}
\end{table}
Resolved

- 4 b-jets
- 2 dijets with $M_{jj} \sim M_{H}$
- $tt\bar{t}$ veto

Boosted:

- Select events with two large-R jets, build from their tracks AntiKt jets $\Delta R = 1.0$ and trim them, using $\Delta R = 0.3$ subjets to get rid of QCD, find b-jets among the subjets
- Validation in signal-depleted sidebands

- **M4b resolution $\sim 15\%$ at 1 TeV**
Conclusion

Search for **heavy resonances** is one of the most direct ways to find new physics at TeV scale.

Diboson final state provides clear experimental signature and allows cross check among different channels:

- Some interesting excess need to be checked with 13 TeV data.

- Run2 offers new opportunity for discoveries:
  - Increase in CM energy -> Increase the mass discovery reach
  - Increase in integrated luminosity -> Enhance sensitivity for rare processes

- Need to be ready for the unexpected
  - Analyze all feasible final state to make sure we leave no stone unturned
KEEP CALM AND CALL FOR BACKUP
Lessons from Run1

1. Detectors perform very well in challenging LHC environment → Higgs discovery with ~half the energy, less luminosity
Lessons from Run 1

1. Detectors perform very well in challenging LHC environment —> Higgs discovery with ~half the energy, less luminosity

2. Plethora of SM precision measurement
Lessons from Run1

1. Detectors perform very well in challenging LHC environment → Higgs discovery with ~half the energy, less luminosity

2. Plethora of SM precision measurement

3. No hints of BSM (at least not significant)

---

**ATLAS Exotics Searches** - 95% CL Exclusion

**Status:** July 2015

<table>
<thead>
<tr>
<th>Model</th>
<th>$f,\gamma$</th>
<th>Jets</th>
<th>$E_{T}^\text{miss}$</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{ACD}_{\text{Glu}}$</td>
<td>$-\mu$</td>
<td>$\geq 1$</td>
<td>Yes</td>
<td>$20.3$</td>
</tr>
<tr>
<td>$\text{ACD}_{\text{QCD}}^{\mu}$</td>
<td>$1$</td>
<td>$1$</td>
<td>Yes</td>
<td>$20.3$</td>
</tr>
<tr>
<td>$\text{ACD}_{\text{QCD}}^{\mu}$</td>
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<tr>
<td>$\text{ACD}_{\text{QCD}}^{\mu}$</td>
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</tr>
<tr>
<td>$\text{ACD}_{\text{QCD}}^{\mu}$</td>
<td>$1$</td>
<td>$1$</td>
<td>Yes</td>
<td>$20.3$</td>
</tr>
</tbody>
</table>

**Extra dimensions**

- CI $\mu$
- Extra dimensions
- CI $\mu$
- Extra dimensions

**Gauge bosons**

- Magnetic monopoles
- Multi-charged particles
- Monotop (non-res prod)
- Higgs triplet

**CI**

- Excited lepton
- Excited lepton

**LRSM**

- Bulk RS
- RS1
- RS1

**HVT**

- Minimal RS
- Minimal RS

**EGM**

- Large RS
- Large RS

**SSM**

- Gauge bosons
- Gauge bosons

**Bulk RS**

- RS1
- RS1

**LRSM**

- Bulk RS
- Bulk RS

**HVT**

- Minimal RS
- Minimal RS

**EGM**

- Large RS
- Large RS

**SSM**

- Gauge bosons
- Gauge bosons

---

*Only a selection of the available mass limits on new states or phenomena is shown.*
Hail to Run2

- Substantial increase in energy for the world’s highest energy collider
- Largest jump in sensitivity to BSM
  - $20 \text{ fb}^{-1} @ 8 \text{ TeV} \rightarrow 100 \text{ fb}^{-1} @ 13/14 \text{ TeV}$
  - Will not happen again for another 2+ decades!!!
- New territory explored essentially for all BSM searches with 0.1-10.0 fb-1 (2015)
Standard $H \rightarrow \gamma\gamma$ sel. + 2 b-jets
- $|m_{\gamma\gamma} - m_{H}| < 2 \sigma m$ & 95 < $m_{jj} <$ 135 GeV
- $|m_{\gamma\gamma bb} - MX| <$ optimized cut, MX dependent

