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Combination of measurements of the top quark mass from data collected by the ATLAS and CMS experiments at $\sqrt{s} = 7$ and 8 TeV

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Abstract

A combination of fifteen top quark mass measurements performed by the ATLAS and CMS experiments at the LHC is presented. The data sets used correspond to an integrated luminosity of up to 5 and 20 fb^{-1} of proton-proton collisions at center-of-mass energies of 7 and 8 TeV, respectively. The combination includes measurements in top quark pair events that exploit both the semileptonic and hadronic decays of the top quark, and a measurement using events enriched in single top quark production via the electroweak *t*-channel. The combination accounts for the correlations between measurements and achieves an improvement in the total uncertainty of 31% relative to the most precise input measurement. The result is $m_{\mathrm{t}} = 172.52 \pm 0.14\,(\mathrm{stat}) \pm 0.30\,(\mathrm{syst})$ GeV, with a total uncertainty of 0.33 GeV.

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*See Appendices B and C for the lists of collaboration members

The mass of the top quark (m_{t}) is a fundamental parameter of the standard model (SM). Its precise measurement provides a crucial input to fits that probe the consistency of the SM [1–5]. The Tevatron experiments CDF and D0 were the first to measure m_{t} [6, 7], and produced a combined result in 2016 [8]. During the 2011–2012 data-taking period of the CERN LHC, proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV produced large numbers of top quarks in pairs via strong interactions or singly via electroweak processes. The two general-purpose experiments at the LHC, ATLAS [9] and CMS [10], performed multiple measurements of m_{t} using these data [11–24]. In this Letter, a combined m_{t} measurement from the ATLAS and CMS experiments is published for the first time. The 15 input measurements utilize up to 5 (20) fb^{-1} of integrated luminosity per experiment at 7 (8) TeV. A detailed estimate of the correlations between the ATLAS and CMS measurements is performed and the measurements are combined using the best linear unbiased estimate (BLUE) method [25, 26]. Not included in this combination are recent measurements of m_{t} performed with a partial 13 TeV data set [24, 27–33], for which the correlations have not yet been studied in detail. These measurements include new analysis techniques and the most precise measurement to date, made by CMS, with an uncertainty of 0.37 GeV [33].

The final state of events containing top quarks is determined by the decay of the W bosons produced in the top quark decays. In the top quark pair ($\mathrm{t\bar{t}}$) production mode, ATLAS and CMS have made measurements in the dilepton ($\mathrm{t\bar{t}} \to \ell^{+}\nu\mathrm{b}\ell^{-}\bar{\nu}\mathrm{\bar{b}}$), lepton+jets ($\mathrm{t\bar{t}} \to \ell^{\pm}\nu\mathrm{bq\bar{q}'\bar{b}}$), and all-jets ($\mathrm{t\bar{t}} \to \mathrm{q\bar{q}'bq\bar{q}'\bar{b}}$) channels. In addition, CMS has performed a measurement using single top quark ($\mathrm{t} \to \ell^{+}\nu\mathrm{b}$, $\mathrm{\bar{t}} \to \ell^{-}\bar{\nu}\mathrm{\bar{b}}$) events.

In the dilepton channel, ATLAS uses the average invariant mass of the two lepton and b-tagged jet pairs as the observable sensitive to m_{t} [15, 18], where a b-tagged jet is any reconstructed jet identified as being likely to originate from a b quark. At $\sqrt{s} = 7$ TeV, CMS uses a kinematic reconstruction with the analytical matrix weighting technique [12] and at $\sqrt{s} = 8$ TeV CMS performs a fit to two dedicated observables [22] to simultaneously extract m_{t} and the global jet energy scale (JES). In the lepton+jets channel [11, 15, 16, 23], both experiments perform a kinematic fit on an event-by-event basis to reconstruct the top quark mass and the invariant mass of the hadronically decaying W boson. The latter is used to constrain the global JES. In addition, ATLAS fits a scale factor for the relative JES between jets originating from b quarks (b quark jets) and light quark / gluon jets [15, 23]. For the all-jets channel, ATLAS uses the ratio of the reconstructed top quark mass to the reconstructed W boson mass [14, 20] to extract m_{t}, while CMS fits the reconstructed top quark mass [13] directly, and at 8 TeV exploits the larger data sample to constrain the global JES using the reconstructed W boson mass [16].

The CMS single top quark analysis fits the invariant mass of the lepton, neutrino, and b-tagged jet [21] to extract m_{t}. Two additional CMS measurements [17, 19] use observables built only from leptons and charged-particle tracks, resulting in m_{t} measurements with low sensitivity to the JES uncertainties. The J/ψ analysis uses the invariant mass of the lepton and the two muons from the J/ψ meson decay [19]. The secondary vertex analysis uses the invariant mass of the lepton and the charged particles from a displaced secondary vertex [17]. Both measurements use $\mathrm{t\bar{t}}$ events from the dilepton and lepton+jets decay modes.

All m_{t} measurements are calibrated using Monte Carlo (MC) simulation. Matrix element (ME) calculations are performed at fixed order in quantum chromodynamics (QCD) and interfaced to a parton shower (PS) algorithm that provides resummation of soft and collinear QCD radiation and a hadronization model that simulates the nonperturbative formation of hadrons. The POWHEG [34–36] generator at next-to-leading-order (NLO) in the strong coupling constant is interfaced with PYTHIA6 [37] to simulate $\mathrm{t\bar{t}}$ production in the ATLAS measurements. The CMS measurements use the MADGRAPH5 [38] generator, which includes leading-order (LO) terms for $\mathrm{t\bar{t}}$ production with up to three additional partons, also interfaced with PYTHIA6. The top quark mass is a renormalization-scheme-dependent parameter in perturbative quantum field theory. The precise identification of the m_{t} parameter in MC simulations within a field-theoretic mass scheme is the subject of theoretical studies [39–42].

The BLUE method defines the estimator $m_{\mathrm{t}} = \sum_i w^i m_{\mathrm{t}}^i$ for the input measurements m_{t}^i. The weights w^i are determined by minimizing the uncertainty in m_{t}, where the covariance between each pair of measurements is the crucial input. The individual analyses i are defined to be orthogonal, such that each measurement is statistically uncorrelated with every other measurement. The exception is the CMS secondary vertex analysis [17], which overlaps statistically with the dilepton and lepton+jets measurements [16, 22]. Given the different nature of the observable in the secondary vertex analysis, the analyses are assumed to be uncorrelated. Taking the maximal statistical correlation allowed by the overlap produces no significant impact on the combination.

The measurements are affected by similar systematic uncertainties, and the assessment of their correlation is central to the combination. As the treatment of systematic uncertainties differs between ATLAS and CMS, for each measurement they are mapped onto 25 categories that group together similar sources of uncertainties. Uncertainty categories can influence m_{t} in opposite directions for different measurements, as seen in the ATLAS combinations [15, 23], and this effect is included via negative correlations. The correlations between pairs of measurements from a single experiment for each category are evaluated by summing the covariance matrices of all the input uncertainty sources, mainly using the correlation assumptions discussed in Refs. [16, 23]. Differences relative to Refs. [16, 23] are discussed in Appendix A. Each input uncertainty source is included irrespective of whether it is statistically significant.

