PROCEEDINGS OF SCIENCE

Top Quark Pair Production at the LHC measured by ATLAS

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After having established the $t\bar{t}$ production mechanism at LHC, interest is now focused on differential spectra of $t\bar{t}$. Latest measurements performed in 7 TeV proton - proton collisions with the ATLAS detector at the Large Hadron Collider will be presented.

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1. Introduction

The Large Hadron Collider (LHC) at CERN provides the opportunity to study top quarks at the highest center-of-mass energies ever produced, which profits from a factor of 10 increase in the production cross-section as compared to the Tevatron. Measuring the properties of top quark pair production is important in understanding many ideas in fundamental physics. The exceptionally large mass of the top quark suggests it may help in understanding the electroweak symmetry breaking mechanism, while measuring the top-antitop ($t\bar{t}$) production cross-section ($\sigma_{t\bar{t}}$) in different decay channels tests the precision of perturbative QCD. In general, studying $t\bar{t}$ events can help constrain Monte Carlo (MC) generator models and theoretical predictions. It has also been shown that the $\sigma_{t\bar{t}}$ as a function of the $t\bar{t}$ invariant mass ($m_{t\bar{t}}$) is particularly sensitive to new physics beyond the Stand Model (SM) [1].

These proceedings will summarize measurements of the differential $t\bar{t}$ production at the LHC using data from the ATLAS detector [2]. A review of the inclusive $t\bar{t}$ cross-section measurements are presented in these proceedings [3]. Four analyses will be presented, the relative differential $\sigma_{t\bar{t}}$ as a function of transverse momentum ($p_{T,t\bar{t}}$), $m_{t\bar{t}}$, and rapidity ($y_{t\bar{t}}$) (Section 4.1) [4], the production cross-section of $t\bar{t}$ events containing additional jets (Section 4.2) [5], the $\sigma_{t\bar{t}}$ while vetoing central jet activity (Section 4.3) [6], and jet multiplicities in $t\bar{t}$ events (Section 4.4) [7].

Three of the analyses use the lepton (electron or muon) plus jets ($l+$jets) $t\bar{t}$ decay channel ($t\bar{t}\rightarrow l\nu b\bar{b}q\bar{q}'$), they are the relative differential $\sigma_{t\bar{t}}$, the cross-section with additional jets, and the jet multiplicities in $t\bar{t}$ events. The remaining analysis, $t\bar{t}$ production while vetoing central jet activity, uses the $t\bar{t}$ decay channel with two leptons ($t\bar{t}\rightarrow l\nu l\nu b\bar{b}$).

2. Signal and Background Sample Generation

The four results presented use similar simulation samples, which I will summarize here, though, details may be found in [4, 5, 6, 7]. In general, the primary $t\bar{t}$ signal is generated using MC@NLO with parton distribution function (PDF) set CTEQ6.6. Parton showers and hadronization are simulated by the generators HERWIG and JIMMY, respectively, using the AUET1 tune. For comparison, the $t\bar{t}$ signal was also generated using POWHEG (NLO), ALPGEN (LO), SHERPA (LO), and ACERMC (LO). POWHEG also uses CTEQ6.6 and is matched to either PYTHIA (with AMBT1 tune) or HERWIG and JIMMY in a similar way to the MC@NLO case. ALPGEN uses CTEQ6L1 (PDF) also matched to HERWIG and JIMMY. SHERPA uses the default underlying event with CTEQ6L1 (PDF). ACERMC uses MRST2007LO (PDF) matched to PYTHIA for hadronic final state with the AMBT1 tune. ACERMC is also used to produce initial state radiation (ISR) variations for comparison to the data.

The primary backgrounds include single top, W/Z+jets, and di-boson decays (WW/ZZ/WZ). The single top sample is generated with MC@NLO, the W/Z+jets is generated using ALPGEN and normalized using a data driven method, and the di-boson sample is generated using HERWIG.

