PROCEEDINGS OF SCIENCE

ATL-PHYS-PROC-2013-273
21 October 2013

Measurement of differential cross sections in top pair production in pp collisions with the ATLAS detector

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Measurements of the differential spectra of $t\bar{t}$ pairs in $\sqrt{s} = 7$ TeV collisions at the ATLAS experiment at the LHC are presented. In the decay channel where exactly one top quark decays to a prompt electron or muon, measurements are presented of the invariant mass of the $t\bar{t}$ system, the p_T of the $t\bar{t}$ system, and the rapidity of the $t\bar{t}$ system. Additionally, measurements are presented of the multiplicity of extra jets that are radiated in association with the $t\bar{t}$ pair. Radiated jets are also studied in the channel where both top quarks decay to a prompt electron or a muon. In this case the flavour of the jets is studied using b-tagging, and the fraction of radiated jets that are heavy flavour (bottom or charm quark-initiated) is measured. In all cases the measurements are unfolded to particle or parton-level quantities and comparisons are made with various predictions from theory. A precise understanding of these distributions is necessary to constrain the backgrounds for many searches for new physics.

The European Physical Society Conference on High Energy Physics -EPS-HEP2013
18-24 July 2013
Stockholm, Sweden

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1. Introduction

In these proceedings several measurements of differential properties of $t\bar{t}$ collision events in $\sqrt{s} = 7$ TeV collisions at the ATLAS experiment at the LHC are presented. In Section 2 differential measurements of various kinematic spectra of $t\bar{t}$ pairs are presented. Comparisons are made with the predictions of a number of Monte Carlo generators as well as with the NLO predictions of MCFM [1]. The prospects for using such measurements to constrain Parton Distribution Functions (PDFs) are discussed. In Section 3 measurements of the multiplicity of extra radiated jets are presented. These measurements are compared to the predictions of a variety of Monte Carlo generators and showering tunes. Finally, in Section 4 a measurement of the fraction of events with extra radiated jets that are heavy flavour (charm or bottom) is presented and compared with the predictions of various generators and showering tunes. All of these measurements are important to understand the backgrounds for many new physics searches.

2. Measurements of differential kinematic spectra

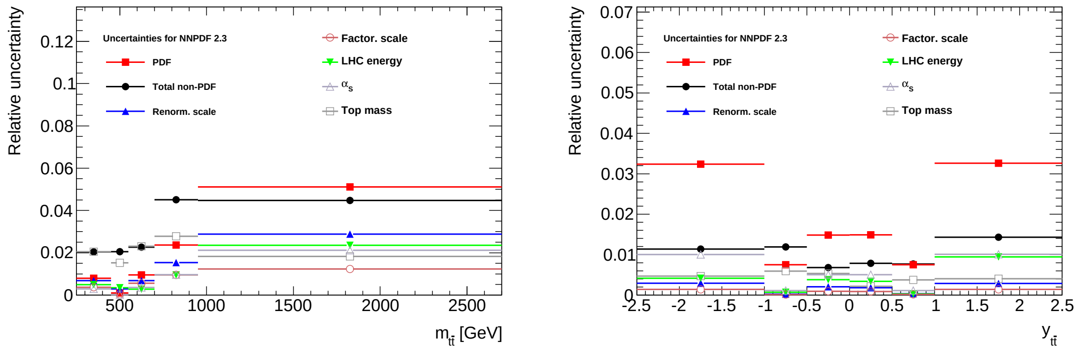
ATLAS has published three measurements of kinematic quantities involving top quarks using 2.05 fb^{-1} of $\sqrt{s} = 7$ TeV data [2]. These measurements are of the invariant mass ($m_{t\bar{t}}$), p_T, and rapidity ($y_{t\bar{t}}$) of the $t\bar{t}$ system in the decay channel with a single prompt lepton. The ATLAS detector itself is extensively documented elsewhere [3]. Events are required to have at least four jets, exactly one electron or muon, a b-tagged jet, and to pass a requirement on the missing transverse energy to reject events with fake leptons. A kinematic likelihood fit is also performed to reconstruct the top quark and W boson masses in the event from the reconstructed objects. This fit is required to pass a minimum χ^2 probability for consistency with a $t\bar{t}$ pair hypothesis.