The correlation strength ρ between ATLAS and CMS for each uncertainty category is assessed based on the similarities of the underlying models and methods, and of the estimates used. Three different cases are identified, with corresponding assumed correlation strengths: $\rho = 0.85$ (strongly correlated), $\rho = 0.5$ (partially correlated), and $\rho = 0$ (uncorrelated). No category was identified to have $\rho = 1$, which reflects the many differences between the two experiments. The correlation coefficient between an ATLAS and CMS measurement for each category is the product of the respective correlation strength and the signs of the impacts of that category on each measurement. In this way, for a given pair of measurements, categories that impact m_{t} in the same (opposite) direction have a positive (negative) correlation. For categories composed of multiple uncertainty sources (e.g., b tagging in ATLAS), the sign of the combined impact is not determined. In this case, the sign of the combined impact is assumed to be positive and it was checked that taking the alternative assumption of a negative sign does not significantly impact the result, with the largest change in the central value (uncertainty) being 41 (7) MeV. In calculating the final covariance matrix, it is assumed that each category is uncorrelated to the others.

Table 1 displays the correlation strengths between ATLAS and CMS for each systematic uncertainty category, and Appendix A provides tables with the uncertainties for all 15 measurements. The corresponding correlation coefficients are available in HEPData [44, 45]. The subsequent paragraphs outline the categorization of systematic uncertainties and their corresponding correlation assessments.

The JES uncertainty is important in many m_{t} measurements. Six categories are used to describe the uncertainties associated with the calibration of the JES that are in common between the experiments [46–49]. The category JES 1 includes contributions from the limited size of the data samples used to derive the JES corrections and contributions due to pileup and its time-

Table 1: Correlation strengths ρ of the systematic uncertainty categories between ATLAS and CMS, as used in the combination. The categories are defined in the text. Categories indicated with the symbol — in the second column correspond to uncertainties specific to a single experiment. The third column shows the range of ρ scanned for stability checks. The changes in the combination's central value m_{t} and uncertainty $\sigma_{m_{\mathrm{t}}}$ corresponding to each correlation variation are shown in the last two columns.

Uncertainty category	ρ	Scan range	$\Delta m_{\mathrm{t}}/2$ [MeV]	$\Delta\sigma_{m_{\mathrm{t}}}/2$ [MeV]
JES 1	0	—	—	—
JES 2	0	$[-0.25, +0.25]$	8	7
JES 3	0.5	$[+0.25, +0.75]$	1	<1
b-JES	0.85	$[+0.5, +1]$	26	5
g-JES	0.85	$[+0.5, +1]$	2	<1
l-JES	0	$[-0.25, +0.25]$	1	<1
CMS JES 1	—	—	—	—
JER	0	$[-0.25, +0.25]$	5	1
Leptons	0	$[-0.25, +0.25]$	2	2
b tagging	0.5	$[+0.25, +0.75]$	1	1
$p_{\mathrm{T}}^{\mathrm{miss}}$	0	$[-0.25, +0.25]$	<1	<1
Pileup	0.85	$[+0.5, +1]$	2	<1
Trigger	0	$[-0.25, +0.25]$	<1	<1
ME generator	0.5	$[+0.25, +0.75]$	<1	4
QCD radiation	0.5	$[+0.25, +0.75]$	7	1
Hadronization	0.5	$[+0.25, +0.75]$	1	<1
CMS b hadron $\mathcal{B}$	—	—	—	—
Color reconnection	0.5	$[+0.25, +0.75]$	3	1
Underlying event	0.5	$[+0.25, +0.75]$	1	<1
PDF	0.85	$[+0.5, +1]$	1	<1
CMS top quark p_{T}	—	—	—	—
Background (data)	0	$[-0.25, +0.25]$	8	2
Background (MC)	0.85	$[+0.5, +1]$	2	<1
Method	0	—	—	—
Other	0	—	—	—

dependent variation. For ATLAS (7 TeV only), it also includes an uncertainty term from the effects of close-by jet activity. This category is uncorrelated between ATLAS and CMS measurements. The category JES 2 corresponds to the uncertainties from the absolute JES determined using γ/Z+jets events that are not included in JES 1. There are significant differences between the ATLAS and CMS approaches [46, 47], including differences in the jet radius, treatment of muons in jets, and methods to correct for additional radiation. Hence, this category is treated as uncorrelated. The category JES 3 corresponds to the modeling uncertainty in the relative η intercalibration [48, 49]. Both experiments use dijet events for this calibration, and the modeling uncertainty originates from the use of different generators to predict the radiation patterns in these events. As similar but not identical generators and techniques are used in both experiments, JES 3 is treated as partially correlated.

The remaining JES categories correspond to the flavor-dependent calibration uncertainties. The category b-JES corresponds to the jet energy response uncertainty for b quark jets. The category g-JES corresponds to the uncertainty in the jet response of gluon jets for CMS and the uncertainty in the difference of the jet response of gluons to light-quark (u, d, s, c) jets for ATLAS. In both cases, MC comparisons determine the flavor-dependent effects, hence a strong correlation is used for the b-JES and g-JES components. The category l-JES includes the combined CMS uncertainty in the jet response of light-quark jets and the ATLAS uncertainty for the flavor composition of jets in $\mathrm{t\bar{t}}$ events. As these uncertainty sources are different, the l-JES component is treated as uncorrelated. One additional flavor uncertainty category CMS JES 1 is included for the CMS 7 TeV measurements, corresponding to the full envelope of the response dependencies for gluons and all quark flavors.

The jet energy resolution (JER) uncertainty affects all measurements, and one category is used for the corresponding uncertainties. ATLAS and CMS both measure the JER using data [48, 49], hence this category is treated as uncorrelated.

The energy scale, efficiency, and resolution of leptons affect the m_{t} measurements, and one category is used for the corresponding uncertainties. ATLAS and CMS both calibrate the lepton energy scales, resolutions, and efficiencies using resonances that decay into dilepton pairs. Since the calibration samples are independent between the two experiments, and detector technologies and reconstruction algorithms are different, this category is treated as uncorrelated.

The selection criteria for many top quark measurements make use of b tagging. The uncertainty in the efficiency and rejection rate of these algorithms can impact the m_{t} measurements, and one category is used for the corresponding uncertainties. Both collaborations use dijet events to calibrate the b-tagging efficiency, employing equivalent methods [50, 51] that depend on similar simulation setups. As the ATLAS b jet calibration (unlike the CMS one) also uses $\mathrm{t\bar{t}}$ events [50], this category is assessed as partially, rather than strongly, correlated.

The missing transverse momentum ($p_{\mathrm{T}}^{\mathrm{miss}}$) is estimated in the two experiments with different algorithms. Thus, the uncertainty in the $p_{\mathrm{T}}^{\mathrm{miss}}$ scale originating from energy deposits not included in the reconstruction of jets or leptons is treated as uncorrelated.

