Combinations of LHC Run I single-top quark measurements

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LHC*top*WG open meeting
28–29 May 2019, CERN

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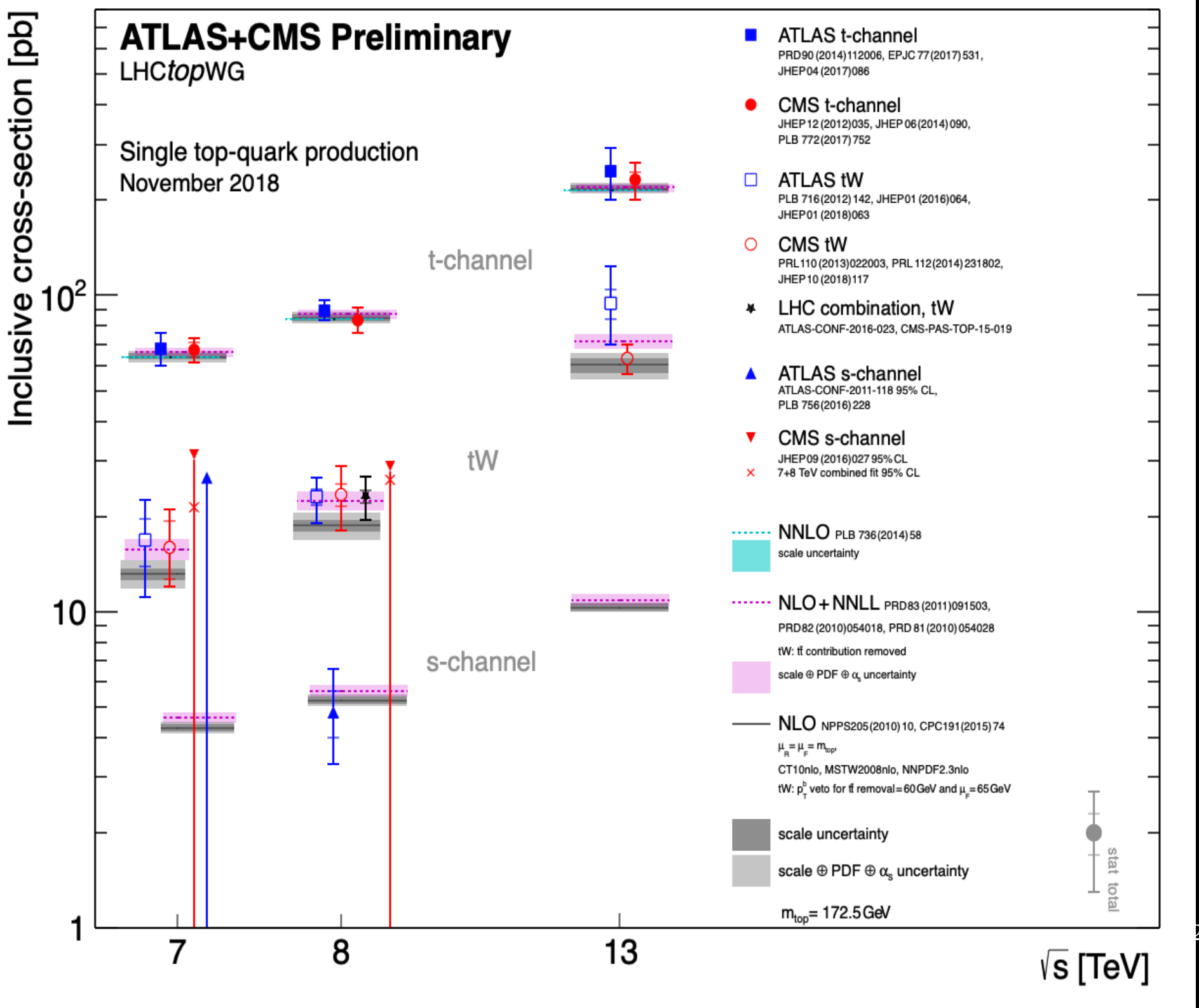
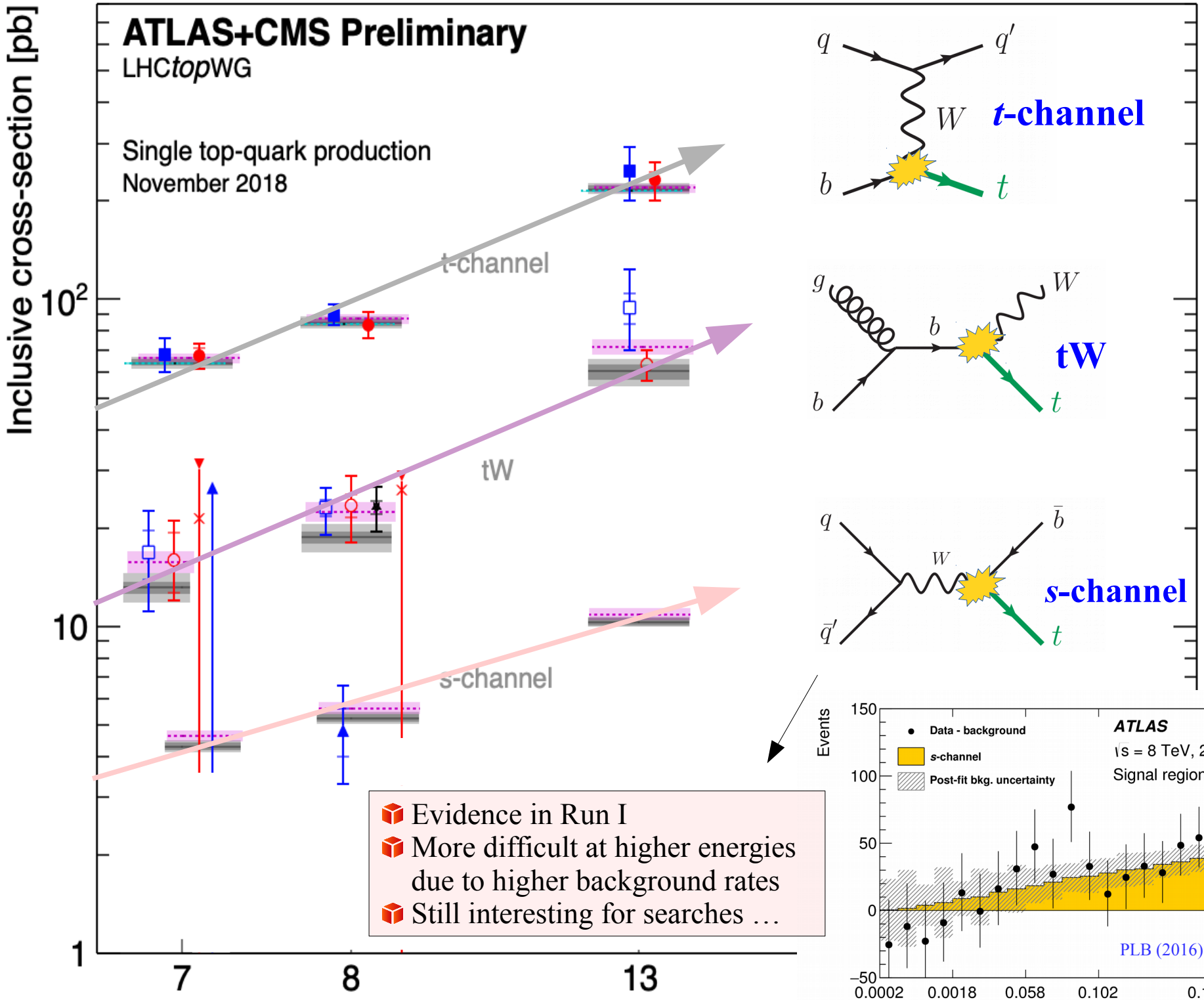
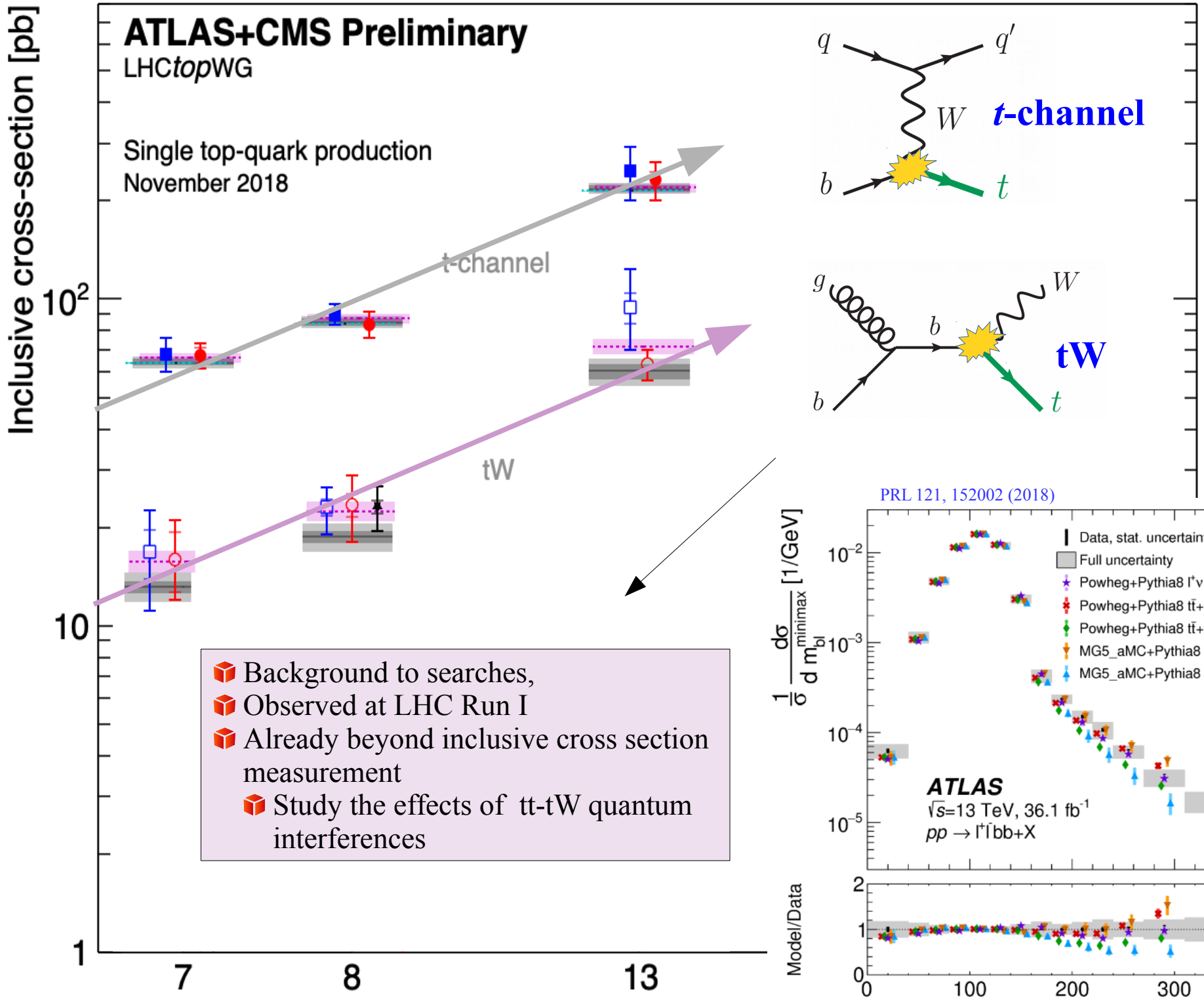

