Searches for Exotic Physics in ATLAS using Substructure Techniques

J. Katharina Behr
On behalf of the ATLAS collaboration
E-mail: katharina.behr@cern.ch

Abstract. The significant increase of the centre-of-mass energy of the Large Hadron Collider (LHC) from 8 to 13 TeV has allowed the LHC experiments to explore previously inaccessible kinematic regimes in their search for phenomena beyond the Standard Model. The sensitivity of these searches depends crucially on the efficient reconstruction and identification of hadronic decays of highly energetic (boosted) objects, the decay products of which are typically collimated into a single large jet with a characteristic substructure. In this contribution, the searches conducted by the ATLAS experiment on data recorded during 2015 and 2016 that rely on jet substructure techniques to identify signatures of interest are reviewed. A particular emphasis is placed on recent developments in the rapidly evolving field of boosted object tagging.

1. Introduction
In the first two years of the first data-taking period in proton-proton (pp) collision at the √s = 13 TeV (Run-2), the ATLAS [1] collaboration has already presented a diverse programme of searches for new phenomena beyond the Standard Model (BSM), probing the predictions of numerous models over an unprecedented kinematic regime. These searches are well-motivated by the known shortcomings of the Standard Model (SM), which explains neither why the Higgs boson is light (hierarchy problem), nor provides a candidate for dark matter. Extensions of the SM include theories with warped extra dimensions (Randall-Sundrum models), new strong interactions, vector-like quarks (VLQs), or models with a second Higgs doublet (2HDMs).

Top quarks, Higgs bosons, and W/Z bosons play a key role in many BSM searches as numerous models predict new particles that couple most strongly to the Higgs and electroweak sector and the third quark generation. At the LHC, a large fraction of these most massive SM particles are produced with large Lorentz boost. If the transverse momentum of a massive particle exceeds twice its rest mass, it is referred to as a boosted object. The efficient reconstruction and identification of boosted object decays is of key importance for BSM searches targeting large BSM particle masses and interactions at the highest accessible energies. Their key property is the angular collimation of their decay products, which for a two-body decay X → ab is given by:

\[ \Delta R(a, b) \approx \frac{2m^X}{p^X_T} \] (1)

where \( \Delta R(a, b) \) denotes the angular separation between the decay products. As a consequence,
hadronically decaying boosted objects can be reconstructed as a single jet with large radius parameter $R$ and a characteristic substructure.

2. Jet Substructure
In ATLAS, hadronically decaying boosted objects are typically reconstructed as anti-$k_t$ \cite{2} $R = 1.0$ jets built from locally calibrated calorimeter clusters. The most powerful discriminating variable between jets initiated by top quarks, Higgs bosons, or $W/Z$ bosons and background jets from light quarks or gluons is, naturally, the jet mass, which is calculated from the sum of the four-momenta of the (massless) jet constituents. A number of variables that describe the internal structure of the jet are used as additional discriminating variables. The two most commonly used jet substructure variables in early Run-2 ATLAS searches are $n$-subjettiness \cite{3}, which describes how compatible the jet substructure is with the $n$-subjets hypothesis, and variables based on energy correlation functions calculated for the jet constituents \cite{4, 5, 6}.

A key issue for analyses at high-luminosity hadron colliders is the presence of contaminations from additional $pp$ interactions in the same and subsequent bunch-crossings, referred to as pile-up. These soft, wide-angle contaminations dilute the jet substructure and bias the jet mass, shifting it towards larger values. In order to restore the discriminating power of these variables, jet grooming procedures have been developed. In ATLAS, the current standard grooming algorithm is trimming \cite{7}, in which the constituents of the ungroomed large-$R$ jets are re-clustered using the $k_t$ algorithm \cite{8, 9} with radius parameter $R = 0.2$. All $k_t R = 0.2$ subjets that carry a transverse momentum of less than 5% of that of the large-$R$ jet are rejected and the trimmed large-$R$ jet is built from the constituents of the remaining subjets.