The high instantaneous luminosity of the LHC results in multiple interactions in each bunch crossing (pileup). As the modeling of pileup relies on simulation, the correlation between ATLAS and CMS is assessed to be strong. While for other categories, the correlation strength is independent of the data set, the pileup category has zero correlation between analyses performed at 7 and 8 TeV due to the different pileup conditions in the two data sets.

The uncertainty in the efficiency of the triggers used to select events typically have a small impact on the measurements. As the triggers are calibrated in independent data sets, the uncertainty is treated as uncorrelated between ATLAS and CMS.

The m_{t} measurements rely on MC simulation of $\mathrm{t\bar{t}}$ events to relate the reconstructed observables to m_{t}. The corresponding modeling uncertainties are encompassed in seven uncertainty categories. The category ME generator includes uncertainties originating from the choice of the ME generator. ATLAS assesses this uncertainty by comparing the results obtained using an MC@NLO [52, 53] sample with the POWHEG sample. CMS assesses this uncertainty by comparing the results obtained using a POWHEG sample with the MADGRAPH sample. As the experiments employ different nominal MC models, the category is treated as partially correlated. The category QCD radiation includes uncertainty sources for the modeling of QCD radiation in $\mathrm{t\bar{t}}$ events. For the ATLAS measurements, samples with parameter variations of the initial- and final-state radiation in PYTHIA, and the h_{damp} parameter in POWHEG (which controls ME/PS matching and effectively regulates high-p_{T} QCD radiation) are used to evaluate these uncertainties. For the CMS measurements, samples with variations of the factorization, renormalization, and matching scales are used. Similarly to the ME category, the QCD radiation category is treated as partially correlated between the two experiments.

In the ATLAS analyses, the uncertainty originating from the hadronization model is evaluated by using an alternative PS and hadronization generator (POWHEG+HERWIG6 [54]). CMS addresses similar uncertainties by separately varying the b quark fragmentation function and the semileptonic branching ratios (CMS b hadron $\mathcal{B}$). As the ATLAS approach changes many aspects of the simulation that are not changed in the two CMS uncertainty sources and the PYTHIA settings in the two experiments are not the same, there is no clear mapping and correlation for these sources. Nevertheless, some degree of correlation is expected, hence the ATLAS hadronization uncertainty is grouped with the CMS uncertainty from the fragmentation model in the category hadronization and this category is assumed to be partially correlated between the experiments. The CMS b hadron $\mathcal{B}$ uncertainty source is treated as uncorrelated with the ATLAS uncertainties. It was verified that the alternative treatment of correlating the ATLAS hadronization uncertainty with the CMS b hadron $\mathcal{B}$ uncertainty had no significant impact on the result.

The uncertainties associated with color reconnection and the underlying event tunes are included in separate categories. The experiments use different PYTHIA settings for the nominal simulation, and these uncertainty categories are taken to be partially correlated. The uncertainty in the parton distribution functions (PDFs) is driven by the input data used in the PDF extractions, and hence this category is taken as strongly correlated between ATLAS and CMS. The CMS analyses account for an uncertainty in the modeling of the top quark p_{T} distribution, represented by a separate category, while for the ATLAS analyses, the alternative MC sample used to evaluate the hadronization uncertainty covers the disagreement between data and simulation [55], and no additional uncertainty is evaluated.

The analyses typically have small contributions from background processes, and background uncertainties have only a small impact on the measurements. Uncertainties in backgrounds estimated from data control samples are included in the category Background (data), treated as uncorrelated between the experiments. Both ATLAS and CMS rely on MC simulation for several backgrounds. The uncertainties in these are included in the category Background (MC), assumed to be strongly correlated.

Every analysis ensures that the m_{t} fit is unbiased. This is done using simulated samples generated with different m_{t} values. The limited sample size introduces a systematic uncertainty (Method) that is statistical and hence uncorrelated between measurements.

A few systematic uncertainties affect only a limited number of analyses (see Appendix A). These uncertainty sources are in the category Other, which is uncorrelated between ATLAS and CMS.

The measurements from each experiment are separately combined, with the ATLAS combination giving $m_{\mathrm{t}} = 172.71 \pm 0.25\,(\mathrm{stat}) \pm 0.41\,(\mathrm{syst})\,\mathrm{GeV}$ and the CMS combination giving $m_{\mathrm{t}} = 172.52 \pm 0.14\,(\mathrm{stat}) \pm 0.39\,(\mathrm{syst})\,\mathrm{GeV}$. The ATLAS combination is very similar to, and supersedes, the result in Ref. [23], with the slight difference originating from changes in the correlation assumptions that are discussed in Appendix A. The CMS measurement is improved compared to the previous combination [16] and supersedes that result. The improvement orig-

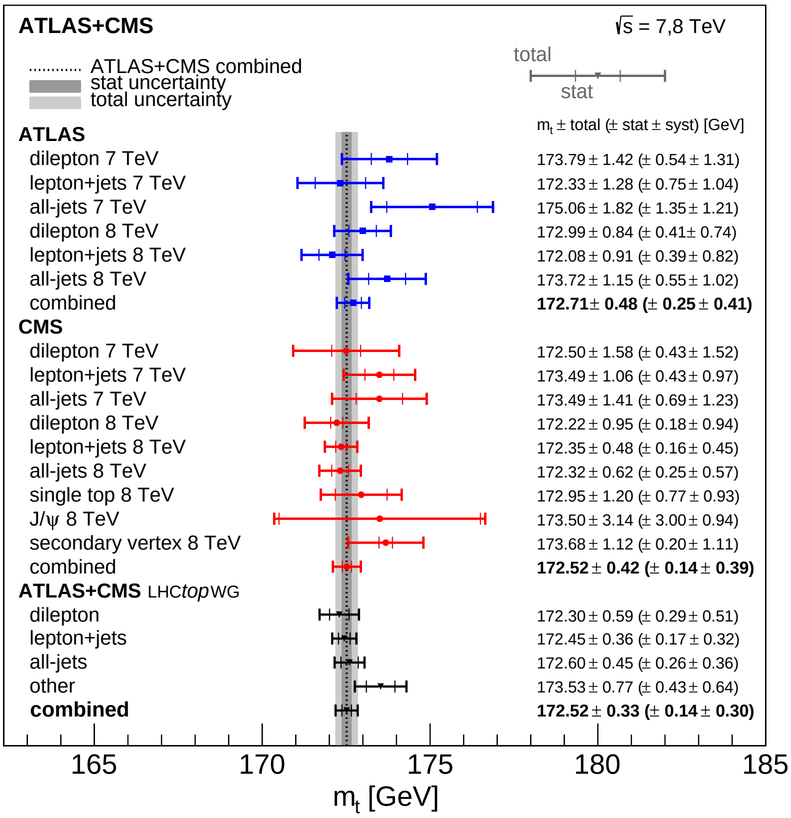

Figure 1: Comparison of the individual m_t measurements and the result of the m_t combination. Also shown are the separate combinations of each experiment and the result of the simultaneous combination for the different decay channels, where the "other" category covers the single top, J/ψ, and secondary vertex measurements.

inates from including a more precise dilepton measurement at 8 TeV together with the single top, secondary vertex, and J/ψ meson measurements, and from including the effect of anticorrelations of the systematic uncertainties between the input measurements. It was verified that performing the combinations with a likelihood-based approach [56] gives identical results.

