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Inclusive Top Quark Pair Production at 7 and 8 TeV with the ATLAS Experiment

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Measurements of the top quark pair production cross-sections in proton-proton collisions with the ATLAS detector at the Large Hadron Collider are presented for data taken at $\sqrt{s} = 7$ TeV, with integrated luminosities between 0.7 fb^{-1} and 4.7 fb^{-1}, and at $\sqrt{s} = 8$ TeV, with an integrated luminosity of 5.8 fb^{-1}. The cross-section has been measured in all three decay channels: the all-hadronic channels, where each top quark decays into a b quark and a hadronically decaying W boson, the lepton+jets channel, where one of the W bosons decays Into a charged lepton and a neutrino, and the dilepton channel, where both W bosons decay into leptons. In addition, decay modes with one of the W bosons decaying into a hadronically decaying τ lepton are presented, while the other W boson can decay into an electron or muon and neutrino or hadronically. Finally, a combination of the results from the different decay channels is performed for the $\sqrt{s} = 7$ TeV analyses.

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1. Introduction

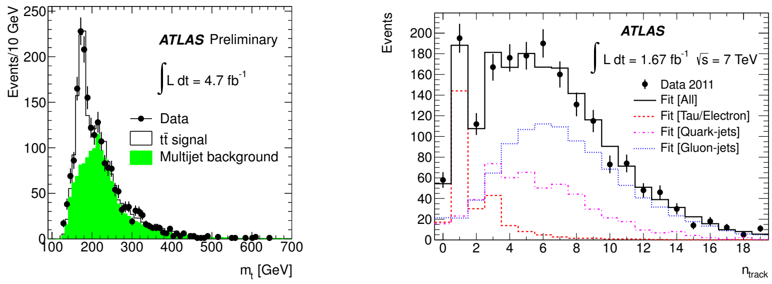
Understanding top quark pair production with high precision and in all possible decay channels is important both as a test of perturbative QCD calculations, which are now available at full NNLO [1, 2, 3, 4, 5, 6] and the Standard Model itself. It also constitutes a tool on the path towards discovery of new physics. While top quark pair production is mediated by strong interaction, the subsequent decay of the top quark follows the electroweak mechanism within the SM, with $t \to Wb$. Since the W boson decays leptonically ($W \to \ell\nu$) and hadronically ($W \to q\bar{q}$), three different decay modes are used to classify top quark pair production events: all-hadronic, lepton+jets and dilepton, where only electrons and muons are considered, but can stem from leptonically decaying τ leptons. Measurements of the top quark pair production cross-sections ($\sigma_{t\bar{t}}$) in these channels are presented for pp collision data collected with the ATLAS detector at $\sqrt{s} = 7$ TeV for the full and partial integrated luminosity. They are complemented by dedicated measurements for the cases of hadronically decaying τ leptons from the W boson decay, in the τ+jets and τ+lepton channel, while leptonically decaying . For pp collisions at $\sqrt{s} = 8$ TeV a measurement in the lepton+jets channel is presented. Simulated signal events are generated using MC@NLO [7] interfaced with HERWIG [8] and JIMMY [9] for parton shower and underlying event modelling.

