Recent single top measurements with ATLAS and CMS

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on behalf of the ATLAS and CMS collaborations

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Outline:

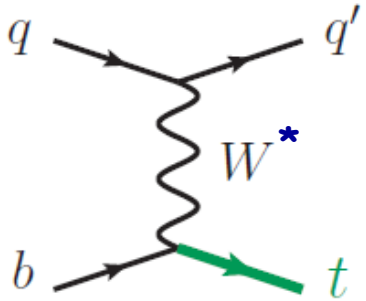
- Motivation
- Individual results for t-channel and tW @ 13 TeV
- ATLAS+CMS combination @ 7 and 8 TeV
- Conclusions

Why study single top production?

- study interplay of EW physics and QCD
- sensitivity to flavour couplings and parton densities

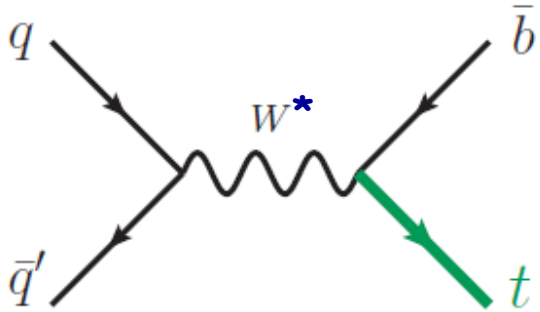
- t-channel virtual W exchange

  $\sigma \sim O(100)$ pb



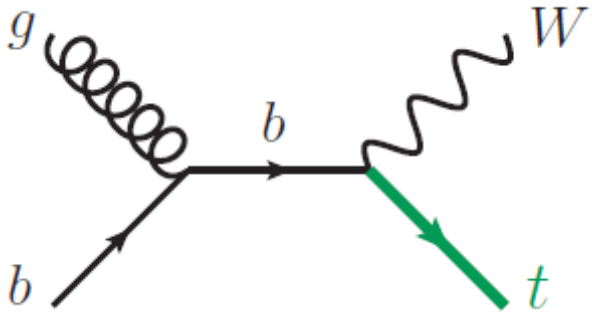
- s-channel virtual W exchange

  $\sigma \sim O(5)$ pb



- real W emission

  $\sigma \sim O(20)$ pb

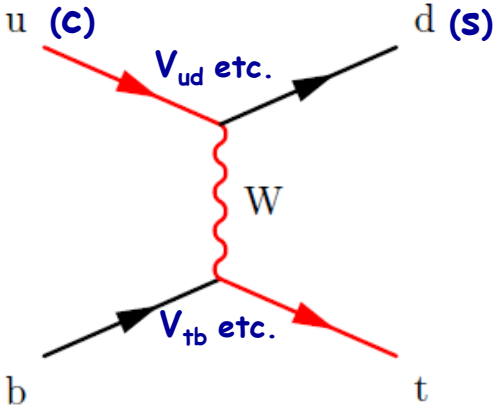


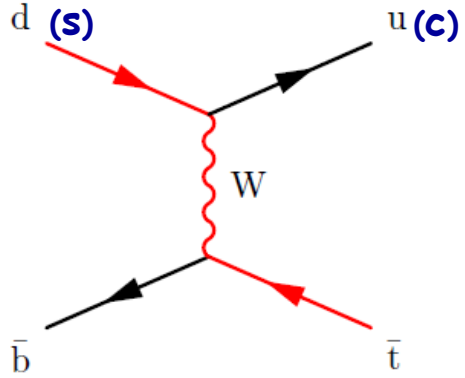
- different initial/final states and/or different colour structure

  -> the three channels **do not interfere**

t-channel single top production

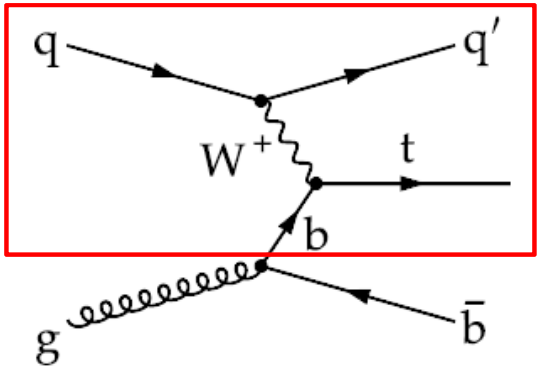
- **5 flavour scheme (5FS) LO:**





flavour coupling

- **4-flavour scheme (4FS) LO:**



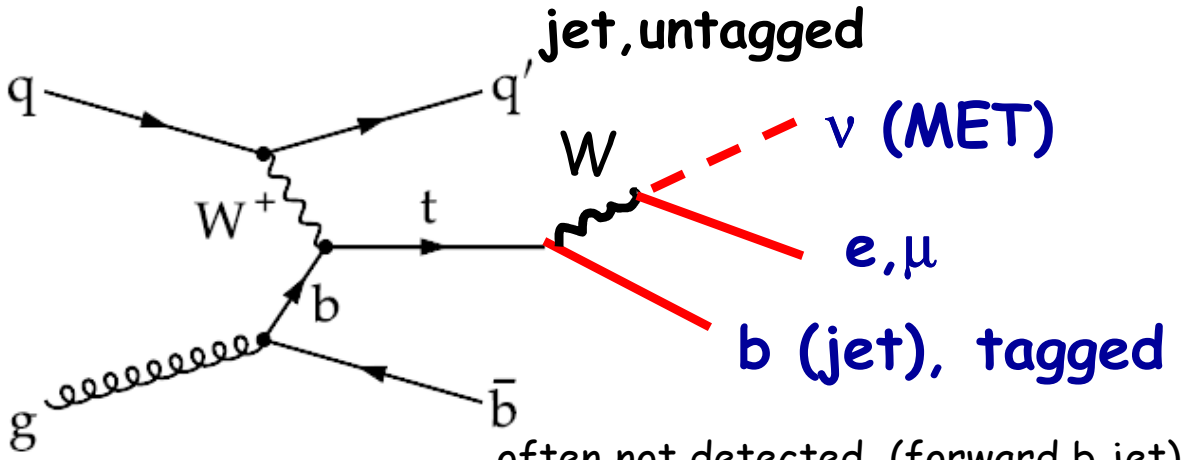
(or NLO correction to 5FS)

-> interplay with QCD

- **t and tbar cross sections differ** (u and d valence PDFs in p differ) and give **different information on proton flavour structure and flavour couplings**

t-channel single top measurements

- e.g. 4-flavour scheme



often not detected (forward b jet)

-> look for

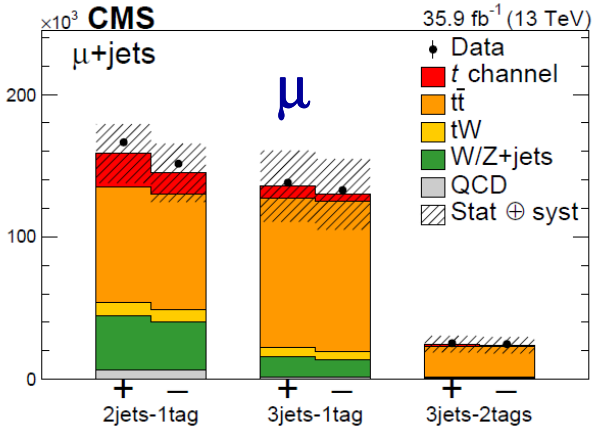
lepton (e,μ), b-tagged jet, untagged jet, MET + potentially further jets

lepton charge determines whether t or tbar

- **latest inclusive result @ 13 TeV:** **arXiv:1812.10514**

(CMS, data 2016, 36 fb^{-1})

define categories (similar for e)

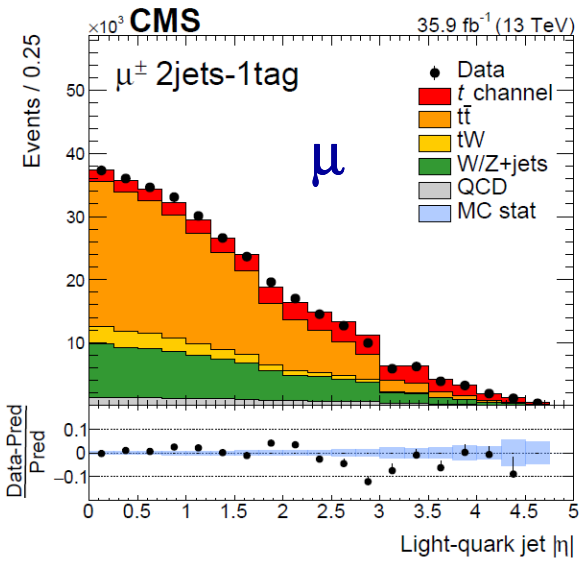


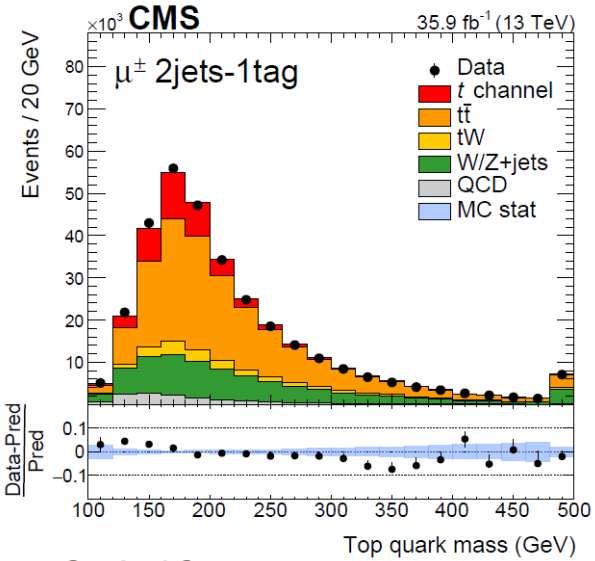
see also: arXiv:1609.03920 (ATLAS, data 2015, 3.2 fb^{-1})
arXiv:1610.00678 (CMS, data 2015, 2.2 fb^{-1})

Input to/output of Boosted Decision Trees

arXiv:1812.10514

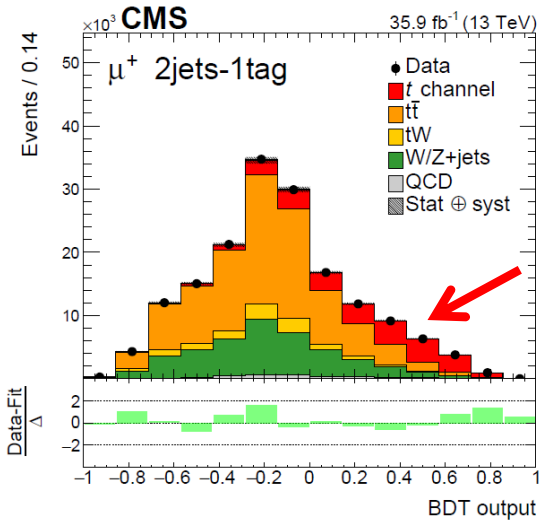
input variables (examples)