The combination of all 15 input measurements gives

$$m_t = 172.52 \pm 0.14\,(\text{stat}) \pm 0.30\,(\text{syst})\,\text{GeV},$$

which is compared with the input measurements in Fig. 1. The LHC combination has the same statistical uncertainty as the CMS combination. This is because the figure of merit in BLUE is the total uncertainty, and the statistical component is a consequence of the optimized weights in the combination. The difference in statistical uncertainty between ATLAS and CMS reflects different analysis choices, as explained in Appendix A.

The combination achieves an improvement in the total m_t uncertainty of 31% relative to the most precise input measurement. The measurements with the largest weight in the combination are the CMS 8 TeV lepton+jets (0.34), dilepton (0.12), and all-jets (0.12) results, and the ATLAS 8 TeV lepton+jets (0.17) and dilepton (0.16) measurements. The hierarchy of the weights originates from the uncertainty of each measurement, as well as the correlation between measurements. For example, the ATLAS 8 TeV lepton+jets measurement has a higher weight than the corresponding dilepton measurement, despite having a larger uncertainty. This is because of the smaller correlation with the precise CMS 8 TeV lepton+jets measurement. The combination shows good compatibility between the measurements, with $\chi^2 = 7.5$ and a corresponding

Table 2: Uncertainties on the m_t values extracted in the LHC, ATLAS, and CMS combinations arising from the same categories as listed in Table 1, sorted in order of decreasing value of the combined LHC uncertainty.

Uncertainty category	Uncertainty impact [GeV]		
	LHC	ATLAS	CMS
b-JES	0.18	0.17	0.25
b tagging	0.09	0.16	0.03
ME generator	0.08	0.13	0.14
JES 1	0.08	0.18	0.06
JES 2	0.08	0.11	0.10
Method	0.07	0.06	0.09
CMS b hadron $\mathcal{B}$	0.07	—	0.12
QCD radiation	0.06	0.07	0.10
Leptons	0.05	0.08	0.07
JER	0.05	0.09	0.02
CMS top quark p_T	0.05	—	0.07
Background (data)	0.05	0.04	0.06
Color reconnection	0.04	0.08	0.03
Underlying event	0.04	0.03	0.05
g-JES	0.03	0.02	0.04
Background (MC)	0.03	0.07	0.01
Other	0.03	0.06	0.01
l-JES	0.03	0.01	0.05
CMS JES 1	0.03	—	0.04
Pileup	0.03	0.07	0.03
JES 3	0.02	0.07	0.01
Hadronization	0.02	0.01	0.01
p_T^{miss}	0.02	0.04	0.01
PDF	0.02	0.06	<0.01
Trigger	0.01	0.01	0.01
Total systematic	0.30	0.41	0.39
Statistical	0.14	0.25	0.14
Total	0.33	0.48	0.42

p-value of 91%. The LHC combination is much closer to the CMS combination than the ATLAS one because the relative weights of the measurements with slightly lower measured m_t are higher in the LHC combination than in the per-experiment combinations. All weights and the individual pulls can be found in Appendix A, along with a combination where all 15 measurements are used to extract separate m_t values for ATLAS and CMS.

Table 2 shows the breakdown of the systematic uncertainty in the combined measurement and the individual ATLAS and CMS combinations. The largest systematic uncertainties are seen to originate from JES, b tagging, and $t\bar{t}$ modeling. The stability of the measurement against the correlation assumptions is checked by varying the correlation strengths for each uncertainty category as shown in Table 1. The ranges reflect the extent of the understanding of the correlations. No variation is performed for categories where there is no ambiguity in the correlation assumption. Table 1 shows the variation in the total uncertainty and central value of the combination under those changes. Both the central value and uncertainty are observed to vary linearly under the variations and the changes are small ($<$30 MeV) compared to the uncertainty in m_{t}. The largest change in central value is seen for b-JES, which is the leading correlated uncertainty source in the combination.

The consistency of the result and the measurements from the different decay channels have been checked by performing the combination with a separate m_{t} parameter for each $\mathrm{t\bar{t}}$ decay channel. The results are also shown in Fig. 1, and the m_{t} values are found to be consistent.

The impact of the limited statistical precision of the estimates of the systematic uncertainties is evaluated by performing pseudo-experiments where the systematic uncertainties of the measurements are varied according to their uncertainties and the combination procedure is repeated. In this procedure, changes in the sign of the impacts of systematic uncertainties are propagated to the signs of the corresponding correlations. The root-mean-square of the measured m_{t} ($\sigma_{m_{\mathrm{t}}}$) is found to be 63 (19) MeV, demonstrating the stability of the combination.

The understanding of top quark production and decay has continued to evolve since the publication of the measurements used in this combination. Developments in the simulations include improved modeling of off-shell effects [57], reduced uncertainties in additional QCD radiation [58, 59], new models of color reconnection [60, 61], MC simulations at next-to-NLO precision in QCD [62], and investigations into the radiation patterns in the top quark decay [63]. Advancements in the modeling, which may either increase or decrease the mass uncertainty, and improvements in analysis techniques [29, 33] are being incorporated into analyses performed at $\sqrt{s} = 13$ TeV, but this is not possible for the analyses used in this combination. A cross-check, detailed in Appendix A, was performed to verify that potential modeling uncertainties in the recoil in the top quark decay [63] do not significantly affect the combination.

In summary, a combination of top quark mass measurements by the ATLAS and CMS experiments at the CERN LHC in proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV has been performed. The combination yields $m_{\mathrm{t}} = 172.52 \pm 0.33$ GeV, which is the most precise result to date.

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A Supplemental material

A.1 Changes to the ATLAS correlations

Two changes in the correlation model for the ATLAS combination are made compared to Ref. [23]. The b tagging algorithm and calibration is different for the 8 TeV all-jets analysis compared to the lepton+jets and dilepton measurements. This prevents a precise correlation assessment for this source. Reference [23] assumed a correlation of $+1$ for this source between the all-jets and lepton+jets/dilepton measurements, and this is modified to 0 for this combination to reflect the use of a different algorithm. The pileup uncertainties were assumed to be uncorrelated between all the analyses in Ref. [23]. For this combination, the pileup uncertainty correlation is assumed to be $+1$ between each analysis at the same energy, reflecting the fact each analysis shares common modeling of the pileup. Zero correlation is assumed between the 7 and 8 TeV data sets, reflecting the significant difference in the pileup conditions. These two changes move the ATLAS combined m_{t} measurement by 20 MeV and have no impact on the uncertainty at the quoted precision.

