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Top-quark production at ATLAS

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Summary. — Studies of the top-quark are an important part of the ATLAS physics program at the LHC. Such studies offer a precision test of the Standard Model, but could also reveal hints of new phenomena. A short summary of the most recent ATLAS results on the study of top-quark production are presented here.

PACS 14.65.-q – Quarks.

1. – Introduction

Over the last two years of running, the LHC has produced millions of top-quark pair events ($t\bar{t}$), due to its high center-of-mass energy and large delivered luminosity. The LHC era has therefore signaled a paradigm shift in the study of top quarks, as the top-quark has gone from being a sought-after signal at the Tevatron to now being a significant background in searches for new phenomena at the LHC. Nonetheless, direct studies of the top-quark at the LHC can still provide a very stringent test of the Standard Model. Also, many new physics scenarios predict enhancements in the top-quark production rate which could be detected in direct studies of top-quark production. The ATLAS experiment [1] has a rich top-quark physics program, which has led to over 25 publications and 50 public results up until now. The most recent ATLAS results on this topic are summarized in this document.

2. – Top-quark pair cross section measurements

While the inclusive top-quark pair cross section at 7 TeV has already been measured to a high precision in the single-lepton (electron and muon) channel, alternate measurements in other channels, and with other techniques, can provide important additional insight.

The first of such measurements is carried out in the hadronically decaying tau (τ_{had})+jets channel. This measurement is important as it is sensitive to flavor-dependent effects, which could be introduced by new phenomena. The analysis strategy consists in using stringent requirements on the event topology (2 b-tagged jets, high missing transverse momentum $E_{\text{T}}^{\text{miss}}$, veto on reconstructed electrons and muons) to isolate $t\bar{t}$ events

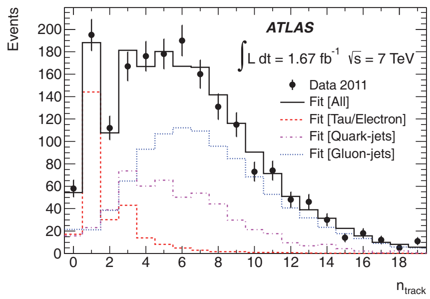

Fig. 1. – The n_{track} distribution for τ_{had} candidates after all selection cuts. The black points correspond to data, while the solid black line is the result of the fit. The red (dashed), blue (dotted) and magenta (dash-dotted) histograms show the fitted contributions from the τ_{had} signal, and the gluon-jet and quark-jet backgrounds, respectively [2].

while keeping the contribution from multijet and electroweak background events as low as possible. The full event selection and methodology is described in detail in [2]. Then, the contribution from events containing real τ_{had} is extracted from a fit on the number of reconstructed charged tracks associated to jets in the event. As τ_{had} decay prominently to one and three charged hadrons (and other neutrals), this leads to an expected excess in the one- and three-track bins. Quark- and gluon-initiated fakes are expected to have a much broader distribution of number of associated tracks, and the associated distributions are estimated from data-driven control samples. The results of this fit are shown in fig. 1. The cross section is then obtained using simulation to estimate the acceptance and efficiency of the event requirements. The systematic uncertainties are dominated by the understanding of the efficiency of the b-tagging algorithm, and the simulation modeling of the acceptance. The final result at 7 TeV is $\sigma_{t\bar{t}} = 194 \pm 18(\text{stat.}) \pm 46(\text{syst.})$ pb, and is in agreement with the Standard Model predictions. It is particularly interesting to note that $t\bar{t}$ events are the main high-statistics source of high transverse momentum (p_{T}) τ_{had}, and this analysis can therefore be regarded as a first step towards the study of the performance of such objects.

All the highest-precision measurements of the $t\bar{t}$ cross section depend on the use of high-performance b-tagging algorithms to reduce contributions from various backgrounds. These b-tagging algorithms are based on lifetime information, and are therefore dependent on a similar set of systematic uncertainties. Obtaining a cross section measurement with a different tagging algorithm would provide a complementary result which is subject to a different set of systematic uncertainties. Such a measurement was carried out in ATLAS using the single-lepton channel. To identify b-jets, a muon-in-jet tagging approach was used (Soft Muon Tagger, or SMT). This approach consists in detecting the semi-leptonic decay $b \to \mu + X$. This introduces different limitations, as the branching ratio for this decay is only in the order of 20%; the branching ratio itself is only known at the 3% level. Muons coming from the decay of light hadrons are rejected by requesting a good match between a charged track from the inner detector and the track associated with the muon candidate in the muon spectrometer. The algorithm offers an excellent rejection of light-jets, with a mistag rate measured in data going as low as one in a thousand. The event selection consists of requirements on the presence of a light lepton (electron or muon), $E_{\text{T}}^{\text{miss}}$, and a jet tagged with the SMT algorithm. The full details of the event selection, along with a description of the SMT algorithm, are provided in [3]. Backgrounds from both multijet and $W +$ jets events are estimated using data-driven