Each of the measured quantities for the analysis are reconstructed using the measured jets, leptons and missing transverse energy. However these quantities have been smeared by the imperfect reconstruction and resolution of the detector. An unfolding procedure corrects for these effects:

$$\sigma_i = \frac{\sum_j M_{ij}^{-1}(N_j - B_j)}{A_i \int \mathscr{L}} \qquad (2.1)$$

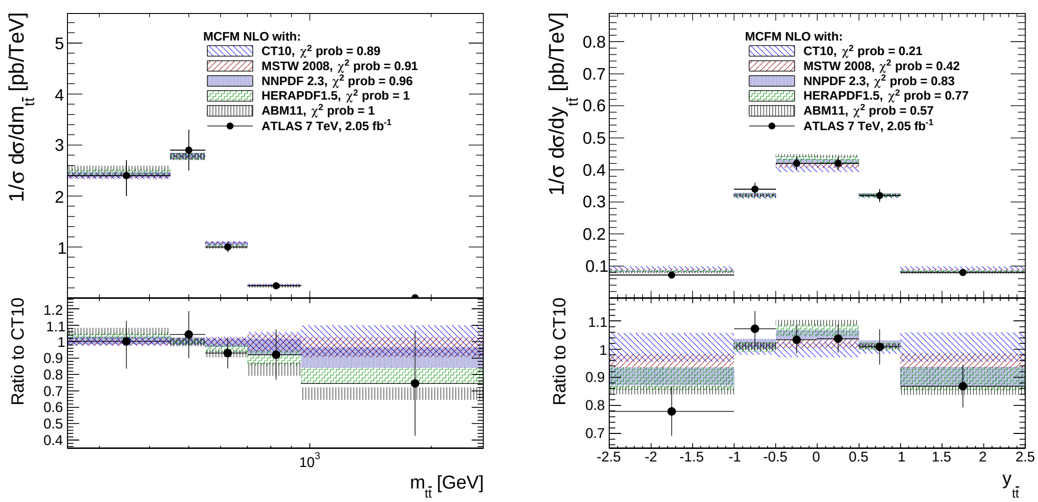
where σ_i is the cross section for a $t\bar{t}$ pair to be produced with true kinematic properties in bin i after final state radiation, M_{ij} is a migration matrix that determines the probability for an event in bin i to be reconstructed in bin j, N_j is the number of reconstructed events in bin j, B_j is the number of estimated non-$t\bar{t}$ background events in bin j, A_j is the probability (“acceptance") for a $t\bar{t}$ pair to be produced and decay in a manner that leads to its identification and reconstruction in bin j, and $\int \mathscr{L}$ is the integrated luminosity of the data that is analyzed.

It is expected that the data from analyses such as this could be used to constrain PDF modeling uncertainties. However, in addition to PDFs, other modeling uncertainties including scale uncertainties, the strong coupling constant (α_S) uncertainty, the top mass uncertainty, and the LHC beam energy uncertainty [4] must be considered. Comparisons of the relative size of the sources of modeling uncertainty have been made [5]. They are shown based upon the predictions of the NLO NNPDF 2.3 PDF set interfaced with NLO MCFM in Figure 1. It can be seen that while PDF



(a) (b)

Figure 1: Relative $t\bar{t}$ modeling uncertainties on the differential cross section as a function of $m_{t\bar{t}}$ (a) and $y_{t\bar{t}}$ (b) are presented using the NNPDF 2.3 PDF set. Further details can be found elsewhere [5].



(a) (b)

Figure 2: Kinematic distributions are compared between the data and NLO MCFM interfaced to five different NLO PDF sets. In this figure the vertical width of the points for each model represents the size of all modeling uncertainties added in quadrature. The distributions that are shown represent (a) the invariant mass of the $t\bar{t}$ system and (b) the rapidity of the $t\bar{t}$ system. Further details can be found elsewhere [5].

uncertainties are the dominant modeling uncertainties for the rapidity distribution, other important uncertainties may effect the $m_{t\bar{t}}$ distribution to a greater extent.

The fully unfolded data is compared to the predictions from five PDF sets in Figure 2. In each case a χ^2 probability is evaluated for consistency between the data and the modeling prediction, accounting for correlations between each bin in the data. Even accounting for all sources of modeling uncertainty, it appears that the discrepancies between the predictions of various PDF sets are large enough that more precise data measurements in the future may be used to constrain which PDFs are correct.

