

# In-situ Jet Calibration and Electro-Weak Induced Production of $W\gamma$ in Association With Two Jets at ATLAS

Benjamin Honan

*School of Physics and Astronomy, University of Manchester, M13 9PL, United Kingdom*

The submitted thesis presents original work pertaining to differential cross-section measurements of  $W\gamma jj$  production in the electro-weak (EW) production mode (no strong coupling vertices at leading order), in addition to the derivation of *in-situ* corrections to the jet energy scale (JES) for large-radius jets<sup>a</sup>, which was performed as the author’s qualification task.

## 1 In-situ Calibration of Large-R Jets

The JES corrects the measured energy of reconstructed jets to that of simulated truth particles. Before the JES can be applied to data, a residual correction is calculated using data-to-simulation ratios primarily to account for detector effects not captured by simulation. This is called the in-situ calibration. The calibration is performed using  $Z$ +jet events in both the electron and muon decay channels. For the first time at ATLAS, calibrations are derived for jets reconstructed using “unified flow object” (UFO) input objects. UFOs form the inputs to the anti- $k_t$  jet reconstruction algorithm, and are built using combined calorimeter and track information. UFO jets are designed to have good performance at high and low  $p_T$ , and in dense environments.

The in-situ calibration is derived with the direct balance method, where the  $p_T$  of the well-measured dilepton (reference) system is balanced against the  $p_T$  of a large-R jet (a so-called  $2 \rightarrow 2$  topology). The in-situ correction is defined as the double ratio of the response  $\mathcal{R}$  in data divided by the response in simulation, where the response is defined as

$$\mathcal{R} \equiv \left\langle \frac{p_T^{\text{jet}}}{p_T^{\text{ref}}} \right\rangle \equiv \langle p_T^{\text{bal}} \rangle, \quad (1)$$

where  $p_T^{\text{ref}}$  is the  $p_T$  of the reference system, and  $p_T^{\text{jet}}$  is the  $p_T$  of the jet being calibrated.

The response is sensitive to secondary effects such as QCD radiation outside of the jet cone. Hence, to reduce the model-dependence of the calibration, events are selected such that they have a near  $2 \rightarrow 2$  topology. The response is calculated as a function of  $p_T^{\text{ref}}$  by fitting a Gaussian to the  $p_T^{\text{bal}}$  distribution for each bin, and taking the mean from the Gaussian.

The calibration is subject to systematic uncertainties which arise from the choice of Monte-Carlo (MC) event generator, lepton scale and resolution effects, and variations in the event selections. The dominant uncertainties are from MC modelling and statistical uncertainties. The total uncertainty on the calibration is below 1% for most bins. The final calibration used by ATLAS analyses is derived by combining the  $Z$ +jet calibration with the  $\gamma$ +jet and multi-jet calibrations (not performed by the author). The  $Z$ +jet calibration was observed to be consistent in shape with the  $\gamma$ +jet calibration, and was found to be relevant in the 200 – 500 GeV range.

## 2 Differential Cross-section Measurements of Electro-Weak $W\gamma jj$ Production

EW- $W\gamma jj$  production is of particular interest because of the sensitivity to vector boson scattering (VBS) interactions. VBS processes are defined by the t-channel exchange of EW bosons

---

<sup>a</sup>A large radius jet is reconstructed using an anti- $k_t$  “ $R$ ” parameter of  $R = 1.0$ , which is useful where there are highly collimated decay products originating from high- $p_T$  massive particles.

(Z,W, $\gamma$ ) resulting in two EW bosons in the final state. Measurements of VBS are well suited for the derivation of constraints on anomalous quartic gauge couplings (aQGCs), as these represent the lowest order processes with quartic interactions between EW bosons. This work contributed to the publication<sup>1</sup>, which also provided the first observation of EW- $W\gamma jj$  production at ATLAS.

Unfolded differential cross-sections are measured for six different observables. These are the dijet invariant mass  $m_{jj}$ , dijet transverse momentum  $p_{T,jj}$ , signed dijet azimuthal angle separation  $\Delta\phi_{jj}^{\text{signed}}$ , lepton transverse momentum  $p_T^\ell$ , signed azimuthal angle separation of the lepton and the photon  $\Delta\phi_{\ell\gamma}^{\text{signed}}$ , and the invariant mass of the lepton-photon system  $m_{\ell\gamma}$ . The measurements are performed in a VBS-enriched kinematic region through the large dijet mass requirement ( $m_{jj} > 1$  TeV), and through a requirement on the rapidity separation of the tagging jets ( $\Delta y(j, j) > 2$ ). Additionally, a signal region (SR) is defined through requirements on the number of jets in the rapidity interval between the tagging jets ( $N_{\text{jets}}^{\text{gap}} = 0$ ), and on the *centrality* of the lepton-photon system ( $\xi_{l\gamma} < 0.35$ ) where

$$\xi_{l\gamma} \equiv \frac{|(y_{l\gamma} - (y_{j1} + y_{j2})/2)|}{|(y_{j1} - y_{j2})|}, \quad (2)$$

and the symbol  $y$  represents the rapidity of the leading jet ( $j1$ ), sub-leading jet ( $j2$ ), or the lepton-photon ( $\ell\gamma$ ) system. Additional object and event selections are applied to reject backgrounds, and to improve the signal purity in the SR. These backgrounds are from strong- $W\gamma jj$  production (defined by  $W\gamma jj$  production diagrams corresponding to cross-sections of the order of  $\alpha_s^2\alpha_{EW}^2$ ), interference between the strong and EW  $W\gamma jj$  modes, prompt backgrounds from  $Z\gamma$  and  $t\bar{t}\gamma$  production, and non-prompt backgrounds arising from mis-reconstructed leptons, photons, or jets. The author was responsible for optimising the SR selection criteria, and contributed to the optimisation of the VBS-enriched region selections.

The signal is extracted and the shape and normalisation of the background is constrained simultaneously using a binned minimum log-likelihood fit. The background constraints are derived primarily in regions of low-signal/high-background purity through the definition of three control regions, CRa, CRb, and CRc. These are defined by inverting the  $\xi_{l\gamma}$  and  $N_{\text{jets}}^{\text{gap}}$  requirements in the definition of the SR. The primary constraint to the strong background is derived in the control region where the  $N_{\text{jets}}^{\text{gap}}$  cut is inverted (CRa). And a residual correction factor,  $c$ , is derived primarily in the control region where the centrality cut is inverted (CRc). This factor is designed to correct for non-closure when transferring the background constraint to the SR. The author determined that  $c$  should purely be an additional normalisation constraint to prevent unstable behaviour in the fit. This was done using a novel method involving correlating pseudo-experiments in individual control regions to their effect on the extracted signal yield.

The dominant uncertainties on the measurement arise from the statistical precision of the data, followed by the uncertainty corresponding to the choice of the strong- $W\gamma jj$  sample generator. The author derived all uncertainties on the extracted signal yields, in addition to the statistical resolution of each source of systematic uncertainty. The final differential cross-sections are derived at particle level by unfolding the differential event yields (the author was responsible for comparing the pre-fit and post-fit unfolded systematic uncertainties). These measurements contribute to the derivation of constraints on aQGCs derived through an effective field theory (EFT) parametrisation. These results include the first LHC constraints of the  $f_{T3}$  and  $f_{T4}$  operator couplings. The author provided the yields and systematic breakdowns for each observable for the EFT fit, but was not responsible for performing the fit and the limit-setting.

## References

1. ATLAS Collaboration, CERN-EP-2024-048, <https://cds.cern.ch/record/2890900>