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Top physics at ATLAS

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Summary. — This paper is an overview of recent results on top-quark physics obtained by the ATLAS Collaboration from the analysis of pp collisions at $\sqrt{s} = 7$ and 8 TeV at the Large Hadron Collider. Total and differential top-quark pair ($t\bar{t}$), single top and $t\bar{t} + \gamma$ cross-sections and top properties measurements are presented.

Introduction

The top quark is the heaviest quark, significantly heavier than its partner, the bottom quark. Once the bottom quark was experimentally discovered in 1977, the existence of a charge-2/3 quark in the third quark generation was expected to preserve the Standard Model (SM) renormalizability. The top quark was eventually discovered by both the CDF [1] and DØ [2] Collaborations in 1995 at the Tevatron collider.

The top quark is special not only due to its large mass, but also due to its short lifetime which prevents it from hadronizing before decaying, *i.e.* there are no bound state hadrons made of top quarks. This allows to experimentally test the properties of the bare top quark itself through its decay products without diluting information in the hadronization process.

As the properties of the top quark are precisely predicted by the SM, top quark physics provides a sensitive probe to test the validity of the SM and a tool to investigate the Higgs boson properties and to potentially discover physics beyond the SM.

This overview will describe some of the recent measurements of top-pair and single-top production cross section and of top-quark mass, covering only a selection of the top physics results achieved by the ATLAS Collaboration using data collected in 2011 (with an integrated luminosity $L = 4.6\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 7\,\mathrm{TeV}$) and in 2012 ($L = 20.3\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 8\,\mathrm{TeV}$). An updated and more complete list is available at the ATLAS public top result website(1). The ATLAS detector and its performance are described in [3].

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(1) `https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults`.

1. – Measurement of the inclusive cross section of top pair in the $e\mu$ channel

The inclusive cross section of the top quark pair production $\sigma_{t\bar{t}}$ has been measured in pp collisions at $\sqrt{s} = 7$ and 8 TeV in the final state with oppositely charged $e\mu$ pair [4]. The measurement was performed with the 7 TeV dataset taken in 2011 corresponding to an integrated luminosity of 4.6 fb^{-1}, and the 8 TeV dataset taken in 2012 of 20.3 fb^{-1}.

The numbers of events with exactly one and exactly two b-tagged jets were counted and used to simultaneously determine $\sigma_{t\bar{t}}$, and efficiency to tag a jet from a top quark decay as a b-quark jet. This method allows a significant reduction the associated systematic uncertainties. The cross section was measured in the total and fiducial (one electron and one muon with $p_T > 25$ GeV and $|\eta| < 2.5$) phase space.

The total cross sections at $\sqrt{s} = 7$ and 8 TeV are measured to be

$$\begin{aligned} \sigma_{t\bar{t}}^{total}(7\,\text{TeV}) &= 182.9 \pm 3.1 \pm 4.2 \pm 3.6 \pm 3.3\,\text{pb}, \\ \sigma_{t\bar{t}}^{total}(8\,\text{TeV}) &= 242.4 \pm 1.7 \pm 5.5 \pm 7.5 \pm 4.2\,\text{pb}, \end{aligned} \tag{1}$$

where four uncertainties arise from data statistics, systematic uncertainties, knowledge of the integrated luminosity and of the LHC beam energy. The results are consistent with the theoretical QCD calculations at the NNLO [5]:

$$\begin{aligned} \sigma_{t\bar{t}}^{th}(7\,\text{TeV}) &= 177.3 \pm 9.0^{+4.6}_{-6.0}\,\text{pb}, \\ \sigma_{t\bar{t}}^{th}(8\,\text{TeV}) &= 252.9 \pm 11.7^{+6.4}_{-8.6}\,\text{pb}, \end{aligned} \tag{2}$$

2. – Top pair differential cross-section measurements

Thanks to the large integrated luminosity, more detailed measurments like differential cross section as a function of $t\bar{t}$ system kinematic variables are possible.

