

LHCTopWG : combinations of top quark results at the LHC

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LHCTopWG

- LHC Top Working Group
 - Forum for discussions (ATLAS + CMS + LHCb + theory) on combinations and interpretation of top physics results at the LHC
 - Integrated in the framework of LPCC (LHC Physics Centre at CERN)
 - So far 75 closed and 15 open meetings (2x yearly)
- Purpose(s)
 - *Main goal:* provide legacy combinations of LHC top quark results
 - Requires detailed understanding of analysis definitions, theoretical models used, categories of systematic uncertainties, correlations, etc
 - Working group structure allows to discuss / compare at deeper level than in usual meetings
 - Maintain independence, but identify ways to make definitions, presentation and systematic treatment more uniform / comparable between experiments

See <https://lpcc.web.cern.ch/lhc-top-wg-wg-top-physics-lhc>

LHCTopWG results

- Combinations of Run1 results
 - Two publications: $t\bar{t}$ charge asymmetry, single top and V_{tb}
 - *Publications in preparation*: W helicity, $t\bar{t}$ cross-section, top quark mass
 - Public notes with preliminary combinations → helped to establish techniques, categorisation of uncertainties
 - Recommendations for more uniform treatment future analysis
- Agreements and reference cross sections / configurations
 - Mapping of Jet Energy Scale and b-tagging uncertainties
 - Reference cross-sections for $t\bar{t}$ (NNLO) and single top (NLO), in close collaboration with theorist on settings and tools for calculations
- Summary plots
 - <https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots>
- Recent topics of discussion
 - Top mass interpretation, Top EFT fits, detailed comparisons between ATLAS, CMS and theory predictions (eg $t\bar{t}$ spin correlations, $p_T(t)$)

BLUE and Beyond

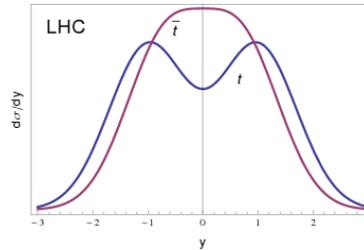
- Combination method used so far: BLUE
 - **B**est **L**inear **U**nbiased **E**stimator
 - Calculates optimal weights in linear combination of input measurements to minimise total uncertainty on combined result
 - Taking uncertainties and correlations into account
 - Well established technique, eg used before at LEP and Tevatron
- Challenges, features, limitations
 - Challenge: need to provide correlations (sometimes just a good guess)
 - BLUE can give neg. weights to correlated, less precise measurements
 - BLUE needs breakdown in independent (uncorrelated) uncertainty sources
 - BLUE does not (trivially) allow physics constraints on uncertainties. A full likelihood fit (as in Higgs combination) could do that, but so far not feasible given the different statistical analysis setups in ATLAS and CMS
- Beyond Blue
 - Considering other techniques for some future combinations
 - Allow any correlation between uncertainty sources in input measurements

Charge asymmetry in $t\bar{t}$

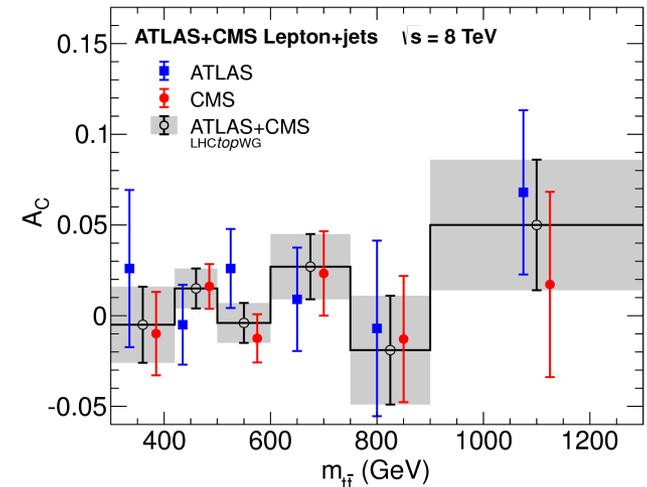
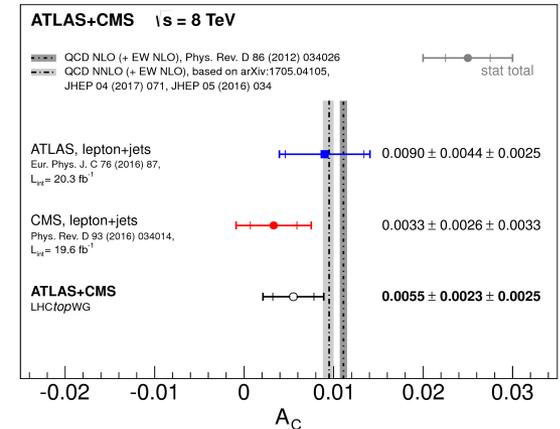
Combination of inclusive and differential $t\bar{t}$ charge asymmetry measurements using ATLAS and CMS data at 7 and 8 TeV

$$A_C = \frac{N^{\Delta|y|>0} - N^{\Delta|y|<0}}{N^{\Delta|y|>0} + N^{\Delta|y|<0}}$$

$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$



- First LHCTopWG publication
- And our first combination including a differential distribution
 - BLUE method + estimates for bin-to-bin correlations between experiments
- Worthwhile improvements wrt inputs, in each case:
 - 7 TeV inclusive 18% - 40%
 - 8 TeV inclusive 17% - 32%
 - 8 TeV differential 9% - 52%

