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Combination of the W boson polarization measurements in top quark decays using ATLAS and CMS data at √s = 8 TeV

The ATLAS and CMS collaborations

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Combination of the W boson polarization measurements in top quark decays using ATLAS and CMS data at $\sqrt{s} = 8$ TeV

The ATLAS and CMS collaborations

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Abstract: The combination of measurements of the W boson polarization in top quark decays performed by the ATLAS and CMS collaborations is presented. The measurements are based on proton-proton collision data produced at the LHC at a centre-of-mass energy of 8 TeV, and corresponding to an integrated luminosity of about 20 fb^{-1} for each experiment. The measurements used events containing one lepton and having different jet multiplicities in the final state. The results are quoted as fractions of W bosons with longitudinal (F_0), left-handed (F_L), or right-handed (F_R) polarizations. The resulting combined measurements of the polarization fractions are $F_0 = 0.693 \pm 0.014$ and $F_\text{L} = 0.315 \pm 0.011$. The fraction F_R is calculated from the unitarity constraint to be $F_\text{R} = -0.008 \pm 0.007$. These results are in agreement with the standard model predictions at next-to-next-to-leading order in perturbative quantum chromodynamics and represent an improvement in precision of 25 (29)% for F_0 (F_L) with respect to the most precise single measurement. A limit on anomalous right-handed vector (V_R), and left- and right-handed tensor (g_L, g_R) tWb couplings is set while fixing all others to their standard model values. The allowed regions are $[-0.11, 0.16]$ for V_R, $[-0.08, 0.05]$ for g_L, and $[-0.04, 0.02]$ for g_R, at 95% confidence level. Limits on the corresponding Wilson coefficients are also derived.

Keywords: Hadron-Hadron scattering (experiments), Top physics

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1 Introduction

The large number of top quarks produced at the CERN LHC provides an excellent laboratory for the study of their production and decay properties. Precise predictions of some of these properties are available in the standard model (SM) of particle physics, and are tested through detailed comparisons to data. Potential deviations between data and predictions could reveal important information on the existence of new physics beyond the SM. The properties of the top quark decay vertex tWb are governed by the structure of the weak interaction. In the SM, this interaction has a $V - A$ structure, where V and A refer to the vector and axial-vector components of the weak current. This structure, along with the masses of the particles involved, determines the fractions of

W bosons with longitudinal (F_0), left-handed (F_L), and right-handed (F_R) polarizations, referred to as *polarization fractions*. Theoretical calculations at next-to-next-to-leading order (NNLO) in perturbative quantum chromodynamics (QCD) predict the fractions to be $F_0 = 0.687 \pm 0.005$, $F_L = 0.311 \pm 0.005$, and $F_R = 0.0017 \pm 0.0001$ [1], assuming a top quark mass of 172.8 ± 1.3 GeV. Thus, the SM predictions can be tested in high-precision measurements of the polarization fractions, and potential new physics processes that modify the structure of the tWb vertex can be probed.

Experimentally, polarization fractions can be measured in events containing top quarks, using the kinematic properties of its decay products.

For semileptonically decaying top quarks, i.e. $t \to W(\to \ell\nu)b$ (with lepton ℓ = electron, muon, or τ), the polarization angle θ^* is defined as the angle between the direction of the charged lepton and the reversed direction of the b quark, both in the rest frame of the W boson. The distribution of the variable $\cos\theta^*$ is particularly sensitive to the polarization fractions. The differential decay rate is given by

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{4}\left(1-\cos^2\theta^*\right) F_0 + \frac{3}{8}\left(1-\cos\theta^*\right)^2 F_L + \frac{3}{8}\left(1+\cos\theta^*\right)^2 F_R. \quad (1.1)$$

In a similar way, θ^* can be defined for the hadronically decaying top quarks, i.e. $t \to W(\to q'\bar{q})b$, by replacing the charged lepton with the down-type quark (q'). In the measurements used in this paper, only angles from top quarks decaying semileptonically to electrons or muons are considered. Imposing a unitarity constraint between the three polarization fractions, $F_0 + F_L + F_R = 1$, results in two independent observables.

The W boson polarization fractions have been measured in proton-antiproton collisions by the CDF and D0 experiments [2] at a centre-of-mass energy of 1.96 TeV with experimental uncertainties of 10–15% in F_0 and F_L. The ATLAS and CMS collaborations have performed measurements at the LHC in proton-proton (pp) collisions at $\sqrt{s} = 7$ [3, 4] and 8 [5–7] TeV, reaching a precision in F_0 and F_L of 3–5%. All measurements are in agreement with the SM NNLO predictions within their experimental uncertainties. However, these experimental uncertainties are larger than those of the current theoretical predictions, which are less than 2%. Improving the experimental precision motivates the combination of the ATLAS and CMS measurements: combining measurements based on independent data sets reduces the statistical uncertainty, while the overall uncertainty can be further decreased by exploiting the differences in experimental systematic effects stemming from the use of the two detectors and different analysis methods.

This paper describes the combination of the W boson polarization fractions measured by the ATLAS and CMS collaborations based on data collected at $\sqrt{s} = 8$ TeV, in final states enhanced in top quark pair ($t\bar{t}$) [5, 6] and single top quark [7] production processes. The paper is structured as follows: the measurements included in the combination are briefly described in section 2. Section 3 lists the sources of systematic uncertainty considered in the input measurements. The correlations between the measured values included in this combination are categorized in section 4, and presented for each source of systematic uncertainty. In section 5, the results of the combination and their interpretation in terms of new physics using the effective field theory approach are described. A summary and conclusions are presented in section 6.

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2 The ATLAS and CMS measurements

Three measurements of the W boson polarization in the top quark decay from top quark pair production events in the ℓ+jets channel and one from events with a single top quark signature are the four input measurements in this combination. The measurements based on $\mathrm{t\bar{t}}$ production events were performed by the ATLAS [5] and CMS [6] experiments, where the latter was separated in electron and muon channels. The measurement from events with a single top quark signature was performed by the CMS [7] experiment.

The measurements were based on pp collision data at $\sqrt{s} = 8\,\mathrm{TeV}$, corresponding to integrated luminosities of 20.2 and 19.7 fb^{-1} for the ATLAS and CMS experiments, respectively. The 7 TeV measurements [3, 4] are not included in this combination since they are based on smaller data sets, and, having relatively large systematic uncertainties, their contribution to the combination is expected to be marginal. All measurements were based on fits where the polarization fractions were adjusted to describe the observed $\cos\theta^*$ distributions of the semileptonically decaying top quark, taking into account the SM predictions for the backgrounds. These measurements are summarized in the rest of the section. Detailed descriptions of the ATLAS and CMS detectors can be found elsewhere [8, 9].

2.1 The ATLAS measurement

The contributing input from the ATLAS experiment to this combination is described in ref. [5] and denoted "ATLAS" in the following. In this measurement, the event selection was defined to efficiently select events from top quark pair decays in the ℓ+jets channel, i.e. exactly one reconstructed electron or muon and at least four jets, of which at least two were tagged as b jets, and minimizing background contributions, e.g. from W/Z+jets and multijet productions. The latter corresponds to events including jets misidentified as leptons, or non-prompt leptons from hadron decay passing the ℓ+jets selection. The $\mathrm{t\bar{t}}$ system was fully reconstructed via a kinematic likelihood fit technique [10], which maps the four decay quarks (two b quarks and two light quarks from the W boson decay) to four reconstructed jets, utilising Breit-Wigner distributions for the W boson and top quark masses, as well as transfer functions to map the reconstructed jet and lepton energies to the parton or true lepton level, respectively.

The W boson polarization was measured in the single-lepton channels from $\mathrm{t\bar{t}}$ events using a template fit method. Dedicated $\mathrm{t\bar{t}}$ templates of the $\cos\theta^*$ distribution for each polarization configuration were produced by reweighting the simulated SM $\mathrm{t\bar{t}}$ events. Additional templates for background processes were also produced.

The templates were fit to the $\cos\theta^*$ distribution in data using different templates for the electron and muon channels, via a binned likelihood fit as:

$$\mathcal{L} = \prod_{k=1}^{n_{\mathrm{bins}}} \frac{N_{\mathrm{exp}}(k)^{\,N_{\mathrm{data}}(k)}}{\Big[N_{\mathrm{data}}(k)\Big]!}\, \exp\left[-N_{\mathrm{exp}}(k)\right] \prod_{j=1}^{n_{\mathrm{bkg}}} \frac{1}{\sqrt{2\pi}\sigma_{\mathrm{bkg},j}} \exp\left(\frac{-(N_{\mathrm{bkg},j} - \hat{N}_{\mathrm{bkg},j})^2}{2\sigma^2_{\mathrm{bkg},j}}\right), \tag{2.1}$$

where $N_{\mathrm{data}}(k)$ and $N_{\mathrm{exp}}(k)$ represented the number of observed and the total number of expected events (sum of signal and background events) in each bin k of the $\cos\theta^*$ distri-

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bution, respectively. The number of events for each background source j is represented by $N_{\mathrm{bkg},j}$. The expected number of events for each background source j, $\hat{N}_{\mathrm{bkg},j}$, and the uncertainties in the normalization of the background events, $\sigma_{\mathrm{bkg},j}$, were used to constrain the fit. Therefore, the uncertainties in the polarization fractions obtained from the fit included both the statistical and systematic uncertainties in the background normalizations. The final result was obtained by a simultaneous fit of the electron and muon channel templates to the data. A common parameter was used to scale each of the backgrounds in the electron and muon channel in a fully correlated manner, except in the case of the nonprompt-lepton background for which two separate, uncorrelated, parameters were used. The contribution from W+jets events was split into different quark flavour samples and scaled by the calibration factors derived from sidebands in data. These procedures were found to cover the corresponding shape uncertainties in the nonprompt-lepton and W+jets contributions. The uncertainty in the shape of the contributions from single top quark and diboson events was found to be negligible.

