Searches for high-mass resonances with the ATLAS detector

Takuya Nobe*

on behalf of the ATLAS collaboration

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*ICEPP, The University of Tokyo and University of Geneva
Introduction

- The Standard Model is well established for physics at O(100)GeV
- There are many mysteries not described by the SM e.g. hierarchy problem, which is a question why EW scale is $10^{17}$ times smaller than Planck scale
- Many new physics models beyond the SM to solve it
  - Supersymmetry, extra dimensions, composite Higgs, …
- Most of them predict **new particles at TeV energy scale**
- ATLAS searches for these signals as less dependent on theoretical models as possible
- This talk presents new ATLAS results of searches for heavy resonances decaying to **diboson** and **tt** using full-run2 dataset 139 fb$^{-1}$
- Reference (will be updated soon): https://twiki.cern.ch/twiki/bin/view/AtlasPublic
• An important technique at m>1 TeV: **boosted object tagging**

• Hadronically-decaying W/Z bosons and top quarks are reconstructed as one **large-R jet** (anti-kT R=1.0)

• Studies of **jet substructure** variables are improved significantly during run-2
Legacy boosted object tagging

- Using large-R jet reconstructed by calorimeter clusters
- Rectangular cuts on jet **mass** and **substructure variable** are applied to enhance signals
  - Top tagger: mass + N-subjettiness ($\tau_{32}$). 80% efficiency v.s. bkg rejection of 5-20 depending on $p_T$
  - W/Z tagger: mass + energy correlation function ratio ($D_2$). 50% efficiency v.s. bkg rejection 50-60
- Many other substructure variables were also tried and $\tau_{32}$ and $D_2$ were chosen to show the best performances

Studies of the substructure variables

- Each substructure variable has strong and weak phase spaces
- Separation power of $\tau_{32}$ is degrading at very high-$p_T$ region, due to the angular resolution of calorimeter clusters

$p_T<1$ TeV

$p_T>1.5$ TeV
DNN-based boosted top tagger

- Multi-variate analysis based on DNN to combine several jet substructure variables

- Supervised training to separate top-jet from QCD-jet bkg

ID tracker v.s. calorimeter

- $\sigma(p_T)/p_T = 0.05\% p_T \oplus 1\%$
- $\Delta\Phi \sim 10\mu$rad
- Resolution of substructure variables gets worse at high-$p_T$ region due to the angular resolution of calorimeter
- Support of ID tracks can improve it

- $\sigma(E)/E = 50\%/\sqrt{E} \oplus 3\%$
- Read-out granularity: $\Delta\eta \times \Delta\Phi = 0.1 \times 0.1$
A new p-flow-like algorithm dedicated to high-p_T jets

- **TrackCalo Cluster (TCC)**: a combination of excellent energy resolution of calorimeter and angular resolution of ID tracks at very high-p_T region

- As with standard p-flow algorithm, take a matching between calo cluster and ID tracks, then, use calorimeter observables for charged-particle energy and ID track observables for charged-particle angles

- Compare its performances with legacy calorimeter jet:
  
  ![Image of performance comparison](https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2018-31/)

  - 10 times better background rejection if we adopt ~25% efficiency
  - 20-30% better signal efficiency at the highest p_T, if we keep the background rejection as the same level as legacy tagger
Search for heavy diboson resonances in semi-leptonic final states in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector
Heavy resonance search status

- ATLAS searches for many narrow-width heavy resonances

- Heavy vector triplet (HVT) is a useful simplified model to introduce new heavy vector resonances (parameterized by $g_V$: $V'VV$ coupling and $c_F$: $V'ff$ coupling)
  - **Model A** ($g_V=1$) motivated by extended gauge theory
  - **Model B** ($g_V=3$) motivated by compositeness

+ we also consider **Model C** ($c_F=0$): a benchmark model for VBF production

https://arxiv.org/abs/1402.4431
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  - **Model A** ($g_V=1$) motivated by *extended gauge theory*
  - **Model B** ($g_V=3$) motivated by *compositeness*
- Full run-2 results of $W'\rightarrow lv/qq$ and $Z'\rightarrow ll/qq$ analyses can be found in: JHEP 03 (2020) 145 PRD 100 (2019) 052013 PLB 796 (2019) 68
Overview of diboson resonance search

- **Semi-leptonic** final states ($WV \rightarrow lvqq/ZV \rightarrow llqq/ZV \rightarrow vvqq$)