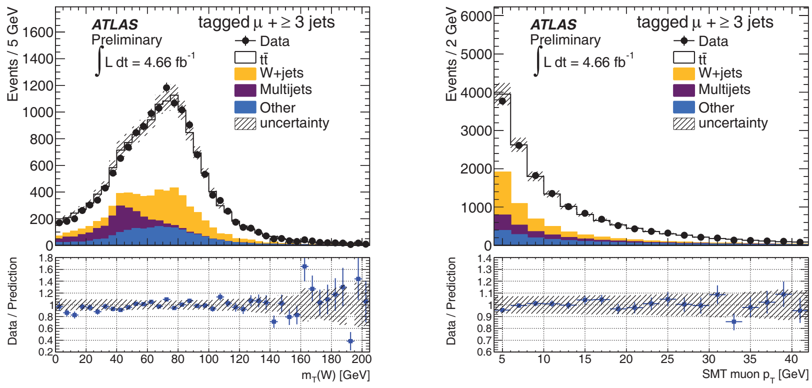

Fig. 2. – The transverse mass of the W, $m_{\mathrm{T}}(W)$ (left) and the transverse momentum, p_{T}, of the soft muons (right). This figure shows only events in the $\mu+$jets channel with at least three jets and at least one SMT tagged jet. "Other" denotes the smaller $Z+$jets, single top and diboson backgrounds which are estimated with Monte Carlo. Uncertainties include statistical and systematic contributions [3].

methods, the former using estimates of the light-lepton fake rates from control samples, and the latter using information from the charge asymmetry of the W production processes in pp collisions. Other backgrounds are estimated directly from simulation. Figure 2 shows excellent agreement between the predictions and the observed data. The resulting measured cross section at 7 TeV is $\sigma_{t\bar{t}} = 165 \pm 2(\mathrm{stat.}) \pm 17(\mathrm{syst.}) \pm 3(\mathrm{lumi.})$ pb. The dominant contributions to the systematic uncertainties come from the background estimates, generator uncertainties, jet energy scale and lepton identification efficiency. It is interesting to note that the uncertainty on the tagging efficiency of the SMT algorithm is at the 1–2% level, and is very low compared to the uncertainty typically associated to lifetime-based taggers.

Studying the $t\bar{t}$ cross section as a function of event observables can also provide a stringent test of Standard Model predictions, and set constraints on the simulation of non-perturbative effects. Two measurements were performed at ATLAS with this particular goal. The first consists of studying the $t\bar{t}$ cross section as a function of the jet multiplicity in the event, and the second as a function of the kinematics of the $t\bar{t}$ system. Both measurements are carried out in the single-lepton (electron or muon) channel, following the event selection described in [4] and [5], respectively. To allow a better comparison to particle-level simulated event samples, the observables used in both analyses are unfolded by studying the typical event migrations when detector effects are factored in. In both cases, the backgrounds are estimated using the same methods as for the muon-in-jet analysis described above. For the analysis focused on the jet multiplicity, the measurement is performed using 4 different p_{T} thresholds for the jets: 25, 40, 60 and 80 GeV. The unfolded distributions are then compared to the predictions from four different combinations of matrix-element generators interfaced to parton shower and hadronization programs. The four combinations are ALPGEN + HERWIG, MC@NLO + HERWIG, ALPGEN + PYTHIA, POWHEG + PYTHIA. Figure 3 shows the final results for the muon and electron channel for a single jet p_{T} bin. As is shown in the figure, good agreement is found between the measured cross section and the various predictions, though MC@NLO + HERWIG appears to be slightly disfavored as the produced jet multiplicity is too low. For the analysis focused on the $t\bar{t}$ system observables, an additional

