# Combination of single top-quark cross-section measurements in the t channel at $\sqrt{s} = 8$ TeV with the ATLAS and CMS experiments

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A combination of measurements of the single top-quark production cross-section in the $t$ channel at $\sqrt{s} = 8$ TeV by the ATLAS and CMS experiments at the LHC is presented. The measurements from ATLAS and CMS are based on integrated luminosities of 5.8 fb$^{-1}$ and 5.0 fb$^{-1}$, respectively. The best linear unbiased estimator (BLUE) method is applied for the combination, taking into account the individual contributions to systematic uncertainties of the two experiments and their correlations. The combined single top-quark production cross-section in the $t$ channel is $\sigma_{t\text{-ch.}} = 85 \pm 4\,(\text{stat.}) \pm 11\,(\text{syst.}) \pm 3\,(\text{lumi.})\,\text{pb} = 85 \pm 12\,\text{pb}$, in agreement with the theoretical predictions.

## 1 Introduction

Single top-quark production in high-energy proton-proton (pp) collisions proceeds dominantly via the $t$ channel in the Standard Model (SM). The next-to-leading order (NLO) QCD prediction, obtained with MCFM [1], of the single top-quark production cross section in the $t$ channel at $\sqrt{s} = 8$ TeV for a top-quark mass of 172.5 GeV is:

$$\sigma^{\text{th}}_{t\text{-ch.}} = 85.8^{+2.6}_{-1.9}\,(\text{scale})^{+0.6}_{-0.7}\,(\text{PDF})\,, \qquad (1)$$

where the first uncertainty is due to the scale dependence and the second uncertainty is due to the parton distribution function (PDF) uncertainty. The approximate next-to-NLO (NNLO) QCD prediction [2] is compatible with the NLO QCD prediction within uncertainties:

$$\sigma^{\text{th}}_{t\text{-ch.}} = 87.2^{+2.1}_{-0.7}\,(\text{scale})^{+1.5}_{-1.7}\,(\text{PDF})\,. \qquad (2)$$

The ATLAS and CMS experiments measured the single top-quark $t$-channel production cross section in pp collisions at $\sqrt{s} = 8$ TeV. ATLAS performed a fit to the distribution of a neural-network discriminant constructed to separate signal from background. On a dataset collected in 2012 corresponding to 5.8 fb$^{-1}$, the following cross-section was measured [3]:

$$\sigma_{t\text{-ch.}} = 95.1 \pm 2.4\,(\text{stat.}) \pm 18.0\,(\text{syst.})\,\text{pb} = 95.1 \pm 18.1\,\text{pb}. \qquad (3)$$

CMS applied kinematic requirements to enhance the signal-to-background ratio and performed a fit to the distribution of the pseudorapidity of the light-quark jet to extract the signal yield.

Shapes for the dominant background processes, top-quark pair production ($t\bar{t}$) and the production of a W boson in association with jets (W+jets), as well as the rate of W+jets events, were determined from control samples in data. The measured cross-section from a data sample collected in 2012 corresponding to an integrated luminosity of 5.0 fb$^{-1}$ is [4] is:

$$\sigma_{t\text{-ch.}} = 80.1 \pm 5.7\,(\text{stat.}) \pm 11.0\,(\text{syst.}) \pm 4.0\,(\text{lumi.})\,\text{pb} = 80.1 \pm 13.0\,\text{pb}. \tag{4}$$

A sizable fraction of the systematic uncertainties are uncorrelated between the two experiments. Hence, a combination of both measurements allows a reduction of the total uncertainty. The combination of ATLAS and CMS measurements of single-top production in the $t$ channel [5] is presented in the following. The combination is performed using the best linear unbiased estimator (BLUE) method [6, 7]. In the present case, systematic uncertainties are known as relative uncertainties, instead of absolute ones. This deviation from the purely Gaussian assumption, underlying the original BLUE formulation, is known to cause a bias which can be significantly mitigated by applying the method iteratively: for each iteration the individual ATLAS and CMS systematic uncertainties (described in Section 2) are rescaled to the central value obtained from the BLUE combination and the procedure is repeated until the updated central value converges to a stable result. The method converges after just a few iterations. This approach was also adopted in Ref. [8] and [9].

