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

—Supplemental Material—

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Changes to the ATLAS correlations

Two changes in the correlation model for the ATLAS combination are made compared to Ref. [1]. 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 [1] 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. [1]. 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.

Further details on the CMS correlations

Several changes in the correlation model for the CMS combination are made compared to Ref. [2]. 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 [2] all correlation signs were assumed to be positive. Another change compared to Ref. [2] 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 [3] 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.

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 [4] in the ATLAS 7 TeV all-jets measurement. All other measurements use full simulation.

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 [5]. 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. [5] 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 [6] offers the possibility to change the recoil scheme. Studies using generator-level PYTHIA8 samples (generated at $\sqrt{s} = 13$ TeV) show that changes in the reconstructed m_t seen when changing the recoil scheme from `RecoilToColoured=On` to recoil-to-top [7] 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.

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 $m_t^{\mathrm{ATLAS}} = 172.72 \pm 0.25\,(\mathrm{stat}) \pm 0.39\,(\mathrm{syst})\,\mathrm{GeV}$ and $m_t^{\mathrm{CMS}} = 172.37 \pm 0.14\,(\mathrm{stat}) \pm 0.38\,(\mathrm{syst})\,\mathrm{GeV}$, 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 [1, 8, 9] 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. 1, which compares the results of this simultaneous combination with the expectation $m_t^{\mathrm{LHC}} = m_t^{\mathrm{ATLAS}} = m_t^{\mathrm{CMS}}$, 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., $m_t^{\mathrm{ATLAS}} = \sum_i w_i m_i + \sum_j \lambda_j m_j$, where m_i are the ATLAS measurements and m_j are the CMS measurements. The weights, shown in Table I, 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.

Numerical details of the combination

Tables II and III show the ATLAS and CMS measurements together with the breakdown of their respective uncertainties, while Table IV shows the pull and weight of each input measurement in the LHC combination, as obtained with the BLUE method. The BLUE method can result in negative weights, as seen in Table IV. This typically happens for measurements with a larger uncertainty than and high correlation to a more precise measurement [10]. Figure 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 V 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 VI.

[1] ATLAS Collaboration, Measurement of the top quark mass in the $t\bar{t} \to$ lepton+jets channel from $\sqrt{s} = 8\,\mathrm{TeV}$ ATLAS data and combination with previous results, Eur. Phys. J. C **79**, 290 (2019).

[2] CMS Collaboration, Measurement of the top quark mass using proton-proton data at $\sqrt{s} = 7$ and $8\,\mathrm{TeV}$, Phys. Rev. D **93**, 072004 (2016).

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[5] H. Brooks and P. Skands, Coherent showers in decays of colored resonances, Phys. Rev. D **100**, 076006 (2019).

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[7] ATLAS Collaboration, Measurement of the top-quark mass using a leptonic invariant mass in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ with the ATLAS detector, J. High Energy Phys. **2023** (06), 019.

[8] ATLAS Collaboration, Measurement of the top quark mass in the $t\bar{t} \to$ lepton+jets and $t\bar{t} \to$ dilepton channels using $\sqrt{s} = 7\,\mathrm{TeV}$ ATLAS data, Eur. Phys. J. C **75**, 330 (2015).

[9] CMS Collaboration, Measurement of the top-quark mass in $t\bar{t}$ events with lepton+jets final states in pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$, J. High Energy Phys. **2012** (12), 105.

[10] R. Nisius, On the combination of correlated estimates of a physics observable, Eur. Phys. J. C **74**, 3004 (2014).

