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# Measurements of additional jet production in top pair events using the ATLAS experiment

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The large centre-of-mass energy available at the Large Hadron Collider (LHC) allows for the copious production of top quark pairs in association with other final state particles with high transverse momenta. The ATLAS experiment has measured several final state observables which are sensitive to additional parton radiation in top anti-top quark final states. Examples are the multiplicity of jets for various transverse momentum thresholds or the probability to emit jets above a given threshold in a fixed rapidity region ("gap fraction"). These measurements are compared to modern Monte Carlo generators based on NLO QCD matrix element or LO multi-leg matrix elements and with systematic model parameter variations.

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## 1. Introduction

The top quark is the most massive of all known elementary particles. Its unexplained large mass suggests a significant connection to the process of electroweak symmetry breaking. Measurements of its properties provide therefore important and precise tests of the SM. In addition, $t\bar{t}$ production can be the main background in many searches for new particles. Deviations from the predictions could be an indication of the presence of new physics and consequently a good description of the SM top quark production is needed. The uncertainties on the modelling limit the precision of its measured properties. One important aspect of the $t\bar{t}$ production modelling is the emission of quark and gluon radiation stemming from either the inital or the final state (ISR, FSR).
Several observables that are sensitive to additional parton radiation in top anti-top quark final states were measured by the ATLAS experiment [1]. Examples are the probability to emit additional jets above a given threshold in a fixed rapidity region [2], or the multiplicity of jets for various transverse momentum thresholds [3]. These measurements use datasets containing integrated luminosities of $2.05\,\mathrm{fb}^{-1}$ and $4.7\,\mathrm{fb}^{-1}$ respectively, which are gathered in proton-proton collisions produced by the LHC [4] at a center-of-mass energy of $\sqrt{s} = 7\,\mathrm{TeV}$. The corresponding results are compared to modern Monte Carlo generators as MC@NLO [5], POWHEG [6], ALPGEN [7] or ACERMC [8], which are based on either NLO- or LO multi-leg calculation of the matrix element. The data is used to constrain the uncertainty on the modelling of the top pair production mechanism.

## 2. Measurement of the jet activity in dependence on the rapidity $|y|$

The $t\bar{t}$ decay into two leptons is ideal to measure the jet activity, since their signature of exactly two jets, induced by $B$-hadron decays, two opposite-charged leptons and two high energetic neutrinos, resulting in a high amount of missing transverse momentum, allows the selection of a very clean sample of top anti-top pairs. The contamination due to bosons produced in association with jets, single top quarks and dibosonic events ($WW$, $WZ$, $ZZ$) is below 6%. To quantify the jet activity arising from quark and gluon radiation produced in association with $t\bar{t}$ pairs, the so-called gap fraction, is introduced:

$$f(Q_0) = \frac{n(Q_0)}{N^{t\bar{t}}} , \tag{2.1}$$

where $N^{t\bar{t}}$ is the number of selected $t\bar{t}$ events and $n(Q_0)$ is the subset of these events having no additional jet with a transverse momentum $p_T$ exeeding the threshold $Q_0$. The gap fraction is therefore large for low jet activity and vice versa. To be independent of detector effects, the data is corrected back to MC particle level by multiplying the gap fraction measured at a specific $Q_0$ value by the factor

$$C(Q_0) = \frac{f^{\mathrm{truth}}(Q_0)}{f^{\mathrm{reco}}(Q_0)} , \tag{2.2}$$

where $f^{\mathrm{truth}}(Q_0)$ and $f^{\mathrm{reco}}(Q_0)$ are the gap fractions at particle- and reconstruction-level respectively. Both quantities are obtained from simulation. The selection of $t\bar{t}$ events at particle-level is applied with the same criteria as at detector-level. Particle jets are therefore clustered by applying the anti-$k_t$ algorithm with a radius parameter of $R = 0.4$ to all stable particles ($c\tau > 10\,\text{mm}$) except for neutrinos and muons. The missing transverse momentum and the corresponding azimuthal angle are calculated using the four momentum of the neutrino, while $b$-tagging is emulated by a spatial matching of $B$-hadrons to particle jets.

