

# Review of recent top-quark LHC combinations

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**Abstract.** A review of recent combinations of top-quark measurements performed at the LHC, by the ATLAS and CMS collaborations, is provided. The typical uncertainty categorisations, and their assumed correlation patterns are presented, together with the results of the combinations of the top-quark pair and single top-quark production cross sections, the top-quark mass, as well as of the  $W$  boson polarisation and the charge asymmetry in  $t\bar{t}$  events.

## 1. Introduction

The TOPLHCWG [1], formed in 2011, constitutes a forum for the study of the experimental and theoretical uncertainties affecting the measurements of the top-quark properties at the LHC. The main objective of the working group consists in the combination of the results of the ATLAS and CMS collaborations and their presentation allowing clear theoretical interpretations. It is structured in several sub-groups to perform specific combination tasks and to conduct topical discussions involving analysts and experts from both collaborations. The scientific output of the working group consists of combinations of individual top-quark measurements and of various sets of recommendations aimed at refining and harmonising the statistical and systematic uncertainty treatment in current and future measurements. In this document a review of the recent LHC combination results of the top-quark properties will be presented. The combinations are performed using the Best Linear Unbiased Estimate (BLUE) method [2, 3]. BLUE determines the coefficients (weights) to be used in a linear combination of the input measurements by minimising the total uncertainty of the combined result. In the algorithm, assuming that individual measurements are unbiased and that all uncertainties are distributed according to Gaussian probability density functions, both statistical and systematic uncertainties, and their correlations, are taken into account. Input to all combinations are the individual results with a detailed breakdown of the uncertainties as well as the assumed correlations between individual sources. The tasks of each combination effort is to determine a mapping between corresponding uncertainties sources and to understand the correlations in each of the categories across different experiments.

## 2. Main systematic uncertainty categories

Due to the large top-quark samples available at the LHC, the precision of the measurements is typically limited by systematic uncertainties. As detailed in the following, these can be grouped into three main categories: theoretical, experimental and background or luminosity related uncertainties. In general all systematic uncertainties of measurements performed within the same experiment and during the same data taking period are considered fully correlated.

### 2.1. Theory based uncertainties

Theory based uncertainties are related to the simulation of top-quark signal events, to the event modelling and the description of the hard scattering environment. Choices to be made in the signal simulation are the proton distribution functions (PDF), the Monte Carlo generator (MC) and the hadronisation model. On the event modelling side, important ingredients are related to the description of the underlying event (UE), via MC tunes, and the settings adopted for the modelling of colour reconnection (CR), extra initial or final state QCD radiation (ISR/FSR) and the description of additional interactions accompanying the hard scatter (see Ref. [4] for further details). Despite some difference in the details of the systematic uncertainty evaluation, and the use of different baseline MC setups in ATLAS with respect to CMS, these uncertainty classes are typically assumed to be fully correlated between measurement from different experiments.

### 2.2. Experimental uncertainties

Experimental uncertainties stem from the modelling of the physics objects used in the analysis for the event reconstruction and from the description of the detector response. These are related to the identification, reconstruction and calibration of leptons, jets, and missing transverse energy,  $E_T^{\text{miss}}$ , in the selected events (see Ref. [5] for further details). The main contributions to the total uncertainty of the measurements typically originate from the jet energy scale (JES) and  $b$ -tagging related uncertainties.

The various sub-components of the JES systematic uncertainty are carefully mapped across experiments and their estimated correlation (range) stems from detailed discussions including experts and analysts from both the ATLAS and CMS collaborations. While some components are statistical or detector specific in nature, those stemming from modelling of the jet (flavour) response, are typically assumed to be correlated (fully or partially). The exact amount of correlations across corresponding JES uncertainty categories and their estimate variation range, useful when evaluating the stability of the combination results, are described in Ref. [6].

Similarly to the JES, although the algorithm implementations and the evaluation of the  $b$ -tagging uncertainties follows different approaches within ATLAS and CMS, a correlation pattern between corresponding uncertainty sources has been identified, flagging as correlated those uncertainty components stemming from general and method specific physics modelling effects (see Ref. [7] for more details).

Additional detector modelling uncertainties, including trigger efficiencies, uncertainties on the data to MC modelling of the lepton identification, reconstructions and energy scale, as well uncertainties stemming from the  $E_T^{\text{miss}}$  and pile-up effects are typically assumed to be uncorrelated between ATLAS and CMS (this applies also to the JES and  $b$ -tagging contributions when sub-dominant).