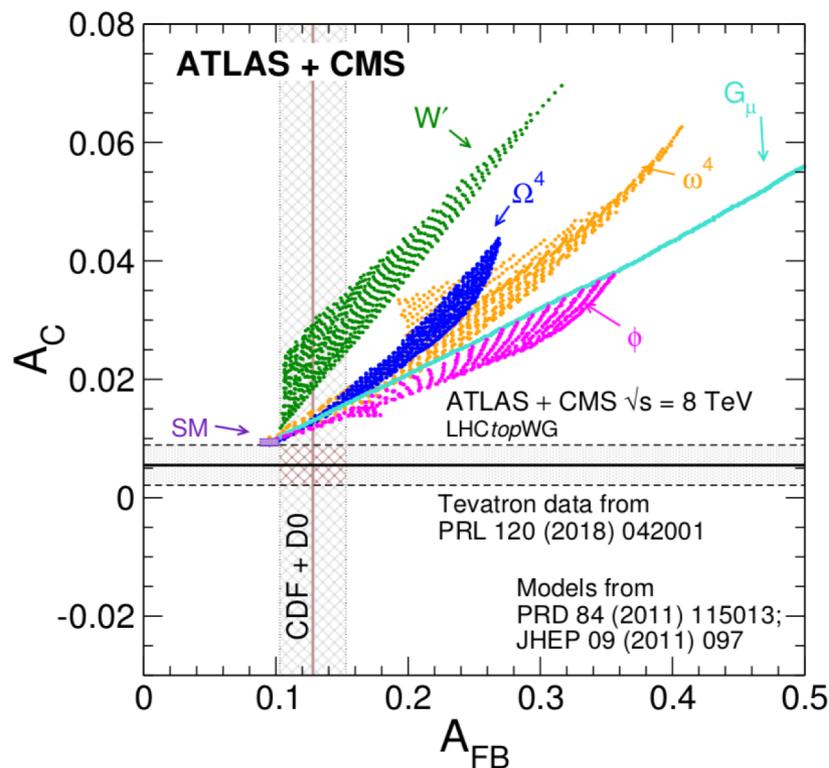
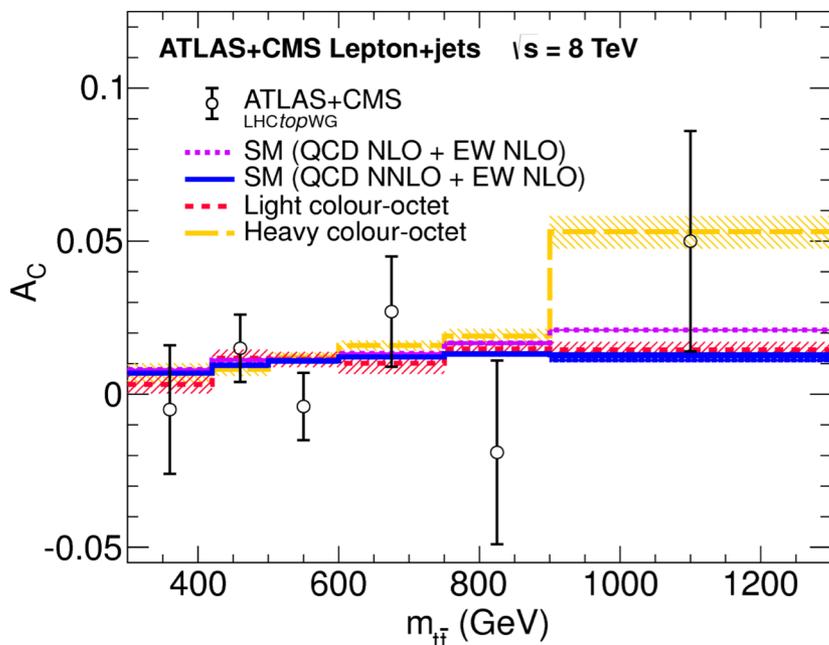


$$A_C^{\text{LHC7}} = 0.005 \pm 0.007 \text{ (stat)} \pm 0.006 \text{ (syst)}$$

$$A_C^{\text{LHC8}} = 0.0055 \pm 0.0023 \text{ (stat)} \pm 0.0025 \text{ (syst)}$$

Charge asymmetry in $t\bar{t}$

- Dedicated NNLO theory predictions provided (thanks!)
- Both Tevatron A_{FB} and LHC A_C consistent with SM, excluding phase space for a number of BSM models



New: Single top and V_{tb}

[JHEP05\(2019\)088](#)

[arXiv:1902.07158](#)

“Combinations of single-top-quark production cross-section measurements and $|f_{LV}V_{tb}|$ determinations at 7 and 8 TeV with the ATLAS and CMS experiments”

\sqrt{s}	Process	ATLAS		CMS	
		σ [pb]	Lumi. [fb^{-1}]	σ [pb]	Lumi. [fb^{-1}]
7 TeV	t -channel	68 ± 8	4.59	67.2 ± 6.1	1.17–1.56
	tW	16.8 ± 5.7	2.05	16^{+5}_{-4}	4.9
	s -channel	—	—	7.1 ± 8.1	5.1
8 TeV	t -channel	$89.6^{+7.1}_{-6.3}$	20.2	83.6 ± 7.8	19.7
	tW	$23.0^{+3.6}_{-3.9}$	20.3	23.4 ± 5.4	12.2
	s -channel	$4.8^{+1.8}_{-1.5}$	20.3	13.4 ± 7.3	19.7

$$|f_{LV}V_{tb}| = \sqrt{\frac{\sigma_{\text{meas.}}}{\sigma_{\text{theo.}} (V_{tb}=1)}}$$