A.2 Further details on the CMS correlations

Several changes in the correlation model for the CMS combination are made compared to Ref. [16]. To be consistent with the correlation model used in the ATLAS combination, the signs of systematic effects are accounted for, leading to negative signs for some of the correlations between analyses. In the previous CMS combination [16] all correlation signs were assumed to be positive. Another change compared to Ref. [16] is that the jet flavor uncertainties are assumed to be uncorrelated to match the ATLAS treatment, while in the original published analyses they were treated as fully correlated. In the updated CMS combination, the effect of this change on the central mass value (uncertainty) is 1 (10) MeV. The tables in the HEPData record [45] show the detailed correlations used in the combination. Sources of uncertainty of a statistical nature or that are unique to a specific analysis are considered uncorrelated between measurements. These include Background (data), Trigger, Method, and Other. JES 1 is assumed uncorrelated between 7 and 8 TeV and correlated otherwise, as it is of statistical nature but is common to measurements at the same center-of-mass energy. Similarly, Pileup is uncorrelated between 7 and 8 TeV. All other sources of uncertainty are considered fully correlated between all measurements.

A.3 Uncertainties in the Other category

The following uncertainty sources are included in the Other category:

- The uncertainties in single top quark modeling that impact the CMS single top quark measurement.
- The uncertainty in the modeling of the J/ψ meson candidate mass distribution that affects the CMS J/ψ measurement.
- The uncertainty in b hadron composition that impacts the CMS secondary vertex measurement.
- Lepton reconstruction and identification uncertainties for the CMS 8 TeV dilepton measurement. The other CMS lepton+jets and dilepton measurements assume that these uncertainties are negligible.
- The uncertainties in the efficiency of jet reconstruction and the selections used to reject jets from pileup that affect ATLAS measurements.

- The uncertainty originating from using fast simulation [65] in the ATLAS 7 TeV all-jets measurement. All other measurements use full simulation.

A.4 Cross-check on modeling of the recoil in the top quark decay

The PS simulation used in PYTHIA has an ambiguity in the choice of recoil particle in the case of additional gluon radiation in the top quark decay [63]. As the shower includes matrix element corrections, this ambiguity does not affect the first gluon emission, but only the subsequent emissions. The effect described in Ref. [63] is expected to mostly change the fraction of out-of-cone radiation of b quark jets. In the PYTHIA6 simulations used in the measurements that enter the combination, only one recoil scheme is available. The PYTHIA8 generator [66] offers the possibility to change the recoil scheme. Studies using generator-level PYTHIA8 samples (generated at $\sqrt{s} = 13\,\text{TeV}$) show that changes in the reconstructed m_t seen when changing the recoil scheme from `RecoilToColoured=On` to recoil-to-top [32] correspond to a change in the b jet energy that is around 70% of the b-JES uncertainty. As a further cross-check, the combination was repeated by adding an additional uncertainty to each analysis equal to 70% of the b-JES uncertainty. The central value and uncertainty of the combination are observed to increase by 35 and 20 MeV respectively. These values are small compared to the total uncertainty, indicating that the result is robust against potential additional modeling uncertainties such as this.

A.5 Simultaneous ATLAS and CMS top quark mass combination

The compatibility of the ATLAS and CMS results is evaluated by performing a combination using all 15 input measurements with one m_t per experiment (m_t^ATLAS and m_t^CMS). This combination yields $m_\text{t}^\text{ATLAS} = 172.72 \pm 0.25\,\text{(stat)} \pm 0.39\,\text{(syst)}\,\text{GeV}$ and $m_\text{t}^\text{CMS} = 172.37 \pm 0.14\,\text{(stat)} \pm 0.38\,\text{(syst)}\,\text{GeV}$, with excellent agreement seen between the two experiments. The larger statistical uncertainty in the ATLAS combination reflects the larger statistical uncertainties in the ATLAS analyses compared to the CMS analyses in the same channels, which in turn reflect the different analysis methods and choices. For example, the ATLAS lepton+jets measurements [11, 15, 23] fit a relative b-to-light JES factor, effectively trading smaller systematic uncertainty for larger statistical uncertainty. This result of the simultaneous combination is displayed in Fig. A.1, which compares the results of this simultaneous combination with the expectation $m_\text{t}^\text{LHC} = m_\text{t}^\text{ATLAS} = m_\text{t}^\text{CMS}$, the result of the default LHC combination using all 15 input measurements with a single extracted m_t (filled circle), and the results of the individual experiment combinations (red and blue lines), where m_t^ATLAS and m_t^CMS are extracted from separate combinations to the 6 ATLAS and 9 CMS measurements, respectively. In the simultaneous combination of all 15 measurements, all measurements contribute to the two parameters m_t^ATLAS and m_t^CMS, i.e., $m_\text{t}^\text{ATLAS} = \sum_i w_i m_i + \sum_j \lambda_j m_j$, where m_i are the ATLAS measurements and m_j are the CMS measurements. The weights, shown in Table A.1, satisfy $\sum_i w_i = 1$ and $\sum_j \lambda_j = 0$, and the equivalent condition applies to the weights for m_t^CMS. The χ^2 of this simultaneous combination is 7.2 (13 degrees of freedom), demonstrating no significant improvement in χ^2 over the single parameter combination (7.5 for 14 degrees of freedom). This reflects the excellent agreement between the ATLAS and CMS measurements of m_t.

A.6 Numerical details of the combination

Tables A.2 and A.3 show the ATLAS and CMS measurements together with the breakdown of their respective uncertainties, while Table A.4 shows the pull and weight of each input measurement in the LHC combination, as obtained with the BLUE method. The BLUE method can