2. Measurement of Top Quark Pair Production in the All-Hadronic Channel

A measurement of $\sigma_{t\bar{t}}$ has been performed in the all-hadronic decay channel using the full data set collected by ATLAS at $\sqrt{s} = 7$ TeV for a corresponding integrated luminosity of 4.7 fb^{-1} [10]. Events with at least 6 jets and ≥ 2 b-jets are selected, using a b-tagging algorithm with 60% efficiency and a light jet rejection factor of about 500. To create a data sample enhanced with all-hadronic top quark pair production, events containing a charged lepton or a significant amount of missing transverse energy, $S(E_T^{miss}) = \frac{E_T^{miss}}{(0.5\times\sqrt{\sum_i^{NJets} p_{T,i}})} > 0.5$, are discarded. The remaining background stems from multijet production, which is modeled from dedicated samples selected in data by dropping the b-tagging requirement. A kinematic likelihood fit is used to determine the best assignment of jets to the hadrons from the top quark decay. The fit makes use of constraints from Breit-Wigner functions for the mass and width of the W bosons, and the mass of the top quark and the anti-top quark are required to be identical. Furthermore, b-tagging is used to assign the b-jets in the top quark decay. The resulting reconstructed mass of the top quark, as shown in Figure 1(a), is then used in an unbinned likelihood fit to extract $\sigma_{t\bar{t}}$. The measured cross-section is $\sigma_{t\bar{t}} = 168 \pm 12\ (\text{stat.})^{+60}_{-57}\ (\text{syst.}) \pm 6\ (\text{lumi.})$ pb, with the dominant uncertainties stemming from the jet energy scale determination, b-tagging performance and the modeling of initial and final state radiation (ISR and FSR).

3. Measurement of $\sigma_{t\bar{t}}$ in the τ+Jets Channel

A measurement in the τ_{had}+jets channel has been performed in 1.67 fb^{-1} of data taken at $\sqrt{s} = 7$ TeV [11]. Events with at least five jets, at least two of them identified as b-jets, and no charged lepton are selected. A significant amount of missing transverse energy is required through $S(E_T^{miss}) > 8$. The τ_{had}-candidate is selected as the highest p_T jet, which is neither a



(a) Reconstructed invariant mass distribution of top quark candidates after an unbinned likelihood fit in the all-hadronic channel [10].

(b) Number of tracks associated with the τ-candidate after the likelihood fit to extract $\sigma_{t\bar{t}}$ in the τ+jets channel [11].

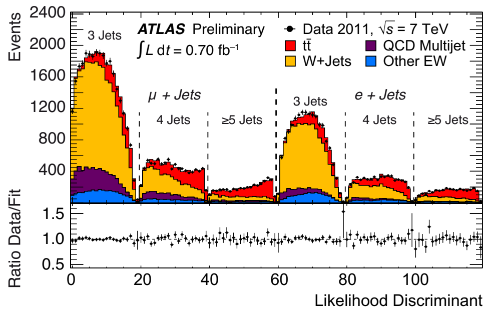
Figure 1: Distributions in the all-hadronic and τ+jets analyses.

b-tagged jet nor part of the three-jet combination yielding the highest p_T-sum. No additional τ-identification algorithm is applied. The number of tracks associated to the τ_{had}-candidate, as shown in Figure 1(b), has a good separation power for signal and the dominant background from gluon or quark jets. A model of the gluon jet background from QCD multijet production is derived from the sideband $3 < S(E_T^{miss}) < 4$. The quark jet model, dominated by $t\bar{t}$ production, is obtained from an event selection where instead of a τ_{had}-candidate a muon is selected. A likelihood fit to the number of track distribution for the τ_{had}-candidate is performed and results in $\sigma_{t\bar{t}} = 194 \pm 18$ (stat.) ± 46 (syst.) pb. Dominant uncertainties stem from the modeling of initial and final state radiation, the choice of the signal generator, which is MC@NLO in the default configuration, and from b-tagging performance.

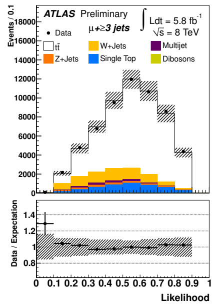
4. Measurements of $\sigma_{t\bar{t}}$ in the Lepton+Jets Channel

Three measurements, two at $\sqrt{s} = 7$ TeV[12, 13] and one at $\sqrt{s} = 8$ TeV[14], have been performed in the lepton+jets channel. In this channel, the dominant background processes are W+jets and QCD multijet production, which are estimated directly from data. Events are selected requiring one charged, isolated and high p_T lepton, at least three jets and a significant amount of missing transverse energy.