- **Analysis comprehensiveness:**
  - 3 production mechanisms considered: gluon-gluon fusion (ggF) / quark-anti-quark annihilation (DY) / vector-boson fusion (VBF)
  - Several benchmark signals with different spin and final states ($WW/WZ/ZZ$)
    - Spin-1 HVT $W' \rightarrow WZ$ and $Z' \rightarrow WW$
    - Spin-0 bulk Randall-Sundrum (RS) radion $R \rightarrow WW/ZZ$
    - Spin-2 bulk RS Graviton $G_{KK} \rightarrow WW/ZZ$
  - Wide mass ranges:
    - High-mass: large-R jet + boosted object tagging technique (merged)
    - Low-mass: two small-R jets (resolved)

- **Analysis improvements** w.r.t. 36 fb$^{-1}$ analysis [*]
  - ML-based VBF/ggF classifier
  - Move to TCC jets
  - $Z \rightarrow qq$ signals are separated to 2 categories ($Z \rightarrow bb$ and the other)
Analysis flow

Collected events (lepton or missing $E_T$ triggers)

Categorization based on # of leptons

0-lepton
mET>250GeV

1-lepton
mET>100(60)GeV

2-lepton
with $p_T>$30GeV

(in each channel) ML-based VBF and ggF/DY categorization

ggF/DY category
RNN score<0.8

VBF category
RNN score>0.8

Resolved analysis

- Kinematic cuts similar to merged analysis applied
- b-tagged/untagged categorization for $Z\rightarrow qq$ candidate

Merged analysis with W/Z tagging using new TCC jets

- In 1-/2-lep channels, $p_{T,V}/m_{VV}>0.35$ (0.25) for ggF/DY (VBF) category
- $W\rightarrow qq$ region and $Z\rightarrow qq$ region are largely overlap. Separate analyses for $W$ and $Z$ interpretations performed
- For $Z\rightarrow qq$ candidate, events are separated into b-tagged and untagged categories

If event is not selected by merged analysis, go to the resolved

Estimate SM bkg $m_{VV}$ shape and search for a “bump”
ML-based ggF/VBF classifier

- Trained to separate VBF signal from ggF signal (signal MC v.s. signal MC)
- Input: 4-momenta of the VBF-jet candidates
  - $W/Z \rightarrow qq$ candidate jets are excluded from the list
  - Up to 2 jets are used; even if there is only 1 VBF-jet candidate, the event is not discarded
- Recurrent (sequential) NN architecture to cope with variable # of input jets

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**ATLAS Simulation Preliminary**

\[ \sqrt{s} = 13 \text{ TeV} \]

$X \rightarrow ZV \rightarrow \ell\ell qq$

- VBF R 1 TeV
- ggF R 1 TeV
- VBF HVT W' 1 TeV
- DY HVT W' 1 TeV
- VBF $G_{KK}$ 1 TeV
- ggF $G_{KK}$ 1 TeV

~50% improvement

Acceptance to VBF signals at the highest-mass point

**ATLAS Simulation Preliminary**

\[ \sqrt{s} = 13 \text{ TeV} \]

$X \rightarrow ZV \rightarrow \ell\ell qq$

- VBF R
- VBF HVT W'
- DY HVT W'
- ggF R
- ggF $G_{KK}$
Optimization of W/Z tagger with TCC

- Mass window and upper cut on D2 are optimized for diboson resonance search, to maximize the sensitivity in each $p_T$ bin → **20-30% better signal efficiency at the highest $p_T$**, while keeping bkg rejection.
Background Estimation

- Normalizations of main sources of bkg: W/Z+jets and $t\bar{t}$ are estimated in dedicated control regions (CRs)

- Merged and resolved analyses focus on different mass range → to absorb a possible mismodeling of MC depending on kinematics, separate normalization factors are used for merged and resolved analyses

- To consider a possible mismodeling of VBF-jet kinematics (and acceptance of RNN cut), different normalization factors for ggF/DY and VBF categories are used

- Consequently, we need many CRs to be involved in the fit

![Diagram showing the relationship between the number of additional b-jets and $m_{W/Z}$]
Systematic uncertainties