3. Event Selections

There is also a common event selection with a slight variation between the analyses using the $l+$jets channel versus the di-lepton channel. In general, an electron (muon) must have transverse energy, E_T, $> 25\,\mathrm{GeV}$ ($p_T > 20\,\mathrm{GeV}$) and a pseudorapidity, η, such that $|\eta| < 2.47$ ($|\eta| < 2.5$). Jets are formed using the anti-k_t algorithm with a $\Delta R = 0.4$ and require no overlap with reconstructed electrons (muons) within $\Delta R < 0.2$ ($\Delta R < 0.4$).

In the $l+$jets channel, each event is required to contain a single electron (or muon) with $E_T > 25\,\mathrm{GeV}$ ($p_T > 20\,\mathrm{GeV}$). The missing transverse energy, E_T^{miss}, is required to be $> 20\,\mathrm{GeV}$ ($> 35\,\mathrm{GeV}$) in the $e+$jets ($\mu+$jets) channel. The reconstructed W transverse mass, m_T^W, is required to be $> 60\,\mathrm{GeV} - E_T^{miss}$ ($> 20\,\mathrm{GeV} - E_T^{miss}$) in the $e+$jets ($\mu+$jets) channel in order to reduce the multi-jets background from misidentified leptons. The event must contain at least four jets with $p_T > 25\,\mathrm{GeV}$ and $|\eta| < 2.5$, and one jet must be a jet from a b-quark.

The measurements presented in the following section represent ATLAS data taken in 2011 at a centre-of-mass energy of 7 TeV corresponding to an integrated luminosity of $0.7 - 4.7\,\mathrm{fb}^{-1}$.

4. Differential Cross-Section Measurements

4.1 Relative Differential Top Quark Pair Production Cross-Section in the $l+$jets Channel

Given the selections described in the previous sections and using events in the $l+$jets channel, the differential $\sigma_{t\bar{t}}$ can be measured with respect to $m_{t\bar{t}}$, $p_{T,t\bar{t}}$, and $y_{t\bar{t}}$. The backgrounds are subtracted from the data to leave a measured signal distribution. These measured spectra exhibit smearing due to inherent experimental effects such as finite detector resolution. In order to obtain the *true* differential spectra from reconstructed data, an unfolding technique is applied which is described using

$$N_i = \sum_j R_{ij}\sigma_j \mathscr{L} + B_i = \sum_j M_{ij} A_j \sigma_j \mathscr{L} + B_i \Rightarrow \sigma_j = \frac{\sum_i M_{ij}^{-1}\left(N_i - B_i\right)}{A_j \mathscr{L}} \tag{4.1}$$

where σ_j is the *true* differential cross-section distribution, N_i is the reconstructed event distribution, B_i is the background distribution, $\mathscr{L}$ is the luminosity, and R_{ij} is the response matrix which can be represented as the product of the migration matrix, M_{ij}, and the acceptance, A_j. Finally, the electron and muon channels are combined using a weighted mean using the covariance matrix between the channels.

In order to reduce the effect of systematic uncertainties, the spectra are normalized by the inclusive cross-section, $\sigma_{t\bar{t}}$, to form the relative spectra. $\sigma_{t\bar{t}}$ can be measured using the full analysis with a single bin, then combining the $e+$jets and $\mu+$jets channels yields $\sigma_{t\bar{t}} = 160 \pm 25$(stat.+syst.) pb. Figure 1 presents the resulting relative differential top quark pair production cross-section as a function of $m_{t\bar{t}}$, $p_{T,t\bar{t}}$, and $y_{t\bar{t}}$ for the $l+$jets channel. They are compared to NLO predictions from MCFM and, for $m_{t\bar{t}}$ only, NLO+NNLL predictions. In the case of $m_{t\bar{t}}$ and $p_{T,t\bar{t}}$, the systematic uncertainty is dominated by the uncertainty on the jet energy scale, while the uncertainty on fake lepton estimation and final state radiation dominates the $y_{t\bar{t}}$ measurement. Within these uncertainties, the results are in good agreement with all higher order QCD predictions.