2.2 The CMS measurements

Three CMS measurements contribute to this combination. The results presented in ref. [6] used similar final states to those in ATLAS: one lepton and four or more jets, of which at least two were tagged as b jets. The $\mathrm{t\bar{t}}$ system was fully reconstructed using a constrained kinematic fit. The unmeasured longitudinal momentum of the neutrino was inferred by the kinematic constraints.

The measurement was performed by maximizing the binned Poisson likelihood function,

$$\mathcal{L} = \prod_{k=1}^{n_{\mathrm{bins}}} \frac{N_{\mathrm{exp}}(k)^{\,N_{\mathrm{data}}(k)}}{\Big[N_{\mathrm{data}}(k)\Big]!}\ \exp\left[-N_{\mathrm{exp}}(k)\right], \tag{2.2}$$

where $N_{\mathrm{data}}(k)$ is the number of observed events in each bin k of the reconstructed $\cos\theta^*$ distribution, and $N_{\mathrm{exp}}(k)$ is the number of expected events from Monte Carlo (MC) simulation for a given polarization configuration $\vec{F} \equiv (F_0, F_{\mathrm{L}}, F_{\mathrm{R}})$, including signal and background events. During each step of the maximization, $N_{\mathrm{exp}}(k)$ was modified for different values of the polarization fractions $\vec{F}$ using a reweighting procedure based on eq. (1.1). Weights are applied to the events at the generated level, so that the $\cos\theta^*$ distribution generated according to eq. (1.1) corresponds to alternative values of $\vec{F}$. Backgrounds that did not involve a top quark did not change $N_{\mathrm{exp}}(k)$ for different values of $\vec{F}$. The ATLAS and CMS measurements considered the variations on $N_{\mathrm{exp}}(k)$ coming from all top quark events passing the selection, either ℓ+jets or non-ℓ+jets, including τ+jets and dilepton $\mathrm{t\bar{t}}$ processes. In addition, the CMS analyses took into account the variations arising from single top quark processes, which were treated as a background in the ATLAS measurement. The normalization of the $\mathrm{t\bar{t}}$ process was left free in the fit.

In order to allow a more detailed account of the correlations with the other measurements, the two lepton channels, e+jets and μ+jets, enter the combination as two separate measurements, referred to as "CMS (e+jets)" and "CMS (μ+jets)" throughout this paper, respectively. In the ATLAS measurement, the fractions were obtained simultaneously using the events from the two channels, therefore this separation is not available.

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The third CMS input [7] included in the combination used a final state targeting t-channel single top quark topologies instead of $\mathrm{t\bar{t}}$ events. The event selection required exactly one electron or muon, and exactly two jets, one of which was tagged as a b jet. This selection is orthogonal to that of the CMS (e+jets) and CMS (μ+jets) analyses, making the three of them statistically independent. Nevertheless, while the expected amount of selected t-channel single top quark events corresponded to only about 13% of the sample, the expected contribution from the $\mathrm{t\bar{t}}$ process amounted to about 35%, and needed to be taken into account as part of the signal. The largest background came from the W+jets process. This contribution was fully estimated from data, and corresponded to about 36% of the selected sample. Other processes, such as multijet and Z+jets production, accounted for the remaining 16% of the sample.

The fitting procedure applied in ref. [6] was slightly modified for the single top quark topology measurement. In this case, because of the different background composition with respect to the $\mathrm{t\bar{t}}$ analysis, the normalizations of the single top quark and $\mathrm{t\bar{t}}$ processes were fixed according to their predicted cross section values. On the other hand, the normalization of the W+jets sample was left free in the fit to be adjusted simultaneously with the F_0 and F_L fractions, and treated independently in the e+jets and μ+jets channels. Moreover, the fractions were extracted by maximizing a combined likelihood function, constructed from the two likelihood functions of the electron and muon channels, taking into account the correlations between them. Therefore, although based on two single-lepton channels, this measurement contributes to the combination as one single input, denoted as "CMS (single top)" in the following.

2.3 The W boson polarization values from the input measurements

The polarization fractions from the input measurements before applying the modifications concerning the combination (as discussed in section 3), and their uncertainties are summarized in table 1. The first quoted uncertainty in the ATLAS measurement includes the statistical uncertainties and uncertainties in the background determination, and the second uncertainty refers to the remaining systematic uncertainty. For CMS measurements, the first uncertainty is statistical, while the second is the total systematic uncertainty, including that on background determination.

In order to harmonize the treatment of the systematic uncertainties evaluation across the input measurements, some of them are modified before performing the combination process. The following modifications are applied (as detailed in section 3):

- The uncertainty values in the ATLAS measurement are symmetrized.
- The $\mathrm{t\bar{t}}$ modelling uncertainties in the CMS (e+jets) and CMS (μ+jets) measurements are recalculated without the contributions from the limited number of events in the samples used to estimate them.
- The uncertainty due to the top quark mass used in the ATLAS measurement is increased from a variation of $\pm 0.7\,\mathrm{GeV}$ to $\pm 1.0\,\mathrm{GeV}$.

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Measurement	F_0	F_L	F_R
ATLAS (ℓ+jets)	$0.709 \pm 0.012 \pm 0.015$	$0.299 \pm 0.008 \pm 0.013$	$-0.008 \pm 0.006 \pm 0.012$
CMS (e+jets)	$0.705 \pm 0.013 \pm 0.037$	$0.304 \pm 0.009 \pm 0.020$	$-0.009 \pm 0.005 \pm 0.021$
CMS (μ+jets)	$0.685 \pm 0.013 \pm 0.024$	$0.328 \pm 0.009 \pm 0.014$	$-0.013 \pm 0.005 \pm 0.017$
CMS (single top)	$0.720 \pm 0.039 \pm 0.037$	$0.298 \pm 0.028 \pm 0.032$	$-0.018 \pm 0.019 \pm 0.011$

Table 1. Summary of the published ATLAS and CMS measurements for 8 TeV data. The first quoted uncertainty in the ATLAS measurement includes statistical uncertainties and uncertainties in the background determination, and the second uncertainty refers to the remaining systematic contribution. For CMS measurements, the first uncertainty is statistical while the second is the total systematic uncertainty, including that on background determination.

3 Sources of systematic uncertainty

The effects of various systematic uncertainties on the input results were studied individually for each measurement. In the ATLAS measurement, the impact of systematic uncertainties was evaluated with alternative pseudo-data distributions built from the altered signal and background contributions. The alternative pseudo-data distributions were produced by varying each source of systematic uncertainty by one standard deviation ($\pm 1\sigma$). The CMS measurements also used pseudo-data to estimate the uncertainties due to parton distribution functions (PDFs), size of the simulated samples, and single top quark analysis specific uncertainties. The other uncertainties were estimated by replacing the nominal sample with alternative samples containing simulated events modified according to each of the systematic variations, and repeating the fit.

As the algorithm used to perform the combination accepts only symmetric uncertainties (more details in section 5), the uncertainties in the ATLAS measurement are symmetrized by assigning the average uncertainty value between the up and down variations in each uncertainty source. A test is performed by replacing the average uncertainty value with the largest shift among the up and down variations. No variation in the combination results is observed, i.e. the central values of the polarization fractions, combination uncertainty, and total correlation remain unchanged. In addition, common uncertainty categories are established by merging and regrouping various uncertainties in each individual input measurement.

In the following, the categorization of the systematic uncertainties considered for the combination is presented. The categories, assumed to be independent from each other, comprise sources of uncertainties that have similar origins, easing the treatment of correlations discussed in section 4.

3.1 Limited size of the data and simulated samples, backgrounds, and integrated luminosity

Statistical uncertainty, background determination, and integrated luminosity (stat+bkg). The uncertainties in the ATLAS measurement from the fit included both the statistical uncertainty in the data and the systematic uncertainty in the background normalizations

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via priors for the background yields. The shape of the multijet processes was determined from data, while for the other background events it was fully determined from simulation. The impact of the 1.9% integrated luminosity uncertainty [11] was found to be negligible because of the background normalization treatment in the fit.

In the CMS measurements, the uncertainties in the expected backgrounds included shape and normalization effects, and were estimated by varying them separately within their uncertainties and repeating the measurement. The multijet background in all CMS measurements as well as the normalization of the W+jets contribution in the CMS (single top) case were derived exclusively from data. All other background processes, as well as $\mathrm{t\bar{t}}$, and single top quark processes in the CMS (single top) measurement were estimated using simulation, normalized to the integrated luminosity of the data samples. These were affected by the uncertainties in their predicted cross sections, and the integrated luminosity determination. The CMS integrated luminosity uncertainty of 2.6% [12] had a sizeable effect only on the CMS (single top) measurement.

Size of simulated samples. This category accounts for the limited number of simulated events for the nominal samples in all input measurements. Both ATLAS and CMS evaluated this uncertainty by performing pseudo-experiments. In the CMS (e+jets) and CMS (μ+jets) measurements, the limited number of simulated events was also considered for the $\mathrm{t\bar{t}}$ samples used for the estimation of the modelling uncertainties. In order to perform a consistent combination, the $\mathrm{t\bar{t}}$ modelling uncertainties in the CMS (e+jets) and CMS (μ+jets) measurements are recalculated without the contributions from the limited number of events in the samples used to estimate them. The impact of this modification on the relative uncertainty in the measurements is found to be in the order of $O(10^{-4})$.

3.2 Detector modelling

Jets. In all input measurements in this combination, the same jet clustering algorithm, the anti-k_{T} algorithm [13, 14], was used, with the radius parameter R of 0.4 and 0.5 for the ATLAS and CMS experiments, respectively. However, in the ATLAS measurement the jets were built from energy deposits in the calorimeter [15], while in the CMS analyses they were reconstructed from particle-flow [16] objects. Thus, the two experiments used different calibration procedures and uncertainties for jets. The following categories comprise various sources of uncertainty related to the reconstruction and energy calibration of jets.