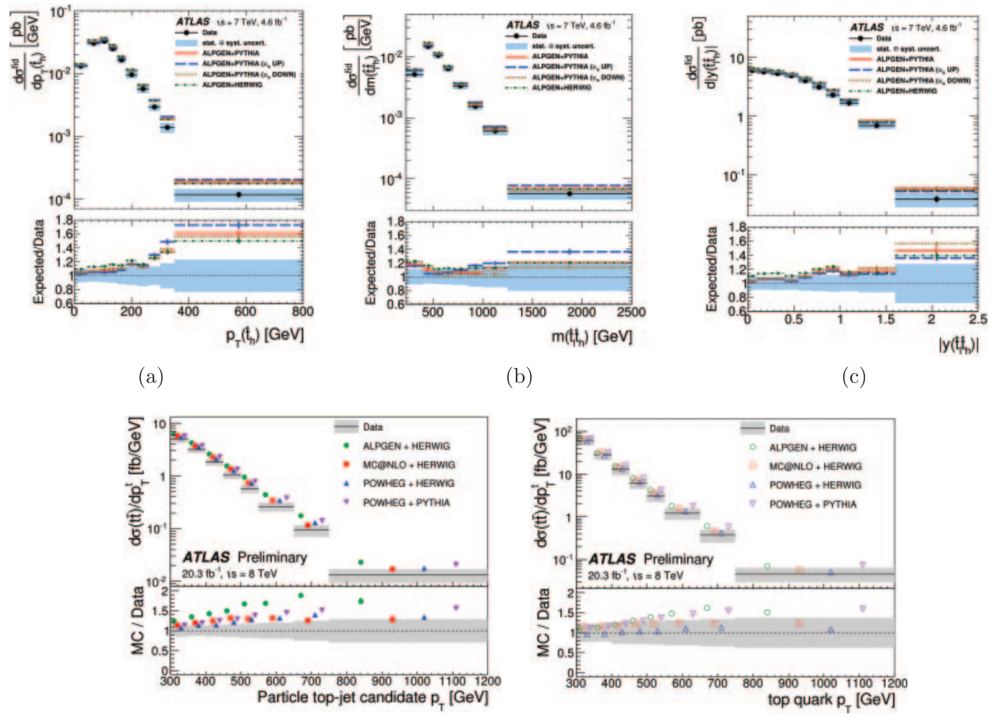
To reconstruct the kinematic of the $t\bar{t}$ events, two topologies are usually considered: *resolved* topology, for top quarks with low-p_T, where the top quark decay products are well isolated and can be reconstructed individually; *boosted* topology, for high-p_T top quarks, where the top decay products are not well isolated and can be reconstructed as a single large-R jet.

The ATLAS experiment has measured the $t\bar{t}$ fiducial differential cross-section $\frac{\mathrm{d}\sigma}{\mathrm{d}X}$ at 7 TeV as a function of the mass, transverse momentum, absolute rapidity of the system using the resolved approach [6] and $\frac{\mathrm{d}\sigma}{\mathrm{d}p_{T,t_{had}}}$ at 8 TeV, using the boosted approach [7].

Both analyses have been performed using a cut-based approach in the lepton+jets channel. Once the reconstructed kinematic distributions are extracted, the cross-section is calculated in the fiducial (and, only in the 8 TeV analysis, full) phase space at the parton level via unfolding methods. The measurements have been compared to NLO predictions from Monte Carlo generators. In general, all measurements show good agreement with the theory, as shown in fig. 1. Both analyses have observed a trend where the theory overestimates the data at high p_T.

3. – Cross section measurement for $t\bar{t}\gamma$ production at $\sqrt{s} = 7$ TeV

The cross section of top-quark pair production in association with a photon has been measured in collisions at a center-of-mass energy of $\sqrt{s} = 7$ TeV using the full 2011 ATLAS data sample [8].



(a) (b) (c)

(d) (e)

Fig. 1. – Top: differential $t\bar{t}$ cross-section at $\sqrt{s} = 7\,\text{TeV}$ as a function of the transverse momentum of the top (a) and mass (b) and rapidity (c) of the $t\bar{t}$ system using the resolved approach. Bottom: differential $t\bar{t}$ cross-section at $\sqrt{s} = 8\,\text{TeV}$ as a function of the transverse momentum of the top in the fiducial (d) and full (e) phase space obtained for highly boosted tops.

