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Combination of ATLAS and CMS top-quark pair cross-section measurements using proton-proton collisions at $\sqrt{s} = 7$ TeV

The ATLAS and CMS Collaborations

Abstract

A combination of top-quark pair production cross-section ($\sigma_{t\bar{t}}$) measurements at a centre-of-mass energy of 7 TeV performed by the ATLAS and CMS experiments at the LHC is presented. The combination includes $\sigma_{t\bar{t}}$ measurements in the lepton+jets, dilepton, and all jets channels which use between 0.7 and 1.1 fb^{-1} of proton-proton collisions. The combined preliminary LHC measurement of the top-quark pair production cross-section is $\sigma_{t\bar{t}} = 173.3 \pm 2.3\ (\mathrm{stat.}) \pm 7.6\ (\mathrm{syst.}) \pm 6.3\ (\mathrm{lumi.})\ \mathrm{pb} = 173.3 \pm 10.1\ \mathrm{pb}$ for a top-quark mass of 172.5 GeV/c^2, corresponding to a total uncertainty of 5.8%. The result is in agreement with the standard model prediction.

1 Introduction

A precise measurement of the top-quark pair production cross-section, $\sigma_{\mathrm{t\bar{t}}}$, is one of the key milestones for the LHC physics programme. It allows for precise tests of the theoretical predictions based on perturbative quantum chromodynamics (QCD), which are now believed to be accurate to approximately 10% [1–5]. Various processes beyond the standard model (SM) may give rise to additional $\mathrm{t\bar{t}}$ production mechanisms that can affect the total production cross-section or change the $\sigma_{\mathrm{t\bar{t}}}$ measured in different top-quark decay channels. In addition, $\mathrm{t\bar{t}}$ production is an important background to the study of the properties of the Higgs boson and various searches for physics beyond the SM.

The $\mathrm{t\bar{t}}$ cross-section for pp collisions at a centre-of-mass energy of $\sqrt{s} = 7$ TeV calculated at approximate next-to-next-leading order (NNLO) in QCD with Hathor 1.2 [6] is $\sigma_{\mathrm{t\bar{t}}} = 167^{+17}_{-18}$ pb for a top-quark mass of 172.5 GeV. The calculation uses the MSTW2008 90% NNLO PDF sets [7]. The systematic uncertainties incorporate PDF+α_S uncertainties, according to the MSTW prescription [8], added in quadrature to the scale uncertainty obtained by independent variations of factorisation and renormalisation scales by the factors of 1/2 and 2.

Within the SM, top-quarks are predicted to decay to a W boson and a b quark with a branching ratio of nearly 100%, and the final-state topologies are determined by the decays of the W bosons [9]. The lepton+jets channel, with a branching ratio of 34.4%, and the di-lepton channel, with a branching ratio of 6.5%, where one or two W bosons decay to an electron or muon and a corresponding neutrino, give rise to final states with one or two leptons, missing transverse momentum, and jets, two of which originate from b quarks. These final states also include the small contributions from $\mathrm{W} \to \tau \to e$ and $\mathrm{W} \to \tau \to \mu$ decays. The all-jets channel, where both W bosons decay hadronically, occurs with a branching ratio of 45.7% and is characterised by a nominal six-jet topology, including two jets that originate from b quarks. Channels with hadronically decaying τ-leptons account for 13.4% of the branching ratio and are of special interest because the existence of a charged Higgs boson with a mass smaller than the top-quark mass could increase the fraction of $\mathrm{t\bar{t}}$ that decay into these channels.

This note presents a combination of measurements of the $\mathrm{t\bar{t}}$ production cross-section in pp collisions at a centre-of-mass energy of $\sqrt{s} = 7$ TeV by the ATLAS collaboration in the lepton+jets, di-lepton (ee, $\mu\mu$, eμ) and all-jets channels [10] and by the CMS collaboration in the lepton+jets, di-lepton (ee, $\mu\mu$, eμ), all-jets and muon plus hadronic τ ($\mu\tau_{had}$) channels [11].

