In-situ Jet Calibration and Electro-Weak Induced Production of Wγ in Association With Two Jets at ATLAS

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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[a], 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.

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 by combining the PFlow[2] and TCC[3] algorithms.

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

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

, where $p_{\mathrm{T}}^{\mathrm{ref}}$ is the p_{T} of the reference system, and $p_{\mathrm{T}}^{\mathrm{jet}}$ 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 $p_{\mathrm{T}}^{\mathrm{ref}}$ 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 used for the Z+jet sample, lepton scale and resolution effects, and variations in the event selection criteria. 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.

[a] 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.

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,γ) resulting in two EW bosons in the final state. These processes are sensitive to anomalous (zero in the standard model) trilinear (aTGC) and quartic (aQGC) gauge couplings. Precise measurements of VBS-sensitive processes are therefore well suited to the derivation of constraints on aQGCs as these represent the lowest order processes involving quartic interactions between EW bosons. This work contributed to the publication [1], 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 $p_{\mathrm{T},jj}$, signed dijet azimuthal angle separation $\Delta\phi_{\mathrm{jj}}^{\mathrm{signed}}$, lepton transverse momentum p_{T}^{ℓ}, 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 measurements are performed in a VBS-enriched kinematic region through the 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 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 $N_{\mathrm{jets}}^{\mathrm{gap}}$ 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 this transfer factor 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 respective effect on the extracted signal yield.

The dominant uncertainty on the measurement arises from the statistical precision of the data. The dominant theoretical systematic uncertainty comes from the choice of the strong-$W\gamma$jj sample generator, and the dominant experimental systematic uncertainties correspond to the jet energy scale and jet energy resolution. The author derived all statistical and systematic 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 after extracting the EW-$W\gamma$jj signal (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 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

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