- *Jet energy scale (JES)*: the JES uncertainty in the ATLAS and CMS analyses was composed of different uncertainty sources, such as jet flavour dependence, the additional interactions in the same or nearby bunch crossings (pileup), calibrations from Z+jets or γ+jets processes, and other components. In general, these components have different level of correlations among the two experiments and have been used to evaluate the total JES correlation (as detailed in section 5.1). The final JES uncertainty used in this combination is quoted in tables 2–4 and results from grouping all JES uncertainty components into a single number.
- *Jet energy resolution (JER)*: this category includes contributions due to the uncertainties in the modelling of the jet energy resolution. The momenta of the jets in

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	ATLAS		
	F_0	F_L	$\rho_{\text{ATLAS}}(F_0, F_L)$
Measured value	0.709	0.299	
Uncertainty category			
Samples size and background determination			
Stat+bkg	0.012	0.008	−1.00
Size of simulated samples	0.009	0.006	−1.00
Detector modelling			
JES	0.005	0.003	−0.94
JER	0.006	0.003	−0.92
JVF	0.003	0.002	−0.99
Jet reconstruction efficiency	<0.001	<0.001	−1.00
Lepton efficiency	0.004	0.002	−0.99
b tagging	0.002	0.001	−0.84
Pileup	*n.a.*	*n.a.*	*n.a.*
Signal modelling			
Top quark mass	0.002	0.007	−1.00
Simulation model choice	0.003	0.004	0.99
Radiation and scales	0.003	0.006	−0.91
Top quark p_T	*n.a.*	*n.a.*	*n.a.*
PDF	0.003	0.004	−1.00
Single top method	*n.a.*	*n.a.*	*n.a.*
Total uncertainties			
Systematic uncertainty	0.014	0.013	−0.82
Total uncertainty	0.019	0.015	−0.80

Table 2. Uncertainties in F_0, F_L and their corresponding correlations from the ATLAS measurement. The uncertainty that is not applicable to this measurement, or which is included in other categories, is indicated by "*n.a.*". The line "Systematic uncertainty" represents the quadratic sum of all the systematic uncertainty sources except for the uncertainty in the background determination, which is included in the "Stat+bkg" category. The quoted correlation values are obtained via the procedures described in section 4.1.

simulation were smeared so that the jet energy resolution in simulation agrees with that in data. Both experiments used a similar method to estimate this uncertainty.

- *Jet vertex fraction (JVF)*: to suppress jets from pileup, in the ATLAS measurement jets were required to fulfil the JVF criterion. The corresponding uncertainty was eval-

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	CMS e+jets			CMS μ+jets		
	F_0	F_L	$\rho_{CMS}^{e+jets}(F_0, F_L)$	F_0	F_L	$\rho_{CMS}^{\mu+jets}(F_0, F_L)$
Measured value	0.705	0.304		0.685	0.328	
Uncertainty category						
Samples size and background determination						
Stat+bkg	0.028	0.011	−0.87	0.016	0.010	−0.88
Size of simulated samples	0.002	0.001	−0.95	0.002	0.001	−0.96
Detector modelling						
JES	0.004	0.003	−1.00	0.005	0.003	−1.00
JER	0.001	0.002	−1.00	0.004	0.003	−1.00
JVF	*n.a.*	*n.a.*	*n.a.*	*n.a.*	*n.a.*	*n.a.*
Jet reconstruction efficiency	*n.a.*	*n.a.*	*n.a.*	*n.a.*	*n.a.*	*n.a.*
Lepton efficiency	0.001	0.002	−1.00	0.001	0.001	−1.00
b tagging	0.001	<0.001	−1.00	0.001	<0.001	−1.00
Pileup	0.001	0.001	−1.00	<0.001	<0.001	−1.00
Signal modelling						
Top quark mass	0.012	0.008	−0.99	0.009	0.006	−1.00
Simulation model choice	0.015	0.010	−0.87	0.008	0.004	0.20
Radiation and scales	0.007	0.005	−1.00	0.014	0.006	−0.83
Top quark p_T	0.011	0.010	−1.00	<0.001	0.001	−1.00
PDF	0.004	0.001	−0.92	0.002	0.001	−0.15
Single top method	*n.a.*	*n.a.*	*n.a.*	*n.a.*	*n.a.*	*n.a.*
Total uncertainties						
Systematic uncertainty	0.024	0.018	−0.93	0.020	0.010	−0.71
Total uncertainty	0.037	0.021	−0.87	0.025	0.014	−0.78

Table 3. Uncertainties in F_0, F_L and their corresponding correlations from the CMS e+jets and μ+jets measurements. The uncertainty that is not applicable to this measurement, or which is included in other categories, is indicated by "*n.a.*". The line "Systematic uncertainty" represents the quadratic sum of all the systematic uncertainty sources except for the uncertainties in the background determination and the integrated luminosity, which are included in the "Stat+bkg" category. The quoted correlation values are obtained via the procedures described in section 4.1.

uated in the measurement by changing the nominal JVF cutoff value and repeating the measurement [17]. In the CMS measurements, pileup events were removed at the event reconstruction level with the particle-flow algorithm. In this case, uncertainties in jet reconstruction due to pileup were covered by the JES and pileup categories, and are not added as a separate source.

- *Jet reconstruction efficiency*: a systematic uncertainty was included in the ATLAS measurement to account for the jet reconstruction efficiency mismatch between simulation and data. In the CMS measurements, this uncertainty is included in the JES uncertainty.

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	CMS (single top)		
	F_0	F_L	$\rho^{st}_{CMS}(F_0, F_L)$
Measured value	0.720	0.298	
Uncertainty category			
Samples size and background determination			
Stat+bkg	0.041	0.031	−0.90
Size of simulated samples	0.020	0.012	−0.96
Detector modelling			
JES	0.004	0.004	−1.00
JER	0.001	0.001	−1.00
JVF	*n.a.*	*n.a.*	*n.a.*
Jet reconstruction efficiency	*n.a.*	*n.a.*	*n.a.*
Lepton efficiency	<0.001	<0.001	−1.00
b tagging	0.006	0.006	−1.00
Pileup	0.003	0.003	−1.00
Signal modelling			
Top quark mass	0.005	0.007	−1.00
Simulation model choice	0.002	0.003	−1.00
Radiation and scales	0.023	0.019	−1.00
Top quark p_T	*n.a.*	*n.a.*	*n.a.*
PDF	0.004	0.004	−0.97
Single top method	0.012	0.015	−1.00
Total uncertainties			
Systematic uncertainty	0.035	0.029	−0.96
Total uncertainty	0.054	0.043	−0.92

Table 4. Uncertainties in F_0, F_L and their corresponding correlations from the CMS (single top) measurement. The uncertainty that is not applicable to this measurement, or which is included in other categories, is indicated by "*n.a.*". The line "Systematic uncertainty" represents the quadratic sum of all the systematic uncertainty sources except for the uncertainties in the background determination and the integrated luminosity, which are included in the "Stat+bkg" category. The quoted correlation values are obtained via the procedures described in section 4.1.

Lepton efficiency. For all measurements, this category accounted for the uncertainties in the scale factors used to correct the simulated samples so that the efficiencies for lepton selection, reconstruction, and identification observed in data were well reproduced by the simulation. Since the samples were collected using single-lepton triggers, uncertainties in

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the trigger efficiencies were also included. All corrections were applied as functions of p_{T} and η of the leptons. This uncertainty was found to be negligible for the CMS (single top) measurement, compared to other uncertainties.

b tagging. In this category, uncertainties on the scale factors used to correct the simulation for different efficiencies for tagging jets originating from b quarks (tag) or for those originating from c or light partons wrongly identified as b jets (mistag) were taken into account. This difference was accounted for by assigning scale factors to the jets, dependent on the p_{T} and η as well as on the flavour of the jet. In the ATLAS measurement, additionally, an uncertainty was assigned to account for the extrapolation of the b tagging efficiency measurement to the high-p_{T} region.

Pileup. In both the ATLAS and the CMS analyses, pileup effects were taken into account in the simulation of signal and background events. The distribution of pileup was adjusted to reflect the measured instantaneous luminosities per bunch in data. In the CMS measurements, this uncertainty was estimated by varying the pp cross section used to estimate the number of pileup in data within its uncertainty, and recalculating the weights applied to the simulation. In the ATLAS measurement, the uncertainty in the description of extra energy deposited due to pileup interactions was treated as a separate missing transverse momentum ($p_{\mathrm{T}}^{\mathrm{miss}}$) scale uncertainty. The impact on the measured W boson polarization fractions from this uncertainty was found to be negligible, and therefore was not considered.

3.3 Signal modelling

Top quark mass. In all four analyses, the effect of the uncertainty in the top quark mass was estimated by repeating the measurements using simulated samples with different input top quark masses for the signal process. In the ATLAS measurement, this effect was evaluated using an uncertainty of $\pm 0.70\,\mathrm{GeV}$ in the top quark mass as given by the ATLAS measurement [18]. In the CMS measurements on the other hand, an uncertainty of $\pm 1.0\,\mathrm{GeV}$ in the top quark mass was assumed. In order to keep consistency across the various input measurements, this effect in the ATLAS measurement is reestimated using the original estimation method described in ref. [5], accounting for a variation of $\pm 1.0\,\mathrm{GeV}$ in the top quark mass. The impact of this modification in the ATLAS input result is negligible.