- Counting experiment
  - Background estimated from $m_{\gamma\gamma}$ sideband and events with <2 b-jets

ATLAS: arxiv. 1406.5053
All leptonic final states

- Advantages:
  - Low backgrounds, high purity
- Disadvantages:
  - Low branching fraction
  - Kinematic reconstruction with at least one neutrino

**Diboson Final States**

- WW (5 fb$^{-1}$)
- ZZ (1 fb$^{-1}$)
- WZ (1 fb$^{-1}$)

3 leptons
$E_T$ miss
$m (l_1, l_2) \sim m_Z$
$m_T (l_3, \nu) \sim m_W$

**WZ->lllv**

- Analysis Strategy:
  - Select three leptons
  - Compute $M_{WZ}$ from MET and W mass constraint
  - Search for bump in $M_{WZ}$ spectrum
All leptonic final states

- Advantages:
  - Low backgrounds, high purity
- Disadvantages:
  - Low branching fraction
  - Kinematic reconstruction with more than one neutrino

3 leptons

W
\text{E}_{\text{miss}}
\frac{m(l_1, l_2)}{m_Z} \approx m_Z
\frac{m_T(l_3, \nu)}{m_W} \approx m_W

WZ \rightarrow \ell l l \nu

- Interpretations:
  - Sequential SM $W'$
  - Heavy vector triplet (weakly coupled resonance and composite Higgs)
  - Technicolor

CMS: arxiv:1407.3476

ATLAS: arxiv.1406.4456
Standard Model inclusive and differential cross sections are measured

Here focus on non-SM part of the analysis

First $V\gamma$ search at LHC

Technicolor models give $a_T \rightarrow W\gamma$ and $\omega_T \rightarrow Z\gamma$

**Selection**

<table>
<thead>
<tr>
<th>$W\gamma$</th>
<th>$Z\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_T (e,\mu) &gt; 25$ GeV</td>
<td>$P_T (e,\mu) &gt; 25$ GeV</td>
</tr>
<tr>
<td>$E_T^{\text{miss}} &gt; 35$ GeV</td>
<td>$P_T (\gamma) &gt; 40$ GeV</td>
</tr>
<tr>
<td>$P_T (\gamma) &gt; 40$ GeV</td>
<td>$M_T(W) &gt; 40$ GeV</td>
</tr>
<tr>
<td>$</td>
<td>M_{l\gamma} - M_Z</td>
</tr>
</tbody>
</table>

**Events / 80 GeV**

\[
\int L \, dt = 20.3 \, \text{fb}^{-1}, \sqrt{s} = 8 \, \text{TeV}
\]

**ATLAS**

Events / 60 GeV

\[
\int L \, dt = 20.3 \, \text{fb}^{-1}, \sqrt{s} = 8 \, \text{TeV}
\]

**ATLAS**

Significance

```
Events / 80 GeV

Significance

$\Delta m_{e\gamma}$ [GeV]

ATLAS

Data 2012

$W(e\nu) + \gamma$

$Z(e^+e^-) + \gamma$

$W(e\nu) + \text{jets}$

$\gamma + \text{jets}$

Other Backgrounds

$m(a_e) = 600 \, \text{GeV} \times 10$

Background Fit $\pm 1 \sigma$

Significance

$\Delta m_{e\gamma}$ [GeV]
```
\[ Z\gamma, \ W\gamma \]

\[ \int L \, dt = 20.3 \text{ fb}^{-1}, \ \sqrt{s} = 8 \text{ TeV} \]

<table>
<thead>
<tr>
<th>( m(T) ) [GeV]</th>
<th>( \sigma_{\text{fid}} \times \text{BR}(X \rightarrow W(l\nu)\gamma) ) [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>10</td>
</tr>
<tr>
<td>600</td>
<td>1</td>
</tr>
<tr>
<td>800</td>
<td>10^{-1}</td>
</tr>
<tr>
<td>1000</td>
<td>10^{-2}</td>
</tr>
<tr>
<td>1200</td>
<td>10^{-3}</td>
</tr>
<tr>
<td>1400</td>
<td>10^{-4}</td>
</tr>
<tr>
<td>1600</td>
<td>10^{-5}</td>
</tr>
</tbody>
</table>