The analysis has performed on $t\bar{t}$ candidate events in the lepton plus jets final state. The $t\bar{t}\gamma$ candidates are the subset of $t\bar{t}$ candidate events with an additional photon. The track-isolation distribution of the photon candidates is used to discriminate between signal photons and neutral hadron decays to final states with photons and hadrons misidentified as photons.

The $t\bar{t}\gamma$ cross section, determined in a fiducial kinematic region within the ATLAS acceptance, is measured to be

$$\sigma^{fid}_{t\bar{t}\gamma} \times BR = 63 \pm 8(\text{stat.})^{+17}_{-13}(\text{syst.}) \pm 1(\text{lumi.})\,\text{fb}, \tag{3}$$

in good agreement with the NLO theoretical prediction $48 \pm 10\,\text{fb}$.

4. – Single top t-channel cross-section measurement at $\sqrt{s} = 8\,\text{TeV}$

At $\sqrt{s} = 8\,\text{TeV}$ the single-top quark production inclusive and fiducial cross-section has been measured in the t-channel production mechanism using the lepton+jets decay topology [9].

To separate t-channel single top-quark signal events from the expected background, several kinematic variables have been combined into one discriminant by employing a neural network (NN).

A binned maximum-likelihood fit to the NN output distribution is performed simultaneously for the two-jet and three-jet samples to extract the t-channel single top-quark cross section. The rates of the background processes have also been fitted within their uncertainties.

The fiducial cross section of t-channel single top-quark production is measured to be

$$\sigma_{f\ id} = 3.37 \pm 0.05(\mathrm{stat.}) \pm 0.47(\mathrm{syst.}) \pm 0.06(\mathrm{lumi.})\,\mathrm{pb},$$

which is in very good agreement with the SM predictions provided by LO and NLO generators.

Using various MC generator models, the fiducial cross-section can be extrapolated to the full phase space and can be compared to the NLO+NNLL calculation. Using aMC@NLO generator an extrapolated total inclusive cross-section of

$$\sigma_{tot} = 82.6 \pm 1.2(\mathrm{stat.}) \pm 11.4(\mathrm{syst.}) \pm 3.1(\mathrm{PDF}) \pm 2.3(\mathrm{lumi.})\,\mathrm{pb}$$

is obtained. The measured cross section is in good agreement with the prediction at next-to-leading order plus contribution due to the resummation of soft-gluon bremsstrahlung (NLO+NNLL) [10] $\sigma_{tot}^{NLO+NNLL} = 87.8^{+3.4}_{-1.9}\,\mathrm{pb}$.

5. – Top mass measurement in the single lepton and dilepton channels

The top quark mass, m_t, is a free parameter of the SM and must be determined experimentally. A precise determination of m_t is crucial since quantum loops including top quarks induce large corrections to theory predictions for many precision electroweak observables, including the mass of the Higgs boson.

The most precise measurement at the moment has been performed in the single lepton and dilepton channels with $4.7\,\mathrm{fb}^{-1}$ of data at $\sqrt{s} = 7\,\mathrm{TeV}$ [11]. This measurement has been performed using, for the first time in ATLAS, a 3-dimensional template technique which determines the top quark mass together with a global jet energy scale factor (JSF), and a relative b-jet to light-jet energy scale factor (bJSF), where light jets refers to u-, d-, c-, s-quark jets. Templates are built for three observables in the single lepton channel: m_t^{reco}, m_W^{reco} and R_{lb}^{reco} (the ratio between the transverse momentum of the b-tagged jet and the average transverse momentum of the two light jets from the hadronic W boson decay). In the dilepton channel templates are built for the m_{lb}^{reco} observable.

All templates are fitted with pre-determined probability density functions (PDFs) in an unbinned likelihood fit to all the events in the data.

The results of the fits for the single channel and dilepton channels are then combined using the BLUE method [12] giving the final result:

$$m_t = 172.99 \pm 0.48(\mathrm{stat.}) \pm 0.78(\mathrm{syst.})\,\mathrm{GeV}.$$

6. – $t\bar{t}$ charge asymmetry measurement at $\sqrt{s} = 7$ TeV

The top-antitop charge asymmetry

$$A_C^{t\bar{t}} = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}, \tag{4}$$

where $\Delta|y| = |y_t| - |y_{\bar{t}}|$, has been measured by ATLAS at $\sqrt{s} = 7$ TeV in the single lepton [13] and dilepton [14] channels. The measurement of $A_C^{t\bar{t}}$ is an important test of quantum chromodynamics (QCD) at high energies and is also an ideal place to observe effects of possible new physics processes beyond the Standard Model (BSM).