Simulation model choice. The impact of using different MC event generators and their interfaced showering and hadronization models was estimated in all input measurements. In the ATLAS measurement, the impact of the choice of different MC event generators was assessed by comparing events produced by POWHEG-BOX [19–23] and MC@NLO [24–26], both interfaced to HERWIG [27] for showering and hadronization. To evaluate the impact of the different parton shower and hadronization models, the POWHEG+HERWIG sample was compared to POWHEG+PYTHIA [28]. For the CMS (e+jets) and CMS (μ+jets) measurements, the uncertainties were estimated by replacing the events produced by MADGRAPH [29] interfaced with PYTHIA with MC@NLO interfaced with the HERWIG generator and additionally, varying the kinematic scale used to match jets to partons (matching

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threshold) by twice and half its central value. In the CMS (single top) measurement, the uncertainty in the choice of different MC generators was estimated as the difference between the POWHEG+PYTHIA and the COMPHEP [30] generators.

Radiation and scales. In all four analyses, this category represents the uncertainty associated with initial- and final-state radiation (ISR/FSR) estimated using simulated samples of $\mathrm{t\bar{t}}$ events where the renormalization and factorization scales (μ_R and μ_F) were simultaneously set to twice and half the default value in the matrix element (ME) calculations. In the CMS measurements, the μ_R and μ_F in the parton shower were also varied simultaneously to those used in the ME calculations. However, in the ATLAS measurement, a different set of tuned parameters of the PYTHIA parton shower with a modified strong coupling α_S was used to account for low and high radiation to match the variation of scales in the ME calculations. The detailed list of modified parameters is given in ref. [31]. Furthermore, in the ATLAS measurement the value of the damping parameter (h_damp) in POWHEG-BOX was set to twice the top quark mass for the high-radiation sample. In addition to changing it in the $\mathrm{t\bar{t}}$ background, the CMS (single top) measurement varied the scales used in the single top quark simulated samples.

Top quark p_T. In previous CMS analyses of $\mathrm{t\bar{t}}$ events, described e.g. in ref. [32], the shape of the p_T spectrum for top quarks was found to be softer than the predictions from MADGRAPH simulation. The effect of this mismodelling on the CMS (e+jets) and CMS (μ+jets) measurements was estimated by reweighting the simulated $\mathrm{t\bar{t}}$ sample to describe the data. The difference in the polarization fractions with the default sample to the reweighted sample was taken as a systematic uncertainty. On the other hand, the top quark p_T distribution did not exhibit, within uncertainties, a significant difference with the predictions in the single top quark enriched phase space, therefore no systematic uncertainty was assigned in the CMS (single top) measurement. In the ATLAS measurement, this mismodelling was checked to be covered by the simulation model choice uncertainties, and therefore no additional uncertainty for the top quark p_T spectrum was considered.

PDF. The uncertainty due to the choice of PDFs in all input measurements was evaluated by varying the eigenvalues of different PDF sets following the PDF4LHC recommendations [33, 34]. In the ATLAS measurement, the differences between three PDF sets: CT10 [35], MSTW2008 [36], and NNPDF 2.3 [37] were taken into account. Uncertainties related to the choice of PDF set in the CMS (e+jets) and CMS (μ+jets) measurements were estimated by replacing CTEQ6L1 [38] used to generate the nominal samples, with NNPDF 2.1 [39] and MSTW2008. A similar procedure was adopted in the CMS (single top) measurement, where the default CTEQ6.6M [40] set was replaced with CT10 instead.

Single top quark analysis method. In addition to the systematic uncertainties considered for the $\mathrm{t\bar{t}}$ measurement, a few specific uncertainties were included for the CMS (single top) measurement. For the specific case of single top quark processes, unlike for $\mathrm{t\bar{t}}$ production, the polarization fractions can also be altered at the production level. To study this effect, pseudo-data were generated from samples simulated using COMPHEP and SINGLE

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Measurement	Fraction	ATLAS F_0	CMS (e+jets) F_0	CMS (μ+jets) F_0	CMS (single top) F_0
ATLAS	F_0	$+1$	$\rho_{\mathrm{LHC}}(F_0, F_0)$	$\rho_{\mathrm{LHC}}(F_0, F_0)$	$\rho_{\mathrm{LHC}}(F_0, F_0)$
CMS (e+jets)	F_0	$\rho_{\mathrm{LHC}}(F_0, F_0)$	$+1$	$\rho_{\mathrm{CMS}}^{\mathrm{e},\mu+\mathrm{jets}}(F_0, F_0)$	$\rho_{\mathrm{CMS}}^{\mathrm{st},\ell+\mathrm{jets}}(F_0, F_0)$
CMS (μ+jets)	F_0	$\rho_{\mathrm{LHC}}(F_0, F_0)$	$\rho_{\mathrm{CMS}}^{\mathrm{e},\mu+\mathrm{jets}}(F_0, F_0)$	$+1$	$\rho_{\mathrm{CMS}}^{\mathrm{st},\ell+\mathrm{jets}}(F_0, F_0)$
CMS (single top)	F_0	$\rho_{\mathrm{LHC}}(F_0, F_0)$	$\rho_{\mathrm{CMS}}^{\mathrm{st},\ell+\mathrm{jets}}(F_0, F_0)$	$\rho_{\mathrm{CMS}}^{\mathrm{st},\ell+\mathrm{jets}}(F_0, F_0)$	$+1$
ATLAS	F_{L}	$\rho_{\mathrm{ATLAS}}(F_0, F_{\mathrm{L}})$	$-\rho_{\mathrm{LHC}}(F_0, F_0)$	$-\rho_{\mathrm{LHC}}(F_0, F_0)$	$-\rho_{\mathrm{LHC}}(F_0, F_0)$
CMS (e+jets)	F_{L}	$-\rho_{\mathrm{LHC}}(F_0, F_0)$	$\rho_{\mathrm{CMS}}^{\mathrm{e+jets}}(F_0, F_{\mathrm{L}})$	$-\rho_{\mathrm{CMS}}^{\mathrm{e},\mu+\mathrm{jets}}(F_0, F_0)$	$-\rho_{\mathrm{CMS}}^{\mathrm{st},\ell+\mathrm{jets}}(F_0, F_0)$
CMS (μ+jets)	F_{L}	$-\rho_{\mathrm{LHC}}(F_0, F_0)$	$-\rho_{\mathrm{CMS}}^{\mathrm{e},\mu+\mathrm{jets}}(F_0, F_0)$	$\rho_{\mathrm{CMS}}^{\mu+\mathrm{jets}}(F_0, F_{\mathrm{L}})$	$-\rho_{\mathrm{CMS}}^{\mathrm{st},\ell+\mathrm{jets}}(F_0, F_0)$
CMS (single top)	F_{L}	$-\rho_{\mathrm{LHC}}(F_0, F_0)$	$-\rho_{\mathrm{CMS}}^{\mathrm{st},\ell+\mathrm{jets}}(F_0, F_0)$	$-\rho_{\mathrm{CMS}}^{\mathrm{st},\ell+\mathrm{jets}}(F_0, F_0)$	$\rho_{\mathrm{CMS}}^{\mathrm{st}}(F_0, F_{\mathrm{L}})$

Table 5. Summary of the correlation categories considered in the combination. The correlations among the F_{L} measurements are not shown for brevity.

Top [41] event generators with varied values of the couplings g_{L}, V_{R}, and V_{L} (as described in section 5.2) both at the single top quark production and decay, and the polarization fractions values were extracted using the analysis fitting framework. The differences between the generated and fitted values were taken as the systematic uncertainty. Secondly, a small difference in the generated W boson polarization fraction values was observed for the $\mathrm{t\bar{t}}$ events, simulated with MadGraph, and single top quark events, simulated with powheg. This difference of about 0.01 was taken into account as an uncertainty in the measurement. Finally, the effect of fixing the signal normalization in the fit was considered. All these uncertainties are merged into a single uncertainty, referred to as *Single top method* in tables 2–4 and 6–7.

In all input measurements, the uncertainty in the modelling of colour reconnection was found to be negligible and therefore was not considered.

4 Correlations and uncertainties in the ATLAS and CMS measurements

4.1 Correlations

Four pairs of longitudinal and left-handed polarization fractions from four input measurements, as described in section 2 are used in the combination. The correlations between the input values are defined taking into account the unitarity relation between the polarization fractions in each measurement and the correlations among the measurements. The groups of correlations are listed in table 5 and defined as follows:

- *Correlations within the same measurement*: because of the unitarity constraint, and given that $F_{\mathrm{R}} \approx 0$, the observed values of F_0 and F_{L} within one single measurement are usually highly anticorrelated. In the ATLAS measurement, this correlation is estimated for each systematic uncertainty source from its corresponding covariance matrix. For categories with multiple sources of systematic uncertainty, the sum of the individual covariance matrices is used to calculate the correlation. In the CMS analyses, this group of correlations is estimated from the covariance propagation of

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Uncertainty Category	$\rho_{\mathrm{LHC}}(F_{\mathrm{i}}, F_{\mathrm{i}})$	$\rho_{\mathrm{CMS}}^{\mathrm{e},\mu+\mathrm{jets}}(F_{\mathrm{i}}, F_{\mathrm{i}})$	$\rho_{\mathrm{CMS}}^{\mathrm{st},\ell+\mathrm{jets}}(F_{\mathrm{i}}, F_{\mathrm{i}})$
Samples size and background determination			
Stat+bkg	0.0	$0.0^{\dagger}$	$0.0^{\dagger}$
Size of simulated samples	0.0	0.0	0.0
Detector modelling			
JES	$0.2^{\dagger}$	1.0	1.0
JER	0.0	1.0	1.0
JVF	0.0^{*}	0.0^{*}	0.0^{*}
Jet reconstruction efficiency	0.0^{*}	0.0^{*}	0.0^{*}
Lepton efficiency	0.0	0.0	0.0
b tagging	0.0	1.0	1.0
Pileup	0.0^{*}	1.0	1.0
Signal modelling			
Top quark mass	1.0	1.0	1.0
Simulation model choice	1.0	1.0	1.0
Radiation and scales	$0.5^{\dagger}$	1.0	$1.0^{\dagger}$
Top quark p_{T}	0.0^{*}	1.0	0.0^{*}
PDF	1.0	1.0	1.0
Single top method	0.0^{*}	0.0^{*}	0.0^{*}