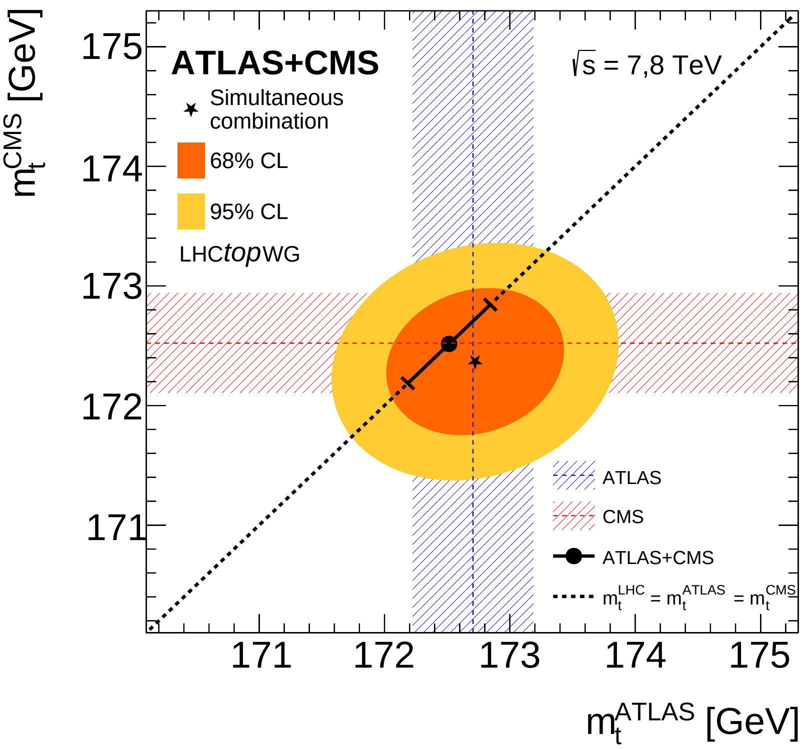


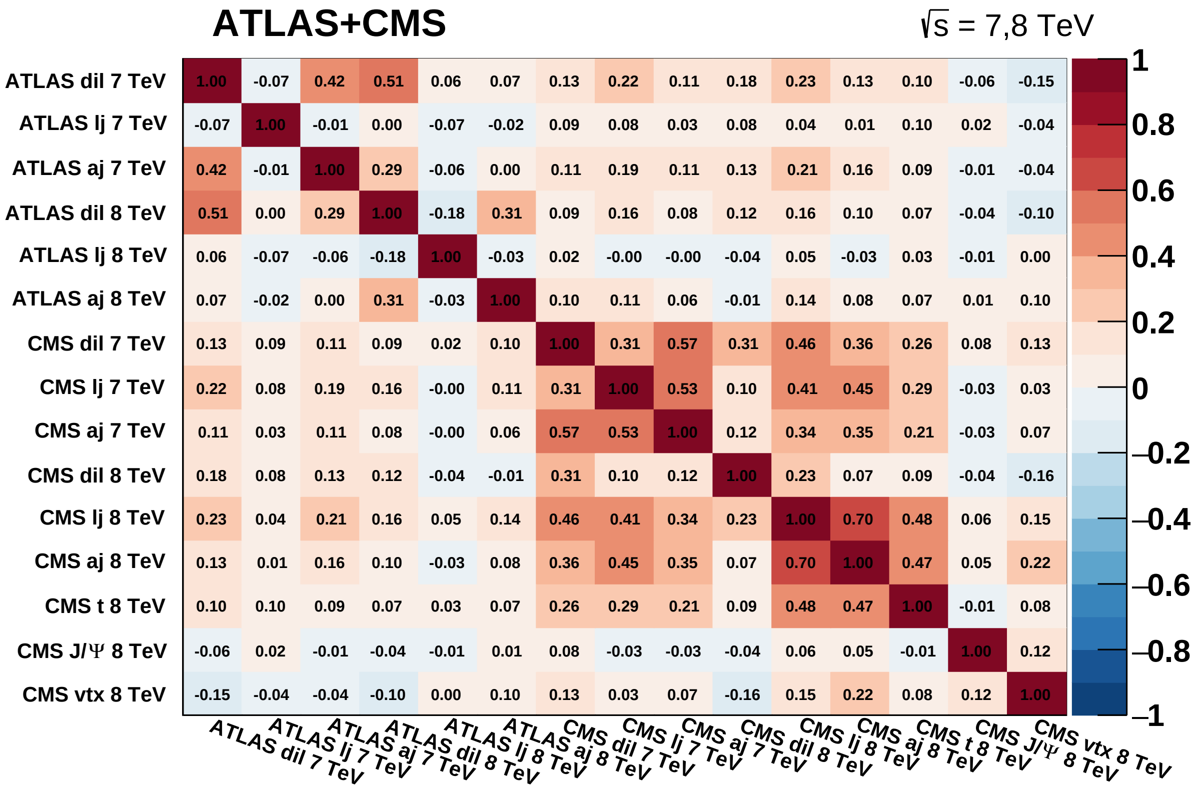
Figure A.1: The simultaneous extraction of the m_{t} measured by ATLAS ($m_{\mathrm{t}}^{\mathrm{ATLAS}}$) and CMS ($m_{\mathrm{t}}^{\mathrm{CMS}}$) from a BLUE combination of the 15 input measurements is shown by the star. The solid ellipses show the regions allowed at 68 and 95% confidence level (CL) by the combination and are in good agreement with the expectation $m_{\mathrm{t}}^{\mathrm{ATLAS}} = m_{\mathrm{t}}^{\mathrm{CMS}}$ (shown by the black dashed line). The observed correlation between $m_{\mathrm{t}}^{\mathrm{ATLAS}}$ and $m_{\mathrm{t}}^{\mathrm{CMS}}$ is 0.15. The dashed blue and red lines and hashed bands show the central values and 68% CL intervals for the individual ATLAS and CMS combinations, which use the 6 ATLAS and 9 CMS measurements, respectively. In addition, the central value of the LHC combination, $m_{\mathrm{t}}^{\mathrm{LHC}}$, which assumes $m_{\mathrm{t}}^{\mathrm{LHC}} = m_{\mathrm{t}}^{\mathrm{ATLAS}} = m_{\mathrm{t}}^{\mathrm{CMS}}$, is shown by the circular marker. The projection of the corresponding diagonal error bar on either axis represents the total uncertainty $m_{\mathrm{t}}^{\mathrm{LHC}}$.

Table A.1: BLUE weights of the simultaneous ATLAS and CMS combination for each input measurement. The input measurements are the ATLAS and CMS 7 and 8 TeV m_{t} measurements in the dilepton ("dil"), lepton+jets ("lj"), and all-jets ("aj") channels, and the CMS 8 TeV m_{t} measurements in the single top ("t"), secondary vertex ("vtx"), and J/ψ analysis ("J/ψ"). The sum of the ATLAS weights in the CMS combined value is zero, and vice versa. The individual weights, however, are different from zero due to the correlation between the different experiments. The weights are rounded to two decimal places; when the full precision is used, the weights for each of $m_{\mathrm{t}}^{\mathrm{ATLAS}}$ and $m_{\mathrm{t}}^{\mathrm{CMS}}$ sum to one.

	ATLAS						CMS								
	2011 (7 TeV)			2012 (8 TeV)			2011 (7 TeV)			2012 (8 TeV)					
	dil	lj	aj	dil	lj	aj	dil	lj	aj	dil	lj	aj	t	J/ψ	vtx
$m_{\mathrm{t}}^{\mathrm{ATLAS}}$	<0.01	$+0.16$	$+0.04$	$+0.33$	$+0.36$	$+0.11$	-0.05	-0.07	$+0.03$	$+0.03$	-0.11	$+0.14$	-0.03	$+0.01$	$+0.05$
$m_{\mathrm{t}}^{\mathrm{CMS}}$	-0.04	$+0.01$	-0.03	$+0.04$	$+0.04$	-0.02	-0.10	$+0.02$	$+0.04$	$+0.18$	$+0.67$	$+0.10$	-0.04	$+0.01$	$+0.11$

result in negative weights, as seen in Table A.4. This typically happens for measurements with a larger uncertainty than and high correlation to a more precise measurement [67]. Figure A.2 shows the correlation between each pair of measurements used in the LHC combination.