3. Searches with Boosted Top Quarks
Searches for massive resonances decaying into a $t\bar{t}$ pair have been the first BSM searches to rely on jet substructure techniques, both at the Tevatron and the LHC. Today a wide and still growing range of dedicated top tagging algorithms or top taggers is on the market, with different taggers suited for different kinematic regimes and final states, as illustrated for example in Section 6 of Ref. \cite{10}. For searches relying on early Run-2 data, the ATLAS collaboration has developed a simple baseline top tagger \cite{11}. It relies on the trimmed jet mass and the $n$-subjettiness ratio $\tau_3$ \cite{3} to identify jets from boosted hadronic top-quark decays, which are reconstructed from trimmed anti-$k_t$ $R = 1.0$ jets. The requirements placed on the two discriminating variables depend on the jet transverse momentum and are optimised to yield the best rejection of background jets from gluons and light quarks for a given signal efficiency. Two working points with an overall signal efficiency of 50% and 80%, respectively, are provided.

This baseline top tagger is used in the search for massive resonances decaying to $t\bar{t}$ in the single-lepton-plus-jets ($\ell\pm$jets, $\ell \in \{e, \mu\}$) final state \cite{12}. The search relies on $\int \mathcal{L} = 3.2 \text{ fb}^{-1}$ of data collected in 2015 and targets the kinematic regime where the hadronically decaying top quark can be reconstructed as a single large-$R$ jet. The presence of a single isolated electron or muon from the semileptonically decaying top quark allows efficient suppression of the background from multijet production. This enables the 80% top tagging working point to be chosen, thus allowing for a larger signal efficiency compared to the tighter 50% top tagging working point. The dominant background component in the signal region is the irreducible background from SM $t\bar{t}$ production which accounts for more than 80% of the total background contribution. No significant deviation of the data from the SM expectation is observed in the reconstructed $t\bar{t}$ invariant mass spectrum (Figure 1a). Upper limits on the cross-section times branching ratio to $t\bar{t}$ are derived for a leptophobic top-colour $Z^\prime_{TC2}$ boson (Figure 1b). The limits at 95% confidence level (CL) range from 300 pb to 0.05 pb for masses from 0.4 TeV to 5 TeV. A $Z^\prime_{TC2}$ boson of width $\Gamma/m = 1.2\%$ (3%) is excluded for masses in the range 0.7 TeV $< m_{Z^\prime} < 2.0$ TeV (0.7 TeV $< m_{Z^\prime} < 3.2$ TeV).
Figure 1: (a) The reconstructed $t\bar{t}$ invariant mass distribution $m_{t\bar{t}}^{\text{reco}}$ in the $\mu$+jets channel. The ratio of the data to the SM expectation is given in the lower panel. The expected signal distribution for a $Z'$ boson with width $\Gamma/m = 1.2\%$ is indicated by a red line. (b) Observed and expected upper limits on the cross-section times branching ratio to $t\bar{t}$ at 95% CL [12].

4. Searches with Boosted $W/Z$ Bosons

Jet substructure techniques play a key role in all searches involving hadronic vector boson decays on $\sqrt{s} = 13$ TeV data that were published by the ATLAS collaboration to date. As in the case of boosted top quarks (Section 3), the ATLAS collaboration has developed a set of baseline $W/Z$ taggers for searches with early $\sqrt{s} = 13$ TeV data [13]. Boosted $W/Z$ bosons, like boosted top quarks, are reconstructed from trimmed anti-$k_t$ $R = 1.0$ jets. The jet mass, naturally, is the most important discriminating variable for the identification of $W/Z$ bosons. Only jets within a mass window around the $W/Z$ boson mass are selected as $W$ or $Z$ boson candidates. The mass window is determined using Monte Carlo simulations and is defined as the smallest window around the peak in the trimmed jet mass distribution for $W$ or $Z$ boson jets, respectively, containing 68% of the jets. In addition, a jet transverse momentum dependent requirement is placed on the energy correlation ratio $D^2_{0,1} = 5$ to further suppress the background from multijets production. Two working points with an overall 25% and 50% signal efficiency, respectively, are provided.