4.2 Top Quark Pair Production with Additional Jets in the $l+$jets Channel

$t\bar{t}$ events containing additional jets ($t\bar{t}j$) are defined as $t\bar{t}$ events containing jets that are not associated with the $t\bar{t}$ decay but originate from the initial or final state radiation. The event selection

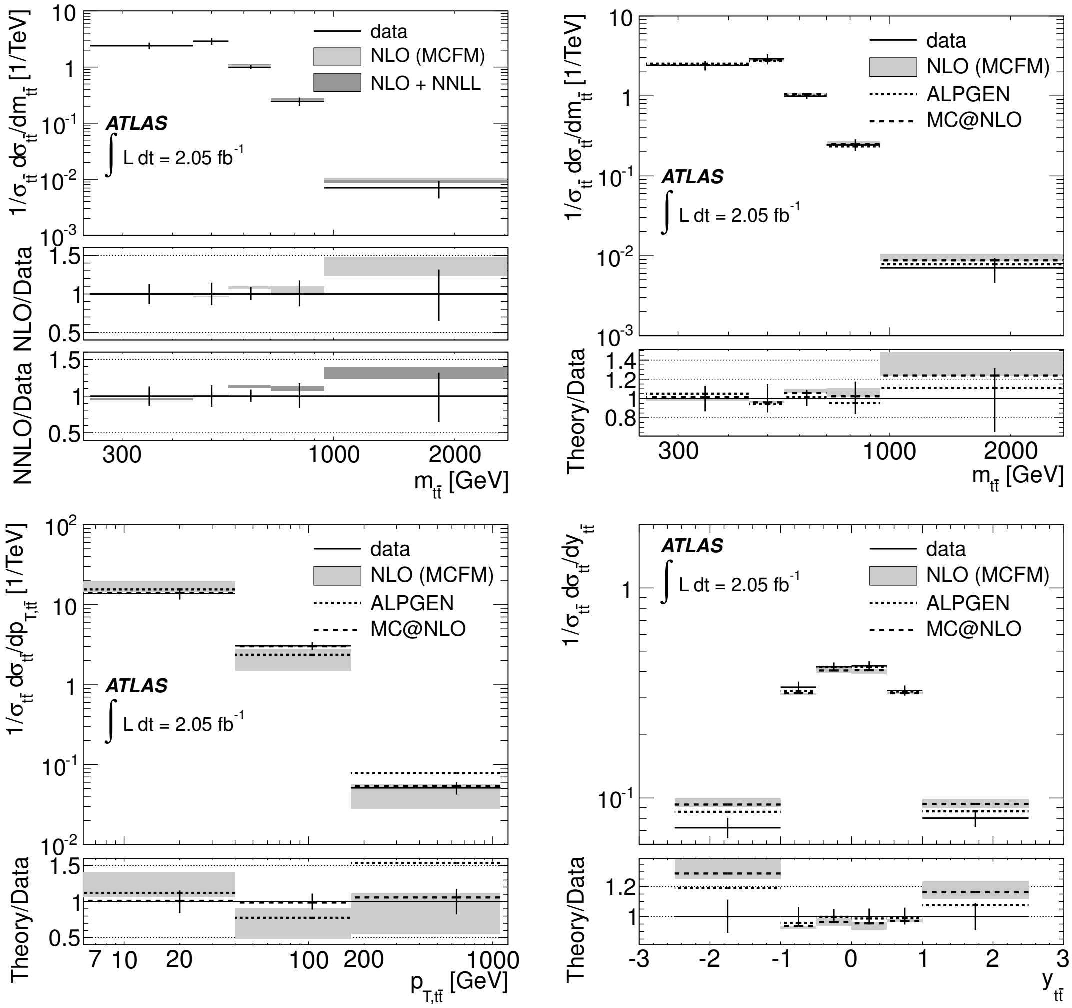

Figure 1: Relative differential cross-section as a function of $m_{t\bar{t}}$ (top left & right), $p_{T,t\bar{t}}$ (bottom left), and $y_{t\bar{t}}$ (bottom right) presented with the MC generators MC@NLO and ALPGEN, as well as the Next-to-Leading Order theoretical prediction from MCFM. In the case of the $m_{t\bar{t}}$, the theoretical predictions at Next-to-Leading Order including Next-to-Next-to-Leading Log corrections are also shown for comparison [4].