The measurement of the gap fraction is performed for multiple values of $Q_0$ and in four different rapidity regions. Where the dominant sources of systematic uncertainty are the jet energy scale (JES), the jet energy resolution (JER) and the unfolding procedure to particle level, while the uncertainties not affecting additional jets, such as the electron energy scale or the muon momentum resolution, are negligible. Results for the most central ($|y| < 0.8$) and the forward rapidity region ($1.5 \leq |y| < 2.1$) are shown in Figure 1. It can be seen that the MC@NLO generator predicts too little jet activity in the central rapidity region, while the other generators show reasonable agreement with the data. All generators produce too much jet activity in the forward region, since their predicted gap fraction is slightly too low for each $Q_0$ value compared to the data.

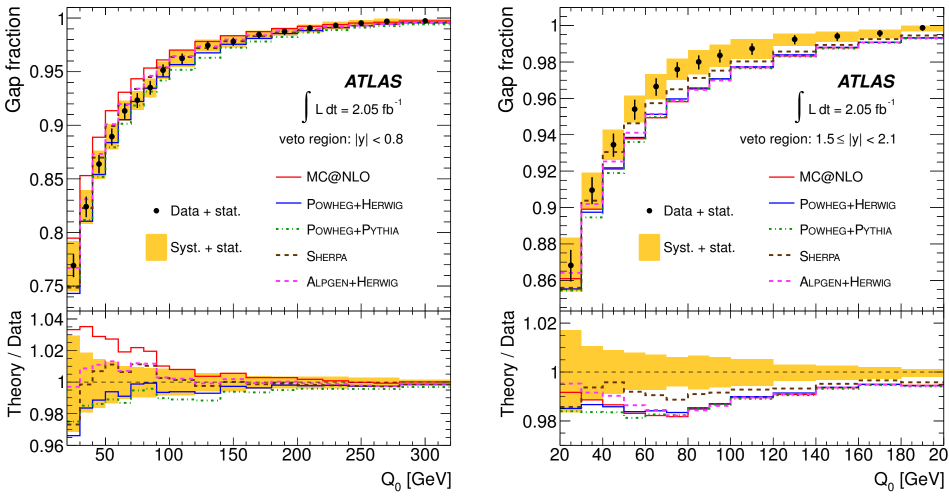

**Figure 1:** The measured gap fraction as a function of $Q_0$ in comparison between data (as black dots) and the theoretical prediction from the NLO and multi-leg LO MC generators (shown as solid or dashed coloured lines). The yellow band corresponds to the total systematic uncertainty on the data. Results are presented in the central (left) and the forward rapidity region (right) [2].

Figure 2 shows the prediction of the ACERMC generator interfaced to PYTHIA for different parton shower parameter settings, where PARP(67) and PARP(64) are varied in order to increase or decrease the amount of ISR with respect to the default tune. These three corresponding MC generator configurations were previously used to estimate the ISR uncertainties in top quark measurements within the ATLAS collaboration. However it can be seen that the spread of the predicted gap fraction is much larger than the experimental precision (up to a factor of two for lower $Q_0$ values). This implies that the difference between those parameter settings overestimates the uncertanties corresponding to the additional jet activity. The parameter settings are now constrained by the data [9].

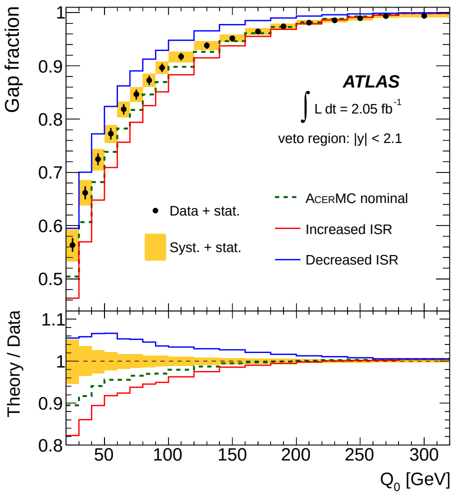

**Figure 2:** The measured gap fraction as a function of $Q_0$ for an absolute rapidity less than 2.1 compared with the prediction from the AcerMC generator, where different settings of the Pythia parton shower parameters are used to produce samples with nominal, increased and decreased initial state radiation (ISR) [2].