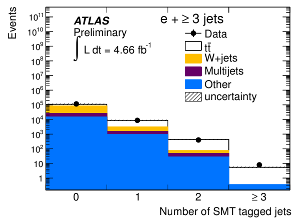
A measurement of $\sigma_{t\bar{t}}$ is performed in 0.7 fb^{-1} of data at $\sqrt{s} = 7$ TeV and makes use of four kinematic variables ($\eta(\ell)$, $p_T(j_1)$, aplanarity, calculated using the p_T of the jets and the charged lepton, and $H_{T,3p}$, the ratio of all transverse momenta of the jets starting with the third jet and the p_z-components of all objects) are combined in a likelihood discriminant [12]. A profile likelihood fit, including systematic uncertainties as nuisance parameters, is performed in this distribution, as shown in Figure 2(a) and allows the impact of uncertainties such as the ones from ISR/FSR and jet energy scale calibrations, to be constrained. Systematic uncertainties not following a continuous parametrization, such as the choice of the signal generator or parton shower model, are not included in the profiling but are evaluated using ensemble tests. The background from W+jets production is fitted as well, while the other backgrounds are constrained by their theoretical uncertainties. The



(a) Likelihood discriminant after the profile likelihood fit for the $\sqrt{s} = 7$ TeV analysis [12].



(b) Likelihood discriminant for $\sqrt{s} = 8$ TeV [13].



(c) Number of SMT tagged jets for the soft muon tagging analysis [14].

Figure 2: Distributions in the lepton+jets analyses.

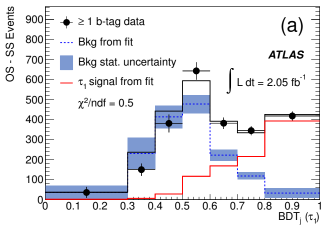
analyses yields $\sigma_{t\bar{t}} = 179.0 \pm 3.9$ (stat.) ± 9.0 (syst.) ± 6.6 (lumi.) pb, the most precise measurement of $\sigma_{t\bar{t}}$ performed by ATLAS to date. Leading uncertainties are the signal modeling and jet energy scale uncertainties.

A similar strategy is employed for the first measurement at $\sqrt{s} = 8$ TeV, using a partial data set of 5.8 fb^{-1} [13]. To further reduce background events from W+jets and QCD multijet production, events are required to contain at least one b-jet and the p_T requirements of the leptons are tightened to 40 GeV. Two variables, $\eta(\ell)$ and aplanarity, are combined into a likelihood discriminant, shown in Figure 2(b). A negative log-likelihood fit without profiling results in $\sigma_{t\bar{t}} = 241 \pm 2$ (stat.) ± 31 (syst.) ± 9 (lumi.) pb, in good agreement with predictions. In the fit the normalization of the W+jets background is determined as well, while other backgrounds are fixed to their theoretical prediction. The main uncertainties are also signal modeling and the jet calibrations.

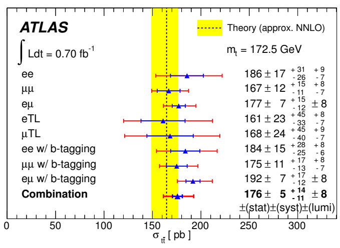
A different analysis technique is used in a measurement at $\sqrt{s} = 7$ TeV with the full data set of 4.66 fb^{-1}, which uses a soft muon tagger (SMT) to tag jets originating from a b-quark [14]. This algorithm targets semimuonic $b \to \mu X$ decays and is based on the use of a quality match between hits in the inner detector and the muon spectrometer. At least one SMT tagged jet is required in the selected events, which enhances the amount of top quark events as shown in Figure 2(c). Counting events passing the selection, the analysis measures $\sigma_{t\bar{t}} = 165 \pm 2$ (stat.) ± 17 (syst.) ± 3 (lumi.) pb, limited by large uncertainties on the background normalization and heavy flavor contribution, the jet energy scale and the $b \to \mu X$ branching ratio.