### 2.3. Background related and luminosity uncertainties

Uncertainties on the background normalisation and shape are in general analysis, kinematic selection, and final state dependent, but can in turn affect the measured top-quark properties. These uncertainties are classified into two main categories, based on their origin: MC-based or data-driven. The former is typically assumed to be fully correlated across measurements from different experiments. The latter category is taken as uncorrelated and applies for example to the data-driven estimate of the contribution of the fake leptons to the signal and to the normalisation of the  $W$ +jets background component.

Finally, the uncertainties stemming from the luminosity measurement are divided into correlated and uncorrelated parts. The correlated part originates from the common methodologies exploited in the Van der Meer scan analyses by both collaborations. On the other hand, the uncorrelated part includes experiment specific effects that could affect the estimated integrated luminosity of a given data sample (for example the beam conditions at the specific LHC interaction point, long term stability of the measurements, and the calibration of the detectors used for the luminosity measurements).

Overview (Sept. 2014)	$\sigma(tt)$ [pb]				$\sigma(t)$ 8 TeV [pb]			
	7 TeV		8 TeV		t – ch		tW	
value	173.3		241.4		85.3		25.0	
statistics (*)	2.8	(0.08) <sup>oo</sup>	1.4	(0.03) <sup>xo</sup>	4.1	(0.11) <sup>xo</sup>	1.5	(0.10) <sup>xo</sup>
MC model/ theory	4.9	(0.23) <sup>●●</sup>	4.1	(0.23) <sup>x*</sup>	7.7	(0.40) <sup>x*</sup>	4.0	(0.72) <sup>x*</sup>
Detector model (†)	4.6	(0.21) <sup>●o</sup>	2.7	(0.10) <sup>xo</sup>	5.5	(0.20) <sup>x*</sup>	1.2	(0.06) <sup>x*</sup>
JES/Jets (⊙)	2.1	(0.04) <sup>●o</sup>	1.7	(0.04) <sup>x*</sup>	4.5	(0.14) <sup>xo</sup>	1.3	(0.08) <sup>xo</sup>
Background	2.3	(0.05) <sup>**</sup>	2.3	(0.07) <sup>x*</sup>	3.2	(0.07) <sup>x*</sup>	0.6	(0.02) <sup>xo</sup>
Luminosity	6.3	(0.39) <sup>**</sup>	6.2	(0.53) <sup>x*</sup>	3.4	(0.08) <sup>x*</sup>	0.7	(0.02) <sup>x*</sup>
Total uncertainty	10.1		8.5		12.2		4.7	
Relative unc. / Comb. improv. [%]	5.8	10.6	3.5	9.6	14.3	10.6	18.8	14.3
Best single meas.	182.9 ± 6.3		242.4 ± 9.5		83.6 ± 7.8		27.2 ± 5.8	
Ref. (ATLAS, CMS)	arXiv 1406.5375		arXiv 1406.5375		JHEP 06 (2014) 090		ATL-CONF 2013-100	

Overview (Sept. 2014)	$m_{\text{top}}$ [GeV]		$W$ polarisation				$A_C$	
			$F_0$		$F_L$			
value	173.29		0.626		0.359		0.005	
statistics (*)	0.24	(0.06) <sup>oo</sup>	0.035	(0.35) <sup>oo</sup>	0.022	(0.38) <sup>oo</sup>	0.007	(0.61) <sup>xo</sup>
MC model/ theory	0.59	(0.38) <sup>●●</sup>	0.034	(0.33) <sup>**</sup>	0.019	(0.30) <sup>**</sup>	0.002	(0.07) <sup>x*</sup>
Detector model (†)	0.32	(0.12) <sup>●o</sup>	0.020	(0.11) <sup>●o</sup>	0.011	(0.11) <sup>●o</sup>	0.004	(0.21) <sup>xo</sup>
JES/Jets (⊙)	0.61	(0.42) <sup>**</sup>	0.020	(0.11) <sup>●o</sup>	0.012	(0.12) <sup>●o</sup>		
Background	0.09	(0.01) <sup>**</sup>	0.019	(0.10) <sup>●o</sup>	0.010	(0.09) <sup>●o</sup>	0.003	(0.11) <sup>x*</sup>
Luminosity								
Total uncertainty	0.95		0.059		0.035		0.009	
Relative unc. / Comb. improv. [%]	0.5	10.4	9.5	22.4	9.7	23.9	181	18.2
Best single meas.	172.22 ± 0.73		0.659 ± 0.027		0.350 ± 0.026		0.006 ± 0.011	
Ref. (ATLAS, CMS)	CMS-PAS-TOP 14-001		CMS-PAS-TOP 13-008		CMS-PAS-TOP 13-008		JHEP 1402 (2014) 107	