ATLAS+CMS Preliminary
LHCtopWG
Single top-quark production
November 2018
Inclusive cross-section [pb]
t-channel
tW
s-channel
ATLAS t-channel
PRD90 (2014) 112006, EPJC 77 (2017) 531, JHEP04 (2017) 086
CMS t-channel
JHEP12 (2012) 035, JHEP 06 (2014) 090, PLB 772 (2017) 752
ATLAS tW
PLB 716 (2012) 142, JHEP01 (2016) 064, JHEP01 (2018) 063
CMS tW
PRL110 (2013) 022003, PRL 112 (2014) 231802, JHEP10 (2018) 117
LHC combination, tW
ATLAS-CONF-2016-023, CMS-PAS-TOP-15-019
ATLAS s-channel
ATLAS-CONF-2011-118 95% CL, PLB 756 (2016) 228
CMS s-channel
JHEP09 (2016) 027 95% CL
7+8 TeV combined fit 95% CL
NNLO PLB 736 (2014) 58
scale uncertainty
NLO+NNLL PRD83 (2011) 091503, PRD82 (2010) 054018, PRD 81 (2010) 054028
tW: tt̄ contribution removed
scale ⊕ PDF ⊕ αs uncertainty
NLO NPPS205 (2010) 10, CPC191 (2015) 74
μR = μF = mtop,
CT10nlo, MSTW2008nlo, NNPDF2.3nlo
tW: pTb veto for tt̄ removal = 60 GeV and μF = 65 GeV
scale uncertainty
scale ⊕ PDF ⊕ αs uncertainty
mtop = 172.5 GeV
stat total
√s [TeV]

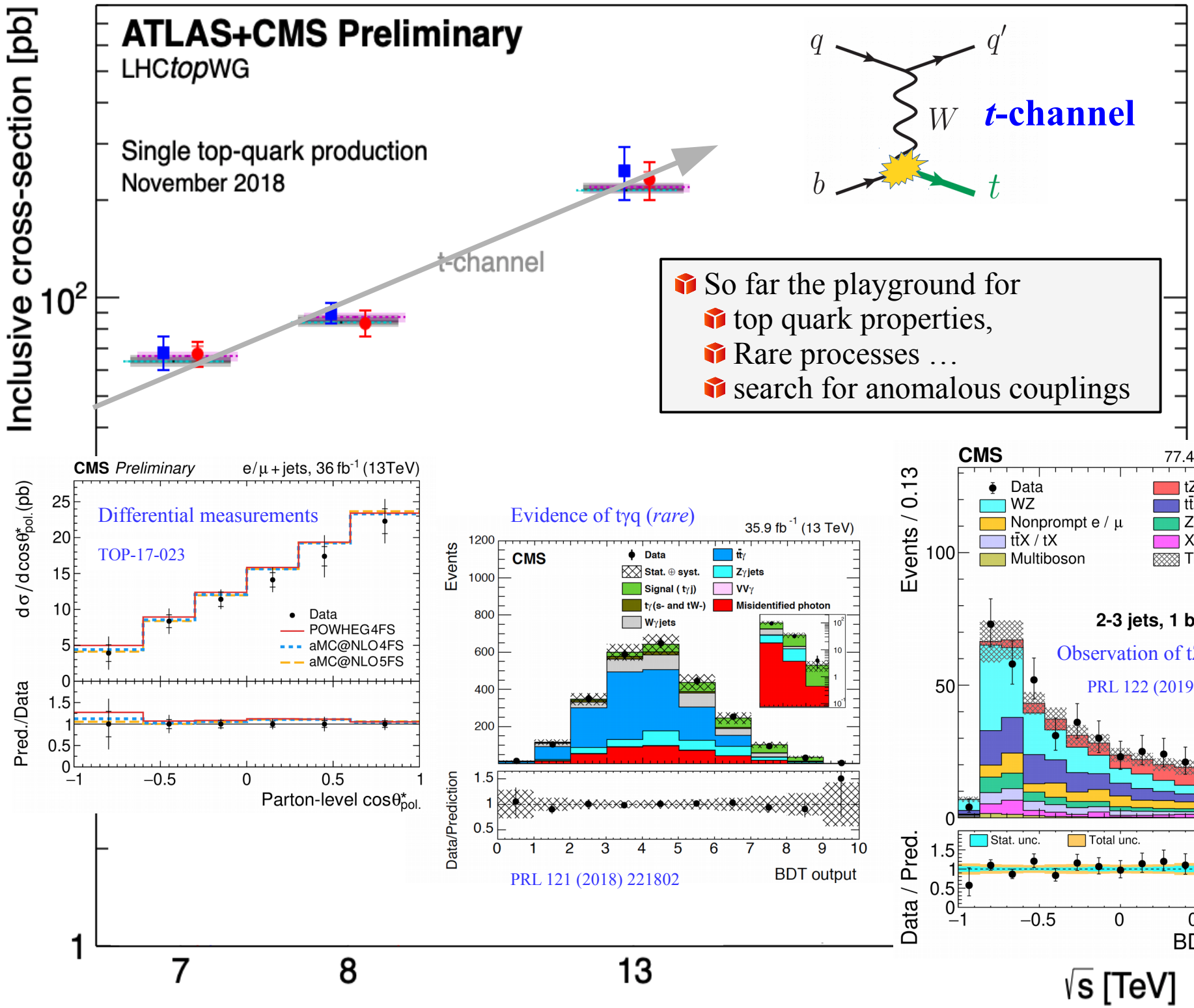


- Evidence in Run I
- More difficult at higher energies due to higher background rates
- Still interesting for searches …



- Background to searches,
- Observed at LHC Run I
- Already beyond inclusive cross section measurement
  - Study the effects of tt-tW quantum interferences

PRL 121, 152002 (2018)



- So far the playground for
  - top quark properties,
  - Rare processes …
  - search for anomalous couplings

Focus of the talk

JHEP

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

The ATLAS and CMS collaborations

E-mail: atlas.publications@cern.ch, cms-publication-committee-chair@cern.ch

Abstract: This paper presents the combinations of single-top-quark production cross-section measurements by the ATLAS and CMS Collaborations, using data from LHC proton–proton collisions at $\sqrt{s} = 7$ and 8 TeV corresponding to integrated luminosities of 1.17 to 5.1 fb^{-1} at $\sqrt{s} = 7$ TeV and 12.2 to 20.3 fb^{-1} at $\sqrt{s} = 8$ TeV. These combinations are performed per centre-of-mass energy and for each production mode: t-channel, tW, and s-channel. The combined t-channel cross-sections are 67.5 ± 5.7 pb and 87.7 ± 5.8 pb at $\sqrt{s} = 7$ and 8 TeV respectively. The combined tW cross-sections are 16.3 ± 4.1 pb and 23.1 ± 3.6 pb at $\sqrt{s} = 7$ and 8 TeV respectively. For the s-channel cross-section, the combination yields 4.9 ± 1.4 pb at $\sqrt{s} = 8$ TeV. The square of the magnitude of the CKM matrix element V_{tb} multiplied by a form factor f_{LV} is determined for each production mode and centre-of-mass energy, using the ratio of the measured cross-section to its theoretical prediction. It is assumed that the top-quark-related CKM matrix elements obey the relation $|V_{td}|, |V_{ts}| \ll |V_{tb}|$. All the $|f_{\mathrm{LV}}V_{tb}|^2$ determinations, extracted from individual ratios at $\sqrt{s} = 7$ and 8 TeV, are combined, resulting in $|f_{\mathrm{LV}}V_{tb}| = 1.02 \pm 0.04$ (meas.) ± 0.02 (theo.). All combined measurements are consistent with their corresponding Standard Model predictions.