- Large-R jet energy scale is the dominant source of uncertainty
- Uncertainty on extrapolation from sideband-CR to SR is taken into account by boson-tagger efficiency SF uncertainty
  - SF is estimated in dedicated control samples
- Theoretical modeling of $m_{VV}$ shapes of $W/Z$+jets, $\bar{t}t$ and SM diboson processes is estimated using simulations with different parameters
  - Variations of QCD scales, ISR/FSR parameters, PDF, etc.
  - Choice of generators (MG v.s. Sherpa for $W/Z$+jets, aMC@NLO v.s. Powheg+Pythia for $\bar{t}t$)

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>$\frac{\Delta \mu}{\mu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>600GeV</td>
</tr>
<tr>
<td>Large-R jet ($p_T$ scale and boson-tagging eff.)</td>
<td>18%</td>
</tr>
<tr>
<td>MC statistics</td>
<td>16%</td>
</tr>
<tr>
<td>$W/Z$+jets shape modeling</td>
<td>11%</td>
</tr>
<tr>
<td>Background normalization (CR stats)</td>
<td>15%</td>
</tr>
<tr>
<td>SM VV shape modeling</td>
<td>12%</td>
</tr>
<tr>
<td>$\bar{t}t$ shape modeling</td>
<td>8%</td>
</tr>
<tr>
<td>Total Systematics</td>
<td>41%</td>
</tr>
<tr>
<td>Data statistics</td>
<td>29%</td>
</tr>
</tbody>
</table>
Results: reconstructed $m_{VV}$ distributions

- Global p-value at $m=1.5\text{TeV}$ (VBF signal): $<2\sigma$
• ~20% better sensitivity is obtained at the highest mass point, compared with 36fb$^{-1}$ analysis repeated with 139fb$^{-1}$
Search for $t\bar{t}$ resonances in fully hadronic final states in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector
Overview of $t\bar{t}$ resonance search

• Top quark is the heaviest particle in the SM and may play an important role in physics BSM

• In some models, KK gluon predominantly decays to top-quark pair $BR(g_{KK}\rightarrow t\bar{t}) \sim 0.9$

• Top-assisted technicolor model as a benchmark of leptophobic $Z'$ with $BR(Z'\rightarrow t\bar{t}) \sim 0.3$

• **Fully-hadronic** final states ($t\bar{t}\rightarrow qqbqqb$)
  
  • Largest branching fraction
  
  • Focus on the highest mass region

• **Analysis improvements**
  
  • A new ML-based top tagger to reduce bkg more
  
  • A new b-tagging based on variable-radius track jets
  
  • Full data-driven background estimation

It is also a bump search against the smoothly falling SM bkg $m_{JJ}$
With old top tagger, fully-hadronic and semi-leptonic channels had similar sensitivities

- Fully-hadronic channel
  - The main source of the background at the highest mass is multijet process (reducible)

- Improvement of boosted top tagging can directly gain the sensitivity

Event selection

- Large-R jet trigger (plateau at $p_T \sim 500$GeV)
- 2 large-R jets with $p_T > 500$, 350GeV (continue to use calorimeter jets)
- Both jets are top-tagged using DNN top tagger
  - Per-jet bkg rejection is improved by factor $\sim 2 \rightarrow \sim 4$ times smaller multijet bkg is expected
- $|\Delta y_{JJ}| < 1.8$, $\Delta \phi > 1.6$ for back-to-back dijet in central rapidity
- $m_{JJ} > 1.4$TeV
Event categorization

- # of b-jets associated with large-R jet is counted using variable-radius (VR) track jets
- Using anti-kT cone parameter depending on $p_T$, we can suppress the effect from close-by/underlying track particles → better b-tag efficiency at very high-$p_T$
- Large-R jet with $\geq 1$ associated b-jets → “b-tagged large-R jet”
- Events are categorized into 2 channels based on #of b-tagged large-R jets
  - SR2b and SR1b
Background Estimation

- Smooth falling function $F(x) = p_0(1-x)^{p_1}x^{p_2+p_3 \log(x)+p_4 \log(x)^2}$ is used, where $x=m_{jj}/\sqrt{s}$

- The function is validated in SRs using background-only sample
  - $t\bar{t}$ MC + high-mass dijet MC + data-driven template of low-mass multijet sample
  - Choice of #of fit parameters optimized; to minimize the **spurious signal yield** obtained by s+b fit to this b-only template
  - Uncertainties on fit parameters are considered as systematic uncertainty
  - Spurious signal yield is considered as additional uncertainty related the choice of fit function (~30-40% at 4TeV)
Signal modeling