is based on two methods to distinguish $t\bar{t}j$ events from non-$t\bar{t}j$ and utilizes MC particle jets. One definition requires a jet to have no quarks, gluons, or photons, that originate from a top quark and have $p_T > 5\,\mathrm{GeV}$, be within $\Delta R < 0.4$ to qualify as being *additional*. Events are classified as $t\bar{t}j$ if they contain at least one such jet. The inclusive cross-section for this definition is written as $\sigma_{t\bar{t}j}$. This cross-section is also measured in the fiducial region, $\sigma^{\mathrm{fiducial}}_{t\bar{t}j\to e+\mathrm{jets}}$ and $\sigma^{\mathrm{fiducial}}_{t\bar{t}j\to\mu+\mathrm{jets}}$. The remaining definition of $t\bar{t}j$ events is model independent and simply requires an event to contain ≥ 5 jets. This cross-section was only measured in the fiducial region, $\sigma^{\mathrm{fiducial}}_{t\bar{t}X\to e+\mathrm{jets}}$ and $\sigma^{\mathrm{fiducial}}_{t\bar{t}X\to\mu+\mathrm{jets}}$.

In order to calculate the cross-sections, the efficiency, ε_{ij}, of observing a non-$t\bar{t}j$ ($i = 0$) or $t\bar{t}j$ ($i = 1$) event is calculated using MC for the 4th exclusive ($j = 4$) and 5th inclusive ($j \geq 5$) jet multiplicity bins. Then the number of $t\bar{t}$ events in each jet multiplicity bin, $N^{t\bar{t}}_j$, can be calculated using a likelihood discriminant template fit. The cross-sections can then be calculated using this system of equations $N_4^{t\bar{t}} = \mathscr{L}\sigma_{t\bar{t}0}\varepsilon_{04} + \mathscr{L}\sigma_{t\bar{t}j}\varepsilon_{14}$, and $N_5^{t\bar{t}} = \mathscr{L}\sigma_{t\bar{t}0}\varepsilon_{05} + \mathscr{L}\sigma_{t\bar{t}j}\varepsilon_{15}$, where $\mathscr{L}$ is the luminosity. In order to get a combined cross-section from the e and μ channels, a log likelihood fit is performed using the number of $t\bar{t}$ events in each channel.

Following this method, the combined $l + jet$ cross-section for $t\bar{t}j$ events was found to be
$\sigma_{t\bar{t}j}$=102±2(stat.)$^{+23}_{-26}$(syst.) pb,
and the fiducial cross-sections are
$\sigma^{\text{fiducial}}_{t\bar{t}j\to e+\text{jets}}$ =2.59±0.09(stat.)$^{+0.26}_{-0.46}$(syst.) pb, $\sigma^{\text{fiducial}}_{t\bar{t}j\to\mu+\text{jets}}$ =3.48±0.08(stat.)$^{+0.43}_{-0.61}$(syst.) pb,
$\sigma^{\text{fiducial}}_{t\bar{t}j\to e+\geq5\text{jets}}$=4.09±0.18(stat.)$^{+0.62}_{-0.85}$(syst.) pb, $\sigma^{\text{fiducial}}_{t\bar{t}j\to\mu+\geq5\text{jets}}$=5.27±0.16(stat.)$^{+1.04}_{-1.20}$(syst.) pb.
For these measurements, the jet energy scale, jet energy resolution, and MC modeling of the signal are the dominant systematic uncertainties. The total cross-section for $t\bar{t}$ production was extracted giving $\sigma_{t\bar{t}} = 189 \pm 4\,(\text{stat.})\,\text{pb}$ which is in good agreement with previous measurements. The ratio, $\sigma_{t\bar{t}j}/\sigma_{t\bar{t}}$, is useful because the large systematic uncertainties partially cancel, yielding $0.54 \pm 0.01(\text{stat.})^{0.05}_{-0.08}(\text{syst.})$.