- Inputs to the combination: t -channel, tW , s -channel at 7 and 8 TeV
- Combine cross-section measurements per mode and per \sqrt{s}
- Single top production rate proportional to square of tWb coupling, providing direct sensitivity to V_{tb} , without assumptions on unitarity of CKM matrix or number of quark generations
- f_{LV} is form factor (=1 in SM), describing possible anomalous couplings

New: Single top and V_{tb}

Uses “iterative BLUE”

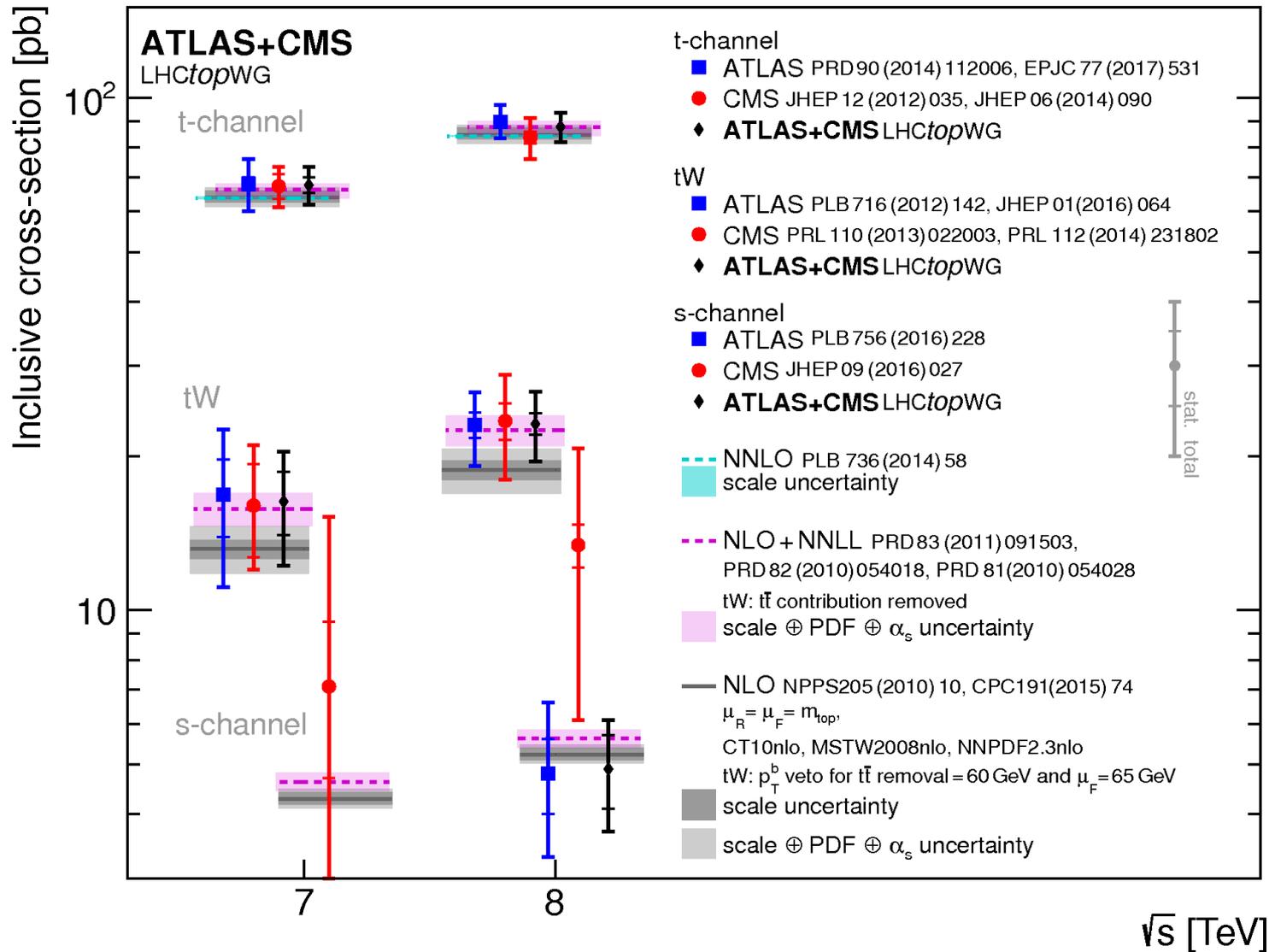
- Takes into account dependence of some uncertainties on central value
- Detailed mapping of uncertainties, and correlations [see *backup*]
- Stability checks to test effect of different correlation assumptions
- Improvements in overall precision: 4-8% (t-channel) and 5-11% (tW)

Examples of uncertainty breakdown after combination:

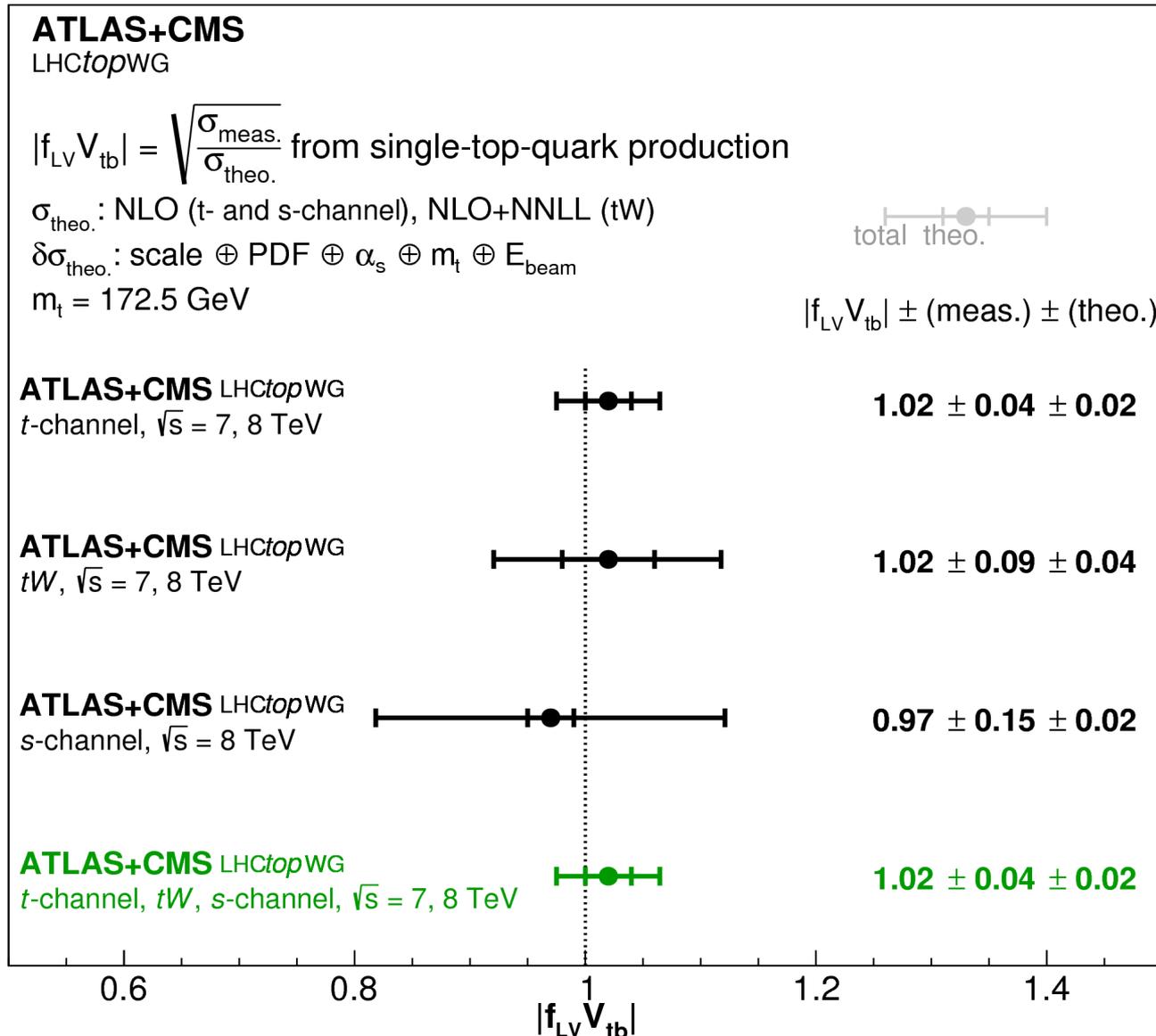
$\sigma_{t\text{-chan.}}, \sqrt{s} = 8 \text{ TeV}$		
Combined cross-section	87.7 pb	
Uncertainty category	Uncertainty	
	[%]	[pb]
Data statistical	1.3	1.1
Simulation statistical	0.6	0.5
Integrated luminosity	1.7	1.5
Theory modelling	5.3	4.7
Background normalisation	1.2	1.1
Jets	2.6	2.3
Detector modelling	1.8	1.6
Total syst. unc. (excl. lumi.)	6.3	5.5
Total syst. unc. (incl. lumi.)	6.5	5.7
Total uncertainty	6.7	5.8

Combined $ f_{LV}V_{tb} ^2$	1.05	
Uncertainty category	Uncertainty	
	[%]	$\Delta f_{LV}V_{tb} ^2$
Data statistical	1.8	0.02
Simulation statistical	0.9	0.01
Integrated luminosity	1.3	0.01
Theory modelling	4.5	0.05
Background normalisation	1.3	0.01
Jets	2.6	0.03
Detector modelling	1.6	0.02
Top-quark mass	0.7	0.01
Theoretical cross-section	4.3	0.04
Total syst. unc. (excl. lumi.)	7.1	0.07
Total syst. unc. (incl. lumi.)	7.2	0.08
Total uncertainty	7.4	0.08

Combined cross sections



Determination of V_{tb}



Top quark mass: status

1. First combination of Tevatron and LHC measurements of the top-quark mass

ATLAS and CDF and CMS and D0 Collaborations. Mar 18, 2014. 34 pp.

ATLAS-CONF-2014-008, CDF-NOTE-11071, CMS-PAS-TOP-13-014, D0-NOTE-6416, FERMILAB-TM-2582-E

e-Print: [arXiv:1403.4427](https://arxiv.org/abs/1403.4427) [hep-ex] | [PDF](#)

[References](#) | [BibTeX](#) | [LaTeX\(US\)](#) | [LaTeX\(EU\)](#) | [Harvmac](#) | [EndNote](#)

[CERN Document Server](#); [ADS Abstract Service](#); [OSTI.gov Server](#); [Interactions.org article](#); [Fermilab Today Result of the Week](#)