2 Combination method

Both the ATLAS and CMS collaborations have performed internal combinations of their $\mathrm{t\bar{t}}$ cross-section measurements using techniques that involve the product of the individual likelihoods of the component analyses that enter the combination. This choice is motivated by the fact that the most precise measurements in the lepton+jets channel utilise the binned maximum likelihood fit to extract $\sigma_{\mathrm{t\bar{t}}}$ [12, 13] that includes many systematic uncertainties as nuisance parameters. This approach allows the systematic uncertainties included in the fit to be constrained in-situ, thereby increasing the precision of the measurement. However the treatment of the various sources of systematic uncertainty varied between the collaborations, making it very difficult to implement the likelihood approach in the combination of the ATLAS and CMS cross-section measurements. Instead, an alternative technique known as the Best Linear Unbiased Estimator (BLUE) method [14, 15] is used.

The BLUE method has been widely used to combine various observables at the Tevatron and

LHC such as the top-quark mass [16, 17] and the W helicity [18, 19]. Moreover, both the ATLAS and CMS collaborations used this method as a cross check for their internal $\mathrm{t\bar{t}}$ cross-section combinations and good agreement with the primary method has been found in both the central value and the overall estimated uncertainty.

The BLUE method determines a set of weights to be used in a weighted sum of the input measurements that minimises the total uncertainty on the combined result, taking into account statistical and systematic uncertainties and their correlations. The standard implementation of the BLUE method requires and returns symmetric uncertainties. Thus the asymmetric uncertainties of the input measurements were symmetrised by taking the average of the positive and negative variations. This has a negligible effect on the result.

The following sections describe the input measurements, and the assignment of systematic uncertainties to different categories to properly take into account their correlations.

3 Input measurements

The LHC combination of $\sigma_{\mathrm{t\bar{t}}}$ takes as input the combined $\mathrm{t\bar{t}}$ cross-section measurements from the ATLAS and the CMS collaborations.

3.1 The ATLAS measurements

The ATLAS combination of $\mathrm{t\bar{t}}$ production cross-section measurements includes the measurements in the di-lepton [20] and lepton+jets [12] channels using 0.70 fb^{-1} of data while the all-jets channel uses 1.02 fb^{-1} of data [21] collected in 2011.

The lepton+jets channel measurement is based on a multivariate discriminant distribution that is simultaneously fit to both e+jets and μ+jets final states, which are each divided into samples containing three, four or five or more jets. The multivariate discriminant is built from four kinematic variables and does not use b jet identification. The measurement in the di-lepton channel is a cut-based analysis, and $\sigma_{\mathrm{t\bar{t}}}$ is measured by event counting. No requirement on the presence of b jets is imposed. The all-jets channel measurement is based on a binned maximum-likelihood fit of the χ^2 from a kinematic fit assuming the $\mathrm{t\bar{t}}$ hypothesis. This analysis requires at least two jets identified as b jets. The measurement in the lepton plus hadronically-decaying τ channel performed by ATLAS was not used in the ATLAS $\sigma_{\mathrm{t\bar{t}}}$ combination because it has significant overlap with events used in the single-lepton measurement [22]. The combination yields $\sigma_{\mathrm{t\bar{t}}} = 177 \pm 3(\mathrm{stat.})^{+8}_{-7}(\mathrm{syst.}) \pm 7(\mathrm{lumi.})$ pb, corresponding to a total uncertainty of 6.2%.

3.2 The CMS measurements

The CMS combination of $\mathrm{t\bar{t}}$ production cross-section measurements includes four final states, three of which are common with the ATLAS combination. The measurement in the di-lepton [23] channel uses 1.14 fb^{-1} of data while the all-jets [24] and $\mu\tau_{had}$ [25] channels use 1.09 fb^{-1} of data collected in 2011.

The CMS single-lepton channel measurement [13] is based on 1.09 fb^{-1}(0.80 fb^{-1}) of data in the μ+jets (e+jets) channel and uses events with at least one jet identified as a b jet. The analysis divides the selected sample into subsamples with different numbers of jets and b tagged jets. The cross-section is extracted from a binned maximum likelihood fit to the secondary vertex mass distributions in the subsamples. The measurements in the di-lepton and $\mu\tau_{had}$ channels are cut-based analyses, and $\sigma_{\mathrm{t\bar{t}}}$ is measured by event counting. At least one jet is required to be b tagged. Since the event selection in the $\mu\tau_{had}$ channel was not designed to be orthogonal to the single-lepton channel, there is an overlap between these two channels. However, given a large uncertainty on $\sigma_{\mathrm{t\bar{t}}}$ measured in the $\mu\tau_{had}$ channel, this has a negligible effect on the combination. The measurement in the all-jets channel extracts $\sigma_{\mathrm{t\bar{t}}}$ via an unbinned maximum likelihood fit to the reconstructed top-quark mass in the sample, with at least two jets identified as b jets. The combination of the four channels yields $\sigma_{\mathrm{t\bar{t}}} = 165.8 \pm 2.2(\text{stat.}) \pm 10.6(\text{syst.}) \pm 7.8(\text{lumi.})$ pb, with a total uncertainty of 8.0%.