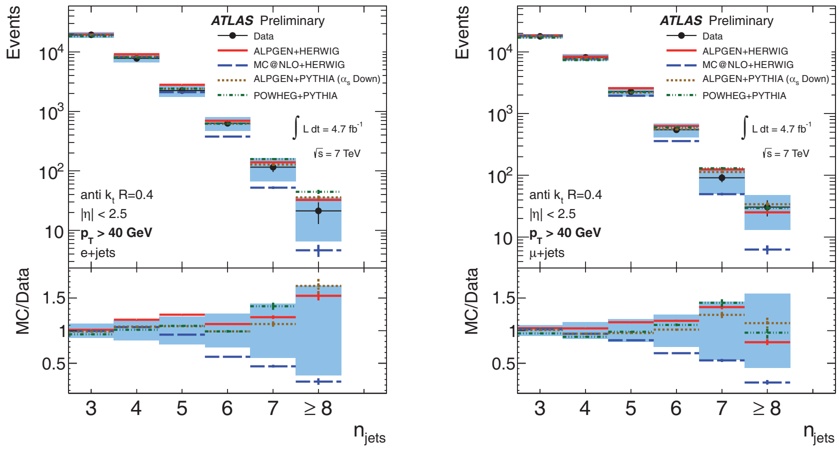

Fig. 3. – The particle-jet multiplicities for the electron (left) and muon channel (right) for the 40 GeV jet p_{T} threshold. The data points and their corresponding statistical uncertainty are shown in black, whereas the total uncertainty (syst. + stat.) is shown as a shaded band. The MC predictions are shown with their statistical uncertainty [4].

step is required to resolve the $t\bar{t}$ kinematics. This is due to the fact that there is no direct way to determine which decay products are associated with either of the produced top-quarks. The method used consists of maximizing a likelihood determinant based on the masses of the particles in the system, the probabilities having the given kinematics for the objects in the event, and the b-tagging probability. Using the solution which maximizes the likelihood, the mass (m), p_{T} and rapidity (y) of the $t\bar{t}$ system is calculated. Figure 4 shows two sample distributions of the differential cross section obtained with this analysis. The measured distributions are found to be in good agreement with the predictions. The systematic uncertainties of the two analyses presented are dominated by the same sources: uncertainties on the jet kinematics and on the event generator configuration used. Such analyses will allow to better constrain theoretical predictions and models, and will lead to reduced uncertainties in future top-quark measurements.

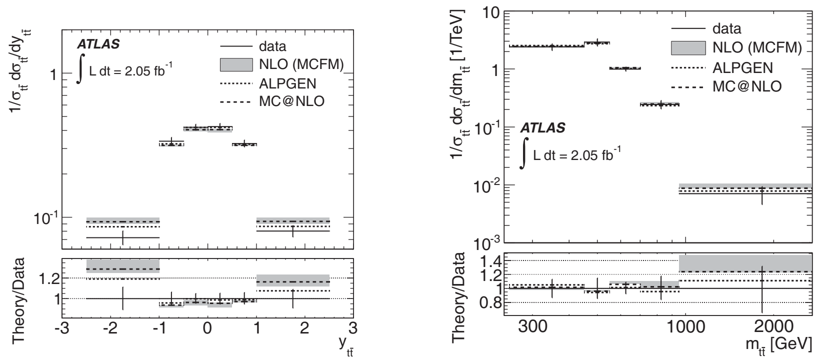

Fig. 4. – Relative differential cross section *versus* $y_{t\bar{t}}$ (left) and $m_{t\bar{t}}$ (right). The measured uncertainty represents 68% confidence level including both statistical and systematic uncertainties. The bands represent theory uncertainties.

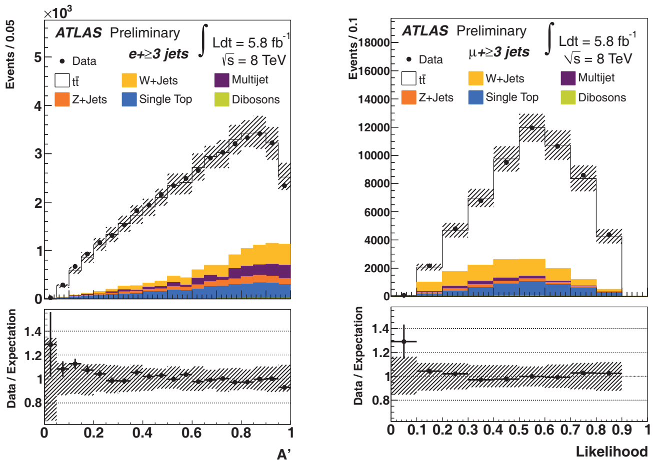

Fig. 5. – Transformed aplanarity A' distribution in the e+jets channel (left). Fit to the likelihood discriminant distribution in data in the $\mu+$jets channel (right). The hatched bands display the combined expected statistical and systematic uncertainty [6].