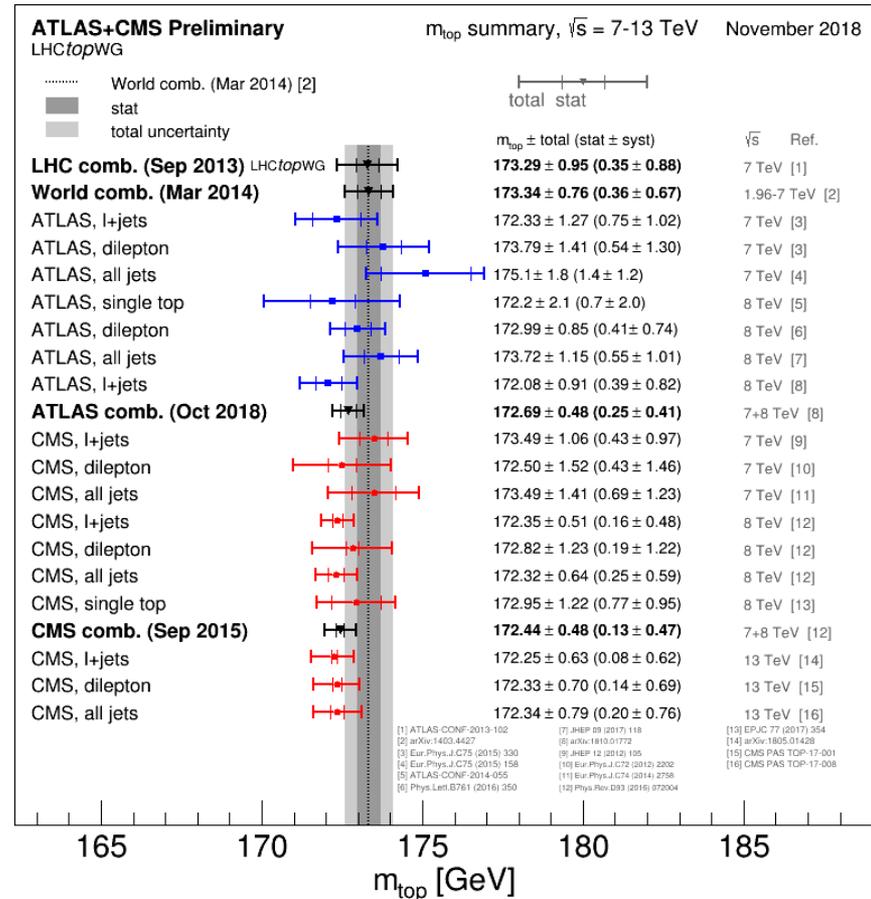
[Detailed record - Cited by 597 records](#) 500+

World Average

- Our most popular combination...!
- Superseded by more recent results at LHC and Tevatron

Plan for new combinations

- LHC: complete set of Run1 results now available
- Perform LHC combination first (detailed mapping uncertainties ready)
- Then update world average including final Tevatron top-quark mass
- Constructive discussions about theoretical interpretation

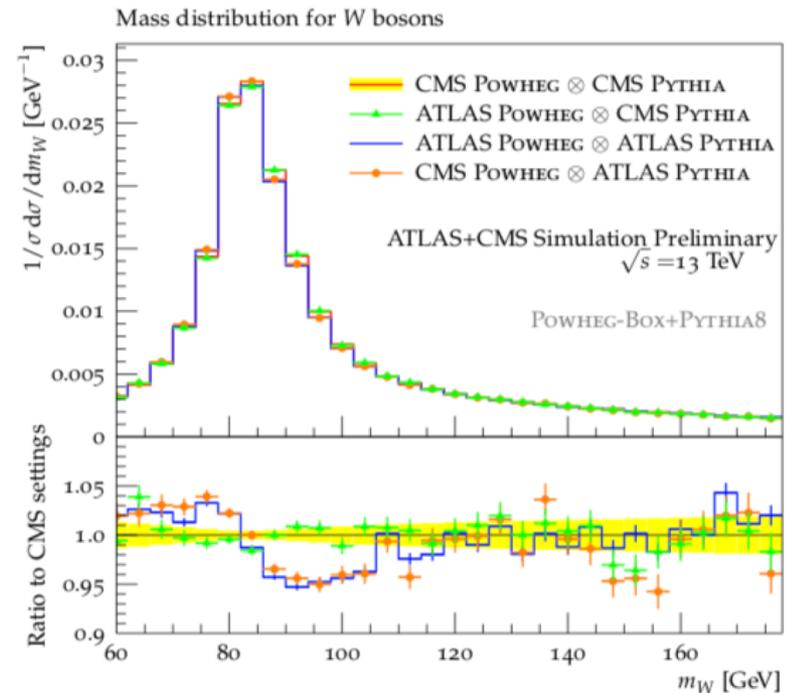


Combinations in preparation

- Legacy Run 1 LHC publications:
 - W helicity in $t\bar{t}$ and limits on anomalous couplings and EFT
 - $t\bar{t}$ inclusive cross section and extraction of top pole mass
 - Top quark mass combination, first LHC and then World Average
 - Differential $t\bar{t}$ distributions
- Towards Run 2 combinations:
 - Public notes of intermediate results possible now, but longer timescale for legacy publications as ATLAS and CMS full-Run2 analyses still in progress
 - Plan to perform preliminary ATLAS+CMS combination of $\Delta\phi$ (II) distribution in di-lepton $t\bar{t}$ events
 - Sensitive to $t\bar{t}$ spin correlations, and in focus recently because of reported differences wrt theoretical predictions
 - Useful exercise to practice mapping of Run2 systematic uncertainties
 - Still open question for which observables Run2 combination will prove most useful – depends on statistical and systematic uncertainties + correlations