4.1. Searches for diboson resonances

The baseline $W/Z$ taggers are used in a number of resonance searches such as the search for resonances decaying to a pair of hadronically decaying vector bosons ($WW$, $ZZ$, and $WZ$) [14], for massive $WW$ and $WZ$ resonances in the $\ell\nu qq$ final state [15], for massive $ZW$ and $ZZ$ resonances in the $\ell\nu qq$ and $\nu\nu qq$ final states [16], and for massive resonances decaying to $Z\gamma$ [17].

Diboson searches in the purely hadronic final state especially benefit from the use of jet substructure techniques, as these not only allow for an effective suppression of the large background from multijet production but also reduce the problem of the combinatorial background that arises in resolved topologies due to incorrect assignments of the small-$R$ jets to the vector boson candidates. Hence the search for massive diboson resonances in the fully hadronic final state focuses on the boosted regime where the events exhibit a simple dijet topology. Signal events are required to have two boson-tagged jets with $p_T > 250$ GeV ($p_T > 450$ GeV for the leading jet) and a dijet invariant mass greater than 1 TeV. To further suppress the background from multijet production, the boson candidate jets must meet the
requirement $N_{\text{trk}} < 30$, where $N_{\text{trk}}$ denotes the number of charged-particles tracks from the primary vertex that are matched to the ungroomed jet via ghost-association [18, 19, 20]. This requirement is motivated both by the larger fraction of gluon-initiated jets in background events as well as the different fragmentation scales for signal and background events that both lead to a larger track multiplicity in background jets. No significant deviation from the SM expectation is found in the dijet invariant mass distribution with $\int L = 15.5 \text{ fb}^{-1}$ of data (Figure 2a) and upper limits at 95% CL are derived on the production cross section times branching ratio to $WZ$ and $WW$ final states of resonances arising within Heavy Vector Triplet (HVT) models (Figure 2b), and to $WW$ and $ZZ$ final states of a bulk Randall-Sundrum graviton.

4.2. Search for dark matter in final states with missing transverse energy and a $W/Z$ boson
The ATLAS baseline boson tagger is also used in a search for dark matter produced in association with a hadronically decaying $W/Z$ boson [21]. The results are interpreted in the context of an effective field theory and a simplified model with an $s$-channel mediator. In the latter case, the $W/Z$ boson is radiated from one of the initial-state partons and recoils against the mediator that decays to a pair of dark datter particles, giving rise to missing transverse momentum $E_T^{\text{miss}}$. Final states in which the $W/Z$ boson can be reconstructed as a single jet allow one to probe large values of $E_T^{\text{miss}}$. No dark matter signal is observed in $\int L = 3.2 \text{ fb}^{-1}$ of data. In the case of the effective field theory, lower limits at 95% CL are derived on the mass scale $M_\phi$ of the effective interaction. For the simplified model, upper limits at 95% CL on the signal strength $\mu$ are set in the two-dimensional plane of the dark-matter ($m_\chi$) versus the mediator mass ($m_{\text{med}}$).