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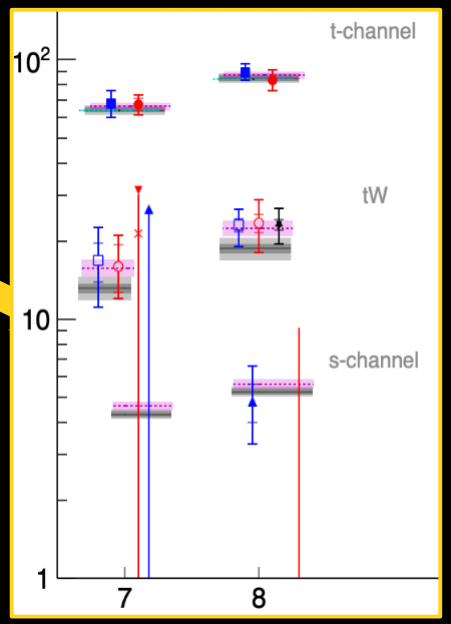
Published in JHEP on May 25th

JHEP 05 (2019) 088



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

The theory framework

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

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

- Similar theory reference is needed for the $|f_{LV}V_{tb}|$ combination
- Experiments used the most precise prediction at the time
- To date, the available results are
  - NLO and NLO+NNLL for all production modes
  - NNLO for *t*-channel

The theory framework

$\sqrt{s}$	Process	Accuracy
7 TeV	t-channel	NLO†
		NLO+NNLL
		NNLO
	tW	NLO
		NLO+NNLL†
	s-channel	NLO†
		NLO+NNLL
8 TeV	t-channel	NLO†
		NLO+NNLL
		NNLO
	tW	NLO
		NLO+NNLL†
	s-channel	NLO†
		NLO+NNLL

- The default prediction is chosen to be NLO with HATHOR
  → *configurable parameters to match the setup in CMS and ATLAS*
  - Used for *s*-channel and *t*-channel
- NLO+NNLL is used for tW
  - The tW-$t\bar{t}$ interference treatment is being developed with HATHOR
  - Different treatment than PDF4HLC for the PDF uncertainty

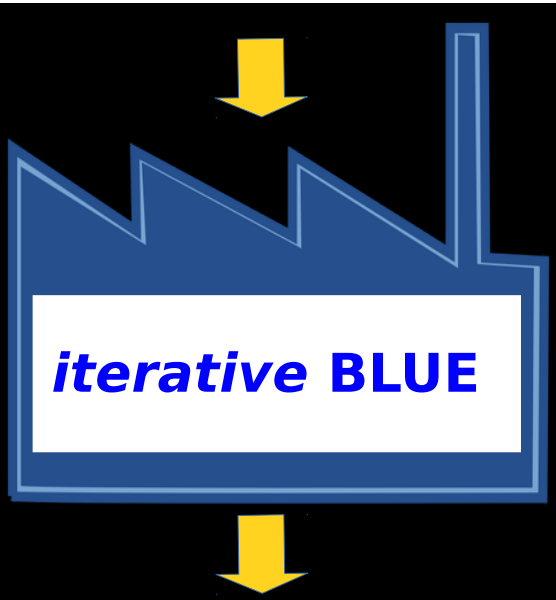
Experimental results and commonalities

		ATLAS		CMS	
$\sqrt{s}$	Process	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

- The final states contain at least one isolated lepton (e/μ) and at least one high-p_T jet
  - b-tagged jets are used to identify the top quark decay signature
- Signal extractions based on ML fit to the output of an MVA distribution except for
  - ATLAS *s*-channel: Matrix Element Method output distribution in signal region and the lepton charge in W+jets control region
  - CMS *t*-channel 8 TeV: the |η| distribution of the recoil jet plus the lepton charge
- POWHEG + PYTHIA is used for signal generation
  - $t\bar{t}$ is generated with POWHEG in ATLAS and with LO MADGRAPH in CMS

Combination method

		ATLAS		CMS	
$\sqrt{s}$	Process	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

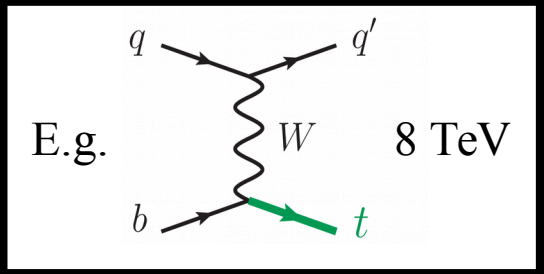


- ✓ Combined cross sections per process per E_{cm}
- ✓ Combined $|f_{LV} V_{tb}|$ from every and all processes

- BLUE: χ^2 minimization via adjusting the weights of input measurements
  - Weight sum equal to one
  - Negative weights are allowed
    → strong correlation
- Iterative to reduce possible bias from dependence of systematics on the central value
  - Convergence: change in central value < 0.01%
- Systematics scaled with cross section in each iteration
  - Data and simulation statistics are not modified
- No iteration in the s-channel combination
  - A background dominated measurement!

Various combinations

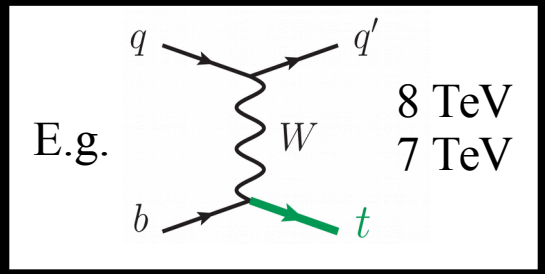
ATLAS + CMS
Same E_{cm}
Same production mode



Cross section

Combined $\sigma_{t\text{-ch}}$ at 8 TeV

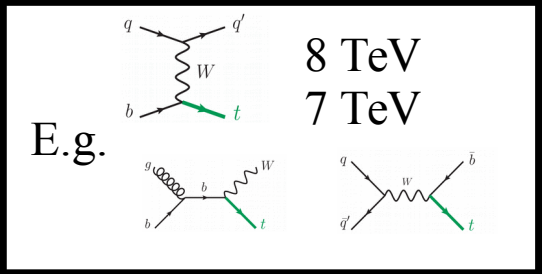
ATLAS + CMS
All E_{cm}
Same production mode



$|f_{LV}V_{tb}|$ per channel

Combined $|f_{LV}V_{tb}|$ in *t*-channel

ATLAS + CMS
All E_{cm}
All production mode

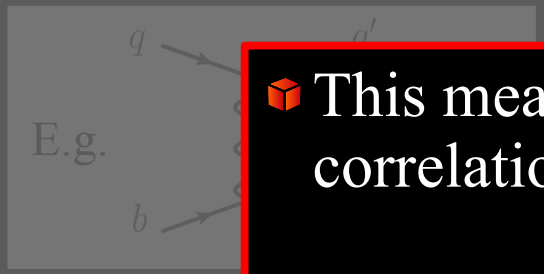


$|f_{LV}V_{tb}|$ Global

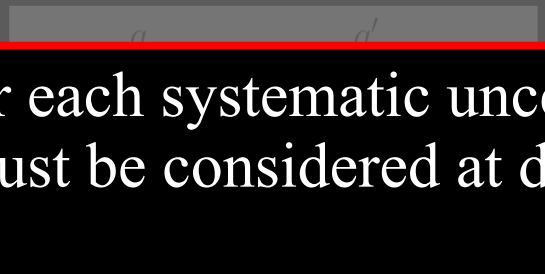
Combined $|f_{LV}V_{tb}|$

Various combinations

ATLAS + CMS
Same E_{cm}
Same production mode



ATLAS + CMS
All E_{cm}
Same production mode



ATLAS + CMS
All E_{cm}
All production mode

- This means for each systematic uncertainty, correlations must be considered at different levels
  - Between ATLAS and CMS
  - Between production modes
  - Between c.o.m energies
- Careful with general statement on correlations: special care needed where particular treatments are done for a given systematic in an analysis

Combined $\sigma_{t\text{-ch}}$ at 8 TeV

Combined $|f_{LV}V_{tb}|$ in *t*-channel

Combined $|f_{LV}V_{tb}|$

Categories of uncertainties and correlations

- Each experiment considers a complete set of uncertainties for every measurement
- In combination, uncertainties are grouped into categories
  - The exact content of the categories and the treatment of individual uncertainties may vary between the experiments
  - Still possible to make assumptions on correlations for uncertainties with similar sources
- Uncertainties are either introduced as nuisance parameters (NP) in the fit or evaluated via pseudoexperiments (PE)

E_{cm}	Process	Uncertainty method ATLAS	Uncertainty method CMS
	t-channel	PE exp. bkg norm.	PE (e.g signal & bkg. model) NP (e.g. bkg norm)
7 TeV	tW	NP	PE for signal & bkg. model NP for the rest
	s-channel	–	PE exp. bkg norm.
	t-channel	PE exp. bkg norm.	PE (e.g signal & bkg. model) NP (e.g. bkg norm)
8 TeV	tW	NP	PE for signal & bkg. model NP for the rest
	s-channel	NP	PE exp. bkg norm.