Table 6. Input correlations across different measurements, as explained in section 4.1. The values stand for the correlations $\rho(F_{\mathrm{i}}, F_{\mathrm{i}})$, with i being either 0 or L. The correlations of the type $\rho(F_0, F_{\mathrm{L}})$ are assumed to be $\rho(F_0, F_{\mathrm{L}}) = -\rho(F_0, F_0) = -\rho(F_{\mathrm{L}}, F_{\mathrm{L}})$. In case an uncertainty is not applicable, the correlation value is set to zero and marked with an asterisk. The correlations marked with a dagger sign are those that are not precisely determined and checks are performed to test the stability of the results against these assumptions.

the expression $F_{\mathrm{R}} = 1 - F_0 - F_{\mathrm{L}}$ as

$$\rho(F_0, F_{\mathrm{L}}) = \frac{\sigma^2(F_{\mathrm{R}}) - \sigma^2(F_0) - \sigma^2(F_{\mathrm{L}})}{2\sigma(F_0)\sigma(F_{\mathrm{L}})}, \tag{4.1}$$

where $\sigma(F_{\mathrm{i}})$ is the uncertainty in the polarization fraction F_{i}, which is directly obtained from the individual measurements. This is done for all sources of systematic uncertainty. For systematic uncertainty categories with multiple sources, e.g. 'stat+bkg' including statistical uncertainty, background determination, and others, $\sigma^2(F_{\mathrm{i}})$ is defined as the quadratic sum of the individual uncertainty sources.

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	ATLAS+CMS combination	
	F_0	F_L
Fractions	0.693	0.315
Uncertainty category		
Samples size and background determination		
Stat+bkg	0.009	0.006
Size of simulated samples	0.005	0.003
Detector modelling		
JES	0.004	0.002
JER	0.004	0.002
JVF	0.001	0.001
Jet reconstruction	<0.001	<0.001
Lepton efficiency	0.002	0.001
b tagging	0.001	0.001
Pileup	<0.001	<0.001
Signal modelling		
Top quark mass	0.003	0.004
Simulation model choice	0.006	0.005
Radiation and scales	0.005	0.004
Top quark p_T	0.001	0.002
PDF	0.001	0.001
Single top method	0.001	<0.001
Total uncertainty	0.014	0.011

Table 7. Results of the ATLAS and CMS combination: W boson polarization fraction values and uncertainties. The combined F_0 and F_L values are anticorrelated, with ρ=−0.85.

This group of correlations is denoted in this document as ρ_{ATLAS}, $\rho_{\text{CMS}}^{\text{e+jets}}$, $\rho_{\text{CMS}}^{\mu\text{+jets}}$, and $\rho_{\text{CMS}}^{\text{st}}$ for the ATLAS, CMS (e+jets), CMS (μ+jets), and CMS (single top) measurements, respectively.

- *Correlations between measurements within the CMS experiment*: for each source of systematic uncertainty, the correlations between the polarization fractions in the CMS (e+jets) and CMS (μ+jets) measurements are denoted $\rho_{\text{CMS}}^{\text{e},\mu\text{+jets}}(F_i, F_j)$, where i and j stand for 0 or L. The correlations between CMS (single top) and CMS (e+jets) are assumed to be the same as those between the CMS (single top) and CMS (μ+jets) measurements for each source of the uncertainty, and are denoted generically $\rho_{\text{CMS}}^{\text{st},\ell\text{+jets}}(F_i, F_j)$. The relations $\rho_{\text{CMS}}(F_0, F_0) = \rho_{\text{CMS}}(F_L, F_L) = -\rho_{\text{CMS}}(F_0, F_L)$

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are assumed in all CMS measurements. In this hypothesis, the strong anti-correlation observed for F_0 and F_L within the same measurement (as described above) is assumed to hold also across different measurements.

The uncertainties associated with the limited size of the data and simulated samples, and background estimation are assumed to be uncorrelated (as also discussed in sections 4.2 and 5.1). The lepton efficiency uncertainty is assumed to be uncorrelated between the CMS (e+jets) and CMS (μ+jets) measurements, and partially correlated with the CMS (single top) measurement. All other sources of uncertainty are assumed to be fully correlated.

- *Correlations between the ATLAS and CMS experiments*: for each source of systematic uncertainty, the correlation between the measured polarization fractions F_i by the ATLAS and CMS experiments, $\rho(F_i^{\text{ATLAS}}, F_j^{\text{CMS}})$ is presented by $\rho_{\text{LHC}}(F_i, F_j)$, where $\rho_{\text{LHC}}(F_0, F_0) = \rho_{\text{LHC}}(F_L, F_L) = -\rho_{\text{LHC}}(F_0, F_L)$ are assumed.

  The uncertainties associated with the detector modelling (except for the JES) as well as the method-specific uncertainty are assumed to be uncorrelated, i.e. $\rho_{\text{LHC}}(F_0, F_0) = 0$.

  The uncertainty associated with the radiation and scales, and the JES are assumed to be partially correlated with $\rho_{\text{LHC}}(F_0, F_0)$ estimated to be 0.5 and 0.2, respectively (see sections 4.2 and 5.1 for details). All other sources of uncertainty are assumed to be fully correlated, i.e. $\rho_{\text{LHC}}(F_0, F_0) = +1$.

4.2 Correlation choices for the partially correlated uncertainties

Although the correlations between the measurements are well known for most of the systematic uncertainty sources, some of them, in particular those that are partially correlated, are not very accurately determined. This section describes how these values are estimated for the combination. Stability tests are performed to verify the robustness of the combination against these correlation assumptions, as discussed in section 5.1.

In the CMS measurements, the uncertainties in the background determination (shape and normalization), integrated luminosity, and the statistical uncertainty were estimated independently and grouped into a single uncertainty category (stat+bkg) for coherence with the ATLAS treatment. The major components of the stat+bkg category in the CMS (e+jets) and CMS (μ+jets) measurements are the uncertainty in the determination of the background events from multijet and W+jets production. The former is estimated from data, and therefore uncorrelated between all CMS measurements, while W+jets production, as well as the other minor backgrounds are estimated from simulation, and therefore at least partially correlated between the measurements. For the CMS (single top) case, the major component of this category is the statistical uncertainty, which is uncorrelated with the other measurements. The normalization of W+jets production, a major background in the CMS (single top) analysis, is estimated from data, and therefore it is uncorrelated to the other CMS measurements. On the other hand, the W+jets production shape, as well as the modelling of other background event sources and signal events, rely on simulation, which may lead to a nonzero $\rho_{\text{CMS}}^{\text{st},\ell\text{+jets}}(F_i, F_i)$ correlation. Neglecting the small correlations

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that could arise from the W+jets production shape and the background modelling from simulation, the values $\rho_{\mathrm{CMS}}^{\mathrm{e},\mu+\mathrm{jets}}(F_{\mathrm{i}}, F_{\mathrm{j}}) = 0$ and $\rho_{\mathrm{CMS}}^{\mathrm{st},\ell+\mathrm{jets}}(F_{\mathrm{i}}, F_{\mathrm{i}}) = 0$ are assumed for the combination, and the impact of this assumption is studied via the stability tests.

In all ATLAS and CMS measurements, the JES systematic uncertainty is estimated from different components, which are characterized by different levels of correlations among the two experiments. These components are categorized as fully correlated, such as gluon-initiated jet fragmentation; partially correlated, such as modelling uncertainties from *in situ* techniques, such as Z-jet, γ-jet, and multijet balance techniques; and uncorrelated, such as statistical and detector-related uncertainties. These correlations have been evaluated and are described in ref. [42]. In the ATLAS measurement, the contribution from the uncorrelated (partially correlated) components to the total JES uncertainty is found to be about 70 (20)%, and the total JES uncertainty is dominated by the uncorrelated jet flavour composition component. In the CMS measurements, because JES uncertainties are small, the breakdown into components was not done. Therefore, assuming a similar JES uncertainty composition between the two experiments, the value of $\rho_{\mathrm{LHC}}(F_{\mathrm{i}}, F_{\mathrm{i}})$ is found to be 0.2.

In the ATLAS and CMS analyses, different approaches were used to estimate the radiation and scales uncertainties, as described in section 3.3. In the CMS (single top) measurement, this uncertainty is estimated by varying the scales μ_{R} and μ_{F} for the simulations of both the $\mathrm{t\bar{t}}$ and the single top quark processes. While the $\mathrm{t\bar{t}}$ component, which is dominant, is fully correlated to the analogous uncertainties in the ATLAS, CMS (e+jets), and CMS (μ+jets) measurements, the smaller component from the single top quark μ_{R} and μ_{F} scales is uncorrelated with the other measurements. Since the effects being studied are the same, but the methods are different, the values of $\rho_{\mathrm{LHC}}(F_{\mathrm{i}}, F_{\mathrm{i}})$ and $\rho_{\mathrm{CMS}}^{\mathrm{st},\ell+\mathrm{jets}}(F_{\mathrm{i}}, F_{\mathrm{i}})$ are not well known, and are assumed to be 0.5 and 1.0, respectively.

4.3 Summary of the uncertainties and correlations of the input measurements

For each systematic uncertainty category, the correlations between the measured polarization fractions for the input measurements are given in table 6. A breakdown of the uncertainties in the input measurements of F_0 and F_{L} as well as their correlations, are presented in tables 2–4. The uncertainties are grouped according to the categories listed in section 3.