## 3. Measurement of the jet multiplicity in $t\bar{t}$ final states

The jet multiplicity for various $p_T$ thresholds is measured in the $t\bar{t}$ single lepton ($e^{\pm}$,$\mu^{\pm}$) final state, which includes events with a transverse momentum of $E_T^{\mathrm{miss}} > 30\,\mathrm{GeV}$, a transverse $W$ mass greater than 35 GeV and at least one $b$-tagged jet. The dominant background processes to this measurement are $W$ bosons associated to jets, QCD multijet events and single top quark production, while smaller contributions arise from $Z$+ jets events and diboson production. After subtracting this background from the measured jet multiplicities in data, an unfolding procedure is applied to correct the spectra back to particle-level:

$$\vec{N}_{\mathrm{part}} = \vec{f}_{\mathrm{part!reco}} \cdot M_{\mathrm{part}}^{\mathrm{reco}} \cdot \vec{f}_{\mathrm{reco!part}} \cdot \vec{f}_{\mathrm{accept}} \cdot \left(\vec{N}_{\mathrm{reco}} - \vec{N}_{\mathrm{bkg}}\right) \tag{3.1}$$

Unfolding corrections include detector efficiencies, resolution effects and biases. Hence $f_{\mathrm{part!reco}}$ and $f_{\mathrm{reco!part}}$ are correction factors applied on events fulfilling the selection on particle (reco) level, while failing it on reco (particle) level. $N_{\mathrm{reco}}$ is the number of reconstructed events, $N_{\mathrm{bkg}}$ is the background contribution, $f_{\mathrm{accpt}}$ is a selection acceptance correction factor and $M_{\mathrm{part}}^{\mathrm{reco}}$ is a response matrix.

The dominant systematic uncertainties on the measured jet multiplicities are the jet energy scale ($3-40\%$), the background normalisation ($3-18\%$), the ISR/FSR modelling ($1-6\%$) and the MC statistic ($1-40\%$) depending on the particular $p_T$ threshold. The unfolded particle-jet multiplicity spectra for the $p_T$ thresholds of 25 GeV and 80 GeV are shown in Figure 3. The data, shown as black points with statistical uncertainies, are compared to the ALPGEN + HERWIG, the ALPGEN + PYTHIA, the MC@NLO + HERWIG and the POWHEG + PYTHIA MC models. The blue shaded band corresponds to the total uncertainty (syst.+stat.).

The MC@NLO generator interfaced with HERWIG agrees with data in the lower $n_{\mathrm{jets}}$ bins, but disagrees at higher jet multiplicities, while the generators POWHEG and ALPGEN are in reasonable