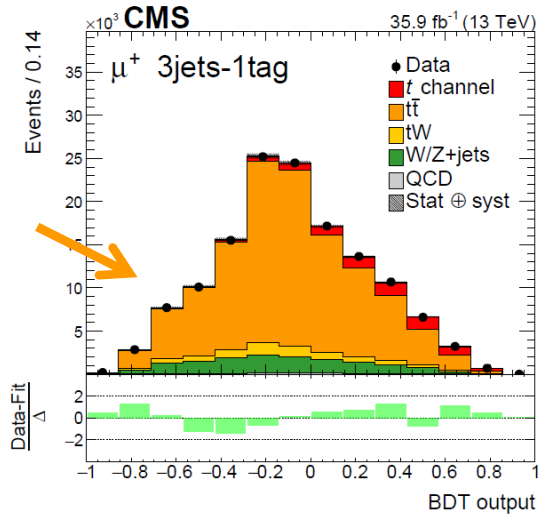


BDT output (examples)

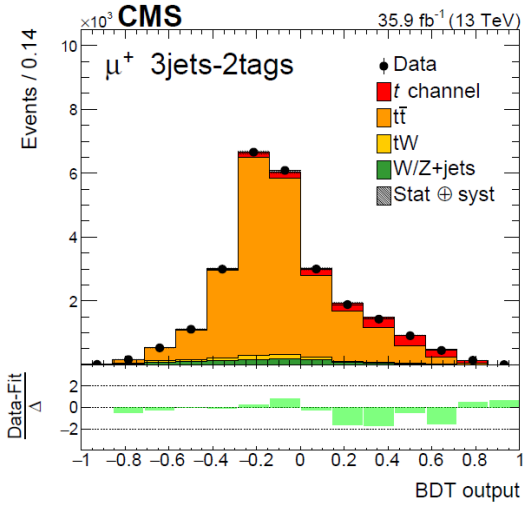
(separately for each lepton/category -> fit all)



single top



ttbar



Total cross section results

arXiv:1812.10514

measurement:

$$\sigma_{t\text{-ch,t}} = 136 \pm 1\,(\text{stat}) \pm 22\,(\text{syst})\,\text{pb}$$

$$\sigma_{t\text{-ch,}\bar{t}} = 82 \pm 1\,(\text{stat}) \pm 14\,(\text{syst})\,\text{pb}$$

$$\sigma_{t\text{-ch,t+}\bar{t}} = 219 \pm 2\,(\text{stat}) \pm 36\,(\text{syst})\,\text{pb}$$

prediction:

HATHOR, NLO QCD + LO EW

$$\sigma_{t\text{-ch,t}} = 136.0^{+4.1}_{-2.9}(\text{scale}) \pm 3.5(\text{PDF}+\alpha_S)\,\text{pb},$$

$$\sigma_{t\text{-ch,}\bar{t}} = 81.0^{+2.5}_{-1.7}(\text{scale}) \pm 3.2(\text{PDF}+\alpha_S)\,\text{pb},$$

$$\sigma_{t\text{-ch,t+}\bar{t}} = 217.0^{+6.6}_{-4.6}(\text{scale}) \pm 6.2(\text{PDF}+\alpha_S)\,\text{pb},$$

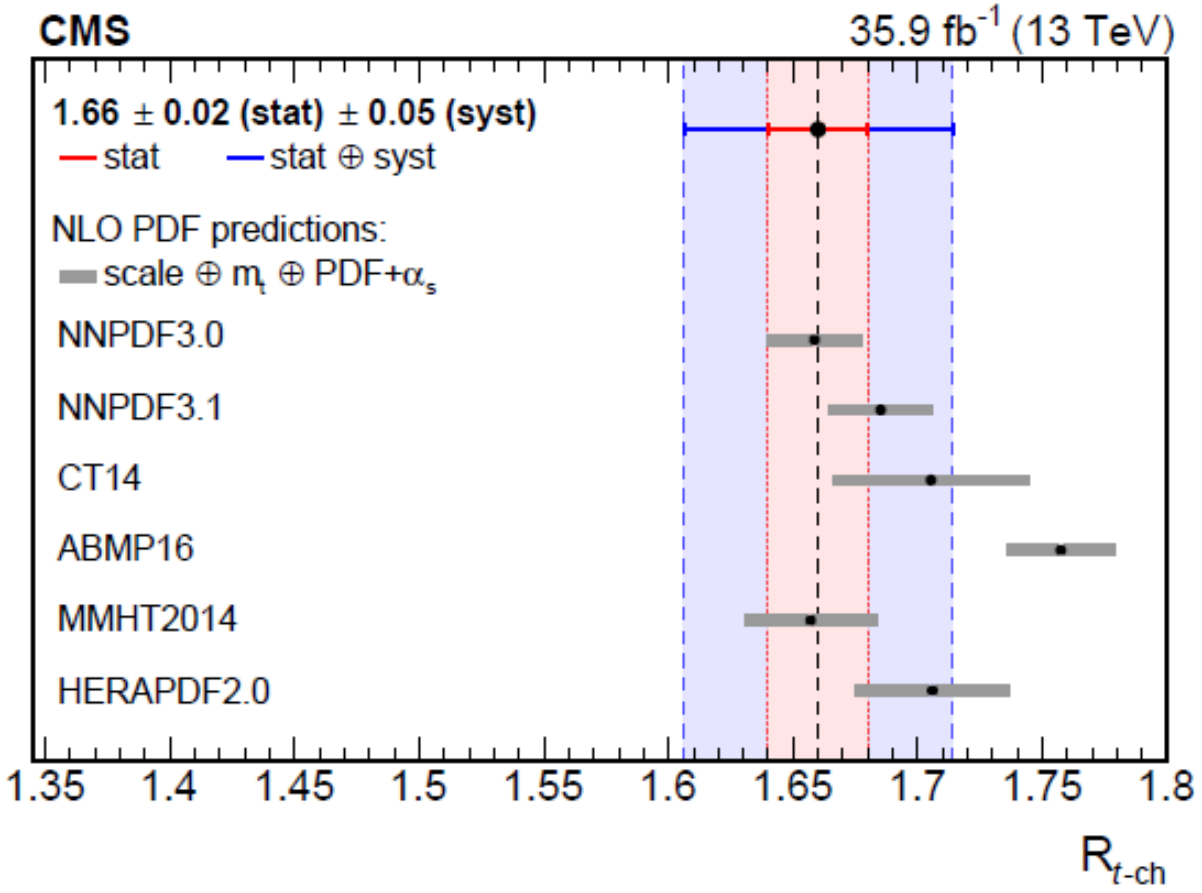
main systematic uncertainty: signal modelling (μ_F, μ_R, PS scales; PDF; …)

- **very good agreement with small uncertainty, SM works!**

Single t/tbar cross section ratio

arXiv:1812.10514

$$R = \frac{\sigma_t}{\sigma_{tbar}}$$



reasonable agreement with all NLO QCD PDF predictions, some PDF discrimination power

Measurement of V_{tb} CKM coupling

arXiv:1812.10514

f_{LV}: potential BSM lepton flavour violation factor

$$|f_{\mathrm{LV}} V_{\mathrm{tb}}| = \sqrt{\frac{\sigma_{t\text{-ch,t+}\bar{\mathrm{t}}}}{\sigma^{\mathrm{theo}}_{t\text{-ch,t+}\bar{\mathrm{t}}}}}$$

result:

$$|f_{\mathrm{LV}} V_{\mathrm{tb}}| = 1.00 \pm 0.08\,(\mathrm{exp}) \pm 0.02\,(\mathrm{theo})$$

very good agreement with SM (expect 1.00)

Differential t channel cross sections

brand new!

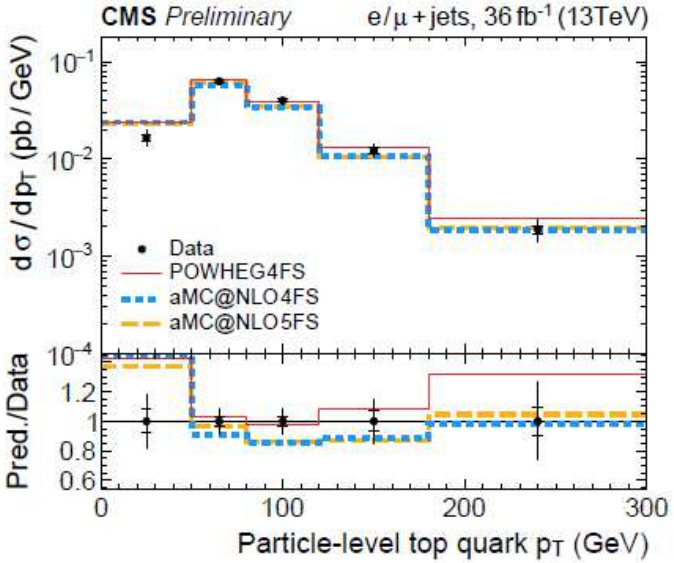
PAS TOP-17-023

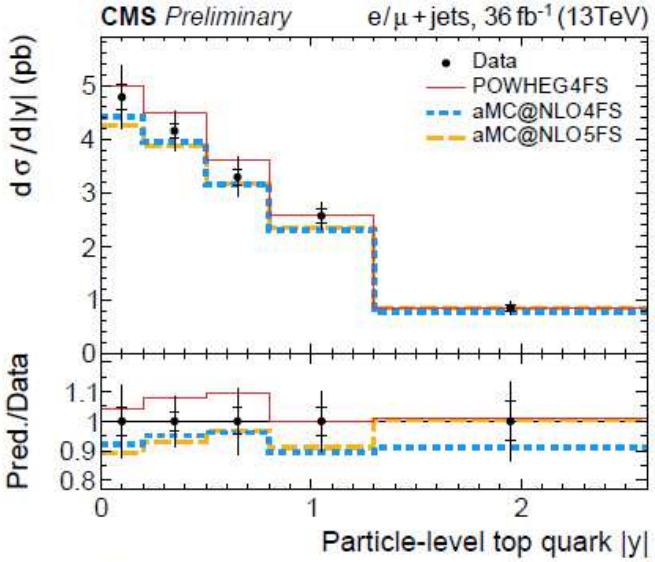
example distributions: particle level, similar plots also available at parton level