5. Searches with Boosted Higgs Bosons decaying to a $b\bar{b}$ Pair
The reconstruction and identification of boosted Higgs bosons decaying to a $b\bar{b}$ pair, described in Ref. [22], follows the same approach that is used in the case of boosted hadronically decaying $W$ and $Z$ bosons. It relies on trimmed anti- $k_t$ $R = 1.0$ calorimeter jets and both the trimmed jet mass and the energy correlation variable $D_2^{b\bar{b}=1}$ have been found to be powerful discriminating variables against light-quark and gluon jets. In addition, $b$-tagging naturally plays a key role in the identification of $h \rightarrow b\bar{b}$ decays. In the boosted regime, it is crucial that the $b$-tagging

Figure 2: (a) The dijet invariant mass distribution for the $WW$ selection. The ratio of the data to the SM expectation is given in the lower panel. (b) Observed and expected upper limits at 95% CL on the cross-section times branching ratio to $WW$ for a $Z'$ boson in a HVT model [14].
algorithms be optimised for high and stable performance at large $b$-hadron momenta and in dense decay topologies where the decay products of the two $b$-hadrons may overlap in the detector. The $b$-quark jet identification relies on anti-$k_T$ $R = 0.2$ track jets that are ghost-associated to the selected large-$R$ calorimeter jet. A tagging algorithm that is based on a Boosted Decision Tree (BDT) and takes as input various jet properties and properties computed by three other $b$-tagging algorithms is used to identify $b$-quark jets [23, 24].

5.1. Search for resonant and non-resonant Higgs pair production in the $bbbb$ final state

Boosted $h \rightarrow bb$ decays play a key role in the search for resonant and non-resonant Higgs pair production in the $bbbb$ final state. The search relies on two separate analysis strategies, one targeted at low invariant di-Higgs masses $m_{hh}$ where the four $b$-quark jets are well separated in the detector, the other targeted at the fully merged regime where the two Higgs bosons are reconstructed as a single large-$R$ jet with $p_T > 250$ GeV ($p_T > 450$ GeV for the leading jet) and selected to have a trimmed jet mass consistent with the Higgs boson mass. The selected events are classified into three categories based on whether each of the two Higgs candidate jets has two associated $b$-tagged track jets ($4b$-tag category), one Higgs candidate has two $b$-tagged track jets and the other one ($3b$-tag category), or whether each Higgs candidate jet has exactly one associated $b$-tagged track jet ($2b$-tag category). While one would expect the $4b$-tag category to be the natural choice for $hh \rightarrow bbbb$ final states, the introduction of the latter two categories serves to recover signal acceptance for large values of $m_{hh}$ where the two $b$-quark jets from a Higgs boson decay are so highly collimated that they can no longer be resolved even with the narrow $R = 0.2$ track jets, as illustrated in Figure 3a. No requirement is placed on $D_2^{b=1}$ or any other substructure variable as the $b$-tagging requirements alone allow for a sufficient suppression of the dominant background from multijet production.

No significant deviation from the SM expectation is found in $\int \mathcal{L} = 13.3$ fb$^{-1}$ of $\sqrt{s} = 13$ TeV data [25]. The exclusion limits are derived for both resonant and non-resonant Higgs pair production. In the former case, the results are interpreted in a bulk Randall-Sundrum (RS) model with $k/M_P^1 = 1.0$. The upper limits at 95% CL on the cross-section times branching ratio to $bbbb$ for a RS graviton range between 1000 and 2 fb for graviton masses in the range between 300 and 3000 GeV, as illustrated in Figure 3b. In the case of non-resonant Higgs pair production the upper limit at 95% CL is 330 fb, which is the most stringent limit to date.