The $t\bar{t}$ pair production cross section was also measured for the first time with 8 TeV collisions. This measurement used the single-lepton (electron or muon) production channel, using the same methodology as the latest measurements from the 7 TeV run. Minor differences were introduced in the event selection to adapt to the higher number of simultaneous pp collisions (pile-up) present during the 8 TeV run. The full event selection is detailed in [6]. A template fit is carried out to extract the $t\bar{t}$ signal. The discriminating variable used is a likelihood constructed using the event transformed aplanarity (A') [6] and the lepton pseudo-rapidity (η) as inputs. The likelihood for each event is calculated based on the expected event kinematics for $t\bar{t}$ signal events and $W+$jets backgrounds, both taken from simulations. Figure 5 shows a very good agreement between the predictions and the observed data in one of the input variables, and the resulting likelihood. The cross section at 8 TeV is $\sigma_{t\bar{t}} = 241 \pm 2(\text{stat.}) \pm 31(\text{syst.}) \pm 9(\text{lumi.})$ pb, and is in agreement with the Standard Model predictions. The systematic uncertainties are driven by the modeling of the $t\bar{t}$ signal acceptance in the simulation.

3. – Single top cross section measurements

The production of single top-quarks occurs in 3 distinct channels. Using the 7 TeV dataset collected by the ATLAS experiment, upper limits were set on the cross section in the s-channel [7], evidence was found for Wt-channel production [8], and t-channel production was observed [9].

Production of single top-quarks in the t-channel occurs in 2 different processes driven by the flavor of the initial state non-b-quark (u or d). In each case, the charge of the produced W-boson is different, which gives an experimental signature allowing the identification of the underlying process. Studying the relative yields of events from both processes allows to set direct experimental constraints on parton density functions (PDFs) in the range $0.02 \leq x \leq 0.5$. Such a study was carried out in the single-lepton channel, allowing for a simple measurement of the W-boson charge. The observable used is R_t, the ratio of events with a u-quark to events with a d-quark in the initial state, and is

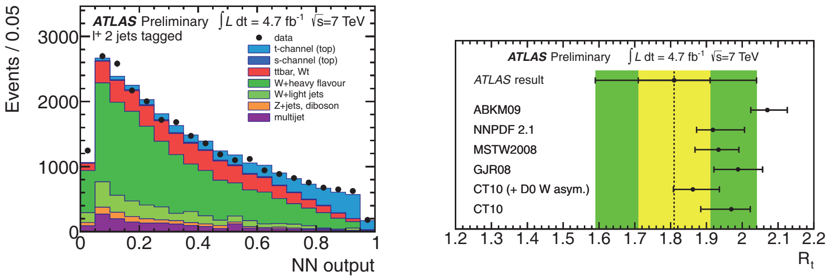

Fig. 6. – Neural network output distribution normalised to the result of the binned maximum-likelihood fit in the 2-jet tagged l^+ dataset (left). Calculated R_t values for different NLO PDF sets (right). The error contains the uncertainty on the renormalization and factorization scales. The black line indicates the central value of the measured R_t value. The combined statistical and systematic uncertainty of the measurement is shown in green, while the statistical uncertainty is represented by the yellow error band [10].

naively expected to be ~ 2. The event selection consists of requiring one b-tagged jet, one reconstructed lepton (electron or muon), and requirements on the $E_{\mathrm{T}}^{\mathrm{miss}}$ and transverse mass of the lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$ system. The full selection and methodology is described in [10]. The analysis strategy consists of using a multivariate neural net discriminant trained using the event variables offering the highest sensitivity for separating the single top-quark signal from $t\bar{t}$ and $W+$jets backgrounds. A fit is then carried out on the neural net output, using simulated samples to obtain templates for the signal and background, and using constraints on the expected normalizations of the various backgrounds. The two measured cross sections at 7 TeV are $\sigma_t = 53.2 \pm 1.7(\mathrm{stat.}) \pm 10.6(\mathrm{syst.})$ pb and $\sigma_{\bar{t}} = 29.5 \pm 1.5(\mathrm{stat.}) \pm 7.3(\mathrm{syst.})$ pb. Both results are in agreement with the Standard Model predictions. Figure 6 shows the distribution of the neural network discriminant, and the final result for R_t, along with a comparison to the predictions from various PDF sets. While the uncertainties on R_t are currently large, more statistics and a better understanding of the systematic uncertainties expected in the future will allow such a measurement to set stringent constraints on PDF sets.