Other working group activities

- Top quark observables and Effective Field Theory
 - Active discussions in recent Open LHCTopWG meetings, with contributions both from theory and experimental side
 - How to optimize analyses for sensitivity to top-quark related EFT operators, and present results to allow global fits
 - Public note with first recommendations from theory: CERN-LPCC-2018-01, [arXiv:1802.07237](https://arxiv.org/abs/1802.07237)
 - + proposal for validation of EFT codes: CERN-LPCC-2019-02, [arXiv:1906.12310](https://arxiv.org/abs/1906.12310)
- Quest for a common MC sample
 - Common MC sample(s) propagated to ATLAS and CMS analyses
 - Benchmark for detailed, direct comparisons configs. & effects
 - Ongoing; first plots available
 - [ATL-PHYS-PUB-2019-021](https://arxiv.org/abs/1902.021), [CMS-DP-2019-011](https://arxiv.org/abs/1901.011)



Conclusions

- First combinations of LHC top measurements published !
 - Two ATLAS+CMS combinations of Run1 top measurements published so far, and several others in preparation
 - Useful improvements in precision
 - Single Run1 "legacy" result for top quark observables
 - Requires/allows deeper understanding and scrutiny of input results
- Fruitful discussions in the working group
 - Discuss theory models and interpretations with world experts
 - Best practices for presentation, theory definitions and models
 - Compare and match systematics prescriptions ATLAS and CMS
- Please join our open LHCTopWG meetings!
 - All meetings <https://indico.cern.ch/category/9219/>
 - Open mailing list: lhc-toplhwcg@cern.ch

BACKUP slides

Single top and V_{tb}

More plots ATLAS link:

<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TOPQ-2017-16/>

CMS link: <http://cms-results.web.cern.ch/cms-results/public-results/publications/TOP-17-006/>

Details of systematic uncertainty mapping (example: 8 TeV t-channel combination)

[JHEP05\(2019\)088](#)

[arXiv:1902.07158](#)

	ATLAS ($\sigma_{t\text{-chan.}}, \sqrt{s} = 8 \text{ TeV}$)		CMS ($\sigma_{t\text{-chan.}}, \sqrt{s} = 8 \text{ TeV}$)		
Cross-section	89.6 pb		83.6 pb		
Uncertainty category	Uncertainty		Uncertainty		ρ
Data statistical		1.4%		2.7%	0.0
Simulation statistical		0.8%		0.7%	0.0
Integrated luminosity		1.9%		2.6%	0.3
Theory modelling	Ren./fact. scales	3.6%	Ren./fact. scales	1.9%	1.0
	NLO match.	3.3%	NLO match., 4FS vs 5FS	4.9%	1.0
	Parton shower	2.1%			1.0
	PDF	1.3%	PDF	1.9%	1.0
Category subtotal		5.5%		5.6%	0.84
Background norm.	$t\bar{t}$, tW and s -chan. norm.	0.1%	$t\bar{t}$ and W +jets norm.	2.2%	0.0
	Other bkg. from MC: norm.	0.9%	Other bkg. from MC: norm.	0.3%	0.0
	Bkg. from MC/data: multijet norm.	0.3%	Bkg. from data: multijet norm.	2.3%	0.0
Category subtotal		1.0%		3.2%	0.0
Jets	JES common	3.2%	JES	4.2%	0.0
	JES flavour	0.2%			0.0
	JetID	0.1%			0.0
	JER	0.4%	JER	0.7%	0.0
Category subtotal		3.2%		4.3%	0.0
Detector modelling	Lepton modelling	1.9%	Lepton modelling	0.6%	0.0
	E_T^{miss} scale	0.4%	E_T^{miss} modelling	0.3%	0.0
	E_T^{miss} resolution	0.2%			0.0
	b -tag	1.1%	b -tag	2.5%	0.0
	Pile-up	0.3%	Pile-up	0.7%	0.0
Category subtotal		2.3%		2.7%	0.0
Total uncertainty		7.3%		9.0%	0.42