A simultaneous combination with one m_{t} parameter per each decay channel is performed to check the consistency of the result (Fig. 1 in the main document). Table A.5 shows the weights for this simultaneous combination. The "Other" channel includes the CMS single top, secondary vertex, and J/ψ analyses. The combined measurement for channel k is $m_t^k = \sum_i w_i m_i + \sum_j \lambda_j m_j$, where the sum over i includes all measurements of channel k and the sum over j includes all other measurements. The weights satisfy $\sum_i w_i = 1$ and $\sum_j \lambda_j = 0$. The correlations between the measurements result in nonzero values of the individual λ_j. The χ^2 of this simultaneous combination is 5.4 (11 degrees of freedom), corresponding to a p-value of 91%. The correlations between the m_{t} values extracted per channel are shown in Table A.6.



	ATLAS dil 7 TeV	ATLAS lj 7 TeV	ATLAS aj 7 TeV	ATLAS dil 8 TeV	ATLAS lj 8 TeV	ATLAS aj 8 TeV	CMS dil 7 TeV	CMS lj 7 TeV	CMS aj 7 TeV	CMS dil 8 TeV	CMS lj 8 TeV	CMS aj 8 TeV	CMS t 8 TeV	CMS J/Ψ 8 TeV	CMS vtx 8 TeV
ATLAS dil 7 TeV	1.00	-0.07	0.42	0.51	0.06	0.07	0.13	0.22	0.11	0.18	0.23	0.13	0.10	-0.06	-0.15
ATLAS lj 7 TeV	-0.07	1.00	-0.01	0.00	-0.07	-0.02	0.09	0.08	0.03	0.08	0.04	0.01	0.10	0.02	-0.04
ATLAS aj 7 TeV	0.42	-0.01	1.00	0.29	-0.06	0.00	0.11	0.19	0.11	0.13	0.21	0.16	0.09	-0.01	-0.04
ATLAS dil 8 TeV	0.51	0.00	0.29	1.00	-0.18	0.31	0.09	0.16	0.08	0.12	0.16	0.10	0.07	-0.04	-0.10
ATLAS lj 8 TeV	0.06	-0.07	-0.06	-0.18	1.00	-0.03	0.02	-0.00	-0.00	-0.04	0.05	-0.03	0.03	-0.01	0.00
ATLAS aj 8 TeV	0.07	-0.02	0.00	0.31	-0.03	1.00	0.10	0.11	0.06	-0.01	0.14	0.08	0.07	0.01	0.10
CMS dil 7 TeV	0.13	0.09	0.11	0.09	0.02	0.10	1.00	0.31	0.57	0.31	0.46	0.36	0.26	0.08	0.13
CMS lj 7 TeV	0.22	0.08	0.19	0.16	-0.00	0.11	0.31	1.00	0.53	0.10	0.41	0.45	0.29	-0.03	0.03
CMS aj 7 TeV	0.11	0.03	0.11	0.08	-0.00	0.06	0.57	0.53	1.00	0.12	0.34	0.35	0.21	-0.03	0.07
CMS dil 8 TeV	0.18	0.08	0.13	0.12	-0.04	-0.01	0.31	0.10	0.12	1.00	0.23	0.07	0.09	-0.04	-0.16
CMS lj 8 TeV	0.23	0.04	0.21	0.16	0.05	0.14	0.46	0.41	0.34	0.23	1.00	0.70	0.48	0.06	0.15
CMS aj 8 TeV	0.13	0.01	0.16	0.10	-0.03	0.08	0.36	0.45	0.35	0.07	0.70	1.00	0.47	0.05	0.22
CMS t 8 TeV	0.10	0.10	0.09	0.07	0.03	0.07	0.26	0.29	0.21	0.09	0.48	0.47	1.00	-0.01	0.08
CMS J/Ψ 8 TeV	-0.06	0.02	-0.01	-0.04	-0.01	0.01	0.08	-0.03	-0.03	-0.04	0.06	0.05	-0.01	1.00	0.12
CMS vtx 8 TeV	-0.15	-0.04	-0.04	-0.10	0.00	0.10	0.13	0.03	0.07	-0.16	0.15	0.22	0.08	0.12	1.00

Figure A.2: Correlation matrix for the ATLAS and CMS 7 and 8 TeV m_{t} measurements in the dilepton ("dil"), lepton+jets ("lj"), and all-jets ("aj") channels, and for the CMS 8 TeV m_{t} measurements in the single top ("t"), secondary vertex ("vtx"), and J/ψ analysis ("J/ψ").

Table A.2: Results and systematic uncertainties of the ATLAS m_t measurements, shown separately for the 7 and 8 TeV results in the dilepton ("dil"), lepton+jets ("lj"), and all-jets ("aj") channels, and for their combination ("comb."). All values are given in GeV.

	ATLAS						
	2011 (7 TeV)			2012 (8 TeV)			comb.
	dil	lj	aj	dil	lj	aj	
m_t	173.79	172.33	175.06	172.99	172.08	173.72	172.71
JES 1	0.54	0.33	0.38	0.35	0.28	0.40	0.18
JES 2	0.30	0.30	0.20	0.41	0.39	0.42	0.11
JES 3	0.43	0.07	0.24	0.08	0.05	0.12	0.07
b-JES	0.68	0.06	0.62	0.30	0.03	0.34	0.17
g-JES	0.03	0.28	0.10	0.02	0.21	0.05	0.02
l-JES	0.02	0.24	0.02	0.01	0.10	0.06	0.01
JER	0.19	0.22	0.01	0.09	0.20	0.10	0.09
Leptons	0.13	0.04	—	0.14	0.16	0.01	0.08
b tagging	0.07	0.50	0.16	0.04	0.38	0.10	0.16
p_T^{miss}	0.04	0.15	0.02	0.01	0.05	0.01	0.04
Pileup	0.01	0.02	0.02	0.05	0.15	0.01	0.07
Trigger	0.01	—	0.01	—	0.01	0.08	0.01
ME generator	0.26	0.22	0.30	0.09	0.16	0.18	0.13
QCD radiation	0.47	0.32	0.22	0.23	0.08	0.10	0.07
Hadronization	0.53	0.18	0.50	0.22	0.15	0.64	0.01
Color reconnection	0.14	0.11	0.22	0.03	0.19	0.12	0.08
Underlying event	0.05	0.15	0.08	0.10	0.08	0.12	0.03
PDF	0.10	0.25	0.09	0.05	0.09	0.09	0.06
Background (data)	0.04	0.11	0.35	0.07	0.05	0.17	0.04
Background (MC)	0.01	0.29	—	0.03	0.13	—	0.07
Method	0.09	0.11	0.42	0.05	0.13	0.11	0.06
Other	0.07	0.12	0.24	0.02	0.10	0.03	0.06
Total systematic	1.31	1.04	1.21	0.74	0.82	1.02	0.41
Statistical	0.54	0.75	1.35	0.41	0.39	0.55	0.25
Total	1.42	1.28	1.82	0.84	0.91	1.15	0.48

Table A.3: Results and systematic uncertainties of the CMS m_t measurements, shown separately for the 7 and 8 TeV results in the dilepton ("dil"), lepton+jets ("lj"), and all-jets ("aj") channels, for the 8 TeV results in the single top ("t"), secondary vertex ("vtx"), and J/ψ analysis ("J/ψ"), and for their combination ("comb."). All values are given in GeV.