Categories of uncertainties and correlations

- Categories are assumed to be uncorrelated among each other
- Assumptions are made between the experiments
  - $|f_{LV}V_{tb}|$: also between production modes and E_{cm}'s
- Stability checks are done for correlations between large uncertainties, σ_{th} and luminosity

Uncertainty category	Correlations assumptions *where unc. available*
Data statistical	Uncorrelated – 0
Simulation statistical	Uncorrelated – 0
Integrated luminosity	Partially correlated – 0.3 → LHC and experiments
Theory modelling	Correlated – 1
Background normalisation	Uncorrelated – 0 → From data
Jets	Uncorrelated – 0
Detector modelling	Uncorrelated – 0
Top-quark mass	Correlated – 1
Theoretical cross-section	Vary dep. on source

ATLAS vs CMS
Same E_{cm}
Same process

Categories of uncertainties and correlations

- Categories are assumed to be uncorrelated among each other
- Assumptions are made between the experiments
  - $|f_{LV}V_{tb}|$: also between production modes and E_{cm}'s
- Stability checks are done for correlations between large uncertainties, σ_{th} and luminosity

Uncertainty category	Correlations assumptions *where unc. available*
Data statistical	Uncorrelated – 0
Simulation statistical	Uncorrelated – 0
Integrated luminosity	Partially correlated – 0.3
Theory modelling	Correlated – 1
Background normalisation	Uncorrelated – 0
Jets	Uncorrelated – 0
Detector modelling	Uncorrelated – 0
Top-quark mass	Correlated – 1
Theoretical cross-section	Vary dep. on source

ATLAS vs CMS

Uncertainty for $|f_{LV}V_{tb}|$ combination

Dependence for cross sections where available

Categories of uncertainties and correlations

- Categories are assumed to be uncorrelated among each other
- Assumptions are made between the experiments
  - $|f_{LV}V_{tb}|$: also between production modes and E_{cm}'s
- Stability checks are done for correlations between large uncertainties, σ_{th} and luminosity

Uncertainty category	Correlations assumptions *where unc. available*
Data statistical	Uncorrelated – 0
Simulation statistical	Uncorrelated – 0
Integrated luminosity	Correlated – 1
Theory modelling	Correlated – 1
Background normalisation	Uncorrelated – 0
Jets	Uncorr. / corr. – 0/1
Detector modelling	Uncorr. / corr. – 0/1
Top-quark mass	(Anti) correlated – (-)1
Theoretical cross-section	Vary dep. on source

Orthogonal samples

Dep. On source, method, …

Production modes

Uncertainty for $|f_{LV}V_{tb}|$ combination

Categories of uncertainties and correlations

- Categories are assumed to be uncorrelated among each other
- Assumptions are made between the experiments
  - $|f_{LV}V_{tb}|$: also between production modes and E_{cm}'s
- Stability checks are done for correlations between large uncertainties, σ_{th} and luminosity

Uncertainty category	Correlations assumptions *where unc. available*
Data statistical	Uncorrelated – 0
Simulation statistical	Uncorrelated – 0
Integrated luminosity	Uncorrelated – 0
Theory modelling	Correlated – 1
Background normalisation	Uncorrelated – 0
Jets	Uncorrelated unless studies available
Detector modelling	Uncorr. / corr. – 0/1
Top-quark mass	(Anti) correlated – (-)1
Theoretical cross-section	Vary dep. on source

E_{cm}

Uncertainties theory cross section

$\sigma_{t\text{-ch}}$ (7 TeV)	
NLO†	$63.9^{+1.9}_{-1.3}$ (scale) $\pm$ 2.2 (PDF+α_s) $\pm$ 0.7 (m_t) $\pm$ 0.1 (E_{beam})

- Fully correlated except for tW: computed with different accuracy
- Fully correlated between E_{cm}
- 50% between different productions
- Fully correlated

Combination of cross section: *t-channel*

7 TeV $\sigma_{t\text{-chan.}} = 67.5 \pm 2.4\ (\text{stat.}) \pm 5.0\ (\text{syst.}) \pm 1.1\ (\text{lumi.})\ \text{pb} = 67.5 \pm 5.7\ \text{pb}$

8 TeV $\sigma_{t\text{-chan.}} = 87.7 \pm 1.1\ (\text{stat.}) \pm 5.5\ (\text{syst.}) \pm 1.5\ (\text{lumi.})\ \text{pb} = 87.7 \pm 5.8\ \text{pb}$

$\sigma_{t\text{-chan.}}$, $\sqrt{s}$ = 7 TeV		
Combined cross-section	67.5 pb	
Uncertainty category	Uncertainty	
	[%]	[pb]
Data statistical	3.5	2.4
Simulation statistical	1.4	0.9
Integrated luminosity	1.7	1.1
Theory modelling	5.1	3.5
Background normalisation	1.9	1.3
Jets	3.4	2.3
Detector modelling	3.4	2.3
Total syst. unc. (excl. lumi.)	7.5	5.0
Total syst. unc. (incl. lumi.)	7.6	5.2
Total uncertainty	8.4	5.7

$\sigma_{t\text{-chan.}}$, $\sqrt{s}$ = 8 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

The best single result: 9.1%
p-value: 93% overall ρ: 20%

The best single result: 7.5%
p-value: 44% overall ρ: 42%

Combination of cross section: *tW*

7 TeV $\sigma_{tW} = 16.3 \pm 2.3\ (\text{stat.}) \pm 3.3\ (\text{syst.}) \pm 0.7\ (\text{lumi.})\ \text{pb} = 16.3 \pm 4.1\ \text{pb}$

8 TeV $\sigma_{tW} = 23.1 \pm 1.1\ (\text{stat.}) \pm 3.3\ (\text{syst.}) \pm 0.8\ (\text{lumi.})\ \text{pb} = 23.1 \pm 3.6\ \text{pb}$

σ_{tW}, $\sqrt{s}$ = 7 TeV		
Combined cross-section	16.3 pb	
Uncertainty category	Uncertainty	
	[%]	[pb]
Data statistical	14.0	2.3
Simulation statistical	0.8	0.1
Integrated luminosity	4.4	0.7
Theory modelling	13.9	2.3
Background normalisation	6.0	1.0
Jets	11.5	1.9
Detector modelling	6.2	1.0
Total syst. unc. (excl. lumi.)	20.0	3.3
Total syst. unc. (incl. lumi.)	20.5	3.3
Total uncertainty	24.8	4.1

σ_{tW}, $\sqrt{s}$ = 8 TeV		
Combined cross-section	23.1 pb	
Uncertainty category	Uncertainty	
	[%]	[pb]
Data statistical	4.7	1.1
Simulation statistical	0.8	0.2
Integrated luminosity	3.6	0.8
Theory modelling	11.8	2.7
Background normalisation	2.2	0.5
Jets	6.2	1.4
Detector modelling	4.9	1.1
Total syst. unc. (excl. lumi.)	14.4	3.3
Total syst. unc. (incl. lumi.)	14.8	3.4
Total uncertainty	15.6	3.6

The best single result: 28%
p-value: 91% overall ρ: 17%

The best single result: 16.5%
p-value: 94% overall ρ: 40%

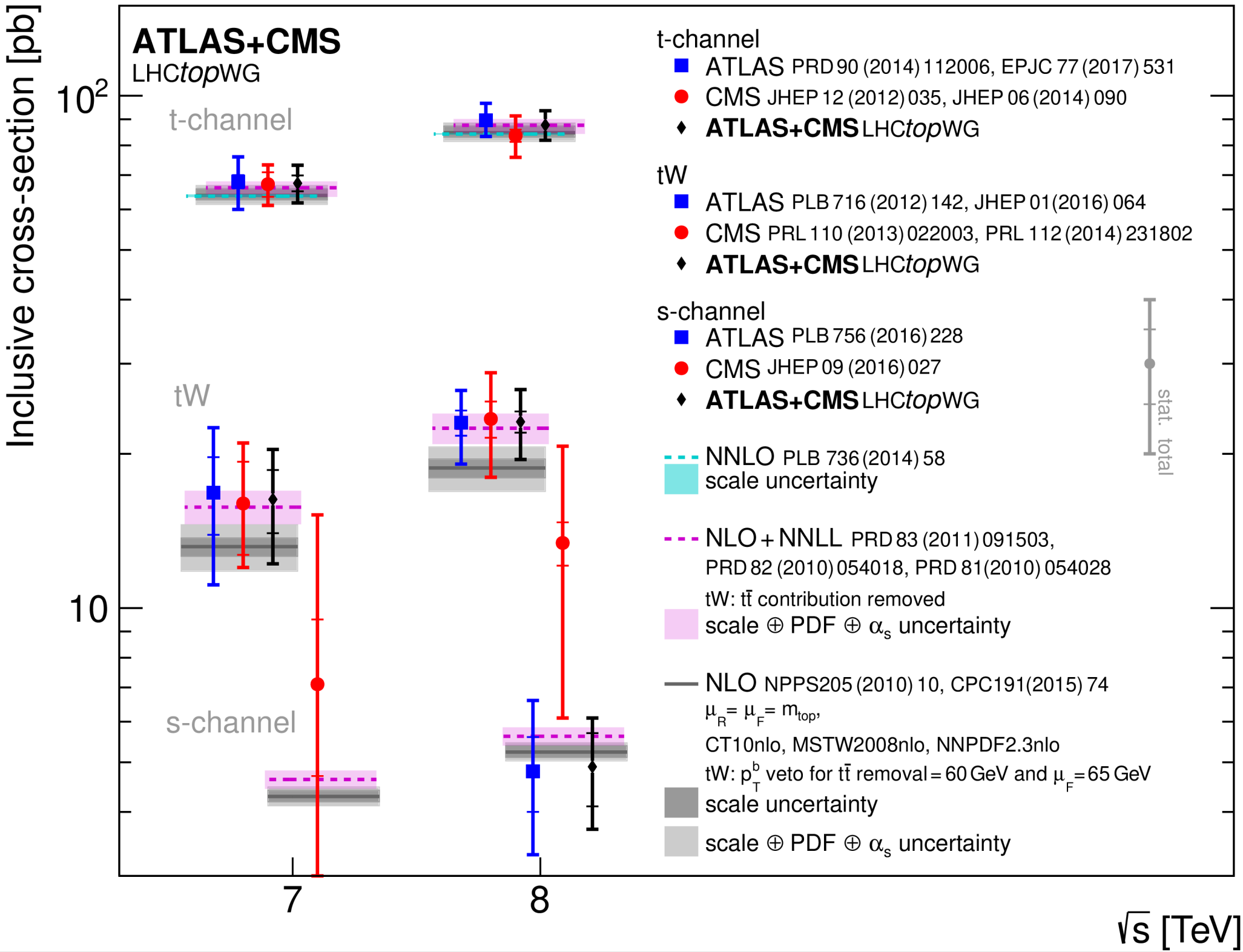
Combination of cross section: *s-channel*