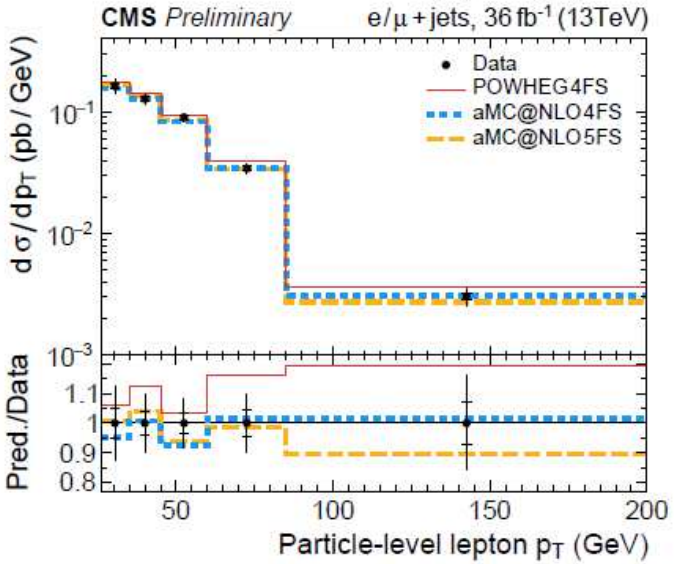
reasonable agreement with NLO+PS QCD theory

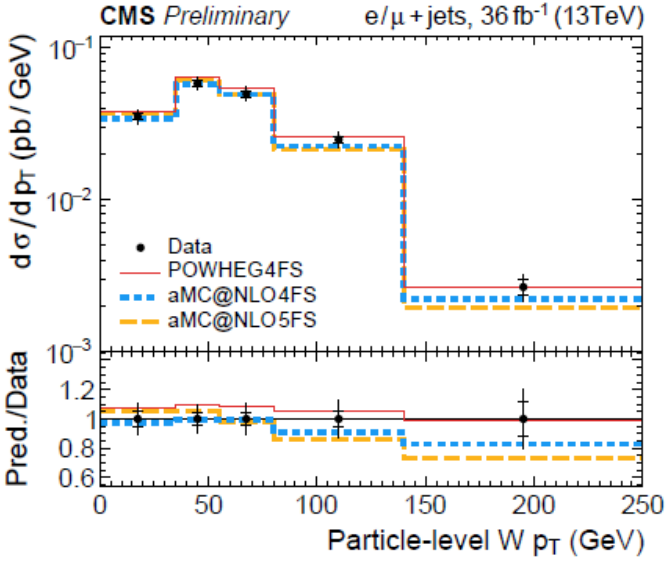
differences 4FS/5FS of similar order as differences data/theory

charge ratio and impact on PDFs
-> talk O. Behnke WG1









Normalized cross sections

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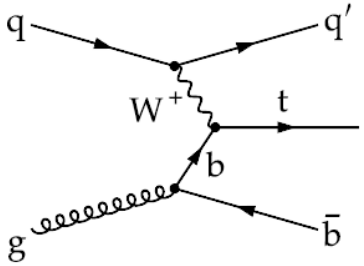
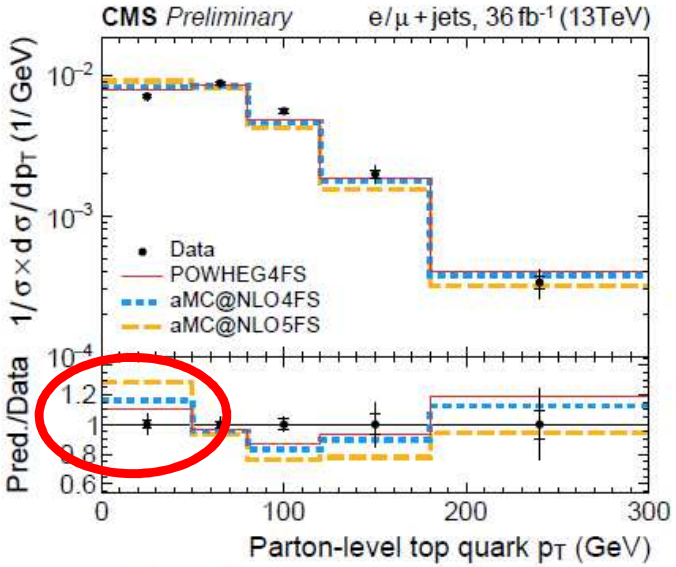
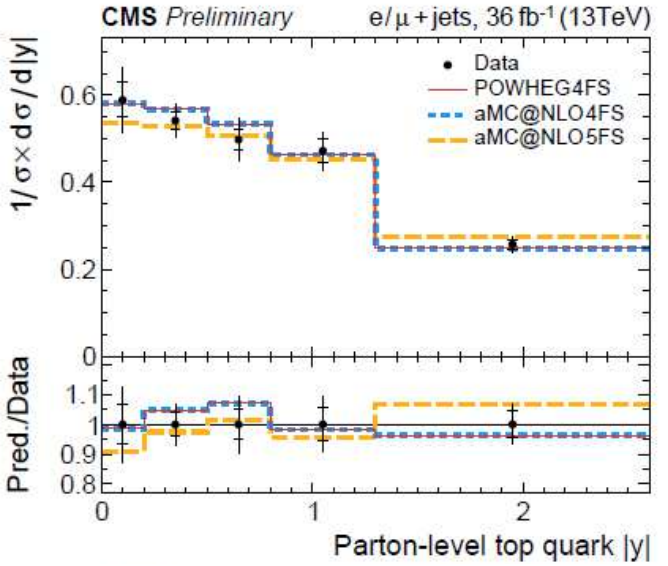
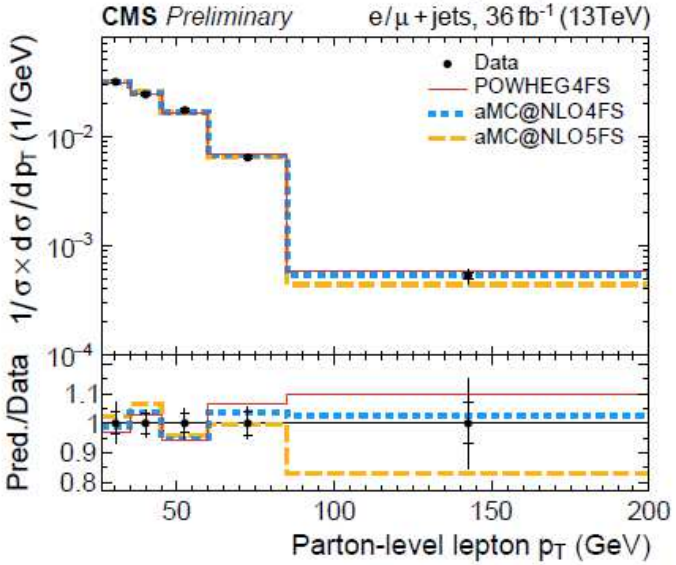
lowest t p_T bin overestimated by theory
(improve PS matching?)

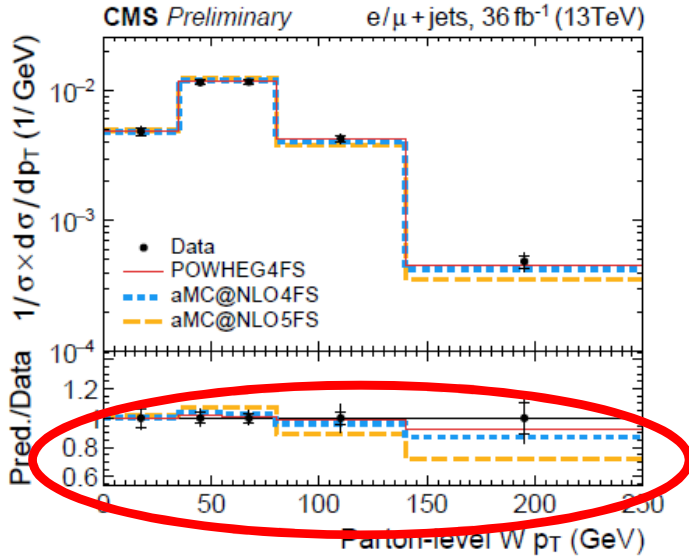


4FS W p_T slope better than 5FS
(better description of 'spectatator' b?)



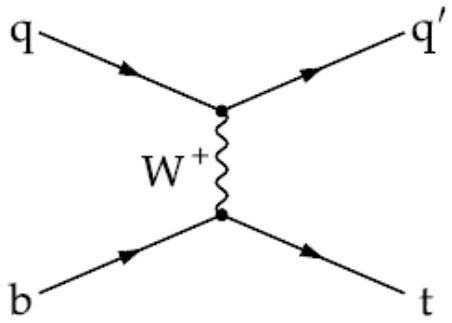






Top quark polarisation

PAS TOP-17-023



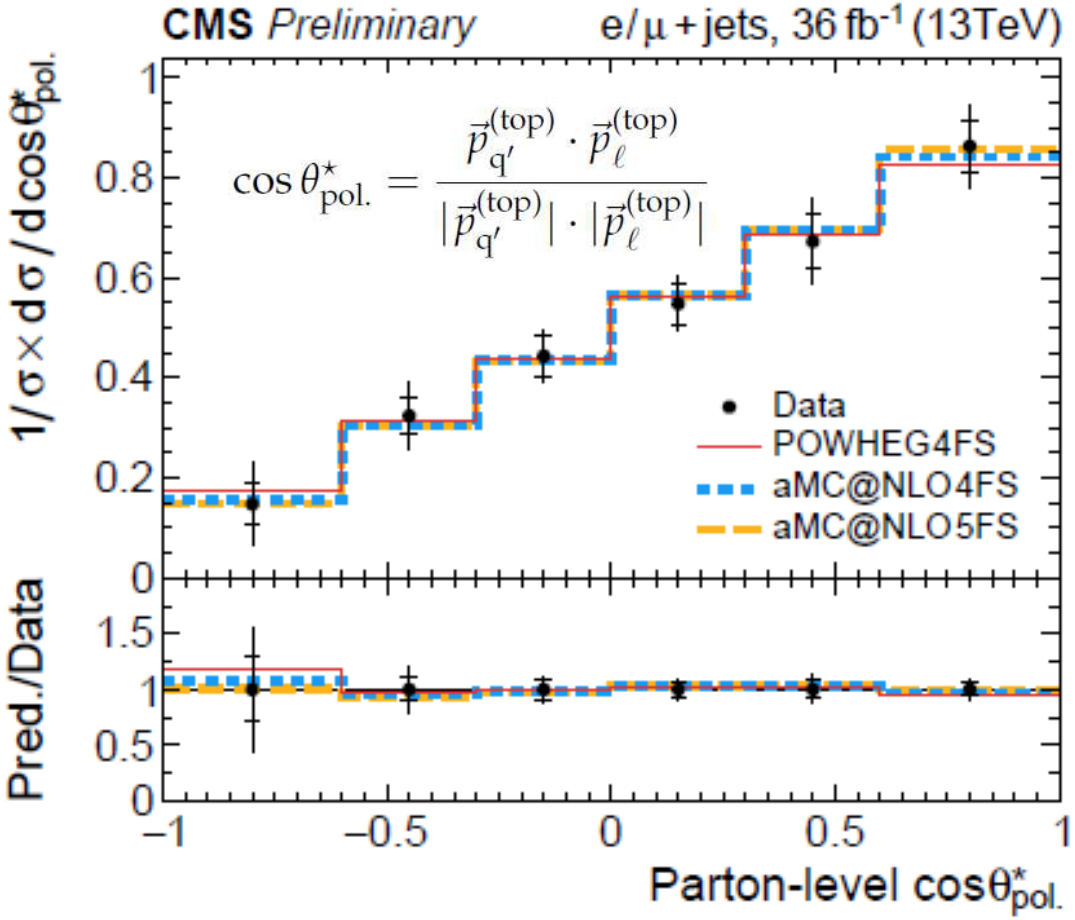
expect spin asymmetry:

$$\frac{\mathrm{d}\sigma}{\sigma \cdot \mathrm{d}\cos\theta^{\star}_{\mathrm{pol.}}} = \frac{1}{2}\left(1 + 2A_{\ell}\cos\theta^{\star}_{\mathrm{pol.}}\right)$$

$$A_{\ell} = \frac{1}{2}P \cdot \alpha_{\ell}$$

top quark polarisation

lepton analysing power



fit result:

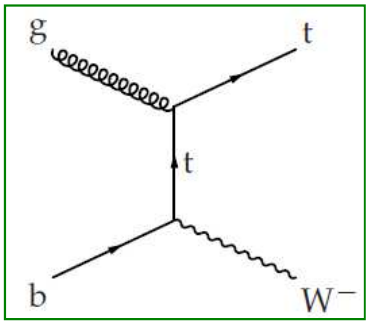
$$A_{\mathrm{e}} = 0.443 \pm 0.048\,(\mathrm{stat{+}exp}) \pm 0.068\,(\mathrm{syst}) = 0.443 \pm 0.083$$
$$A_{\mu} = 0.398 \pm 0.042\,(\mathrm{stat{+}exp}) \pm 0.047\,(\mathrm{syst}) = 0.398 \pm 0.063$$
$$A_{\mathrm{e}+\mu} = 0.439 \pm 0.032\,(\mathrm{stat{+}exp}) \pm 0.053\,(\mathrm{syst}) = 0.439 \pm 0.062$$

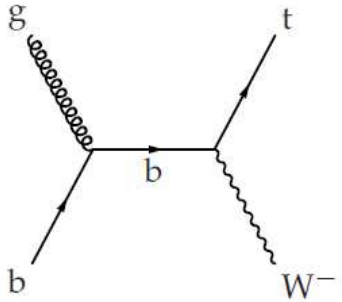
good agreement with SM

V-A (POWHEG): 0.436

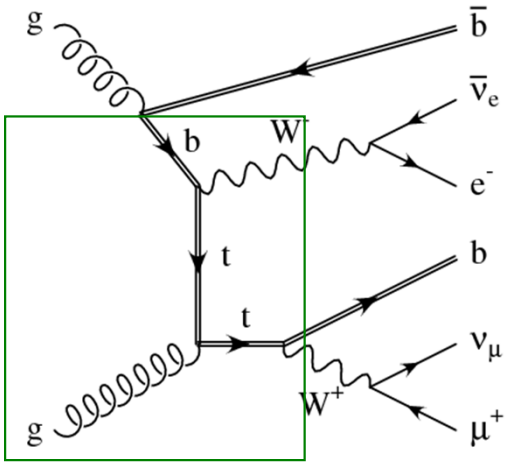
Associated tW production

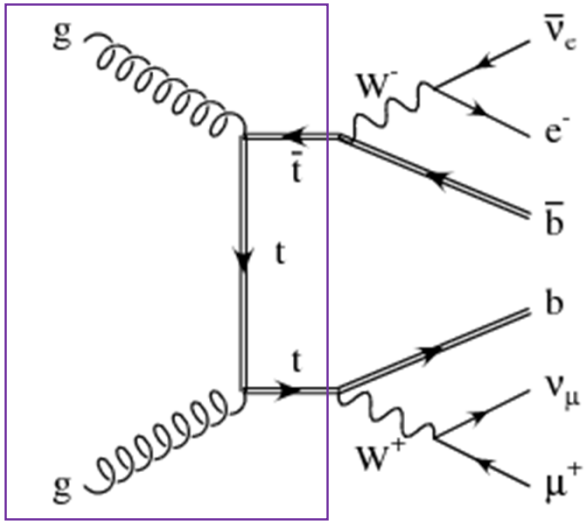
- Study interplay of EW physics and QCD
- Real W emission, LO 5FS





- Interference with inclusive gg->ttbar, LO 4FS or NLO 5FS





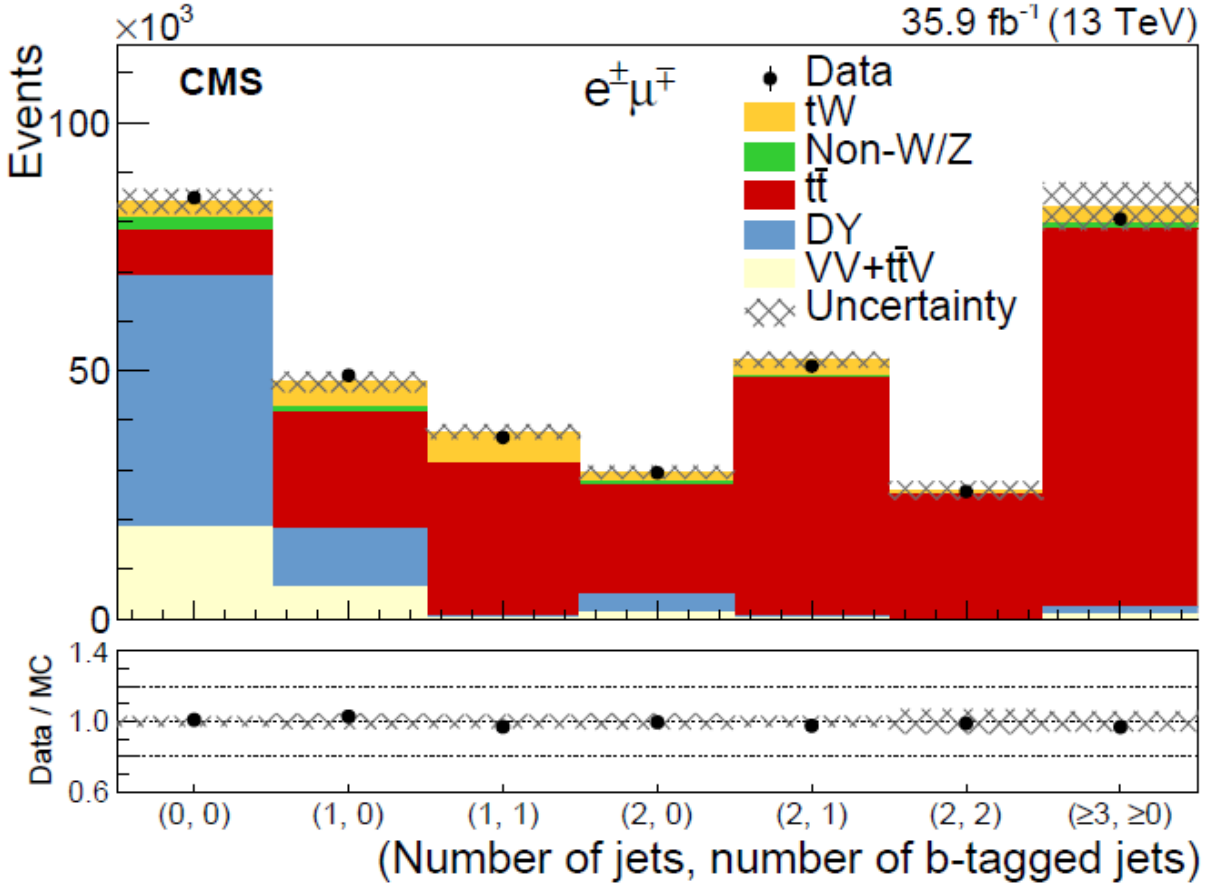
see also
talk Poncelet
this morning

tW total cross section @ 13 TeV

arXiv:1805.07399

Use dilepton (e+μ) channel: one from W, one from t accompanied by b jet and MET (two neutrinos)

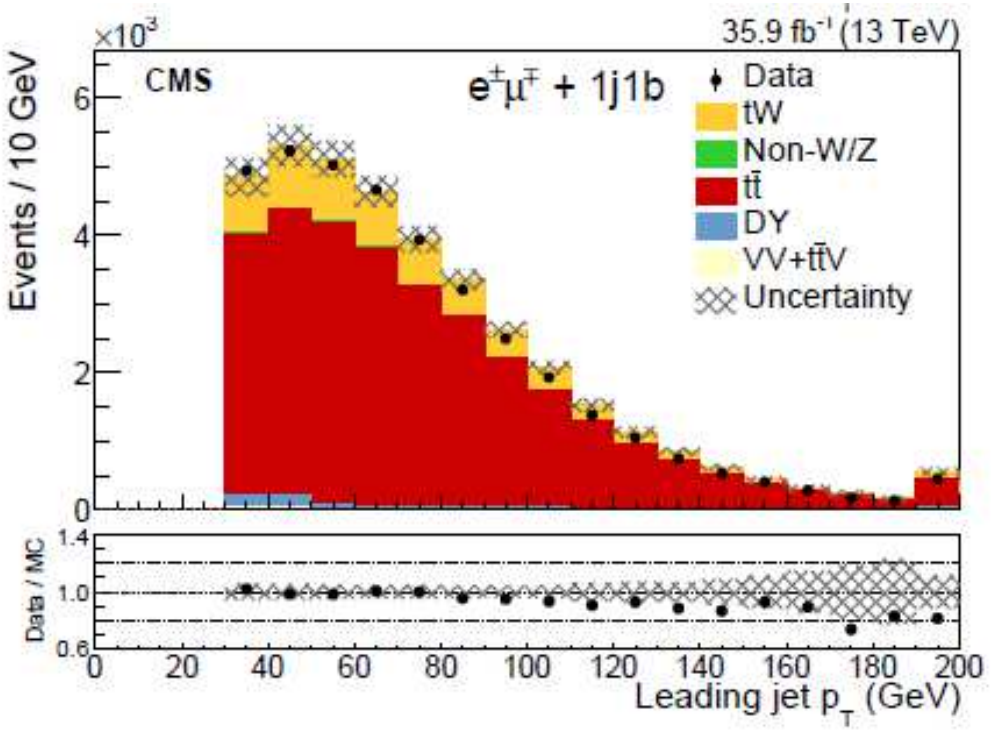
categories:



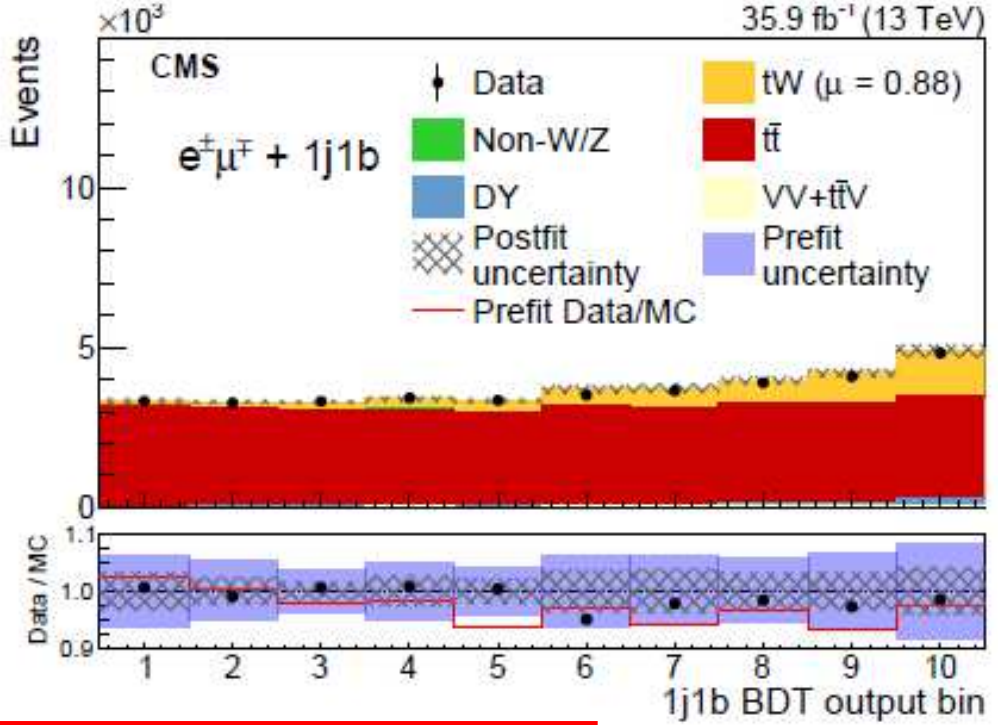
tW total cross section @ 13 TeV

arXiv:1805.07399

Example of BDT input variable



BDT output

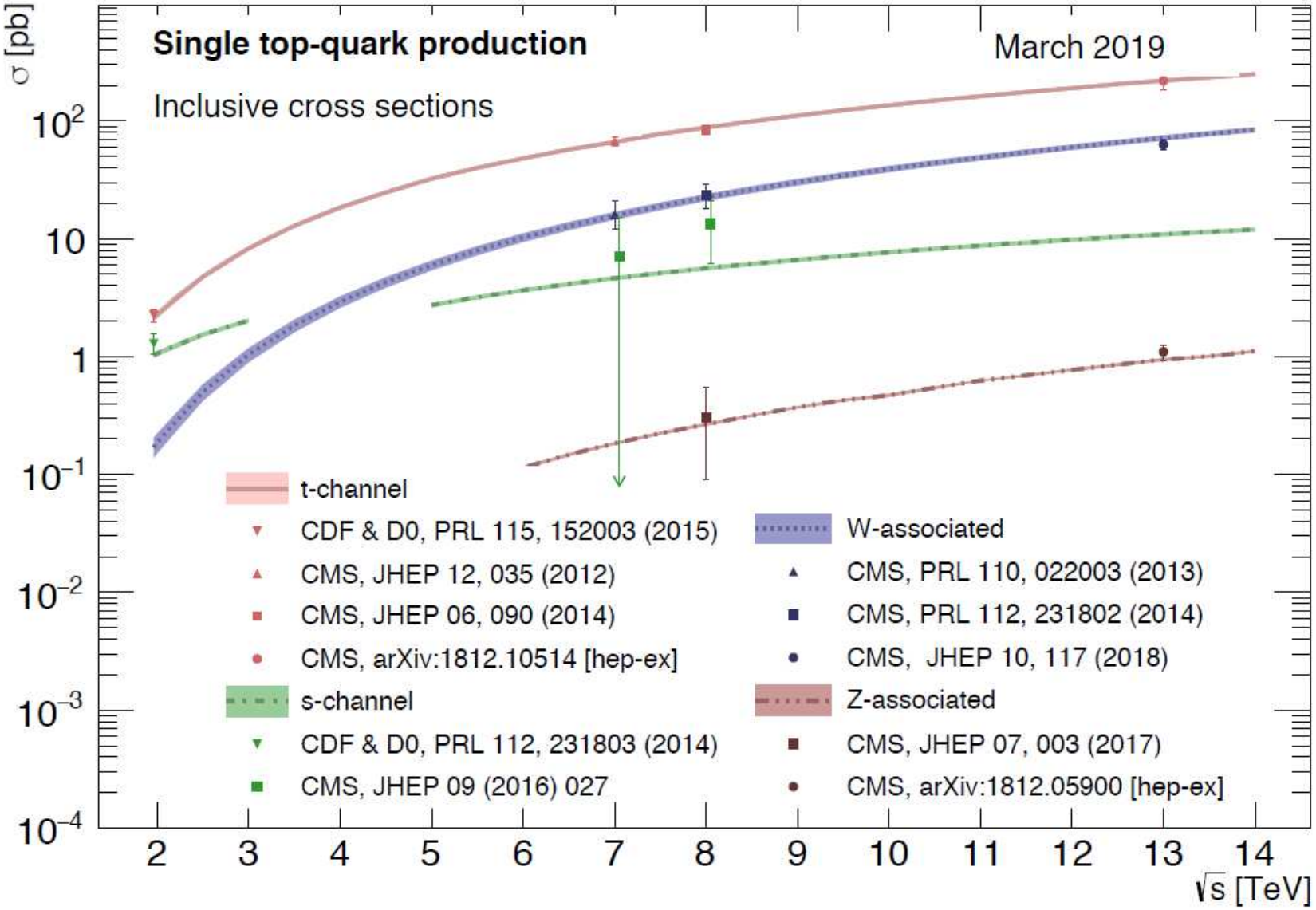


$\sigma(tW) = 63.1 \pm 1.8_{stat} \pm 6.4_{sys} \pm 2.1_{lumi}$ pb

approx. NNLO QCD: $71.7 \pm 1.8_{scale} \pm 3.4_{PDF}$ pb

see also arXiv:1612.07231 (ATLAS, 2015 data, 3.2 fb^{-1})

Inclusive cross section summary plot

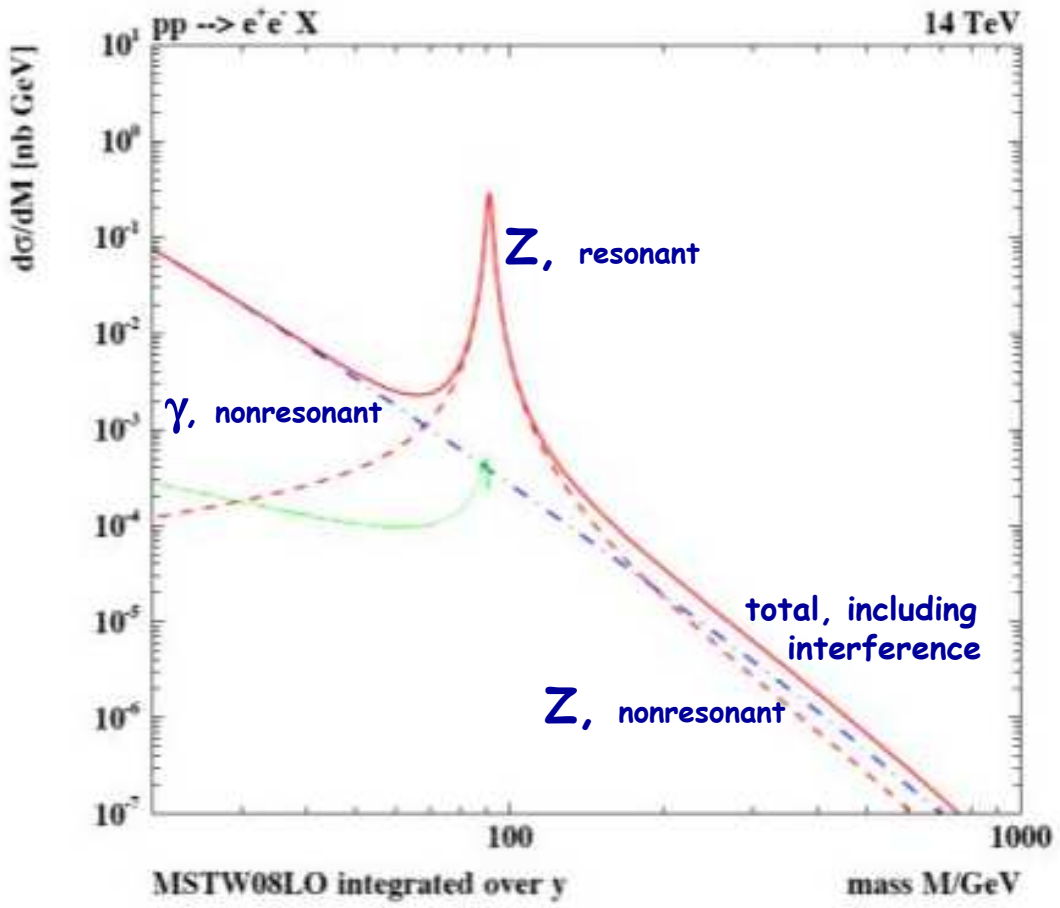


ATLAS results see below

tWb - ttbar interference

analogy: Z/γ* interference,

Drell-Yan, qqbar -> Z/γ* -> leptons



Z <-> t

γ* <-> Wb

(other t resonant)