4.3 Top Quark Pair Production with a Central Jet Veto in the Di-lepton Channel

The theoretical description of quark and gluon radiation used by common MC generators used in simulating $t\bar{t}$ events contribute large uncertainties to many top related measurements, such as production cross-sections, spin correlations and charge asymmetry. Understanding the jet activity in the central rapidity region can be used to constrain these models and therefore reduce the related uncertainties. Central jet activity in $t\bar{t}$ events can be characterized using the gap fraction, which is defined as $f(Q_0) = n(Q_0)/N$. N is the number of $t\bar{t}$ events. $n(Q_0)$ is the number of $t\bar{t}$ events without an additional jet with $p_T > Q_0$ and rapidity within one of four defined central regions, (a) $|y| < 0.8$, (b) $0.8 < |y| < 1.5$, (c) $1.5 < |y| < 2.1$, and (d) $|y| < 2.1$. Detector effects can be unfolded from the data using MC simulation to calculate the ratio of the gap fraction derived from truth information divided by the gap fraction derived from reconstructed information.

Figure 2 shows the gap fraction in the four rapidity regions and compares with predictions from standard $t\bar{t}$ generators. In all four regions, the generators yield results in good agreement with the data. However, in the most central region (a) the MC@NLO prediction is too large though it has been seen before that MC@NLO produces too few high energy jets at central rapidities. In the most forward region (c), it can be seen that all generators produce too much central jet activity. This measurement was also used to study the initial and final state radiation and the results can be used to constrain the modeling of these processes. The uncertainties of these measurements are dominated by jet related systematic uncertainties.

4.4 Jet Multiplicity in Top Quark Pair Events in the $l+$jets Channel

The measurement of reconstructed jet multiplicities in $t\bar{t}$ events is measured in the $l+$jets channel. Figure 3 shows the jet multiplicities for two jet-p_T thresholds, $p_T > 25\,\text{GeV}$ and $p_T > 60\,\text{GeV}$, and for the $e+$jets and $\mu+$jets decay channels. They are compared to MC@NLO predictions along with an initial state radiation variation calculated by varying the parton shower parameters used by PYTHIA in conjunction with the ACERMC generator. No significant difference between the measured jet multiplicities and those of the predictions can be seen.