## 2 Uncertainty categories

The sources of uncertainties determined by ATLAS and CMS are organized in various categories as shown in Table 1, together with the assumed values of correlations between the two experiments. The correlation estimates reflect the present understanding and the limitations due to the different choices made by the experiments when evaluating the individual uncertainty sources. The impact of the assumptions about correlation coefficients is evaluated by performing stability cross-checks described in Section 3.2, in which correlations are changed with respect to the values reported in Table 1. A more complete discussion about uncertainties and their treatment in ATLAS and CMS can be found in [5].

**Statistics:** Statistical uncertainties due to the size of the available data sample and from the limited size of the simulated samples are uncorrelated between ATLAS and CMS.

**Luminosity:** The uncertainty due to the determination of the integrated luminosity is separated into a luminosity-calibration contribution, correlated between ATLAS and CMS, and an uncertainty associated with the long-term stability of relative-luminosity measurements, that is entirely detector specific and therefore uncorrelated between the two experiments.

**Simulation and modeling:** Theoretical uncertainties affect the predicted signal and background rates and the modeling of simulated samples. In some cases, different approaches are adopted in ATLAS and CMS. In particular, ATLAS quotes an uncertainty due to the modeling of initial-state radiation (ISR) and final-state radiation (FSR), while CMS quotes an uncertainty due to the assumed factorization and renormalization scale ($Q^2$). Those uncertainties, as well as the uncertainties due to PDF and $t$-channel generator, are assumed to be 100% correlated in the two experiments.

**Jets:** Uncertainties related to the jet energy scale (JES), jet resolution, and jet reconstruction efficiency could be potentially correlated, due to contributions from theory modeling uncertainties. The uncertainties are anyway assumed to be uncorrelated in the two experiments, and this assumption is varied in the stability studies.

**Background normalization:** Two sources of uncertainty affect the normalization of the different background components: normalization from theoretical predictions, which is assumed to be 100% correlated, and the extraction of rates and/or shape from data, which is uncorrelated between ATLAS and CMS.

**Detector modeling:** We consider all sources of uncertainties due to the modeling of detector effects to be uncorrelated, except for the b-tagging efficiency uncertainty for which theoretical modeling uncertainties, although not dominant, are correlated. Since this uncertainty is sizable a conservative correlation factor of 50% is assumed. This value is varied in the stability studies.

Table 1: Categories of sources of uncertainties for the ATLAS and CMS measurements with assumed correlation factors ($\rho$). The relative cross-section uncertainty corresponding to each source of uncertainty is shown for both measurements. The total uncertainty, shown for each measurement, is the quadratic sum of all individual uncertainties.

| Category | ATLAS | | CMS | | $\rho$ |
|---|---|---|---|---|---|
| Statistics | Stat. data | 2.4% | Stat. data | 7.1% | 0 |
| | Stat. sim. | 2.9% | Stat. sim. | 2.2% | 0 |
| Total | | **3.8%** | | **7.5%** | **0** |
| Luminosity | Calibration | 3.0% | Calibration | 4.1% | 1 |
| | Long-term stability | 2.0% | Long-term stability | 1.6% | 0 |
| Total | | **3.6%** | | **4.4%** | **0.78** |
| Simulation and modeling | ISR/FSR | 9.1% | $Q^2$ scale | 3.1% | 1 |
| | PDF | 2.8% | PDF | 4.6% | 1 |
| | t-ch. generator | 7.1% | t-ch. generator | 5.5% | 1 |
| | $t\bar{t}$ generator | 3.3% | | | 0 |
| | Parton shower/had. | 0.8% | | | 0 |
| Total | | **12.3%** | | **7.8%** | **0.83** |
| Jets | JES | 7.7% | JES | 6.8% | 0 |
| | Jet res. & reco. | 3.0% | Jet res. | 0.7% | 0 |
| Total | | **8.3%** | | **6.8%** | **0** |
| Backgrounds | Norm. to theory | 1.6% | Norm. to theory | 2.1% | 1 |
| | Multijet (data-driven) | 3.1% | Multijet (data-driven) | 0.9% | 0 |
| | | | W+jets, $t\bar{t}$ (data-driven) | 4.5% | 0 |
| Total | | **3.5%** | | **5.0%** | **0.19** |
| Detector modeling | b-tagging | 8.5% | b-tagging | 4.6% | 0.5 |
| | $E_T^{miss}$ | 2.3% | Unclustered $E_T^{miss}$ | 1.0% | 0 |
| | Jet Vertex fraction | 1.6% | | | 0 |
| | | | pile up | 0.5% | 0 |
| | lepton eff. | 4.1% | | | 0 |
| | | | $\mu$ trigger + reco. | 5.1% | 0 |
| | lepton res. | 2.2% | | | 0 |
| | lepton scale | 2.1% | | | 0 |
| Total | | **10.3%** | | **6.9%** | **0.27** |
| Total uncert. | | **19.2%** | | **16.0%** | **0.38** |