Figure 1 presents the total correlation values between the input measurements. Typically, F_0 and F_{L} are highly anticorrelated within the same measurement. The three $\mathrm{t\bar{t}}$ measurements (ATLAS, CMS (e+jets), and CMS (μ+jets)) are also correlated or anticorrelated, with the absolute values of the correlations ranging around 30 to 40%. The correlations of the CMS (single top) measurement with the CMS (e+jets) and CMS (μ+jets) measurements are around 20% in the absolute value, and are generally smaller with the ATLAS measurement.

5 Results

The combination is performed by finding the best linear unbiased estimator (BLUE) [43, 44] with the method implemented in ref. [45]. The BLUE method finds the coefficients of the

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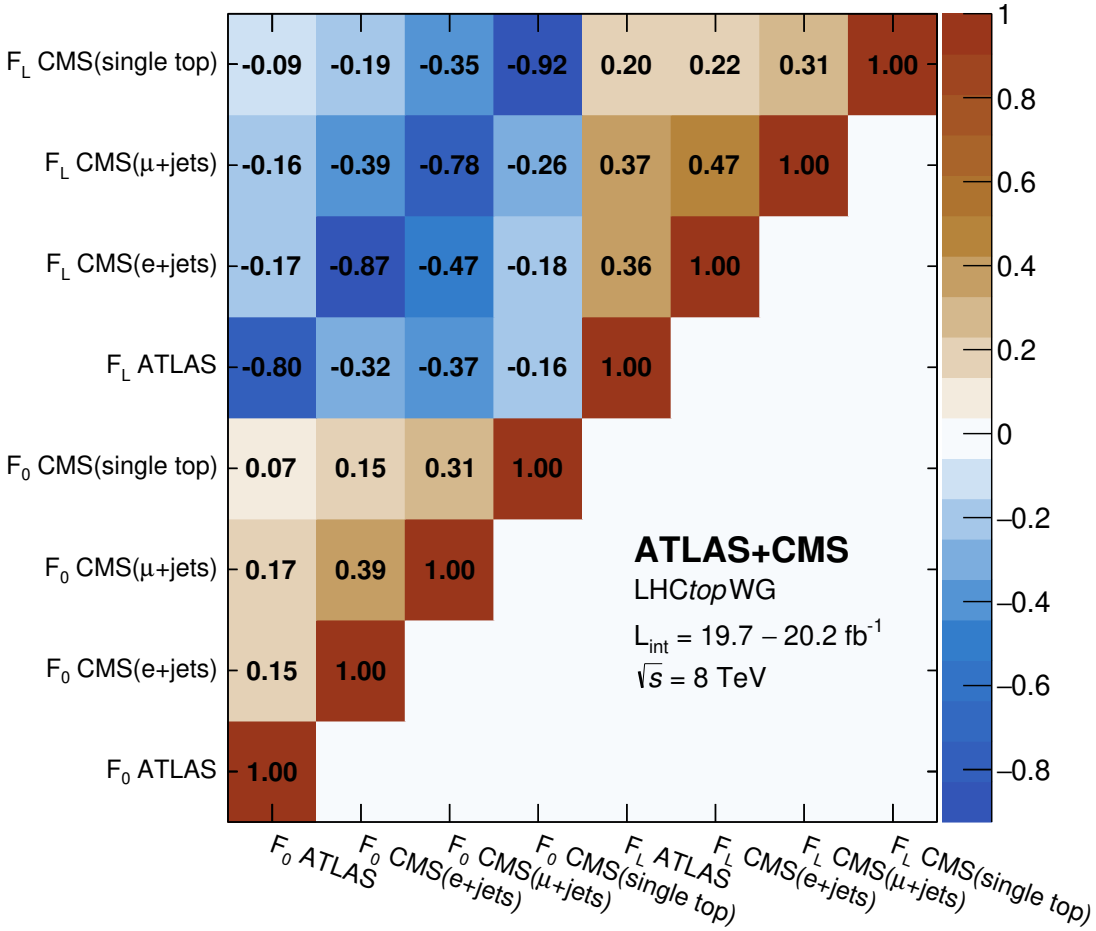

Figure 1. The total correlation between the input measurements of the combination.

linear combination of the input measurements by minimizing the total uncertainty of the combined result, taking into account both the statistical and systematic uncertainties, as well as the correlations between the inputs. In this analysis, the measurements of F_0 and F_L are combined while F_R is obtained as $F_R = 1 - F_0 - F_L$. As no further constraints on the observables were placed, values outside the range [0, 1] are allowed for the three polarization fractions. The total correlation between F_0 and F_L obtained from the combination is taken into account in the estimation of the uncertainty in the F_R value.

The results of the combination of the polarization fractions measurements are

$$\begin{aligned} F_0 = &\quad 0.693 \pm 0.009\,(\text{stat+bkg}) \pm 0.011\,(\text{syst}), \\ F_L = &\quad 0.315 \pm 0.006\,(\text{stat+bkg}) \pm 0.009\,(\text{syst}), \end{aligned}$$

with a total correlation of -0.85. Using the unitarity constraint on the polarization fractions, the fraction of events with a W boson with right-handed polarization is calculated to be

$$F_R = -0.008 \pm 0.005\,(\text{stat+bkg}) \pm 0.006\,(\text{syst}),$$

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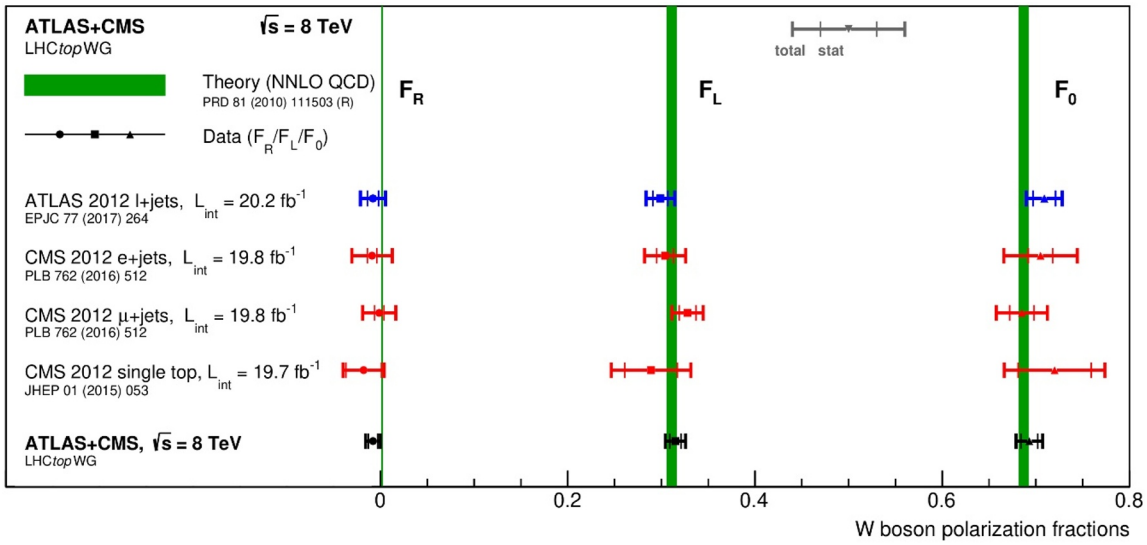

Figure 2. Overview of the four measurements, as well as the results of the combination. The inner and outer error bars correspond to the statistical and the total uncertainties, respectively. The inner bars for the combination include also the background determination uncertainties. The vertical solid line indicates the predictions of NNLO QCD calculations [1].

where the first quoted uncertainty includes the statistical part and uncertainties in the background determination, and the second uncertainty refers to the remaining systematic contribution. From these results, an upper limit of $F_{\mathrm{R}} < 0.007$ at 95% confidence level (CL) is set. The limit is set using the Feldman-Cousins method [46], considering that F_{R} follows a normal distribution, and that it is physically bound to $F_{\mathrm{R}} \geq 0$. The relative uncertainty on F_0 and F_{L} is 2.0 and 3.5%, respectively, including systematic and statistical components.

Figure 2 shows an overview of the four measurements included in the combination and the result of the combination together with the polarization fractions predicted by NNLO QCD calculations. The uncertainties in the NNLO predictions, presented with vertical bands, include an uncertainty of 1.3 GeV in the top quark mass, uncertainties in the b quark and W boson masses, and in α_{S}. The combined F_{R} value is negative, as this is not explicitly forbidden in the combination, but compatible with the predictions within the uncertainties. The measurements are consistent with each other and with the NNLO QCD prediction.

The χ^2 and upper tail probability of the combination are 4.3 and 64% respectively. The combination includes four sets of measurements, each composed of two highly anti-correlated observables, and two fit parameters of the combination, i.e. the combined F_0 and F_{L}. A detailed breakdown of the uncertainties is presented in table 7. The dominant uncertainties are those arising from the statistical uncertainty on data and background estimation (stat+bkg), followed by the uncertainties in the radiation and scales modelling, the limited size of the simulated samples, and simulation model choice. The total detector modelling uncertainty is minor, smaller than the uncertainties in the stat+bkg category. The measurement with the highest impact in the determination of F_0 is ATLAS, while CMS

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(μ+jets) dominates the combined F_{L} determination. The impact of the CMS (e+jets) and CMS (μ+jets) measurements is not directly comparable to the other input measurements that already include the electron and muon channels together. As a test, the combination is repeated, using a pre-combined CMS (e+jets) + CMS (μ+jets) input, and the results are unchanged. The ATLAS+CMS combined fractions and uncertainties are identical in both cases, with a small variation on the resulting (F_0, F_{L}) correlation, being 1.5% smaller for the cross-check combination.