- Observed 95% CL upper limit
- Expected 95% CL upper limit
- Expected \( \pm 1 \sigma \)
- Expected \( \pm 2 \sigma \)
- \( a_T \rightarrow W(l\nu)\gamma \)

\[ \text{ATLAS} \]

\[ \int L \, dt = 20.3 \text{ fb}^{-1}, \ \sqrt{s} = 8 \text{ TeV} \]

<table>
<thead>
<tr>
<th>( m(\omega_T) ) [GeV]</th>
<th>( \sigma_{\text{fid}} \times \text{BR}(X \rightarrow Z(l^+l^-)\gamma) ) [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>10</td>
</tr>
<tr>
<td>400</td>
<td>1</td>
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<tr>
<td>600</td>
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<tr>
<td>1600</td>
<td>10^{-6}</td>
</tr>
</tbody>
</table>

- Observed 95% CL upper limit
- Expected 95% CL upper limit
- Expected \( \pm 1 \sigma \)
- Expected \( \pm 2 \sigma \)
- \( \omega_T \rightarrow Z(l^+l^-)\gamma \)

\[ \text{data well described by SM backgrounds} \]

\[ \text{Exclude: } m(\omega_T) < 900 \text{ GeV} \]

\[ \text{Exclude: } m(a_T) < 1000 \text{ GeV} \]
Boosted boson tagging

**Boson jets**
- Two narrow regions with high energy for each quark
- Each of the quark carries comparable fraction of the boson momentum in the lab frame

**QCD jets**
- Narrow region with high energy density
- High energy density region has most of the momentum of the jet

1. **Fat jet**: large distance parameter to pick up all the radiation from the original decay
2. **Grooming**:
   - Signal: take out jet constituents that don’t belong to the signal decay
   - Background - Preserve background characteristics in the jet
3. **Tagging**:
   - Use differences in Signal and Background jet characteristics to reject background jets
JetMass grooming

- Splitting: use substructure of jet: $\sqrt{ys}$ and mass drop
- Filtering: remove soft radiation
JetMass grooming

- Trimming (http://arxiv.org/abs/0912.1342)
- Removes soft constituents from pile-up, ISR and multiple parton interaction by comparing the pT of each constituents to the jet pT: $p_T^i/p_T^{jet} < f_{cut}$
JetMass grooming

- Pruning http://arxiv.org/abs/0912.0033
- For each jet in reclustering, remove softer constituent from jet if wide-angled: $R_{12} > R_{\text{cut}} \cdot 2m/p_T$ or
- soft: $\min(p_{T,1}, p_{T,2})/p_{T,1} + p_{T,2} < Z_{\text{cut}}$
Definition of substructure variables

- **Splitting scale** *Phys. Rev. D* 65 (2002) 096014
  - $k_t$ distance between the two proto-jets of the final clustering step:
    \[ \sqrt{d_{12}} = \min(p_{T1}, p_{T2}) \times \Delta R_{12} \]
  - Hardest proto-jets are combined in last step of reclustering for $k_t$ algorithm
  - Symmetric energy distribution for W-jets, asymmetric for QCD jets

- **Momentum balance** *Phys. Rev. Lett.* 100 (2008) 24200
  \[ \sqrt{y_f} = \frac{\min(p_{T1}, p_{T2})}{m_{12}} \times \Delta R_{12} \]

- **N-subjettiness** *JHEP* 03 (2011) 015
  - Describes how likely it is that a jet is composed out of $N$ subjets:
    \[ \tau_N = \frac{\sum_k p_{T,k}(\min(\Delta R_{1,k}, R_{2,k}, \ldots, R_{N,k}))^3}{\sum_k p_{T}(R_0)^3} \]
  - Powerful discrimination using the ratio: $\tau_2/\tau_1$

Run2: Energy correlator functions (http://arxiv.org/abs/1305.0007)
Table 4: Summary of the systematic uncertainties affecting the shape of the signal dijet mass distribution and their corresponding models. $G(x|\mu, \sigma)$ in the table denotes a Gaussian distribution for the variable $x$ with mean $\mu$ and standard deviation $\sigma$.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
<th>Constraining pdf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet $p_T$ scale</td>
<td>2%</td>
<td>$G(\alpha_{PT}</td>
</tr>
<tr>
<td>Jet $p_T$ resolution</td>
<td>20%</td>
<td>$G(\sigma_{R_{E}}</td>
</tr>
<tr>
<td>Jet mass scale</td>
<td>3%</td>
<td>$G(\alpha_{m}</td>
</tr>
</tbody>
</table>
VV→qqqq (ATLAS)