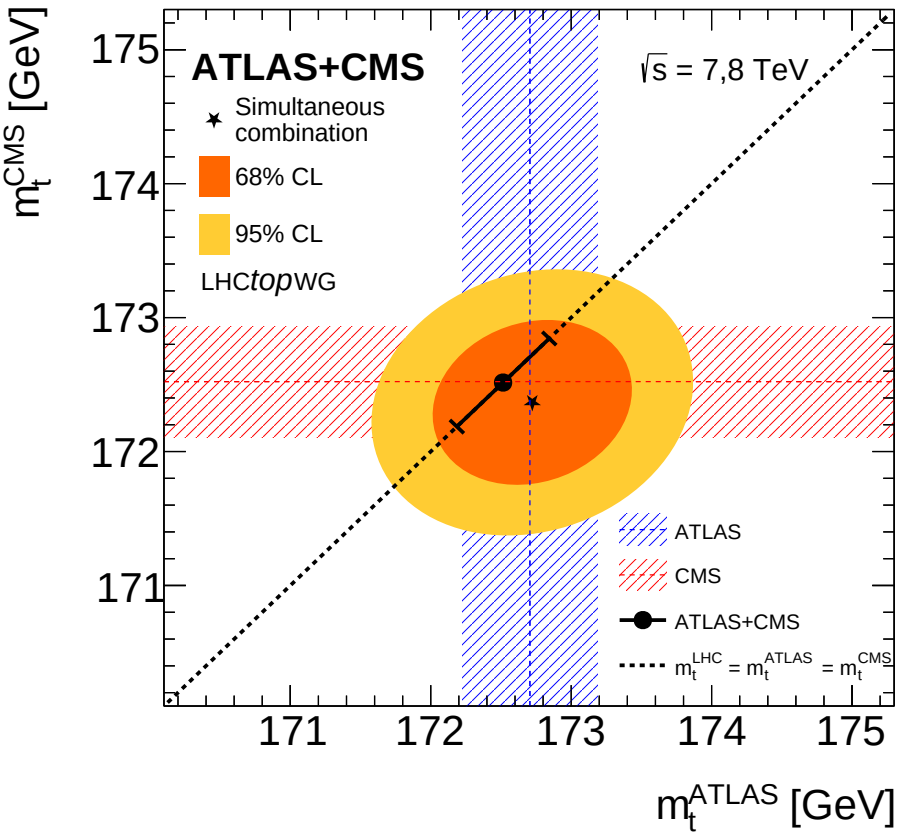

FIG. 1. The simultaneous extraction of the m_t measured by ATLAS (m_t^{ATLAS}) and CMS (m_t^{CMS}) from a BLUE combination of the 15 input measurements is shown by the star. The solid ellipses show the regions allowed at 68 and 95% confidence level (CL) by the combination and are in good agreement with the expectation $m_t^{\mathrm{ATLAS}} = m_t^{\mathrm{CMS}}$ (shown by the black dashed line). The observed correlation between m_t^{ATLAS} and m_t^{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_t^{LHC}, which assumes $m_t^{\mathrm{LHC}} = m_t^{\mathrm{ATLAS}} = m_t^{\mathrm{CMS}}$, is shown by the circular marker. The projection of the corresponding diagonal error bar on either axis represents the total uncertainty m_t^{LHC}.

TABLE I. 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_t^{ATLAS} and m_t^{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_t^{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_t^{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

TABLE II. 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
$p_{\mathrm{T}}^{\mathrm{miss}}$	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 III. 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
$p_{\mathrm{T}}^{\mathrm{miss}}$	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 IV. 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

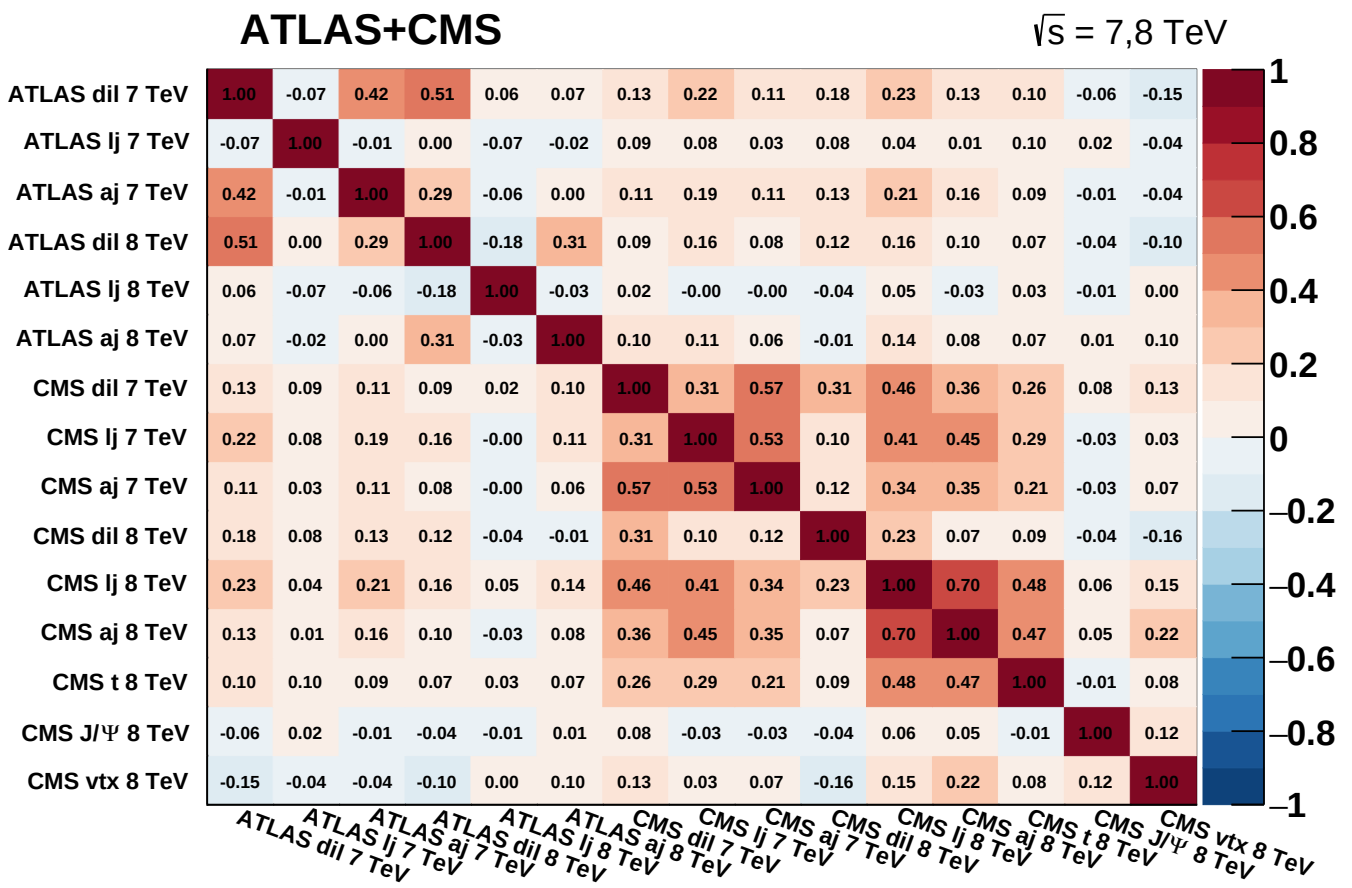

FIG. 2. Correlation matrix for the ATLAS and CMS 7 and 8 TeV m_t measurements in the dilepton ("dil"), lepton+jets ("lj"), and all-jets ("aj") channels, and for the CMS 8 TeV m_t measurements in the single top ("t"), secondary vertex ("vtx"), and J/ψ analysis ("J/ψ").

TABLE V. 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 VI. 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