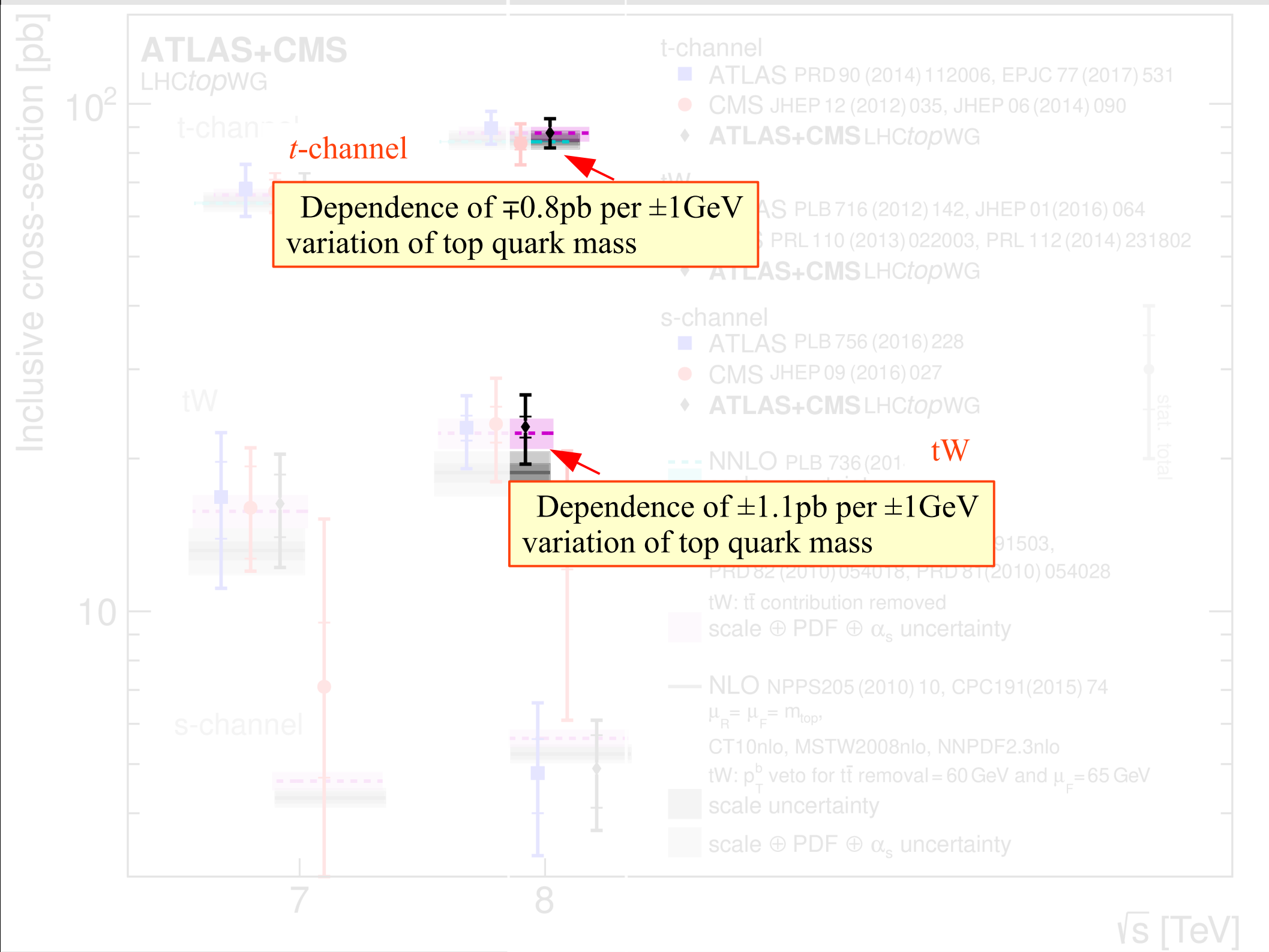
8 TeV $\sigma_{s\text{-chan.}} = 4.9 \pm 0.8\ (\text{stat.}) \pm 1.2\ (\text{syst.}) \pm 0.2\ (\text{lumi.})\ \text{pb} = 4.9 \pm 1.4\ \text{pb}$

$\sigma_{s\text{-chan.}}$, $\sqrt{s} = 8$ TeV		
Combined cross-section	4.9 pb	
Uncertainty category	Uncertainty	
	[%]	[pb]
Data statistical	16	0.8
Simulation statistical	12	0.6
Integrated luminosity	5	0.2
Theory modelling	14	0.7
Background normalisation	8	0.4
Jets	13	0.6
Detector modelling	8	0.4
Total syst. unc. (excl. lumi.)	25	1.2
Total syst. unc. (incl. lumi.)	25	1.2
Total uncertainty	30	1.4

The best single result: ~30%

p-value: 23% overall ρ: 15%


ATLAS+CMS
LHCtopWG
Inclusive cross-section [pb]
10^2
10
t-channel
tW
s-channel
7
8
$\sqrt{s}$ [TeV]
t-channel
ATLAS PRD 90 (2014) 112006, EPJC 77 (2017) 531
CMS JHEP 12 (2012) 035, JHEP 06 (2014) 090
ATLAS+CMS LHCtopWG
tW
ATLAS PLB 716 (2012) 142, JHEP 01(2016) 064
CMS PRL 110 (2013) 022003, PRL 112 (2014) 231802
ATLAS+CMS LHCtopWG
s-channel
ATLAS PLB 756 (2016) 228
CMS JHEP 09 (2016) 027
ATLAS+CMS LHCtopWG
stat.
total
NNLO PLB 736 (2014) 58
scale uncertainty
NLO + NNLL PRD 83 (2011) 091503,
PRD 82 (2010) 054018, PRD 81(2010) 054028
tW: $t\bar{t}$ contribution removed
scale ⊕ PDF ⊕ α_s uncertainty
NLO NPPS205 (2010) 10, CPC191(2015) 74
$\mu_R = \mu_F = m_{top}$,
CT10nlo, MSTW2008nlo, NNPDF2.3nlo
tW: p_T^b veto for $t\bar{t}$ removal = 60 GeV and μ_F = 65 GeV
scale uncertainty
scale ⊕ PDF ⊕ α_s uncertainty


ATLAS+CMS
LHCtopWG
t-channel
Dependence of ∓0.8pb per ±1GeV variation of top quark mass
tW
Dependence of ±1.1pb per ±1GeV variation of top quark mass
s-channel
Inclusive cross-section [pb]
√s [TeV]
10²
10
7
8
t-channel
ATLAS PRD 90 (2014) 112006, EPJC 77 (2017) 531
CMS JHEP 12 (2012) 035, JHEP 06 (2014) 090
ATLAS+CMS LHCtopWG
PRL 110 (2013) 022003, PRL 112 (2014) 231802
ATLAS+CMS LHCtopWG
s-channel
ATLAS PLB 756 (2016) 228
CMS JHEP 09 (2016) 027
ATLAS+CMS LHCtopWG
NNLO PLB 736 (201
PRD 82 (2010) 054018; PRD 81(2010) 054028
tW: tt̄ contribution removed
scale ⊕ PDF ⊕ α_s uncertainty
NLO NPPS205 (2010) 10, CPC191(2015) 74
μ_R = μ_F = m_top,
CT10nlo, MSTW2008nlo, NNPDF2.3nlo
tW: p_T^b veto for tt̄ removal = 60 GeV and μ_F = 65 GeV
scale uncertainty
scale ⊕ PDF ⊕ α_s uncertainty