In another test, the CMS (single top) measurement was removed from the combination. The impact on the combined fractions and uncertainties is less than 1.5%.

The combination yields an important improvement in precision, as compared to the most precise individual published measurements [5, 6]. Improvements of 25 and 29% relative to the most precise single measurement are found for the precision of the combined measurements of F_0 and F_{L}, respectively. The improvement is estimated with respect to the published values of the W boson polarization fraction determination that is given in table 1. The total correlation between the combined fractions is similar to those in the input measurements, and their uncertainties are smaller. These two factors lead to a combined right-handed polarization fraction F_{R} that is almost a factor two more precise than in previous publications.

5.1 Stability tests

The hypotheses assumed for the correlations between the measurements, as defined in sections 4.1 and 4.2, are based on the best knowledge of the similarities and differences in the detectors, analysis methods, and simulations used in each measurement. Nevertheless, some of these correlations cannot be precisely determined. The checks described in this section are performed to test the stability of the results against this potential lack of knowledge.

$\rho_{\mathrm{LHC}}(F_i, F_i)$ *hypothesis (with* $i = 0, L$*) for the JES uncertainty.* The correlation value $\rho_{\mathrm{LHC}}(F_{\mathrm{i}}, F_{\mathrm{i}}) = 0.2$ was estimated according to the prescription given in ref. [42] and the description in section 4.2. The impact of this assumption is evaluated by repeating the combination by varying $\rho_{\mathrm{LHC}}(F_{\mathrm{i}}, F_{\mathrm{i}})$ in the interval between 0.0 and 0.4, in steps of 0.1. The fraction values and uncertainties remained unchanged in the entire probed range. The χ^2 of the fit, the probability, and the total (F_0,F_{L}) correlation are found to be stable with a relative shift of less than 0.5%.

$\rho_{\mathrm{LHC}}(F_i, F_i)$ *and* $\rho_{\mathrm{CMS}}^{\mathrm{st},\ell+\mathrm{jets}}(F_i, F_i)$ *hypotheses for the radiation and scales uncertainties.* Although addressing similar effects, the radiation and scales uncertainties are estimated in three different ways for ATLAS, CMS (single top), and the other CMS measurements, with different levels of correlations among them. Therefore, the two hypotheses, $\rho_{\mathrm{LHC}}(F_{\mathrm{i}}, F_{\mathrm{i}}) = 0.5$ and $\rho_{\mathrm{CMS}}^{\mathrm{st},\ell+\mathrm{jets}}(F_{\mathrm{i}}, F_{\mathrm{i}}) = 1$, are tested simultaneously, by variation in steps of 0.1 in the interval between 0 and 0.5 for $\rho_{\mathrm{LHC}}(F_{\mathrm{i}}, F_{\mathrm{i}})$ and between 0.6 and 1.0 for $\rho_{\mathrm{CMS}}^{\mathrm{st},\ell+\mathrm{jets}}(F_{\mathrm{i}}, F_{\mathrm{i}})$. The resulting polarization fraction mean values and uncertainties remained unchanged in the whole ranges. Small variations, below the percent level, are observed for the total correlation and fit probability.

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JES versus radiation and scales correlations. Since the JES and radiation and scales uncertainties are among the dominant sources of uncertainty with significant correlation between measurements, an additional test was performed varying the two correlation hypotheses simultaneously, rather than separately. The results of this test also show stable combination with maximum relative shifts of about 2% for the χ^2 and probability and about 0.6% for the total correlation. The combined fractions and uncertainties are found to be stable, with negligible variations for all probed hypotheses.

$\rho_{\mathrm{CMS}}^{e,\mu+\mathrm{jets}}(F_i, F_i)$ and $\rho_{\mathrm{CMS}}^{\mathrm{st},\ell+\mathrm{jets}}(F_i, F_i)$ hypothesis for statistical+background uncertainty. Small correlations that could arise from the background modelling from simulated samples are neglected in the combination by assuming $\rho_{\mathrm{CMS}}^{\mathrm{e},\mu+\mathrm{jets}}(F_\mathrm{i}, F_\mathrm{i}) = 0$ and $\rho_{\mathrm{CMS}}^{\mathrm{st},\ell+\mathrm{jets}}(F_\mathrm{i}, F_\mathrm{i}) = 0$. In order to investigate the effect of these hypotheses, the combination was repeated by varying $\rho_{\mathrm{CMS}}^{\mathrm{e},\mu+\mathrm{jets}}(F_\mathrm{i}, F_\mathrm{i})$ and $\rho_{\mathrm{CMS}}^{\mathrm{st},\ell+\mathrm{jets}}(F_\mathrm{i}, F_\mathrm{i})$, using for both the same correlation values in the range [0.0, 0.7] in steps of 0.1. In the interval between 0.0 and 0.6, the fraction values are varied by a maximum of 1.3%, with F_0 going from 0.693 to 0.687, and F_L from 0.314 to 0.319. At 0.7, the combination yields $F_0 = 0.684 \pm 0.014$ and $F_\mathrm{L} = 0.321 \pm 0.010$, which is the maximum variation observed in all tests performed in this study. However, in this case the fit probability decreases to 28%, suggesting that the correlation assumption of 0.7 is less favoured. The fit combination does not converge for unreasonable values, i.e. correlation values above 0.7.

In conclusion, the tests reported in this section indicate that the combined results are robust against variations of some poorly known or unknown input correlations. The correlations are varied over a large range, and in all cases the observed deviation from the nominal results are well covered by the uncertainties in the combined result.

5.2 Limits on anomalous couplings

The result of the combination of the polarization fractions measurements can be used to set limits on beyond-the-SM physics contributing to the tWb vertex. In the two approaches presented in this section, only new physics contributions to the top quark decay vertex are considered — effects at the production vertex in single top quark processes are disregarded.

In a first approach, the structure of the tWb vertex is parameterized in a general form in effective field theory, expanding the SM Lagrangian to include dimension-six terms

$$\mathcal{L}_{\mathrm{tWb}} = -\frac{g}{\sqrt{2}}\bar{\mathrm{b}}\,\gamma^\mu\,(V_\mathrm{L}P_\mathrm{L} + V_\mathrm{R}P_\mathrm{R})\,\mathrm{t}\;\mathrm{W}^-_\mu - \frac{g}{\sqrt{2}}\bar{\mathrm{b}}\,\frac{i\sigma^{\mu\nu}\mathrm{q}_\nu}{m_\mathrm{W}}\,(g_\mathrm{L}P_\mathrm{L} + g_\mathrm{R}P_\mathrm{R})\,\mathrm{t}\;\mathrm{W}^-_\mu + \mathrm{h.c.}, \tag{5.1}$$

where $V_{\mathrm{L,R}}$ and $g_{\mathrm{L,R}}$ are left- and right-handed vector and tensor couplings, respectively. Here, $P_{\mathrm{L,R}}$ refers to the left- and right-handed chirality projection operators, m_W to the W boson mass, and g to the weak coupling constant, as detailed in refs. [47, 48]. In the SM, V_L is given by the Cabibbo-Kobayashi-Maskawa (CKM) matrix element V_tb, with a measured value of ≈ 1, while $V_\mathrm{R} = g_\mathrm{L} = g_\mathrm{R} = 0$ at the tree level. Using this formalism, the polarization fractions can be translated into the couplings V_L, V_R, g_L, and g_R (as discussed e.g. in ref. [49]). The two independent W boson polarization measurements, F_0 and F_L, cannot fully constrain the four tWb couplings. Therefore additional assumptions have to be made. Figure 3 shows the limits on the left- and right-handed tensor couplings,

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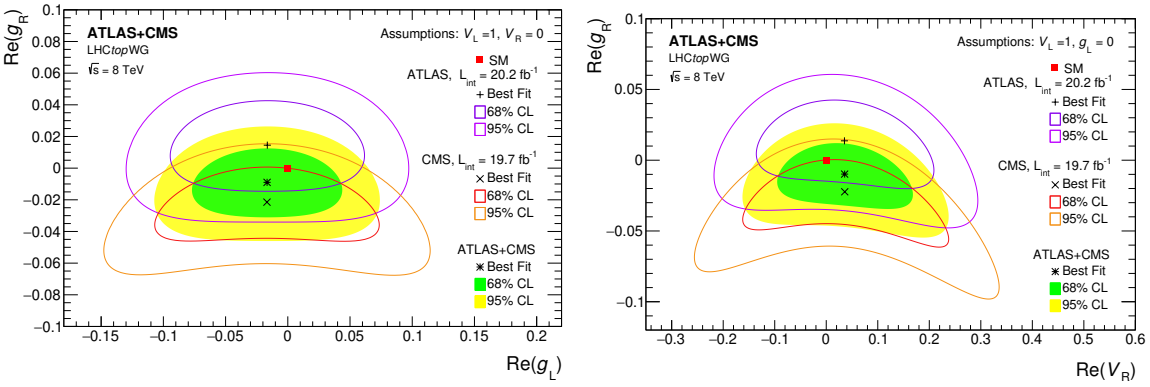

Figure 3. Allowed regions for the tWb anomalous (left) left- and right-handed tensor couplings, and (right) right-handed vector and tensor coupling. The limits are obtained from the ATLAS, CMS, and the combined measurements of the W boson polarization fractions at 68 and 95% CL. The limits from CMS are obtained using the pre-combined result of all CMS input measurements. The anomalous couplings are assumed to be real.