Single top and V_{tb}

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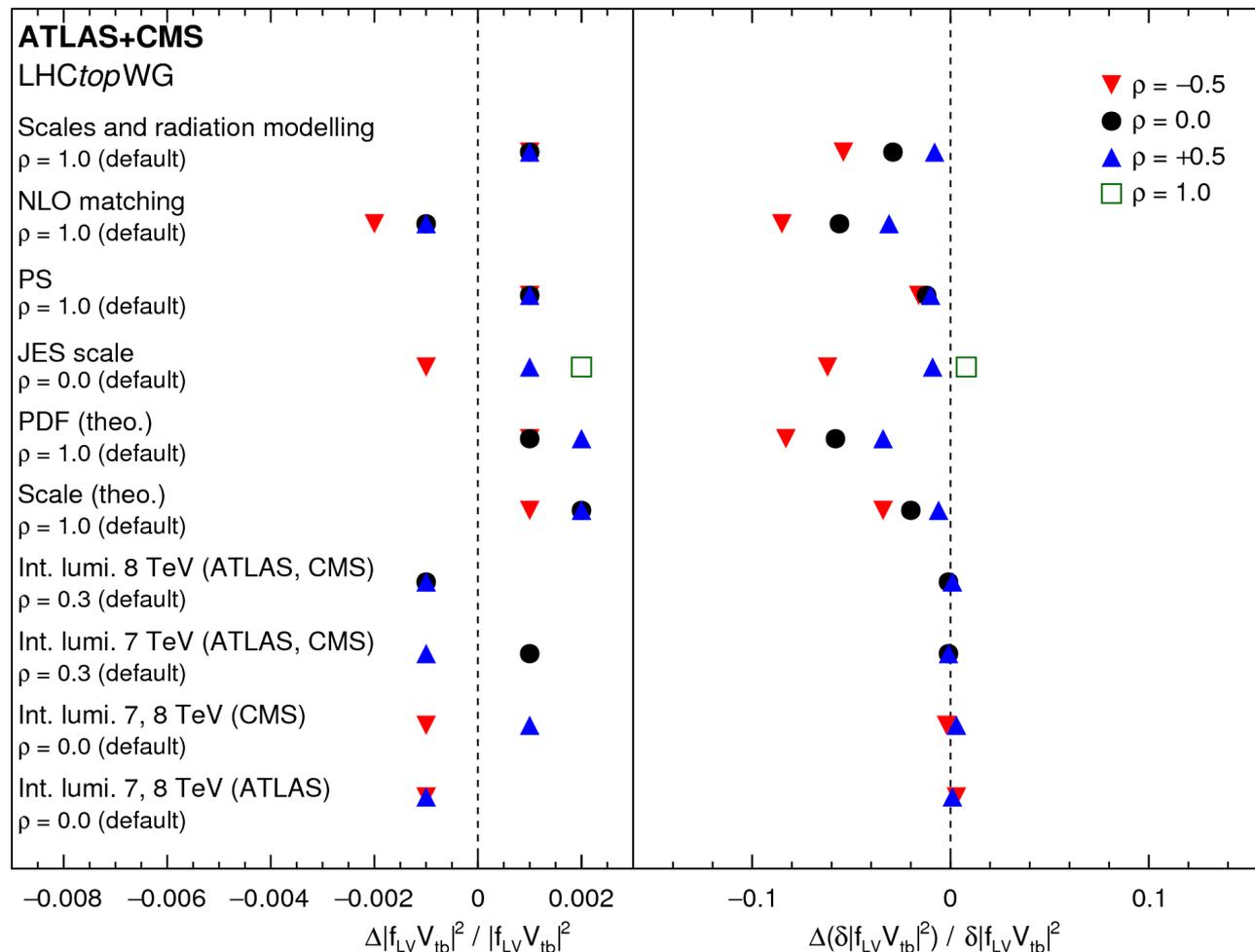
CMS link: <http://cms-results.web.cern.ch/cms-results/public-results/publications/TOP-17-006/>

Stability of correlation assumptions

- Relative change in central value (left) and final uncertainty (right)

[JHEP05\(2019\)088](#)

[arXiv:1902.07158](#)



Single top and V_{tb}

Inputs for $|f_{LV} V_{tb}|^2$ combination:

	<i>t</i> -channel ATLAS 8 TeV	<i>t</i> -channel CMS 8 TeV	<i>t</i> -channel ATLAS 7 TeV	<i>t</i> -channel CMS 7 TeV	<i>tW</i> ATLAS 8 TeV	<i>tW</i> CMS 8 TeV	<i>tW</i> ATLAS 7 TeV	<i>tW</i> CMS 7 TeV	<i>s</i> -channel ATLAS 8 TeV
$ f_{LV} V_{tb} ^2$	1.06	0.99	1.06	1.05	1.03	1.05	1.07	1.02	0.92
Uncertainties:									
Data statistical	0.01	0.03	0.03	0.06	0.06	0.09	0.18	0.21	0.15
Simulation statistical	0.01	0.01	0.02	0.02	0.01	0.03	0.02	–	0.11
Integrated luminosity	0.02	0.03	0.02	0.02	0.05	0.03	0.07	0.04	0.05
Theory modelling									
ISR/FSR, ren./fact. scale	0.04	0.02	0.03	0.04	0.09	0.13	0.05	0.03	0.06
NLO match., generator	0.03	0.05	0.02	0.04	0.03	–	0.11	–	0.10
Parton shower	0.02	–	–	0.01	0.02	0.15	0.16	0.10	0.02
PDF	0.01	0.02	0.03	0.01	0.01	0.02	0.02	0.02	0.03
DS/DR scheme	–	–	–	–	0.04	0.02	–	0.06	–
Top-quark p_T rew.	–	–	–	–	–	<0.01	–	–	–
Background normalisation									
Top-quark bkg.	<0.01	0.02	0.02	0.01	0.02	0.02	0.06	0.06	0.05
Other bkg. from sim.	0.01	<0.01	<0.01	0.03	0.02	0.03	0.09	0.04	0.05
Bkg. from data	<0.01	0.02	0.01	0.01	<0.01	–	0.02	–	0.01
Jets									
JES common	0.03	0.04	0.08	0.01	0.05	0.04	0.17	0.15	0.05
JES flavour	<0.01	–	0.02	–	0.02	–	–	–	0.01
JetID	<0.01	–	0.01	–	<0.01	–	0.05	–	0.01
JER	<0.01	0.01	0.02	<0.01	0.07	0.01	0.02	0.04	0.11
Detector modelling									
Leptons	0.02	0.01	0.03	0.04	0.03	0.02	0.07	0.05	0.02
HLT (had. part)	–	–	–	0.02	–	–	–	–	–
E_T^{miss} scale	<0.01	<0.01	0.03	<0.01	0.06	<0.01	–	0.03	0.01
E_T^{miss} res.	<0.01	–	–	–	<0.01	–	–	–	0.01
<i>b</i> -tag	0.01	0.02	0.04	0.02	0.01	0.01	–	0.02	0.07
Pile-up	<0.01	0.01	<0.01	0.01	0.03	<0.01	0.11	0.01	0.01
Top-quark mass	0.01	<0.01	0.01	–	0.05	0.05	–	–	–
Theoretical cross-section									
PDF+ α_s	0.03	0.03	0.04	0.04	0.06	0.07	0.08	0.07	0.03
Ren./fact. scale	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02
Top-quark mass	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02
E_{beam}	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Total systematic uncertainty	0.09	0.09	0.13	0.10	0.18	0.23	0.34	0.24	0.24
Total uncertainty	0.09	0.10	0.13	0.12	0.19	0.24	0.38	0.32	0.28