In the dilepton channel a lepton based asymmetry can be also defined:

$$A_C^{ll} = \frac{N(\Delta|\eta| > 0) - N(\Delta|\eta| < 0)}{N(\Delta|\eta| > 0) + N(\Delta|\eta| < 0)}, \tag{5}$$

where $\Delta|\eta| = |\eta_{l^+}| - |\eta_{l^-}|$. The expected value of A_C^{ll} is smaller than $A_C^{t\bar{t}}$, since the directions of the leptons do not fully follow the direction of the parent top quarks. However, A_C^{ll} can be measured more precisely, since it is determined without the need for a full reconstruction of $t\bar{t}$ kinematics.

Both asymmetries are evaluated without acceptance cuts at parton level from the reconstructed $\Delta|y|$ ($\Delta|\eta|$) distrubutions, corrected for the effects of detector resolution and efficiency.

The asymmetries are measured to be

$$\begin{aligned} A_C^{t\bar{t}} &= 0.024 \pm 0.015(\text{stat.}) \pm 0.009(\text{syst.}), \\ A_C^{ll} &= 0.021 \pm 0.025(\text{stat.}) \pm 0.017(\text{syst.}) \end{aligned} \tag{6}$$

and are in agreement with the Standard Model predictions computed at NLO in QCD and including electroweak corrections (NLO QCD+EW) [15]

$$\begin{aligned} A_C^{t\bar{t}} &= 0.0123 \pm 0.0005(\text{scale}), \\ A_C^{ll} &= 0.0070 \pm 0.0003(\text{scale}). \end{aligned} \tag{7}$$

7. – Spin correlation measurement at $\sqrt{s} = 8$ TeV

ATLAS has perfomed studies of the correlation of the spin of top and antitop quarks in $t\bar{t}$ events at $\sqrt{s} = 7$ [16] and 8 TeV [17]. The $t\bar{t}$ spin correlation can be defined as $A = \frac{N_{like} - N_{unlike}}{N_{like} + N_{unlike}}$, where N_{like} (N_{unlike}) is the number of events where the top quark and top antiquark spins are parallel (antiparallel) with respect to the spin quantization axis. The measurement of this parameter provides important precision tests of the predictions of the Standard Model and is sensitive to many new physics scenarios.

In the 8 TeV measurement, the quantization axis is chosen to be that of the helicity basis, using the direction of flight of the top quark in the center-of-mass frame of the $t\bar{t}$ system. The analysis has been performed by selecting events in the dilepton channel (ee, $\mu\mu$ and $e\mu$) and using the azimuthal angle $\Delta\phi$ between the charged leptons as the observable sensitive to the $t\bar{t}$ spin correlation.

A binned likelihood fit is used to extract the spin correlation from the $\Delta\phi$ distribution in data. This is done by defining a coefficient f_{SM} that measures the degree of spin correlation relative to the SM prediction.

The measured value of f_{SM} for the combined fit is

$$f_{SM} = 1.20 \pm 0.05(\text{stat.}) \pm 0.13(\text{syst.}). \tag{8}$$

This agrees with previous results from ATLAS using data at a center-of-mass energy of 7 TeV [16], in particular with the best previous measurement using $\Delta\phi$ of $f_{SM} = 1.19 \pm 0.09(\text{stat.}) \pm 0.18(\text{syst})$.

8. – Conclusions

The study of top quarks can answer fundamental questions on the SM. This quark is undoubtedly a peculiar particle, with a Yukawa coupling of the order of one and it is a powerful probe of physics beyond the SM. Its production mechanism in *pp* collisions is described very well by the SM, as well as its decay.

All the measurements shown in this paper are limited by systematic uncertainties. ATLAS is looking forward to refine the current measurements, as well as to produce new results using the latest data collected at $\sqrt{s} = 13$ TeV.

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