5.2. Search for dark matter in final states with missing transverse energy and a Higgs boson

Boosted $h \rightarrow bb$ decays also play an important role in the search for dark matter produced in association with a single Higgs boson [26]. In contrast to the mono-$V$ signature (Section 5.1), Higgs radiation off the initial-state partons is Yukawa-suppressed. Hence the Higgs boson would be part of the interaction that produces the dark matter, thus providing a direct probe of the interaction between dark matter and the SM sector. The search results are interpreted in the context of a simplified model in which the Higgs boson is radiated off an $s$-channel vector mediator, and in the context of a Two-Higgs-Doublet Model with an extra vector mediator $Z'$ (2HDM+$Z'$) that decays into a Higgs boson and a heavy pseudoscalar $A$, which in turn decays into a pair of dark matter particles. Signal events are selected via both a resolved approach, in which the two $b$-jets from the Higgs boson decay are reconstructed as two separate small-$R$ jets, and a boosted approach, where the Higgs boson is reconstructed as a trimmed anti-$k_T$ $R = 1.0$ jet with two associated $b$-tagged track jets. No dedicated mass or substructure requirements are imposed. The resolved approach is used in the regime 150 GeV < $E_T^{\text{miss}} < 350$ GeV, while the boosted approach is used to probe the region with $E_T^{\text{miss}} > 350$ GeV. No deviation from the SM expectation is observed in the $E_T^{\text{miss}}$ distribution with $3.2$ fb$^{-1}$ of data. Exclusion limits are derived in the $m_A$-$m_{\text{med}}$ plane in the case of the simplified model, and in the $m_A$-$m_{\text{med}}$ plane...
Figure 3: (a) Acceptance times efficiency for the 2b-, 3b-, and 4b-tag regions in the search for Higgs pair production as a function of the mass of a hypothetical resonance. (b) Observed and expected upper limits at 95% CL on the cross-section times branching ratio for a RS graviton decaying to $b\bar{b}b\bar{b}$ via a pair of Higgs bosons [25]. The limits are taken from the analysis (resolved/boosted) that yields the tighter limits for a given signal hypothesis.

plane for $m_\chi = 100$ GeV in the case of the 2HDM+$Z'$ benchmark.

6. Searches involving various different Boosted Objects

The ATLAS collaboration has published a variety of searches in final states that involve two or more different boosted objects. These include searches for massive resonances decaying to a $W$ or $Z$ and a Higgs boson in the $q\bar{q}(1)+b\bar{b}$ [27] and the $\nu\nu, \ell\nu, \ell\ell+b\bar{b}$ final states [28], searches for pair production of vector-like top quarks $T$ decaying via $T\bar{T}\rightarrow Wb\bar{b}$ [29], or $T\bar{T}\rightarrow Zt+X$ [30], and a search for new phenomena in $tt$ final states with additional heavy-flavour jets [31].

For the sake of brevity, only the latter will be discussed in further detail. The search targets a variety of signal processes, including pair production of VLQs, four-top ($tt\bar{t}\bar{t}$) production in the SM and via hypothetical BSM processes, as well as associated production of heavy flavour quarks with heavy neutral ($A/H$) and charged ($H^\pm$) Higgs bosons in a 2HDM, namely $t\bar{t}A/H\rightarrow t\bar{t}\ell\ell$, $bbA/H\rightarrow b\bar{b}\ell\ell$, and $tbH^\pm\rightarrow b\bar{b}t\ell$. The search strategy is optimised for $T\bar{T}$ production where at least one of the VLQs decays to a top quark and a Higgs boson. Given that $h\rightarrow b\bar{b}$ is the dominant Higgs boson decay mode with a branching ratio of $\approx 56\%$, the signal is characterised by large jet- and $b$-tag multiplicities. To provide sensitivity to a large range of decay modes over a large kinematic regime, 20 orthogonal signal regions are defined, belonging either to the $\ell$+jets final state, characterised by the presence of an isolated electron or muon, large $E_T^{miss}$, and at least six small-$R$ jets, or the jets+$E_T^{miss}$ final state, characterised by the presence of at least seven small-$R$ jets and large $E_T^{miss}$. The regions are further distinguished based on the number of $b$-tags and the number of large-$R$ jets.

Unlike the large-$R$ jets in the searches discussed in the previous sections, the large-$R$ jets used in this search are re-clustered jets [32] built from fully calibrated anti-$k_T$ $R = 0.4$ jets with $p_T > 25$ GeV that pass a requirement on the jet vertex fraction [33] that rejects pile-up jets. These preselection requirements on the small-$R$ input jets effectively act like trimming. The
re-clustered jets are required to have $p_T > 300$ GeV and a mass$^2$ greater than 100 GeV in order to select jets associated with hadronically decaying Higgs bosons or top quarks.