3. Measurements of the multiplicity of radiated jets

A differential analysis of jets in $t\bar{t}$ events in the single lepton decay channel has been performed at ATLAS [6] using 4.7 fb^{-1} of $\sqrt{s} = 7$ TeV data. The selection requirements are similar to those of the kinematic differential cross section measurement of Section 2. However, due to combinatoric difficulties in many-jet final states, no kinematic fitter is run to reconstruct the top quark decays. Instead the number of observed jets is simply compared with expectations.

The number of reconstructed jets are unfolded to the number of expected jets clustered using stable, final state particles. This unfolding is done according to the following formula:

$$N^i_{\text{part}} = f^i_{\text{part!reco}} \; M^{ij}_{\text{reco} \to \text{part}} \; f^j_{\text{reco!part}} \; f^j_{\text{accept}} \; (N^j_{\text{reco}} - N^j_{\text{background}}) \tag{3.1}$$

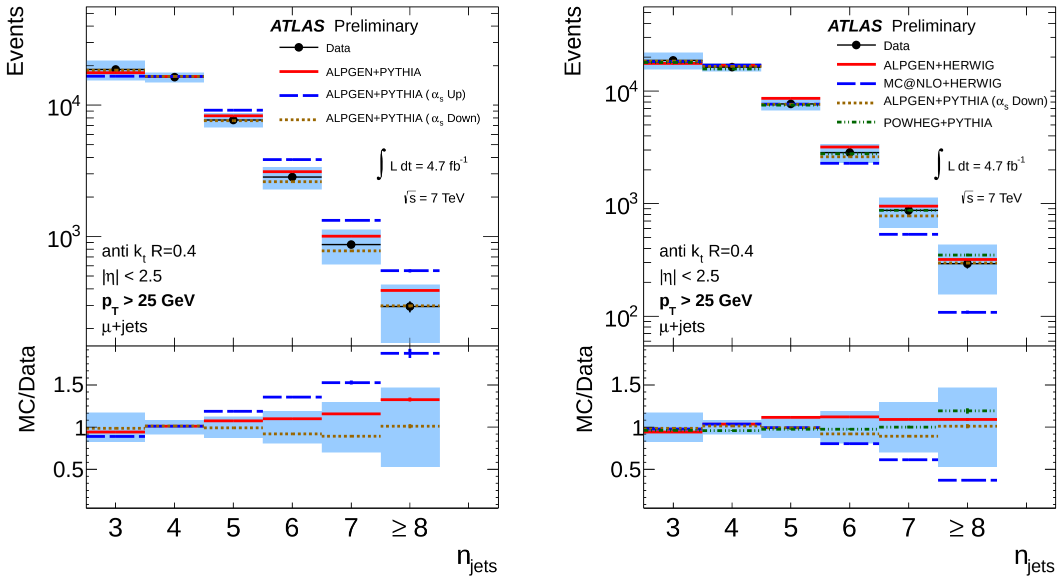
Here, N^j_{reco} is the number of events with j reconstructed jets, $N^j_{\text{background}}$ is the number of non-$t\bar{t}$ background events, f^j_{accept} corrects for the acceptance of non-jet based selection requirements, $f^j_{\text{reco!part}}$ corrects for events which pass the reconstructed jet requirements but not the particle-level jet requirements, $M^{ij}_{\text{reco} \to \text{part}}$ is a matrix that corrects for the jet resolution effects that may lead to a different number of reconstructed jets than particle jets in a given event, and $f^i_{\text{part!reco}}$ corrects for events which are identified at parton level but are not reconstructed. Finally, N^i_{part} is the resulting unfolded distribution of the number of parton jets.

Unfolded results are compared to the predictions of a wide variety of generators and showering schemes. In Figure 3a a comparison is made with ALPGEN showered with PYTHIA under a variety of settings for the strong coupling constant α_S. A strong dependence on the number of radiated jets is observed, and it is observed that a lower setting leads to the best agreement with data. In Figure 3b comparisons are made with additional generators including MC@NLO showered with HERWIG, POWHEG showered with PYTHIA, and ALPGEN showered with HERWIG. Decent agreement is observed with most generators except for MC@NLO plus HERWIG. It may be that the HERWIG showering underestimates the number of radiated jets when coupled with MC@NLO, while it leads to good agreement in association with jets from the matrix element in ALPGEN. Additional comparisons with higher p_T jet thresholds [6] also lead to the same observations.

