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

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The submitted thesis presents original work documenting the differential cross-section measurements of $W\gamma$jj production in the electro-weak (EW) production mode (no strong coupling vertices at leading order). These are the first differential measurements of this process that include data-driven constraints of the dominant background. Additionally, the thesis documents the author's qualification task work which is the derivation of *in-situ* corrections to the jet energy scale (JES) for large-radius jets (defined as jets reconstructed using the anti-$k_t$ algorithm with $R = 1$) using $Z$+jet events, for an entirely new type of jet definition.

## 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 the LHC, 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 $p_{\mathrm{T}}$, and in dense environments.

The in-situ calibration is derived with the direct balance method, where the $p_{\mathrm{T}}$ of the well-measured dilepton (reference) system is balanced against the $p_{\mathrm{T}}$ of a large-R jet (a so-called $2 \to 2$ 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

$$\mathcal{R} \equiv \left\langle \frac{p_{\mathrm{T}}^{\mathrm{jet}}}{p_{\mathrm{T}}^{\mathrm{ref}}} \right\rangle \equiv \langle p_{\mathrm{T}}^{\mathrm{bal}} \rangle, \tag{1}$$

where $p_{\mathrm{T}}^{\mathrm{ref}}$ is the $p_{\mathrm{T}}$ of the reference system, and $p_{\mathrm{T}}^{\mathrm{jet}}$ is the $p_{\mathrm{T}}$ 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 $2 \to 2$ topology. The response is calculated as a function of $p_{\mathrm{T}}^{\mathrm{ref}}$ by fitting a Gaussian to the $p_{\mathrm{T}}^{\mathrm{bal}}$ 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 through the combination of the $Z$+jet calibration with the $\gamma$+jet and multi-jet calibrations. 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. This work is currently being written up in a paper documenting the ATLAS run-2 large-R jet calibration, with an expected completion date of April 2025.

## 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

(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 [Eur. Phys. J. C (2024) 84: 1064], 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 $m_{\mathrm{jj}}$, dijet transverse momentum $p_{\mathrm{T},jj}$, signed dijet azimuthal angle separation $\Delta\phi_{\mathrm{jj}}^{\mathrm{signed}}$, lepton transverse momentum $p_{\mathrm{T}}^{\ell}$, signed azimuthal angle separation of the lepton and the photon $\Delta\phi_{\ell\gamma}^{\mathrm{signed}}$, and the invariant mass of the lepton-photon system $m_{\ell\gamma}$. The author derived the differential event yields including the signal and background constraints, and all uncertainties on these measurements. The measurements are performed in a VBS-enriched kinematic region through a large dijet mass requirement ($m_{\mathrm{jj}} > 1$ 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 ($N_{\mathrm{jets}}^{\mathrm{gap}} = 0$), and on the *centrality* of the lepton-photon system ($\xi_{l\gamma} < 0.35$) where

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

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 $tx\gamma$ 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 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 $N_{\mathrm{jets}}^{\mathrm{gap}}$ requirements in the definition of the SR. The primary constraint to the strong background is derived in the control region where the $N_{\mathrm{jets}}^{\mathrm{gap}}$ cut is inverted (CRa), and a residual correction factor, $c$, is derived primarily in the control region where the centrality cut in 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 a normalisation constraint to prevent unstable behaviour in the fit. This was done using a completely novel method designed by the author 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. For each systematic variation, the signal is extracted for 1000 toy experiments in order to determine the statistical resolution corresponding to each source of 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, but did not perform the unfolding). The $p_{\mathrm{T}}$ and mass measurements contribute to the derivation of constraints on aQGCs derived through an effective field theory (EFT) parametrisation. The angular cross-sections can be used to explore new sources of CP-violation in the gauge boson sector. Our EFT limits 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.