4 Classification of uncertainties

In this section we briefly describe the systematic uncertainties evaluated by the ATLAS and CMS measurements and their assignment to categories used for the combination. Whenever possible the same categories are used as in the LHC top-quark mass combination [17].

- **Detector model**: This class of uncertainty includes contributions due to uncertainties in the modelling of detector effects in the simulation. For ATLAS these include uncertainties in the electron, muon and jet identification efficiencies, electron energy scale and resolution, muon momentum scale and resolution, jet resolution, the calculation of the missing transverse momentum, trigger and in the b jet identification in the all-jets channel. For CMS, this class includes uncertainties in the modelling of efficiencies for lepton triggering, reconstruction and identification, in b tagging calibration and in the data-driven W+jets heavy flavour fractions determination which depends on it, in the trigger in the all-jets channel, in the hadronic τ decay modelling and in the effects of pileup. These uncertainties are taken as uncorrelated between the two collaborations.
- **Jet energy scale**: This class of uncertainty includes contributions due to the uncertainties in the modelling of the jet calibration in the simulation. For ATLAS it has several components, such as the uncertainties in the overall (η and p_{T} dependent) jet calibration, in the effects of pileup, in the underlying event model, and in the calibration of jets originating from b quarks. The measurements by CMS use the overall uncertainty in the jet energy calibration. This uncertainty is taken as uncorrelated between the two collaborations and the effect of this assumption on the combined $\sigma_{\mathrm{t\bar{t}}}$ has been studied and is discussed in Section 5.
- **Signal**: This class of uncertainty stems from the limitations of the $\mathrm{t\bar{t}}$ signal modelling and includes several components:
  - **Monte Carlo**: This sub-category includes uncertainties coming from the choice of the Monte Carlo (MC) generator for ATLAS. For CMS, it also includes the uncertainty related to the modelling of underlying event in the all-jets channel and uncertainties associated with modelling of τ decays in the $\mu\tau_{had}$ channel.
  - **Parton shower**: This sub-category includes uncertainties due to the parton shower model used by both ATLAS and CMS.
  - **Radiation**: This is the part of the modelling uncertainty due to the description of initial and final state radiation (ISR/FSR). The ATLAS measurements evaluate this uncertainty by varying related Pythia modelling parameters to increase or decrease the amount of ISR and FSR. The CMS measurements vary the factorisation and renormalisation scales used to generate $\mathrm{t\bar{t}}$ signal in Madgraph by a factor of two up and down.

  - **Parton distribution functions**: This sub-category includes the uncertainty related to the proton PDF.

  All uncertainties in this category are taken as fully correlated between the two collaborations and the effect of this assumption on the combined $\sigma_{t\bar{t}}$ has been studied and is discussed in Section 5.