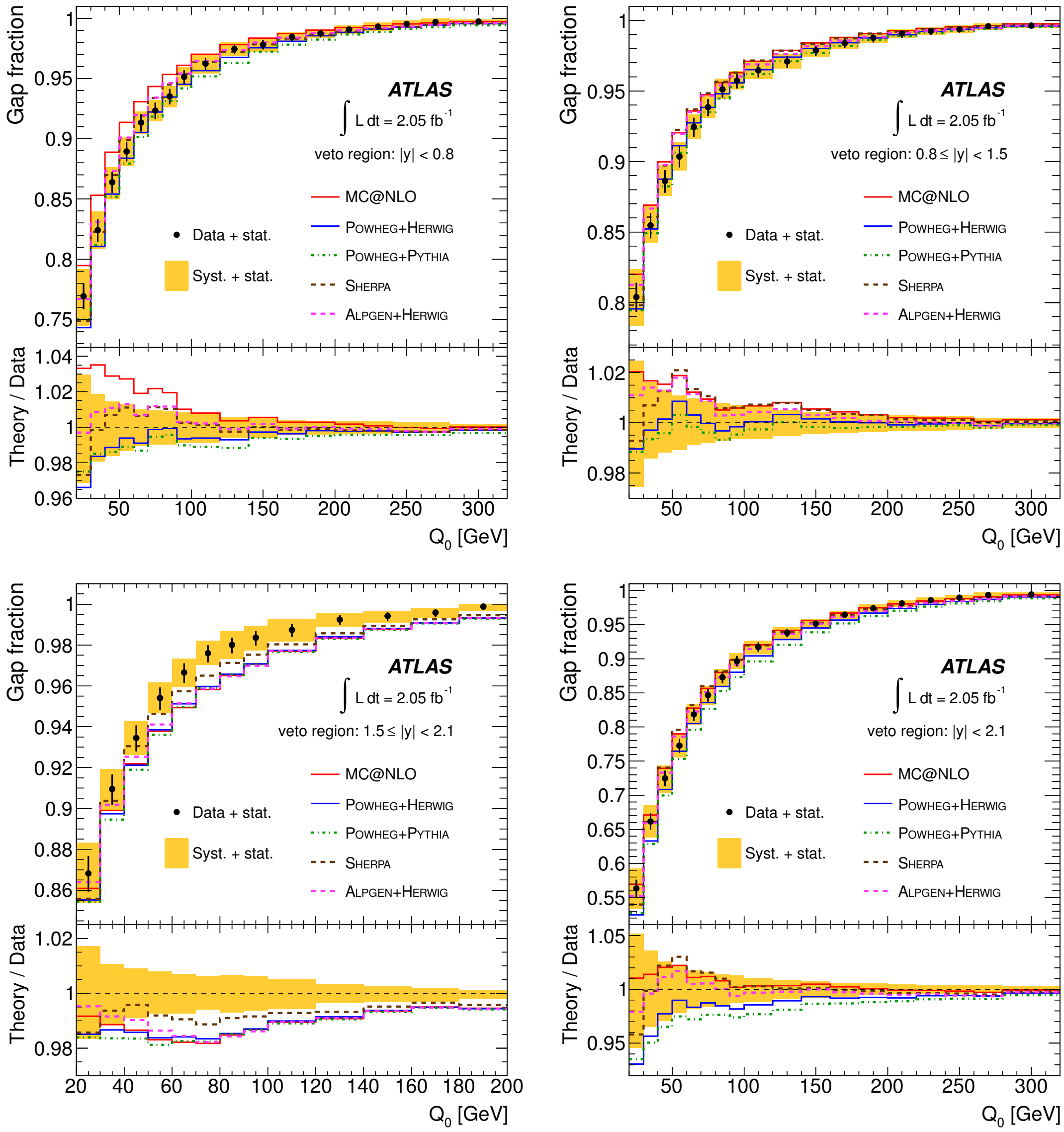

Figure 2: Gap fraction (see text for definition) as a function of maximum allowed jet p_T within a rapidity region of $|y| < 0.8$ (top left), $0.8 \leq |y| < 1.5$ (top right), $1.5 \leq |y| < 2.1$ (bottom left), and $|y| < 2.1$ (bottom right). The predictions are shown from MC generators MC@NLO, POWHEG coupled to HERWIG/JIMMY, POWHEG coupled to PYTHIA, SHERPA, and ALPGEN coupled to HERWIG/JIMMY [6].

5. Conclusion

The LHC is an effective top factory, providing an unprecedented ability to study this massive quark. The results of the relative differential $t\bar{t}$ production cross-section, the $t\bar{t}j$ production cross-section, and the jet multiplicities in $t\bar{t}$ events are limited by systematic uncertainties and agree with higher order QCD predictions. These measurements provide a strong test of perturbative QCD. Examining $t\bar{t}$ production without central jet activity displays the modeling weaknesses of jet production in popular MC generators and can be used to improve these generators.