5. Measurement of $\sigma_{t\bar{t}}$ in the τ+Lepton Channel

A measurement in the τ_{had}+lepton channel has been performed in 2.05 fb^{-1} of data at $\sqrt{s} = 7$ TeV [15]. After selecting one charged and isolated lepton and at least two jets, all jets with 20 GeV $< E_T <$ 100 GeV with one to three associated tracks are considered τ_{had}-candidates. For further τ-identification boosted decision trees (BDTs) based on tracking and calorimeter variables are used separately for 1-prong (τ_1) and 3-prong (τ_3) hadronic τ decays. First, a BDT trained on the difference between τs and electrons is used to reduce the electron background with a rejection factor of about 60, maintaining an efficiency of 85% for real τs. BDTs trained to separate jets and τ leptons build the discriminating variable exploited in this analysis. Figure 3(a) shows the distribution used in the fit. The background from QCD multijet production with jets faking τs is found to be symmetric in lepton charge and the same-sign lepton pair contributions are subtracted from the opposite-sign distribution. The background model for the remaining background processes is obtained by selecting data events with no b-tagged jet. A combination of χ^2-fits of the signal and background templates to data for 1/3-prong τ-candidates leads to $\sigma_{t\bar{t}} = 186 \pm 13$ (stat.) ± 20 (syst.) ± 7 (lumi.) pb. Limiting factors for this analysis are the systematic uncertainties from b-jet tagging, ISR and FSR modelling and the τ-identification.



(a) Fitted distribution of the boosted decision tree output for 1-prong τs [15].



(b) Results of a profile likelihood fit to the number of events for all dilepton selections [16].

Figure 3: Distribution in the τ+lepton channel and fit results in the dilepton channel.

6. Measurement of $\sigma_{t\bar{t}}$ in the Dilepton Channel

In the dilepton channel 0.7 fb^{-1} of data taken at $\sqrt{s} = 7$ TeV has been analyzed in seven different analysis bins: ee, $e\mu$ and $\mu\mu$ with and without requiring a b-tagged jet, and two lepton+track selections (eTL, μTL) [16]. In all cases at least two jets and a significant amount of missing transverse energy or H_T is required, supplemented by the selection of two opposite sign leptons or a lepton and an additional isolated track. The dominant backgrounds arise from Z/γ^*+jets production, which can be reduced by excluding events with $m_{\ell\ell}$ close to m_Z, and other processes through jets faking isolated leptons. The background from Z/γ^*+jets production is estimated in data by selecting events with $|m_{\ell\ell} - m_Z| < 10$ GeV and extrapolating the normalization into the signal region.

Backgrounds from processes with jets faking leptons are estimated using a 'matrix method' based on probabilities of leptons before requiring any isolation to pass the calorimeter and track-based isolation requirements of the analysis. Counting the events in all bins and performing a simultaneous profile likelihood bin, yields the results shown in Figure 3(b). The combination of all channels results in $\sigma_{t\bar{t}} = 176 \pm 5\ (\text{stat.})^{+14}_{-11}\ (\text{syst.}) \pm 8\ (\text{lumi.})$ pb, with the dominant uncertainties stemming from the modeling of $t\bar{t}$ prdocution and jet related uncertainties.

7. Summary and Conclusions

Measurements in all decay channels of top quark pair production were performed by the ATLAS collaboration and show good agreement with theoretical predictions. The precision of a single measurement, in the lepton+jets channel, reaches 6.6% and a combination of this measurement, the measurement from the dilepton channel and a previous version of the all-hadronic measurement can be exploited in a combined fit, leading to $\sigma_{t\bar{t}} = 177 \pm 3\ (\text{stat.})^{+8}_{-7}\ (\text{syst.}) \pm 7\ (\text{lumi.})$ pb [17]. All measurements are limited by systematic uncertainties, most notably the uncertainty on the modeling of top quark pair production, which could be further reduced in the future through an extensive program of differential measurements of $\sigma_{t\bar{t}}$.

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