Combination of $|f_{LV}V_{tb}|$

- Re-evaluate all $|f_{LV}V_{tb}|$ and uncertainties based on reference predictions for cross section
- Global combination does not include CMS *s*-channel
  - Strong correlation with *t*-channel
  - Results vary with assumptions

	t-channel ATLAS 8 TeV	*t*-channel CMS 8 TeV	*t*-channel ATLAS 7 TeV	*t*-channel CMS 7 TeV	*tW* ATLAS 8 TeV	*tW* CMS 8 TeV	*tW* ATLAS 7 TeV	*tW* CMS 7 TeV	*s*-channel ATLAS 8 TeV
$\lvert f_{LV}V_{tb}\rvert^2$	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
Jet ID	<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
b-tagging	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

$$|f_{LV}V_{tb}|^2 = 1.05 \pm 0.02\ (\text{stat.}) \pm 0.06\ (\text{syst.}) \pm 0.01\ (\text{lumi.}) \pm 0.04\ (\text{theo.})$$

$$\begin{aligned} |f_{LV}V_{tb}| &= 1.02 \pm 0.01\ (\text{stat.}) \pm 0.03\ (\text{syst.}) \pm 0.01\ (\text{lumi.}) \pm 0.02\ (\text{theo.}) \\ &= 1.02 \pm 0.04\ (\text{meas.}) \pm 0.02\ (\text{theo.}) = 1.02 \pm 0.04, \end{aligned}$$