- **Background from data**: This class of uncertainty includes the uncertainties in the modelling of the background determined from data. For the ATLAS measurements, these originate from uncertainties in the shapes of the QCD multijet background in the lepton+jets channel, in the normalisation and shapes of the multijet background in the all-jets channel, and in the normalisation and shapes of the fake background in the di-lepton channel. For the CMS measurements, this class includes uncertainties in the QCD multijet background in the lepton+jets channel, uncertainties in the fake background normalisation in di-lepton and $\mu\tau_{had}$ channels, uncertainties in the data-driven Z+jets background estimate in the di-lepton channel and total uncertainty in the multijet background in the all-jets channel. This uncertainty class is taken as uncorrelated between the two collaborations.
- **Background from Monte Carlo**: This class of uncertainty represents the uncertainty due to the modelling of the background sources determined from MC simulation. For both the ATLAS and CMS measurements, these originate from uncertainties in the normalisation and shapes of the W+jets background in the lepton+jets channel and from the theoretical uncertainties on the cross-sections used to normalise sub-dominant background processes evaluated from Monte Carlo simulation. The uncertainty related to the Z+jets background shape in the di-lepton channel is also included by ATLAS. This uncertainty class is taken as fully correlated between the two collaborations.
- **Method**: This class of uncertainty represents the uncertainties specific to the technique used to extract $\sigma_{t\bar{t}}$ and is uncorrelated between the collaborations. For ATLAS it stems from the limited number of events in the simulated samples used to derive templates in the lepton+jets channel and for the efficiency measurement in the di-lepton channel.
- **Luminosity**: This is the uncertainty originating from the uncertainty of the integrated luminosity determination. At the LHC the luminosity is calibrated based on dedicated van der Meer scans [26] and the associated uncertainty has a contribution from the bunch current uncertainty common for both the CMS and ATLAS experiments and from the individual experimental uncertainties in the luminosity measurement itself. The luminosity uncertainty on $\sigma_{t\bar{t}}$ is therefore expected to have a correlated and an uncorrelated component. Given that the luminosity uncertainty is the dominant source of uncertainty on both the ATLAS and CMS measurements of $\sigma_{t\bar{t}}$, accounting for 60% and 53% of the total uncertainty respectively, the proper modelling of the correlation is important. Simplified assumptions of no correlation or full correlation can change the combined cross-section from 172.9 pb to 173.6 pb and can increase the uncertainty by up to 1.1 pb.

  The estimate of the 2011 integrated luminosity and its uncertainty is periodically revised. For the dataset used in this combination the luminosity uncertainty due to bunch current uncertainty was determined to be 3.0% for the ATLAS detector and 3.1% for the CMS detector [27]. The full uncertainty on the luminosity is 3.7% for ATLAS and ranges from 4.5% to 6.0% for CMS depending on the analysis channel, and results in luminosity-induced uncertainties on the cross-section of 3.8% and

4.7% for ATLAS and CMS respectively. To account for the partial correlation of the luminosity-induced uncertainty on the cross-section, the latter uncertainties are divided into two components, *bunch current* and *luminosity measurement*, treated as fully correlated and uncorrelated between the experiments, respectively.

- W **leptonic branching ratio**: This is the uncertainty of 0.8% on the W-boson leptonic branching ratio [9]. This uncertainty is used by CMS but not by ATLAS. For the LHC combination the ATLAS measurement is modified to also include this uncertainty. The W-boson leptonic branching ratio is taken as a correlated systematic uncertainty.
- **Top-quark mass**: This uncertainty stems from the dependence of the acceptance on the top-quark mass. The CMS combined $\sigma_{\mathrm{t\bar{t}}}$ includes this source of uncertainty while the ATLAS measurements typically provide the dependence of the acceptance on the top-quark mass in an analytic form. However since this information is not available for all measurements included in the combination this source of uncertainty is removed from the CMS combined $\sigma_{\mathrm{t\bar{t}}}$ and the LHC measurement is quoted at a top-quark mass of 172.5 GeV.

5 Cross-checks

To check the stability of the combined $\sigma_{\mathrm{t\bar{t}}}$ result with respect to the assumed correlation between the ATLAS and CMS sources of uncertainty, the correlation coefficient was varied between 0 and 1 in steps of 0.2 for the "Jet energy scale" (JES) and two signal modelling contributions (i.e., "Monte Carlo" and "Radiation").

The JES uncertainty is expected to have a non-zero correlation between the collaborations given that the uncertainty includes a number of effects coming from MC modelling. On the other hand, the JES uncertainty represents only 24% of the total uncertainty for both CMS and ATLAS and the effect of the variation of the correlation is expected to be small. Indeed if the JES uncertainty is assumed to be fully correlated between the two collaborations $\sigma_{\mathrm{t\bar{t}}}$ increases by 0.1 pb and the total uncertainty increases by 0.2 pb. An assumption of 50% correlation does not change the result within rounding. In reality given that the JES calibration is performed by CMS and ATLAS following very different algorithms and the uncertainties are dominated by the detector calibration effects [28, 29] the correlated part of this uncertainty is significantly below 50%. Thus taking it as uncorrelated between the two collaborations has no effect on the combined $\sigma_{\mathrm{t\bar{t}}}$.