Table 2: Contribution of each uncertainty category to the combined cross-section uncertainty.

| Source | Uncertainty (pb) |
|---|---|
| Statistics | 4.1 |
| Luminosity | 3.4 |
| Simulation and modeling | 7.7 |
| Jets | 4.5 |
| Backgrounds | 3.2 |
| Detector modeling | 5.5 |
| Total systematics (excl. lumi) | 11.0 |
| Total systematics (incl. lumi) | 11.5 |
| Total uncertainty | 12.2 |

# 3 Result

## 3.1 Combined single top-quark cross section

The total covariance matrix, determined as the sum of all covariance matrices from the uncertainty categories reported in Table 1, is:

$$\mathbf{C} = \begin{pmatrix} 269 & 84 \\ 84 & 182 \end{pmatrix} \mathrm{pb}^2 \,, \tag{5}$$

which has an overall correlation of 0.38. The BLUE weights are determined to be 0.35 for ATLAS and 0.65 for CMS, and the combined result is:

$$\sigma_{t\text{-ch.}} = 85.3 \pm 12.2\,\mathrm{pb}\,. \tag{6}$$

The $\chi^2$ of the combination is 0.79, with one degree of freedom.

The contribution of each uncertainty category to the combined cross-section uncertainty is shown in Table 2. The combined result with separate uncertainty contributions from statistics, luminosity, and all other systematics uncertainties is:

$$\sigma_{t\text{-ch.}} = 85.3 \pm 4.1\,(\mathrm{stat.}) \pm 11.0\,(\mathrm{syst.}) \pm 3.4\,(\mathrm{lumi.})\,\mathrm{pb} = 85.3 \pm 12.2\,\mathrm{pb}. \tag{7}$$

The improvement on the relative uncertainty of the combined result (14.3%) is significant compared to the uncertainties on ATLAS (19.2%) and CMS (16.0%) measurements. The absolute uncertainty on the combined cross section is also slightly improved with respect to the smallest uncertainty on the individual measurements used in the combination.

## 3.2 Stability tests

The stability of the cross-section combination with respect to the assumed correlations between ATLAS and CMS uncertainties is tested by varying the correlation factors of the following uncertainties: the correlation factors of the uncertainties assumed to be fully correlated are varied, separately, from the default value of $\rho = 1.0$ to 0.5 or 0; the systematic uncertainties treated in this way are those for the luminosity calibration, ISR/FSR, $Q^2$ scale, PDF, $t$-channel generator, and backgrounds normalized to theory predictions; the correlation factor of the b-tagging uncertainty, assumed to be partially correlated, is varied from $\rho = 0.5$ to 0 or 1; the correlation factor of the JES uncertainty, assumed to be uncorrelated, is varied from $\rho = 0$ to 0.5 or 1, in order to see the impact of a possible residual correlation. Table 3 summarizes the result of these tests. For each source of uncertainty the correlation factor $\rho$ is varied from its default value to the tested values and the corresponding shifts (in pb) on the combined central value and on the measured uncertainty are reported.