4. Measurement of the flavour of radiated jets

One of the most significant backgrounds to searches for many new processes, including the associated production of $t\bar{t}$ with a Higgs boson, is the production of $t\bar{t}$ events in association with one or more heavy flavour radiated jets. The flavour of radiated jets in association with $t\bar{t}$ has been measured in $\sqrt{s} = 7$ TeV collisions [7]. This analysis is performed in a channel with two leptons plus missing transverse energy in order to minimize the presence of charm jets that are occasionally misidentified as b jets in a single lepton analysis. At least two jets are b-tagged, and a third jet is also required to be present. Studies of all three jets must be performed to see if one of them might be an extra radiated heavy flavor jet. Overall the analysis then measures the quantity R_{HF}:

$$R_{\text{HF}} = \frac{\sigma(t\bar{t} + \text{HF jet})}{\sigma(t\bar{t} + \text{jet})}, \qquad \sigma(t\bar{t} + \text{HF jet}) = \frac{N_{\text{HF}}}{\int \mathscr{L} \varepsilon} \tag{4.1}$$



(a) (b)

Figure 3: Unfolded jet multiplicity distributions in single lepton $t\bar{t}$ events are compared between data and a variety of generators and showering schemes. The dominant uncertainty in the data is the jet energy scale uncertainty. Further details can be found elsewhere [6].

where $\sigma(t\bar{t}+\text{jet})$ represents the cross section to produce a $t\bar{t}$ pair in association with a particle jet, and $\sigma(t\bar{t}+\text{HF jet})$ represents the same cross section but where the extra jet is initiated by either a charm or a bottom quark. Here, the cross-sections are defined in the usual way, based upon the number of events divided by the integrated luminosity and the selection efficiency, ε.

The denominator on the left of Equation 4.1 is measured simply by simply counting the number of events with two b-tags, subtracting the expected backgrounds, and unfolding to a cross-section result. For the numerator, however, it is necessary to measure the number of these events that have an extra heavy flavour jet. To do this the invariant mass distribution of the reconstructed secondary decay vertices within the b-tagged jets is formed. The distribution for tagged jets that originate from direct top decays is taken from control regions in the data, while the distributions for extra radiated tagged jets in $t\bar{t}$ events and from background processes is modeled in the simulation and validated in control regions of the data. This distribution is formed in three regions of increasing b-flavour purity based upon the tightness of the tagger that is used, and all three regions are fit to determine the number of radiated heavy flavour jets in the data as shown in Figure 4.

The fit of Figure 4 is performed using separate templates for b, c, and light flavour tagged jets. However due to the limited number of events in the 7 TeV dataset, the statistical resolution of the number of radiated b or c jets is poor when the flavours are considered individually. Instead the total number of heavy-flavour $b+c$ jets is measured. This choice leads to a complication, however, when evaluating the cross section for the process because the acceptance efficiency factor, ε, includes the probability for the heavy flavour jet to be tagged. Since ε is much larger for b-jets than it is for c-jets, the resulting heavy-flavour cross-section is strongly dependent on what fraction ($F_{b/\text{HF}}$) of the radiated heavy flavour jets originate from b-jets. The effects of this on the analysis result, R_{HF},

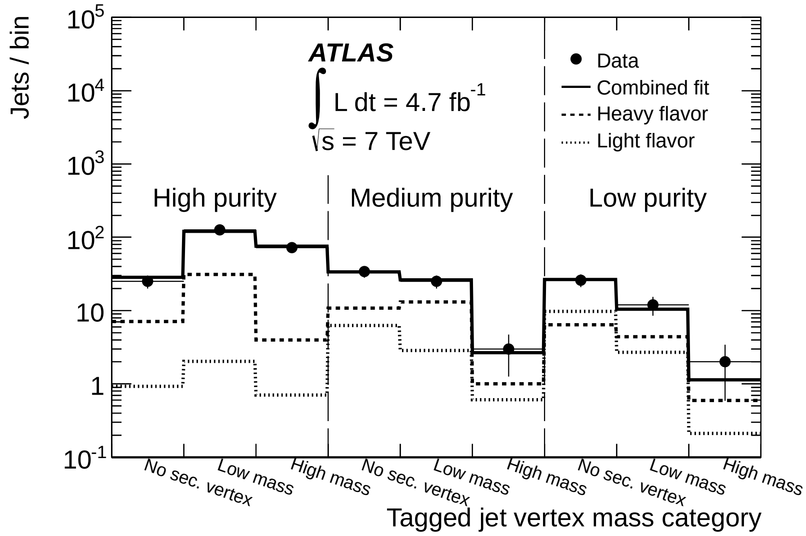


Figure 4: The distribution that is fitted in order to determine the number of heavy-flavour jets that are radiated in association with $t\bar{t}$ pairs. The invariant mass of secondary vertices in b-tagged jets is fit in three regions of b-flavour purity to determine the fraction of events with extra heavy flavour jets. Further details can be found elsewhere [7].