A first measurement of the t-channel single top-quark production cross section with 8 TeV collisions was also carried out. For this measurement, the signal was extracted using the same technique as described above. Small adjustments were made to the event selection to cope with the higher pile-up associated with the 8 TeV run and are described in [11]. The resulting measured cross section at 8 TeV is $\sigma_t = 95 \pm 2(\mathrm{stat.}) \pm 18(\mathrm{syst.})$ pb, and is in good agreement with the Standard Model predictions.

4. – Measurement of the charge asymmetry

The Standard Model predicts a small asymmetry of the $t\bar{t}$ production under charge conjugation. Various new phenomena could lead to an enhancement of this asymmetry. To verify the agreement with the Standard Model predictions, a measurement of the charge asymmetry was carried out in the dilepton channel at ATLAS. Events are required to have two opposite sign leptons (electrons or muons). Specific requirements are applied to the events with same-flavor and opposite flavor leptons, to specifically rejects $Z+$jets and $W+$jets backgrounds, and are described in [12]. Two separate quantities are studied: the $t\bar{t}$ charge asymmetry, which requires the use of a technique to recover the missing in-

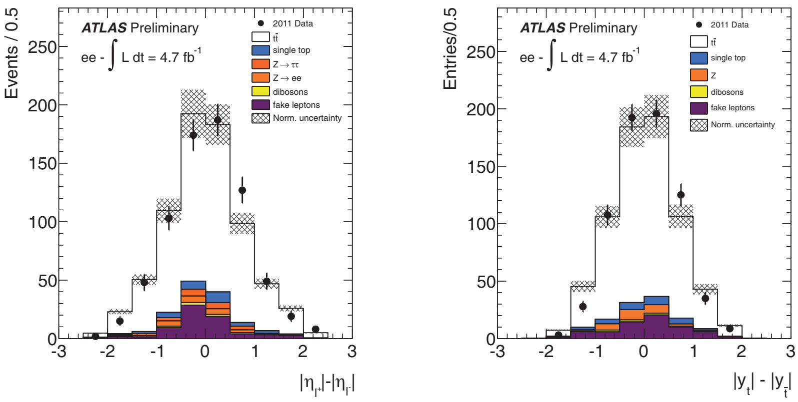

Fig. 7. – The measured $|\eta_{l+}| - |\eta_{l-}|$ (left) and $|y_t| - |y_{\bar{t}}|$ (right) distributions for lepton pairs after the selection in the ee channel where the points are the data and the solid lines the Monte Carlo simulation estimates. The shaded area represents the systematic uncertainties on the signal and background normalization [12].

formation from the kinematics of the two neutrinos produced, and the lepton/anti-lepton charge asymmetry, a simpler quantity which is sensitive to the same effects. To resolve the full kinematics of the $t\bar{t}$ system, a matrix-element method is used. This method consists of using all possible solutions for the resolved kinematics for each event, and assigning a weight obtained from the matrix-element calculation to each different solution. Figure 7 shows the measured rapidity differences used in calculating the asymmetries. The final values obtained at 7 TeV are $A_{t\bar{t}} = 0.057 \pm 0.024(\text{stat.}) \pm 0.015(\text{syst.})$ and $A_{l\bar{l}} = 0.023 \pm 0.012(\text{stat.}) \pm 0.008(\text{syst.})$. The Standard Model predictions for these two quantities are $A^{SM}_{t\bar{t}} = 0.006 \pm 0.002(\text{stat.})$ and $A^{SM}_{l\bar{l}} = 0.004 \pm 0.001(\text{stat.})$. The current results are too statistically limited to derive a definite conclusion. However, the precision of this measurement is expected to improve once it is repeated with the larger 8 TeV dataset.