These tests indicate that the result is stable with respect to the assumptions about the systematic uncertainty correlations, and that the combination yields an improvement with respect to the individual measurements. However, a better assessment of the systematic uncertainty correlations across experiments will be the aim of future measurements and combinations.

Table 3: Results of the stability tests performed on the correlation assumptions about the uncertainty categories. For each test the correlation factor $\rho$ is varied from its default value to a test value and the corresponding shifts on the combined central value and on the measured uncertainty are reported.

| Source | Default $\rho$ | Test $\rho$ | Shift: central value (pb) | Shift: uncertainty (pb) |
|---|---|---|---|---|
| Luminosity calibration | 1 | 0.5/0 | +0.1/+0.1 | -0.1/-0.2 |
| Simulation and modeling | 1 | 0.5/0 | +0.4/+0.7 | -0.5/-1.1 |
| JES | 0 | 0.5/1 | -0.4/-0.8 | +0.3/+0.6 |
| b-tagging | 0.5 | 0/1 | +0.2/-0.3 | -0.2/+0.2 |

# 4 Summary

The ATLAS and CMS measurements of single top-quark production cross sections in the $t$ channel are combined using the BLUE method. The combined cross section is determined to be:

$$\sigma_{t\text{-ch.}} = 85 \pm 4\,(\text{stat.}) \pm 11\,(\text{syst.}) \pm 3\,(\text{lumi.})\,\text{pb} = 85 \pm 12\,\text{pb}\,. \tag{8}$$

The result of the combination of ATLAS and CMS measurements is shown together with the individual ATLAS and CMS measurements and compared to theory predictions [1, 2] (see Section 1) in Fig. 1. The result is in agreement with both NLO and approximate NNLO predictions. The systematic uncertainty, dominated by theoretical uncertainties, is the largest contribution to the total uncertainty. The result was found to be stable with respect to the variation of the correlation assumptions of each of the uncertainty category considered.

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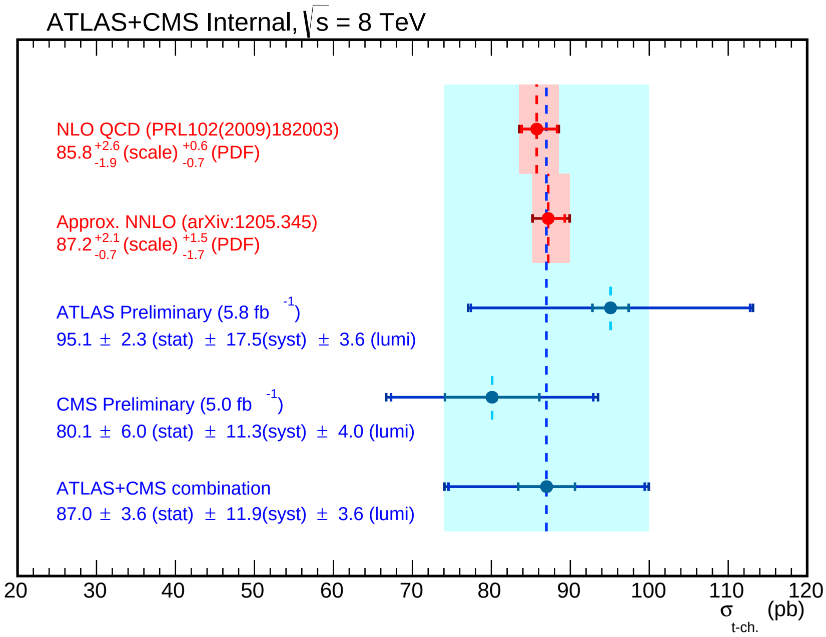


Figure 1: Single top-quark production cross-section measurements performed by ATLAS and CMS, and combined result (light-blue band), compared with SM predictions [1, 2] (pink bands). Statistical, systematic, and luminosity uncertainties are represented by blue error bars, ordered from the innermost to the outermost. For theoretical predictions the renormalization/factorization scale uncertainty and PDF uncertainty are represented by red error bars, ordered from the innermost to the outermost.


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