No significant deviation from the SM expectation is found in any of the signal regions. Upper limits on the signal production cross-section are placed for various benchmark scenarios of $T\bar{T}$ production as well as on the other models discussed above. For a $T$-quark doublet (singlet), $T$-quark masses below 1160 GeV (1020 GeV) are excluded at 95% CL (Figure 4a).

![Figure 4](image)

(a) Observed and expected upper limits on the cross-section for $T\bar{T}$ production for a $T$-quark doublet benchmark [31]. (b) Background rejection versus signal efficiency for the variation of a lower selection requirement on the jet mass of trimmed (red) and ungroomed (blue) variable-$R$ and trimmed anti-$k_T$ $R = 1.0$ jets (black). Signal jets are top-quark-initiated jets from simulated $Z' \rightarrow t\bar{t}$ events; background jets are taken from simulated dijet events [34].

7. Novel Substructure Techniques for Future Searches

The field of jet substructure is evolving fast with new techniques being explored to further increase the sensitivity of searches (and increasingly also measurements) in the boosted regime. For the sake of brevity, only two examples are highlighted here. The first one is related to the energy correlation variables discussed in Section 2. Recently, a new set of discriminating variables, based on generalised energy correlation functions, has been proposed [35]. It includes a class of variables optimised for good discrimination power after the removal of soft radiation and specifically designed to replace variables such as $D_2^{\beta=1}$ for groomed jets.

The second example concerns the reconstruction of the boosted object itself. All searches involving boosted objects to date rely on jets with a fixed angular size, set by the $R$-parameter of the jet algorithm, while in fact the collimation of the decay products, described by Equation 1, implies that the jets associated with hadronically decaying top quarks, $W/Z$ and Higgs bosons will continue to shrink with increasing transverse momentum of the mother particle. For example, the two $b$-hadrons from the decay of a Higgs boson with a transverse momentum of 1 TeV are expected to be within $\Delta R < 0.25$, implying that a jet with a significantly smaller size than the traditionally used $R = 1.0$ jets would be sufficient to reconstruct the boosted Higgs boson decay. Variable-$R$ jets [36] provide a more natural approach to the reconstruction

$^2$ The mass is calculated from the sum of the massive four-vectors of the small-$R$ constituent jets.
of boosted objects as their effective size scales inversely with their transverse momentum [34]. Thus the jet shrinks around the increasingly collimated decay products, minimising the jet area and reducing the impact of contaminations from pile-up or initial-state radiation. Significant performance improvements are found with variable-\( R \) jets for a number of discriminating variables used in boosted object taggers, most notably the jet mass, as illustrated in Figure 4b.

8. Conclusion

The ATLAS collaboration has published results from a wide range of searches for BSM physics in final states with boosted objects, making use of a variety of substructure techniques to enhance the signal significance. No significant deviation from the SM expectation has been found to date and the lower exclusion limits on the masses of a number of hypothetical BSM particles have been pushed further into the TeV regime. As data-taking at \( \sqrt{s} = 13 \) TeV continues in 2017 and beyond at increasing luminosities, searches will be able to further explore the kinematic ranges characterised by final states with extremely boosted particles where data statistics is still poor. The challenge now lies in resolving substructure at scales below the calorimeter resolution and at unprecedented levels of pile-up. The field of jet substructure still continues to evolve at a fast rate with applications in a growing number of BSM searches and even measurements.