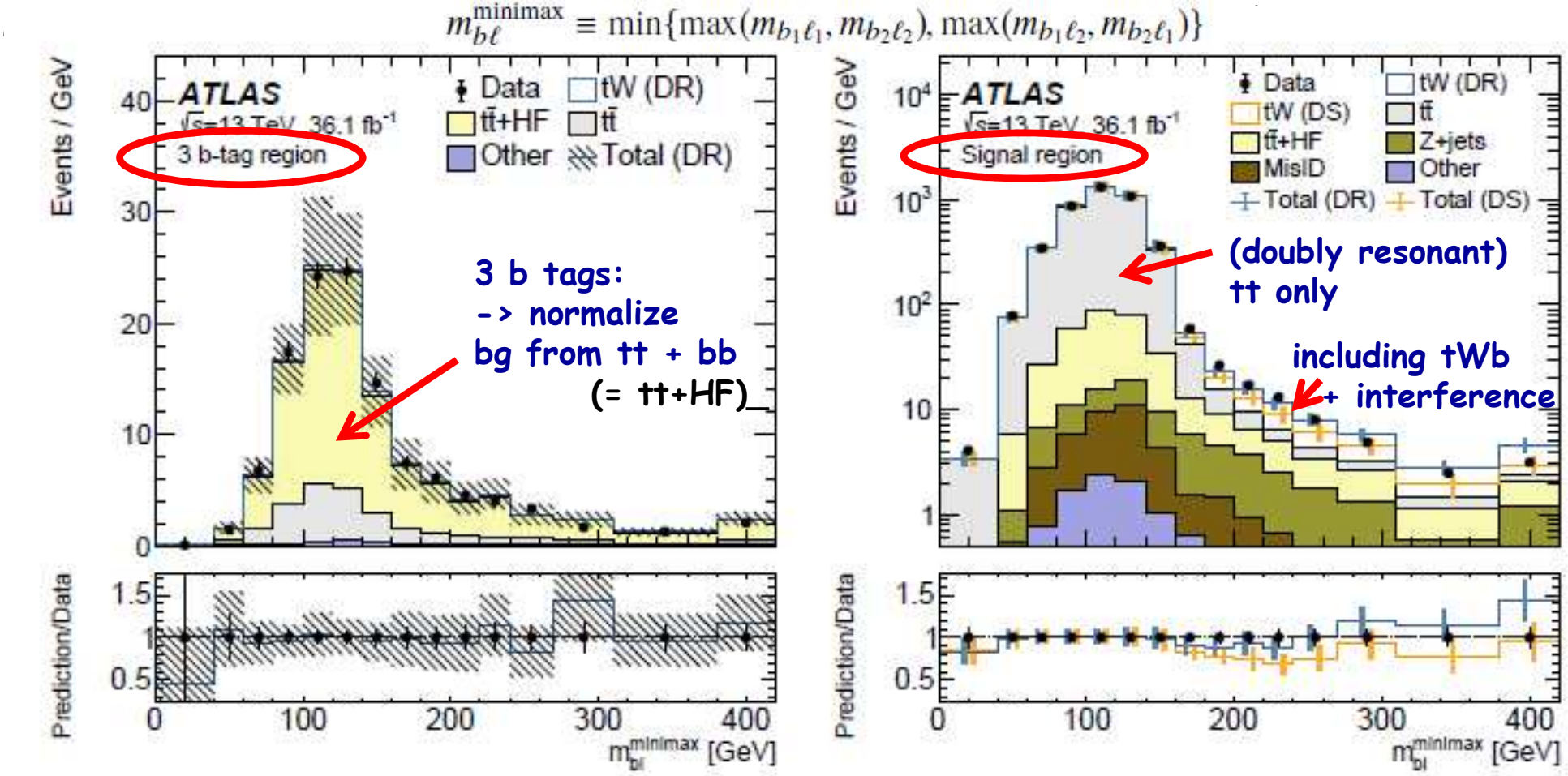
adapted from plot by U.Klein

tt/tWb differential cross section

arXiv:1806.04667

test tWb – ttbar interference

similar signature as for inclusive measurement, use
'best' m(b+lepton) to discriminate resonant and nonresonant states

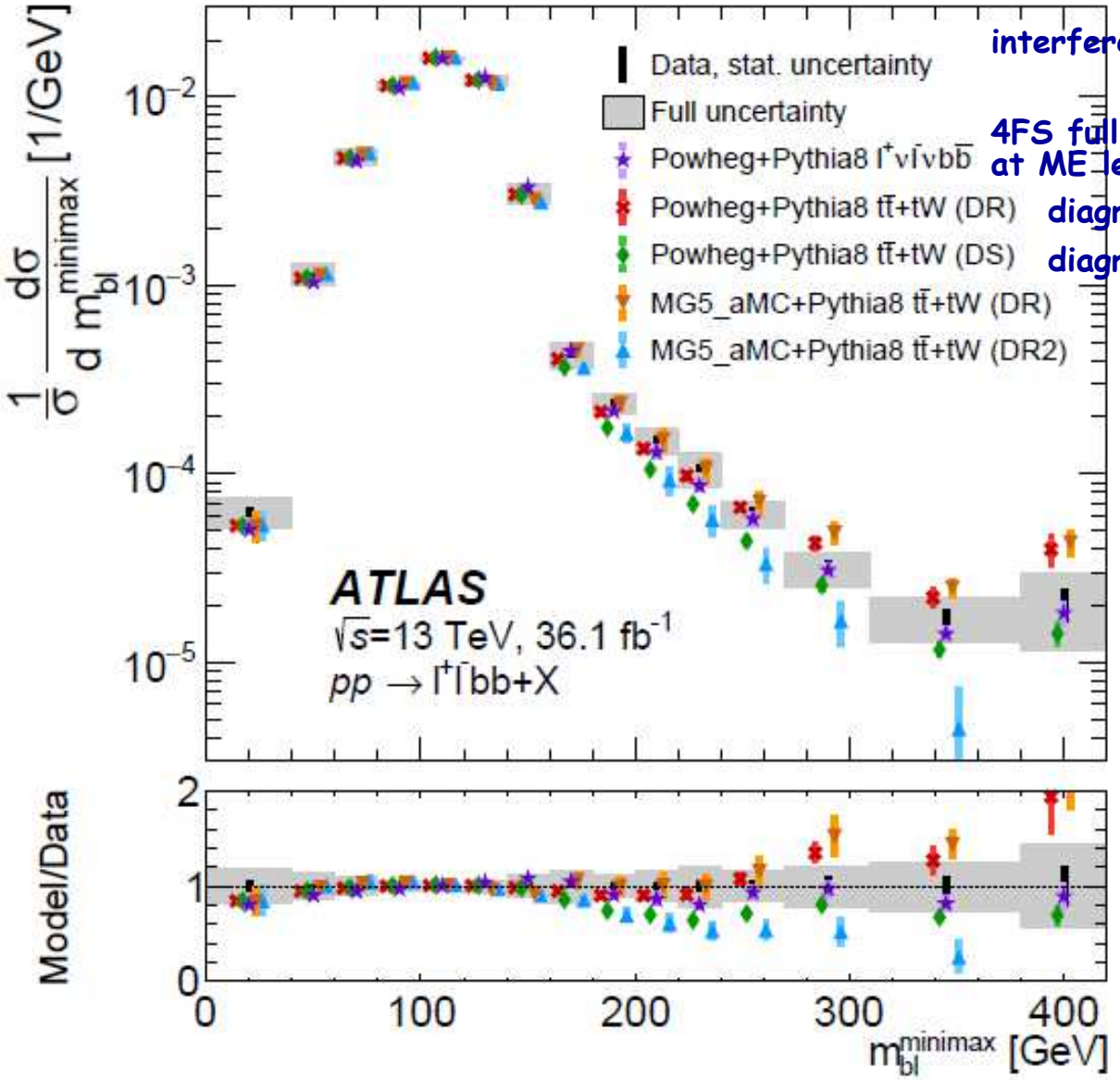


tt/tWb differential cross section

arXiv:1806.04667

interference is important

direct full interference implementation best



interference:

4FS full treatment at ME level

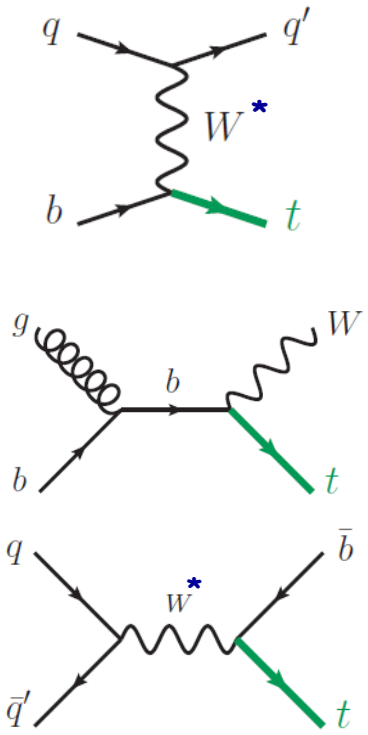
diagram removal

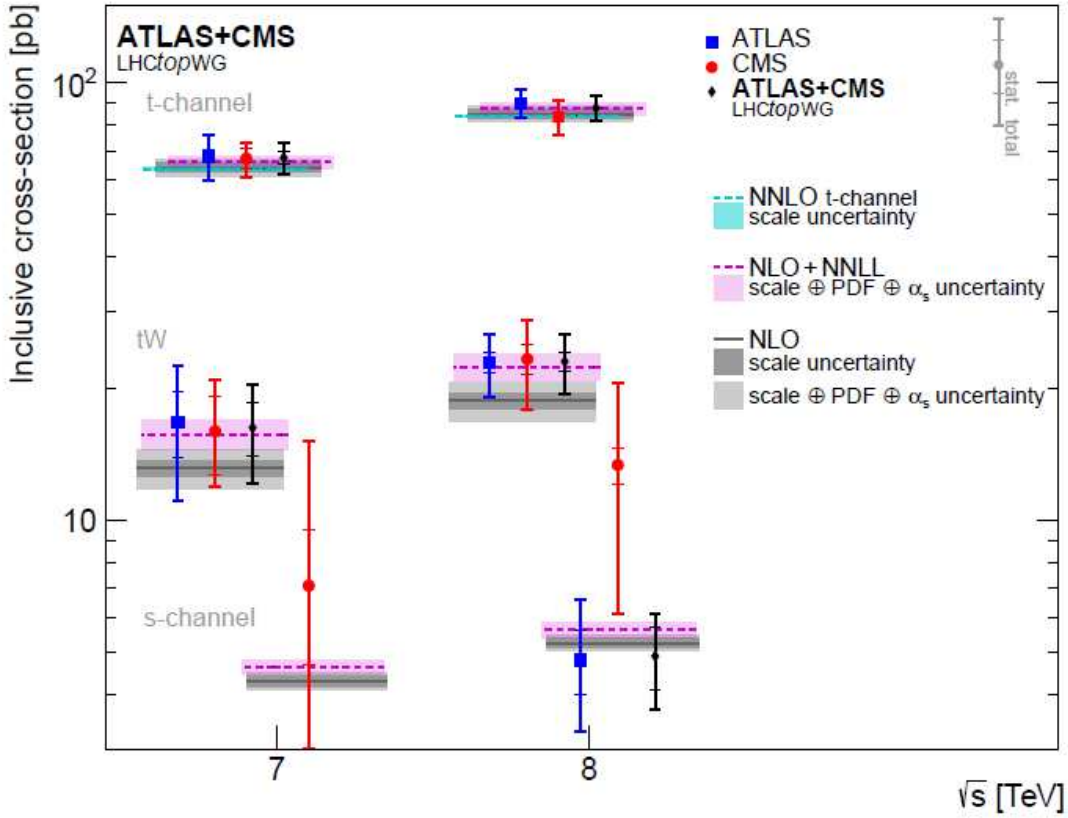
diagram subtraction

Combination of single top cross sections @ 7 and 8 TeV

- **Run 1 combination of 11 ATLAS and CMS results** (references see backup)