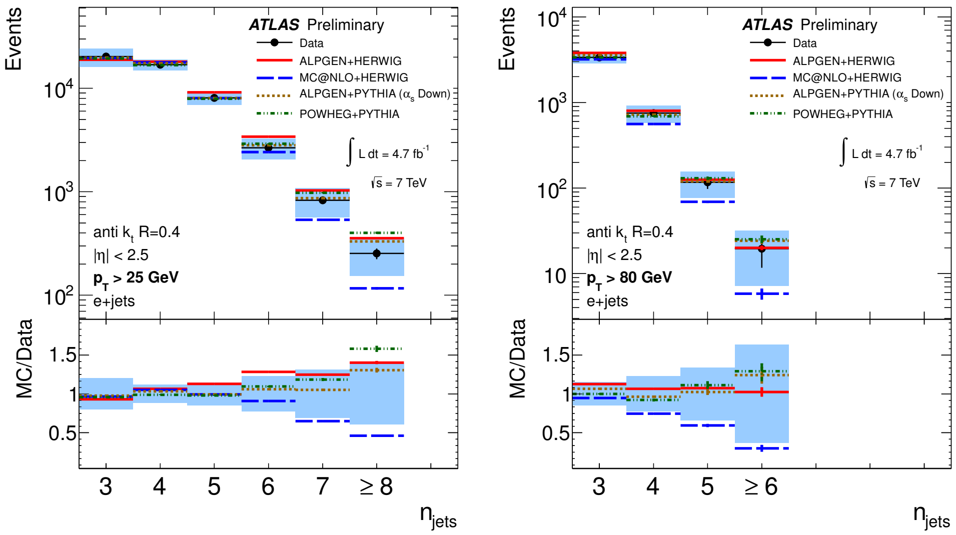

**Figure 3:** The reconstructed jet multiplicities unfolded to MC particle-level in the electron channel for the pT thresholds of 25 GeV (left) and 80 GeV (right) [3].

agreement with the data. In a second step different tunes for the ALPGEN generator interfaced to PYTHIA are compared to the data. Within those tunes [10] the value of $\alpha_S$ as it is used in the ME calculation was varied with respect to the nominal value. This comparison is shown in Figure 4. It can be seen that the down variation of $\alpha_s$ has the best agreement with the data. The default tune is on the edge of the uncertainties and the up variation of $\alpha_s$ leads to an overestimation of the number of events having more than four jets.

## 4. Conclusion

Measurements of the gap fraction and the reconstructed jet multiplicity in $t\bar{t}$ events were presented. The results of these measurements allow for an improvement of the theoretical description of the additional jet activity in association with $t\bar{t}$ production. The data have been used to constrain the uncertainties on the modelling of additional radiation.

The gap fraction measurement has shown that the MC@NLO generator underestimates the jet activity slightly in the central region, while all generators show small deviations to the data in the forward rapidity region where the jet activity is overestimated. Similar results are obtained from the measurement of the reconstructed jet multiplicities. It was shown that the MC@NLO generator tends to underestimate the number of jets produced in association with top anti-top quark pairs.

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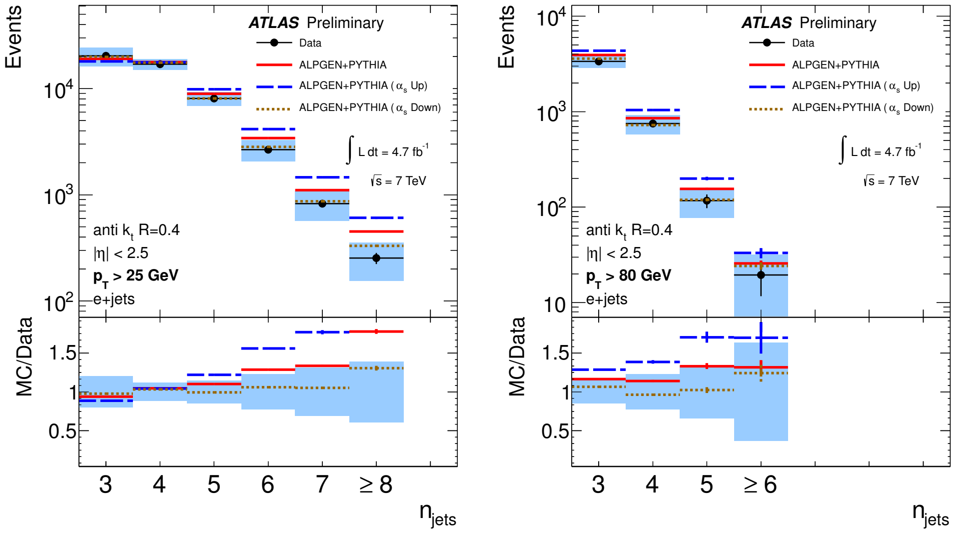

**Figure 4:** The particle-jet multiplicities for the electron channel and the jet pT thresholds 25 GeV (left) and 80 GeV (right). The data are shown in comparison to the ALPGEN+PYTHIA and ALPGEN+PYTHIA $\alpha_s$ variations. The data points and their corresponding statistical uncertainty are shown in black whereas the total uncertainty (syst. + stat.) is presented as a shaded band [3].

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