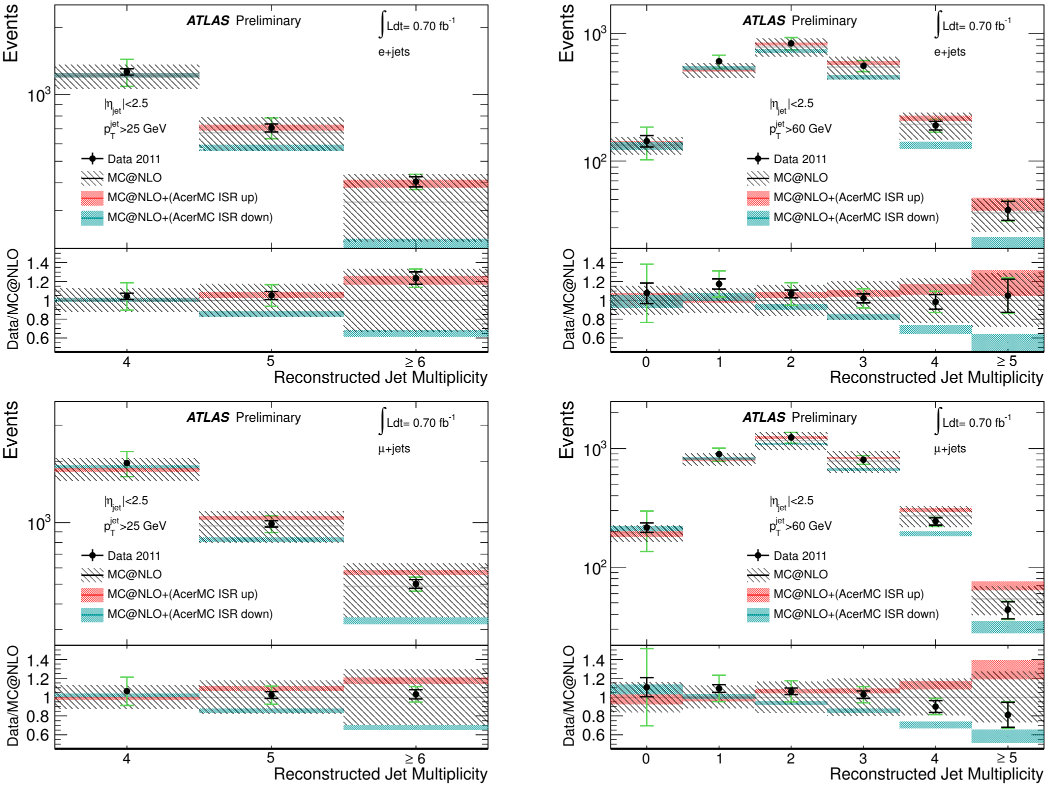

Figure 3: Reconstructed jet multiplicities in $t\bar{t}$ events for $e+$jets (top) and $\mu+$jets (bottom) decay channels for two jet-p_T thresholds $> 25\,\mathrm{GeV}$ (left) and $> 60\,\mathrm{GeV}$ (right). Also presented are the predictions from MC generator MC@NLO, including an example which includes a variation of the initial state radiation modeling parameters [7].

References

[1] R. Frederix and F. Maltoni, *Top pair invariant mass distribution: a window on new physics*, *JHEP* **01** (2009) 047, [`arXiv:0712.2355 [hep-ph]`]

[2] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, *JINST* **3** S08003

[3] ATLAS Collaboration, *ATLAS results on inclusive top quark pair production cross section at the LHC*, in proceedings of *ICHEP2012* (2012)

[4] ATLAS Collaboration, *Measurements of top quark pair relative differential cross-sections with ATLAS in pp collisions at $\sqrt{s} = 7$ TeV*, submitted to *Eur.Phys.J. C*, [`arXiv:1207.5644 [hep-ex]`]

[5] ATLAS Collaboration, *Measurement of the cross section in $t\bar{t}$ + jets using a kinematics fit method with the ATLAS detector*, https://cdsweb.cern.ch/record/1460395 [`ATLAS-CONF-2012-083`]

[6] ATLAS Collaboration, *Measurement of ttbar production with a veto on additional central jet activity in pp collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector*, *Eur.Phys.J.* C72 (2012) 2043 [`arXiv:1203.5015 [hep-ex]`]

[7] ATLAS Collaboration, *Reconstructed jet multiplicities from the top-quark pair decays and associated jets in pp collisions at $\sqrt{s} = 7$ TeV measured with the ATLAS detector at the LHC*, https://cdsweb.cern.ch/record/1385518 [`ATLAS-CONF-2011-142`]