- Signal MC samples are described by Gaussian + CrystalBall, then we can interpolate to every mass points

- Uncertainty on signal acceptance is estimated
Results: reconstructed $m_{JJ}$ distributions

- Model-independent p-value scan by BumpHunter, maximum local significance is $\sim 2\sigma$ and global significance is $< 1\sigma$

- CLs method used to calculate upper limits
Cross-section upper limits

- $Z'_\text{TC2}$ signal is excluded at $m<\sim 4\text{TeV}$ (1.2% width) and $m<\sim 4.8\text{TeV}$ (3% width)
Cross-section upper limits

- $Z'_{TC2}$ signal is excluded at $m<\sim4$ TeV (1.2% width) and $m<\sim4.8$ TeV (3% width)

- Great sensitivity gain exceeding increase of statistics!!
$p_T=1.96\,\text{TeV}$
$(\eta, \phi) = (0.64, 0.41)$
$m_J = 152\,\text{GeV}$

$m_{JJ'} = 4.8\,\text{TeV}$

$p_T=1.92\,\text{TeV}$
$(\eta, \phi) = (-0.72, -2.71)$
$m_J = 173\,\text{GeV}$
Summary

• New **ATLAS** results of searches for heavy resonances decaying to $VV$ and $t\bar{t}$ have been presented

• New **boosted object tagging** techniques
  
  • Bottom-up approach: a new p-flow algorithm (**TCC**) dedicated to high-$p_T$ jets improved the W/Z tagging efficiency by ~30% at $p_T=2.5$TeV

  • **ML-based top tagger** to combine several substructure variables improved per-jet background rejection by factor 2 while keeping the signal efficiency

• In addition, many new ideas to improve the analyses implemented

  • ML-based ggF/VBF classification

  • B-tagging with new VR track jets

• In both analyses, no significant excess observed above SM predictions

• The world best lower limits are set on the masses of hypothetical new particles
Extra materials
Track-Calorimeter Cluster (TCC)

\[ \text{TCC}_{1} = \left( p_{T}^{c_{1}}, \eta^{t_{1}}, \phi^{t_{1}}, m^{c_{1}} \right) = 0 \]
\[ \text{TCC}_{2} = \left( p_{T}^{c_{2}}, \eta^{c_{2}}, \phi^{c_{2}}, m^{c_{2}} \right) = 0 \]
\[ \text{TCC}_{3} = \left( p_{T}^{c_{3}}, \eta^{t_{3}}, \phi^{t_{3}}, m^{t_{3}} \right) = 0 \]

\[ \text{TCC}_{4} = \left( p_{T}^{c_{2}}, \frac{p_{T}^{t_{2}}}{p_{T}^{t_{2}} + p_{T}^{t_{3}}}, \eta^{t_{2}}, \phi^{t_{2}}, m^{c_{2}} \right) = 0 \]
\[ \text{TCC}_{5} = \left( p_{T}^{c_{2}}, \frac{p_{T}^{t_{3}}}{p_{T}^{t_{2}} + p_{T}^{t_{3}}}, \eta^{t_{3}}, \phi^{t_{3}}, m^{c_{2}} \right) = 0 \]
D_2 and \( \sqrt{d_{12}} \)

- Decay of W/Z: 2-prong-like
  - A variable: \( D_2^{\beta=1} = E_{\text{CF3}} \left( \frac{E_{\text{CF1}}}{E_{\text{CF2}}} \right)^3 \)
    is used to enhance signals

\[
E_{\text{CF1}} = \sum_{i} p_{T,i}
\]

\[
E_{\text{CF2}} = \sum_{ij} p_{T,i} p_{T,j} \Delta R_{ij}
\]

\[
E_{\text{CF3}} = \sum_{ijk} p_{T,i} p_{T,j} p_{T,k} \Delta R_{ij} \Delta R_{jk} \Delta R_{ki}
\]

- kT-splitting scale
  - Recluster the jet by kT algorithm
  - At the final step of kT algorithm, \( \sqrt{d_{12}} = \min(p_{T1}, p_{T2}) \Delta R_{12}/R \)
  - small \( \sqrt{d_{12}} \rightarrow p_T \) of 2 subjets are balanced

There're 2 high-p_T constituents with large \( \Delta R_{ij} \), and no the other constituents with high-p_T:

- \textbf{large } E_{\text{CF2} } \textbf{ but small } E_{\text{CF3} }
The other SRs (VV resonance)