Single top and V_{tb}

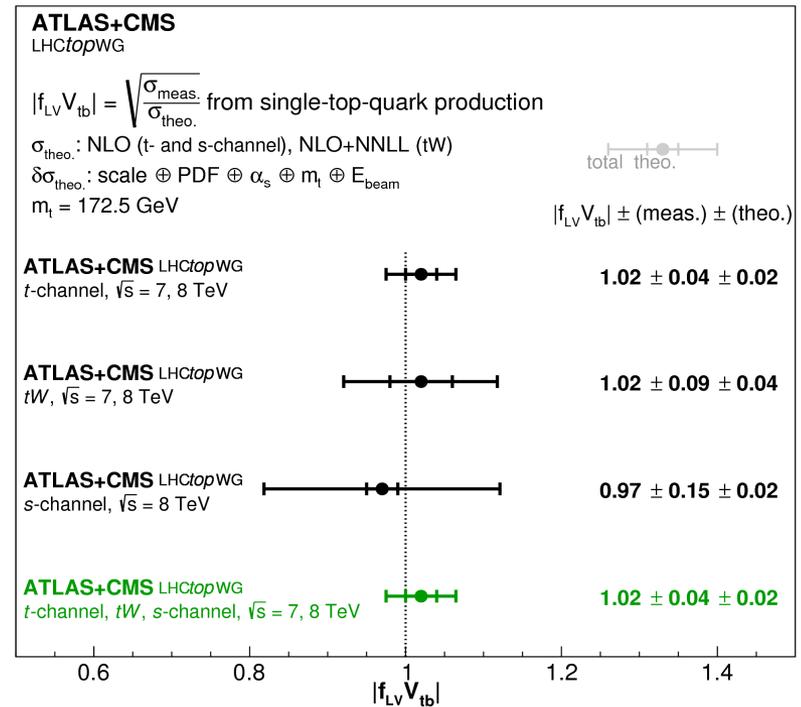
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CMS link: <http://cms-results.web.cern.ch/cms-results/public-results/publications/TOP-17-006/>

BLUE weights in the overall $|f_{LV}V_{tb}|^2$ combination

Process	\sqrt{s}	Experiment	BLUE weight
t -channel	8 TeV	ATLAS	0.56
		CMS	0.27
	7 TeV	ATLAS	0.07
		CMS	0.15
tW	8 TeV	ATLAS	0.05
		CMS	-0.04
	7 TeV	ATLAS	-0.02
		CMS	0.02
s -channel	8 TeV	ATLAS	-0.07



Single top and V_{tb}

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Theory predictions used :

Predicted cross-sections for single-top-quark production at $\sqrt{s}=7$ and 8 TeV at the LHC. Uncertainties include scale and PDF+ α_s variations, except for the NNLO predictions, which only contain the scale variation. The PDF+ α_s uncertainties are evaluated according to the PDF4LHC prescription only for the NLO predictions. The uncertainties associated with the top-quark mass m_t and beam energy E_{beam} are also given for the NLO predictions for the t- and s-channels, and for the NLO+NNLL prediction for tW production. The value of m_t is set to 172.5 GeV in all predictions. The cross-sections marked with † are those used in the $f_{LV}V_{tb}$ combination.

\sqrt{s}	Process	Accuracy	$\sigma_{\text{theo.}}$ [pb]
7 TeV	t-channel	NLO [†]	$63.9_{-1.3}^{+1.9}$ (scale) ± 2.2 (PDF+ α_s) ± 0.7 (m_t) ± 0.1 (E_{beam})
		NLO+NNLL	$64.6_{-1.7}^{+2.6}$ (scale+PDF+ α_s)
		NNLO	$63.7_{-0.3}^{+0.5}$ (scale)
	tW	NLO	$13.2_{-0.6}^{+0.5}$ (scale) ± 1.3 (PDF+ α_s)
		NLO+NNLL [†]	15.74 ± 0.40 (scale) $_{-1.14}^{+1.10}$ (PDF+ α_s) ± 0.28 (m_t) ± 0.04 (E_{beam})
	s-channel	NLO [†]	$4.29_{-0.10}^{+0.12}$ (scale) ± 0.14 (PDF+ α_s) ± 0.10 (m_t) ± 0.01 (E_{beam})
NLO+NNLL		$4.63_{-0.18}^{+0.20}$ (scale+PDF+ α_s)	
8 TeV	t-channel	NLO [†]	$84.7_{-1.7}^{+2.6}$ (scale) ± 2.8 (PDF+ α_s) ± 0.8 (m_t) ± 0.2 (E_{beam})
		NLO+NNLL	$87.8_{-1.9}^{+3.4}$ (scale+PDF+ α_s)
		NNLO	$84.2_{-0.2}^{+0.3}$ (scale)
	tW	NLO	$18.77_{-0.82}^{+0.77}$ (scale) ± 1.70 (PDF+ α_s)
		NLO+NNLL [†]	22.37 ± 0.60 (scale) ± 1.40 (PDF+ α_s) ± 0.38 (m_t) ± 0.06 (E_{beam})
	s-channel	NLO [†]	$5.24_{-0.12}^{+0.15}$ (scale) ± 0.16 (PDF+ α_s) ± 0.12 (m_t) ± 0.01 (E_{beam})
NLO+NNLL		5.61 ± 0.22 (scale+PDF+ α_s)	