	95% CL interval		
Coupling	ATLAS	CMS	ATLAS+CMS combination
$\mathrm{Re}(V_\mathrm{R})$	$[-0.17, 0.25]$	$[-0.12, 0.16]$	$[-0.11, 0.16]$
$\mathrm{Re}(g_\mathrm{L})$	$[-0.11, 0.08]$	$[-0.09, 0.06]$	$[-0.08, 0.05]$
$\mathrm{Re}(g_\mathrm{R})$	$[-0.03, 0.06]$	$[-0.06, 0.01]$	$[-0.04, 0.02]$

Table 8. Allowed ranges for the anomalous couplings V_R, g_L, and g_R at 95% CL. The limit on each coupling is obtained while fixing all other couplings to their SM value. The limits from CMS are obtained using the pre-combined result of all CMS input measurements. The anomalous couplings are assumed to be real.

while the other couplings are fixed to their SM values, as well as limits on the right-handed vector and tensor couplings, with the other couplings fixed to their SM values. Limits on these anomalous couplings are set using the EFT*fitter* tool [50]. The anomalous couplings are assumed to introduce no additional CP violation, and are taken to be real. The allowed regions at 68 and 95% CL and the most probable couplings values are shown, as derived from the measured polarization fractions reported in refs. [5, 6], and from the combined results presented in this paper. A second region allowed by the W boson polarization measurements around $\mathrm{Re}(g_\mathrm{R}) = 0.8$ is excluded by the single top quark cross section measurements [51, 52], and therefore is not shown in this figure. Table 8 shows the 95% CL intervals for each anomalous coupling, while fixing all others to their SM values. These limits correspond to the set of smallest intervals containing 95% of the marginalized posterior distribution for the corresponding parameter.

In a similar way, limits are set in terms of Wilson coefficients. In this second approach, effects of beyond-the-SM physics at a high scale Λ are described by an effective Lagrangian [47, 53–56] as

$$-L^\mathrm{eff} = \mathcal{L}^\mathrm{SM} + \Sigma_x \frac{C_x}{\Lambda^2} O_x + \mathcal{O}\left(\frac{1}{\Lambda^3}\right) + \cdots \tag{5.2}$$

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	95% CL interval		
Coefficient	ATLAS	CMS	ATLAS+CMS combination
$C^*_{\phi\phi}$	$[-5.64, 7.68]$	$[-3.84, 4.92]$	$[-3.48, 5.16]$
C^*_{bW}	$[-1.30, 0.96]$	$[-1.06, 0.72]$	$[-0.96, 0.67]$
C_{tW}	$[-0.34, 0.67]$	$[-0.62, 0.19]$	$[-0.48, 0.29]$

Table 9. Allowed ranges for the Wilson coefficients $C^*_{\phi\phi}$, C^*_{bW}, and C_{tW} at 95% CL. The limit on each coefficient is obtained while fixing all other coefficients to their SM values. The limits from CMS are obtained using the pre-combined result of all CMS input measurements. The numerical values are obtained by setting the Λ scale to 1 TeV, and the coefficients are assumed to be real.

where O_x are dimension-six gauge-invariant operators and C_x are the complex constants known as Wilson coefficients that give the strength of the corresponding operator. Only dimension-six operators are considered in this analysis. The relevant operators affecting the general effective tWb vertex can be found, e.g. in ref. [56]. Three of these operators are of particular interest, since the measurement of the W boson polarization is able to constrain their corresponding Wilson coefficients. These operators are:

$$\begin{aligned} O_{\phi\phi} &= \mathrm{i}(\tilde{\phi}^\dagger D_\mu \phi)(\bar{\mathrm{t}}_\mathrm{R}\gamma^\mu \mathrm{b}_\mathrm{R}), \\ O_{\mathrm{tW}} &= (\bar{\mathrm{q}}_\mathrm{L}\sigma^{\mu\nu}\tau^I \mathrm{t}_\mathrm{R})\tilde{\phi}\mathrm{W}^I_{\mu\nu}, \quad \text{and} \\ O_{\mathrm{bW}} &= (\bar{\mathrm{q}}_\mathrm{L}\sigma^{\mu\nu}\tau^I \mathrm{b}_\mathrm{R})\phi\mathrm{W}^I_{\mu\nu}, \end{aligned} \tag{5.3}$$

where ϕ represents a weak doublet of the Higgs field, t_R and b_R are the weak singlets of the right-handed top and bottom quark fields, $\mathrm{q}^\mathrm{T}_\mathrm{L} = (\mathrm{t}, \mathrm{b})_\mathrm{L}$ denotes the $\mathrm{SU}(2)_\mathrm{L}$ weak doublet of the third generation left-handed quark fields, and τ^I is the usual Pauli matrix. Assuming the Wilson coefficients to be real, they can be trivially parameterized as functions of the anomalous couplings of eq. (5.1) (as shown e.g. in refs. [48, 56]), thus, as functions of the W polarization fractions. The limits on each Wilson coefficient are derived from the measured fractions, as done for the anomalous couplings, fixing all others to their SM value, i.e. to zero. They are shown at 95% CL in table 9.

6 Summary

The combination of measurements of the W boson polarization in top quark decays performed by the ATLAS and CMS collaborations is presented. The measurements are based on proton-proton collision data produced at the LHC at a centre-of-mass energy of 8 TeV, and corresponding to an integrated luminosity of about $20\,\mathrm{fb}^{-1}$ for each experiment. The fractions of W bosons with longitudinal (F_0) and left-handed (F_L) polarizations were measured in events containing a single lepton and multiple jets, enhanced in $\mathrm{t\bar{t}}$ or single top quark production processes. The results of the combination are

$$\begin{aligned} F_0 &= 0.693 \pm 0.009\,(\text{stat+bkg}) \pm 0.011\,(\text{syst}), \\ F_\mathrm{L} &= 0.315 \pm 0.006\,(\text{stat+bkg}) \pm 0.009\,(\text{syst}), \end{aligned}$$

where "stat+bkg" stands for the sum of the statistical and background determination uncertainties, and "syst" for the remaining systematic uncertainties. The fraction of W

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bosons with right-handed polarization, F_{R}, is estimated assuming that the sum of all polarization fractions equals unity, and by taking into account the correlation coefficient of the combination, -0.85. This leads to

$$F_{\mathrm{R}} = -0.008 \ \pm 0.005\,(\mathrm{stat+bkg}) \pm 0.006\,(\mathrm{syst}),$$

which corresponds to $F_{\mathrm{R}} < 0.007$ at 95% confidence level.

The results are consistent with the standard model predictions at next-to-next-to-leading-order precision in perturbative quantum chromodynamics. A limit on each anomalous tWb coupling is set while fixing all others to their standard model values, with the allowed regions being $[-0.11, 0.16]$ for V_{R}, $[-0.08, 0.05]$ for g_{L}, and $[-0.04, 0.02]$ for g_{R}, at 95% confidence level. All couplings are assumed to be real. Limits on Wilson coefficients are also derived in a similar manner.

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18: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
19: Also at University of Hamburg, Hamburg, Germany
20: Also at Brandenburg University of Technology, Cottbus, Germany
21: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary, Debrecen, Hungary
22: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
23: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary, Budapest, Hungary
24: Also at IIT Bhubaneswar, Bhubaneswar, India, Bhubaneswar, India
25: Also at Institute of Physics, Bhubaneswar, India
26: Also at G.H.G. Khalsa College, Punjab, India
27: Also at Shoolini University, Solan, India
28: Also at University of Hyderabad, Hyderabad, India
29: Also at University of Visva-Bharati, Santiniketan, India
30: Now at INFN Sezione di Bari[a], Università di Bari[b], Politecnico di Bari[c], Bari, Italy
31: Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
32: Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
33: Also at Riga Technical University, Riga, Latvia, Riga, Latvia
34: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
35: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
36: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
37: Also at Institute for Nuclear Research, Moscow, Russia
38: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
39: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
40: Also at University of Florida, Gainesville, U.S.A.
41: Also at Imperial College, London, United Kingdom
42: Also at P.N. Lebedev Physical Institute, Moscow, Russia
43: Also at California Institute of Technology, Pasadena, U.S.A.
44: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
45: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
46: Also at Università degli Studi di Siena, Siena, Italy
47: Also at INFN Sezione di Pavia[a], Università di Pavia[b], Pavia, Italy, Pavia, Italy
48: Also at National and Kapodistrian University of Athens, Athens, Greece
49: Also at Universität Zürich, Zurich, Switzerland
50: Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria, Vienna, Austria
51: Also at Burdur Mehmet Akif Ersoy University, BURDUR, Turkey
52: Also at Şirnak University, Sirnak, Turkey

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55: Also at Beykent University, Istanbul, Turkey, Istanbul, Turkey
56: Also at Istanbul Aydin University, Application and Research Center for Advanced Studies (App. & Res. Cent. for Advanced Studies), Istanbul, Turkey
57: Also at Mersin University, Mersin, Turkey
58: Also at Piri Reis University, Istanbul, Turkey
59: Also at Ozyegin University, Istanbul, Turkey
60: Also at Izmir Institute of Technology, Izmir, Turkey
61: Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey
62: Also at Marmara University, Istanbul, Turkey
63: Also at Milli Savunma University, Istanbul, Turkey
64: Also at Kafkas University, Kars, Turkey
65: Also at Istanbul Bilgi University, Istanbul, Turkey
66: Also at Hacettepe University, Ankara, Turkey
67: Also at Adiyaman University, Adiyaman, Turkey
68: Also at Vrije Universiteit Brussel, Brussel, Belgium
69: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
70: Also at IPPP Durham University, Durham, United Kingdom
71: Also at Monash University, Faculty of Science, Clayton, Australia
72: Also at Bethel University, St. Paul, Minneapolis, U.S.A., St. Paul, U.S.A.
73: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
74: Also at Bingol University, Bingol, Turkey
75: Also at Georgian Technical University, Tbilisi, Georgia
76: Also at Sinop University, Sinop, Turkey
77: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
78: Also at Nanjing Normal University Department of Physics, Nanjing, China
79: Also at Texas A&M University at Qatar, Doha, Qatar
80: Also at Kyungpook National University, Daegu, Korea, Daegu, Korea

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