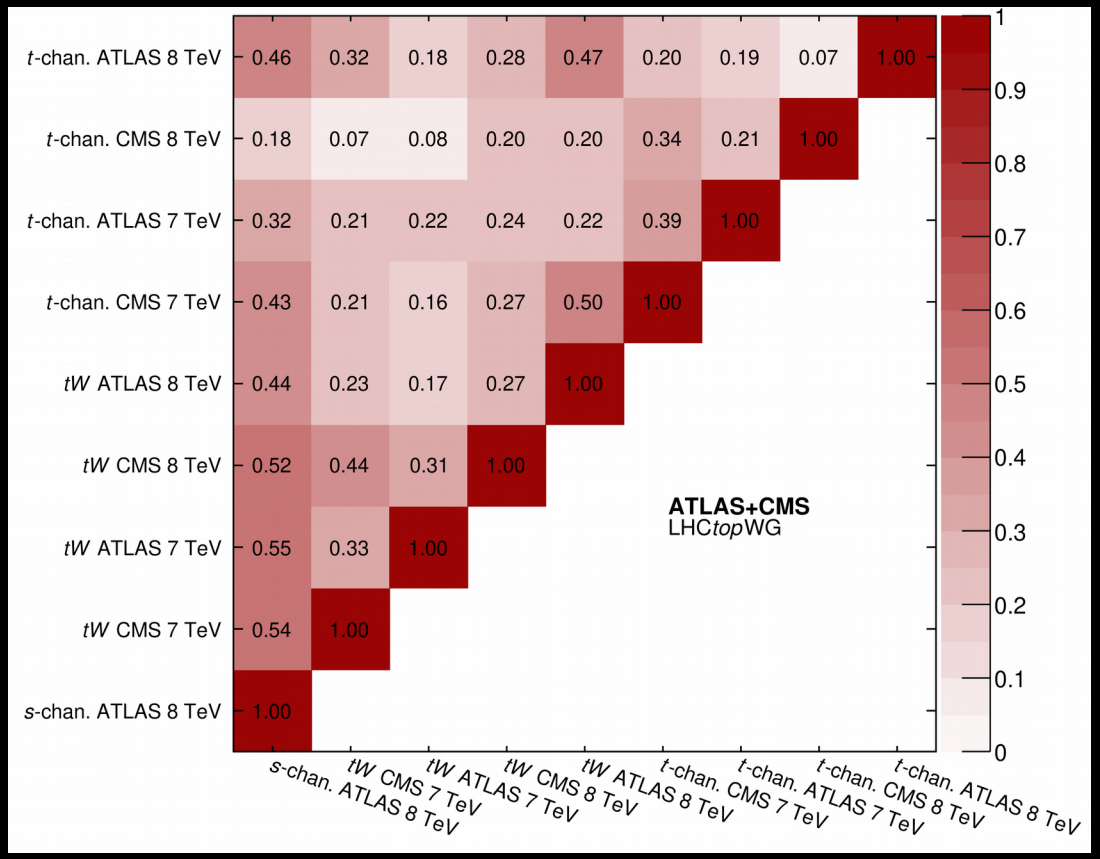
Combined precision: 3.7%

Most precise single result: 4.7%

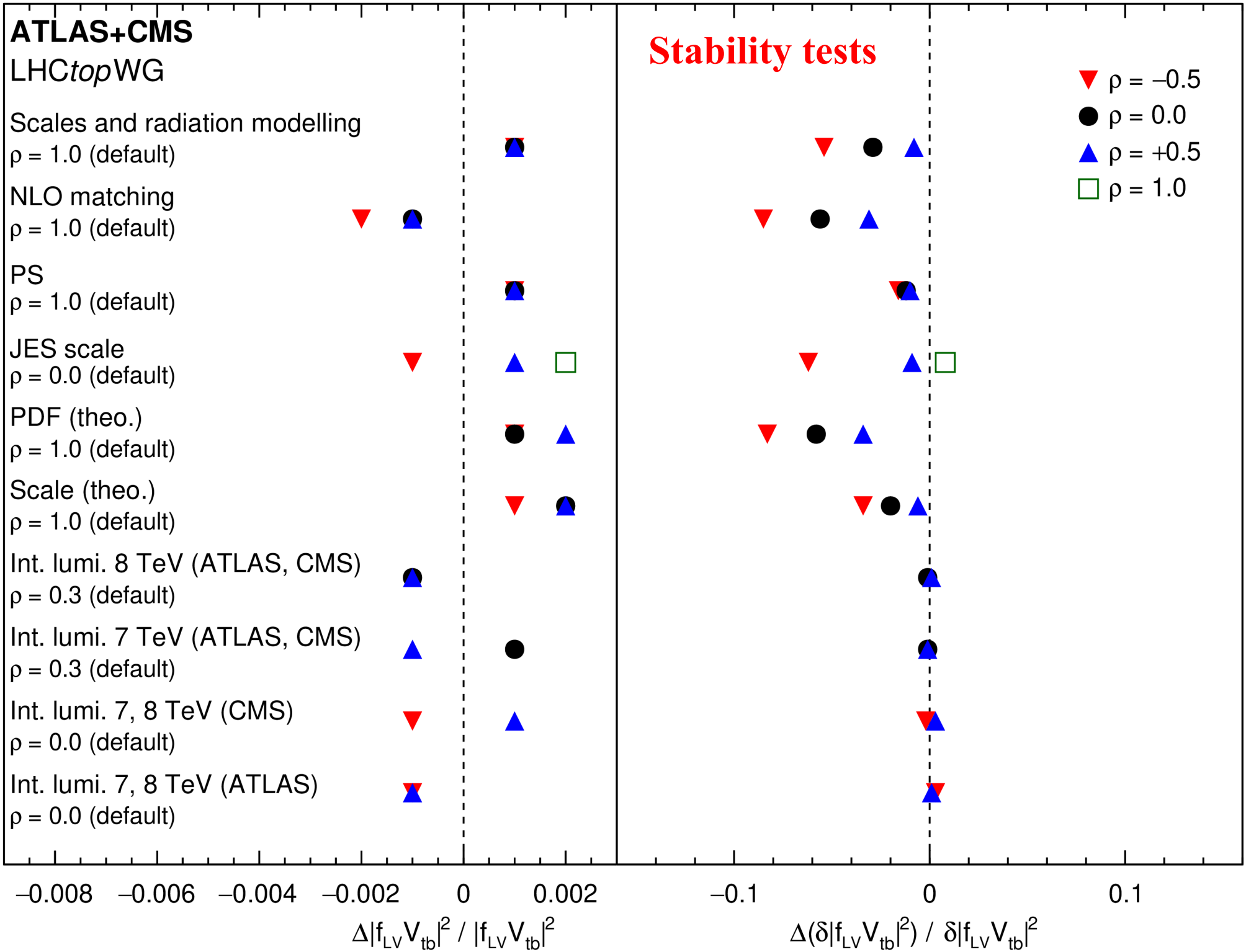
Combination of $|f_{LV}V_{tb}|$

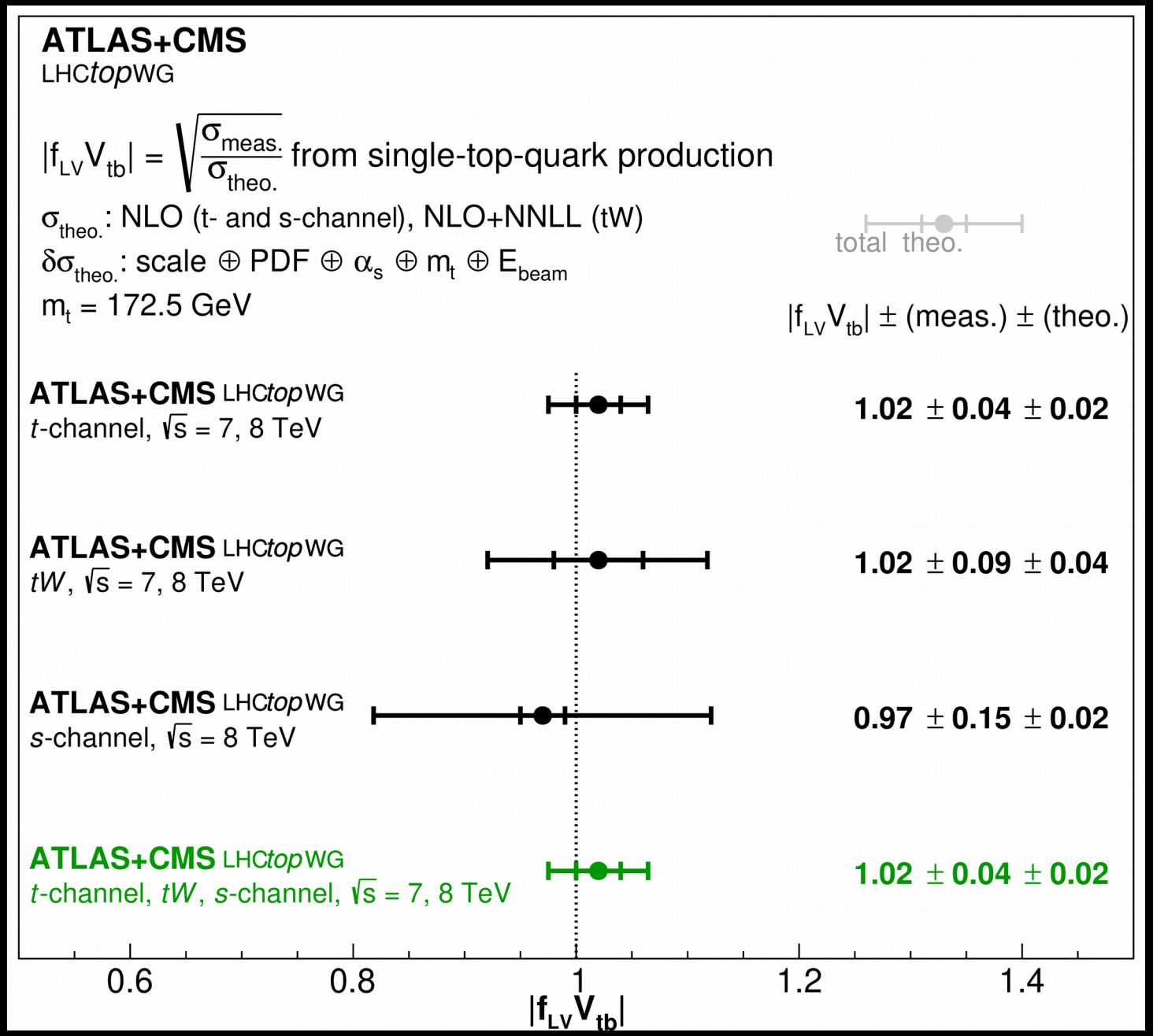
Combined $\lvert f_{\mathrm{LV}} V_{tb}\rvert^2$	1.05	
Uncertainty category	Uncertainty	
	[%]	$\Delta\lvert f_{\mathrm{LV}} V_{tb}\rvert^2$
Data statistical	1.8	0.02
Simulation statistical	0.9	0.01
Integrated luminosity	1.3	0.01
Theory modelling	4.5	0.05
Background normalisation	1.3	0.01
Jets	2.6	0.03
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

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



- Correlations all below 60%
- Large correlations happens
  - Within the same experiment and E_{cm}
  - Large contribution from the same modeling unc.


ATLAS+CMS
LHCtopWG
Stability tests
ρ = –0.5
ρ = 0.0
ρ = +0.5
ρ = 1.0
Scales and radiation modelling
ρ = 1.0 (default)
NLO matching
ρ = 1.0 (default)
PS
ρ = 1.0 (default)
JES scale
ρ = 0.0 (default)
PDF (theo.)
ρ = 1.0 (default)
Scale (theo.)
ρ = 1.0 (default)
Int. lumi. 8 TeV (ATLAS, CMS)
ρ = 0.3 (default)
Int. lumi. 7 TeV (ATLAS, CMS)
ρ = 0.3 (default)
Int. lumi. 7, 8 TeV (CMS)
ρ = 0.0 (default)
Int. lumi. 7, 8 TeV (ATLAS)
ρ = 0.0 (default)
–0.008
–0.006
–0.004
–0.002
0
0.002
–0.1
0
0.1
Δ|f_LV V_tb|² / |f_LV V_tb|²
Δ(δ|f_LV V_tb|²) / δ|f_LV V_tb|²


ATLAS+CMS
LHCtopWG
$|f_{LV}V_{tb}| = \sqrt{\frac{\sigma_{meas.}}{\sigma_{theo.}}}$ from single-top-quark production
$\sigma_{theo.}$: NLO (t- and s-channel), NLO+NNLL (tW)
$\delta\sigma_{theo.}$: scale ⊕ PDF ⊕ α_s ⊕ m_t ⊕ E_{beam}
m_t = 172.5 GeV
total theo.
$|f_{LV}V_{tb}| \pm$ (meas.) $\pm$ (theo.)
ATLAS+CMS LHCtopWG
t-channel, √s = 7, 8 TeV
1.02 ± 0.04 ± 0.02
ATLAS+CMS LHCtopWG
tW, √s = 7, 8 TeV
1.02 ± 0.09 ± 0.04
ATLAS+CMS LHCtopWG
s-channel, √s = 8 TeV
0.97 ± 0.15 ± 0.02
ATLAS+CMS LHCtopWG
t-channel, tW, s-channel, √s = 7, 8 TeV
1.02 ± 0.04 ± 0.02
0.6
0.8
1
1.2
1.4
$|f_{LV}V_{tb}|$

Summary and outlook

- The combination of all single top quark measurements are presented
  - Impressive performance by ATLAS and CMS in providing measurements and performing the combination

- Single top is interesting and one can combine various parameters from its measurements
  - The current paper presents the cross section and $|f_{LV}V_{tb}|$

Some thoughts for future

- Moving beyond BLUE combination: Convino or even better, simultaneous fitting of distributions

- Considering additional properties: $\sigma_t/\sigma_{anti\text{-}t}$
  - Plan ahead particularly for assessing correlations on PDF uncertainty

- Combination of differential measurements
  - Plan ahead for binning, etc.

BACKUP

More into correlation assumptions

- **Integrated luminosity (0.3)**
  - Within the same experiment, 0 between E_{cm}'s and 1 between production modes
  - Between the two experiments:
    - Correlated component: beam currents during vander Meer scans at LHC
    - Uncorrelated component: long-term monitoring

	ATLAS (%)		CMS (%)	
	7 TeV	**8 TeV**	**7 TeV**	**8 TeV**
Uncorrelated	1.7	1.8	2.1	2.5
Correlated	0.5	0.6	0.5	0.7

- **Background normalization (0)**
  - Either data-driven (QCD, fake leptons) or constrained to data in the signal extraction fit

More into ρ assumptions: *theory modeling*

- **Scale and radiation**
  - Consistent variations of parameters, also in signal and backgrounds
    - Unless background model is determined from data (e.g. CMS *t*-ch at 8 TeV)

- **NLO method**
  - ATLAS: comparison of POWHEG, MCatNLO and MG_aMCatNLO in signal and $t\bar{t}$
  - CMS (*t*-ch): COMPHEP vs MG at 7 TeV, POWHEG and MG_aMCatNLO at 8 TeV

- **Parton shower and hadronisation**
  - ATLAS: PYTHIA vs HERWIG in signal and $t\bar{t}$
  - CMS: vary the threshold of ME/PS matching in the MLM method
  - *Note:* in both PYTHIA vs HERWIG considered in JES and b-tag uncertainties

- **tW-$t\bar{t}$ interference:** only in tW analysis, DR vs DS approach

- **Top quark p_T spectrum:**
  - ATLAS: covered by PS and hadronisation, also relatively small
  - CMS: difference between with and w/o top quark p_T reweighting
    - Exception: data-driven shapes in *t*-channel 8 TeV

- **Top quark mass:**
  - Relatively small, not available for all analyses …
  - ATLAS provides dependences while CMS provide uncertainties

More into ρ assumptions: *jets*

- **Jet energy scale**
  - Different components: calibration, jet flavor, …
    - ATLAS: combine all (JES common) but jet flavor
    - CMS: combine all and uses η- and p_T-dependent
    - Correlated between all channels at the same E_{cm}, except *t*-channel (dominated by forward jet)

- **Jet Identification**
  - ATLAS: correlated among channels in the same E_{cm}, uncorrelated otherwise
  - CMS: included in the overall JES

- **Jet Energy Resolution**
  - Correlated among channels in the same E_{cm}, uncorrelated otherwise

More into ρ assumptions: *detector modeling*

- **Lepton modeling**
  - Trigger, identification, reconstruction
  - Uncorrelated unless channels at the same E_{cm}
- **Hadronic part of l+jets trigger:** only used in one analysis
- **E_T^{miss} modeling**
  - ATLAS: separate evaluation for scale and resolution
  - CMS: combined evaluation for scale and resolution
  - CMS additional: unclustered energy
  - Correlated among channels in the same E_{cm}, uncorrelated otherwise
- **B-tagging**
  - Correlated among channels in the same E_{cm}, uncorrelated otherwise
- **Pile up**
  - Correlated among channels in the same E_{cm}, uncorrelated otherwise