**Table 1.** Summary of the LHC combination results as of September 2014. For each combination, the combined result, the total uncertainty ( $\sigma_{\text{tot}}$ ) and its breakdown into different uncertainty classes ( $\sigma_i$ ) is provided [(\*) includes MC statistics and method calibration uncertainties. (†) when not available separately, this uncertainty class includes luminosity and JES systematic uncertainties. (⊙) when not available separately, this category includes the jet resolution and reconstruction systematics]. Values in brackets are defined as  $\sigma_i^2/\sigma_{\text{tot}}^2$ , and quantify the relative importance of each source of uncertainty with respect to the total. In addition, the relative precision of the combined result and the relative improvement with respect to the most precise input measurement are also provided. The last row in the table reports the most precise single measurement to date with the corresponding reference (the colour code indicates whether the measurements are from the ATLAS or CMS collaboration. The symbols o, \*, ● describes sources of uncertainties with are uncorrelated, partially correlated, or fully correlated respectively. Each pair of symbols stands for the correlation of measurements from the same experiment or across different experiments, respectively. For example ●o indicates a source of uncertainty which is fully correlated for measurements stemming from the same experiment, but that it is assumed to be uncorrelated between ATLAS and CMS (*e.g.* the detector modelling uncertainty). The symbol × is used when only one measurement per experiment is used in the combination. Cross section total uncertainties are quoted without the beam energy contribution.

### 3. LHC combination overview

Several LHC combinations of the top-quark production cross sections and top-quark properties have been performed in the last few years. These will be briefly described in the following subsections. An overview of all results is given in Table 1, together with some details on the total uncertainty breakdown, on the baseline correlation assumptions for different uncertainty sources (within and across experiments), as well as on the most precise single measurement available at the time of the TOP2014 conference.

### 3.1. Top-quark production cross sections

The combination of the top-quark production cross sections (denoted in the following as  $\sigma(t\bar{t})$  or  $\sigma(t)$ ) are performed using LHC data at different centre of mass energies ( $\sqrt{s} = 7, 8$  TeV), as well as exploiting different production mechanisms ( $t\bar{t}$  pair- and single top-quark production in the  $Wt$ - and  $t$ -channel).

The LHC combination of  $\sigma(t\bar{t})$  at 7 TeV [8] uses as inputs the individual ATLAS and CMS combinations, both featuring measurements from different  $t\bar{t}$  final states. The result  $\sigma(t\bar{t}|7 \text{ TeV}) = 173.3 \pm 10.1$  pb, achieves a relative precision of 5.8%, and it is dominated by uncertainties stemming from the luminosity measurements and MC modelling. The breakdown of the uncertainties of the combined result, according to statistics and systematic effects originating from the MC or detector modelling, JES and jet reconstruction, background modelling and the luminosity is listed in Table 1, together with the references and the results of the most precise single measurements available at the time of the TOP2014 conference. Although individual experiment results with improved precision are already available, the next combination effort is planned after the completion of the final LHC Run-I results in both collaborations. Using  $\sqrt{s} = 8$  TeV  $pp$  data, a combination of the  $\sigma(t\bar{t})$  has been performed using as inputs the ATLAS and CMS cross section measurements from the  $e\mu$  dilepton channel [9]. The result,  $\sigma(t\bar{t}|8 \text{ TeV}) = 241.4 \pm 8.5$  pb, corresponds to a relative uncertainty of 3.5%, and as in the case of the corresponding 7 TeV result, it is dominated by uncertainties on the luminosity measurement and on the MC modelling.

Measurement of the single top-quark production cross section at  $\sqrt{s} = 8$  TeV in the  $Wt$ - and  $t$ -channel are available and yielded the results:  $\sigma(t - ch|8 \text{ TeV}) = 85.3 \pm 12.2$  pb and  $\sigma(Wt|8 \text{ TeV}) = 25.0 \pm 4.7$  pb, respectively [10, 11]. The combined  $Wt$ -channel cross section results is used also to set a lower limit on the CKM matrix element  $V_{tb}$ :  $|V_{tb}| > 0.79$  at 95% CL. Both combined cross section results are dominated by systematic uncertainties originating for the MC modelling. The  $t$ -channel combination is based on partial data samples, corresponding to about one fourth of the available  $pp$  collision statistics at  $\sqrt{s} = 8$  TeV. The planned update of the combination will profit from newly available measurements with increased precision, as well as from the ongoing harmonisation efforts on the treatment of the MC generator uncertainties.