is illustrated in Figure 5. The measured $F_{b/\mathrm{HF}}$ value from the three-component fit of Figure 4 with the unphysical value of -0.02 is shown, along with the significant statistical uncertainties. This fit result is consistent at roughly the two sigma level with the LO predictions from $t\bar{t}$ events generated with MADGRAPH or with ALPGEN plus HERWIG. The simulated value of $F_{b/\mathrm{HF}}$ from ALPGEN is therefore used to determine the baseline analysis result, and an asymmetric systematic modeling uncertainty is taken that covers the analysis result that arises if the measured data value for $F_{b/\mathrm{HF}}$ is used instead. This modeling uncertainty on $F_{b/\mathrm{HF}}$ ends up being the largest uncertainty of the analysis.

R_{HF} is measured to be $(7.1 \pm 1.3\ (\mathrm{stat})^{+5.3}_{-2.0}\ (\mathrm{syst}))\%$, consistent with the LO predictions of $(3.4 \pm 1.1)\%$ using ALPGEN plus HERWIG and $(5.2 \pm 1.7)\%$ using POWHEG plus HERWIG. Future measurements using more statistics will allow for the simultaneous measurement of the individual b and c flavour fractions with higher statistical precision and without the currently-limiting uncertainty from $F_{b/\mathrm{HF}}$.

5. Conclusions

Measurements of a variety of differential distributions using $\sqrt{s} = 7$ TeV collisions at ATLAS have been presented. Measurements of the kinematic distributions of $t\bar{t}$ pairs show promise for constraining PDF uncertainties if experimental uncertainties can be reduced in future measurements. Measurements of the multiplicity of jets in $t\bar{t}$ events provide important information for validating different generators and shower models. Finally, a first measurement of the flavour of an additional radiated jet in $t\bar{t}$ events has been performed. While experimental uncertainties are significant, they promise to become much smaller in future measurements with additional statistics. All

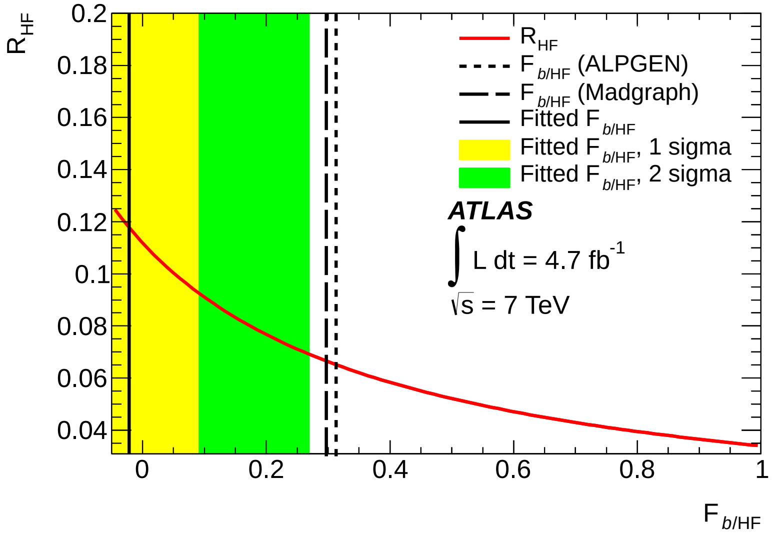


Figure 5: The dependence of the measured fraction of radiated jets in $t\bar{t}$ events that are heavy-flavour, R_{HF}, depends strongly on the fraction of these heavy-flavour jets that originate from b jets rather than c jets ($F_{b/\mathrm{HF}}$) as shown in the red distribution. The fitted value of $F_{b/\mathrm{HF}}$ is shown in the solid vertical black line at -0.02. This negative value, while unphysical, has significant statistical uncertainties. This is shown in the yellow (green) band that represents a 1-sigma (2-sigma) statistical uncertainty. Also shown are the leading order predictions of $F_{b/\mathrm{HF}}$ according to $t\bar{t}$ events generated using MADGRAPH and ALPGEN.

of these measurements are important for understanding backgrounds that are key to a wide variety of searches for new physics.

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