  major milestone! arXiv:1902.07158





- **Challenge: properly deal with correlations of systematic uncertainties**
- **All results in good agreement with each other and with NNLO or NLO (+NNLL) QCD + LO EW theory**

Systematic uncertainties

arXiv:1902.07158

Example: t-channel

(a)

$\sigma_{t\text{-chan.}}$, $\sqrt{s} = 7$ 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

(b)

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

significant correlation between ATLAS and CMS results (theory modelling, also see backup)

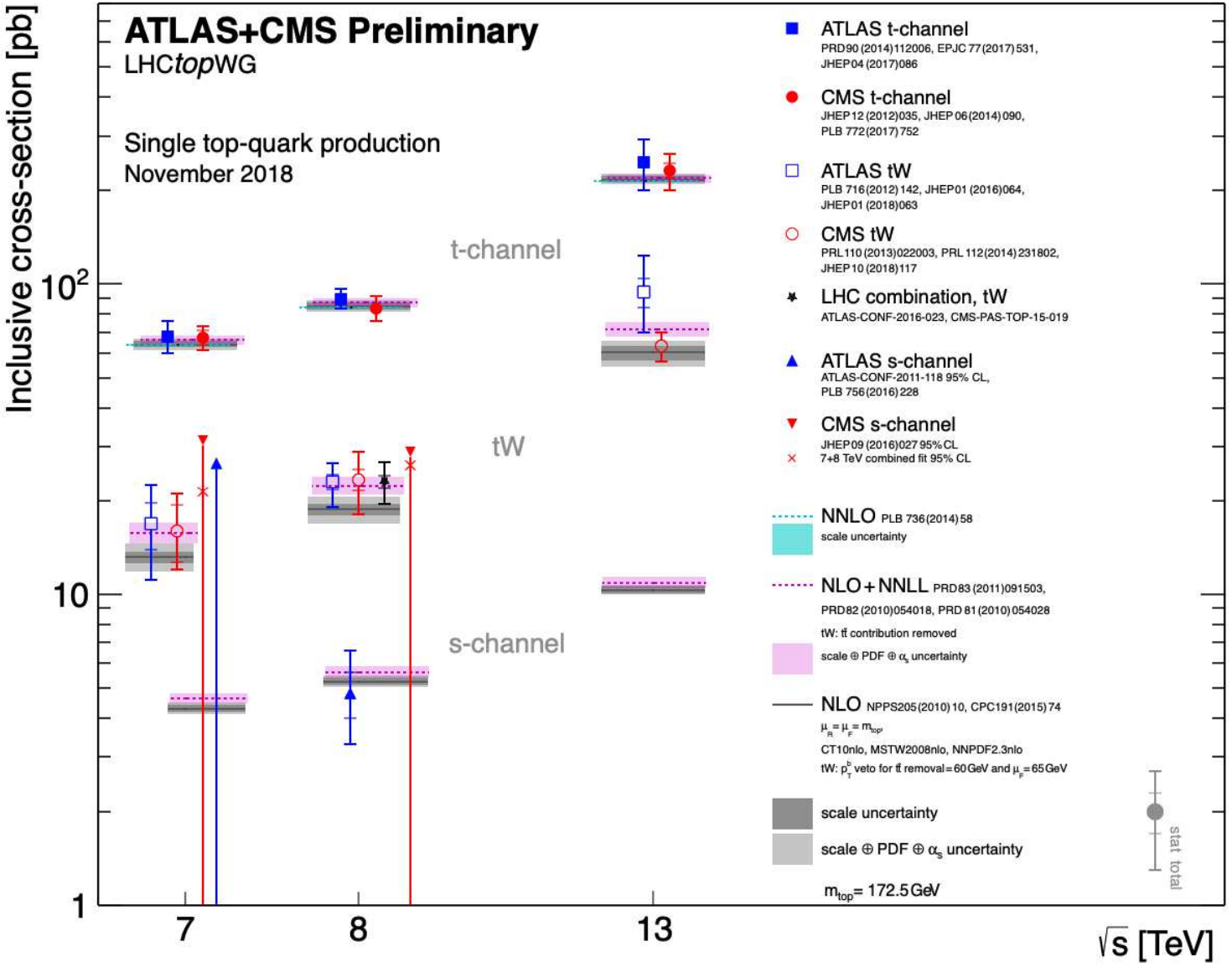
-> total uncertainty improvement < $\sqrt{2}$

ATLAS/CMS Combination

arXiv:1902.07158

comparison to 13 TeV

(status fall 2018)



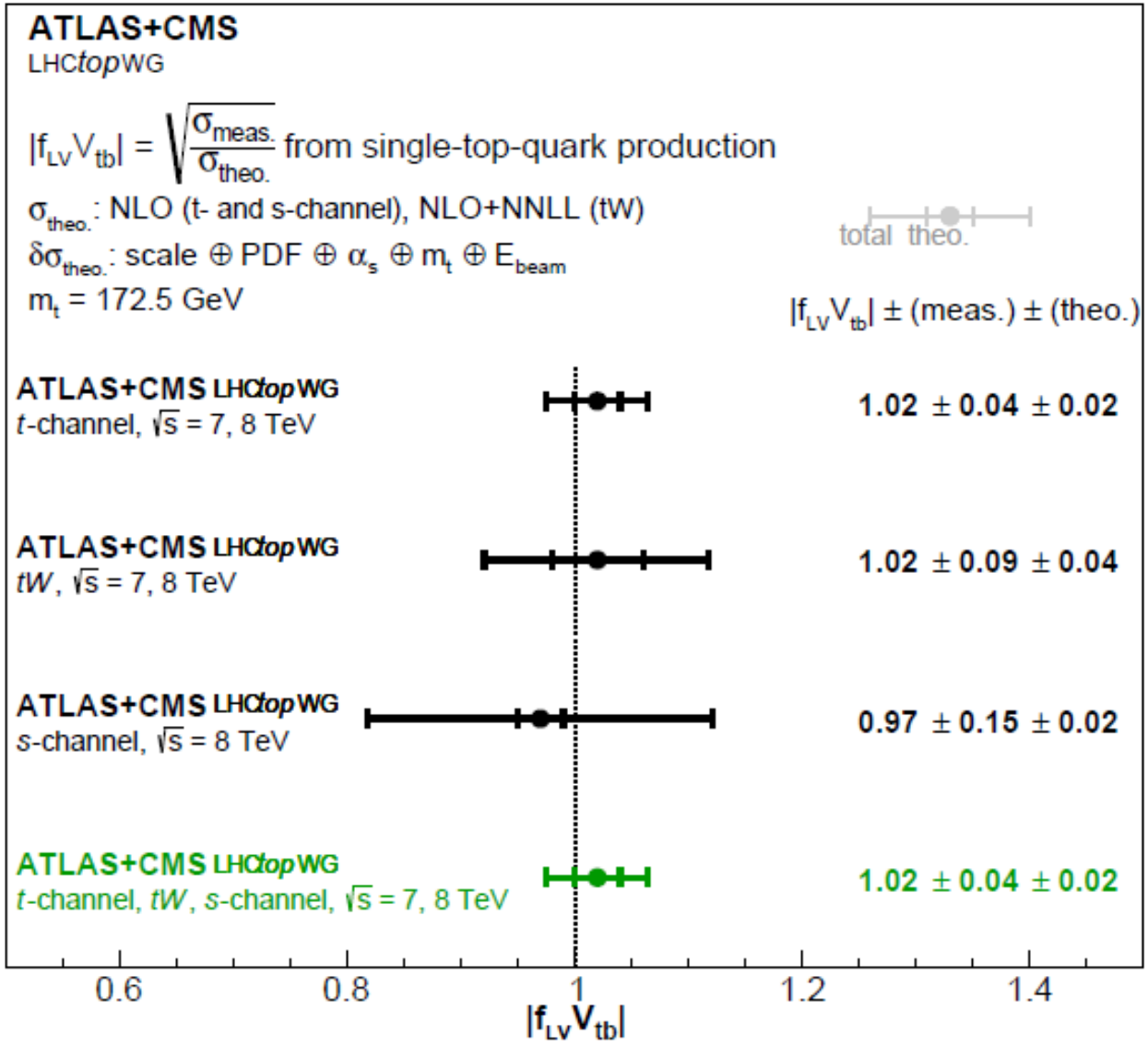
Combination of $|f_{LV}V_{tb}|$

arXiv:1902.07158

$$|f_{LV}V_{tb}| = \sqrt{\frac{\sigma_{t\text{-ch},t+\bar{t}}}{\sigma^{\text{theo}}_{t\text{-ch},t+\bar{t}}}}$$