Multijet bkg is not negligible only in resolved 1-lep channel. It is estimated by data-driven method (ABCD)
Limits on the other signal models (VV)
Pileup dependency of DNN top tagger

Data 2015+2016
Trimmed anti-\(k_t\), \(R=1.0\) jets
Top tagger (\(\varepsilon_{\text{sig}} = 80\%\)): DNN
\(\rho_{_1} > 350\) GeV

\(\frac{\text{Data}}{\text{Pred.}}\)

\(\varepsilon_{\text{sig}}\)

1.5
1
0.5
0.2
0.8

10 20 30 40
\(\mu\)

\(\text{ATLAS}\)
\(\sqrt{s} = 13\) TeV, 36.1 fb\(^{-1}\)

\text{Pileup dependency of DNN top tagger}

\(\text{ATLAS}\)
\(\sqrt{s} = 13\) TeV, 36.7 fb\(^{-1}\)
Trimmed anti-\(k_t\), \(R=1.0\) jets
Multijet selection
Top tagger (\(\varepsilon_{\text{sig}} = 80\%\)): DNN

\(\frac{1}{\varepsilon_{\text{bkg}}}\)

\(5 10 15 20 25 30 35 40\)
\(\mu\)

\(\text{Data} 2015+2016\)
Pythia8
Herwig++
Stat. uncert.
Total uncert.
VR track-jet b-tagging performance

- Control plot:
  - 2 b-jets from Higgs decay can be separated by VR track jets
  - Similarly, efficiency to b-jets in dense environment (inside boosted top decay) is also improved
Extended ABCD method to extract multijet template from data

<table>
<thead>
<tr>
<th></th>
<th>Leading large-R jet</th>
<th>is top-tagged? b-tagged?</th>
</tr>
</thead>
<tbody>
<tr>
<td>(tb)</td>
<td>A (6.1%)</td>
<td>SR1(b) (23%)</td>
</tr>
<tr>
<td>(t\bar{b})</td>
<td>B (0.5%)</td>
<td>E (1.8%)</td>
</tr>
<tr>
<td>(\bar{t}b)</td>
<td>C (0.4%)</td>
<td>G (2.3%)</td>
</tr>
<tr>
<td>(\bar{t}\bar{b})</td>
<td>D (&lt; 0.1%)</td>
<td>F (0.3%)</td>
</tr>
</tbody>
</table>

- Ratio (\(B \to A\)) and (\(H \to I\)) are applied to TR to estimate multijet bkg in SR1\(b\)
- Ratio (\(B \to A\))\(\times\)(\(B \to E\)) and (\(H \to I\))\(\times\)(\(H \to G\)) are applied to TR to estimate multijet bkg in SR2\(b\)
- Regions C, D and F are used to evaluate the correlation between leading and subleading jets
  - e.g. double ratio (\(H \to G\))/\(D \to C\) is applied to (\(B \to A\)) factor
  - (\(D \to F\))/\(B \to E\) is applied to (\(H \to I\)) factor
Acceptance x efficiency (tt analysis)

**ATLAS Simulation Preliminary**
\[ \bar{s} = 13 \text{ TeV} \]

**SR1b**

\[ 1 \text{TeV} \leq \text{m}(Z'_{\text{TC2}}) \leq 5 \text{TeV} \]

**ATLAS Simulation Preliminary**
\[ \bar{s} = 13 \text{ TeV} \]

**SR2b**

\[ 1 \text{TeV} \leq \text{m}(Z'_{\text{TC2}}) \leq 5 \text{TeV} \]

\[ \text{Acceptance} \times \text{Efficiency} \]
Bulk RS model

- Spin-2 Graviton mainly couples to $W/Z$/$\text{top}/h$
- Spin-0 Radion to stabilize the compactified extra dimension $r_c$, which also predominantly decays into $W/Z$/$\text{top}/h$ and gluons

[Graph 1: BR vs $M_{Gr}$ (GeV)]

[Graph 2: BR($R') > XX$ vs $m_{R'}$ (GeV)]

Polarization of final-state bosons

• Depends on models and it is an interesting research topic in the next round of the analysis

• Our tagger is currently optimized to logitudinally-polarized W/Z bosons

• Graviton in a standard RS model (RS1) has transversely polarized but mostly excluded by diphoton/dilepton channels

• Bulk RS Gravition has ~100% longitudinal polarized bosons in the final state