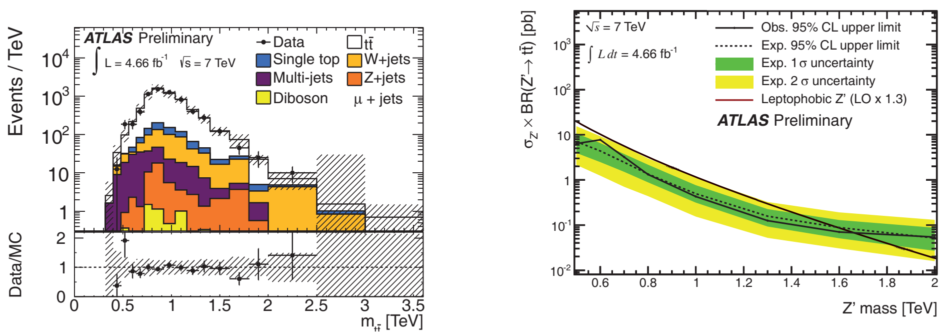

Fig. 8. – Comparison of the data and the Standard Model prediction for the $t\bar{t}$ invariant mass using the boosted selection in the $\mu +$ jets channel (left). The shaded areas indicate the total systematic uncertainties. Expected (dashed line) and observed (solid line) upper limits on the cross section times the branching fraction of Z' using the combined resolved and boosted selections (right). The dark (green) and light (yellow) bands show the range in which the limit is expected to lie in 68% and 95% of pseudo-experiments, respectively, and the smooth solid (red) lines correspond to the predicted cross section times branching fraction [13].

5. – Searches in the $t\bar{t}$ final state

Various models for new phenomena predict the existence of particles which decay primarily to top-quark pairs. It is therefore important to perform searches for resonant production in the $m_{t\bar{t}}$ spectrum. Such a search was carried using the 7 TeV dataset at ATLAS in the lepton + jets channel. High values of $m_{t\bar{t}}$ are probed; consequently, it is necessary to develop a dedicated selection for events where the top-quark decay products are merged into the same cone. For such events (labeled the "boosted" scenario), a single large jet ($D = 1.0$) is required, along with a narrow jets ($D = 0.4$). In the opposite scenario, where all decay products are well separated (labeled the "resolved" scenario), a standard requirement of 4 narrow jets is used instead (or 3 jets if one jet has a mass larger than 60 GeV). The mass of the $t\bar{t}$ system is calculated by solving for the event kinematics, assuming that the $E_{\mathrm{T}}^{\mathrm{miss}}$ originates purely from the one neutrino in the event, and by applying constraints on the masses of the reconstructed particles (t and W) in the event. The backgrounds are estimated using the same methods as described for the single-lepton measurements in sect. **2**. The full details of the analysis can be found in [13]. Figure 8 shows the $m_{t\bar{t}}$ for the boosted scenario, and the limits set on various models. A good agreement is found between the Standard Model predictions and the observed distribution. The dominant systematic uncertainties are driven by the jet energy scale uncertainty and the normalization of the $t\bar{t}$ signal. Such a measurement offers a great test-bench for boosted reconstruction techniques. As higher-energy regimes will be probed by future experiments, more measurements will contain final states which cannot be resolved using "traditional" techniques. Developing methods such as the one used for this measurement is therefore crucial for future investigations.

6. – Conclusions

The analyses summarized here have measured the various properties of the production of top-quarks with increasing precision. These measurements provide stringent tests of the Standard Model, and offer important constraints on the various models used in simulations. Also, many novel methods have been developed, and will be useful for future analyses.

REFERENCES

[1] The ATLAS Collaboration, *JINST*, **3** (2008) S08003.
[2] The ATLAS Collaboration, *Eur. Phys. J. C*, **73** (2013) 2328.
[3] The ATLAS Collaboration, ATLAS-CONF-2012-131.
[4] The ATLAS Collaboration, ATLAS-CONF-2012-155.
[5] The ATLAS Collaboration, *Eur. Phys. J. C*, **73** (2013) 2261.
[6] The ATLAS Collaboration, ATLAS-CONF-2012-149.
[7] The ATLAS Collaboration, ATLAS-CONF-2011-118.
[8] The ATLAS Collaboration, ATLAS-CONF-2011-104.
[9] The ATLAS Collaboration, ATLAS-CONF-2011-101.
[10] The ATLAS Collaboration, ATLAS-CONF-2012-056.
[11] The ATLAS Collaboration, ATLAS-CONF-2012-132.
[12] The ATLAS Collaboration, ATLAS-CONF-2012-057.
[13] The ATLAS Collaboration, ATLAS-CONF-2012-136.