References

[1] ATLAS Collaboration (ATLAS) 2008 JINST 3 S08003
[2] Cacciari M, Salam G P and Soyez G 2008 JHEP 0804 063 (Preprint 0802.1189)
[3] Thaler J and Van Tilburg K 2011 JHEP 03 015 (Preprint 1011.2268)
[4] Larkoski A J, Salam G P and Thaler J 2013 JHEP 06 108 (Preprint 1305.0007)
[5] Larkoski A J, Moult I and Neill D 2014 JHEP 12 009 (Preprint 1409.6298)
[6] Larkoski A J, Moult I and Neill D 2016 JHEP 05 117 (Preprint 1507.03018)
[7] Krohn D, Thaler J and Wang L T 2010 JHEP 1002 084 (Preprint 0912.1342)
[8] Ellis S D and Soper D E 1993 Phys. Rev. D 48 3160–3166 (Preprint hep-ph/9305266)
[9] Catani S, Dokshitzer Y L, Seymour M and Webber B 1993 Nucl.Phys. B406 187–224
[10] ATLAS Collaboration 2013 ATLAS-CONF-2013-084 https://cds.cern.ch/record/1571040
[11] ATLAS Collaboration ATL-PHYS-PUB-2015-053 http://cds.cern.ch/record/2116351
[12] ATLAS Collaboration ATL-PHYS-PUB-2015-014 http://cds.cern.ch/record/2141001
[13] ATLAS Collaboration ATL-PHYS-PUB-2015-053 http://cds.cern.ch/record/2041461
[14] ATLAS Collaboration ATL-PHYS-PUB-2015-055 http://cds.cern.ch/record/2206157
[15] ATLAS Collaboration ATL-PHYS-PUB-2015-062 http://cds.cern.ch/record/2206199
[16] ATLAS Collaboration ATL-PHYS-PUB-2015-082 http://cds.cern.ch/record/2206275
[17] ATLAS Collaboration 2017 Phys. Lett. B764 11–30 (Preprint 1607.06363)
[18] Cacciari M and Salam G P 2008 Phys. Lett. B659 119–126 (Preprint 0707.1378)
[19] Cacciari M, Salam G P and Soyez G 2008 JHEP 04 005 (Preprint 0802.1188)
[20] ATLAS Collaboration 2013 JHEP 09 076 (Preprint 1306.4946)
[21] ATLAS Collaboration 2016 Phys. Lett. B763 251–268 (Preprint 1608.00372)
[22] ATLAS Collaboration ATL-PHYS-PUB-2016-039 http://cds.cern.ch/record/2206038
[23] ATLAS Collaboration 2016 JINST 11 P04008 (Preprint 1512.01094)
[24] ATLAS Collaboration ATL-PHYS-PUB-2016-012 https://cds.cern.ch/record/2160731
[25] ATLAS Collaboration ATL-PHYS-PUB-2016-049 http://cds.cern.ch/record/2206131
[26] ATLAS Collaboration 2017 Phys. Lett. B765 11–31 (Preprint 1609.04572)
[27] ATLAS Collaboration ATL-PHYS-PUB-2016-083 http://cds.cern.ch/record/2206276
[28] ATLAS Collaboration (ATLAS) 2017 Phys. Lett. B765 32–52 (Preprint 1607.05621)
[29] ATLAS Collaboration ATL-PHYS-PUB-2016-102 http://cds.cern.ch/record/2219436
[30] ATLAS Collaboration ATL-PHYS-PUB-2016-101 http://cds.cern.ch/record/2217232
[31] ATLAS Collaboration ATL-PHYS-PUB-2016-104 http://cds.cern.ch/record/2220371
[32] Nachman B, Nef P, Schwartzman A, Swiatkowski M and Wanotayaroj C 2015 JHEP 02 075
[33] ATLAS Collaboration (ATLAS) 2016 Eur. Phys. J. C76 581 (Preprint 1510.03823)
[34] ATLAS Collaboration ATL-PHYS-PUB-2016-013 https://cds.cern.ch/record/2199360
[35] Moult I, Ncub L and Thaler J 2016 JHEP 12 153 (Preprint 1609.07483)
[36] Krohn D, Thaler J and Wang L T 2009 JHEP 06 059 (Preprint 0903.0392)