Since the approach to the evaluation of the signal modelling uncertainties varies significantly between the ATLAS and CMS measurements one might argue that these uncertainties should not be treated as 100% correlated. For example, the "Monte Carlo" uncertainty includes additional components for CMS, such as underlying event model and τ modelling effects. The "Radiation" uncertainty is evaluated using variations of the different parameters in different generators. However, the tests show that the assumption that all signal modelling uncertainties are fully correlated between the CMS and ATLAS measurements leads to a conservative estimate of the uncertainty on the combined $\sigma_{\mathrm{t\bar{t}}}$. For example, if the "Monte Carlo" uncertainty is treated as uncorrelated, the uncertainty goes down by 0.1 pb and $\sigma_{\mathrm{t\bar{t}}}$ changes by 0.1 pb as well. The variation of the assumed correlation for the "Radiation" uncertainty has an effect of similar size.

6 LHC combination

Table 1 summarizes the ATLAS and CMS measurements with the breakdown of the uncertainties and their correlations used as inputs to the LHC combination and the result of the combination. It is interesting to note that despite the fact that ATLAS and CMS have different approach to the evaluation of various components of the signal modelling uncertainty, which is reflected in the different partitioning amongst the different subcategories, the total signal modelling uncertainty is approximately the same between the two collaborations.

The combination yields $\sigma_{t\bar{t}} = 173.3 \pm 2.3(\text{stat.}) \pm 7.6\ (\text{syst.}) \pm 6.3\ (\text{lumi.})$ pb. The resulting weights for ATLAS (CMS) are 67% (33%) in the combined result. The two measurements are consistent with each other with a χ^2 p-value of 47%; the total correlation between the measurements is 30%. The variations of the correlations discussed in Section 5 change these values by not more than 1%. The combined $t\bar{t}$ production cross-section has an uncertainty of 5.8%, thus improving the precision of the $\sigma_{t\bar{t}}$ measurement with respect to the more precise ATLAS result by 7% relative. The uncertainty is currently dominated by the uncertainty on the luminosity determination, which contributes 6.3 pb to the total systematic uncertainty of 9.8 pb, followed by the detector and signal modelling.

	ATLAS	**CMS**	**Correlation**	**LHC combination**
Cross-section	177.0	165.8		173.3
Uncertainty				
Statistical	3.2	2.2	0	2.3
Jet Enegy Scale	2.7	3.5	0	2.1
Detector model	5.3	8.8	0	4.6
Signal model				
Monte Carlo	4.2	1.1	1	3.1
Parton shower	1.3	2.2	1	1.6
Radiation	0.8	4.1	1	1.9
PDF	1.9	4.1	1	2.6
Background from data	1.5	3.4	0	1.6
Background from MC	1.6	1.6	1	1.6
Method	2.4	n/e	0	1.6
W leptonic branching ratio	1.0	1.0	1	1.0
Luminosity				
Bunch current	5.3	5.1	1	5.3
Luminosity measurement	4.3	5.9	0	3.4
Total systematic	10.8	14.2		9.8
Total	11.3	14.4		10.1

Table 1: Table of uncertainties in the $t\bar{t}$ cross-section used in the BLUE combination. Cross-sections and uncertainties are in pb. Symbol "n/e" stands for "not evaluated".

Figure 1 shows a summary of the CMS and ATLAS measurements used as inputs to the LHC combination along with the internal ATLAS and CMS combinations and the LHC combined $\sigma_{t\bar{t}}$ compared to the theoretical calculation.

As a cross-check the combination was performed using the so-called Asymmetric Iterative BLUE (AIB) approach [31]. Unlike the BLUE implementation used to obtain the result presented above, AIB can take asymmetric uncertainties as input. It uses the starting combined value to calculate the uncertainties and will iterate until the starting value and the output are the same. This is important when combining measurements where the magnitude of the uncertainty depends on the measurement itself which is the case for the cross-section combination. The result obtained with AIB is $\sigma_{t\bar{t}} = 173.3 \pm 10.1$ pb, identical to the one obtained with the