	CMS									
	2011 (7 TeV)			2012 (8 TeV)						comb.
	dil	lj	aj	dil	lj	aj	t	J/ψ	vtx	
m_t	172.50	173.49	173.49	172.22	172.35	172.32	172.95	173.50	173.68	172.52
JES 1	0.77	0.24	0.69	0.31	0.10	0.16	0.40	<0.01	0.11	0.06
JES 2	0.54	0.02	0.35	0.17	0.12	0.19	0.21	<0.01	0.13	0.10
JES 3	0.06	0.01	0.08	0.03	0.01	0.02	0.05	<0.01	0.01	0.01
b-JES	0.70	0.61	0.49	0.37	0.32	0.29	0.38	—	—	0.25
g-JES	—	—	—	0.07	0.08	0.02	—	—	—	0.04
l-JES	—	—	—	0.04	0.06	0.01	0.07	—	—	0.05
CMS JES 1	0.58	0.11	0.58	—	—	—	—	—	—	0.04
JER	0.14	0.23	0.15	—	0.03	0.02	0.05	<0.01	0.05	0.02
Leptons	0.14	0.02	—	0.25	0.01	—	0.05	0.10	0.24	0.07
b tagging	0.09	0.12	0.06	0.01	0.06	0.02	0.10	—	0.02	0.03
p_T^{miss}	0.12	0.06	—	0.01	0.04	—	0.15	—	—	0.01
Pileup	0.11	0.07	0.06	0.05	0.06	0.06	0.14	0.07	0.05	0.03
Trigger	—	—	0.24	—	—	0.01	—	0.02	—	0.01
ME generator	0.04	0.02	0.19	0.07	0.12	0.16	—	0.37	0.42	0.14
QCD radiation	0.58	0.30	0.33	0.24	0.09	0.18	0.35	0.74	0.20	0.10
Hadronization	—	—	—	0.38	0.01	0.04	—	0.30	0.54	0.01
CMS b hadron $\mathcal{B}$	—	—	—	0.12	0.16	0.13	0.15	—	0.16	0.12
Color reconnection	0.13	0.54	0.15	0.13	0.01	0.16	0.05	0.12	0.08	0.03
Underlying event	0.05	0.15	0.20	0.11	0.08	0.14	0.20	0.13	—	0.05
PDF	0.09	0.07	0.06	0.17	0.04	0.03	0.11	0.11	0.04	<0.01
CMS top quark p_T	—	—	—	0.51	0.02	0.06	—	—	—	0.07
Background (data)	—	—	0.13	—	—	0.20	—	—	0.44	0.06
Background (MC)	0.05	0.13	—	—	0.03	—	0.17	0.01	—	0.01
Method	0.40	0.06	0.13	—	0.04	0.06	0.39	0.22	0.62	0.09
Other	—	—	—	0.03	—	—	0.25	0.09	0.09	0.01
Total systematic	1.52	0.97	1.23	0.94	0.45	0.57	0.93	0.94	1.11	0.39
Statistical	0.43	0.43	0.69	0.18	0.16	0.25	0.77	3.00	0.20	0.14
Total	1.58	1.06	1.41	0.95	0.48	0.62	1.20	3.14	1.12	0.42

Table A.4: Pulls and weights of each input measurement in the LHC combination. The input measurements are the ATLAS and CMS 7 and 8 TeV m_{t} measurements in the dilepton (“dil”), lepton+jets (“lj”), and all-jets (“aj”) channels, and the CMS 8 TeV m_{t} measurements in the single top (“t′), secondary vertex (“vtx”), and J/ψ analysis (“J/ψ”). The pull for measurement i is defined as $(m_i - m_c)/\sqrt{\sigma_i^2 - \sigma_c^2}$, where m_i (σ_i) is the central value (uncertainty) of the measurement and m_c (σ_c) is the central value (uncertainty) of the LHC combination. The weights are rounded to two decimal places; when the full precision is used, the weights sum to one.

	ATLAS						CMS								
	2011 (7 TeV)			2012 (8 TeV)			2011 (7 TeV)			2012 (8 TeV)					
	dil	lj	aj	dil	lj	aj	dil	lj	aj	dil	lj	aj	t	J/ψ	vtx
Pull	+0.93	−0.15	+1.43	+0.61	−0.51	+1.09	−0.01	+0.96	+0.71	−0.33	−0.47	−0.37	+0.38	+0.31	+1.08
Weight	−0.02	+0.07	+0.00	+0.16	+0.17	+0.03	−0.08	−0.01	+0.03	+0.12	+0.34	+0.12	−0.03	+0.01	+0.08

Table A.5: Weights for each input measurement for the simultaneous combination of the four different channels. The input measurements are the ATLAS and CMS 7 and 8 TeV m_{t} measurements in the dilepton (“dil”), lepton+jets (“lj”), and all-jets (“aj”) channels, and the CMS 8 TeV m_{t} measurements in the single top (“t”), secondary vertex (“vtx”), and J/ψ analysis (“J/ψ”). The CMS alternative measurements are assigned to the “Other” channel.

	ATLAS						CMS								
	2011 (7 TeV)			2012 (8 TeV)			2011 (7 TeV)			2012 (8 TeV)					
	dil	lj	aj	dil	lj	aj	dil	lj	aj	dil	lj	aj	t	J/ψ	vtx
ll	+0.02	+0.03	−0.07	+0.55	+0.18	−0.08	+0.10	−0.02	−0.07	+0.33	−0.19	+0.22	−0.08	<0.01	+0.08
lj	−0.04	+0.09	+0.01	+0.09	+0.18	+0.03	−0.10	+0.03	+0.03	+0.05	+0.71	−0.06	−0.06	+0.01	+0.06
aj	−0.03	+0.08	+0.05	+0.04	+0.17	+0.15	−0.13	−0.13	+0.13	+0.12	−0.12	+0.67	−0.05	+0.01	+0.04
Other	+0.02	+0.05	+0.03	+0.02	+0.12	+0.04	−0.18	−0.04	+0.10	+0.14	−0.12	−0.18	+0.46	+0.05	+0.49

Table A.6: Correlation matrix for the simultaneous combination of the dilepton (“dil”), lepton+jets (“lj”), all-jets (“aj”), and other (“Other”) channels.

	dil	lj	aj	Other
dil	1.00	0.29	0.24	<0.01
lj	0.29	1.00	0.59	0.31
aj	0.24	0.59	1.00	0.34
Other	<0.01	0.31	0.34	1.00

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