	ATLAS ($\sigma_{t\text{-chan.}}$, $\sqrt{s}$ = 7 TeV)		CMS ($\sigma_{t\text{-chan.}}$, $\sqrt{s}$ = 7 TeV)		
Cross-section	68.0 pb		67.2 pb		
Uncertainty category	Uncertainty		Uncertainty		ρ
Data statistical		**2.7%**		**5.8%**	**0.0**
Simulation statistical		**1.9%**		**1.9%**	**0.0**
Integrated luminosity		**1.8%**		**2.2%**	**0.3**
Theory modelling	Ren./fact. scales, ISR/FSR	2.6%	Ren./fact. scales	3.5%	1.0
	NLO match., PS ($t\bar{t}$, t-chan.)	2.2%	Sig. modelling (NLO method)	4.3%	1.0
			Parton shower	0.8%	1.0
	PDF	3.2%	PDF	1.4%	1.0
Category subtotal		**4.7%**		**5.8%**	**0.85**
Background norm.	Bkg. from MC: norm.	1.6%	Bkg. from MC: norm.	2.7%	0.0
	Bkg. from MC/data: multijet norm.	1.4%	Bkg. from data: multijet norm.	1.3%	0.0
Category subtotal		**2.1%**		**3.0%**	**0.0**
Jets	JES common	7.6%	JES	0.9%	0.0
	JES flavour	1.8%			0.0
	JetID	1.1%			0.0
	JER	1.9%	JER	0.3%	0.0
Category subtotal		**8.1%**		**0.9%**	**0.0**
Detector modelling	Lepton modelling	2.8%	Lepton modelling	3.5%	0.0
			HLT (had. part)	1.5%	0.0
	$E_{\mathrm{T}}^{\mathrm{miss}}$ modelling	2.6%	$E_{\mathrm{T}}^{\mathrm{miss}}$ modelling	0.1%	0.0
	b-tagging	3.9%	b-tagging	2.2%	0.0
	Pile-up	0.2%	Pile-up	0.6%	0.0
Category subtotal		**5.5%**		**4.4%**	**0.0**
Total uncertainty		**11.7%**		**10.2%**	**0.20**

	ATLAS ($\sigma_{t\text{-chan.}}$, $\sqrt{s}$ = 8 TeV)		CMS ($\sigma_{t\text{-chan.}}$, $\sqrt{s}$ = 8 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
	$E_{\mathrm{T}}^{\mathrm{miss}}$ scale	0.4%	$E_{\mathrm{T}}^{\mathrm{miss}}$ modelling	0.3%	0.0
	$E_{\mathrm{T}}^{\mathrm{miss}}$ resolution	0.2%			0.0
	b-tagging	1.1%	b-tagging	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**

	ATLAS (σ_{tW}, $\sqrt{s}$ = 7 TeV)		CMS (σ_{tW}, $\sqrt{s}$ = 7 TeV)		
Cross-section	16.8 pb		16.0 pb		
Uncertainty category	Uncertainty		Uncertainty		ρ
Data statistical		**17.0%**		**20.8%**	**0.0**
Simulation statistical		**2.0%**		**0.0%**	**0.0**
Integrated luminosity		**7.0%**		**4.3%**	**0.3**
Theory modelling	ISR/FSR, scales	5.0%	ISR/FSR, scales	2.8%	1.0
	$tW/t\bar{t}$ NLO match.	10.0%			1.0
	$tW/t\bar{t}$ PS	15.0%	tW ME/PS match. thr.	10.1%	1.0
	PDF	2.0%	PDF	2.1%	1.0
			DR/DS scheme	5.9%	1.0
Category subtotal		**18.8%**		**12.2%**	**0.74**
Background norm.	$t\bar{t}$ norm.	6.0%	$t\bar{t}$ norm.	6.0%	0.0
	Z+jets, diboson norm.	8.0%	Z/γ^*+jets norm.	4.2%	0.0
	Bkg. from data: fake lept. norm.	2.0%			0.0
Category subtotal		**10.2%**		**7.3%**	**0.0**
Jets	JES	16.0%	JES	15.1%	0.0
	JetID	5.0%			0.0
	JER	2.0%	JER	3.6%	0.0
Category subtotal		**16.9%**		**15.6%**	**0.0**
Detector modelling	Lepton modelling	7.0%	Lepton modelling	5.2%	0.0
			$E_{\mathrm{T}}^{\mathrm{miss}}$ modelling	2.5%	0.0
			b-tagging	1.9%	0.0
	Pile-up	10.0%	Pile-up	1.5%	0.0
Category subtotal		**12.2%**		**6.2%**	**0.0**
Total uncertainty		**35.1%**		**30.6%**	**0.17**

	ATLAS (σ_{tW}, $\sqrt{s}$ = 8 TeV)		CMS (σ_{tW}, $\sqrt{s}$ = 8 TeV)		
Cross-section	23.0 pb		23.4 pb		
Uncertainty category	Uncertainty		Uncertainty		ρ
Data statistical		**5.8%**		**8.1%**	**0.0**
Simulation statistical		**0.5%**		**2.4%**	**0.0**
Integrated luminosity		**4.6%**		**3.0%**	**0.3**
Theory modelling	ISR/FSR	8.8%	Ren./fact. scales	12.4%	1.0
	NLO match.	2.5%			1.0
	Parton shower	1.7%	Parton shower	14.1%	1.0
	PDF	0.6%	PDF	1.7%	1.0
	$tW/t\bar{t}$ overlap	3.5%	tW DR/DS scheme	2.1%	1.0
			Top-quark p_{T} reweight.	0.4%	0.0
Category subtotal		**10.0%**		**19.0%**	**0.75**
Background norm.	$t\bar{t}$ norm.	1.9%	$t\bar{t}$ norm.	1.7%	0.0
	Z+jets, diboson norm.	2.0%	Z+jets norm.	2.6%	0.0
	Bkg. from data: fake lept. norm.	0.3%			0.0
Category subtotal		**2.8%**		**3.1%**	**0.0**
Jets	JES common	5.3%	JES	3.8%	0.0
	JES flavour	1.9%			0.0
	JetID	0.2%			0.0
	JER	6.5%	JER	0.9%	0.0
Category subtotal		**8.6%**		**3.9%**	**0.0**
Detector modelling	Lepton modelling	3.0%	Lepton modelling	1.8%	0.0
	$E_{\mathrm{T}}^{\mathrm{miss}}$ scale	5.5%	$E_{\mathrm{T}}^{\mathrm{miss}}$ modelling	0.4%	0.0
	$E_{\mathrm{T}}^{\mathrm{miss}}$ resolution	0.2%			0.0
	b-tagging	1.0%	b-tagging	0.9%	0.0
	Pile-up	2.7%	Pile-up	0.4%	0.0
Category subtotal		**6.9%**		**2.0%**	**0.0**
Total uncertainty		**16.8%**		**21.7%**	**0.40**

	ATLAS ($\sigma_{s\text{-chan.}}$, $\sqrt{s}$ = 8 TeV)		CMS ($\sigma_{s\text{-chan.}}$, $\sqrt{s}$ = 8 TeV)		
Cross-section	4.8 pb		13.4 pb		
Uncertainty category	Uncertainty		Uncertainty		ρ
Data statistical		**16.0%**		**10.0%**	**0.0**
Simulation statistical		**12.0%**		**0.0%**	**0.0**
Integrated luminosity		**5.0%**		**4.0%**	**0.3**
Theory modelling	Ren./fact. scales	7.0%	Ren./fact. scales	30.0%	1.0
	$t\bar{t}$, t-chan. generator	11.0%			1.0
	Parton shower	2.0%	Parton shower	7.0%	1.0
	PDF	3.0%	PDF	7.0%	1.0
			Top-quark p_{T} reweight.	6.0%	0.0
Category subtotal		**13.5%**		**32.2%**	**0.56**
Background norm.	t-chan., $t\bar{t}$ norm.	5.0%	t-chan., $t\bar{t}$ norm.	12.0%	0.0
	W/Z+jets, diboson norm.	6.0%	W/Z+jets, diboson norm.	12.0%	0.0
	Bkg. from data: multijet norm.	1.0%	Bkg. from data: multijet norm.	2.0%	0.0
Category subtotal		**7.9%**		**17.1%**	**0.0**
Jets	JES common	5.0%	JES	32.5%	0.0
	JES flavour	1.0%			0.0
	JetID	1.0%			0.0
	JER	12.0%	JER	10.2%	0.0
Category subtotal		**13.1%**		**34.1%**	**0.0**
Detector modelling	Lepton modelling	2.4%	Lepton modelling	1.0%	0.0
	$E_{\mathrm{T}}^{\mathrm{miss}}$ scale	1.0%	$E_{\mathrm{T}}^{\mathrm{miss}}$ modelling	6.0%	0.0
	$E_{\mathrm{T}}^{\mathrm{miss}}$ res	1.0%			0.0
	b-tagging	8.0%	b-tagging	14.0%	0.0
	Pile-up	1.0%	Pile-up	9.0%	0.0
Category subtotal		**8.5%**		**17.7%**	**0.0**
Total uncertainty		**30.2%**		**54.0%**	**0.15**