treat all correlations

best direct measurement of V_{tb} so far

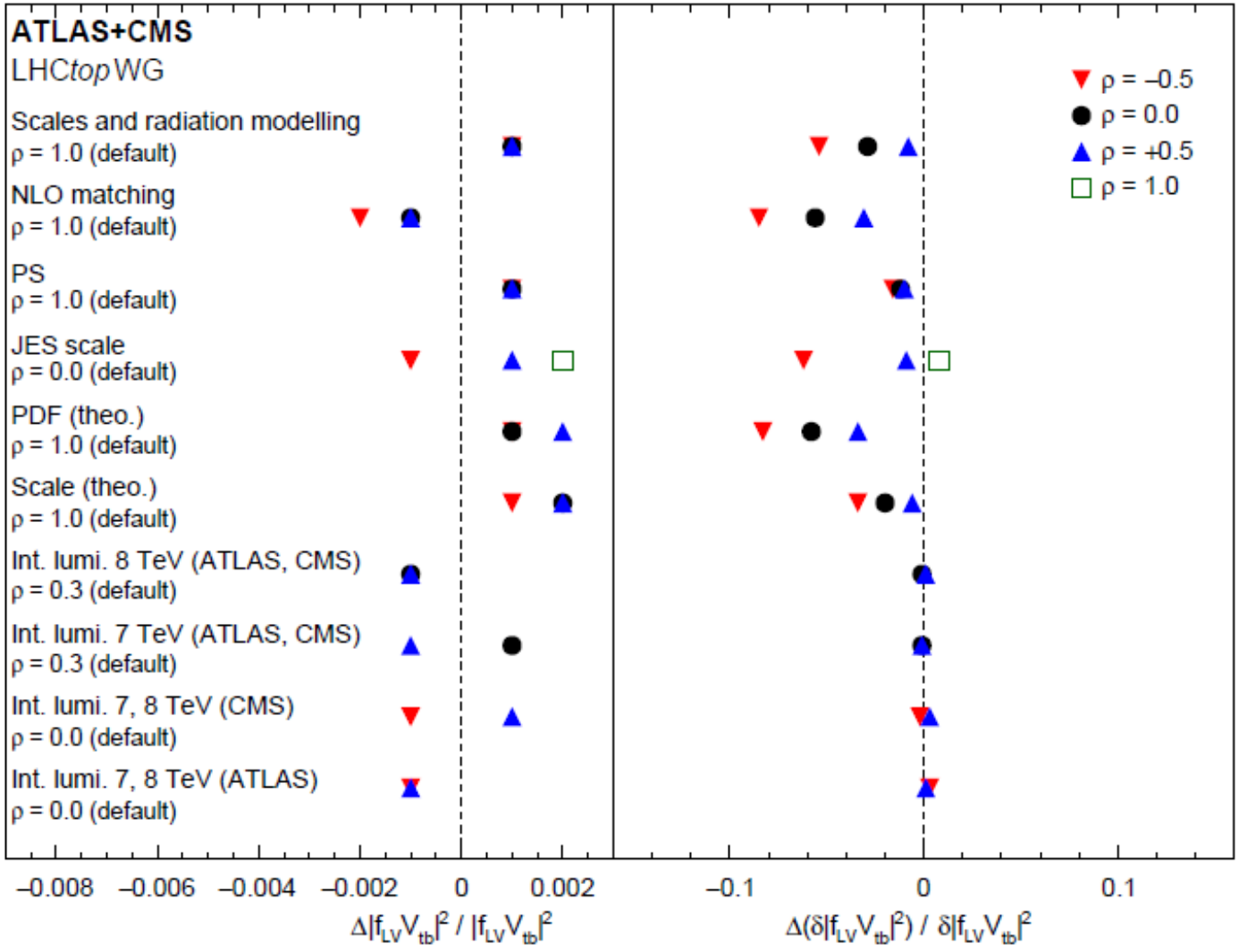


|fLV Vtb|, treatment of systematic uncertainties

arXiv:1902.07158

correlation treatment:

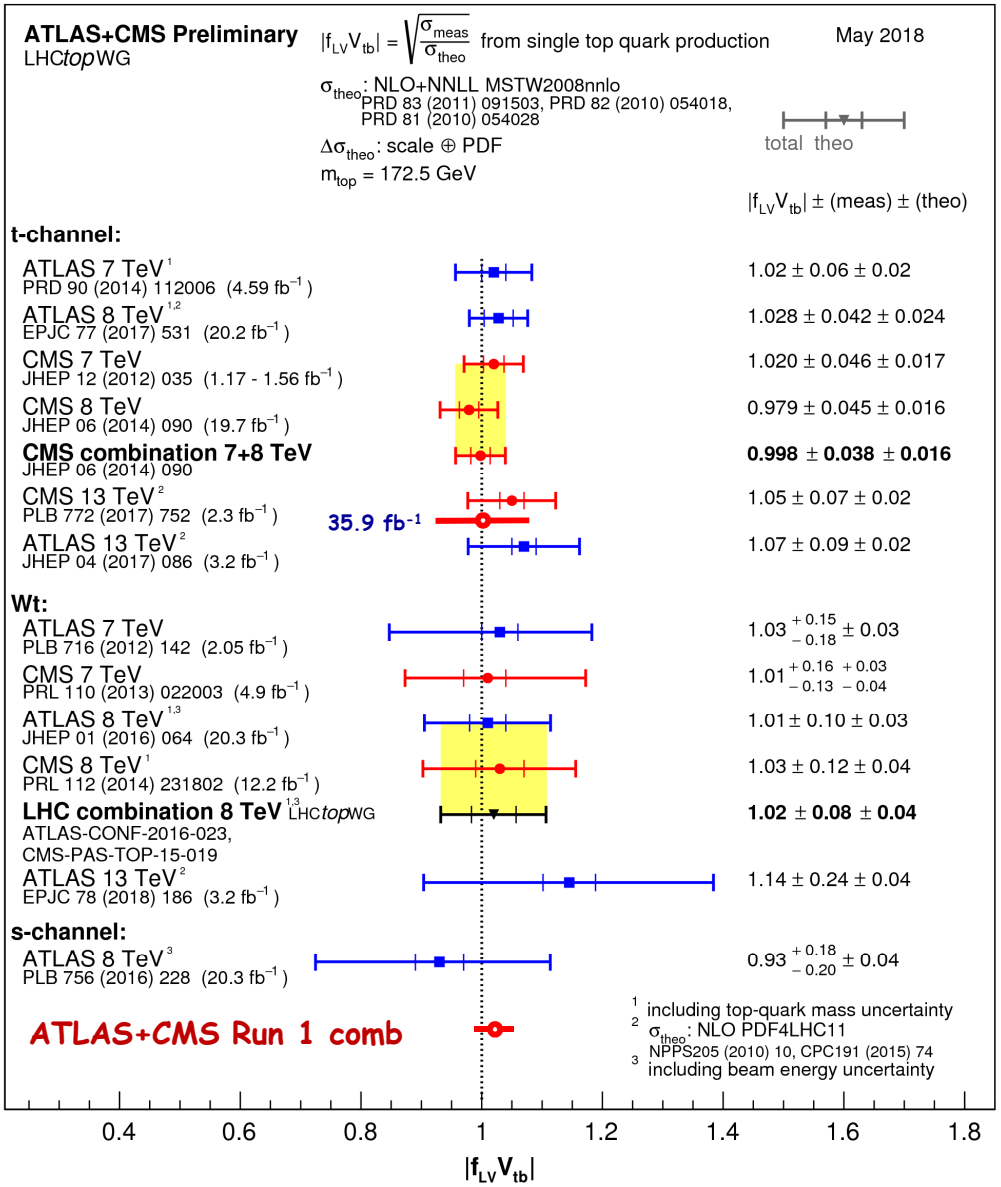
stability tests



-> change of correlation assumptions has negligible impact

$|f_{LV}\,V_{tb}|$, comparison to earlier results

arXiv:1902.07158



best direct measurement of V_{tb} so far

Conclusions

- Measurements of single top quark production at LHC are great tool to test EW theory, QCD and their interference, constrain PDFs (see talk O. Behnke in WG1 session) and measure V_{tb} (check for deviations coming from new physics)
- Single top production has been measured by both ATLAS and CMS at 7, 8, and 13 TeV in the t-, tW-, and s-channel processes.
- Latest differential measurements of t channel at 13 TeV show slight preference for 4-flavour scheme calculations (W p_T), and further theory optimisation potential for low p_T end of single t spectrum. Spin correlations agree with V-A.
- Latest measurements of associated tW production at 13 TeV show good agreement for total cross section.
- Measurement of tWb-ttbar interference in differential tW cross section shows preference for direct implementation of interference at matrix element level.
- Combination of t-, s-channel and tW total cross sections from ATLAS and CMS at 7 and 8 TeV show good consistency, yield (slightly) improved precision and show no deviations from Standard Model expectations.

  Achieve so far best direct measurement of V_{tb} .

Backup

ATLAS and CMS single top combination

References for input data sets:

arXiv:1902.07158

ATLAS Collaboration, *Comprehensive measurements of t-channel single top-quark production cross sections at $\sqrt{s}$ = 7 TeV with the ATLAS detector*, Phys. Rev. D **90** (2014) 112006, arXiv: 1406.7844 [hep-ex].

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ATLAS Collaboration, *Fiducial, total and differential cross-section measurements of t-channel single top-quark production in pp collisions at 8 TeV using data collected by the ATLAS detector*, Eur. Phys. J. C **77** (2017) 531, arXiv: 1702.02859 [hep-ex].

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ATLAS Collaboration, *Evidence for the associated production of a W boson and a top quark in ATLAS at $\sqrt{s}$ = 7 TeV*, Phys. Lett. B **716** (2012) 142, arXiv: 1205.5764 [hep-ex].

CMS Collaboration, *Evidence for Associated Production of a Single Top Quark and W Boson in pp Collisions at $\sqrt{s}$ = 7 TeV*, Phys. Rev. Lett. **110** (2013) 022003, arXiv: 1209.3489 [hep-ex].

ATLAS Collaboration, *Measurement of the production cross-section of a single top quark in association with a W boson at 8 TeV with the ATLAS experiment*, JHEP **01** (2016) 064, arXiv: 1510.03752 [hep-ex].

CMS Collaboration, *Observation of the Associated Production of a Single Top Quark and a W Boson in pp Collisions at $\sqrt{s}$ = 8 TeV*, Phys. Rev. Lett. **112** (2014) 231802, arXiv: 1401.2942 [hep-ex].

ATLAS Collaboration, *Evidence for single top-quark production in the s-channel in proton–proton collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector using the Matrix Element Method*, Phys. Lett. B **756** (2016) 228, arXiv: 1511.05980 [hep-ex].

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treatment of systematic uncertainties

arXiv:1902.07158

example:
t channel
@ 8 TeV

Table 10: Measured cross-sections, uncertainty components, their magnitudes (relative to the individual measurements) and the correlation (ρ) between the ATLAS and CMS $\sigma_{t\text{-chan.}}$ measurements at $\sqrt{s}$ = 8 TeV. Uncertainties in the same row can be compared between experiments, as detailed in the text. The naming conventions follow those of the corresponding experiments.

	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**