### 3.2. Top quark mass

Several combinations of the top-quark mass ( $m_{\text{top}}$ ) including LHC [12, 13] and Tevatron [14] results are available to date (see Refs. [14, 15] for more details about the  $m_{\text{top}}$  world combination).

Despite the availability of updated individual measurements, the LHC  $m_{\text{top}}$  combinations constituted important milestones for the subsequent combination of Tevatron and LHC results [14], and motivated several topical discussions and harmonisation efforts (partly still ongoing) within both collaborations. These are aimed at an improved treatment of the correlation between JES systematic sub-components [6], and at alleviating possible double counting effects between the JES and MC modelling systematics (in particular as far as uncertainties from the choice of the hadronisation models are concerned). The latest combined LHC  $m_{\text{top}}$  result ( $m_{\text{top}} = 173.29 \pm 0.95$  GeV) has a relative uncertainty of 0.5%, and features individual input measurements in different  $t\bar{t}$  final states, with total uncertainties ranging from 1.06 GeV to 1.63 GeV. The dominant contributors to the total uncertainty of the combined  $m_{\text{top}}$  results are the systematic uncertainties related to the JES, and those stemming from the MC modelling of the  $t\bar{t}$  signal.

### 3.3. $W$ polarisation and charge asymmetry

Combined results of the  $W$  polarisation and of the charge asymmetry in  $t\bar{t}$  events are available and described in Refs. [16] and [17], respectively. The  $W$  helicity fractions ( $F_0$ ,  $F_L$  and  $F_R$ ) from measurements in different  $t\bar{t}$  final states, are combined using a multi-parameter BLUE implementation in which the correlation between the  $F_L$  and  $F_R$ , are taken into account ( $F_R = 1 - F_L - F_0$ ). The results,  $F_0 = 0.626 \pm 0.059$  and  $F_L = 0.359 \pm 0.025$ , correspond to relative total uncertainties below 10%, and are affected similarly from the statistical uncertainties and from systematic uncertainties related to the

MC modelling. The combined  $W$  helicity fractions have been used to constrain anomalous couplings ( $g_R, g_L$ ) affecting the  $Wtb$  vertex in the framework of new physics models. As in the case of other LHC combinations described in this review, individual results with improved total uncertainties have recently become available and will be included in future combinations.

The combination of the charge asymmetry measurements from ATLAS and CMS features top-quark based asymmetry results from the  $t\bar{t}$  lepton plus jets final state, corrected for detector and acceptance effects. The input measurements as well as the combined result ( $A_C = 0.005 \pm 0.009$ ) are currently dominated by statistical uncertainties. Due to the large statistical components of the input measurements, the combination improvement amounts to about 20% for both top-quark properties measurements.

#### 4. Comments and Conclusions

In general, statistically limited measurements (*e.g.*  $W$  polarisation and charge asymmetry) are characterised by the largest gain in combination precision, and they are largely unaffected by variation of the assumptions on the systematic uncertainty correlations. On the other hand, systematics dominated measurements, (*e.g.*  $m_{\text{top}}$  and measurements of the  $t\bar{t}$  production cross section), typically present challenging combinations, and might be significantly affected by variations of the baseline correlation assumptions across the different uncertainty sources. At the same time, they offer a great opportunity to foster further harmonisation efforts and trigger refinement of the MC modelling uncertainties as well as of specific aspects of the MC simulations. In this context, they offer the largest gain in understanding the complementarity and differences between measurements and approaches adopted by different experiments.

The TOPLHCWG has been very successful in the past few years. Several results have been obtained and made public, including the combination of the production cross sections ( $t\bar{t}$  pairs and single top-quark production in the  $Wt$ - and  $t$ -channel),  $m_{\text{top}}$ ,  $W$  helicity and  $t\bar{t}$  charge asymmetry measurements. These have been accompanied by various sets of recommendations on specific systematic uncertainty splittings and their correlations between the ATLAS and CMS experiments.

New combinations efforts (*e.g.* including additional top-quark properties and differential cross section measurements) and updates of the presented combined results are ongoing and will further improve our knowledge of the top-quark physics sector in the coming years. These are expected to profit from the progress obtained in the categorisation of the JES and  $b$ -tagging systematics across experiments, as well as from the ongoing harmonisation efforts on the treatment and evaluation of the MC modelling systematic uncertainties.

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