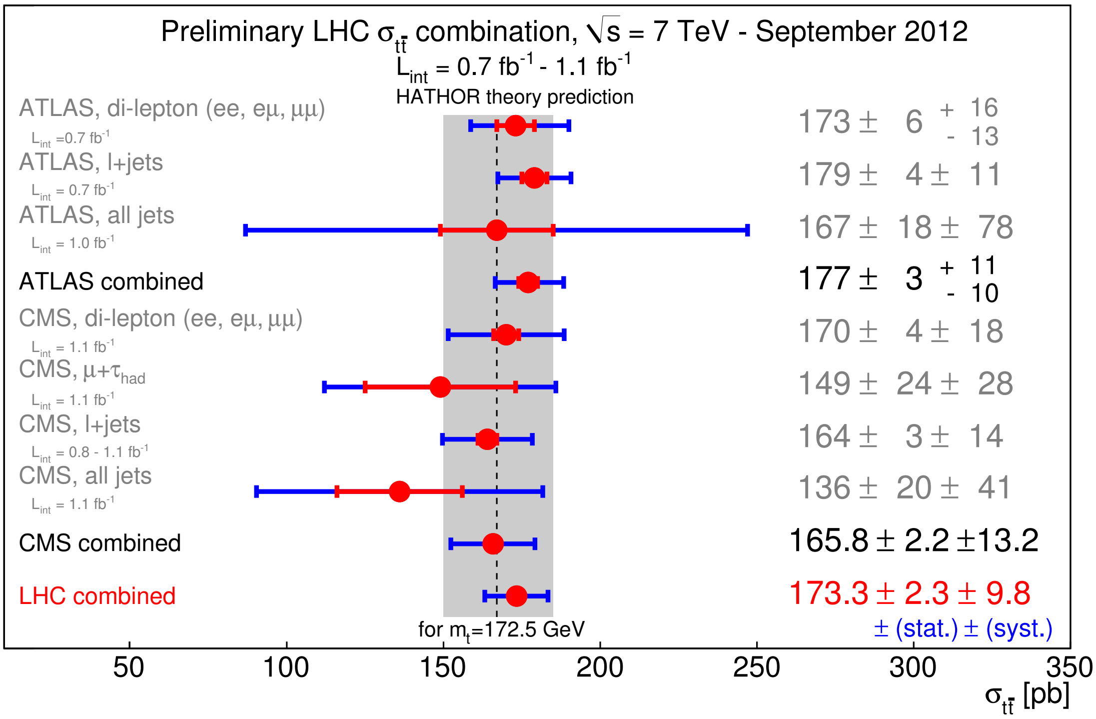

Figure 1: Input $\sigma_{t\bar{t}}$ measurements by the ATLAS and CMS collaborations and the result of the LHC combination. The band corresponds to the approximate NNLO in QCD calculation with Hathor 1.2 [6] of $\sigma_{t\bar{t}} = 167^{+17}_{-18}$ pb .

standard BLUE implementation within rounding. The weights of the measurements are also the same.

7 Conclusion and outlook

A combination of top-quark pair production cross-section measurements at a centre-of-mass energy of 7 TeV performed by the ATLAS and CMS collaborations at the LHC using a dataset of up to 1.1 fb^{-1} is presented. The combined preliminary LHC result is $\sigma_{\mathrm{t\bar{t}}} = 173.3 \pm 2.3\,(\mathrm{stat.}) \pm 7.6\,(\mathrm{syst.}) \pm 6.3\,(\mathrm{lumi.})\ \mathrm{pb} = 173.3 \pm 10.1$ pb for a top-quark mass of 172.5 GeV, corresponding to a total uncertainty of 5.8%. The result is in agreement with the standard model prediction of $\sigma_{\mathrm{t\bar{t}}} = 167^{+17}_{-18}$ pb.

The future measurements using all available data at $\sqrt{s} = 7$ TeV are expected to increase the precision on $\sigma_{\mathrm{t\bar{t}}}$ compared to the preliminary results presented here [30]. In particular, the uncertainty on the luminosity determination for the full 2011 dataset is smaller by almost a factor of two for both collaborations and the contribution of the correlated part of the uncertainty is negligible. The uncertainties related to the detector model that depend on the amount of data available for the calibration of objects will also be reduced. Thus the uncertainties on the $\mathrm{t\bar{t}}$ signal modelling and the precise knowledge of the correlations between its different components are expected to become a limiting factor for the future combinations. Therefore, as is also discussed in the first LHC top-quark mass combination note [17], a harmonisation of the methodologies used to assess the various sources of the signal modelling uncertainties between the two collaborations is critical, as well as a better understanding of these sources. This includes the use of common Monte Carlo samples and common procedures to evaluate the uncertainties. For the sources of uncertainty that depend both on the detector and the theory or modelling, in the future it would be beneficial to present the results separating these two components whenever possible.

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