Table 5: Summary of the systematic uncertainties affecting the signal normalisation and their impact on the signal.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency of the track-multiplicity cut</td>
<td>20.0%</td>
</tr>
<tr>
<td>Jet mass scale</td>
<td>5.0%</td>
</tr>
<tr>
<td>Jet mass resolution</td>
<td>5.5%</td>
</tr>
<tr>
<td>Subjet momentum-balance scale</td>
<td>3.5%</td>
</tr>
<tr>
<td>Subjet momentum-balance resolution</td>
<td>2.0%</td>
</tr>
<tr>
<td>Parton shower model</td>
<td>5.0%</td>
</tr>
<tr>
<td>Parton distribution functions</td>
<td>3.5%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>2.8%</td>
</tr>
</tbody>
</table>
Track jet double ratio method

In situ method using track jets in dijet sample: \textit{JetMassScaleUncertaintyGuide}

- Ratio of calorimeter and track jet mass:
  \[ r_{m, \text{data/MC}}^{\text{track jet}} = \frac{m_{\text{jet}}^{\text{data/MC}}}{m_{\text{track jet}}^{\text{data/MC}}} \]

- If detector effects are well modeled in simulation, the ratios in data and MC should be in decent agreement.

- Data/MC comparison:
  \[ R_{\text{track jet}}^{m} = \frac{r_{m, \text{data}}^{\text{track jet}}}{r_{m, \text{MC}}^{\text{track jet}}} \]

- The comparison of data and MC as a function of kinematic jet variables provides an estimation of the calibration uncertainty.

- The jet mass calibration is probed in different kinematic regions (\( \eta, p_T \))
Technicolor Models, Heavy Vector Triplet

- Technicolor (TC): effective theories with a new strong force dynamics to provide mechanism for EWSB
  - Composite Higgs state for EWSB, no hierarchy problem
  - Explorable at LHC: Minimal Walking Technicolor (MWT)
  - Search for narrow resonances in dilepton, diboson final states or WH/ZH associate production

- HVT:
  - not sensitive to details of underlying model
  - A simplified Lagrangian can be used, limits derived on $\sigma \times \text{BR}$ can then be translated into any specific model
  - Works for on shell resonances, it doesn’t include off-shell effects!

- Two benchmark models
  - Model A $\rightarrow$ weakly coupled vector resonances from extension of the gauge group
  - Model B $\rightarrow$ HVT are produced in a strong scenario e.g. composite higgs model
Heavy vector triplet

★ New heavy vector boson triplet $V^a_\mu (a = 1, 2, 3)$ and the simplest Lagrangian

$$\mathcal{L}_V = -\frac{1}{4} D_{\mu} V^a_\nu D^{\mu} V^a_\nu + \frac{m^2}{2} V^a_\mu V^a_\mu$$

$$+ i g_V c_H V^a_\mu H^\dagger \tau^a D^\mu H + \frac{g^2}{g_V} c_F V^a_\mu J^\mu_F$$

$$+ \frac{g_V}{2} c_{VVV} \epsilon_{abc} V^a_\mu V^b_\nu D^{\mu} V^c_\nu + g_V^2 c_{VVHH} V^a_\mu V^a_\mu H^\dagger H - \frac{g}{2} c_{VVV} \epsilon_{abc} W^{\mu} V^a_\mu V^b_\nu V^c_\nu$$

where $g_V$ represent the “typical” strength of $V$ interactions (“weekly coupled” $g_V \simeq 1$, “strongly coupled” $g_V \simeq 4\pi$) and the parameters $c (c_H, c_\ell, c_q, c_3)$ define deviation from “typical” size.

★ This $\mathcal{L}$ is the most general compatible with SM gauge invariance and CP symmetry for operators of energy dimension $\leq 4$.

★ This is justified if the effect of higher dimensional operators is negligible (especially for the strong coupling case) and this is the case if $\xi = v^2/f^2$ is small (EWPT demands $\xi \lesssim 0.2$).

★ Production is mainly Drell-Yan while VBF could be interesting at LHC run-2 for a scenario with suppressed coupling to fermions ...